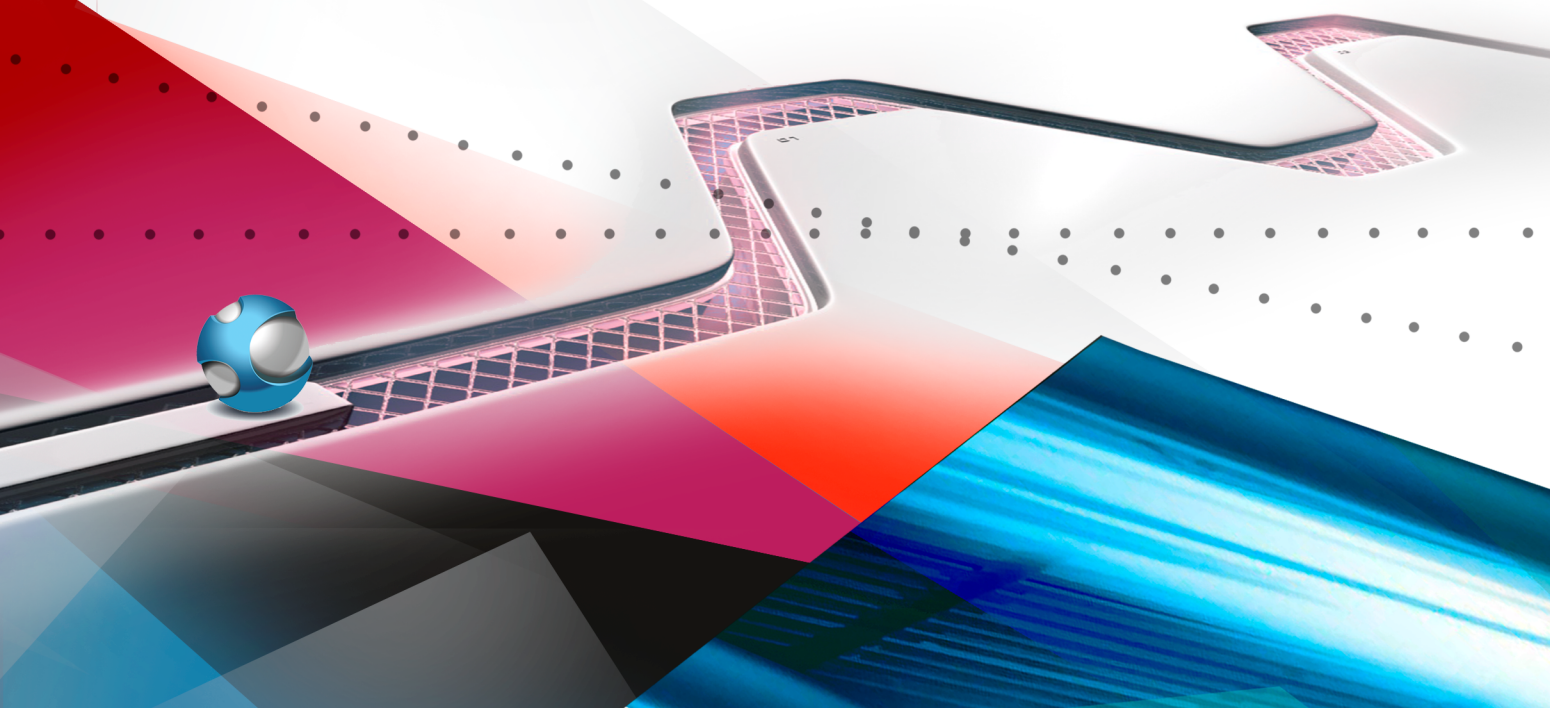
# JINR Long-Term Development Strategy up to 2030 and beyond

Science & Technology



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JOINT INSTITUTE FOR NUCLEAR RESEARCH

# JINR Long-Term Development Strategy up to 2030 and beyond

## Science & Technology

Dubna
2020

# Foreword



With this document, the Joint Institute for Nuclear Research presents the physics part of its Long-Term Development Strategy up to 2030 and Beyond.

Looking onto the many scientific projects worldwide and their long timescales from conception to start of operation, it becomes clear to me that JINR has to look forward several decades into the future in order to be competitive with other scientific facilities in the world. This is why I launched in 2017 the development of a proper strategy for the future of JINR, assuring completion and exploitation of the excellent JINR projects presently under construction, and looking decades into the future.

It gives me great pleasure to see that the Joint Institute for Nuclear Research presents in this document its Long-Term Development Strategy for a promising and ambitious scientific future.

This Scientific Long-Range Plan is the fruit of more than two years of intense discussions of JINR scientists in a concerted action by the whole JINR physics community and international experts.

In 2017, I initiated the establishment of an International Working Group (IWG) of outstanding scientists who are worldwide recognized experts in their field of research. Together with this group, we determined the subfields of modern science to be addressed in the future at JINR. Seven working sub-groups have been established spanning the areas of basic and applied science and technologies: Low-Energy Nuclear Physics, Relativistic Heavy-Ion and Spin Physics, Particle and High-Energy Physics, Neutrino and Astro-Particle Physics, Condensed Matter and Neutron Nuclear Physics, Radio- and Astrobiology, Theoretical Physics, Information Technologies & High-Performance Computing.

The members of each working sub-group were selected to provide a broad representation of specific topics in the subfields. The working sub-groups were given the charge to delineate the most exciting physics in their subfields, to highlight recent achievements, and to discuss the future perspectives.

Draft reports from the working sub-groups were presented and discussed at a number of meetings of the JINR Science and Technology Council and of the JINR Scientific Council (SC) in 2019. The Editorial Board was established in order to generate an integrated balanced document.

Based on this work, the following Scientific Long-Range Plan (SLRP) emerged where new facilities, those already under construction, and upgrades are presented. After an Executive Summary, the integral document features the development of the research in several important fields of science JINR has chosen to work in, with the intention to be at the forefront of these fields in the next decades.

In February 2020, the SC discussed thoroughly the draft presented by IWG. Preceding the meeting of the SC, preliminary reports of the working sub-groups were posted on the JINR website. The SC recommended that the JINR Committee of Plenipotentiaries (CP) approve the SLRP. The Editorial Board implemented changes and suggestions from the members of the SC made during the meeting. In June 2020, the CP approved the SLRP and charged the Directorate to continue the strategic planning towards development of the next JINR 7-year plan.

The SLRP of JINR is and will be integral part of the European Strategy for Nuclear Physics, of the European and Worldwide Particle Physics Strategies, as well as of Global Strategies of Astro-Particle Physics, Biophysics, and Neutron Research.

Furthermore, the Institute will take all measures for strengthening its expertise in latest technologies, e.g., in micro-electronics, ASIC-chip design and detector design, as well as in material research and accelerator technologies.

Large efforts are planned for the educational and training program to assure continuous expertise and know-how needed for meeting the scientific and technical challenges ahead.

With this spirit, JINR can move forward as one of the largest basic research centers of the world.

The JINR Directorate is very grateful for this intense, fruitful and honest interaction between JINR scientists, their partners in JINR member states and world leading scientists, which helped formulating an ambitious vision for the medium- and long-term future of JINR. I am especially pleased to see the many young scientists who have contributed to this SLRP with ambitious goals and projects.

I very much hope that this plan will convince the JINR member states to seek avenues for accomplishing the objectives outlined in the SLRP.

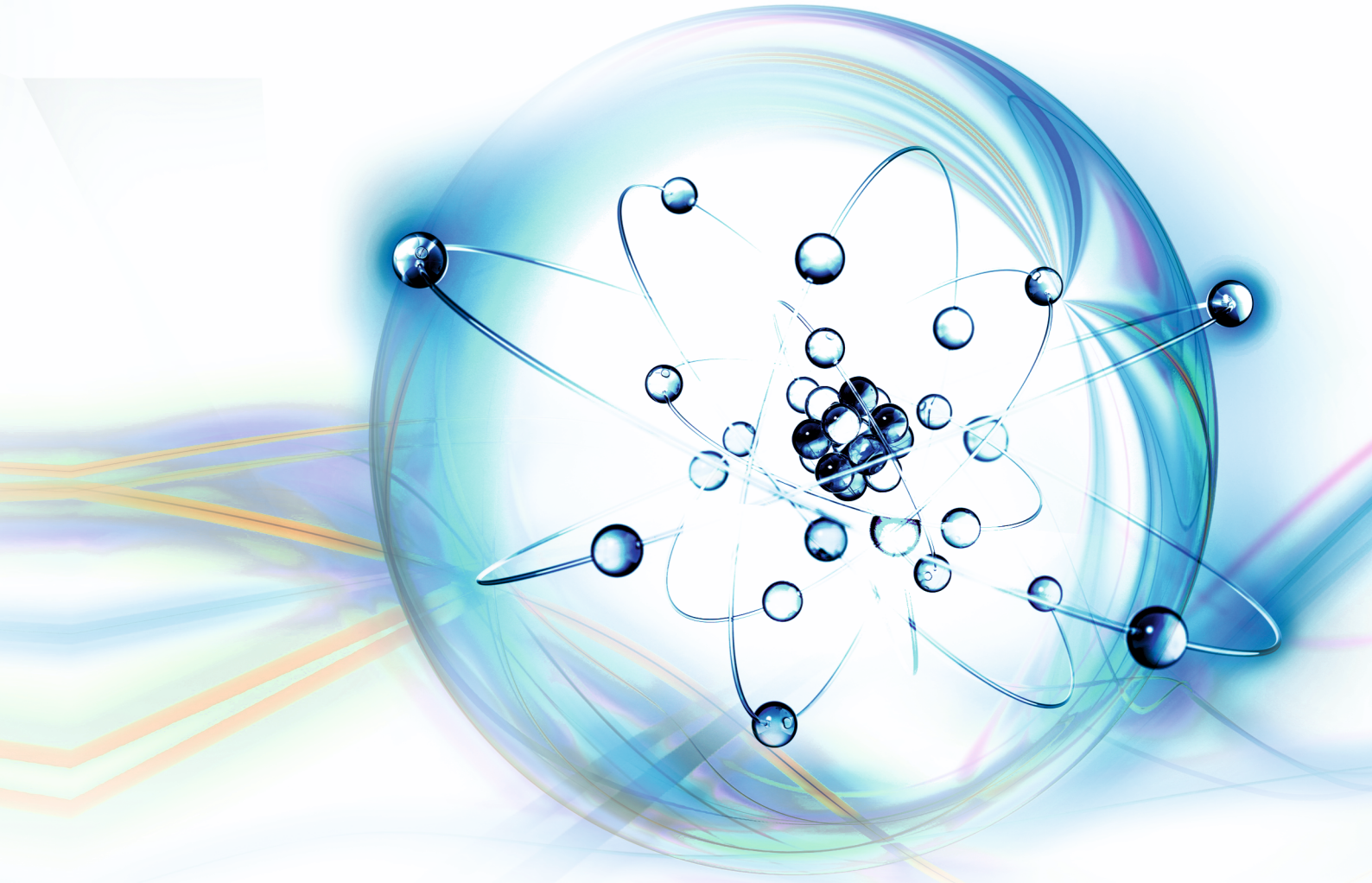


*Victor MATVEEV*
JINR Director



JINR Long-Term Development Strategy up to 2030 and Beyond

# Executive Summary



## Preamble

The strategy for further development of JINR (till 2030 and further on) as an international intergovernmental scientific research organization is based on the Charter-defined main objective of JINR, which is to unify the efforts, scientific and material potentials of the Institute member states for investigations of the fundamental properties of matter.

The goal of this Long-Range Plan is to assure that JINR stays attractive for the JINR Member States (scientists, engineers, technicians and students, member state governments), as well as for the international community of scientists in the coming future. This strategy asks for consolidation and strengthening of the unique JINR status as one of the few major international organizations where basic research has been and is carried out successfully and effectively at the world's top level in an unprecedented wide range of important scientific directions during the last 60 years.

This report on the Strategy for a Long-Range Plan is the fruit of intense discussions of JINR scientists with worldwide recognized experts of their research domain. Workshops and meetings took place where ideas and plans were discussed and evaluated. The JINR directorate is very grateful for this intense, fruitful and honest interaction between JINR scientists, their partners in JINR member states and world leading scientists, which helped formulating a vision for the medium- and long-term future of JINR.

The JINR Strategic Long-Range Plan sees a vigorous determination of this Institute to stay at the forefront of Science in the chosen fields of Basic Research. This plan is and will be integral part of the European Strategy for Nuclear Physics, of the European and Worldwide Particle Physics Strategies, as well as of Global Strategies of AstroParticle Physics, Biophysics, and Neutron Research.

Based on this work, the following plan emerged where both new facilities and those already under construction have been positively evaluated, such as the

- Flagship facility *Super Heavy Element Factory*,
- Flagship facility *NICA* with its fixed target program and the collider mode for Heavy Ion collisions,
- *NICA facility for Spin Physics* with polarized beams,
- Flagship neutrino telescope *Baikal-GVD*,
- New *Pulsed Neutron source DNS-IV*, based on a high-intensity pulsed neutron reactor IBR-3 with Np-237 core,
- Irradiation facilities for material and biophysics and radiation biological experiments,
- New *Rare Isotope Facility DERICA*,
- New *Biomedical Research Center for Proton Therapy*,
- Continuous expansion of "Govorun" supercomputer and creation of a dynamically growing IT platform, which responds to the rapidly developing IT world.

JINR has long participated actively in forefront external experiments off-site, in Heavy-Ion Physics, Particle Physics and Neutrino Physics. The proposed plan foresees a continuation of participation in experiments at accelerator centers around the world (CERN, BNL, DESY, FAIR, GSI) and Neutrino experiments that provide unique conditions to perform studies in the fields of high-energy heavy-ion physics and spin physics. However, the key factor must be a **mutual benefit** from the exchange of data, of new scientific technologies and of theoretical know-how. JINR participation will depend on the **discovery potential** of the experiments and of JINR researchers playing a **leading role**. Special recognition is given to the strong collaboration of JINR – CERN and JINR – international FAIR/GSI facility in Germany on the detector, accelerator and IT projects, benefitting strongly all three institutes.

## Executive Summary

Despite of many hard years in the past, JINR succeeded to play an important part in the pursuit of knowledge at the forefront of Science. A successful future of JINR should be based on JINR's unique traditions and its selection of scientific research directions at the forefront of basic research, in a spirit of international collaboration and competition and with the openness to structural and methodical changes in multidisciplinary collaborations.

As outlined in this report, a great expertise and knowledge has been accumulated in the Laboratories of JINR during the last decades. Although collaboration between the Laboratories was always a highly important factor for development of new scientific directions and particular projects at JINR, the exchange of expertise and knowledge between



Veksler and Baldin Laboratory of High Energy Physics



Dzhelepov Laboratory of Nuclear Problems



Bogoliubov Laboratory of Theoretical Physics



Frank Laboratory of Neutron Physics



Flerov Laboratory of Nuclear Reactions



Laboratory of Information Technologies



Laboratory of Radiation Biology

These laboratories are the research pillars JINR is based on

the JINR Laboratories must be strengthened by increased cross communication between them and aligned coherently for meeting new challenges of Science and for staying competitive in the world. The planned multidisciplinary large-scale projects of JINR in several research areas, presented in this report, are the best testimony for that necessity and for the existing willingness of the JINR staff to implement the related priorities and strategic developments.

However, looking at the new ambitious projects foreseen at JINR like future projects at NICA, rare isotope facility DERICA and at the NuPECC Long Range Plan 2017, Update of the European Strategy for Particle Physics by the European Strategy Group 2020, there are two scientific/technical fields which require the creation of new centres for meeting the challenges of advanced instrumental detectors and novel accelerator technologies, as well as modern digital and information approaches:

a) New JINR Centers of Competence for Sensors/Detectors and Micro-electronics must be created, in order to bring JINR expertise up to international standards in these fields and to eliminate political influence in the progress of JINR projects. R&D of gaseous or solid-state sensors/detectors, at reactors, cyclotrons, synchrotrons, colliders and in cosmic ray detector installations of largest size will benefit immensely from such a center. CHIP design and novel detector design will be possible at JINR. With the existing irradiation facilities at JINR, this group can meet the demand of radiation-hard detector and electronic system development of all sizes. This center must have close ties to LIT in order to become leading in modern digital and information approaches.
b) A new JINR Center of Competence for Accelerator Science and Technology must be created, which covers the wide areas JINR scientists will be working in: from keV's to GeV's, and very high energy ion beams, electron beams from keV's up to TeV's, from cyclotrons, linacs, synchrotrons to new modern accelerator technologies, coupled to modern digital and information approaches. There is plenty of expertise in the different laboratories, and the new center will coherently house all that, and allow the JINR with its ambitious goals to actively participate in Global research facilities.

With this spirit and the newly created Centers of Competence for Sensors/Detectors and Micro-electronics and for Accelerator Science and Technology, JINR can move forward as one of the largest basic research centers of the world.

The program of the long-term development of JINR outlined in this report must ensure attractiveness in all possible aspects — highest-quality science, education, innovations, atmosphere of mutually beneficial scientific creativity, comfortable and secure living conditions, etc. The JINR member states should see clear advantage and benefit from integration of their financial and human resources within JINR to participate in research activities they could not do or afford alone.

JINR has chosen to work on several important fields of Science with the intention to be at the forefront of all of these selected fields.

Most research is being pursued in experiments at the JINR site, others require participation in international collaborations off-site. Here is the list of research topics pursued by JINR today and planned for the future:

- Low-Energy Nuclear Physics,
- Relativistic Heavy-Ion and Spin Physics,
- Particle and High-Energy Physics,
- Neutrino and Astro-Particle Physics,
- Condensed Matter and Neutron Nuclear Physics,
- Radio- and Astrobiology, Nuclear Medicine,

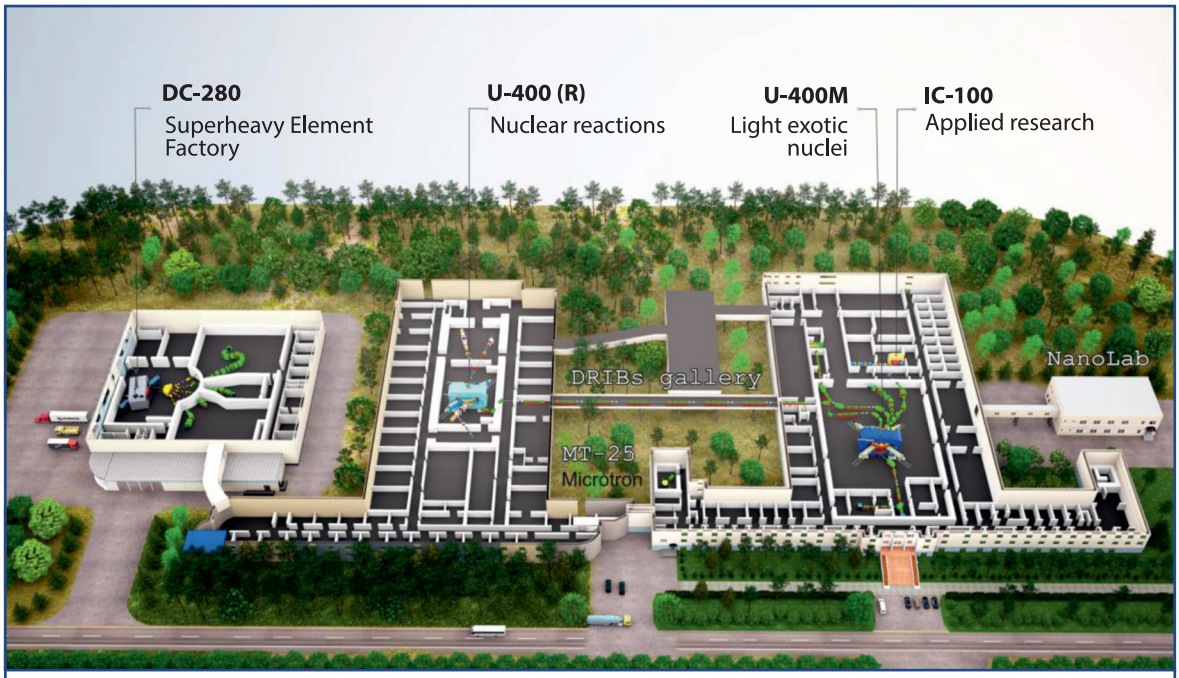
- Theoretical Physics,
- Information Technologies & High-Performance Computing.

## Low-Energy Nuclear Physics

Since its foundation and up to now, the main direction of scientific research of the **Flerov Laboratory of Nuclear Reactions (FLNR)** of JINR has been and still is the worldwide recognized synthesis of new elements of the Mendeleev Periodic Table, the study of their properties, via nuclear spectroscopy (α-, β-, γ-spectroscopy) and via chemical analysis.

The pursuit of this research will be the main part of FLNR's program for the next decade: looking for the limits of the existence of nuclear matter by focusing on the boundaries of the island of stability of Super Heavy Elements (SHE), the hypothetical region of the nuclear map where long-lived SHE isotopes could be found. For that endeavour, a **SHE Factory** is being constructed based on the DC-280 heavy-ion cyclotron, the world's top accelerator among others of the same type. Substantial increase (more than a factor of 10) in the efficiency of experiments is needed for the synthesis of the heaviest elements 119 and 120 and for the study of nuclear and chemical properties of already known elements. On the detection side, the new gas-filled recoil separator (DGFRS-II) will play an important role. The construction of a specialized complex comprising radiochemical laboratories of Class 1 certification for the manufacture and regeneration of highly radioactive targets is foreseen, completing the SHE Factory.

FLNR's research program has been expanded into the region of neutron-rich isotopes of Super Heavy Elements near the island of stability, since the neutron shell $N = 184$ should have a stabilizing effect on the nuclear lifetime. In addition, the hypothetical closed shell at $Z = 114$ should also be of maximum support for the synthesis of nuclei with the number of neutrons close to 184. FLNR proposes to reach the neutron excess not by using beams of neutron-rich radioactive nuclei, because of their low intensity, but rather by




The layout of the FLNR accelerator complexes

using more neutron-rich target nuclei (e. g., $^{251}$Cf). In target production, our international collaboration is of great importance and will be pursued further.

Another scientific avenue in the field of SHE is emerging: Multi-nucleon transfer reactions in near-barrier collisions of actinides are promising in synthesizing new neutron-rich isotopes of Super Heavy Elements. These reactions can lead to the formation of neutron-rich super heavy nuclei, inaccessible via fusion reactions. This method allows the synthesis of a number of new isotopes of light Super Heavy Elements, up to the beta-stability line. Unfortunately, no universal detector concept exits; however, the FLNR is looking into upgrades and modifications of existing detectors like ACCULINNA-2, SHELS, DGFRS-II, MAVR, GALS and CORSET.

Another ambitious scientific goal is measuring the masses of SHE and the FLNR is planning a special mass detection system, consisting right after the target of a pre-separator, followed by a cryogenic gas ion catcher and a time-of-flight mass spectrometer.

The JINR FLNR experimental program for 2024–2030 is aimed at studying the properties of the radioactive decay and the structure of isotopes of heavy and super-heavy elements using the new DC-280 accelerator, the DGFRS-III setup, and the detecting system GABRIELA.

## Nuclear Physics with Beams of Rare Isotopes

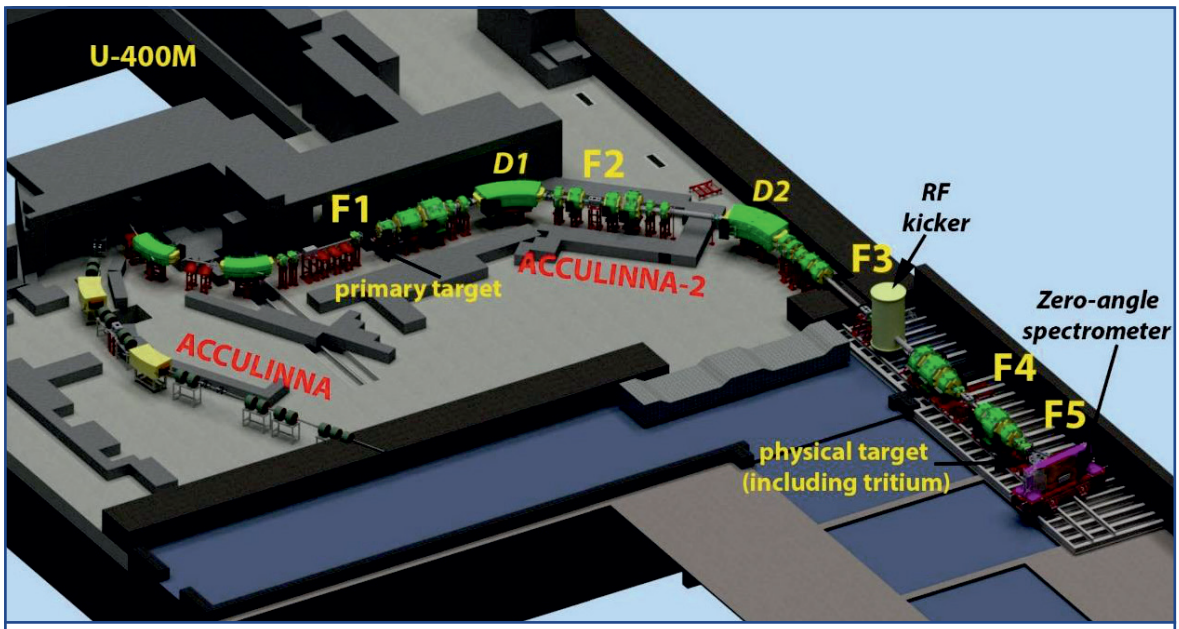
The aim of the Rare Isotope Beam (RIB) studies is to provide full knowledge of the nuclear chart from nuclear-stable isotopes to the limits of nuclear structure existence. The information obtained from Rare Isotope studies is indispensable to resolve fundamental problems of nuclear physics (structure, reactions, origins of the nuclear forces) and nuclear astrophysics (nucleo-synthesis, properties of the neutron matter). Radioactive ion beam (RIB) facilities allow the study of exotic nuclear systems far from the β-stability line.

Within this long-range program, JINR looks at another promising Nuclear Physics program, heavily promoted in the world of nuclear physics in the last 3 decades. Beams of rare isotopes far off the line of stability would be complementing the study of Super Heavy Elements pursued in FLNR, and allow JINR staying at the forefront of nuclear physics and providing state-of-the-art research in nuclear physics for the member states of JINR and the international nuclear physics community.

At low energies, the FLNR is pursuing an experimental program on relatively light exotic nuclear systems at the fragment separators ACCULINNA-1 and COMBAS, installed on the primary beam line of the U-400M cyclotron. Recently, the new-generation separators, ACCULINNA-2 and MAVR, were put into operation. ACCULINNA-2 is a fragment separator, installed at the DRIBs complex (Dubna Rare Isotope Beams) at the U-400M cyclotron to produce in the "in-flight" mode secondary beams of radioactive exotic nuclei.

The JINR FLNR will also ensure the continuation of the experimental research in the field of light exotic nuclei located at the borders of nuclear stability, with studies of nuclear haloes, neutron skins, cluster states, of exotic multi-neutron decays (2-nucleon virtual states, 2*n*- and 4*n*-radioactivity), two-proton radioactivity, search for new magic numbers and spectroscopy of exotic nuclei, and even reactions with halo nuclei.

Encouraged by leading international scientists of the NUSTAR community, JINR has proposed to develop and build a powerful **RIB facility DERICA** (Dubna Electron–Rare Isotope Collider fAcility) covering broad range of modern nuclear physics with intense secondary




Layout of the fragment separators ACCULINNA and ACCULINNA-2 at the U-400M cyclotron

RIB (new isotope synthesis and production, its masses, lifetimes and decay modes, nuclear reactions and spectroscopy).

The **DERICA concept** combines in-flight production of RIBs by projectile fragmentation technique (primary beams up to uranium with energy ~ 100 AMeV), stopping RIBs by gas catcher, reacceleration by LINAC-synchrotron combination, storage rings, usage of reaccelerated RIBs for reaction studies. The emphasis of the project is *storage ring physics with ultimate aim of electron–RIB scattering studies in collider experiments*. The realization of this new advanced program may lead to a necessity to reconsider the existing JINR structure and creating the new laboratory or the inter-laboratory center.

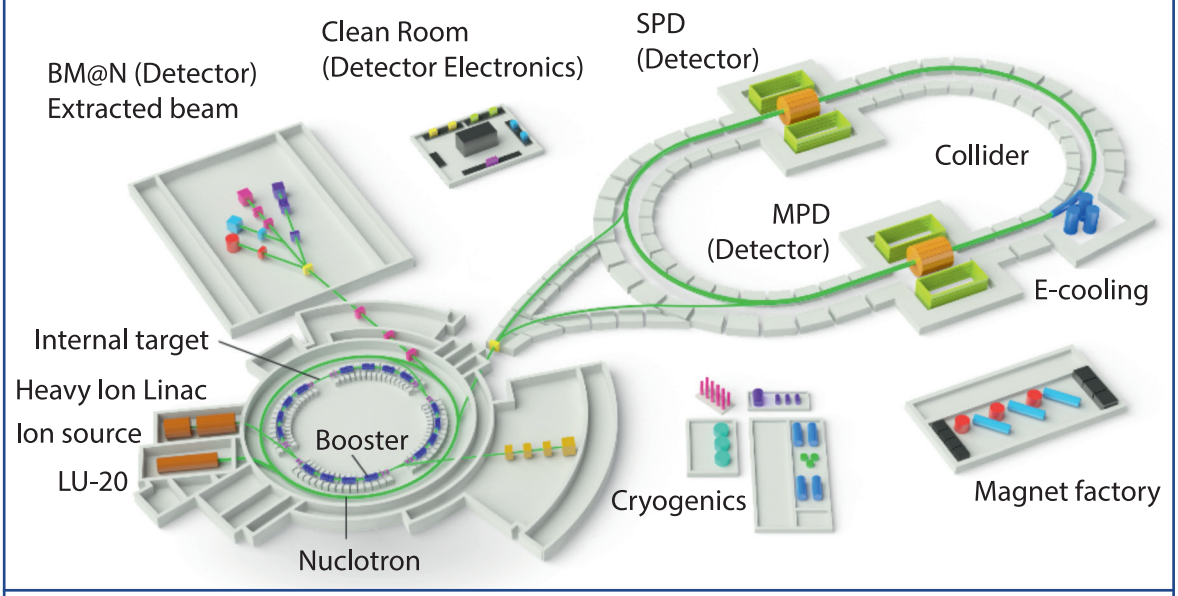
Empowered by the SHE Factory of FLNR and later by the DERICA complex, JINR at Dubna will be a worldwide unique laboratory complementing the top nuclear physics facilities at FAIR/GSI in Germany, RIKEN in Japan, FRIB in the USA and GANIL/SPIRAL 2 in France.

## NICA Relativistic Heavy-Ion Physics

From the beginning of the relativistic heavy-ion research in the early 1970s, JINR has been an important player with its on-site program at the Synchrophasotron, and then Nuclotron, and its participation in the heavy-ion program at the CERN-SPS first in WA98 and NA49, then in ALICE.

These activities have been the motivation and source for the Mega-Science project NICA and the Long-Range Plan presented below. The dominant tasks in the near and long-term future are:

a) The timely completion of the construction of the NICA project, its commissioning and a smooth operation.
b) Completion of the detectors, the BM@N at the Nuclotron, and the MPD at NICA and successful data collection over the decades to come.
c) After several years of running in the start version of MPD, an Upgrade of the MPD detector is foreseen, responding to a possible increase in luminosity of NICA, and by adding detectors in the forward rapidities as planned in the original layout of MPD.

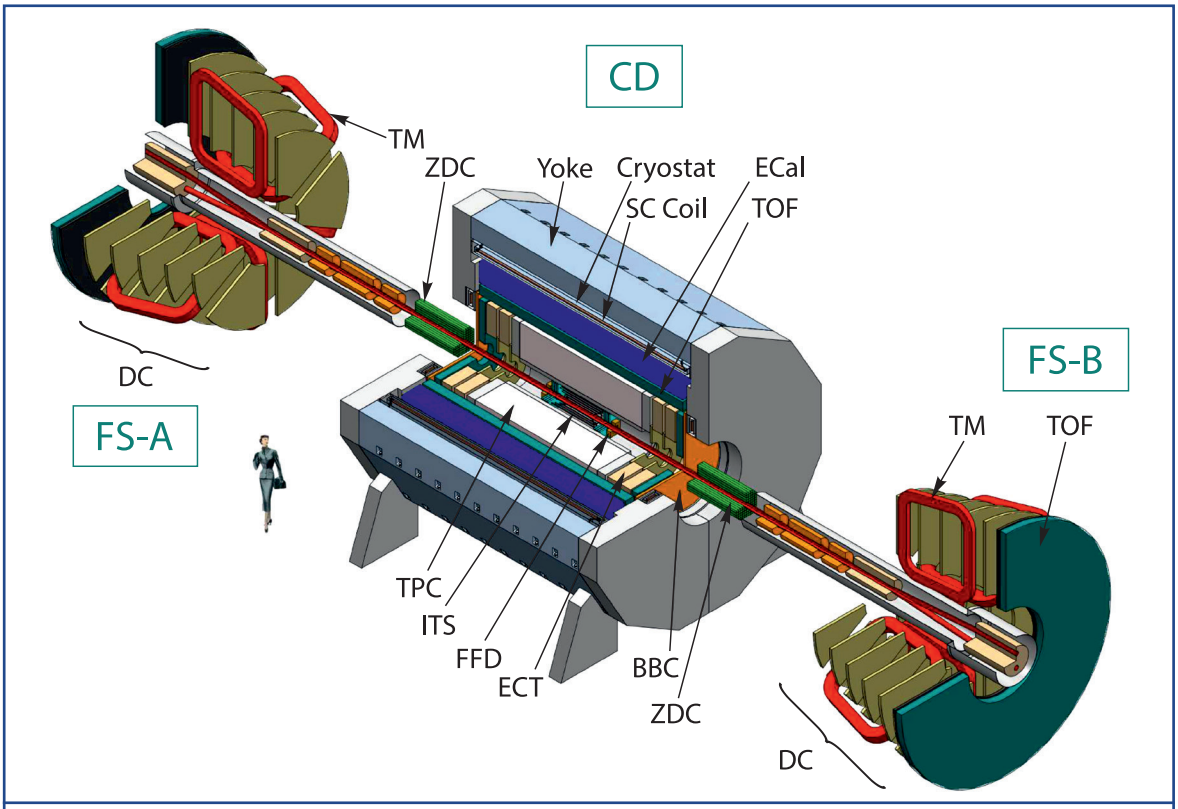



The NICA accelerator complex

d) Studies of possible future extension of NICA for acceleration of electrons, opening new physics potential via *e–p* and *e–A* collisions.

Both detectors, BM@N and MPD, have seen the formation of their respective international experiment collaborations.

To operate the infrastructure of the NICA accelerator complex, it is planned to increase the number of staff of the VBLHEP to 1000 employees. The total estimated number of scientists and specialists involved in conducting of the research at the NICA complex will reach 3000 by 2035.




The Multi-Purpose Detector (MPD) in its final version with forward spectrometers

## JINR participation in fore-front external experiments off-site

Furthermore, of strategic importance is the JINR participation in fore-front external experiments off-site, e.g., at existing facilities, like the LHC, SPS, RHIC and STAR, and at facilities under construction, e.g., the international FAIR facility in Germany, or in planning, like the forseen Electron–Ion Collider (EIC) facility in the USA. However, the key factor must be a mutual benefit from the exchange of data, of new scientific technologies and of theoretical know-how. The JINR strategy for cooperative research at other accelerator centres will be linked closely to the discovery potential of the experiment and of the value to JINR, and also to FAIR and the future of CERN within EU global strategies.

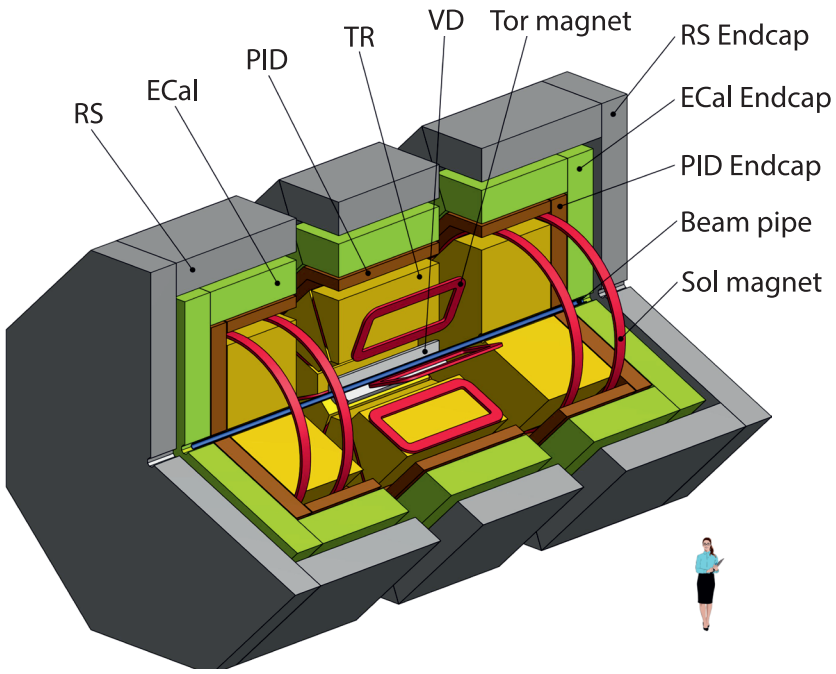


Artistic view of the NICA Innovation Center

## NICA Spin Physics

Spin Physics was also a key program at the Synchrophasotron and has been expanded at the Nuclotron. Still as of today, studying the gluon structure of the nucleon is of fundamental importance as it is needed to understand the nucleon internal structure as a whole. The unpolarized gluon content of the proton is well-known while our knowledge of polarized parton distributions is limited.

**Polarized proton and deuteron beams** will be made available at NICA, and experiments with them will be possible at the second intersection point of the Collider. The luminosity is expected to be in the range of $10^{30}$–$10^{32}$ $cm^{-2} \cdot s^{-1}$. The opportunity to have such high luminosity collisions of polarized protons and deuterons at the NICA collider allows for studies of a great variety of spin and polarization dependent effects in the hadron–hadron collisions: Measurements of asymmetries of the "Drell–Yan pair production" (DY) in collisions of non-polarized, longitudinally and transversally polarized protons and deuterons will provide an access to all leading twist collinear and TMD PDFs of quarks and an-




Conceptual design of Spin Physics Detector (SPD) from 2014

ti-quarks in nucleons. The measurements of asymmetries in production of $J/\Psi$ and direct photons will be performed as well simultaneously with DY using dedicated triggers. The set of these measurements will supply complete information for tests of the quark-parton model of nucleons at the QCD twist-two level with minimal systematic errors.

The proposed detector design must meet a set of requirements corresponding to the main physics goals and allow for possible further reconfiguration and upgrade of the facility:

— Close to $4\pi$ geometrical acceptance;
— High-precision (~ 50 μm) and fast vertex detector;
— High-precision (~ 100 μm) and fast tracking system,
— Good particle ID capabilities;
— Efficient muon range system,
— Good electromagnetic calorimeter,
— Low material budget over the track paths,
— Trigger and DAQ system adequate for event rates at luminosity of $10^{32}$ $cm^2 \cdot s^{-1}$.

The international SPD collaboration has presented a Conceptual Design of Spin Physics Detector (SPD) at the NICA collider. Various technical options are under discussion and simulations before finalizing a Technical Design Report at end of 2021. The plan is that SPD is ready for data taking when the NICA collider is operational.

## Particle Physics at the LHC and Beyond

JINR is deeply involved in international Particle Physics, has made important hardware contributions to scientific and technical infrastructures inside and outside of JINR, and has been strongly involved in the harvesting of scientific results through participation in data analysis. There are two experimental laboratories at JINR working in Particle Physics: the Dzhelepov Laboratory of Nuclear Problems (DLNP) and the Veksler and Baldin Laboratory of High Energy Physics (VBLHEP). The JINR overall strategic position in the particle

physics program presented in the report aims to be well integrated into the European and worldwide particle physics strategies and should guarantee JINR playing an important role in this field of Science.

The JINR strategy is based on a balance between home and international experiments. Both must be scientifically solid, well defined, expanding new frontiers in our understanding of physical laws that govern the Universe. The researchers from all the JINR member states should be able to participate in stimulating research and exploit the potential of the unique JINR infrastructure, which some university groups cannot afford.

In this report, a scientific program with several research directions in particle physics and astrophysics for mid-term (2023–2030) and further for the long-term (2030-2037) periods will be presented.

The main directions of research for the mid- and long-term periods are related to

- Precision exploration of strongly interacting states, including proton structure, QCD phases, like quark–gluon plasma, new hadronic states, including exotic multi-quark states.
- Study of electro-weak and flavour physics.
- Further insights in understanding the Universe evolution in collider experiments, including the search for dark matter.
- Astrophysical and cosmological observations and investigations of gravitational waves, multi-messenger astronomy and dark sectors in non-accelerator experiments.
- Experimental and theoretical determination of a model, Beyond the Standard Model (BSM).
- Development of accelerator science and technologies.

Many, if not all, of these directions are interwoven and interconnected. There is a strong synergy between these branches of research, as well as between the expertise of the different laboratories of JINR.

A solid research program for the next two decades is shortly reviewed below or in greater detail in terms of manpower, cost and schedule, in the main text.

## Accelerator-based research and accelerator technologies

- JINR, a more than 25-year-long-standing member of the ALICE, ATLAS and CMS Collaborations at CERN LHC, is one of the major participants with great investments into these projects. The major discovery of the experiments was the observation of the Higgs boson production and its decay, and the Quark–Gluon Plasma at very high temperatures.

From 2023 till 2026, LHC will be upgraded to a High Luminosity-LHC (HL-LHC) with an increase of the luminosity by a factor of 5 to 7.5, reaching the record 3000 inverse femtobarn and 14 TeV beam center-of-mass energy by the end of its Run 5. The integrated luminosity by 2038 will be 20 times larger than all currently accumulated statistics, opening the room for further insights and discoveries.

JINR plans to invest further in **ATLAS**, for production of 32 quadruplets of NSW and upgrade of RPC of the Muon System, upgrade of electronics of LAr EM Calorimeter, Tile Hadronic Calorimeter, TDAQ System and production of the HGTD. In **CMS** the investment will concern the upgrade of the endcap muon system, based on precision cathode strip chambers (CSCs), and the construction of the high granularity hadron calorimeters (HGCALs).

In total, JINR envisages to invest about **22–26M USD** in ATLAS and CMS till 2037.

- In the long-term period, after the High Luminosity-LHC upgrade, JINR is urged to play a leading role in physics analyses like precision measurements within the SM, searches for BSM physics, including Super-Symmetry and exotics, studies of the hadron structure.
- The worldwide accelerator community explores different scenarios of pushing the energy and luminosity frontiers even further for the post HL-LHC era. The current considerations include proton, electron and proton–electron colliders with possible sites at CERN (CLIC, LHeC, FCC, HE-LHC), Japan (ILC), USA (EIC) and China (CEPC, SPPC), exploring various new ideas of accelerator technologies.

The JINR researchers will join in these efforts and develop the necessary expertise whenever required to play a leading role in these explorations. As in the past years when JINR was recognized internationally as a potential site for the ILC, the new young JINR generation of scientists will look out for potential large-scale contributions of JINR in these global projects.

- At lower energies DLNP is involved in the experiments Mu2e, COMET, BES-III and PANDA at FAIR. VBLHEP is dominantly engaged in the Nuclotron and NICA experiments BM@N, MPD and SPD, and smaller ones like DSS, SCAN-3, HyperNIS, Alpom-2, but also in the CERN experiments COMPASS-2, NA61, NA62, NA64 at the SPS, or in STAR at RHIC and in FAIR experiments HADES, CBM and PANDA.

Certainly, participation of JINR in these off-site experiments — some ongoing, some under construction — will be evaluated as to scientific benefit and discovery potential, and in view of priorities of JINR. As mentioned before, the key factor must be a mutual benefit from the exchange of data, of new scientific technologies and of theoretical know-how.

## Neutrino Physics and Astro-Particle Physics

Neutrino Physics plays a key role in understanding of the laws governing the Universe. Nowadays, the significance of Neutrino Physics is steadily increasing since it has entered its precision era.

JINR, due to the explorations led by B. Pontecorvo since the 1950s, developed a strong and influential neutrino school with about 100 researchers working in this field today. JINR leads the world's largest **Neutrino Program** covering all sources of neutrinos, strong theoretical investigations and data analysis. A full support of the Neutrino Program is requested for strengthening the research by the JINR scientists in advanced experiments and keeping the competence and know-how developed so far.

Together with INR (Moscow), JINR plays a leading role in the construction, data taking, reconstruction, calibration and data analysis of **Baikal GVD (Gigaton Volume Detector)** with an aim to build a 0.4 $km^3$ detector by 2021 and 1.1–1.2 $km^3$ detector by 2027. JINR invests about **6M USD** per year to accomplish these goals. Today, Baikal-GVD is the largest neutrino telescope in the Northern Hemisphere with its 1/4 $km^3$ detector.

JINR intends to strengthen further its leading position by increasing substantially efforts in the data analysis for yielding the highest quality scientific results in observation of ***ultra-high astrophysical neutrinos*** and related studies. Any efforts in profound limnological and environmental studies of Lake Baikal are possible and welcomed. The perspectives of Baikal-GVD are well defined for mid- and long-term periods as described in more defail in the main text.




Five clusters of the Baikal-GVD neutrino telescope installed by 2019

The major motivation of **JUNO**, the reactor antineutrino experiment, is the determination of neutrino mass ordering at confidence level of 3–4 standard deviations. JINR is a major JUNO collaborator with well visible financial and intellectual contributions. JINR also has a clear research program outlined in the report.

The next breakthrough in the determination of neutrino mass ordering and CP- violation in the lepton sector can be expected from a global analysis of neutrino data and from precision measurements at accelerator long-baseline experiments like **DUNE** in the United States or **HyperKamiokande** in Japan. JINR, successfully participating in the NOvA experiment, intends joining one of these. The decision will be taken based on an expected accuracy of their measurement, claimed to be comparable, and on a possible leading and visible role of JINR.

## Multi-messenger astronomy including gravitational wave detection

It is understood nowadays that phenomena which occurred in the Universe, should be studied by simultaneous observations of different signals. These multi-messengers could give a further insight into the evolution of the Universe.

Baikal-GVD mentioned above is one of the cornerstones of this approach. The **TAIGA** installation — a set of gamma and muon telescopes hosted in Siberia, in Tunka Valley, to the south of Lake Baikal, can be regarded as a supplemental instrument in terms of multi-messenger astronomy. Together, Baikal-GVD and TAIGA can provide a unique multi-messenger observation of the Universe integrated into the global network. This direction of research is of great importance and will be seriously reconsidered by the JINR management for strengthening its gamma-rays counterpart. TAIGA is an international collaboration, achieving the world-level quality standards in technologies, commissioning, soft-

ware and data analysis. JINR will take all necessary measures to attract world-class experts for leading this project.

The discovery of gravitational waves is one of the most remarkable discoveries ever, which opened a new window to observe the Universe. Russia currently lacks any gravitational wave detector and this disparity must be removed. JINR scientists propose to pursue this direction of research, which requires developing a new expertise in many fields ranging from General Relativity to precision laser interferometry. The important point to note is that JINR has already made the first step towards this direction, having installed its brand new laser inclinometer at the VIRGO detector. At mid-term, JINR will develop the presently missing needed expertise and prepare itself for competent collaboration at existing gravitational wave detectors like **LIGO** or **VIRGO**, and/or the third-generation detector **Einstein**.

As a long-term program, JINR may consider building its own gravitational wave detector in Russia, which will enormously boost GW astronomy in Russia and the JINR member states. The flat large area around Dubna was already positively evaluated for the large system of the ILC and can serve extremely cost-effectively to such a GW Laser system

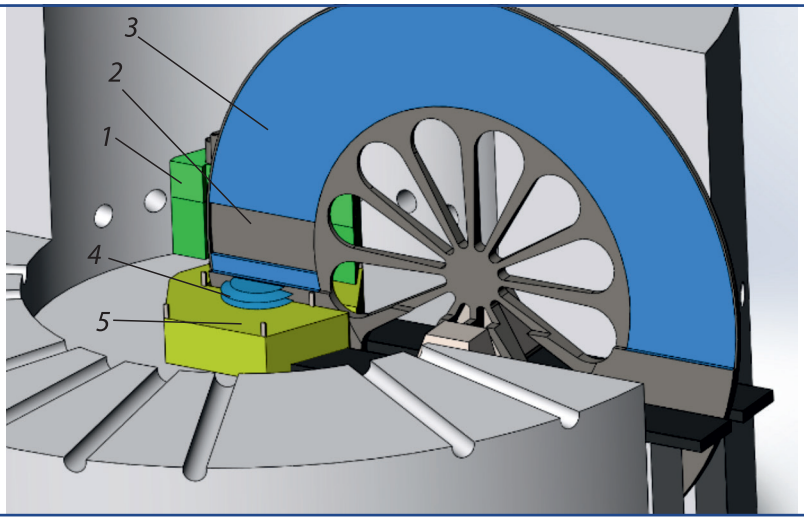
## Neutron Research in Condensed Matter and Neutron Physics

JINR has a long tradition in Condensed Matter and Neutron Physics research employing neutrons from their on-site research reactors. JINR intends to stay at the forefront of this science by building the best neutrons source possible.

Neutrons are used for studying fundamental symmetries and interactions, structure and properties of nuclei, but nowadays neutrons are mostly required in investigations of condensed matter including solid states, liquids, biological systems, polymers, colloids, chemical reactions, engineering systems, etc. The use of cold neutrons (wavelengths from 4 to 20 Å) in neutron scattering research allows for studies of nanoscale objects and becomes the current trend worldwide, particularly studies of nano-structured objects required by medicine and biology. At the same time, using very cold neutrons (VCN) with wavelengths from 20 to 100 Å, one can approach new levels of measurement accuracy in several techniques, e.g., neutron spin-echo and reflectometry. Moreover, VCN are also a very promising tool for research in the field of particle physics and studies of fundamental interactions (e.g., measurements of the neutron lifetime, search for neutron–antineutron oscillations, etc.). Ultracold neutrons (UCN) are the well-established experimental tool for research in the field of particle physics and fundamental interactions. Further increase in the intensity of UCN sources will allow both improving the accuracy of such experiments and significantly expanding the scope of the UCN's usage, for example, for studies of surfaces and thin films.

Considering the present-day tendency in neutron facility development, after 2030 only five sources will be available including three currently operating facilities: ISIS (Didcot, UK), SINQ (PSI, Villigen, Switzerland), FRM II (TU Munich, FRG), and two new sources (ESS (Lund, Sweden) and steady-state reactor PIK (PNPI NRC KI, Gatchina, Russia), both under construction with the start of operations planned for 2023–2024.

Thus, the need for a next-generation high-flux neutron source is driven by a growing interest in neutron investigations against the background of a steadily decreasing number of neutron sources in the world, as evidenced by the analysis of a specially established ESFRI Physical Sciences and Engineering Strategy Working Group. Such a new source will in a great extent compensate the losses of the neutron beam time in Europe and attract




Schematic view of IBR-3: *1* — reactor core, *2* — empty sector of reactivity modulator, *3* — reactivity modulator coated with titanium hydride, *4* — moderator, *5* — beryllium reflector

users that are currently served at ILL and medium-flux reactors in Germany, France and Hungary.

JINR has proposed to build a new advanced neutron source, DNS-IV (Dubna Neutron Source of IV generation), on site. In combination with modern moderators, neutron guides and neutron scattering instruments, DNS-IV promises to become one of the best neutron sources in the world and will open unprecedented possibilities for scientists from JINR member states and worldwide for research in condensed matter physics, fundamental physics, chemistry, material and life science.

DNS-IV will provide shorter neutron pulses, however containing the same number of neutrons as at the European Spallation Source (ESS, to be operational in 2024). Indeed, it will be as good as ESS for low-resolution experiments and significantly outperform it for high- resolution experiments.

From the different concepts studied, a pulsed neutron reactor IBR-3 with Np-237 core was chosen for the DNS-IV project. Therefore, the pulsed neutron reactor IBR-3 with NpN fuel has currently become the working project with a planned start of the DNS-IV operation in 2036–2037. A rough cost estimate today is at about 440 M€. More exact figures are expected by the end of 2022 in the preliminary design stage of the project.

## Theoretical Physics

Throughout the JINR history, research in theoretical physics has always been one of the pillars of the JINR scientific program, which has contributed to many major advances in Science. The Bogoliubov Laboratory of Theoretical Physics is one of the worldwide biggest research centers specialized in theoretical research at the frontiers of fundamental physics. BLTP has an expertise in a wide range of areas related to the theory of fundamental interactions, nuclear theory, condensed matter physics and modern mathematical physics. Studies at BLTP are carried out in close cooperation with scientists from many world leading research centers and in coordination with the JINR experimental program.

Scientific and organizational policy of the Laboratory relies on multidisciplinary theoretical physics on the basis of advanced mathematics, support of the JINR experimental

program, strengthening of the scientific brainpower through the interplay of research and education. These principles as well as forming the international scientific task force groups dedicated to the enhanced study of the emergent hot topics will be in focus of a long-range development of theoretical physics at JINR.

BLTP and JINR will stay attractive to the international scientific community by organizing series of topical workshops, conferences, and schools for young scientists. A special emphasis will be placed on active participation of BLTP in educational programs of JINR as well as on its direct cooperation with universities of the JINR member states. The unique feature of Dubna International School of Theoretical Physics (DIAS-TH) is its coherent integration into the scientific life of BLTP and JINR, ensuring regular and natural participation of the leading scientists in education and training activities.

## Theory of fundamental interactions

Theory of fundamental interactions of elementary particles based mostly on quantum field theory plays the central role in describing the properties of matter at the microscopic level. In particular, it is forming the solid background of quantitative analysis of both accelerator and non-accelerator experiments involving leptons, hadrons and heavy ions. The JINR long term research program in this field of theoretical physics will include a wide range of the most significant topics, running from the high-precision tests of the Standard Model and critical phenomena in Hadronic Matter to Dark Matter and Dark Energy problems.

Major attention will be paid to phenomenology of the Standard Model, searches for signatures of new physics beyond the Standard Model, neutrino physics, hadron structure and spin physics, heavy flavour physics and hadron spectroscopy, critical phenomena in hot and dense Hadronic Matter in the presence of strong electromagnetic fields, the Dark Matter problem, and astrophysical aspects of elementary particle physics. Theoretical research in the field of particle and relativistic heavy ion physics will be focused on the support of physics programs of major international collaborations with JINR participation (LHC, RHIC, FAIR, etc.), and those at the JINR basic facilities, primarily, of the NICA/MPD and NICA/SPD projects.

## Nuclear theory

The central questions of nuclear physics are: How do the forces between nucleons form bound nuclei? How does the nuclear chart emerge from the underlying interactions? How does the complexity of the bound and continuum nuclear structures arise from the interaction between nucleons? Which role if any at all can the internal quark structure of the nucleons and their color degrees of freedom play in description of the dynamics of nuclear reactions? In order to get answers to these questions, it is necessary to develop a unified theoretical approach to treat few- and many-body systems including a consistent description of nuclear reactions. This approach will play an important role in explanation of the experimental data and in guiding the experimental programs in nuclear structure of exotic nuclei, nuclear dynamics, and nuclear astrophysics. At the same time, nuclear theory will be involved in a variety of interdisciplinary investigations in particle, atomic, and statistical physics.

Investigation of the properties of exotic and superheavy nuclei is the goal of the experimental projects DRIBs III and "The Factory of Superheavy Elements" at JINR and projects in Europe, the United States, China, and Japan. Parallel to these experiments, microscopic self-consistent nuclear models will be elaborated which include non-harmonic and frag-

mentation effects beyond the mean field approximation. The models are to predict the rates of various nuclear reactions for astrophysical purposes. Nuclear reactions in stellar environment will be studied with the rigorous methods of the few-body theory as well. In the context of multidisciplinary research, the methods of the few-body theory will be developed in application to ultra-cold atoms and molecules in confined geometry of laser traps.

## Theory of condensed matter

Research program will be based on both a systematic development of the general methods of statistical physics and studies in the condensed matter physics tightly correlated with practical problems in the field of nanotechnology for creation of new materials and electronic devices.

Models in condensed matter physics will be studied by using methods of equilibrium and non-equilibrium statistical mechanics with the aim of revealing general properties of many-particle systems based on the ideas of self-similarity and universality. Along with that, theoretical research will be focused on the analysis of systems with strong electronic correlations such as transition metal compounds, high-temperature superconductors, colossal magneto-resistance compounds (manganites), heavy-fermion systems, low-dimensional quantum magnets with strong spin-orbit interaction, topological insulators, etc. A theory group will accompany the experimental studies of particular materials conducted at the Frank Laboratory of Neutron Physics. Investigations in the field of nanostructures and nano-scaled phenomena will be performed to find physical characteristics of nano-materials, which are promising for various applications in modern nanotechnologies. The problem of quantum transport in carbon-based and molecular devices as well as the resonance tunnelling phenomena in various hetero-structures and layered superconductors is of special interest and will be investigated.

## Modern mathematical physics

Superstring theory, the most serious and worldwide pursued candidate for the unification of all fundamental interactions including quantum gravity, will be one of the central topics in mathematical physics studies at BLTP. This requires a wide range of precise classical and quantum superstring solutions, application of modern mathematical methods to the fundamental problems of supersymmetric gauge theories, development of microscopic description of Black Hole physics, elaboration of cosmological models of the early Universe. In applying and developing new ideas generated with the string theory, it is crucial to use mathematical methods of the theory of integrated systems, quantum groups and non-commutative geometry, super-field methods, including the method of harmonic superspaces.

## High-performance computing

Implementation of the outlined research program in theoretical physics, first of all related to Lattice QCD and, in general, theory of dense and hot Hadronic Matter, multi-loop calculations in the Standard Model, astrophysical and cosmological modelling, will necessarily boost development of high-performance computing infrastructure of JINR to the highest level.

# Radiobiological and Astrobiological Research at Charged Particle Beams of Different Energies

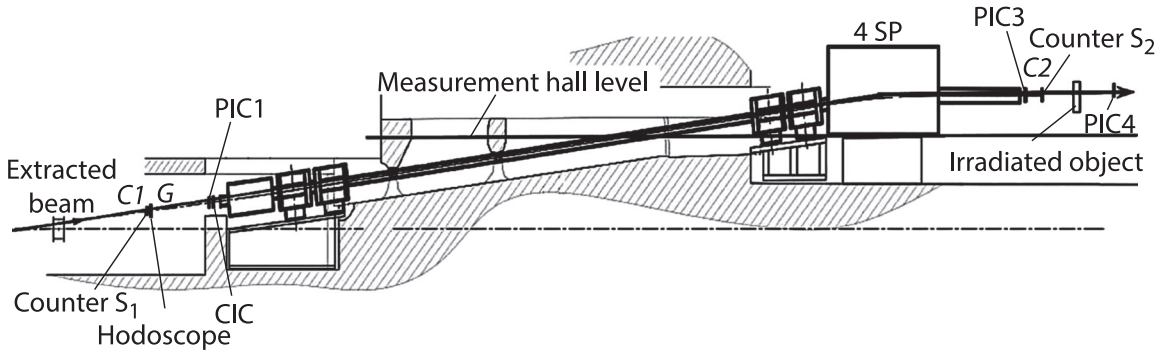
Heavy charged particles are an excellent tool to address fundamental problems of modern radiation biology and genetics. In contrast to photon radiation, which uniformly deposits energy within the cell nucleus, heavy charged particles densely release energy along their tracks. It results in complex and clustered DNA damage and determines the particles' high biological efficiency. In Space, high-charge and energy (HZE) ions of the Galactic Cosmic Rays (GCR) make a great contribution to the health risk to astronauts during manned deep space missions. Furthermore, hadron beams — protons and carbon ions — are beneficial for radiation cancer treatment, especially for deep-seated tumours, due to their depth-dose distribution with a sharp maximum at the end of the particle range (the Bragg peak). Charged particle tumour therapy and space radiation protection are becoming increasingly urgent fields of modern radiobiological studies.

Astrobiology is studying life in the broadest sense: its origin, evolution, and presence in the Universe. To answer the question of the exogenous origin of life, the early stages of transition "from the inanimate to life" can be reproduced in ground experiments using particle beams as an energy source.

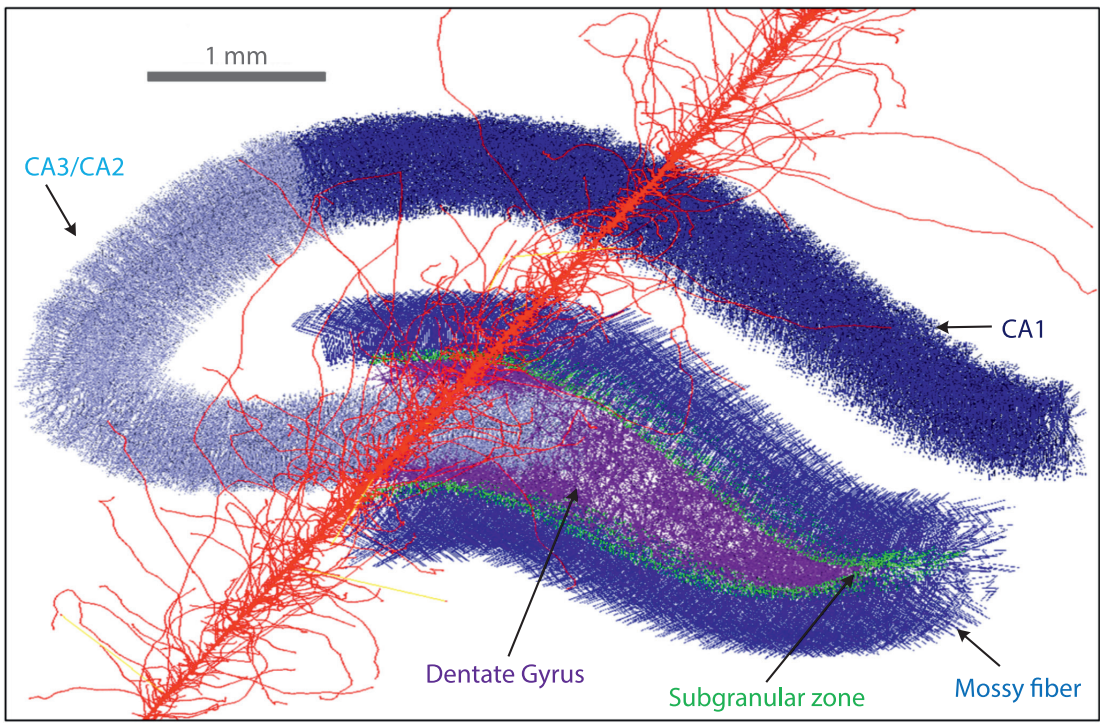
The great advantage of conducting research at the Laboratory of Radiation Biology (LRB) is the availability of numerous radiation sources, including heavy ion beams of different energies. JINR's basic facilities offer an excellent opportunity of modelling the biological action of space radiation. The LRB has proposed a novel Nuclotron-based technique of modelling of radiation fields with continuous particle energy spectra generated by GCR inside spacecraft in deep space.

Another major advantage is an excellent opportunity to perform large-scale *in vivo* animal exposures in collaboration with leading experts in this field — first of all, with RAS Institute of Biomedical Problems. The worldwide unique experiments on primates for the estimation of radiation risks of CNS (central nervous system) disorders and carcinogenesis are in progress at the LRB.

A new method of the enhancement of low-LET (linear energy transfer) ionizing radiation's biological effectiveness by the transformation of non-lethal DNA damage to lethal has been invented and recently patented by the LRB. The method has been tested *in vivo* and *in vitro*, which makes it very promising for radiation medicine.




A schematic layout of the Nuclotron beam extraction channel and beam detectors behind the irradiated biological objects




A Monte Carlo simulation of a 600 MeV/n $^{56}$Fe ion track structure in a three-dimensional model of the rat hippocampus including main zones and cell types indicated by different colours

The LRB develops the hierarchy of mathematical models to simulate radiation-induced pathologies at different organization levels and time scales. In addition to the traditional Monte Carlo technique, the LRB's approach involves computational methods from different knowledge areas (molecular dynamics and simulation of brain neural networks). The computation of radiation damage to the CNS structures was initiated and is continued by NASA and the LRB.

For the first time, the synthesis of prebiotic compounds in the "formamide + catalysts" system under exposure to particle beams has been performed in collaboration with Italian universities within the framework of research on the Panspermia hypothesis.

The key to the successful fulfilment of the 2030 Program is the possibility to conduct radiobiological research at the Nuclotron (VBLHEP). For that a special irradiation station with large-area illumination is requested for irradiation of material, inorganic and organic, as well as rodents and primates. When in the future highly localized irradiation with sub-millimetre resolution is envisioned, as, e.g., needed for cell size irradiation, the beam line design could follow the outlines of micro-beams, i.e. high precision down to micron level, as existing at GSI Darmstadt.

The Laboratory of Radiation Biology, a strong new member of the recently formed International Biophysics Collaboration, collaborates with the following scientific institutions of JINR members and other countries: Armenia (YSU), Belarus (IRB NASB), Bulgaria (IE BAS, IM BAS, NCRRP), the Czech Republic (CTU, IBP ASCR, NPI ASCR), Italy (UNITUS, UNIUD, La Sapienza Univ.), Mongolia (NUM), Poland (SzU), Romania (IBR, UMF, UAIC), Russia (IBP RAS, IP, MSU, ITEP, IHNAN RAS, IMP, SRI RAS), and Slovakia (CU).

## Information Technologies

The mission of the Laboratory of Information Technology (LIT) is two-fold:

- to serve the scientists of JINR and its member states in the pursuit of their research projects by developing *Methods, Algorithms and Software for Modelling Physical Systems, Mathematical Processing and Analysis of Experimental Data*;
- to assure that the IT infrastructure and IT know-how of JINR experts are always of latest state of the art as to performance and energy efficiency (see, e.g., Green Cube at GSI).

Since JINR and other big science centers depend on the commodity IT hardware, a long-term view needs to prepare for great flexibility in the system. Presently, the JINR Infrastructure has been developed in close connection with CERN and other Institutes of Nuclear and High Energy Physics. During the last 15 years, a distributed computing infrastructure has been created for processing and storing data from LHC experiments. Each of the four outstanding scientific experimental facilities ATLAS, CMS, ALICE and LHCb at the LHC is being run by collaborations, each of which has several thousand scientists from several hundred institutes distributed worldwide.

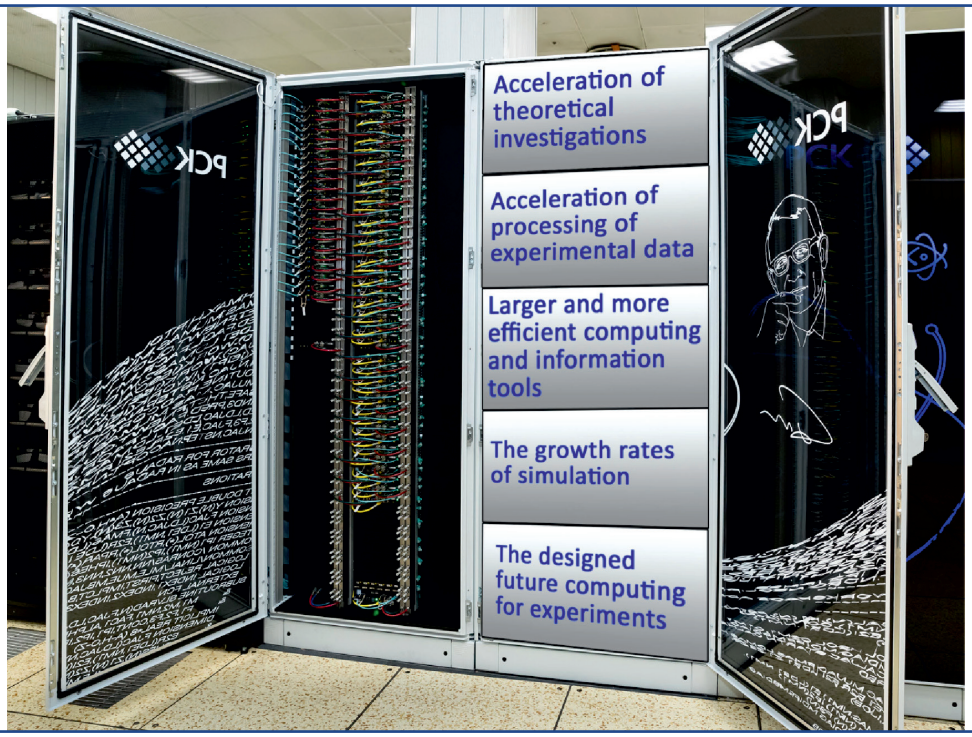
Therefore, a geographically distributed computing environment for processing and storage of experimental data of all LHC experiments, i.e. the Worldwide LHC Computing Grid (WLCG), has been created. About 1 000 000 processors geographically distributed in more than 170 data processing centers from 42 countries are combined into a unified computing environment within the WLCG infrastructure, capable of managing hundreds of petabytes of data, providing access to the entire community to computing resources and data storage systems and integrating national and international structures. JINR is a strong part in this system.

Projecting the development of Information Technologies of the Institute into the future must take into account the latest development of some large experiments, where huge computing power is or will be installed at the front end of the detectors, thus reducing substantially the amount of data transmitted to the distributed computing centers in the world. At the same time, data taking rates in the LHC experiments are increasing steadily, leading to an increase in data volumes.

The original concept of grid as an implementation of the HTC (High Throughput Computing) concept has changed to a complex, heterogeneous computing system combining computing resources of various concepts: HTC, HPC (High Performance Computing), computing resources provided on a voluntary basis (Volunteer computing), commercial and non-commercial cloud computing resources.

Currently, research on the development of novel architectural and functional principles of the WLCG distributed computing infrastructure is carried out by the community of LHC computer specialists and other scientific world centers in the field of high-energy physics; in 2020 it is planned to complete the preparation of relevant technical projects (Computing TDR). JINR specialists are part of that community of experts.

It should be noted that the JINR research program for next decades is aimed at conducting ambitious and large-scale experiments on the Institute basic facilities and in the framework of the worldwide cooperation. This program is connected with the implementation of the NICA megaproject, the construction of new experimental facilities, the JINR neutrino program, the modernization of the LHC experimental facilities (ALICE, ATLAS, CMS), the programs on condensed matter physics and nuclear physics. The implementation of the projects mentioned above requires adequate and commensurable investments in



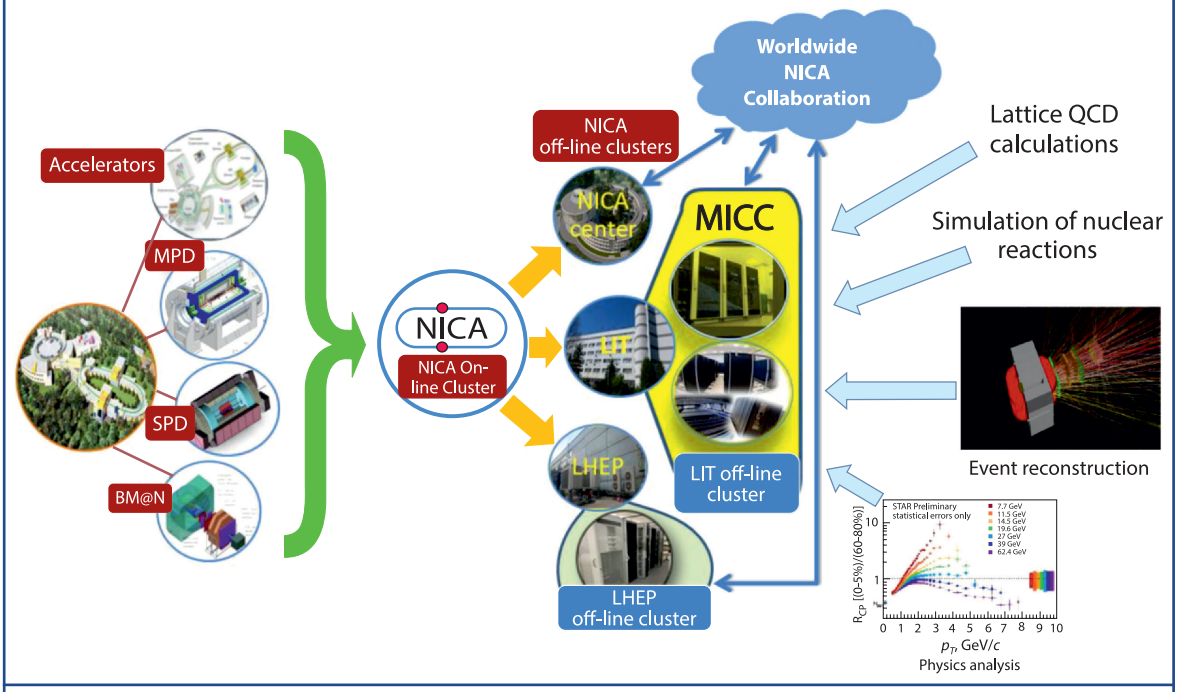

"Govorun" supercomputer

the systems providing the processing and storage of increasing data volumes. The experience of recent years shows that the progress in obtaining research results directly depends on the performance and efficiency of computing resources. In this regard, the further development and performance extension of the JINR Multifunctional Information and Computing Complex (MICC) as well as the provision of novel IT solutions to the Complex users and the increase in its operation efficiency are the uppermost tasks of the Laboratory of Information Technologies.

The JINR computing infrastructure consists of numerous computing components and IT technologies to solve JINR tasks, from theoretical studies to experimental data processing, storage and analysis. The JINR LIT MICC is the key element of this infrastructure and plays a defining role in research, which requires modern computing power and data storage systems. They are the IT ecosystem for the NICA project (BM@N, MPD, SPD), Tier-1 of the CMS experiment at JINR, Tier- 2/CICC providing support to experiments at the LHC (ATLAS, ALICE, CMS), FAIR (CBM, PANDA) and other large-scale experiments as well as support to users of JINR Laboratories and the JINR member states (MPD/NICA, BESIII, LRB, FLNR, DLNP, BLTP, FLNP); the integrated cloud environment of the JINR Member States for support of JINR users and experiments (NICA, ALICE, BESIII, NOvA, Daya Bay, JUNO, etc.); the HybriLIT platform with the "Govorun" supercomputer as a major resource for high-performance hybrid computing.

Besides carrying out massively parallel calculations, it is planned to use the supercomputer "Govorun" for modelling an entire system of computing for all experiments of the NICA complex.

Other promising directions of modern information technologies are Machine Learning and Artificial Intelligence, as well as Quantum Computing and Quantum Computer Science. The observed growth rate of the number of qubits, which characterizes the maximum possible amount of input data for a quantum computer, is clearly higher than linear




NICA computing concept and challenges

one, which shows the accelerated technical progress in creating equipment for quantum computers.

The JINR IT will actively observe these developments in close collaboration with the CERN IT Division as well as the IT department of GSI/FAIR.

In summary, the LIT plans to establish an **IT ecosystem**, i.e. a dynamically growing IT platform, which responds to the rapidly developing IT world. The connection to CERN will influence the JINR strategy. Different to most other IT groups in the world, the JINR LIT is providing and will provide forefront service to scientists working in JINR collaborations, on- and off-site of Dubna by continuing developing, according to its mission, *Methods, Algorithms and Software for Modelling Physical Systems, Mathematical Processing and Analysis of Experimental Data*. Although many of these tasks are being done by individual experts in experiment collaborations, LIT as base of these experts can guarantee a high level of professionalism strongly needed in Data- and Code-handling.

The LIT manpower development must reflect the fast-changing world of IT by providing attractive positions to both promising young and highly qualified IT specialists.

## Biomedical Research Center in Dubna

JINR has accumulated more then 50-years' experience in treating cancer patients with proton beams of the Phasotron facility, as well as in the field of design and construction of specialized accelerators for nuclear medicine. The LRB explores the patterns and mechanisms of the molecular disturbance formation in genetic apparatus of human and animal cells under the action of proton beams on various biological objects. The latest results obtained appear as a breakthrough in the efficiency of proton beams for the treatment of cancer tumors.

Since hadron therapy centers are needed in the Moscow region and in most JINR member states, JINR is working on planning a modern biomedical research center on site at Dubna in collaboration with the radiological department of the medical clinic MSC-9 in Dubna.

With the expertise of VBLHEP and FLNP on practically all accelerator systems for beams of protons to very heavy ions, JINR has the needed resources to join the international development of medical accelerators for proton and ion therapy, or medical isotope production of up to alpha-emitting isotopes like Ac-225 or At-211. LRB, as member of the International Bio-Physics Collaboration, has also access to the latest state of ion therapy research as performed at the Heidelberg Ion Therapy Center, at GSI and at the Marburg Ion Therapy Center. In this global and local framework, JINR is well positioned to plan a medical radiation center with latest state-of-the-art accelerator technology as well as most modern radionuclide treatment in Brachytherapy or in immunotherapy with alpha or beta emitters. It could further team up with Russian institutions like MEPhI in working on nano-particle carriers for medical radioactive isotopes.

A pragmatic approach for an early start could be commercially available accelerators with an additional proton beam channel for radiobiological research.

A truly world-class center could be composed of a complex of low-energy cyclotrons and a medium-energy cyclotron (70 MeV protons), producing light and heavy isotopes for medical applications, and the above-mentioned proton cyclotron of 225 MeV protons for large-tumor irradiation. Finally, a synchrotron for highly localized precision beams of heavy ions with $N/Z = 2$ ions, i.e. $^{4}$He and $^{12}$C beam at energies up to 225 MeV/A, would make the center a unique one in the world, responding to all needs for an optimal treatment of cancer patients.

## Biomedical research center for proton therapy of oncological diseases in Dubna

The first sessions of the clinical use of proton beams generated by the phasotron (before reconstruction of the synchrocyclotron) of JINR, the institute's first proton accelerator, were started in 1967. Since 1999, a radiological department has been operating in Dubna at MSC-9 of the FMBA of Russia. For the first time in Russia, the technique of three-dimensional conformal proton radiation therapy was implemented. Between 2000 and 2018, about 1300 patients (including non-Russian citizens from JINR member states) with various neoplasms took proton radiation therapy using phasotron beams.

JINR, having many years of experience in creating accelerators and physical facilities for basic and applied research, is developing medical accelerator technology, collaborating with IBA, the world leader in the field of proton therapy facilities, and is developing, assembling, tuning and launching specialized medical cyclotrons for these goals. More than 10 years ago, JINR and IBA jointly developed the project of the world's first superconducting carbon cyclotron C400. This accelerator is currently under construction in Caen, France. Along with this, calculations and modernization of the serial proton cyclotron C230 were carried out. The first copy of C235-V3 was assembled, configured, and launched at JINR in 2012. Currently, the C235-V3 has been installed, launched, and has become part of the first medical center with proton therapy in Russia — the Federal High-Tech Center for Medical Radiology of the FMBA of Russia in Dimitrovgrad.

The Laboratory of Radiation Biology is conducting studies of the action of proton beams on various biological objects in order to study the patterns and mechanisms of the formation of molecular disturbances in the genetic apparatus of human and animal cells, the formation of various kinds of mutations, and is studying the neuroradiobiological effects of radiation.

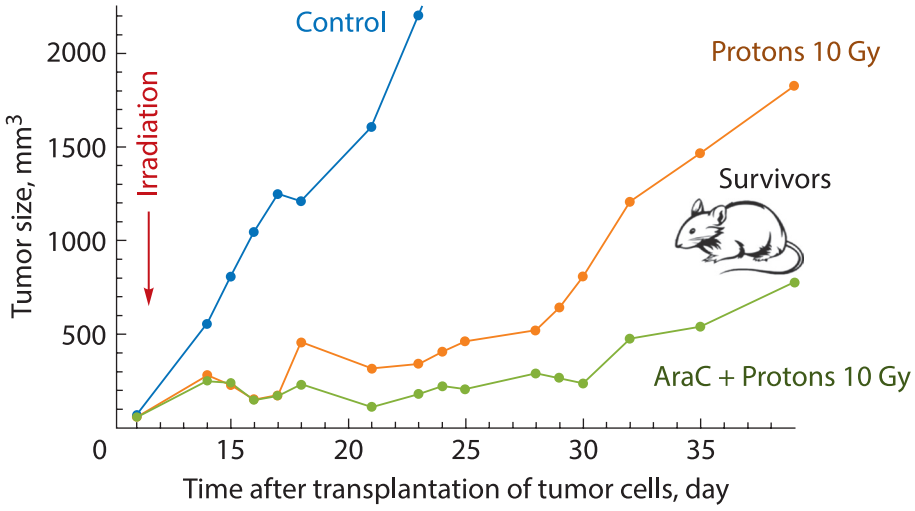
In vitro experiments have established that under the action of ionizing radiation on human cells in the presence of this drug, the transformation of single-stranded DNA breaks into lethal double-stranded breaks occurs, which leads to a sharp increase in cell death. A patent has been obtained for the invention of a new method for enhancing the radiation effect on living cells.

A group of specialists from the JINR LRB and the Center for Medical Radiology (Obninsk) performed studies of the effectiveness of the proposed method in the treatment of melanoma. A group of animals (mice) was inoculated with a melanoma tumor, and the tumor was irradiated with protons at the Bragg peak in the group with and without drug administration. On day 30, control animals without irradiation and without drug administration died. On day 40, both groups of irradiated animals with and without drug administration were alive and differences were found in the size of tumors relative to the two groups: with proton irradiation + drug administration the size was ~2.5–3.4 times smaller than with proton irradiation only, as shown in the figure below.

The application of the proposed approach, which provides a significant increase in the biological efficiency of proton beams and gamma therapeutic units, significantly brings together the fields of use of proton and carbon accelerators for therapeutic purposes.

These circumstances give reason to believe that the combined use of the officinal drugs should be promising for use in the clinic of radiation therapy.

Many years of practical experience in treating cancer patients with proton beams, a team of trained specialists in the field of radiation medicine, and the presence of a radiological




Kinetics of the development of melanoma tumor in mice in experiments in Obninsk in the summer of 2019. In blue, data for mice without proton irradiation and without AraC drug administration; in orange, data for mice with proton irradiation and without AraC administration; in green, data for mice with both proton irradiation and AraC administration

department at MSC-9 of the FMBA of Russia create the conditions for the continuation and development of hadron therapy at the JINR in the coming years. The treatment of patients with the participation of JINR specialists should naturally be combined with biomedical research at the Institute.

Recent results of a study of the action of proton beams on various biological objects in order to study the patterns and mechanisms of the formation of molecular disturbances in the genetic apparatus of human and animal cells promise a breakthrough in the effectiveness of using proton beams for the treatment of cancer. For their continuation, a medical center with a modern and reliable proton accelerator is required, which must be certified for the irradiation of cancer patients. The world experience in creating such medical centers shows that treating patients and conducting research on proton beams can be successfully combined using the same accelerator, using additional beam conclusions and spreading the time of patient irradiation and scientific research. The fastest and cheapest option for creating a compact biomedical proton center is currently the IBA Proteus ONE compact turnkey module, which has passed all the necessary certification in Russia.

The creation of a joint biomedical research radiation medical center based on Proteus ONE in collaboration with IBA could become a pilot project to create a series of compact and relatively inexpensive proton therapy centers for leading oncological clinics in Russia. In view of the foregoing, the creation in Dubna of a joint JINR – FMBA of Russia biomedical research radiation medical center would be an important step in providing the necessary medical care to cancer patients in the northwestern part of the Moscow region and other regions of Russia, as well as JINR member countries, based on high-tech equipment.

## Detector Technologies

JINR is internationally recognized for its advancement of detector technologies. However, this expertise must be strengthened further for reaching latest high-tech standards and pushing further the frontiers. Therefore, a considerable amount of knowledge and expertise must be elaborated in modern electronics, robotics and precision mechanics. The close collaboration of JINR with the detector laboratories of GSI and CERN is greatly appreciated. The JINR management will take all the necessary measures to attract to JINR world-level experts to lead perspective directions within detector technologies, microelectronics and ASIC chip design, and to provide the means for equipping JINR detector laboratories with state-of-the-art equipment and instrumentation.

## Human Resources — Education and Training Programs

The necessity of a well-defined educational program at JINR is evident and must be continuously adapted to guarantee new highly trained generations of researchers, engineers and technicians. Such a program will rely on on-site educational and training programs, but it will also depend on the strong interaction with universities and training centers in the JINR member states. Only in close collaboration with these institutions, a sustainable development of JINR and a successful realization of the projects described above can be guaranteed. The creation of a higher engineering school in Dubna based on the Dubna State University is of great importance.

The proven and new methods of training and recruiting of personnel include:

- Supervision of practical, bachelor, master, and PhD works prepared by students belonging to scientific and technical departments of universities from the JINR member states.
- Excursions to the various JINR facilities and lectures about activities of each of the JINR laboratories for students.
- Planning of various supplementary schools for students of local universities during scientific conferences organized by JINR.

Great importance is given to the educational and training program for guaranteeing new highly qualified generations of researchers, technicians and engineers, well trained for meeting the challenges of the future. Competing with Industry on salaries and benefits, in Russia and abroad, is a challenge.

Moreover, JINR plans to develop a strong, innovative and bright outreach program meeting the world-class standards of this new field of communication. The outreach service that provides an accurate and appealing information to a wide audience is understood nowadays to be inevitable.

Furthermore, for the numerous international projects of JINR and their national and international collaborators, special efforts will be made to constantly improve a user-friendly environment on site at JINR.

## Conclusion

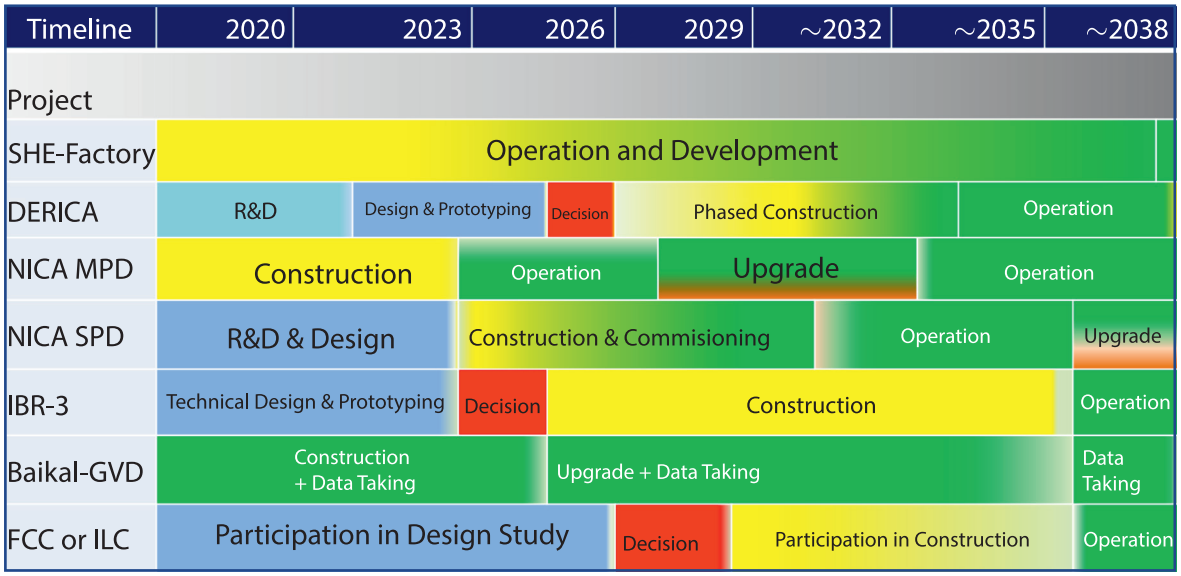
This JINR Strategic Long-Range Plan sees a vigorous determination of this Institute to stay at the forefront of Science in the chosen fields of Basic Research. For that, several new facilities are proposed or under construction, such as the

- Super Heavy Element Factory,
- NICA facility with its fixed target program and the collider mode for Heavy Ion collisions,
- NICA facility for Spin Physics with polarized beams,
- Neutrino telescope Baikal-GVD,
- New Pulsed Neutron source based on a high-intensity pulsed neutron reactor IBR-3 with Np-237 core,
- Irradiation facilities for material science and biophysics and radiation biological experiments,
- New Rare Isotope Facility DERICA,
- Biomedical Research Center for Proton Therapy,
- Continuous expansion of "Govorun" supercomputer and creation of a dynamically growing IT platform, which responds to the rapidly developing IT world.

In addition, JINR participation in forefront external experiments off-site, in Heavy Ion Physics, Particle Physics and Neutrino Physics will be continued, if the discovery potential of the experiments is high and if JINR researchers can play a leading role. The proposed plan foresees a continuation of participation in experiments at accelerator centers around the world (CERN, BNL, DESY, FAIR, GSI) and in Neutrino experiments, recognizing the mutual benefit from the exchange of data, of new scientific technologies and of theoretical know-how. Special recognition is given to the strong collaborations on the detector and accelerator projects of JINR with GSI and the international FAIR facility in Germany, as well as with CERN, benefitting strongly all partner institutes.

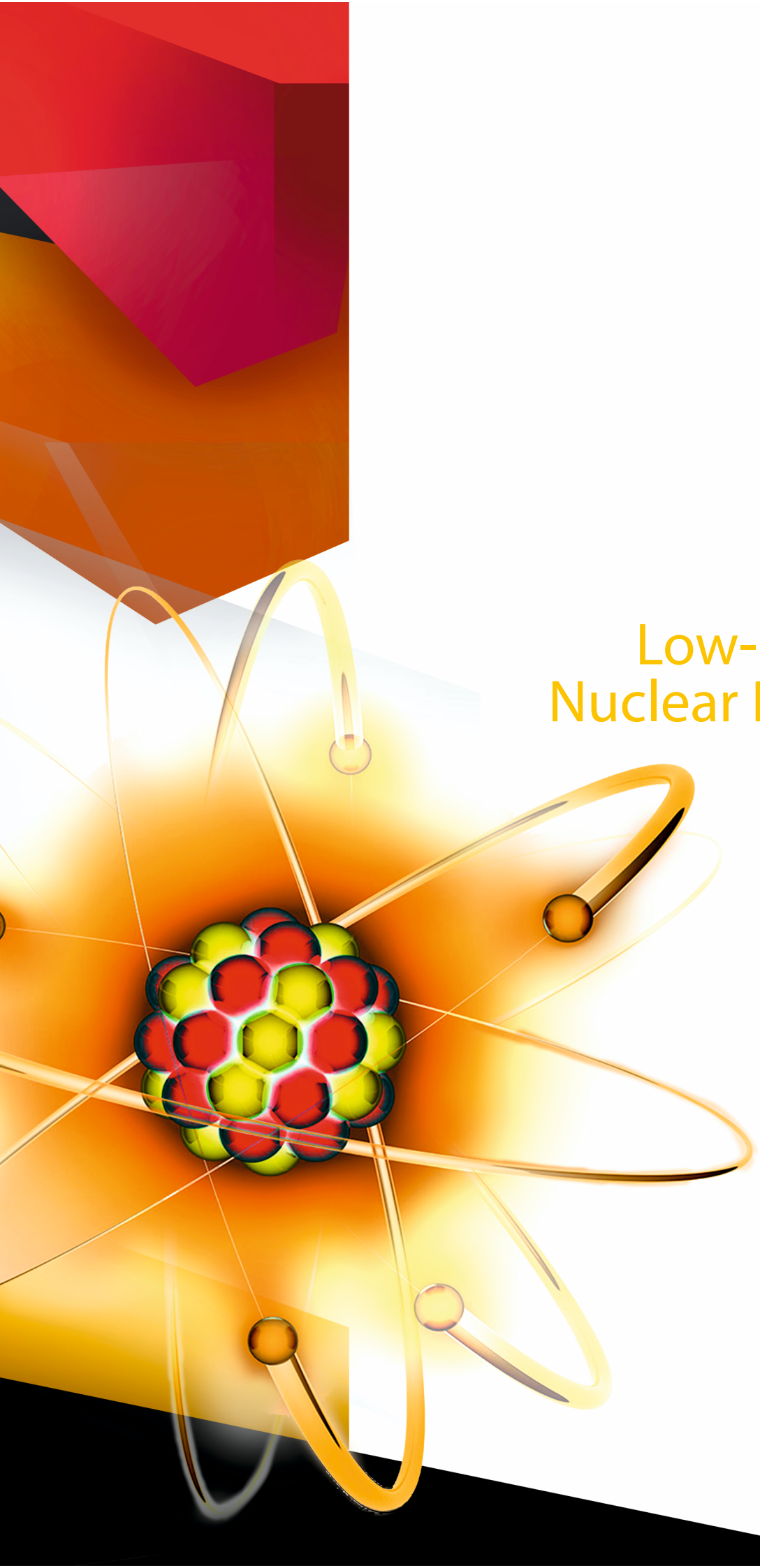
Furthermore, the Institute will take all measures for strengthening its expertise in latest technologies, e.g., in micro-electronics, ASIC-chip design and in detector design, as well as material research and accelerator technologies, not to forget the human resources for reaching these goals.

Large efforts are planned for the educational and training program to assure continuous expertise and know-how needed for meeting the scientific and technical challenges ahead.





JINR Long-Term Development Strategy up to 2030 and Beyond



# 1

# Low-Energy Nuclear Physics

## Executive Summary

Since its foundation and up to now, the main direction of scientific research of the Flerov Laboratory of Nuclear Reactions (FLNR) of JINR has been the worldwide recognized synthesis of new elements of the Mendeleev Periodic Table, the study of their properties, via nuclear spectroscopy ($\alpha$-, $\beta$-, $\gamma$-spectroscopy) and via chemical analysis.

The pursuit of this research will also be the main part of FLNR's program for the next decade: looking for the limits of the existence of nuclear matter by focusing on the boundaries of the island of stability of superheavy elements (SHE). For that endeavour, a SHE Factory is planned based on the DC-280 heavy-ion cyclotron, the world's top accelerator among others of the same type. Substantial increase (dozen times) in the efficiency of experiments is needed for the synthesis of the heaviest elements 119 and 120 and for the study of nuclear and chemical properties of already known elements. On the detection side, the new gas-filled recoil separator (DGFRS-II) and other future setups installed at the SHE Factory will play an important role. The construction of a specialized complex comprising radiochemical laboratories of Class 1 certification for the manufacture and regeneration of highly radioactive targets as well as a new 28 GHz ECR source is foreseen, completing the SHE Factory.

FLNR's research program has been expanded into the region of neutron-rich isotopes of superheavy elements near the island of stability, since the neutron shell $N = 184$ should have a stabilizing effect on the nuclear lifetime. In addition, the hypothetical closed shell at $Z = 114$ should also be of maximum support for the synthesis of nuclei with the number of neutrons close to 184. We propose to reach the neutron excess not by using beams of neutron-rich radioactive nuclei, because of their low intensity, but rather by using more neutron-rich target nuclei (e. g., $^{251}$Cf). In target production, our international collaboration is of great importance and will be pursued further.

Another ambitious scientific goal is measuring the masses of SHE and this laboratory is planning for a special mass detection system, consisting right after the target of a pre-separator, followed by a cryogenic gas ion catcher and a time-of-flight mass spectrometer.

The JINR FLNR experimental program in the field of SHE for 2024–2030 is aimed at studying the properties of the radioactive decay and the structure of isotopes of heavy and superheavy elements as well as chemical properties of SHE using the new DC-280 accelerator, the DGFRS-III setup, and corresponding detections systems.

Multi-nucleon transfer reactions in near-barrier collisions of actinides are promising in synthesizing new neutron-rich isotopes of heavy and superheavy elements. These reactions can lead to the formation of neutron-rich superheavy nuclei, inaccessible via fusion reactions. This method allows the synthesis of a number of new isotopes of light superheavy elements, up to the beta-stability line. Unfortunately, no universal detector

concept exits; however, FLNR is looking into the use of the existing detectors like SHELS, MAVR, and CORSET as well as development of new ones.

Radioactive ion beam (RIB) facilities allow the study of exotic nuclear systems remote from the $\beta$-stability line. At low energies, the FLNR is pursuing an experimental program on relatively light exotic nuclear systems at the fragment separators ACCULINNA-1 [38] and COMBAS, installed on the primary beam line of the U-400M cyclotron. Recently, the new-generation separators, ACCULINNA-2 and MAVR, have been put into operation. ACCULINNA-2 is a fragment separator installed at the U-400M cyclotron to produce in the "in-flight" mode the secondary beams of radioactive exotic nuclei. This allows studies of nuclear haloes, neutron skins, cluster states, of exotic multi-neutron decays (2-nucleon virtual states, 2*n*- and 4*n*-radioactivity), two-proton radioactivity, search for new magic numbers and spectroscopy of exotic nuclei, reactions with halo nuclei. Further development of the RIBs research program is seen in extension of available primary beams.

In material research and technology, high-energy heavy-ion beams have been proven to be powerful tools for material modification and are being widely used in radiation solid state physics. An important feature of heavy ions is the possibility of tailoring micro- and macroscopic properties of materials and creation of nano-dimensional structures. High damage production rates, typical for energetic heavy ions, open a way for rapid simulation of radiation damage produced by neutron irradiation in materials showing promise for nuclear applications. FLNR accelerators of heavy ions U-400 and IC-100 opened up unique opportunities for experimental researches in an energy range 1–20 MeV/A for ions from B to Bi.

Finally, all these research topics require a strong development of the experimental infrastructure, outlined further down. The first-priority project of the SHE Factory at FLNR will be a worldwide unique facility complementing the top nuclear physics facilities at GSI in Germany, RIKEN in Japan, BLNL in USA, and GANIL/SPIRAL 2 in France. Modernization and development of other FLNR's accelerator complexes (U-400M and U-400R) will allow realizing a highly demanding experimental program on the world-top level.

With this long-range program, FLNR intends to stay at the forefront of nuclear physics and wants to provide state-of-the-art research in nuclear physics for the member states of JINR and the international nuclear physics community.

## The main areas of nuclear research at FLNR

The research program of the Flerov Laboratory of Nuclear Reactions is, on the one hand, continuing on the successful Past; on the other hand, it takes on the challenge to stay at the forefront of nuclear physics research by strengthening its existing program and by opening up for great opportunities in nuclear physics research.

The main areas of nuclear research at FLNR are and will be the following:

— Synthesis of heavy and superheavy elements and study of their properties;
— Study of the properties of light exotic nuclei near the borders of nucleon stability;
— Study of nuclear reaction mechanisms leading to the formation of heavy and superheavy elements and the analysis of reactions with radioactive nuclei.

The development of the FLNR experimental infrastructure under the Seven-Year Plan of 2017–2023 (see Fig. 1) foresees the construction of three main accelerator complexes

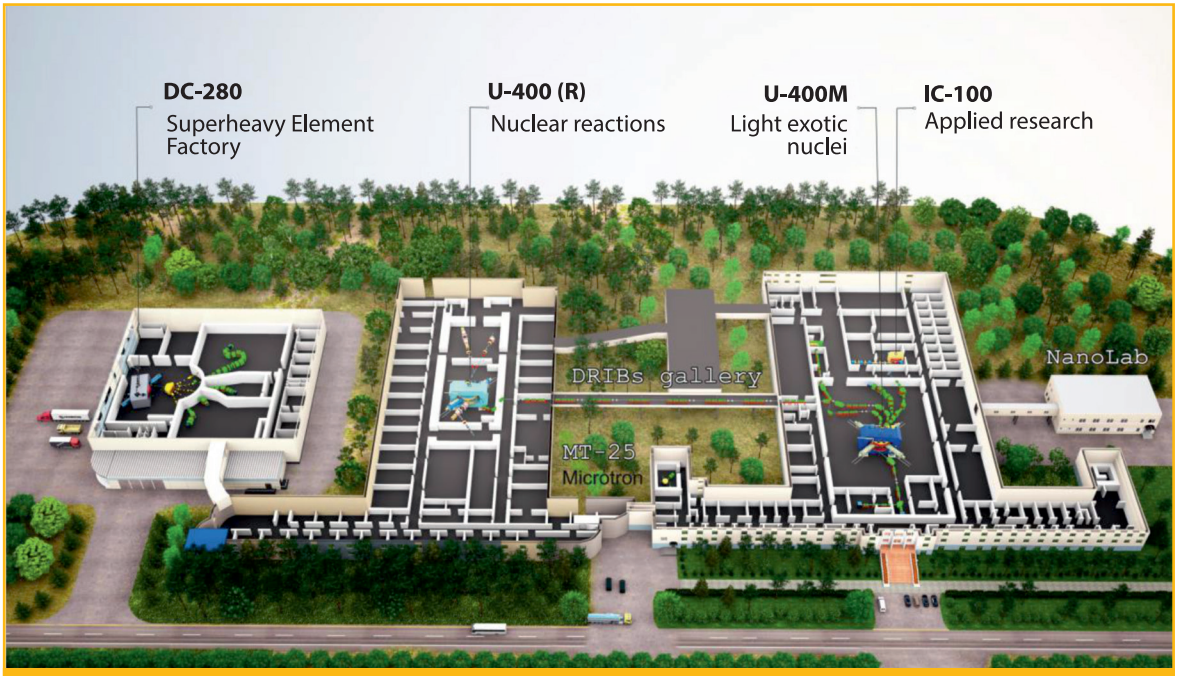



**Fig. 1. The layout of the FLNR accelerator complexes**

equipped with modern experimental setups meeting the goals of the FLNR research program. Each of the accelerator complexes will focus on the following physics tasks:

- SHE Factory based on the DC-280 accelerator: synthesis of heavy and superheavy nuclei and the study of their properties;
- U-400M accelerator complex: study of light exotic nuclei;
- U-400R accelerator complex: study of nuclear reactions.

## Synthesis of heavy and superheavy nuclei and study of their properties

The main direction of scientific research of FLNR since its foundation and up to now is the synthesis of new elements of the Mendeleev Periodic Table and the study of their properties. Particular attention was given to the synthesis of superheavy elements as well as their search in nature. These studies are primarily interwoven with the question of the limits of the existence of nuclear matter as well with the determination of the boundaries of the *Island of stability of SHE*, a hypothetical region of the nuclear map where long-lived isotopes of SHE could be found.

One of the greatest JINR achievements of last years was the discovery of six heaviest elements of the Mendeleev Periodic Table in hot fusion reactions using the $^{48}$Ca beam and actinide targets (see review [*Oganessian Yu. Ts., Utyonkov V. K.* // Rep. Prog. Phys. 2015. V. 78. P. 036301] and references therein). The priority for the discoveries of five of them was assigned to an international collaboration of JINR with the Livermore and Oak Ridge National Laboratories (USA). These include flerovium (Fl, 114), moscovium (Mc, 115), livermorium (Lv, 116), tennessine (Ts, 117), and oganesson (Og, 118).

Substantial increase (dozen times) in the efficiency of experiments is needed for the continuation of the research program in the field of SHE. This includes: synthesis of yet unknown elements with atomic numbers $Z$ = 119, 120, and heavier, synthesis of new iso-



**Fig. 2. DC-280 cyclotron of the SHE Factory**

topes of SHE, study of nuclear and chemical properties of already known elements, etc. A big step forward in this research will become possible through the construction of the world's first Factory of Superheavy Elements at JINR. The Factory will become a world base for future studies of superheavy nuclei and will reinforce the priority of all the JINR member states as leaders in the field of synthesis and study of superheavy elements.

A key element of the SHE Factory is the DC-280 heavy-ion cyclotron ( Fig. 2), the world's top accelerator among others of the same type. The accelerator was designed at JINR and manufactured with the participation of many JINR member states. The design beam intensity of accelerated $^{48}$Ca ions is 10–20 pμA, which is much higher than those attained at currently existing accelerators.

The first experimental setup of the SHE Factory is a new gas-filled recoil separator, DGFRS-II (Fig. 3). A key feature of the setup is the high efficiency of the collection of superheavy nuclei (over 60%), which is twice the one attained with the previous separator. Another setup installed at the SHE Factory will be a special gas-filled separator (DGFRS-III) equipped with two specialized channels for nuclear spectroscopy of SHE and for studying their chemical properties. Further development of the SHE Factory will expand the capacity of the acceleration complex to implement its experimental program.

Another important direction of research in the field of SHE concerns investigation of mechanisms of nuclear reactions leading to formation of SHE, especially to their neutron-enriched isotopes, which are expected to be the most stable ones.

Promising studies in the synthesis and study of SHE were discussed at a number of conferences and workshops. The main tasks in SHE research addressed during the discussions are:

- Elements beyond $Z = 118$; expansion of the Periodic Table;
- Nuclides beyond $^{294}$Og; expansion of the chart of the nuclides;
- Connecting "hot-fusion" and "cold-fusion" regions;
- Chemistry (well) beyond the standard Periodic Table;

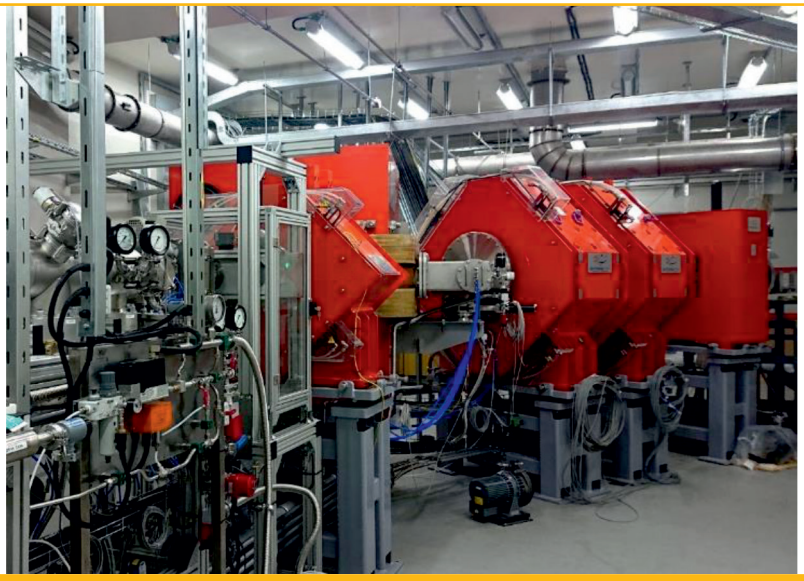


Fig. 3. DGFRS-II of the SHE Factory

- Excursion into the $N = 184$ region of longer-lived superheavy elements;
- Pinning down the presence of exotic topologies;
- Delineating the role of superheavy nuclei in the Cosmos.

The bulk of the open issues are expected to be successfully resolved at the SHE Factory of JINR.

## Synthesis of new elements

Among the above-mentioned research directions, synthesis of new elements 119 and 120 is of highest importance and will certainly become the SHE Factory's top priority. According to theoretical predictions, the $^{249}Bk + {}^{50}Ti \rightarrow {}^{299}119^*$, $^{249-251}Cf + {}^{50}Ti \rightarrow {}^{299-301}120^*$, and $^{248}Cm + {}^{54}Cr \rightarrow {}^{302}120^*$ reactions are most promising for the synthesis of elements 119 and 120 (Fig. 4).

The expected cross sections are of several dozens of picobarns. The experimental program aimed at synthesizing even heavier elements will be tailored to the results of experiments on the synthesis of elements 119 and 120 planned for the next seven years.

**Required experimental equipment**: The task can be fulfilled at the SHE Factory using gas-filled recoil separator (DGFRS-II).

## Synthesis of new isotopes of already known superheavy elements (Expansion of the chart of nuclides)

The expansion of the region of known nuclei towards both neutron excess and neutron deficiency is extremely promising and crucial to understanding the properties of superheavy nuclei located near the island of stability. An interesting region of the nuclide chart (Fig. 4) is located among isotopes synthesized in "cold" and "hot" fusion reaction. This part of the nuclide chart was shown [*Zagrebaev V. , Karpov A., Greiner W.* // Phys. Rev. C. 2012. V. 85. P. 014608] to be filled through "ordinary" fusion reactions with a $^{48}Ca$ beam and more neutron-deficient targets than those that have already been used ($^{233,235}U$, $^{239,240}Pu$, $^{241}Am$, $^{243}Cm$, and others). Cross sections are expected to be on the order of 1 pb, which is high enough for an experimental study.

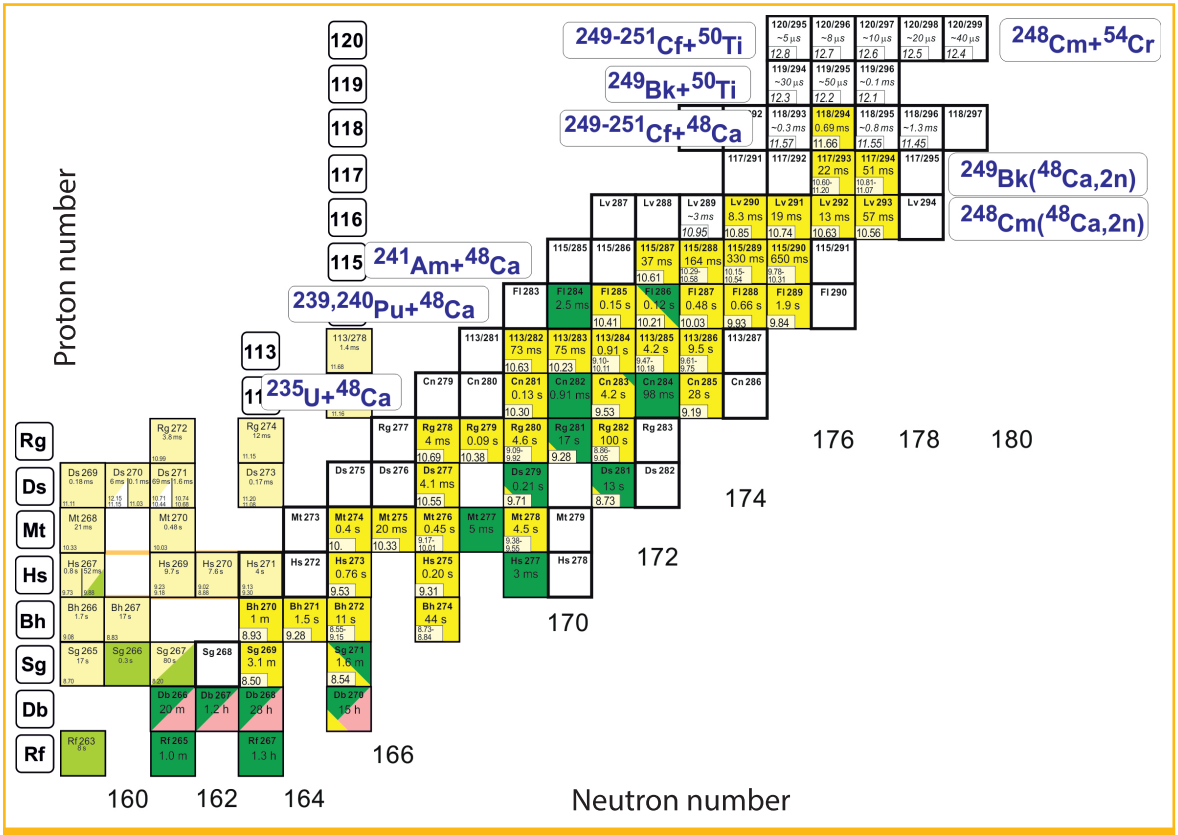



**Fig. 4. Upper part of the nuclide chart. New nuclides that can be synthesized in the above reactions are marked with white squares. $^{283}$Fl decay results in the known $^{71}$Hs isotope**

**Required experimental equipment**: The task can be fulfilled at the SHE Factory using gas-filled recoil separator (DGFRS-II).

## Synthesis of neutron-rich isotopes of superheavy elements (Journey towards the region of longer-lived superheavies)

Experiments reaching the region of neutron-rich isotopes of superheavy elements in the vicinity of the island of stability are of great importance. The properties of neutron-rich nuclei are of particular interest as they should most strongly manifest the stabilizing effect of the neutron shell $N = 184$. In addition, the effect of the hypothetical shell $Z = 114$ should also be at its maximum for nuclei with the number of neutrons close to 184. Studying systems with higher neutron excess can be achieved using beams of neutron-rich radioactive nuclei. As of today, however, the use of radioactive beams for these purposes seems not to be very promising due to their low intensity compared with the intensities of beams of stable nuclei, on the one hand, and because of the lack of the increase in the fusion-survival cross section during the transition to radioactive beams, on the other [1]. Thus, a more promising path to the synthesis, in our opinion, is via:

- ***Using more neutron-rich targets***

The shift of 1–2 neutrons to the right is still possible in fusion reactions with the use of more neutron-rich targets (for example, $^{251}$Cf). The cross sections for the formation of a new isotope $^{296}$118 calculated in [2] in a 3*n* channel of the $^{48}$Ca + $^{251}$Cf fusion reaction were about 1 pb.

**Required experimental equipment**: The task can be fulfilled at the SHE Factory using gas-filled recoil separator (DGFRS-II) and neutron-rich targets.

- ***Focusing on the 2n channel of fusion–fission reactions***

Another way for possible shifting by 1 neutron to the right is the synthesis of superheavy nuclei in projectile–target combinations employed earlier, but focussing onto the 2*n* evaporation channel instead. According to the calculations, this should lead to a several-fold (~ 2–4) reduction in the cross section (compared to the one in the 3*n*–4*n* channel), which is however still within the capacities of the SHE Factory.

- ***Measuring electron capture decay***

One of the main decay modes of the isotopes of superheavy elements located to the right from those synthesized earlier was predicted to be the electron capture [3]. This is due to the close proximity to the closed shell $N = 184$ and, as a consequence, to a drastic increase in the half-lives of spontaneous fission and alpha decay. Sequence of electron capture decays may allow to shift shifting towards the region of beta-stable SH nuclei, which are expected to be the most long-lived.

Obvious difficulties in the experimental identification of electron capture events impede the immediate implementation of this scheme in full. However, the possibility of producing neutron-rich superheavy nuclei (due to the decay of protons into neutrons) and even (!) approaching the centre of the island of stability — one of the most crucial objectives of SHE studies — makes experiments aimed at searching for not-yet-observed electron capture in this region of the nuclide chart quite promising.

**Required experimental equipment**: The task can be fulfilled at the SHE Factory using gas-filled recoil separator (DGFRS-II) and neutron-rich targets.

- ***Studies of pxn and αxn channels of fission–fusion reactions***

One of the ways of advancing in the region of neutron-rich SHE can be based on the detection of evaporation residues produced during the emission of a charged particle (proton or alpha particle) and several neutrons. First experiments on the detection of survival products in *pxn* channels conducted for the $^{50}$Ti + $^{209}$Bi reaction proved the efficiency of the method [4].

Thus, during the irradiation of the actinide target $^{248}$Cm with $^{48}$Ca in *p*2*n* and *p*3*n* channels, neutron-rich isotopes of moscovium ($^{293,294}$Mc) can be produced.

In the region of excitation energies from 40 to 45 MeV, survival cross sections for channels with proton evaporation are expected [5, 6] to vary from 1 to 10% of the cross section for the production of evaporation residues in *xn* channels, depending on the reaction. For *αxn* channels, the values vary from 0.3 to 10%. The corresponding cross sections can be obtained experimentally using high-intensity beams of $^{48}$Ca at the SHE Factory.

**Required experimental equipment**: The task can be fulfilled at the SHE Factory using gas-filled recoil separator (DGFRS-II).

- ***Multi-nucleon transfer reactions***

The reactions of multi-nucleon transfers during deep-inelastic collisions of heavy ions with energies near the Coulomb barrier were considered as a method for producing new nuclei since the discovery of this type of nuclear reaction in 1966 by Volkov et al. The interest in deep-inelastic transfer processes that has grown in recent years is caused, first of all, by the widely discussed possibility of synthesizing unknown neutron-rich medium-mass nuclei, as well as heavy and superheavy nuclei. One of the main objectives of

the study of such nuclei is a detailed understanding of the astrophysical r-process, which proceeds through neutron-rich nuclei far from the line of β-stability. Such nuclei located in the vicinity of closed neutron shells form the so-called waiting points of the r-process. Knowledge of the properties of these nuclides plays a key role in modelling the r-process.

One of the least studied regions of the nuclide map is located near the neutron spherical shell $N = 126$. This is due to the low values of the cross sections for fragmentation reactions, the only method for the synthesis of neutron-enriched nuclei in this area that has been used to date. Since the fragmentation cross sections rapidly decrease with each step in the direction of the neutron excess, the search and study of alternative effective methods for producing these nuclei is an urgent task.

Multi-nucleon transfer reactions in near-barrier collisions of actinides ($^{238}$U beam on the heaviest available actinide target) are predicted to be promising in synthesizing new neutron-rich isotopes of superheavy elements. In these collisions, the formation of compound nuclei is certainly impossible, but the time of contract can be long enough to cause transfer of a large number of nucleons. Cross sections for the formation of cold nuclei [7] thus exceed a threshold value at 1 pb only in the region of light superheavy nuclei ($Z = 104–108$). An important feature of multi-nucleon transfer reactions is that they lead to the formation of neutron-rich superheavy nuclei inaccessible via fusion reactions, which allows the synthesis of a number of new isotopes of light superheavy elements, up to the beta-stability line.

Low-energy collisions of actinides are of interest because of the possibility to observe spontaneous electron–positron emissions when forming a nuclear molecule possessing an overcritical electric field. The fundamental process of quantum electrodynamics was predicted over thirty years ago [8] but has not yet been experimentally confirmed. Another interesting phenomenon expected for these reactions is triple quasi-fission forming two strongly coupled fragments in the lead region [9, 10].

The experimental study of multi-nuclear transfer reactions involves a fair number of difficulties owning to a great variety of reaction channels and special features of their kinematics (wide angular and energy distributions of products). Existing experimental setups worldwide used for the study of nuclear reactions with heavy ions have severe limitations. A complete study of multi-nucleon transfer reactions should comprise the determination of the energies of reaction products, their charges, masses, and angles of scattering. The register of corresponding particles (neutron, gamma) is also desired.

The complete picture of the process illustrated in a single experiment is hampered by lack of cutting-edge experimental setups. R&D programs should be started to develop and define a dedicated detector setup for heavy-ion reactions at these low energies, covering most of the phase space of the reaction products. The following FLNR setups located at the U-400(R) experimental hall can be used at present and can be part of upgraded setups in the future for the program of studying the multi-nucleon transfer reactions:

(1) SHELS for the measurement of reaction product yields and their energy distributions at forward angles;
(2) MAVR for the measurement of yields of light reaction products in wide angular and energy ranges;
(3) GALS for the measurement of integral cross sections for the production of fragments with lose of information on the reaction kinematics (emission angles and energies);
(4) CORSET for the study of the kinematics of reactions allowing the determination of the masses of primary fragments formed in reactions in wide angular and energy ranges. The main limitations of the setup: it cannot measure the charge of the fragment;

uncertainty in mass measurements (about 4 a.m.u.), and the lack of information on survived reaction products.

In addition, new setups can be constructed, such as:

(1) Velocity filter on a turntable platform allowing working at different angles.

(2) Telescope for measuring time-of-flight, energy and angles of the products of binary reactions of heavy ions and for the identification of daughter nuclei after the beta decay.

Discussion, designing, and manufacturing of these setups will require several years. It is expected that they can be ready by the end of 2023–2024 so that they may start to work at the modernized U-400R cyclotron complex. The multi-nucleon transfer reactions for synthesis and study of heavy actinides and light superheavies can be conducted at the SHE Factory when the uranium beam is available there. This requires installation of an additional ECR ion source, which is planned for 28 GHz. This ion source is under development at FLNR and expected to be ready by 2024.

## Nuclear SHE spectroscopy

Once superheavy elements are synthesised and detected, more detailed information on their properties, like mass, decay channels, etc. is to be gathered. This will be possible by detailed studies of their decay properties (α-, β-, γ-spectroscopy) and by accurate mass measurements.

The spectroscopic data on isotopes of transuranium elements available at present is extremely limited (Fig. 5) and thus any new data especially in the SH mass region is of great interest and of great demand.

The spectroscopy of the isotopes of transuranium elements in the focal plane of the spectrometer (registration of alpha particles, gamma- and X-ray quanta, and conversion electrons) allows us to determine transitions from mother nucleus (ground state) to daughter nucleus (ground, excited and isomeric states), and transitions of isomeric states to ground and excited states in the mother nucleus.

To study the structure of heavy and superheavy elements, stopped in the focal plane, only one method for registration of nuclear radiation is applicable, which follows from the cross sections for the formation of nuclei at the picobarn level. It assumes detection with high-energy resolution of alpha particles and gamma quanta from the decays of ground and low-lying excited and isomeric states of both the recoil nuclei, implanted into the focal detectors of kinematic separators, and their daughter products.

The main experiments for studying the properties of the radioactive decay and the structure of isotopes of heavy and superheavy elements under the JINR FLNR experimental program for 2024–2030 will be conducted using the new DC-280 accelerator, the DGFRS-III setup, and the detecting system GABRIELA.

Using a cryogenic gas ion catcher is another promising approach to studying SHE properties. Such a catcher for separation of nuclei of SHE has its limits only in terms of separation time that is ~30 ms or longer. There are currently 31 isotopes of elements with $Z \geq 110$ with lifetimes of 30 ms or longer while the overall number of the known isotopes is 45.

All the isotopes of nuclei with $Z \geq 110$ synthesized and studied up till now are in the neutron-deficient region and thus can undergo $\beta^+$ decay and electron capture. Electron capture can be observed by registering characteristic X-rays emitted when outer-shell elec-

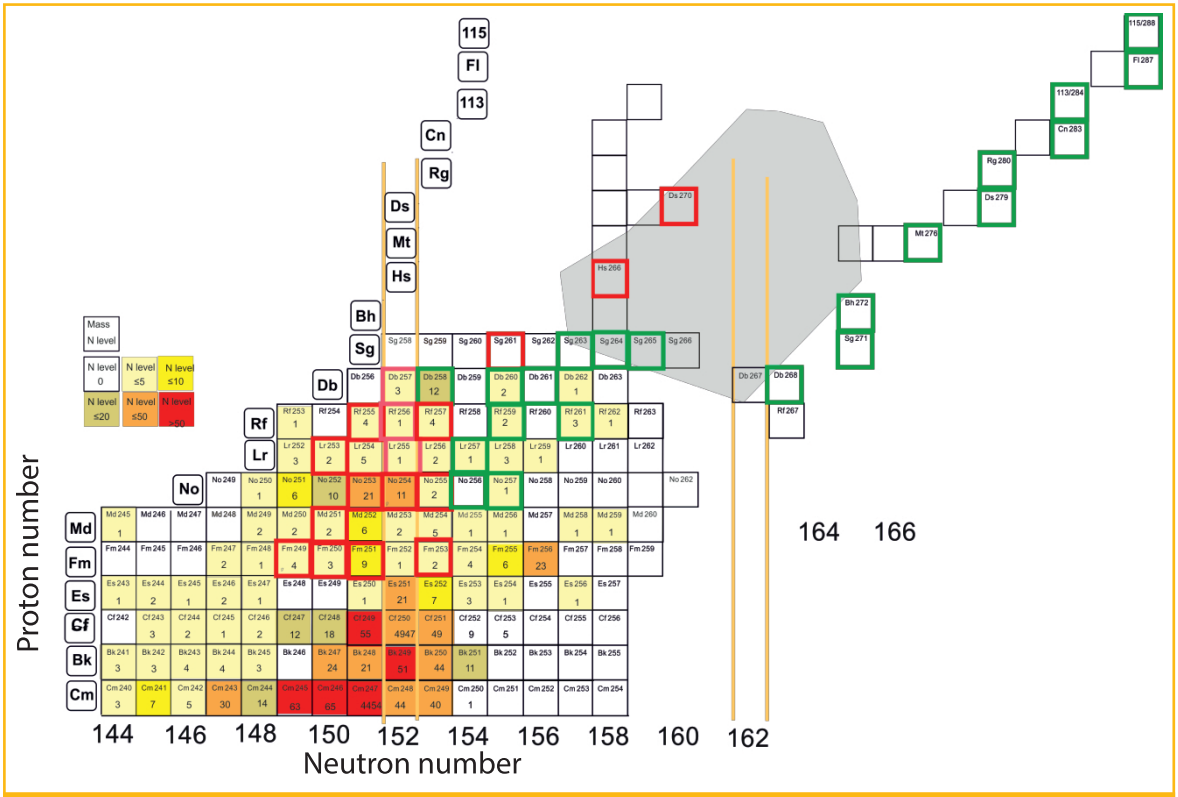



**Fig. 5. Spectroscopic data on isotopes of transuranium elements. The number of measured levels is shown by figures and is highlighted with colours. A small number of isotopes have been thoroughly studied to date (marked with red colour). Green colour is used to indicate isotopes whose spectroscopic properties are to be studied in scheduled experiments**

trons fill a vacancy (essentially a K-shell). As noted above, electron capture can both help synthesize unknown nuclei and advance into the region of a larger number of neutrons in these nuclei.

## Study of the chemical properties of superheavy elements

Relatively high stability of new superheavy nuclei opens up new avenues of enquiry in the study of the chemical behaviour of superheavy elements. It is interesting to compare the properties of SHE with the properties of their light analogues from the Mendeleev Periodic Table, thus evaluating a hypothesis about the influence of relativistic effects on the law of periodicity of chemical properties in the SHE region. The answer to this fundamental question is extremely important for the chemical identification of synthesized elements.

First results on the chemical identification and study of the properties of SHE with $Z = 112–114$ in the elementary state obtained at the FLNR U-400 accelerator complex revealed their high volatility and low chemical activity affecting the search for superheavy elements in nature. Detailed studies with higher statistical significance will continue at the SHE Factory.

The construction of a new experimental base at the SHE Factory within the current seven-year period (2017–2023) will become key to further work on the study of the chemical properties of SHE. The new infrastructure will comprise:

- New target assemblies for experiments at the DC-280 accelerator with the ion beam intensity up to 10 pμA;
- A pre-separator of nuclear reaction products for selective separation of isotopes of elements under investigation, which will considerably improve background conditions and the reliability of results;
- A gas ion catcher with speedy transport (30–40 ms) of reaction products, which will open up many new and exciting possibilities for exploiting the chemical properties of more short-lived isotopes of new elements.

New setups will allow investigations that today are out of reach of experimental techniques and will push existing technologies beyond current limits — one atom during one week of irradiation. Besides conventional experiments on the study of SHE properties in elementary states, new experiments on the study of the chemical compounds of the heaviest nuclei with $Z = 115–118$ and with ultra-short lifetimes (0.1–0.5 s) will be conducted.

Synthesis of SHE and the study of their properties require the construction of a specialized complex comprising radiochemical laboratories of Class 1 certification for the manufacture and regeneration of highly radioactive targets. Such a complex will add a "finishing touch" to the SHE Factory project and will become the JINR key infrastructure for its further development and the application of radioactive isotopes in other fields.

## Measurement of masses of superheavy atoms

The determination of the masses of superheavy nuclei (atoms) is very important both for further experimental studies in the field and for the development of theoretical models, including those defining the masses of as-yet-undiscovered nuclei. At present the only source of reliable experimental evidence on SHE masses is the alpha decay ($Q_\alpha$) measured with an accuracy of about 30 keV. In the case of decay from the ground state of the mother nucleus into the ground state of the daughter nucleus, $Q_\alpha$ allows us to determine the difference between the masses of these nuclei. Therefore, mass measurement of any of the nuclei in the alpha-decay chain with a precision of about 30 keV will give the masses of all the nuclei in the chain.

One of the most efficient and rapid techniques for measuring nuclei masses is based on the use of multiple-reflection time-of-flight spectrometers. The main parameters of the modern spectrometer are the following:

- mass resolution $M/\Delta M \leqslant 600\,000$;
- precision of mass determination ~ $10^{-7}$;
- measurement duration (time for multiple time-of-flight between the mirrors) ~ 10 ms;
- sensitivity of statistically significant data is ~ 10 ions;
- measurement frequency up to 400 hz;
- transmission efficiency up to 70%.

Figure 6 depicts a block diagram of the experimental setup. The setup comprises the following main elements: a target unit, a pre-separator for recoil nuclei (DGFRS-III), an ion gas catcher, and a mass spectrometer with a registration system complex in the focal plane. The elements currently lacking at FLNR are the gas ion catcher and time-of-flight mass spectrometer.

The gas ion catcher is under development at FLNR. We follow the design of one of the most efficient gas ion catchers, which was designed at GSI [11]. The working gas in the

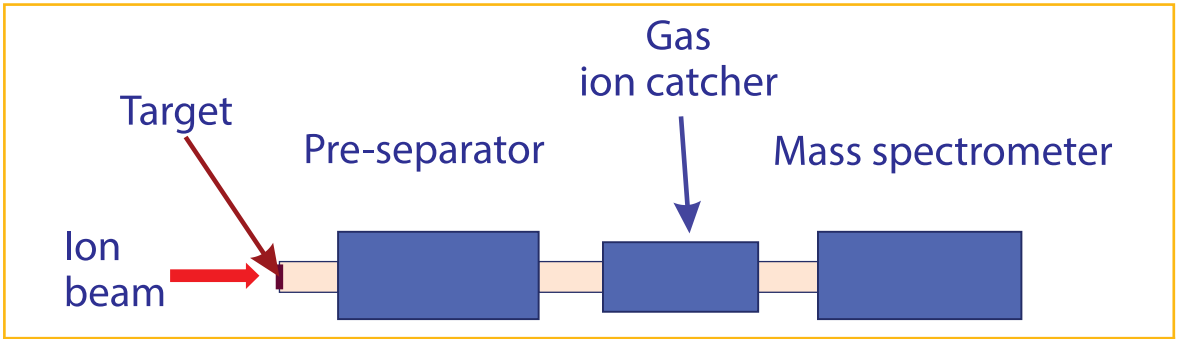



**Fig. 6. The block diagram of the setup for measuring the masses of SHE nuclei**

setup is cooled down to 40 K, without the necessity of ultra-deep gas purification. The extraction time of such a gas cell is ~30 ms with the efficiency up to 70% [12, 13]. Having these parameters, the MR-ToF MS is able to successfully compete with Penning traps for the atomic mass measurements with lifetimes at the level of a few seconds or shorter.

## Properties of nuclei far from the β-stability line

Radioactive ion beam (RIB) factories are well suited for the study of exotic nuclear systems remote from the β-stability line. The principal scientific goal of these facilities is the study of nuclei oversaturated with neutrons or protons, situated near or beyond the nuclear drip lines.

The experimental program on the study of relatively light exotic nuclear systems of the current and previous 7-year periods at FLNR has been carried out at the fragment separators ACCULINNA and COMBAS installed on the primary beam line of the U-400M cyclotron. Recently, the new-generation separators, ACCULINNA-2 (Fig. 7) and the high-resolution analyser MAVR, have been put into operation. ACCULINNA-2 is a fragment separator, installed at the U-400M cyclotron to produce in the "in-flight" mode the secondary beams

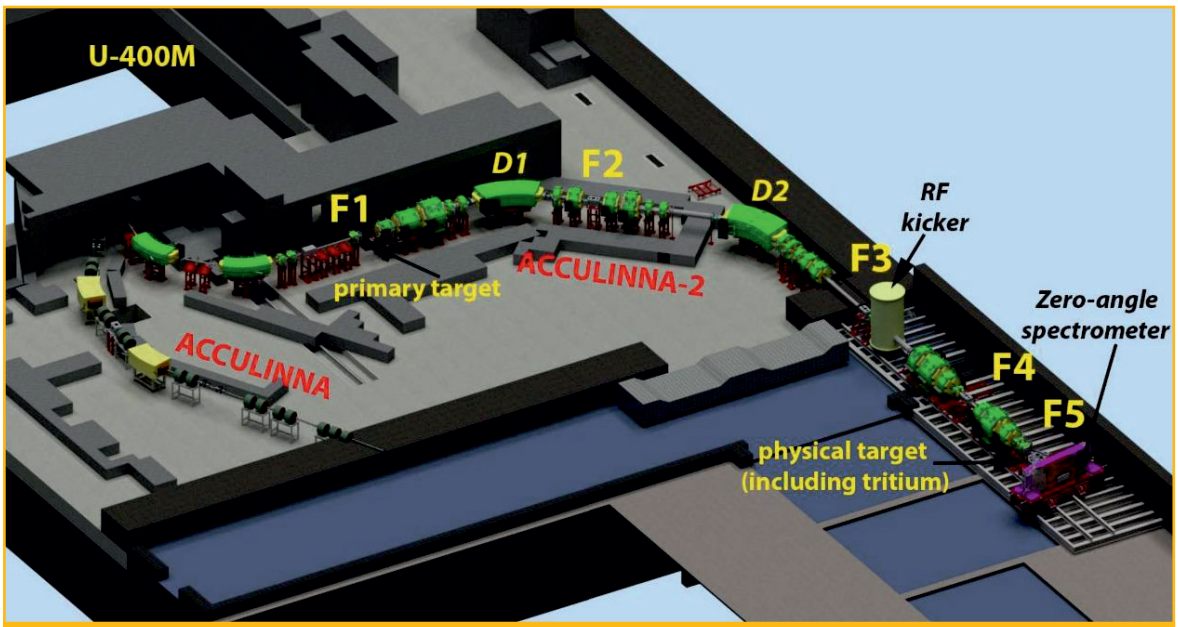



**Fig. 7. Layout of the fragment separators ACCULINNA and ACCULINNA-2 at the U-400M cyclotron**

of radioactive exotic nuclei. Fragment separator ACCULINNA-2 is equipped with a number of supplementary tools to be fully put into operation by 2023. These include:

- A vertically deflecting radio-frequency kicker (RF kicker) is installed just after the achromatic focal plane F3, providing additional purification of a secondary beam. For separation of charged reaction products, a zero-degree spectrometer is placed downstream of the physical target in the F5 focal plane. This will improve considerably the cumulative energy resolution of experiments with observation of beam-like products.
- By 2023 we expect to have put into operation a unique complex of a cryogenic gas target that will provide safe operation with gases (helium and hydrogen isotopes including tritium in gaseous or liquid states). The lowest temperature at the target cell should reach 11 K.
- Rare modes of decay of nuclei far from the stability line (two-proton radioactivity, β-delayed decays) are to be explored with a unique Optical Time-Projection Chamber (OTPC), allowing 3D reconstruction of the decay of an exotic nucleus to charged particles.

The development of new detector systems and mastering modern digital technologies include:

- New generation of micro-strip silicon detectors dedicated for tracking/spectroscopy experiments.
- Radiation-hard and extremely fast silicon detectors providing a very good time resolution σ ~ 50 ps) for TOF measurements and beam diagnostics.
- A multi-module array of neutron detectors on the base of stilbene crystals, scintillation fibres and conventional multi-layer plastic scintillator arrays for experiments on the study of decay correlations of neutron-rich nuclear systems.
- Arrays of CsI, $LaBr_3$ etc. crystals for the charged-particle and gamma-ray detection.

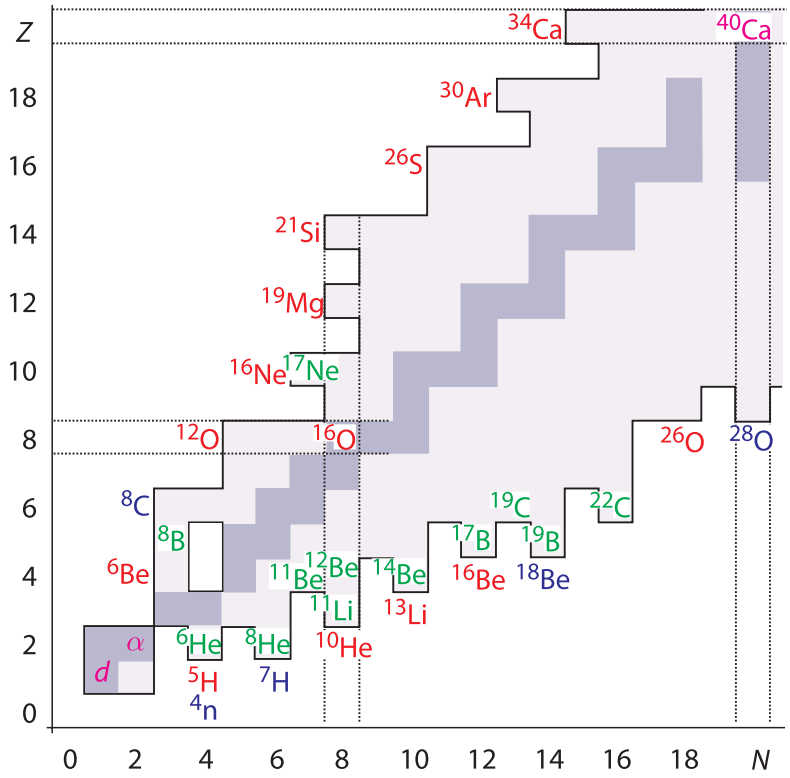



**Fig. 8. The lightest nuclei on the nuclide map. The well established nucleon drip lines are presented with thick solid lines. The stability valley is shown in bluish tone**

- New 4$\pi$ detection system DEMAS-MULTI comprising 90 $^{3}$He neutron counters, $CeBr_3$ scintillators and γ-clovers.

The ACCULINNA-2 separator yields RIB with intensities 20–30 times larger than the ACCULINNA separator launched more than 20 years ago. The performance of ACCULINNA-2 is analogous to that inherent to the RIPS (RIKEN) or LISE (GANIL) fragment separators, which were the landmark facilities of the previous generation of RIB arrangements. Modernization of the U-400M driver cyclotron (planned for 2020–2022) will give solid basis to the scientific program at ACCULINNA-2, meaning more stable delivery of a broader variety of primary beams of somewhat larger energy than today.

The domain of drip-line nuclei shown in Fig. 8 is accessible at the Flerov Laboratory today and in near future. It embraces a region of light nuclei where transfer reactions make an effective tool allowing reaching the neutron/proton drip lines.

## Nucleon haloes, neutron skins

Weakly bound few-body exotic systems show properties very different from those of the nuclei, which are not too far from the valley of stability. The halo phenomenon is important for a better understanding of nuclear structure close to the drip lines.

Along the neutron drip line, the relatively small enhancement of the total binding occurring for paired neutrons has important impact. Experiments giving new knowledge about the properties of the interleaving neutron-unbound nuclei should be put into the agenda of the research aimed at understanding the character of neutron–nucleus interaction far from stability, the coupling to the continuum in neutron-rich systems, and delicate structures inherent to the multi-neutron haloes or skins. Studies of the adjacent neutron-unbound odd-*N* nuclei could yield information on the nucleon orbitals important for the description of the heavier bound nuclei. Concerning the drip line, nuclei of beryllium, boron and carbon, the spectra of $^{13}$Be, $^{16}$B, $^{18}$B, and $^{21}$C are of special interest.

Nucleon knockout and the more conventional transfer reactions are complementary methods. While knockout reactions mainly probe hole strengths, the nucleon transfer reactions like (*d*, *p*), (*t*, *d*), (*t*, *p*) and ($^{3}$He, *d*) populate particle orbitals. Adding to the arsenal of methods the nucleon pickup reactions from the RIB projectile nuclei, e.g., reactions of the (*d*, $^{3}$He), (*p*, *d*), and (*p*, *t*) types, one can populate nucleon-hole states in exotic nuclei. The orbital angular momentum quantum numbers, the relative location of single-particle states, and spectroscopic factors are accessible in experiments employing direct reactions. Transfer reactions provide access to many excited states simultaneously, and their strong kinematic matching allows the optimum choice of reactions populating the nuclear states with orbital angular momentum of the interest.

## Exotic multi-neutron decays (2-nucleon virtual states, 2*n*- and 4*n*-radioactivity)

Beyond the drip lines, we get at the regions of strong nuclear instability. Here, in the region of light neutron-rich nuclear systems, the experimental observations could be especially confusing. In the absence of strong potential barriers the observables becoming typical for the neutron decays are often sensitive to the reaction mechanism. Also, the appearance of novel dynamics forms is not impossible here. These include the possible existence of hypothetical two-neutron virtual states [15] and two/four-neutron radioactivity [16]. The search for the few-neutron radioactive decays is inspired by the discovery of the two-proton radioactivity [41, 17]. In contrast with the situation coming across near

the proton drip line, the long-lived one-neutron emitters are practically impossible, while the 2*n*- and 4*n*-emitters may have quite long lifetimes, even falling in the radioactivity timescale. The discovery of such a novel type of radioactive decay is a challenging task requiring elaborate experimental approaches. At present time, the studies of nuclear systems with large neutron excess are active in different centres having intermediate-energy RIBs. Different authors published the results of their experiments devoted to the studies of the true two-neutron emitters $^{10}$He [18, 19], $^{13}$Li [20], $^{16}$Be [21], and $^{26}$O [22, 23].

The excitation spectra of $^{7}$H, $^{11–13}$Li, $^{13–16}$Be, $^{16–19}$B, etc. will be a first-priority task for the group of the ACCULINNA-2 separator. The study will include precise determinations of ground-state masses made for these nuclei. It is worth noting that currently none of the neutron separation energies is known to better than 10% for these nuclei. Transfer reactions of the (*t*, *p*) and (*d*, *p*) type, studied in inverse kinematical conditions, are the most suitable ones for the precise mass measurements.

## New magic numbers and intruder states

There are basic problems in the field of exotic nuclei where ACCULINNA-2 operates. One example is the ascertainment of the patterns associated with the closed-shell breakdown at the magic neutron number $N = 8$ and the manifestation of *s–d* intruder states in the neutron-rich nuclei $^{9,10}$He, $^{10,11}$Li, $^{11,12}$Be. Clarification of filling sequences arising in the *s–d* neutron shell in a number of neutron-excess nuclei (e.g., $^{15}$Be, $^{16,18}$B, $^{17,19}$C) and the interplay of *s*- and *d*-wave states in their even-*N* neighbours is another basic problem, which calls for thorough investigation. On the proton-excess side, similar phenomena call for the study of the possible two-proton halo structure, with a $^{15}$O core, predicted by theory for $^{17}$Ne. Of special interest is the termination of the *s–d* shell occurring in the C, N, O, F and Ne nuclei in the vicinity of neutron number $N = 16$. The 20–30*A* MeV beams of $^{24}$O, $^{26,27}$F, $^{28,29,30}$Ne provided at ACCULINNA-2 are well suited for studying resonant states of nuclei (e.g., $^{24–26}$O) lying near and beyond the drip line.

## Two-proton radioactivity

The upgrade of the U-400M cyclotron planned for the period 2020–2022 will open ways to the whole series of proton-rich nuclei with $Z \leq 36$, lying close and beyond the proton drip line. These include a number of nuclei predicted to exhibit 2*p*-radioactivity. Furthermore, great interest is in the dynamics of the 2*p* decay of resonant states, e.g., of $^{6}$Be, $^{12}$O, $^{16}$Ne, $^{26}$S, $^{30}$Ar, $^{48}$Ni, etc. The detection of the 2*p*-decay branch for the first excited state of $^{17}$Ne will clarify the issues related to the $Z = 8$ waiting point affecting the rp-process in the sites of hot stellar burning.

The properties of nuclei $^{21}$Si, $^{30}$Ar and $^{34}$Ca with half-lives shorter than 100 ps can be ascertained well due to the excellent choice of RIBs provided by the ACCULINNA-2/U-400M complex. In particular, the rare phenomenon of the β-delayed 3*p* decay of $^{31}$Ar [29] could be investigated in great detail. The quest for $^{21}$Si and $^{26}$S is challenging because it is very probable that the two-proton emission is the main decay mode of these nuclei. Quite detailed studies of the 2*p*-decay mode will be feasible for the nuclei having lifetime $T_{1/2} > 50$ ps. This becomes realistic because one can produce these nuclei in transfer reactions induced by RIBs. The (*p*, *d*)- and (*p*, *t*)-type reactions are favourable to cope with this task. For the $^{21}$Si and $^{26}$S nuclei, their formation and decay, occurring in flight, should be verified by the detection of the daughter nucleus and the two emitted protons.

## Spectroscopy of exotic nuclei

At ACCULINNA, a notable experiment series of transfer reactions via correlation techniques have been performed, and excitation spectra in exotic nuclei have been measured. Such a technique has been applied before to identify the spin-parity of excited states displaying the emission of spinless particles. In the experiments performed at ACCULINNA, the method was further developed [30, 31]. As is well known, highly aligned states are produced in direct reactions. In the rest frame of the exotic nucleus, formed as the reaction product, the highest degree of spin alignment is obtained in respect to the axis parallel to the transferred momentum vector. The decay of the aligned configuration may produce sharp correlation patterns. The interpretation of the observed correlations may appear to be unique, this was the case, for example, with the spectrum of $^{9}$He populated in the (*d*, *p*) reaction [32].

Typically, the resonance states of light drip-line nuclei (especially on the neutron-excess side) are broad and overlapping, and their correlation patterns are affected by interference. Therefore, even weakly populated states may become apparent due to the contribution made to the interference patterns. The addition of amplitudes acts in this situation as a kind of "quantum amplifier" giving access to the details of the spectrum which otherwise would be too complicated for their revelation.

## Cluster states

Many nuclei up to the *sd* shell are known to have cluster structures in the ground state and at excited states. Rotational bands with a well-expressed molecular structure, characterized by large deformation, have been observed. Good candidates for such studies are the heavy isotopes of He, B, C, O, Ne, etc.

The correlation measurements and the complete kinematics studies, discussed above, form the most common way for elucidating clustering aspect of nuclear dynamics. The importance of the Optical Time-Projection Chamber [33, 29] should be specially emphasized here. It gives opportunity to make complete kinematics measurements in experiments where the "useful" counting rates are just units and tens of events. This is important for the studies of exotic nuclear systems attainable with low production rates.

## Reactions with halo nuclei

Fusion reactions detected with the beams of halo nuclei have been of increased interest from experimental and theoretical points of view. In particular, much effort has been devoted to the subject of near-barrier fusion of light, weakly bound projectile nuclei. Unusual effects are expected here both from the halo structure of these nuclei and from the specific tunnelling mechanism of the composed weakly bound system which is of general interest for quantum theory. One example of this type of effects represents the recent study of the fusion reaction $^{6}$He + $^{206}$Pb carried out at DRIBs-3 [35]. Another example is the study of complete and incomplete fusion reactions of $^{6}$He and $^{6}$Li projectiles with $^{165}$Ho and $^{116}$Er target nuclei [36]. The upgraded DRIBs-3 complex will give higher intensity and higher quality beams of $^{6}$He nuclei and also a variety of other exotic beams ($^{8}$He, $^{9}$Li, $^{12}$Be, etc.), thus offering prospects for new insights into the process of low-energy fusion and multi-nucleon-transfer reactions of light exotic nuclei hitting against heavy targets.

## Astrophysical applications

Nowadays, the nuclear astrophysics research is an integral part of the novel forms of nuclear dynamics study. Finite nuclear matter is the only directly accessible "testing ground" for theoretical models that are meant to look into the states of the infinite stellar matter.

Nuclear reactions in stars involve short-lived proton-rich and neutron-rich nuclei that can be studied only with radioactive beams. The cross sections of interest have to be obtained indirectly by the study of resonance reactions made via inverse kinematics on hydrogen and helium target nuclei. Transfer reactions allow determining level schemes and spectroscopic properties of nuclear states. Peripheral transfer reactions are suitable for measuring the quantities called Asymptotic Normalization Coefficients (ANCs), determining stellar capture rates. Transfer reactions performed with the RIBs delivered by DRIBs-3, such as ($d$, $n$), ($d$, $p$), ($t$, $d$), ($p$, $d$), or ($^3$He, $d$) can be used to extract the proton spectroscopic factors, ANCs, or neutron spectroscopic factors in mirror nuclei.

Two-proton radiative capture along the rp-process path is poorly understood so far. This process is directly related to two-proton radioactive decay. Of great importance will be experiments around the critical waiting points $^{64}$Ge, $^{68}$Se, and $^{72}$Kr. The $^{15}$O waiting point is also important for the passage of the rp-process. The two-proton capture is a possible alternative to the ($\alpha$, $p$) reaction as a pathway for the rp-process allowing the search for a weak 2$p$-decay branch of the first excited $3/2^-$ state in $^{17}$Ne. Decay of this state via emission of $\gamma$ quanta, yet the two-proton decay was also predicted theoretically at the level $\Gamma_{2p}/\Gamma_{\gamma} \sim 10^{-5}$–$10^{-6}$ [37]. This assumption is still not confirmed experimentally [39, 40] but might be feasible with the use of intense $Z = 8$–$10$ radioactive beams provided by DRIBs-3.

## Material science studies with heavy-ion beams

High-energy heavy-ion beams have been proven to be powerful tools for material modification and are being widely used in radiation solid state physics. An important feature of heavy ions is the possibility of tailoring micro- and macroscopic properties of materials and creation of nano-dimensional structures. High damage production rates, typical for energetic heavy ions, open a way for rapid simulation of radiation damage produced by neutron irradiation in materials showing promise for nuclear applications.

FLNR accelerators of heavy ions U-400 and IC-100 opened up unique opportunities for experimental researches in an energy range 1–20 MeV/A for ions from B to Bi. Main directions of ongoing and planned investigations are:

- Simulation of fission product impact in nuclear reactor materials and inert matrix fuel hosts with heavy-ion beams of fission fragments energy.
- Study of surface modification and nanoscale damage formation on the surface of materials enhanced by single swift heavy ions in electronic stopping regime.
- Study of structural effects of dense ionization produced by swift heavy ions in radiation-resistant insulators.
- Elaboration of the basic principles of high-energy ion implantation technology — the study of gettering effects, modification of electrically active dopant profiles and defect structure evolution in semiconductive materials, induced by high-energy ions.

## Human resources

Development of the Laboratory projects will require increase of personnel from the existing staff of 450 persons to about 480–500 persons in the next 10 years, focusing mainly on increasing the engineering and technical staff. Therefore, close collaboration with leading technical universities and institutes is necessary for sustainable development of FLNR. In this respect, a recently signed agreement between JINR, the Bauman Moscow State Technical University and the Government of Moscow Region on establishment of a higher engineering school in Dubna based on the Dubna State University is of great importance. Furthermore, improving our user-friendly environment for national and international collaborators requires additional resources.

Other proven and also new methods of training and recruiting of personnel include:

- Supervision of practical, bachelor, master, and PhD works prepared by students studying at scientific and technical departments of universities from the JINR member states.
- Excursions to the facilities and lectures about activity of the Flerov Laboratory for students.
- Planning various supplement schools for students of local universities during scientific conferences organized by FLNR.
- Investing into development of the human capital and training of the employees in the world leading educational centers.

## General summary

Finally, during the next 7-year period of 2024–2030, the following is planned:

1. The first priority of the long-term development of FLNR is synthesis of SHE and their isotopes as well as study of their chemical and nuclear properties at the SHE Factory, including:

— Development of experimental facilities of the SHE Factory.
— Implementation of an experimental program in the field of SHE.
— Construction of a specialized complex comprising radiochemical laboratories of class 1 certification for the manufacturing and regeneration of highly radioactive targets used, first of all, for the SHE research.
— Development of a new 28 GHz ion source in order to, first of all, extend the list of ions available at the SHE Factory up to uranium.

The SHE Factory will become a world base for future studies of superheavy nuclei and will reinforce the priority of all the JINR member states as leaders in the field of synthesis and study of superheavy elements.

2. Other priorities of FLNR until 2030 are:

— Reconstruction of the U-400 accelerator complex, including the construction of a new experimental building, the modernization of the cyclotron to U-400R and the creation of new facilities for studying nuclear reactions with heavy ions. Implementation of the experimental program of the U-400R complex.
— Continuation of experimental research in the field of light exotic nuclei located at the borders of nuclear stability on the modernized U-400M cyclotron, using the ACCULINNA-2 fragment separator and the DRIBs complex to produce post-accelerated beams of radioactive nuclei.

Modernization and development of these FLNR's accelerator complexes, construction, in particular, of a unique cryogenic system for tritium and other gaseous target materials, will allow realization of a highly demanding experimental program on the world-top level.

3. Continuation of discussion of long-term plans for the development of the complex of FLNR scientific and technical facilities.

The majority of experiments currently carried out at FLNR are performed in a broad international collaboration with leading institutions from the JINR member states and beyond. This practice will be continued in future. The total available beam time of three FLNR's cyclotrons (DC-280, U-400R, and U-400M) is expected to be of about 15 000 hours annually. This will allow us to formulate a user policy and open the FLNR facilities for external users.

The FLNR budget necessary for implementation of the development and research program in the period of 2024–2030 should be in line with the Laboratory budget for the current 7-year period.

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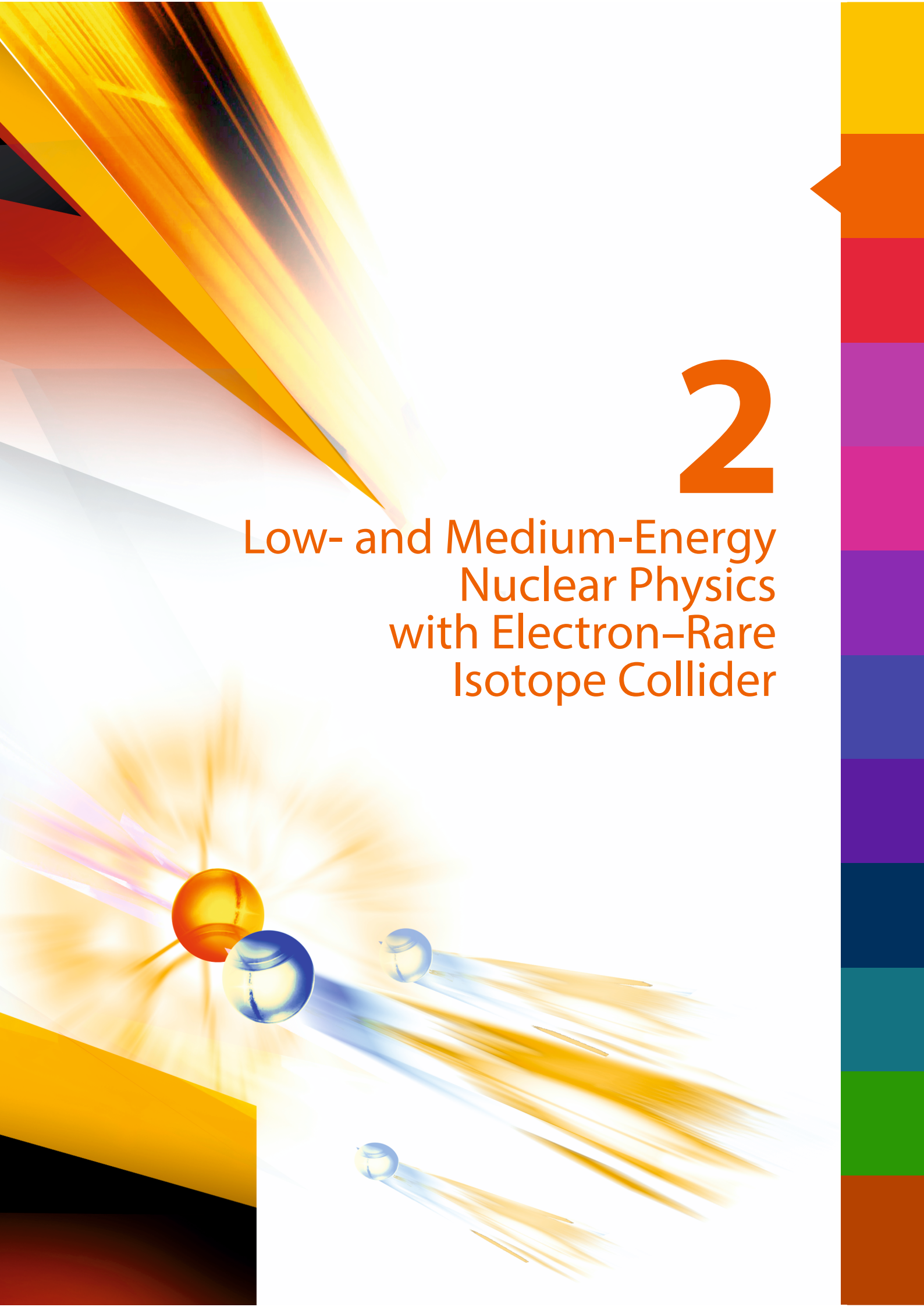
JINR Long-Term Development Strategy up to 2030 and Beyond

# 2

# Low- and Medium-Energy Nuclear Physics with Electron–Rare Isotope Collider



## Executive Summary

Within this long-range program, JINR looks at another Nuclear Physics program, heavily promoted in the world of nuclear physics in the last 3 decades. Beams of rare isotopes far off the line of nuclear stability would be complementing the study of superheavy elements pursued at the JINR Flerov Laboratory of Nuclear Reactions (FLNR), and would guarantee JINR staying at the forefront of nuclear physics and providing state-of-the-art research in nuclear physics for the member states of JINR and the international nuclear physics community.

The aim of the Rare Isotope Beam (RIB) studies is to provide full knowledge of the nuclear chart from nuclear-stable isotopes to the limits of nuclear structure existence. The information obtained from rare isotope studies is indispensable to resolve fundamental problems of nuclear physics (structure, reactions, origins of the nuclear forces) and nuclear astrophysics (nucleosynthesis, properties of the neutron matter).

Encouraged by leading international scientists of the NUSTAR community, JINR has decided to develop and build a powerful RIB facility DERICA (**D**ubna **E**lectron–**R**are **I**sotope **C**ollider f**A**cility) covering a broad range of modern nuclear physics aspects (new isotope synthesis and production, determination of its masses, lifetimes and decay modes, studies of nuclear reactions and spectroscopy). The **DERICA concept** combines in-flight production of RIBs by projectile fragmentation technique (primary beams up to uranium with energy ~ 100 AMeV), stopping RIBs by gas catcher, reacceleration by LINAC-synchrotron combination, and usage of reaccelerated RIBs for reaction studies. The emphasis of the project is **storage ring physic**s with ultimate aim of **electron–RIB scattering studies in the collider experiments**.

Elastic and inelastic electron scattering provides a powerful tool for examining nuclear structure. The most reliable evidence how nuclei actually look comes from electron scattering. However, up to now, the electron scattering studies are limited to stable isotopes. The aim of the DERICA project is to extend this powerful method, which has already provided enormous amount of information about the structure of stable nuclei, to the study of nuclei outside the "valley of stability". DERICA will be a unique and unprecedented tool for nuclear spectroscopy of rare isotopes, i.e., nuclei far from stability. For achieving that goal, the front end of the accelerator complex needs to produce beams of highest intensities. The strong R&D project initiated by JINR was launched several years ago to push the limit of beam intensities to much higher values than available now.

Empowered by the superheavy element research "SHE Factory" of FLNR and later by DERICA, JINR will become a worldwide unique facility complementing the top nuclear physics facilities such as FAIR (GSI) in Germany, RIBF (RIKEN) in Japan, FRIB (MSU) in the USA and SPIRAL2 (GANIL) in France.

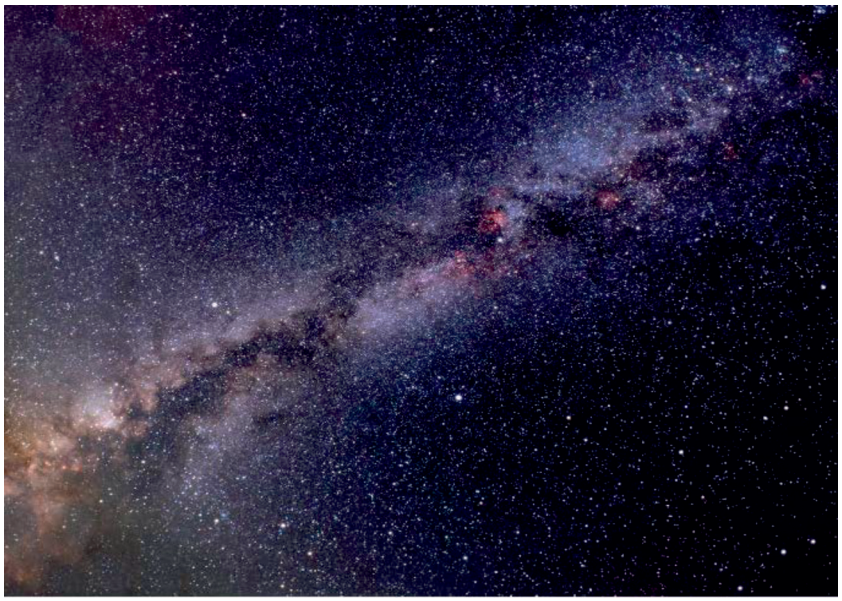
## Introduction

In 2012 the 100-year "anniversary of atomic nucleus" — the discovery of Ernest Rutherford — was celebrated. Although studied for more than a century, nuclear physics and nuclear astrophysics are today vibrant and still have many unanswered fundamental questions. Some of them are listed below:

- Can we explain the nucleon–nucleon force by the underlying QCD structure?
- There are powerful theoretical methods for studies of different aspects of nuclear structure (ab-initio, density functional, shell model). Could there be a unified theory of nuclear structure and nuclear reactions?
- Symmetries and phases of the nuclear matter and nuclear many-body systems are to be understood.
- New magic numbers emerge when passing away from the nuclear *stability valley*. How is the shell structure changing far away from stability? Does it actually persist at all?
- Where are the limits of *existence of nuclear systems*? Even beyond the limits of the nuclear system existence (nuclear stability), certain aspects of the nuclear structure may persist in continuum. Where are the limits of *existence of nuclear structure*?
- Study of exotic short-lived nuclei away from *stability valley* is very far from complete. New forms of nuclear dynamics arise far from the stability line, for example, proton/neutron halos and skins. Related questions about open quantum systems and few-body correlations arise here.
- What are the origins of the heavy elements? How does the synthesis of the elements take place in astrophysical environments?
- Physics of stellar explosions (core-collapse, thermonuclear supernovae, nucleosynthesis…): studies of these phenomena need extensive information about nuclei far from the stability valley.
- Emergence of the new collective modes far from stability line and their relation to nuclear matter and neutron star properties remains a challenging issue.

As part of the long-term program, JINR intends to open another program in nuclear physics, supplementing the study of superheavy elements. Actively promoted in the world of nuclear physics in the last 3 decades, **Rare Isotope Beam (RIB) facilities** continue to be built worldwide as the key tools for studying nuclear properties up to the limit of stability. The ultimate aim of the RIB studies is to provide full coverage of the nuclear chart for nuclear-stable isotopes and to advance our knowledge to the limits of the nuclear structure existence. The information obtained in the RIB studies is indispensable to resolve fundamental problems of nuclear physics (masses, radii, structure, lifetimes, reactions, origins of the nuclear forces) and nuclear astrophysics (nucleosynthesis, properties of the neutron matter). Elastic and inelastic electron scattering provides a powerful tool for examining nuclear structure. The most reliable evidence of how the nucleus actually looks comes from electron scattering. However, up to now, the electrons scattering is restricted to stable isotopes.

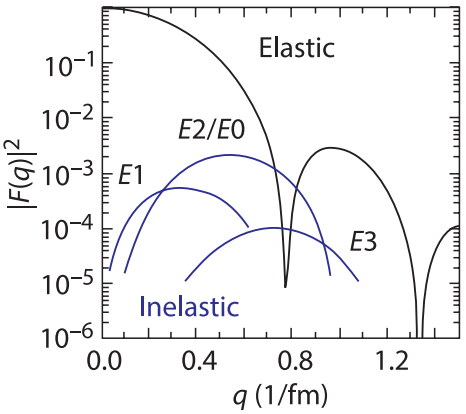
Masses and the radial quantities are the most important characteristics of the nuclei. Just a bit more than 100 years ago a variety of odd speculations were produced by scientists on the way to understand where from the stars take the energy for their shine. When the masses of nuclei were precisely measured, this knowledge immediately emerged as granted. The "mass defect" in the nuclear synthesis reactions was only of the order $10^{-3}$ of the participant masses. However, according to Einstein's relation $E = Mc^2$ these tiny values were converted into formidable amounts of radiative energy.



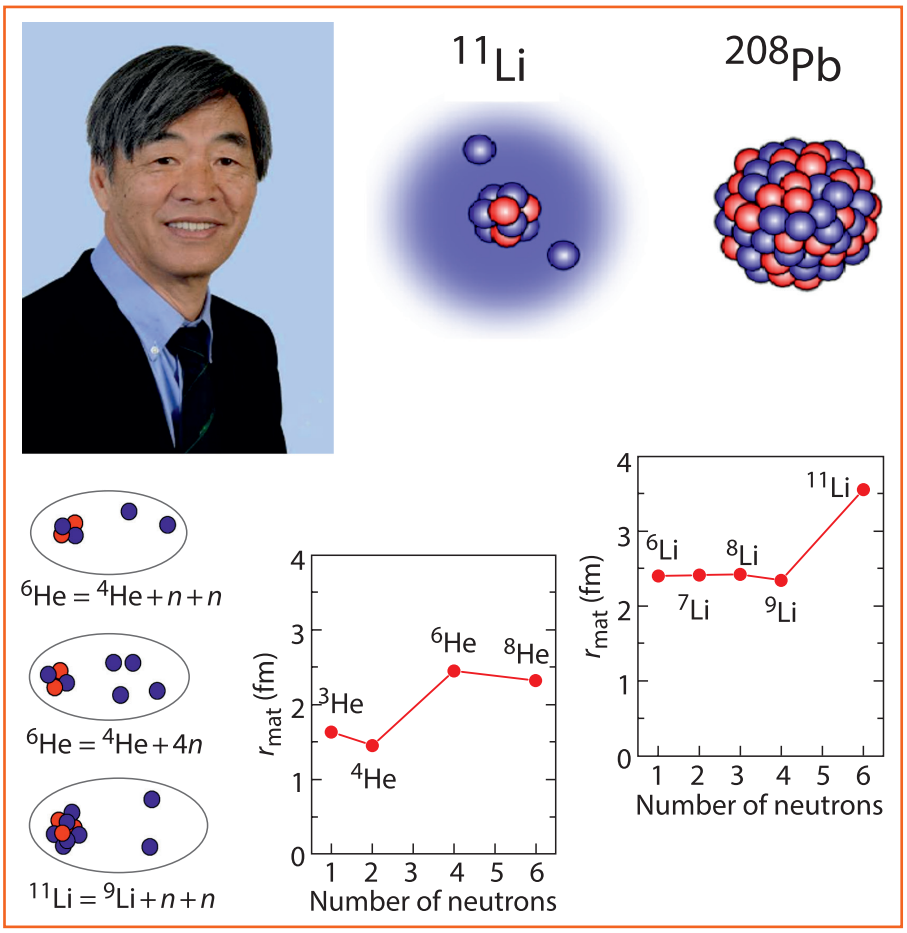
$$M_1 + M_2 \rightarrow M_3 + \gamma$$
$$M_1 + M_2 - M_3 = \Delta M$$
$$\Delta E = \Delta M c^2$$

It required essentially more time to get reliable knowledge about radial properties of the nuclei. In 1961 Robert Hofstadter got the Nobel prize "for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons…". The major idea of the approach is simple and elegant: electron interacts with nuclear matter *relatively weakly* (only electromagnetic interaction) and thus can easily penetrate in the nuclear interior. The electromagnetic probe is the best studied theoretically and thus it allows straightforward interpretation of the experimental data. Moreover, this is not just charge radius $r_{ch}$, which is measured, but electromagnetic form






$$q = 2k \sin(\theta/2)$$
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{PWBA}} = \frac{\sigma_M}{1 + (2E / M_A)\sin^2(\theta/2)} |F_{\text{ch}}(q)|^2$$
$$F_{\text{ch}}(q) = 4\pi \int_0^\infty dr r^2 j_0(qr)\rho_{\text{ch}}(r)$$
$$F_{\text{ch}}(q) / Z = 1 - \frac{q^2}{6}\langle r_{\text{ch}}^2 \rangle + \ldots$$




factors $F_{ch}(q)$. They contain detailed information both about charge density distribution $\rho_{ch}(r)$ and about nuclear excitations (so-called inelastic form factors).

When Isao Tanihata measured the nuclear radii in the lightest isotopic chains in 1988 at the BEVALAC in Berkeley — this was a kind of shock. It appeared that near borderlines of nuclear stability — just where a turnover happens from "ordinary" isotopes to "exotic" ones — the mean radius of the nucleus grows abruptly. Such behaviour was in a sharp contrast with the routine idea about nuclide as a droplet of "nuclear liquid" with the radius which is well approximated by a "liquid drop" expression $r = r_0 A^{1/3}$. Theoreticians, however, have already had an explanation at hand: such nuclides are analogous to planetary systems with dense "core" (central sun) and 1–4 nucleons (planets), orbiting at large distances from the core. For example, in the "classical" halo nucleus $^{11}$Li the size of such "valence orbitals" is comparable to the size of much heavier lead nuclei containing 208 nucleons. This was the emergence of the concept of "halo nuclei".

In his experiment Tanihata used very "simple instrument" — the nuclear absorption. How to apply the precision approach of Hofstadter electron scattering to exotic nuclei far from stability valley? Two issues are important here. (1) It is difficult to make a target of exotic nuclei (their lifetimes are typically too short for this). (2) What was the main advantage of electron scattering — small cross sections for interaction with nucleons — here becomes an important obstacle: exotic nuclei are simply not available in significant quantities. The solution to both problems is to use an electron–ion collider. The relativistic exotic nuclei are kept in orbit in a storage ring, forming the target for electron scattering, and each exotic ion returns to the collision point approximately 500 000 times per second (~ 0.5 MHz). Thus, once produced, each exotic ion is multiply "reused" in the collider compensating for the small electron–ion cross section.

For the first time this idea was considered in the USSR: the K4-K10 storage ring complex was a large-scale modernization project of the JINR Flerov Laboratory. This development was to bring FLNR to a short-list of the world-leading facilities in the field of exotic nuclei. However, it was 1990 and, in the following, "turbulent" years these plans could not be implemented. The "Fallen Banner" was taken up in 2003 by Tanihata — a pioneer of the exotic nuclei radii studies — the basic idea of the electron–RIB collider MUSES at RIKEN was inherited from Russian colleagues. Politically the MUSES project "lost" to projects that could be implemented in a shorter time frame and, thus, were expected to pay "scientific dividend" faster. The idea of an electron–RIB collider was revived in the ELISE project at FAIR in 2007. However, the FAIR facility is now focused only on the first-stage (so-called Modularized Start Version) experiments. Thus, the future constructions of all second-stage projects of FAIR (including ELISE) has become uncertain.

At JINR, beams of rare isotopes far from the line of stability would be complementing the study of superheavy elements pursued at FLNR, and allow JINR staying at the forefront of nuclear physics and providing state-of-the-art research in nuclear physics for the JINR member states and for the international nuclear physics community.

Encouraged by leading international scientists of the FAIR NUSTAR community, JINR has proposed develop and build a powerful RIB facility DERICA (**D**ubna **E**lectron–**R**are **I**sotope **C**ollider f**A**cility) covering a wide range of modern nuclear physics aspects (new isotope synthesis and production, measurements of its masses, lifetimes and decay modes, nuclear reactions and spectroscopy).

## DERICA concept

DERICA concept (see Fig. 1) is based on a combination of the most advanced technologies in nuclear physics experiments. It combines in-flight production of RIBs by projectile fragmentation technique (primary beams up to uranium with energy ~100 AMeV) with ISOL-type technique of stopping RIBs in gas catcher and charge breeding, followed by reacceleration in LINAC-synchrotron combination. Sophisticated usage of reaccelerated RIBs for reaction studies and for storage ring experiments (experimental areas of the low-energy ring LERing and Collector Ring CR) is foreseen. DERICA's ultimate challenge is to operate the e–RIB collider. This collider mode demands extremely high luminosity of the collider, which requests highest intensities of secondary ion beams generated in the fragment separator DFS. This instrument should be specifically adapted to preparation of clean RIBs for stopping in the gas cell. The request for high intensity of the resulting RIB is obviously translated into a request for high-intensity of the primary heavy-ion beam. Therefore, a heavy-ion superconducting "continuous wave" LINAC-100 with record intensities (e.g., from 3 emA of Ca to 1 emA of U, ~ 1 MW power in the primary beam) is planned.

The ultimate goal of the DERICA project is to extend the powerful method of electron scattering on nuclei, which has already provided a wealth of information about the structure of stable nuclei, to the study of nuclei outside the valley of stability using its electron–RIB collider. Thus, DERICA will be a unique and unprecedented tool for nuclear spectroscopy of rare isotopes, i.e., nuclei far from stability. For achieving that goal, the front end of the accelerator complex has to produce beams of highest intensities. To this end, R&D project was launched several years ago to push the limits of beam intensities to highest values. The beam intensity of any linear accelerator is limited by the intensity which is generated by the ion source and preserved by the low-velocity transport system before injection into LINAC. The DERICA concept foresees the development and construction of world-

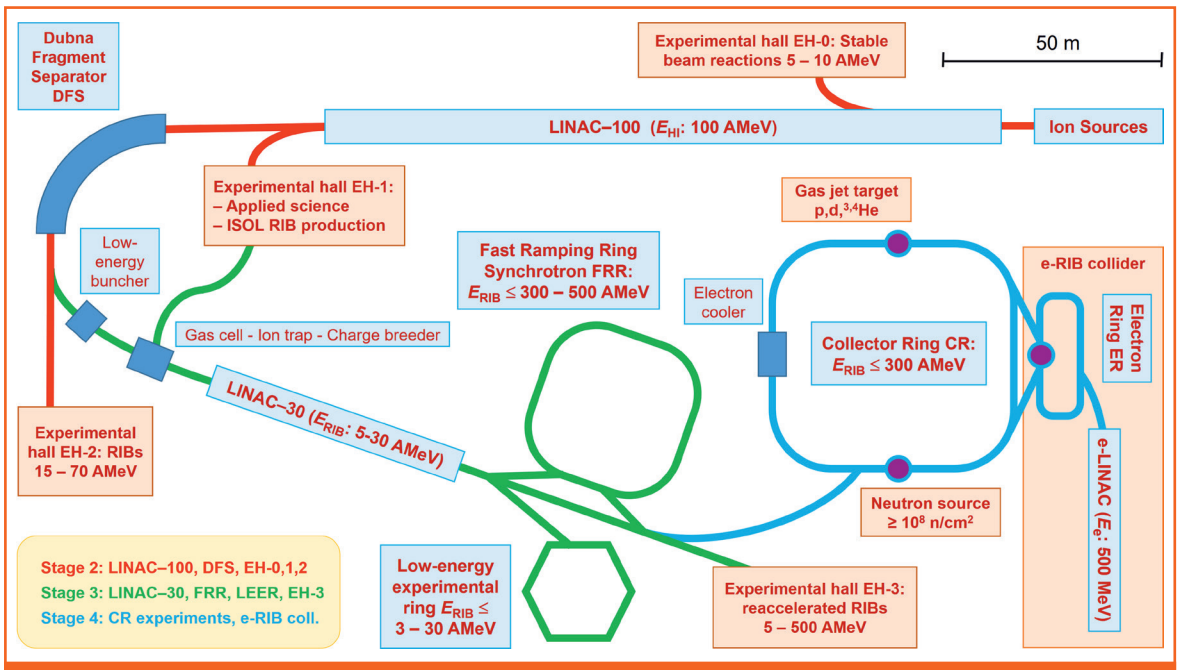



**Fig. 1. DERICA project, stages 2–4. Colours of the beamlines correspond to the stages of the project. Stage 2 (red): low-energy reactions with stable beams (in Experimental Hall EH-0), applied studies with stable 25–100 AMeV beams in EH-1, and direct reaction studies with intermediate energy (20–70 AMeV) RIBs in EH-2. Stage 3 (green): reaction studies with reaccelerated (5–500 AMeV) RIBs in EH-3, experiments in low-energy storage ring. Stage 4 (blue): storage ring experiments in high-energy storage ring CR and e-RIB collider experiments**

class LINAC "front end", consisting of a highly efficient electron-cyclotron resonance (ECR) ion source, dedicated low-energy beam transport line, and large-acceptance RFQ accelerator (see Fig. 2). The success of the entire DERICA facility depends on the requested "record" front-end performance, which is planned to be demonstrated in 2020–2023. Based on this demonstration and on R&Ds for the other key components of the project, the feasibility of the whole DERICA scheme should be demonstrated in the preparatory phase in 2021–2024.

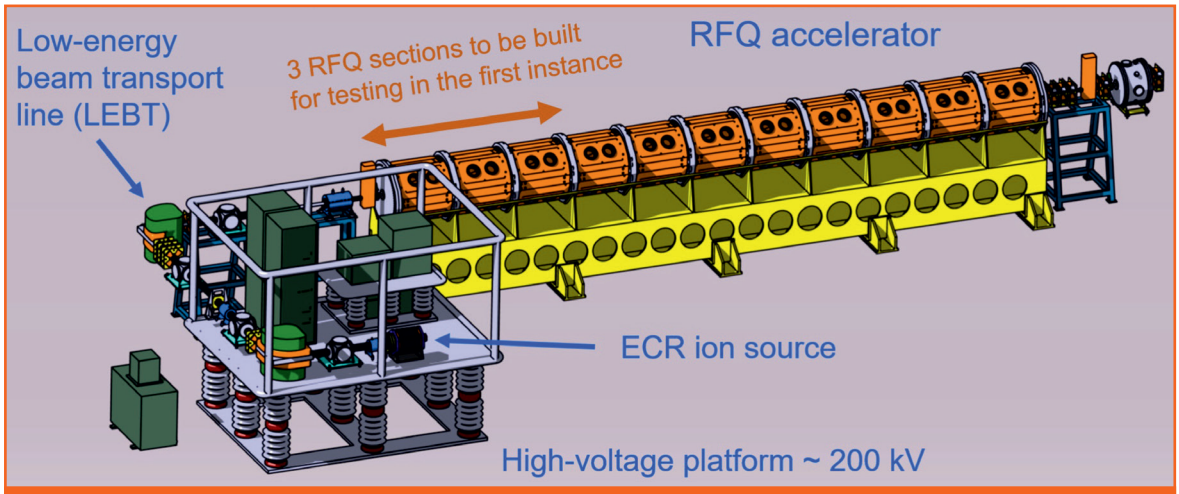



**Fig. 2. Schematic view of the prototype front end of the prospective heavy-ion cw-LINAC**

DERICA at JINR will be able to become a worldwide unique facility complementing top nuclear physics facilities like FAIR (GSI) in Germany, RIBF (RIKEN) in Japan, FRIB (MSU) in the USA and SPIRAL2 (GANIL) in France.

## DERICA project timeline

The timeline for development of the DERICA facility includes four major stages during the years 2020–2035 (see Fig. 1). New scientific opportunities are arising at each stage with an interval of few years. The first scientific/application results can be expected in around 5 years after construction start: they are connected with operation of the low-energy (less than 7 AMeV) normal-conducting section of LINAC-100.

**Stage 1.** Development of the prototype front end for LINAC-100: the ability to build superhigh-current continuous wave acceleration to be confirmed. CDR for LINAC-100, CDR for fragment separator DFS, CDR for Ring Branch. TDR for LINAC-100 building. 2020–2023.

**Stage 2.** New facility buildings are constructed; "driver" accelerator LINAC-100 (~ 100 AMeV acceleration for $A/Z = 6$ ions) and fragment separator DFS are installed (see Fig. 3). Low-energy reactions with stable beams (~ 6–7 AMeV, experimental hall EH-0), applied studies (experimental hall EH-1), and intermediate-energy RIBs (~ 20–70 AMeV, experimental hall EH-2).

(i) LINAC-100(6) starting configuration begins low-energy operation (6 AMeV room temperature resonators only, experimental hall EH-1), 2023–2027.
(ii) LINAC-100(50) advanced configuration for intermediate-energy operation. Fragment separator DFS starts operation in the low-intensity regime (50 AMeV, experimental hall EH-2), 2027–2030.
(iii) LINAC-100 is installed in full configuration. Fragment separator DFS is ready for operation in the full-intensity regime (100 AMeV, experimental hall EH-2), 2031–2033.

**Stage 3.** System for RIB reacceleration (gas cell — ion trap — ion source/charge breeder — LINAC-30) are installed in experimental hall EH-2. Together with fast ramping ring synchrotron FRR the reaccelerated RIBs in the range ~ 5–300 AMeV are available (experimental hall EH-3 and low-energy storage ring). 2026–2033.

**Stage 4.** Construction of storage rings. Experiments, including electron–RIB collider studies, can be conducted in three experimental areas of the Ring Branch. 2027–2035.

Expected construction time ~ 16 years and facility cost ~ 300 M$. The facility should employ about 200 staff members.

## Scientific challenges of the DERICA project

The development of electron collider with exotic radioactive ions is the ultimate goal of the DERICA project. However, that goal will be attacked only after the successful launch of several world-class experiments of the DERICA project, after their functionality will be reliably confirmed, and after they will begin to produce excellent scientific results.

Within the DERICA project the topic of electron collider with exotic radioactive ions will be addressed, but in a new technological framework. Both the layout and the timeline of that project avoid a "trap" which hampered the previous projects in this field. Namely, the approach to building modern RIB factories with a very comprehensive research program appears to be very expensive and slow. On the other hand, it is certainly unacceptable to

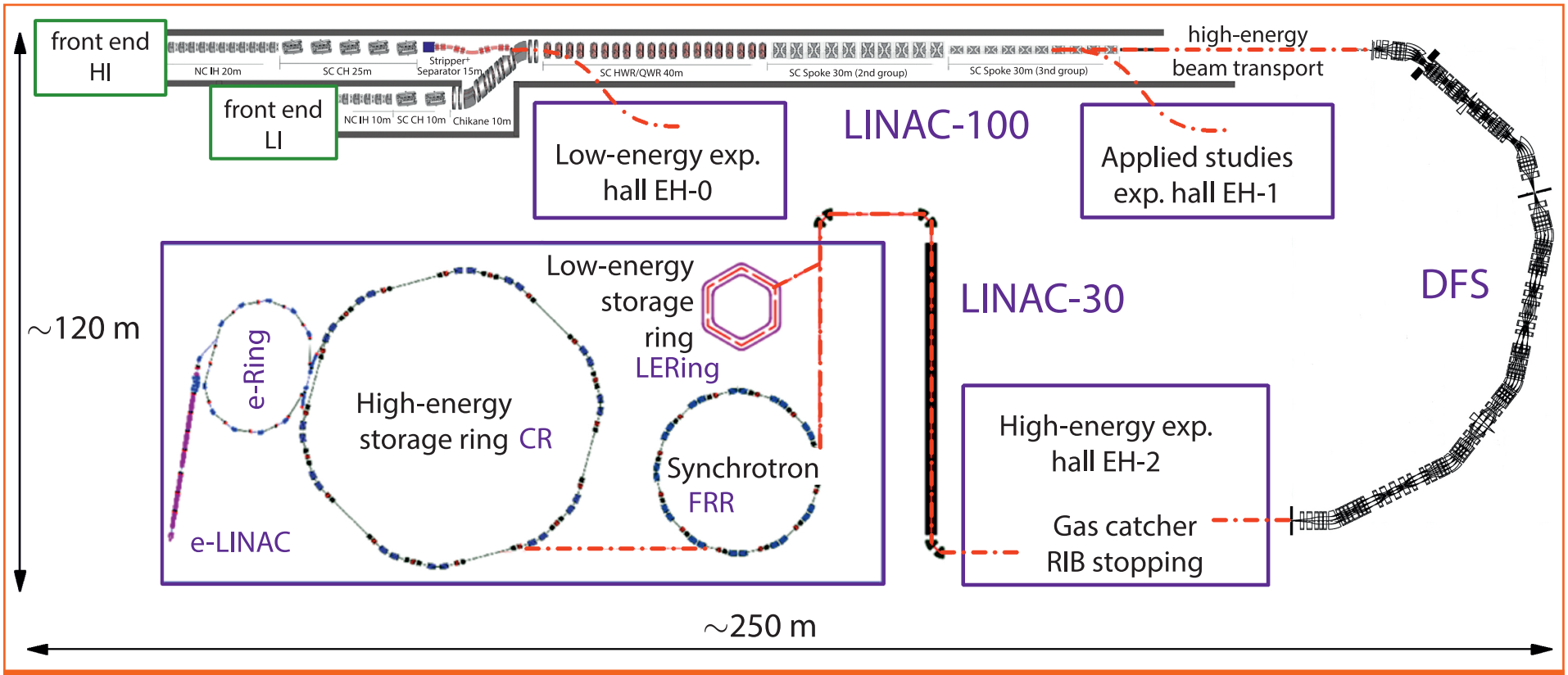



**Fig. 3. Preliminary schematic layout of the DERICA facility. The designs of LINAC-100 with one universal front end or with separate front ends for heavy ions (HI) and light ions (LI) are under consideration. The length of the high-energy beam transport line depends on the foreseen energy upgrade options**

develop "facility for one experiment", and certain compromise becomes inevitable. The development of DERICA is organized in such a way that well-defined technical stages allow solving various scientific problems of global interest and importance.

Already at the very first stage of the project, LINAC-100 + DFS combination will ensure the production of secondary RIBs of record intensity for the energy range 20–70 AMeV. This energy range is optimal for studies of exotic nuclei in direct reactions — and this approach remains the most universal to date.

In the next stage the technology of the post-accelerated RIBs will be developed. Intensities of post-accelerated RIBs fall by about order of magnitude. However, for high-intensity secondary beams this technology can lead to the expansion of experimental opportunities. The point is that ordinary technology of using of "hot" RIBs from fragment separators works "event by event", which allows intensities of no more than $10^6$ particles per second. Thus, for primary intensities exceeding $10^6$ particles per second the use of post-accelerated beams is a natural solution for the intensity issue.

Construction of storage rings opens the next chapter of the DERICA project. Even without collider, storage rings are extremely powerful tools. First of all, storage ring is a very high resolution spectrometer for mass measurements. Storage rings can also preserve high ionization states of heavy ions that mimic the situation of nuclear astrophysics — behaviour of hot matter in the Universe. The astrophysical "curriculum" also includes the studies of radiation capture reactions. In the storage rings such reactions can be studied using the "windowless" (gas jet) targets, getting rid of the background processes. Extreme dilute character of the gas jet target is compensated in this case by the multiple "reuses" of exotic ions circulating in the storage ring. Absolutely unique topic for research can be unification of storage ring with free neutron target. The neutron concentration in such a target can be provided by a powerful neutron source, surrounded by layers of moderators and reflectors. Again, the dilute character of such a target is compensated by the revolution frequency of ions in the storage ring.

## Hot topics of the modern nuclear physics expected to be tackled by DERICA

Below the most important problems which can be solved in DERICA experiments are listed briefly.

**Nuclear structure.** Quest for the limits of existence. Halos, Open Quantum Systems, Few Body Correlations. Changing shell structure far away from stability. Skins, new collective modes, nuclear matter, neutron stars. Symmetries and phases of the nuclear many body systems. Unified theory of nuclear structure (ab-initio, density functional, shell model). Paving the way for theoretical framework with predictive power for nuclei beyond experimental reach. Underlying QCD structure → complex nucleon–nucleon force. Study of exotic short-lived nuclei far off stability valley (proton/neutron skins or halos, new magic numbers…). At what ratio of protons to neutrons can nuclei exist? What are the limits of the nuclear structure existence?

**Astrophysics.** Origin of elements — how are elements heavier than iron formed? Physics of stellar explosions (core-collapse, thermonuclear supernovae, nucleosynthesis). Compact objects and the explosions on their surfaces (x-ray bursts).

## Cross-disciplinary and applied aspects of the DERICA project

The use of the DERICA facility is not limited to nuclear physics. DERICA may be helpful in solving the following cross-disciplinary issues:

— High-intensity heavy-ion irradiation for volumetric modification of massive materials and development of high-performance technology for irradiating multilayer targets. Material science with intense beams of highly charged ions.

— Simulation of a heavy-ion component in cosmic ray spectrum in testing of the microelectronics elements used in the space industry by irradiation of multilayer targets.

— DERICA as a neutron source. For operation with intense heavy (e.g., U) beam the target and beam dump areas for DFS are expected to generate above $5 \times 10^{14}$ neutrons per second in 4π geometry. For DFS this is unwanted background to be suppressed. Continuous neutron flow from the beam dump and possibly for pulsed regime with extracted beam pulses are demanded in neutron scattering experiments.

## Cross-laboratory cooperation

The most important cross-laboratory synergy aspects of the DERICA project development are:

— The development of the front end for the LINAC-100 accelerator in the framework of the DERICA project is strongly based on the world-class experience of high-intensity ion sources development at JINR FLNR. The program of the prospective 28 GHz ECR ion source development has recently started at FLNR having in mind operation of the reconstructed U-400 (or U-400R) cyclotron with heavier ion beams, up to U. However, the full potential of such an ion source can be realized as an integral part of the modern linear accelerator.

— The development of the low-energy normal-conducting part for the LINAC-100 accelerator and the entire LINAC-30 accelerator in the DERICA project is a natural continuation of the inter-laboratory and inter-institutional collaboration established during the development of RFQ injector of light ions LU-20 for the NICA project. This collaboration involves the leading accelerator experts from JINR (LHEP and FLNR), Russian institutions (ITEP, MEPhI, BINP, VNIITF, INR RAS), and from leading foreign nuclear physics centers (GSI, LNL-INFN, MSU, etc.). In the framework of the DERICA project, the technologies of high-intensity heavy-ion accelerators with a high duty cycle (potentially — with continuous wave regime) will be developed.

— Superconducting resonators are one of the key components for development of the driver accelerators in several important modern fields: spallation neutron sources, free electron lasers, radioactive ion beam production. The R&D for radio-frequency superconductivity in the Russian Federation has been stalled in the last 25 years. Over the past 5–7 years these works were reanimated at JINR VBLHEP in collaboration with MEPhI, PTI (Minsk), NPI BSU (Minsk). This activity is aiming at prospective superconductivity upgrade of the NICA injector complex. The dedicated scientific research program in the framework of the Union State of the Russian Federation and the Republic of Belarus was prepared and is now being finalized. Development of technology of superconducting resonator construction should become the basis for future accelerator projects in the Russian Federation, and the DERICA project can be foreseen as the next (after NICA) "principal consumer" of this technology.

— The beam dump for the intense primary beam at DFS fragment separator of the DERICA project is a powerful source of neutrons. They are produced by stopping, for example, 100 AMeV primary uranium beam in (according to different ideas) liquid lead or lead-tin eutectics. Neutron flux above $5 \times 10^{14}$ $s^{-1}$ can be expected. Being unwanted background within DFS operation, those neutrons can be interesting "product" for studies within scientific program of the JINR Frank Laboratory of Neutron Physics (FLNP). Scientific opportunities of use of neutrons at DERICA DFS beam dump are under investigation at FLNP.

## International collaboration

Modern powerful "RIB factories" are in different stages of construction in the world: FAIR (Darmstadt, Germany), SPIRAL2 (GANIL, France), FRIB (East Lansing, USA), HIAF (Huizhou, China), RAON (Daejeon, South Korea). The DERICA project is intended to be in this row of the world-leading RIB facilities. Modern linear accelerator programs for RIB research are active at LNL-INFN (Legnaro, Italy), TRIUMF (Vancouver, Canada), ISOLDE (CERN), SPIRAL2, FRIB, HIAF, RAON. Modern storage ring complexes for RIB physics are functioning and planned at FAIR, IMP (Lanzhou, China), HIAF. Expertise transfer in the field of accelerator, fragment-separator, and storage ring design and operation from Legnaro, CEA (Sacle, France), and FAIR to DERICA can be foreseen.

## Highly upgradable facility design

The preliminary LINAC-100 layout suggests long high-energy beam transport line before DFS (see Fig. 3). This enables possible extension of driver accelerator to LINAC-200. The DFS design should also be versatile enough to include the opportunity to upgrade to higher primary beam energies. The target and beam dump areas should be constructed to withstand the highest radiation load foreseen for the facility. The possibility to use the target area as a neutron source and the possibility to augment the target area with ISOL-type facility are to be considered and reflected in the prospective design.

## DERICA status

After having drafted the design of DERICA in a worldwide collaboration, the JINR (Dubna) and BINP (Novosibirsk) submitted in April 2018 a joint proposal for the construction of an accelerator and storage ring radioactive ion beam facility DERICA to the Russian Ministry of Education and Science within the call for proposals of "megascience"-class facilities to be constructed in the Russian Federation. In September 2018 the proposal has successfully passed assessment in the Russian Academy of Sciences and is now on a short list of the recommended projects.

Letter of Intent for the DERICA project is published in [*Grigorenko L. V. et al.*, Physics–Uspekhi. 2019. V. 62. P. 675–690, http://derica.jinr.ru/pdf/publications/2019-Grigorenko-UFN_DERICA_en.pdf]. Status of the DERICA project and the most recent information can be obtained at http://derica.jinr.ru.

## Summary

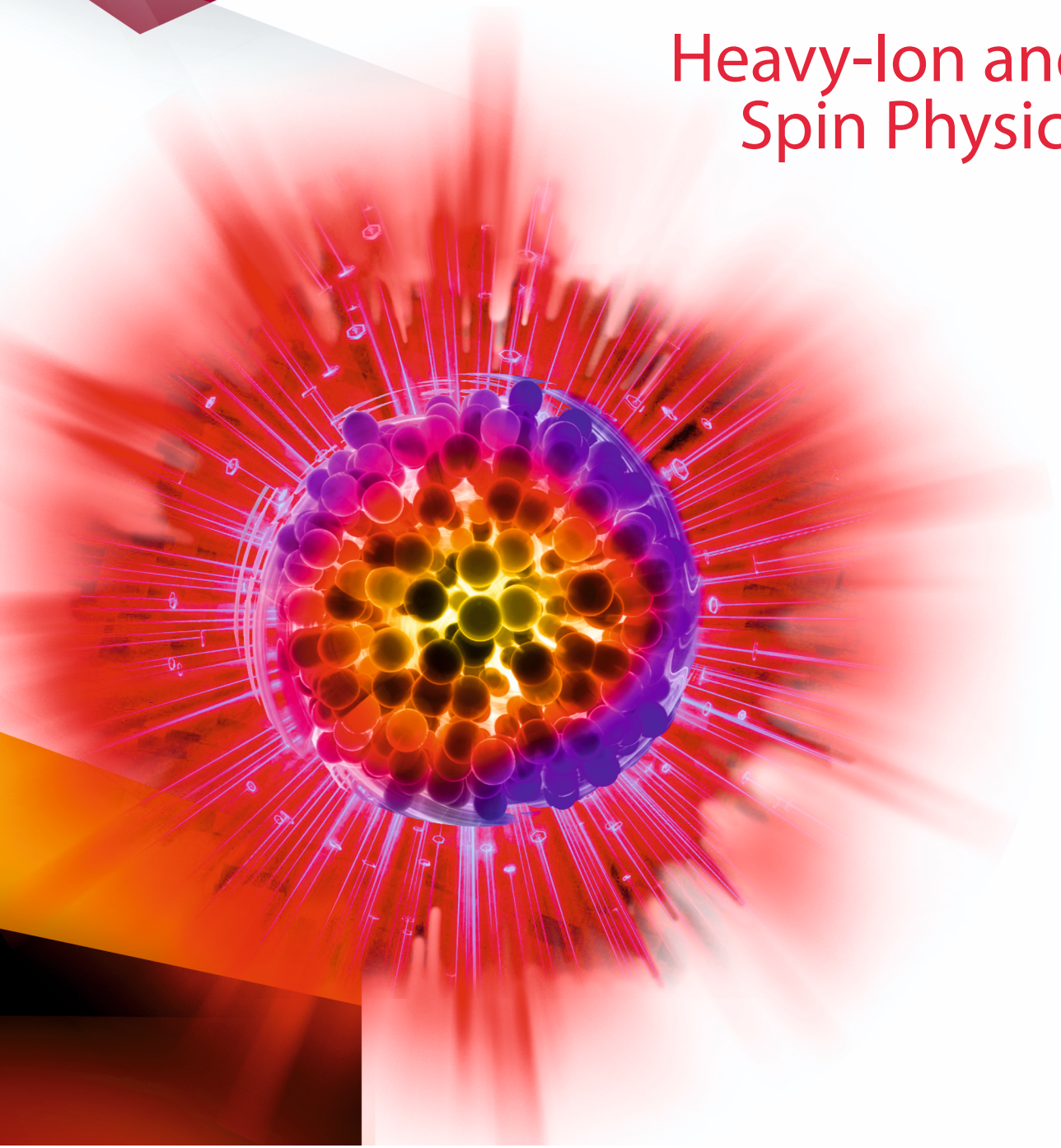
The *e*–RIB collider of DERICA and all the facilities upstream are demanding forefront technologies at the edge of technical capabilities of modern accelerators. These technologies should provide record precision, selectivity, resolution for shortest lifetimes of investigated exotic nuclei. The development of the DERICA project should become a strong driver for development in the Russian Federation and in JINR member states of a number of key technologies, such as radio-frequency superconductivity, high-intensity acceleration of electrons and ions, high-vacuum technology and power RF technology. The collider expertise in the Russian Federation is now concentrated in Novosibirsk and is focused on electron colliders. With the development of the NICA project at Dubna, the rise of the new center of expertise in ion colliders can be foreseen at JINR, and the DERICA project fits well in this line of development. In certain sense, the DERICA project is not an isolated initiative with the well-defined start and end points, but a long-term vision of the development strategy of fundamental low-energy nuclear physics in the Russian Federation and in JINR member states for decades ahead.



JINR Long-Term Development Strategy up to 2030 and Beyond

# 3

# Heavy-Ion and Spin Physics



## Executive Summary

From the beginning of the relativistic heavy-ion research in the early 1970s, JINR has been an important player with its on-site program at the Synchrophasotron, and then Nuclotron, and its participation in the heavy-ion program at the CERN-SPS first in WA98 and NA49, then in ALICE. Spin physics was also a key program at the Synchrophasotron and has been expanded at the Nuclotron. Both these research areas have been the source for the Mega-Science project NICA and the Long-Range Plan presented below. The dominant tasks in the near and long-term future are:

a) The timely completion of the construction of the NICA project, its commissioning and a smooth operation.

b) Completion of the detectors, the BM@N and the MPD and SPD at NICA, and successful data collection over the decades to come.

c) After several years of running in the start version of MPD, an Upgrade of the MPD detector is foreseen, responding to a possible increase in luminosity of NICA, and by adding detectors in the forward rapidities as planned in the original layout of MPD.

d) Studies of possible future extension of NICA for acceleration of electrons, opening new physics potential via *e–p* and *e–A* collisions.

To operate the infrastructure of the NICA accelerator complex, it is planned to increase the number of staff in the laboratory to 1000 employees. The total estimated number of scientists and specialists involved in conducting of the research at the NICA complex will reach 3000 by 2035.

Furthermore, of strategic importance is the JINR participation in fore-front external experiments off-site, e.g., at existing facilities, like the LHC, SPS, RHIC and STAR, and at facilities under construction, e.g., the international FAIR facility in Germany, or in planning, the proposed electron–ion collider (EIC) facility in the USA.

In view of the dominant tasks outlined above, VBLHEP management intends to reduce the present amount of its off-site involvement to less than 100 of its FTEs and an adequate budget of about 3–5 M$/year. In comparison with groups of other international laboratories in international collaborations, this allows one to collaborate in about 6–8 experiments with a strong force.

The JINR strategy for cooperative research at other accelerator centres will be linked closely to the updated European Strategy for Particle Physics, expected to be available in 2020.

## The NICA project

For the next two decades, the principal focus in heavy-ion physics and spin physics, which will influence to a large extend the JINR strategic development as a whole, is the completion and full exploitation of the mega-science project NICA. NICA is the JINR flagship facility in high-energy heavy-ion and spin physics. The project has been approved by the JINR Committee of Plenipotentiaries and has been supported by a separate agreement between the Government of the Russian Federation and the JINR "For construction of the basic configuration of the Nuclotron-based Ion Collider fAcility (NICA)".

The aim of the NICA project is to create a world-class experimental base for conducting fundamental research in contemporary High Energy Physics (HEP) as well as applied research in microelectronics, medicine and biology making use of accelerator and beam technologies.

The main goals comprise investigation of hot and dense strongly interacting matter, search for a mixed phase and critical point in the QCD phase diagram (see Fig. 1) in the poorly explored region of high baryon chemical potential and clarify the basis of QCD in the non-perturbative regime and other theoretical approaches for the description of strongly interacting matter. The NICA energy range ($\sqrt{s_{NN}}$ = 2–11 GeV for heavy-ion collisions*) is believed to be particularly interesting because it covers the region of maximal net baryon density at the time of "freezing". In this regime, the system takes a maximum amount of space-time in the form of a mixed phase of quark–hadron matter where hadron and quark–gluon phases coexist. The NICA scientific program could shed light on key

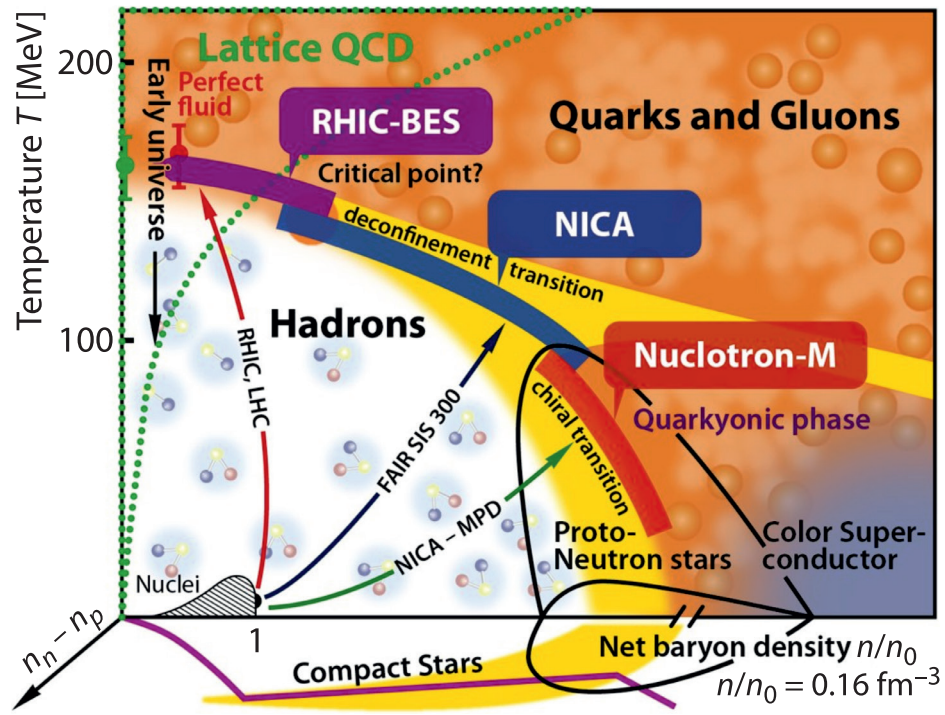



**Fig. 1. QCD phase diagram**

* For collision of polarized protons and deuterons the energy ranges are $\sqrt{s_{pp}}$ = 12–27 GeV and $\sqrt{s_{NN}}$ = 4–13 GeV, respectively.

questions in the field of strong interactions, namely how to further probe the quark–gluon plasma and its two fundamental characteristics, deconfinement and chiral symmetry restoration, whether there is a first-order phase transition at high baryon density, and what do we know about the multidimensional internal structure of the nucleon (distribution of charge, mass, spin…) and how to extract it.

The scientific program of the NICA project is included in the European Particle Physics Strategy plans as a part of the global European strategy. The NICA facility shall be open not only to JINR and member-state scientists but also to the international scientific community at large. The exploitation of the science at NICA is foreseen to be carried out in the framework of international collaborations centred around the three currently planned experiments, MPD and SPD at the Collider and BM@N at the Nuclotron.

JINR is committed to provide adequate facilities and infrastructure for outside users carrying out research at the NICA complex. This refers to short-term visitors as well as students and young scientists expected to spend extended periods of time at the laboratory. As such, the NICA facility shall play an important role in enabling the next generation of scientists in high-energy heavy-ion physics to make new discoveries in physics.

The major components of the NICA complex are listed below:

1. **Accelerator complex:** It is composed of the upgraded superconducting synchrotron Nuclotron including extraction and transport beam lines; the injection complex (new heavy-ion source, source for polarized particles and linear accelerator injectors); the new superconducting synchrotron Booster; the Collider consisting of two superconducting storage rings with two interaction points where collisions of heavy ions and polarized particles can be studied (see Fig. 2).

2. **Three experimental facilities:**

**Baryonic Matter at Nuclotron (BM@N)**, designed to study dense baryonic matter in fixed target experiments using extracted beams from the Nuclotron (see Fig. 3);

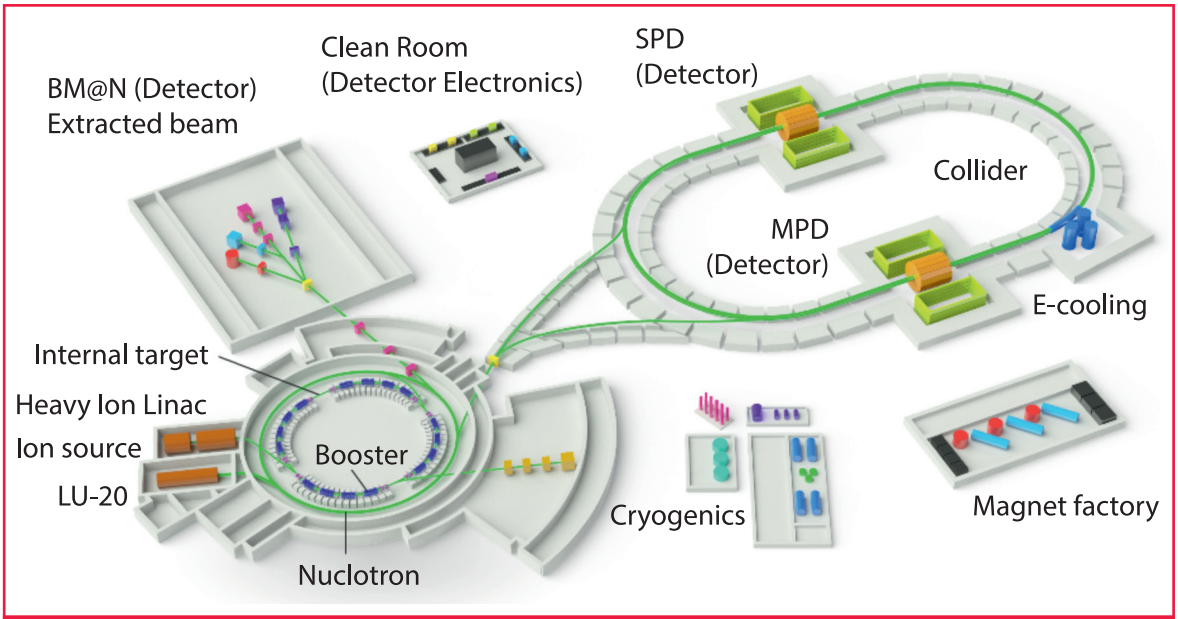



**Fig. 2. The NICA accelerator complex**

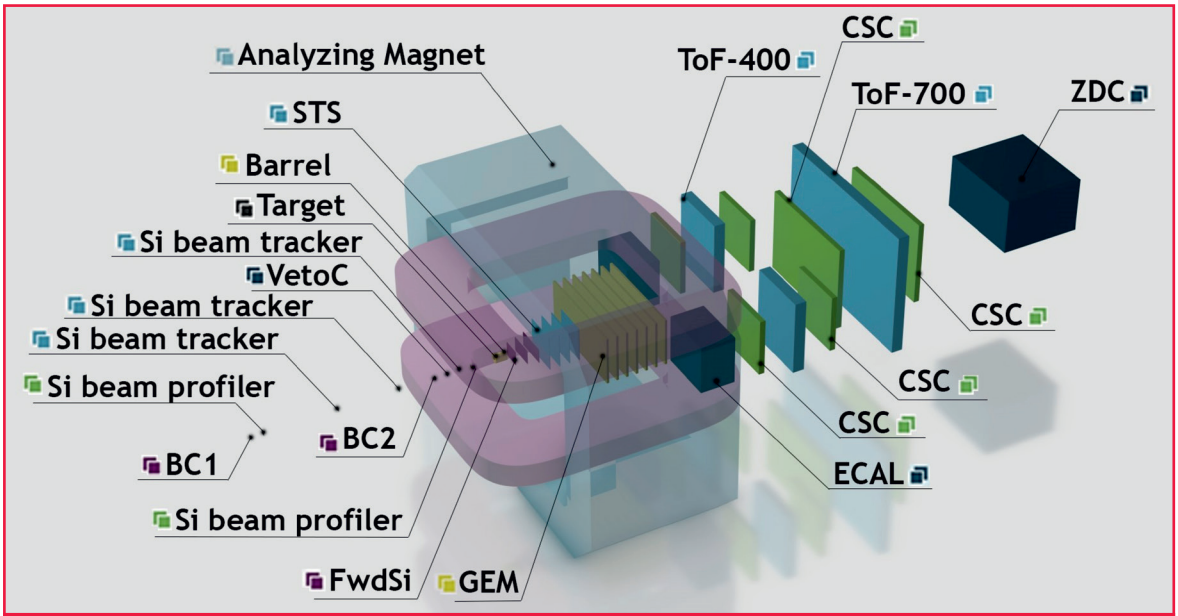



**Fig. 3. The BM@N experimental setup**

**Multi-Purpose Detector (MPD)**, designed to study dense baryonic matter created in heavy-ion collisions in the Collider (see Fig. 4);

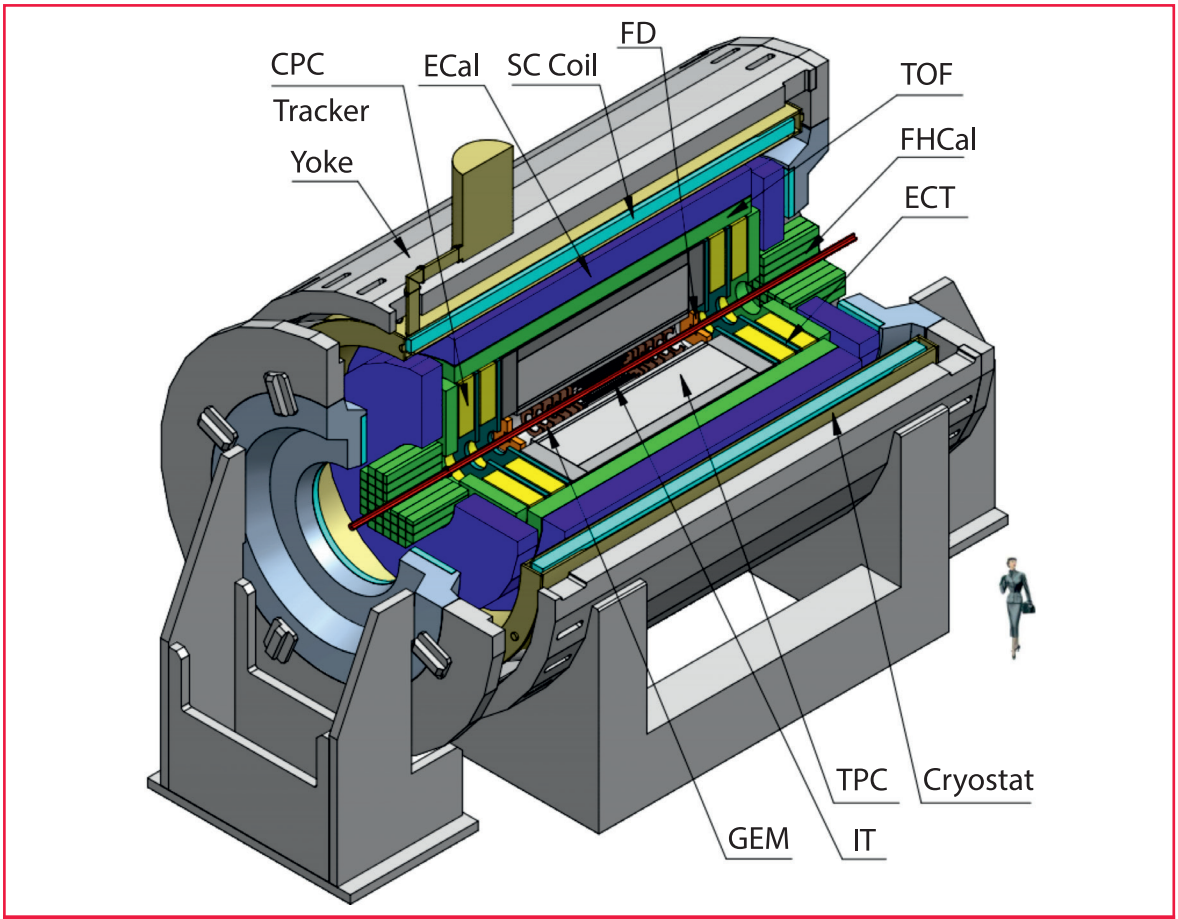



**Fig. 4. The MPD experimental setup start version**

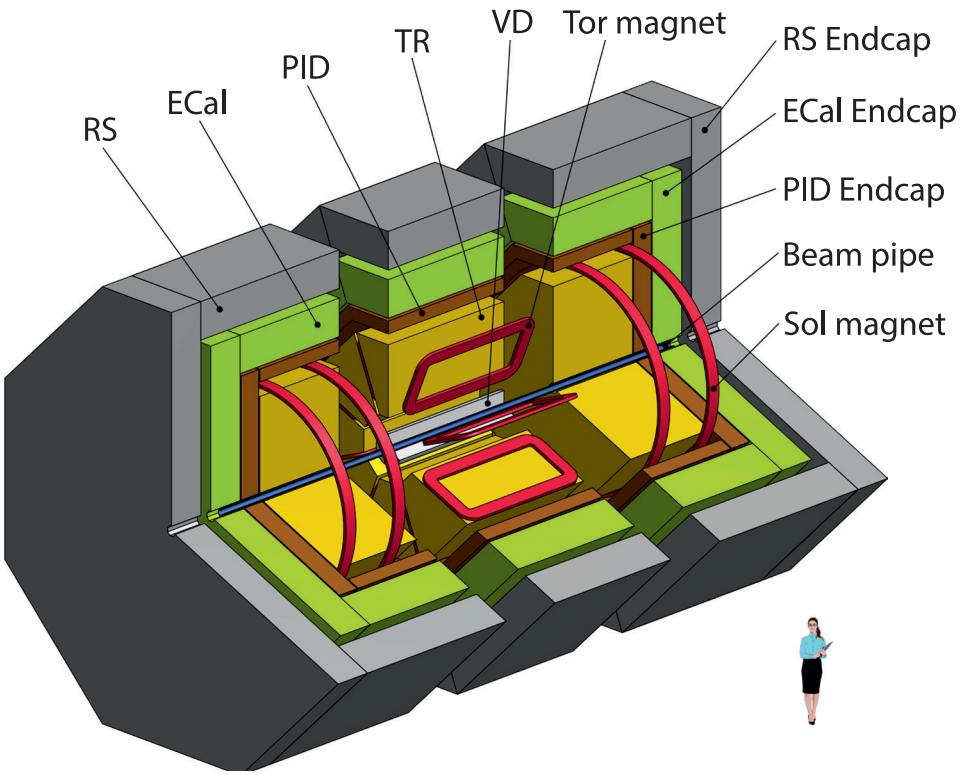



**Fig. 5. Schematic view of the SPD experimental setup**

**Spin Physics Detector (SPD)**, intended to study the nucleon spin structure and polarization phenomena by performing experiments with colliding polarized proton and deuteron beams (see Fig. 5);

**3. A complex of buildings**, including the Collider complex and experimental halls for MPD and SPD detectors; NICA Innovation Centre (see Fig. 6); experimental hall and areas for applied research; cryogenic complex building; buildings for energy supply systems, etc.;

**4. Innovation block**, including transfer channels and areas for innovation and applied research at the linear accelerators and with extracted Nuclotron beams;

**5. Computing and information block**, including an IT center with its relevant networking infrastructure and a set of IT services for storing, processing and analysis of experimental data.

General information for the NICA complex is available at http://nica.jinr.ru. Detailed info is available at http://nucloweb.jinr.ru/nica/CDR.html. For the scientific program, see the White Paper at: http://mpd.jinr.ru/wp-content/uploads/2016/04/WhitePaper_10.01.pdf. For the designs of the BM@N, MPD and SPD detectors, look at http://nica.jinr.ru/files/BM@N/BMN_CDR.pdf, http://nica.jinr.ru/files/CDR_MPD/MPD_CDR_en.pdf and http://spd.jinr.ru/wp-content/uploads/2019/03/PAC_Text-ProjectSPD-NICA.pdf, respectively.

According to the adopted Seven-Year Plan (2017–2023) for the Development of JINR, the construction of the basic configuration of the NICA complex, as well as the process of commissioning of its main components, is expected to be completed by 2021 and the



**Fig. 6. Artistic view of the NICA Innovation Centre**

regular operational phase should start right after that. A comprehensive report on the progress in construction of all the elements of the NICA complex achieved as of 2018 is available at http://nica.jinr.ru/docs/Report_NICA_SB_(12)_short.pdf.

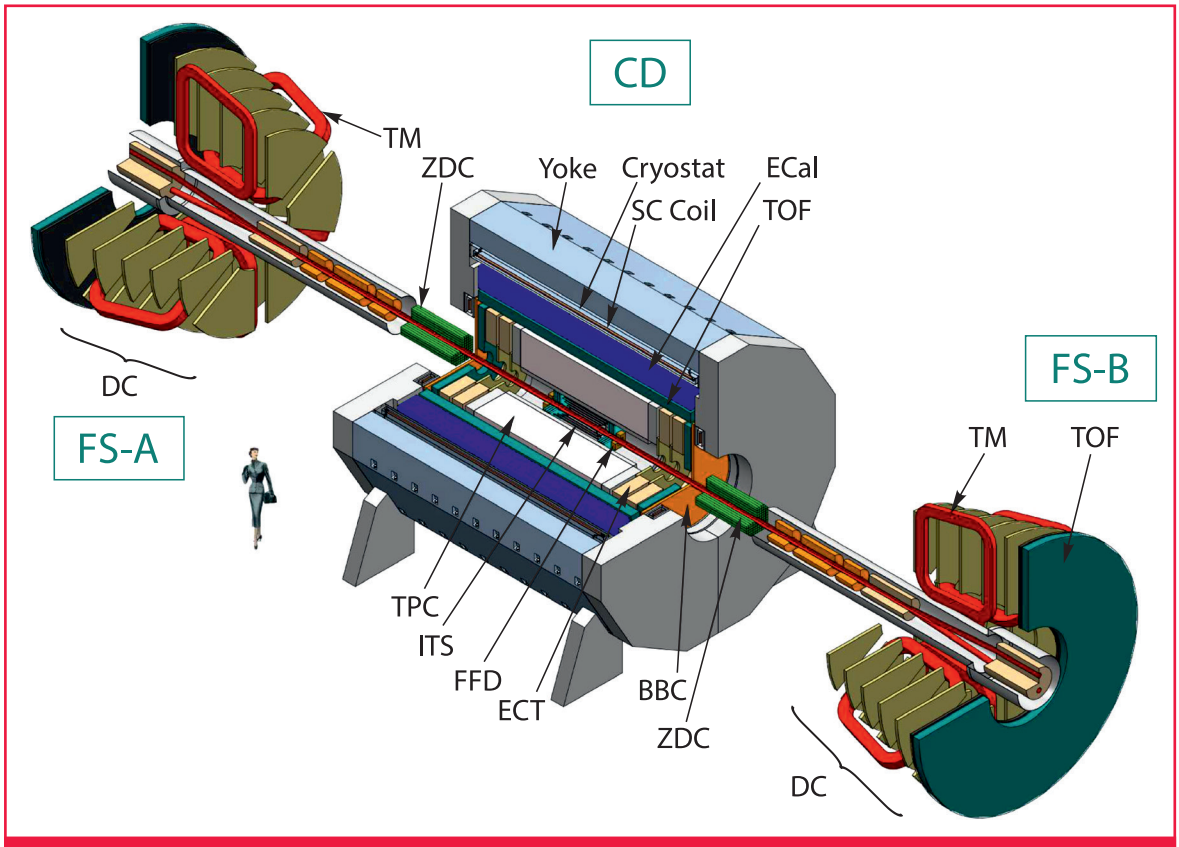



**Fig. 7. MPD in its final version with forward spectrometers (end caps)**

In the next 25–30 years, the potential of the NICA accelerator complex should be fully exploited and further developed. During the next ten years, this is foreseen as follows:

- The commissioning of the basic Collider configuration and the first stage of the MPD facility should start at the beginning of the next decade. Right after that, studies of symmetric* heavy-ion collisions with luminosity $L \sim 10^{25}$ cm$^{-2} \cdot$ s$^{-1}$ would become possible. Next, the completion of the MPD barrel part in its full configuration and commissioning of the full-scale BM@N set-up should be accomplished.
- During the second half of the decade, the luminosity shall be increased to its design value of $\sim 10^{27}$ cm$^{-2} \cdot$ s$^{-1}$. The MPD detector shall be supplemented with end-caps. Polarized proton and deuteron beams will be made available at NICA and experiments with them will start with the Spin Physics Detector (SPD) situated at the second interacting point of the Collider. The luminosity is expected to be in the range of $10^{30}$–$10^{32}$ cm$^{-2} \cdot$ s$^{-1}$. An interesting addition to the physics programs of both MPD and SPD would be the study of ultra-peripheral nuclear collisions.

Meanwhile, the upgrade of the Nuclotron beam extraction channels based on superconducting technology is foreseen. It will be supplemented by the construction of a superconducting magnetic energy storage device (SMES)**. R&D and project preparation for upgrading the magnetic system of the Nuclotron using, in particular, high-temperature superconductor*** is also envisaged.

## Future lines of development of the NICA accelerator complex

In formulating strategic plans beyond 2030, four directions have been identified that are scientifically promising, technically feasible, and can be seen as natural extensions of the planned NICA program:

— Upgrading of the NICA rings to obtain asymmetric**** heavy-ion collisions with luminosity $L \sim 10^{27}$ cm$^{-2} \cdot$ s$^{-1}$ and collisions of polarized protons with polarized deuterons with $L \sim 10^{32}$ cm$^{-2} \cdot$ s$^{-1}$;

— A feasibility and design study for the acceleration of twisted states of particles and of states with large orbital momentum; experiments with such states;

— A feasibility and design study for an electron accelerator at a few GeV energy and, possibly, for a high-energy photon beam. The latter could be based, for example, on backward Compton scattering of a laser beam off a few GeV electron beam.

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* Both NICA rings operate with equal magnetic rigidities.

** The energy storage device is placed between the high-voltage network and the superconducting load (the Booster and Nuclotron magnets). It allows for significantly decreasing the power consumption from the network as well as the influence of the accelerators on the network stability and, vice versa, the network influence on the accelerators. As a storage device we propose a high-temperature superconducting magnet with stored energy of 3 MJ.

*** The Nuclotron magnetic system has been in operation since 1993. Soon it will come to a state where an upgrade will be mandatory. It is proposed to start R&D, prototyping and manufacturing of new magnets (possibly using high-temperature superconductors) with the aim to replace the overaged ones.

**** The NICA storage rings operate with different magnetic rigidities.

The study of *ep* and *eA* collisions, in particular with polarized beams, offers the possibility of conducting numerous studies on the internal structure of the nucleons and nuclei, and to understand the emergence of the global properties of the nucleon from its constituents. The study of deuterons will have an impact on the flavour decomposition of nucleon parton distribution functions, shed light on nuclear wave functions, and unravel correlations inside the nucleus. The study of heavier nuclei can improve the determination of nuclear parton distribution functions: they are also essential ingredients for the interpretation of heavy-ion physics and remain, at the moment, still poorly constrained.

The inclusion of polarization will offer the possibility to study crucial aspects of hadronic and nuclear structure beyond the reach of most present-day facilities. For instance, the possibility of running with polarized beams of deuterons, due to their spin-one nature, generates a rich set of measurable structure functions. Most of them are presently unexplored and contain qualitatively different information compared to the standard spin-half ones.

A broad program to study the multidimensional structure of the proton is going on in several facilities worldwide (e.g., CERN, BNL, and JLab). Of particular relevance in this program is the study of single-spin asymmetries, which implicitly require going beyond the mono-dimensional and leading-order description of hadronic structure. One of the crucial aspects of a future NICA program would be the possibility of comparing *p–p* and *e–p* collision results in order to test the peculiar universality properties of multidimensional parton distribution functions (e.g., the sign change of the so-called Sivers function, one of the mechanisms generating single-spin asymmetries). Moreover, the inclusion of *e–A* collision data will make it possible to extend these investigations to the multidimensional structure of the nuclei and the mechanisms generating nuclear single-spin asymmetries.

The *γ–p* beams may allow the study of the photo-production of $J/\psi$ and Υ, the latter being presently studied with limited statistics or in symmetric systems such as *p–p*, preventing an unambiguous rapidity, and hence Bjorken-*x*, determination. Depending on the proton beam energies, these studies could contribute to shedding light on the $J/\psi$ and Υ formation at threshold and on the gluon structure of the nucleon.

In addition, the production of di-lepton pairs in *e–A* and *γ–A* interactions is of great interest, allowing studies of the electromagnetic interactions in the region of strong fields. The coupling $Z\sqrt{\alpha}$ is large, so conventional perturbative calculations of the processes are questionable and higher-order terms may become important.

Thus, after 2030, the functional and physical program of the NICA complex can be significantly expanded by creating research opportunities in collisions of electron and photon beams with protons and heavy nuclei. This would make JINR one of the unique accelerator centres in the world. Therefore, a feasibility and design study for the search for the proton and deuteron electric dipole moment (EDM) with the NICA rings will be started as soon as resources are free for that work.

A few attempts have been made recently to search for EDM of protons and deuterons at accelerator facilities, in particular at BNL and FZU. Unfortunately, the necessary sensitivity was not achieved. An interesting proposal has been announced at the Jefferson Lab to use the proposed electron–ion complex JLEIC for such a search.

The NICA collider rings are very suitable for attempting those measurements on the proton and deuteron due to the possibility of transforming the two storage rings into an **8-shape accelerator structure** and use of the so-called spin transparency (ST) mode, also known as spin-frozen mode, for the spin control. The ST mode is thought to be one

of the possible technical solutions for polarization control at NICA. The idea of the EDM measurement is to create additional precession of the particle magnetic moment (the EDM is parallel to it) by the high-frequency accelerating electric fields in the NICA arcs. A scheme that introduces additional electric fields for deflection of the beam from one ring to the other that would also create a precession is another option.

## VBLHEP participation in experimental collaborations on-site as of today

In-house experiments realized by international collaborations include:

1. **Hyper-NIS.** In total, 17 FTE work in this experiment on its preparation for commissioning tests.
2. **Scan-3.** In total, 10 FTE work in this experiment on its preparation for commissioning tests.
3. **FAZA.** In total, 8 FTE work in this experiment on its preparation for commissioning tests.
4. **DSS.** In total, 10 FTE work in this experiment on data taking and analysis, as well as on its maintenance, preparation for commissioning tests and upgrade.
5. **Alpom-2.** In total, 1 FTE works in this experiment on data analysis.

   In the framework of the NICA project implementation, the VBLHEP scientists participate in the experiments:

6. **BM@N.** In total, 74 FTE work in this experiment on R&D of the detector, its preparation for commissioning, development of corresponding electronics, DAQ, slow control, trigger; development of the scientific program and MC simulation; software development, data taking and data analysis; theoretical investigations.
7. **MPD.** In total, 113 FTE work in this experiment on R&D and manufacturing of the detector, its preparation for commissioning tests, development of corresponding electronics and DAQ; development of the scientific program and MC simulation; software development; theoretical investigations.
8. **SPD.** In total, 22 FTE work in this experiment on R&D of the detector, its preparation for commissioning tests, development of the scientific program and MC simulation; software development; theoretical investigations.
9. **Nuclotron–NICA.** In total, 485 FTE work in this experiment on development and creation of the accelerators of the NICA complex and corresponding infrastructure.

## Involvement in other experiments off-site as of today

Traditionally, the HEP scientific program of JINR includes participation in experiments at accelerator centres around the world (e.g., CERN, BNL, DESY, GSI) that provide unique conditions to perform studies in the fields of high-energy heavy-ion physics and spin physics. The key factor here is a mutual benefit from the exchange of new scientific information and methodological and technological know-how.

VBLHEP scientists participate in these international experiments in Particle and Heavy-Ion Physics:

1. **ATLAS.** In total, 10 FTE work in this experiment on both upgrade and physics analysis.

2. **CMS.** In total, 28 FTE (and 5.9 FTE from other laboratories) work in this experiment on upgrade, physics analysis, and maintenance of detectors within their responsibility.
3. **COMPASS-2.** In total, 9 FTE work in this experiment on data taking, analysis, and maintenance of detectors within their responsibility.
4. **ALICE.** In total, 11 FTE work in this experiment on both upgrade and physics analysis.
5. **PANDA.** In total, 8 FTE work in this experiment on MC generators.
6. **NA-61.** In total, 3 FTE work in this experiment on data taking, data analysis and maintenance of detectors within their responsibility.
7. **NA-62.** In total, 11 FTE work in this experiment on data taking, data analysis, MC, and maintenance of the straw-tube-based tracking detector within their responsibility; they also make necessary theoretical investigations.
8. **NA-64.** In total, 10 FTE work in this experiment on manufacturing and maintenance of the straw-tube-based tracker detector, DAQ, MC simulation, online monitor code and analysis software development, data taking and data analysis; theoretical investigations, work on the experiment extension proposal.
9. **STAR.** In total, 22 FTE work in this experiment on data analysis, software development, data taking.
10. **CBM-HADES.** In total, 5 FTE work in this experiment on data taking, analysis, and maintenance of detectors within their responsibility.

For the Medium- and Long-Range Plan, VBLHEP sees its first and utmost priority in the construction, commissioning and operation as well as in further upgrades of the Mega-Science project NICA. Therefore, the laboratory management intends to reduce the present amount of its off-site involvement to less than 100 of its FTEs. In comparison with experimental groups of other international laboratories in international collaborations, this allows for collaborating in about 6–8 experiments with a strong force.

The continuing participation in the experiments NA61 and COMPASS at SPS, ALICE at LHC and STAR at RHIC is foreseen, since it is complementing the on-site research in line with the JINR culture of participating in fore-front research off-site. These activities have been of invaluable importance for the development of JINR in the last decades and for the preparation and realization of the physics and technical program at the NICA complex. However, JINR participation will depend on discovery potential of the experiments.

Strategically important is the JINR participation in experiments at the future electron–ion collider (EIC) facility to be built in the USA and in fixed-target experiments at the international FAIR facility.

The EIC is of extreme importance for determining the initial conditions related to the saturation of the soft-gluon density (colour glass condensate) and required to understand the behaviour and accompanying phase transitions of the excited (quark–gluon) matter produced in high-energy heavy-ion collisions. Besides, the coverage of the soft-gluon (low-$x$) region allows for a decisive reduction of the existing uncertainty in the gluon contribution to the proton spin.

The FAIR, thanks to the higher event rates and to the availability of an antiproton beam, will provide complementary data, not accessible at NICA, encompassing study of extremely rare signals of, e.g., exotic hadron states.

The experiments at CERN's LHC have a unique potential for measuring the polarization effects with non-polarized proton beams like decay angular distributions of known or newly discovered particles to determine their spin and discrete symmetry properties. In

addition, spin measurement is crucial in distinguishing major scenarios of TeV-scale new physics if, and when, it would be discovered at the LHC. This is the case for R-parity preserving supersymmetry, Little Higgs models with T-parity, extra-dimensional models with KK-parity, and a large class of similar models and scenarios.

JINR physicists are also interested in exploration of the spin structure of the electroweak interactions by measuring the lepton angular distribution coefficients in Drell–Yan processes, including study of forward-backward asymmetry, Lam–Tung relation breaking, and constrains of the electroweak mixing parameter, as well as non-direct searches for signals from new physics beyond the Standard Model.

The JINR strategy for cooperative research at other accelerator centres will be linked closely to the updated European Strategy for Particle Physics, expected to be available in 2020 .

## Budget considerations and estimates for mid-term plans

**1. At certain external accelerator facilities**, a continuation of JINR participation in the experiments is requested, but JINR contributions and resources are to be identified and budgeted, including operation and running costs — if charged:

a) NA61 at SPS,
b) COMPASS at SPS,
c) ALICE at LHC,
d) STAR at RHIC,
e) ATLAS and CMS, see Particle Physics Report,
f) EIC facility to be built in the USA,
g) Fixed-target experiments at the international FAIR facility,
h) Research Topic and Budget for EIC in the USA,
i) Research Topic and Budget for CBM,
j) Budget for PANDA.

The overall budget for off-site research will be less than 3–5 M$/year, as first estimates indicate. The near-term program proposals are being evaluated by the HEP-PAC.

The participation of JINR in very large accelerator R&D is of priority for future developments, like FCC, but most favourably with work projects at JINR site.

**2. At the VBLHEP**

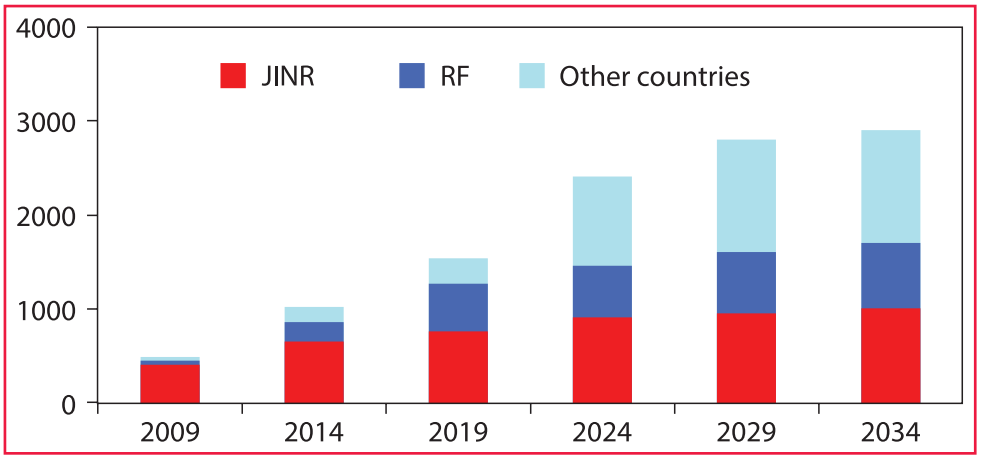
The NICA accelerator complex and the experiments BM@N and MPD (in its start version) are financially covered by the present budget plan including the MEGA Science Grant and new contributions from members of the collaborations.

The following projects are planned:

a) The MPD detector shall be supplemented with end-caps for realizing the full version of the MPD.
b) Polarized proton and deuteron beams will be made available at NICA. For the Spin Physics Detector (SPD) to be located at the second interacting point of the Collider, planning has been approved. There is presently no budget secured for that detector although the SPD collaboration is existing and working.
c) The upgrade of the Nuclotron beam extraction channels based on superconducting technology is foreseen and needs financing.

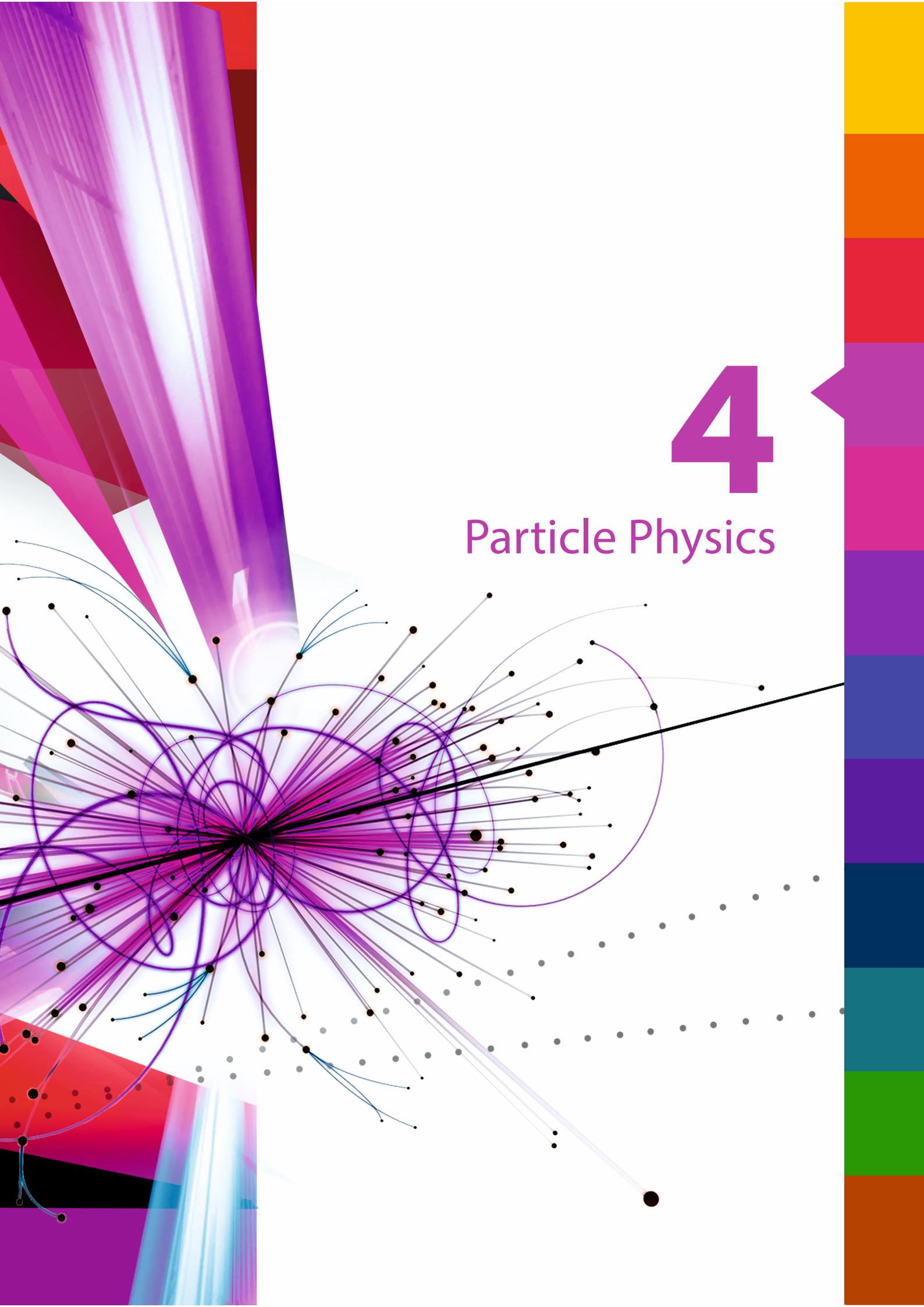
## Human resources

To operate the infrastructure of the NICA accelerator complex, it is planned to increase the number of staff of the laboratory to 1000 employees, out of which 450 are in the accelerator division, 300 in the infrastructure, and 300 in NICA experiments. The total estimated number of scientists and specialists involved in conducting the research at the NICA complex will reach 3000 by 2035 (see diagram).





JINR Long-Term Development Strategy up to 2030 and Beyond



# 4

# Particle Physics

## Executive Summary

JINR is a multidisciplinary international research institute deeply involved in international science, especially in Particle Physics. It made important hardware contributions to scientific and technical infrastructures within and beyond JINR, and took an active part in the harvesting of scientific results in data analysis. The JINR Particle Physics Program intends to stay well integrated into the European and worldwide Particle Physics Strategies.

The JINR strategy is based on a balance between home and international experiments. Both of them must be scientifically solid, well defined, and expand new frontiers in our understanding of physical laws that govern the Universe. Especially in Particle Physics, researchers from all the JINR member states should be able to participate in a stimulating research at the facilities like the LHC at CERN, exploiting at the same time the potential of the unique JINR infrastructure, which some university groups of its member states do not often enjoy.

Thus, a scientific program with several research directions, to be carried out at JINR in Particle Physics, is presented in this report for the mid-term (2024–2030) and long-term (2031–2037) periods.

The main directions of research for the medium and long terms are related to:

- Precision exploration of strongly interacting states, including proton structure, QCD phases, like quark–gluon plasma, new hadronic states, including exotic states.
- Electro-weak and flavor physics.
- Studies for better understanding of the evolution of the Universe through high–energy hadron–hadron collisions, as well as through searches for dark matter and dark sectors at colliders and in non-accelerator experiments.
- Experimental and theoretical determination of a model, beyond the Standard Model (SM), free from the SM shortages.
- Accelerator science and technology.

Many, if not all, of these directions are interwoven and interconnected. There is a strong synergy between these branches of research, as well as between the expertise of the JINR various laboratories. A solid research program for the next two decades is shortly reviewed below and in greater detail in the main text.

### Accelerator-Based Physics and Accelerator Technologies

JINR has been a standing member of both the ATLAS and CMS collaborations for over 25 years, and remains one of the key participants with great investments into these projects. The major discovery of both experiments was the observation of the Higgs boson production and its decay.

About halfway within the mid-term period of the JINR Strategy LRP — from 2023 till 2026 — the LHC will be upgraded to increase the luminosity by a factor of 5 to 7.5, reaching the record 3000 inverse femtobarn and 14 TeV beam center-of-mass energy by the end of its Run 5. By 2038 the integrated luminosity will be 20 times larger than all currently accumulated statistics, which will open a door to new insights and discoveries.

JINR plans to invest further in ATLAS about **4M USD** for the production of 32 quadruplets of NSW and upgrade of RPC of the Muon System, upgrade of electronics of LAr EM Calorimeter, Tile Hadronic Calorimeter, TDAQ System and production of the HGTD, and about **3M USD** in CMS for the upgrade of the endcap muon system, based on precision Cathode Strip Chambers, and construction of the High Granularity Hadron Calorimeters. In total, JINR envisages to invest about **22–26M USD** in ATLAS and CMS till 2037.

In the long-term period, after the HL-LHC upgrade, JINR should play a leading role in physics analyses like precision measurements within the SM, searches for BSM Physics, including dark matter, supersymmetry and exotics, studies of the hadron structure.

JINR has made substantial contributions to both LHC experiments and plans to continue doing so. Based on its scientific expertise and technical infrastructure, JINR intends to play an important role in the LHC physics and specifically in these two flagship experiments, which a single JINR member state cannot achieve.

The worldwide accelerator community explores different scenarios of pushing the energy and luminosity frontiers even further for the post-HL-LHC era. The current considerations include proton, electron and proton–electron colliders with possible sites at CERN (CLIC, LHeC, FCC, HE-LHC), Japan (ILC) and China (CepC, SppC), where various new ideas of accelerator technologies are to be explored.

The JINR researchers will join in these efforts and gain the necessary expertise whenever required to play a leading role in these investigations. As in the past years, when JINR was internationally recognized as a potential site for the ILC, a new young generation of JINR's scientists is going to look out for feasible large-scale contributions of JINR to these global projects.

Since the planning horizon extends beyond 2040, when new generations of scientists play a crucial role, JINR will develop a dedicated, clear-cut and elaborate educational program to guarantee a smooth know-how transfer and constant growth of new knowledge.

## Detector Technologies and Training

JINR is internationally recognized for its advancement of detector technologies. This expertise will be deepened henceforth by using modern high-tech standards and pushing further the frontiers. Yet, a considerable amount of knowledge must be acquired in modern electronics, robotics and precision mechanics. JINR will take all the necessary measures to attract to JINR world-level experts to lead perspective directions within detector technologies.

Finally, it is well recognized that an elaborate educational program at JINR must be developed to guarantee new highly trained generations of researchers. Moreover, JINR intends to develop a strong, innovative and bright outreach program meeting the world-class standards in this new field of communication. An outreach service that provides accurate and appealing information about the institutes research activities to a wide audience is understood today as of highest importance and a responsibility of scientists towards the society.

# Introduction

## Particle Physics Challenges

A vast variety of elementary particles and their interactions are best described by the Standard Model of Particle Physics. The SM is a quantum field theory (QFT) model with the $SU(3)_C \times SU(2)_L \times U(1)$ gauge group founded theoretically and experimentally in the 1960s–1970s. Although the SM is believed to be theoretically self-consistent and considered to provide a tremendous number of successful experimental predictions, it fails to fully explain the baryon asymmetry, it lacks a viable candidate for a dark matter particle and it cannot incorporate the general theory of relativity or account for accelerating expansion of the Universe, hypothetically explained nowadays by the dark energy impact.

Yet, the SM can accommodate but cannot explain hierarchical masses of quarks and leptons and patterns of their weak mixing matrices. Neither does it address the particular gauge symmetry in nature, nor the number of fermion families, nor the origin of CP-violation. Therefore, it is believed that there must be a model beyond the SM capable of getting rid of shortages of the SM. There are basically three directions of a search for physics beyond the SM:

1. Identifying phenomena diverging from the SM expectations at high energies.
2. Looking for specific predictions of new models.
3. Increasing the measurement precision to test further the SM predictions. These are the decays of particles that are usually examined in finest details. Such studies correspond to low energies.

Since the most challenging problems (baryon asymmetry, dark matter and dark energy) of the SM come from cosmological and astrophysical observations, nowadays it is believed that studying the evolution of the Universe could provide deeper insights into Elementary Particle Physics.

Among various observation channels the following ones, which are expected to assure a breakthrough in resolving some of the puzzles of the Universe, should be highlighted:

1. Search for sources of ultra-high energy photons and neutrinos in the cosmic radiation.
2. Multi-Messenger Astronomy.
3. Relic neutrino observation.
4. Diffuse neutrino observation.
5. Gravitational waves observation.

It is reasonable to be optimistic about this scientific program which not only balances the above-mentioned research directions, but also has every likelihood of bringing us towards some future pioneering philosophy within both Particle Physics and Astrophysics.

## Past Research Projects

This section will briefly review the most remarkable results in Particle Physics achieved with a decisive role of the JINR scientists over the last seven years. These attainments are to be considered separately in Physics and technologies. All the JINR contributions to both groups of these results are summarized below.

### Discoveries in Physics

1. **Higgs boson discovery.** This result was obtained by the ATLAS [1] and CMS [2] collaborations. DLNP and VBLHEP contributed mostly to ATLAS and CMS, respectively.

2. **Discovery of a family of exotic charmonium-like particles containing four quarks.** The discovery was done by the scientists from the BES-III [3] and BELLE [4], LHCb [5] experiments.
3. **Discovery of the direct CP-violation in the K0 system (NA48).**

JINR's contributions to the above-mentioned discoveries are briefly summarized in some detail below.

### ATLAS and CMS Experiments at the LHC at CERN

JINR has been a standing member of both the ATLAS and CMS collaborations for over 25 years, and remains one of the key participants with great investments into these projects. In compliance with its responsibilities, JINR performed for the ATLAS experiment:

- Design, production and commissioning of the detector modules for the Muon Spectrometer, Liquid Argon and Tile Calorimeters, and for the Inner Tracker.
- Calibration of the ATLAS calorimeters and preparation for data-taking.
- Participation in the development of the ATLAS Trigger DAQ (TDAQ).
- Creation of the ATLAS GRID at JINR (one of the best in Russia).
- Modelling and optimization of the ATLAS magnet system.
- Design, production and assembly of the elements of the ATLAS magnet system.

It should be mentioned that only Italy, the USA, CERN and JINR have contributed to all main subsystems (TileCal, Muon, LAr, ID, TDAQ) of the ATLAS detector.

JINR and its member states, participating in the CMS experiment within Russia and Dubna Member States CMS Collaboration (RDMS CMS Collaboration), contributed to CMS and to the physics data analyses:

- Full responsibility for design, construction, maintenance and operation of the Endcap Hadron Calorimeters (by VBLHEP and RDMS).
- Full responsibility for design, construction, maintenance and operation of the First Forward Muon Stations (ME1/1) (by VBLHEP and RDMS).
- Participation in design and construction of the Preshower for the Endcap Electromagnetic calorimeters (by VBLHEP and RDMS).
- Computing based on the GRID technology, including CMS Tier-1 and Tier-2, connected with some physics tasks.
- Participation in the detector operation and data taking shifts, including the fast detector monitoring, monitoring of data taking and data quality certification (by VBLHEP, LIT).

The key and decisive commitment to the discovery of the Higgs boson of the RDMS scientists from the JINR member states was honoured with the commendation by the CMS Spokesperson Joe Incandela in his letter addressed to the RDMS authors of the discovery on 31 July 2012.

For outstanding contributions in the CMS and ATLAS experiments resulting in the discovery of the Higgs boson, the leader of the Russian team in ATLAS A. M. Zaitsev (IHEP) and the RDMS CMS Spokesperson I. A. Golutvin (JINR) were awarded the P. A. Cherenkov Prize of RAS in 2014.

### BES-III Experiment

The JINR group has long participated in the Beijing Spectrometer III (BES III) experiment at the Beijing Electron–Positron Collider II (BEPC II) at the Institute of High Energy Physics (IHEP). BES-III is designed to study the physics of charm, charmonium, and light hadron decays. It also performs studies of the tau lepton, tests of QCD, and searches for physics beyond the Standard Model.

The JINR group has participated in:

- Development of the offline software and analysis tools, in particular used in the discovery of exotic charmonium-like particles.
- Design and development of the distributed computing system.
- Data taking and data analysis (light hadron spectroscopy, Charm and Charmonium Physics).

## Technological Breakthroughs Achieved by JINR Particle Physics Groups

1. **Precision Laser Inclinometer (PLI).** The DLNP researchers invented a brand-new instrument to measure the surface inclination angle. The precision reached the record $2.4 \cdot 10^{-11}$ rad/Hz$^{1/2}$ in the frequency range of $10^{-6}$ to 12.5 Hz. This device is indispensable to the particle beams improvement at CERN, earthquake monitoring, applications in gravitational wave detectors (PLI installation at VIRGO is displayed in Fig. 1) and elsewhere. The DLNP researchers created the concept of the instrument, performed necessary R&D activities, and obtained several patents.

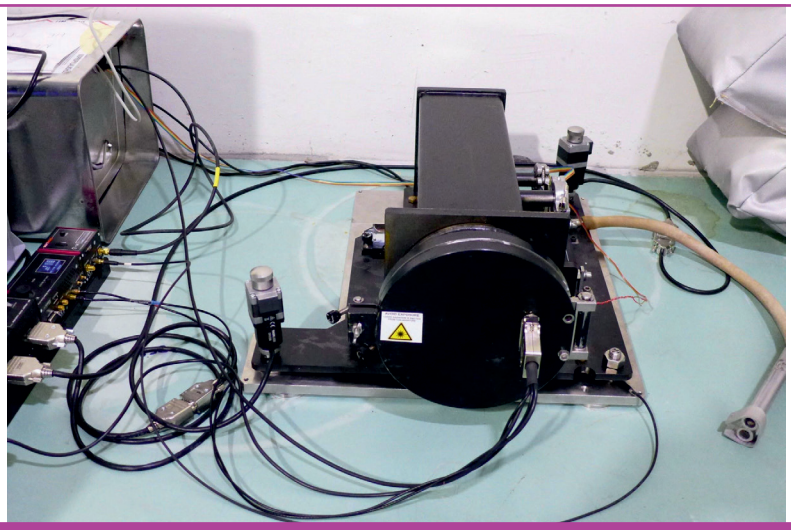


**Fig. 1. Precision Laser Inclinometer developed by DLNP and installed as a part of VIRGO detector (*image credit: Yu. A. Budagov, M. V. Lyablin*)**

2. **SiPM in calorimetry.** The first large-scale application of SiPM for electromagnetic calorimetry with a large dynamic range in Particle Physics (COMPASS experiment at CERN and MPD project at NICA), extensive use of SiPM in hadron calorimetry (CMS experiment upgrade at CERN).
3. **Development of advanced pixel detectors based on a Medipix chip and GaAs sensors for synchrotron radiation sources and for applied research.** The first hybrid pixel detectors based on GaAs:Cr sensor and Medipix chip were developed in collaboration with CERN and the National Research Tomsk State University (TSU). The large-area detectors Hexa and Double-Hexa were produced in collaboration with TSU and DESY, with the financial support of the Ministry of Education and Science of the Russian Federation. The GaAsPix detector network was designed and installed at CERN in the ATLAS cavern to monitor the radiation background. The semiconductor detector characterization lab and microCT lab were established at JINR.

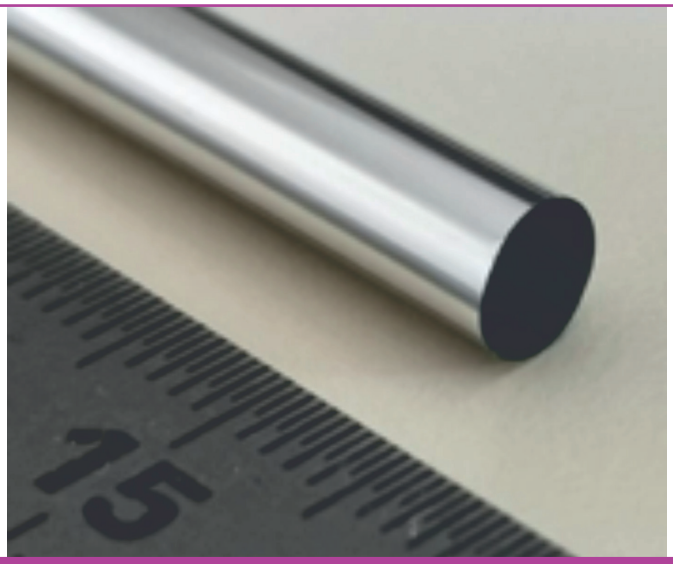


**Fig. 2. A straw tube with wall thickness of 12 micron and 5 mm diameter was produced at DLNP (*image credit: Z. Tsamalaidze*)**

4. **R&D of the large-area Micromegas chamber detector for the ATLAS upgrade.** The technology of mass production of large-area Micromegas chambers for New Small Wheels of the ATLAS Muon Spectrometer was developed in the framework of the ATLAS upgrade project. The production site was set up at JINR DLNP, and the detector construction is underway.
5. **R&D of bulk Micromegas detectors.** The new laboratory for R&D of MPGD detectors was founded at DLNP. Every step of the technology to produce bulk Micromegas detectors, inspired by original development by CERN and CEA Saclay, was carefully reconsidered and elaborated to adapt for tools and equipment existing at DLNP. In contrast to the technological line which provides production and testing of Micromegas chambers for the outer part of large sectors of NSW ATLAS (type LM2), where component materials are supplied from CERN in a centralized fashion for all participants of the project (INFN and German clusters, CEA Saclay, AUTh, JINR), this new line provides the complete production cycle. Thus, JINR became the third research center in the world, after CERN and CEA Saclay, that possesses the full technological chain of equipment and is capable of producing bulk Micromegas detectors.
6. **Development of the straw tube methodology.** A straw tube with wall thickness of 12 micron and 5 mm diameter was produced at DLNP for the COMET experiment (a ready-made straw tube is shown in Fig. 2). Tests show that straw tubes meet all the required specifications.
7. **Development of Si strip detectors.** Based on the Dubna silicon program, silicon coarse strip Preshower detectors for the CMS endcap electromagnetic calorimeters were widely applied in HEP for the first time (18 $m^2$, 144 000 channels in CMS), as well as the Silicon Option for the Endcap HCAL invented for CMS LoI in 1992 (*Golutvin I. A. et al.* RD35: "Silicon Hadron Calorimeter module for LHC", CERN/DRDC/91-54, DRDC/P34, January 13th, 1992). Today, 25 years later, the idea of Si tracking calorimetry is accepted by CMS at the modern level as a High Granularity Calorimeter for HL-LHC.
8. **Development of Cathode Strip Chambers (CSC).** The first wide application of CSC was proposed by JINR for the CMS Endcap Muon System. The innermost ME1/1 sta-

tions of the Endcap Muon System located in a 4 Tesla solenoid was developed by JINR in cooperation with Minsk. Other endcap stations were built by the US institutes in cooperation with Gatchina.

9. **Plastic scintillators with embedded WLS fibers, so-called sigma tiles, proposed for Hadron calorimetry.** CMS endcap calorimeters were developed by RDMS in cooperation with the Rosatom State Corporation and MZOR, Minsk. 600 tons of brass absorber were made of military shells.
10. **Bending beam of particles.** The technology of the accelerator beam extraction using crystal bent channelling was developed and realized at the leading world accelerator centres.
11. **Gas Electron Multiplier (GEM) technology.** A wide-aperture central tracking system of the BM@N experiment is based on large-area triple Gas Electron Multipliers (GEM) produced at the CERN PH DT and MPT workshop in cooperation with JINR VBLHEP. The detectors are operational at high radiation loadings and in strong magnetic fields, have high spatial resolution and high geometrical efficiency. BM@N GEM chambers with the size of 1632 × 450 mm are the biggest GEM detectors presently produced in the world.
12. **Time-of-Flight detectors.** A ToF detector with excellent time resolution of better than 50 ps was designed by JINR in collaboration with CERN and some China's universities.
13. **Film-free gas-discharge detectors.** The VBLHEP groups developed and realized the method of the production of film-free gas-discharge detectors: wire chambers (realized at the Synchrophasotron and U-70), large-aperture proportional chambers for the NA-4 experiment at CERN, drift tube chambers based on the straw-tube technologies. These detectors are used in the COMPASS, CBM, NA-62, NA-64, OKA, COMET, MPD, SPD, Thermalization and ATLAS (TRT) experiments.
14. **Record polarized nuclear target.** The DLNP researchers designed and constructed polarized proton and deuterium targets operating at 15–30 mK. The targets are currently in use in Mainz.

## Present Research Projects of JINR Particle Physics Groups

The *DLNP scientists* participate in a number of home and international experiments in Particle Physics.

The experiments in Particle Physics include:

1. **ATLAS.** In total, 29 FTE work in this experiment on both upgrade and physics analyses.
2. **Mu2e.** In total, 10.6 FTE work in this experiment on DAQ and data analysis.
3. **COMET.** In total, 15.4 FTE work in this experiment on R&D of straw tubes and calibration of crystals.
4. **BES-III.** In total, 4.5 FTE work in this experiment on data analysis, software development, MC generator for electron–positron scattering, studies of physics potential of the CLIC project.
5. **PANDA.** In total, 9 FTE work in this experiment on MC generators, a muon detection system prototype.

The *VBLHEP scientists* participate in a number of international experiments in Particle Physics (Heavy Ion experiments are included in the list since they focus also on Particle Physics):

1. **ATLAS.** In total, 10 FTE work in this experiment on both upgrade and physics analysis.
2. **CMS.** In total, 28 FTE (and 5.9 FTE from other laboratories) work in this experiment on upgrade, physics analysis, and maintenance of detectors within their responsibility.
3. **COMPASS-2.** In total, 9 FTE work in this experiment on data taking, analysis, and maintenance of detectors within their responsibility.
4. **ALICE.** In total, 11 FTE work in this experiment on both upgrade and physics analysis.
5. **PANDA.** In total, 8 FTE work in this experiment on MC generators.
6. **NA-61.** In total, 3 FTE work in this experiment on data taking, data analysis and maintenance of detectors within their responsibility.
7. **NA-62.** In total, 11 FTE work in this experiment on data taking, data analysis, MC, and maintenance of the straw tube-based tracking detector within their responsibility; also, they make necessary theoretical investigations.
8. **NA-64.** In total, 10 FTE work in this experiment on manufacturing and maintenance of the straw tube-based tracker detector, DAQ, MC simulation, online monitor code and analysis software development, data taking and data analysis; theoretical investigations, work on the experiment extension proposal.
9. **STAR.** In total, 22 FTE work in this experiment on data analysis, software development, data taking.
10. **CBM-HADES.** In total, 5 FTE work in this experiment on data taking, analysis, and maintenance of detectors within their responsibility.

In the framework of the NICA project implementation, the VBLHEP scientists participate in the experiments:

11. **BM@N.** In total, 74 FTE work in this experiment on R&D of the detector, its preparation for commissioning, development of corresponding electronics, DAQ, slow control, trigger; development of the scientific program and MC simulation; software development, data taking and data analysis; theoretical investigations.
12. **MPD.** In total, 113 FTE work in this experiment on R&D and manufacturing of the detector, its preparation for commissioning tests, development of corresponding electronics and DAQ; development of the scientific program and MC simulation; software development; theoretical investigations.
13. **SPD.** In total, 22 FTE work in this experiment on R&D of the detector, its preparation for commissioning tests, development of the scientific program and MC simulation; software development; theoretical investigations.
14. **Nuclotron–NICA.** In total, 485 FTE work in this experiment on development and creation of the accelerators of the NICA complex and corresponding infrastructure.

In-house experiments realized by international collaborations include:

15. **Hyper-NIS.** In total, 17 FTE work in this experiment on its preparation for commissioning tests.
16. **Scan-3.** In total, 10 FTE work in this experiment on its preparation for commissioning tests.
17. **FAZA.** In total, 8 FTE work in this experiment on its preparation for commissioning tests.

18. **DSS.** In total, 10 FTE work in this experiment on data taking and analysis, as well as on its maintenance, preparation for commissioning tests and upgrade.
19. **Alpom-2.** In total, 1 FTE works in this experiment on data analysis.

JINR systematically invests resources in the development of both the national research infrastructure and experimental facilities, allowing present and future generations to work in the top-ranked scientific surroundings.

### Staff and Equipment

DLNP and VBLHEP were the first two laboratories — the real founders of JINR back in 1956.

### DLNP

Nowadays, the DLNP scientists run a wide range of experimental projects both at home and elsewhere. There are a variety of unique competences accumulated in methodology, detector construction, data analysis.

The scientific program of DLNP includes Particle Physics, accelerator technologies, Neutrino Physics and Astrophysics, Radiation Medicine, Genetics and molecular genetics studies, Radiochemistry and Nuclear Spectroscopy, ultra-cold temperatures as major directions.

From the 727 employees of DLNP, 278 are scientists, 304 are engineers and specialists, 121 are technicians and 24 are from administration. 39 of the scientists have a Doctor of Science degree, while 141 have a PhD degree.

DLNP has its own Information Technology Division, responsible for computer resources, data storage, internet access and lots of various services, and an Engineering Design Department with about two dozen highly qualified engineers.

The laboratory is equipped with several dozens of machines, including modern numerical CNC machines (SafanDarley, HAAS), 3D printers and scanners. There are also a proton synchrophasotron, a linear electron accelerator, radiochemical equipment, microelectronics for R&D and production lines, as well as various tools and instruments for R&D of particle detectors.

### VBLHEP

The 1207 VBLHEP employees can be broken down into 310 of scientists, 578 engineers and specialists, 260 technicians and 57 working in administration. 60 of the scientists have a Doctor of Science degree, while 141 have a PhD degree. The VBLHEP management intends to keep the number of FTEs working in Off-Site experiments below 100 in order to fulfil its responsibilities for the NICA project.

### Expertise to Be Developed

JINR is determined to develop the following currently missing expertise for achieving the research goals presented in this report:

- Application Specific Integrated Circuit (ASIC).
- FPGA Electronics.
- Robotics.
- Quantum Computing.
- General Relativity and Gravitational Interferometry.
- Project management.

## ATLAS and CMS

The LHC operates at the nominal collision energy of 13–14 TeV and luminosity of $3\times10^{34}$ cm$^{-2}\cdot$s$^{-1}$ and will carry on till the end of 2023 collecting 300 fb$^{-1}$ of integrated luminosity at this stage (The LHC Run 3).

The third LHC long shutdown (Long Stop 3, LS3) is scheduled for 2024–2026. From 2026 on, the LHC is expected to operate at an increased luminosity of $5\times10^{35}$ cm$^{-2}\cdot$s$^{-1}$ which will allow during the LHC Runs 4 and 5 for increasing the statistics by more than one order of magnitude up to 3000 fb$^{-1}$.

JINR intends to continue its involvement in the CERN-LHC program by participating in the ATLAS, CMS as well as the ALICE collaborations. An adequate matching of human resources to financial and hardware contributions must be targeted.

### Motivation for Continuation of the Participation in the ATLAS and CMS Program

ATLAS and CMS are general-purpose experiments, designed to study the physics of *pp* collisions at the LHC. Their prime goals are to explore physics at the TeV scale and examine the mechanism of electroweak symmetry breaking through the studies of the Higgs particles discovered in 2012 and searches for:

- extra Higgs bosons beyond the Standard Model,
- supersymmetric partners of the SM particles,
- extra dimensions at TeV-energy scale,
- hints for unification of all fundamental interactions,
- deviations from the SM predictions.

These experiments will provide precision tests of the SM and measurements of EW and QCD processes.

For the Higgs boson in particular, the coupling constants to the SM particles will be measured with a precision of 5–14% and 2–10% given the integrated luminosities of 300 and 3000 fb$^{-1}$, respectively. Apart from that, collecting ~1200 fb$^{-1}$ of integrated luminosity will enable observation of rare Higgs-boson decays such as $H\to\mu\mu$. This will also help clarify the problem of the $B_0\to\mu\mu$ branching ratio which, according to the data of the first LHC run, slightly disagrees with the SM prediction by some 2 standard deviations.

### International Context

The ATLAS and CMS international collaborations were established more than 25 years ago to search primarily for the Higgs boson existence with the help of the LHC.

Nowadays, the collaborations include more than 8000 and 5000 participants in ATLAS and CMS, respectively, from more than 200 institutes in about 50 countries.

During these 25 years, very complex ATLAS and CMS detectors were designed, constructed, commissioned, and used to successfully investigate a variety of physics phenomena, including a long-awaited Higgs boson discovery in 2012.

The JINR contribution to this achievement is of fundamental importance. The JINR teams are going to increase their contributions to the ATLAS and CMS physics programs as indicated further in the next section.

Scientists from almost all JINR member states do work in the ATLAS and CMS experiments as JINR groups.

## JINR LHC Group Program for the Mid-Term Period

The JINR scientists target investigations in the following:
- Studies of the proton structure, hadronization, QCD coupling and of hadron spectra.
- Tests of the Standard Model at the LHC energies.
- Searches for Supersymmetry.
- Searches for new heavy particles and new interactions.
- Precision measurements of the properties of elementary particles and heavy baryons.
- Searches for signals predicted by scenarios of low-energy multidimensional gravity, extended gauge models, models with dark matter candidates, and scenarios with fermion flavour violation.

Also, both the ATLAS and CMS teams plan a number of upgrades, maintenance and R&D works in these experiments. Those are highlighted in the next section, indicating also the required resources.

## JINR LHC Group Program for the Long-Term Period

Scientists from JINR are going for new results in such important tasks as:
- Studies of the proton structure and of hadron spectra.
- Tests of the Standard Model at the LHC energies and higher statistics.
- Searches for Supersymmetry.
- Searches for new heavy particles and new interactions
- Measurement with greater accuracy of the properties of known elementary particles, such as *W* and *Z* bosons, top quark, and heavy baryons.
- The upgrade work in the framework of the ATLAS and CMS Upgrade Projects during the long technical stop LS4 (2030) and LS5 (2034).
- R&D works for the upgrade of the ATLAS and CMS detector systems planned for LS4 (2030) and LS5 (2034).
- Maintenance of the ATLAS and CMS detectors system within the JINR responsibilities.

## Required Resources

In the framework of Phase II (2017–2027) of the ATLAS upgrade, the JINR group will participate in:
- Production of new sRPC modules and gas system development for the muon spectrometer.
- Development of readout electronics, mass production of patch-cords for optical links and their radiation tests at the IBR-2 reactor for the liquid argon electromagnetic calorimeter.
- Procurement of various components of the TDAQ system, etc.

The CMS team will work on:
- Upgrade in the framework of the CMS Upgrade Project during the long technical stop LS3 (2024–2026).
- R&D for the upgrade of the CMS detector system planned for the LS4 (2030) and the LS5 (2034).
- Maintenance of the CMS detector system within the JINR responsibilities (endcap muon and hadron calorimetry systems).
- Upgrade of the First Forward Muon Station (ME1/1) and other ME2,3,4/1 muon stations.

- Participation in the construction of new High Granularity Hadron Calorimeters (HGCAL).
- Procurement of various components of the HGCAL, etc.

The MOUs have been signed by the Director of JINR V. A. Matveev. The overall JINR contribution to Phase II of the ATLAS upgrade is **3.4M CHF**, including Common Fund. This work will be done by the team that is presently involved in the Phase-I related activities. The overall contribution of JINR to Phase II of the CMS upgrade is **2.8M CHF**, including Common Fund. This work will be done by the team that is presently involved in the Phase-I upgrade activities and R&D for Phase II.

- During the mid-term period, JINR expects to invest **3.4M USD** to ATLAS and **2.8M USD** to CMS.
- During the long-term period, JINR expects to invest **3.4M USD** to ATLAS and **2.8M USD** to CMS.

## Future Colliders

### Motivation

After the discovery of the Higgs boson at the LHC, the Standard Model is now a complete theory. However, there remain a number of open questions which cannot be answered within the SM framework. Among them are the problems of hierarchy, fine-tuning, scale of neutrino masses, dark matter and many others. It is widely believed that sooner or later SM will be superseded by a new theory able to answer the fundamental questions of that kind. The development of such a theory needs an experimental insight from high-energy collider experiments.

Historically, the new particles are often discovered at hadron colliders which are capable of reaching very high energies. The discovery is then followed by high-precision measurements of the properties of the new particles. Electron–positron colliders with their clean experimental environment are optimally suited for such a precision measurement. For example, *W* and *Z* bosons have been discovered at the hadron *pp* collider, while their properties were measured down to a permille level at the $e^+e^-$ colliders LEP and SLD. The tiny effects of radiative corrections observed at LEP and SLD allowed one to predict the masses of the top quark and Higgs boson, which in turn were discovered at the Tevatron and LHC.

It is expected that the New Physics phenomena can be observed at future $e^+e^-$ colliders as tiny deviations from the Standard Model predictions via the measurements of top and Higgs properties at sub-percent level. Another possibility is the extremely precise measurement of *W* and *Z* boson properties at the level better than $10^{-4}$. A direct discovery of new particles is also possible, since LHC experiments cannot cover the full spectrum of all the possible New Physics signatures.

### International Context

Currently, 4 projects of the future electron–positron colliders are being actively developed: CEPC (China), CLIC and FCC (CERN), and ILC (Japan). CLIC and ILC are linear colliders, while CEPC and FCC are circular ones, with possible upgrade to proton–proton or electron-proton collisions to provide a significant increase in collision energy. For CEPC and ILC the expected maximum $e^+e^-$ collision energy is 240–250 GeV ("Higgs-factory"). FCC is planned to reach the top-pair threshold (350–360 GeV). CLIC plans to start operation at 380 GeV and then increase the energy up to 3000 GeV, making possible a direct search

of New Physics. Additionally, CEPC and FCC are capable of providing an ultra-high luminosity running at 91 GeV ($(0.7–5)\cdot 10^{12}$ *Z* bosons, "TeraZ-factory"), which would allow for improving the LEP precision by 2 orders of magnitude.

CLIC and FCC are the international collaborations coordinated by CERN. Both CERN member states and non-member states are actively involved in the projects. ILC is expected to receive the largest single contribution from Japan. However, it is a wide international collaboration, with non-Japanese contribution expected to be more than a half of the total project. CEPC is expected to receive at least 75–80% of its budget from China. However, an international collaboration is currently being formed to attract the contributions of technology and expertise, which is especially important given that no HEP project of comparable scale has been developed in China so far.

It is obvious that all the four machines cannot be constructed simultaneously. Most likely, one or two projects will be chosen out of the four. The active construction phase is expected to begin in 2028–2030, with first collisions in 2035–2037. It is therefore very important that at the current stage JINR keeps a critical level of involvement in all projects of the future collider.

## Proposed Research

JINR physicists have accumulated a vast experience in physics at electron–positron colliders. JINR group participated in DELPHI experiment at LEP in 1987–2005 and in BES-III experiment at BEPCII since then. The ZFITTER program developed at JINR was the standard tool for the LEP data analysis.

Currently a wide R&D program is being carried out at the Institute. JINR can provide an important contribution to the design and construction of the future collider and its detectors; data taking, processing and analysis; theoretical calculations for the interpretation of the experimental observables.

The following activities have already been started or are foreseen for both mid- and long-term periods:

- Accelerator technology R&D based on precision laser inclinometer developed at JINR.
- Development of novel particle detectors, in particular compact forward calorimeter developed in the FCAL collaboration, pixel detectors based on GaAs sensors and MPGD detectors (Micromegas, RPC, etc.) which are currently being developed at JINR.
- Development (and later implementation) of the experimental program of the future colliders in the following fields: precision measurement of the Higgs boson properties; observation of the triple-Higgs vertex; top quark physics; physics of two-photon collisions; direct searches for the new phenomena at high energies.
- Creation of the theoretical program for complete one-loop calculations of the electron–positron annihilation into different final states including the polarization effects.
- Participation in the GRID computing infrastructure for the decentralized data processing.

## Required Resources

The active construction phase is expected to begin around 2030. This stage will require a substantial increase in resources.

Since all these top accelerator projects will have a price tag in the order of many billions of dollars, JINR member states must have early discussions of how to participate under the JINR umbrella in such a unique worldwide facility.

For the R&D in accelerator technology as well as detector design, with prototype construction for both,

- **8M USD** are expected for the mid-term period.
- **35M USD** are expected for the long-term period.

## NICA SPD

Being a JINR on-site mega-science project, NICA is reviewed in a separate document. The consideration here concerns mainly DLNP participation in the NICA SPD experiment. Due to its polarized beams, NICA will be a forefront facility for spin physics in the world.

### Motivation

The share of the nucleon spin between spins and orbital momenta of quarks and gluons still remains an open question. Further studies of this phenomena could provide further insights into the QCD structure of hadrons. The measurement of the spin effects related with the transverse motion of partons inside the nucleon is the main goal of the SPD experiment.

NICA SPD is presently working on a conceptual design report (CDR), but the management has decided to construct the SPD hall already in the present construction period.

### International Context

Scientists from JINR member states and abroad are expected to increase their participation, thus establishing a truly international environment in NICA SPD experiment.

### Proposed Research

The current considerations deal with the spin structure of hadrons and Transverse-Momentum-Dependent (TMD) Parton Distribution Functions (PDFs). The comprehensive research program is being determined.

The TMD PDFs will be accessed via such hard processes like Drell–Yan process, charmonia production and prompt-photon production in the center-of-mass energy range from 10 to 27 GeV in *p*–*p* and *d*–*d* collisions with luminosity up to $10^{32}$ $cm^{-2} \cdot s^{-1}$.

The DLNP team intends to perform the measurement of the transverse single and longitudinal double spin asymmetries in prompt-photon and charmonia production with accuracy below 2% in order to access the helicity and Sivers PDFs for gluons. Charmonia production mechanisms will also be tested. DLNP also participates actively in the development of the SPD muon system and DAQ system. Preparation of the TDR should be finished till 2023 and the time scale for realization of the project extends beyond 2025.

### Required Resources

- For the mid-term period, JINR plans to invest **21M USD** which break down:
  - R&D, construction and commissioning of data acquisition system: **10M USD**.
  - R&D, construction and commissioning of muon system: **10M USD**.
  - Travel expenses: **1M USD**.
- For the long-term period, JINR plans to invest **8M USD** for the detector maintenance.

## Summary

The proposed long-term Strategy for Elementary Particle Physics and Astrophysics at JINR is based on four pillars: Accelerator-Based Physics and Accelerator Technologies, and Detector Technologies, supplemented by a well though educational and outreach program.

This strategy carefully strengthens traditional JINR strong expertise in particle physics and detector technologies.

## Timeline

Tables 1 and 2 provide compact summaries on the timelines of the mid- and long-term experimental activities. The cell colours in the tables are summarized in what follows.

| Cell color | R&D | Construction Commissioning | Data taking | STOP | Decision Point |
|---|---|---|---|---|---|

**Table 1. Timeline of projects from the mid-term Strategy for Elementary Particle Physics and Astrophysics at JINR. (*Full costs of 1 FTE about 50 k$ in 2020 $*)**

| | 24 | 25 | 26 | 27 | 28 | 29 | 30 | Main physics goal **Invest.-Budget, USD** |
|---|---|---|---|---|---|---|---|---|
| **ATLAS** | LS3 upgrade | | RUN 4 | | | | | Beyond the SM, precision EW and QCD **3.4M +39 FTE** |
| | | | LS4, LS5 R&D | | | | | |
| **CMS** | LS3 upgrade | | RUN 4 | | | | | Beyond the SM, precision EW and QCD **2.8M + 28 FTE** |
| | | | LS4, LS5 R&D | | | | | |
| **Future Colliders** | | | | | | | | Beyond the SM, precision EW and QCD **8M** |
| **NICA-SPD** | | | | | | | | TMD PDF **21M + 50 FTE** |

**Table 2. Timeline of projects from the long-term Strategy for Elementary Particle Physics and Astrophysics at JINR. (*Full costs of 1 FTE about 50 k$*)**

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | Main physics goal **Budget, USD** |
|---|---|---|---|---|---|---|---|---|
| **ATLAS** | LS3 upgrade | | RUN 4 | | | | | Beyond the SM, precision EW and QCD **3.4M +39 FTE** |
| | | | LS4, LS5 R&D | | | | | |
| **CMS** | LS3 upgrade | | RUN 4 | | | | | Beyond the SM, precision EW and QCD **2.8M + 28 FTE** |
| | | | LS4, LS5 R&D | | | | | |
| **Future colliders** | | | | | | | | Beyond the SM, precision EW and QCD **35M** |
| **NICA-SPD** | | | | | | | | TMD PDF **8M+ 50 FTE** |

## International Context

JINR Strategy for Elementary Particle Physics is a careful balance of home and foreign experiments. All JINR member states have a unique possibility to enjoy both a rich, modern JINR infrastructure and participation in the world-class leading experiments in the fields of particle physics.

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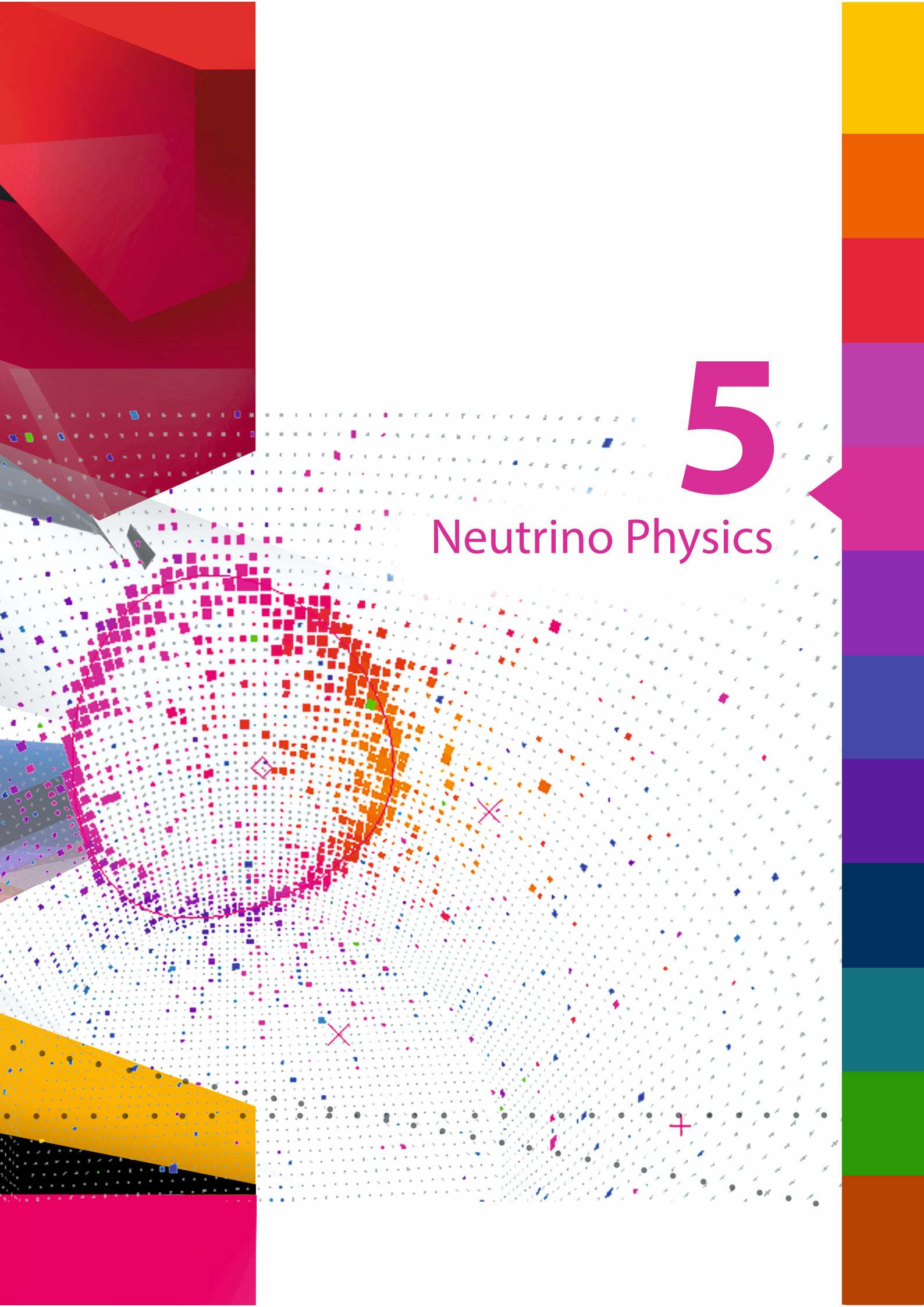
# JINR Long-Term Development Strategy up to 2030 and Beyond



# 5 Neutrino Physics

## Executive Summary

Neutrino Physics plays a key role in understanding the laws governing the Universe. Nowadays, the significance of Neutrino Physics is steadily increasing since it has entered its precision era.

JINR, due to the explorations led by B. Pontecorvo since the 1950s, developed a strong and influential neutrino school with about 100 researchers working in this field today. JINR leads the world's largest **Neutrino Program** *covering experimentally all sources of neutrinos*, accompanied by strong theoretical investigations and sophisticated data analysis. The JINR management intends to fully support the Neutrino Program for strengthening the research by the JINR scientists in advanced experiments and further developing the competence and know-how.

Together with INR (Moscow), JINR already plays a leading role in the construction, data taking, reconstruction, calibration and data analysis of **Baikal-GVD (Gigaton Volume Detector)** with an aim to build a 0.4 $km^3$ detector by 2021 and 1.1–1.2 $km^3$ detector by 2027. JINR invests about **6M USD** per year to accomplish these goals. In 2019, Baikal GVD is the largest neutrino telescope in the Northern Hemisphere with its 1/4 $km^3$ detector. The **TAIGA** installation, a set of gamma and muon telescopes hosted in Siberia, in Tunka Valley, to the south of Lake Baikal, can be regarded as a supplemental instrument in terms of multi-messenger astronomy. Together, Baikal-GVD and TAIGA might form a unique multi-messenger observation tool for events occurring in the Universe integrated into the global international network. These days, exciting observations of great activities on Betelgeuse demand well-orchestrated and simultaneous observations of gamma and neutrinos to be ready if and when Betelgeuse turns into a supernova. This direction of research is of great importance and will be seriously considered by the JINR management for strengthening its gamma-ray counterparts.

The scientific program with several research directions to be carried out at JINR in Neutrino Physics and Astrophysics is presented in this report for the mid-term (2024–2030) and long-term (2031–2037) periods.

The main directions of research in neutrino physics for the medium and long terms are related to:

- Observation of neutrino interactions from neutrinos from accelerator-based sources, from nuclear reactors and from cosmic sources with very large and sophisticated instruments.
- Studies for further insight into the evolution of the Universe through astrophysical and cosmological observations boosted by the development of new instruments, like gravitational wave (GW) detectors (a new channel for Multi-Messenger Astronomy), as well as through searches for dark matter and dark sectors at colliders and in non-accelerator experiments.

As a long-term program, JINR may consider building its own gravitational wave detector in Russia, which will enormously boost GW astronomy in Russia and the JINR member states. The flat large area around Dubna was already positively evaluated for the large system of the ILC and can serve extremely cost-effectively to such a GW Laser system.

# Introduction

## Neutrino Physics

Neutrino Physics is of great value to our comprehension of the laws reigning over the Universe. Nowadays, the significance of Neutrino Physics is steadily increasing since its precision era has already started.

Due to the explorations headed by Bruno Pontecorvo since the 1950s, JINR developed a strong and influential neutrino school with about 100 researchers working in this field today. JINR leads the world's largest **Neutrino Program** covering all sources of neutrinos, assisted by strong theoretical investigations and detailed data analysis. JINR plans for a full support of the Neutrino Program encouraging the participation of its scientists in advanced experiments for keeping up their research competence and the know-how gained so far.

### Cosmic neutrinos

JINR plays, along with INR (Moscow), a leading role in the construction, data taking, reconstruction, calibration and data analysis of the **Baikal Gigaton Volume Detector** (**Baikal-GVD**) with an aim to build a 0.4 $km^3$ detector by 2021 and a 1.1–1.2 $km^3$ detector by 2027. JINR invests about **6M USD** per year to accomplish these goals. In 2019, Baikal-GVD is still the largest neutrino telescope in the Northern Hemisphere with its 1/4 $km^3$ detector.

JINR is about to strengthen further its leading position by substantially increasing efforts in data analysis to yield the highest-quality scientific results in the observation of ultra-high astrophysical neutrinos and related studies. Furthermore, any attempts to perform profound limnological and environmental explorations of Lake Baikal are welcomed by JINR. The perspectives of Baikal-GVD are well defined for the medium and long terms and described in more detail below.

### Neutrinos from nuclear reactors

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment designed to determine neutrino mass hierarchy and precisely measure oscillation parameters. It detects reactor neutrinos from the Yangjiang and Taishan Nuclear Power Plants, observes supernova neutrinos, thus allowing studies of atmospheric, solar neutrinos and geoneutrinos, and of exotic searches, with a 20-thousand-ton liquid scintillator detector of unprecedented 3% energy resolution (at 1 MeV) at 700-meter deep underground.

The major motivation for JUNO, the reactor antineutrino experiment, is the determination of the neutrino mass ordering at confidence level of 3–4 standard deviations. JINR is a key JUNO collaborator with well visible financial and intellectual contributions. JINR also has a clear research program outlined below. The JINR group is to broaden its role in the software development and data analysis for the long-term period.

### Neutrinos from accelerator-based sources

The next breakthrough in the determination of the neutrino mass ordering and CP-violation in the lepton sector can be expected from a global analysis of neutrino data and from precision measurements in accelerator long-baseline experiments. **Deep Underground Neutrino Experiment** (**DUNE**) is an experiment under construction, with a near detector at Fermilab and a far detector at the Sanford Underground Research Facility that will observe neutrinos produced at Fermilab. **HyperKamiokande** in Japan is to observe neutrinos also from the accelerator at J-PARC in Japan. The NOvA (NuMI Off-axis $\nu_e$ Appearance) experiment uses two detectors: a 300 metric-ton near detector at Fermilab and a much larger 14 metric-kiloton far detector in Minnesota just south of the U.S.–Canada border.

JINR, presently successfully participating in the NOvA experiment, is considering joining at least one of these experiments. The decision should be taken based on a) the accuracy of their measurements, which, however, are presently expected to be comparable to each other, and b) on the size of the requested JINR contribution which needs to be big enough for a leading laboratory in the collaboration.

## Multi-Messenger Astronomy Including Gravitational Wave Detection

It is understood nowadays that different observations of the same phenomenon occurring in the Universe via different signal detection systems could give a further insight into the evolution of the Universe. Such an observation of one single phenomenon via several different signals is called multi-messenger astronomy. These days, exciting observations of great activities on Betelgeuse demand well-orchestrated and simultaneous observations of gamma and neutrinos to be ready if and when Betelgeuse turns into a supernova. Multi-messenger astronomy is absolutely needed to exploit such a rare event, especially so close to Earth.

**Baikal-GVD** mentioned above is one of the cornerstones of this approach. The **TAIGA** installation, a set of gamma and muon telescopes hosted in Siberia, in Tunka Valley, to the south of Lake Baikal, can be regarded as a supplementing instrument in terms of multi-messenger astronomy. Together, **Baikal-GVD** and **TAIGA** might form a unique multi-messenger observation tool for events occurring in the Universe. This direction of research, being of potentially great importance, is seriously considered by the JINR management for the strengthening of its gamma-ray counterparts. **TAIGA** is planned to be set up as a truly international collaboration, achieving the world-level quality standards in the technologies, commissioning, software and data analysis. JINR will take all necessary steps for attracting world-class experts to lead this project.

The recent discovery of gravitational waves is one of the most remarkable discoveries ever, which opened a new window to observe the Universe. Russia currently lacks any gravitational wave detector and this disparity must be removed. JINR proposes to enter this field of research, which requires developing new expertise in many fields ranging from General Relativity to precision laser interferometry. It should be noted that JINR has already made the first step forward in this direction, having installed its brand-new laser inclinometer at the VIRGO detector. In the medium term, JINR plans to develop a necessary expertise missing by now and prepare itself for the competent collaboration at the existing gravitational wave detectors like **LIGO**, **VIRGO**, **KAGRA** and/or at the third-generation detector **Einstein**.

In the medium to long-term period, JINR will consider plans to build its own gravitational wave detector in Russia which will enormously boost GW Astronomy in Russia and in JINR's member states as well.

## Short Summary of Past Research Projects

This section will briefly review the most remarkable results in Neutrino Physics and Astrophysics achieved with a decisive contribution of the JINR scientists over the last seven years. These attainments are to be considered separately in Technological Breakthroughs. All the JINR contributions in this field are summarized below.

### Discoveries in Physics

1. **Discovery of a non-zero value of the lepton mixing angle $\theta_{13}$ and of the third mode of neutrino oscillation. The most precise measurement of this parameter.** This discovery was done in the Daya Bay experiment [1, 2].
2. **Discovery of the muon neutrino oscillation to a tau neutrino.** This observation at five standard deviations confidence level was done in the OPERA experiment [3–5].
3. **Geoneutrinos.** Antineutrinos produced by the crust and mantle of the Earth were first discovered in the BOREXINO [6] and KamLAND [7] experiments.
4. **The first spectroscopic measurement of *pp* and $^{7}$Be solar neutrinos and the first observation of matter effect in neutrino oscillation.** These observations were performed within the BOREXINO experiment [8].

JINR's contributions to the above-mentioned discoveries are briefly summarized in some details below.

### Daya Bay Experiment

- Production and commissioning of the wavelength shifter PPO for the liquid scintillator of the Daya Bay detectors.
- Data analyses. In particular, the results of the data analysis 2016 [9] were based on the analysis performed by JINR.
- The JINR scientists were awarded **"The Breakthrough Prize in Fundamental Physics 2016"** as members of the Daya Bay Collaboration.

### BOREXINO Experiment

- Commissioning of CTF (BOREXINO prototype) and of the BOREXINO photomultipliers (tests, cabling, mounting, cleaning, calibration, software).
- Leading analyses of solar and geoneutrinos, and searches for non-standard interactions.

### OPERA Experiment

- The JINR team, along with a French group from Strasbourg, created the main tracking detector — the Target Tracker, which provided the neutrino interaction position in the setup. Since the beginning of the experiment, JINR has taken a **leading role** in the Target Tracker data analysis.
- The software algorithms developed at JINR allowed efficient location of the neutrino interaction vertex in the OPERA emulsion target brick — an important step without which the tau neutrino search would have been impossible.
- JINR participated in the emulsion analysis, having created the dedicated nuclear emulsion scanning facility equipped with two up-to-date automatic microscopes.
- Many OPERA results were published with an active participation of the JINR team as editors or internal referees, and also reported many times within major international conferences.

## Technological Breakthroughs

1. **Construction of a 1/4 cubic kilometer Baikal Neutrino Telescope.** The Baikal-GVD collaboration, led by both the JINR and INR scientists, has started the construction of the neutrino telescope of a cubic kilometer size in Lake Baikal. By now, the assembled facility is already considered to be the largest in the Northern Hemisphere.
2. **Breakthrough in the reading speed from nuclear emulsion.** Researchers from the OPERA collaboration managed to increase the speed of nuclear emulsion processing by a factor of one thousand, now reaching the record 5000 $cm^2$ per hour. This advancement opened new possibilities for studies of short-lived particles in the DsTau and FASER experiments at CERN, tau neutrinos in SHiP at CERN, searches for dark matter in NEWS-dm at Gran Sasso. This technology is also used in applied research such as cosmic-ray muon radiography of volcanoes, archeology and geoscience. Led by scientists from Nagoya (Japan) and Napoli (Italy), the JINR physicists contributed to this research in the development of software and emulsion processing, a part of which was carried out at the DLNP scanning facility. The first tau neutrino observed by the OPERA experiment is depicted in Fig. 1.

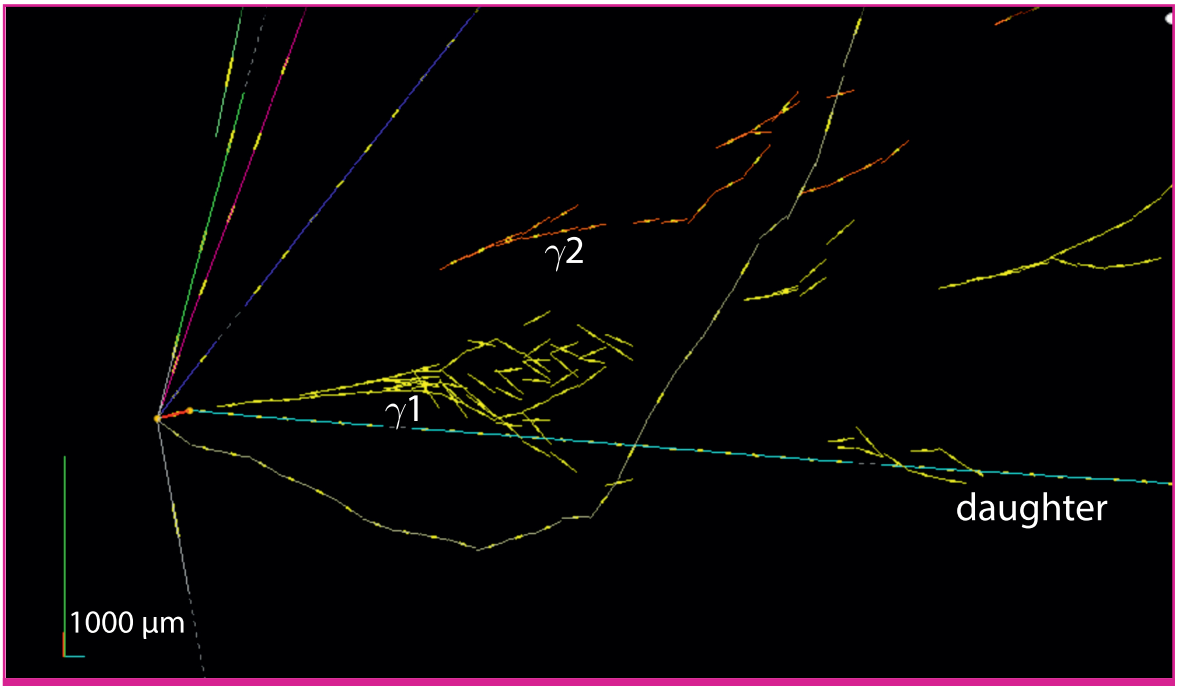



**Fig. 1. The first tau neutrino interaction observed in the OPERA nuclear emulsion. The tau lepton track can be seen as a short red line connecting two displaced vertices. The tau lepton decayed presumably into a rho-minus meson and a tau neutrino. The rho-minus meson subsequently decayed into pi-minus (a long track labeled as "daughter") and pi-zero mesons. The latter almost immediately decayed into two photons which both produced electromagnetic showers labeled as γ1 and γ2 (*Image credit: the OPERA collaboration*)**

## Short Summary of Present Research Projects

The DLNP scientists participate in a number of home and international experiments in Neutrino Physics and Astrophysics.

The unique feature of DLNP is its Neutrino Program — the world's largest one. It includes the following experiments.

1. **Baikal-GVD.** In total, 25 FTE work in this experiment on its construction, calibration, data taking and data analysis.
2. **Daya Bay.** In total, 8 FTE work in this experiment on data analyses.
3. **JUNO.** In total, 22 FTE work in this experiment on design, production and commissioning of high-voltage units for 20 thousand 20" PMTs and for 25 thousand 3" PMTs; commissioning of the TopTracker detector; PMT tests and their characterization by the JINR PMT scanning stations; muon track reconstruction code development; development of the Global Neutrino Analysis (GNA) software.
4. **NOvA.** In total, 14 FTE work in this experiment on hardware and software development; data taking and analysis.
5. **BOREXINO.** In total, 4 FTE work in this experiment on data analysis.
6. **DANSS.** In total, 10.5 FTE work in this experiment on its construction, calibration, data taking and data analysis.
7. **GERDA.** In total, 5.4 FTE work in this experiment on development of germanium semiconductor detectors and data taking.
8. **GEMMA-III and vGEN.** In total, 10 FTE work in this experiment on development of germanium semiconductor detectors, data taking and data analysis.
9. **SuperNEMO.** In total, 5 FTE work in this experiment on data taking and data analysis.
10. **EDELWEISS.** In total, 9 FTE work in this experiment on data taking and data analysis.
11. **TAIGA.** In total, 11.2 FTE work in this experiment on detector construction and data taking.

## National and International Networking Context

The overwhelming majority of the JINR scientific research activities in Neutrino Physics and Astrophysics is embedded into the international context due to the very nature of the structure of the modern astroparticle community and special features of data taking in international collaborations. JINR systematically invests resources in the development of both the national research infrastructure and experimental facilities, allowing present and future generations to work in the top-ranked scientific surroundings.

## Staff and Equipment

### DLNP

Nowadays, the DLNP scientists run a wide range of experimental projects both at home and elsewhere. There are a variety of unique competences accumulated in methodology, detector construction, data analysis.

The scientific program of DLNP includes Particle Physics, accelerator technologies, Neutrino Physics and Astrophysics, Radiation Medicine, Genetics and molecular genetics studies, Radiochemistry and Nuclear Spectroscopy, ultra-cold temperatures as major directions.

From the 727 employees of DLNP, 278 are scientists, 304 are engineers and specialists, 121 are technicians and 24 are from administration. 39 of the scientists have a Doctor of Science degree, while 141 have a PhD degree.

DLNP has its own Information Technology Division, responsible for computer resources, data storage, internet access and lots of various services, and an Engineering Design Department with about two dozen highly qualified engineers.

The laboratory is equipped with several dozens of machines, including modern numerical CNC machines (SafanDarley, HAAS), 3D printers and scanners. There are also a proton synchrophasotron, a linear electron accelerator, radiochemical equipment, microelec-

tronics for R&D and production lines, as well as various tools and instruments for R&D of particle detectors.

### Expertise to Be Developed

JINR is determined to develop the following currently missing expertises for achieving the research goals presented in this report:

- Application Specific Integrated Circuit (ASIC).
- FPGA Electronics.
- Robotics.
- Quantum Computing.
- General Relativity and Gravitational Interferometry.
- Project Management.

## Baikal-GVD

### Motivation

The major motivation for the **Baikal-GVD** cubic-kilometer neutrino telescope is related to an unambiguous identification of sources of neutrinos with ultra-high energy (UHE) belonging to PeV energy range. An identification of such sources could give us a new knowledge and deeper insights on the Universe evolution, formation of galaxies and black holes, on natural accelerators of particles, boosting them to extreme energies and related phenomena.

The Baikal-GVD experiment presently under construction will be a multipurpose research facility, intended to deliver data with unprecedented precision in neutrino physics and to make important contributions to dark matter searches, cosmic ray physics and limnology.




**Fig. 2. Five clusters of the Baikal-GVD neutrino telescope installed by 2019**

Five clusters installed by 2019 made Baikal-GVD the largest neutrino telescope in the Northern Hemisphere. A schematic view of the five clusters is shown in Fig. 2.

The **Baikal-GVD** experiment is expected to play a leading role in the multi-messenger astronomy determining the worldwide activity together with other neutrino and gamma telescopes and with gravitational wave detectors. An identification of UHE neutrino sources is expected to make a breakthrough in our understanding of the Universe evolution, galaxy formation, providing further tests of the theory of general relativity, and giving insights on natural particle accelerators. The Baikal Neutrino Telescope will be also unique as a precision monitor of Lake Baikal, sensitive to tiny variation of its water properties, thus providing a great new tool for limnology.

The Baikal Neutrino Telescope will be a unique laboratory on the territory of Russia providing great opportunities for scientific research to new generations.

Depending on the results obtained by the end of the mid-term period, a decision to increase further the fiducial volume might be taken at that time. One can foresee in an optimistic scenario that an increase of the volume by a factor of two will make a precision neutrino astronomy possible.

The Baikal-GVD experiment is considered a flagship INR and JINR experiment.

## International Context

The Baikal-GVD construction, data taking and analysis, under leadership of INR (Russian Academy of Sciences) and JINR, is considered as a "home" experiment with its installation on the territory of Russia.

A number of institutions from Russia and JINR member states (Czech Republic, Slovakia, Poland) joined the experiment, making important contributions. Further internationalization of the project is expected.

## Proposed Research

There are three phases of construction of the Baikal-GVD project considered:

1. Phase I. By 2021, 0.45 $km^3$ detector should be constructed, which would correspond to the actual fiducial volume of the IceCube detector.
2. Phase II. By 2027, the detector should increase up to 1.2 $km^3$ volume.
3. Phase III. By 2037, the detector should increase up to 2.4 $km^3$ volume.

The proposed research for the mid-term period reads:

- R&D for the new electronics, fully digital trigger and optical links for the data transfer.
- Construction of the phase II detector.
- Development of algorithms for the track-reconstruction, particles energy and direction reconstruction, identification of neutrino flavour.
- Development of multi-messenger alert system and integration into the worldwide multi-messenger network.
- Accurate measurement of atmospheric muon and neutrino fluxes.
- Data analysis and search for UHE neutrinos.
- Search for UHE neutrino sources.
- Search for magnetic monopoles and dark matter particles.

The proposed research for the long-term period reads:

- Multi-messenger astronomy within the worldwide multi-messenger network.

- Precision measurement of atmospheric muon and neutrino fluxes.
- Identification of UHE neutrino sources.
- Search for magnetic monopoles and dark matter particles.

### Required Resources

- R&D and Phase II detector installation require about 45M USD for the mid-term period.
- R&D and Phase III detector installation require about 90M USD for the long-term period.

## JUNO

### Motivation

JUNO is a multipurpose experiment studying reactor antineutrinos. The JUNO detector is shown in Fig. 3.

The major physics program includes:

- Determination of neutrino mass ordering at confidence level of 3–4 standard deviations, as the main scientific goal of the JUNO experiment.
- Determination of lepton mixing angles and neutrino mass splitting with an accuracy better than 1% in a single experiment. This precision will be comparable to that in the quark sector.
- Observation of SuperNova (SN) neutrinos with an unprecedented statistics and details. If SN explosion happened at a distance of about 10 kpc, JUNO would observe about ten thousand SN neutrinos. Such an observation enables testing of the SN models and independently determining the neutrino mass ordering.

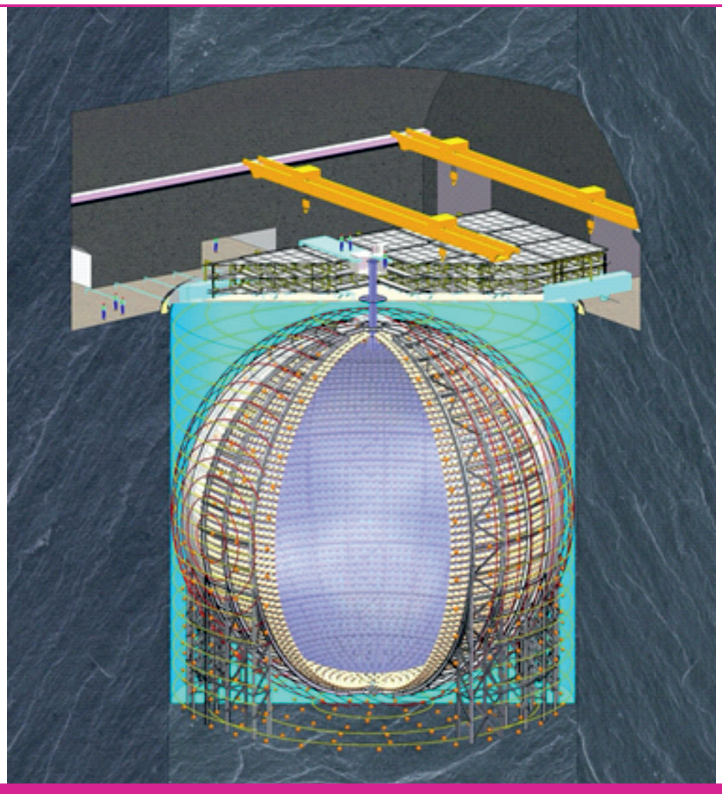


**Fig. 3. Schematic view of the JUNO central detector. The diameter of the sphere, filled with 20 thousand tons of liquid scintillator and surrounded by about 20 thousand 20" PMTs and 25 thousand 3" PMTs, is about 40 meters (*Image credit: JUNO Collaboration*)**

- Observation of diffuse SN neutrinos. 1–4 neutrinos/year. If measured it would be a discovery.
- Geoneutrinos detection. JUNO will observe up to 40 times larger statistics of geoneutrinos than the present world dataset.
- Solar neutrino detection.
- Atmospheric neutrino detection.
- Proton decay to kaon and neutrino.
- Potential upgrade of JUNO to search for 0νββ with the world record sensitivity.

## International Context

The JUNO experiment consolidates effort of a large international community from China, Russia, Europe, South America. The total number of collaboration members is close to 700. JINR plays a major role in the experiment both financially and intellectually.

The common work towards the construction of the 1st multi-kiloton liquid scintillator detector will be more effective and will help in the formation of the new generation of scientists in the international environment.

Scientists from JINR member states Armenia, Slovakia, and the Czech Republic are involved in the JUNO experiment.

## Proposed Research for the Mid-Term Period

1. Development of the Global Neutrino Analysis (GNA) fitter and determination of neutrino mass ordering.
2. Determination of lepton mixing angles and neutrino mass splitting.
3. Analysis of geoneutrinos.
4. Analysis of solar neutrinos.

## Proposed Research for the Long-Term Period

1. Precision measurement of neutrino mass ordering and lepton mixing angles.
2. Probe the unitarity of lepton mixing matrix.
3. Precision measurement of geoneutrinos signal.
4. Analysis of solar neutrinos.
5. Search for proton decay.
6. Search for neutrinoless double beta decay.

## Required Resources

**At the phase of R&D and detector construction**, JINR invested in total about **6M USD** as its hardware contribution to the project. These include

- **2M USD for HV units.** Design, production and commissioning of high-voltage units for 20 thousand 20" photomultipliers and for 25 thousand 3" photomultipliers.
- **1M USD for TopTracker.** This includes 0.8M USD as in-kind contribution and 0.2M USD for TopTracker support system.
- **2M USD for JUNO Computing Farm.** JINR will be one of three European centers for data storage, Monte Carlo Production and Reconstruction Processing of JUNO.
- **1M USD for a purchase of SiPM for Taishan Antineutrino Observatory (TAO).** TAO main objective is a record measurement of nuclear reactor spectrum with a precision of 2%.

The resources needed for **2023–2030** for operation phase are estimated as **7.5M USD** in total. The breakdown:

Hardware contribution to the construction of the 1st multi-kilo-ton liquid scintillator detector:

Equipment done.

a) Small scale R&D: **0.7M USD**.
b) Team expenses on site: **0.4M USD**.

Manpower FTEs: 22

- Travel expenses: **1.4M USD**.
- Detector Maintenance and Operation: **5M USD**.

The resources needed for **2023–2030** for operation phase are estimated as **6.4M USD** in total. The breakdown:

- Travel expenses: **1.4M USD**.
- Experiment fee: **5M USD**.

## NOvA/DUNE/HyperKamiokande

### Motivation

The **NOvA** experiment is an accelerator-based neutrino experiment with off-axis beam sent from Fermilab to Minnesota across about 810 km. The primary goal of NOvA is neutrino mass ordering determination and measurement of CP-violation in the lepton sector.

The next breakthrough in the determination of the neutrino mass ordering and CP-violation in the lepton sector can be expected from a global analysis of neutrino data and from precision measurements at accelerator long-baseline experiments like **DUNE** in the United States or **HyperKamiokande** in Japan.

JINR, successfully participating in the **NOvA** experiment, is considering to join at least one of these. The decision is expected to be taken based on a possible sizeable JINR contribution to the hardware and analysis, needed for being respected as a leading laboratory.

### International Context

Both **DUNE** and **HyperKamiokande** are truly international collaborations. All JINR member states will have a possibility to become collaborators of **DUNE** or **HyperKamiokande** if join the corresponding JINR group.

### Proposed Research

**NOvA** is expected to stop data taking around 2024–2025.

JINR plans the following research in the **NOvA** experiment during the mid-term period:

- Continue data analysis on neutrino mass ordering, CP-violating phase for the lepton sector.
- Continue searches for SN.

In parallel to data analysis in the **NOvA** experiment, JINR plans to perform R&D for future experiments with neutrino from accelerators **DUNE** or **HyperKamiokande**. JINR is expected to contribute substantially to the detector construction and physics analysis. The exact detector module is yet to be identified during the mid-term period, close to the termination of the **NOvA** experiment.

The following possibilities are being considered:
- DUNE experiment:
  - Straw-tube tracker system for the Near Detector.
  - Light detection system of the Near Detector ArgonCube TPC.
- HyperKamiokande experiment:
  - R&D of the read-out system.
  - PMT testing facility.
  - Purchase of a portion of PMTs.

For the physics research, based on the present successful experience in NOvA, the JINR team can continue with:
- Development of reconstruction and particle identification algorithms.
- Measurement of neutrino mass ordering and CP-violation in the lepton sector.
- Search for exotic phenomena: Supernova triggering and analysis, etc.

### Required Resources

JINR is expected to contribute substantially in the detector R&D and construction at the level of
- **10M USD** during the long-term period.
- **1.5M USD** during the long-term period.

## Edelweiss, GERDA, SuperNEMO, DANSS, nuGEN, RICOCHET, GEMMA-III, KATRIN

### Motivation

**GERDA** and **SuperNEMO** search for neutrino nature — either it is a Dirac or Majorana particle, in attempts to detect neutrinoless double beta decay of carefully selected best candidate nuclei.

The **KATRIN** experiment attempts to provide the best determination of neutrino mass from a careful measurement of electron's energy spectrum from tritium decays.

Experiments at Kalinin Nuclear Power Station investigate the magnetic moment of neutrino (**GEMMA-III**), coherent antineutrino–nucleus scattering (**nuGEN**) and search for a hypothetical sterile neutrino state (**DANSS**). The **RICOCHET** experiment will supersede the nuGEN experiment aiming at more precise measurements of CEvNS, and searches for New Physics with CEvNS, via bolometric technique and nuclear recoils from 20 eV.

### Proposed Research

- Data analysis, calibration, software for simulation and reconstruction (for all).
- Design and production of high-purity germanium bolometers (Edelweiss, GERDA), detector constructions (GEMMA-III, nuGEN, DANSS, GERDA, SuperNEMO).

### Required Resources

- For the mid-term period, JINR expects to invest **10.5M USD** into R&D, detectors commissioning and construction.
- For the long-term period, JINR investments are estimated as **7M USD**.

## DarkSide-20k, ARGO

### Motivation

The **DarkSide-20k** experiment searches for dark matter signals exploiting 20 tons liquid argon time projection chamber and germanium bolometers. Its data taking is expected till 2028. During the mid-term period, R&D for the new much larger and more sensitive detector **ARGO** is expected. Its commissioning is expected by mid-2029.

### Proposed Research

- For the mid-term period, data analysis of DarkSide-20k.
- For the long-term period, R&D of the ARGO detector components. The components are yet to be determined. Data analysis of the ARGO detector.

### Required Resources

- R&D, detector construction and commissioning are estimated to be **0.7M USD** for the mid-term period.
- Data taking is estimated to be **0.7M USD** for the long-term period.

## TAIGA

### Motivation

The **TAIGA** experiment searches for sources of gammas within the energy range of 1–100 TeV. Such sources are hypothesized to be related to those of UHE neutrinos, thus making an important contribution to multi-messenger astronomy.

### Proposed Research

- Data analysis, calibration, software for simulation and reconstruction.
- Design and production of 14 gamma imaging telescopes.
- Search for source of gammas within the energy range of 1–100 TeV.

### Required Resources

JINR is expected to contribute to the detector R&D and construction of IACT telescopes at the level of

- **1.8M USD** during the mid-term period.
- **1.8M USD** during the long-term period.

## Gravitational Wave Detector

### Motivation

General theory of relativity predicts the existence of gravitational waves (disturbances of space-time) propagating with the speed of light. Gravitational waves (GW) are produced by violent processes occurring in the Universe, like coalescence of black holes, neutron stars, supernova explosions, releasing extreme energies like several masses of the Sun in the form of GW.

Observations of GWs by LIGO and Virgo (see Refs. [10–12] and references therein) explained the origin of short gamma-ray bursts, proved the mechanism of heavy elements

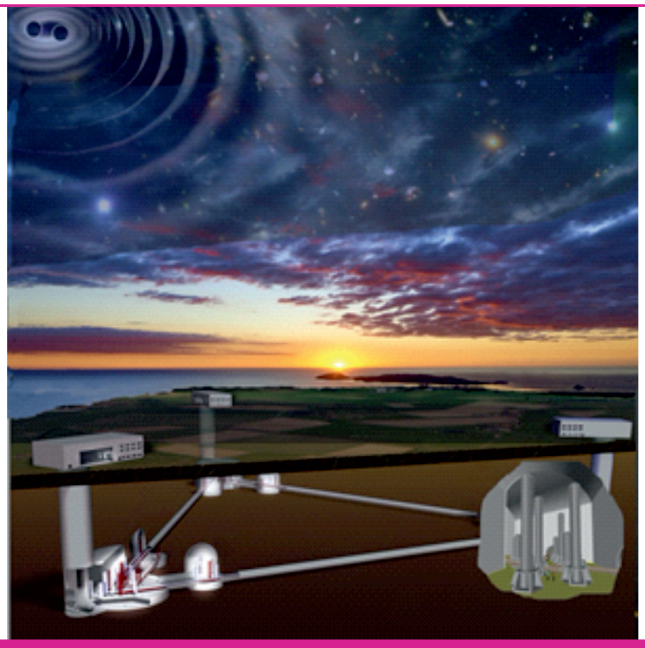


**Fig. 4. Schematic view of the Einstein telescope (*image credit: Einstein Telescope project*)**

synthesis via the so-called r-process nucleosynthesis, revealed a previously unknown population of stellar-mass BHs, and provided the first measurement of the Hubble constant with GWs. A new observation channel in the multi-messenger astronomy is definitely coming to life.

However, all these great discoveries are just the first steps of the newly born gravitational astronomy. Next generations of GW detectors are planned, like the Einstein experiment [13], schematically displayed in Fig. 4, which is expected to be orders of magnitude more sensitive than the current second-generation of GW detectors.

Figure 5 displays the astrophysical reach for equal-mass, non-spinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer.

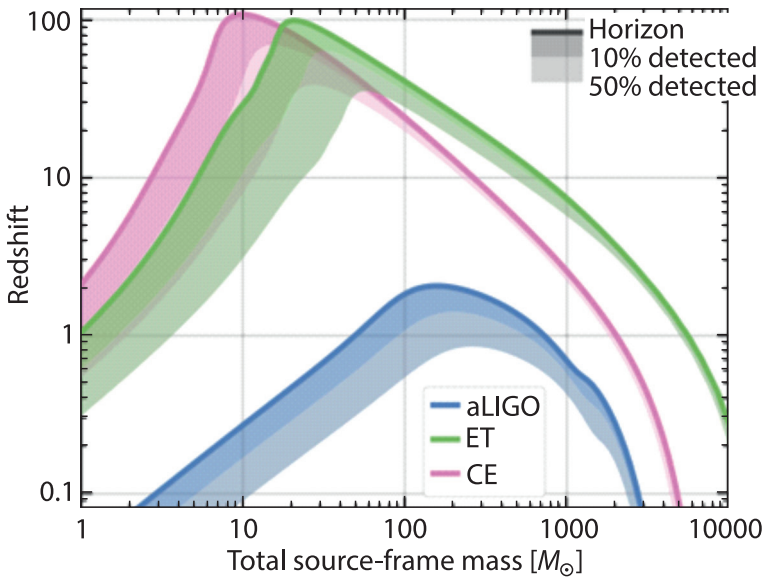



**Fig. 5. Astrophysical reach for equal-mass, non-spinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer. Figure from Refs. [13, 14]**

JINR should not remain outside of this great new science. JINR is in the process of joining VIRGO through the precision laser inclinometry devices invented at JINR DLNP. During the mid-term period, JINR will increasingly gain competence in this new field.

During the long-term period, JINR should be fully integrated into this activity, increasing its competence by appropriate participation in already existing GW detectors, joining Einstein GW detector design and construction, and hopefully developing own, Russia-based GW detector.

### International Context

This activity should be placed into a fully international environment, involving scientists from JINR member states.

### Proposed Research

- R&D of various detector components: vacuuming, ultra-cold temperature detectors, laser interferometry, precision mechanics, stabilization, photon detection devices.
- Gaining the competence in GW physics and related detection technologies.
- Development of CDR of GW detector.
- Data analysis of VIRGO and Einstein.

### Required Resources

- **1.4M USD** are expected to be invested for R&D during the mid-term period.
- **35M USD** are expected to be invested for R&D and detector construction during the long-term period.

## Summary

The proposed long-term Strategy for Neutrino Physics and Astrophysics at JINR is based on a world recognized JINR Neutrino School established by Bruno Pontecorvo. It is enhanced further by world-class experimental program in Neutrino Physics, Multi-Messenger Astronomy, including Gravitational Wave Detection and Detector Technologies, supplemented by a well though educational and outreach program.

This strategy carefully strengthens traditional JINR strong expertise in neutrino physics. At the same time, it pushes further the frontiers by developing new expertise in newly born fields like multi-messenger astronomy and gravitational wave detections where great and deep insights on the Universe formation and evolution is expected. The strong interplay with particle physicists in the same laboratory is of great intellectual benefit.

## Timeline

Tables 1 and 2 provide compact summaries on the timelines of the mid- and long-term experimental activities. The cell colors in the tables are explained here:

| Cell color | R&D | Construction Commissioning | Data taking | STOP | Decision Point |
|---|---|---|---|---|---|

**Table 1. Timeline of projects from the Mid-Term Strategy for Elementary Particle Physics and Astrophysics at JINR**

| | 24 | 25 | 26 | 27 | 28 | 29 | 30 | Main physics goal **Budget, USD** |
|---|---|---|---|---|---|---|---|---|
| **BAIKAL-GVD** | | | | | | | | UHE neutrino sources **45M** |
| | Phase II | | | | Phase III | | | |
| | R&D for Phase III | | | | | | | |
| **JUNO** | | | | | | | | Neutrino mass ordering, precision lepton mixing, SN, proton decay **7.5M** |
| **NOvA** | | | Stop data taking. Data analysis continue | | | | | Neutrino mass ordering, CP-violation in the lepton sector **10M** |
| **DUNE** | | | | | | | | |
| **HyperKamiokande** | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| **DarkSide-20k ARGO** | DarkSide-20k data taking | | | | | | | Dark matter search **0.7M** |
| | ARGO R&D | | | | | | | |
| **TAIGA** | Data taking TAIGA IACT+ TAIGA HiSCORE | | | | | | | High energy cosmic ray and gamma spectrum above $10^{15}$ eV **1.8M** |
| | One TAIGA IACT gamma-telescope/year | | | | | | | |
| **Edelweiss** | R&D for new detector and cryogenic system | | | | Next phase of bolometric search in LSM | | | Dark matter search |
| **GERDA** | R&D Legend-1000 | | LEGEND-1000 | | | | | Search for neutrinoless double-beta decay |
| **SuperNEMO** | | | | | | | | |
| **DANSS** | Data taking with DANSS-2 and NEUTRINO-6 | | | | | | | Search for sterile neutrinos, monitoring of nuclear reactors |
| | Construction, tests | | | | | | | |
| **nuGEN RICOCHET** | | | | | | | | Coherent neutrino-nucleus scattering |
| | Phase I @ILL | Phase II @ Nuclear Power Plant | | | | | | |
| **GEMMA-III** | Runs with new generation of detectors, with continuous increasing of detectors' mass and sensitivity | | | | | | | Magnetic moment of neutrino |
| **KATRIN** | Data taking in 3 months cycles, calibrations, methodical studies, systematic understanding and compacting of data | | | | | | | Direct measurement of neutrino mass. Search for heavy neutrinos **10.5M** |
| **VIRGO** | | | | | | | | Observation of GW, cosmological studies **1.4M** |

**Table 2. Timeline of projects from the Long-Term Strategy for Elementary Particle Physics and Astrophysics at JINR**

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | Main physics goal<br>**Budget, USD** |
|---|---|---|---|---|---|---|---|---|
| **BAIKAL-GVD** | | | | | | | | UHE neutrino sources<br>**45M** |
| | Phase II | | | | Phase III | | | |
| | R&D for Phase III | | | | | | | |
| **JUNO** | | | | | | | | Neutrino mass ordering, precision lepton mixing, SN, proton decay<br>**6.4M** |
| **DUNE/Hyper Kamiokande** | | | | | | | | Neutrino mass ordering, CP-violation in the lepton sector<br>**1.5M** |
| **ARGO** | | | | | | | | Dark matter search<br>**0.7M** |
| **Edelweiss** | | | Based on situation with DM | | | | | Dark matter search |
| **TAIGA** | | | | | | | | High energy cosmic ray and gamma spectrum above $10^{15}$ eV<br>**1.8M** |
| | One TAIGA IACT gamma-telescope/year | | | | | | | |
| **LEGEND-1000** | | | | | | | | Search for neutrinoless double-beta decay<br>**3M**<br>Direct measurement of neutrino mass. Search for heavy neutrinos<br>**4M** |
| **SuperNEMO** | | | | | | | | |
| **KATRIN** | | | | | | | | |
| **VIRGO Einstein** | | | | | | | | Observation of GW, cosmological studies<br>**35M** |

## International Context

The presented JINR Strategy for Neutrino Physics and Astrophysics is a careful balance of home and foreign experiments. All JINR member states have a unique possibility to enjoy both a rich, modern JINR infrastructure and participation in the world-class leading experiments in the fields of neutrino physics and astrophysics.

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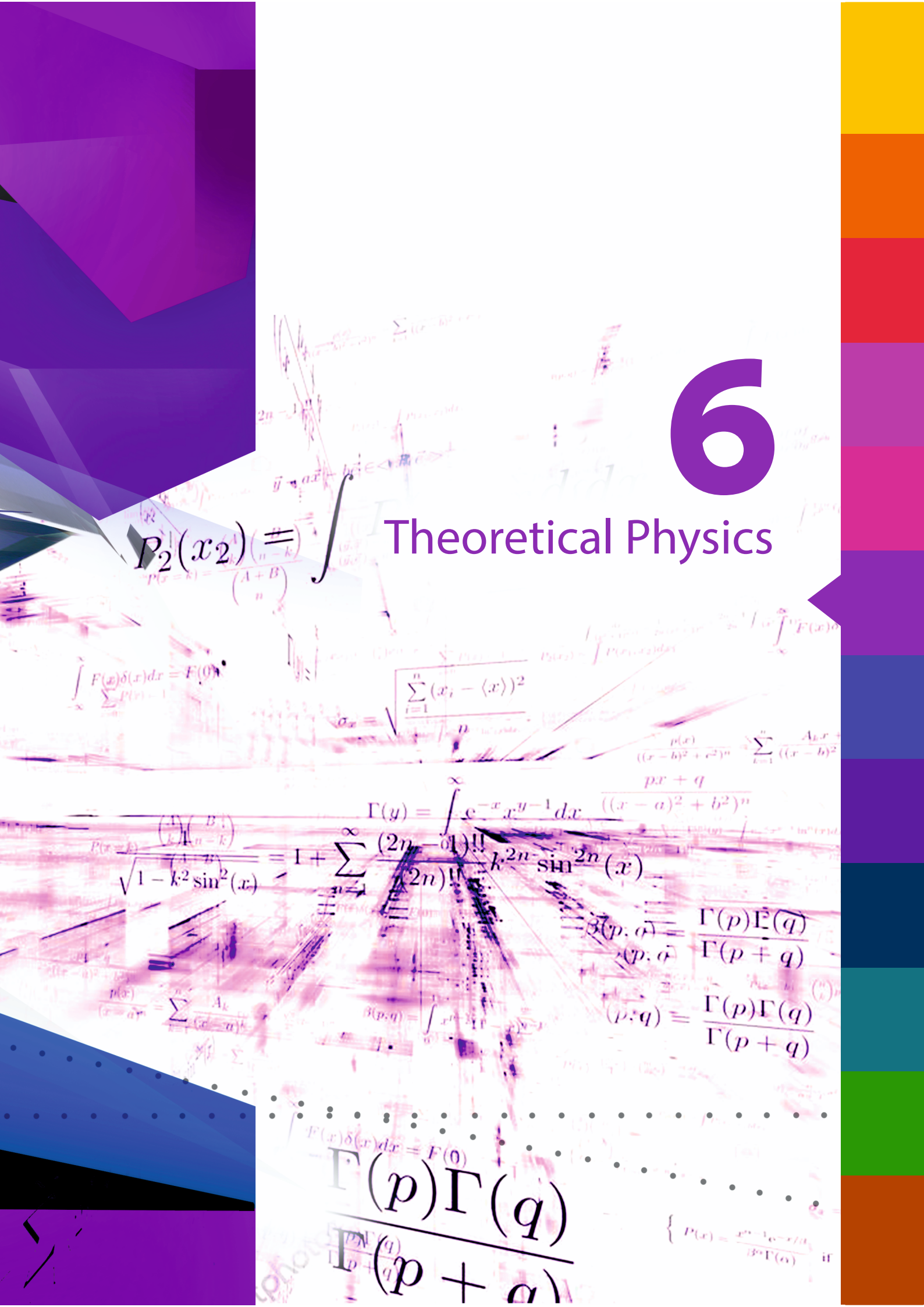
JINR Long-Term Development Strategy up to 2030 and Beyond

# 6

# Theoretical Physics



## Executive Summary

Throughout the JINR history, research in theoretical physics has always been one of the pillars of the JINR scientific program which has contributed to many major advances in Science. The Bogoliubov Laboratory of Theoretical Physics is one of the worldwide biggest research centres specialized in theoretical research at the frontiers of fundamental physics. BLTP has an expertise in a wide range of areas related to the theory of fundamental interactions, nuclear theory, condensed matter physics and modern mathematical physics. Studies at BLTP are carried out in close cooperation with scientists from many world leading research centres and in coordination with the JINR experimental program.

Scientific and organizational policy of the Laboratory relies on multidisciplinary theoretical physics on the basis of advanced mathematics, support of the JINR experimental program, strengthening of the scientific brainpower through the interplay of research and education. These principles as well as forming the international scientific task force groups dedicated to the enhanced study of the emergent hot topics will be in focus of a long-range development of theoretical physics at JINR.

BLTP and JINR will stay attractive to the international scientific community by organizing series of topical workshops, conferences, and schools for young scientists. A special emphasis will be placed on active participation of BLTP in educational programs of JINR as well as on its direct cooperation with universities of the JINR member states. The unique feature of the Dubna International School of Theoretical Physics (DIAS-TH) is its coherent integration into the scientific life of BLTP and JINR, ensuring regular and natural participation of the leading scientists in education and training activities.

### Theory of fundamental interactions

Theory of fundamental interactions of elementary particles based mostly on quantum field theory plays the central role in describing the properties of matter at the microscopic level. In particular, it is forming the solid background of quantitative analysis of both accelerator and non-accelerator experiments involving leptons, hadrons and heavy ions. The JINR long term research program in this field of theoretical physics will include a wide range of the most significant topics, running from the high-precision tests of the Standard Model and critical phenomena in Hadronic Matter to Dark Matter and Dark Energy problems.

Major attention will be paid to phenomenology of the Standard Model, searches for signatures of new physics beyond the Standard Model, neutrino physics, hadron structure and spin physics, heavy flavour physics and hadron spectroscopy, critical phenomena in hot and dense Hadronic Matter in the presence of strong electromagnetic fields, the Dark Matter problem, and astrophysical aspects of elementary particle physics. Theoretical re-

search in the field of particle and relativistic heavy ion physics will be focused on the support of physics programs of major international collaborations with JINR participation (LHC, RHIC, FAIR, etc.), and those at the JINR basic facilities, primarily, of the NICA/MPD and NICA/SPD projects.

## Nuclear theory

The central questions of nuclear physics are: How do the forces between nucleons form bound nuclei; how is the nuclear chart emerging from the underlying interactions; how does the complexity of the bound and continuum nuclear structures arise from the interaction between nucleons? In order to get answers to these questions, it is necessary to develop a unified theoretical approach for treating few- and many-body systems and including a consistent description of nuclear reactions. This approach will play an important role in explanation of the experimental data and in guiding the experimental programs in nuclear structure of exotic nuclei, nuclear dynamics, and nuclear astrophysics. At the same time, nuclear theory will be involved in a variety of interdisciplinary investigations in particle, atomic, and statistical physics.

Investigation of the properties of exotic and Super Heavy nuclei is the goal of the experimental project DRIBs III at JINR and projects in Europe, the United States, China, and Japan. Parallel to these experiments, microscopic self-consistent nuclear models will be elaborated which include nonharmonic and fragmentation effects beyond the mean field approximation. The models are to predict the rates of various nuclear reactions for astrophysical purposes and can be applied to production rates for isotopes far off stability as measured in the future projects. Nuclear reactions in stellar environment will be studied with the rigorous methods of the few-body theory as well. In the context of multidisciplinary research, the methods of the few-body theory will be developed in application to ultra-cold atoms and molecules in confined geometry of laser traps.

## Theory of condensed matter

The research program will be based on both a systematic development of the general methods of statistical physics and studies in the condensed matter physics. It will be tightly correlated with practical problems in the field of nanotechnology for creation of new materials and electronic devices.

Theoretical models in condensed matter physics will be studied by using methods of equilibrium and non-equilibrium statistical mechanics with the aim of revealing general properties of many-particle systems based on the ideas of self-similarity and universality. Along with that, theoretical research will be focused on the analysis of systems with strong electromagnetic correlations such as transition metal compounds, high-temperature superconductors, colossal magneto-resistance compounds (manganites), heavy-fermion systems, low-dimensional quantum magnets with strong spin-orbit interaction, topological insulators, etc. A theory group will accompany the experimental studies of particular materials conducted at the Frank Laboratory of Neutron Physics. Investigations in the field of nanostructures and nanoscaled phenomena will be performed to find physical characteristics of nanomaterials, which are promising for various applications in modern nanotechnologies. The problem of quantum transport in carbon-based and molecular devices as well as the resonance tunnelling phenomena in various heterostructures and layered superconductors are of special interest and will be investigated.

### Modern mathematical physics

Superstring theory, the most serious and worldwide pursued candidate for the unification of all fundamental interactions including quantum gravity, will be the central topic in mathematical physics studies at BLTP. This requires a wide range of precise classical and quantum superstring solutions, application of modern mathematical methods to the fundamental problems of supersymmetric gauge theories, development of microscopic description of Black Hole physics, elaboration of cosmological models of the early Universe. In applying and developing new ideas generated with the string theory, it is crucial to use mathematical methods of the theory of integrated systems, quantum groups and non-commutative geometry, superfield methods, including the method of harmonic superspaces.

### High-performance computing

Implementation of the outlined research program in theoretical physics, first of all related to Lattice QCD and, in general, theory of dense and hot Hadronic Matter, multi-loop calculations in the Standard Model, astrophysical and cosmological modelling, will necessarily boost development of high-performance computing infrastructure of JINR to the highest level.

## Long-Range Program in Theoretical Physics

### Theory of fundamental interactions

The main research directions will be

- the quantum field theoretical (QFT) description of the strong, electromagnetic and weak interactions of elementary particles within the Standard Model (SM) and beyond,
- the detailed description of the hadron structure in QCD with special attention paid to hadron spin physics in a broad sense, the critical phenomena occurring in hadronic matter under the influence of high energy and baryonic charge densities and strong electromagnetic fields.

In particular, the future studies will concern precision tests and extensions of the SM, hot topics in neutrino physics, QCD and hadron matter physics related to the running and future experiments at JINR and worldwide and based on development of new QFT methods, refinement of already existing techniques and advanced models.

#### The Standard Model and its extensions

The focus point of the research program will be state-of-the-art multi-loop calculations in the Standard Model, its supersymmetric extensions, in QCD as well as in the models of modern statistical physics complemented by the study of integrability in gauge theories with extended supersymmetry. QFT models with the AdS-CFT correspondence, and higher spin models will be a main stream in development of QFT methods. The new methods for calculation of the radiative corrections in non-perturbative approach for the sake of studying the problems like the false vacuum decay will also be in focus. Study of various possibilities for extension of the Standard Model will concern the Minimal Supersymmetric Standard Model (MSSM), the two-Higgs doublet model, the Next-to-Minimal SUSY model, supersymmetric Standard Model with R-parity violation and some other emergent scenarios.

The research will search for possibilities for experimental evidence for existence of new particles (super-particles, additional Higgs bosons, including charged ones); data from experiments based on the LHC, and search for the dark matter particles in non-accelerator experiments will be studied.

### Precision tests of the Standard Model

High-precision tests of the SM at LEP1, LEP2, Tevatron, and nowadays at the LHC confirmed the high predictive power of the model at the quantum level. However, the tests of the SM have to be continued, especially at high energy scales, where one might expect observations of new physical phenomena. In addition to the direct access to such energy scales at colliders, attention will be paid to the possibilities which are provided by the extremely accurate measurements of the muon anomalous magnetic moment, of rare decays, of the proton charge radius, etc.

New high-precision predictions will be deduced for the cross sections of the electroweak particle interactions studied at modern and planned high-energy colliders, including the LHC, ILC, and FCC. A high accuracy of theoretical predictions will be achieved by taking into account radiative corrections within the SM framework. Emphasis will be placed on the processes involving electroweak vector bosons, the top quark, and the Higgs boson, the study of which is of ultimate importance for verification of the Standard Model.

Precision tests of the Standard Model require an improvement of the accuracy of its predictions by multi-loop calculations or/and development of new better types of perturbation theory. The low energy predictions from pQCD can be treated by the analogous methods. In particular, Fractional Analytic Perturbation Theory (FAPT) combines the renormalization group method and dispersion relations and leads to non-standard, non-power series that have a wider range of applicability, improved convergence, and have no Landau singularity at finite transferred momentum. FAPT will be applied in calculations of various amplitudes in the regimes non-accessible within the standard perturbation expansions.

The active theoretical support for experiments on electron-positron colliders of intermediate energies (meson factories) will be continued, in particular to the physics program of the Super Charm-Tau Factory (INP SB RAS, Novosibirsk). A new Monte Carlo event generator will be constructed for describing the processes of Bhabha scattering and electron-positron annihilation taking into account polarization of the initial particles.

In the field of **heavy flavour physics**, the program of calculating observables in exclusive processes with open charm hadrons will be realized. Quantitative estimates of the Wilson coefficients for four-quark operators, which are not presented in the Standard Model, will be obtained, and physical characteristics of semi-leptonic decays of open-charm hadrons (D mesons, $\Lambda_c$ baryons) will be calculated in connection with experiments carried out by collaborations Belle (Japan), BESIII (China), as well as for future experiments on a new Super Charm-Tau Factory in Novosibirsk.

Low energy processes aimed to check the Standard Model and increase precision in parameters of fundamental interactions will complement the high energy tests. Calculations of hadronic contributions to the hyperfine splitting of the levels in muonic hydrogen atoms and to the anomalous magnetic moment of muon are the high-priority tasks. A spectrum of rotational and vibrational states in molecular ions of hydrogen isotopes with a relative precision $10^{-12}$ should be obtained within the nonrelativistic QED approximation. That would allow one to increase precision values of the Rydberg constant, elec-

tron, proton and deuteron masses, and to give independent determination of the proton charge radius provided that corresponding experiments will be carried out.

### Neutrino physics

The neutrinos remain one of the most enigmatic of the fundamental fermions, and the answers to several undeniably principal questions are still not known. The subjects of main interest are absolute neutrino mass scale, their hierarchy (spectrum) and mechanism of the mass generation, physical nature of the neutrino fields which may be described by Dirac, Majorana, or ELKO (eigen-spinors of charge conjugation operator) spinors, mechanism of the CP violation in the neutrino sector, fundamental nature of the neutrino flavour oscillations in vacuum and matter. Determining the answers (or even partial answers) to these hard questions would be an indispensable step towards completion and extension of the Standard Model (SM) of particle physics. Moreover, it may lead to hints of physics beyond the SM, since neutrinos may obtain their mass in a different way than other fundamental fermions.

The problem of neutrino interactions with matter is closely intertwined with studying the neutrino mass spectrum and mixing. In order to extract the neutrino mixing angles and squared-mass splitting from the data of the neutrino oscillation experiments with reactor, accelerator, atmospheric, solar, and astrophysical neutrinos, we need to know the cross sections of exclusive and inclusive neutrino interactions with nuclear targets within a rather wide energy region. The neutrino-matter interactions are related to a physics beyond SM as the possible non-standard weak currents which may violate the lepton number conservation and μ-τ reflection symmetry thus affecting the flavour transition probabilities in matter; the non-standard second-class electroweak hadronic currents may affect the neutrino-nucleon cross sections and polarization of the final-state particles. Studying these effects and their astrophysical applications is an interesting item in the context of neutrino physics.

An essential part of the mentioned problems will be the subject of extensive joint theoretical and experimental studies by the physicists of BLTP and DLNP. The Baikal GVD (Giant Volume Detector) project is devoted to detecting the high-energy neutrinos from astrophysical point and diffuse sources, like active galactic nuclei (blazars, quasars, BL Lac objects, etc.), coalescing binaries (black holes, neutron stars), extragalactic jets, etc. Detecting neutrino events and their joint analysis with observed electromagnetic and gravitational-wave signals will open the long-awaited era of "multi-messenger astronomy" and dramatical increase in our understating of natural high-energy particle accelerators. Theoretical problems related to these astrophysical studies include modelling the atmospheric muon and neutrino backgrounds, neutrino propagation through heterogenic media while taking into account neutrino flavour mixing (including possible mixing with hypothetical sterile neutrino fields), coherent scattering (MSW effect), absorption and regeneration due to charged and neutral current interactions of neutrinos with matter. Thus, the GVD project alone naturally connects theoretical and phenomenological studies of neutrino oscillations in matter and neutrino interactions with nuclei. Another experimental project NOvA, devoted to searching for the CP violation and neutrino mass spectrum problem, relates to the same fields but at lower energies. The BLTP based theoretical group will proceed to participate actively in the international collaboration GENIE (Neutrino Event Generator & Global Analysis of Scattering Data) which builds a "Monte Carlo bridge" between theoretical and experimental neutrino physics. The group is also involved in several international projects on neutrinoless double beta decay and related items, such as NEMO-3, KamLAND-Zen, LEGEND, SuperNEMO. The main aim of these

projects is the solution of the fundamental dilemma: Are the neutrinos Dirac or Majorana particles?

### Hard scattering in QCD

With the advent of new accelerators with very high luminosity in recent years, it has become possible to study exclusive reactions also in hard scattering regime. For future accelerators like the EIC or the ILC, such studies are expected to constitute a large fraction of the research programs.

The great physics interest in hard exclusive reactions is due to the fact that one has learned how to relate the information obtained from such processes to well-defined QCD correlators involving the wave function of the hadron in question. This is possible within a formalism involving a new kind of parton distributions and distribution amplitudes, called Generalized Parton Distributions (GPDs) and Generalized Distribution Amplitudes (GDAs), introduced and developed with active participation of BLTP theorists.

Recently, understanding of three-dimensional (3D) structure functions of nucleons has become one of hot topics in hadron/particle physics. The principle intention of these studies is, first, to apprehend the source of nucleon spin which should include the contributions emanating from partonic orbital angular momenta. At present, the different theoretical and experimental studies have mostly been focused on GPDs together with the transverse-momentum-dependent parton distributions (TMDs). The latter involves the nontrivial information on the non-perturbative primordial transverse momenta of partons inside hadrons.

It is natural to determine the unintegrated transverse-momentum-dependent parton densities and fragmentation functions if one omits the integration over transverse momentum. In this sense, the TMDs play a role of more fundamental objects which present detailed information on non-perturbative phenomena compared to the ordinary integrated functions. Therefore, it is very important to develop the approaches based on the different factorization procedures where the TMDs are the main ingredients. Both GPDs and TMDs can be considered as the main suppliers for mapping of the 3D hadron structure owing to the deeply virtual Compton scattering and semi-inclusive lepton and hadron scattering processes.

There is another type of 3D structure functions called generalized distribution amplitudes (GDAs) which can be measured by time-like processes, typically by the two-photon process to produce a hadron pair in the final state. As mentioned above, it is the s-t crossed channel to the virtual Compton scattering.

Of importance is the study of the single spin (left-right) asymmetries (SSA) measured in the Drell–Yan-type processes with the transversely polarized nucleon: (i) the first process corresponds to the standard Drell–Yan process in the inclusive mode, (ii) the second process is related to the first case but with the (almost) on-shell photon. In this case, the two hadron collisions should be studied, where one of the hadrons possesses the transverse polarization, which produce the direct photon in the final state.

The experimental investigations of 3D/spin hadron structure including various non-perturbative ingredients is performed and planned at various facilities, including COMPASS, JLab, J-PARC, NICA (mostly the SPD detector). A close collaboration with experimentalists will be enhanced, with the special emphasis on the development and support of NICA-SPD program.

### Theory of hadronic matter

The nature of theoretical investigations in the field of hadronic matter under extreme conditions has a multidisciplinary and multilevel character. It requires the solution of a number of fundamental problems of strong interactions as well as implementation of the state-of-the-art phenomenological models directly related to experiments with relativistic heavy ion collisions and the physics of compact stars. Accordingly, the JINR strategy for theoretical studies in this field will be based on a coherent implementation of a wide range of methods of quantum chromodynamics, relativistic nuclear physics, kinetic theory and hydrodynamics, and theory of critical phenomena in finite and short-lived statistical systems. As can be seen from the already running project "Theory of hadronic matter under extreme conditions", BLTP has developed the level of its own expertise and broad international collaboration that is required for productive implementation of this highly challenging but only feasible approach to the problem. One of the strategic organizational aims is the enhancement of communication between different approaches, maximizing the actual use of their complementarity for systematic theoretical study of collective phenomena in hadronic matter typical for relativistic heavy ion collisions. The general scientific purpose of theoretical research at JINR is the detailed elaboration of the fundamental theoretical background of hadronic matter physics to such a degree that it permits the formulation of a robust experimental physics program with several clearly identified and formulated main problems in focus. The cooperation with experimental collaborations in the field of RHI, first of all the MPD and BM@N collaborations, will be strengthened.

For the current time, the rapid progress in computer performance along with algorithmic achievements has made it possible to perform lattice QCD calculations (LQCD) on a highly detailed lattices and also to work with light quarks at physical masses in order to describe the properties of hadronic matter in a much more optimal setup than a decade ago. The functional renormalization group (FRG), a nonperturbative QFT method, has been developed to the level which became comparable with LQCD in accuracy and has allowed one to directly compute real time correlation functions, in a way applicable not only at finite temperature but also at finite baryonic density, which makes it a highly valuable adjunction to LQCD. FRG has also been proven to be a particularly suitable framework for studying the properties of the QCD quantum effective potential. The effective potential is necessary for ab initio verification of self-consistency of mean field models of confinement, chiral symmetry realization and hadronization in QCD. The development of such models, the domain model of QCD vacuum in particular, has set up the frame for analytical studies of the properties of the effective meson actions with simultaneous incorporation of static and dynamical quark confinement and proper mechanisms of breakdown of the chiral symmetry. This has opened new perspectives for studying in detail the mechanisms of deconfinement and chiral symmetry restoration under extreme conditions.

State-of-the-art hydrodynamic, kinetic and hybrid approaches to the task of modelling different stages of heavy ion collisions have seen a further development. In particular, the Parton-Hadron-String-Dynamics (PHSD) transport model has been recognized as a powerful method in application to highly complicated problems of relativistic heavy ion collisions. The statistical approaches capable of treating strongly interacting systems with finite size and short life time were developed. These methodological developments allow one to approach in practice the fundamental task of describing the collision of relativistic heavy ions, emphasizing its character as a rapidly evolving finite statistical system, which goes far beyond the exploration of equilibrium QCD.

The role of strong background electromagnetic and chromomagnetic fields, as well as vorticity generated in heavy ion collisions, was demonstrated via hydrodynamical and transport models to heavy ion collisions, in LQCD computations, as well as in FRG and analytical models of QCD vacuum. In particular, it has been realized that electromagnetic fields can lead to specific polarization effects in QCD vacuum which may trigger the phase transformations in hadronic matter and generate various asymmetries observable in heavy ion collisions.

The above-mentioned developments as well as the start-up of the high-performance computing facility Govorun (LIT JINR) have created at JINR a solid background for high-profile theoretical studies of the hadron matter properties. Among others, the following specific tasks are particularly mapped out as short- and mid-term priorities.

### Lattice QCD

Studies of dense baryonic matter based on numerical simulation of QCD will be vigorously continued. Even if the direct simulation of QCD at finite chemical potential is not possible due to sign problems, quest for collateral solutions to the problem will be continued, particularly through the lattice simulation at imaginary chemical potential and analytical continuation to real values. Combined use of LQCD and FRG techniques may provide an appropriate framework for investigation of QCD properties at large baryonic density. Another already verified option is the use of QCD-like theories free from the sign problem. Investigations of transport properties of QCD under extreme conditions (large baryonic density, strong magnetic field, high temperature) are on the agenda. The dependence of electric conductivity of hadronic matter on baryon density, temperature, masses of quarks, strength of magnetic field will be computed by means of improved methods for the extraction of the conductivity from Euclidean correlation functions.

### Modelling the phase transformations in QCD

Detailed mechanisms of deconfinement and chiral symmetry restoration during phase transformations in QCD under the influence of strong electromagnetic field, nonzero baryon and energy densities will be studied by means of analytical self-consistent mean field approach, motivated by the properties of QCD quantum effective action, supported by the FRG calculations of QCD effective action. Special attention will be paid to behaviour of gluon and quark condensates, topological charge density as functions of temperature, density and strength of electromagnetic fields.

### In-medium effects

Description of the particle freeze-out with account of in-medium changes of particle spectra will be studied within the effective QCD motivated hadron models by virtue of FRG techniques in particular. Two limits will be analysed — continuous freeze-out vs. sudden freeze-out. In the strongly correlated system, particles participating in strong interaction acquire a non-trivial self-energy possessing both real and imaginary parts, interrelated by the dispersion relations. The latter one is a measure of a rate with which the particle participates in inelastic and elastic collisions. The in-medium polarization operator leads to the non-trivial spectral density or/and the spectrum of the in-medium excitations with the specific quantum numbers. The study of how these changes can be traced in observables measurable in HICs is of paramount importance. Production of strangeness (especially of multi-strange hadrons ) or charm could be one of the promising windows to look after the effects. Particle fluctuations are another interesting observable.

Kinetics of particles with non-trivial spectral densities is a further object of intensive studies. Several approximations are usually to be done to write a kinetic equation in a closed form. Since several forms of the kinetic equations exist, one has to study which form is more applicable. As a minimal inclusion of in-medium effects, mean-field potentials acting on hadrons and partons have to be consistently included in the transport model (e.g., PHSD). At the most violent stage of nucleus collisions, the kinetic approach is more efficient to be replaced by the hydrodynamic description. Viscous effects are known to be important and have to be included in an agreement with the underlying kinetic equation.

### Theoretical analysis of data from NICA and FAIR

This work implies refinement of the 3FD model and THESEUS event generator based on it. The refinement will proceed in several directions:

- refinement of the EoS used in the 3FD model based on new results in the lattice QCD combination with FRG, and in astrophysics (neutron star merger);
- extension of ability of the 3FD model and THESEUS generator to predict and analyse new classes of observables (light (hyper)nuclei, fluctuations, etc.);
- refinement of the dynamics incorporated in 3FD model, microscopic evaluation of the friction force in the quark-gluon phase.

Spin observables (polarization) deserve special attention. This is a comparatively new topic. Though presently many open questions concerning this topic remain, both of conceptual and technical nature, it is expected that the spin physics in heavy-ion collisions will become one of the major topics at NICA.

## Theoretical nuclear physics

The central questions of nuclear physics are:

- How do the forces between nucleons form bound nuclei?
- How does the nuclear chart emerge from the underlying interactions?
- How does the complexity of the bound and continuum nuclear structures arise from the interaction between nucleons?

In order to get answers to these questions, it is necessary to develop a unified theoretical approach to treat few- and many-body systems including a consistent description of nuclear reactions. These approaches play an important role in explanation of the experimental data and in guiding the experimental programs in nuclear structure of exotic nuclei, nuclear dynamics, and nuclear astrophysics. At the same time, nuclear theory is involved in a variety of investigations in particle, atomic, and statistical physics.

Much of our understanding of nuclei comes from nuclear reaction experiments. A proper description of nuclear reactions requires a combination of nuclear structure models and development of the methods describing nuclear reaction mechanisms. It will include an application of the Faddeev formalism to reactions with light weakly bound projectiles and a development of the theory of the multinucleon transfer, fusion, and quasi-fission reactions. At the same time, many of nuclear structure characteristics can be understood by concepts similar to those used to describe simple Fermi systems. For instance, the important characteristics of nuclear structure require an investigation of the shape phase transitions and shape coexistence phenomena, especially important for understanding the properties of exotic nuclei. Thus, a particular challenge in nuclear theory is to bridge the gap between different scales in nuclear physics for achieving a unified description.

Faddeev equations will be applied to investigate the properties of lightest nuclei and some other few-body systems, ab initio shell model methods will be developed for investigation of the properties of light and medium mass nuclei, while the approaches based on the Energy Density Functionals (EDF) with realistic nucleon interaction will be used for studying of the structure of heavy and super-heavy nuclei. The important area of the research will be related to the investigations of nuclear properties and mechanisms of low-energy nuclear reactions important for understanding of the star evolution.

Our future theoretical studies will be closely coordinated with programs at facilities in operation or under construction, which exploit various high-intensity beams of stable and/or radioactive ions in JINR (SHE factory, ACCULINA-2) and the world (FAIR, ISOL facilities HIE-ISOLDE, SPES, SPIRAL2, FRIB or DERICA at JINR).

The fully quantum model for a halo-nucleus breakup will be developed. In investigating collisions with weakly bound nuclei, one can apply the Faddeev formalism, the continuum coupled-channels methods, few-body reaction formalisms. Few-body systems provide us with important observables for testing and constraining nuclear forces. The understanding of the properties of few-body systems is important for extending microscopic methods for description of heavier nuclei. Studies of universal laws in three-particle systems at ultralow energies and numerical calculations of characteristics of ultra-cold three-atom systems in Efimov or pre-Efimov situations are of great interest. One should study the low-dimensional few-body systems with the aim to describe the resonant processes and to model the critical phenomena in nuclear and high energy physics.

To establish the interplay between the atomic and nuclear physics, the ionization/excitation of atoms and nuclei in a strong laser field will be studied by applying the Faddeev reduction of wave function in the non-stationary Schrödinger equation. The dynamic-adiabatic theory and theory of hidden intersections of potential energy curves will be applied to calculate inelastic transitions in atomic collisions. The numerical approaches will be developed based on finite-element method and parametric basis functions. The approaches will be applied to the analysis of bound and metastable states, and to scattering processes in few-particle systems.

The magic numbers are well-known for the nuclei near the line of stability. However, it is not fully clear how magic numbers evolve as a function of the neutron-to-proton ratio. Comparison of the theoretical results with available experimental energies of first excited states would be a good test of the nuclear-shell-model inputs. The role of neutron-proton $T = 0$ pairing in the region of $N = Z$ nuclei has to be understood.

Microscopic calculations based on the state-of-the-art nuclear models that start from the realistic effective interactions between nucleons (i.e., EDF theory) provide us with a valuable tool to connect with experiments at existing and future rare isotope beam facilities like, e.g., at JINR DERICA. To provide reliable predictions, the form and parameters of the density functional will be extrapolated far beyond the stability valley. Special attention will be paid to isovector properties of EDF that plays a crucial role in nuclei with large neutron-proton asymmetry. The developed self-consistent EDF methods will be applied to the area of beta decay (especially in the context of astrophysical r-process) and other weak-interaction responses of nuclei and nuclear matter in various astrophysical scenarios.

Nuclear reactions and nucleosynthesis in different astrophysical sites based on the data obtained by space orbital and neutrino observatories will be explored and elucidated. Specifically, low-energy dipole excitations, presumably playing a prominent role in stel-

lar nucleosynthesis, have to be investigated. This study can be related to the future experiments at ELI-NP. Investigating nuclear properties as a function of intrinsic excitation energy is crucial to reveal the effects beyond a mean-field description. With increasing excitation energy, the continuum domain takes over due to a decreasing nucleon threshold, and, for super-heavy nuclei, the lowering of the fission barrier.

To understand the stability of heaviest nuclei, one should explore their shell structure. The vast majority of level assignments are derived from alpha-decay spectroscopy. So, the microscopic study of alpha decays of heavy nuclei is required. The alpha decays from the isomeric states have to be analysed, including the fission of nuclei from an isomeric state.

Our understanding of nuclear properties comes from the experiments involving nuclear reactions. A proper description of nuclear reactions requires a combination of suitable models of nuclear structure and reactions. In nuclear reactions, one should reveal important dynamical features such as fusion, quasi-fission, capture, and breakup. The transfer reaction formalism can be improved by incorporating non-local interactions and pair or cluster transfers. Several developments would be desirable: Improvements in effective nucleus-nucleus potentials by using the microscopic in-puts, accurate treatment of breakup reactions with calculation of spectroscopic factors for each decaying configuration, improvement of energy-density functional to make it suitable for description of the nucleus-nucleus interaction.

Extraction of valuable information from the reaction observables requires, in addition to an adequate modelling of the reaction dynamics, the realistic nuclear structure models and a proper understanding of how the structure information can be extracted from the reaction dynamics.

Fusion of nuclei leads to formation of a hot compound nuclear system following dissipation of their relative kinetic energy. The challenge of theory is to incorporate dissipation into the models and retain the essence of quantum many-body nature of the colliding nuclei. The methods of the theory of open quantum systems will be used for this aim.

Exploring formation of super-heavies in fusion and transfer reactions will be intensified. The di-nuclear system model suggested at BLTP will be improved by incorporating microscopically calculated transport coefficients and nucleus-nucleus potential. The features of quasi-fission will be further studied. The challenge is to find out firm criteria to discriminate fission from quasi-fission. New isotopes of heavy nuclei, which are not reachable in complete fusion reactions, can be produced in transfer reactions. These possibilities will be investigated and the available experimental yields have to be described. The study of production of new isotopes of super-heavies in charge particle evaporation channels will be continued to find out the most suitable reactions for future experiments. Progressing to yet heavier elements requires the use of heavier projectiles due to the present lack of targets beyond Cf.

The increased disparity between the number of neutrons and protons in radioactive nuclei leads to enhancement of clustering phenomena in nuclear structure, weak binding energy and possibility of exotic decay modes. A development of few-body cluster models which allow us to transparently understand peculiarities in nuclear structure at extremes of the neutron-proton map would be of priority. Structures of light nuclei in the valley of stability, nuclear systems at driplines and beyond will be the prime goal of our theoretical efforts.

In view of development of the European ELI research centre which involves two JINR member countries, investigations of non-linear quantum processes in very strong polarized electromagnetic fields which are achieved in short high-frequency laser pulses are of interest. In particular, particle production as a result of interaction of photons with such laser pulses will be studied.

It is planned to explore three-nucleon systems within the relativistic extension of the Faddeev equations (the Bethe–Salpeter–Faddeev formalism). Their binding energies, electromagnetic form factors and polarization observables will be calculated. Anomalous magnetic moment of quark will be studied as well.

## Theory of complex systems and advanced materials

The scientific program of research in the theory of complex systems and advanced materials will be focused on the development of analytical and numerical methods for studying complex many-body systems that are of current interest in modern condensed matter physics, the development of mathematical models of such systems and the identification of universal laws on an example of studied models. Particular attention will be paid to both lattice and field-theory models of equilibrium and non-equilibrium statistical systems and to modelling a wide class of new materials, including nanostructured materials, which are of great practical importance. The concepts of scaling and universality allow us to go beyond the model approach and to apply the results obtained to broad classes of phenomena studied in the physics of condensed matter. The results obtained will be used in carrying out experimental studies of condensed matter at JINR. It is important to note the markedly growing interdisciplinary nature of research, where Condensed Matter physics and Statistical physics closely intersect with Atomic and Nuclear physics, Particle physics, Mathematical physics, Astrophysics, and Biology. Below, in a structured form, the planned main topics of theoretical research are presented in the framework of the stated theme.

### Complex systems

Experimental studies directly point to an important relationship between the structural and physical properties of materials. In particular, correlations between magnetism and structural properties of heavy rare-earth metals at high pressures are observed. A combined theoretical and experimental study of effects of high pressure on the structural, electronic and magnetic properties of heavy rare-earth metals is planned. Changes of the lattice and magnetic structural properties under an applied pressure will be measured at the Laboratory of Neutron Physics, JINR. The measured data will be interpreted by using both the model analysis and the ab initio band structure calculations, based on methods of density-functional theory at the Laboratory of Theoretical Physics, JINR.

Pronounced correlations between the physical properties of various fractal systems and their geometrical structure at nano- and micro-scales have been observed. Theoretical and experimental investigations of the structure of complex hierarchical systems, including surface fractals and multifractals, will be performed for the purpose of explaining physical characteristics of nanomaterials with applications to modern nanotechnologies. Experimental methods are based on small-angle scattering of neutrons, which is relevant to the use of IBR-2 pulsed reactor at JINR FLNP, as well as x-rays and/or light scattering.

Investigations of electron properties, collective excitations (charge density waves, spin waves), phase transitions in complex systems such as strongly correlated electromagnetic systems, low-dimensional quantum magnets with complicated lattice are some of the

most important problems in condensed matter physics. These studies will be performed on the basis of the non-perturbative methods of Green functions developed at JINR BLTP. The results obtained will be used to explain the experimental results found in investigations of copper-oxide compounds and two-dimensional electron systems with the graphene-like structure. Cuprate high-temperature superconductors belong to one of the most intricate strongly correlated electron systems. Their theoretical analysis is challenging, because the traditional methods like the perturbation theory and the adiabatic continuation fail. It is planned to apply tools based on the quantum Monte Carlo method, which were developed at BLTP, to study the properties of the superconducting phase in cuprates. This will allow a description of the structure of the Fermi surface in doped cuprates explaining possible mechanisms of high-temperature superconductivity.

It is planned to develop theoretical description of equilibrium and non-equilibrium properties of finite quantum systems, including trapped atoms and molecules, dipolar and spinor nano-systems, and complex quantum networks. The main purpose is to investigate the possibility for regulating the properties of such finite quantum systems for quantum information processing. The following theoretical methods, developed at JINR BLTP will be used: scale separation approach, self-consistent theory of strongly correlated systems with spontaneous symmetry breaking, self-similar approximation theory. Also, numerical calculations will be employed.

### Advanced materials

One of the main topics of modern condensed matter physics is the study of nano-structures and nano-materials. This is not only due to the fundamental nature of their physical properties, but also owing to the practical importance for the creation of new electronic devices, storage devices, processing and transmission of information, sensors and biosensors, and others.

Two-dimensional materials play a special role: graphene, phosphorene, silicene, and others. Theoretical investigations are planned of the influence of localized boundary states in various two-dimensional materials on electronic transport. In particular, effects such as electron-phonon interaction, the role of the substrate and external electromagnetic radiation will be taken into account. A theoretical study of thermal and electronic transport in polycrystalline two-dimensional structures is also planned. It will help to improve the quality of modern thermoelectric materials. In addition, the effect of structural defects on the kinetic properties of new materials will be investigated. The functionalization of new nanomaterials plays an important role. A detailed theoretical analysis of the physical properties of fluorinated and oxidized graphene is planned. Experimental studies are carried out in cooperation between the Institute of Semiconductor Physics of the SB RAS (synthesis, characterization) and the FLNR of JINR (ion irradiation for the creation of nanopores). There are also arrangements for close collaboration with experimental groups from Bulgaria (Institute of Solid State Physics, BAS, Sofia) and Russia (North-Eastern Federal University in Yakutsk and Kazan Federal University).

The two-dimensional materials are actively used as elements for developing highly sensitive sensors for detection of various objects: from toxic metals and gases to complex biomolecules and even bacteria. Particular attention is paid to the sensors based on graphene because of their unique physical properties: attachment of biological molecules (proteins, DNA, RNA) to graphene increases the selectivity and sensitivity of the sensor, which opens up wide possibilities for using such devices as express analysers in medical research. It is planned to study the transport properties of systems formed by

low-dimensional structures with detector biomolecules attached to them, in order to analyse the sensory characteristics of these devices. The quantum electrodynamic and correlation effects in atomic systems in nanostructured and biological materials will be studied for the description of the processes of transmission and processing of quantum information.

Investigation of resonance, chaotic and topological features of Josephson nano-structures and superconducting devices is planned. Dynamics and current-voltage characteristics of superconductor-ferromagnet-superconductor structures for superconducting spintronics will be studied.

The solution of many stated problems relies on computer modelling within the framework of packages for quantum chemical calculations, molecular dynamics and density functional. For this reason, it is planned to work closely with LIT JINR, first of all, by using the supercomputer "Govorun" and later by selecting specific computer architectures.

### Models of statistical systems

During last years, a significant advance in understanding of limit shapes, universal fluctuations and correlations in models of equilibrium and non-equilibrium statistical physics was achieved. Among the equilibrium models being studied are the dimer packings, lattice polymers, polymers in random media, vertex and spin lattice models, where the subject of studies is, for example, a limited macroscopic shape of interfaces between different thermodynamic phases as well as their random fluctuations and correlations between them. In the non-equilibrium context, similar questions are addressed to stochastic models of non-equilibrium lattice gases or traffic flows as well as to models of interfaces growth subject to a random force, where the macroscopic description is given in terms of hydrodynamic-like equations, while the random fluctuations reveal the universal properties.

The studies of statistics of particle flows on the lattices in stochastic models like exclusion processes with generalized interactions, zero-range processes and avalanche processes are planned. Their evolutions are also tightly connected with the evolution of interfaces subject to random forces. The universal fluctuations and correlations of particle flows in these models will be characterized. The formation of macroscopic jams will be described. The phase diagrams of the models on finite segments will be constructed. The statistics of avalanches in the interface growth “Raise and Peel model” will be studied. The probability of nonlocal configurations in the Branching Polymers or Spanning Trees models, their limit shapes and fluctuations in the scaling limit will be obtained. Statistics of the boundary of visited domain in the Eulerian Path model proposed at BLTP will be studied.

In addition to the studies of models of equilibrium and non-equilibrium statistical physics, major attention will be paid to the development of mathematical methods related to the theory of integrable systems, theory of phase transitions and conformal field theories. The theory of elliptic hypergeometric functions and integrals proposed at BLTP will be further developed. This theory gives the most modern mathematical apparatus for studies of both the lattice and field theory models of the physics of complex systems. The properties of elliptic Fourier transform necessary for an analysis of these models will be studied. The structure properties of quantum matrix algebras will be investigated, the differential geometry of quantum matrix groups will be developed. Concrete realizations and the representation theory of these objects, which are important building blocks of new integrable models of statistical and quantum physics, will be constructed.

## Modern mathematical physics: Gravity, supersymmetry and strings

Modern mathematical physics plays an extraordinary role both in mathematics and in theoretical physics. It is a bridge for the circulation of ideas. At the same time, the main purpose of research in modern mathematical physics is the development of mathematical methods for solving the most important problems of modern theoretical physics: clarifying the nature of fundamental interactions and their symmetries, construction and study of effective field models arising in the theory of strings and other extended objects, uncovering of the geometric description of quantum symmetries and their spontaneous breaking in the framework of search for a unified theory of all fundamental interactions, including quantum gravity.

Mathematical physics in recent years has been characterized by increasing interest in identifying and effective use of integrability in various areas, and in applying powerful mathematical methods of quantum groups, supersymmetry and non-commutative geometry to quantum theories of fundamental interactions as well as to classical models. The main goals and tasks of the research include: development of new mathematical methods for investigation and description of a variety of classical and quantum integrable models and their exact solutions; analysis of a wide range of problems in supersymmetric theories including models of superstrings and superbranes, study of non-perturbative regimes in supersymmetric gauge theories; development of cosmological models of the early Universe, primordial gravitational waves and black holes. The main problems to be studied are as follows.

Study of the structure of superfield counter-terms and other invariants in $N = (1,0)$, $N = (1,1)$ and $N = (2,0)$ supersymmetric gauge theories in 6 dimensions by the harmonic superspace methods will be undertaken. In particular, of high importance is the formalism of harmonic superfields with the maximal number of manifestly realized supersymmetries.

Multiparticle systems with extended Poincaré $d = 1$ and superconformal supersymmetries and various SU(m|n) deformed supersymmetries will be investigated.

New models of multiparticle mechanics with extended supersymmetry on curved spaces as a continuation of studies related to the models of supersymmetric and superconformal mechanics in flat space will be constructed.

The complex/quaternionic Euclidean and projective spaces of super-integrable analogues of known oscillator-like systems, allowing the interaction with constant magnetic/instanton field, and further supersymmetrisation of them, including analogues of the Smorodinsky–Winternitz and Rosokhatius systems and their "weak" $N = 4$ supersymmetric extensions, study their symmetry algebra and classical and quantum-mechanical solutions, will be constructed. In carrying out this theme, research will be continued on twistor formulations of particles and superparticles of fixed spin (helicity), as well as higher spin particles.

The generalized (deformed) Calogero–Moser systems, in particular, the relations of the generalized KP hierarchies with the Calogero–Moser systems and their spin versions, as well as the construction of classical integrable systems on quiver varieties and their quantization, will be studied in detail.

A special Bohr–Sommerfeld geometry of algebraic varieties, in particular, construction of finite dimensional moduli spaces of stable special Bohr–Sommerfeld cycles, construction

of the Landau–Ginzburg models on the moduli spaces of the special Bohr–Sommerfeld cycles over Fano varieties, will be developed.

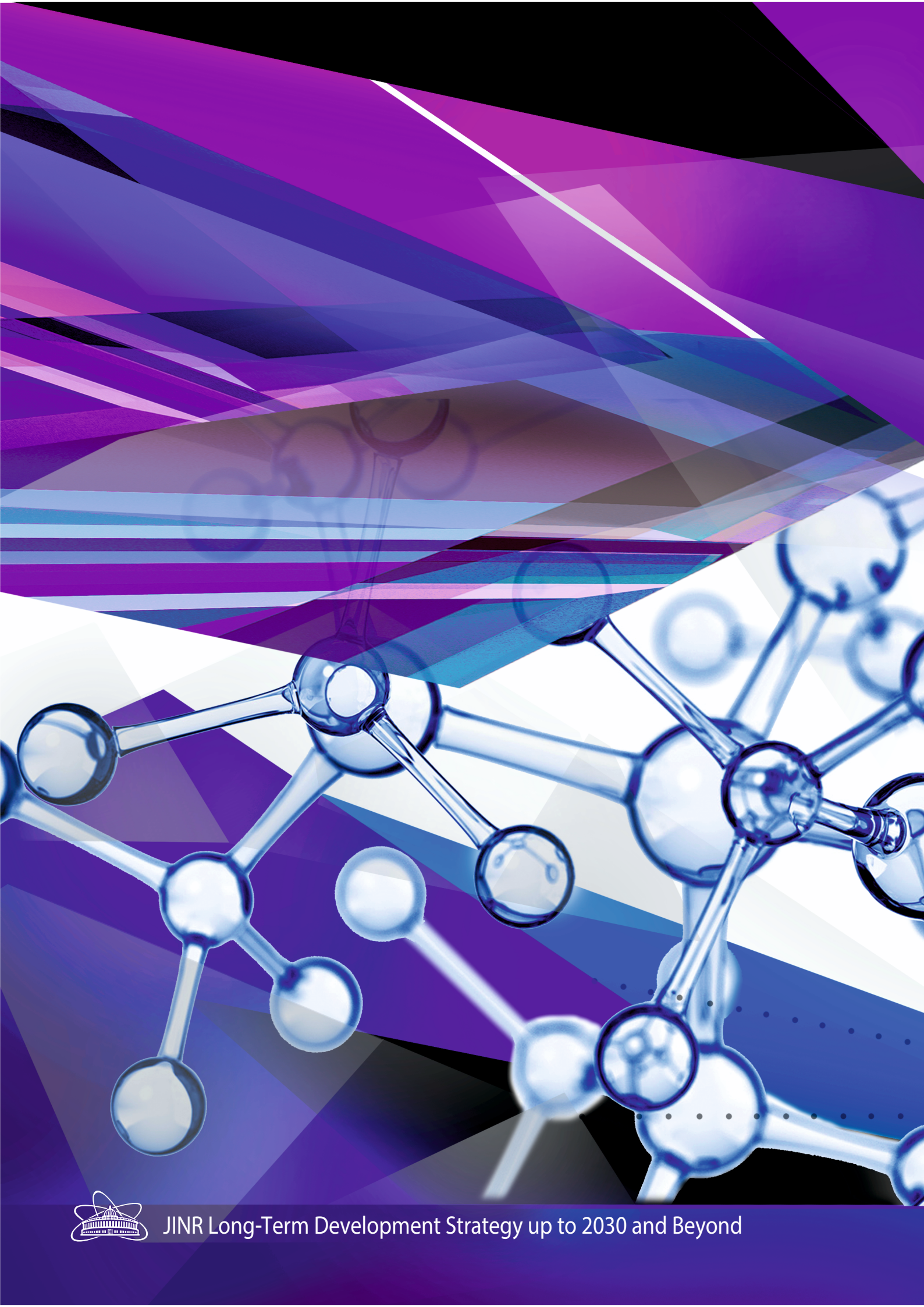
Investigations of the confinement-deconfinement transformation, using exact solutions of the holographic flow of renormalization group (RG) with SL(2,C)-symmetry and AdS-fixed point, including the construction of holographic RG flows with a couple of effective charges, are planned. Interpretation of the flows as a collection of branes in the corresponding supergravity theory and studies of the transport coefficients of quark–gluon plasma using holographic approach in 5 dimensional Kerr-AdS solution will be made.

Owing to the birth of gravitational-wave astronomy and the acquisition of new observational data (LIGO, VIRGO, etc.), it became possible to test both various theories of modified gravity and effective models of black holes and other compact highly gravitating objects. In this regard, the following research directions will be outlined:

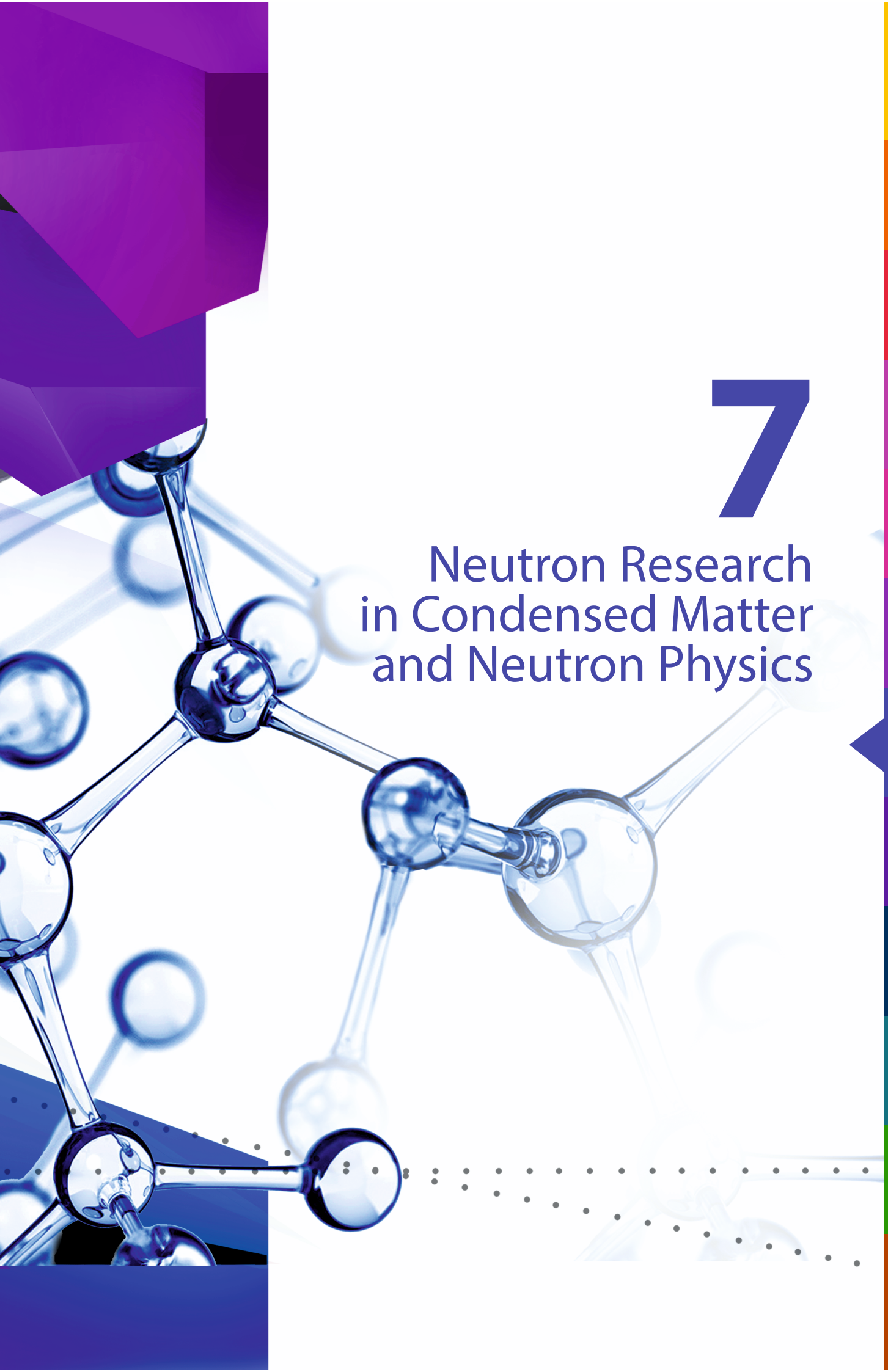
- the study of the cosmological consequences of various theories of modified gravity;
- the development and study of new modified gravity theories, capable of explaining inflation and modern dark energy in a single approach;
- the construction of effective models such as rotating single and double black holes and other compact objects (such as NUT solutions) in various theories of gravity;
- the development of new approaches and methods of mathematical physics for the study of effective models of compact objects in various theories of modified gravity;
- the studying of various boundary effects in conformal theories, such as Casimir effect, and their possible holographic description in dual gravity theories in order to comprehend the behavior of these effects in the strong coupling regime;
- the calculation of the Casimir effect due to the interaction of the quantum field with another quantum field confined in the spatially non-connected regions (two half-spaces, for instance) and elaboration of the methods explicitly taking this interaction into account without replacing it by effective boundary conditions;
- the elaboration of spectral geometry methods (zeta functions, heat kernel expansions) for differential operators on the singular background or with singular potential, along with the development of the spectral summation method with the goal to employ it in boundary problems with matching conditions on the interfaces between different material media.

## Summary

The strategy of development of theoretical physics at JINR will be based on studies of the coherent set of fundamental problems at the frontiers of modern physics defined by the current and future experimental program of JINR as well as its own, purely theoretical, priorities. Accordingly, the main objective of theoretical research will be not only a high-grade support of in-home and worldwide experimental program of JINR but also securing the predictive power of JINR scientific potential in whole, and high level of receptivity of JINR to new worldwide trends in fundamental physics.



JINR Long-Term Development Strategy up to 2030 and Beyond



# 7

# Neutron Research in Condensed Matter and Neutron Physics

## Executive Summary

Neutrons are used for studying fundamental symmetries and interactions, structure and properties of nuclei, but nowadays neutrons are mostly required in investigations of condensed matter including solid states, liquids, biological systems, polymers, colloids, chemical reactions, engineering systems, etc. Thanks to their exceptional features, the neutrons in many ways are an ideal probe for investigating materials because of significant advantages over other forms of radiation used for studies of microscopic structure and dynamics.

The use of cold neutrons (wavelengths from 4 to 20 Å) in neutron scattering research allows for studies of nanoscale objects and becomes the current trend worldwide, particularly studies of nano-structured objects required by medicine and biology. At the same time, using very cold neutrons (VCN) with wavelengths from 20 to 100 Å, one can approach new levels of measurement accuracy in several techniques, e.g., neutron spin-echo and reflectometry. Moreover, VCN are also a very promising tool for research in the field of particle physics and studies of fundamental interactions (e.g., measurements of the neutron lifetime, search for neutron–antineutron oscillations, etc.). Ultracold neutrons (UCN) are the well-established experimental tool for research in the field of particle physics and fundamental interactions. Further increase in the intensity of UCN sources will allow both improving the accuracy of such experiments and significantly expanding the scope of the UCN's usage, for example, for studies of surfaces and thin films.

Considering the present-day tendency, after 2030 only five sources will be available including three currently operating facilities: ISIS (Didcot, UK), SINQ (PSI, Villigen, Switzerland), FRM II (TU Munich, FRG), and two new sources (ESS (Lund, Sweden) and steady-state reactor PIK (PNPI NRC KI, Gatchina, Russia), both under construction with the start of operations planned for 2023–2024.

Thus, the need for a next-generation high-flux neutron source is driven by a growing interest in neutron investigations against the background of a steadily decreasing number of neutron sources in the world, as evidenced by the analysis of a specially established ESFRI Physical Sciences and Engineering Strategy Working Group. Such a new source will in a great extent compensate the losses of the neutron beam time in Europe and attract users that are currently served at ILL and medium-flux reactors in Germany, France and Hungary.

**We propose to build a new advanced neutron source DNS-IV at JINR.** To be constructed in the combination with modern moderators, neutron guides and neutron scattering instruments, DNS-IV promises to be one of the best neutron sources in the world and will open unprecedented possibilities for scientists from JINR member states and worldwide

for research in condensed matter physics, fundamental physics, chemistry, material and life science.

Being built in Russia, such a new very intense neutron source of the fourth generation will allow for the realization of the challenging research program and warranty the scientists from JINR member states the long-term access to one of the most advanced neutron sources in the world.

**DNS-IV will provide shorter (0.3 ms against 2.8 ms) neutron pulses than ESS**, however containing the same number of emitted neutrons as at ESS, having peak neutron flux density approximately ten times higher than at ESS. Indeed, it will be as good as ESS for low-resolution experiments, however **outperform parameters of high-resolution instruments and options at ESS**. DNS-IV will be complementary to the high-flux PIK reactor, so that the tandem of these two sources using the whole spectra of neutron scattering methods will provide unique possibilities for research both in traditional fields and in new ones, e.g., living matter. It is especially important for nuclear physics, the scientific basis for nuclear power engineering.

**JINR is the most appropriate place for a new source** due to the long-term development of neutron research here and the presence of the highly qualified and experienced scientific, engineering and technical personnel.

Though the decision to build the pulsed neutron source is justified, we considered **two possible technical solutions**:

1) **The IBR-3 facility** that follows the traditional concept of JINR, originating from the construction of the IBR in 1960. This high-intensity pulsed neutron source will be constructed on the basis of a periodically pulsing fast-neutron nuclear reactor with the Np-237 active core. Powerful fission pulses (and, correspondingly, fast neutron pulses) will be produced in the reactor core by the modulator of reactivity during a short period of time, when the reactor is supercritical for the prompt neutrons.
2) **The spallation neutron source with subcritical assembly**. The spallation reaction caused by the collision of the high-energy protons with neutron-rich nuclei results in the much higher neutron yield than the fission reaction. The idea for DNS-IV is to use the accelerator with reduced power, however to compensate the losses of the neutrons by their multiplication (neutron multiplication factor of about 20–50) in the subcritical assembly made of the of Pu-239 dioxide.

Both options have been under the feasibility study at the Dollezhal Research and Development Institute of Power Engineering (NIKIET, Moscow). The final recommendation is based on such criteria as achievable neutron characteristics, nuclear safety, engineering complexity, timeline and expected costs. It was found that the engineering complexity of 2nd option makes its realization rather uncertain, both in time and in costs. Therefore, **the pulsed neutron reactor IBR-3 has currently become the working project with the planned start of the DNS-IV operation in 2036–2037**.

It is important to note that the construction work at the new source will be carried out without phasing out IBR-2, so that the commissioning of the new source should take place during the final operation years of IBR-2. This will allow new technical and instrumental decisions to be tested at neutron beams of IBR-2 and ensure the continuous access to neutrons for scientists from the JINR member countries.

## Moderators and neutron delivery systems

The development of the concept of modern neutron moderators and neutron delivery systems based on the latest developments in this field at JINR and ESS is essential for achieving record neutron fluxes at instruments, which can assure the maximal use of the spatial and time structure of the delivered neutron beams.

Fission or spallation neutrons with high energies of a few MeV are not usable for purpose of neutron investigations and will slow down till energies of thermal motion of atoms. Depending on the temperature of the moderator, the neutron spectra can be cooled down to the energies of thermal motion of atoms, 0.02 eV (thermal neutrons) or even lower, to 1–5 meV (cold neutrons) and 0.1 μeV (very cold and ultra-cold neutrons).

The most effective **thermal grooved moderators** will be used at DNS-IV. **Cold moderators** will use low-temperature cryogenic liquids (hydrogen or deuterium) or solid materials (methane and mesitylene) cooled to cryogenic temperatures. Over the past seven years, the IBR-2 at the JINR FLNP has gained extensive experience in the use of mesitylene as a cold moderator material.

In all cases the use of grooved moderators in coupled geometry instead of a plane moderator increases the yield of neutrons by a factor of two.

New **low dimensional cold moderators** with three times increased brilliance of the emitted neutron beams, which have been developed within last few years, will allow for tripling the intensity at the neutron instruments that operate with highly collimated neutron beams (SANS diffractometers and reflectometers).

Effective **VCN moderator** will be based on new technologies — effective VCN production, optical systems for the VCN extraction, and will be tested at the IBR-2 reactor.

At present there are **no UCN sources** that use the pulsed time structure of the neutron source, so that the productivity of all modern UCN sources is determined by the average flux density. Meanwhile, it is already shown theoretically that the UCN density can be significantly increased and approach one corresponding to the peak power rather than the mean power of a pulsed neutron source. Such a UCN source that will provide the unprecedented density of UCN will be developed within the scope of the present project.

## Neutron delivery system and instruments

The most efficient geometries of neutron guides — elliptic, parabolic and ballistic — will be used to minimize the losses and to tailor the phase space of the neutron beams according to individual requests of instruments. Such neutron guides will deliver to the samples only "useful" neutrons, thus maximizing the intensity at the samples, when minimizing the background of undesirable neutrons. A smart design of neutron instruments will benefit from the time structure of the pulsed neutron source and allow for simultaneous measurements over a wide energy and angular ranges of scattered beams. The performance of each instrument will be thoroughly simulated by established simulation packages (McStas and VITESS) in the iterative procedure aiming at the optimization of instrument geometries and design for achieving the world-class performance.

Some of neutron instruments will profit a lot from the access to both thermal and cold neutrons. This will be accomplished by a specific design of in-pile parts of neutron guides that will "see" both cold and thermal moderators, thus allowing for the bi-spectral beam extraction.

## IBR-2 instruments continuous upgrade and development

In the period 2020–2037 the IBR-2 instruments will be continuously upgraded and developed, providing new ideas for the DNS-IV instrumentation — moderators, neutron delivery system and instruments themselves. What is important is that the IBR-2 pulse duration is very close to the planned DNS-IV one, so many solutions for neutron guides, choppers, etc. could be transferred directly to DNS-IV.

## DNS-IV project risk assessment

Though results of feasibility study carried out by NIKIET ensure us that the desired neutron flux density can be achieved using Np-237 fuel for DNS-IV, there is a risk associated with the fuel production technology.

To minimize this risk, we have already established working relations with the Bochvar All-Russian Scientific Research Institute for Inorganic Materials (VNIINM) that will prepare the roadmap on the NpN fuel fabrication (with technical and economical estimations) at the stage of conceptual design.

The back-up solution is the use of plutonium oxide fuel (as at the operating IBR-2 reactor).

## Project costs and operating costs

Project costs for the IBR-3 construction are currently estimated as 370 M€. Final and more precise estimate will be made at the preliminary design stage by the end of 2022 (see roadmap, Fig. 12).

The annual operating costs are estimated on the basis of exploitation experience of the IBR-2 reactor. The estimate amounts to 2–3 M€ including 150 staff and power consumption costs.

# Present status and trends in the fields of research, open problems in which JINR can occupy its unique niche

Neutrons are used for studying fundamental symmetries and interactions, structure and properties of nuclei, but nowadays neutrons are mostly required in investigations of condensed matter including solid states, liquids, biological systems, polymers, colloids, chemical reactions, engineering systems, etc. What mainly underpins our present-day quality of life depends upon our understanding and consequent control of the behavior of materials. Thanks to its exceptional features, the neutron in many ways is an ideal probe for investigating materials, having significant advantages over other forms of radiation used for studies of microscopic structure and dynamics. Zero electrical charge allows neutrons to penetrate materials deeply, up to few ten cm (cf. with a few micrometers for the synchrotron radiation). The anomalously large inherent magnetic moment allows them to reveal the dynamics and structure of microscopic magnetic structures at the same time. Neutron beams with wavelength around 2 Å, which corresponds to typical atomic distances, and energies equivalent to the temperature of the sample are ideally suited to investigations of atomic structures and observations of atomic movements. Furthermore, neutrons can distinguish between different isotopes of the same chemical element, which leads to unique contrast for different materials in complex environments. For example, in contrast to X-rays, hydrogen is visible even on the background of heavy

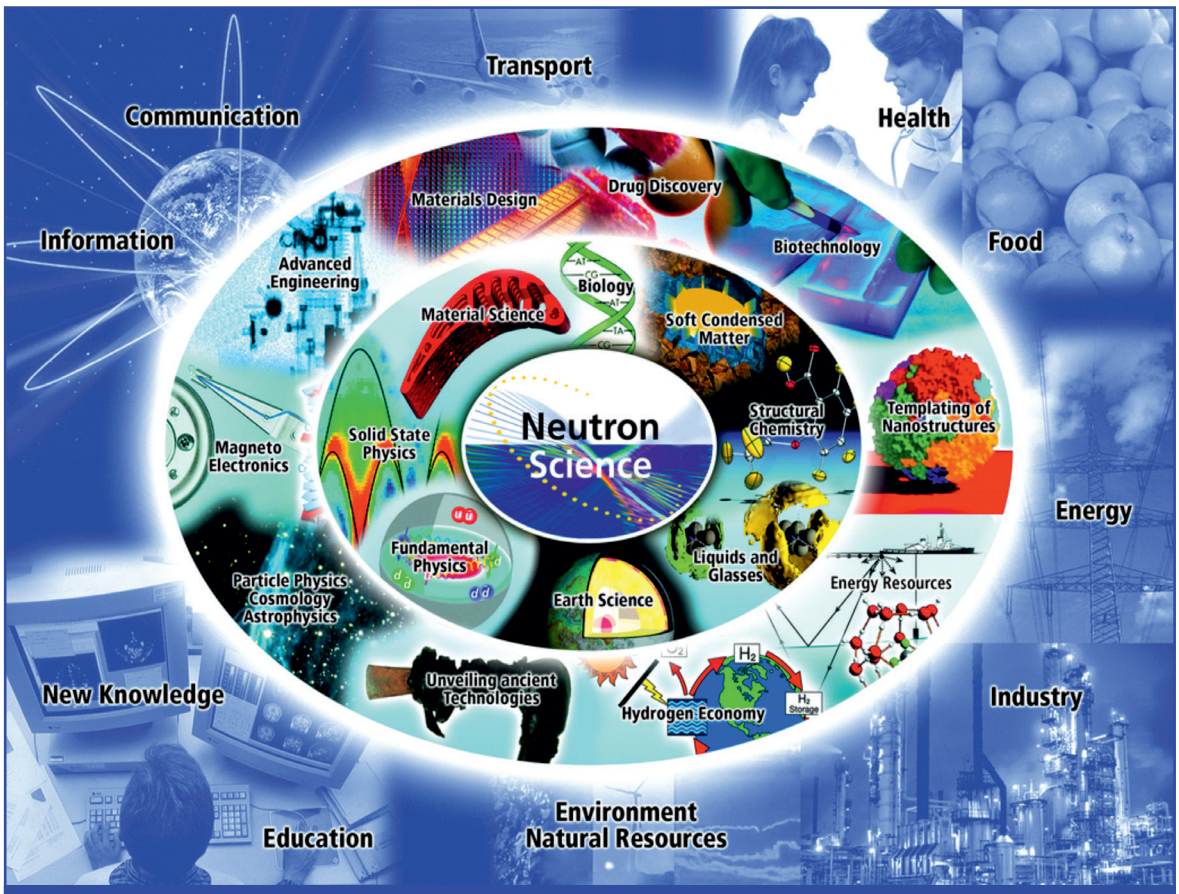



**Fig. 1. The science around modern high flux neutron source incorporates both fundamental and applied research**

atoms and the replacement of hydrogen by the chemically equivalent deuterium can be used to label different sections in very complex biological macromolecules.

Nobody can predict scientific challenges 20–30 years ahead. We can, however, extrapolate from the present and foresee where major advances might be possible. A general scheme of participation of neutron investigations in the process of interaction of science with various branches of the economy is presented in Fig. 1. This scheme is, of course, idealized and suggests that science nourishes technologies with its discoveries, and the economy poses challenges to science. In reality, science develops according to its own laws and problems arise naturally with the development of the experimental base, and our understanding of the laws of Nature. Nevertheless, in the organization of activities of large research centers based on mega-facilities, this scheme should be taken into consideration.

Below, we consider some scientific problems, for the solution of which we need advanced neutron sources with outstanding parameters (for more details, see [1]).

## Condensed matter research

Nowadays, more than 90% of extracted neutron beams are used for condensed matter research related to a wide variety of scientific fields such as solid-state physics, soft matter (complex liquids, non-crystalline solids, polymers), chemistry, molecular biology, materials sciences and engineering sciences. New fields of research are constantly emerging. For example, one can mention the recently growing interest in the structure and properties

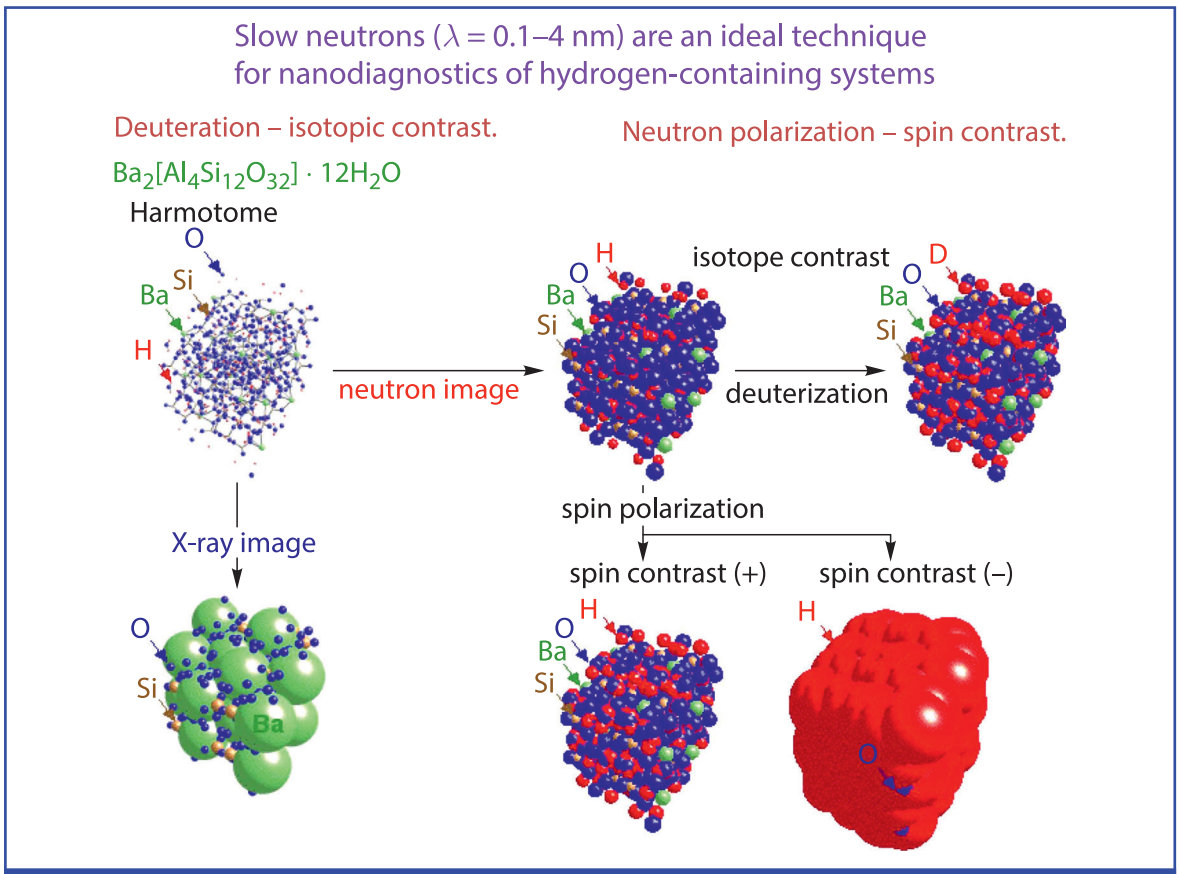



**Fig. 2. Neutron sensitivity to the magnetic structure and isotopic contrast provides much more information compared to X-rays**

of food and objects of cultural heritage. Over the past years, several new problems have appeared in all mentioned sciences where neutron scattering can provide very useful information on the structure and dynamics. Practically every new phenomenon and new material (especially in solid-state physics) is probed by neutrons at a very early stage of research. For example, a lot of possibilities are opening in the use of isotope substitution as illustrated in Fig. 2.

A special role in the study of condensed matter is played by polarized neutrons, which provide much more detailed information about the structure of matter not only in inorganic magnetic materials (as can be seen from Fig. 3) but also in biological objects. In this case, the use of polarized neutrons makes it possible to enhance the contrast of the structure image, which is an important complementary technique to the widely used isotopic contrast method. The figure shows the difference in the small-angle neutron scattering spectra in magnetic colloids using polarized and non-polarized neutrons.

Being a system with an infinite number of degrees of freedom like the particle world, condensed matter is a permanent source of new phenomena. From this point of view, the main strategy of any user research center based on a large facility consists of the development and construction of advanced experimental techniques and instruments to be ready for new challenges and to offer scientists from different research centers new possibilities for their studies. The construction of a new-type pulsed neutron source in Dubna in 1960 led to the appearance of several new experimental techniques. For example, time-of-flight (TOF) neutron diffractometry that was born in Dubna in 1963 [2] was further developed in many neutron centers including FLNP. The High-Resolution Fouri-

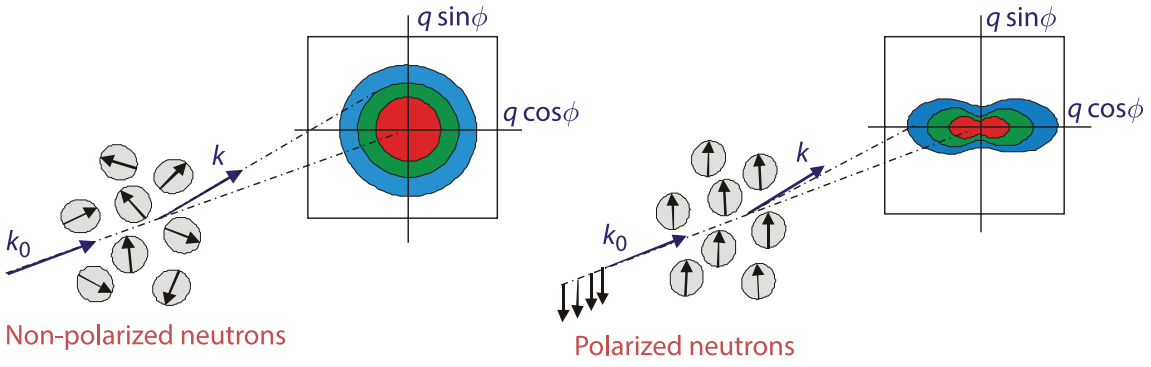



**Fig. 3. Small-angle scattering of the non-polarized and polarized neutrons**

er Diffractometer (HRFD) and Real Time Diffractometer (RTD) at the IBR-2 reactor are remarkable examples of the realization of TOF neutron diffractometry [3]. Both instruments will provide much more possibilities being installed at a neutron source that will be more intense than the IBR-2 reactor. A very important method, inelastic neutron scattering, is very difficult for implementation at IBR-2. Investigations of atomic and molecular dynamics are an essential tool for neutron scattering, and for full-scale experiments a neutron flux of one order higher than that at IBR-2 is crucial. Nowadays, small-angle scattering and reflectometry are becoming more and more popular; FLNP was among the leaders in the realization of these methods.

## Living matter

During the last decades the focus of modern research has shifted towards the study of soft matter with attempts to investigate living matter. Living matter is the most complicated and interesting subject for modern science. Living systems have a number of specific features. They have long-living, slow-relaxing structures, which are far from equilibrium;

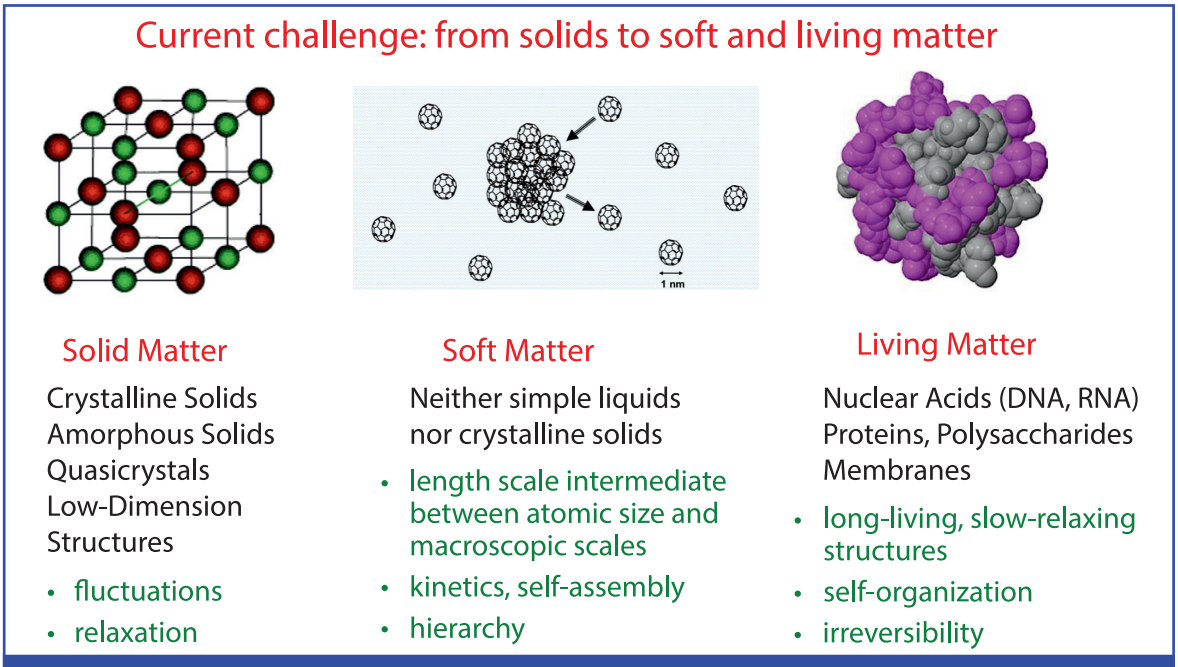



**Fig. 4. Neutrons are providing us the bridges from solid to soft matter and later to the living one**

another important property is the irreversibility of many processes. We can explore some features of living matter such as kinetics, structure hierarchy, self-assembly by studying soft matter. Therefore, one of the main directions of the research program for a new neutron source could be related to the study of soft and living matter and key problems of biophysics with application in biomedicine and pharmacology, which is in line with the modern trends in the world science.

In fact, this field of research is at the limits and in some cases even beyond the possibilities of present-day physics. In this respect, we need the advanced development of all experimental techniques, which are available now.

## Bioscience

In the 21st century, bioscience will become one of the most rapidly developing areas of research, providing solutions to major challenges facing humankind. Today, we have considerable progress in deciphering the nature and the origin of problems concerning human health. One of the most important approaches is to make use of techniques that allow scientists to "see" the structure and dynamics of biologically significant materials at the atomic and molecular scale in the ideal case under conditions as close to physiological as possible. There are several complementary methods — X-ray and neutron scattering, nuclear magnetic resonance (NMR) and electron microscopy which are used together to determine the shape and internal structure of bioactive molecules such as proteins, as well as to understand the mechanisms of their functioning. By using X-ray crystallography, one can determine the positions of atoms in very small crystals containing large numbers of identical proteins. NMR methods allow one to obtain three-dimensional structures of proteins in solutions or in solid environment. Also, cryoelectron microscopy gives images of the overall shape of large complexes of biological molecules due to the possibility of measurements in water, the natural media for life objects.

Neutrons, like X-rays, reveal a microscopic structure through the scattering from the ensembles of atoms in a sample. Neutron beams are much less intense than X-ray beams produced at large-scale facilities and neutron crystallography requires larger samples than in analogous X-ray experiments; nevertheless, neutron methods play a unique role in life and health sciences, because neutron nicely "sees" hydrogen even in the environment of heavy atoms just in contrast to X-rays where hydrogen is practically invisible at the background scattering of much heavier atoms.

**However, the use of the unique neutron probe is currently limited by a low intensity of neutron beams, which leads to the requirement of relatively large samples and limits the magnitude of the effects under investigations. A more intense neutron source will allow for studies of much smaller objects and/or much weaker effects, thus opening completely new scientific opportunities.** Some of them are listed below:

- ***In solid-state physics:*** research into nanocrystals, low-dimensional systems, magnetism and superconductivity.
- ***In chemistry:*** in situ real-time measurements for synthesis of novel materials.
- ***In Earth and environmental sciences:*** structural studies of complex minerals at high temperatures and high pressures for the understanding of basic geological processes.
- ***In engineering sciences:*** nondestructive control of engineering products and machine components to improve industrial technologies.
- ***In soft matter research:*** structural and real-time studies of polymers, colloids, liquid crystals, nanoliquids for a lot of industrial processes.

- ***In biology and biotechnology:*** structural studies of macromolecular complexes, kinetic measurements during DNA synthesis, drug design and delivery, etc.

## Nuclear physics

Since its emergence, neutron nuclear physics has demonstrated its effectiveness, becoming the basis of nuclear power engineering and a tool for studying the nuclear structure and properties of fundamental interactions. The tasks that this area of research faced in the early 21st century (*Aksenov V. L.* // Particles and Nuclei. 2000. V. 31 (6). P. 1303) are still of particular importance. They echo the questions that were formulated by the international scientific community when discussing the prospects for the development of nuclear physics (NuPECC, Long Range Plan 2017). High-precision determination of neutron properties, parameters of its decay and neutron cross sections, studies of neutron-induced fission and nuclear reactions with neutrons are valuable and sometimes unique sources of information for solving cosmology problems, studying the properties of the universe at an early stage of its formation, properties of nuclear matter and fundamental interactions. Nuclear neutron methods (such as activation analysis) have found wide applications as a powerful analytical method in environmental, biological research and archeology. These methods are widely known to be used to study the surface of planets of the Solar System. The application of these methods in several industries holds much promise. The study of cross sections for interactions of neutrons with nuclei for the needs of nuclear power engineering is still of considerable significance.

Nuclei are collections of protons and neutrons. This can be plotted on a kind of nuclear landscape with a long valley of stability. On either side of the valley of stability are areas inhabited by unstable nuclei with an increasing number of protons and neutrons. These areas are bounded by the so-called driplines. It is known where the proton dripline is, but only the lower part of the neutron dripline has been investigated so far. Studies of extreme nuclei provide stringent tests for nuclear models and also for the theories of underlying nuclear forces. Nuclei with high proton-to-neutron ratios can be obtained relatively straightforwardly with the help of accelerators. The obtaining of neutron-rich nuclei is more difficult, and only few facilities worldwide can produce their reasonable amounts.

Neutron-rich nuclei located close to the r-process path can be created by nuclear fission. The fission itself is also a rich source of information: the abundances of fission fragments produced, and their excited states depend on the nuclear structure. A high-flux neutron source can provide very exotic neutron-rich nuclides with very high production yields. The pathway of the r-process can be determined by mass measurements for a set of these nuclides.

## Basic research

The discovery of the Higgs boson opens a new era in physics. The established theory describing weak, strong and electromagnetic interactions of all known particles is the Standard Model (SM) of particle physics. However, it does not seem to be a complete theory. What is new physics beyond SM? In this respect, precision experiments with low-energy neutrons can provide a great deal of new information. For example, the discovery of neutron–antineutron ($n\bar{n}$) oscillations could answer crucial questions of particle physics and cosmology. Why do we observe more matter than antimatter in the Universe? Another related intriguing subject potentially accessible with this process concerns the mechanism responsible for neutrino mass generation. A high neutron flux combined with the

progress made in neutron optics offers a remarkable opportunity to perform a sensitive experiment dedicated to search for such oscillations. The next flagship experiment could be direct measurement of neutron–neutron cross section. Very intriguing perspectives are arising in experiments on the problem of quantum measurements.

The extensive field of research is opened with the use of UCN. Traditional attempts are related to new physics beyond the SM through measurements of neutron lifetime $\tau_n$ and electric dipole moment (EDM). However, it seems that recent observations of UCN quantum states in a gravitational field have much prospect. Indeed, it is a new research field including the investigation of dark matter and dark energy and especially precise measurements of structure and dynamics of surfaces at nanoscale.

UCN physics is traditional for FLNP. Note that UCN have been discovered at FLNP by F. L. Shapiro's group in 1968. FLNP scientists are taking part almost in all leading experiments with UCN in the world and have a few new ideas to be implemented at a new more intense neutron source.

## Flagship experiments

Several research areas mentioned above have a relatively long history and impose high requirements for the parameters of the neutron source, primarily for the high neutron intensity. The increase in intensity makes it possible not only to improve the rate of statistics collection, but also to study systematic effects at a new level, which is an important factor for high-precision experiments. New prospects for increasing the accuracy of experiments are also associated with the possibility of creating high-intensity sources of ultracold neutrons and very cold neutrons on the new neutron source. In combination with the pulsed mode of operation of the source, this opens up new methodological possibilities, for example, for measuring the neutron lifetime. At the stage of developing the source, a number of design solutions can be built in, which will allow measurements to be carried out in the optimal geometry (neutron–neutron scattering, neutron–antineutron

| *Investigations* | *Expected results* |
|---|---|
| Structure and dynamics of soft and biological systems with high flux and polarized neutrons | Primary and tertiary structures<br>Intramolecular dynamics<br>Bioenergetics of a cell<br>Biomedicine and pharmacology |
| Crystal and magnetic structure with high resolution and real-time diffraction at high pressure and magnetic fields | New functional materials |
| Neutron–antineutron oscillations | Beyond the Standard Model |
| Dark matter and dark energy with UCN | New Physics |
| New Quantum phenomena with neutrons | New aspects of quantum mechanics and consciousness |
| Neutron-rich nuclei at isotope separator on-line system with neutrons, fission | Nuclear "Standard Model" |
| Irradiation, isotopes | Radiobiology, medicine |

**Fig. 5. Flagship research directions for the DNS-IV**

oscillations) and during the construction of the source the necessary infrastructure can be prepared (for example, devices for polarization of nuclear targets and neutrons) [4, 1].

In conclusion, we will formulate in a short form scientific opportunities with the DNS-IV pulsed neutron source:

## World neutron landscape and the DNS-IV source

The need for a next-generation neutron source is driven not only by the development of neutron research at JINR, but also by a growing interest in these investigations against the background of a steadily decreasing number of neutron sources in the world, as evidenced by the analysis of a specially established ESFRI Physical Sciences and Engineering Strategy Working Group.

The following two schematic figures (Figs. 6 and 7) after Th. Brückel from Jülich Forschungszentrum illustrate the changing European landscape of neutron sources.

In Europe, there are only ten leading neutron centers with developed user systems (Table 1). Considering the present-day tendency, after 2030 only five sources will be available including three currently operating facilities: ISIS (Didcot, UK), SINQ (PSI, Villigen, Switzerland), FRM II (TU Munich, FRG), and two new sources (ESS (Lund, Sweden) and steady-state reactor PIK in the Petersburg Nuclear Physics Institute of the National Research Center "Kurchatov Institute" (Russia)) which are under construction at the moment. Over the last years this situation has sparked lively discussions on new neutron sources in Europe. A medium-power source (which is much cheaper compared to ESS) based on a deuteron linear accelerator with a Be target has recently been proposed to be constructed at the Jülich Research Center. Similar sources for Saclay and Bilbao are under consideration.

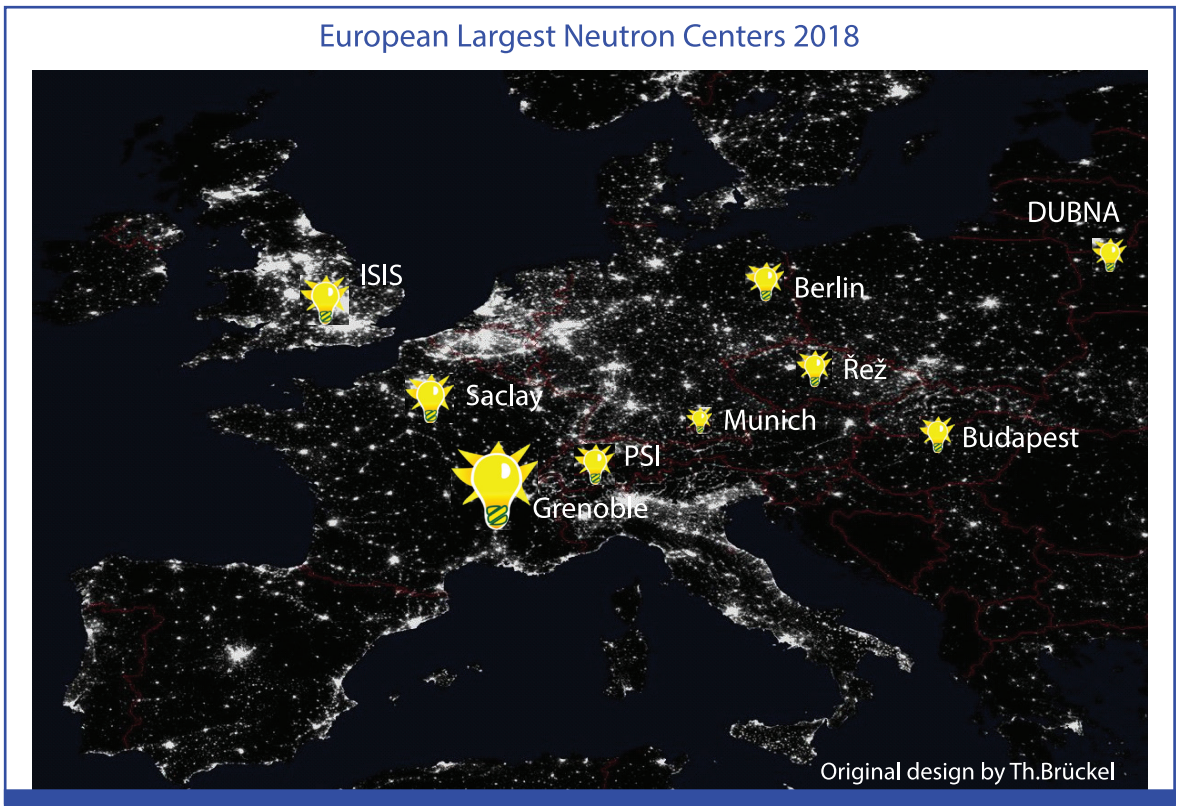



**Fig. 6. European neutron landscape in 2018**

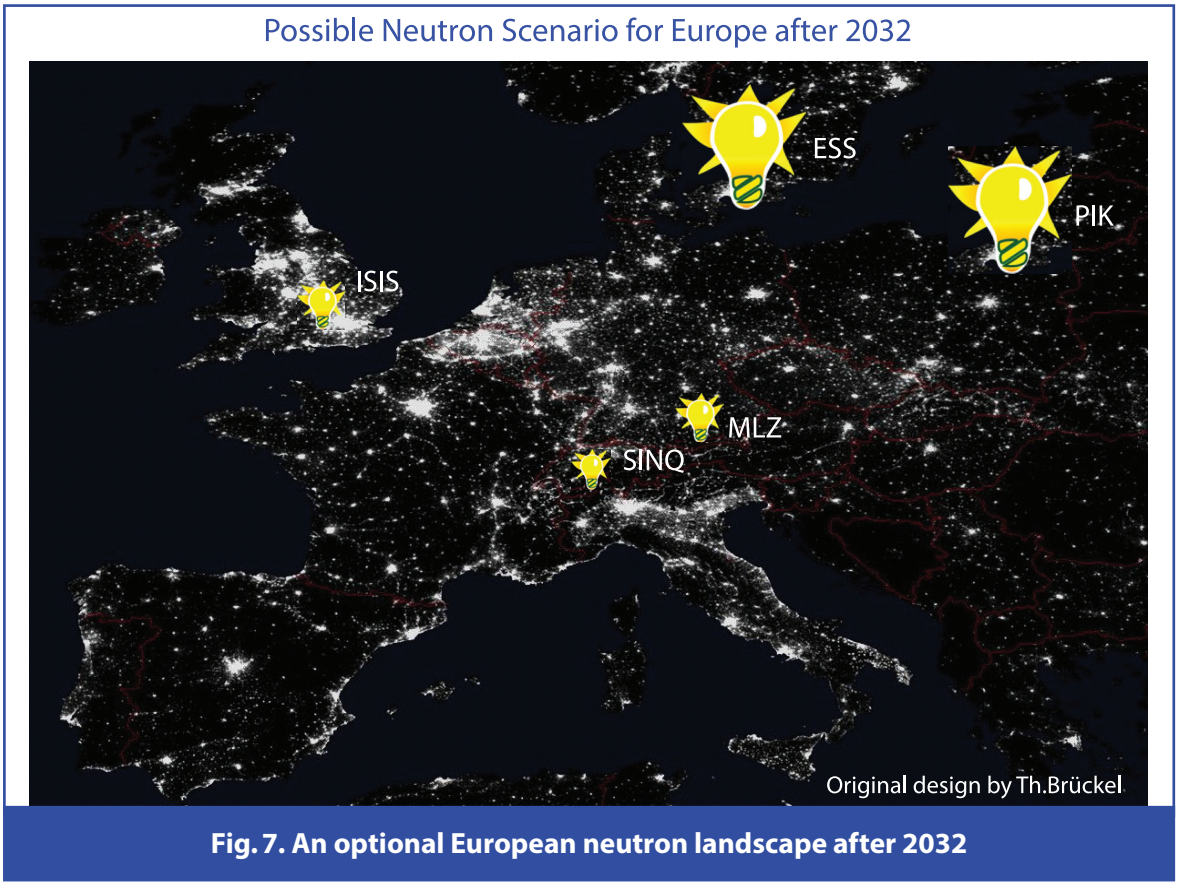



**Fig. 7. An optional European neutron landscape after 2032**

**Table 1. Advanced neutron sources within the European strategy on neutron scattering [5]**

| Source | Commis-sioned, year | Thermal power, MW | Average neutron flux, $cm^{-2} \cdot s^{-1}$ | Peak neutron flux, $cm^{-2} \cdot s^{-1}$ | Operation, days per year | Number of stations | Possible number of stations | Number of users per year | Operating costs, $10^6$ Euros |
|---|---|---|---|---|---|---|---|---|---|
| FRM II, Münich | 2005 | 20 | $8 \times 10^{14}$ | | 240 | 23 in operation, 7 under construction | 35 | 1000 | 55 |
| BER II, Berlin | 1991 | 10 | $1.2 \times 10^{14}$ | | 220 | 16 in operation | 20 | 400 | 25 |
| ILL, Grenoble | 1975/1995 | 58 | $1.3 \times 10^{15}$ | | 200 | 27 + 10 CRG* | > 40 | 1400 | 80 + CRG |
| ESS, Lund | In progress | 5, LP | | $4 \times 10^{16}$ | 200 | 20 after 2025 | > 20 | | 103 |
| PIK, Gatchina | In progress | 100 | $5 \times 10^{15}$ | | 200 | 22 after 2022 | > 40 | | 30 |
| LLB, Saclay | 1985 | 14 | $3 \times 10^{14}$ | | 200 | 22 | 25 | 600 | 25 |
| SINQ, Villigen | 1996 | 1 | $1.5 \times 10^{14}$ | | 200 | 15 | 20 | 600 | 30 |
| ISIS/ISIS-II, Abingdon | 1985/2009 | 0.2, SP | | $4.5 \times 10^{15}$ | 180 | 34 | 41 | 1500 | 55 |
| IBR-2, Dubna | 1984/2012 | 2, LP | | $2 \times 10^{16}$ | 108 | 14 | 14 | 200 | 1 |
| WWR, Budapest | 1959/1993 | 10 | $2.1 \times 10^{14}$ | | 140 | 14 | 14 | 100 | 10 |

*CRG — abbr. for Collaborative Research Group instruments.

Table 2 shows only the world's leading pulsed sources as reference points.

**Table 2. The world leading pulsed sources [5]**

| State, city | Name, start of operation/ refurbish-ment | Target power, MW | Neutron flux in pulse, $10^{14}$ $cm^{-2} \cdot s^{-1}$ | Thermal neutron pulse duration, μs; frequency, $s^{-1}$ | Averaged in time neutron flux, $10^{12}$ $cm^{-2} \cdot s^{-1}$ | Number of beams/cold moderators | Experimental stations | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Diffraction | Small angle | Reflectometer | Inelastic | Other |
| **England** Chilton | ISIS I, 1985 ISIS II, 2009 | 0.2 | 10 45 | 20–30; 50 20–30; 5 | 1.5 0.7 | 16/2 13/1 | 10 6 | 2 4 | 3 5 | 7 2 | 1 2 |
| **USA** Los Alamos | MLNSC, 1985 | 0.1 | 7 | 20–30; 20 | 0.4 | 16/2 | 4 | 2 | 3 | 2 | 2 |
| Oak Ridge | SNA, 2006 STS, project | 1 0.5 | 12 50 | 20–50; 60 50–200; 10 | 4 10 | 14/1 | 7 | 2 | 3 | 7 | 3 |
| **Japan** Ibaraki | JSNS, 2009, plan | 1 | 20/65 | 20–50; 25 | 10/30 | 21/1 | 7 | 1 | 2 | 3 | 7 |
| **China** Donguan | CSNS, 2018, plan | 0.1 | ~5 | 20–50; 25 | ~1 | 20 | | | | | |
| **Russia** Dubna | IBR-2, 1984/2012 | 2 | 60 | 310; 5 | 10 | 14/2 | 6 | 1 | 3 | 2 | 2 |
| **Sweden** Lund | ESS, 2019, plan | 5 | 50–75 | 2800; 14 | 200–300 | 16/1 first phase | 5 | 2 | 2 | 6 | 1 |

The need for a next-generation neutron source is driven by a growing interest in these investigations against the background of a steadily decreasing number of neutron sources in the world, as evidenced by the analysis of a specially established ESFRI Physical Sciences and Engineering Strategy Working Group [6].

To balance the world neutron landscape, one more intense pulse neutron source of the fourth generation is needed in Russia. For the advanced research program outlined in the previous secion, we need the following parameters for the neutron flux density: in pulse $\Phi > 10^{16}$ $cm^{-2} \cdot s^{-1}$ and averaged in time $\Phi > 10^{14}$ $cm^{-2} \cdot s^{-1}$.

The pulsed neutron sources discussed above are used mainly for neutron scattering as one can see in Table 2. Remember that neutron sources for beam research can be either steady-state (mostly reactors) or pulsed (mostly accelerators). The latter sources vary in pulse width: $\Delta t < 10$ μs (very short pulse), $10 < \Delta t < 50$ μs (short pulse), $\Delta t > 100$ μs (long pulse). For traditional neutron spectroscopy in nuclear physics where resonance neutrons are used, for the most part, very short pulses are needed (Table 3). For neutron spectroscopy in condensed matter where thermal neutrons are used, predominantly short pulses are required. The successful experience of the IBR-2 reactor operation ($\Delta t$ = 320 μs) has drawn the attention of neutron society to long-pulse sources (LPS). ESS, for example, will have $\Delta t$ = 2800 μs. The main advantage of LPS is high neutron flux and, as a result, a possibility to perform not only scattering experiments on condensed matter but also experiments on fundamental physics and nuclear physics. We can conclude that a new neutron source will be particularly high in demand being a long-pulse source. For JINR with its IBR-2 experience, a long-pulse source would be suitable. It would also be highly preferable to have a short-pulse option. In this case, all possibilities of neutrons can be used.

The problem of neutron sources is particularly acute in Russia (Fig. 8). The diagram shows the neutron sources that can be used for research on extracted beams (see Table 4).

**Table 3. Short-pulse neutron sources for nuclear physics**

| Neutron source (laboratory) | $\langle I_n \rangle$, $10^{15}$ $s^{-1}$ | $\Delta t$, ns | $Q$, $10^{30}$ $s^{-3}$ | Number of instruments for nuclear physics experiments |
|---|---|---|---|---|
| **LANSCE** (LANL, USA) | 10 | 1–125 | 0.64* | 8 (total, partial cross sections) + ICE House test facility |
| **n_TOF** (CERN, Switzerland) | 0.4 | 10 | 4 | 6 (total, capture, fission, scattering, ($n$, $\alpha$)) |
| **ORELA** (ORNL, USA) | 0.13 | 2–30 | 0.14* | 5 (total, partial cross sections) |
| **GELINA** (IRMM, Belgium) | 0.025 | 1 | 25 | 5 (total, partial cross sections) |
| **GNEIS** (PNPI, Gatchina) | 0.3 | 10 | 3 | 3 (total, capture, fission) + ISNP/GNEIS test facility |
| **IREN** (JINR, Dubna, project) | 1.0 | 400 | 0.0062 | under construction |

$\langle I_n \rangle$ — average intensity of neutrons emitted in 4π solid angle;
$\Delta t$ — neutron pulse width;
$Q = \langle I_n \rangle / (\Delta t)^2$ — quality coefficient of the neutron source;
* — present value corresponding to the maximum pulse width.

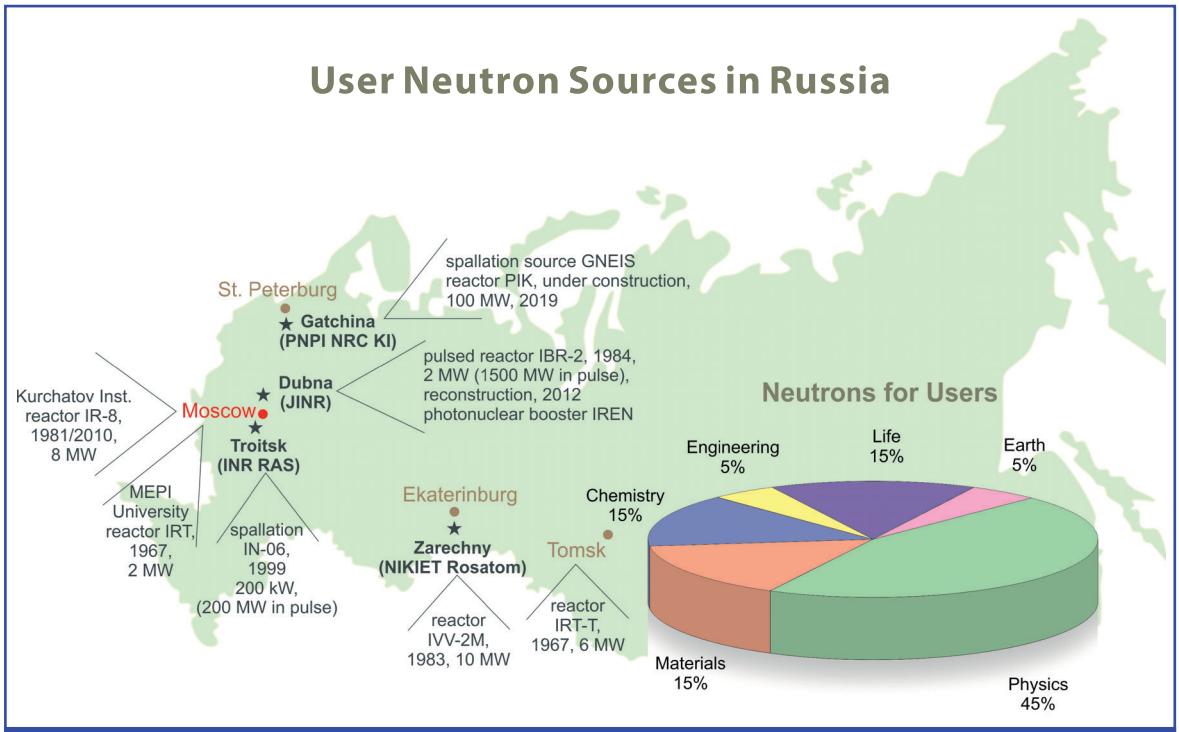



**Fig. 8. User neutron sources in Russia**

At present, only the IBR-2 reactor is used in the format of international standards. After the IBR-2 reactor is put out of service, there will remain only one research reactor in Russia — reactor PIK in the NRC "Kurchatov Institute" (Gatchina). The other sources will be decommissioned due to the expiration of their expected service life.

A new intense neutron source of the fourth generation is required on the territory of Russia. This source will be complementary to the PIK reactor as these two sources will give the possibility to use the whole spectra of neutron scattering methods in traditional fields of research as well as in new ones such as living matter research. It is especially important for nuclear physics, the scientific basis for nuclear power engineering. And Dubna is the most appropriate place due to the long-term development of neutron research here. Such a source erected at the JINR will replace IBR-2 and continue its tradition of the world class user facility for all JINR member states.

**Table 4. Characteristics of neutron sources in Russia for studies with extracted beams**

| Facility | Organization | Commissioned, year | Power, MW | Neutron flux, $10^{14}$ cm$^{-2}\cdot$s$^{-1}$ | Number of stations |
|---|---|---|---|---|---|
| IR-8 | NRC KI, Moscow | 1957/1981/2012 | 2/5/8 | 1 | 4 + 5 |
| WWR-M reactor | PNPI NRC KI, Gatchina | 1959/1978 Prolonged shutdown since 2016 | 5/18 | 4.5 | 12 |
| WWR-Ts reactor | Branch of RIPC, Obninsk | 1964 | 13 | 1 | 3 |
| IWW-2M reactor | IRM, Zarechny | 1966/1983 | 15 | 2 | 5 |
| IRT-T reactor | RI TPI, Tomsk | 1967/1977 | 6 | 1.2 | – |
| IPT reactor | NRU MEPhI, Moscow | 1967/1975 Prolonged shutdown since 2013 | 2.5 | 0.3 | 4 |
| GNEIS (pulsed) $\Delta t$ = 10 ns | PNPI NRC KI, Gatchina | 1973/1983 | $3 \times 10^{-3}$ | 1 | 3 |
| IN-06 sources (pulsed) $\Delta t$ = 100–200 μs | INR RAS, Troitsk | 1999 | $3 \times 10^{-1}$ | 1 | 7 + 2 |
| IREN (pulsed) $\Delta t$ = 100 ns | JINR, Dubna | 2010 | $4 \times 10^{-3}$ | 0.1 | 3 |
| IBR-2 (pulsed) $\Delta t$ = 200 μs | JINR, Dubna | 1982/2011 | 2/2 | 100 (peak) | 17 |
| PIK reactor | PNPI NRC KI, Gatchina | 2019, planned | 100 | 45 | 22 after 2022 |

## Preliminary concepts of a new neutron source

### IBR-3

Fundamentally, the IBR-3 facility (NEPTUN) follows the traditional concept of JINR, originating from the construction of the IBR in 1960 — a high-intensity pulsed neutron source for physical research on the extracted beams is constructed on the basis of a periodically pulsing fast-neutron nuclear reactor [7–9]. Fission power pulses (and, corresponding-

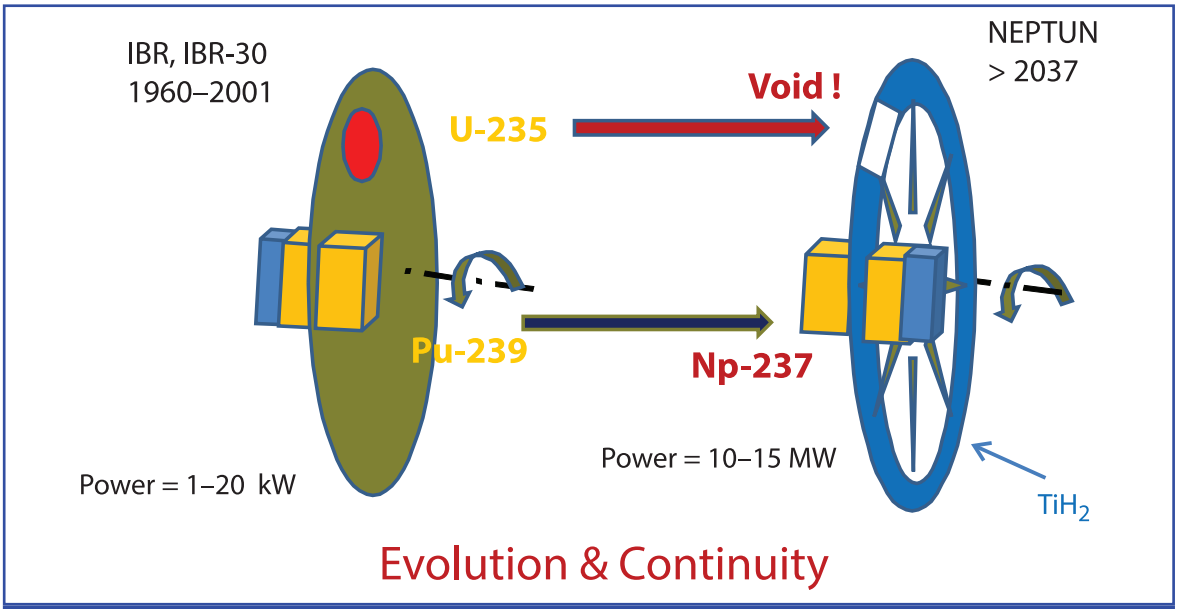



**Fig. 9. From IBR-2 to IBR-3**

ly, fast neutron pulses) are produced by the modulator of reactivity in the reactor core during a short period of time, when the reactor is supercritical for the prompt neutrons. Slow neutrons are obtained by the slowing down of fast neutrons by external hydrogen-containing moderators.

The differences between the IBR-3 (labelled NEPTUN) and IBR and IBR-2M reactors are as follows (see Figs. 9 and 10):

1. Neptunium (Np-237) nitride is proposed as nuclear fuel instead of Pu-239 (IBR) and plutonium oxide (IBR-2M);
2. The modulator of reactivity is a rotating disk stuffed with the titanium hydride over the entire periphery, except for an empty sector matching to the size of the reactor core. The supercriticality is achieved when the empty sector passes between the two halves of the reactor core. This method of modulation of reactivity is much more efficient than the movable reflector as at IBR-2M;
3. Hydrogen-containing moderators are placed directly at the boundaries of the core and surrounded by the beryllium reflector.

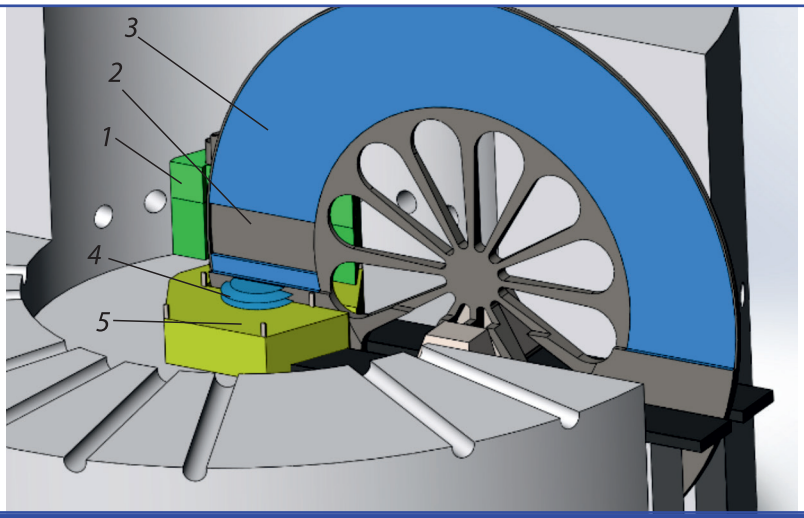



**Fig. 10. Schematic view of IBR-3: *1* — reactor core, *2* — empty sector of reactivity modulator, *3* — reactivity modulator coated with titanium hydride, *4* — moderator, *5* — beryllium reflector**

IBR-3 with the reactor thermal power of 10–12 MW and modified moderator placement geometry will provide an order of magnitude higher neutron flux density, up to $10^{14}$ $cm^{-2} \cdot s^{-1}$. Moreover, the neptunium (Np) loading of the reactor will allow for a significant, 3–4 times lower than at IBR-2, reduction of neutron background between pulses due to the threshold nature of the energy dependence of the Np fission cross section.

**The Dollezhal Research and Development Institute of Power Engineering (NIKIET, Moscow) made a feasibility study of the NEPTUN reactor and found it possible to reach designed neutron flux density. Therefore, the pulsed neutron reactor IBR-3 has currently become the working project with the planned start of the DNS-IV operation in 2036–2037.**

## Moderators, neutron delivery system and instruments

In order to take the full advantage from a new high-flux neutron source, it must be equipped with the most efficient transformers of neutron spectra (moderators), most

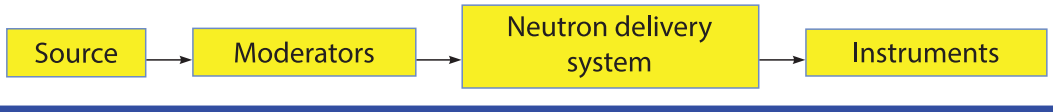



**Fig. 11. Schematic diagram of the neutron instrument on extracted beam**

efficient system for the extraction of neutrons from the moderators and their delivery to neutron instruments and, finally, specially designed instruments that can assure the maximal use of the spatial and time structure of the delivered neutron beams (Fig. 11).

### Moderators

Fission or spallation neutrons with high energies of about MeV or few MeV correspondingly are not usable for the purpose of neutron investigations, so that they must be slowed down till energies of thermal motion of atoms. This is achieved by neutron moderators, where high-energy neutrons undergo multiple collisions with atoms of the moderator material and lose energy till they come into the thermal balance with the moderator material. Depending on the temperature of the moderator, the neutron spectra can be cooled down to the energies of thermal motion of atoms, 0.02 eV or even lower, to 1–5 meV (cold neutrons) and 0.1 μeV (very cold and ultracold neutrons).

The development of the concept of modern neutron moderators and neutron delivery systems based on the latest developments in this field at JINR and ESS is absolutely essential for achieving record neutron fluxes at instruments.

### Thermal moderators

The most effective moderators are grooved moderators that will be used at DNS-IV.

### Cold moderators

Neutrons cooled down to cryogenic temperatures have wavelength above 4 Å and are requested for high-resolution angular measurements (SANS, reflectometry) and high-resolution energy measurements (spectroscopy, neutron spin-echo). Cold moderators generally exploit low-temperature cryogenic liquids (hydrogen or deuterium), but in some cases the solid materials are used. Solid methane and mesitylene, which are comparable in performance to liquid hydrogen, are among them. For relatively weak sources, methane is used as a solid block without fractionation. However, for high-power sources, this method of using methane is not suitable because of the radicals accumulated in it and radiolytic hydrogen, which can break the cold moderator vessel. Therefore, methane can only be used as separate pellets, which are continuously exchanged in the moderator chamber. Now, such a technology with methane has not been implemented anywhere in the world and it needs to be developed. Developments in the preparation of methane pellets exist.

Mesitylene or its mixture with other aromatic hydrocarbons is a sufficiently effective material for use in cold moderators. It slows down neutrons well to low energies, is not explosive, does not accumulate radicals much, is resistant to decomposition under the influence of radiation, and it can be used in a wide temperature range. Over the past seven years, the IBR-2 at the JINR FLNP has gained extensive experience in the use of mesitylene as a cold moderator material. The individual beads of 3.5–3.8 mm are loaded into the moderator chamber with a flow of cold gaseous helium and remain there for the entire reactor cycle of ~10 days with continuous cooling of cold gaseous helium. After

completion of the cycle, the cooling stops, mesitylene is melted and removed from the moderator chamber. For a more powerful source, it is possible to organize a continuous / periodic change of material in the moderator chamber without stopping experiments on extracted beams. This technology requires additional study that will be carried out within this project.

In both cases of solid methane and mesitylene, the use of a grooved moderator in coupled geometry instead of a plane moderator increases the yield of cold neutrons by a factor of 2.

A new low-dimensional cold moderator with 3 times increased brilliance of the emitted neutron beams has been developed within last few years. Such a high-brilliance source allow tripling the intensity at the neutron instruments that operate with highly collimated neutron beams (SANS diffractometers and reflectometers). Such a moderator was manufactured at the Research Centre Jülich and is ready for the installation at the ESS.

### Moderators for very cold neutrons

The use of cold neutrons (wavelengths from 4 to 20 Å) in neutron scattering research allows for studies of the nanostructured objects offered by medicine and biology and becomes the current trend worldwide. At the same time, using very cold neutrons (VCN) with wavelengths from 20 to 100 Å, one can approach new levels of measurement accuracy in a number of techniques, e.g., neutron spin-echo and reflectometry. Moreover, VCN are also a very promising tool for research in the field of particle physics and studies of fundamental interactions (e.g., measurements of the neutron lifetime, search for neutron–antineutron oscillations, etc.).

Unfortunately, VCN are currently not really used because of a low flux density of these neutrons at the extracted beams. However, a pulsed neutron source producing relatively long neutron pulse at low repetition rate (like the IBR-2) will fundamentally change the situation and allow for the production of VCN with maximum efficiency. This is because, on the one hand, the moderation of neutrons to low energies and their escape from the moderator volume take a considerable time (about hundreds of microseconds); on the other hand, the transportation of VCN at a distance of about 10 m from the source into an experimental zone takes about 100 ms. Indeed, to keep the advantage of the TOF technique allowing using the pulsed density of neutrons without losses of intensity, the source repetition rate should not be more than 10 Hz to avoid the pulse overlapping.

Research with VCN at the new neutron source will require designing the dedicated moderator and neutron beam optics. It must take into account the specific of VCN: relatively long moderation times and escape times from the moderator volume, large losses in matter. Appropriate developments will be based on the latest advances in the moderators for cold neutrons and neutron optics to obtain the maximum flux of VCN at the sample position under the best background conditions. All these new technologies — effective VCN production, optical systems for the VCN extraction and advanced methods for VCN applications — will be used at IBR-2.

### Source of ultracold neutrons

Ultracold neutrons (UCN) are the well-established experimental tool for research in the field of particle physics and fundamental interactions. Further increase in the intensity of UCN sources will allow both improving the accuracy of such experiments and significantly expanding the scope of the UCN's usage, for example, for studies of surfaces and thin films.

However, at present there are no UCN sources that use the pulsed time structure of the neutron source. The productivity of all modern UCN sources is determined by the average flux density. Indeed, the UCN source at DNS-IV with mean power of 10 MW will be at the level of the best UCN sources in the world.

Meanwhile, it is already shown theoretically that the UCN density can be significantly increased and approach one corresponding to the peak power rather than the mean power of a pulsed neutron source. The accumulation of high-intensity UCN pulses can be realized by the fast and tight UCN valve and the UCN time-focusing system at the end of a neutron guide. Relatively rare neutron pulses of DNS-IV significantly simplify technical requirements to these devices and make them feasible. Such a UCN source that will provide the unprecedented density of UCN will be developed within the scope of the present project.

The moderator option that will simultaneously produce VCN and UCN will also be considered.

## Neutron delivery systems

The delivery of neutrons from moderators to neutron instruments will be achieved by a system of neutron guides. The most efficient neutron guides geometries — elliptic, parabolic and ballistic — will be used to minimize the losses and to tailor the phase space of the neutron beams according to individual requests of instruments. Such neutron guides will deliver to the samples only "useful" neutrons, thus maximizing the intensity at the samples, when minimizing the background of undesirable neutrons. For this purpose, each instrument will be equipped with its own dedicated neutron guide. Some of neutron instruments will profit a lot from the access to both thermal and cold neutrons. This will be accomplished by a specific design of in-pile parts of neutron guides that will "see" both cold and thermal moderators, thus allowing for the bi-spectral beam extraction.

## Instruments

### IBR-2 instruments continuous upgrade and development

In the period 2020–2037 the IBR-2 instruments will be continuously upgraded and developed, providing new ideas for the DNS-IV instrumentation — moderators, neutron delivery system and instruments themselves. What is important is that the IBR-2 pulse duration is very close to the planned DNS-IV one, so many solutions for neutron guides, choppers, etc. could be transferred directly to DNS-IV.

### DNS-IV instruments development

We will perform a smart design of neutron instruments that will benefit from the time structure of the pulsed neutron source and allow for simultaneous measurements over a wide energy and angular ranges of scattered beams. The performance of each instrument will be thoroughly simulated by established simulation packages (McStas and VITESS) in the iterative procedure aiming at the optimization of instrument geometries and design for achieving the world-class performance. This should result in the final adjustment of the requirements to the time structure of the neutron beams.

It is important to note that the construction work at the new source will be carried out without phasing out the IBR-2, so that the commissioning of the new source should take place during the final operation years of IBR-2. This will allow new technical and instrumental decisions to be tested at neutron beams of IBR-2.

# Project status and roadmap, risk assessment

## DNS-IV roadmap

This section provides conclusions for the presented short description of the DNS-IV conceptual research. It was carried out at the Frank Laboratory of Neutron Physics of JINR in cooperation with the Dollezhal Research and Development Institute of Power Engineering (NIKIET), which has performed the engineering design of most research reactors in Russia, including JINR reactors, and in other countries, including some JINR member states.

Next steps for the realization of DNS-IV are as follows:

— technical study;

— R&D phases;

— engineering design;

— construction phase;

— start of facility operation.

The suggested timetable is shown in Fig. 12.

The technical study has identified several areas at the frontiers of existing technology where R&D is needed. High-priority areas involve the development of a target station, neptunium nitride fuel elements, thermal stress and radiation effects in target materials, moderators, accelerators, and neutron instruments.

The goals of the R&D phase are to provide the database for the engineering design and prepare the technical and economic basis for a final conclusion about the construction of DNS-IV which would minimize costs and technical risks.

The main expected results of the R&D phase will be:

— resolution of key technical issues which have been identified;

— validated database for the engineering design;

— accurate cost estimate;

— determination of site requirements and safety aspects, including licensing issues;

— timetable and budget profile for construction.

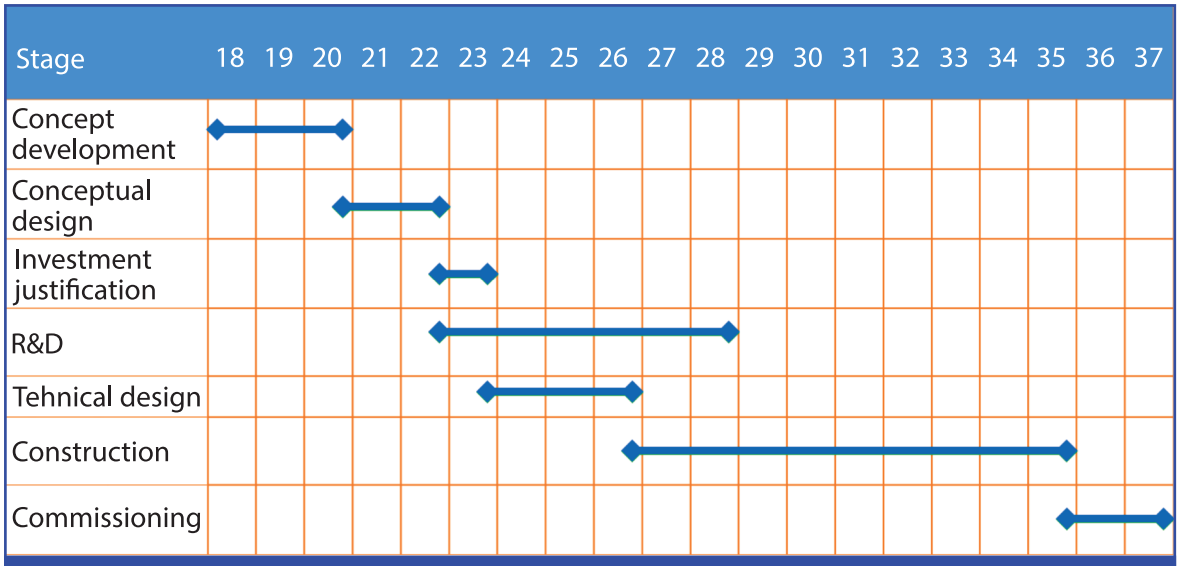



**Fig. 12. DNS-IV roadmap (preliminary)**

## Placement and costs

It is an important point to make a site-independent (green field) cost estimate for construction and operation of DNS-IV. The preferable place for the new neutron source would be nearby the IBR-2 reactor as it will make it possible to use the existing engineering infrastructure and reduce the total cost by decreasing significantly the cost for site preparation. We should add to the total cost the above-mentioned staff costs for construction and development phases. It will account for some 20% of this total. Project costs will be finally and more precisely estimated at the preliminary design stage by the end of 2022 (see roadmap, Fig. 12). Here, very rough estimates are presented.

Looking back in history is often an entertaining insight in the evaluation of resources needed for similar projects. Taking the IBR-2 cost as the reference point and making time corrections, we could estimate the IBR-3 construction cost, if we knew all the relevant inflation indices for similar constructions.. The very first real cost estimation of the IBR-2 construction was presented in the report of the USSR State Design Institute of 1967. It amounts to 12.7 MRoubles. Later on (in1968) this value was corrected to 16.7 MRoubles; the final correction made in 1975 finalised the IBR-2 construction cost at 20.8 MRoubles, which corresponds to 38.3 M$ (official exchange rate 54.36 USSR roubles for 100 US dollars). Projected to December 2018, a price of 185.4 M$ could be deduced. Today, of course, the structure of the reactor project cost in the USSR and modern Russian Federation is quite different.

The cost evolution of the PIK reactor at Gatchina cannot serve as a calibration since it has too long a history of construction under different economical situations.

For another estimation a reactor project in Germany may be looked at, which is closer in time to the present: Construction of the FRM-II reactor at Garching. The total costs of FRM II built in 1997–2000: 680 million German Marks or 340 M€. Taking into account the average inflation rate of 2% for 20 years, it will amount to 510 M€ in Euros of 2020. However, inflation indices for nuclear technical equipment are hard to come by. From experience at the NICA project, today technical construction projects in Russia cannot benefit any longer from the still significant difference in labor costs in Russia and Germany or elsewhere in the world. Cost lowering measures could be obtained by using a certain part of the infrastructure of IBR-2, e.g., power lines and transformers, a part of neutron instruments, etc. About 20% of the estimated sum of construction costs is added as contingency. Rough estimates of the DNS-IV construction cost is given below (Table 5) based on 2019 prices.

The annual operating costs are estimated on the basis of exploitation experience of the IBR-2 reactor. The estimate amounts to 4–5 M€ including 150 staff and power consumption costs (IBR-2 operational cost for 2018, including salary, amounts to 2.5 M$).

**Table 5. Projected DNS-IV construction cost estimates**

| Component | Cost, M€ |
|---|---|
| Reactor | 150 |
| Moderators complex | 50 |
| Neutron beams instrumentation | 100 |
| R&D | 20 |
| Engineering infrastructure | 50 |
| Sub-total | 370 |
| Contingency 20% | 75 |
| Total: | 445 |

## Status of the project

- At the 42nd meeting of the PAC for Condensed Matter Physics of JINR on June 22, 2015 in the report on the FLNP proposals to the JINR seven-year development plan for 2017–2023, the issue of creating a new source was raised for the first time.
- At the 45th meeting of the PAC for Condensed Matter Physics of JINR on January 19, 2017 two design concepts of a new source drawn up in the Laboratory were presented and an overview of the situation with neutron sources in Europe for the coming decades was given. By now, at several meetings of the PAC for Condensed Matter Physics, the FLNP scientists have presented the technical details of the two proposed concepts and provided a preliminary rationale for the scientific program for the new neutron source.
- In the framework of the preparation of the JINR Strategic Development Program until 2030, an international Working Group of the Commission for JINR Strategic Long-Range Planning (co-chaired by Profs. V. Aksenov (JINR) and A. Ioffe (Jülich Centre for Neutron Science, Forschungszentrum Jülich, Germany) was established to coordinate and elaborate the scientific and technical justification of the project on the construction of the fourth-generation Dubna neutron source. Three meetings of this Working Group were held in 2018 and 2019.
- In December2018, the International Workshop "Advanced ideas & experiments for DNS-IV" was convened.
- In June 2019, the PAC for Condensed Matter Physics strongly supported the opening of a new theme "Development of the Conceptual Design of a New Advanced Neutron Source at JINR" with the following deliverables for next 3 years:

| No. | Work description | Date | Result/deliverable | Costs, k$ |
|---|---|---|---|---|
| 1. | Analysis of scientific rationale for a new source | 07/2019–01/2020 | First draft of the White Book | 10 |
| 2. | Preparation of the White Book | 06/2020 | Final version of the White Book | 20 |
| 3. | Feasibility studies for two types of periodic high-flux neutron sources: pulsed reactor (PR) and accelerator-driven (ADNS) (NIKIET & FLNP JINR) | 07/2019–06/2020 | Technical reports | 800 |
| 4. | Preparatory work for the development of the production technology for fuel/target for the new source | 06/2020–12/2021 | Report | 800 |
| 5. | The concept of the arrangement of neutron moderators and neutron beams extraction | 07/2019–06/2022 | Final concept for neutron moderators and in-pile neutron guides | 100 |
| 6. | Simulation of the performance of neutron scattering instruments at a new source | 10/2019–12/2021 | Reports | 150 |
| 7. | Preparation of technical specification for neutron instruments and in-pile parts of neutron guides required for the technical design of the source | 12/2021–06/2022 | Technical specifications | 90 |
| 8. | Prototyping of the fuel elements | 01/2021–12/2022 | Experimental report | 500 |
| 9. | Simulation and preparation of the preliminary safety report | 01/2021–12/2022 | Draft of the safety report | 200 |
| | | | **Total:** | **2670** |

The construction of DNS-IV will bring new opportunities and challenges for industries of JINR member states, especially related to nuclear power industry sectors. We believe that the return for science and technology, which DNS-IV can deliver during 40 years of its expected service life, will be more than enough to justify the commitment of funds.

### Risk assessment

Though results of feasibility study carried out by NIKIET ensure us that the desired neutron flux density can be achieved using Np-237 fuel for DNS-IV, there is a risk associated with the fuel production technology.

To minimize this risk, we have already established working relations with the Bochvar All-Russian Scientific Research Institute for Inorganic Materials (VNIINM) that will prepare the roadmap on the NpN fuel fabrication (with technical and economical estimations) at the stage of conceptual design.

The back-up solution is the use of plutonium oxide fuel (as at the operating IBR-2 reactor).

## Training of young scientists and specialists

JINR has a well-developed and active Training Center for JINR member states which trains specialists in many areas of science.

On the base of the Frank Laboratory of Neutron Physics, the chair on neutron scattering of the Lomonosov Moscow State University has trained young scientists and specialists during the last decades.

## Interaction with other fields of science and socially significant applications

The construction of the Dubna neutron source of the fourth generation (DNS-IV) will have significantly higher parameters than at the IBR-2 reactor, even be competitive to the European Spallation Source (ESS), and will open new possibilities in the use of neutron scattering in other fields of science such as chemistry, molecular biology, material and engineering sciences.

Great opportunities will be opened for such socially significant applications as medico-biological investigations, pharmacology, neutron diagnostics of cultural heritage and archaeometry.

The construction of DNS-IV will bring new opportunities and challenges for industries of JINR member states, especially related to nuclear power industry sectors. The return for science and technology, which DNS-IV can deliver during 40 years of its expected service life, will be more than sufficient to justify the commitment of funds.

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JINR Long-Term Development Strategy up to 2030 and Beyond



# 8

# Radiation- and Astrobiology

## Executive Summary

Heavy charged particles are an excellent tool to address fundamental problems of *modern radiation biology and genetics*. In contrast to photon radiation, which uniformly deposits energy within the cell nucleus, heavy charged particles densely release energy along their tracks. It results in complex and clustered DNA damage and determines the particles' high biological efficiency. Therefore, high-charge and energy (HZE) ions of the Galactic Cosmic Rays (GCR) make a great contribution to the health risk to astronauts during manned deep space missions. Furthermore, hadron beams — protons and carbon ions — are beneficial for radiation cancer treatment, especially for deep-seated tumors, due to their depth-dose distribution with a sharp maximum at the end of the particle range (the Bragg peak). Therefore, **charged particle tumor therapy** and **space radiation protection** are becoming increasingly urgent fields of modern radiobiological studies.

*Astrobiology* is studying life in the broadest sense: its origin, evolution, and presence in the Universe. To answer the question of the exogenous origin of life, the early stages of transition "from the inanimate to life" can be reproduced in ground experiments using particle beams as an energy source.

## Introduction

The research performed by the Laboratory of Radiation Biology (LRB) at JINR's basic facilities in previous years allowed solving one of the central problems of radiobiology: evaluation of the relative biological effectiveness (RBE) of particle beams, which was shown to depend not only on their physical characteristics but also on the biological factor: the ability of the cell to repair DNA damage. Based on the developed concepts, the mechanisms of radiation-induced mutagenesis in prokaryote and lower eukaryote cells were studied in detail. A new concept to revise the traditional approach to astronauts' radiation risk evaluation was proposed, which includes the risk of the central nervous system (CNS) disorders [1].

The LRB is currently conducting research on the following **Research Projects:**

### Molecular radiobiology

To investigate the molecular lesions induced in DNA by ionizing radiation, immunocytogenetic and immunohistochemical techniques based on fluorescent labeling of proteins involved in the repair of the most severe radiation-induced DNA damage — double-strand breaks (DSB) — have been widely used in recent years at the LRB. It allows the quantification of DNA damage (radiation-induced foci (RIF)) and visualization of repair kinetics — particularly, of clustered DNA damage produced by high-LET radiation. Previously, the induction of clustered DNA damage and its repair after the irradiation with heavy ion

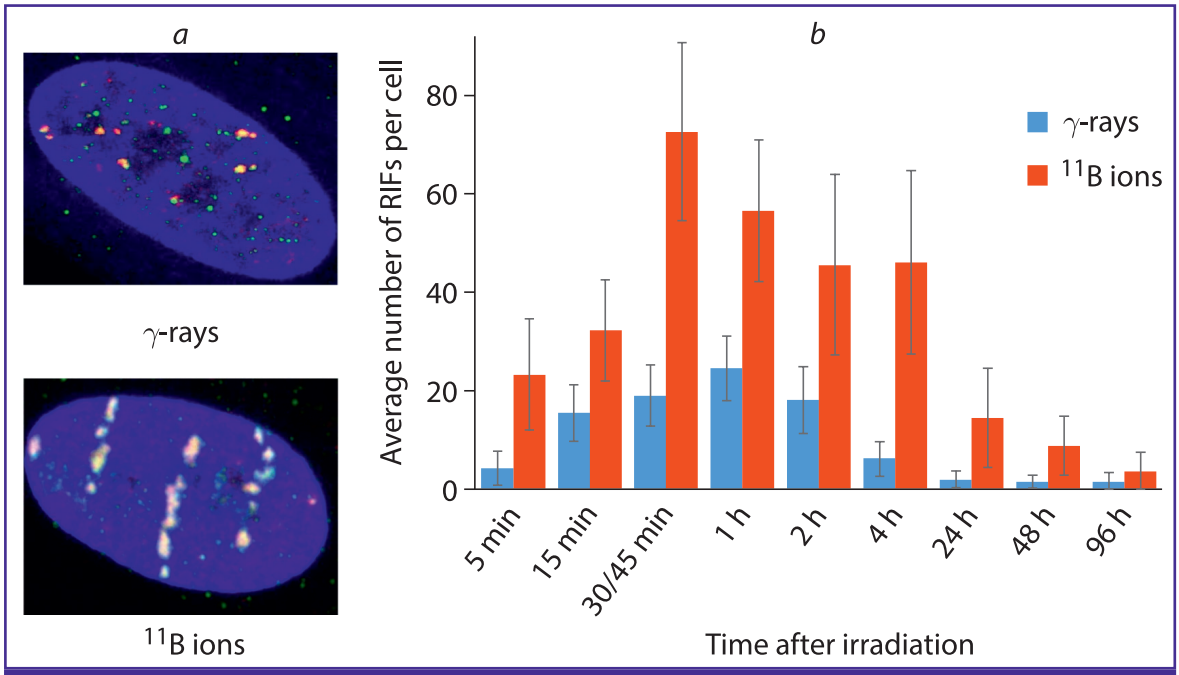


**Fig. 1. RIF visualization (*a*) and their repair kinetics (*b*) after exposure to γ-rays and 50 MeV/n $^{11}$B ions**

beams (30–50 MeV/n $^{11}$B, $^{15}$N, and $^{20}$Ne beams at U-400M, FLNR, and 500 MeV/n $^{12}$C and 2.5 GeV/n $^{78}$Kr beams at the VBLHEP Nuclotron) and with protons (the Medical-Technical Complex (MTC), DLNP) was studied in normal human cultured cells of different origin and compared with photon radiation (Fig. 1).

## Radiation cytogenetics

Chromosome aberrations (CA) are considered a sensitive and reliable indicator of radiation exposure. Their assessment in human peripheral blood lymphocytes (PBL) is a valuable method of modern human biodosimetry (IAEA, 2011). Classical cytogenetic metaphase and anaphase methods as well as the chemically induced PCC (premature chromosome condensation) assay have been widely used at the LRB to evaluate the biological effectiveness of particle beams at JINR's facilities, namely, 150 MeV and spread-out Bragg peak (SOBP) protons used for patient treatment, 30–50 MeV/n ions from $^{11}$B to $^{20}$Ne at the U-400M (FLNR), and 400 MeV/n $^{12}$C ions at the Nuclotron; for investigations of biological effects of low-dose ionizing radiation and adaptive response; and for studies of the modifying action of DNA synthesis inhibitors on the biological effectiveness of particle beams.

## Radiation physiology

To assess the radiation risk to astronauts caused by GCR exposure during deep space flights, morphofunctional changes in the central nervous system of animals irradiated with photons and protons (DLNP) have been investigated. Pathomorphological changes in the CNS have been studied on histological slides of the rodent brain and spinal cord using light microscopy. Functional changes in the central nervous system have been recorded using test systems to assess behavioral responses, such as long-term and short-term memory, emotional reactivity, anxiety level, and motor reflexes.

## Radiation physiology research on primates

The main goal of primate radiation exposure is to investigate and predict via modeling the human ability to perform under radiation exposure during deep space flights. The monkey is an optimal biological object as it allows not only studying the human-like organisms' responses to irradiation, but also modeling the basic elements of operator activity. Pilot experiments on primate head irradiation with proton beams (Fig. 2, DLNP MTC) and carbon and krypton ions (Fig. 3, VBLHEP Nuclotron) have demonstrated more pronounced cognitive disorders after heavy ion exposure.

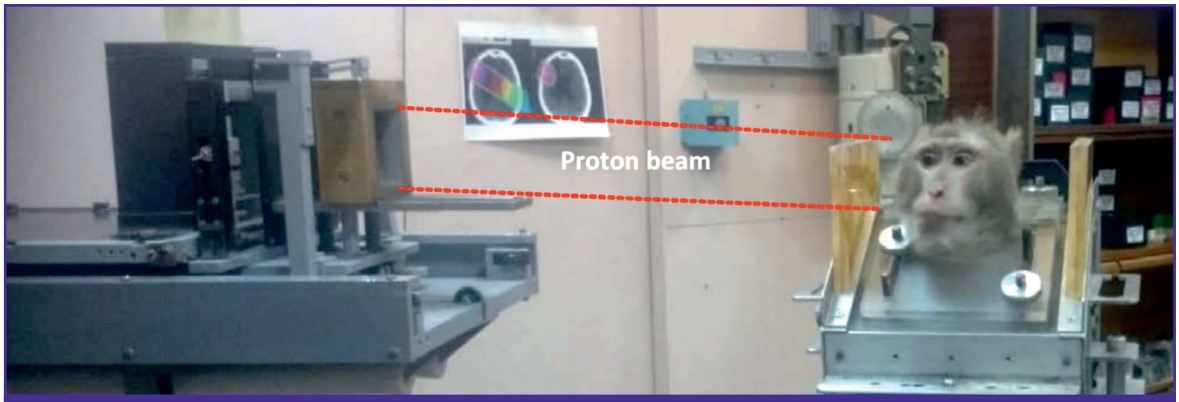


**Fig. 2. First experiments on primate irradiation at a medical proton beam**

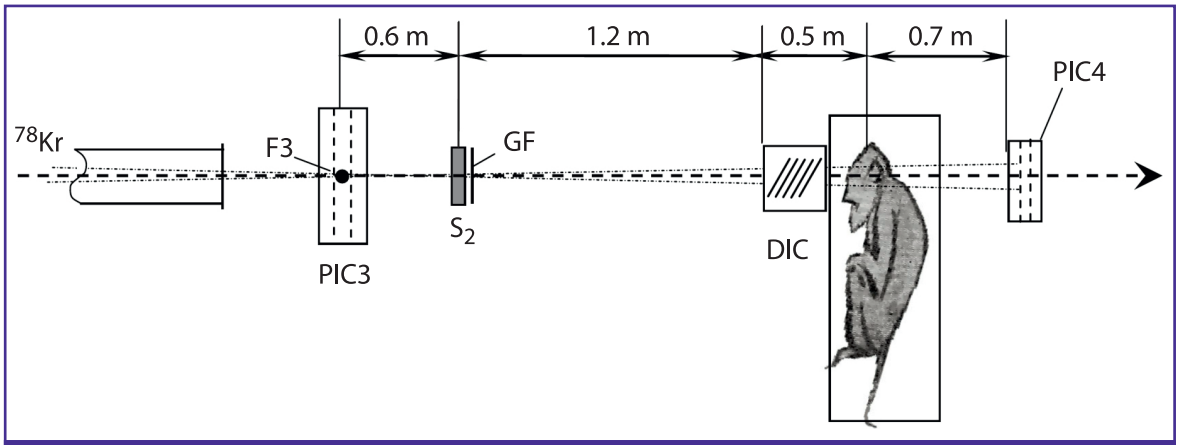


**Fig. 3. A scheme of monkey irradiation with the $^{78}$Kr ion beam at the Nuclotron (VBLHEP), showing the scintillation counter ($S_2$), radiochromic film (GF), dosimetric ionization chamber (DIC), and multiwire proportional ionization chambers (PIC3 and PIC4)**

## Molecular radiobiological aspects of radiation therapy

Earlier LRB's research showed that the cell exposure to γ-rays and particles in the presence of DNA synthesis inhibitors cytosine 1-β-D-arabinofuranoside (AraC) and hydroxyurea (HU), which transform non-lethal simple DNA lesions into enzymatic DSB (eDSB), increases the biological effectiveness of radiation. The DNA DSB formation by accelerated proton exposure in the presence of modifying agents increased by a factor of 15 for up to 24 hours post-irradiation (Fig. 4) due to the increased eDSB yield, while the minimal yield was observed without modifiers. AraC and HU are officinal drugs used clinically for the treatment of different tumors.

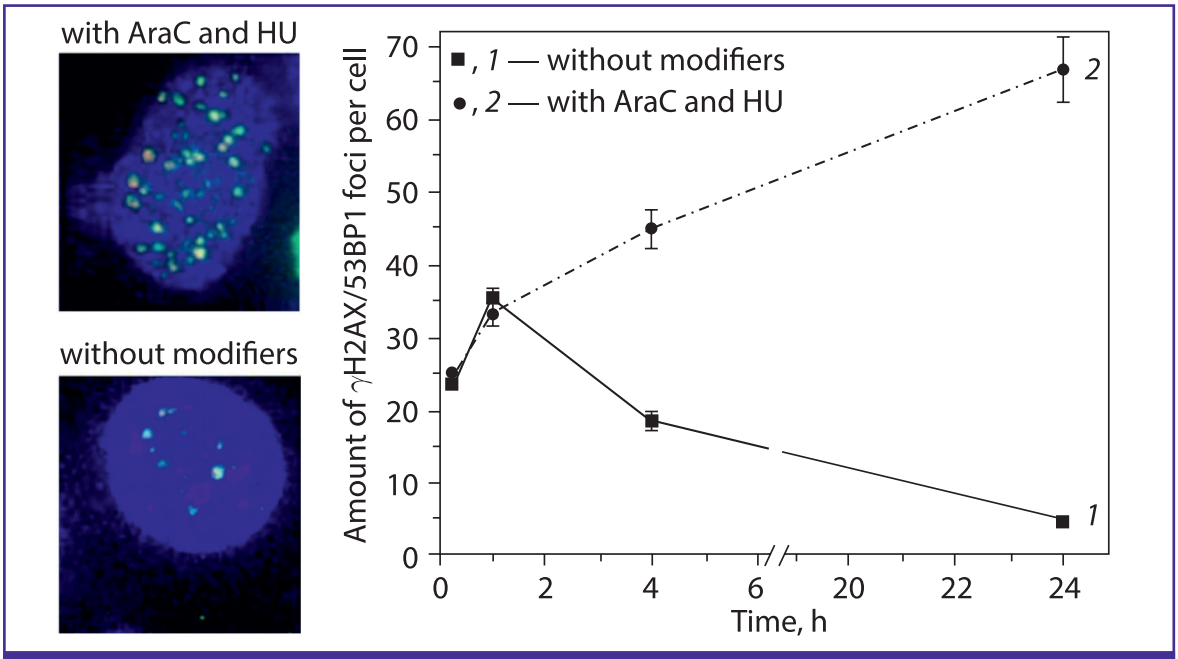


**Fig. 4. Images of individual RIF (γH2AX/53BP1 foci) after 24 h and the kinetics of their formation and elimination in human cell nuclei after exposure to Bragg peak protons (170 MeV, 1.25 Gy) under normal conditions and in the presence of AraC and HU**

## Mathematical modeling of radiation-induced effects

Mathematical and computer modeling is performed to explain and predict the results of the LRB's radiobiological experiments at the Institute's nuclear physics facilities. Modeling of radiation-induced mutagenesis and Monte Carlo simulation of energy deposition in particle tracks has been performed. The computation of radiation damage to the CNS structures was recently started and is continued independently by NASA and the LRB.

## Radiation research

The LRB's specialists participate in the design of the shielding of the NICA collider and booster and prediction of the radiation environment at the NICA complex. For the surveillance of the NICA collider's radiation conditions and establishment of zoned radiation monitoring, a portable autonomous multi-sphere neutron spectrometer has been developed.

The LRB is involved in the design of nuclear planetology instruments. Together with the FLNP and SRI RAS (Moscow), an experimental stand with fast neutron generators has been put into operation to test and calibrate planetological neutron detectors, where space equipment is tested on a model of planetary soil.

## Astrobiology

In recent pioneering experiments performed at JINR in cooperation with its Italian colleagues on the irradiation of water solutions of formamide ($NH_2COH$) with 170 MeV protons and 500 MeV/n carbon ions in the presence of meteorite matter as a catalyst, production of a wide range of prebiotic compounds has been observed, including nucleic bases, carboxylic acids, sugars, and amino acids. These compounds were not found previously in experiments with the thermal factor instead of radiation.

## International networking and context

In carrying out research, the LRB collaborates with the following scientific institutions of JINR member and other countries: Armenia (YSU), Belarus (IRB NASB), Bulgaria (IE BAS, IM BAS, NCRRP), the Czech Republic (CTU, IBP ASCR, NPI ASCR), Italy (UNITUS, UNIUD, La Sapienza Univ.), Mongolia (NUM), Poland (SzU), Romania (IBR, UMF, UAIC), Russia (IBP RAS, IP, MSU, ITEP, IHNAN RAS, IMP, SRI RAS), and Slovakia (CU).

The main advantage of conducting research at the LRB is the availability of multiple radiation sources, including heavy ion beams of different energies. JINR's basic facilities offer an excellent opportunity of modeling the biological action of space radiation. The LRB is one of the world's few laboratories where it is possible to conduct large-scale *in vivo* animal exposures, including unique experiments on primates. The use of a primate animal model for the estimation of radiation risks of CNS disorders and carcinogenesis is at present available only at the LRB. In addition, the computational studies of radiation damage to the CNS structures were initiated exclusively by NASA and the LRB. The code developed by the LRB to model energy deposition in neurons has been included in the distribution of Geant4-DNA Monte Carlo simulation toolkit. For the first time, the synthesis of prebiotic compounds in the "formamide + catalysts" system under exposure to particle beams has been performed at the LRB in collaboration with scientists of the University of Tuscia (Viterbo, Italy) within the framework of research on the Panspermia hypothesis.

# Infrastructure

## Equipment

The Laboratory of Radiation Biology occupies two separate buildings located 2 km from each other. The LRB's main building (Building 113) is home to the Molecular Radiobiology, Cytogenetics, Mathematical Modeling, and Lower Eukaryote Genetics Sectors; the Department of Radiation Research, Laboratory's Directorate, technical and logistic services, and classrooms of Dubna University's Department of Biophysics. At Building 71, the Radiation Physiology and Astrobiology Sectors and a vivarium with support services are located.

### Sources of ionizing radiation

JINR's following sources of photon and particle ionizing radiation are used in the radiobiological research conducted by the LRB (Fig. 5):

- $^{60}$Co $\gamma$-radiation source at the Rocus-M facility (DLNP MTC);

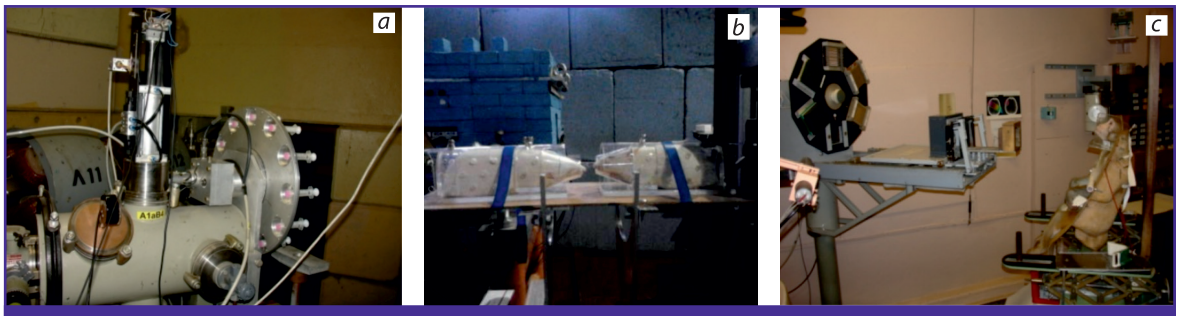


**Fig. 5. Irradiation of biological objects at JINR facilities: *a*) the Genom-M facility at the U-400M cyclotron (FLNR); *b*) irradiation of rats at a Nuclotron ion beam (VBLHEP); *c*) irradiation of monkeys at the DLNP medical proton beam**

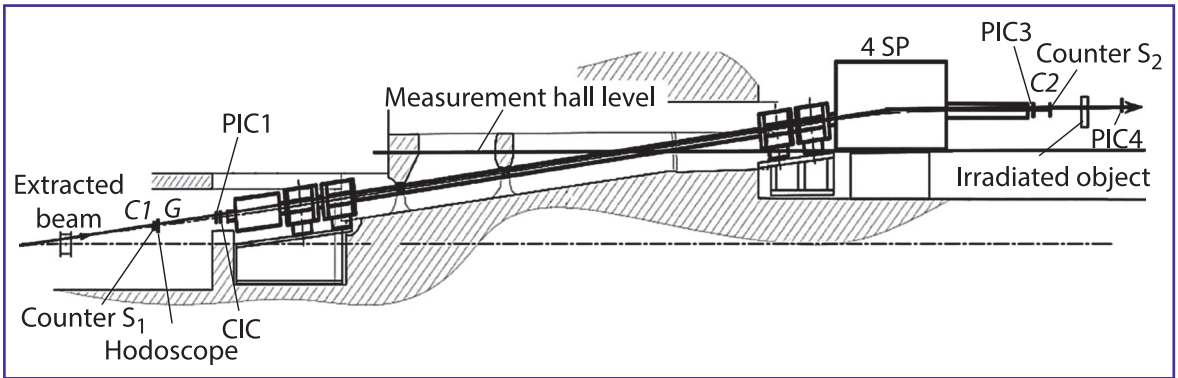


**Fig. 6. A schematic layout of the Nuclotron beam extraction channel and beam detectors behind the irradiated biological objects**

- 170 MeV and spread-out Bragg peak (SOBP) medical proton beams (DLNP MTC);
- U-400M accelerator (FLNR) equipped with the Genome-M facility for the automatic irradiation of thin biological samples. The experiments were performed with 20–50 MeV/n boron, nitrogen, and oxygen ions;
- Nuclotron (VBLHEP) (Fig. 6) with external beamline for irradiation of samples and objects. Experiments were performed with 500 MeV/n carbon ion beams, and a single exposure to 2.5 GeV/n $^{78}$Kr ions was conducted.

The biological action of particle beams is described in terms of Relative Biological Effectiveness (RBE), defined as a ratio of absorbed doses which produce the same biological effect $RBE = D_\gamma / D_{ion}|_{isoeffect}$. The $^{60}$Co $\gamma$-radiation is used as reference radiation.

## Education and personnel policy

The LRB's total staff is 97, approximately a half of them are young researchers below the age of 35.

For more than 20 years, the Department of Biophysics, Dubna State University, has been offering graduate and postgraduate programs, including bachelor's education in nuclear physics and technology (the program *Human and Environmental Radiation Safety*); master's education in physics (the program *Radiation Biophysics and Astrobiology*); and postgraduate education in radiobiology. The Department meets the LRB's demand for young staff.

The LRB also participates in the training and educational programs for young specialists and students from JINR member states and other countries organized by the JINR University Center.

# Future Research Projects

The LRB's radiobiological experiments planned at JINR's accelerated charged particle beams will be focused on studying heavy ion action at the molecular, cellular, tissue, and organism levels of biological organization. Special attention will be paid to research on experimental animals' CNS disorders because the CNS must be considered a critical system when evaluating the radiation exposure risk for the interplanetary mission crews and considering the possible side effects of the radiotherapy of brain tumors.

## Molecular radiobiology

It is planned to continue at the LRB research on DNA clustered damage induced by densely ionizing radiation and its repair in CNS cells and tissues with a view to evaluating the risk to astronauts associated with GCR exposure during deep space flights, as well as the specifics of DNA repair in radiation-resistant tumor cells in order to search for new approaches to the radiation therapy of cancer.

### Main topics of future research

- Evaluation of the induction of clustered DNA DSBs by high-LET heavy ion exposure and their repair kinetics in **radiation-resistant** U87 glioblastoma **tumor cells** using the fluorescent labeling of the repair proteins γH2AX, 53BP1, OGG1, and XRCC1.
- Studying the formation and elimination kinetics of clustered DNA DSBs after accelerated heavy ion exposure in the nuclei of human **neural** stem cells, mature neurons, and **glial cells** using the immunocytochemical staining of the repair proteins γH2AX and 53BP1 in combination with the cell subpopulation markers NeuN, doublecortin, GFAP, BrdU, and Calbindin.
- Studying the pattern of damage formation and elimination ***in vivo*** in different rodent CNS structures at different times (up to three months) after exposure to γ-rays and high-LET heavy ions.
- Investigation of the internal structure of clustered radiation-induced foci (RIF) produced by high-LET ion beams using confocal and single molecule localization microscopy (high-resolution nanoscopy).
- The contribution of different repair pathways (non-homologous end joining (NHEJ) and homologous recombination (HR)) to clustered DNA damage elimination in human fibroblasts after exposure to photons, protons, and heavy ions will be determined using the immunocytochemical staining of the repair proteins γH2AX, RAD51 (HR), and 53BP1 (NHEJ).
- Studying apoptosis induction in human skin fibroblasts and mammalian CNS neurons after high-LET heavy ion exposure; studying the kinetics and level of the expression of the genes which encode proteins involved in apoptosis.

## Radiation cytogenetics

A new technique of multicolor Fluorescence In Situ Hybridization (mFISH) was recently introduced at the LRB, which allows identification of each pair of human and animal chromosomes and detection of all possible rearrangements between them including com-

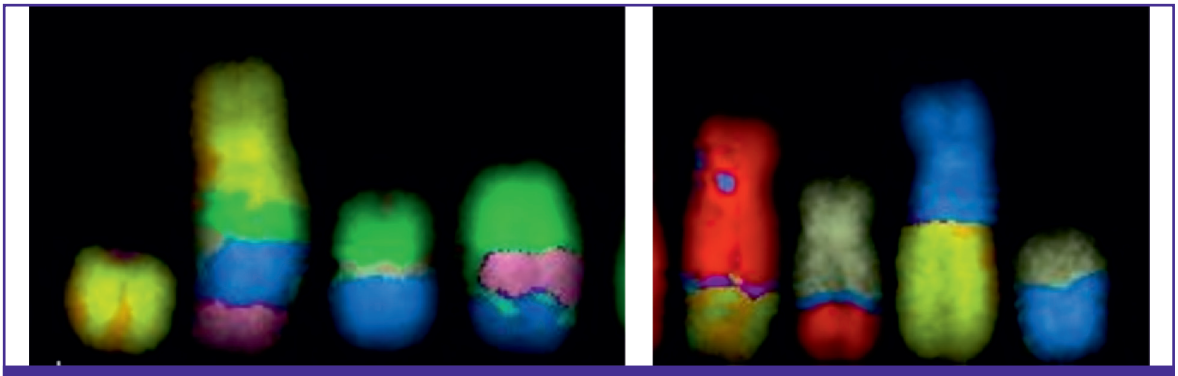

**Fig. 7. An mFISH visualization of complex chromosome aberrations**

plex CA (three and more breaks in two and more chromosomes) (Fig. 7). Complex CA is considered a marker of high-LET radiation exposure and reflects the cluster character of DNA damage formation along the particle tracks. This type of CA was undetectable by routine methods.

The mFISH method is of much promise concerning the long-term consequences of the organism's radiation exposure since it allows the evaluation of heritable symmetric aberrations: translocations which can persist for a long time after exposure in the progeny of irradiated cells.

### Main topics of future research

- mFISH evaluation of the biological effectiveness of therapeutic proton beams (150 MeV and spread-out Bragg peak, the DLNP Medical-Technical Complex) on human normal (lymphocytes) and tumor (Cal51 carcinoma) cells. The action of accelerated protons on human normal and tumor cells has not yet been studied by the mFISH method.
- mFISH evaluation of the biological effectiveness of 30–50 MeV/n $^{14}$N and other ions at the U-400M (FLNR). The action of 30–50 MeV/n heavy ion beams, which have high biological effectiveness, has not yet been studied.
- To contribute to space research-relevant radiation risk assessment, the evaluation of **long-term consequences** of radiation exposure will be performed. In parallel to *in vivo* studies of the radiation-induced CNS damage (see Molecular Radiobiology and Radiation Physiology), it is planned (this requires no additional number of animals) to evaluate CA induction in bone marrow and blood cells of animals (mice, rats) at different times after exposure (up to 6–8 months) to γ-rays, protons (DLNP MTC), and 250–800 MeV/n heavy ions (Nuclotron). For this study, mFISH will be combined with the standard metaphase assay.
- The evaluation of CA in **primate** blood by the standard metaphase assay will be performed within the framework of radiation physiology research on primates along with studying the response of the hematopoietic, immune, and other regulatory systems of the organism to radiation exposure.

## Radiation physiology

It has been shown that heavy charged particle exposure of laboratory animals even to low doses leads to a serious disorder of mental and motor functions [2]. Therefore, the main goal of future radiation physiology research at the LRB will be to contribute to **space research** and estimate the health **risks** to the astronauts from radiation exposure to GCR during manned space flights — mainly, the ergonomic risk of CNS disorders.

To clarify the possible **mechanisms** of radiation-induced CNS damage and cognitive deficit, it is planned to investigate the glial cells' vital role. **Demyelination** is considered as one of the most probable causes of ionizing radiation-induced cognitive deficit due to the radiation-induced death of oligodendrocytes [3]. Another probable cause is a chronic **neuroinflammation** caused by activated microglia [4]. Both mechanisms were recently shown to play a role in different neurodegenerative diseases like multiple sclerosis, Huntington's, Parkinson's, and Alzheimer's. However, no progress has been made in understanding the basis of radiation-induced cognitive disorders.

### Main topics of future research

- **Morphofunctional changes in the CNS after exposure to sparsely and densely ionizing radiation.** To evaluate the damaging action of γ-rays, protons (DLNP), and 250–800 MeV/n heavy ions (Nuclotron) on the CNS structure and functions, it is planned to

perform a whole range of histological studies of the rodent brain and spinal cord using light, fluorescent, and electron microscopy. Immunohistochemical methods are going to be used to identify neurodegenerative changes, neuroinflammation, apoptotic and necrotic changes, amyloid growths, and vascular pathologies. Morphometric parameter analysis will be done using scanning systems and the ImageJ software.

- **The functional condition** of the CNS in these experiments will be evaluated using a whole set of modern zoopsychology techniques and equipment, including test systems for assessing long-term and short-term memory, emotional reactivity, the anxiety level, and motor reflexes. Behavior parameters will be analyzed with modern video tracking tools, the Noldus Ethovision software package, and the newest electrophysiological equipment.
- Suppression of **neurogenesis** after ionizing radiation exposure of rats in the postnatal period will be studied.
- It is planned to perform *in vivo* and *in vitro* exposures to γ-rays, protons (DLNP MTC), and heavy ions (VBLHEP Nuclotron) to evaluate the damage to **glial** cells.
- Radiation-induced **immune response** will be studied in mouse brain homogenates and in glial cell culture after exposure to sparsely and densely ionizing radiation. In particular, it is planned to determine the level of the secretion of pro-inflammatory cytokines, including Il-1 beta, Il-6, TNF alpha, and MCP-1, at different times after exposure.
- The influence of sparsely and densely ionizing radiation on the **viability of oligodendrocytes** and their precursors and on the axon **myelination** level will be studied**.** With this aim, it is suggested to do the immunochemical analysis of the brain tissue in histological sections and in cell culture using antibodies to the NG2 and PDGFR proteins (OPC markers) and MBP, O4, and MOG (mature oligodendrocyte markers).
- In a **search for radioprotectors,** it is planned to test on rodents pharmacological drugs, biogenic amines, and antioxidants or their combinations concerning the prevention and therapy of damage caused by chronic radiation exposure.

## Radiation physiology research on primates

The radiation physiology research on primates will be performed in collaboration with the RAS Institute of Biomedical Problems, RAS Institute of Medical Primatology, RAS Institute of Higher Nervous Activity and Neurophysiology, and Moscow State University. It will include evaluation of the higher nervous activity; studying the response of the hematopoietic, immune, and other regulatory systems of the organism to radiation exposure; studying the long-term effect of exposure on lifetime and cancer development; and estimation of the radiation risk of an interplanetary mission based on the obtained experimental data.

The research will be performed on 3.5–5-year old *Macaca mulatta* monkeys divided into two groups of the same number of monkeys (the experimental and control ones), 10–15 animals in each.

### Main topics of future research

- In deep space flights, of the highest danger will be high-energy heavy charged particles. Therefore, the action of accelerated charged particles (high-energy protons at DLNP; 250–800 MeV/n heavy ions at VBLHEP Nuclotron) on the cognitive functions of monkeys will be studied. Irradiation of specific brain structures requires a narrowly collimated heavy ion beam at the Nuclotron, and special beam line with adequate optics and collimators is foreseen.

- It would be optimal to model the space flight radiation factors using prolonged γ-exposure (chronic) at doses corresponding to the interplanetary flight conditions and periodic high-energy proton and heavy-ion exposures.
- Research on the synchronous combined action of anti-orthostatic hypokinesia (AOH) and prolonged γ-irradiation on the CNS functions. It is planned to irradiate monkeys fixed on an AOH table and, immediately during exposure, study learning processes and repeating operator activity skills.
- During these experiments it is planned to study:
  a) The cognitive disorders, using an automated computer psychomotor test system for the continuous monitoring of the capacity for mental work, the active wakefulness level, and motivation;
  b) The neurochemical mechanisms of higher nervous activity disorders: to evaluate the activity ratio of the neuromediator to neuromodulator brain systems;
  c) The electrophysiological changes in different brain structures — based on the electroencephalography and magnetic resonance imaging;
  d) The hematological changes (clinical blood test every two months) and evaluation of bone marrow hematopoiesis (every four months).

## Molecular radiobiological aspects of radiation therapy

The biological effectiveness of the particle beam plays an important role in tumor treatment. It depends on many factors, which can be subdivided into two groups: *physical* (LET, dose rate, etc) and *biological* — in particular, the cell repair status. The transformation of non-lethal simple DNA lesions into lethal eDSBs by the regulation of DNA repair processes in the presence of special modifiers is a potential way to increase the biological effectiveness of gamma and proton medical beams. A combined application of special drugs and radiation exposure can be promising for radiation therapy as it would bring the area of the therapeutic use of protons closer to that of carbon ions.

### Main topics of future research

- Evaluation of the effect of DNA synthesis inhibitors **on the survival of normal human cells after SOBP proton** and photon exposure (by the criteria of colony formation and apoptosis progress).
- Studying the effect of DNA synthesis inhibitors on foci induction in **radioresistant human tumor cells** (in particular, glioblastoma) by accelerated protons and γ-rays.
- Studying the effect of DNA synthesis inhibitors on the biological effectiveness of proton and γ-ray exposure ***in vivo*.** DNA DSB induction in different parts of the central nervous system by proton and γ-ray exposure with and without radiation effect modifiers will be studied in experiments on rodents.
- **Preclinical animal studies:** evaluation of the modifying effect of **DNA synthesis inhibitors on the efficiency of proton treatment of transplanted tumors** (in particular, melanoma) **in mice.**

## Mathematical modeling of radiation-induced effects

Future work will be focused on the development of the **hierarchy of models** that would allow systematizing experimental data and studying the pathways of how radiation-induced pathologies develop at different **organization levels** (from the molecule to cell population) and **time scales** (acute and long-term radiation effects). The supercomputer

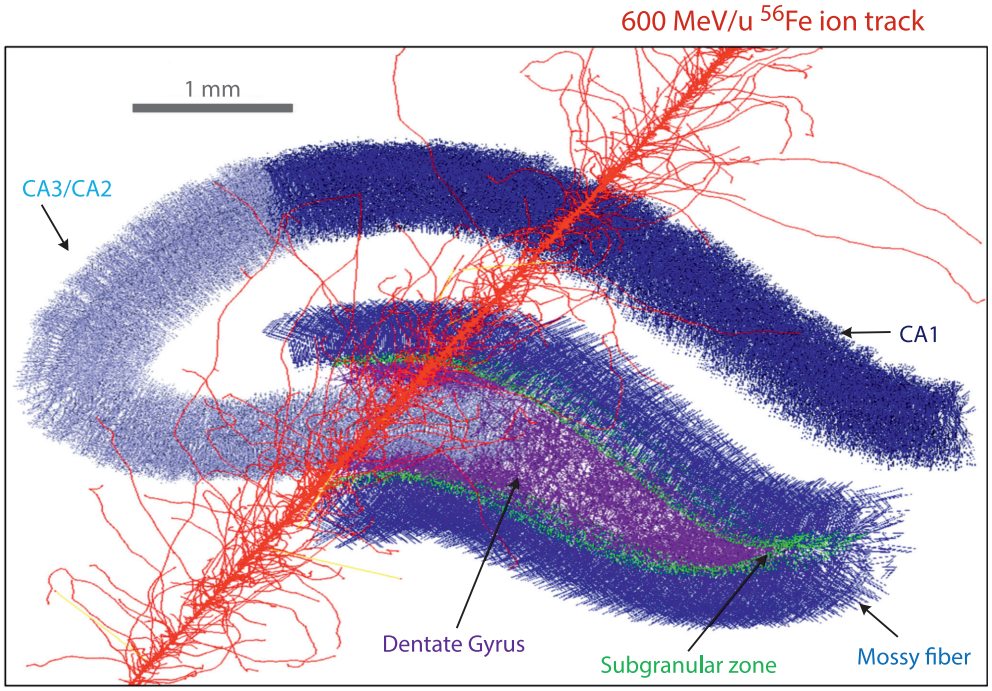


**Fig. 8. A Monte Carlo simulation of a 600 MeV/n $^{56}$Fe ion track structure in a three-dimensional model of the rat hippocampus including main zones and cell types indicated by different colors**

of the JINR Multifunctional Information and Computing Complex will be used. As the result, this multi-level calculation scheme would allow a **theoretical evaluation of the radiation risk**.

### Main topics of future research

- **Monte Carlo simulation** of energy deposition events and water radiolysis in the tracks of charged particles hitting brain cells and structures (Fig. 8). It is suggested to model the passage of monoenergetic particle beams and radiation fluxes corresponding to GCR spectra and secondary radiation particles produced in different shielding types.
- Modeling the formation and distribution of the main types (e.g., DNA base lesions, single- and double-strand breaks) **of molecular damage** in the following targets: the cell nucleus and DNA, cytoskeleton, mitochondria, membrane ion channels, and synaptic receptors. A method to compute the probabilities of bond breakage, ionizations, and chemical modifications of biomolecules is going to be developed.
- Modeling **DNA damage repair,** and gene and structural **mutation** formation after accelerated heavy charged particle exposure. The influence of the possible repair pathways and the spatial distribution of lesions on the efficiency of their detection and repair will be studied. A detailed analysis of the most probable mutation types will be performed for selected genes.
- **Molecular dynamics** studies of the effect of genetic mutations or chemical modifications on protein structures and analysis of changes in their functional activity.
- For modeling **radiation-induced oxidative stress** emerging as a consequence of heavy charged particle passage through the cell, a nonlinear dynamic model will be developed. The obtained data will become the basis for mathematical models **of intracellular transport and signaling disorders**.

- Modeling radiation-induced cell population dynamics and neurochemistry, including suppression of **neurogenesis** and **gliogenesis, demyelination,** and **neuroinflammation**, which affect the activity of the brain neural networks.
- **Simulating the functional activity of brain neural networks** after accelerated heavy charged particle exposure. This will lead to a theoretical evaluation of possible cognitive disorders, which can be compared with observed behavioral reactions, electroencephalography data, and functional magnetic resonance imaging.

## Radiation research

### Main topics of future research

- Improvement of accelerator-based radiobiological experiment techniques:
  a) Work is underway on the construction of two beam lines at the Nuclotron (VBLHEP) for applied research in materials science and radiobiology at heavy ion beams (250–800 MeV/n carbon, neon, argon, iron, and krypton ions). Both beam lines will work with ions of reduced energy and intensity up to $10^8$ ions/cycle. Proper beam optics is required for the irradiation of biological samples, animal heads, and parts of their brain. The spatial irregularity and charge spectrum of the irradiation field should not exceed 5%. The Measuring Pavilion for radiobiological experiments should consist of the following main nodes: a cabin for monkeys or other biological objects, a set of beam diagnostic equipment, and a room for staff with proper shielding. Specially designed chairs for irradiation of monkeys are placed in an irradiation cabin. Before the irradiation the animals need to be kept in a specially designed room near the Measuring Pavilion maintaining the same conditions as in the irradiation cabin including heating, ventilation, lighting and video control.
  b) The Nuclotron-based **modeling of radiation fields generated by GCR inside spacecraft** in deep space. An irradiation facility simulating the hadron exposure in Space with continuous particle energy spectra could be constructed after the completion of the **NICA project**.
  c) The upgrade of the U-400M (FLNR) allows increasing energies of accelerated ions up to 100 MeV/n. It will make it possible to irradiate the brain of small laboratory animals (mice and rats) with higher LET ion beams compared to those at the Nuclotron. The highest energy of the ions extracted from U-400M is now about 50 MeV/n. The upgrade the LRB's Genome-M setup for the automated irradiation of biological samples will be performed to match the parameters of new beams.
- **Surveillance of the NICA collider's radiation conditions and establishment of zoned radiation monitoring** using portable autonomous multi-sphere neutron spectrometers.
- **Monte Carlo calculations of radiation transport in matter** with the MCNPX, GEANT4, and FLUKA software toolkits for the realistic estimation of astronauts' effective doses for different flight duration, solar activity, and radiation shielding of habitable module.

## Astrobiology

Astrobiological research will be an attempt to represent a sequence of processes that can result in the formation of a complete, chemically active prebiotic medium. It is planned to continue the experiments on radiation exposure of the formamide+catalysts system to find (I) the optimal conditions for prebiotic compounds synthesis and (II) the conditions under which the oligo- and polymer biomolecules can be assembled.

### Main topics of future research

- Studies of the possible **sources, ways, and conditions of the formation of the first prebiotic compounds.** To find the optimal ways of prebiotic compound synthesis, it is planned to include in research the synthesis of prebiotic compounds from $NH_2COH$ in the presence of catalysts from meteorite material: (I) at different energies of charged particles (50, 155, 500 MeV/n); (II) in combination with thermal and ultraviolet exposure; (III) in the presence of catalysts of terrestrial origin; (IV) in the presence of liquid water; (V) in the presence of components of terrestrial hydrothermal systems. Next steps will be to demonstrate clearly the synthesis of nucleosides from a mixture of a nucleic base and sugar exposed to a 170 MeV proton beam and the synthesis of nucleotides — elements of DNA and RNA — from a mixture of nucleosides and phosphate groups under radiation exposure; as well as to find the conditions under which oligo- and polymer biomolecules can be assembled.
- **Micropaleontological studies of meteorites and terrestrial rocks.** The LRB performs scanning electron microscopy studies of organic matter and microfossils in meteorites and terrestrial rocks. It is planned to increase the LRB's meteorite collection and prepare microfossil atlases for a number of meteorites.

## Infrastructure Development

### Equipment

The LRB's further development requires no new space for equipment and staff. For the development of future research in **molecular radiobiology and cytology,** it is planned to purchase the following equipment:

- A four-laser flow cytofluorimeter sorter with accessories and reagents for genetic engineering;
- A system of cytogenetic image scanning, processing, and analysis;
- A station for automated cell cultivation and analysis;
- A real-time amplifier capable of providing a temperature gradient;
- A gel- and chemodocumenting system with a built-in transilluminator;
- A solid state thermostat with cooling and mixing features for conducting restriction and ligation reactions.

To conduct **research in radiation physiology,** it is planned to purchase the following equipment:

- A functional magnetic resonance imaging (fMRI) system suitable for monkey and small animal tomography;
- A fluorescent tomography system for animal imaging *in vivo*;
- A hematological analyzer of animal blood corpuscles.

The infrastructure necessary for the **computational experiments** will be upgraded to reach performance of up to 10 TFLOPS using a CPU (double precision) and 100 TFLOPS using a GPU (single precision).

### Required ionizing radiation sources

For reference measurements of particle beams relative biological effectiveness in comparison to conventional radiation, it is planned to purchase LRB own radiation sources

including X-ray machine operating at 250 kV with maximum dose rate up to 6 Gy/min, and high-intensity alpha particle source ($^{241}$Am source with branching ratio up to 85%). Experimental rooms with proper radiation monitoring control will be prepared for irradiation of samples, objects and animals.

Analysis of nanoscale biological samples (mutant and oxidized proteins, lipids, etc.) is to be performed at FLNP using small-angle neutron scattering technique.

Accelerator beam-based research will be further conducted at JINR's three laboratories:

- At the 170 MeV and SOBP medical proton beams of the DLNP Medical-Technical Complex.
- The 230 MeV superconducting SC200 proton accelerator, which is being created jointly with Chinese specialists as a replacement of the DLNP's Phasotron, will be actively used by the LRB's radiobiologists.
- At the U-400M accelerator (FLNR). The planned upgrade of the accelerator will increase the beams' energies up to 100 MeV/n, and it can significantly broaden the range of their applications (in particular, animal exposures will be possible).
- **The key to the successful fulfillment of the 2030 Program is the possibility to conduct radiobiological research at the Nuclotron (VBLHEP).** Of the greatest interest for fundamental and applied radiobiological research will be carbon, iron and iron-group beams with energies of 250–800 MeV/n.
- LRB needs radiobiological irradiation facilities at JINR accelerators that must be designed and produced with proper beam optics and monitoring, as well as an adequate experimental target area for irradiation of samples, objects and animals. Support of engineers and technicians from the accelerator laboratories is needed, but training and creation of LRB staff in these technologies is foreseen.

The demand for beam time for radiobiological experiments at each accelerator is about 200–250 hours per year. In the future, after FAIR project completion at the GSI, it will be highly practical to conduct similar radiobiological experiments there with the LRB's colleagues from other countries.

## International cooperation

The LRB's staff participation in the development of applied packages for the GEANT4-DNA modeling software toolkit will be continued as closer work with the GEANT4 Collaboration — in particular, as participation in the organization of specialized workshops. A promising area of cooperation in neurophysiology is joint work with the LRB partners in Cuba (CAS, CEA, CNEURO). The LRB is a member of the recently formed International Biophysics Collaboration, which coordinates radiobiological and medical research at NICA, FAIR, RAON, ELIMED, FRIB, and other facilities. This will ensure closer collaboration with GSI (Darmstadt) and elaboration of the program of joint research at NICA and FAIR beams.

## Human resources development

The Department of Biophysics, Dubna State University, meets the LRB's demand for young staff, and this practice must be continued in the future. To solve the top-priority tasks set in the Program, attraction of highly qualified specialists is needed. For this purpose, JINR seeks outstanding postdoctoral fellows and announces calls for applications for a number of vacant positions in the framework of the Distinguished Postdoctoral Research Fellowship Program.

The LRB is the youngest laboratory of JINR. To fulfill this Research Program and to maintain JINR ability to compete with world leading research centers in the field of radiobiology and radiation medicine, it is required to open up to five new positions for LRB scientific staff per year. In addition to radiobiologists, positions for a small team of specialized beam technicians, engineers and physicists need to be opened in order to meet the need for proper operation of the complex irradiation programs. Upon reaching 2030 the total LRB staff could be extended up to 150 people.

### Budgetary considerations

The budget for beamlines and irradiation stations is between 1–5 M$, and maintenance and operation costs are of the order of 100–200 k$ per irradiation site. The equipment cost is about 10 M$.

## Summary

The great advantage of conducting research at the LRB is the availability of numerous radiation sources, including heavy ion beams of different energies. JINR's basic facilities offer an excellent opportunity of modeling the biological action of space radiation. The LRB has proposed a novel Nuclotron-based technique of modeling of radiation fields with continuous particle energy spectra generated by GCR inside spacecraft in deep space.

Another major advantage is an excellent opportunity to perform large-scale *in vivo* animal exposures in collaboration with leading experts in this field — first of all, with RAS Institute of Biomedical Problems. The worldwide unique experiments on primates for the estimation of radiation risks of CNS disorders and carcinogenesis are in progress at the LRB.

A new method of the enhancement of low-LET ionizing radiation's biological effectiveness by the transformation of non-lethal DNA damage to lethal has been invented and recently patented by the LRB. The method has been tested *in vivo* and *in vitro,* which makes it very promising for radiation medicine.

The LRB develops the hierarchy of mathematical models to simulate radiation-induced pathologies at different organization levels and time scales. In addition to the traditional Monte Carlo technique, the LRB's approach involves computational methods from different knowledge areas (molecular dynamics and simulation of brain neural networks). The computation of radiation damage to the CNS structures was initiated and is continued by NASA and the LRB.

For the first time, the synthesis of prebiotic compounds in the "formamide + catalysts" system under exposure to particle beams has been performed in collaboration with Italian universities within the framework of research on the Panspermia hypothesis.

All of the above provides confidence that the LRB will become an essential part of the International Biophysics Collaboration and will be an important player in the field of modern radiobiology.

**The key to the successful fulfillment of the 2030 Program is the possibility to conduct radiobiological research at the Nuclotron (VBLHEP).**

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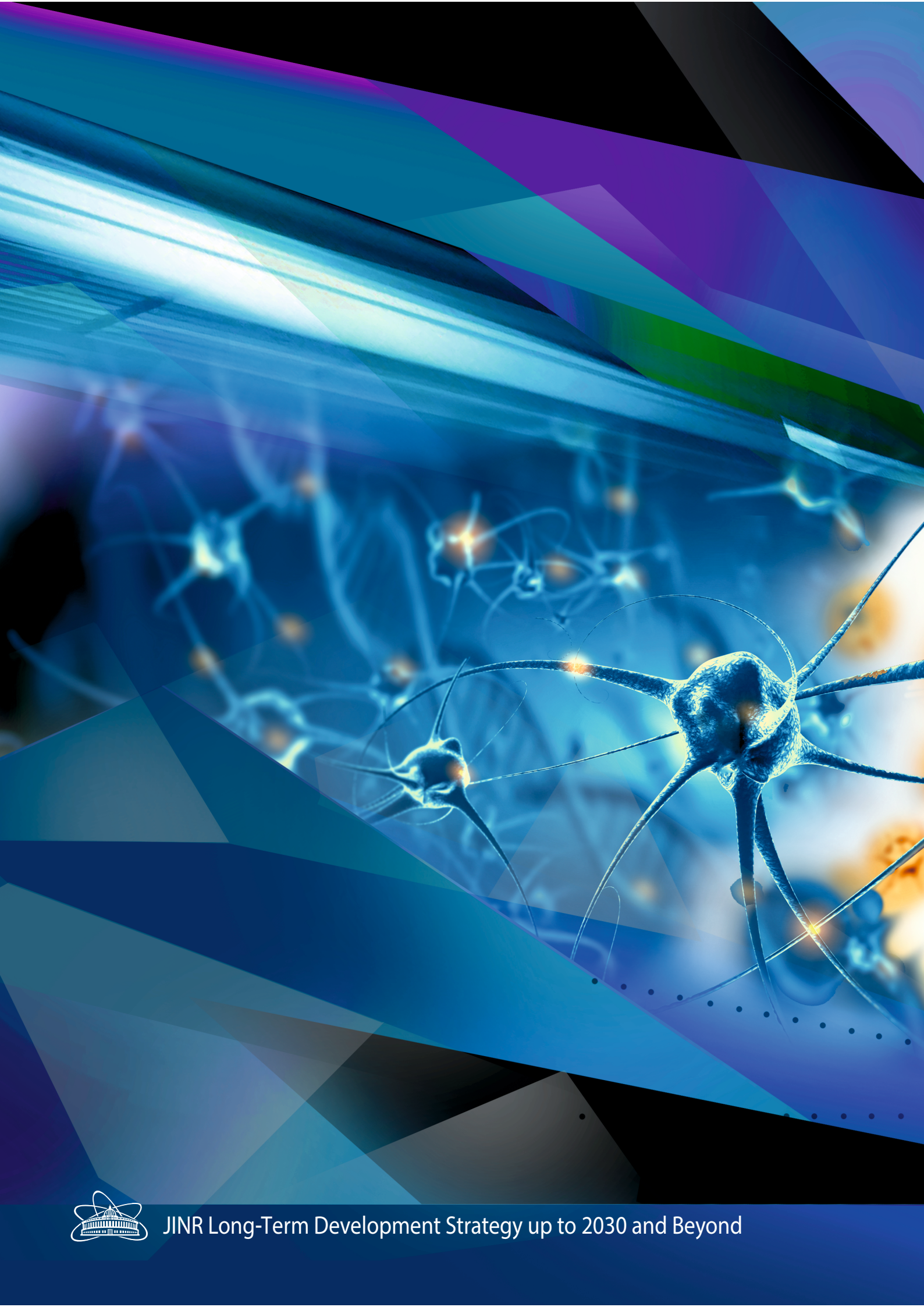

# JINR Long-Term Development Strategy up to 2030 and Beyond



# 9

# Biomedical Research Center

## Executive Summary

JINR has accumulated half a century of experience in treating cancer patients with proton beams of the so-called phasotron (synchrocyclotron), as well as in the field of development and creation of specialized accelerators for these purposes. Recently a new method of the enhancement of low-LET ionizing radiation's biological effectiveness by the transformation of non-lethal DNA damage to lethal has been invented and patented by the JINR LRB. This promises a breakthrough in the effectiveness of using proton beams for the treatment of cancer and creates the conditions for the establishment of a research biomedical center for proton therapy of cancer. It is proposed to use the commercially available accelerator with an additional proton beam lines for biological research as the technical basis of the new biomedical research center.

## Introduction

In Russia, about 500 thousand people fall ill with cancer annually and up to 270 thousand people die of cancer. Currently, 3.2 million cancer patients are registered. According to doctors, the number of patients in Russia for whom radiation therapy using proton beams can give significant advantages is more than 50 thousand patients per year.

The main task of the radiation therapy of cancer is to deliver a therapeutic dose to the tumor with minimal risks of normal tissue complications. From this standpoint, hadron beams — protons and carbon ions — are beneficial for cancer treatment, especially for deep-seated tumors. In contrast to photon beams, they have an inverted depth — dose profile (the Bragg curve): the dose increases with penetration depth from a low dose at the entrance (healthy tissues) to a sharp maximum at the end of particle range (the Bragg peak). Besides the dose delivery, the biological effectiveness of the particle beam plays an important role in tumor treatment. It depends on many factors, which can be subdivided into two groups: *physical* (particles' linear energy transfer (LET), dose rate, etc.) and *biological* (the cell cycle phase, repair status, tumor micro-environment, oxygen concentration, etc.).

From the physical standpoint, light ions (usually carbon ions) have an advantage over protons due to very dense ionization at the Bragg peak. For 250–300 MeV/n carbon ions, the difference in biological effectiveness is threefold and greater. Using carbon ions in cancer therapy is promising, especially for the treatment of radiation-resistant tumors. With this in mind, a number of countries (Japan, Germany, China, France) have created and are creating specialized centers for carbon therapy on the basis of accelerator sets of various types. It should be noted, though, that such accelerators are much more expensive than the proton machines, so carbon therapy centers are still limited in number, and the treatment cost is extremely high.

Exploiting the *biological factor* may also be beneficial, especially with the use of more accessible proton accelerators. The most severe DNA lesions induced by ionizing radiation are DNA double-strand breaks (DSBs). DSBs are formed either as a direct break of

two complementary sites (dDSB) or from other lesions as a "side effect" emerging during repair enzymes' functioning — the so-called eDSB. The probability of cell death after radiation exposure depends on the number of DNA DSBs of different nature. High-LET radiation is more efficient in DSB induction and, accordingly, has higher biological efficiency. At low LET values, the most frequently formed damage is base damage and DNA single-strand breaks (SSBs). Thus, the transformation of non-lethal simple DNA lesions into eDSBs by regulation of DNA repair processes is a potential way to increase the efficiency of low-LET proton beams in therapeutic use.

## Proton therapy at JINR

The first sessions of the clinical use of proton beams generated by the phasotron of JINR, the institute's first proton accelerator, were started in 1967 on the initiative and ongoing support of the director of the Laboratory of Nuclear Problems (DLNP) Prof. V. Dzhelepov. This accelerator was launched in 1949 and was created for fundamental research in the field of nuclear physics [1, 2].

At present, the phasotron is the oldest among the accelerators of this type operating in the world. The proton energy at the output of the accelerator is 660 MeV, the weight of the magnets reaches 8000 tons, the consumed electric power is about 3 MW and it is served by a relatively large staff of about 50 people. The total operating costs from the JINR budget for maintaining the operation of the phasotron annually amount to about $1 million. It should be noted that when the proton beam is decelerated from 660 to 100–200 MeV (typical energy of the therapeutic beam for irradiating tumors), the beam initially extracted from the accelerator is lost, which does not allow forming a dose field in the treatment room with the best parameters for radiation therapy. In addition, significant beam losses during its transportation and deceleration lead to significant radiation activation of accelerator structural elements.

Currently, more than 100 patients have irradiation courses on the proton beam of the phasotron annually. Since 1999, a radiological department has been operating in Dubna at MSC-9 of the Federal Medical-Biological Agency (FMBA) of Russia. For the first time in Russia, the technique of three-dimensional conformal proton radiation therapy was implemented. Between 2000 and 2018 about 1300 patients (including non-Russian citizens from JINR member states) with various neoplasms took proton radiation therapy using phasotron beams.

Given the design features of the phasotron, it is obvious that the use of such a device for the treatment of cancer patients is not only extremely inefficient economically, but also organizationally unreliable and therefore the accelerator requires an early replacement with a modern specialized proton machine. The creation of a new center for biomedical research, in which almost all the JINR member states are interested, on the basis of a new compact specialized proton accelerator, is very relevant today and will solve two problems at the same time: reduce operating costs for research and form a therapeutic and research proton beam with the best parameters.

Currently, JINR, having many years of experience in creating accelerators and physical facilities for basic and applied research, is developing medical accelerator technology, collaborating with IBA, the world leader in the field of proton therapy facilities, and is developing, assembling, tuning and launching specialized medical cyclotrons for these goals. More than 10 years ago, JINR and IBA jointly developed the project of the world's first superconducting carbon cyclotron C400 [2, 3]. This accelerator is currently under construction in Caen, France. Along with this, calculations and modernization of the se-

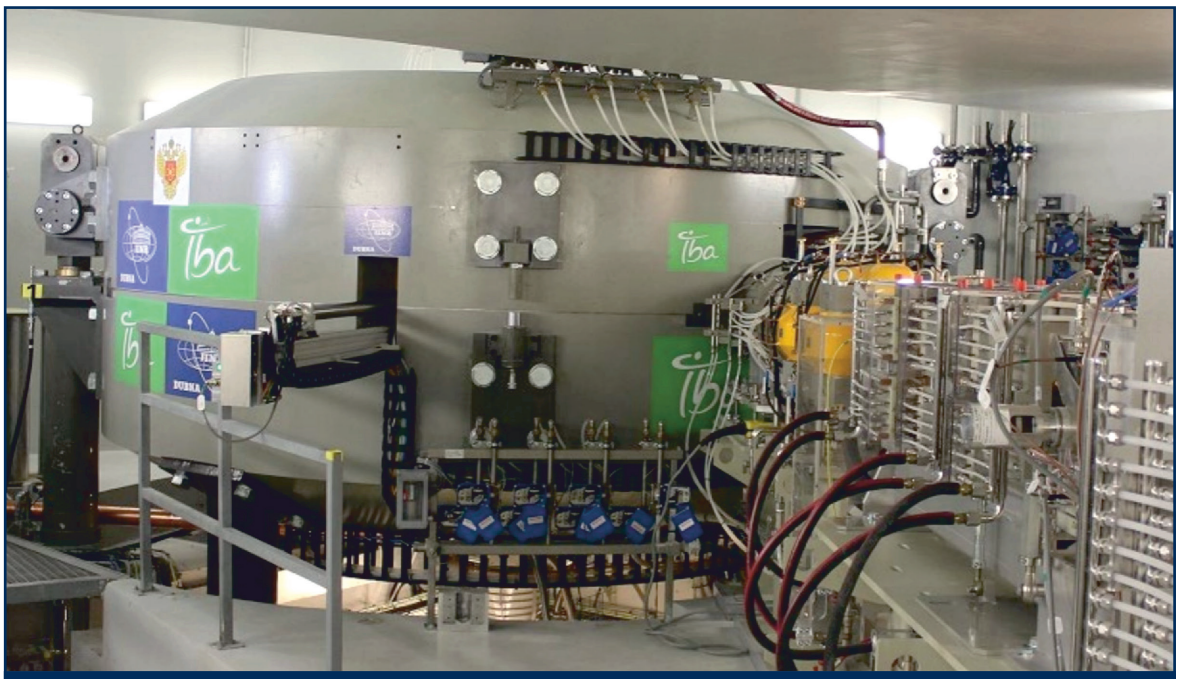

**Fig. 1. The IBA C235-V3 proton cyclotron, designed and launched jointly with JINR, at the Federal Center for Medical Radiology of FMBA of Russia in Dimitrovgrad**

rial proton cyclotron C230 were carried out. The first copy of C235-V3 was assembled, tuned and commissioned at JINR in 2012 [4]. Currently, the C235-V3 has been installed, launched, and has become part of the first medical center with proton therapy in Russia — the Federal High-Tech Center for Medical Radiology of the FMBA of Russia in Dimitrovgrad (Fig. 1) and has started the operation since 2019.

Since 2016, at JINR, in collaboration with the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) in Hefei, China, a small-sized superconducting proton cyclotron SC200 has been developed and is currently being commissioned [5]. The second version of this cyclotron [6] has been designed and will be manufactured specifically for JINR. Our version of SC230 (Fig. 2) can be placed in the wiring room of the phasotron beams and provide proton beam up to 230 MeV for treating cancer patients of the JINR Medico-Technical Complex. This will make it possible to turn off the unreliable and expensive phasotron in the next two to three years, while preserving the long-standing traditions of proton therapy and the staff of highly skilled specialists in this field in Dubna.

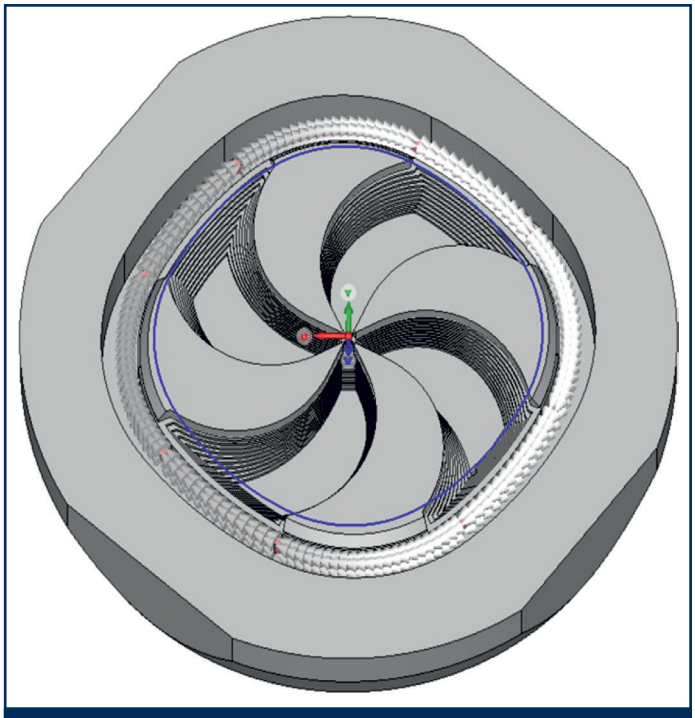

**Fig. 2. Computer model of the SC230 cyclotron**

## Radiobiological studies in the field of radiation medicine

The first radiobiological experiments at JINR using proton beams of the synchrocyclotron were started in 1959. The aim of these works was to establish the relative biological effectiveness (RBE) of high-energy protons. The experiments were conducted on the irradiation of various biological objects: from viruses to various mammals with protons with energies from 25 to 645 MeV. The reactions of various cellular and tissue systems under the influence of acute, fractionated, and chronic proton irradiation were studied [7]. The modifying effect of various types of physical and chemical agents on radiation effects was also investigated.

In experiments conducted on cell cultures and animals with inoculated tumors, the main radiobiological parameters of protons with an energy of 180 MeV were determined, which made it possible to subsequently begin radiation treatment of patients. Radiobiologists studied the biological effectiveness of the proton medical beam in various parts of the Bragg curve, the magnitude of the "oxygen effect", the effect of some radioprotectors.

Later, specialists undertook studies of the biological effect of π mesons on a beam formed on the same DLNP accelerator. Priority data were obtained on the relative biological effectiveness and the "oxygen coefficient" of this type of radiation, which was thought to be effective when used in radiation therapy of tumors. Subsequently, studies were carried out on the biological effect of ultrahigh-energy neutrons with a long-range goal of using this type of particles when irradiating radio resistant large tumor formations.

Later on, LRB specialists developed an efficient approach for targeted radionuclide therapy of melanoma tumors [8]. Methylene blue (MB) possesses a high affinity for melanin and, therefore, accumulates preferentially in melanoma cells. MB serves as a carrier for radioisotopes and, once taken up by melanoma cells, acts as a selectively localized source of radiation. The experiments with $^{131}$I and $^{211}$At bound to MB demonstrated exceptional efficiency in treating melanoma both *in vitro* (cell cultures) and *in vivo* (mice).

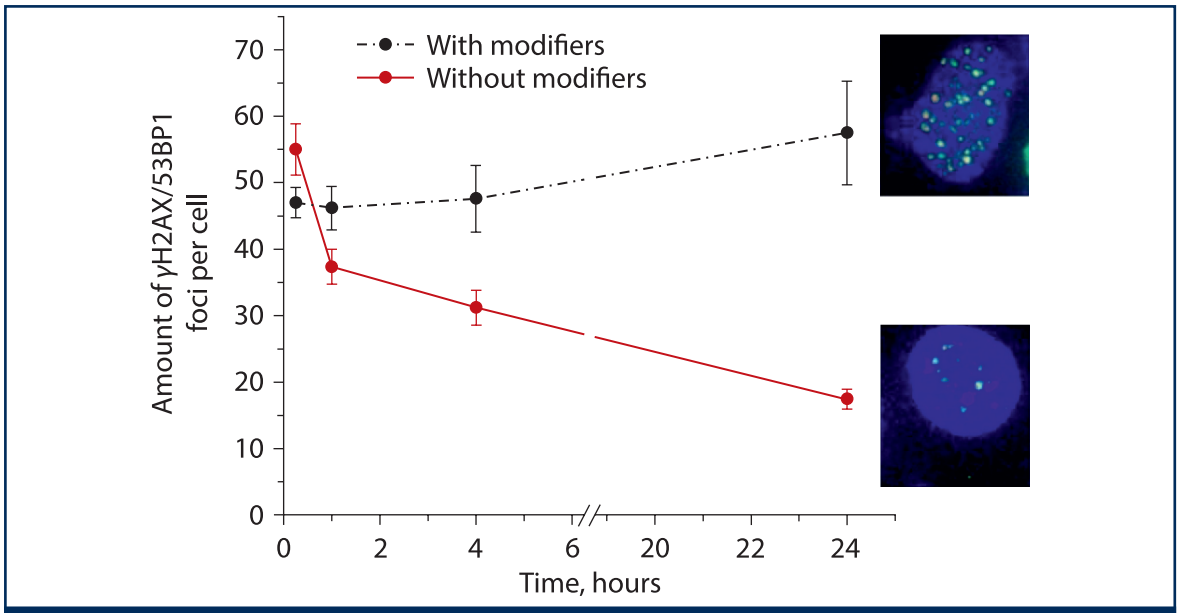


**Fig. 3. Images of radiation induced foci (γH2AX/53BP1 foci) after 24 h and the kinetics of their formation and elimination in glioblastoma cell nuclei after exposure to Bragg peak protons (170 MeV, 1.25 Gy) under normal conditions and in the presence of AraC and HU**

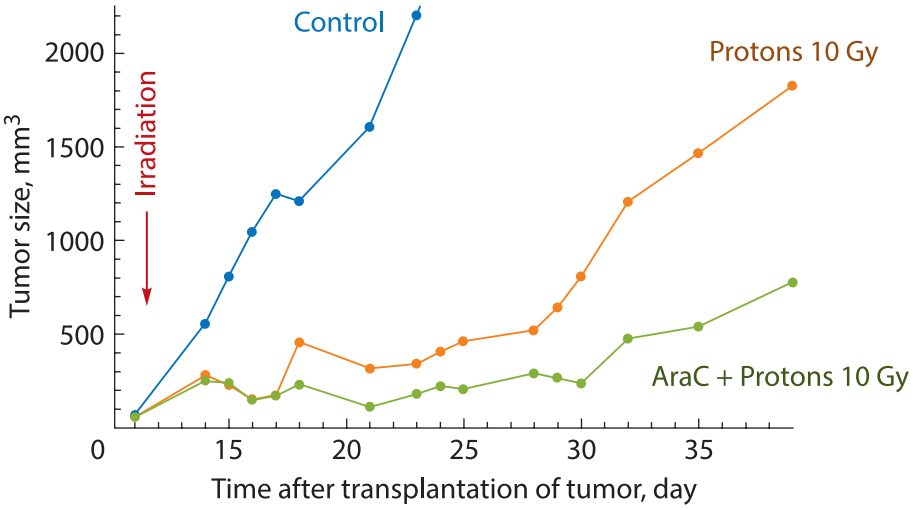


**Fig. 4. Melanoma tumor growth kinetics in mice: non-irradiated control animals (blue); Bragg peak proton irradiation of tumor at a dose of 10 Gy with (green) and without (orange) drug administration in mice**

Currently, the Laboratory of Radiation Biology is conducting studies of proton action at the molecular, cellular, tissue, and organism levels of biological organization. Special attention is paid to the molecular radiobiological aspects of radiation therapy using tumor cell cultures and small laboratory animals [9–12]. LRB's research demonstrated that the cell exposure to γ-rays and particle beams in the presence of DNA synthesis inhibitors cytosine 1-β-D-arabinofuranoside (AraC) and hydroxyurea (HU), which transform non-lethal simple DNA lesions into enzymatic DSB (eDSB), increases the biological effectiveness of radiation. AraC and HU are officinal drugs used clinically for the treatment of different tumors.

The DNA DSB formation by accelerated proton exposure in the presence of modifying agents is increased for up to 24 hours post-irradiation due to the increased eDSB yield, while the minimal yield was observed without modifiers. Experiments were conducted on the radioresistant human glioblastoma cells (U87) irradiated by proton beam in the presence of AraC (Fig. 3). Under the action of accelerated heavy ions, the modifying effect of these agents decreases with increasing LET of particles and disappears at high LET of accelerated ions. A patent has been obtained for the invention of a new method for enhancing the radiation effect on living cells.

This research has been continued on experiments with animals [12]. A group of mice were inoculated with a melanoma tumor. The tumors were exposed to Bragg peak protons with and without drug administration in mice. The control (non-exposed) animals died of tumor development on the 30th day after exposure. On the 40th day, both irradiated groups were alive. The tumor growth rate in the irradiated animals was threefold lower in the group exposed in the presence of AraC (Fig. 4).

***For the successful continuation of research program in the field of radiation medicine, a reliable specialized accelerator complex is required.***

## Project proposal for the establishment of the Proton Therapy Biomedical Research Center in Dubna

Many years of practical experience in treating cancer patients with proton beams, a team of trained specialists in the field of radiation medicine, and the presence of a radiological

department at MSC-9 of the FMBA of Russia create the unique conditions for the continuation and development of hadron therapy at the JINR in the coming years. The treatment of patients with the participation of JINR specialists should naturally be combined with biomedical research.

Recent results obtained on the enhancement of low-LET ionizing radiation's biological effectiveness in the presence of special drugs promise a breakthrough in the effectiveness of using proton beams for the treatment of cancer. For their continuation, a medical center with a modern and reliable proton accelerator is required, which must be certified for the irradiation of cancer patients. The world experience in creating such medical centers shows that treating patients and conducting research on proton beams can be successfully combined using the same accelerator with an additional beamline and spreading the time of patient irradiation and scientific research.

The fastest and cheapest option for creating a compact biomedical proton center could be commercially available accelerator. As an example, one may consider IBA Proteus ONE compact turnkey module, which has passed all the necessary certification in Russia.

Proteus ONE is (Fig. 5):
- Superconducting synchrocyclotron with proton energy 230 MeV
- One treatment room, 220° compact gantry (PBS spot scan)
- The ability to create a specialized proton beam output for biomedical research
- The maximum size of the irradiated field 20 cm × 24 cm
- Required area (Hopper) 32.6 m × 16.1 m (area 524.86 $m^2$)
- Advantage — Compact size, smaller investment
- Number of patients up to 400 per year (this figure will be less when distributing beam time between the medical and scientific programs of the Center)

The commercial cost of creating the Proteus ONE complex, including all equipment, gantry, cabins, a specialized channel for scientific research, construction and installation works, etc., is about 25–30 million Euros. In the case of direct participation of JINR special-

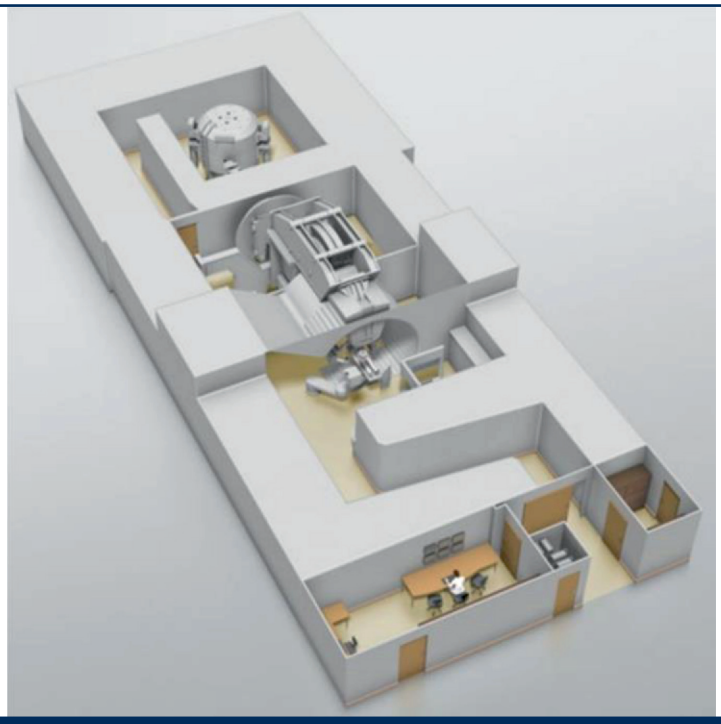

**Fig. 5. General view of the Proteus ONE module**

ists in the assembly, commissioning and launch of the Proteus ONE complex in Dubna, IBA offers special conditions for JINR to significantly reduce costs.

Prerequisites for creating a radiological proton therapy complex in Dubna based on IBA accelerator equipment:

- 50 years of JINR experience in the field of proton therapy;
- the radiological department at MSC-9 of the FMBA of Russia and special relations with the FMBA of Russia;
- a team of trained JINR specialists in the field of nuclear medicine and radiation biology;
- many years of fruitful cooperation between JINR and IBA, the world leader in the field of proton therapy;
- localization of design (if necessary), assembly, commissioning, start-up and maintenance of accelerators for hadron therapy in Dubna;
- a significant reduction in the cost of IBA equipment and the entire project as a whole with the participation of JINR specialists in it.

Currently, patients are irradiated at the phasotron, the oldest JINR accelerator, which is located on the technical site of the JINR DLNP in the immediate vicinity and in the sanitary protection zone of the IBR-2 nuclear reactor. Special safety and security regimes of the site area create significant difficulties for working with patients and interfere with the work of the scientific center. For this reason, the new biomedical center should be moved out of the JINR protected area.

The creation of new biomedical research radiation medical center could become a pilot project to create a series of compact and relatively inexpensive proton therapy centers for leading oncological clinics in Russia.

## Summary

JINR has accumulated half a century of experience in treating cancer patients with proton beams initiated by academicians V. P. Dzhelepov and N. N. Blokhin. For the first time among European countries, proton beams with the necessary physical-dosimetry characteristics for clinical use were formed and their radiobiological characteristics were studied by radiobiologists. Using a wide range of methods, we studied the relative biological effectiveness of accelerated charged particles in different parts of the Bragg curve, the magnitude of the oxygen effect, and other characteristics that have to be studied before the clinical use of proton beams. Under the guidance of radiologists from the Oncological Scientific Center of the Russian Academy of Sciences, and later from other centers, the first successful clinical trials of a new method of irradiation of cancer patients were conducted on the basis of the radiological department MSC-9 of the FMBA of Russia. Up to this date, about 1,500 patients have took treatment courses at the beams of the JINR medical complex. During this period, vast experience has been gained in the clinical use of proton beams, and a school of highly qualified physicists and radiobiologists has been established that continues successful research in this area.

For more than twenty years, the University of Dubna has trained specialists in physics and radiobiologists who have successfully mastered the modern methods used in various fields of dosimetry physics and radiation biology of accelerated charged particles.

Recently, JINR radiobiologists have been developing fundamentally new approaches to increase the biological effectiveness of proton beams, which significantly brings together the field of application of hadron accelerators for therapeutic purposes.

It is planned to use the compact accelerator complex with an additional proton beam channel for biological research as the technical basis of the new medical research center.

A possible option could be commercially available IBA Proteus ONE complex that has all the necessary permits for working with patients in Russia.

In view of the foregoing, the creation of biomedical research center based on the high-tech equipment would be an important step in providing the necessary medical care to cancer patients from the northern part of the Moscow region and other regions of Russia, as well as from the JINR member states.

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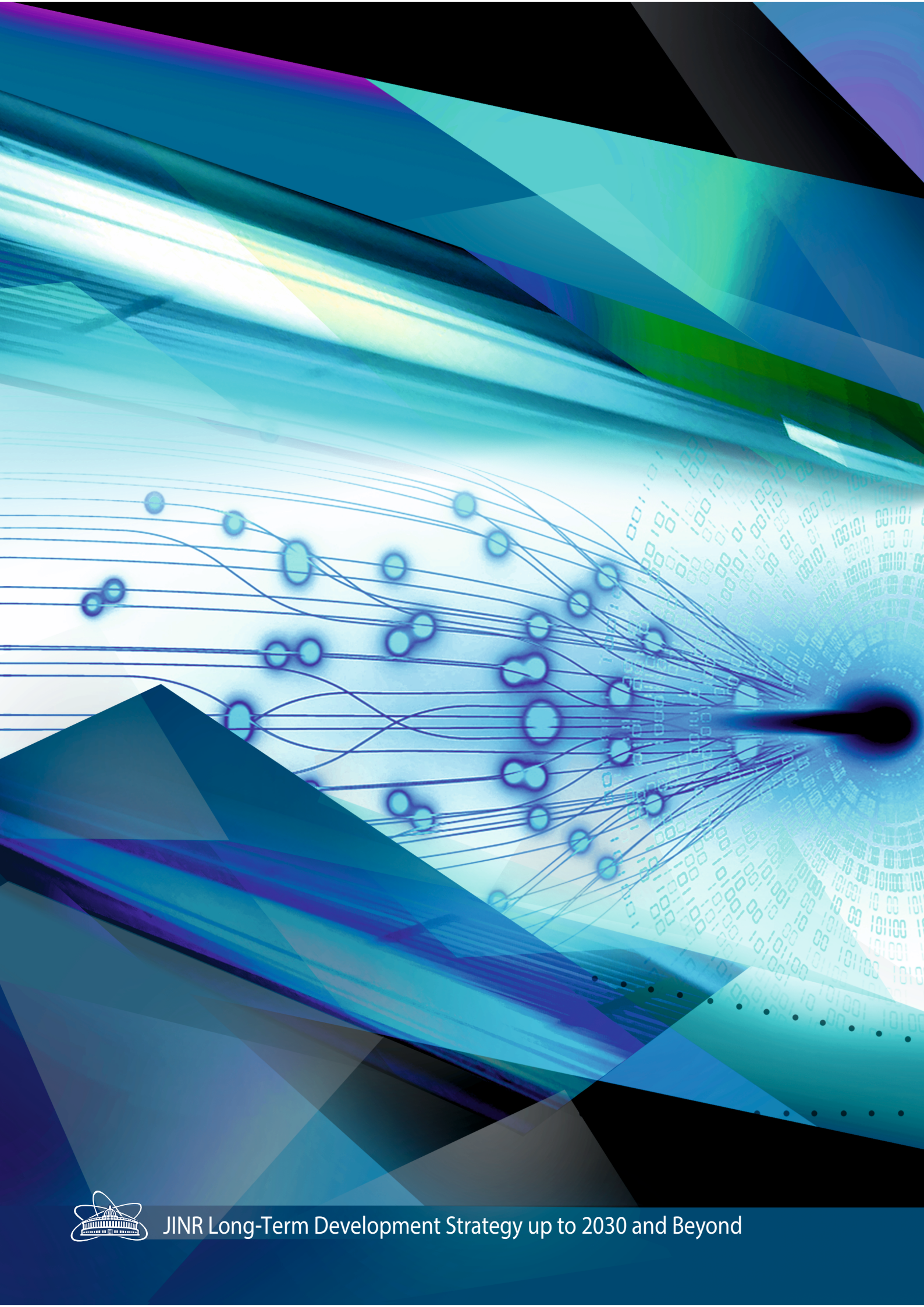


# JINR Long-Term Development Strategy up to 2030 and Beyond

# 10

# Information Technologies

## Executive Summary

The mission of the Laboratory of Information Technology (LIT) is two-fold:

a) to serve the scientists of JINR and its Member States in the pursuit of their research projects by developing *Methods, Algorithms and Software for Modelling Physical Systems, Mathematical Processing and Analysis of Experimental Data*;

b) to assure that the IT infrastructure and IT know-how of JINR experts are always of latest state of the art.

Since JINR and other big science centres depend on the commodity of IT hardware, a long-term view must look for great flexibility in the system. Presently, the JINR Infrastructure has been developed in close connection with CERN and other Institutes of Nuclear and High Energy Physics. During the last 15 years, a distributed computing infrastructure has been created for processing and storing data from the LHC experiments. Each of the four outstanding scientific experimental facilities at the LHC, namely ATLAS, CMS, ALICE and LHCb, is being run by collaborations, each of which has several thousand scientists from several hundred institutes distributed worldwide.

Therefore, a geographically distributed computing environment like grid for processing and storing experimental data of all LHC experiments, i.e. the Worldwide LHC Computing Grid (WLCG), has been created. About 1 000 000 processors are geographically distributed in more than 170 data processing centres from 42 countries. They are combined into a unified computing environment within the WLCG infrastructure, capable of managing hundreds of petabytes of data, providing access to computing resources and data storage systems for the entire community, and integrating national and international structures. JINR is a strong part in this system.

Projecting the development of Information Technologies of the Institute into the future must take into account the latest development of some large experiments, where huge computing power is or will be installed at the front end of the detectors, thus substantially reducing the amount of data transmitted to the distributed computing centres in the world. At the same time, data taking rates in the LHC experiments are steadily increasing, leading to an increase in data volumes.

The original concept of grid as an implementation of the HTC (High Throughput Computing) concept has changed to a complex, heterogeneous computing system combining computing resources of various concepts: HTC, HPC (High Performance Computing), computing resources provided on a voluntary basis (Volunteer computing), commercial and non-commercial cloud computing resources.

Currently, research on the development of novel architectural and functional principles of the WLCG distributed computing infrastructure is carried out by the community of LHC computer specialists [1] and other scientific world centres in the field of high-energy

physics; in 2020, it is planned to complete the preparation of relevant technical projects (Computing TDR). JINR specialists are part of today's community of experts.

It should be noted that the JINR research program for the next decades is aimed at conducting ambiguous and large-scale experiments at the Institute basic facilities and in the framework of worldwide collaborations. This program is connected with the implementation of the NICA megaproject, the construction of new experimental facilities, the JINR neutrino program, the modernization of the LHC experimental facilities (CMS, ATLAS, ALICE), the programs on condensed matter physics and nuclear physics. The implementation of the projects mentioned above requires adequate and commensurable investments in the IT systems providing the processing and storage of increasing data volumes. The experience of recent years shows that the progress in obtaining research results directly depends on the performance and efficiency of computing resources. In this regard, the further development and performance extension of the JINR LIT Multifunctional Information and Computing Complex (MICC) [2,3] as well as the provision of novel IT solutions to the Complex users and the increase in its operation efficiency are the uppermost tasks of the Laboratory of Information Technologies.

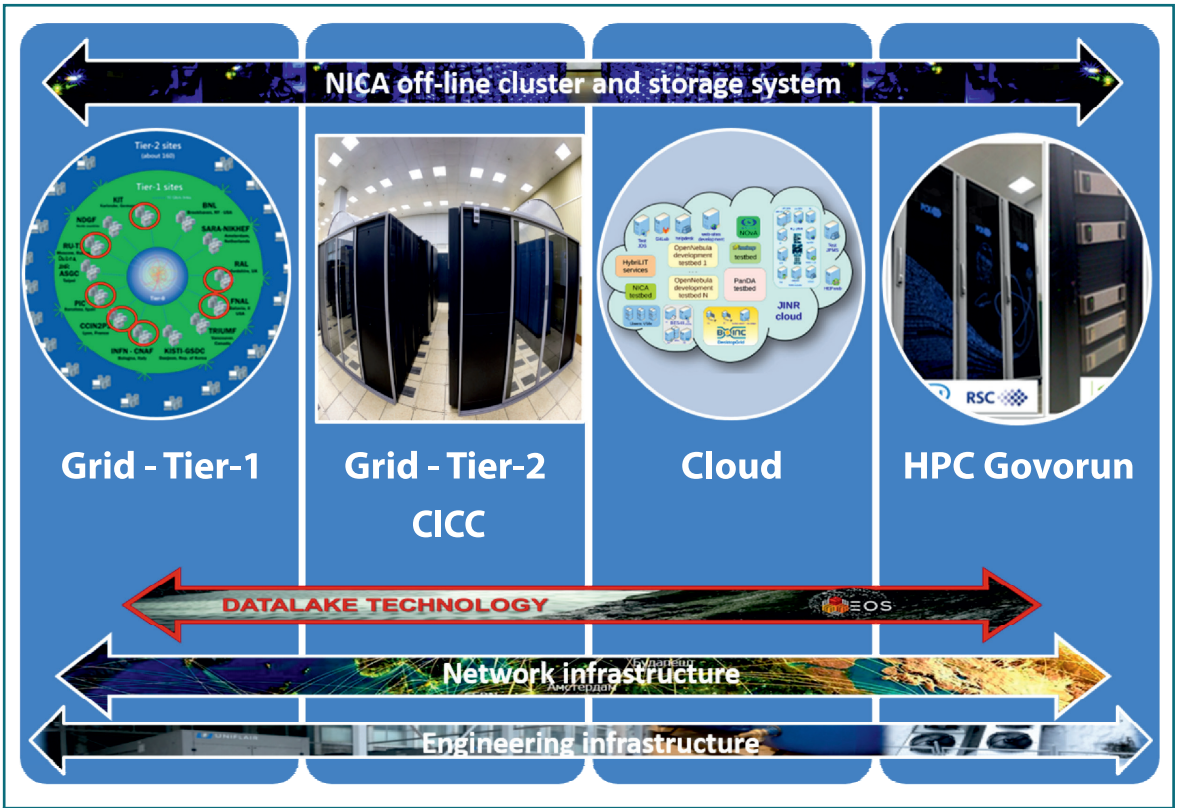
The JINR computing infrastructure consists of numerous computing components and IT technologies to solve JINR tasks, from theoretical studies to experimental data processing, storage and analysis. The JINR MICC is the key element of this infrastructure and plays a defining role in research, which requires modern computing power and data storage systems. They are the IT ecosystem for the NICA project (BM@N, MPD, SPD), Tier1 of the CMS experiment at JINR, Tier2/CICC providing support to the experiments at the LHC (ATLAS, ALICE, CMS), FAIR (CBM, PANDA) and other large-scale experiments as well as support to users of JINR Laboratories and the JINR Member States (MPD/NICA, BESIII, LRB, FLNR, DLNP, BLTP, FLNP); the integrated cloud environment of the JINR Member States [4] for support of JINR users and experiments (NICA, ALICE, BESIII, NOvA, Daya Bay, JUNO, etc.); the HybriLIT platform [5] with the "Govorun" supercomputer as a major resource for high-performance hybrid computing.

In summary, LIT plans to establish an IT ecosystem, i.e. a dynamically growing IT platform, which responds to the rapidly developing IT world. The connection to CERN and FAIR will influence the JINR strategy. Different to most other IT groups in the world, JINR LIT is providing and will provide forefront service to scientists working in JINR collaborations, on- and off-site of Dubna, by continuing developing *'Methods, Algorithms and Software for Modelling Physical Systems, Mathematical Processing and Analysis of Experimental Data'*. Although many of these tasks are being done by individual experts in experiment collaborations, LIT as a base of these experts can guarantee a high level of professionalism strongly needed in Data- and Code-handling.

The LIT manpower development must reflect the fast-changing world of IT by providing attractive positions to both promising young and highly qualified IT specialists.

## Today's computing at JINR

The JINR computing complex has undergone numerous transformations over the years. Today the Multifunctional Information and Computing Complex (MICC) of the Laboratory of Information Technologies (LIT) at JINR is the key element of the computing infrastructure and plays a defining role in research, which requires modern computing power and data storage systems. The MICC is regarded as the JINR basic facility "Networks and ECM", which is a combination of complexes, subsystems and other organizational units, includ-




Structure of the MICC

ing WLCG grid centres of Tier1 and Tier2 levels for data processing and storage; the cloud infrastructure; the HybriLIT platform with the "Govorun" supercomputer, data storage; the data transmission network; the engineering infrastructure; the monitoring system. Today the main goal is the effective operation of all the components and the centre as a whole, which is able to store a diverse set of equipment.

A modern JINR computing complex should meet the following requirements: multi-functionality, high performance, high reliability, fault tolerance and availability, information security, scalability as well as a customized software environment for different user groups. To fulfil these requirements in a 24 x 7 x 365 mode, the MICC needs a constant upgrade and expansion of the complex's possibilities. The rapid development of information technologies does not allow one to fully define specific solutions that will determine the MICC development for the coming years; however, the trends for this upgrade are clear enough.

The experience gained at LIT shows the necessity of taking into account the expected technological evolution in meeting future user needs. Moreover, there is a tendency to more extensive use of specialized equipment to perform complex tasks computationally. The latter means that the deployment of heterogeneous equipment will be required in data processing centres, and experience and skills will be needed to support these resources.

## Network infrastructure at JINR

A high-performance network infrastructure is crucial for the development of IT in the modern world. In the last year, the following projects were carried out at JINR:

- Work related to increasing the bandwidth of the Moscow–JINR telecommunication channel to 3 x 100 Gb/s;
- Installation and configuration of the equipment of the Institute backbone computing network to 2 x 100 Gb/s and the distributed computing cluster network between JINR facilities to 400 Gb/s.

The development of the JINR network infrastructure is dependent on the modernization and increase in the bandwidth of external telecommunication channels, the JINR local area network, the MICC network infrastructure and the NICA megaproject. In the near future, it is planned to develop the communication component of network subsystems of the MICC and the NICA megaproject using the Multisite cluster network technologies at a speed of more than 400 Gb/s to create a network infrastructure for acquiring and transmitting data between the BM@N, MPD, SPD facilities and on/off-line clusters. The given direction presupposes laying new optical network links between LIT and VBLHEP as well as ensuring maximum reliability and fault tolerance of this network.

Increasing the performance of the network segment of the MICC/Tier2 system will allow speeding up access to data stored in the databases of the LHC experiments.

It is noteworthy that the increase in the bandwidth of external and internal telecommunication channels beyond the present plan will be defined by the needs of network-connected facilities, including the needs of the NICA megaproject.

One more important direction is the development of network services supporting the network functioning, namely Network services (NOC Cluster) of e-mail, name management (DNS), data caching (Proxy), resource management (IPDB), authorization (Radius, Tacacs, Kerberos), monitoring (NMIS); Service of Single Sign-On (SSO); Information security system; System of testing of users for the knowledge of the operation rules in the JINR computing network, etc.

## Grid at JINR

The grid centre resources of the JINR MICC are part of the global grid infrastructure WLCG (Worldwide LHC Computing Grid), developed for the LHC experiments. JINR LIT actively participates in the WLCG global project. The work on the use of the grid infrastructure within the WLCG project is carried out in cooperation with such collaborations as CMS, ATLAS, ALICE and major international centres, which operate as Tier1 centres of the CMS experiment (CH-CERN, DE-KIT, ES-PIC, FR-CCIN2P3, IT-INFN-CNAF, US-FNAL-CMS) and as Tier2 grid centres located in more than 170 computing centres of 42 countries worldwide. Since the beginning of 2015, a full-scale WLCG Tier1 site for the CMS experiment at the LHC has been operating in JINR LIT.

The importance of developing, upgrading and expanding the computing performance and data storage systems of the centre is dictated by the research program of the CMS experiment, in which JINR physicists take an active part within the RDMS CMS collaboration. The fact of the creation and support of the work of the JINR Tier1 site demonstrates recognition of the high qualification level of the JINR LIT staff ensuring the functioning of this MICC component. There are only seven similar CMS centres in the world, and the JINR site is regularly ranked second in the number of processed events showing almost 100% level of availability and reliability.

Tier2 at JINR operates within the MICC computing component, which currently provides the majority of JINR users and user groups, as well as users of virtual organizations (VO)




**Experiments that are processed by the MICC within and outside grid**

of the grid environment, with computing power, storage systems and access to data. For supporting a batch processing system, a special server with a cluster resource allocation system and a job scheduler is installed; it allows processing data for all the four experiments at the LHC (ALICE, ATLAS, CMS, LHCb) and supports some virtual organizations working within grid (BESIII, BIOMED, COMPASS, FUSION, MPD, NOvA, STAR, etc.).

In terms of hardware, a linear increase in the characteristics of Tier1, Tier2/CICC is planned.

It is planned to launch Run 3 at the LHC by the summer of 2021. The CMS and ATLAS plans do not require a cardinal increase in computing and storage resources at this stage. ALICE plans to increase its resource needs for Run 3 almost by a factor of two. The fulfilment of the seven-year plan figures will ensure the required level of resources for all the LHC collaborations at Tier1 and Tier2 at JINR.

In the coming years, it is necessary to increase the information storage capacity on the EOS system, which was put into operation at the beginning of 2019. This data storage and access system should become the major system for all MICC components, and later for all JINR computing resources. There are prospects of using EOS for WLCG collaborations.

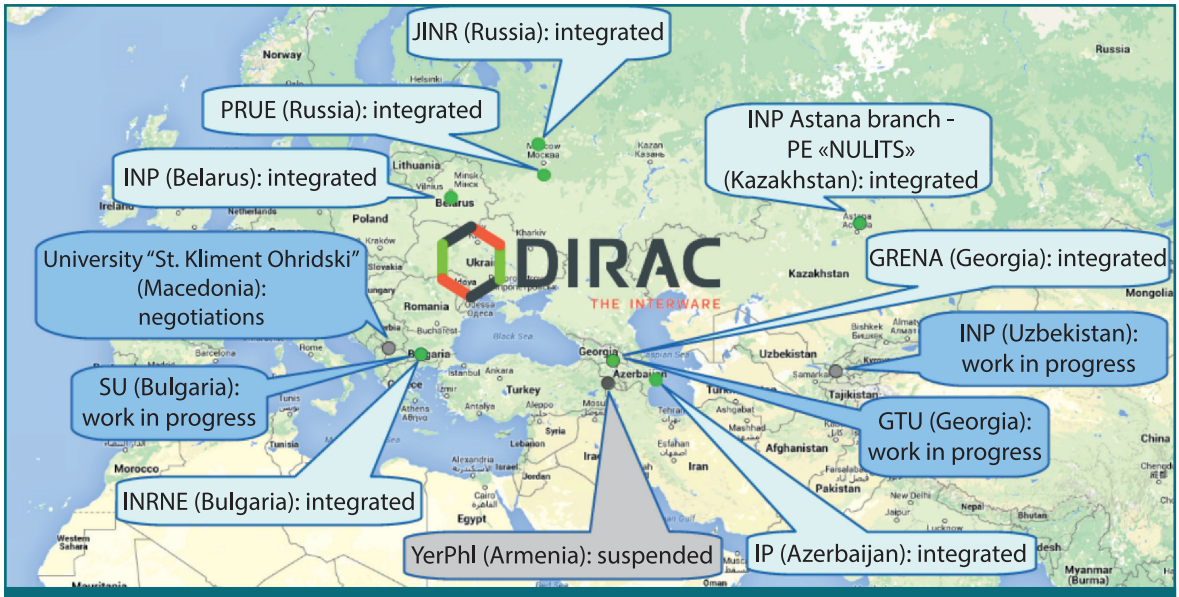
The development of the data storage system on robot tape libraries is required; however, the development of other storage media is to be closely watched. In addition to this facility for the CMS experiment at Tier1, it is required to create a facility for the NICA experiments in 2020–2021, as well as other WLCG collaborations and user groups. The update of the existing tape library to increase its capacity is needed.

## Cloud infrastructure at JINR

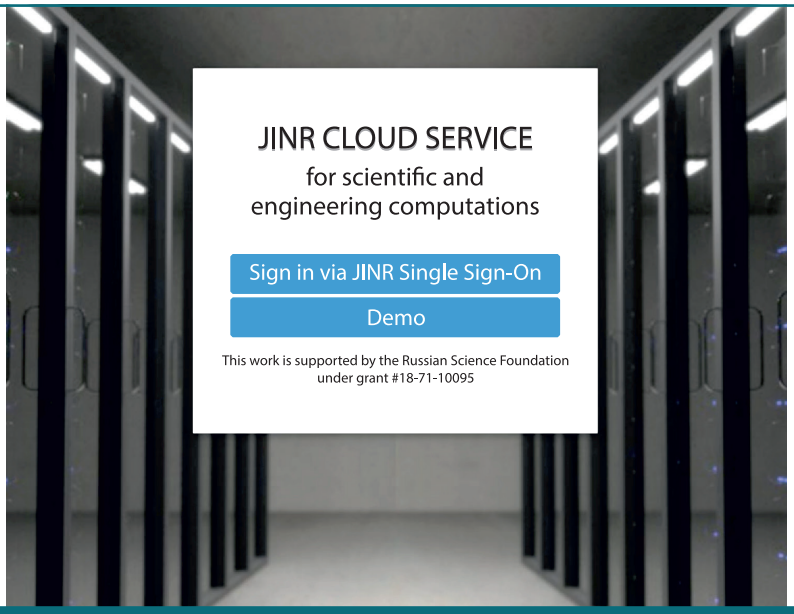
As the resource base of the JINR cloud develops, its computing resources and storage disk space are planned to be provided to individual JINR users, as well as to various scientific projects, for which JINR has certain obligations. A significant increase in the demand for cloud resources is expected from neutrino experiments (NOvA, JUNO, Daya Bay, Baikal-GVD, etc.). The transition of users of the above-mentioned experiments to the use of centralized cloud resources will eliminate the burden for local scientific groups to independently support computing resources and data storages, and they will be able to fully concentrate on their research.

One of the directions of the cloud technology development worldwide is the integration of cloud resources of geographically distant organizations.

The work in a similar direction is also being carried out at JINR LIT together with the organizations from its Member States, such as the Astana branch of the Institute of Nuclear Physics, i.e. the private establishment "Nazarbayev University Library and IT Services" (INP, Astana, Kazakhstan), the Scientific Research Institute for Nuclear Problems of the Belarussian State University (INP, Minsk, Belarus), Yerevan Physical Institute (YerPhI, Yerevan, Armenia), the Institute of Physics of the National Academy of Sciences of Azerbaijan (IP, Baku, Azerbaijan), Plekhanov Russian University of Economics (PRUE, Moscow, Russia), the Institute for Nuclear Research and Nuclear Energy of BAS (INRNE, Sofia, Bulgaria), Sofia University "St. Kliment Ohridski" (SU, Sofia, Bulgaria), Georgian Research and Educational Networking Association (GRENA, Tbilisi, Georgia), Georgian Technical University (GTU, Tbilisi, Georgia), the Institute of Nuclear Physics (INP, Tashkent, Uzbekistan) and the University "St. Kliment Ohridski" (Bitola, Macedonia). The figure shows a map indicating the geographical location of the participating organizations of the Cloud Computing and Information Platform (CCIP). At present, the integration of the JINR Member State organizations' clouds into the DIRAC-based distributed platform is at different stages. Their technical integration has been accomplished, while the work on testing and debugging is in progress.




**Geographical location of the organizations of the JINR Member States involved in the JINR distributed information and computing environment**




**Screenshot of the login page of the cloud service for scientific and engineering calculations**

The work on enabling the use of resources of the given CCIP by users of experiments at the NICA accelerator complex and neutrino programs, in which JINR takes part and which do not have their own distributed infrastructure (for example, Baikal-GVD), is in progress.

With regard to building CCIP, it seems promising to study the possibility of integrating the distributed information and computing environment of JINR and the organizations of its Member States into the EOSC infrastructure with support of scientific services provided by the platform.

## HPC and "Govorun" supercomputer

JINR LIT is closely observing the development of Computing projects in the EU. There are two major trends of the HPC development, i.e. a significant increase in performance up to a post-exaflop scale and the integration of existing supercomputers.

In particular, within the EuroHPC project created in 2018 with the participation of 25 European countries, by the end of 2020 it is planned to equip the European Union with a world-class supercomputer infrastructure, which will be available to users from science, industry, small and medium enterprises and the public sector. It is planned to put into operation two exaflop systems by 2023. The EU has also launched a project in the field of combining supercomputers including grid technologies for creating a supercomputer infrastructure PRACE (Partnership for Advanced Computing in Europe). By 2028, according to the document Update on European HPC from March 2018, which outlines the landscape of the European HPC ecosystem, post-exaflop supercomputers, as well as hybrid HPC+Quantum Computing systems, are expected to emerge. JINR HPC specialists are going to evaluate the experience and best practices of these European projects. LIT is working on a possible cooperation to provide interoperability between the "Govorun" supercomputer and other supercomputer centres.

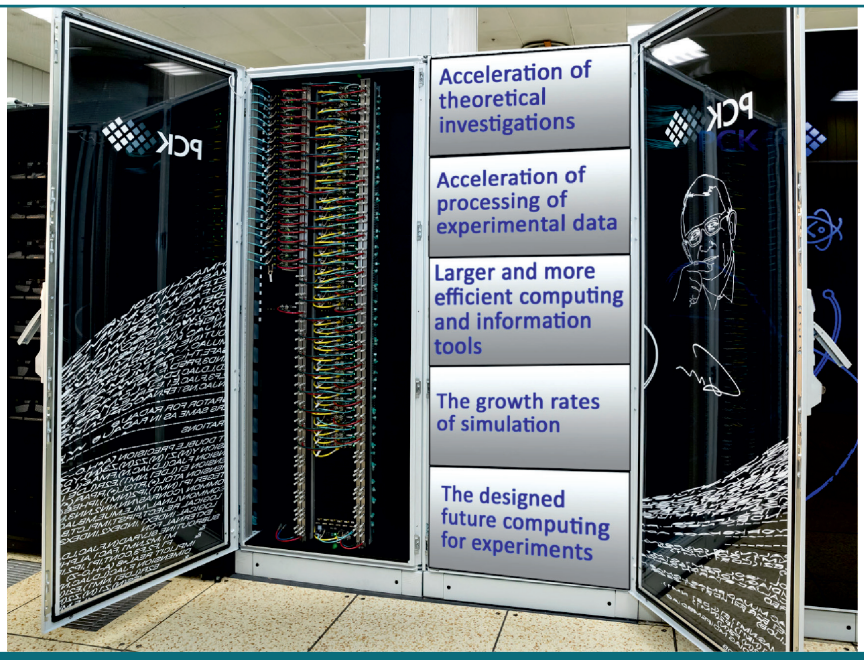
In the USA, there are a number of programs aimed at the development of supercomputer systems including:

- CORAL (Collaboration of Oak Ridge, Argonne, and Livermore), the goal of the program is to build in the USA three supercomputers with a capacity of more than 1 exaFLOPS each. Machines for ALCF and OLCF have already been announced, but they are expected to be commissioned in 2021–2022;
- ASCR (Advanced Scientific Computing Research), a program aimed at the development of computing for research needs of the Department of Energy;
- ECP (Exascale Computing Project), a project for preparing the next generation of supercomputers for the use. It is focused on the development of compatible software.

The major goal of modern experiments on the collision of ultra-relativistic heavy ions, in which JINR participates, is to study the properties of quark-gluon matter at extremely high energy density and/or baryon charge density in the presence of strong electromagnetic fields. The RHIC and LHC experiments study quark-gluon matter at extremely high energy density and almost zero baryon density. In contrast to these experiments, the main purpose of the experimental programs of the accelerator and detector complexes NICA (JINR, Dubna) and FAIR (GSI, Darmstadt) will be to study the properties of quark-gluon matter at high baryon density and relatively moderate energy density.

Theoretical studies in this field of physics are aimed at substantiating physical programs of the given experimental projects. They are complex and related to resource-intensive extra-massively parallel calculations. These theoretical studies are based on computing of different observables via several methods, e.g.:

- quantum chromodynamics on a lattice (LQCD);
- quantum field continuum approaches to the study of critical phenomena based on the functional renormalization group (FRG) and Dyson–Schwinger (DSE), Bethe–Saltpeter (BS) and Faddeev equations;
- modelling of the dynamics of heavy ion collisions (statistical, hydrodynamic and hybrid models);
- calculations in quantum field models of quantum chromodynamics vacuum;
- and others.




**"Govorun" supercomputer**

An important feature of modern lattice computing in LQCD is the necessity to model dynamic quarks, the contribution of which is taken into account using the fermion determinant. The lattice calculation with the fermion determinant is the most resource-intensive operation in modelling. In modern computing this operation is performed on NVIDIA GPU graphics cards using the CUDA technology.

To support the development of the JINR BLTP project "Theory of hadron matter under extreme conditions", especially for lattice calculations, numerical modelling of the collision dynamics and computations within modern functional approaches, the "Govorun" supercomputer has been created at JINR LIT; it has a module structure including nodes with graphics accelerators NVIDIA V100, multi-core processors Intel Skylake and Intel Xeon Phi, which allowed starting such computing at JINR.

It is very important to ensure a high data exchange rate between computing units and a large amount of disk space for data storage, which is crucial for, e.g., lattice calculations. Thus, the scalable "Govorun" supercomputer included in the MICC meets all requirements for modern high-performance (HPC) systems by its technical characteristics, which allowed significantly speeding up theoretical studies and brought JINR computing capabilities in this field of research to a competitive level.

Planned future studies require more numerous or massive computing resources, i.e. multi-GPU architectures and resources with many thousands of graphics processors or novel multi-core CPU architectures.

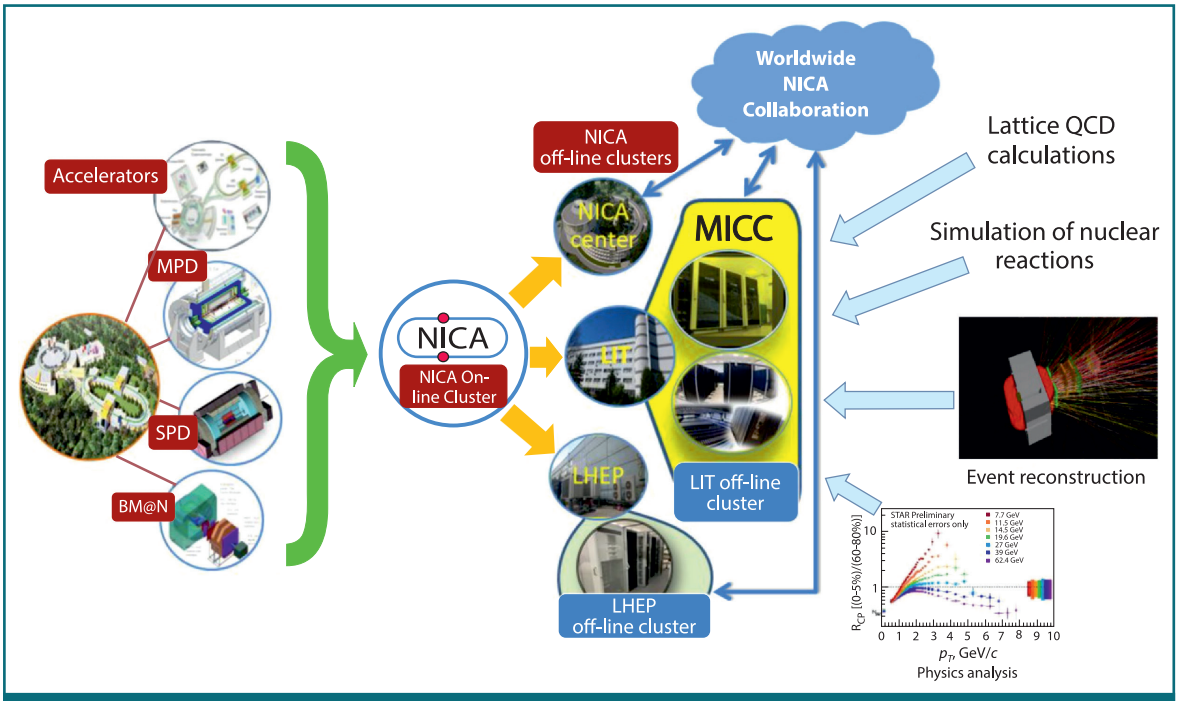
At the same time, it is necessary to ensure proper **support for the software development**: new software will be needed to fully use novel hardware architectures; moreover, most of them will have more complicated memory hierarchy. In addition, significant progress can be achieved with the development of novel and optimized algorithms.

## "Govorun" supercomputer and NICA

Besides carrying out massively parallel calculations, it is planned to use the "Govorun" supercomputer for modelling an entire system of computing for all experiments of the NICA complex.

The implementation of various computing models of the NICA megaproject requires confirmation of the models' performance, i.e. meeting the requirements for temporal characteristics of data acquisition from detectors with their subsequent transfer to processing, analysis and storage, as well as the requirements for the effectiveness of modelling and processing of events in the experiment. System tests in a real software and hardware environment must contain all the required components. At the moment, the "Govorun" supercomputer is such an environment. It contains the latest computing resources.

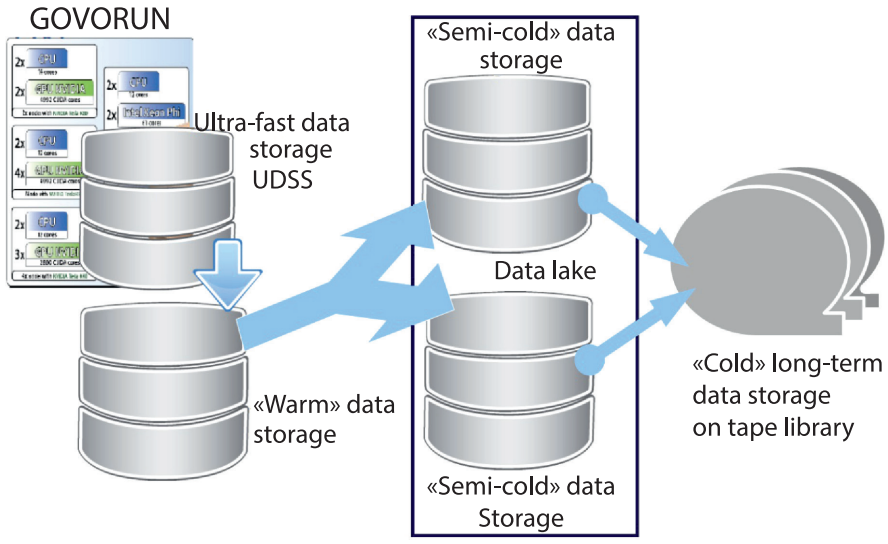
However, to perform a full cycle of testing, e.g., the MPD-computing framework, including the acquisition and processing of all data of the MPD detector, as well as of the simulated data from theories into the computing environment, the supercomputer should be supplemented with an ultra-fast data storage system (UDSS) that ensures a high data acquisition speed. Such a solution is proposed to be implemented on the basis of novel products Intel 3DNAND and Intel Optane. The proposed UDSS will allow saving and processing experimental data with a speed of hundreds of gigabytes per second for volumes of 0.5–5 PB, with the possibility of the linear extension of performance and capacity of the system up to 1000 times.




**NICA computing concept and challenges**

It is noteworthy that UDSS has the potential for linearly upgraded productivity (speed of working with data) and for increasing the storage volume without changing the principles of the architectural design of the system. At the same time, the hyper-convergence and software-defined architecture of UDSS allows a maximum of flexibility in data storage system configurations.

At present, the "Govorun" supercomputer is used for experiment simulations, i.e. the Skylake and KNL components for generating data of events from the MPD detector and saving them on UDSS with a subsequent transfer to semi-cold storages managed by the EOS and ZFS file systems. The DIRAC software is used to manage jobs and the process of




**Scheme of using UDSS implemented in the "Govorun" supercomputer**

Reading out and Writing data from different types of storages and cold long-term data storage on the tape library.

This approach will allow one to check a basic stack of data storage and transmission technologies, as well as to simulate data flows, choose optimal distributed file systems and increase the efficiency of event modelling and processing.

## Data storage systems

Novel computing and network technologies such as distributed cloud systems and the availability of broadband software-defined networks open up new possibilities for international cooperation; however, they require the further development of computing models. Recently, the trend of using and working with data storage systems has shifted from a simple approach separating organization, management, access and its hierarchy to the DOMA (Data Organization, Management and Access) model, a more flexible system combining all aspects.

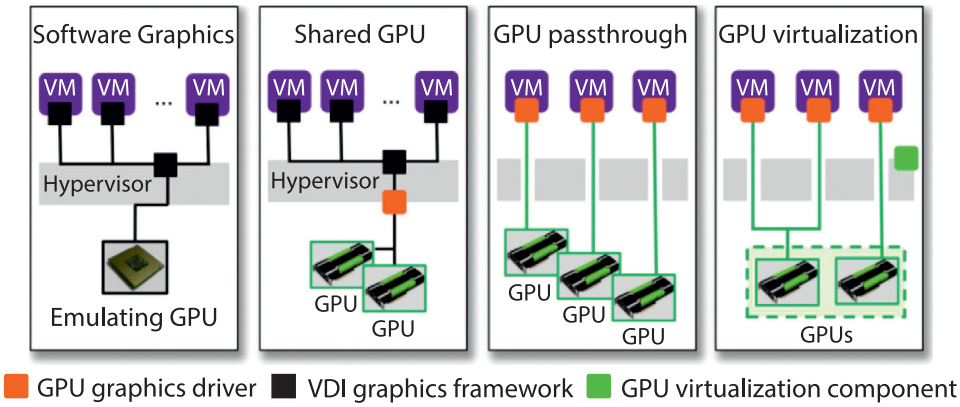
The aspects of storage and access to data can be divided into the following main categories:

- data storage volumes;
- access speed of read-out and writing;
- reliability of data storage;
- security issues while accessing and defining the authority of access to data by different users and user groups;
- organization of storage, update and access to unified software for users and user groups.

At present, for storing data of local experiments, users and collaborations, in which JINR has obligations, LIT uses about 10 petabytes on disks and 11 petabytes on a tape robot. In the next three years it is necessary to increase volumes of storing such data up to 80 petabytes on disks and 80 petabytes on tape robots. So far, requests for such volumes are foreseen from 3 major sources of data acquisition: the LHC experiments (ALICE, ATLAS, CMS), the NICA experiments (B@MN, MPD, SPD) and neutrino experiments. In 5 years, due to the upgrade of the LHC to the HL-LHC, the launch of NICA at full luminosity and the development of cooperation with other collaborations worldwide, necessary data storage volumes will increase by an order of magnitude from the today's level.

## Software at JINR

To effectively use modern computing equipment, parallel programming is necessary. Required software skills exceed those that can currently be assumed from an average physicist. This situation requires increased efforts in the field of personnel training on modern programming technologies, as well as the development of appropriate data processing systems by experts. In recent years, the successful experience in working with software packages within the framework of FairROOT developed by GSI has been gained. This new structure with an open source code will be the basis for developing software for specific experiments in the next decade. The given structure allows experiments to fully use the capabilities of modern computing systems and reduces the cost of development and maintenance. The transition from single-core to multi-core architectures with wide vector processing units, accelerator cards such as graphics processors, the availability of commercial high-speed networks, as well as multi-level memory and storage solutions,

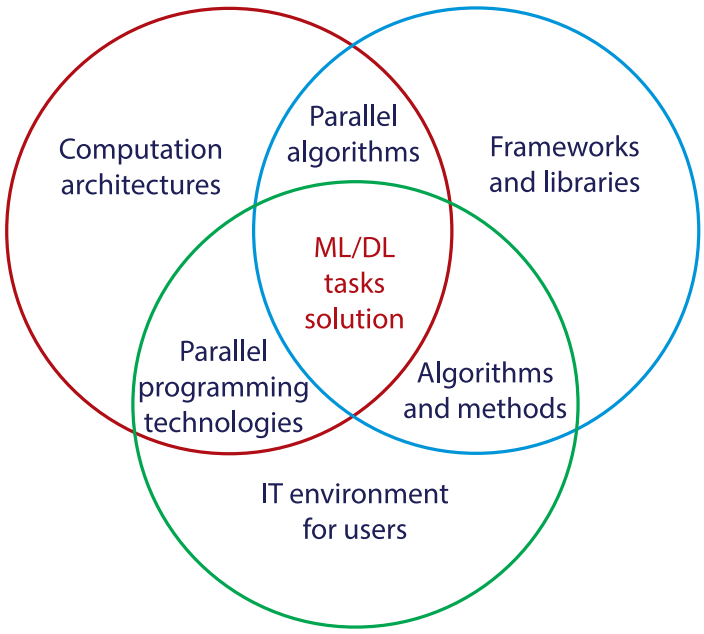



**Schematic representation of implementations of VMs with a remote access function, with support of the central processor and the graphics accelerator**

have changed the way of the implementation of algorithms. Skilled software experts need to be trained in this area, be it at the commercial hardware provider or be it at LIT.

At JINR, the software and information environment of the HybriLIT heterogeneous platform contains the HLIT-VDI service, which is designed to work with applied software using advanced graphics interfaces. This service allows one to work with such application packages as Wolfram Mathematica, Maple, Matlab, GEANT4, etc. through remote access to virtual machines, which ensures performing small computing inside VMs, as well as resource-intensive calculations on the computing nodes of the "Govorun" supercomputer.

The active implementation of the neural network approach, methods and algorithms of Machine Learning and Deep Learning (ML/DL) for solving a wide range of problems is defined by many factors. The development of computing architectures, especially while using DL methods for training convolutional neural networks, the development of libraries, in which various algorithms are implemented, and frameworks, which allow building




**Venn diagram on the implementation of the neural network approach, methods and algorithms of ML/DL to solve applied tasks**

different models of neural networks (see the Venn diagram shown below), can be referred to as key points. To provide all the possibilities both for developing mathematical models and algorithms and for carrying out resource-intensive computations including graphics accelerators, which significantly reduce the calculation time, an ecosystem for tasks of ML/DL and data analysis has been created and is actively being developed for HybriLIT platform users.

The created ecosystem has two components:
- the computing component aimed at carrying out resource-intensive, massively parallel tasks of neural network training using NVIDIA graphics accelerators;
- the component for the development of models and algorithms on the JupyterHub basis, i.e. a multi-user platform for working with Jupyter Notebook (known as IPython with the possibility to work in a web browser), including several libraries and frameworks.

## Infrastructure

The engineering infrastructure of computing centres must ensure the reliable, uninterrupted and fault-tolerant operation of the information and computing system and the network infrastructure.

Another integral feature of the engineering infrastructure is its scalability, the possibility of reacting to computing equipment growth prospects for the coming 3–5 years.

Modern and future computing complexes are characterized by high performance combined with low power consumption. An example is the "Govorun" supercomputer, which is a hyper-convergent calculator built on 100% liquid cooling in a "hot water" mode and has an energy efficiency of less than 1.06.

## Big Data at JINR

Big Data are often defined as datasets that exceed traditional storage and processing systems in volume, speed and diversity.

In the modern world, such amount of data is produced everywhere. The contribution of Science to the data growth increases all the time. Thus, in the course of the Large Hadron Collider (LHC) operation at CERN, particle collisions are detected by millions of sensors generating huge amounts of data. The total amount of information produced by four experimental facilities at the LHC is about 20 PB per year, the amount of accumulated data is currently about 200 PB, which is comparable and sometimes even exceeds the data accumulated in storages of traditional generators and Big Data providers such as, for example, Facebook, whose photo and video storage amount is at least 100 PB. It is noteworthy that the data flow after the LHC upgrade to *High Luminosity LHC* will grow by more than an order of magnitude.

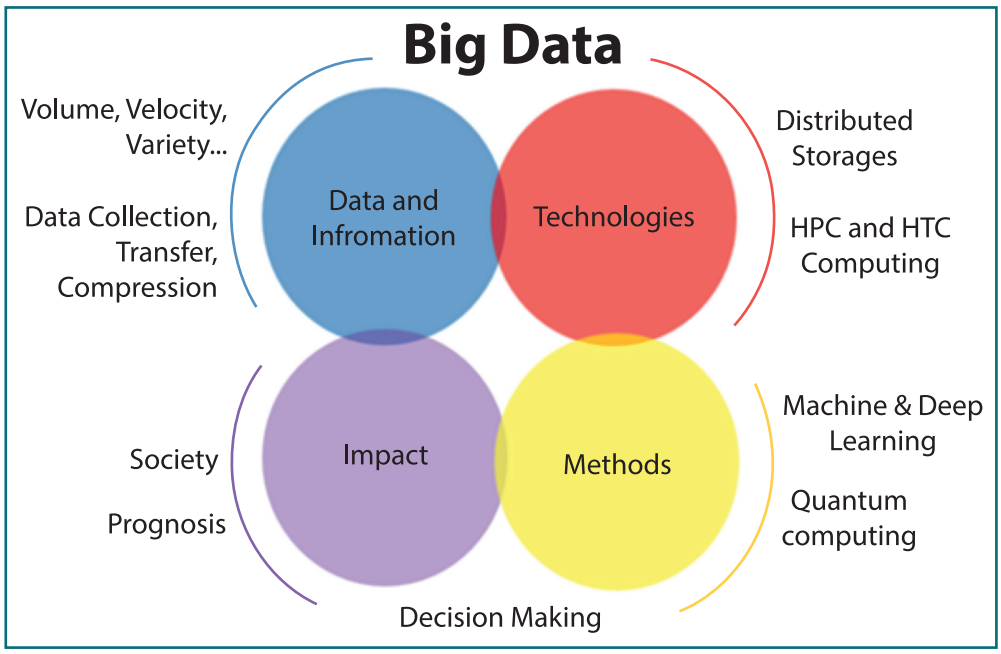
Big Data are not only data themselves, but also processing technologies and usage scenarios, which can be divided into several main categories:
- new algorithms suitable for providing search in huge data sets and their processing;
- new data management technologies that allow working with complex, heterogeneous and distributed data sources;
- high-performance computing systems;
- architectures and algorithms that allow processing stream data coming from high-speed networks, instruments and sensors;

- high-performance and highly reliable distributed file systems capable of working with petabyte range data;
- a set of techniques to integrate heterogeneous data from different sources, i.e. data fusion and integration.

It should be underlined that methods, algorithms and technologies forming a group of notions "Artificial Intelligence" (AI) are an integral part of Big Data, an important component of the ecosystem. At present, "Artificial Intelligence" presented by methods, technologies and Machine Learning (ML) systems based on so-called Deep Learning (DL) neural networks is very rapidly and successfully developing, being at the peak of interest not only in IT itself, but also in economics, industry, other applied fields, and in the general public.

In more recent decades, science experiments such as at CERN have produced data on similar scales to current commercial "big data". However, due to differences in data structures and required precision, scientists have tended to analyse their data using specialized custom-built high-performance computing (supercomputing) clusters and grids, rather than clouds of cheap commodity computers as in the current commercial wave, implying a difference in both culture and technology stack (https://en.wikipedia.org/wiki/Big_data).

An important trend in the development of Big Data is the transition from descriptive and diagnostic analytics (that is, mainly from establishing cause-and-effect relationships) through predictive analytics (what will happen in the future if certain actions are taken) to prescriptive analytics (choosing alternative actions based on an assessment of likely outcomes) and further to cognitive analytics. Cognitive analytics presupposes modelling and forecasting results using machine-learning methods that allow one to extract new knowledge from mixed data. The application of Big Data technologies together with "data lakes" and supercomputer technologies provides new opportunities for the development of large-scale mega science research projects (such as the MPD, SPD and BM@N experiments at the NICA accelerator complex and a group of experiments of the JINR Neutrino Program). Within the JINR information and computing infrastructure, the creation of a software and analytical platform for solving a wide range of actual problems of physical analysis and modelling, as well as a number of operational issues of distributed



computing systems, will allow solving certain types of tasks at various stages of conducting a physical experiment on a new level — from modelling of a facility and its various systems to the reconstruction of events, physical analysis, monitoring of the functioning of detectors, the prediction of possible nonstandard situations, etc.

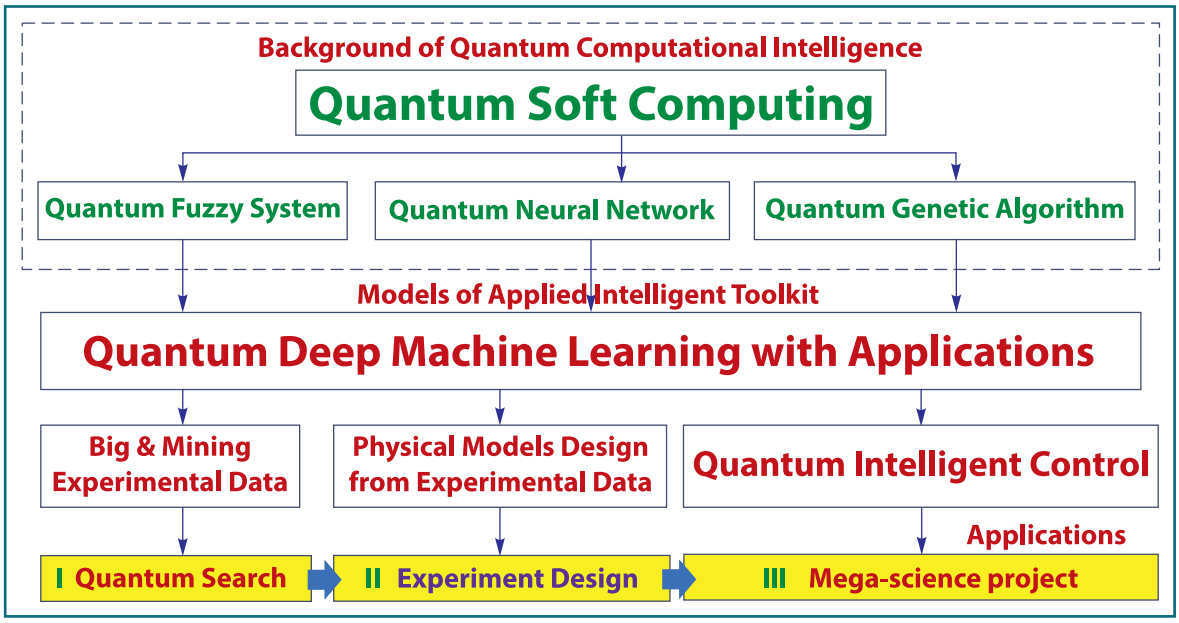
## Quantum computing

Other promising directions of modern information technologies are quantum computing and quantum computer science [6].

Quantum applications are the following:

- Quantum decision making and quantum search algorithms in intelligent control and unstructured large DB (Big Data information processing);
- Quantum intelligent control in mega-science projects;
- Intelligent cognitive robotics;
- Quantum soft computational intelligence toolkit.

Quantum computing, which has been rapidly developing in recent years, could offer new possibilities for processing big data from the LHC. Improving the reliability of the system, reducing the time of preparation and adjustment of the experimental mode is possible due to the involvement of end-to-end quantum information technologies of intelligent control and increasing the level of intelligence of the subsystems of the accelerator complex.



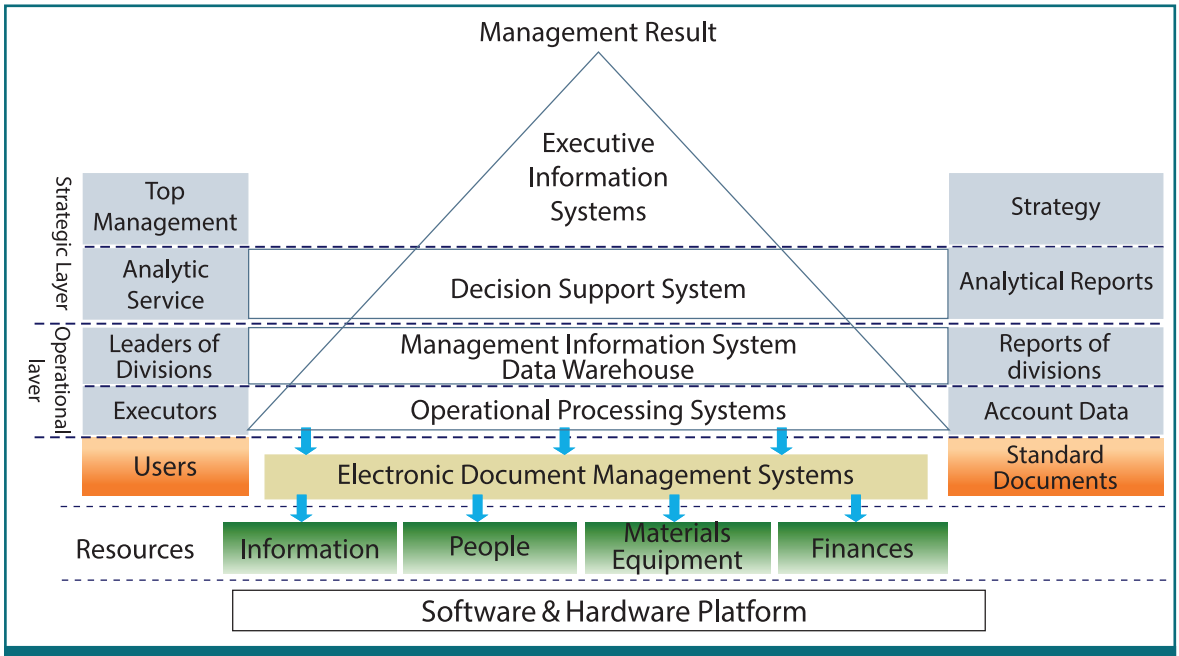

The growth rate of the number of qubits, which characterizes the maximum possible amount of input data for a quantum computer, is clearly higher than the linear one, which shows the accelerated progress in creating the equipment for quantum computers.

The JINR IT will actively observe this development in close collaboration with the CERN IT Division.

## Information system at JINR

Information technologies can help to solve the task of complex automation of all activities of an organization. In the modern world, e.g., a Corporate Information System (CIS) is an essential tool for organizing business in any sphere of human activities, as it allows automating business processes of financial, personnel and material management, providing a holistic picture of organization activities and helping to make management decisions. The objective of CIS is the effective management of all resources of the organization (material, technical, financial, technological, informational, human, intellectual) for the successful accomplishment of the mission (for scientific organizations it is achieving scientific results, meeting the information needs of the scientific community). Currently there are no standards nor a clear definition of the notion of a corporate information system.

Structurally, CIS is presented in the form of a two-level management pyramid: the lower layer is operational, the upper layer is strategic. At the entrance, CIS receives information from bottom-up about main resources (financial, material, personnel, informational), which must be managed, and the output is the result of main activities of the organization. As it moves up along the pyramid, primary information is structured, convolved and filtered. Thus, for senior management, reports reflecting the indicators needed for elaborating strategic decisions on management and development are generated and submitted top-down.




**Structure of the corporate information system**

Different information systems, covering such areas as financial management, accounting and taxation, personnel and salary accounting, scientific information systems and publication archives, project management, service centre, business analytics, materials and equipment management, operate at JINR:

- 1C information platform;
- JINR video portal;

- JINR Document Server, i.e. an Open Access (OA) repository of articles, preprints and other documents reflecting and contributing to research activities underway at JINR;
- platform for organizing and supporting scientific events;
- personal information system (PIN);
- monitoring and accounting systems;
- tool for planning activities for the NICA experiment;
- project management system;
- Information system of technical support Help Desk.

The CIS component, referred to as CRIS & OAR, which includes the Current Research Information System (CRIS) and the Open Access Repository (OAR), is highly important for a scientific organization.

The aggregation of institutional information systems, namely personnel, project, fund and other management systems, is necessary for the exchange and effective data reuse. This task cannot be solved only at the system level. A person is required to continuously manage all resources: personalities (personnel manager), projects (research project manager), finances (financial director), materials and equipment (facility manager), bibliographic information (bibliography specialist, librarian, content manager, identification manager). The key mechanism of the aggregation is the Authority Control subsystem, which provides communication and control of objects of authoritative records with resources of the corporate system.

## Personnel training at JINR

To implement the strategy for the development of IT technologies at JINR, it is necessary to systematically train and retrain specialists in modern information technologies, based on all the existing and future components of the MICC. At present, the education and testing polygon of the HybriLIT platform is used for training students, post-graduate students and young scientists in:

- parallel programming technologies to develop programs allowing one to perform calculations on hybrid computing architectures;
- modern tools for development, debugging and profiling of parallel applications;
- tools and frameworks for solving problems of machine and deep learning;
- data analysis, as well as in the usage of specialized software packages for solving problems that require massively parallel calculations in physics, biophysics, etc;
- special attention will be given to the directions of IT specialists' training for solving JINR tasks related to data processing and analysis for experiments of mega science projects including the NICA project and the neutrino program.

The following training courses are planned:

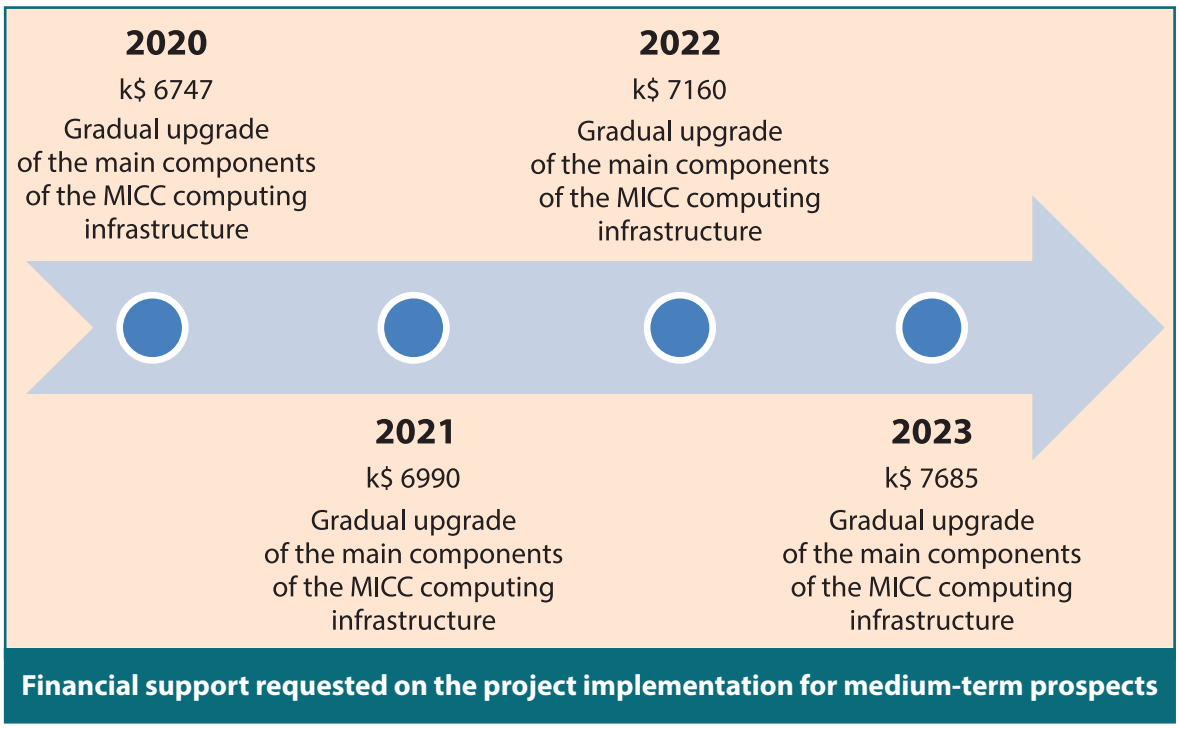
- regular courses on modern IT technologies both for the Institute staff and for students and young scientists from the JINR Member States within the practices organized by the UC (JINR University Centre);
- special courses from leading software developers;
- special courses and seminars within conferences and schools organized by JINR;
- special courses organized in the JINR Member States within international cooperation programs.

One of the key points for keeping excellent staff at LIT and JINR is to offer conditions competitive with the industrial world. Since so many JINR scientists and projects are de-

pendent on the support of LIT, not only a special salary structure, but also an atmosphere where creative individuals can develop their ideas with full responsibility, must be provided.

## Objectives on medium-term prospects (3–4 years)

- Development and improvement of the JINR telecommunication and network infrastructure.
- Stage-by-stage modernization of the JINR MICC engineering infrastructure.
- Modernization and development of the IT infrastructure of the NICA project.
- Extension of the performance and capacity of storage systems of the Tier1 data processing centre for the CMS experiment. Modernization and development of the resources being part of the Tier-2/CICC integral component which provides support for the experiments using the grid environment and cooperating with physical groups in JINR, as well as for non-grid JINR users and its Member States (MPD/NICA, BESIII, LRB, FLNR, DLNP, BLTP, FLNP). Extension of the cloud component in order to enlarge a range of services provided to users, as well as to create an integrated cloud environment for experiments of JINR (NICA, ALICE, BESIII, NOvA, Daya Bay, JUNO, etc.) and its Member States using the containerization technology.
- Enlargement of the HybriLIT heterogeneous platform with the "Govorun" supercomputer.
- Significant extension of the resources of the MICC components to meet the requirements of neutrino experiments.
- Development of a unified system for computing resource management aimed at Big Data processing and of a unified data management system for all MICC components (JINR data lake).
- Development of the concept and stage-by-stage implementation of a scalable software and analytical platform within the Big Data approach for acquiring, storing, processing and analysing, finding relevant information and visualizing results for the experiments at the NICA accelerator complex and a group of experiments within the JINR Neutrino Program.
- Development of methods and software for the effective application of Big Data analytics for resource-intensive calculations on coprocessors and graphics processors for modelling, reconstructing and processing experimental data (at the NICA accelerator complex, within the JINR neutrino program, the experiments at the LHC).
- Development of techniques for the reconstruction of events and intelligent monitoring of detectors using methods and technologies of Big Data and machine learning, novel mathematical methods such as DQC (Dynamic Quantum Clustering), Complex Networks, etc.
- Use of technologies of machine learning and artificial intelligence to optimize the functioning of distributed computing of physical experiments and intelligent monitoring of distributed computing systems.
- The educational program "Data Science" within the "International IT School on Big Data" organized by JINR is highly important for the training of specialists for JINR, including for solving computing problems. It includes lectures and tutorials on methods and technologies for processing and analysing Big Data, distributed computing and machine learning in the framework of both university programs and international schools for students, young scientists and specialists.




## Budget

Given the previous experience of the development of the MICC components, the financial support requested on the project implementation for medium-term prospects (4 years) comprises about 30 000 kUSD. The financial support for an additional expansion of data storage systems for the neutrino program and the NICA project will be provided within the budget of specific experiments.

## Long-term concept of a scientific IT ecosystem at JINR

Based on the above, a concept for the development of IT technologies and scientific computing is being formulated as a scientific IT ecosystem, combining a great number of various technological solutions, concepts and principles.

The creation of this scientific IT ecosystem will enable one to significantly reduce the time spent on the implementation of JINR experimental projects that require theoretical, applied calculations during the project stage, the work on constructing computing models for experiments, the solution of problems related to data processing and analysis, as well as the creation of an information environment for managing all project components. Thus, the overall work efficiency could be improved at JINR.

For developing this IT ecosystem, information and communication support based on the latest technological network solutions is needed for providing a higher bandwidth and reliability of the network operation. The continually developed network infrastructure will respond to the increasing needs for effective and fast processing and storage of data, obtained from both the LHC and future experimental projects where JINR scientists are involved.

Another key basis of the scientific IT ecosystem is a distributed software-configured HPC platform combining supercomputer (heterogeneous), grid and cloud technologies. This

allows one to optimally solve various scientific and applied problems requiring both massively parallel computing and the use of Big Data methods and technologies. The proposed platform will enable one to use or switch to novel computing architectures in the most effective way.

In addition, within the scientific IT ecosystem, a task will be solving the problem of managing team robotic devices based on artificial intelligence methods. The development of this direction requires the involvement of the latest computing architectures, fundamental aspects of artificial intelligence for robotics, including learning how to learn, combining advanced pattern recognition and model-based reasoning. Some promising direction in robotic technologies is the creation of so-called "robot swarms". Robot swarms allow simpler, less expensive, modular robotic units to be reconfigured into a team depending on the task at hand, while being as effective as a larger, task-specific, monolithic robot, which may be more expensive and have to be rebuilt depending on the task. The robot swarm can be used at macro-, micro-, and nanoscales with a plethora of application areas. The creation of centralized, distributed and decentralized manage systems of the robotic team or robot swarms will allow servicing experimental installations in places that are not accessible to humans, including installations of the mega science class such as NICA.

The development of the scientific IT ecosystem depends on novel technologies for data acquisition and analysis, as well as for data sharing. This system must be open to new computing methods such as quantum, cognitive calculations, machine learning methods and data mining, as well as to any developments of new algorithmic bases.

The IT ecosystem will be a basic platform for training IT specialists, capable of developing algorithmic and software solutions in all fields needed at JINR.

In summary, the following topics are of strategic importance for the long-term JINR IT ecosystem:

**Telecommunication technologies:**
- Networks with terabit data transmission rates;
- Networks based on new principles of the organization including cognitive, hybrid, adaptive, reconfigurable and heterogeneous (on-demand networks, networks of networks, software-configured networks, etc.);
- Network systems with a guaranteed dynamic resource allocation;
- Research systems of a new generation allowing to transfer a large amount of data;
- Networks allowing performing distributed processing of exabyte data volumes.

**Computing systems:**
- Distributed software-configured HPC platform combining supercomputer (heterogeneous), grid and cloud technologies in order to effectively use novel computing architectures.

**Algorithms and software for:**
- Distributed solution of individual classes of complex computing problems;
- Machine learning;
- Formalization and extraction of knowledge from poorly structured and unstructured data;
- Computing based on quantum formalism;

software – algorithmic robot control platform based on artificial intelligence methods.

**Technologies of data processing and analysis:**

- Services for distributed and parallel computing (meta-computing) for increasing the research efficiency through the use of supercomputers;
- Development of scalable algorithms and software for processing multi-parameter, multi-dimensional, hierarchical and multi-series data sets of an exabyte volume;
- Analytics systems of a new generation based on effective methods and algorithms for formalizing and extracting knowledge and Big Data processing;
- Predictive modelling of computer models of mega-experiments and functioning of perspective systems.

**Information security:**

- Protection of computer infrastructure systems based on fundamentally new paradigms including quantum cryptography and computing, neurocognitive principles;
- Use of perspective tools and software systems for data protection taking into account new principles of data organization and interaction of data objects including the global integration of information systems, universal access to applications, new Internet protocols, virtualization, social networks, mobile device data and geo-location.

## Concise SWOT* analysis

***Strengths***

- The staff members of LIT cope with the implementation of current tasks, the modernization and upgrade of computing components and data storage systems.
- Multi-year successful experience in the WLCG project for processing data from the LHC experiments.
- The MICC components operate at the level of the best international standards in a 24 x 7 mode.
- The modern hyper-convergent supercomputer has been built on liquid cooling and modern processors.
- The network infrastructure is updated.
- The mechanism for monitoring the functioning of all MICC components has been established.
- Cooperation with MICC users.

***Weaknesses***

- Weak control over users' actions.
- Absence of a centralized user support system.
- The procurement system is slow and bureaucratic.
- Slow modernization of the elements of the engineering and network infrastructure.
- Volatility of prices on the equipment from leading manufacturers of computing and related equipment in the region.

***Opportunities***

- Understanding the need for investment and support of the developed IT infrastructure by the JINR Directorate.
- Resources of students from Dubna University and other institutes as a potential source of personnel for servicing the MICC components.

***Threats***

- Rapid pace of obsolescence of the computer and network equipment.

* SWOT — Strengths, Weaknesses, Opportunities, Threats.

- Virus and hacker attacks outside and inside, often due to users' carelessness.
- Depreciation and obsolescence of the engineering equipment, the modernization of which is delayed due to the excessive bureaucracy of the decision-making procedure.

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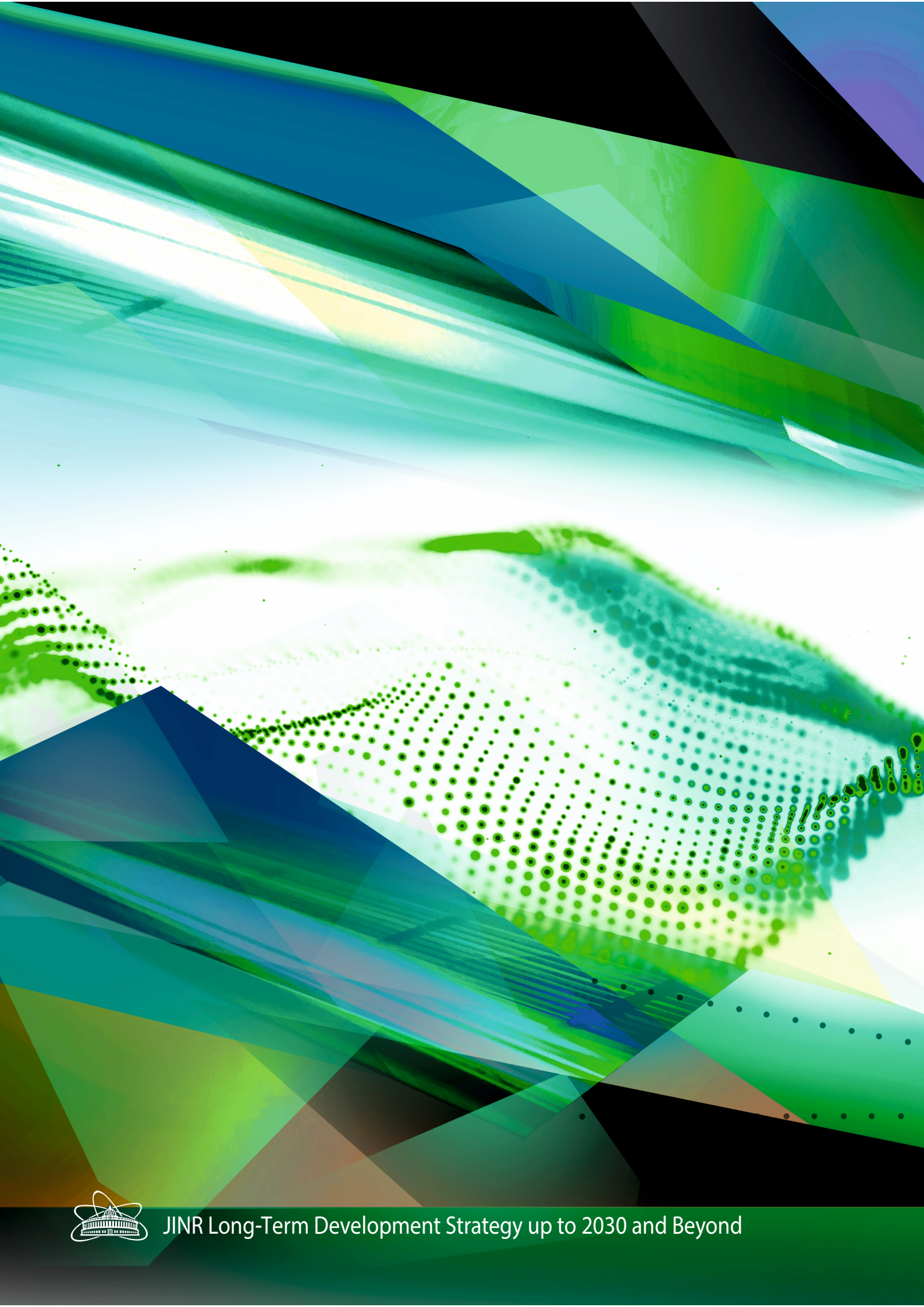
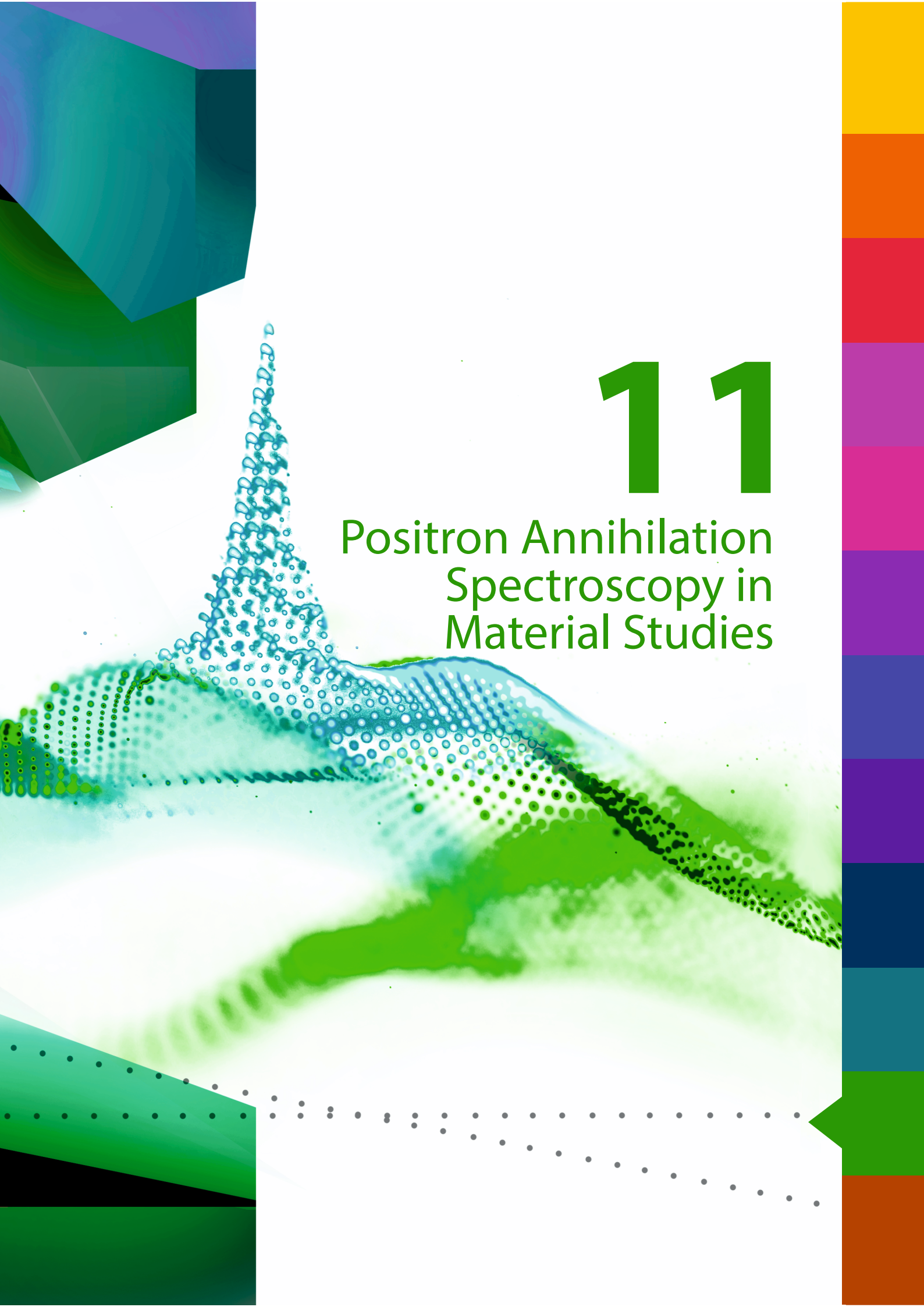


JINR Long-Term Development Strategy up to 2030 and Beyond



# 11

# Positron Annihilation Spectroscopy in Material Studies

Positron annihilation spectroscopy (PAS) is a method dedicated to detection of open-volume type of defects. Nowadays, this technique is of great interest due to the practical character of obtained results. It makes it possible to connect changes of electrical, optical, mechanical and magnetic properties of materials caused by the presence of defects in their structure. PAS gives possibility to determine the defect concentration and its type starting from a single vacancy up to pore size. Such small defects as single vacancy cannot be detected by most of the methods, even for transmission electron microscopy. Nowadays, many investigations at JINR are focused on the studies of materials by ion exposure. PAS has frequently shown its usefulness in such research, which together with other experimental techniques gives information about damages of materials. In next years, major tasks of works performed at JINR will include studies of new highly irradiation resistant materials for Generation IV reactors. Besides this, research is being conducted over the surface modification caused by different processes such as, e.g., ion implantation, surface mechanical attrition treatment, oxidation, obtaining of protective thin layers.

Slow positron beam operating at JINR is a continuous beam based on the cryogenic $^{22}$Na source with an activity of 30 mCi. It allows obtaining a monochromatic flux of positrons with intensity up to $10^6$ $s^{-1}$ and carry out layer-by-layer scanning of defects in a subsurface zone of samples at depths from zero to several micrometers by varying the positron energy. Currently, PAS measurements can be carried out only using a Doppler broadening method. The newly mounted ion source allows one to etch sample surface and perform low-energy in situ irradiation. This should enable the study in the following years of the influence of crystal lattice defects on deuteron fusion reaction rates at low energies. The growing interest in PAS techniques forces their further development. The works on modification of beam to pulsed beam are in progress, which gives an additional possibility of positron lifetime measurements. In future, a new technique of coincidence Doppler broadening is planned to be implemented. The conventional measurements employing $^{22}$Na positrons emitted directly to the samples can be conducted using both mentioned methods.



JINR Long-Term Development Strategy up to 2030 and Beyond

# 12

# Collaboration between the JINR Laboratories

As shown in Fig. 1 of the Executive Summary, there are 7 laboratories which are the research pillars JINR is based on. In the history of JINR, collaboration between the laboratories was always a highly important factor for development of new scientific directions and particular projects. Two kinds of interaction between the JINR laboratories can be noted:

a) Scientists from one laboratory are using experimental possibilities and unique techniques and methods, developed in another laboratory, for their own research.
b) Joint research teams with scientists and engineers from two or more labs, working together for one experiment.

The analysis of the situation as of today has shown that the exchange of expertise and knowledge between the JINR laboratories must be strengthened much more for exploiting the richness and resources of JINR, and new structures have to be implemented at JINR, for meeting new challenges of Science and for staying competitive in the world.

In this chapter, further details are given on the cross communication between the laboratories complementing the information given in the main chapters of the scientific fields. The summary will point to the necessary steps for meeting the challenges of the future.

## Bogoliubov Laboratory of Theoretical Physics

Theoretical investigations at the Bogoliubov Laboratory of Theoretical Physics are always carried out in close coordination with the experimental groups from the other laboratories of JINR. Besides participation in the analysis of the results of current experimental researches, BLTP plays an active role in the design and preparation of scientific programs of the future experiments.

The key direction of the planned cooperation between BLTP and the other laboratories of JINR is the support and participation in experiments at the JINR basic facilities and at international scientific facilities. Some examples are following: The theoretical investigations of hot and dense nuclear matter achieved in heavy-ion collisions will be carried out in connection with the development of the NICA facility at VBLHEP. The studies of neutrino properties will be used in the analysis of the Baikal GVD data in coordination with DLNP. Research in the field of nuclear structure and nuclear reactions will be applied for description of the experimental results expected at the DRIBS-III facility of FLNR. The theoretical advances in the investigation of condensed matter physics and new materials will lead to further improvement of collaboration with FLNP. The developed methods of mathematical modelling can be useful in radiobiological studies at LRB. The need for extensive data analysis will require joint efforts of BLTP and LIT for effective use of existing computing power and implementation of new specific computer architectures.

*To summarize, BLTP has strong ties to most laboratories of JINR and will stay an important asset of JINR's participation in domestic and all experiments wordwide.*

## Laboratory of Information Technologies

The major feature of Information Technology today and in the future is the need for its use in all types of the JINR activity, i.e. from the scientific to administrative one. As a result, all work in this field is performed in close cooperation with research groups and their IT specialists from all JINR laboratories and its member states.

The development and support of the JINR network infrastructure at today's level is of paramount importance and will be solved together with specialists from the JINR subdivisions. Only such mutually beneficial cooperation can ensure the functioning of this complex network infrastructure.

The development of computing is always a response to user requests and the exchange of experience. The joint project with the Bogolubov LTP, i.e. the "Govorun" supercomputer, can serve as an example. The operation of the first modification of the "Govorun" supercomputer made it possible to perform resource-intensive calculations in the field of lattice quantum chromodynamics, to increase the efficiency of modelling the dynamics of collisions of relativistic heavy ions, to accelerate the generation and reconstruction of events for the experiments of the NICA project, to calculate radiation safety of the JINR experimental facilities, to significantly speed up studies in the field of radiation biology, and other scientific and applied tasks.

Special attention will be given to a close interaction of LIT experts on the data and computing center of JINR with IT specialists working on front-end computing in large-scale and data-intensive experiments in the different laboratories. JINR will profit from a strong cross-cooperation of these individual IT specialists.

The strategic task to support the concerted cooperation within large-scale projects is the creation of working groups, the complementarity of the knowledge of their members of which covers computing methods, mathematical problems, a deep understanding of numerical analysis problems, as well as a profound knowledge of the physics side of the problem under consideration.

In light of new challenges related to quantum computing and the application of intelligent cognitive robots for the tasks of JINR and its member states, the **creation of a research and development group** on the basis of the JINR University Centre to train personnel in this field becomes a promising direction.

*To summarize, LIT has strong ties to all JINR laboratories including the administration department by providing service as well as scientific and technical collaboration.*

## Flerov Laboratory of Nuclear Reactions

Cooperation of FLNR with other JINR laboratories has a long history and will be obviously continued in the future. At present, it proceeds in the following main directions:

1. **Use of beams produced by FLNR accelerator complex for needs of the JINR labs.** As an example, FLNR regularly provides beams of heavy ions for the Laboratory of Radiation Biology from the U-400M cyclotron. Gamma quanta and neutron beams produced by the microtron MT-25 equipped with a proper converter are used by DLNP and VBLHEP for testing of radiation hardness of various components of detectors, which are developed, primarily, in the framework of NICA@MPD and JINR–CERN col-

laborations. Beams of the microtron are utilized as well by DLNP for the purposes of radiation molecular biology studies.

2. **Cooperation in the field of accelerator science and engineering.** In this respect, one should mention long-term cooperation of groups developing ion sources of ECR (FLNR) and EBIS (VBLHEP) types. It is of high importance for future upgrade of the NICA injection line. The FLNR–DLNP collaboration was important for 3D modelling of the main and flat-top dees of the DC-280 cyclotron (SHE Factory). The VBLHEP input to the SHE Factory project (beam wobbler for the Dubna Gas-Filled Recoil Separator, DGFRS-2) and production of scanning system for set-up working on electronics testing for radiation hardness (Roscosmos) should be acknowledged.
3. **Scientific collaboration.** A classic example of scientific cooperation concerns the one between theory and experiment. The FLNR–BLTP fruitful collaboration has a very long history and continues at present in the directions of nuclear reaction studies, nuclear structure, and radioactive decays in the fields of light exotic and superheavy nuclei. In the direction of nanotechnologies/applied research, FLNR is currently collaborating-with LRB in developing of perspective materials for burn treatment. Development of track-etched membrane-based sensors for Raman spectroscopy are done with FLNP. There are some other activities at present and many examples in the past.
4. **IT technologies.** FLNR is one of the active users of the JINR LIT high-performance IT infrastructure.

*To summarize, FLNR supportis a user community by providing access to its accelerator beams. The expertise of FLNR in accelerator technologies (ion sources, UHV, beam handling and diagnostics, beam optics) is a great asset of JINR and needs to be made fully accessible to all other accelerator projects at JINR. Furthermore, a closer collaboration in the field of sensor/detector development and new digital solutions with other laboratories will benefit the laboratory.*

## Particle Physics (Dzhelepov Laboratory of Nuclear Problems and Veksler and Baldin Laboratory of High Energy Physics )

Besides the high energy program at the NICA, these laboratories are heavily involved in many international collaborations. There exists a good collaboration atmosphere between DLNP and VBLHEP, and a unique close connection with the Bogoliubov Laboratory of Theoretical Physics. Naturally, both laboratories are well connected with LIT and are even driving the IT development in JINR due to the strong link to the JINR involvement in the LHC experiments ALICE, ATLAS, and CMS, where demands on IT are very high.

Since the JINR Particle Physics Program intends to stay well integrated into the European and worldwide Particle Physics Strategies, it must have proper expertise to truly making important contributions to the challenging international collaborations and projects.

This is why it is written in the main chapter of Particle Physics report above, " Yet, a considerable amount of knowledge must be acquired in modern electronics, robotics and precision mechanics. JINR will take all the necessary measures to attract to JINR world-level experts to lead perspective directions within detector technologies".

It should be emphasized that at JINR, like at CERN, users will profit extremely from the presence of a joint micro-electronics group and of detector groups for gaseous and sol-

id-state detectors. They should be open for collaboration with laboratories of JINR member states.

When launched at JINR, such groups or centers of competence must also be at the forefront of technology for detection systems, e.g., for deep underground detectors, for the upgrade of MPD or for the design and construction of SPD detectors at NICA, as well as for the most challenging upgrades of the LHC detectors, and of course also for the R&D for detection systems in the Future Circular Collider (FCC). Enriched by such centers of competence, JINR will be an even more attractive international research facility.

## Laboratory of Radiation Biology

Multidisciplinary radiobiological research carried out by LRB requires strong cross-cooperation between JINR laboratories. *Accelerator beam-based radiobiological research* is conducted with the help of engineers and technicians of the Phasotron at DLNP, U-400M cyclotron at FLNR and Nuclotron at VBLHEP. Mutual efforts will be directed to work towards constructing new and upgrading existing *irradiation facilities for radiobiological experiments* with latest state-of-the-art *detection technologies*. Within the framework of the NICA project, it is planned to continue LRB's participation in the creation of a special station for the irradiation of biological objects at the VBLHEP Nuclotron. Further upgrade will be continued of LRB's Genom automated irradiation facility at the U-400M cyclotron at FLNR. New project of *JINR Biomedical Center for radiation therapy* of oncological diseases will require cooperation of specialists of the JINR Medical-technical Complex at DLNP and of LRB. Analysis of nanoscale biological samples (mutant proteins, lipids, etc.) is planned at FLNP using *small-angle neutron scattering* technique. In the field of applied materials science, LRB assists FLNR in the development of *perspective materials* for burn treatment. Supercomputer infrastructure of LIT is used for numerical simulations in radiation biology with the use of software for molecular dynamics and Monte Carlo codes for particle transport. Within a framework of LIT–LRB joint project, it is planned to develop information system for the automated analysis of biological samples using *machine learning technologies*. Involvement of highly qualified specialists of BLTP in radiobiological studies would strengthen the theoretical basis of *mathematical modelling* in this research area. The JINR University Center ensures *attraction and education of young specialists* from JINR member states for their further participation in LRB projects.

*To summarize, LRB is clearly dependent on support from and collaboration with other laboratories. Newly created centers for Sensor/Detector Technologies and for Accelerator Science and Technologies will be instrumental in providing latest state-of-the-art detection systems and adequate irradiation facilities. In addition, the application of new information technologies in data processing will also benefit the laboratory.*

## DERICA Project

The DERICA project is pushing limits on many technologies. It requires the full potential of the accelerator teams of JINR and the best coordinated effort to meet the challenges of the various projects.

The most important cross-laboratory synergy aspects of the DERICA project development are listed here:

1. The development of the front end for the LINAC-100 accelerator in the framework of the DERICA project is strongly based on the world-class experience of high-intensity ion sources development at JINR FLNR. The program of the prospective 28 GHz ECR ion source development is recently started at FLNR having in mind operation of the reconstructed U-400 (or U-400R) cyclotron with heavier ion beams, up to U. However, the full potential of such an ion source can be realized as an integral part of the modern linear accelerator.
2. The development of the low-energy normal-conducting part for the LINAC-100 accelerator and the whole LINAC-30 accelerator in the framework of the DERICA project is a natural development of the inter-laboratory and inter-institutional collaboration established during the development of RFQ for injector of light ions LU-20 for the NICA project. This collaboration involves the leading accelerator experts both from JINR VBLHEP and FLNR, Russian institutions (ITEP, MEPhI, BINP, VNIITF, INR RAS), and from leading foreign nuclear physics centers (GSI, LNL-INFN, MSU, etc.). In the framework of the DERICA project, the technologies of high-intensity heavy-ion accelerators with high duty cycle (potentially — with continuous wave regime) will be developed.
3. Superconducting resonators are one of the key components for development of the driver accelerators for several important modern fields: spallation neutron sources, free electron lasers, radioactive ion beam production. The R&D for radio-frequency superconductivity in the Russian Federation in the last 25 years were stalled. In the last 5–7 years these works were reanimated at JINR VBLHEP in collaboration with MEPhI, PTI (Minsk), NPI BSU (Minsk). This activity is aiming at prospective superconductivity upgrade of the NICA injector complex. The dedicated scientific research program in the framework of the Union State of the Russian Federation and the Republic of Belarus was prepared and is now being finalized. Development of the technology of superconducting resonator construction should become the basis for future accelerator projects in the Russian Federation, and the DERICA project can be foreseen as the next (after NICA) "principal consumer" of this technology.
4. The beam dump for the intense primary beam at the DFS fragment separator of the DERICA project is a powerful source of neutrons. They are produced by stopping, for example, 100 AMeV primary uranium beam in presumably liquid lead or lead-tin eutectics. Neutron flux above $5 \times 10^{14}$ $s^{-1}$ can be expected. Being unwanted background within DFS operation, those neutrons can be an interesting "product" for studies within the scientific program of the JINR FLNP. Scientific opportunities of the use of neutrons at the DERICA DFS beam dump are under investigation at FLNP.

*To summarize, this project has been started in collaboration with many laboratories and institutes. A newly created center of competence for Accelerator Science and Technologies is the needed pole of the DERICA accelerator project management, guaranteeing drawing of the full potential of JINR.*

*A newly created center of competence for Sensor/Detector Technologies will be instrumental in providing latest state-of-the-art detection systems for DERICA.*

## Dubna Neutron Source IV (Frank Laboratory of Neutron Physics)

The planned Dubna neutron source of the fourth generation (DNS-IV) will have significantly higher parameters than at IBR-2 reactor, even be competitive to the European Spallation Source (ESS). It will open unprecedented possibilities for scientists from JINR member states and worldwide for research in condensed matter physics, fundamental physics, chemistry, material and life science.

The main project leader is FLNP with a longstanding experience in reactor operation. FLNP plans to collaborate closely with leading science centres in Russia like the Bochvar All-Russian Scientific Research Institute for Inorganic Materials (VNIINM), or the Dollezhal Research and Development Institute of Power Engineering (NIKIET). FLNP is well connected to the European neutron science community.

Within JINR, LIT will of course be a collaborator in the design planning of the project as well as in the preparation for modern digital applications like automatization and robotics and AI. LRB will be a prime user for radiobiological research.

## Conclusion

There exists in general a good interconnection of the JINR laboratories, collaboration of scientists is existing and working well when motivations are common. There is good collaboration between most laboratories with LIT, some are having their "own" IT experts, which are shielded from other laboratories. The many theorists from BLTP are distributed into the scientific projects of the JINR laboratories, which is a unique situation in the world.

Problems were solved when scientists of two JINR laboratories worked side by side in an international experiment, but did not form one single JINR team. But some JINR laboratories have still invisible walls which blocks flow of technical expertise from one laboratory to another laboratory in dire need of that expertise.

These points clearly show that JINR is presently not exploiting its full potential and that it can increase the richness it has today in the individual laboratories by opening the invisible walls surrounding its 7 pillars of science.

There is dire need for collecting all the accelerator know-how of JINR labs in **a center of competence for accelerator science and technology**. In return, the JINR laboratories and the ambitious projects presented in this Long Range Plan will have a much better chance of being realized at the forefront of science.

Furthermore, in order of staying attractive for its member states as a world leading science laboratory, JINR must develop a culture of modern microelectronics and digital know-how used in state-of-the-art detectors and operation of complex systems. Collaboration with CERN is great, but dependence on another institute is not. JINR needs **a center of competence for gaseous, liquid and solid-state detectors/sensors and a competence center for microelectronics and ASIC design**.

Finally, in light of new challenges related to quantum computing LIT requests, quantum control and the application of intelligent cognitive robots for the tasks of JINR and its member states, the **creation of a research and development group** on the basis of the JINR University Centre.

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