PROCEEDINGS OF SCIENCE

Progress of the NICA project

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General goal of the project is to start in the coming 5÷7 years experimental study of hot and dense strongly interacting QCD matter and search for possible manifestation of signs of the mixed phase and critical endpoint in heavy ion collisions. The Nuclotron-based Ion Collider fAcility (NICA) and the Multi Purpose Detector (MPD) are proposed for these purposes.

NICA is the new accelerator complex being constructed on the JINR site. It builds on the experience and technology developed at the Nuclotron facility and incorporates new technological concepts.

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[1] Speaker

1. Introduction

An essential part of the JINR scientific program resulted from many discussions in view of the Dubna Nuclotron upgrade is dedicated to the study of hot and dense baryonic matter [1, 2, 3, 4]. Realization of this ambitious goal is related to the construction of a new JINR accelerator complex NICA [5] to provide collisions of heavy ions over a wide range of atomic masses at a centre-of-mass energy up to $\sqrt{s_{NN}}$ = 11 GeV (for Au^{79+}) and an average luminosity of L = 10^{27} cm^{-2} s^{-1}.

General challenge of heavy ion collider experiment is to achieve a high luminosity level in a wide energy range starting with about 1 GeV/u. To reach this goal the beam in the collider rings has to be of about $2 \cdot 10^{10}$ ions in each ring distributed over 15 – 20 bunches. Key solutions proposed in this project and allowing meeting these requirements are:

- Use the experience and technologies developed at the existing Nuclotron facility,
- Upgrade of the Nuclotron and reaching its parameters required for NICA,
- Development of highly charged heavy ion sources and construction of a new one based on Electron String Ion Source (ESIS),
- Design & construction of a new linear accelerator as injector,
- Design & construction of a new booster synchrotron equipped with electron cooling system,
- Design & construction of two new superconducting storage rings equipped with electron or/and stochastic cooling system to provide collider experiment with heavy ions like Au, Pb or U at the kinetic energy up to 4.5 × 4.5 GeV/u with average luminosity of 10^{27} $cm^{-2} \cdot s^{-1}$ and to provide collisions of light ions in the total energy range available with the Nuclotron.

At the first stage of the project realization the collider rings will be operated without the beam acceleration in a symmetric mode: both the rings will be filled with the same ion species Au × Au, d × d or p × p. Further development of the facility presumes filling of the rings with different ions (asymmetric mode) and, possibly, a slow acceleration of the ions in the collider rings to an experiment energy.

The collider rings have two interaction points. In one of them the MPD detector will be located. The design of this interaction point provides collisions at zero crossing angle. In this report we consider the symmetric mode of the collider operation and the main attention is given to the luminosity formation in gold-gold collisions.

The new facility will allow also an effective acceleration of light ions to the Nuclotron maximum energy and an increase of intensity of polarized ion beams up to the level of 10^{11} particles.

2. Scientific goals

The global scientific goal of the NICA/MPD Project is to explore the phase diagram of strongly interacting matter in the region of highly compressed and hot baryonic matter. Such matter exists in neutron stars and in the core of supernova explosions, while in the early Universe we meet the opposite conditions of very high temperature and vanishing baryonic density. In terrestrial experiments, high-density nuclear matter can transiently be created in a finite reaction volume in relativistic heavy ion collisions. In these collisions, a large fraction of the beam energy is converted into newly created hadrons, and new color degrees of freedom [6, 7] may be excited. The properties of excited resonances may noticeably be modified by the surrounding hot and dense medium. At very high temperature or density, this hadron mixture melts and their constituents, quarks and gluons, form a new phase of matter, the quark-gluon plasma. Different phases of strongly interacting matter are shown in the phase diagram of Fig.1.

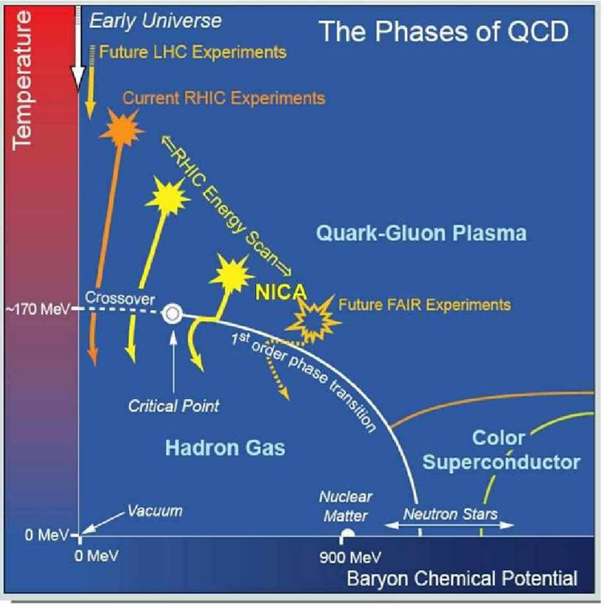

Fig.1: The phase diagram of strongly interacting QCD matter as it was presented in the USA NSAC Long range plan in autumn 2007 with the NICA domain added. Phase boundaries, critical end-point, and conjectured dynamical trajectories for an expansion stage are plotted as well.

As it is seen from the phase diagram, the heavy-ion experiments at BNL-RHIC as well as the coming CERN-LHC experiments probe the region of high temperature and low net baryon density where circumstantial evidence has been obtained for a new phase, strongly interacting quak-gluon matter existing above a critical temperature Tc ≈ 160 MeV. In the other corner of the phase diagram, at lower temperature and moderate baryonic density, the GSI-SIS experiments definitely show no hint at a phase transition but certainly point to in-medium modification effects. At still higher density and low temperature the matter is deconfined and, as predicted, correlated quark-antiquark pairs form a color superconductive phase. Such phase may be created in the interior of neutron stars. We are interested in an intermediate region of the phase diagram, where essential evidence was obtained by the NA49 collaboration within the CERN-SPS energy scan program that the system enters a new phase at a beam energy of about 30 AGeV. The fascinating particularity of this energy range is the critical end point located according to the recent lattice QCD calculations at T_E = (162±2) MeV and baryon chemical potential μ_E =(360±40) MeV [8], whereas model predictions are strongly scattered throughout the regions of T_E ~ 50 and μ_E ~ 200-1400 MeV [9]. The importance of this finding was well understood at GSI where the CBM (Compressed Baryon Matter) experiment was proposed within the FAIR project. This understanding was recently shared by the BNL-RHIC which suggested to decrease its beam collider energy to reach this domain of the phase diagram. The low-energy RHIC at BNL[10], CBM at FAIR (GSI) [11] and the proposed NICA/MPD at JINR [5, 12], as well as the CERN-SPS [13] working with lighter systems, may be considered as complementary basic facilities aimed at the study of relevant physics problems of hot and dense baryonic matter.

The phase diagram translates into a visible pattern the properties of strong interactions and their underlying theory, Quantum Chromo Dynamics (QCD). In particular, such fundamental QCD phenomena as confinement and broken chiral symmetry, which quantitative understanding is still lacking, are a challenge for future heavy-ion research. As is demonstrated in Fig.2, the domain of excited dense baryonic matter accessible in the planned NICA/MPD Project is located roughly between dynamical trajectories presented for two colliding ions at limiting colliding energies covering the range of quasi-equilibrium states with the baryon density up to $n_B \approx 8n_0$.

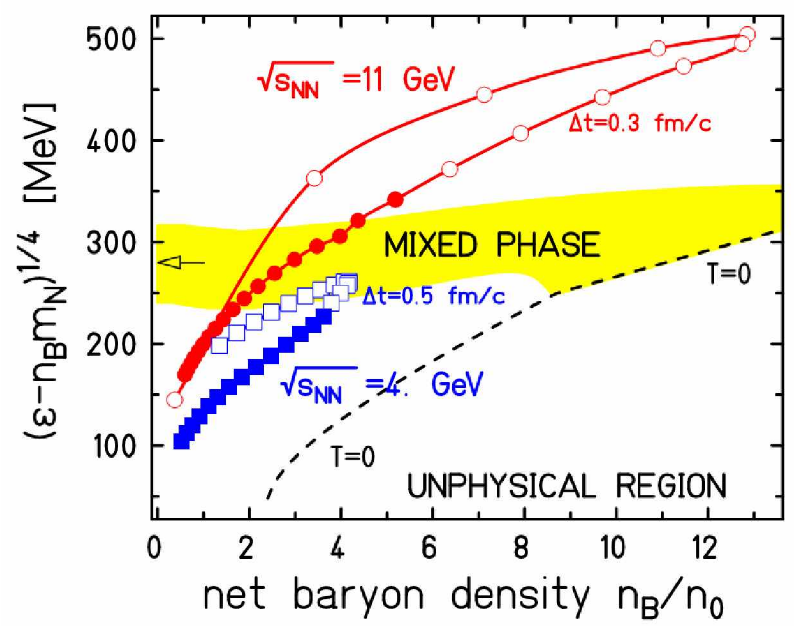

Fig.2. The phase diagram in terms of the reduced energy density vs. the net baryon density. The dynamical trajectories are shown for central (b = 2 fm) Au+Au collisions at two limiting NICA energies. The highly non-equilibrium part of the trajectories, starting from still not interacting two contra-streaming flows, are calculated within the kinetic QGSM (open symbols) and subsequent locally equilibrium evolution is considered within the 3D relativistic hydrodynamics (filled ones). The obtained results correspond to the Lorentz-contracted cylinder of the radius R = 5 fm and the length $L = 2R/\gamma$ where γ is center-of-mass γ-factor. Time differences between points are 0.3 and 0.5 fm/c for $\sqrt{s_{NN}}$ = 11 and 4 GeV, respectively. The shaded region is a quark-hadron mixed phase estimated according to a phenomenological two phase [14]. The dashed curve separates an unphysical region by condition T = 0.

The hadronic phase at high net baryon densities and moderate temperatures as well as new states of matter beyond the deconfinement, chiral transition and in a mixed phase may be reached in this sector of the phase diagram. Therefore, the major goal of the NICA/MPD Project is the study of in-medium properties of hadrons and the nuclear matter equation of state, including a search for possible signals of deconfinement and/or chiral symmetry restoration phase transitions and the QCD critical endpoint in the region of the collider energy $\sqrt{s_{NN}} = 4 \div 11$ GeV/u. Due to the high complexity of this task and large uncertainty in the predicted signals, an accurate scaling of the considered phase diagram domain in collision energy, impact parameter and system size is utterly needed.

To reach this goal, the envisaged experimental program includes the simultaneous measurement of the observables which are presumably sensitive to high density effects and phase transitions. The observables measured on event-by-event basis are particle yields, their phase-space distributions, correlations and fluctuations. Different spices probe different stages of the nucleus-nucleus interaction due to their differences in mass, energy and interaction cross sections.

Hadrons containing heavy strange quarks are of particular interest. These strange heavy hadrons are created in the early high-temperature and high-density stage but may decouple soon due to their low interaction cross section with surrounding matter.

Among various characteristics the elliptic flow deserves special attention because this collective motion is formed mainly in the early stage of the collision. The space-time information on the final state of the system, which depends on its preceding evolution, is provided by the measurement of identical particle interference.

3.Structure of the facility

The proposed facility (Fig.3) consists of:

- ESIS-type ion source that provides Au^{32+} ions at intensity of $2\cdot10^9$ ions per pulse of about 7 μs duration at repetition rate up to 50 Hz.
- Injector on the basis of linear accelerator consisting of RFQ and RFQ Drift Tube Linac (RFQ DTL) sections. The linac accelerates the ions at $A/q \leq 6$ to the energy of 6 MeV/u at efficiency not less than 80%.
- Booster synchrotron, which has maximum magnetic rigidity of 25 T·m and the circumference of about 215 m. The Booster 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 Au^{32+} ions in the Booster is 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%.
- The Nuclotron accelerator having maximum magnetic rigidity of 45 T·m and the circumference of 251.52 m provides the ion acceleration to the experiment energy.
- Two collider rings with maximum magnetic rigidity of 45 T·m and the circumference of about 252 m. The maximum field of superconducting dipole magnets is 4.5 T. For luminosity preservation an electron and/or stochastic cooling system will be constructed.

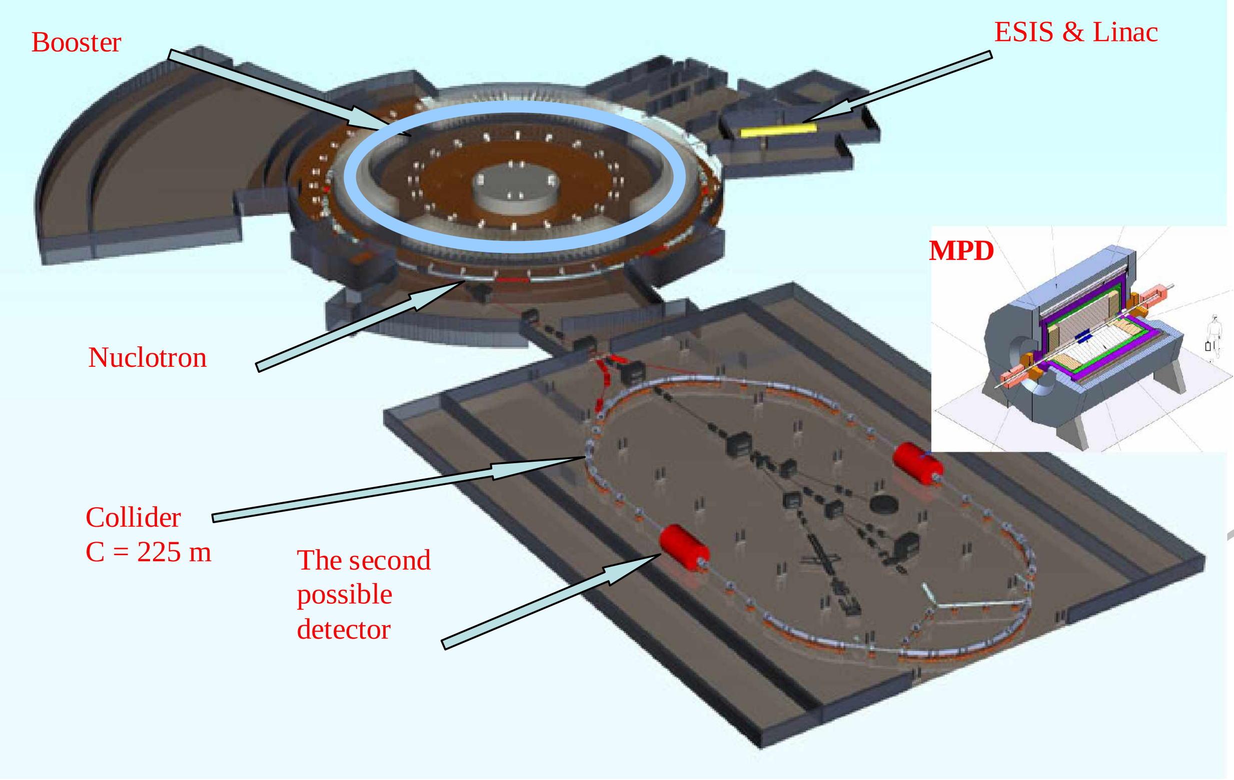

Fig.3. NICA location in the existing buildings.

Table 1. General parameters of the NICA rings.

	Booster	Nuclotron	Collider
Ring circumference, m	215	251.52	252
Injection energy, MeV/u	6	600	1000 - 4500
Maximum kinetic energy, MeV/u	600	1000 - 4500	1000 -4500
Magnetic rigidity, Tm	2.4 - 25	8.2 - 45	14 - 45
Bending radius, m	14	22	10
Magnetic field, T	0.17 – 1.8	0.37 – 2.0	1.56 – 4.5
Number of dipole magnets	40	96	24
Number of quadrupoles	48	64	32
Magnetic field ramp time, s	2.65*	1.27	>45
d*B*/d*t*, T/s	1	1	0
RF harmonics number	4 / 1	1	102
RF frequency range, MHz	0.6 – 1	0.857 – 1.17	105 – 117
RF voltage, kV	4	15**	100
Residual gas pressure (equivalent for Nitrogen atmosphere at room temperature), Torr	10^{-11}	10^{-8}	10^{-10}

* The magnetic field ramp duration of the booster includes 0.65 s for the beam acceleration to 100 MeV/u, 1 s of the electron cooling, 1 s for the acceleration to 600 MeV/u.

** The RF voltage amplitude corresponds to the bunch acceleration. The bunch compression system will be operated at about 120 kV.

The peak operating mode for the dipoles in the collider corresponds to B_{max} = 4.5 T at dB/dt ≈ 0.1 T/s. A twin bore structural dipoles and quadrupoles with Cosθ-type superconducting coils are proposed for the NICA collider.

4. Luminosity of heavy ion collisions

The required luminosity level was estimated from the following basic initial parameters:

• Ion kinetic energy	$1 \div 4.5$ GeV/u.
• The detector covers solid angle close to	4π.
• Total cross section of heavy ions interaction (Au+Au)	7 barn
• Fraction of central collisions	5%.
• Fraction of events with strange particles	6%
• Fraction of events with lepton pairs in domain of ρ meson	10^{-4}.

The following interaction rate characterizes the detector capability at the luminosity equal to 10^{27} cm^{-2} s^{-1}:

• Frequency of interactions	7×10^{3} Hz.
• Total number of interactions per year assuming the statistics is being collected for 50% of the calendar time	1×10^{11}.
• A number of central interactions per year	5×10^{9}.
• A number of central interaction with strange particle generation per year	3×10^{8}.
• A number of central interaction with lepton pairs in the domain of ρ meson per year	5×10^{5}.

From these estimations it is possible to conclude, that the collider operation at luminosity of between $10^{26} \div 10^{27}$ cm$^{-2}\cdot$s^{-1} allows to perform experiments which should measure all hadrons comprising multi-strange hyperons, their phase-space distributions and collective flows. This includes also event-by-event observables.

The Multi Purpose Detector (MPD) is under design for the first stage of the NICA operation (Fig.4). The detector will provide a possibility for accurate and controlled selection of central collisions allowing the scanning of events in centrality. Tracking detectors are situated in the magnetic field of about 0.5 T produced by a super-conducting solenoid. The MPD has the length equal to 8 m and the diameter of 5 m.

The option allowing to measure lepton pairs comprising a muon arm will be considered as a second stage of the NICA project. This requires additional experienced manpower for simulations, design and construction, and substantial technical and financial resources. The design of the second stage detector will be based on the luminosity value obtained at the NICA during realization of the first stage.

It is suggested to achieve the required luminosity level at the ion bunch intensity (10^{9} ions per bunch) already used at RHIC in routine operation. The luminosity by two orders of magnitude larger than the luminosity in RHIC at low energy operation will be reached by means of the following peculiarities of the NICA design.

- **Collider operation at low beta function in the interaction point.** This is possible due to short interaction region (of about 10 m) that allows to have maximum beta functions in the triplets of about 90 m at the beta function of 0.5 m in the collision point. At such conditions the beam radius in the lenses of the low beta insertion section is about 4 cm that requires reasonable aperture of the lenses.

- **Short bunch length.** The rms bunch length of about 30 cm makes possible to avoid “the hour glass effect” and to concentrate 80% of the luminosity inside the inner tracker of the detector.
- **Collider operation at the beam emittance corresponding to the space charge limit.** In the NICA energy range the luminosity is limited by the incoherent tune shift value. If the ion number per bunch and the tune shift are fixed the luminosity is scaled with the energy as $\beta^3\gamma^3$. The formation and preservation of low emittance value, corresponding to achievable tune shift, is produced by beam cooling application at the experiment energy.
- **Large collision repetition rate.** The collider is operated at the bunch number of 10 ÷ 20 in each ring. This is achieved at well established injection kicker parameters (the kicker pulse duration is about 100 ns) by means of injection into the collider of bunches of short length. The bunch of the required length is formed in the Nuclotron after the acceleration. Small longitudinal emittance value, required for the bunch compression in the Nuclotron, is provided by the electron cooling of the ion beam in the Booster.
- **Long luminosity life-time.** For luminosity preservation the electron or stochastic cooling system is used. In equilibrium between intrabeam scattering and the cooling the luminosity life-time is limited mainly by the ion interaction with the residual gas atoms. The vacuum conditions in the collider rings are chosen to provide the beam life time of a few hours. The beam preparation time is designed to be between 2 and 3 minutes. Therefore, the mean luminosity value is closed to the peak one.

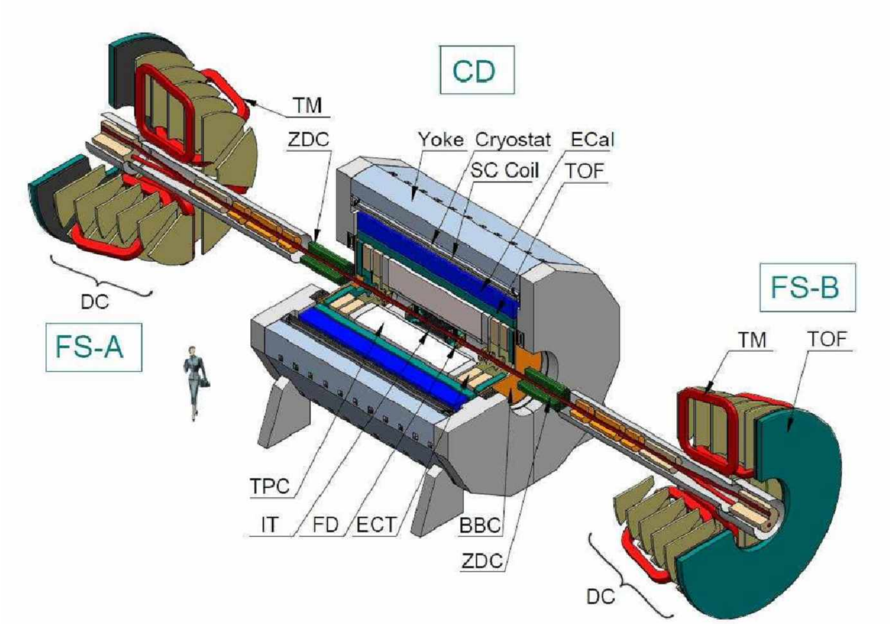

Fig.4. General view of the MPD detector with end doors retracted for access to the inner detector components. The detector is represented by three major parts: CD-central parts, and (FS-A, FS-B) - two forward spectrometers with toroidal magnets (TM) (optional). The subsystems are indicated: super-conductor solenoid (SC Coil) and magnet yoke, inner detector (IT), straw-tube tracker (ECT), time-projection chambers (TPC), time-of-fight stop counters (TOF), electromagnetic calorimeters (ECT, ECal), fast forward detectors (FD), beam-beam counter (BBC), and zero degree calorimeter (ZDC).

An increase of the bunch intensity allows increasing the luminosity at the same value of the tune shift. To keep the constant tune shift the beam emittance has to be increased proportionally to the bunch intensity and the luminosity is scaled linearly with the ion number.

At the maximum experiment energy the peak luminosity can be increased either – by increase of the bunch intensity or by decrease of the beta function in the collision point. After optimization of the collider regime and achievement of a maximum bunch intensity one can expect increase of the peak luminosity to the level of $(2\div3)\cdot10^{27}$ $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$.

At minimum experiment energy the peak luminosity is limited by geometry of the collider optic structure. At small value of the beta function in the interaction point (IP) its maximum value depends on the distance from the IP to the quadrupole lenses. In this project the nearest quadropole lens is located at 5 m from the IP. At the beta function in the IP of 0.5 m the maximum beta function is about 90 m. At 1 GeV/u the apertures of the quadrupoles of the low beta insertion have to be larger than about 80 mm. The possibility to increase the luminosity in this energy range is related to design of large aperture lenses and an increase of the bunch intensity.

5. Operation scenario

The proposed NICA injection chain is developed to guarantee the achievement of the bunch intensity of 10^9 ions and provide a technical reserve required for future development of the facility. The structure of the NICA injection chain is similar to that one proposed for RHIC on the basis of EBIS-type ion source. Sufficient advantage of the proposed injection chain is the electron cooling of the ion beam at intermediate energy in the Booster. The ion energy at the electron cooling is chosen to be 100 MeV/u (the maximum electron energy is of 55 keV). In this energy range the conventional electron cooling system of relatively low price can be used. On the other hand this energy is large enough to avoid sufficient ion losses on the residual gas atoms during the cooling. Main goal of the electron cooling application is to decrease the beam longitudinal emittance to the value required for effective bunch compression in the Nuclotron at the extraction energy.

Vacuum conditions in the Booster permit to accelerate the ions to its final energy with efficiency not less than 90%. The Booster maximum energy is chosen to provide large stripping efficiency of the heavy ions and to avoid the ion losses on residual gas atoms during further acceleration in the Nuclotron. Efficiency of the beam acceleration in the Nuclotron is assumed to be not less than 90%. Total efficiency of the injection chain from the ion source to the collider is assumed to be about 40%. To have the bunch intensity above 10^9 ions a few consequent injection pulses $(2 \div 3)$ into the Booster are necessary.

The beam storage in the Booster can be produced either in the longitudinal phase space or in the transverse one. For this purpose a few single turn injections are performed at the magnetic field plateau. If necessary the bunch intensity can be enlarged by increasing of the consequent injection number. The maximum number of the injection pulses is limited by the Booster acceptance and is equal to about 10. However, optimal number keeping in mind the following operations with the beam is about $2\div3$.

Without a beam cooling during the experiment the beam emittance and the bunch length increase in collider rings due to intrabeam scattering (IBS) process. The IBS leads to the emittance growth approximately as the square root of time. The expected IBS growth time values in the collider are of the order of 50 s at 3.5 GeV/u ion energy. The bunches can be refreshed in the collider with periodicity determined by the beam preparation time, which is equal to 2 – 3 minutes (one bunch per 4 – 5 s). In this case the average luminosity is about two times less than the peak one. Such a regime of the collider operation is acceptable, however it requires permanent work of the injection chain.

The situation can be significantly simplified by a beam cooling application during the experiment. In the equilibrium between the IBS and the cooling the luminosity life-time is limited mainly by the ion loss due to interaction with residual gas atoms. The vacuum conditions in the collider rings are chosen to provide the beam life time of a few hours. In this case the average luminosity value is closed to the peak one. The collider rings are filled ones at the beginning of the experiment and the beams have to be refreshed after a long time about 1 h. Meanwhile the injection chain can be used for another experiments being performed in parallel.

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