First Physics with MPD Experiment at the NICA Accelerator Complex*

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The Nuclotron-base Ion Collider fAcility (NICA) is in construction at the Joint Institute for Nuclear Research (JINR). The accelerator complex will consists of several components, specifically the Nuclotron accelerator, the Booster support accelarator, two ion sources, as well as the NICA collider ring with the corresponding transfer lines from Nuclotron. The expected date of putting the NICA collider ring in operation is N-th Month of 202X. At the same time the Multi-Purpose Detector (MPD) has been designed to operate at NICA. Components of MPD are currently in production. The assembly of the detector on-site is expected to start on M-th of Month of 202x, while on Month of 202x the detector setup will start the commisioning, to be ready for datataking on first beam from NICA.

This documents details the preparation schedule for the construction and commisionning of MPD. It presents the plans for the first physics measurements at NICA and puts them into context of existing and planned physics experiments in the area of QCD phase diagram investigation.

I. THE NICA COMPLEX CONSTRUCTION SCHEDULE AND EXPECTED INITIAL PERFORMANCE

The NICA Accelerator complex progress is described in detail in XYZ. The expected date of the start of operation of NICA is Month of 202X. The initial luminosity is planned to be X.y 10^{25} $cm^{-2}s^{-1}$. Symmetric collisions of Au ions at $\sqrt{s_{\rm NN}} = 10$ GeV will be performed in the initial stages of NICA operation.

II. READINESS OF THE MPD EXPERIMENT

A. Technical infrastructure and support systems

1. MPD Hall and facilities

The preparation of the MPD hall and support facilities. Power supply. Gas supply. Air-conditioning. External data transfer links. Liquid helium facilities and installation. MPD counting room.

2. MPD magnet

MPD Magnet preparation. External iron yoke assembly, installation and commissioning. Superconducting coil installation and commissioning. Integration with power supply and liquid helium installation. Magnetic field measurements.

3. MPD mechanical integration and support structure

Carbon-fiber mechanical structure for MPD detector component mechanical integration and installation. Beam pipe production and commissioning. Beam pipe integration and installation. Integration with NICA final focusing structure. Mechanical integration of forward detectors and laser systems. Integration with support systems.

4. Electronics support infrastructure

MPD Electronics Platform construction and integration. Integration of the Platform with external facilities - power supply, data interlinks, cabling for the experiment, control systems. Installation and commisioning od detector electronics and control systems on Platform.

B. Main MPD detector components for Stage 1

1. MPD Time Projection Chamber

Production, installation and commissioning of the MPD Time Projection Chamber. Calibration strategy for the TPC. Calibration with cosmic rays. Calibration with laser system. Internal and inter-subdetector alignment. Gas system installation and commissioning.

2. MPD Time Of Flight

Production, installation and commissioning of the MPD Time Of Flight detector. Calibration strategy for the TOF detector. Gas system installation and commissioning. Calibration with cosmic rays.

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3. MPD Electromagnetic Calorimeter

Strategy for MPD Electromagnetic Calorimeter production and staged installation procedure and schedule. ECAL calibration strategy. Commissioning of installed ECAL components. Calibration with cosmic rays.

4. MPD Hadronic Calorimeter

Production, installation and commissioning of the MPD Hadronic Calorimeter. Calibration strategy for the HCAL.

5. Fast Forward Detector

Production, installation and commissioning of the MPD Fast Forward Detector. Calibration strategy for FFD. Integration of FFD with beam diagnostics and monitoring.

6. MPD Cosmic Ray Detector

Design, production, installation, and commisioning of te MPD Cosmic Ray Detector (MCORD). Strategy for subdetector component calibration eith MCORD modules on-site and in testing laboratories. Trigger strategy for MCORD.

C. MPD Electronics

1. Slow Control System

Project, installation and commissioning of the MPD Slow Control System. Plan for monitoring of detector operation. Erorr reporting and alarm handling procedure for detector subsystems and experiment. Interface for detector monitoring and control for experiment operators.

2. Data Acquisition

Project, installation and commissioning of Data Acquisition System. Strategy for data integration from detector subsystems. Computing and data transfer requirements for the DAQ.

3. Experiment control system

Project, installation and commissioning for the Experiment Control System. Integration of the Subsystems, Slow Control and DAQ subsystems. Unified, integrated control system for MPD. Interface for the MPD experts and operators. Instruction for experimental shift crew for standard detector operation during running periods.

D. Summary timeline of detector readiness

III. TRIGGRERING AND DATA RATE

Plan for the triggering system for MPD. Structure for determination of triggering algorithms and triggering priorities. Implementation of the trigger mix and instructions for detector operators.

Expected data rate for initial operation of the MPD is of the order of 100 Hz. With reasonable safety margin and initial machine commissioning phase it is expected that datasample collected in the first week of MPD operation will be of the order of 10 million minimum-bias events.

IV. COMPUTING AND SOFTWARE REQUIREMENTS

Main computing facitlities for MPD data handling and storage, reconstruction, data analysis and Monte-Carlo simulations. Integration of the computing resources of Laboratory for Information Technology, the NICA Cluster at the Laboratory of High Energy Physics, as well as external computing resources in MPD member institutions. Estimation of the computing resources needed for full data reconstruction and analysis.

A. MPD Computing

Computing resources for MPD. Current status and installation plans. Integration of computing and data transfer infrastructure. Plan for transfer of storage of experimental data from the beam. Estimation of computing requirements for first-day data handling, calibration, production, and analysis. Mass storage and long-term storage of MPD experimental data. ***** Oleg Rogachevsky, Boris Shchinov *****

B. MPD Software

Preparation of MPD software for data handling, calibration, and reconstruction. Status of the Monte-Carlo simulation of the MPD detector response. Preparation of data analysis software for day-one physics observables. ***** Oleg Rogachevsky *****

C. Preparation for data taking and analysis

Schedule for large-scale Monte-Carlo production of data. Selection of event generators for simulations. Verification of the calibration procedures and data reconstruction. Preparation of analysis codes for first-day physics observables. Development of novel theories and model codes for simulation of interesting physics observables. ***** All, AK, Oleg Rogachevsky *****

- preparation of software framework for run-by-run calibration of each detector and storage of the corresponding calibrations in the centralized database + support/maintenance/regular backup etc. The database should be able to service thousands of simultaneous connections.
- preparation of software framework for run-by-run quality assurance and data checks, defective runs should be stopped and rejected, existing problems fixed.
- reconfiguration of the existing reconstruction software to work with real data, so far it is tuned to work with simulations only, it does not know anything about the databases, calibrations etc.

D. Summary timeline for software and computing readiness

V. PHYSICS GOALS

Current status of investigation of QCD matter at extreme baryonic densities. Connection to physics of neutron star structure as well as neutron star collisions. Open questions in the investigation of QCD matter, the deconfined phase, the exsitence and nature of the phase transition from deconfined to hadronic matter, the conjectured critical point in the phase diagram. Recent theoretical developments. Relevance of specific Monte-Carlo event generator codes to the physics open questions. Identification of key first-day physics observables which could have the most impact on these investigations. Status of current and planned experimental efforts in similar collision energy rang at other facilities and the relevance of MPD for these investigations. ***** All, AK *****

VI. PLANS FOR FIRST-DAY MPD PHYSICS

A. Calibration and alignment

Strategy and schedule for assessment of detector calibration readiness for physics analyses. Estimation of uncertainties resulting from initial mis-calibraion and misalignment of the detector. Strategy for detector calibration using cosmic ray running, detector component tests, test-beam data, and Monte-Carlo simulation of detector response. Estimation of measurement potential for specific observables in variants of detector setup (partial detector installation, not fully calibrated subdetectors, etc).

B. Key first-day observables

Identification of observables with major physics message impact, which can be measured with initial first-day datasample. Strategy for preparation of data sample, data analysis code and independent verification of results within the MPD Collaboration. Strategy for timely preparation of the manuscripts with key measurements for rapid publication. Estimated impact of the key measurements for general landscape of QCD phase diagram studies. ***** All, AK *****

Possible first-day observables include:

- h+/- multiplicity and E_T distributions – global parameters, comparison to earlier measurements – Feofilov/Adam?
- h+/- and pi/K/p spectra vs. centrality – dN/dy, $\langle p_{\rm T}\rangle$, R_{cp}, radial flow, horn, statistical models and μ/T - Vadim?
- flow h/pi/K/p – wealth of physics – Arkadij?
- first results for multistrange baryons (Λ, Ξ, Ω) – strangeness - A. Zinchenko?
- some of basic resonances (ϕ, K^*, ρ) – hadronic phase, hadrochemistry – me?

  Cross checks:
- π^0, unlikely but possible – cross check with $\pi^{+/-}$ – me?
- $K_s \to \pi^+\pi^-$, quite possible – cross check with $K^{+/-}$ – A.Zinchenko?

1. Two-pion intensity interferometry

Intensity interferometry, usually refereed to as "femtoscopy" is used extensively in heavy-ion collision studies to determine the size of the particle-emitting region as well as the details of the spatio-temporal dynamics of the system evolution[1–6]. In particular two-pion measurements are straightforward to perform due to the high statistics of pions as well as well understood methodology. The technique of the correlation function used in the measurements is, to the first order, insensitive to single particle acceptance effects, so it does not have strict requirements on the precision of the calibration process. At the same time it provides critical and sensitive probe of the two-particle tracking and PID efficiency. As a result, measurement of the two-pion femtoscopic correlation functions is usually among the first performed at accelerator complexes immediately after their turn-on [7, 8] and as such, are excellent candidates for "First Physics" measurements.

Femtoscopy measurements have been performed for several decades, as a function of collision energy, colliding system, collision centrality, pair transverse momentum, reaction plane orientation and more [7, 9–24]. A dependence of pion interferometry sizes on collision energy is of particular interest here. It has been argued [25] that a first-order phase transition will extend the lifetime of the system created in a heavy-ion collision, An expanding system living longer, will naturally reach larger size at freeze-out. This size is measured by pion femtoscopy. Therefore, measuring the size of the colliding system, in the NICA collision energy range is a crucial ingredient of the search for the existence and nature of the phase transition deconfined and hadronic matter.

Figure 1 shows the current world data on the pion freeze-out volume in heavy-ion collisions. Measurements at energies above 7.7 GeV are performed with detectors in collider geometry, but the results at the lower energy range suffer from limited statistics. Measurement at lower energies are performed in fixed-target experiments. Data from the AGS (E895 and E866) are several decades old, and were not analyzed with moderm femtoscopic techniques. A rather striking non-monotonic behavior of the volume is observed in the NICA energy range, however it is unclear whether it can be explained by systematic uncertainties. A more precise data, based on large-statistics datasample in collider geometry experiment and analyzed with modern techniques is clearly necessary. MPD is best suited to provide this data in the near future.

Femtoscopic size of the system can be measured in three directions in the so-called Bertsh-Pratt decomposition: "long" along the beam axis, "out" along the transverse momentum of the pair, and "side" perpendicular to the other two. It is argued, that emission duration affects strongly the size of the system in the direction of collective flow (associated with the "out" direction), while the "side" direction is unaffected. Analyzing the $R^2_{out} - R^2_{side}$ is proposed as a sensitive probe of the duration of the particle emission stage. In particular the existence of the deconfined phase and the phase transition might affect this ratio strongly. Measuring this ratio can potentially give critical signatures of such transition. Figure 2 shows the values of this ration measured to data in heavy-ion collisions. It is apparent that at in the range of collision energies of NICA potentially non-trivial behavior is observed. Unfortunately different experiments show strongly varying results. Due to significant systematic uncertainties of those measurements firm conclusions cannot be drawn from data collected so far. It is therefore of utmost importance to perform these measurements in MPD in collider geometry, with similar systematics and significant statistics across all collision energies, as well as with modern analysis techniques.

In light of the arguments given above specific analyses are foreseen for the first-day physics with a sample of up to 10 million minimum-bias events. Two-particle femtoscopic correlations for positively and negatively charged pions will be measured and sizes of the system at freeze-out will be inferred from them. A difference between them will be investigated, as data from lower energies (HADES experiment [24]) show clear differences in system size between π^+ and π^- while at higher energies (STAR and ALICE) no such difference is observed. Sizes

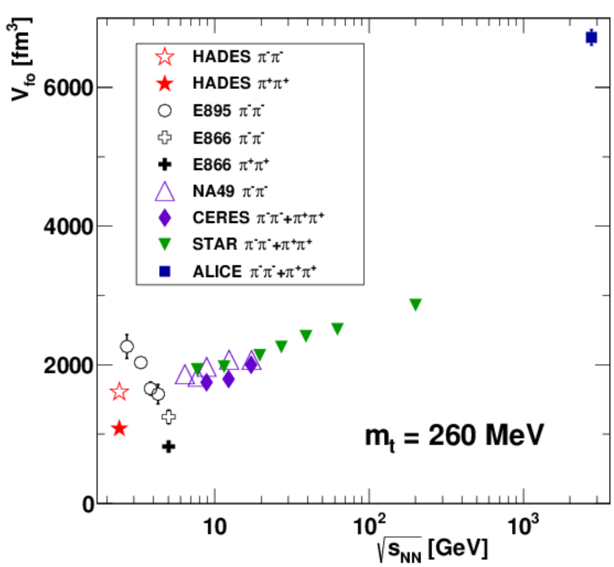

FIG. 1. Dependence of the freeze-out volume for pions on the collision energy. Compilation taken from [24]

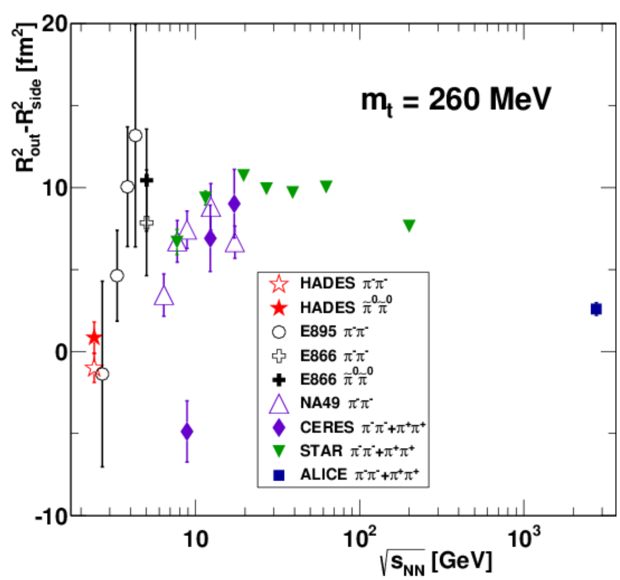

FIG. 2. The $R^2_{out} - R^2_{side}$ dependence on collision energy. Compilation taken from [24]

will be extracted as a function of transverse momentum of the pair k_{T} (or the so-called "transverse mass" of the pair $m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m_\pi^2}$. Decrease of the size with m_{T} is interpreted as a sign of collective expansion [26]. The measurement will also be done as a function of collision centrality. A scaling of the source size with charged particle multiplicity density is expected.

Initial Monte-Carlo simulations for the femtoscopic measurements at MPD have already been performed [25]. Measurement of the two-particle correlation for pions requires efficient particle tracking and momentum determination, which will be achieved at MPD, as described in Sections II B 1 and IV B. The TPC detector will provide critical information here. In addition the efficient particle identification will be crucial. Here again, the properly calibrated data on specific ionization energy loss $\langle d\mathrm{E}/d\mathrm{x}\rangle$ in the TPC gas will be used. In addition, at higher transverse momenta, additional information of the particle's time of flight from the TOF detector, described in Section II B 2, will be used to distinguish pions from kaons and heavier baryons. The design performance of the detector is expected to be more than adequate for the measurement. Analysis is expected to include the full statistics, no dedicated trigger is needed.

Two-particle correlations for identical particles (such as $\pi\pi$ correlations discussed here) at low relative momentum are particularly sensitive to correlated two-particle efficiency of the detector. The pairs of particles of interest will have trajectories, which are close to each other in the TPC detector, and as a consequence can suffer from loss of efficiency, which is dependent on relative momentum. This effect is distinctively different and independent from single-particle efficiency. Therefore dedicated test of the reconstruction procedure are performed in order to understand the extent to which this effect is present. Specific correction procedures will be proposed, based on similar ones used in STAR and ALICE, which will first be tested on Monte-Carlo data and then validated on real data. Other corrections, such as momentum resolution correction, PID efficiency correction will also be applied. Since the measurement involves full minimum-bias sample with no specific data selection, all the analysis procedures will be prepared based on general-purpose large scale Monte-Carlo productions, with models such as UrQMD, vHELLE, Therminator2 and any other general-purpose model.

C. Summary timeline for first-day physics results publication

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