The Nuclotron-based Ion Collider Facility Project.
The Physics Programme for the Multi-Purpose Detector

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Abstract. The Nuclotron-based Ion Collider Facility (NICA) is a new accelerator complex under construction at the Joint Institute for Nuclear Research (JINR), Dubna, Russia. The main goal of the planned facility is to provide accelerated particle beams for a wide range of experimental studies of the hot and dense strongly interacting QCD matter generated during collisions. The NICA project in its entirety allows for a fixed target experimental site, as well as two interaction points. The heavy ion programme includes two planned detectors: Baryonic Matter at Nuclotron (BM@N) - a fixed target experiment with extracted Nuclotron beams; and a collider-mode experiment at one of the interaction points - the MultiPurpose Detector (MPD). For the NICA collider, the accelerated beams by design will consist of particles ranging from protons and light nuclei to fully stripped gold ions. Beam energies will span \( \sqrt{s_{pp}} = 12 - 27 \text{ GeV} \) with luminosity \( L_{pp} \geq 1 \times 10^{30} \text{ cm}^{-2} \text{s}^{-1} \), and \( \sqrt{s_{AuAu}} = 4 - 11 \text{ GeV} \), and average luminosity \( L_{AuAu} = 1 \times 10^{27} \text{ cm}^{-2} \text{s}^{-1} \). The second interaction point is planned to be occupied by a third experiment - Spin Physics Detector (SPD), which will focus on the investigation of nucleon spin structure and polarization phenomena through the use of polarized proton and deuteron beams. A brief overview of the Multi-Purpose Detector is presented along with the major sub-detector systems. The MPD research programme will focus on multiple observables including collective flow, particle multiplicity and spectra. Special attention will be given to strangeness production and vector mesons, event-by-event fluctuations and hadron femtoscopy measurements. Several feasibility studies are referenced.

1. Introduction
The Nuclotron-based Ion Collider Facility (NICA)(Fig.1) is an accelerator complex now under construction at the Joint Institute for Nuclear Research (JINR), Dubna, Russia [1]. The main goal of this facility is to provide heavy-ion collisions for the investigation of the hot and dense barionic matter produced at relatively low energies compared to previous experiments at RHIC and SPS (Fig.2), [2]. Thus formulated, the experimental programme at NICA includes simultaneous measurements of observables that are sensitive to high-density effects and phase transitions.

The proposed research programme envisions a wide range of collision systems in both fixed target and collider modes, accommodating both heavy ion physics and polarization physics on one hand; and radiobiological, advanced applied research and educational programmes on the other.
2. Nuclotron-based Ion Collider facility NICA

The NICA project in its full configuration incorporates several existing facilities, as well ones still under development. Acceleration particles will be supplied by four sources (for light and heavy ions) and two linacs, comprising the injection complex. The light ion sources are: laser, duoplasmatron sources, source of polarized protons and neutrons, modernized LU-20 accelerates for beam injection into the Nuclotron (synchrotron accelerator). Heavy ions are provided by the KRION-6 electron string source, with capability of supplying ions of Au$^{31+}$. The heavy ions are delivered to HILac (heavy-ion linac), which accelerates them to 3.24 MeV/u and injects them to the synchrotron Booster. The main task for the booster accelerator is to accumulate and accelerate of $2 \cdot 10^9$ Au$^{31+}$ ion bunches up to energy required for effective ionizing stripping. The maximum energy of Au$^{79+}$ ions accelerated in the Booster is 600 MeV/u. Afterwards, the accelerated and stripped bunches are injected to the Nuclotron, which further increases the ion energy up to 4.5 GeV/u. The required bunch intensity is about $1 - 1.5 \cdot 10^9$ ions. Two collider rings are constructed one above the other. Four RF systems are used in order to achieve optimal beam storage and bunch formation in the collider. Twenty-two bunches per ring will be stored. For luminosity preservation, an electron and/or a stochastic cooling system will be used [3]. Beam energies will span $\sqrt{s} = 12 - 27$ GeV with luminosity $L \geq 1 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$ and $\sqrt{s_{\text{AuAu}}} = 4 - 11$ GeV, and average luminosity $L = 1 \cdot 10^{27}$ cm$^{-2}$s$^{-1}$ (for $^{197}$Au$^{79+}$), respectively. The manufacture for the Dubna type super-conducting magnet and testing are in operation at JINR since 2015. The final configuration comprising of almost 450 magnet systems is under production for both the NICA Booster and Collider, as well as the FAIR SIS100 accelerator at GSI laboratory.

![Figure 1. Schematic view of the NICA complex.](image1)

![Figure 2. Landscape of present and future heavy-ion experiments.](image2)

Two NICA experiments are dedicated to the exploration of the QCD phase diagram: Baryonic Matter at Nuclotron (BM@N)[4] - a fixed target experiment in the beam extracted from the Nuclotron, which will cover the lower energy region, and the Multi-Purpose Detector (MPD)[5] at one of the collider interaction points (IP).

Both BM@N and MPD will perform measurements of particle yields and spectra, ratios, hadron femtoscopy and collective flow; observation of in-medium modification of hadron properties like low-mass dilepton enhancement; study of deconfinement (chiral) phase transition at high baryon density through observation of onset of enhanced strangeness production; search for QCD Critical Point via studies of event-by-event fluctuations and correlations; investigation of the Chiral Magnetic (Vortical) effect through measurements of $\Lambda$-polarization; investigation of hyperon-nucleon interactions in dense nuclear matter via studies of hypernucleus production, and their properties.

At the second interaction point of the collider facility, a Spin Physics Detector is proposed to investigate problems related to the origin of spin and a number of scattering problems. The NICA
accelerator will be capable of running in polarized beam modes for protons and deuterons. The high intensity and high polarization (> 50%) of the colliding beams present a unique possibility for spin physics research, which is of crucial importance for the solution of the nucleon spin problem (spin puzzle) - one of the main tasks of modern hadron physics.

3. Multi-Purpose Detector MPD

The Multi Purpose Detector (MPD) (Fig. 3) is designed as a 4π spectrometer capable of detecting charged hadrons, electrons and photons in heavy-ion collisions at high luminosity in the energy range of the NICA collider. The estimated event rate for AuAu collisions at minimum bias is at a maximum of about 7 kHz, and the total charge particle multiplicity exceeds 1000 in the most central collisions at \( \sqrt{s_{NN}} = 11 \text{ GeV} \). As the average transverse momentum of the particles produced in a collision at NICA energies is below 500 MeV/c, the detector design requires a very low material budget. Two stages of realization are planned for the MPD. A barrel setup is constructed at the present first stage.

The large solenoid of MPD by design envelops the main barrel sub-detector systems. It is equipped with a superconducting NbTi winding and a flux return iron yoke. A magnetic field of up to 0.6 T with low inhomogeneity in the main tracker area at about 0.1% and a radial component of magnetic induction below 0.775 mm is achieved.

The main tracking detector in MPD barrel is the Time Projection Chamber (TPC). The TPC is a cylindrical gas detector 2.7 m in diameter and 3.4 m in length. The central high voltage electrode and the voltage dividing network create a uniform electric field for drift particles in the active volume. TPC’s readout system is based on Multi-Wire Proportional Chambers (MWPC) with cathode readout pads. TPC will provide a sufficient transverse momentum resolution (with a resolution < 1 cm) and energy loss measurements (\( dE/dx \) resolution better than 8%) for hadronic and leptonic tracks at pseudo-rapidities \( |\eta| < 1.5 \) and \( p_T > 100 \text{ MeV/c} \). Precise primary and secondary track reconstruction and also precise primary (Interaction point) and secondary (decay) vertex reconstruction are of top TPC priority [6].

The Time of Flight System (TOF) will provide time of flight measurements with geometrical efficiency above 95% and resolution in the range 60-80 ps [7]. The basic element of the TOF system will be a Multigap Resistive Plate Chamber (MRPC). Combined, the measurements from TPC and TOF will provide an efficient \( \pi/K \) PID separation up to 1.5 GeV/c, \( \pi/p \) separation up to 3 GeV/c, and a very good electron/hadron separation [8].

The Forward Detector (FD) consists of two modular sets of Cherenkov detectors placed at a distance of 130 cm to the left and to the right from the interaction point. FD provides a trigger system for data taking and start time for TOF with resolution better than 50 ps [9].
The Electromagnetic Calorimeter is constructed by alternating lead+scintillator plates. The scintillator light is carried by wave length shifting fibers and readout by avalanche photodiodes (MAPD). The primary role of the electromagnetic calorimeter is to measure the position and energy of electrons and photons. For an increased energy resolution of electromagnetic showers, a projective geometry targeting the IP is used. ECal will provide energy resolution of 5% at 300 MeV, and time resolution better than 0.5 ns [10].

Two sets of Forward Hadron Calorimeter (FHCal) are allocated at 3.2 m at the forward and backward region pseudo-rapidity from 2.2 to 4.8. Each detector consists of 45 modules providing the necessary transverse granularity. The main goal of FHCal is to provide energy measurements of spectator energy for centrality determination and event-plane reconstruction [11].

Within the NICA timetable, MPD will be commissioned by the end of 2020 and will start physical data taking by 2021. In order to increase low momentum track and primary vertex resolution, the addition of an Inner Silicone Tracker (IT) and Gas Electron Multipliers (GEM) close to the interaction point are planned. Also, end-caps on both sides of the barrel are considered: ECT, ETOF, ECAL.

4. Physics Programme for MPD

The NICA/MPD physics programme will focus on a variety of experimental observables, already employed in previous programs at RHIC and SPS for the study of a QGP-state of matter formation. The observables include particle yields and spectra, event-by-event fluctuations of multiplicity and transverse momentum of identified and reconstructed particle decays, as well as the corresponding joint distributions and collective properties. Several feasibility studies demonstrating the research prospects for MPD are referenced in the text below.

4.1. Anisotropic Flow Studies

The observation of an azimuthally anisotropic flow is one of the key observables for establishing that a QGP state of matter has formed in heavy-ion collisions. The initial spatial eccentricity in the collision geometry leads to a non-uniformity in parton interaction which results in anisotropic particle emissions. Flow studies provide information on the transport properties of the medium and the equation of state. The anisotropic flow measurements of both identified charged particles and reconstructed particle decays will be a key measurement in the MPD research programme. The reconstructed and generated(true) values of differential flow coefficients are in good agreement. Due to limits in TPC event-plane resolution, FHCal is used to determine the reaction plane. These results present a good agreement between generated and reconstructed proton differential directed and elliptic flow (Fig.6) [12].

4.2. Strangeness at MPD

Production of strange particles is of particular interest because enhanced production of hadrons containing one or multiple strange quarks in A+A collisions (relative to the yields from elementary pp reactions) was predicted as a signal for the QGP formation. The enhancement of
the strangeness was experimentally observed at SPS and RHIC, and it is more pronounced for hyperons with larger strangeness content. Furthermore, at NICA energies there are predictions of considerable enhancement of nuclear clusters with strangeness, thus allowing a better understanding of the dynamics of hypernuclei, hyperon-nucleon and hyperon-hyperon interactions, relevant for neutron star theoretical models.

Feasibility studies on strangeness at MPD with realistic simulations demonstrate good signal-to-background ratios for both hyperons and hypernuclei (Fig.7) [13] [14] which is crucial for extracting parameters from the reconstructed decays, including momentum slope parameters, collective flow [15] and polarization studies.

Figure 7. Reconstructed invariant mass distributions of hyperons(Λ, Ξ−, Ω−) (top) and hypernuclei (4ΛHe, 3ΛH) (bottom).

4.3. Dilepton Studies

Dileptons are good probes to indicate in-medium modifications of spectral functions due to chiral symmetry restoration in A+A collisions; and the effect is proportional to baryon density. The reconstruction of low-mass vector mesons ρ, ω, φ by measurements of their dileptonic and hadronic decay channels is one of high importance for the MPD research programme (Fig.8). In comparison to other heavy-ion experiments realistic simulations show that a good signal-to-background ratio is achieved (Fig.9) [16]. Preliminary studies of hadronic channel decays also demonstrate good MPD capabilities.

Figure 8. Reconstructed invariant mass of φ and ω vector mesons.

Figure 9. Signal-to-background ratio of dileptons for HIC experiments.
4.4. Other Key Observables
The NICA/MPD physics programme entails a vast volume of research possibilities, such as the charge dependence of azimuthal correlations between produced hadrons, baryon stopping power, and hadron femtoscopy correlations. Currently feasibility studies show good prospects for such studies at MPD[17].

5. Conclusion
In the landscape of Heavy Ion Collisions, the NICA accelerator facility will provide a wide range of experiments, collision energies, system sizes and physics observables. Models predict that at the NICA energy range, a high net-barion density is reached in the interacting QCD matter. For a further understanding of QCD it is important to study the equation of state, to search for phase transitions, chiral symmetry restoration in multiple collision systems. The NICA collider will present competitive and complementary results to those of accelerators at BNL, CERN and GSI, and generate data to shed light on multiple problems for which accurate experimental measurements are not present. The Multi-Purpose Detector is designed with a good acceptance and is characterized by low material budget in a modular configuration. Three upgrade stages are planned. Several Feasibility Studies based on realistic monte carlo simulations highlight the good capabilities of MPD and the viability of several research programmes. Mass production and assembly of the main sub-detector systems of MPD is in early stages, as most of design and integration are near completion.

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