Review

of the scientific and technical justification for the extension of the project "JINR Participation in the STAR Project" (02-1-1066-1-2010/2026) in 2027–2029 and the project report for 2024–2026.

The authors of the project presented a report for the period of work in 2024–2026 and made proposals for its extension to 2027–2029.

The main objectives of the project are:

1. To collect experimental data for the Hot QCD Physics program on p-p, p-Au, Au-Au, and O-O interactions at $\sqrt{s_{NN}} = 200$ GeV in the new, extended geometry of the STAR facility.
2. To collect experimental data for the Cold QCD Physics program on the interaction of polarized protons p↑p↑ with an energy of $\sqrt{s_{NN}} = 510$ GeV in the new, extended geometry of the STAR facility.
3. To process and analyze data for the BES-II energy scanning program in collider and fixed-target experiments.

The energy scanning program covers the energy range of gold nuclear collisions from 3 to 27 GeV in fixed-target and collider modes to search for the critical point and signatures of phase transitions in nuclear matter. The Hot QCD Physics program focuses on gold nuclear collisions with a maximum energy of 200 GeV to collect a huge data set (18 billion nucleus-nucleus collision events) to study the microstructure of quark-gluon plasma. The Cold QCD Physics program focuses on polarized proton collisions with a maximum energy of 510 GeV to elucidate the nature of spin and lay the foundation for future measurements at the Electron-Ion Collider (EIC). It should be noted that the collaboration has successfully completed the data collection tasks for the Hot QCD Physics and Cold QCD Physics programs. The group will be working in 2022–2026. JINR took an active part in sessions on collecting statistics in experiments at the STAR facility (in remote mode).

The STAR facility was built at Brookhaven National Laboratory with the critical participation of the Joint Institute for Nuclear Research to conduct experiments at the Relativistic Heavy Ion and Polarized Proton Collider (RHIC). The STAR facility successfully operated at the collider for 25 years. All detectors for the Barrel and Endcup calorimeters, including the high-voltage power supply systems for the Endcup calorimeter, were developed at JINR and have successfully operated for a long period.

The main objective of the physics program at the RHIC accelerator complex was to obtain a new state of nuclear matter formed in collisions of heavy ions (Cu, Au, $^{96}_{44}$Ru, $^{96}_{40}$Zr, U, O), to study its properties with various probes in a wide range of energies (3–200 GeV) and collision centrality, and to determine the phase diagram of nuclear matter.

Based on the results of studies conducted at the STAR facility, it has been concluded that collisions of heavy ions at the maximum energy of RHIC produce strongly interacting nuclear matter of quarks and gluons, more reminiscent of a perfect liquid than a perfect gas. This matter is characterized by a strong suppression of the yields of particles with

high transverse momenta, a large elliptical flux of hadrons with light and heavy strange quarks, the presence of strong $\Delta\eta$ and $\Delta\varphi$ correlations (the "ridge" effect), and "quark scaling." Experiments with polarized proton beams with jet production at an energy of 510 GeV revealed a positive integral contribution of gluons to the proton spin, and with the production of W bosons, a difference in the spin-dependent distributions of sea u- and d-quarks in the proton was discovered.

One of the JINR team's main objectives in the STAR experiment in 2024–2026 was participation in the BES-II energy scanning program. As a result of the BES-I and BES-II programs, the energy range from 3 to 200 GeV was scanned, corresponding to temperature ranges of 60–160 MeV and baryon chemical potential of 720–25 MeV.

In 2024–2026, with the participation of the JINR group, a number of new results were obtained in the energy scanning program:

- The dependence of the cumulant ratio C4/C2 for net protons in the most central and peripheral events was obtained and a discrepancy within the limits of (2–5)σ was established in the energy region $\sqrt{s_{NN}}$ = 19 GeV (Phys. Rev. Lett. 135, 142301
- (2025). The dependence of the nuclear modification factor of charged hadrons on the transverse momentum for collision energies of 19.6 and 27 GeV was established and a comparison was made with the Monte Carlo models UrQMD (cascade) and SMASH
- + vHLLE (hydrodynamic).
- The dependence of the yields of φ-meson production in Au-Au collisions at energies of 19 .6 and 27 Ge V and 9 centrality classes on the transverse momentum in the central rapidity region was established.
- The analysis of the spectra of charged and strange particles at energies of 7.7, 11.5, 19.6, 27 and 39 GeV was carried out and the thermodynamic properties of the nuclear environment (temperature and baryon chemical potential) were determined within the framework of the shock wave model.
- The analysis of femtoscopic correlations of identical pions formed in Au + Au collisions at energies of 3.0, 3.2, 3.5, 3.9, 4.5 GeV was carried out and a systematic difference in the behavior of the radii of positively and negatively charged pions was established.
- The analysis of the spectra of K_S^0 mesons in Au-Au collisions at an energy of 19.6 GeV was carried out within the framework of the *z*-scaling theory and the regularities of the scaling function were established in a wide range of the similarity variable, including the cumulative region.
- The fractal analysis was carried out using the Monte Carlo SePaC method for Au-Au events obtained using the AMPT (multiphase transport model) generator, Monte Carlo fractals, events with randomly distributed particles and a comparison with ST AR data at an energy of 200 GeV.
- The analysis of femtoscopic correlations of K_S^0-K_S^0 meson pairs was carried out using the statistics of 500 million events in Au-Au collisions at an energy of 19.6 GeV and seven centrality classes in the momentum range from 5 MeV/c to 6 GeV/*c*.

- A comparison of the effectiveness of different machine learning models for particle identification based on information from TPC and TOF detectors was carried out on MC data obtained for the MPD detector.

The project's continuation for 2027–2029 includes new research areas. One of the project's main objectives for the next few years remains the processing of data obtained during the BES-II program. Analysis of the energy scanning program's results is important not only for further planning of the experimental program at the STAR facility but also for identifying research areas that require high-precision measurements at the MPD facility at the NICA collider. It should be noted that fixed-target data analysis is essential for experiments using Nuclotron extracted beams, such as BM@N.

A three-year extension of the project (2027–2029) is currently being proposed, but it should be understood that processing the STAR experimental data, and particularly the Hot QCD Physics and Cold QCD Physics programs, will continue for at least 10–15 years, as the so-called "golden dataset" has been obtained, which includes p-p, p-Au, Au-Au, measurements on light nuclei, and data on polarized protons. These data will undoubtedly be useful in planning and analyzing experiments, both for future experiments at the Electron-Ion Collider (EIC) and for the NICA accelerator complex, including the SPD experiment. It should be noted that studies of nucleus-nucleus interactions at RHIC's highest energies, but in an extended pseudorapidity range, will yield fundamentally new information on the dynamics of nucleus-nucleus collisions and the manifestation of the spin structure of protons and nuclei.

Given the extensive experience of joint work with the Laboratory of Information Technologies and Brookhaven National Laboratory in processing experimental data from the STAR facility using GRID technologies at the JINR Multifunctional Information and Computing Complex, the organization of such work in 2027–2029 on processing data from the Hot QCD Physics and Cold QCD Physics programs could become a significant contribution of JINR to the collaboration in the STAR experiment.

Among the project objectives proposed by the JINR team for 2027–2029, I would like to highlight the following:

1. Using the correlation femtoscopy method for a systematic study of the spatiotemporal parameters of particle production during energy scanning, taking into account various fluctuations.
2. Studying the production of strange particles (mesons and baryons) as sensitive probes of the state of nuclear matter to search for and study the signatures of nuclear matter phase transitions depending on the energy and centrality of the collision over a wide range of transverse momentum values.
3. Studying the structure of events using fractal analysis, cumulative particle production depending on energy and multiplicity, and studying the modification of spectra in the nuclear medium.
4. Studying the energy and angular dependence of global polarization, as well as the chiral magnetic effect.
5. Developing and applying machine learning methods to analyze data in collider experiments.
6. Saving the necessary experimental data from the RHIC collider at JINR. Conversion of the collected data to pico- and femto-DST formats and their storage on the JINR LIT server

(200 TB). This data can be used for additional analysis when planning and conducting experiments under the NICA accelerator complex, regardless of external circumstances.

The physics results obtained by the JINR group are regularly presented at international conferences. More than 15 papers were presented in 2024–2026. In 2024–2025, over 14 publications were prepared with the participation of JINR group staff.

It should be noted that the group includes university students and young scientists. In 2024–2025, five undergraduate and master's thesis were prepared and defended. Three young scientists are working on their PhD theses on topics covered by the BES-II program.

The young scientists of the JINR group in the STAR experiment received a grant from the Russian Science Foundation for "Measuring the Thermodynamic Characteristics of a Dense Baryon Medium Formed in Heavy Ion Collisions at Energies of 3–27 GeV" (RSF 22-72-10028, RSF 25-72-30005).

The experience of the staff involved in the STAR experiment is extremely important for the preparation of the physics project for the heavy ion research program at the MPD/NICA complex in the energy range $\sqrt{s_{NN}}$ = 4–11 GeV and for the polarization research program at SPD/NICA in the energy range $\sqrt{s}$ =12–25 GeV.

I recommend accepting the report on the project "JINR Participation in the STAR Experiment" (02-0-1066-2007/2029-1) for 2024–2026 and continuing work on the project in 2027–2029. I believe the resources requested by the authors in the scientific and technical justification for extending the project to 2027–2029 are justified.

Head of Department, LHEP
Doctor of Physical and Mathematical Sciences V.P. Ladygin

vladygin@jinr.ru