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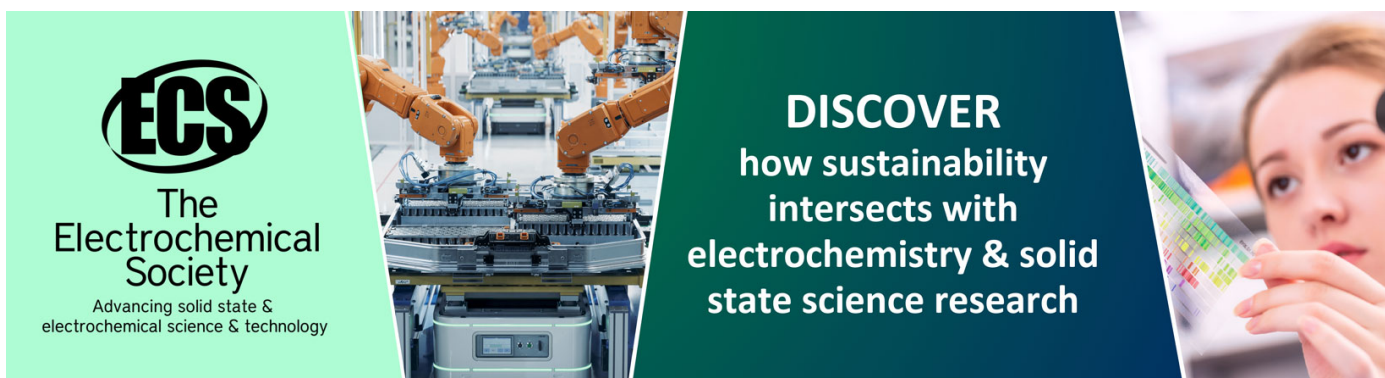
Status of the MPD Experiment at JINR

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Status of the MPD Experiment at JINR

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Abstract. The Mega-Science project NICA (Nuclotron-based Ion Collider fAcility) is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna. The Multi-Purpose Detector (MPD) is part of this complex, as a main physics experiment operating there. It aims to study the phase diagram of QCD matter at maximum baryonic density, determine the nature of the phase transition between the deconfined and hadronic matter and perform a search for the conjectured critical point in the diagram. Status of the preparation of critical elements of the infrastructure will be discussed, including the construction of the MPD subsystems.

The designed physics performance of the detector components will be discussed. Spectra of identified hadrons, including hyperons and hypernuclei will be discussed, with emphasis on differential measurement and total yield extraction. The quality of directed and elliptic flow determination will be discussed, with comparison to model expectations. The sensitivity of event-by-event fluctuations and femtosopic measurements to the nature of the phase transition and the presence of a critical point will be given. Performance of the electromagnetic calorimeter working in conjunction with the tracking system for the di-lepton measurements and the potential for identification of charmed mesons will be described. In summary, all the main components of the physics program of the MPD Collaboration will be presented.

1. Introduction

The investigation of the phase diagram of the strongly interacting matter has been the focus of many years of research at several experimental facilities, including the Super Proton Synchrotron (SPS) at CERN [1, 2, 3, 4], as well as the Beam Energy Scan program at the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory (BNL) [5, 6, 7]. The existence of a deconfined phase, where quarks and gluons are no longer bound into hadrons, the so-called Quark Gluon Plasma has been confirmed in collisions at the energy frontier at RHIC and Large Hadron Collider (LHC) energies. In such collisions maximum energy densities are reached, while the net baryon density is close to zero. The transition to the ordinary hadronic matter is of the cross-over type there. The theoretical calculations on the lattice predict that at large net baryon densities the transition is of the first order. That implies the existence of the conjectured critical point in the phase diagram. Matter created in collisions at lower energies is reaching lower temperatures and baryon densities above 300 MeV, where the search for these features may be performed, and the determination of the Equation Of State (EOS) of nuclear matter may be achieved.

Recent discovery of a neutron star merger via the observation of the gravitational wave [8], as well as accompanying signal in the traditional electromagnetic observations [9] was the first example of the so-called multi-messenger astronomy. It is expected that such observations may become more frequent, giving unique experimental insight into the behavior of nuclear matter



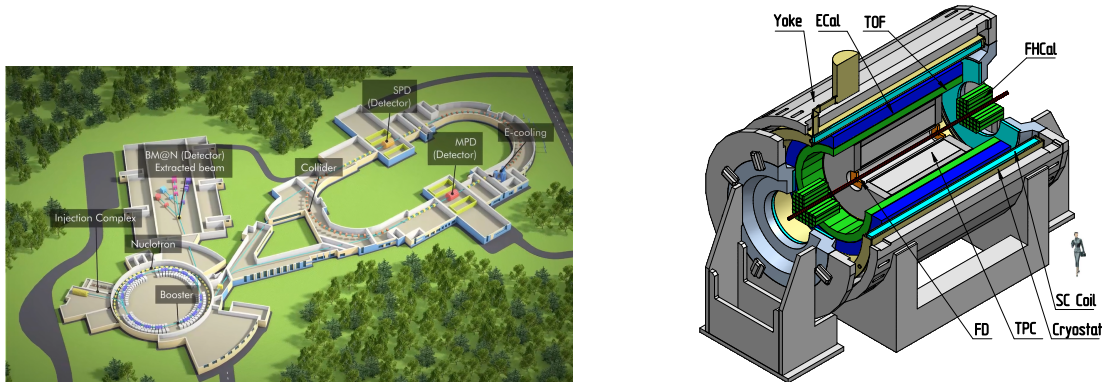


Figure 1. (left) The general overview of the NICA Accelerator Complex. (right) The schematic view of the MPD detector in Stage 1.

at extreme conditions. Simulations of neutron star collisions are driven by the EOS, which is investigated in heavy-ion collisions. In fact it is expected that in certain regions of the neutron star collision zone matter may reach temperatures and baryonic densities of the same order as in the collisions mentioned above. This presents a unique opportunity to study the same phenomena in fundamentally different experimental regimes, which provides crucial cross-checks for any theoretical understanding of the EOS.

The new experimental and accelerator complex: the Nuclotron-based Ion Collider fAcility (NICA) is being constructed at the Joint Institute for Nuclear Research (JINR) in Dubna. The design parameters of NICA in the collider mode are Au+Au collisions in the $\sqrt{s_{NN}}$ range of 4-11 GeV per nucleon pair. The facility will also provide collisions of polarized protons and deuterons at the second stage of operation. The main detector dedicated to QCD physics at NICA is the Multi-Purpose Detector (MPD), which is being constructed at one of the two beam crossings at NICA. This work will shortly describe the status of MPD construction as well as main physics goals of the experiment.

2. NICA Accelerator Complex

The NICA Accelerator Complex, shown schematically in Fig. 1, is located in the Veksler-Baldin Laboratory for High Energy Physics (VBLHEP) of JINR. The Nuclotron accelerates (polarized) protons, (polarized) deuterons as well as heavy ions up to Bi, delivering maximum kinetic energy of 10.71 GeV/u for protons and 3.8 GeV/u for Au ions. It is in operation since 1993 and has recently undergone significant upgrade. The specific ion sources together with LU-20 Linac provide light ions (up to C) to Nuclotron. The beams can be then extracted to the Fixed Target Area, where the Baryonic Matter at Nuclotron (BM@N) experiment is currently operating. All systems mentioned above are fully commissioned and operational. The heavy ion beams originate in the KRION source and are first accelerated in the HILac linear accelerator. Both are fully commissioned and operational. Beams will then transfer to the Booster auxiliary accelerator. Its main purpose is the storage of ions with A/Z not larger than 3 and initial acceleration to 600 MeV/u, which allows full stripping of ions during the transfer to Nuclotron. Booster is currently in construction, commissioning of critical systems is expected in 2020 and 2021. Together, Booster and Nuclotron will provide heavy-ion beams. The final part of the complex is the NICA storage and acceleration with the racetrack shaped ring of 503,04 m circumference. It will provide collisions of Au (and other) ions in the range of 4 to 11 GeV center-of-mass energy with $1 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity. Two collision points are located at two straight sections of NICA - the MPD experiment will be located around one of them. Civil construction of buildings

for NICA and its transfer lines is significantly advanced, while installation and commissioning of the accelerator components is planned for 2021 and 2022. First beam in NICA is expected in 2022.

3. The MPD apparatus

The civil construction for MPD Hall, where MPD apparatus will be located is finished. The general schematic view of the apparatus is shown in the right panel of Fig. 1. The central-barrel detectors will be housed inside the large-aperture magnet. The outer iron yoke, serving also as structural support for the setup is already delivered to JINR and its assembly will take place in summer of 2020. The superconducting solenoid is manufactured and will be transported to JINR in late 2020 and assembled with the yoke. Together, they will provide a uniform magnetic field of up to 0.5 T along the beam axis. A dedicated carbon fiber support structure will be attached to the magnet structure, and will allow installation of the remaining MPD subsystems.

The main tracking detector of MPD will be the Time Projection Chamber, a gaseous detector, with cylindrical shape enclosing the beam pipe, 340 cm in length, with 140 cm and 25 cm outer and inner radii respectively. It will provide 3D tracking of charged particles, as well as measurement of specific ionization energy loss for particle identification for $|\eta| < 1.2$. Expected relative transverse momentum resolution of less than 2.5% below 1 GeV/c and primary vertex z-coordinate better than 200 μm for events with track multiplicities above 200 will be achieved. The main components of the TPC vessel have been manufactured. Mass production of the TPC read-out chambers is ongoing.

The TPC will be surrounded by cylindrical barrel of the Time-of-Flight (TOF) detector, based on the Multigap Resistive Plate Chambers (MRPC) detectors, with strip read-out. Total of 28 modules with 13440 channels are in production and commissioning. The TOF will provide the measurement of the particle's arrival time with the time resolution of the order of 50 ps, as well as the position of the track. By performing the TPC-TOF matching, particle identification will be possible allowing to distinguish pions from kaons up to 1.5 GeV/c and protons from pions and kaons up to 2.5 GeV/c.

The Electro-Magnetic Calorimeter (ECal) will consist of shashlyk-type towers of approximately 11 interaction lengths with lead absorber and plastic scintillators. It will be a cylinder surrounding the TOF, consisting of almost 40 000 towers arranged in projective geometry. Its main purpose is to measure the position and total energy of electrons and photons in heavy-ion collisions. The production of ECal modules has already started, with the installation of the limited number of finished ECal sectors expected for first data-taking.

In the forward direction two detectors will be installed. The forward Hadronic Calorimeter (FHCAL) will provide centrality determination as well as reaction plane measurement. It is composed of 88 modules placed in two parts on the opposite side of the interaction point. Each module consists of 42 lead-scintillator sandwiches read out by WLS fibers. All FHCAL modules are produced and ready for installation.

The Fast-Forward Detector (FFD) will provide fast triggering for nucleus-nucleus collisions, as well as a start time T0 for the TOF. The two Cherenkov modular arrays are placed at $2.7 < |\eta| < 4.1$, close to the beam pipe. All components of the FFD have been manufactured.

In summary, in the first stage MPD will be able to provide full tracking of charged particles in the central barrel, together with full particle identification, including the separation of electrons from hadrons as well as total energy measurement for photons. Centrality determination, as well as reaction plane measurement will be possible, as well as precise determination of primary and secondary vertices. With these capabilities the physics program of the MPD is expected to be rich and should enable direct comparison with results obtained at similar collision energies at RHIC and SPS.

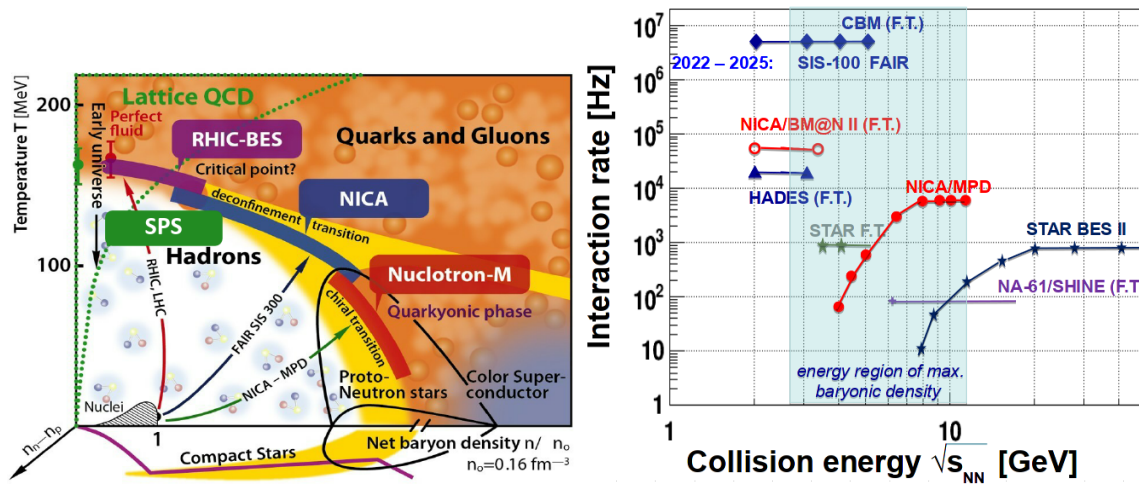


Figure 2. (left) The schematic view of the QCD Phase diagram. (right) The collision energies and expected interaction rates of currently ongoing and planned experimental programs.

4. The physics program of the MPD experiment

The main goal of the physics program of the MPD experiment is the characterization of the QCD phase diagram, shown schematically in Figure 2, in the less explored area of large temperatures and large baryochemical potential. The region of maximum temperatures and vanishing baryon density has been explored by the experiments at the LHC, as well as measurements at top RHIC energy. The production of QGP was confirmed at these conditions, and the transition back to hadronic matter has been discovered to be of the cross-over type. At larger baryon densities models consistently predict the existence of first-order phase transition between QGP and hadronic matter. That implies the existence of the critical end-point in the diagram. The search for this point is being carried out at RHIC Beam-Energy Scan (BES) program as well as in SPS. So far no conclusive evidence for the existence of the critical point has been found.

As can be seen from Fig. 2 NICA will provide competitive experimental conditions for the exploration of the phase diagram area of interest. The $\sqrt{s_{NN}}$ range of 4-11 GeV for heavy-ion collisions allows to explore the area of maximum baryon density. The expected luminosity is at least an order of magnitude larger than in other facilities at similar $\sqrt{s_{NN}}$. Moreover, the MPD has collider geometry, with large and uniform acceptance which changes little with collision energy, allowing for measurements of several key observables with reduced systematic uncertainty. In general the discovery potential at NICA is unique and complementary to similar measurements at lower energies at FAIR as well as at higher energies at SPS and RHIC BES.

Initial measurements at MPD will need precise determination of several key characteristics in data. The track multiplicity in the TPC as well as energy deposit in FHCAL will enable determination of the event centrality. To associate the experimentally determined quantities to the geometrical parameters, such as impact parameter and number of participants/spectators, a Modified Wounded Nucleon model will be used, also known as MC-Glauber [10]. Multiplicity density per unit of pseudorapidity is related to the achieved energy density in the collision [11]. Its measurement will allow to test, whether densities needed for the creation of QGP are reached in the collisions at NICA. When combined with PID it will also determine the transverse energy density, which is related to the internal pressure in the extremely dense matter produced in collisions of heavy-ions [12].

The ratio of production of identified hadrons with respect to their anti-particles is directly related to the charge transport mechanism in the collision. The ratio will be measured separately

for π^+/π^- , K^+/K^- , and $p/\bar{p}$, as a function of collision energy and centrality. When extrapolated to full 4π acceptance, the data will provide total yields of various particle types, including the ones reconstructed via their decay topology. Transverse momentum spectra for all those particle types will be measured in wide acceptance in η and p_T . A wealth of information can be deduced from such data, including the freeze-out temperature and baryochemical potential of the produced system. This will allow precise positioning of each collision category (e.g. vs. centrality and collision energy) on the phase diagram of QCD. The reconstruction of particles with non-zero strangeness, including multi-strange baryons such as Ξ and Ω , will allow to address critical questions, such as onset of deconfinement, the possible existence of the critical point as well as the degree of thermalization in the system.

The study will be extended to reconstruction of strongly decaying resonances, such as $\rho(770)$, $K^*(892)$, $\phi(1020)$, $\Sigma(1385)$, and $\Lambda(1520)$. They will be included in the fits with the statistical model mentioned above, but they can also provide unique information on the rescattering phase. Resonances' lifetime is comparable with the duration of the phase, during which they can undergo rescattering and regeneration. By comparing the observed yield of resonances with respect to the statistical model expectation, the duration of the phase can be inferred [13, 14].

QCD matter created in heavy-ion collisions is strongly interacting, and is subject to intense density gradients, leading to large pressure and development of collective behavior of matter. It manifests itself as various types of flow. In the transverse plane the matter generally flows outwards from the collision axis, resulting in radial flow. It modifies strongly the inclusive transverse momentum spectra of particles with different mass, from which its measurement can be inferred. Just after the collision the spectator nucleons still remain close to the created system, preventing the flow of matter in their direction. This results in the so-called directed flow v_1 . Its measurement in RHIC BES energies [15] reveals intriguing non-monotonic behavior, which will be investigated in MPD thanks to its excellent acceptance and PID capabilities. In the transverse plane the cross-section of colliding nuclei has an almond shape, leading to the development of elliptic flow v_2 . Its measurement reveals how efficient is the transfer of spatial anisotropy to the momentum one, allowing for the determination of crucial properties of the system, such as shear viscosity to entropy ratio η/s , as well as possible changes to the speed of sound c_s near the phase transition, resulting in the softening of the EOS.

The size and dynamic evolution of the system created in heavy-ion collisions can be studied via the femtoscopy technique, relying on the measurement of two-particle correlation as a function of pair relative momentum. Analysis for pairs of identical charged pions will be performed at MPD vs. centrality and pair transverse momentum. The size of the system will be measured. The dependence of this size on the momentum is interpreted as a consequence of dynamical radial expansion. It has also been argued [16], that a specific ratio of system sizes in the transverse plane is directly sensitive to the existence of the first order phase transition.

The event-by-event fluctuations of total event multiplicity, mean transverse momentum and conserved charges, as well as multiplicities of identified hadrons should show a non-monotonic behavior in the vicinity of a critical point. MPD, as a collider experiment, offers large acceptance (at least $|\eta| < 1.2$ and $0.2 < p_T < 3.0$ for identified particles), approximately constant with respect to collision energy. Such conditions allow to significantly reduce systematic uncertainties in fluctuation measurements making MPD ideally suited to perform this search.

The EMCal will provide data on photon production at NICA. Of special interest is the measurement of low to intermediate p_T direct photons, which carry information about the initial temperature of the system [17, 18, 19], which can be compared to the critical temperature of the phase transition to the deconfined phase of approximately 160 MeV. Photon measurement will also allow for identification of π^0 and η mesons as a function of centrality and p_T , which will serve as a cross-check for charged meson data. EMCal, when combined with tracking and charged particle rejection from TPC and TOF will also provide a clean sample of electrons.

This will allow a study of light vector meson, as well as extensive investigation of the di-lepton production at a wide range of invariant mass, as well as the total transverse momentum of the pair. NICA offers a favorable conditions for such studies, as the expected background from charm production is expected to be significantly reduced, when compared to collisions at higher energies.

5. Summary

The status of the preparation of the NICA Accelerator Complex has been briefly presented. The Nuclotron, as well as two main injector chains are commissioned and operational. Booster auxiliary accelerator is in final stages of assembly. The civil construction for NICA is progressing according to schedule. First beams in NICA are expected in 2022. The civil construction for MPD Hall has been finished and the assembly of detector magnet has started. Production of subdetector components for TPC, TOF, ECal, FHCAL and FFD are in progress with commissioning of the MPD setup expected to start in 2021.

The physics program of MPD has been briefly discussed with the emphasis on data from initial NICA operation, where collisions of heavy ions are expected. Measurements of collision centrality and event plane, together with full tracking are foreseen. Full characterization of the particle production in the soft regime is planned, with an important component of electromagnetic probes. Data will allow for the search for the signatures of the deconfined matter, the existence and nature of the phase transition to ordinary hadronic matter, as well as possible existence of a critical point in the phase diagram of the QCD matter. We are looking forward to first data-taking at NICA with MPD.

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