Draft Exec Summary of full SLRP JINR

Executive Summary

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, 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 recognizes 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.

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 multi-disciplinary collaborations.

Fig.1 These laboratories are the research pillars JINR is based on.

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 the JINR Laboratories must be strengthened by increased cross communication between them for meeting new challenges of Science and for staying competitive in the World, For reaching that goal, the mutually complementary scientific and technical cultures developed in different laboratories need to mingle, ensuring the high-level cooperation and knowledge exchange between the Laboratories. 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 willingness of the JINR staff to go that way. With this spirit, JINR can move forward as one of the largest basic research centres 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:

- Nuclear Physics
- Particle and High-Energy Physics
- Neutrino and Astro-Particle Physics
- Relativistic Heavy-Ion and SPIN Physics
- Condensed Matter and Neutron Nuclear Physics
- Theoretical Physics
- Radio- and Astrobiology, Nuclear Medicine
- Information Technologies & High-Performance Computing

Nuclear Physics

Since its foundation and up to now, the main direction of scientific research of the Laboratory of Nuclear Reactions (FLNR) of JINR has been and still is the World wide recognized synthesis of new elements of the Mendeleev's 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 also 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). For that endeavour, a planned 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 (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 building complex comprising radiochemical laboratories of Class 1 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 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.
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, our laboratory is looking into upgrades and modifications of our existing detectors like ACCULINNA-2, SHELS, DGFRS-1, 2MAVR, GALS and CORSET.
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 FLNR JINR experimental programme 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-3 setup, and the detecting system GABRIELA.

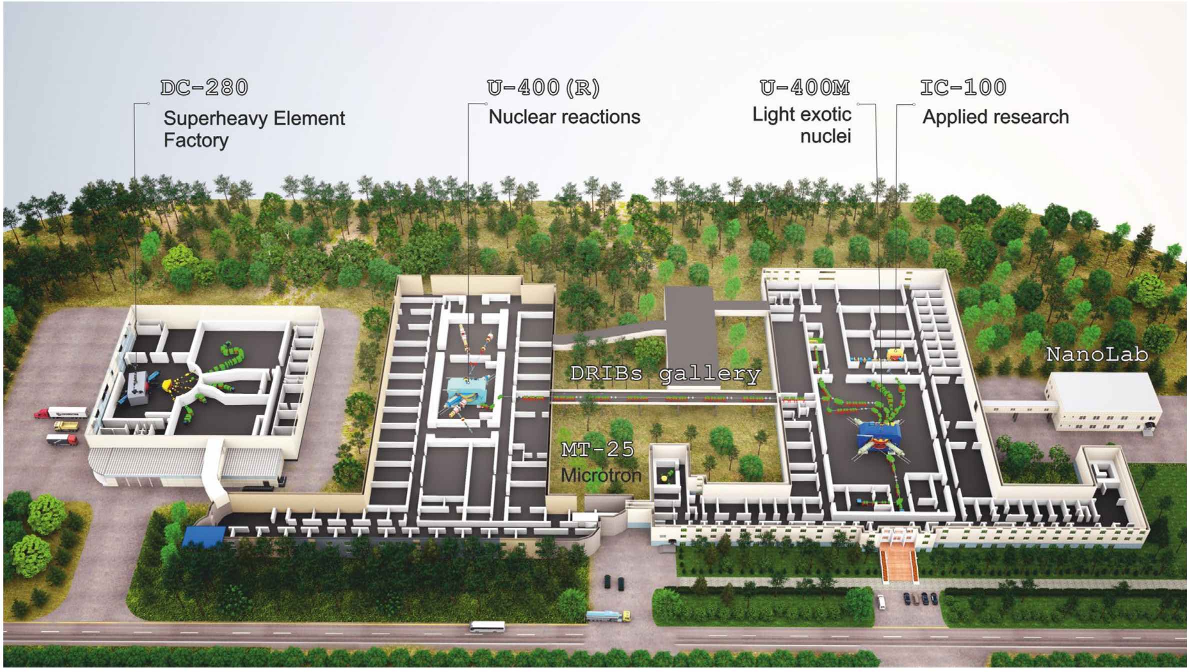

Fig. The layout of the FLNR accelerator complexes.

Radioactive ion beam (RIB)-facilities allow the study of exotic nuclear systems remote from the β-stability line. 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 U400M 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 U400M cyclotron to produce in the "in-flight" mode secondary beams of radioactive exotic nuclei.

This allows continuation of 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, 2n- and 4n-radioactivity), two- proton radioactivity, search for new magic numbers and spectroscopy of exotic nuclei Reactions with halo nuclei.

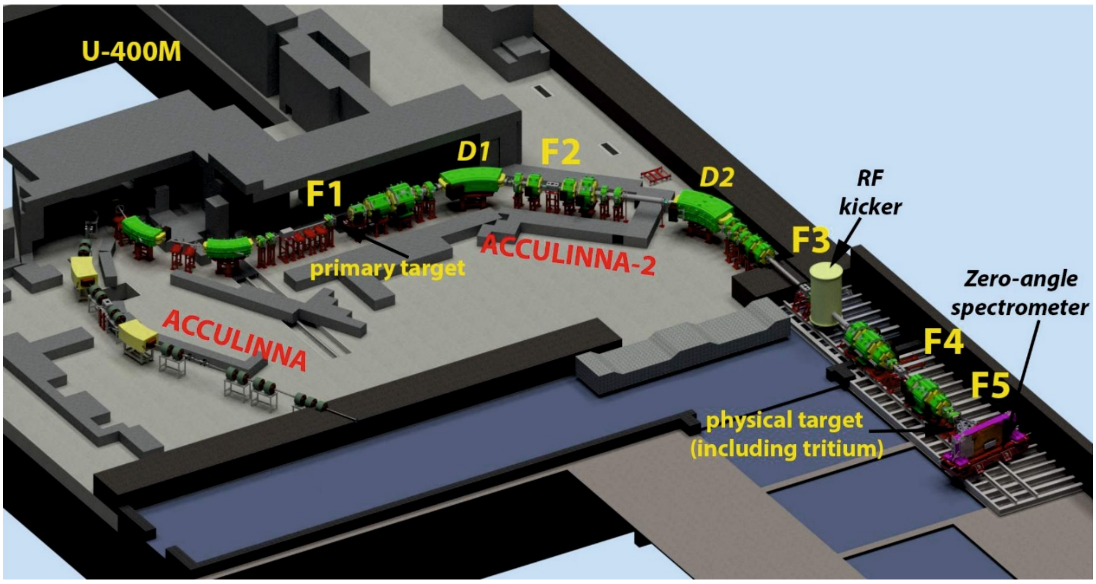

Fig. Layout of the fragment-separators ACCULINNA and ACCULINNA-2 at the U400M cyclotron.

Nuclear Physics with beams of Rare Isotopes

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.

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). Encouraged by leading international scientists of the NUSTAR community, JINR has proposed to develop and to build a powerful RIB facility DERICA (Dubna Electron – Rare Isotope Collider fAcility) covering broad range of modern nuclear physics aspects (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 FLNP and later by DERICA, JINR DUBNA will be a world-wide unique laboratory complementing those top nuclear physics facilities at FAIR/GSI in Germany, RIKEN in Japan, FRIB in the USA and GANIL/SPIRAL 2 in France.

Particle Physics at LHC and beyond

JINR is deeply involved in international science of 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-Baldin Laboratory of High Energy Physics (VBLHEP). The JINR particle physics program presented in the report should 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-terms 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.

- Electro-weak and Flavour physics.

- Further insights in understanding of the Universe evolution by astrophysical and cosmological observations and by developing new instruments, like gravitational waves, multi-messenger astronomy and searches for dark matter and dark sectors at colliders and non-accelerator experiments.

- Experimental and theoretical determination of a model, beyond the Standard Model (SM).
- 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 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, is one of the major participants with great investments into these projects. The major discovery of both 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 increase the luminosity by a factor of 5 to 7.5, reaching the record 3000 inverse femto-barn 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 about **4M USD** 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 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 world-wide 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), 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 of course dominantly engaged in the Nuclotron and NICA experiments BM@N and MPD and SPD, and smaller ones like DSS, SCAN-3, HYPER-NIS, 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 experiments - some ongoing, some under construction- will be evaluated as to scientific benefit and discovery potential, and in view of priorities of JINR.

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 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** <u>covering all sources of neutrinos</u>, 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 0.4km^3 detector by 2021 and 1.5 km^3 detector by 2027. JINR invests about **5M USD** per year to accomplish these goals. In 2019, Baikal GVD is the largest neutrino telescope in the northern hemisphere with its ¼ km^3 detector.

Fig.: **Baikal GVD (Gigaton Volume Detector)** Five clusters of Baikal-GVD neutrino telescope installed by 2019

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-terms as described in more detail (see PP-report in Sec. 3.4, 4.1. below)

The major motivation of **JUNO,** the reactor antineutrino experiment, is the determination of neutrino mass ordering at 3-4 standard deviations confidence level. 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 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 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, software 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. Important 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. In the 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

NICA Relativistic Heavy Ion Physics

From the beginning of the relativistic heavy ion research in the early 1970's, 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.

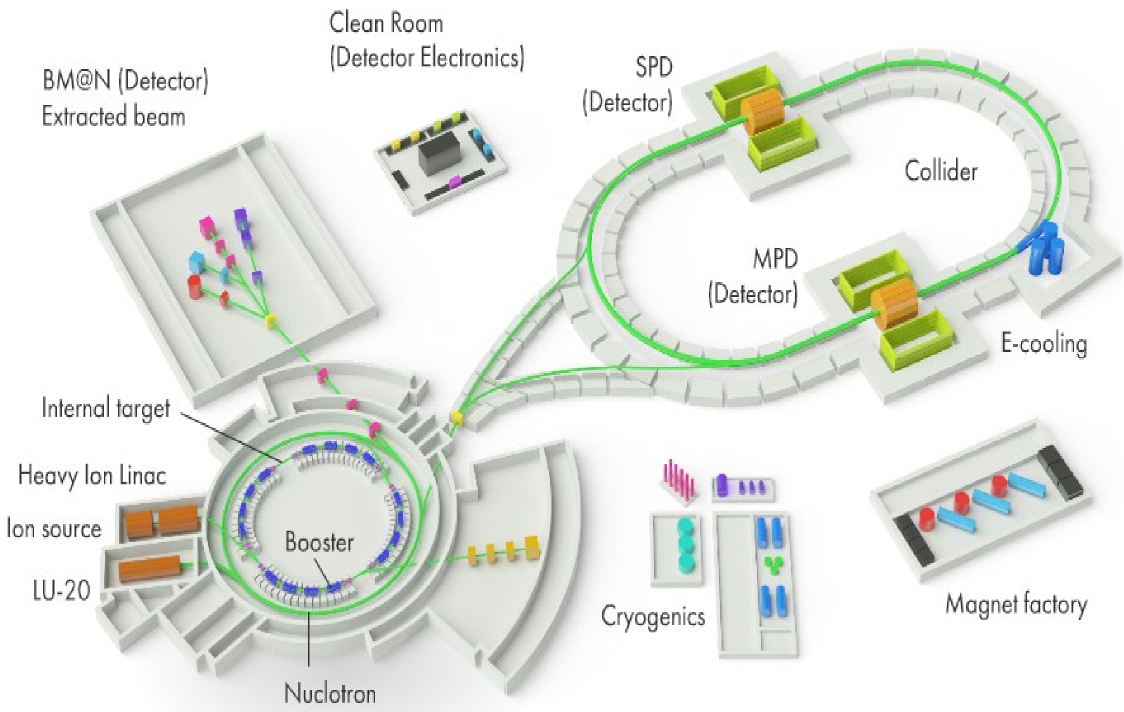

Figure: *The NICA accelerator complex*

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

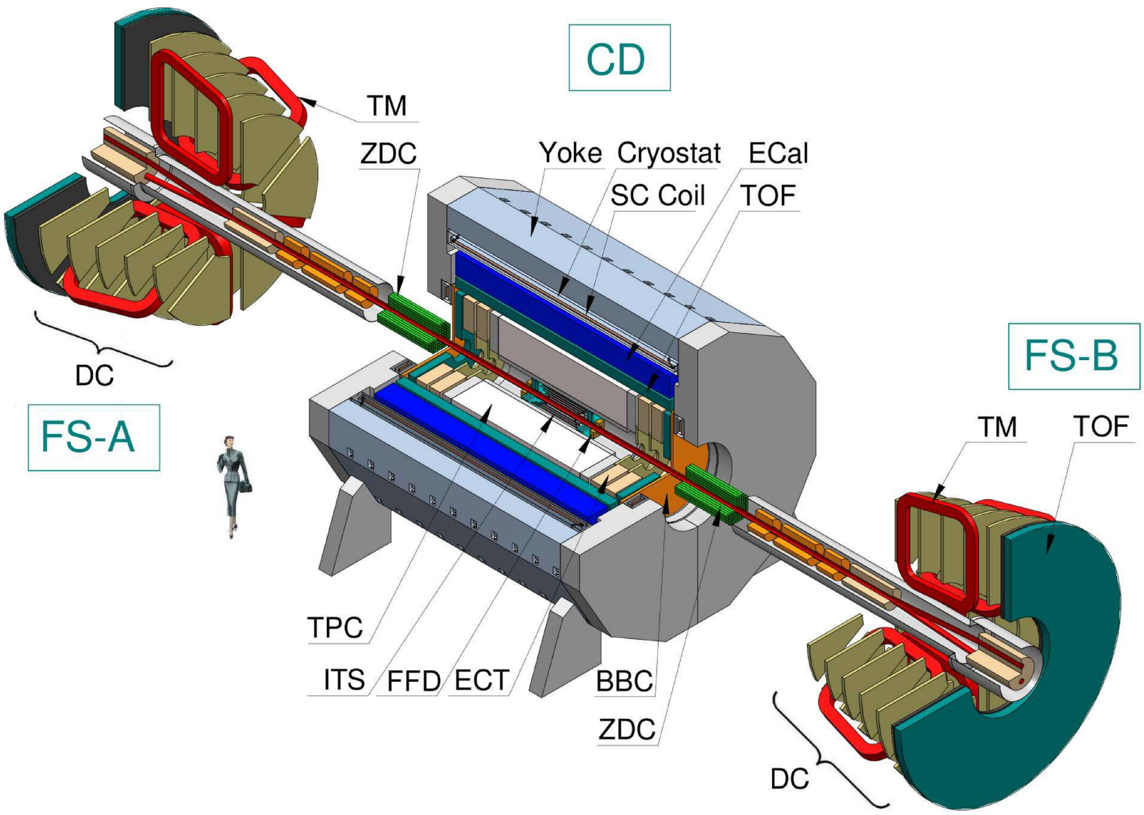

Figure: The Multi Purpose Detector (MPD) in its final version with forward spectrometers

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 laboratory to 1,000 employees. The total estimated number of scientists and specialists involved in conducting of the research at the NICA complex will reach 3000 by 2035.

JINR participation in fore-front external experiments off-site

Furthermore, of strategic importance is the JINR participation in fore-front external experiments off-site, like, e.g., at existing facilities, like at LHC, SPS, RHIC and STAR, and at facilities under construction, like, e.g., the international FAIR-facility in Germany, or in planning, the proposed electron-ion collider (EIC) facility in the USA. 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 the updated European Strategy for Particle Physics, expected to be available in 2020.

Figure : *Artistic view of the NICA Innovation Centre*

NICA Spin Physics

The 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 interacting point of the Collider. The luminosity is expected to be in the range of 10^{30}-$10^{32}cm^{-2}s^{-1}$. 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:

– Drell-Yan (DY) pair production and prompt-photon processes with longitudinally and transversely

This will allow measurements of asymmetries of the “Drell-Yan pair production” (DY) in collisions of non-polarized, longitudinally and transversally polarized protons and deuterons which provide an access to all leading twist collinear and TMD PDFs of quarks and anti-quarks in nucleons. The measurements of asymmetries in production of J/Ψ 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

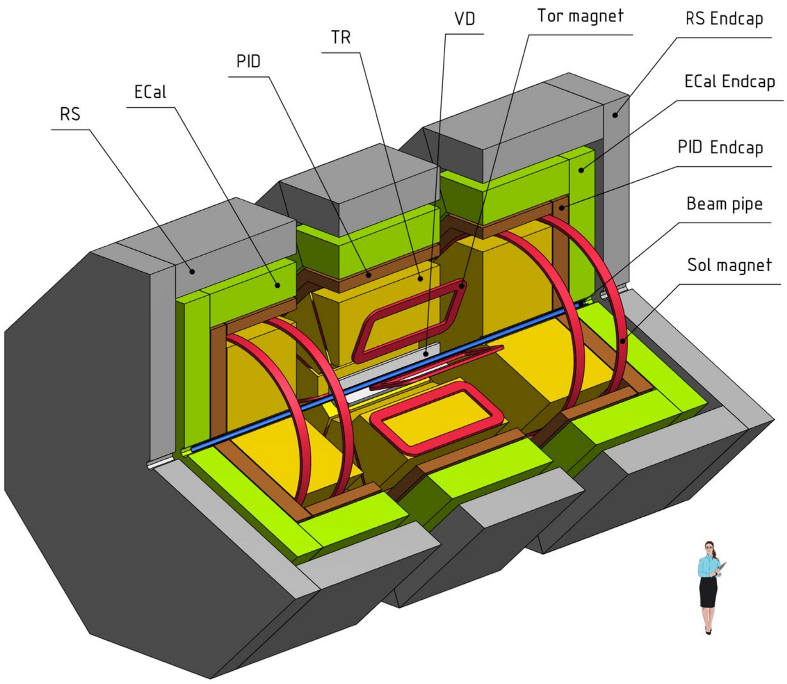

Figure: Conceptual design of Spin Physics Detector (SPD) from 2014

goals and allow for possible further reconfiguration and upgrade of the facility:– Close to 4π geometrical acceptance;– High-precision (~ 50 μ**m**) and fast vertex detector;– High-precision (~ 100 μ**m**) 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 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 end of 2021. Plan is that SPD is ready for data taking when NICA collider is operational.

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 4Å to 20Å) 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 20Å to 100Å 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 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.

JINR has proposed to build a new advanced neutron source, DNS-IV (Dubna Neutron Source IV-th 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 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 currently became the working project with a planned start of the DNS-IV operation is 2036-2037. A rough cost estimate today is at about 440 M€. More exact figures are expected end of 2022 in the preliminary design stage of the project.

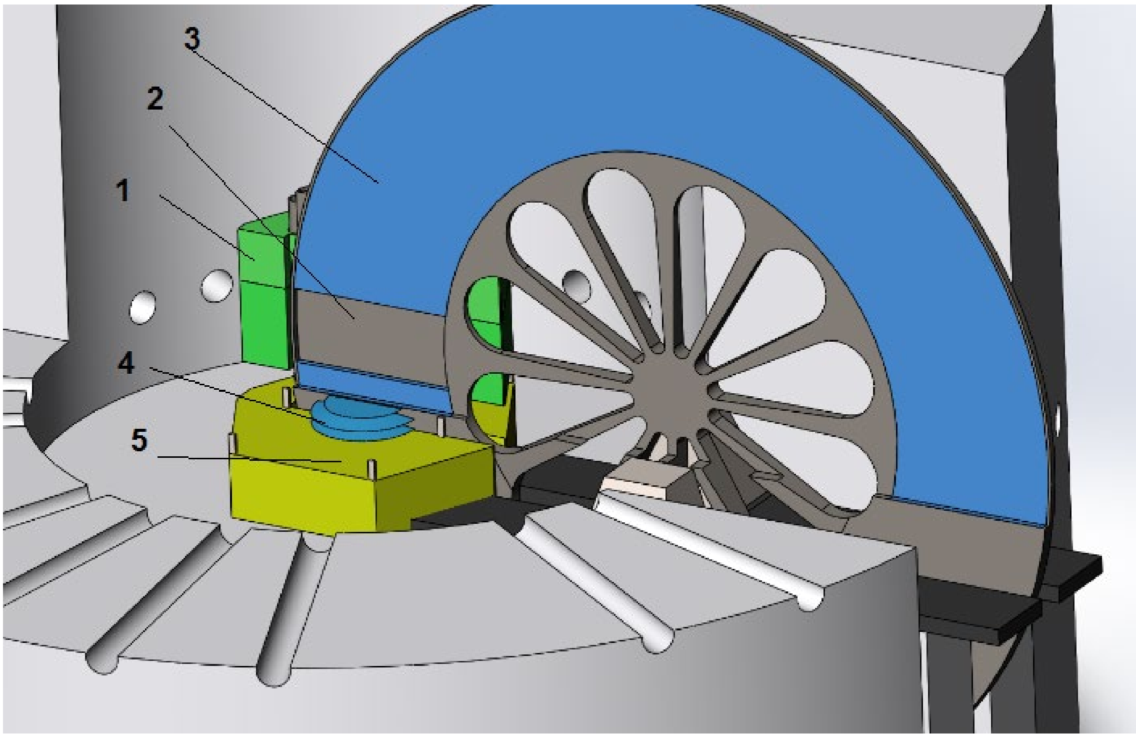

Figure : schematic view of the IBR-3: 1- reactor core reactor core, 2 - empty sector of reactivity modulator, 3 - reactivity modulator coated with titanium hydride coating, 4 - moderator, 5 - beryllium reflector.

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 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 “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 emphasized in 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 does the forces between nucleons form bound nuclei? How the nuclear chart emerges from the underlying interactions? How does the complexity of the bound and continuum nuclear structures arises from the interaction between nucleons? Which role if any at all the internal quark structure of the nucleons and their color degrees of freedom can play in description 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 Super Heavy nuclei is the goal of the experimental projects DRIBs III and “The factory of Super Heavy 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 fragmentation 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 devises.

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. A wide range of precise classical and quantum superstring solutions, application of modern mathematical methods to the fundamental problems of super-symmetric 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 super-spaces.

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 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 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 is 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.

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.

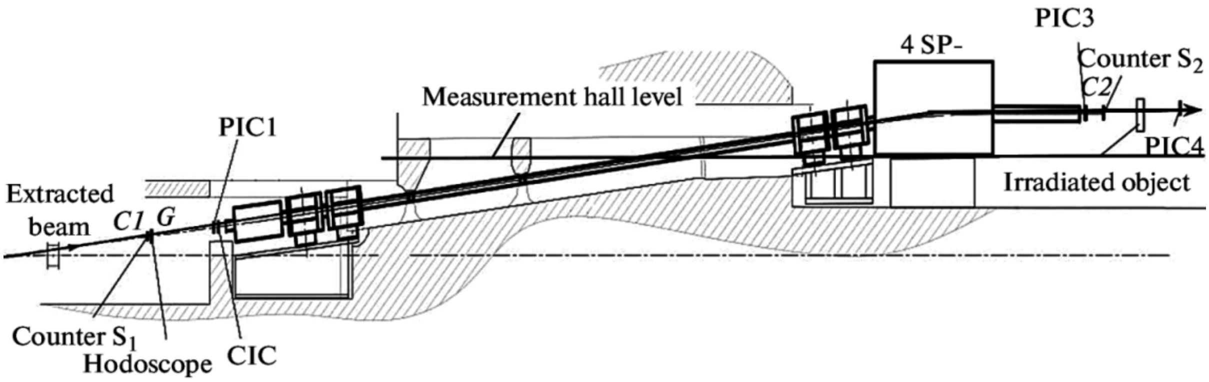

Fig.: A schematic layout of the Nuclotron beam extraction channel and beam detectors behind the irradiated biological objects.

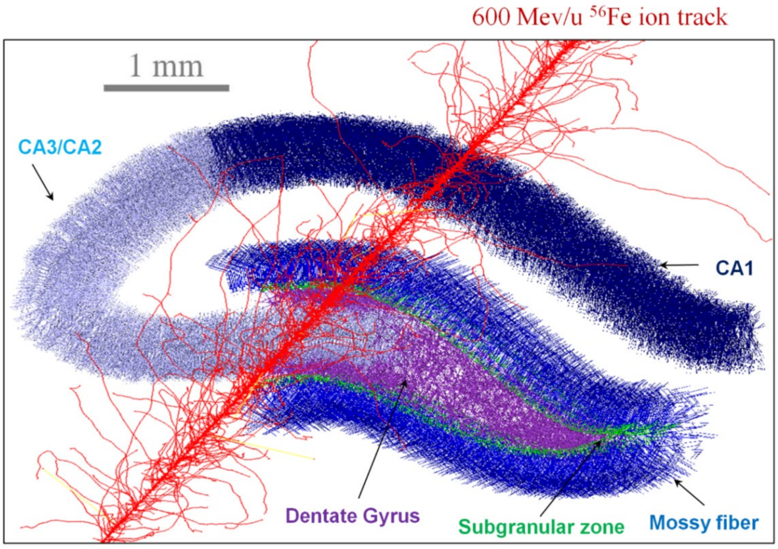

Fig. A Monte Carlo simulation of a 600 MeV/n ^{56}Fe ion track structure in a three-dimensional model of the rat hippocampus including main zones and cell types indicated by different colours.

The 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 Technology

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 is always of latest state of the art.

Since JINR and other big science centres depends 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 are 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 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 centres from 42 countries are combined into a unified computing environment within the WLCG infrastructure, capable of managing hundreds of petabytes of data, and 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 centres 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 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 that community of experts.

It should be noted that the JINR research program for next decades is aimed at conducting ambiguous and large-scale experiments on the Institute basic facilities and in frames 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 (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 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 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 Multifunctional Information and Computing Complex (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, LNP); 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.

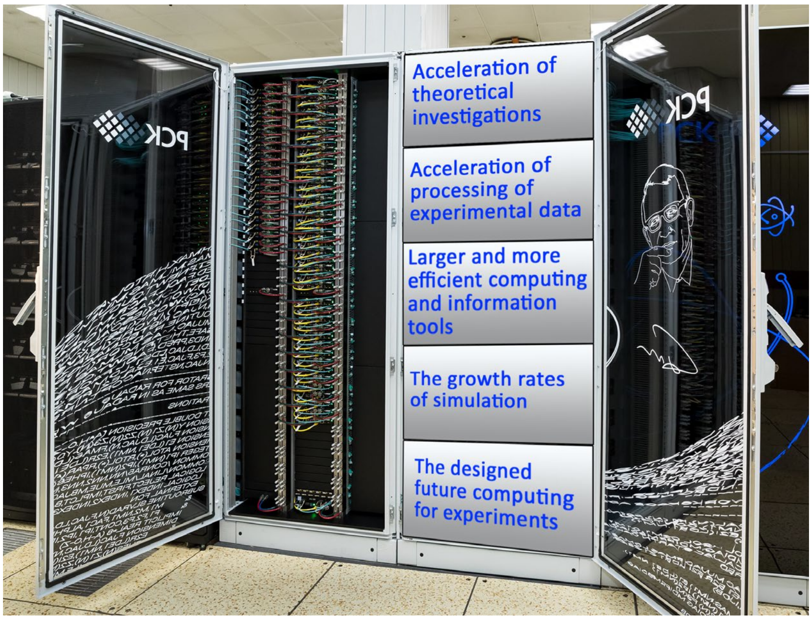

Fig. “GOVORUN” supercomputer.

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.

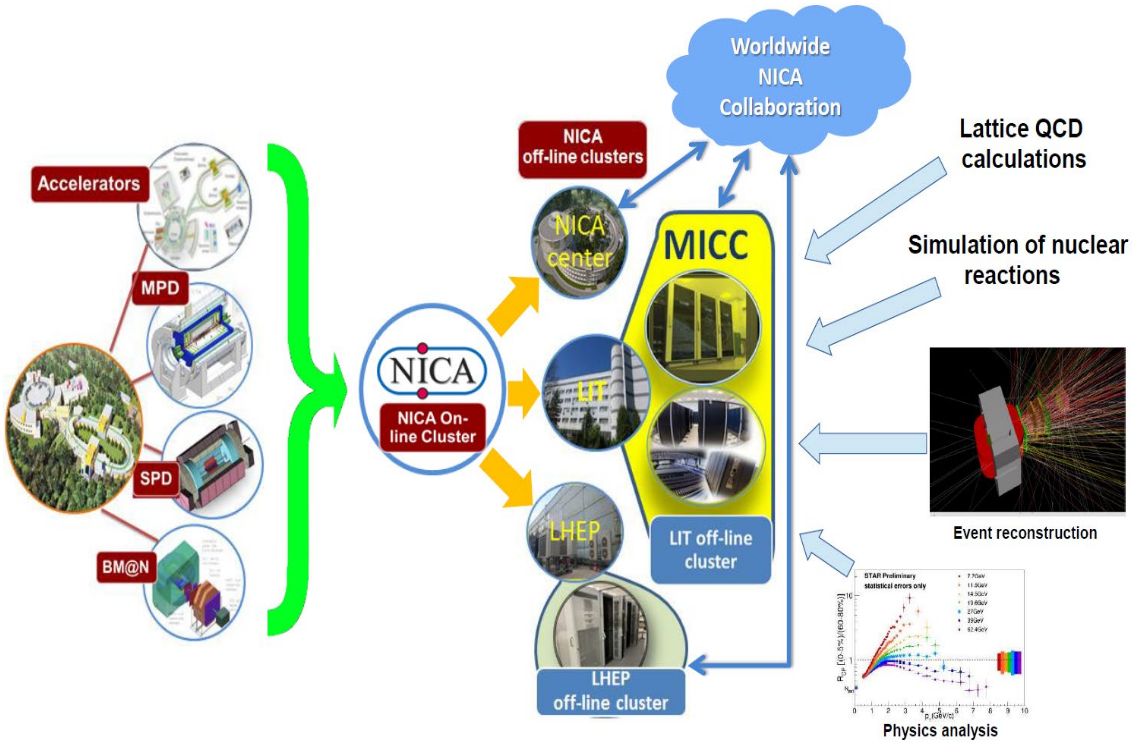

Fig. NICA computing concept and challenges.

Other promising directions of modern information technologies are 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 one, which shows the accelerated technical progress in creating equipment for quantum computers.
The JINR IT will actively observe this development in close collaboration with the CERN IT Division.

In summary, the LIT plans to establish an IT-eco System, 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 '*Methods, Algorithms and Software for Modelling Physical Systems, Mathematical Processing and Analysis of Experimental Data'*. Although many of this 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 to become 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 the VBLHEP and the 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 Ac225 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 centered to plan a medical radiation center with latest state of the art accelerator technology as well as most modern radio nuclide treatment in Brachy therapy or in immuno- therapy 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 like IBA Proteus ONE compact complex with an additional proton beam channel for biological research, or a special beam line from the NICA Booster.

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 MSCh-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 (FCMC) of the FMBA of Russia in Dimitrovgrad.

The Laboratory of Radiation Biology (LRB) 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. The application of the new approach, based on application of some well-known drugs provides a significant increase in the biological efficiency of proton beams and gamma therapeutic units, significantly brings together the field of use of proton and carbon accelerators for therapeutic purposes.

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 LRB JINR 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 died without irradiation. On day 40, both groups of irradiated animals are alive and differences in the size of tumors in the groups: proton irradiation and proton irradiation + the drug reaches ~ 2.5 ÷ 3.4 times (Fig.1).

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 field of use of proton and carbon accelerators for therapeutic purposes.

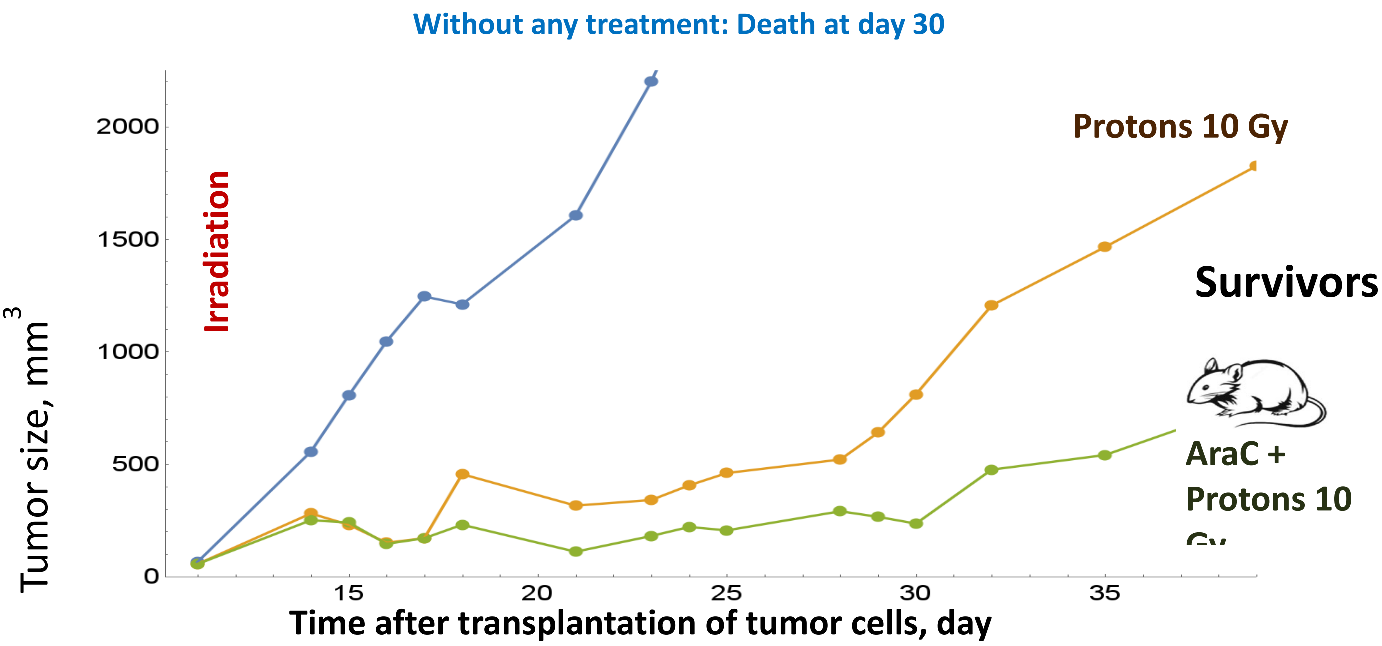

Fig. 1 Kinetics of the development of a melanoma tumor in mice without proton irradiation (blue without AraC) and with proton irradiation (orange without AraC and green with AraC) in experiments in Obninsk in the summer of 2019.

These circumstances give reason to believe that the combined use of the official drugs used should be promising for use in the clinic of radiation therapy and significantly brings together the field of application of proton and carbon accelerators for therapeutic purposes.

Many years of practical experience in treating cancer patients with proton beams, a team of trained specialists in the field of radiation medicine, the presence of a radiological department at MSC-9 of the FMBA of Russia creates 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, JINR 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 region 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 JINR management will take all the necessary measures to attract to JINR world-level experts to lead perspective directions within detector technologies, micro-electronics and ASIC chip design.

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 depends also on the strong interaction with universities and training centres 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.

Proven and or new methods of training and recruiting of personnel include:

- Supervision of practical, bachelor, master, and PhD works prepared by students studied at scientific and technical departments of universities from the JINR Member.
- Excursions to the facilities and lectures about activities of each of the JINR Laboratory for students.
- Planning various supplement schools for students of local universities during scientific conferences organized by JINR.

Very large importance is given to the educational and training program for guaranteeing new highly trained 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 taken to constantly improve a user-friendly environment on site at JINR.

Conclusion of Executive summary:

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,
- the NICA facility with its fixed target program and the collider mode for Heavy Ion collisions,
- the NICA facility for Spin Physics with polarized beams,
- the new Pulsed Neutron source based on a high intensity pulsed neutron reactor IBR-3 with Np-237 core,
- irradiation facilities for material and biophysics and radiation biological experiments
- the new Rare Isotope Facility DERICA,
- Biomedical Research Centre for Proton Therapy,
- Continuous expansion of GOVORUN Supercomputer and creation of a dynamically growing IT platform, which responds to the rapidly developing IT-World.

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.