Studies of Baryonic Matter at the Nuclotron

BM@N Project

Prologation for 2017-2021

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Development of the JINR Basic Facility for Generation of Intense Heavy Ion and Polarized Nuclear Beams Aimed at Searching for the Mixed Phase of Nuclear Matter and Investigation of Polarization Phenomena at the Collision Energies up to $\sqrt{s} = 11$ GeV/n

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Introduction

Relativistic heavy ion collisions provide the unique opportunity to study nuclear matter under extreme density and temperature. In the collision, nuclear matter is heated up and compressed for a very short period of time. At moderate temperatures, nucleons are excited to baryonic resonances which decay by the emission of mesons. At higher temperatures, also baryon-antibaryon pairs are created. This mixture of baryons, antibaryons and mesons, all strongly interacting particles, is denoted as hadronic matter or baryonic matter if baryons dominate. If the energy density in the formed fireball is sufficiently large the quark-gluon substructure of nucleons becomes visible. At even higher temperatures or densities hadrons melt, and the constituents, quarks and gluons, form a new phase, the Quark-Gluon Plasma (QGP). At these extreme conditions the following features of strongly interacting matter can be studied: the equation-of-state (EoS) of strongly interacting matter at high temperatures and high net-baryon densities; the microscopic structure of strongly interacting matter as a function of temperature and baryon density; the in-medium modifications of hadrons which might provide information on the onset of chiral symmetry restoration. Theoretical models, however, suggest different possible scenarios to describe these features of strongly interacting matter. So that new experimental data with high resolution and statistics are needed in order to disentangle different theoretical predictions [1,1,1.2].

2. Physical motivation: Nuclotron heavy-ion physics program

The ratio of produced mesons to baryons in the fireball increases with the collision energy. A nucleus-nucleus collision at the Nuclotron beam kinetic energy in the range from 1 to 4.5 GeV per nucleon produces a baryon dominated fireball contrary to higher energies at RHIC or SPS. According to the QGSM transport model calculations [2,3] at the Nuclotron energies the nucleon densities in the collision zone of two gold nuclei exceed the saturation density by a factor of 3 - 4. At these densities nucleons start to overlap, and it is expected that under such extreme conditions the onset of chiral symmetry restoration might occur although quarks are still confined [2.4-2.8]. It will reveal in in-medium modification of hadrons, in particular, in collisional broadening, dropping mass of vector mesons decaying into di-leptons which are not much affected by final-state interactions.

The relevant degrees of freedom at the Nuclotron energies are first of all nucleons and their excited states followed by light and strange mesons. Also the partonic degrees of freedom should show up in small space-time volumes and leave their traces in final hadronic observables. The focus of experimental studies will be on hadrons with strangeness, which are early produced in the collision and not present in the initial state of two colliding nuclei, unlike nucleons made up from light (u, d)-quarks. The measured production yields of light and strange mesons, as well as of hyperons and anti-hyperons are show in figure 2.1 as a function of the nucleon-nucleon collision energy in c.m.s. The Nuclotron heavy ion beam energy range corresponds to $\sqrt{s_{NN}}$ = 2.3 - 3.5 GeV. It is well suited for studies of strange mesons and multi-strange hyperons which are produced in nucleus-nucleus collisions close to the kinematic threshold. Heavy-ion collisions are a rich source of strangeness, and the coalescence of lambda-hyperons with nucleons can produce a variety of light hyper-nuclei [2.7,2.8]. The study of the hyper-nuclei production is expected to provide new insights into the properties of the hyperon-nucleon and hyperon-hyperon interactions. Figure 2.2 presents the yields of hyper-nuclei as a function of the nucleon-nucleon collision energy in c.m.s. in Au+Au collisions, predicted by a thermal model [2.10]. The maximum in the hyper-nuclei production rate is predicted at $\sqrt{s_{NN}}$~ 4 - 5 GeV, which is close to the Nuclotron energy range.

In sum, the research program on heavy-ion collisions at the Nuclotron [2.11,2.12] includes the following topics: investigation of the reaction dynamics and nuclear EoS, study of the in-medium properties of hadrons, production of (multi)-strange hyperons at the threshold and search for hyper-nuclei. In order to interpret experimental data from heavy-ion collisions and to provide normalization for the measured A+A spectra, a study of elementary reactions (p+p, p+n(d)) is planned.
Figure 2.1. Yields of mesons and (anti-) hyperons as a function of the nucleon- nucleon collision energy in c.m.s. in Au+Au/ Pb+Pb collisions, taken from [2.9]. The Nuclotron BM@N heavy ion beam energy range corresponds to $\sqrt{s}_{NN} = 2.3$ - 3.5 GeV.

Figure 2.2. Yields of hyper-nuclei as a function of the nucleon-nucleon collision energy in c.m.s. in Au+Au collisions, calculated with a thermal model [2.10]. The predicted yields of $^3$He and $^4$He nuclei are included for comparison. The Nuclotron BM@N energy range $\sqrt{s}_{NN} = 2.3$ - 3.5 GeV is specified.

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

BM@N (Baryonic Matter at Nuclotron) is the first experiment at the accelerator complex of NICA Nuclotron. The schematic view of the NICA-Nuclotron complex and the position of the BM@N setup are presented in figure 3.3. The sources of light and heavy ions, the beam Booster, Nuclotron accelerator and NICA collider are shown. The heavy-ion physics program of the NICA accelerator complex and the MPD experiment planned at the NICA collider are described in [3.13-3.16]. The aim of the BM@N experiment is to study interactions of relativistic heavy ion beams with fixed targets [3.12]. The Nuclotron will provide verity of beams from protons to gold ions with the
kinetic energy of ions ranging from 1 to 6 GeV per nucleon. The maximum kinetic energy for ions with the ratio of the charge to the atomic weight (Z/A) of 1/2 is 6 GeV per nucleon. The maximum kinetic energy for heavy ions with the ratio of Z/A ~ 1/3 is 4.5 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 planned intensity of the gold ion beam accelerated and accumulated in the Nuclotron and the Booster and transported to the BM@N experimental zone is up to $10^7$ ions per second. The gold ion beam is expected in the end of 2018. In the period before 2018 the following ions are foreseen to accelerate: the polarized deuteron beam in 2016, the carbon, argon and krypton beams in 2017. In this period of operation the planned intensity of the beam interacting with the target inside the BM@N setup is $10^6$ ions per second. The proton-proton interactions will be studied after the Nuclotron upgrade in 2018 using the proton beam and the liquid hydrogen target.

Figure 3.4 shows the diagram of the interaction rates accepted by data acquisition systems of heavy ion experiments running at different energies of colliding nuclei. The beam energy range in the BM@N experiment overlaps partially with that in the HADES experiment. The interaction rate of triggered non peripheral central and intermediate events at the second stage of the BM@N experiment is expected to be around 50 kHz. It is limited by the capacity of the readout electronics and data acquisition system.

Figure 3.4. Heavy ion experiments: interaction rate and nucleon-nucleon collision energy in c.m.s.
A sketch of the proposed experimental set-up is shown in figure 3.5. The experiment combines high precision track measurements with time-of-flight information for particle identification and uses total energy measurements for the analysis of the collision centrality. The charged track momentum and multiplicity will be measured with the set of two coordinate planes of GEM (Gaseous Electron Multipliers) detectors located downstream of the target in the analyzing magnet and the drift/straw chambers (DCH, Straw) situated outside the magnetic field. The GEM detectors sustain high rates of particles and are operational in the strong magnetic field. The gap between the poles of the analyzing magnet is around 1 m. The magnetic field can be varied up to 1.2 T to get the optimal BM@N detector acceptance and momentum resolution for different processes and beam energies. The design parameters of the time-of-flight detectors based on multi-gap resistive plate chambers (mRPC-1,2) with a strip read-out allow us 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. The zero degree calorimeter (ZDC) is designed for the analysis of the collision centrality by measuring the energy of forward going particles. The T0 detector, partially covering the backward hemisphere around the target, is planned to trigger central heavy ion collisions and provide a start time (T0) signal for the mRPC-1.2 detectors. An electro-magnetic calorimeter will be installed behind the outer drift/straw chambers and mRPC-2 wall to study processes with electro-magnetic probes (γ, ℓ+) in the final state.

The first technical run of the BM@N detectors was performed with the deuteron and carbon beams in March 2015. The view of the BM@N setup in the run is presented in figure 3.6. The experimental data from the drift chambers, time-of-flight detectors, zero degree calorimeter, start time and trigger detectors were readout using the integrated data acquisition system. Meanwhile, the GEM detectors for the BM@N central tracker are being produced at the CERN workshop. The GEM detectors with the maximum size of 200 to 45 cm$^2$ are foreseen for the BM@N central tracker. The configuration of the central tracker in 2016 is based on at least six GEM planes of the half size. It will be extended up to eight GEM stations of the full size by the end of 2018. At the second stage of the BM@N experiment in 2020, at least four planes of two-coordinate silicon strip detectors will be installed between the GEM tracker and the target to improve the track reconstruction in Au+Au collisions. Presently, the detectors of this type are being developed for the CBM experiment [3.17]. Beam parameters and setup at different stages of the experiment are summarized in table 1.
3.2 BM@N performance and feasibility study

3.2.1 BMNROOT simulation and data analysis software

At present, the activities on the detector and beam line construction are complemented with intensive Monte Carlo simulation studies for optimization of the detector set-up. Monte-Carlo simulations aimed in the optimization of the BM@N design have been performed with a sample of generated Au+Au events. For these simulations a dedicated software framework (BMNRoot) has been developed. To obtain realistic detector responses very detailed geometrical description of each of the subdetectors was performed.

3.2.2 BM@N simulations and feasibility study

A focus in the simulation study is made on the detection of strange hyperons and hyper-nuclei in central (0-3 fm) Au+Au collisions at the maximal beam kinetic energy of 4.5 AGeV ($\sqrt{s_{NN}} = 3.46$ GeV). The simulation of Au+Au collisions is performed using the URQMD and DCM-QGSM models for heavy ion collisions. The products of collisions are transported through the BM@N setup using the GEANT program and reconstructed using the track reconstruction algorithm for multi-particle events developed for the CBM experiment [3.21].

Table 1. Beam parameters and setup at different stages of the experiment

<table>
<thead>
<tr>
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<th>2016</th>
<th>2017 spring</th>
<th>2017 autumn</th>
<th>2019</th>
<th>2020 and later</th>
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<td>Au</td>
<td>Au, p</td>
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<td>1M</td>
<td>1M</td>
<td>10M</td>
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<td>20k</td>
<td>20k</td>
<td>50k</td>
</tr>
<tr>
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<td>8 GEM half pl.</td>
<td>10 GEM half pl.</td>
<td>8 GEM full pl.</td>
<td>12 GEMs or 8 GEMs + Si planes</td>
</tr>
<tr>
<td>expeim. techn. status</td>
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<td>techn. run</td>
<td>physics run</td>
<td>stage 1 physics</td>
<td>stage 2 physics</td>
</tr>
</tbody>
</table>

Figure 3.6. BM@N setup in the first technical run in March 2015.
Figure 3.2.1. Left plot: large GEM system configuration with 12 stations aimed for measurements of Au+Au collisions. Right plot: GEM system inside the magnet.

Figure 3.2.1 shows the GEM system configuration with 12 stations foreseen for measurements of Au+Au collisions (large configuration). The detailed description of the GEM detector configuration is given in [3.22]. Figure 3.2.2 illustrates the amount of scattering material on the way of particles (material budget) in % units of the radiation length in the phase space of azimuthal and polar angles φ-θ. The large GEM stations consist of two 2-coordinate GEM detectors with the size of 200 x 45 cm². The sizes of the forward GEM stations are optimized to get maximal acceptance for the products of the cascade decay of Ξ⁻ hyperons, which also cross the first large GEM station. The strip pitch of the large GEM stations is 800 μm, the strip pitch of the first four forward GEM stations is 400 μm.

![Material budget of 12 GEM stations in the θ-φ space.](image)

Figure 3.2.2. Material budget of 12 GEM stations in the θ-φ space.

The residuals of the GEM strip clusters to the reconstructed tracks in Au+Au collisions are shown in figure 3.2.3. The coordinate resolution of the GEM planes in the X projection is around 60 μm. The resolution in the Y projection is worse due to the small inclination angle of the second coordinate to the vertical axis (7.5 degree for stations 1-4, 15 degree for stations 5-12).

![X and Y-coordinate track residual distributions for the GEM stations with the pitch of 800 μm.](image)

Figure 3.2.3. X and Y-coordinate track residual distributions for the GEM stations with the pitch of 800 μm.
Figure 3.2.4. Left plot: distribution of primary protons generated in Au+Au collisions at the beam kinetic energy of 4.5 AGeV in the phase space of the transverse momentum and rapidity in the laboratory frame. Right plot: acceptance of the GEM tracker for primary protons as a function of the particle transverse momentum and rapidity.

Figure 3.2.4 illustrates the distribution of primary protons generated in Au+Au collisions at the beam kinetic energy of 4.5 AGeV in the phase space of the transverse momentum and rapidity in the laboratory frame. The reconstruction efficiency of the GEM tracker for primary protons for the same phase space is shown on the right plot. The reconstruction efficiency of the GEM tracker with respect to generated primary particles (protons and pions) and with respect to reconstructable particles is presented in figure 3.2.5 as a function of the particle momentum. Reconstructable particles are those having points in at least 3 consecutive GEM stations.

Figure 3.2.5. Left plot: reconstruction efficiency with respect to generated primary particles vs momentum for primary protons and pions for the magnetic field $B = 0.44$ T. Right plot: reconstruction efficiency with respect to reconstructable particles.

The momentum resolution is shown in figure 3.2.6 as a function of the particle momentum for the magnetic field values in the centre of the magnet $B = 0.44$ and 0.22 T. The resolution of the $K^0_S$ invariant mass peak is also shown for the magnetic field values of 0.44 and 0.22 T.

Figure 3.2.6. Left plot: momentum resolution of the GEM tracker vs particle momentum. Right plot: $K^0_S$ invariant mass peak for two values of the magnetic field $B=0.44$ and 0.22 T.
The vertex impact parameter resolution of charged particles reconstructed in the GEM tracker is presented in figure 3.2.7. The distributions of the reconstructed primary vertex positions are also shown.

Figure 3.2.7. Left plot: vertex impact parameter resolution of charged particles reconstructed in the GEM tracker in the X and Y projections shown as a function of the particle momentum. Right plot: reconstructed vertex distributions in the X and Y projections.

Figure 3.2.8 presents the distributions of the invariant mass of decay products of Λ hyperon, Ξ⁻ hyperon and hyper-triton \(^3\Lambda\)H reconstructed with the GEM tracker in simulated central Au+Au collisions at the beam kinetic energy of 4.5 AGeV. The obtained results indicate that the proposed set-up has a reasonable reconstruction capability for strange hyperons produced in high multiplicity central Au+Au collisions. The reconstructed signals of Ξ⁻ hyperon and hyper-triton \(^3\Lambda\)H correspond to 0.9M and 2.6M of central collisions, respectively. Taking into account the signal reconstruction efficiency, data acquisition capacity of 20 kHz of triggered central collisions and the duty factor of the Nuclotron beam of 0.5, the expected statistics of Ξ⁻ hyperons and hyper-tritons \(^3\Lambda\)H for a month of the BM@N operation are 7.5M and 8.5M, respectively. The capacity to measure strange hyperons and hypernucleus is the instrument for further detailed studies of their production mechanisms in strongly interacting nuclear matter. The expected statistics is sufficient to perform measurements of strange hyperon and hyper-nuclei production yields and ratios, transverse momentum spectra, rapidity and angular distributions, as well as studies of fluctuations of event properties and various correlations between products of interactions.
Figure 3.2.8. Distributions of the invariant mass of decay products of Λ hyperon, Ξ⁻ hyperon and hyper-triton $^3\Lambda H$ reconstructed with the GEM tracker in central Au+Au collisions at the beam kinetic energy of 4.5 AGeV. Right bottom: topology of the cascade hyperon decays.

The start configuration of the BM@N central tracker is presented in figure 3.2.9. The central tracker set-up is simulated with 5 GEM detectors of the size of 66 x 41 cm² and two GEM detectors of the size of 163 x 45 cm². These detectors are combined into 6 GEM stations. The beam crosses the detectors in the middle of the sensitive planes. This configuration is planned for the BM@N technical runs with the deuteron and carbon beams in 2016. All the GEM detectors are two coordinate detectors and have the strip pitch of 800 μm. The inclination angles of the X and X' coordinates of the GEM detectors to the vertical axis are 0 and 15 degree, respectively. Central events (0-3 fm) of C+C collisions with the beam kinetic energy of 4.0 AGeV are generated using the UrQMD generator. Figure 3.2.10 illustrates the reconstructed signals of Λ hyperon and $K^0_S$ meson in the effective mass spectra of $(p,\pi^-)$ and $(\pi^+,\pi^-)$, respectively. The reconstruction efficiency for Λ and $K^0_S$ is sufficient to perform studies of their production close to the kinematical threshold.

Figure 3.2.9. Start detector configuration with 6 GEM stations inside the magnet planned for the measurement of d+C and C+C collisions. Z-positions of stations are at the distances of 30, 45, 60, 80, 100, 130 cm from the target situated at the front edge of the magnet pole along the beam direction.

Figure 3.2.10. Distributions of the invariant mass of decay products of Λ hyperon (left) and $K^0_S$ (right), reconstructed in C+C collisions at 4.0 AGeV using the start detector configuration with 6 GEM stations.

3.3 Central tracker

3.3.1 GEM tracker

The central tracker of the BM@N experiment is based on two-coordinate triple GEM detectors. The GEM (Gas Electron Multiplier) detectors have the established technology developed at the CERN workshop and have been used in various experiments (COMPASS, JLAB, STAR, CMS). The microscopic structure of one GEM layer and the transverse structure of the triple GEM
detector are shown in figure 3.3.1. Due to the tight structure the GEM detectors are operational in the strong magnetic field and can sustain fluxes up to $10^6$ particles per cm$^2$.

Figure 3.3.1. Left plot: Microscopic structure of one GEM layer. Right plot: Schematic transverse structure of the triple GEM detector.

Figure 3.3.2. GEM detector with the size of 66 x 41 cm$^2$ at the final stage of the production at the CERN workshop.

The GEM detector produced for the BM@N experiment at the CERN workshop is presented in figure 3.3.2. Presently these detectors are under extensive tests in the LHEP laboratory with the aim to measure the detection efficiency, response uniformity, cross talk between strips, as well as to finalize the front-end, readout electronics and DAQ. The amplitude distributions from cosmic particles measured in two-coordinate strips of the GEM detector are presented in figure 3.3.3.

Figure 3.3.3. Amplitude distributions produced by cosmic particles in the X strips at 0° and X'(Y) strips (inclined at 15°) of the GEM detector with the size of 66 x 41 cm$^2$.

The two-dimentional correlation plots of coordinates and amplitudes in the X (0°) and X'(Y) (15°) strips of the GEM detector with the size of 66 x 41 cm$^2$ are presented in figure 3.3.4. Distribution of the number of 800 μm strips activated by cosmic particles in one coordinate of the GEM detector is also shown. The one coordinate detection efficiency is around 95%.
Figure 3.3.4. Correlation plots of measured coordinates (left plot) and amplitudes (center) in the X (0°) and X'(Y) (15°) strips of the GEM detector with the size of 66 x 41 cm². Distribution of the number of strips activated by cosmic particles in one coordinate of the GEM detector (right plot).

Schematic view of the two-coordinate GEM detector with the size of the sensitive area of 163 x 45 cm² is presented in figure 3.3.5. Presently, the GEM detector of this size is in production at the CERN workshop. We plan to use these detectors already in the BM@N technical runs in 2016. Figure 3.3.6 gives the general view of the start detector configuration with 6 GEM stations. The results of the simulations for the start detector configuration are given in section 3.2.2.

Figure 3.3.5. Schematic view of the two-coordinate GEM detector with the size of 163 x 45 cm².

Figure 3.3.6. Left plot: general view of the start detector configuration with 6 GEM stations planned for the BM@N technical runs in 2016. Right plot: general layout of the GEM FEE electronics.
3.3.2 Forward silicon detectors

Technical details of the forward silicon detectors are given in the internal documents [3.32]. Forward silicon detectors will be installed between the target and the GEM stations to increase the tracking efficiency and improve the precision of the primary vertex reconstruction. Figure 3.3.7 shows the effect of two forward silicon detectors with 2.5 degree stereo angle between two coordinates to the reconstruction efficiency of the central tracker based on 12 GEM stations. The occupancy of 100 μm strips of the silicon detector in Au+Au collisions at the kinetic energy of 4.5 AGeV is below 10%. Schematic views of the silicon detector modules and the silicon detector plane are given in figure 3.3.8. Fast signals from readout chips will be used to form a trigger signal for multi-particle events (section 3.7.2).

Figure 3.3.7. Left plot: Reconstruction efficiency with respect to reconstructable particles in 12 GEM stations (red histogram) and in 12 GEM + 2 coordinate silicon planes with the stereo angle of 2.5 degree (blue histogram). Right plot: occupancy of 100 μm strips in two coordinates of the silicon plane in Au+Au collisions at the beam kinetic energy of 4.5 AGeV.

Figure 3.3.8. Schematic view of the silicon detector modules and combined view of the silicon detector plane.

3.3.3 STS tracker (BM@N II)

The technical details of the CBM STS tracker are given in the CBM STS TDR report [3.17]. Four first STS stations could be developed and installed into the BM@N set-up at the second stage of the BM@N experiment in 2020.

3.4 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 (mRPC-1,2) situated at distances of around 4 m and 7 m from the target as it is illustrated in figure 3.5. 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. Figure 3.40 illustrates the resolution of the π/K separation by the ToF detectors and the geometrical acceptance of the mRPC-1,2 walls ToF-400 and ToF-700.

3.4.1 Start detector T0

The details of the T0 detector design, the start time measurements in beams of light nucleus and heavy nucleus and the measured time resolution are described in section 3.7.1 and in the document [3.70].

![Figure 3.40](image1.png)

Figure 3.40. Left plot: resolution of the π/K separation presented as a function of the particle momentum for two values of the ToF system time resolution and for two distances between T0 and mRPC detectors. Right plot: geometrical acceptance of the ToF-400 and ToF-700 mRPC walls for detection of charged pions produced in central Au+Au collisions.

3.4.2 ToF-400 mRPC detector

The details of the ToF-400 mRPC detector and the measured time resolution are described in the document [3.42]. The schematic layout and the position of the ToF-400 wall are shown in figure 3.42.

![Figure 3.42](image2.png)

Figure 3.42. Schematic layout of the ToF-400 mRPC wall and its position behind the analyzing magnet.
3.4.3 ToF-700 mRPC detector

The details of the ToF-700 mRPC detector and the measured time resolution and efficiency are described in the document [3.43]. Figure 3.43 illustrates the geometrical layout of the ToF-700 mRPC wall and the schematic view of ToF-700 in the installed position.

![Figure 3.43. Geometrical layout of the ToF-700 mRPC wall and schematic view of ToF-700 in the installed position.](image)

3.5 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 as well as with clusters in the electro-magnetic ECAL calorimeter. It consists of big drift chambers which will be complemented with straw tube detectors to perform track measurements in Au+Au collisions.

3.5.1 Drift chambers

The Drift Chamber (DCH) consists of 4 double coordinate planes with the following parameters: the wire inclination angles of 0, 90, ±45°, the wire pitch of 10 mm, the outer dimensions of the sensitive area of Y_{out} ± 1.2 m, X_{out} ± 1.2 m, the beam hole radius of R_{min} = 10 cm, 256 wires per coordinate plane, 2048 wires per chamber. The outer view of the DCH chambers is shown in figure 3.5.1. The description of the DCH chamber is done in the document [3.50]. The performance of the DCH chambers to measure the angular distribution and momentum of the deuteron beam in the first technical run are illustrated in figure 3.5.2 and 3.5.3.

![Figure 3.5.1. Two DCH chambers installed in the BM@N experimental zone.](image)
Figure 3.5.2. Left plot: map of the vertical component of the magnetic field of the spectrometrical magnet measured at the horizontal plane of the beam. Right plot: angular distributions of the deflected deuteron beam measured in two DCH chambers for different values of the magnetic field.

Figure 3.5.3. Left plot: Mean angles (radians) and r.m.s. of the deflected deuteron beam measured in two DCH chambers for different values of the magnetic field integral. The red and dash lines show the nominal value of the momentum of the deuteron beam of 8.68 GeV/c with the accelerator momentum uncertainty of 2%. Right plot: momentum of the deuteron beam calculated from the angular distributions for different values of the magnetic field integral. The red line with the colored error bar gives the nominal value of the beam momentum with the accelerator uncertainty.

Figure 3.5.4 presents distributions of the averaged number of tracks <Ntr> crossing one wire of the DCH chamber installed at a distance of 7 m from the interaction point (IP). The distributions are simulated in Cu+Cu and Au+Au collisions with the beam kinetic energy of 4.5 AGeV generated with the QGSM model. The efficiency to detect a track is defined as $\varepsilon \sim 1/<\text{Ntr}>$ and is estimated to be $\varepsilon \geq 0.91$ and $\varepsilon \geq 0.75$ for Cu+Cu and Au+Au collisions, respectively. In dependence on the collision centrality the efficiency varies within the limits of 0.88–0.92 and 0.7–0.8 for Cu+Cu and Au+Au collisions, respectively. The track reconstruction efficiency in two DCH chambers in Au+Au (Cu+Cu) collisions is estimated to be $\varepsilon_{\text{DCH1+DCH2}} \geq 0.55$ ($\geq 0.91$), if there is a requirement of at least 3 hits in 4 double coordinate planes in one DCH chamber. Such a requirement should reduce the combinatorial background in multi-track events. Due to the low DCH track efficiency in Au+Au collisions, the drift chambers will be supplemented by Straw tube detectors.
Figure 3.5.4. Left plots: averaged number of tracks per one DCH wire (X and Y coordinates, 6 cm per bin) in Cu+Cu collisions with the beam kinetic energy of 4.5 AGeV. Right upper plots: averaged number of tracks per one DCH wire (X and Y coordinates, 6 cm per bin) in Au+Au collisions with the beam kinetic energy of 4.5 AGeV. Right lower plots: averaged occupancy per DCH wire (X and Y coordinates, 6 cm per bin) in one Au+Au collision.

3.5.2 Straw detectors

To increase the track reconstruction efficiency in Au+Au collisions, two Straw tube detectors will be constructed and installed in addition to the existing DCH chambers. The proposed design of the Straw detector is the following: it consists of 3 double coordinate planes; the straw tube angles relative to the vertical axis are $0, \pm 10^\circ$; the straw tube diameter is 6 mm, the outer dimensions are $Y_{out} \pm 1$ m, $X_{out} \pm 1.5$ m; the straw tubes are divided into the upper and lower parts with independent readout (galvanic separation, without the support frame). The averaged number of tracks $<N_{tr}>$ crossing one straw of the Straw detector installed at a distance of 7 m from the interaction point (IP) in Au+Au collisions with the beam energy of 4.5 AGeV is shown in figure 3.5.5. The efficiency to detect a track in one coordinate plane of the Straw detector is estimated to be $\varepsilon \sim 1/<N_{tr}> \geq 0.87$. In dependence on the collision centrality the minimum efficiency is varies in the limits of 0.85 – 0.9. The track reconstruction efficiency in two Straw detectors in Au+Au collisions is estimated to be $\varepsilon (\text{Straw1+Straw2}) \geq 0.91$, if there is a requirement of hits in at least 2 out of 3 double coordinate planes in one Straw detector. The resulting efficiency for the reconstruction of the combined track segments in two DCH chambers (at least 2 hits in 4 planes) and one Straw detector (at least 2 hits in 3 planes) is estimated to be $\varepsilon \geq 0.9$. 
Figure 3.5.5. Averaged number of tracks (upper plot) and occupancy (lower plot) per one straw tube in X coordinate in Au+Au collisions with the beam kinetic energy of 4.5 AGeV.

3.6 Calorimeters

3.6.1 Zero degree calorimeter ZDC

The zero degree calorimeter (ZDC) is foreseen for the analysis of the collision centrality by measuring the energy of forward going particles. The design and present status of the ZDC calorimeter is described in the document [3.60]. Figure 3.6.1 illustrates the response of the ZDC calorimeter to the carbon beam hitting different modules of the calorimeter. These data measured in the BM@N technical run were used to calibrate the calorimeter energy response. The results of the energy measurement for the fractions of the beam (carbon and beryllium) with using the ZDC calibration parameters are shown in figure 3.6.2. The uncertainty of the beam energy measured at different positions of the ZDC calorimeter is 7%.

Figure 3.6.2. Energy measured in the ZDC calorimeter for the selected carbon (A=12) and beryllium (A=9) fractions of the beam with the kinetic energy of 3.5 AGeV.
3.6.2 Electro-magnetic calorimeter ECAL

The purpose of the electro-magnetic calorimeter is to study processes with electro-magnetic probes (γ, e±) in the final state. The physics program of the BM@N experiment with the electro-magnetic calorimeter includes the following studies:

1. Study of known resonances and search for new resonances decaying into two γ quanta [3.61].
2. Study of the yield excess of η0-mesons in nucleus-nucleus interactions [3.62].
3. Study of gamma femtometry – two photon interference [3.63].
4. Study of soft photon spectra at photon energies below 50 MeV, where the yield of γ quanta exceeds in ~ 4 – 8 times the theoretical expectations [3.64, 3.65].
5. Search for the correlation between the phenomena of pion condensation and abnormal soft photons [3.66].

The detailed justification of the BM@N physics program with the electro-magnetic calorimeter is given in the document (in Russian) [3.68]. The available modules of the MPD ECAL calorimeter will be installed behind the DCH chambers and ToF-700 wall already in 2016 to serve as an electro-magnetic calorimeter in the BM@N experiment. The description of the MPD ECAL, the energy resolution measured in the beam tests are given in the document [3.69].

3.7 Trigger system

3.7.1 Trigger, T0 and beam detectors

The details of the trigger, T0 and beam detectors are described in the document [3.70]. The detector system is schematically shown in figure 3.7.1. The system provides:

- effective triggering nucleus-nucleus collisions in the target,
- define start signal for the ToF detectors with picosecond time resolution,
- monitoring beam characteristics and background induced by upstream interactions of beam ions with beam line materials.

Figure 3.7.1. A scheme of the trigger – T0 detector system on the BM@N beam line (not in scale): BC1 and BC2 – the scintillation beam counters, T0C – the T0 counter (Cherenkov or scintillation), VC – the scintillation veto-counter, BD – the scintillation-strip barrel detector, SiD – the forward silicon detector, T – the target.

The beam detector set and thickness of the detectors depend on mass of heavy ions. In 2016 the BM@N will run with d- and C-beams without vacuum pipe. In these runs the beam counter BC1 is based on 70×70×5 mm plastic scintillator coupled with PMT FEU-87, the beam counter BC2 is small size scintillator and it defines the size of beam spot on the target. The T0C counter provides the start pulse for TOF detector. Three different versions of the T0C counter with quartz
radiators and fast scintillator BC-418 will be tested with deuteron beam in June – July 2016. The photons are registered by MCP-PMT from Photonis and SiPMs from Sensl. The veto-counter (VC) is 10-mm plastic scintillator with diameter of 100 mm and a hole with diameter of 27 mm.

In 2016 the nuclear interaction in the target is triggered by detection of charged particles in a range of polar angle $10^\circ < \theta < 150^\circ$ using a new system of barrel detector (BD) and forward silicon detector (SiD). The BD granularity is 40 channels and it consists of 40 scintillation strips BC-418 with cross section of $7 \times 7$ mm$^2$ and 150-mm length. Each the strip is connected with SiPM 6×6 mm from Sensl. The SiD is the first detector of BM@N tracking system and it also provides 40 channels of fast pulses for the interaction trigger. Thus, the system of these detectors has granularity of $40 + 40 = 80$ channels and it can be used for selection of central collisions by threshold on multiplicity of detected charged particles.

The aim of the Cherenkov modular array T0D is production of start pulse for TOF detector in runs with heavy-mass ions by detection of high-energy photons and charged pions. Also it takes part in triggering interactions of heavy nuclei.

The detector module with picosecond time resolution (shown in figure 3.7.2) is developed for T0/BM@N and FFD/MPD detectors for study of Au + Au collisions at Nuclotron and NICA energies [3.71 – 3.73]. The high energy photons are registered via electrons produced in conversion process in 10-mm lead plate. The Cherenkov photons produced in 15-mm quartz radiator and 2-mm quartz window are detected by Planacon MCP-PMT XP85012/A1-Q from Photonis.

![Figure 3.7.2. The view of module of T0-detector: 1 – Pb plate (converter of high energy photons), 2 – quartz radiator bars, 3 – MCP-PMT XP85012/A1-Q, 4 – FEE board, 5 – module housing, 6 – HV connector, 7 – SMA outputs of analog signals, 8 – HDMI cable (LVDS signals + LV for FEE).](image)

The experimental study of detector performance was carried out with four detector modules irradiated 3.5-GeV deuteron beam of Nuclotron. The analog signals were fed to two digitizer units DRS4 Evaluation board (V4) with 200-ps binning. The LVDS signals were fed to inputs of VME module TDC32VL, 32-channel 25 ps multihit time stamping TDC produced at JINR.

The quartz radiators with two different cross sections were tested in the modules. The small one only covered the area of photocathode of MCP-PMT and has cross section of $53 \times 53$ mm, the large radiator $59 \times 59$ mm has dimension equal to size of MCP-PMT including dead area along MCP-PMT perimeter. The measurements with TDC32VL showed that the modules with smaller quartz radiator gave better pulse height and time resolution. Typical pulse height distributions obtained with these modules are shown in figure 3.7.3 and the result of TOF measurements are shown in figure 3.7.4.
Figure 3.7.3. Typical pulse width distributions obtained with TDC32VL for modules with different quartz radiators.

Figure 3.7.4. The result of TOF measurements with TDC32VL obtained for modules with different quartz radiators: a – 53 × 53 mm, b – 59 × 59 mm.

At present, design of the T0D modular array is under study. A schematic view of example of T0-detector array with 12 modules and 48 channels is shown in figure 3.7.5. The detector performance was studied by MC simulation with LAQGSM + GEANT4 codes.

Figure 3.7.5. A schematic view of T0-detector with 12 Cherenkov modules.
The multiplicity of signals from T0-detector array and efficiency of triggering Au + Au collisions depends on centrality of the collisions. A number of signals from detector channels increases from peripheral to central collisions and this fact can be used for fast selection of events on centrality in L0-trigger. As one can see in figure 3.7.6, the efficiency is ~100% for \( b < 10 \text{ fm} \) for both energies of Au ions 2 and 4 A GeV.

![Figure 3.7.6. Number of hits in detector channels (a) and efficiency of triggering Au + Au collisions by the T0-detector (b) as a function of impact parameter for two beam energies of 2 and 4 A GeV.](image)

The first experimental test of the T0D array shown in figure 3.7.7 was carried out during the BM@N run 2015 with magnetic field of 0.5T. The beam line with detectors is shown in figure 3.7.8. The layout of beam detectors and T0 detector is shown in figure 3.7.8. The pulse height distributions and time resolution were studied with 3.5-GeV/u carbon beam. The carbon ions interacted with a copper target and the modules detected secondary photons and charged particles. A beam Cherenkov detector (CD) with 8-mm quartz radiator at 47° to the beam axis generated start signals with time resolution \( \sigma_t = 27 \text{ ps} \) for TOF measurements. To restore the gain of MCP-PMT in magnetic field, the high voltage was increased. Additional HV value was set from 20 to 250 V for modules with different orientation to the magnetic field direction. The modules at angles of 0° and 180° showed better time resolution than the modules with other orientation. A constant shift of pulses in time scale is observed due to an influence of magnetic field on electron path inside MCP-PMT. The data analysis is in progress.

![Figure 3.7.7. The T0D array in BM@N run 2015.](image)
3.7.2 Trigger electronics

A scheme of trigger electronics is shown in figure 3.7.9. The main trigger unit receives pulses from the detectors, accelerator spill pulse, and DAQ busy pulse. The unit distributes pulses to trigger logic part based on FPGA and feeds detector LVDS pulses to TDC72 modules of TOF electronics. Also it provides the low voltage power for detector FEE. All these electronics operates under control of a Detector Control System developed for BM&N experiment.

Figure 3.7.8. The layout of beam detectors and T0 detector in BM@N run 2015.

Figure 3.7.9. Scheme of trigger electronics.
The first version of the main trigger unit, called L0 Trigger Unit (T0U), was developed for BM@N run 2015. The T0U has a modular structure – it has a motherboard and 4 different type mezzanine boards. The motherboard performs following jobs:

- input signals distribution to external electronic (TDC72, etc.) and to trigger processor,
- Trigger generation basing on input signals. The trigger processor is build using Altera Cyclone V GX FPGA,
- powering, monitoring and control of mezzanine cards including:
  - power supply board (PSB) for FEE of the beam and T0 detectors,
  - four discriminator cards (DIB),
  - four TTL-NIM convertor cards (TIB),
  - one Ethernet interface card (ETB),
- accumulation of the trigger monitoring information. This information could be sent to the control and trigger monitoring PCs via optical link, Ethernet or USB 2.0.

A view of T0U module is shown in figure 3.7.10.

The Power Supply Board (PSB) provides three independent voltages to supply the detector FEE being controlled and monitored with high precision. Every channel could be switched on or off independently. The channel output voltage and current are read back by 12-bit ADC. The communication to the slow control system is done via RS serial link.

![Figure 3.7.10. A view of T0U module: 1 – the output connector for pulses to TDC72; 2 – the input connector for HDMI cable from detector FEE; 3 – the power supply board; 4 – the board of output trigger pulses.](image)

Realization of the BM@N trigger logics

The most complicated device is a trigger module. It performs processing of input signals and generates a trigger signal for other BM@N detectors. The simplified block-diagram of T0U trigger module is shown in figure 3.7.11.
To control all trigger system hardware we use software servers with GUI to control settings and to monitor actual trigger system element states. Servers provide an access to the hardware and perform hardware registers polling. Each hardware device has its own server presenting at a GUI in an intuitive-clear way an actual device state and possible commands, which could be sent to the hardware. The GUI presents a logical view of the device, for example, the T0U server GUI contains a picture very close to figure 3.7.11 and a user is able to modify structure of trigger by few mouse clicks. It is also possible to see counts in input channels and in the most important points of trigger processor.

During the operation, all servers record actual settings and states to their local archives in a text format. Each record contains a timestamp and a set of numbers. To interface with the higher level DCS system each server publishes its data and states in a Windows named shared memory also in a text format. The server data block has a JSON structure. Every time when a content of corresponding data block is changed the corresponded Windows named event is triggered and all clients receiving server data are able to retrieve corresponding data set.

At the present moment the summary state of the trigger system is published to the Central DCS system via TCP/IP server publishing the Trigger system state with brief description of the error state if any error occurs. In addition to common status it also contains the most important information accumulated during the last spill. For example this block contains counts of all beam counters, amount of generated triggers and amount of triggers rejected during event readout by DAQ when the system is busy. Transition between states are done automatically when shifter switches on or off corresponding hardware.

**Trigger logic for BM@N runs 2016**

In 2016 for BM@N runs with d- and C-beams the following set of trigger logic is realized in trigger electronics and software:

**Beam trigger (BT)**

Logic 1: $BT(1:N) = BC1&T0C&BC2&VC\text{veto}$

where $N$ – the reduction factor.
The beam trigger requires a coincidence of beam detector pulses shown in figure 3.7.12.

Figure 3.7.12. The coincidence of beam detector pulses.

**Interaction triggers**

Logic 2 (Minimum bias) = BT & ( (N_{BD} + N_{SiD}) > N1))
Logic 3 (Central + Semi-central) = BT & ((N_{BD} + N_{SiD}) > N2)
Logic 4 (Central) = BT & ((N_{BD} + N_{SiD}) > N3)
Logic 5 BT & (N_{BD} > N1 and N_{SiD} > N2)

where $N_{BD}$ and $N_{SiD}$ – the multiplicity of pulses from BD and SiD, N1, N2, N3 – the biases on the multiplicity for selection of peripheral (bias N1), semi-central and central (bias N2), and central AA-collisions (bias N3) as it is shown in figure 3.7.13.

Figure 3.7.13. Selection of peripheral (bias N1), semi-central and central (bias N2), and central AA-collisions (bias N3) by interaction trigger where $N = N_{BD} + N_{SiD}$.

**Special trigger for two track events**

Logic 6 BT & (N_{BD} = 2 & 180 deg.)

In special runs in 2016 the BM@N experiment will use beam of deuterons interacting with polyethylene and carbon target with triggering two protons in the barrel detector as it is shown in figure 3.7.14. The trigger looks for 2 pulses from opposite strips with 20 possible combinations.
Figure 3.7.14. A scheme of triggering two protons in the barrel detector in special runs in 2016.

3.8 Read-out electronics and DAQ system

The details of the readout electronics and the DAQ system are described in the documents [3.80, 3.81].

3.9 Slow control system

The details of the slow control system are described in the document [3.90]. The parameters of the detectors are stored via the TANGO interface into a data base. The access to the data base is performed using the software interface [3.91] developed within the BMNROOT software.

3.10 Experimental zone

Figure 3.10.1. Scematic view of the experimental hall 205 for the extracted beams and the BM@N experimental zone.
Figure 3.10.2. Upper plot: Equivalent doses (mkSv/hour) inside and around the BM@N experimental zone exposed in the beam of $10^9$ protons/sec. Lower plots: Distributions of the particle fluxes presented in different views of the BM@N experimental setup. The calculations are performed using the FLUKA simulation package. The details of the calculations are described in the document [3.101].

3.10.1 Spectrometrical Magnet

Figure 3.10.3. General and side views of the BM@N spectrometrical magnet.

Figure 3.10.4. Two dimentional (X-Z) distributions of the magnetic field components $B_y$, $B_x$, $B_z$ (kGauss) measured in the horizontal plane at $Y=25$ cm from the magnet median plane.

3.10.2 Steering magnets and beam line for BM@N

The details of the beam line from the Nuclotron to the BM@N experiment are described in the document [3.102].
Figure 3.10.5. Left plot: Horizontal and vertical beam size envelopes (2σ) in the BM@N area. The positions of the target, the edges of the pole of the spectrometrical magnet and the beam dump are shown. Right plot: Horizontal and vertical profiles of the carbon beam at 1 m in front of the target.

Figure 3.10.6. Angular distributions (rad) of the deuteron beam in horizontal and vertical projections.

Figure 3.10.7. Left plot: two dimensional distribution of the fractions of nucleus as measured in the carbon beam before the interaction (horizontal projection) and after the interaction with the target (vertical projection). Right plot: one dimensional distributions of nucleus fractions before the interaction (red histogram) and the after interaction (blue histogram) measured by the beam counters.
References


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### Schedule and required resources for Proposal realization

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