**APPROVED**

**JINR DIRECTOR**

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**PROJECT PROPOSAL FORM**

Opening/renewal of a research project/subproject of the large research infrastructure project within the Topical plan of JINR

**1. General information on the research project of the theme/subproject of the large research infrastructure project (hereinafter LRIP subproject)**

* 1. **Theme code / LRIP** (for extended projects) - *the theme code includes the opening date, the closing date is not given, as it is determined by the completion dates of the projects in the topic.*

**1.2 Project/LRIP subproject code** (for extended projects)

**1.3 Laboratory** BLTP

**1.4 Scientific field Theoretical Physics**

**1.5 Title of the project/LRIP subproject Theory of Hadronic Matter under Extreme Conditions**

**1.6 Project/LRIP subproject leader(s) V.V. Braguta, E.E. Kolomeitsev, S.N. Nedelko**

**1.7 Project/LRIP subproject deputy leader(s) (scientific supervisor(s))**

**2 Scientific case and project organization**

**2.1 Annotation**

Modern heavy ion accelerators make it possible to study the properties of strong interactions of elementary particles, which are described by quantum chromodynamics (QCD) under the influence of extreme external conditions. In particular, the quark-gluon matter that is created in such experiments is expected to have a temperature of several hundred MeV, the baryon chemical potential of about 100 MeV, external magnetic field eB ~ 1 GeV^2 and relativistic rotation with an angular velocity of ~ 10 MeV. Such conditions significantly change the properties of QCD. In the presented project, it is planned to study the properties of QCD at nonzero baryon density, high temperature, large external magnetic field and relativistic rotation using lattice simulation.

**2.2 Scientific case** (aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks)

The theory of strong interactions, quantum chromodynamics (QCD), is one of the most interesting and complex theories in modern theoretical physics. The complexity of QCD is related to the strong interaction between elementary excitations (quarks and gluons) at low energies, which leads to a significant change in the properties of these excitations. For this reason, QCD belongs to the class of strongly correlated systems that cannot be studied analytically based on the first principles.

There are many effective phenomenological models that are used to explain the nonperturbative properties of QCD. An important drawback of all these theories is the fact that they are not based on the first principles and contain uncontrollable systematic errors.

In the current situation, the most perspective approach to the theory of strong interactions, is the method of lattice simulation of QCD, which is well recognized in quantum field theory and, without a doubt, the most successful in studying the properties of QCD. Success of the Lattice simulation of QCD is based on several facts. Firstly, the method is based on principles of quantum field theory. Secondly, the uncertainties of the method well studied, controlled and subject to systematic improvement. Finally, due to the development of computer technology and algorithms, it is possible to study QCD with properties as close as possible to to reality (with dynamical quarks, physical masses of pi-mesons, large physical volumes and small lattice steps). Thanks to the development of lattice simulation of QCD at zero and nonzero temperature has been well studied.

Another area of ​​the phase diagram that is important to study is QCD with nonzero baryon density. The study of this area is important for understanding of various astrophysical phenomena, as well as descriptions results of the planned NICA and FAIR experiments. Unfortunately, the direct application of the lattice simulation method to the study of QCD properties at nonzero baryon density is impossible. This is related to the so-called "sign problem". The essence of this problem is as follows: when simulating QCD with dynamical quarks an important element of the calculations is the fermion determinant, which is positive definite at zero chemical potential, which makes it possible to use Monte Carlo methods (importance sampling) to calculate integrals over gluon degrees of freedom. The nonzero baryon density, which is introduced into the theory with the help of the corresponding chemical potential, leads to the fact that the fermionic determinant becomes complex and rapidly oscillating, which does not allow one to directly apply Monte Carlo methods standard in lattice QCD. The sign problem leads to the fact that the properties of QCD with nonzero baryon density are poorly understood.

However, there are a number of methods that allow one to overcome the sign problem. One of such methods is lattice simulation of QCD with nonzero imaginary chemical potential. The method is based on the fact that if real chemical potential in the fermionic determinant is replaced by the imaginary one, then the determinant becomes positive definite, i.e. lattice simulation is possible. The results obtained by simulating QCD with an imaginary chemical potential can be analytically continued into the region of the real chemical potential. Note that this approach is widely used by various lattice groups.

In the presented project, it is planned to study the properties of QCD at non-zero baryon density, non-zero temperature and non-zero magnetic field using lattice simulation with an imaginary chemical potential, dynamic u-, d-, and s--quarks and the physical mass of the pi-meson. To conduct such a study, a program written by our group that implements advanced supercomputer technologies and algorithms will be used.

It is expected that quark-gluon matter, which is produced in the process of collision of heavy ions, is not only highly heated, is affected by a strong magnetic field, but and has a non-zero angular velocity of rotation. Therefore, to interpret the results heavy ion collision experiments an important theoretical problem is the study of the properties of rotating quark-gluon matter. In the presented project, we are planning for the first time to study the properties of rotating quark-gluon matter in the framework of lattice simulation.

In more detail, within the framework of the project it is planned to solve the following scientific problems:

1. It is planned to study various issues related to the influence of rotation on the properties of gluodynamics and QCD. In particular, it is planned to study the equation of state of a rotating QCD, the effect of rotation on the confinement/deconfinement phase transitions and the breaking/restoration of chiral symmetry, the effect of rotation on the interaction potential of static quarks, inhomogeneous phases of rotating quark matter, etc.
2. It is planned to study the simultaneous influence of the magnetic field and the baryon density on the QCD equation of state. In this case, lattice calculations will be carried out with the physical masses of dynamic u-, d-, s-quarks.

It is important to note that the planned studies to be carried out within the framework of the project are important for understanding the results of the NICA experiment, and many of the planned results will be obtained for the first time.

**2.3 Estimated completion date**

**2.4 Participating JINR laboratories**

LIT

**2.4.1** **MICC resource requirements**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Computing resources** | **Distribution by year** | | | | |
| 1st year | 2nd year | 3rd year | 4th year | 5th year |
| Data storage (TB)  - EOS  - Tapes |  |  |  |  |  |
| Tier 1 (CPU core hours) |  |  |  |  |  |
| Tier 2 (CPU core hours) |  |  |  |  |  |
| SC Govorun (CPU core hours)  - CPU  - GPU | CPU: 1.3\*107  GPU:  2.7\*104 | CPU: 1.3\*107  GPU:  2.7\*104 | CPU: 1.3\*107  GPU:  2.7\*104 | CPU: 1.3\*107  GPU:  2.7\*104 | CPU: 1.3\*107  GPU:  2.7\*104 |
| Clouds (CPU cores) |  |  |  |  |  |

**2.5. Participating countries, scientific and educational organizations**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Country** | **City** | **Participants** | **Type**  **of agreement** |
| IHEP | Russia | Protvino | Bonyakov V.G., Rogalev R.N., Kudrov I.E. |  |
| DVFU | Russia | Vladivostok | Molochkov A.V., Goj V.A., Girasimenyuk N.V. |  |

**2.6. Key partners** *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

**3. Manpower**

**3.1. Manpower needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№**  **n/a** | **Category of personnel** | **JINR staff,**  **amount of FTE** | **JINR Associated**  **Personnel,**  **amount of FTE** |
| 1. | research scientists | 14 | 1 |
| 2. | engineers | 0 | 0 |
| 3. | specialists | 0 | 0 |
| 4. | office workers | 0 | 0 |
| 5. | technicians | 0 | 0 |
|  | **Total:** | **14** | **1** |

**3.2. Available manpower**

**3.2.1. JINR staff**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **No.** | **Category of personnel** | **Full name** | **Position** | **Amount**  **of FTE** |
| 1. | research scientists | Braguta Viktor Valerievich | Head of sector | 100% |
| 2. |  | Voskresenskij Dmitrij Nikolaevich | Chief Researcher | 100% |
| 3. |  | Ivanov Yurij Borisovich | Leading researcher | 100% |
| 4. |  | Kolomejczev Evgenij Eduardovich | Leading researcher | 100% |
| 5. |  | Trambak Bhattacharyya | Senior researcher | 100% |
| 6. |  | Roenko Artyom Aleksandrovich | Senior researcher | 100% |
| 7. |  | Masayasu Hasegawa | Senior researcher | 100% |
| 8. |  | Voronin Vladimir Eduardovich | Researcher | 100% |
| 9. |  | Simon Liebing | Researcher | 100% |
| 10. |  | Nikolskij Aleksej Vladimirovich | Junior researcher | 100% |
| 11. |  | Sychev Dmitrij Aleksandrovich | Trainee researcher | 100% |
| 12. |  | Tsegelnik Nikita Sergeevich | Trainee researcher | 100% |
| 13. |  | David Montenegro | Researcher | 100% |
| 14. |  | Yonggoo Heo | Researcher | 100% |
| 15. |  | Snigiryov Aleksandr Mikhajlovich | Leading researcher | 50% |
|  | **Total:** | **15** |  |  |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Category of personnel** | **Partner organization** | **Amount of FTE** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
| 4. | technicians |  |  |
|  | **Total:** |  |  |

**4. Financing**

**4.1 Total estimated cost of the project/LRIP subproject**

The total cost estimate of the project (for the whole period, excluding salary).

The details are given in a separate table below.

**4.2 Extra funding sources**

Expected funding from partners/customers – a total estimate.

**Project (****LRIP subproject) Leader** \_\_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: \_\_\_\_\_\_\_\_\_

Date of decision of the laboratory's STC: \_\_\_\_\_\_\_\_\_ document number: \_\_\_\_\_\_\_\_\_

Year of the project (LRIP subproject) start: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

(for extended projects) – Project start year: \_\_\_\_\_\_\_

**Proposed schedule and resource request for the Project / LRIP subproject**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Expenditures, resources,**  **funding sources** | | | | **Cost (thousands**  **of US dollars)/**  **Resource requirements** | | **Cost/Resources,**  **distribution by years** | | | | | | | | | |
| 1st year | | 2nd year | | 3rd year | | 4th year | | 5th year | |
|  | | | International cooperation | |  | |  | |  | |  | |  | |  |
| Materials | |  | |  | |  | |  | |  | |  |
| Equipment, Third-party company services | |  | |  | |  | |  | |  | |  |
| Commissioning | |  | |  | |  | |  | |  | |  |
| R&D contracts with other research organizations | |  | |  | |  | |  | |  | |  |
| Software purchasing | |  | |  | |  | |  | |  | |  |
| Design/construction | |  | |  | |  | |  | |  | |  |
| Service costs (*planned in case of direct project affiliation)* | |  | |  | |  | |  | |  | |  |
| **Resources required** | **Standard hours** | Resources | |  | |  | |  | |  | |  | |  | |
| * the amount of FTE, | |  | |  | |  | |  | |  | |  | |
| * accelerator/installation, | |  | |  | |  | |  | |  | |  | |
| * reactor,… | |  | |  | |  | |  | |  | |  | |
| **Sources of funding** | **JINR Budget** | JINR budget *(budget items)* | |  | |  | |  | |  | |  | |  | |
| **Extra fudning (supplementary estimates)** | Contributions by  partners  Funds under contracts with customers  Other sources of funding | |  | |  | |  | |  | |  | |  | |

Project (LRIP subproject) Leader\_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/

Laboratory Economist \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/

**APPROVAL SHEET FOR PROJECT / LRIP SUBPROJECT**

TITLE OF THE PROJECT

**Theory of Hadronic Matter under Extreme Conditions**

SHORT DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/LRIP SUBPROJECT CODE

THEME / LRIP CODE

NAME OF THE PROJECT LEADER : **V.V. Braguta, E.E. Kolomeitsev, S.N. Nedelko**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  | |
| AGREED |  |  |  | |
| JINR VICE-DIRECTOR | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF SCIENTIFIC SECRETARY | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| LABORATORY DIRECTOR | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF LABORATORY ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| LABORATORY SCIENTIFIC SECRETARY | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_  DATE |  |
| THEME / LRIP LEADER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_  DATE |  |
| PROJECT / LRIP SUBPROJECT LEADER | \_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| APPROVED BY THE PAC | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DA | |