REFEREE'S REPORT
on the project
"Studies of Baryonic Matter at the Nuclotron (BM@N)"
(theme 02-0-1065-2007/2023) in 2022-2026

The theoretical and experimental investigation of the properties of strongly interacting matter at high temperatures and densities is one of the most exciting research programs of modern high-energy nuclear physics. Determination of the phase diagram of nuclear matter is a key task of all present experiments at heavy-ion accelerators like LHC and SPS at CERN, RHIC at BNL, and SIS18 at GSI. Future projects FAIR at GSI and NCA at JINR are expected to clarify the role of quark and gluon degrees of freedom in phase transition of strongly interacting nuclear matter.

Main goal of the BM@N project is to study properties of the baryon matter produced in heavy ion collisions with the fixed target in the range from 1 to 4.5 GeV per nucleon. BM@N set-up is created by the international collaboration to perform scientific program at the NICA-Nuclotron accelerator complex in VBLHEP JINR (Dubna). Discovery of clear signatures of phase transitions, critical points, and study of phases of the matter are high priority tasks of modern investigation in high energy nuclear physics. It is also expected that the obtained results could shed light on the properties of neutron stars.

We consider that the research program of the BM@N project has a high physical motivation.

Thermodynamics is the only possible tool for the study of multiparticle nuclear systems. Therefore, the search for correspondence between the theoretical and experimental thermodynamic quantities like pressure, temperature, chemical potential, and others which play an important role for determination of Equation-of-State (EoS) and for study properties of the nuclear system like compressibility, heat capacity, magnetic susceptibility and others is of extremally importance. The unusual features of nuclear matter connect with the existence of baryons and mesons with strange quarks. EoS is one of ingredients for description of the nuclear matter in the framework of hydrodynamic approach. In the approach the properties of matter like the direct and elliptic flows of different strange and non-strange particles (π, p,K) and nuclei (d, T, He), and vorticity are extensively studied.

It is expected that results from of the BM@N research program can give new constraints on the statistical and hydrodynamical models.

The study of subthreshold strangeness production in heavy-ion collisions is another direction of investigations within BM@N setup. It is expected that production of multi-strange hyperons and (anti-)hyperons (Ξ and Ω) is sensitive to properties of the high-density matter and can constrain the possible EoS equations. Therefore, the measurement of multi-strange hyperons will be a central goal of the BM@N research program at the Nuclotron.

Hypothesis of mixed phase of nuclear matter is extremely popular. It based on assumption that the phases with hadron and quark-gluon degrees of freedom can be exist simultaneously at high energy density. It is also assumed that the thermodynamical equilibrium both for nonstrange and strange baryons, and multi-strange hyperons exist nearby a phase transition line.

Some evidence of the deconfined phase have been obtained at RHIC and LHC at high energy density of the produced nuclear matter. The energy density reached at Nuclotron can be sufficiently high to see the onset of deconfinement. Therefore, the BM@N research program includes the measurement of the excitation function of multi-strange hyperons in Au+Au collisions to explore the onset of equilibration of multi-strange hyperons at high net-baryon densities.

Hyperons can be also used as probes of the nuclear matter. If the hyperon chemical potential in dense nuclear matter falls below the chemical potential of neutrons and protons, these particles will decay into hyperons. Calculation results by using statistical model and transport models show that light hypernuclei and even double-lambda hypernuclei can be abundantly produced in heavy-ion collisions at Nuclotron and NICA energies. This opens additional opportunity for the upgraded

BM@N experiment, to measure light hypernuclei in Au+Au collisions at the Nuclotron beam energies..

Detector for studies of Baryonic Matter at Nuclotron (BM@N)

Project contains information on BN@N detector and accelerator complex. BM@N is the first fixed target experiment at the accelerator complex of NICA-Nuclotron. The Nuclotron will provide acceleration of beams from protons to gold ions with the kinetic energy from 1 to 6 GeV per nucleon. The maximum kinetic energy of protons is 13 GeV. The beam line between the Nuclotron and the BM@N experiment is around 160 meter in length. It comprises 26 elements of magnetic optics: 8 dipole magnets and 18 quadruple lenses. An upgrade program of the beam line is foreseen to minimize the amount of scattering material on the way of heavy ions to the BM@N setup. The intensity of the gold ion beam at BM@N is planned to be few 10^6 ions/s. The acceleration of the gold ion beam is expected after the Nuclotron upgrade in 2022. The acquisition rate of central, or intermediate interactions is expected to range from 20 to 50 kHz at the second stage of the BM@N experiment in 2022.

The Project contains main characteristics of the experimental setup. These are Central and Outer trackers, Time-of-Flight (ToF) system, Calorimeters, Trigger system and Beam detectors, Read-out electronics and DAQ system.

The experiment combines the high precision measurement of track parameters with ToF information for particle identification and presumes a measurement of the total energy by the hadron calorimeter to analyze the collision centrality.

The charged track momentum and multiplicity will be measured using a set of forward silicon detectors (FwdSi), large aperture silicon tracking system (STS), 7 planes of two-coordinate GEM (Gaseous Electron Multiplier) detectors mounted downstream of the target inside of the analyzing magnet. The GEM detectors are operational at high particle densities and in strong magnetic fields.

The magnetic field can reach a maximum value of 1 T, which makes it possible to optimize the BM@N geometrical acceptance and resolution on momentum for different processes and energies of the beam. The outer tracking system will consist of cathode strip chambers which will supplement the existing drift chambers to increase the effectiveness of track measurement in Au+Au collisions. The ToF detectors based on the multi-gap Resistive Plate Chamber (mRPC) technologies with strip readout provide an opportunity to separate hadrons (π, K, p) and light nuclei with momentum up to few GeV/c. The Zero Degree Calorimeter (ZDC) detector is foreseen for the extraction of the collision centrality by measuring the energy of the fragments of colliding particles. The scintillator multiplicity Barrel detector is planned to generate a trigger signal for the data acquisition system. A set of beam trigger detectors will also provide a starting signal (T0) for the ToF detectors.

In 2022, after the heavy ion program upgrade, the BM@N experiment will start with middle size ion (Kr, Xe) beams. At the second stage of the BM@N experiment after 2023, four two-coordinate planes of the STS detectors will be installed in front of the GEM detectors to improve track reconstruction in heavy ion collisions. The STS FEE electronics is capable to register interactions with the event rate of 50 kHz, which is the primary goal of the BM@N experiment.

Project describes the configuration of the BM@N central tracker, beam parameters and event rates in future BM@N heavy ion runs.

BM@N performance in the first experimental runs was described in the Project.

Technical runs with the BM@N detector were performed in the deuteron beam in December 2016 and in the carbon beam in March 2017. The kinetic energy was 4 GeV/nucleon for the deuteron beam and was varied from 3.5 to 4.5 GeV/nucleon for the carbon beam.

The extended configuration of the BM@N set-up was realized in the next runs with the argon and krypton beams performed in March 2018. The set-up comprised six 2-coordinate planes GEM detectors, three forward silicon strip Si planes, outer tracker based on two drift chambers DCH and a cathode strip chamber CSC, full ToF system consisting of ToF-400 and ToF-700, extended trigger system T0T, hadron ZDC and electromagnetic ECAL calorimeters. The collected data were used to check efficiencies of sub-detectors and develop algorithms for the event reconstruction and analysis. The minimum bias data with different targets were analyzed with the aim to reconstruct tracks, primary and secondary vertices using the central tracking detectors.

Results of Λ yields in minimum bias C+C, C+Al, C+Cu obtained by BM@N were compared with the Monte Carlo simulations (DCM-QGSM and UrQMD models) and with HADES and Propane Chamber data. Results of Λ yields in minimum in argon-nucleus interactions were also studied and found in agree with carbon-nucleus data. Charged kaons and pions, as well as protons and light nuclear fragments, were identified in the experimental data obtained in interactions of the 3.2 AGeV argon ion beam with fixed targets (C,Al,Cu,Sn,Pb) using the central tracking system and the time-of-flight system of ToF-400 and ToF-700 based on the mRPC detectors.

The analysis to correct the identified data for the detector acceptance and efficiencies and extract the yields of $\pi^{\pm}$, $K^{\pm}$ mesons, Λ hyperons and light nuclear fragments (He^3, d/He^4) in argon-nucleus interactions is in progress.

Simulation of the central tracker for the heavy ion program has been performed. Results for efficiency of the Λ decay product reconstruction in the hybrid FwdSi+GEM tracker in simulated Kr+Pb interactions, momentum resolution as a function of the particle momentum calculated for different values of the magnetic field, efficiency of primary charge particles, signals of Ξ^- hyperon and ${}_{\Lambda}H^3$ hypernucleus in the corresponding invariant mass spectrum reconstructed in the hybrid STS+GEM tracker were obtained.

Detail information on subdetectors of BN@M setup are also presented in the project.

These are Central and Outer trackers, Time-of-Flight system, Calorimeters, Trigger system, Read-out electronics and DAQ system. The BmnRooT framework and analysis software was also described.

Central tracking system of the BM@N experiment should provide precise momentum measurements of the cascade decays products of multi-strange hyperons and hyper-nuclei produced in central Au-Au collisions in conditions of high beam intensities in collisions with large multiplicity of charged particles. The basic requirements for the system are capability of stable operation in conditions of high radiation loadings up to 10^5 Hz/cm^2, high spatial and momentum resolution, geometrical efficiency better than 95%, maximum possible geometrical acceptance within the BM@N experiment dimension, operation at 0.8 T magnetic field. Detectors based on the GEM technology possess all the mentioned characteristics combined with the capability of stable operation in a strong magnetic field up to 1.5 T.

BM@N GEM detectors

Two coordinate triple GEM detectors were chosen for the central part of the BM@N tracking system. Beam tests of seven GEM chambers equipped with FEE were performed in 2018 with the Argon and Krypton beams. The tracks of charged particles were reconstructed and track detection efficiency of the GEM chambers at the level of 95% was obtained.

Front-end electronics and DAQ system

For heavy ion program with the beam intensities up to few 10^5 Hz GEM front-end electronics is based on the charge sensitive pre-amplifier chip from IDEAS, Norway. The chip has 32 channels. The integral linearity is 1% and 3% for positive and negative charges, respectively. Each read out card includes four chips which are installed, bonded, and filled with black compound. For heavy ion program with the beam intensities up to few 10^6 Hz some GEM electronics are partially designed and tested. Before 2023 new electronics will be developed.

Gas distribution system

GEM chambers can be operated with Ar(70)/CO_2(30), Ar(90)/C_4H_{10}(10), Ar(80)/C_4H_{10}(20) gas mixtures. The gas system consists of the mixer system which delivers quantity, mixing ratio and pressure conditioning to downstream elements, and the distribution system, which delivers the gas in well-defined quantities to the individual detectors.

Integration into the BM@N setup

The final configuration of the central tracking system consists of 7 GEM detectors above the vacuum beam pipe and 7 GEM detectors below the vacuum beam pipe. The full configuration with 14 GEM detectors (~90000 readout channels) is planned to be integrated in the BM@N experimental setup at the middle of 2021. The GEM performance and characteristics are described in the TDR report.

Forward silicon detectors

Forward silicon detectors (FwdSi) are installed between the target and the GEM stations to increase the tracking efficiency and improve the precision of the primary vertex reconstruction. Design of the detectors (FwdSi) and results of simulation of the hybrid central tracking system based on the FwdSi and GEM detectors are presented in the Project.

Forward Silicon Detector upgrade plan

To increase the readout event rate capacity of the FwdSi tracker up to final 50 kHz it is planned to upgrade FEE electronics after the ongoing R&D will be done. The total number of the FwdSi readout channels is 81920.

STS tracker

In 2022 BM@N experiment will be upgraded to fit occupancy challenge of Au+Au collisions with beam energies up to 4.5A GeV. A new hybrid tracking system based on four large aperture stations of double-sided microstrip silicon sensors of high granularity followed by 7 planes of two-coordinate GEM detectors and a vacuum beam pipe will be installed. Results of the physics performance simulations of the hybrid tracker are presented in the Project.

The Silicon Tracking System (STS) of the BM@N consists of four stations equipped with 292 double-sided micro-strip silicon sensors providing information on the position, time and energy released by the particle passing through a sensor of the STS. The STS configuration is described in detail in the Project.

Silicon planes are currently under development following the design used for the STS of the CBM experiment. The BM@N STS project will be performed in two steps: firstly, two stations with 44 modules will be assembled, installed, and commissioned at the end of 2022, the full configuration will be ready in 2023-2024.

Outer tracker

The purpose of the Outer tracker is to provide link between tracks measured in the central tracker and hits in the ToF-400 and ToF-700 detectors. The granularity of DCH is sufficient to perform measurements of interactions with light ions (up to Ar) and not sufficient to perform track separation in middle and heavy nucleus collisions. Therefore, the DCH will be replaced by cathode strip chambers.

Cathode Strip chambers

The full configuration of the outer tracking system for heavy ion program will consist of six planes of CSC (cathode strip chamber). The CSC detectors are situated outside the magnetic field with the aim to make precise link to the tracks, reconstructed in the GEM detectors inside the analyzing magnet. Tracks refined in CSC are used to improve particles momentum reconstruction and to find corresponding hits in the time-of-flight systems ToF400 and ToF700.

The first CSC detector was designed and assembled at LHEP JINR in 2018. The CSC was installed upstream the ToF-400 time-of-flight detector.

The detail description of design of CSC, test results of the CSC detector and the FEE, Gas distribution system and readout electronics as a part of the BM@N experimental setup were described in Project.

Tracks of charged particles are reconstructed in the GEM central tracking system and extrapolated into the CSC. The efficiency distribution over the chamber surface is presented.

The full configuration with 6 CSC detectors equipped with the new electronics (~35000 readout channels) is planned to be integrated into the BM@N experimental setup at the end of 2022. The upgrade of the CSC FEE is planned on 2023.

ToF system

The time-of-flight (ToF) system is based on the start time T0 detector installed near to the target and two walls of multi-gap resistive plate chambers situated at distances of around 4 m (ToF-400) and 7 m (ToF-700) from the target. The time resolution of the ToF system of 80-100 ps is sufficient to discriminate between hadrons (π, K, p) as well as light nuclei with the momentum up to few GeV/c produced in multi-particle events.

All subsystems work well, but it is planned the specific upgrade to get best performance of the ToF-400. DAQ electronics for ToF-400 will be modified to reach trigger data rate of 50 kHz.

Service systems

The mRPC works with a non-flammable Freon-rich gas mixture. The simple open gas loop system based on MKS mass flow meters is used. Flows are monitored by a process control computer which continuously calculates and adjusts the mixture percentages supplied to the ToF. The same system is also used for ToF-700. New distribution module for divide gas flow between ToF-400 and ToF-700 systems is planned to produce. All main equipment for upgrade is purchased in 2020. The parameters as temperature, voltage, current, gas flow and etc for control the Time-of-Flight system of the BM@N are monitored. The slow control system has been developed. The data of the slow control system are used during experimental data analysis. All the slow control equipment components are acquired in 2017.

ToF-700 mRPC detector

Time-of-flight detector ToF-700 placed at about 7 m from the target provides BM@N with the pion/kaon separation up to 3 GeV/c and proton/kaon separation up to 5 GeV/c. ToF-700 system consist of 58 glass multigap Timing Resistive Plate Chambers. A number of FEE channels for ToF-700 is 3136. ToF-700 data analysis software was developed in the BmnROOT package framework. The analysis includes few stages and considers TDC non-linearity corrections, VME crates Time Stamp differences, time corrections versus the T0 pulse width, time corrections versus the T0F pulse width, equalization of each strip time response for the main time peak. Finally, track reconstructed in GEM+DCH detectors and ToF-700 data are used to reconstruct proton tracks and calculate the time correction for each strip.

Calorimeters of BM@N setup

A new **forward hadron calorimeter** (FHCal) will be served as a Zero Degree Calorimeter (ZDC) at the BM@N setup. It will be used to measure the centrality and reaction plane orientation in planned heavy ion experiments. In 2020 this calorimeter was completely assembled, including the installation of FEE boards with photodetectors in all calorimeter modules, as well as readout electronics. The calorimeter has modular structure in the transverse plane and consists of 54 individual modules. The inner part of FHCal consists of 34 modules each has a length equal to 4 nuclear interaction lengths. The outer part consists of 20 modules length equivalent to about 5.6 nuclear interaction lengths. The modules were initially constructed for the CBM hadron calorimeter at the FAIR accelerator complex and will be temporary used in the hadron calorimeter of the BM@N experiment until the commissioning of the CBM experiment. All FHCal modules have sampling structure. The CBM modules have 60 lead/scintillator layers, while the MPD/NICA modules have 42 similar layers. Each layer consists of 16 mm lead plates and 4 mm scintillator plates. In 2020 the calorimeter was installed at the BM@N, equipped with FEE and readout electronics. The installation and adjustment of the 54 FEE readout electronics boards were carried out. Commissioning and energy calibration of the FHCal with cosmic muons was started in 2021.

Fragment quartz hodoscope for FHCal

The presence of a beam hole in the calorimeter leads to a significant leakage of heavy fragments through this hole and, therefore, to a non-monotonic dependence of the deposited energy in the calorimeter on the collision's centrality. To solve this problem, it was proposed to use together with the FHCal a nuclear fragment hodoscope (FQH), which will measure the charges of heavy fragments. The FQH consist of 16 quartz plates 160 mm long, 4 mm thickness and 10 mm width. Simulation of

Au+Au collisions at 4.5 AGeV with the DCM-QGSM model showed a clear correlation of the FQH signal amplitude and energy deposition in the FHCal. The FQH and FHCal are ready for first beam runs after finishing the BM@N upgrade.

Upgrade of the forward calorimeter system

It is proposed to extend forward calorimeter system, which include now FHCal and FQH, and add the ScWall (Scintillator Wall) detector to have the possibility to measure not only the centrality and reaction plane in heavy ion collisions but also to measure fragmentation of nucleus. The new forward calorimeter system including the ZDC, FQH and ScWall will be able to measure the fragmentation, centrality, and reaction plane in heavy ion reactions. It was shown in the simulation that such detector system will significantly improve the centrality resolution for semi-central events. It is planned that the construction of the ScWall will be performed during 2021-2022 and commissioning of new forward calorimeter system will be done in 2022. The full forward calorimeter system will be used in the BM@N heavy ion physics experiments.

Electro-magnetic calorimeter ECAL

The purpose of the electro-magnetic calorimeter is to study processes with electro-magnetic probes (γ, $e^{\pm}$) in the final state. The physics program of the BM@N experiment with the electro-magnetic calorimeter includes the study of known resonances and search for new resonances decaying into two γ quanta, the yield excess of η^0-mesons in nucleus-nucleus interactions, gamma femtometry, soft photon spectra at photon energies below 50 MeV, search the correlation between the phenomena of pion condensation and abnormal soft photons. The available modules of the MPD ECAL calorimeter will be installed behind the GEM detectors to serve as an electro-magnetic calorimeter in the BM@N experiment.

Trigger system and beam detectors

A system of trigger detectors consists of a set of scintillation and Cherenkov beam counters BC1, BC2(T0) and VC multiplicity detectors in the target area BD and SiD; target area multichannel detectors – a scintillation barrel detector BD and a silicon detector SiD; two forward detectors – a detector of charged nuclear fragments of beam ion FD and a forward hadron calorimeter FHCal. The detail description and characteristics of the trigger detectors of BM@N setup are given in the Project.

BM@N DAQ system and computing

The core function of the DAQ system is realization of data transfer from the detector to the storage system. It includes the data flow from readout electronics to the First Level Processor (FLP) fabric, to the Event Building (EB) and to the Storage System. Main DAQ components are data transfer networks, data processing servers, online storage system, Readout electronics interface, Clock and Time Synchronization (Timing) System and Trigger Distribution.

DAQ system at BM@N consist of electronic modules which include DAQ electronics, digitizing modules for all detectors at BM@N, detector control modules, front-end electronics, and specific modules; network infrastructure which includes White Rabbit Network, Data Transfer Network, Slow Control Network and First Level Processors (FLP); data processing, management, analyzing, utility, and control software.

The BmnRoot framework and analysis software

The activities on the detector and beam line construction are complemented with intensive Monte Carlo simulation studies for optimization of the detector setup. Monte-Carlo simulations aimed in the optimization of the BM@N design have been performed with a sample of generated Au+Au events and lighter ion interactions. A dedicated BmnRoot framework intended to process both simulated and obtained experimental data is developed. The same software package is used to define the experimental setup, provides detector performance studies, event simulation, and development of algorithms to be used for digitization, reconstruction, and physics analysis of particle collision events with a fixed target. BmnRoot is implemented on the basis of the CERN ROOT6 environment and object-oriented FairRoot framework of the FAIR collaboration at GSI Institute. BmnRoot is available in the JINR GitLab repository providing GIT Continuous Integration tests to ensure software correctness.

To study physics feasibilities of the experiment, BmnRoot supports a wide list of Monte-Carlo event generators with the proper physics effects, such as DCM-QGSM and DCM-SMM. Particle propagation through the detectors in simulation is performed using Geant-3 or Geant-4. The Fluka transport package is used to estimate radiation doses and neutron fluxes in the BM@N experimental zone.

The preliminary results obtained for the current configuration of the BM@N experiment show that for one month of the BM@N operation a storage size of approximately 340 TB is required for raw data and 85 TB to save reconstructed digits and DST files (3 software versions). Assuming 4 months of BM@N operation per year, the distributed storage should allow allocating up to 1.7 PB per year for BM@N data. It is important to note that the size of BM@N event is directly proportional to multiplicity, which is a function of interaction centrality. The amount of data taken in experimental runs varies with the detector setup, collision system and trigger conditions.

The description of BM@N experimental zone is presented in the Project. Simulations of radiation protection of the experimental zone were performed using FLUKA program to optimize the concrete shielding. A vacuum beam pipe will be integrated into the experimental setup to minimize the amount of scattering material on the way of heavy ion beam. The beam pipe will consist of three parts: section before the target, inside the analyzing magnet and after the analyzing magnet. The beam pipe before the target is produced from stainless steel and consists of standard vacuum modules and boxes for the beam detectors. This configuration of the beam pipe was designed, manufactured, and tested. A carbon beam pipe will be installed inside the analyzing magnet. Such configuration allows us to install different set-ups of tracking detectors using demountable flangeless connectors. The total length of the carbon beam pipe is 5 m. The thickness of the walls is 1 mm. It is design to sustain vacuum up to 10^{-3} Torr. The beam pipe after the analyzing magnet will be made of aluminum with a diameter of 125 mm and a wall thickness of 1 mm.

The BM@N collaboration includes highly qualified specialists from JINR and institutes of JINR Member States that have experience of participation in international projects.

The physics program of the BM@N experiment with considering the development of the accelerator complex NICA-Nuclotron, the full implementation of all subsystems and their upgrade is justified. The program presented in the Project is of interest for heavy ion nuclear physics community, the planned results are physically motivated.

Schedule of the commissioning of the installation components and their modernization, testing and physical runs is realistic.

The resources required for the project "Studies of Baryonic Matter at the Nuclotron (BM@N)" (theme 02-0-1065-2007/2023) in 2022-2026 are reasonable. I recommend supporting and prolong this work with the first priority and present the Project at the JINR PAC.

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