NICA heavy-ion collider at JINR (Dubna). Status of accelerator complex and first physics at NICA.

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Abstract. The NICA facility is under active realization at the Joint Institute for Nuclear Research (JINR, Dubna). Its main goal includes experimental studies of hot and dense baryon rich matter forming in heavy ion collisions to search for possible manifestations of phase transitions and critical phenomena, as well as investigation of nucleon spin structure with polarized proton and deuteron beams. The NICA general design, construction status, and prospects for physics program are presented.

1. The Nuclotron-based Ion Collider fAcility

The Nuclotron-based Ion Collider fAcility (NICA) goal is to study hot and dense strongly interacting baryon matter and spin physics. The NICA facility developing at JINR is now in the pre-commissioning phase [1, 2, 3, 4] (Fig.1).

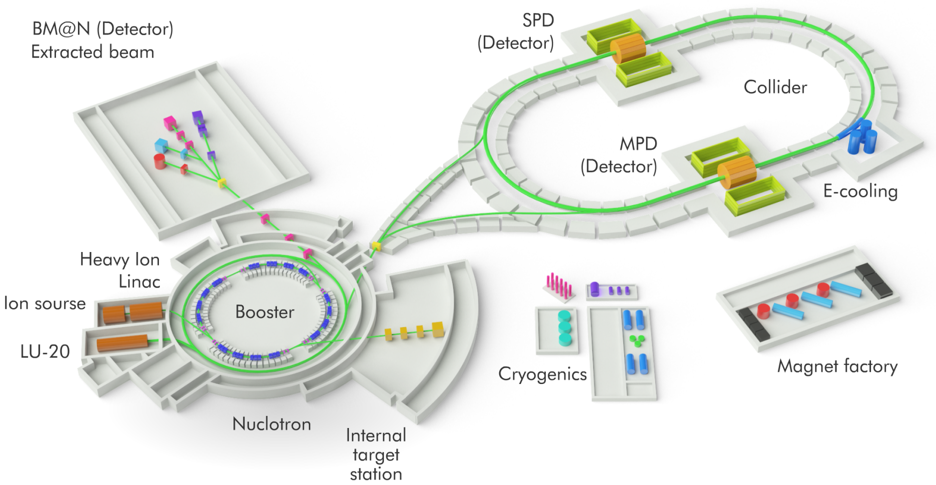


Figure 1. The Nuclotron-based Ion Collider fAcility.

An injection part of the NICA accelerator complex consists of new 3.2 MeV/u heavy ion linac, new 580 MeV/u superconducting Booster synchrotron (for partially stripped heavy ions), modernized 3.9 GeV/u superconducting synchrotron Nuclotron (for completely stripped heavy ions). Electron cooling system in Booster at maximum electron energy of 50 keV is used to accumulate ions at injection energy and increase the beam phase space density at 65 MeV/u. This injection part of the complex had successfully started its cruise operation in March 2022 providing ion beam accelerated in Booster-Nuclotron tandem and slow extracted (up to 10 sec.) to two fixed target experiments: Short Rage Correlation (SRC) [5] and Baryonic Matter at Nuclotron (BM@N) [6]. The collider part of the NICA complex is presently at the stage of final production and mounting. Both collider rings will be equipped with electron cooling systems of maximum 2.5 MeV electron energy and stochastic cooling systems of 0.7 −− 3.5 GHz bandwidth. The systems will be used to support beam accumulation and to prevent emittance growth due to intrabeam scattering. Three types of RF systems are used for longitudinal phase space manipulations: barrier bucket RF-1 for the beam accumulation, from continuous beam to 22 bunches bunching by RF-2 (4 stations per ring), and the formation of dense and short bunches by RF-3 of the 66th revolution harmonic (8 stations per ring) for operating at the collisions. Several laboratories participate in the design and construction of the NICA accelerator complex. Among them, the contribution of the Budker Institute is the most significant: all RF systems and beam cooling systems were created by this institute and are in stage of mounting. The assembling of two Collider storage rings (circumference is 503.02 m) with two interaction points had been started in December 2021 and planned to be completed in 2023.

The Multi-Purpose Detector (MPD) located in the 1st interaction point is the heavy-ion experiment at the NICA collider. In its initial stage of operation, planned to start at the end of 2023, 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 with the expected luminosity of $10^{24} cm^{-2}s^{-1}$. The MPD is an international collaboration consisting of 31 institutions from 10 countries with more than 450 participants. The MPD aims to study the phase diagram of QCD matter at maximal possible baryon densities, to determine the nature of the phase transition between the deconfined and hadronic matter and to search for the critical end point. It is particularly well suited for searching for the existence of a critical point from the ratios of conserved charge cumulants as a function of collision energy and system size, for studying signatures of vortex motion and magnetic field, for chiral symmetry restoration effects by measuring dileptons in the intermediate mass region, and for searching for exotic hadrons and light nuclei to study their influence on the equation of state at high baryon densities (see [14] and references therein). The full-scale stage of the project NICA is related to a formation of the colliding beams with the design luminosity ($L \sim 10^{27} cm^{-2}s^{-1}$) at operation of all RF systems and HV electron cooling system in 2025, which is more than an order of magnitude higher than the luminosity that was achieved in the BES program at RHIC.

The 2nd interaction point will host the Spin Physics Detector (SPD) to study the spin structure of the proton and deuteron and the other spin-related phenomena with polarized proton and deuteron beams at collision energies up to 27 GeV and luminosities up to $10^{32} cm^{-2}s^{-1}$. The SPD is planned to operate as a universal facility for comprehensive study of the unpolarized and polarized gluon content of the nucleon at large Bjorken-x, using different complementary probes (charmonia, open charm and prompt photon production processes) and measurements of specific single and double spin asymmetries. The SPD is an international collaboration consisting of 33 institutions from 14 countries with around 300 participants. Start of 1st stage SPD operation is scheduled for 2026.

2. BM@N experiment

BM@N is the first experiment which is already operational at the Nuclotron/NICA. The purpose of the BM@N experiment is to study relativistic heavy ion beam interactions with fixed targets [7, 8, 9] in the energy range of high baryon densities [10]. At the Nuclotron energies the nucleon density in a fireball created by two colliding heavy nuclei is 3-4 times higher than the saturation density[11]. In addition, these energies are high enough to study strange mesons and (multi)-strange hyperons produced in nucleus-nucleus collisions close to the kinematic threshold [12, 6]. The primary goal of the experiment is to constrain parameters of the Equation of State (EoS) of high density nuclear matter. Studies of the excitation function of strange particle production below and close to the kinematical threshold provide the means to differentiate hard from soft behaviour of EoS [13]. The BM@N physics program also includes study of in-medium properties of hadrons in dense nuclear matter and searches for light hypernuclei. The Nuclotron will provide the experiment with beams of a variety of particles, from protons to gold ions, with a kinetic energy ranging from 1 to 6 GeV/nucleon for light ions with Z/A ratio of 0.5 and up to 4.5 GeV/nucleon for heavy ions with Z/A ratio of 0.4. The planned intensity of a heavy ion beam is few 10^6 ions/s. The acquisition rate of non-peripheral collisions, i.e., central or intermediate interactions, is expected to reach 50 kHz.

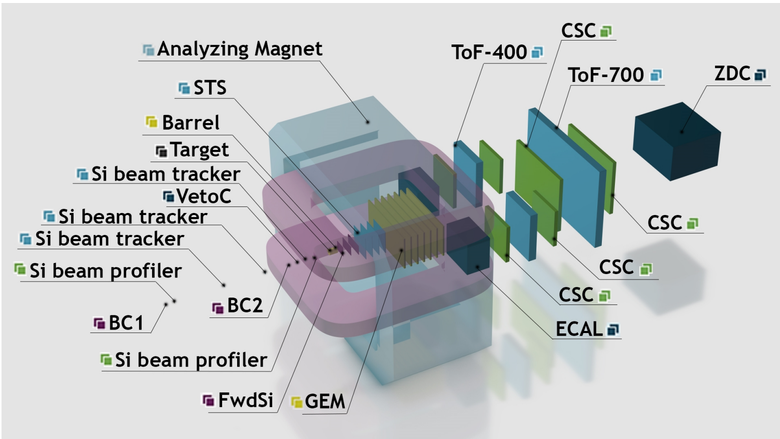
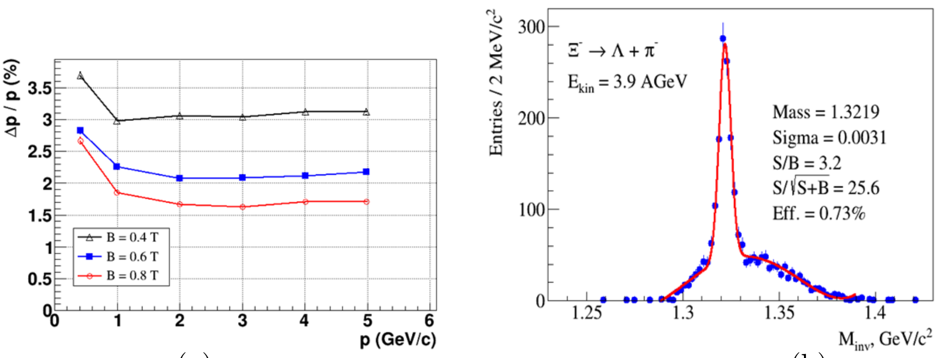


Figure 2. Scheme of the BM@N set-up for heavy ion program.

The layout of the upgraded BM@N configuration for heavy ion program is shown in Fig.2. The experiment combines a high precision measurement of track parameters with time-of-flight information for particle identification and presumes a measurement of the total energy by a hadron calorimeter to analyze the collision centrality. The charged track momentum and multiplicity are measured using a set of forward silicon detectors (FwdSi) and a full set of large acceptance two-coordinate GEM detectors mounted downstream of the target inside the analyzing magnet. Installation of a large apperture silicon tracking system (STS) is planned on the next stage of the experiment. The vertical gap between the poles of the analyzing magnet for detector installation is about 1 m. The magnetic field reaches a maximum value of 1 T, which makes it possible to optimize the BM@N geometrical acceptance and momentum resolution for different processes and energies of the beam. A thin carbon vacuum beam pipe is installed into the setup to reduce background interactions of heavy ion beams with the air. The purpose of the outer tracking system based on a set of cathode strip chambers (CSC) is to extrapolate tracks of charged particles to the identification system (ToF). A Zero Degree Calorimeter (ZDC) is installed for extraction of the collision centrality by measuring the energy of the fragments of colliding heavy nuclei. Feasuibility studies show reasonable performance of the BM@N experiment to measure multi-strange hyperons in reactions at kinetic energies of the beam in the range from 1.5 to 4 AGeV. A charged particle momentum resolution is shown in Fig. 3a as a function of the momentum for different values of the magnetic field. The variation of the magnetic field is required to keep the constant curvature of the incoming beam inside the vacuum beam pipe for different energies of the beam. The reconstructed signal of Ξ^- hyperons in the cascade decays $\Xi^- \to \pi^-\Lambda \to p\pi^-$ is illustrated in Fig. 3b. The first heavy ion run of the BM@N experiment to study interactions of the xenon beam with the CsI target is planned in 2022.



(a) (b)

Figure 3. (a) Charged particle momentum resolution as a function of the momentum for different values of the magnetic field. (b) Reconstructed signal of Ξ^- hyperons in the invariant mass spectrum of (Λ, π^-).

3. MPD experiment

The MPD physics program is described in detail in [12, 14].

The MPD set-up has been designed as a 4π spectrometer capable of detecting of charged hadrons, electrons and photons in heavy-ion collisions at high luminosity in the energy range of the NICA Collider. To reach this goal, the detector will comprise a precise 3-D tracking system and a high-performance particle identification (PID) system based on the time-of-flight measurements and calorimetry. The basic design parameters have been determined by physics processes in nuclear collisions at NICA and by several technical constrains guided by a trade-off of efficient tracking and PID against a reasonable material budget. At the design luminosity, the event rate in the MPD interaction region is about 6 kHz; the total charged particle multiplicity exceeds 1000 in the most central Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV (in 4π region). 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.

The full setup includes a superconducting solenoid, a time-projection chamber (TPC), a barrel time-of-flight detector (ToF), an electromagnetic calorimeter (ECal), a front hadron calorimeter (FHCal), and a fast forward detector (FFD) and Forward tracker based on cathode pad chamber (CPC) and Inner tracking system (ITS). The entire central detector (CD) is a cylinder 9 m long and about 6.6 m in diameter. The MPD layout is shown in cross section in Fig. 4.

A detailed description of the detector components can be found in MPD TDR [15].

For registration of particles produced at very small angles, FFD and FHCal are used. The signals from these two detectors are used in the first level trigger and for determination the centrality of the collision and restore the point of interaction of nuclei.

The ion beams collide inside a straight section of the vacuum chamber with a 1.7 m long central beryllium part with two aluminium tips 3.5 m long each. It is planned to build the first stage of the MPD setup, which consists of the superconducting solenoid, TPC, barrel TOF, Ecal, FHCal and FFD. The cross-sectional view of the MPD Central Detector is shown in Fig. 5.

The TPC [16] is the main tracking detector of the MPD central barrel. It does 3-dimensional precise tracking of charged particles and provides the relative momentum resolution for charged

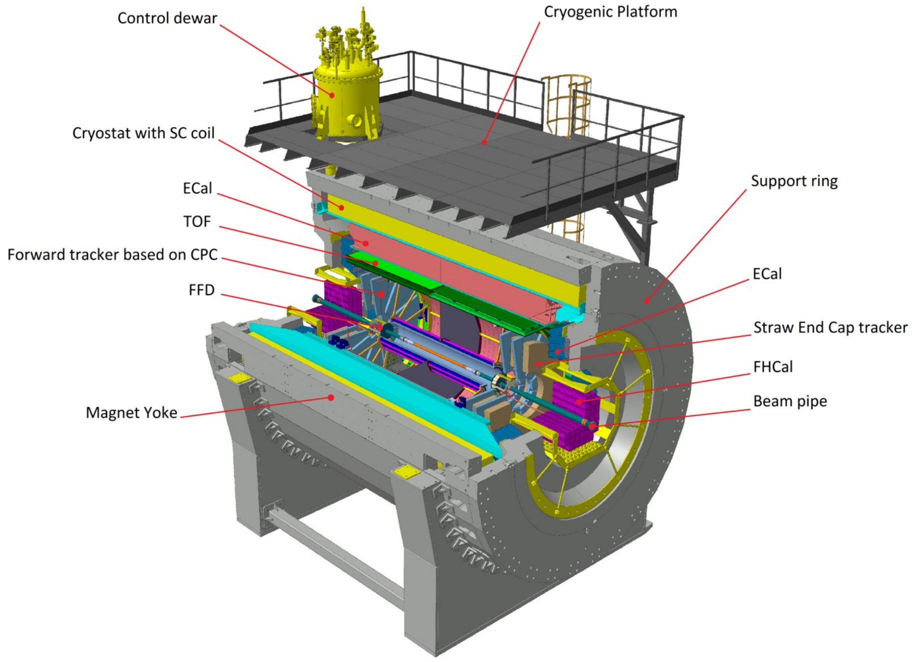


Figure 4. The overall schematic view of the MPD subsystems in its full configuration.

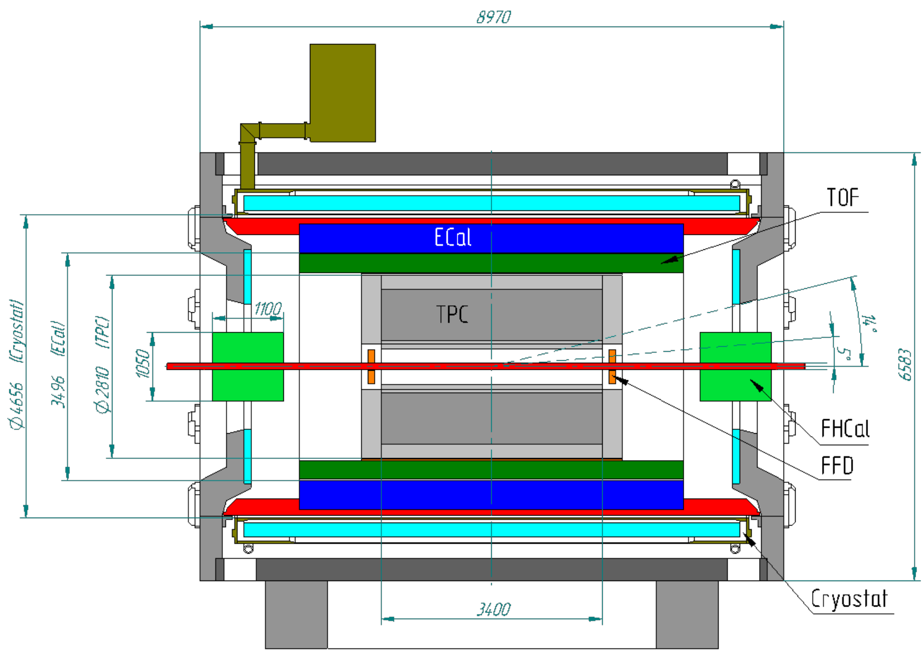


Figure 5. Cutaway side view of a basic configuration of the MPD Central Detector.

particles under 3% in the transverse momentum range $0.1 < p_T < 1$ GeV/c and at overall acceptance of $|\eta| < 1.2$.

The TPC has 53 rows which provides the same numbers of measurements of hit position along particle track and ionization losses in the gas of TPC. The ionization losses information is used for particle identification.

The TOF system based on Multi gap Resistive Plate Chambers (MRPC) provides time-of-

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flight measurements with accuracy better than 80 ps and position crossed particles with precision about 0.5 cm [17]. This information is used together with momenta measurements from TPC for secondary particle identification. MRPC design has triple-stack structure with 5 gaps of 200 μm each are used. Signals are read from both sides of the 1 cm wide strip.

Combined particles identification by TOF and energy losses in the TPC provides good particles separation with low contamination.

The primary role of the electromagnetic calorimeter [18] is to measure the spatial position and energy of electrons and photons produced in heavy ion collisions. The ECal is designed with projective geometry in both directions. Shashlik type modules of the ECal made of layers of 300 μm thick Pb plates interleaved with 1.5 mm scintillator plates. The smallest unit of ECal is a tower which is made of 210 layers of Scintillator–Pb sandwiches with a size of 4 x 4 cm^2. ECal thickness just above 11 X0 and the correspondent energy leak from the backend of the calorimeter; though the leak does not exceed $10 - 12$ % in the ECal energy range.

The FHCal [19] is designed for determination of the collision centrality and the orientation of the reaction plane for collective flow studies. An event-by-event determination of these quantities is of crucial importance for the analysis of many physics' observables. The detector will measure the energy of noninteracting nucleons and fragments (spectators) in nucleus-nucleus collisions. The energy resolution of FHCal is $\frac{\sigma E}{E} = \frac{60\%}{\sqrt{E(GeV)}}$.

The FHCal is consists of two hadron calorimeters with 45 modules each placed symmetrically from the interaction point. It is a fully compensating modular lead-scintillator calorimeter with high and uniform energy resolution. Each individual module consists from 42 lead/scintillator layers with a surface of 15 x 15 cm^2. The scintillation light is read out via wavelength shifting (WLS) fibers by silicon photomultipliers (SiPM) (multipixel avalanche photodiodes (MAPD)).

The FFD [20] is the key detector for fast and effective triggering on nucleus-nucleus collisions at the center of the setup with approximately 100% efficiency for central and semi-central Au+Au collisions measuring z-position of the collision with an uncertainty smaller than ± 5 cm. FFD must be able to see each beam crossing (the dead time must be less of 75 ns) and generate the start pulse t_0 for the TOF detector with time resolution $\sigma_{t0} < 50$ ps.

The FFD efficiently detects the high-energy photons by their conversion to electrons in a lead plate with thickness of 10 mm corresponding to $\sim 2X_0$. The electrons leave the lead plate and pass through a quartz radiator generating Cherenkov light with excellent time characteristics. The Cherenkov light is collected on a photocathode of multianode MCP-PMT XP85012 (Planacon) from Photonis.

It is a plan to roll out MPD on the collider beam at the end of 2023. Detectors of MPD could be used for the luminosity tunning control of the collider beams.

4. SPD experiment

The Spin Physics Detector (Fig.6) is a universal experimental setup in the second interaction point of the NICA collider intends to study the spin structure of the proton and deuteron and the other spin-related phenomena with polarized proton and deuteron beams at a collision energy up to 27 GeV and a luminosity up to 10^{32} cm^{-2} s^{-1}. In the polarized proton-proton collisions, the SPD experiment will cover the kinematic gap between the low-energy measurements at ANKE-COSY and SATURNE and the high-energy measurements at the Relativistic Heavy Ion Collider, as well as the planned fixed-target experiments at the LHC. The possibility for NICA to operate with polarized deuteron beams at such energies is unique.

SPD is planned to operate as a universal facility for comprehensive study of the unpolarized and polarized gluon content of the nucleon at large Bjorken-x, using different complementary probes such as: charmonia, open charm, and prompt photon production processes. The experiment aims at providing access to the gluon collinear and Transverse Momentum Dependent parton distributions such as helicity, Sivers, and Boer-Mulders functions in the nucleon, as well as the gluon transversity distribution and tensor PDFs in the deuteron, via the measurement of specific single and double spin asymmetries. The results expected to be obtained by SPD will play an important role in the general understanding of the nucleon gluon content and will serve as a complementary input to the ongoing and planned studies at RHIC, and future measurements at the EIC (BNL) and fixed-target facilities at the LHC (CERN). Simultaneous measurement of the same quantities using different processes at the same experimental setup is of key importance for minimization of possible systematic effects. The aforementioned processes cover the kinematic range of x from 0.05 to 0.9 ($< x >= 0.3$) for $Q^2 > 10GeV^2/c^2$. Other polarized and unpolarized physics is possible, especially at the first stage of NICA operation with reduced luminosity and collision energy of the proton and ion beams. The SPD physics program is described in detail in [21, 22, 23]. It covers not less than 5 years of the NICA collider running. The measurements at SPD have bright perspectives to make a unique contribution and challenge our understanding of the spin structure of the nucleon and the nature of the strong interaction.

The SPD experimental setup (Fig.6) is designed as a universal 4π detector with advanced tracking and particle identification capabilities based on modern technologies that will be installed in the SPD experimental hall of the NICA collider. The silicon vertex detector (VD) will provide resolution for the vertex position on the level of below 100 μm needed for reconstruction of secondary vertices of D-meson decays. The straw tube-based tracking system (ST) placed within a solenoidal magnetic field of up to 1 T at the detector axis should provide the transverse momentum resolution $\sigma_{p_T}/p_T \approx 2\%$ for a particle momentum of 1 GeV/c. The time-of-flight system (PID) with a time resolution of about 60 ps will provide 3σ π/K and K/p separation of up to about 1.2 GeV/c and 2.2 GeV/c, respectively. Possible use of the aerogel-based Cherenkov detector in the end-caps will extend this range. Detection of photons will be provided by the sampling electromagnetic calorimeter (ECal) with the energy resolution $\sim 5\%/\sqrt{E}$. To minimize multiple scattering and photon conversion effects for photons, the detector material will be kept to a minimum throughout the internal part of the detector. The muon (range) system (RS) is planned for muon identification. It can also act as a rough hadron calorimeter. The pair of beam-beam counters (BBC) and zero-degree calorimeters will be responsible for the local polarimetry and luminosity control. To minimize possible systematic effects, SPD will be equipped with a free-running (triggerless) DAQ system. A high collision rate (up to 4 MHz) and a few hundred thousand detector channels pose a significant challenge to the DAQ, online monitoring, offline computing system, and data processing software.

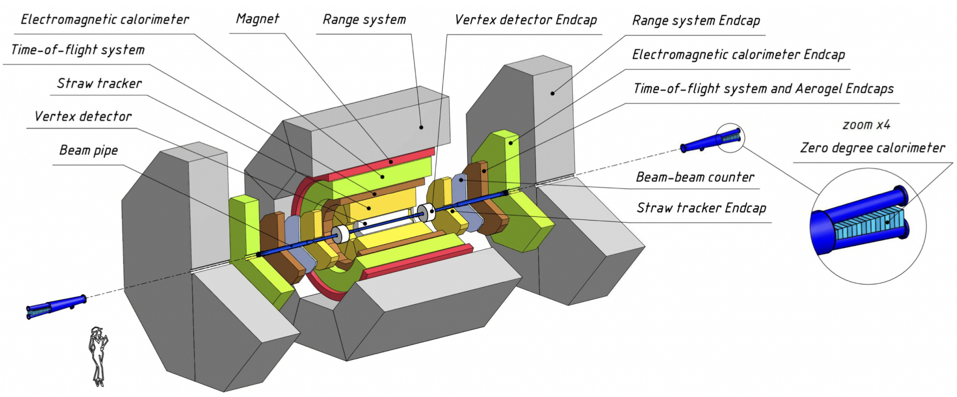

Figure 6. General layout of the SPD setup.

The SPD operation should start already in 2028 using the possibilities of polarized p-p and d-

d collisions at $\sqrt{s} < 9.4$ GeV and $\sqrt{s} < 4.5$ GeV/nucleon, respectively, as well as A-A collisions. The starting configuration should consist of the range system, solenoidal magnet, straw tube-based tracking system, and a pair of zero-degree calorimeters. A simple micromegas-based central tracker will be installed in the central region instead of the sophisticated silicone vertex detector to keep a reasonable momentum resolution.

5. Summary

The NICA facility will allow to study the strongly interacting matter with maximal possible baryon density which can be reachable in accelerator experiments. The BM@N experiment is already started with ion beams accelerated in Booster-Nuclotron. The construction of the NICA collider and the MPD detector is in the pre-commissioning stage now. The MPD will be the primary experiment at the NICA collider which will fill the energy gap in the landscape of heavy-ion collision experiments devoted to the exploration of the QCD phase diagram. The MPD is unique since it is collider experiment with homogeneous coverage of the kinematic variables rapidity and transverse momentum in the NICA energy range. The SPD experiment will serve as an important contribution to general understanding of the spin structure of hadrons and QCD fundamentals. Its expected results will be complementary to the ongoing and planned measurements at RHIC, and future facilities such as EIC at BNL and fixed-target LHC projects at CERN. The NICA experimental physics program is rich and open for challenging ideas from theorists and experimentalists worldwide.

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