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# ELECTRON COOLING IN THE NICA PROJECT: STATUS AND PROBLEMS

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*Abstract*

The Nuclotron-based Ion Collider fAcility (NICA) project at the Joint Institute for Nuclear Research (JINR, Dubna, Russia), reached the phase of mounting and commissioning of the accelerator complex elements. The first stage of the project is "The Baryonic Matter at Nuclotron" (BM@N), fixed target experiment. It requires operation of the heavy ion synchrotron Booster, where electron cooler is used for formation of ion beam of a high intensity. One of limitation of intensity of partially ionized heavy ion beams is recombination with cooling electrons. This process is planned to be studied on the Booster, which is under mounting presently. The experiments at NICA collider with the heavy ion beams is the second stage of the project. High energy electron cooler that is under fabrication at BINP is a key tool for NICA collider allowing to reach the project luminosity in all ion energy range of $\sqrt{s_{NN}} = 4 \div 11$ GeV/u. Recombination of bare nuclei of heavy ions in the electron cooler leads to significant beam losses that shorten ion life time and may generate considerable background in NICA detector (MultiPurpose Detector — MPD). The third stage is spin physics studies in collisions of polarized protons ($\sqrt{s_{NN}} = 27$ GeV) and deuterons. This stage expect the use of the Spin Physics Detector — SPD. The report presents status of the NICA project development and discusses the problems described above.

## INTRODUCTION: THE NICA PROJECT AT JINR

The NICA project aims to design, construction and commissioning at JINR a modern accelerator complex based on existing synchrotron Nuclotron equipped with two detectors: MPD and SPD. Experimental studies planned at NICA will be dedicated to search of the mixed phase of baryonic matter and the nature of nucleon/particle spin. Briefly speaking, we intend to study the Universe as it was $13.799 \pm 0.021$ billion years ago [1] and of the order of $10 \div 100$ μs after Big Bang, the first goal. The second goal is to understand the nature of particle spin, so called "spin puzzle".

The project development has three stages as described in the Abstract and in the [2]. The scheme below (Fig. 1) demonstrates all main elements of the NICA.

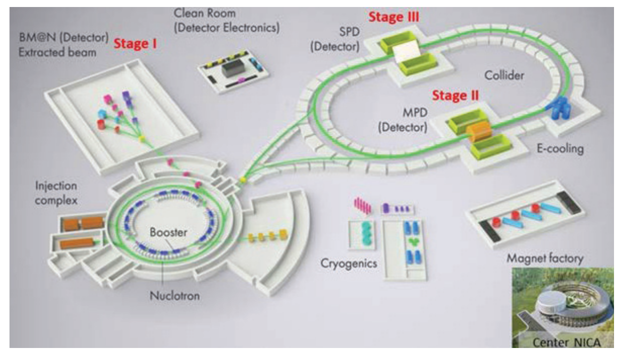


Figure 1: Scheme of the NICA facility.

## NICA STAGE I: EXPERIMENT "THE BARYONIC MATTER AT NUCLOTRON"

For the full configuration of the Stage I we need [2] the following elements and accelerators.

1. Injector: Cryogenic ion source KRION + Heavy ion Linear Accelerator (HILAC) + Beam transfer line (BTL) from HILAC to the Booster;
2. KRION is in the stage of "working prototype" that will be used for generation of heavy ion beam. The main goal is generation of $^{197}Au^{31+}$. The HILAC was commissioned in 2016. Construction of the BTL is close to completion and will be tested with the ion beam this year;
3. Booster — superconducting (SC) synchrotron is under mounting (Fig. 2, 3). Its electron cooler was constructed by BINP and is under commissioning in the working position on the Booster. First test of the SC focusing system of the Booster is planned at the end of this year, ion beam injection into Booster is expected in May 2020;
4. BTL Booster-Nuclotron (under manufacturing at BINP, to be finally delivered to JINR in July 2020, commissioning — October 2020);
5. Upgrade of BTL Nuclotron-BM@N for transportation of ions accelerated in Nuclotron and extracted by slow extraction system. The upgrade includes improvement of vacuum condition in the channel and development of power supplies for the channel magnets.

The first run of BM@N experiment with heavy ions at maximum energy of Nuclotron is scheduled for November 2020.

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Figure 2: SC magnets of the Booster in the yoke of the dismounted Synchrophasotron.

Figure 3: Power supplies of the Booster magnets mounted on the top the yoke.

## ELECTRON COOLING APPLICATION TO THE NICA BOOSTER

Injection of ions into Booster will be fulfilled by one of three schemes: single turn or multiturn injection and multicycle injection at the ion energy of 3.2 MeV/u. All the schemes will use electron cooling (electron energy of 1.765 keV) The electron cooler of the Booster is mounted already in working position and commissioned with electron beam [3].

The basic type of ions to be injected into Booster is $^{197}Au^{31+}$. The ion charge state is chosen by criterion of minimum recombination rate: this state has 48 electrons, which completely fill the subshells up to [Kr]$5s^2 4d^{10}$ [4]. As result, the recombination coefficient for this ion is equal to $\alpha = 10^{-7}$ $cm^3 \cdot s^{-1}$. At Booster electron cooler parameters and electron beam current of 0.2 A it gives the ion lifetime of 13.3 s, when vacuum lifetime at injection energy and vacuum of $10^{-11}$ Torr is 4.4 s.

Such a choice provides also the minimum recombination rate at the ion energy of 50 MeV/u (electron energy of 27.233 keV) during acceleration in the Booster when the plateau of 1 s duration is made for electron cooling of ions. The recombination lifetime on the plateau differs from it on the injection energy by the value of Lorenz factor squared and at electron beam current of 1 A is 11.1 s.

Note the application of $^{197}Au^{30+}$ would reduce recombination time by 5 ÷ 10 times [4].

## STAGE II: SEARCH FOR THE MIXED PHASE AND NEW PHYSICS IN HEAVY ION COLLISIONS AT NICA COLLIDER

At this stage the most promising part of the NICA project program will be implemented. Three new elements of the NICA will have to be constructed — two rings SC collider, BTL from Nuclotron to Collider (BTL NC) and MPD.

BTL NC was designed in cooperation with the company SigmaPhi and is under manufacturing presently. Beginning of delivery of the BTL elements is planned for the end of the year. Mounting and commissioning of the BTL of 340.5 m length will be fulfilled in 2020.

The Collider mounting will be started September 2021 and first beam injection is planned for February 2022. Presently its SC focusing system is under fabrication: 18 of 88 SC "twin" dipoles and 1 SC "twin" quadrupole lens have been fabricated (Fig. 4) and passed magnetic measurements at liquid helium temperature (the term "twin" means here the magnets have design where two identical magnets of two Collider rings are placed one above other).

Figure 4: SC "twin" dipoles of Collider.

Main elements of the Collider are under fabrication as well. Essential part of them was designed and being fabricated at BINP. First of all, it relates to RF stations (Fig. 5) and High Voltage Electron Cooler (HVEC) [5].

Figure 5: Members of NICA Machine Advisory Committee are introduced to RF-2 first station at test.

Application of the HVEC at NICA Collider has several specific features never met before:

1. Energy range 1 ÷ 4.5 GeV/u for $^{197}Au^{79+}$ ions (0.55 ÷ 2.45 MeV electrons);

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2. Electron beam current 0.1 ÷ 1.0 A at such high energy;
3. Solenoid magnetic field up to 0.2 T;
4. Two cooling electron beams operated simultaneously;

All these features make the project of HVEC rather challenging. Besides the "old" and well known problems (that does not make them easy) remain:

5. Suppression of ion beam space charge and intrabeam scattering (IBS);
6. Suppression of ion recombination with cooling electrons.

## NICA COLLIDER: PROBLEMS AND SOLUTIONS

The HVEC is designed to solve several problems. The first of them is ion storage in the Collider rings.

*Ion stacking*. In NICA ions generated in the ion source KRION come through BTL to the Booster, are accelerated in it, stripped at extraction to bare nuclei state, transferred to Nuclotron and, after acceleration up to storage energy, transferred in one of two Collider rings. Injection of the ions into Collider rings is produced by turns with periodicity of $T_{inj} = 8.04$ s. Ion accumulation in Collider rings is carried out using "barrier" RF voltage [6]. During the time $T_{inj}$ between two injection pulses the new injected ions are cooled by electron beam or/and stochastic cooling system and merge with previously stored ions ("stack"). The time dependence of the maximum ion betatron amplitude in the stack after $n$-th injection $x_{max}(t)$ can be described by the recurrent formula

$$x_{max}^{(n)}(t) = x_{inj}\left(\sum_{m=1}^{n} e^{-(m-1)\alpha}(1+r)^{m-1}\right)\cdot e^{-\alpha(t-n)},$$
$$(n-1) \le t \le n \quad (1)$$

Here $n$ is number of injection pulse, $\alpha = T_{inj}/\tau_{cool}$ is cooling decrement, $\tau_{cool}$ is cooling time, $t$ is time in $T_{inj}$ units, parameter $r = \Delta x / x_{max}$ is increase of the stack $x$-size under action of aftereffect ripples of the kicker pulse. We note that in stacking scheme with barrier RF the aftereffect ripples of the kicker pulse affect the stack, and not the injected bunch.

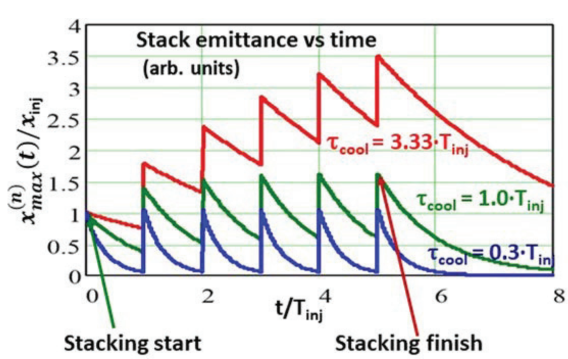


Figure 6: Dynamics of the maximum ion betatron amplitude in the stack size for $\tau_{cool}/T_{inj}$: 0.3, 1.0 and 3.33.

Depending of cooling time (parameter $\alpha$) the maximum ion betatron amplitude in the stack size (Fig. 6) comes to saturation (blue and green curves), either can grow up unlimitedly (red curve).

The cooling time requirement follows from the saturation condition:

$$x_{eq} = x_{max}^{(n+1)} = x_{max}^{(n)}. \quad (2)$$

Here $x_{eq}$ is saturation ("equilibrium") size of the stack just after $(n+1)$-st injection. Its value we find from Formula (2) and the equality:

$$x_{max}^{(n+1)} = x_{max}^{(n)} e^{-\alpha}(1+r) + x_{inj},$$

According (2) we can insert in here $x_{eq}$ instead $x_{max}^{(n+1)}$ and $x_{max}^{(n)}$ and find

$$x_{eq} = \frac{x_{inj}}{1-(1+r)e^{-\alpha}}. \quad (3)$$

This Formula allows us to find $x_{eq}$ if ignoring other effects, e.g. described below. We note this consideration assumes independence of cool of beam transverse size (betatron amplitude).

*Space charge and IBS*. The estimates of space charge and IBS effects were made for ion beam linear density $dN_i/ds$ of coasting beam depending of ion momentum spread (Fig. 7). The black dot curves describe equilibrium between IBS and electron cooling at given cooling time $\tau_{cool}$ values. Herewith the beam emittance is defined from the equilibrium condition, IBS increments were calculated following [7]. Longitudinal effect of the beam space charge was calculated by well-known Keil-Schnell Criterion a $(Z/n)_{max}$ Ohm (blue solid curve with dots). Red dot-dashed curve shows limitation caused by barrier RF voltage. As result, we obtain some area of the parameters $dN_i/ds$ and $\Delta p/p$ where accumulated coasting beam is stable (shown in grey). Red dot horizontal line shows project value of linear density and red dot vertical one indicates the $\Delta p/p$ value corresponding $1/3$ of separatrix $\Delta p/p$.

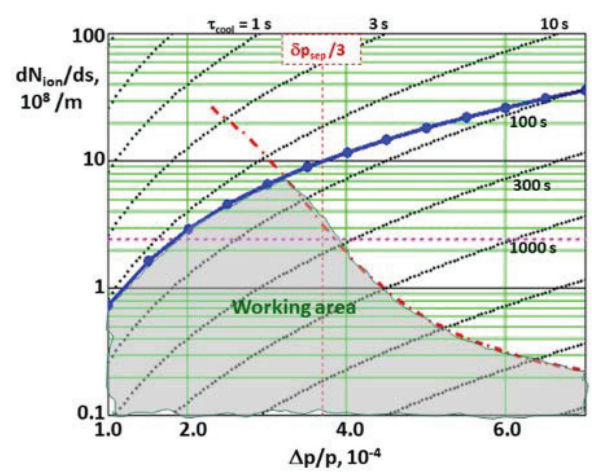


Figure 7: Estimates of critical parameters of the ion beam in NICA Collider at ion stacking.

This consideration allows us to conclude the area of stable coasting beam parameters is sufficiently large for the

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beam before bunching. Formation of the bunched ion beam is presented in [8].

*Recombination in HVEC and its suppression*. The recombined ions flux from the electron cooler is harmful for several reasons. First of all, it shortens ion beam lifetime. Then, these ions may generate parasitic signals (background) in the MPD. This can be prevented by collimation. And finally, this flux increases radiation level in vicinity of the NICA facility.

One can estimate the flux magnitude using experimental data on the recombination of bare nuclei in electron coolers [4]. Dependence of experimental value of recombination rate coefficient $\tau_{rec}$ on electron energy shift (electron temperature $T_e$ in the ion rest frame) can be approximated as follows:

$$\alpha_{rec}(T_e) = 10^{-13} \cdot Z^2 T_e^k \text{ cm}^3/\text{s}, k = -0.3849673, \quad (4)$$

Then one can calculate ion lifetime the NICA Collider using the formula

$$\tau_{rec} = \eta_{cool} \frac{\gamma^2}{\alpha_{rec} n_e} \quad (4)$$

where $\eta_{cool}$ is ratio of the cooling section length to the Collider ring circumference, ne is cooling electron density in the Lab. frame, $\gamma$ is the Lorenz factor. The results of $\tau_{cool}$ and $\tau_{rec1}$ for the NICA Collider at ion energy of 4 GeV/u and electron beam current of 1 A are given in table 1. The calculations of $\tau_{cool}$ (column 2) and $\tau_{rec1}$ (column 3) have been performed by V. Parkhomchuk [5][1] using BETACOOL code [11] and the Bell formula [12]. The results of $\tau_{rec2}$ (column 4) were calculated by formulas (4), (5).

Table 1: Cooling and Recombination Time Values for NICA Collider

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| $T_e$, eV | $\tau_{cool}$, s | $\tau_{rec1}$, s | $\tau_{rec2}$, s |
| 0.1 | 18.45 | 87.6 | 295 |
| 1.0 | 21.91 | 209.9 | 717 |
| 10 | 28.8 | 1153 | 1740 |
| 100 | 40.35 | 4843 | 2800 |

*Luminosity Optimization*. Luminosity of the NICA Collider was calculated using optimization method proposed in [13]. The method is based on two effects limitations: so called Laslett betatron tune shift $\Delta Q$ and beam-beam betatron tune shift $\xi$. Their sum has not to exceed certain value $\Delta Q_{\max}$. As is known for experiment, the beam is stable if $\Delta Q_{\max} = 0.05$. For NICA Collider in ion mode the dominant Laslett tune shift (Fig. 8a). Method of choice of optimal values of other parameters is described in [13], the results are demonstrated in Fig. 8b. However, luminosity of NICA Collider can be limited by intensity of the injection chain and MPD capability.

[1] The calculations in [5] have been done for enlarged ring circumference that is corrected in present article.

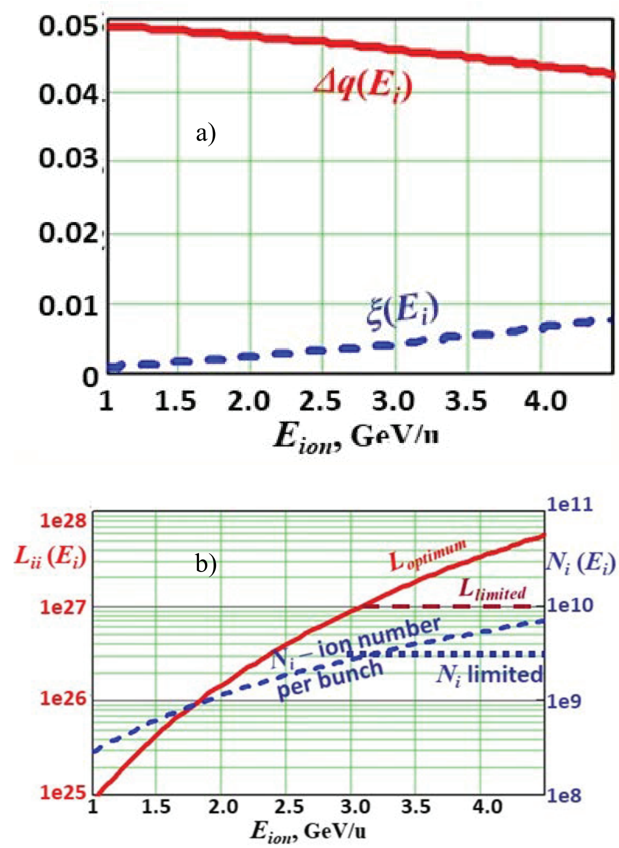


Figure 8: Tune shifts of betatron frequencies caused by beam space charge action (a) and number ion per bunch and luminosity (b) vs ion energy.

## STOCHASTIC COOLING

Both electron and stochastic cooling methods are complimentary and will be applied to ion beams of the NICA Collider. This version of the stochastic cooling method is under active development [9], [10]. Implementation of the proton mode is much more complicated problem. We lose stochastic signal value by the factor $Z = 79$ and get increasing of cooling time by factor $N_{proton}/N_{ion}$. This problem is under investigation as well by NICA group.

## CONCLUSION

The presented report describes the current status of the NICA project with focusing on the problems related to application of electron cooling at the steps of ion injection and acceleration in the NICA Booster and ion storage in the NICA Collider. Bunched beam formation in the Collider is described in [8]. Both talks demonstrate that electron cooling is a key issue of the NICA project and its implementation is realistic.

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