HEAVY ION COLLIDER FACILITY NICA AT JINR (DUBNA): STATUS AND DEVELOPMENT

GRIGORY TRUBNIKOV†, NIKOLAY AGAPOV, ALEXANDER KOVALENKO, VLADIMIR KEKELIDZE, RICHARD LEDNICKY, VICTOR MATVEEV, IGOR MESHKOV, ALEXANDER SORIN

JINR, Joliot Curie, 6, Dubna, 141980, Russia

The project of Nuclotron-based Ion Collider fAcility NICA/MPD (MultiPurpose Detector) under development at JINR (Dubna) is presented. The general goals of the project are providing of colliding beams for experimental studies of both hot and dense strongly interacting baryonic matter and spin physics (in collisions of polarized protons and deuterons). The first program requires providing of heavy ion collisions in the energy range of $\sqrt{s_{NN}} = 4 \div 11$ GeV at average luminosity of $L = 1 \cdot 10^{27}$ cm$^{-2} \cdot$s^{-1} for ^{197}Au^{79} nuclei. The polarized beams mode is proposed to be used in energy range of $\sqrt{s_{NN}} = 12 \div 27$ GeV (protons) at luminosity of $L \geq 1 \cdot 10^{30}$ cm$^{-2} \cdot$s^{-1}. The report contains description of the facility scheme and characteristics in heavy ion operation mode, status and plans of the project development.

1. Introduction

The 7-years plan of Joint Institute for Nuclear Research (JINR) has been approved for 2010-2016 years. In accordance with this plan a project Nuclotron based Ion Collider fAcility (NICA) aimed to study of hot and dense baryonic matter and spin physics is realizing at JINR as a flagship project in high energy physics (HEP).

A study of hot and dense baryonic matter should shed light on: in-medium properties of hadrons and nuclear matter equation of state (EOS); onset of deconfinement (OD) and/or chiral symmetry restoration (CSR); phase transition (PT), mixed phase (see fig.1 left) and critical endpoint (CEP); possible local parity violation in strong interactions (LPV) [1, 2, 3, 4]. It is indicated in series of theoretical works, in particular, in [3] that heavy ion collisions at $\sqrt{s_{NN}}$ = 11 GeV allow to reach the highest possible baryon density in the lab (fig.1 right).

† E-mail: trubnikov@jinr.ru

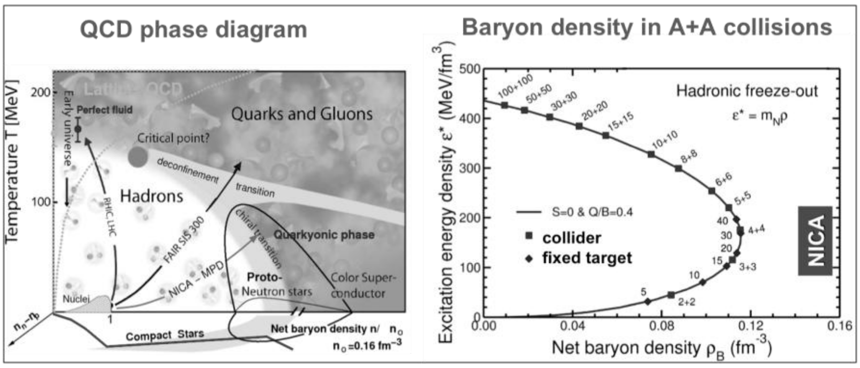


Figure 1: left: phase diagram for QCD matter (mixed phase is indicated by yellow); right: freezout diagrams for baryonic matter indicating baryon dencity reachable at different energies in collider and fixed target experiments [3] (the region covered by the NICA experiments is indicated).

The NICA will also provide the polarized proton and deuteron beams up to the c.m.s. energy of 27 GeV for pp collisions with the luminosity higher than L = $10^{30}cm^{-2}s^{-1}$. The high intensity and high polarization (> 50%) will provide 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 the modern hadron physics.

2. Accelerator Facility NICA

The Nuclotron - is an existing accelerator facility of JINR in HEP putting in operation in 1993. It is based on the unique technology of superconducting fast cycling magnets developed at JINR. The Nuclotron provides proton, polarized deuteron and multi charged ion beams. The magnetic field of dipole magnets B = 1.8 T to the ion beam energies: 5.2 GeV/u for d (A=2, Z=1); 3.3 GeV/u for Xe (A=124, Z=42); and 4.05 GeV/u for Au (A=197, Z=79). The new accelerator facility NICA includes: an injector complex providing wide spectrum of ions up to $^{197}Au^{32+}$ at energy 3.5 MeV/u with an expected intensity $2x10^9$; a booster accelerating ions up to 600 MeV/u; the Nuclotron continuing acceleration up to maximum energy (4.5 GeV/u) and two storage rings with two interaction points (IP). The ions are fully stripped before the injection to the Nuclotron. The major parameters of NICA collider are following: Bρmax = 45 Tm; vacuum in a beam chamber: 10^{-11} Torr; maximum dipole field 2T; kinetic energy from 1 GeV/u to 4.5 GeV/u for Au^{79+}; zero beam crossing angle at IP; 9 m space for each detector allocation at IP’s; the reference luminosity for heavy ions L = $10^{27}cm^{-2}s^{-1}$. The required Nuclotron upgrade has started in 2008 and will be completed by 2015, including a booster and new linac. The overall construction schedule foresees that the storage ring and basic infrastructure facility should be available for the first ion collisions already in 2017 [5]. More detailed information is presented in [6].

The comparison of the NICA accelerator complex with the existing heavy ion machines and ones being in preparation is indicated in fig.2 (the energy scale is recalculated to the c.m. system related to the Au + Au collision).

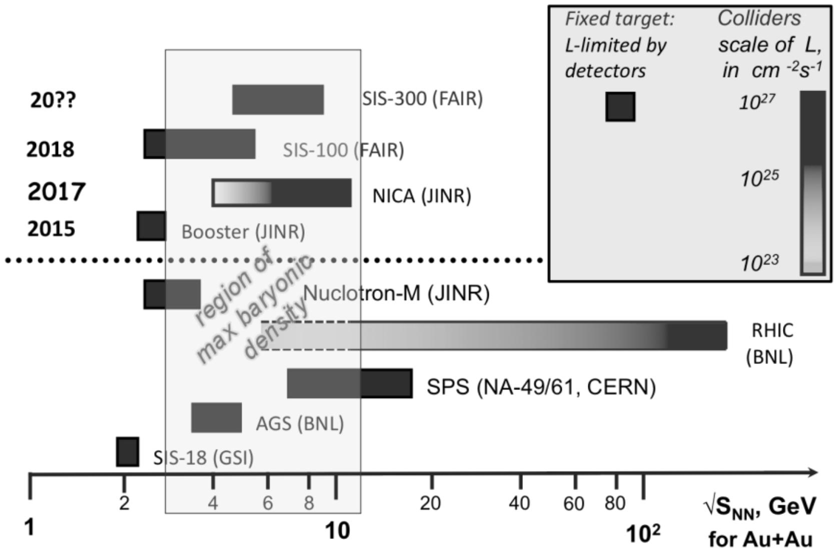


Figure 2: Comparison of the running heavy on machines with ones being in construction (shadow in the frame indicates the region with maximum baryonic density).

In the first IP the MultiPurpose Detector (MPD) will be installed, while a detector for the second IP is not yet designed. A call for the corresponding proposal is announced.

3. Nuclotron-M & NICA project

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) is a new accelerator complex (Fig. 3) being constructed at JINR. It is aimed to provide collider experiments with

- heavy ions $^{197}Au^{79+}$ at$\sqrt{s_{NN}}$ = 4÷11 GeV (1÷4.5 GeV/u ion kinetic energy) at average luminosity of $1{\cdot}10^{27}$ cm$^{-2}{\cdot}$s^{-1} (at $\sqrt{s_{NN}}$ = 9 GeV);
- light-heavy ions colliding beams of the same energy range and luminosity;

- polarized beams of protons $\sqrt{s}$ = 12÷27 GeV (5÷12.6 GeV kinetic energy) and deuterons $\sqrt{s_{NN}}$ = 4÷13.8 GeV (2÷5.9 GeV/u ion kinetic energy) at average luminosity ≥ (1÷10)·10^{30} cm^{-2}·s^{-1}.

The proposed facility consists of the following elements (Fig. 3):

– "*Old*" *injector* (pos. 1): set of light ion sources including source of polarized protons and deuterons and Alvarez-type linac LU-20;

– "*New*" *injector* (pos. 2, under construction): ESIS-type ion source that provides $^{197}Au^{31+}$ ions of the intensity of 2·10^9 ions per pulse of about 9 μs duration at repetition rate up to 50 Hz and linear accelerator consisting of RFQ and RFQ Drift Tube Linac (RFQ DTL) sections. The linac accelerates the ions at $A/q \leq 6$ up to the energy of 3 MeV/u at efficiency not less than 80 %.

– *Booster-synchrotron* housed inside Synchrophasotron yoke (pos. 3).

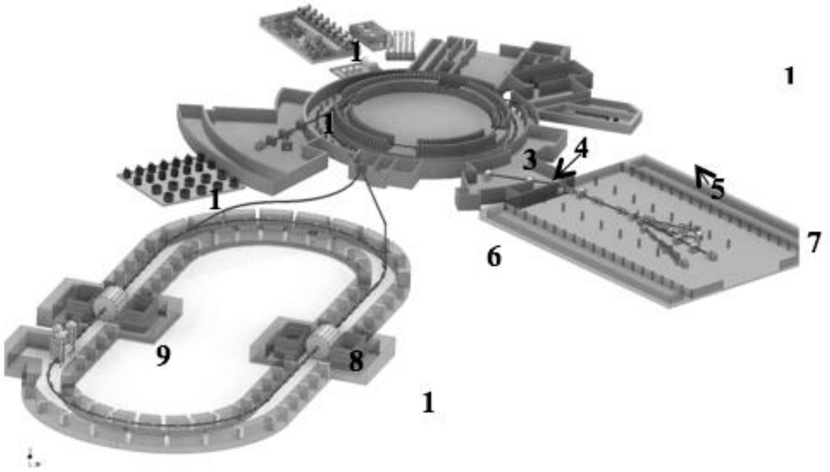


Figure 3: Scheme of NICA facility: 1 – light and polarized ion sources and "old" Alvarez-type linac; 2 – ESIS source and new RFQ linac; 3 – Synchrophasotron yoke; 4 – Booster; 5 – Nuclotron; 6 – beam transfer lines; 7 – Nuclotron beam lines and fixed target experiments; 8 – Collider; 9 – MPD; 10 – SPD; 11 – new research area, 12 – cryogenic plant, 13 – auxiliary equipment.

The Booster (pos. 4) has superconducting (SC) magnetic system that provides maximum magnetic rigidity of 25 T·m at the ring circumference of 211 m. It is equipped with electron cooling system that allows to provide cooling of the ion beam in the energy range from injection energy up to 100 MeV/u. The maximum energy of $^{197}Au^{31+}$ ions accelerated in the Booster is of 600 MeV/u. Stripping foil placed in the transfer line from the Booster to the Nuclotron allows to provide the stripping efficiency at the maximum Booster energy not less than 80 %.

– *Nuclotron* – SC proton synchrotron (pos. 5) has maximum magnetic rigidity of 45 T·m and the circumference of 251.52 m provides the acceleration of completely stripped $^{197}Au^{79+}$ ions up to the experiment energy in energy range of 1÷4.5 GeV/u and protons up to maximum energy of 12.6 GeV.
– *Transfer line* (pos. 6) transports the particles from Nuclotron to Collider rings.
– *Two SC collider rings* (pos. 8) of racetrack shape have maximum magnetic rigidity of 45 T·m and the circumference of about 400 m. The maximum field of SC dipole magnets is 1.8 T. For luminosity preservation an electron and stochastic cooling systems will be constructed.
– *Two detectors* – MultiPurpose Detector (*MPD*, pos. 9) and Spin Physics Detector (*SPD*, pos. 10) are located in opposite straight sections of the racetrack rings.
– *Two transfer lines* transport particle beams extracted from Booster (pos. 11) and Nuclotron (pos. 12) to the new research area, where fixed target experiments both basic and applied character will be placed.

Table 1. Main parameters of NICA accelerators

Acceleration	**Booster project**	**Nuclotron**		**Collider project**
		Project	**Status (Apr'11)**	
Circumference, m	211.2	251.5		503.0
Max. magn. field, T	2.0	2.0	2.0	1.8
Magn. rigidity, T·m	25.0	45	39.5	45
Cycle duration, s	4.0	4.02	5.0	≥ 1000
B-field ramp, T/s	1.0	1.0	1.0	< 0.1
Accelerated/stored particles	p-$^{197}Au^{79+}$, p↑, d↑		p-Xe, d↑	p ÷ $^{197}Au^{79+}$, p↑, d↑
Maximum energy, GeV/u				
Protons	–	12.6	–	12.6
Deuterons	–	5.87	5.1	5.87
Ions, GeV/u	$^{197}Au^{31+}$ 0.4	$^{197}Au^{79+}$ 4.5	$^{54}Xe^{24+}$ 1.0	$^{197}Au^{79+}$ 4.5
Intensity, ion number per cycle (bunch)				
Protons	$1{\cdot}10^{11}$	$1{\cdot}10^{11}$	$1{\cdot}10^{11}$	$1{\cdot}10^{11}$
Deuterons	$1{\cdot}10^{10}$	$1{\cdot}10^{10}$	$1{\cdot}10^{10}$	$1{\cdot}10^{10}$
$^{197}Au^{79+}$	$2{\cdot}10^{9}$	$2{\cdot}10^{9}$	$1{\cdot}10^{6}$ ($^{54}Xe^{24+}$)	$1{\cdot}10^{9}$

The NICA parameters (Table 1) allow us to reach the goals of the project formulated above. One of NICA accelerators – Nuclotron is used presently for fixed target experiments on extracted beams (Fig. 3, pos. 7).

4. Collider luminosity

The collider design has to provide the project luminosity and its maintenance during a long time necessary for an experiment performance. That requires, correspondingly:

1) formation of ion beams of high intensity and sufficiently low emittance,
2) ion beam life time.

Beam intensity is limited, in principle, by beam space charge effects, which can be estimated by so called "tune shift criteria". *The first one*, and most strong of them usually, is so called betatron oscillation tune shift (or *"The Laslett tune shift*"):

$$\Delta Q = \frac{Z^2}{A} \cdot \frac{r_p N_i}{\beta^2 \gamma^3 4\pi \varepsilon_{geom}} \cdot k_{bunch}, \quad k_{bunch} = \frac{C_{Ring}}{\sqrt{2\pi} \cdot \sigma_s}. \tag{1}$$

Here Ze and A are ion charge and mass number, r_p is proton classic radius, N_i is ion number per bunch in the bunched ion beam, β, γ are the ion Lorentz factors, k_{bunch} is bunch factor, C_{Ring} is the Collider ring circumference, σ_s is bunch length (σ-value for Gaussian beam), ε_{geom} is the ion bunch "geometrical" transverse emittance (do distinguish with "normalized" one ε_{norm} used below). *The second criterion* is so called *beam-beam parameter* that describes ion betatron tune shift related to scattering of ion on the electromagnetic field of encountering ion bunch:

$$\xi = \frac{Z^2}{A} \cdot \frac{r_p N_i \left(1 + \beta^2\right)}{4\pi \beta^2 \gamma \varepsilon_{geom}} \tag{2}$$

For practical estimates one can use the numerical criterion for beam stability as follows:

$$\Delta Q_{total} \equiv \Delta Q + n_\xi \xi \le 0.05. \tag{3}$$

n_ξ is number of interaction points.

One of instabilities and major problems of the NICA collider is suppression of intrabeam scattering (IBS) in intense ion bunches. The last one defines mainly the beam life time. For this purpose we have proposed to use both electron cooling [7] and stochastic cooling [8] methods. In the first case we assume achievement of equilibrium between cooling and space charge forces when space charge tune shift ΔQ_{total} reaches a resonant value (e. g., 0.05). We call it *space charge dominated regime* (SCD regime). Then using Formulae (1), (2) and well-known expression for luminosity of round colliding beams one can derive simple relations between parameters:

$$L \propto \Delta Q_{total}^2 \cdot \varepsilon_{geom} \cdot f_L(E_{ion}) \cdot f_{HG}, N_i \propto \Delta Q_{total} \cdot \varepsilon_{geom} \cdot f_N(E_{ion}), \tag{4}$$

where E_i is ion energy, f_L, f_n are the functions describing energy dependence of parameters, f_{HG} is hour-glass effect function. We see that maximum luminosity is achieved if beam emittance ε_{geom} has maximum, i. e. coincides with the ring acceptance. At some circumstances the luminosity can be limited by "not the beam reasons (e. q., detector performance). Then one can optimise the SCD regime decreasing equilibrium emittance and N_i (Fig. 4). Such an optimisation can be done with variation of N_i number. In the case of limited luminosity one can also avoid SCD regime decreasing ion number and allowing, by weakening cooling force, the beam emittance keeping ΔQ_{total} below resonant value. We call it *IBS Dominated regime* (IBS DR) when equilibrium state is provided with equality IBS and cooling rates:

$$R_{IBS} = R_{cool}. \tag{5}$$

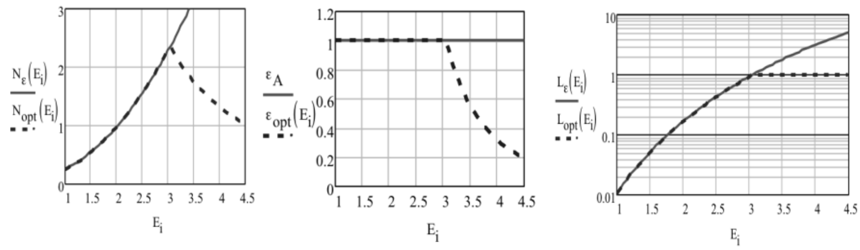


Figure 3: : Space charge dominated regime; ion number per bunch (a), beam emittance (b) and luminosity (c) versus ion energy in two cases: full acceptance if filled with ions (solid curves) and luminosity is limited (dash curve); the ring acceptance = 40 π·mm·mrad, parameter units: $[N_i] = 10^9$, $[\varepsilon]$ = π·mm·mrad, $[L] = 10^{27}$ cm^{-2}·s^{-1}

(with polarized deuterons) and physics of flavours. At the same time, the Nuclotron beams are used for research in radiobiology and applied research. Then, at fixed luminosity, similar by to Formulae (4) one can write

$$L = \text{const}, N_i \propto \sqrt{L \cdot \varepsilon_{geom}} \cdot \varphi_L(E_i), \Delta Q_{total} \propto \sqrt{\frac{L}{\varepsilon_{geom}}} \cdot \psi_L(E_i) < \Delta Q_{\max}. \quad (6)$$

As we see, minimum ΔQ_{total} corresponds to maximum emittance, i. e. full acceptance filling with ions. Simultaneously, it gives us maximum τ_{IBS} at relatively increased ion number (Fig. 5). One should mention that at IBS DR ion number dependence of energy is rather weak – proportional to $(N_{ion}/C)^{-1/2}$.
For NICA parameters, as it follows from Fig. 5, IBS DR regime can be used at $E_i > 3$ GeV/u where $\Delta Q < 0.05$. At the same energy range we plan to use stochastic cooling. At lower energy electron cooling application is preferable (if not to say more realizable) [7, 8]. However, then another problem appears: ion recombination with cooling electrons. This effect can be significantly diminished by increase of cooling electrons temperature [9].
The described approach (SC and IBS dominated regimes) can be developed even further. One can, for instance, increase luminosity in low energy range (below 3 GeV/u) by enlarging minimum beta-functions in IP area. That will be followed by decrease of beta-functions in the lenses of final focus and lead correspondingly to increase of the ring acceptance. Those steps are planned for future development.

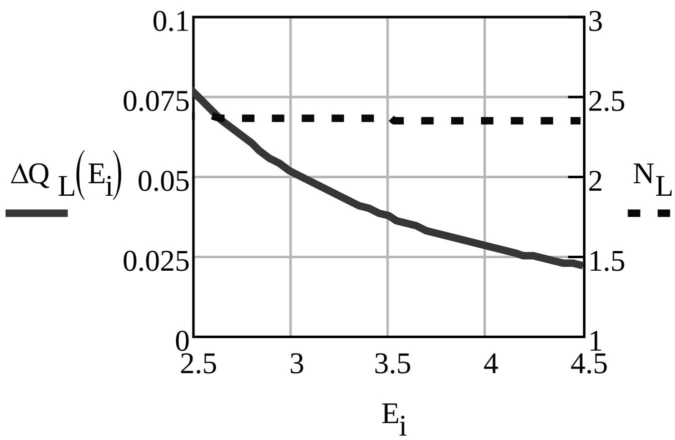


Figure 3: IBS dominated regime; beam tune shift ΔQ_{total} (red solid curve) and ion number per bunch N_i (blue dash curve) at constant luminosity $L = 1 \cdot 10^{27}$ cm$^{-2} \cdot$s^{-1} and beam emittance of 1.0 π·mm·mrad; $[N_i] = 10^9$

5. NICA cryogenic system

The NICA cryogenics (Fig. 6) will be based on the modernized liquid helium plant that was built in the early 90's for the Nuclotron. The main goals of the modernization consist of increasing of the total refrigerator capacity from 4000 W to 8000 W at 4.5 K and construction a new distribution system of liquid helium. These goals will be achieved by construction of a new 1000 l/hour helium liquefier, "satellite" refrigerators located near the accelerator rings, and a liquid nitrogen system that will be used for shield refrigerating at 77 K and at the first stage of cooling down of three accelerator rings with the total length of about 1.5 km and "cold" mass of 220 tons.

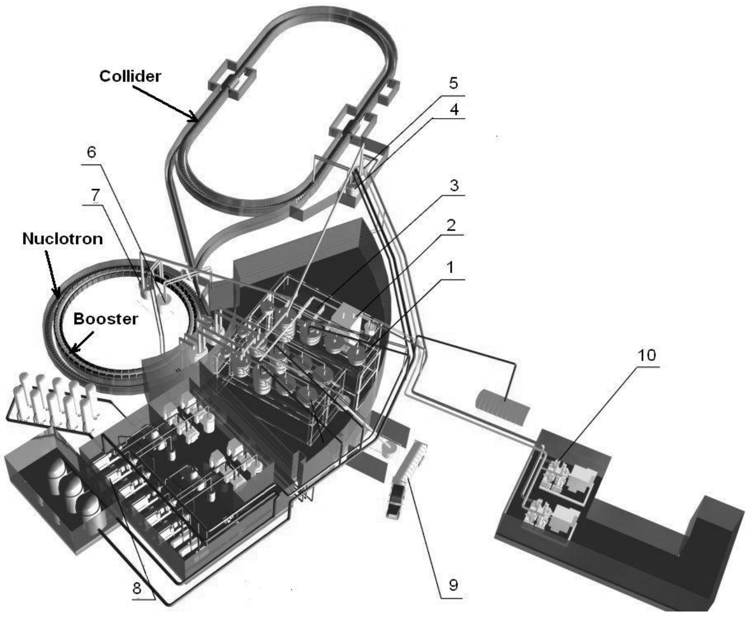


Figure 6: The general view of the NICA cryogenic system. New units for the NICA accelerators: 1 – 1000 l/h Helium liquefier OG-1000; 2 – 1300 kg/h Nitrogen liquefier OA-1,3; 3 – draining and oil-purification units; 4 – satellite refrigerator of the collider; 5 – 500 kg/h Nitrogen re-condenser RA-0,5 of the collider; 6 – 500 kg/h Nitrogen re-condenser RA-0,5 of the Booster; 7 – satellite refrigerator of the Booster; 8 – 6600 N·m^3/h screw compressors Kaskad-110/30; 9 – liquid Helium tank; 10 – Nitrogen turbo compressors

6. The BM@N Experiment

The energy of the extracted beams provided by upgraded Nuclotron-NICA finally will be reached 6 GeV/u for typical values of A/Z = 2. A typical variety of possible beams and their intensities are presented in Table 2. To realize the first stage of experiments at extracted beams with a fixed target a new setup – BM@N (Baryonic Matter at Nuclotron) will be constructed using existing wide aperture dipole magnet, tracking chambers, time of flight (TOF) system, hadron calorimeter and fast counter detector providing trigger signal.

Table 2: The Nuclotron-NICA beams.

beam	p	d	^{7}Li	^{12}C	^{40}Ar	^{56}Fe	^{84}Kr	^{124}Xe	^{197}Au
Part. /pulse	5 x10^{12}	5 x10^{12}	5 x10^{11}	2 x10^{11}	2 x10^{11}	5 x10^{10}	10^{9}	10^{9}	10^{9}

At the second stage an upgrade is foreseen to accomplish the setup with a silicon vertex detector (in cooperation with the partners from GSI, Darmstadt), with the electromagnetic calorimeter, and possibly with the neutron detector.

7. The MPD Experiment.

The MPD experimental program is aimed at investigating both: the hot and dense baryonic matter, and the nuclon spin structure and polarization phenomena. A list of the first priority physics tasks to be performed in the experiment includes:

- in heavy ion program: measurement of a large variety of signals at systematically changing conditions of collision (energy, centrality, system size) using as bulk observables the following:

- 4π geometry particle yields (OD, EOS);
- multi-strange hyperon yields and spectra (OD, EOS);
- electromagnetic probes (CSR, OD);
- azimuthal charged-particle correlations (LPV);
- event-by-event fluctuation in hadron productions (CEP);
- correlations involving π,K, p, Λ (OD);
- directed and elliptic flows for identified hadron species (EOS,OD);

reference data (i.e. p+ p) will be taken at the same experimental conditions;

- in spin physics:

- a study of polarization phenomena with polarized hyperons;
- a study of nuclon spin structure via the Drell-Yan (DY) processes.

The MPD experiment should be competitive and at the same time complementary to ones carried out at RHIC [10], and constructed in the framework of FAIR [11] project. The MPD is a typical collider detector based on the solenoidal superconducting magnet. It will be installed in the first IP of NICA. The major sub-detectors of the MPD are (see fig. 7): solenoidal superconducting magnet with a magnetic field of 0.5 T (~5 m in diameter and ~8 m in length); time projection chamber (TPC); inner tracker (IT); time-of-flight (TOF) system; electromagnetic calorimeter (ECal); end cap tracker (ECT): and two forward spectrometers based on toroid magnets (optional). There are foreseen three stages of putting MPD into operation. The first stage of operation involves magnet, TPC, TOF, Ecal (partially) and IT (partially), and should be ready for the first collision beams in 2017. Processes studied with MPD were simulated using the dedicated software framework (MPD ROOT). This software is based on the object- oriented framework FAIR ROOT [12] and provides a powerful tool for detector performance studies, development of algorithms for reconstruction and physics analysis of the data. Evaluated rate in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.1 GeV (10% central interactions) taking into account the luminosity of L = $10^{27}cm^{-2}s^{-1}$ is ~7 kHz.

More than ten working groups from 12 institutions are intensively working on sub-detector R&D, and on prototyping of all detector elements. More detailed information could be found in the corresponding conceptual design report [13].

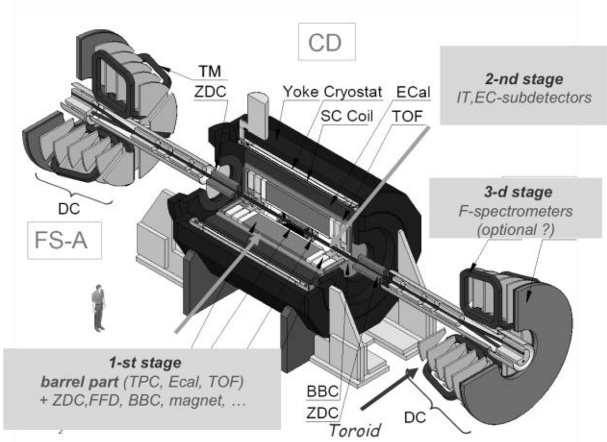
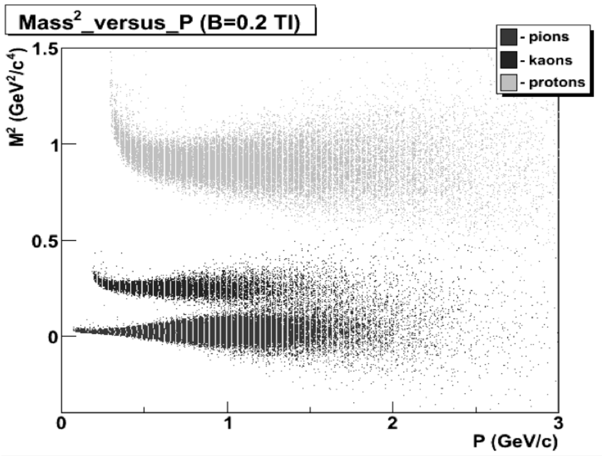


Figure 7: General view of the MPD, and sets of sub-detectors to be put in operation at different stages.

It was shown that MPD is well optimized ti study in-medium effects caused by high baryon densities, such as: changing particle properties in hot and dense medium (broadening of spectral functions etc.), event-by-event dynamical fluctuations of strange to non-strange particle ratios, and others.

(a)



(b)

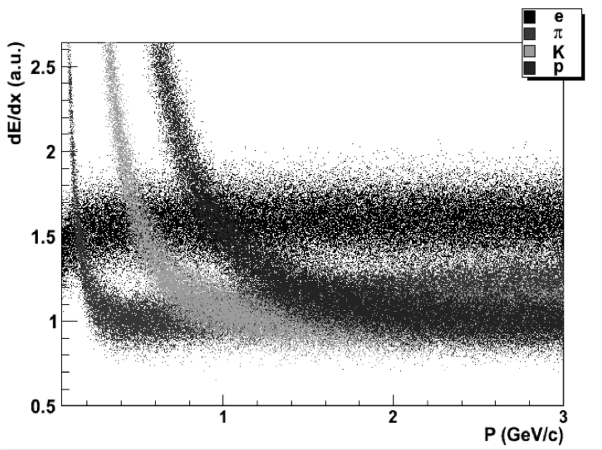


Figure 8: (a): particle id using TOF system. (b): particle id in the TPC by measuring the losses due to the ionization

These studies could be done with better precision than those performed at present experiments. The simulations of MPD experiment shows that high statistics of studied events could be accumulated (~10^9 minimum bias events and ~10^8 central events per week) which provide the best precision for femtoscopy study with respect to RP and correlation of multistrange particles. In ten weeks of running more than ~10^7 of Ω-hyperon decays will be recorded.

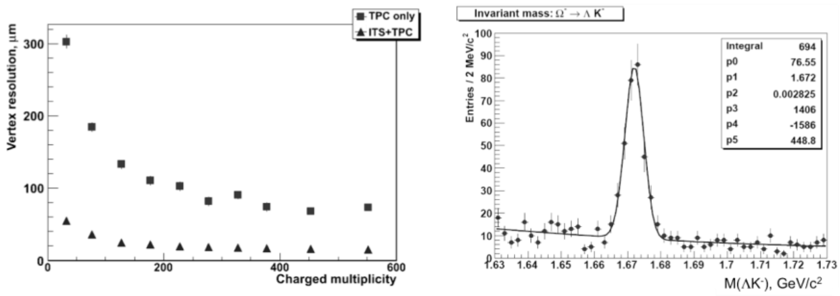


Figure 9: Left: vertex resolutions versus multiplicity for events reconstructed with TPC only (squares), and for events reconstructed using both sub-detectors - TPC and IT (triangles); Right: reconstructed invariant mass of Ω–>ΛK^- decay products (vertex reconstruction with TPC and IT, and particle ID with TPC and RPC)

Charged particles are reliably identified using both techniques: measuring dE/dx of tracks in TPC, and by TOF system (see Fig.8). It was obtained sufficiently high resolution of vertices reconstruction illustrated in Fig.9 (left). This figure (right) shows as well an example of Ω–>ΛK^- decay reconstruction implementing full chain of simulation: central Au+Au collision generation at $\sqrt{s_{NN}}$ = 7.1 GeV hyperon productions and decays; decay product detection and their reconstruction using necessary MPD subdetectors.

The MPD performance in general satisfies the required parameters for proposed experimental program. The further optimization of MPD element design is continued. The corresponding infrastructure is developed as well at the site in the Veksler and Baldin Laboratory of High Energy Physics (JINR, Dubna).

7. Detector for the second IP

The NICA program foresees that a detector will be designed and installed in the second IP. The physics program of the related experiment should be dedicated, first of all, to the spin physics: a study of the Drell-Yan (DY) processes, not requiring the input from the poorly known fragmentation functions, which can be done in the kinematic region not available in other experiments. The creation of motivated collaboration has started. The proposal could be prepared and presented to the JINR scientific committees. The time scale of this experiment will be defined after the consideration of the corresponding proposal.

References

1. A.N. Sissakian, A.S. Sorin, M.K. Suleimanov, V.D. Toneev, and G.M. Zinovjev, *Part. Nucl. Lett.* **5**, 1 (2008).
2. M. Gazdzicki, M. Gorenstein, and S. Mrowczynski, *Phys. Lett*. **B585**, 115 (2004).
3. J. Cleymans, and J. Randrup, *Phys.Rev*. **C74**, 04791 (2006).
4. B. Mohanty, *J. Phys. G: Nucl. Part. Phys.* **38**, 124023 (2011).
5. A. Sissakian et al., Design and Construction of Nuclotron-based Ion Collider facility (NICA) Conceptual Design Report (JINR, Dubna, 2008); http://www.nica.ru.
6. V.G. Trubnikov et. al., XXXVI International Conference on High Energy Physics, Melbourne, (2012).
7. S. Yakovenko, E. Ahmanova, A. Kobets et al., Cooler for Collider NICA, Proc. of COOL'2011, TUPS13.
8. G. Trubnikov, Application of Cooling Methods in the NICA Project, Proc. Of COOL'2011, MOIO07.
9. A. Philippov, A. Kuznetsov, I. Meshkov, Radioactive Recombination of Bare Nuclei and Ions in Electron Cooling System, Proc. of COOL'2011, THCOB01
10. G. S. F. Stephans, J. Phys. G32, S447 (2006), nucl-ex/0607030.
11. P. Senger, *J. Phys*. **G30**, S1087 (2004).
12. D. Bertini et al., *J. Phys. Conf. Ser.* **119**, 032011 (2008), http://cbmroot.gsi.de.
13. A. Sissakian et. al, Multi Purpose Detector Conceptual Design Report, v.1.2 (JINR, Dubna, 2010); http:// www.nica.ru, (2001).