**Questionnaire (for projects seeking continuation):**

**Project STAR (JINR participation)**

**A. Scientific merit**

1.   Goals of the experiment:

1a. Give a short description of the goals of the experiment:

The goal of the STAR project (JINR participation) is to study the properties of nuclear matter at extreme densities and temperatures, to search for signatures of quark deconfinement and possible phase transitions in heavy ion collisions over a wide energy range at the Relativistic Heavy Ion Collider (RHIC). The research program also includes the study of the structure functions of quarks and gluons in collisions of transversely and longitudinally polarized protons.

1b. Explain what the project adds to the international scenario:

The STAR experiment is unique in its capabilities:

* the energy range in the collider mode √SNN = 7.7-200 GeV, and in the fixed target mode √SNN = 3-7.7 GeV;
* RHIC is an amazingly versatile machine, colliding p+p, p+Al, p+Au, d+Au, He3+Au, O+O,Cu+Cu, Cu+Au, Zr+Zr, Ru+Ru, Au+Au, U+U;
* the possibility to perform experiments with longitudinally and transversely polarized protons at a maximum energy of 510 GeV;
* the possibility of particle reconstruction with light (u, d, s) and heavy (c, b) quarks, photons, leptons, lepton pairs, jets, light nuclei, antinuclei, hypernuclei and antihypernuclei as probes.

In the STAR experiment, highest-priority world-class physical results have been obtained:

* For the first time at a maximum collider energy of 200 GeV, a new state of strongly interacting nuclear matter (Perfect Liquid), was discovered in collisions of gold nuclei, and its properties were studied in processes with the production of light, heavy quarks and jets (elliptical flow, nuclear modification factor, Δη-Δφ correlations, quark NCQ scaling).
* For the first time in world practice, within the framework of the same experiment, a program of energy scanning in the energy range of 3-200 GeV was carried out. It gives possibility to study the phase diagram of nuclear matter over a wide range of temperatures (Tch = 60-160 MeV) and baryon densities (µB = 25-720 MeV).
* For the first time, the interaction of antiprotons was studied by the method of femtoscopic correlations and the charge symmetry of matter and antimatter was established (Nature, 527 (2015) 345).
* For the first time in processes with the production of hypertritia and anti-hypertritia, CPT symmetry has been verified (Nature Physics, 16 (2020) 409).
* For the first time in nucleus-nucleus collisions, the effect of rotation of the nuclear matter was discovered and the global polarization of hyperons was measured (Nature, 548 (2017) 62).
* For the first time in collisions of gold nuclei at the energy of 200 GeV, the symmetry of produced matterand antimatter was established (Nature, 473 (2011) 353).
* For the first time in an experiment with beams of longitudinally polarized protons at the energy of 510 GeV and with jet production, a positive integral contribution of gluons to the proton spin was found.
* In processes with the production of W, Z bosons, the asymmetry of spin-dependent sea anti-u and anti-d quark distributions in a proton has been discovered.

**B. Achievements**

2.   Contributions of the JINR group:

2a. List of the specific contributions of the JINR group in hardware (including the use of JINR computing resources for the project), software development, and physics analyses:

The main JINR contribution to the STAR experiment is the manufacture and stable long-term operation of the barrel and end-cap electromagnetic calorimeters of the STAR facility. These detectors are the key elements for the polarization research program.

Development of various software components: the method of kinematic and topological fitting for the reconstruction of hyperons, the development of a programs set for the alignment of TPC and the silicon vertex detector of the STAR setup, the development of algorithms for the particle identification in the TPC (identity method), the development of algorithms for the jets and neutral pion reconstruction in the end-cap electromagnetic calorimeter.

Simulation of asymmetries of direct photon and jet production in proton-proton collisions using the spin-dependent gluon distributions.

Monte Carlo simulation of the effect of global polarization of lambda hyperons in the overlapping STAR / RHIC and NICA / MPD energy ranges.

Participation in the production and assembly of a reaction plane detector (EPD) for the energy scanning program.

Development of the JINR software infrastructure for the STAR data processing at JINR (STAR-JINR end-to-end GRID production). Use of LIT computer power to prepare data obtained from the STAR experiment in the PicoDST format.

Development of the phenomenological approach and analysis of the STAR data using the z-scaling model. The method is based on the fundamental physical principles, such as relativistic invariance, self-similarity, locality and fractality in processes of multiple production in p+p, p+A and A+A collisions. Within the framework of this approach, the analysis of STAR data over the energy range of 7.7-200 GeV was carried out and estimation of the energy losses of constituents traveling in the nuclear matter were made. The results are important for the search for signatures of the phase transitions and a critical point of the nuclear matter.

Development of the method of event-by-event analysis to search for fractal structures in nucleus-nucleus collisions at different energies and collision centralities as one of the approaches for searching for signatures of phase transitions in nuclear matter.

The scaling properties of strange particles production in proton-proton collisions at RHIC energies were investigated.

Development and application of the correlation femtoscopy methods for studying Λ-Λ correlations and antiproton-antiproton interactions.

2b. List of the responsibilities of the JINR group members within the management structure of the collaboration, if any, giving the name of the JINR member, the managerial role and the appointment period:

Richard Lednicky, Yury Panebrattsev – members of the STAR Council.

Olga Evdokimov (Barannikova) is a former member of the JINR group in the STAR experiment (currently professor at UIC Chicago). She was a deputy spokesperson of STAR for a long time, and until 2020 was Chair of the STAR Council).

3.   Publications:

List the papers published in the refereed literature (no conference proceedings) to which the JINR group made ~~had~~ a major contribution (e.g. author of the analysis, promoter of the experiment, corresponding author, implementation realization of the key equipment, etc.). Give the title of the paper, the reference and describe in 1-2 sentences the JINR contribution in 1-2 sentences. Only the papers published since the last approval of the project should be listed.

Mention the total number of papers published by the project in the same time period:

The STAR collaboration papers with JINR group participation:

1. “Net-proton number fluctuations and the Quantum Chromodynamics critical point”, Phys. Rev. Lett. 126, 92301 (2021).

(participation in the data analysis)

2.“Measurement of the longitudinal spin asymmetries for weak boson production in proton-proton collisions at = 510 GeV”, Phys. Rev. D 99 (2019) 051102.

(realization of the key equipment, participation in the data analysis)

3.“Longitudinal double-spin asymmetry for inclusive jet and dijet production in pp collisions at = 510 GeV”, Phys. Rev. D 100 (2019) 052005.

(realization of the key equipment, participation in the data analysis)

4.“Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton”, Nature Physics, 16 (2020) 409–412.

(participation in the data analysis)

5.“Global polarization of Χ, Ξ and Ω hyperons in Au + Au collisions at  = 200 GeV”. Phys. Rev. Lett. 126 (2021) 16, 162301.

(participation in the data analysis)

6.“Global and local polarization of Λ hyperons in Au + Au collisions at 200 GeV from STAR”. Nuclear Physics A 982 (2019) 511–514.

(participation in the data analysis)

The JINR group has prepared the following publications on the research of relativistic nuclei and proton structure based on the STAR data measurements:

1. M.V. Tokarev, I. Zborovsky, A.O. Kechechyan

” Validation of *z*-scaling for negative particle production in Au + Au collisions from BES-I at STAR”, Nucl. Phys. A993 (2020) 121646 (47 p.).

1. M.V. Tokarev, I. Zborovsky, A.O. Kechechyan, T.G. Dedovich

“*z*-Scaling in *p* + *p*, anti-*p* + *p* and Au + Au Collisions at RHIC, Tevatron and LHC”, Physics of Particles and Nuclei, 2020, Vol. 51, No. 2, pp. 141–171.

1. I. Zborovsky , M.V. Tokarev,

“Self-Similarity, Fractality and Entropy Principle in Collisions of Hadrons and Nuclei at Tevatron, RHIC and LHC”, Published in the Proceedings of the 40th International Conference on High Energy physics – ICHEP2020, July 28 – August 6, 2020, Prague, Czech Republic, Proceedings of Science, 2020, PoS (ICHEP2020) 575.

1. M.V. Tokarev, A.O. Kechechyan, I. Zborovský

“Self-Similarity of Negative Particle Production in Au + Au Collisions at STAR”, Physics of Particles and Nuclei Letters, 2019, Vol. 16, No. 5, pp. 510–515.

1. M.V. Tokarev, I. Zborovsky

“Self-Similarity, Fractality and Entropy Principle in Collisions of Hadrons and Nuclei at Tevatron, RHIC and LHC”,

Phys. Part. Nucl. Lett., 2021, v.18, № 3, pp. 302–314.

1. T.G. Dedovich, M.V.Tokarev,

” Reconstruction of the Dimension of Complete and Incomplete Fractals“, Physics of Particles and Nuclei Letters, 2019, Vol.16, № 3, pp. 240–250.

1. T.G. Dedovich, M.V.Tokarev,

“Criteria of fractal reconstruction and suppression of background events by SePaC method”, Physics of Particles and Nuclei Letters, 2021, Vol. 18, No. 1, pp. 93–106.

The total number of papers published by STAR in the same time period is more than 60.

4.   PhD theses:

List the PhD theses completed within the last 3 years or expected to be completed within one year by JINR students within the project, giving the student’s name, thesis title, and graduation year:

The PhD thesis of Alexei Aparin was completed in 2017. In the last 3 years, 7 BSc and MSc theses were completed.

5.   Talks:

5a. List the invited plenary talks given by the members of the JINR group at international conferences, workshops, etc. since the last approval of the project: give the name and the date of the Conference, the title of the talk, and the speaker’s name:

The members of the JINR group prepared the following reports at international conferences, meetings of the STAR collaboration, and seminars:

1. “*z*-Scaling from hundreds of MeV to TeV”, Relativistic Nuclear Physics from hundreds of MeV to TeV”, May 26–June 1, 2019, Stara Lesna, Slovakia.
2. “High-*pT* spectra of *h*– hadrons in Au + Au collision at = 9.2 GeV”, STAR Collaboration Meeting, 14–25 September, 2020, Indian Institute of Science Education and Research (IISER) Tirupati, India.
3. “Search for fractal structures in Au + Au events at 200 GeV”, STAR Collaboration Meeting, 14–25 September, 2020, Indian Institute of Science Education and Research (IISER) Tirupati, India.
4. “Self-similarity, fractality and entropy principle in collisions of hadrons and nuclei at RHIC, Tevatron and LHC”, 40th International Conference on High Energy physics – ICHEP2020, July 28 – August 6, 2020, Prague, Czech Republic.
5. “Self-similarity of the proton spin”, Workshop “Physics programme for the first stage of the NICA SPD experiment”, JINR, Dubna, LHEP, 5–6 October 2020.
6. “Lambda hyperon reconstruction in nucleus-nucleus collisions and global polarization”, Workshop in the National Center of Nuclear Research, Baku 21.01.2020.
7. “STAR Recent Results on Heavy-Ion Collisions”, LXX International Conference NUCLEUS-2020, online conference, 11–17 October 2020.

5b. Give a similar list of parallel talks.

**C. Plans and requests**

6.   Plans:

Describe the plans of the JINR group within the project, in physics analysis, data taking, software development. Detector R&D, detector operation and maintenance, upgrade activities … for the period of time of the requested extension.

In the proposed project it is planned to perform the following:

1. Analysis of the experimental data obtained in BES-II. STAR measurements with high statistics at a minimum collider energy of 7.7 GeV and a minimum beam energy in experiments with a fixed 3 GeV target are especially important for calibrations and comparison with the planned measurements at the NICA/MPD and BM@N facilities. Measurements at RHIC are important for JINR, since they will provide preliminary information on physical processes in the energy range of the NICA collider, which will have a higher luminosity during the measurements.

2. BES-II data analysis to obtain the momentum spectra, to verify the self-similarity of particle production, to estimate the constituent energy losses, to study the cumulative particle production and to search for phase transition signatures.

3. Event-by-event data analysis of Au + Au collisions at energy =200 GeV and different centralities obtained by STAR Collaboration at RHIC, with the aim to search for fractal structures in nuclear matter. The further development of the method for fractal analysis of events of nucleus-nucleus interactions.

4. Participation in the Hot QCD Physics Program with an emphasis on the study of pseudorapidity dependence of global hyperon polarization.

5. Participation in the Cold QCD Physics Program and study of spin effects in collisions of polarized protons with protons and nuclei.

***Cold QCD Physics with p↑ + p↑ Collisions at 510 GeV:***

* inclusive transverse spin asymmetries at forward rapidities;
* transversity, Collins function and interference fragmentation function;
* Sivers and Efremov-Teryaev-Qiu-Sterman function.

***Polarized p↑ + p and p↑ + A collisions at 200 GeV:***

* forward transverse spin asymmetries;
* Sivers effect;
* transversity and related quantities.

6. Analysis of the data from fixed target experiments

* high moments of proton multiplicity distributions,
* new results on hypernuclei production (, ).

7. There is an enhanced interest in the production of light ions, which surprisingly appears to be in agreement with the predictions of the particle number ratios in both statistical and coalescence models. The first model is unjustified due to a huge difference between the temperature of chemical freeze-out of ~ 160 MeV and the binding energy of a few MeV. A possibility to distinguish these models has been suggested based on the yields of 4Li and 4He.

8. New BES-II net-proton kurtosis and light nuclei yield ratio measurements and their data analysis, including measurements at the minimal collider energy of 7.7 GeV and additional measurements at 17.3 GeV.

9. Further development and application of the methods of correlation femtoscopy developed at JINR based on particle momentum and spin correlations due to quantum statistics and final state interaction. It will allow us for a systematic study of the space-time picture of particle production and a study of their strong interaction, including the interaction in various combinations of hyperons, kaons and nucleons; the latter being necessary for obtaining the equation of the state of dense nuclear matter and determining the properties of neutron stars.

10.  Monte Carlo simulation and software development:

- event-by-event Monte Carlo simulation and comparison with the STAR data

- development of particle identification methods

- using the event plane detector for data analysis

- development of machine learning techniques for data analysis

11. Software infrastructure for the STAR data processing at JINR. STAR-JINR end-to-end GRID production.

7.   Group size, composition, and budget:

7a. List the JINR personnel involved in the project, including the name, the position (e.g. PI, researcher, post-doc, student, engineer, technician, etc.), and the FTE. Mention the total number of people in the collaboration.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **№** | **Name** | **Position** | **FTE** | **Country/Lab** |
| 1 | A. Aitbaev | student | 0.5 | Kazakhstan |
| 2 | A.A. Aparin | researcher | 1 | LHEP |
| 3 | G.S. Averichev | researcher | 0.5 | LHEP |
| 4 | H.N. Agakishiev | researcher | 1 | LHEP |
| 5 | N.A. Balashov | programmer | 0.2 | LIT |
| 6 | T.G. Dedovich | researcher | 1 | LHEP |
| 7 | I.Zh. Bunzarov | researcher | 0.5 | Bulgaria |
| 8 | N.Y. Chankova-Bunzarova | researcher | 0.5 | Bulgaria |
| 9 | V.B. Dunin | engineer | 0.5 | LHEP |
| 10 | P. Filip | researcher | 0.5 | Slovakia |
| 11 | A.O. Kechechyan | researcher | 1 | LHEP |
| 12 | O. Kenzhegulov | student | 0.5 | Kazakhstan |
| 13 | K.V. Klygina | engineer | 1 | LHEP |
| 14 | V.V. Korenkov | researcher | 0.2 | LIT |
| 15 | A.A. Korobitsyn | researcher | 1 | LHEP |
| 16 | R. Lednický | project leader | 0.5 | LHEP |
| 17 | V.V. Lyuboshitz | researcher | 1 | LHEP |
| 18 | S.I. Manukhov | student | 0.5 | LHEP |
| 19 | V.V. Mitsyn | programmer | 0.2 | LIT |
| 20 | M.P. Osmachko | engineer | 0.5 | LHEP |
| 21 | G.A. Ososkov | researcher | 0.2 | LIT |
| 22 | Yu.A. Panebrattsev | project leader | 1 | LHEP |
| 23 | S.S. Panyushkina | student | 0.5 | LHEP |
| 24 | E.A. Pervyshina | student | 0.5 | LHEP |
| 25 | E.V. Potrebenikova | programmer | 1 | LHEP |
| 26 | N.E. Sidorov | programmer | 0.5 | LHEP |
| 27 | E. Shakhaliev | researcher | 1 | Azerbaijan |
| 28 | S.I. Snigirev | student | 0.5 | LHEP |
| 29 | M.V. Tokarev | researcher | 1 | LHEP |
| 30 | A. Tutebaeva | student | 0.5 | Kazakhstan |
| 31 | N.I. Vorontsova | engineer | 0.5 | LHEP |
| 32 | S.F. Vokal | researcher | 0.5 | Slovakia |
| 33 | I. Zborovsky | researcher | 0.5 | Czech Republic |

7b. Present the JINR group budget for the period of time of the requested extension, specifying the main budget items (equipment, computing, salaries, common funds, travel expenses, etc.):

The table below shows the request of funding for the project in 2022–2024.

Table. Project cost estimation

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **№** | **Name** | **Full Cost**  **(kUSD)** | **Expenses per Year (kUSD)** | | |
| **2022** | **2023** | **2024** |
| 1 | Materials and Equipment | **75,0** | 25,0 | 25,0 | 25,0 |
| 2 | Payments for agreement-based research | **45,0** | 15,0 | 15,0 | 15,0 |
| 3 | Travel Expenses | **165,0** | 55,0 | 55,0 | 55,0 |
|  | **Total direct expenses** | **285,0** | **95,0** | **95,0** | **95,0** |

7c. Indicate the use or needs of JINR computing resources for the group and for the project, if any.

All members of the JINR group are provided with computer resources (PC), have access to the computer resources of JINR LIT and the RHIC Computer Facility at BNL.