IL NUOVO CIMENTO **47 C** (2024) 238
DOI 10.1393/ncc/i2024-24238-1

Colloquia: HADRON2023

Initial physics performance and status of the MPD at NICA

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received 21 December 2023

Summary. — The Multi-Purpose Detector (MPD) is one of the two heavy-ion experiments under construction at the Nuclotron-based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research (JINR) in Dubna, which is designed to run in the collider mode. In its initial stage of operation, the MPD will study collisions of heavy ions in the energy range $\sqrt{s_{NN}} = 4$–11 GeV, starting with Bi+Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV. The MPD is an international collaboration consisting of 35 institutions from 11 countries with more than 500 participants. The MPD aims to study the phase diagram of QCD matter at maximum baryonic density, to determine the onset and the nature of the phase transition between the deconfined matter and to search for the conjectured critical end point. In this document, we describe the MPD detector and its physics program, with emphasis on the first physics measurements with beams as well as the expected performance of all the detector subsystems.

1. – Introduction

The Quantum Chromodynamics (QCD) phase diagram is a topic of great interest, it helps us to understand the evolution of the early universe and the transition from the deconfined matter to the hadronic matter. To study its rich structure, several facilities as the Super Ion Synchroton (SIS), the Alternative Gradient Synchrotron (AGS), the Super Proton Synchrotron (SPS), the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), among others, has been developed. Its experimental results in combination with lattice QCD calculations indicate that at low bariochemical potential and temperature around 155–160 MeV there is a smooth crossover between the hadronic phase and the deconfined matter [1]. However, for higher baryon densities as those in neutron stars or neutron star mergers, the description is far from complete. It is expected a first-order phase transition [2] and the appearing of a critical end point (CEP). Different calculations show that the most probable heavy-ion collision energy to

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search for the CEP is below $\sqrt{s_{NN}} = 6$–7 GeV [3]. There are several ongoing facilities like STAR BES and FXT program at RHIC [4], and NA61-SHINE [5] and future facilities like CBM at FAIR [6], NA60+ at CERN SPS [7] besides the MPD at NICA that are focused on exploring this region. The overlap of these experiments with MPD will allow to obtain independent validation of the results.

The MPD experiment is part of the Nuclotron Ion Collider fAcillity (NICA) Complex under construction by the Joint Institute for Nuclear Research (JINR). It was designed to study the strong interacting matter created in collisions with ions like C, Xe, Au, Bi, among others with a collision energy range from $\sqrt{s_{NN}} = 4$ to 11 GeV.

2. – The NICA complex

The main elements of the NICA complex, as is shown on the left panel of fig. 1, are the light- and heavy-ion injection chains, the Super Conducting (SC) Booster Synchrotron, the Ion Superconducting Synchrotron, the fixed target experiment BM@N (Baryonic Matter at Nuclotron), the SPD (Spin Physics Detector) and the MPD. The light-ion chain implements a high-frequency resonant linear accelerator LINAC LU-20 to accelerate protons and light ions (to Mg magnesium ions with the ratio of mass number to charge $A/Z \leq 3$) up to 5 MeV/u. The light ions are injected directly into the Nuclotron. In the case of heavy ions (ions with $A/Z \leq 6$), they are produced by a cryogenic heavy ion source (KRION) of Electron String Ion Source (ESIS) type, they are accelerated up to 3.24 MeV/u before be injected into the SC Booster Synchrotron. The Booster has a perimeter of 210.96 m and is located inside the yoke of the Synchrophasotron magnet. It can accumulate up to 2×10^9 ions and accelerate them up to ~ 600 Mev/u in the case of $^{197}Au^{31+}$, before injecting them into the Nuclotron. The Nuclotron accelerator was upgraded in 2013, is the main accelerator, it has a perimeter of 252.52 m, it can accumulate up to 1×10^9 of ions and accelerate them up to 1–4.5 GeV/u. The beams can be transferred to the collider or delivered to the fixed-target experiment, the BM@N that has been upgraded to its full configuration and carried out its first run in December 2022–January 2023 with Xe beam on CsI target. The collider is a ring with a racetrack shape with two arcs and two long straight sections and 503 m of circumference. It is under construction inside a tunnel with additional buildings for the experiment facilities

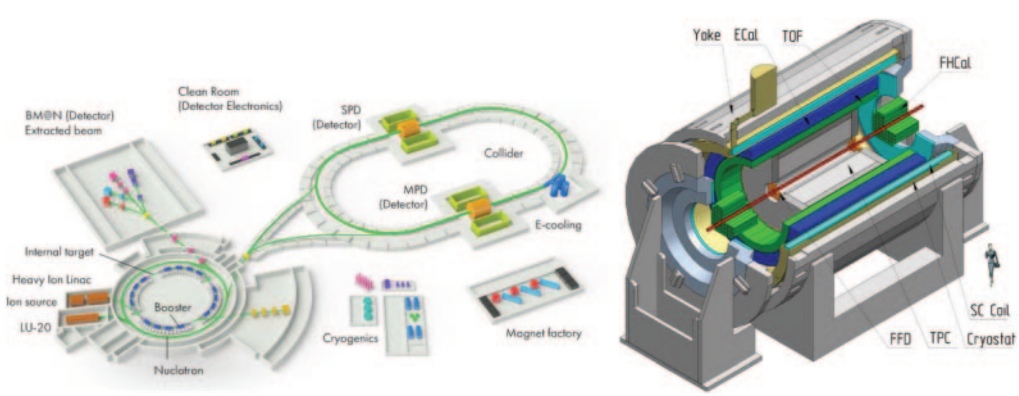

Fig. 1. – Schematic diagram of NICA complex (left), and first stage of MPD experiment in which the main elements (right) appear.

MPD and SPD in the straight parts and the electron cooler. The civil construction of the collider is finished and about 30% of all elements of the Collider and magnetic cryostat system are installed in the tunnel and the installation of RF stations is underway. The first beams at the NICA collider are expected in 2025.

3. – MPD detector

The MPD is an international scientific collaboration established in 2018 to construct, commission and operate the detector, 35 institutions from 11 countries (Armenia, Bulgaria, China, Georgia, Kazakhstan, Mexico, Moldova, Mongolia, Russia, Serbia and Slovakia) besides JINR are currently participating, with more than 500 researchers.

The MPD consists of various subsystems, that will be installed in two stages. The first stage of data taking shown in the right panel of fig. 1 will include the TPC (Time Projection Chamber), the TOF (Time of Flight), the FFD (Fast Forward Detector), the ECal (Electromagnetic Calorimeter) and the FHCal (Forward Hadron Calorimeter), that will be supported by the outer magnet yoke. The superconducting coil SC will produce a uniform magnetic field of up 0.5 T directed along the beam axis in the central part of the setup. The 800 ton SC solenoid and the platform for the electronic equipment designed for data readout from MPD subsystems was moved for the first time to its current configuration in the MPD hall in April of 2023. The beam line will be surrounded by the TPC, the main tracking system. It is a gaseous chamber, a barrel of 3.4 m width, under a uniform electrical field provided by the read-out chambers (ROC) consisting of Multi Wire Proportional chambers located at the end caps. In conjunction with the TOF, it will provide precise momentum measurements and particle identification for $|\eta| < 1.6$. The TOF is based on the technology of Multigap Resistive Plate Chambers (MRPC) and will provide information on the time of flight of particles produced in the collision. Calibration will be performed with cosmic rays. The ECal is placed between the TOF and magnet, it will be used for detection of electromagnetic showers and photon and electron measurements. It consist of *shashlyk*-style modules with plastic scintillator and lead absorbers fixed in a projective geometry. In the forward direction, on the TPC border, there is the FFD, that covers a pseudorapidity of $2.9 < \eta < 3.3$, which will work like a wake up trigger to provide a fast timing signal for the TOF. And finally, the FHCal is located near the MPD magnet end-caps, with pseudorapidity acceptance of $2 < \eta < 5$ units. It will be used to determine the centrality of the collision and the orientation of the reaction plane. More detailed information can be found in [8].

The MPD is in the final stage of production, commissioning and first data taking will be in 2025. It will start with Bi+Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV with a reduced luminosity of 10^{25} cm^{-2}s^{-1} for alignment calibration and first physics measurements.

The simulation and data analysis will employ the Software framework MpdRoot, an object oriented set of tools to simulate, transport and reconstruct MC events within MPD experiment [9, 10]. It provides an interface to most Monte Carlo event generators which model heavy ion collisions at NICA energies. The data analysis will be organized by a centralized system of wagons in order to use the available resources in an efficient way. The computing resources are going to manage data for BM@N, SPD and MPD experiments. The main elements of the cluster are at VBLHEP (Veksler and Baldin Laboratory of High Energy Physics) and LIT (Laboratory of Information Technologies). The LIT NICA cluster is part of the Multifunctional Information and Computing Complex (MICC) that will manage its connection with computing complexes of other organizations involved in NICA like UNAM in Mexico. Computing resources are integrated using the DIRAC interware, that also provides mass production of simulated and experimental data [11].

4. – The physics program

The physics analyses are organized in different dedicated groups which have prepared a detailed plan of measurements to achieve the main goal to study the properties of the strongly interacting matter and explore the region of high baryon density of the QCD phase diagram, to obtain a more detailed information of the equation of state (EoS), and search for the CEP. Selected physics measurements are presented and discussed in the first collaboration paper [8].

One of the main studies is the centrality determination which together with reaction plane determination, characterize the size of the overlap region and is the basis for further analysis. The centrality was determined by the multiplicity obtained with the TPC. Two different approaches have been used the Γ-fit method and the MC Glauber which relate multiplicity and centrality classes with the impact parameter. The results show a very good agreement between the average impact parameter directly obtained from the generator and the one estimated from the MC Glauber model [12, 13]. An additional model to get the centrality is the energy deposition and space distribution of spectators in the FHCal. In this approach the three-dimensional energy distribution in the FHCal is fitted by a linear function in which the parameters like the height, the radius and the volume of the cone provide an estimation of the total spectator energy. This fit gives a correlation between the maximum energy and the deposited energy that allows to separate the centrality classes. Also, the energy deposited in the FHCal is used to get the event plane angle [14]. Inclusive p_T spectra for pions, kaons and protons will be measured as a function of collision centrality, comparison with different models will allow to study chiral symmetry restoration and the temperature and barion-chemical potential at freeze out [15]. Another observable under study that can be determined at MPD is the anisotropic collective flow as a function of centrality, that will allow to probe the EoS and the transport properties of the matter created in the collision [16]. It has also been shown that it is possible to identify strange particles such as Λ, Ξ, Ω and hypernuclei $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He whose lifetimes provide information about the hyperon-nucleon interaction strength [17]. Besides, our recent analysis has shown that the MPD experiment has the capability to explore hot physics topics like: critical fluctuations for (net) proton/kaon multiplicity distributions; measurement of the hyperon global polarization in mid-central collisions, filling the gap of the polarization excitation function at NICA energies and studying the spin alignment of vector mesons ($K^*(892)$ and $\phi(1020)$); phenomena that can depend on multiple physics mechanism like the vorticity, the magnetic field, the mass of the particles, among others.

5. – Conclusions

The MPD Collaboration is steadily coming to the final integration of the detector data taking. The physics program for the first years of MPD data taking is formulated and the first physics paper was recently published. The MPD will provide a unique opportunity for investigating properties of nuclear matter at maximal densities to map the QCD phase diagram, to search for phase transition and the critical end point. First operations of the MPD detector are expected with cosmic studies. Commissioning and start of data taking with Bi + Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV at the NICA complex are expected in 2025.

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