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STRATEGIC PLAN FOR THE CONSTRUCTION AND DEVELOPMENT OF THE LHEP BASIC FACILITIES AND FOR CONDUCTING OF PHYSICS RESEARCH AT THESE FACILITIES, AS WELL AS AT OTHER ACCELERATOR CENTERS IN THE WORLD, FOR THE NEXT THREE DECADES

Introduction

The proposed strategy for the development of the Veksler and Baldin Laboratory of High Energy Physics (LHEP) is based on the understanding of the importance of and need for continuation and broadening of the research in physics of fundamental interactions of elementary particles and relativistic nuclear physics.

I. The main feature of the coming period of the Laboratory activity, which influences to a large extend the JINR strategic development as a whole, is the implementation of the mega-science project "NICA Complex". The project is approved by the Committee of Plenipotentiaries of the Institute and supported by the separate Agreement between the Government of the Russian Federation and the Joint Institute for Nuclear Research "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 at LHEP for conducting fundamental research in contemporary High Energy Physics (HEP) as well as applied research with the use of accelerator and beam technologies in microelectronics, medicine and biology.
Below the major components of the complex are listed:

1. Accelerator complex, which includes the upgraded superconducting synchrotron Nuclotron and extraction and transport beam channels; the injection complex (new ion source and source for and polarized particles, linear accelerators); superconducting booster-synchrotron; superconducting storage rings for colliding of heavy ions and polarized particles;

2. Experimental facilities: BM@N – for study of dense baryonic matter with extracted beams of the Nuclotron; MPD – for study of dense baryonic matter created by heavy ion collisions at NICA; SPD – for study of the nucleon spin structure by performing experiments with colliding of polarized beams;

3. Research infrastructure, which includes the buildings of the collider complex and experimental halls for the MPD and SPD detectors; NICA Innovation Center; experimental hall and areas for applied research; the cryogenic complex; energy supply, etc.;

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

5. Computing and information block, which includes IT center with respective networking infrastructure and set of IT services for storing, processing and analysis of the accumulated experimental.

General information on the NICA complex is available on the Web site: http://nica.jinr.ru. More detailed info is available at http://nucloweb.jinr.ru/nica/CDR.html. For the scientific program ("White Paper") see: http://mpd.jinr.ru/wp-content/uploads/2016/04/WhitePaper_10.01.pdf , for the designs of the BM@N, MPD and SPD detectors - at http://nica.jinr.ru/files/BM@N/BMN_CDR.pdf, http://nica.jinr.ru/files/CDR_MPD/MPD_CDR_en.pdf and http://nica.jinr.ru/files/Spin_program/spd-v21.pdf , respectively.

According to the adopted Seven-year plan for the development of JINR, during years 2017-2023 the construction of the basic configuration of the NICA complex should be finished and the process of putting into operation of the main components should be started.
A comprehensive report on the progress in construction of the all the elements of the NICA complex achieved by the end of year 2017 is available at *(Report to NICA Coordination Committee, Jan. 2018)*

The **Table** below, in particular Sections 1,1a-1e shows the time scale for operation in different modes of the accelerator complex (symmetric and asymmetric colliding beams), publication of results, as well as experiments' and facilities upgrade, including provisions for electron-nucleus and photon-nucleus interactions.

II. Traditionally, the LHEP scientific program includes participation in experiments at accelerators around the world that provide unique conditions to perform experiments at the forefront of HEP. The key factor here is a mutual benefit from the exchange of new scientific information, methodological or technological know-how.
The world's unique accelerator complex for multi-TeV hadron collisions is, and for the next decades will be, the LHC at CERN. Our cooperation with CERN ensured the JINR's participation in research yielding first class scientific results such as the first observation of the Higgs boson by ATLAS and CMS collaborations, new phenomena in nucleus-nucleus collisions at the highest attainable energies in the center-of-mass system, in particular with the ALICE detector.
It is anticipated that the LHEP groups will participate further in the upgrade of the detectors and in the experiments at the HL-LHC complex.
Participation in the experimental programs of the HE-LHC (High Energy LHC) and FCC (Future Circular Collider) is under consideration. Still,

cooperation on particular aspects of the accelerator R&D for FCC, which is linked closely to the further development of the NICA complex, has started and it is planned to foster it in the future.
Participation in future experiments for investigation of the properties of the quark-gluon plasma (phase transition, critical end-point and others) at the accelerators of BNL, FAIR, JPARC and, probably, at JLAB is also feasible.

III. Intensive secondary beams, a polarized muon beam and antiproton beam, are of great interest, also. Experiments with colliding electron-nuclei and photon-nuclei beams, that might be available in the LHEP in the future, could open up broad field of new opportunities for studying of the nuclear matter and strong nuclear forces.

Table

No.	FOCUS AREAS AND OBJECTIVES	2017-2023	2024-2030	2031-2037	2038-2044	2045- 2051
1	Construction, start-up and operation of the NICA complex	2020 – commissioning of the basic configuration, 2023 – design configuration. Symmetric[1] heavy ion collisions, $L=10^{25}$ $cm^{-2}s^{-1}$	Symmetric heavy ion collisions, $L=10^{27}$ $sm^{-2}s^{-1}$. Polarized proton and deuteron collisions, $L=10^{30-32}$ $cm^{-2}s^{-1}$	Asymmetric[2] heavy ion collisions, $L=10^{27}$ $cm^{-2}s^{-1}$. Polarized proton and deuteron collisions, $L=10^{32}$ $cm^{-2}s^{-1}$	Electron-nuclei head-on and co-moving collisions	
1a	Construction, start-up and operation of the MPD experiment	2020 – commissioning of the first stage of the facility, 2023 – full configuration of the central (barrel) part ready for operation. Data taking and analysis, first physics results.	End-caps commissioned. Data taking and their analysis. Publications.	Data taking and analysis. Publications.	Upgrade of the detector, data taking and analysis. Publications.	
1b	Construction, start-up and operation of the BM@N experiment	2017 – commissioning of the configuration for experiments with extracted light ions, 2019 – baseline configuration for experiments with heavy-ion beams. 2023 – commissioning of the designed full-scale	Data taking and analysis. Obtaining physics results. Upgrade of the apparatus.	Completion of data taking. Physics analysis, publication of the results.		

[1] Beams with common magnetic rigidity.
[2] Beams with different magnetic rigidities.

		configuration. Data taking and analysis, first physics results				
1c	Setting up conditions for and implementation of a research program on spin physics at the Nuclotron and NICA collider	Generation and usage of polarized proton and deuteron beams, design and start of construction of the SPD set-up	Construction and commissioning of the SPD detector, conducting experiments with polarized proton and deuteron beams. Study of ultra-peripheral nuclear collisions	Data taking and analysis, publication of the results. Experiments with twisted states of particles and states with large orbital momentum.	Data taking and analysis, publication of the results. Feasibility and design study for measurements of the deuteron EDM in the NICA rings.	Deuteron EDM measurement in the NICA collider rings.
1d	Development of infrastructure for research in hadron therapy and applied research in radiobiology and radiation-hard microelectronic elements, based on the LHEP accelerator complex	Design and commissioning of extracted beams for applied research and the appropriate infrastructure	Carrying out research and innovation projects	Carrying out research and innovation projects	Carrying out research and innovation projects	
1e	Development of the LHEP accelerator complex	Achieving of the results foreseen in the Seven-year plan for the development of JINR	Achieving the beam parameters of the full-scale configuration of the NICA complex. Upgrade of the Nuclotron beam extraction channels based on superconducting technology.	Feasibility and design study for acceleration of twisted states of particles and of states with a large orbital momentum. Feasibility and design study of electron accelerator and start of its construction	Carrying out experiments with intersecting electron-ion beams. Feasibility and design study Feasibility and design study for generation of a high-energy photon beam based on backward Compton scattering of a	Studies with head-on photon-nucleus collisions. Program of experiments in this interaction mode.

					laser beam off a few GeV electron beam.	
2	Participation in R&D and in joint experiments in other world laboratories	Participation with significant contribution in joint experiments in other accelerator labs according to the Seven-year plan for the development of JINR. Forming the lab strategy for cooperative research at other accelerator centers based on the updated European Strategy for Particle Physics (2020)[3].	Participation with significant contribution in upgrading the experimental equipment and carrying out experiments with proton-proton and heavy ion at the HL-LHC at CERN, FAIR at GSI, RHIC at BNL and elsewhere. Participation with significant contribution in searches for new physics at the SPS and HL-LHC at CERN.	Participation in the design, construction and conducting experiments with super high energy beams at future accelerators.	Participation in the design, construction and conducting experiments with super high energy beams at future accelerators.	
3	Operation, upgrade and further development of the LHEP accelerator complex	Upgrade of the Nuclotron magnets high current leads with implementation of high-temperature superconductor.	Construction of superconducting magnetic energy storage (SMES). R&D and project preparation for upgrading of the magnetic system of the Nuclotron using, in particular, high-			

[3] https://europeanstrategygroup.web.cern.ch/EuropeanStrategyGroup

			temperature superconductor.			
4	Main physics goals	Achieving the results foreseen in the Seven-year plan for the development of JINR. Participation in the preparation of the research program and R&D for FCC, ILC and other future colliders	**NICA**: Achieving of the physics goals formulated in the NICA White Paper[4]. Search for super weakly interacting "dark" matter particles with SPS beams. Search for signals of new physics and precision measurements of the Higgs boson properties at the HL-LHC. Analysis of femtoscopic correlations of rare particle pairs: φ-φ-, K*-K. Study of the chiral magnetic effect (CME) and chiral vortical effect (CVE), global polarization of hyperons and vector mesons, resonance pair production (J/ψ - J/ψ, ρ-ρ, ρ-J/ψ) in ultra-peripheral collisions of heavy ions at the HL-LHC.	**NICA**: Study of rare processes in dense nuclear matter, production of hyper-nuclei and neutron-rich nuclei. Joint analysis of the high-precision experimental data obtained at various energies (AFTER@LHC,....). Search for signals of new physics and precision measurements of the Higgs boson properties at future super high-energy accelerators. Precision measurements of the parameters of the quark-gluon plasma.	**NICA:** NICA participation in future network structures for joint analysis of accelerator (LHC,…) and non-accelerator (astrophysics, condensed matter physics…) data. Study of quark-gluon plasma matter effects on rare processes such as Z-jet production, t(a)t and tW pair creation. Study of the unreachable now region of the x-Q^2 phase space up to $x = 10^{-7}$ in ultra-peripheral interactions of nuclei and protons with nuclei at super high energies.	
5	Development of the accelerator technology and					

[4] http://mpd.jinr.ru/wp-content/uploads/2016/04/WhitePaper_10.01.pdf

	radiation detection methods					
6	Applications					

Some clarifications related to the corresponding cells in the Table and ideas for further discussion

2. (For more detailed discussion see the **Appendix.**)

3.

- Construction of Superconducting Magnetic Energy Storage (SMES). The energy storage is placed between the high-voltage network and the superconducting load (Booster and Nuclotron magnets). It allows decreasing significantly the power consumption from the network as well as the influence of the accelerators on its parameters and, vise-versa, the network influence on the accelerators. As a storage, a high-temperature superconducting magnet with stored energy of 3 MJ is proposed. Commissioning by 2025.
- R&D and preparation of a project for the Nuclotron magnetic system upgrade by using, in particular, a high-temperature superconductor. The Nuclotron magnetic system has been in operation since 1993. Soon it will come to a state that an upgrade is mandatory. It is proposed to start R&D, prototyping and manufacturing of new magnets (possibly with high-temperature superconductor) with an aim to replace overage ones.
- Reorganization of the entire JINR power network is needed. It is proposed to take CERN as an example, to develop a project and start to implement it step by step: a few-fold increase of the input power, implementation of an automatic consumption control system (per phase) at each setup and for JINR as a whole, unified concept for network power supply and grounding of physical setups (like at CERN), transition to the European TN-S system.

4.

- Physics challenges at HL-LHC (and, in future, at HE-LHC):
  - Direct search for physics beyond the Standard Model at TeV energies: supersymmetry, low energy gravity, “dark” matter, extended gauge sector of the Standard Model (SM), new particles and interactions;
  - Precision measurements of the Higgs boson properties: mass, width, spin, parity, interaction constants, rare (or forbidden in SM) decays;
  - Precision tests of SM: search for rare decays, study of hadron structure, and study of SM processes with large 4-momentum transfer.

- Physics challenges at SPS: physics of quark flavors, study of QCD processes including perturbative and non-perturbative regimes, study of spin hadron structure, heavy ion physics.

5.

- Radiation-hard detectors and read-out electronics, for example, radiation-hard position-sensitive detectors based on SiPM (practical applications), special radiation-hard front-end chips for data read-out and processing at the detectors with 32-256-512 channels and data transfer speed of 3-25-50 Gbit/sec;
- R&D for new types of gaseous detectors, e.g. straw tubes with cathode readout, flat GEMs that can withstand MHz load, etc.;
- Development of read-out systems with throughput up to 1 Tbit/sec.

6.

- Neutron source for application purposes;
- Experimental study of the possibility to use natural uranium and thorium in the ADS scheme for power production;
- Research in the field of smart materials based on ion-track technologies exploiting NICA beams.
- Development and implementation of analytical devices for nano-admixture analysis, development of an analytical center at LHEP.
- Investigation of radiation hardness of materials for the NICA complex and other purposes: superconductors, electronic components, insulation materials, scintillation materials.

Appendix: Participation in joint experiments at facilities in other centers around the world

- Participation in joint experiments at facilities in other centers (carrying out R&D, development of facilities and programmes for physical research) should fit into the European Strategy for Particle Physics [4]. Currently, three types of future accelerators are widely discussed: proton-proton accelerators, lepton colliders and γγ-colliders. Some of the main characteristics of proton-proton and electron-positron colliders are given in Tables 1, 2[5].

Table 1. Proposed proton-proton colliders

Facility	Years	E_{cm} (TeV)	Luminosity (10^{34} cm^{-2} s^{-1})	Int. luminosity (fb^{-1})	Comments
Design LHC	2014–2021	14	1–2	300	
HL-LHC	2023–2030	14	5	3000	Luminosity leveling
HE-LHC	>2035	26–33	2	100–300 per year	dipole fields 16–20 T
V-LHC	>2035	42–100			new 80 km tunnel

Table 2. Proposed electron-positron colliders

Facility	Years	E_{cm} (GeV)	Luminosity (10^{34} cm^{-2} s^{-1})	Int. luminosity (fb^{-1})	Tunnel length (km)
ILC 250	> 2025	250	0.75		
ILC 500		500	1.8		≈30
ILC 1000		1000			≈50
CLIC 500	> 2030	500	2.3 (1.3)[a]	500	≈13
CLIC 1400	> 2038	1400 (1500)[a]	3.2 (3.7)[a]	1500	≈27
CLIC 3000	> 2047	3000	5.9	2000	≈48
LEP3	> 2022	240	1	100/year and exp.	LEP/LHC
T-LEP		350	0.65		80 (ring)

[5]M. Krammer, *The update of the European strategy for particle physics*, Phys. Scr. T158 (2013) 014019

Taking into account previous successful VBLHEP participation in experiments at hadron accelerators as well as the extensive experience of participating in CERN experiments, it is a natural and logical to continue and extend the LHEP collaboration in the framework of international collaborations for research at the CERN accelerator complex at all stages (preparation of physics programme, R&D, development and upgrade of the experimental setups, participation in physics analysis and data taking). Taking into account the already established program of physics research at CERN at the high luminosity LHC (HL-LHC) until 2030-2035, the approved and launched program for upgrades of the detector systems, this step is even more obvious. In addition, CERN continues to develop the experimental program at the SPS beams for searches beyond the Standard Model (NA64, SHiP), experiments with heavy ion beams (NA61/SHINE), studies of hadron structure (COMPASS), etc. The program for these experiments and studies has been approved until at least 2023. Joint research programs with CERN ensure the participation of LHEP physicists in obtaining results at Nobel Prize level and access to advanced technologies in high-energy accelerators, particle detectors, IT and computing. The experience and know-how obtained is further used in the development of the research infrastructure and physics projects at the LHEP basic facilities.

- JINR scientists participate successfully in joint experiments for studying of quark-gluon plasma, properties of the phase transition and critical point at CERN (SPS-NA61, LHC-ALICE), BNL RHIC-BES (STAR) in the energy range from 20 GeV to 5 TeV (per nucleon pair). A lot of data has been obtained on dense baryonic matter: strangeness, "charm" and "beauty" production, correlations, particle flows. In the region of lower energies and high baryon density it is interesting and promising to continue the JINR participation in the programs for beam energy scan in the NA61 and STAR experiments.
  At higher energies and zero baryon potential, it is very interesting to study formation of a hot quark-gluon plasma by continuing the participation in the experiments at the HL-LHC and FCC colliders. For HL-LHC, it is planned to increase the integrated luminosity 10 times (up to 10 nb^{-1} for Pb-Pb and up to 50 nb^{-1} for p-Pb) with the upgrade of the ALICE detector that was specially designed to study the collisions of heavy ions. This will allow conducting a more detailed study of energy losses by jets and single particles in the medium , "charm" and "beauty" behavior in QGP, anti-hyperons and dibaryons, to significantly improve the accuracy and the covered range of the standard observables — particle flows and femtoscopic correlations for rare particle pairs.
  For collisions of Pb-Pb ions at $\sqrt{s_{NN}}\approx 39$ TeV and p-Pb at ≈63 TeV at the FCC a luminosity of $13 \cdot 10^{27}$ $cm^{-2}s^{-1}$ and integral luminosity of 8 nb^{-1} per month[6] is foreseen. New studies of the effect of the quark-gluon plasma on rare process with the formation of Z-jets, t(a)t and tW pairs

[6]FCC Collaboration, https://fcc.web.cern.ch/.
M. Schaumann, Phys. Rev. ST Accel. Beams 18 (2015) 9, 091002 [arXiv:1503.09107 [physics.acc-ph]].
J. Jowett, FCC Week 2015, March 2015, https://indico.cern.ch/event/340703/session/74/contribution/113.
N. Armesto, et.al., «Nuclear collisions at the Future Circular Collider» Nuclear Physics A Vol 956, 2016, 854-85

are proposed. A detailed study of the temperature dependence of the hydrodynamics parameter η/s (shear viscosity) that determines the property of the quark-gluon plasma as a quantum liquid is possible. Study of the QCD dense matter and gluon saturation in the initial state is feasible. Currently not available region in the x-Q^2 phase space up to x values ~ 10^{-7} could be studied in ultra-peripheral interactions of nuclei exploiting virtual processes like γγ, γp, γA. Those ultra-peripheral collisions could also serve as a source of photons for precision studies of interesting exclusive processes.

- Future perspective searches at the HL-LHC

The second stage of the LHC operation (Run2) at 13 TeV (an increase of the collision energy up to the design value of 14 is planned, too), will continue up to the second long stop (Long Stop 2, LS2) in 2018. It is expected that the Run2 integrated luminosity L_{int} will reach 100-120 fb^{-1}. The achieved increase in the beams collision energy of almost two times (from 8 to 13 TeV) with respect to the LHC start transforms to an increase of the parton luminosity from 2 to 100(!) times, i.e. 100 fb^{-1} at 8 TeV is equivalent to 1 fb^{-1} at 13 TeV. This means that only in a few months during the second phase of the LHC will more data on the processes with large 4-momentum transfer will be collected than during the entire first stage.

After the LS2, running at the design energies of 13-14 TeV and with luminosity of 10^{34} $cm^{-2}s^{-1}$ (Run3) will continue until the end of 2023 (the expected by the end of the Run3 integrated luminosity is L_{int} ~ 300 fb^{-1}). Starting in 2026, an upgrade of the machine, the HL-LHC will start running with a luminosity of 5×10^{35} $cm^{-2}s^{-1}$. HL-LHC is planned to run for 7 years. During this period, the statistics of the obtained data will be increased 10 times compared to the end of 2021 (end of the data taking at LHC at the nominal luminosity) and almost 60 (!) times in comparison with the present. The expected value of the integral luminosity at the end of this phase is L_{int} ~ 3000 fb^{-1}.

The main goal of the new research is certainly further thorough study of the Higgs boson nature and search for possible deviations from the SM predictions, which would indicate signals of new physics phenomena. The main question that the LHC experiments will try to answer is: *Is there a new physics at TeV energy scale?* Especially this concerns additional Higgs bosons with larger masses and low-energy supersymmetry, for the existence of which this search will be crucial.

In particular, the characteristics of the Higgs boson, for example, the constants of its interactions with the SM particles will be measured with the accuracy of up to 5-14% and 2-10% at 300 fb^{-1} and 3000 fb^{-1}, respectively. In addition, after collecting of ~1200 fb^{-1} it will be possible to observe rare decays of the Higgs boson, such as for example $H \rightarrow \mu\mu$. In addition, for instance, the issue with the decay $B^0 \rightarrow \mu\mu$ will be clarified; according to the Run1 data this decay shows a slight deviation from the SM prediction at the level of 2σ statistical significance.

The increase in statistics will allow not only increasing the expected limits on the masses of new particles (2-3 times), predicted by various models beyond the SM, but also if they are discovered, it would be possible to separate various hypotheses about their origin by determination of their spin and interaction constants.