Electron And Stochastic Beam Cooling For Intensive Heavy Ion Beams At Nica Complex: Experiments And Plans

E. Syresin[1] Y. Tamashevich[1†] V. Lebedev[1] A. Butenko[1] I. Gorelyshev[1] I. Meshkov[1] K. Osipov[1]
Yu. Prokofichev[1] V. Shpakov[1] S. Semenov[1] A. Sergeev[1] A. Sidorin[1] R. Timonin[1] G. Trubnikov[1]
M. Bryzgunov[2] A. Bubley[2] V. Panasyuk[2] V. Parkhomchuk[2] V. Reva[2]

[1]Joint Institute for Nuclear Research, Dubna, Russia
[2]Budker Institute of Nuclear Physics, Novosibirsk, Russia

Abstract: The Nuclotron-based Ion Collider fAcility (NICA) is currently under construction at JINR, with the first beam tests of the Collider scheduled for the second half of 2025. The NICA project aims to provide colliding beams for studying heavy fully stripped ion collisions at energies of up to 4.5 GeV/u. The NICA accelerator complex comprises several components: the operational heavy ion linac HILAC with an energy of 3.2 MeV/u, the superconducting Booster synchrotron with a maximum energy of 600 MeV/u, the superconducting Nuclotron synchrotron capable of accelerating gold ions to 3.9 GeV/u, and two storage rings with two interaction points currently being installed. Two electron cooling systems are included—one in the Booster synchrotron with a maximum electron energy of 60 keV, and another in the Collider with two electron beams, each with a maximum energy of 2.5 MeV. Additionally, two stochastic cooling systems are implemented. The status of the NICA accelerator complex, including its cooling systems, is presented. Experimental results from electron cooling studies conducted during the commissioning of the injection complex are reported. Plans for further development and application of electron and stochastic cooling systems are also described.

Keywords: NICA, Electron Beam Cooling, Stochastic Beam Cooling, Heavy Ion Beams, Ion Collider

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1. NICA INJECTION COMPLEX

The Nuclotron-based Ion Collider fAcility (NICA) is currently being commissioned at JINR [1, 2]. The NICA complex consists of two collider rings designed for head-on collisions at two interaction points and an injection system [3, 4], which includes a linac and two synchrotrons: the Booster and the Nuclotron.

The Krion-6T ion source [5] provides a beam of highly multicharged ions. For Collider operations, $^{209}Bi^{35+}$ and $^{197}Au^{79+}$ ions are planned, while $^{124}Xe^{28+}$ ions were used during Run IV (September 2022 – February 2023). These ions are also expected to be used during the initial stages of Collider commissioning. In Run IV, approximately 25% of the ions extracted from the source had the desired charge state, with a typical intensity of about 10^8 ions per pulse for the targeted charge. After electrostatic acceleration to 17 keV/u, the beam is further accelerated in the RFQ and two sections of the DTL heavy ion linac (HILAC) [6] to an energy of 3.2 MeV/u. The beam is then injected into the Booster via single-turn injection.

The Booster is a superconducting synchrotron designed to accelerate heavy ions to an energy of 600 MeV/u (A/Z≈6). According to the Collider design report [3], the required beam intensity is approximately 10^9 ions per pulse from the injection complex, with a cycle duration of 4–5 seconds.

The xenon ion beam extracted from the Krion-6T ion source exhibited 5-6 different charge states, with the targeted charge state (Z=28) constituting approximately 25% of the beam. Typically, the intensity of $^{124}Xe^{28+}$ ions at the HILAC exit is about 5×10^7 ions, with a total beam pulse duration of 12–15 μs. This intensity, however, is still about an order of magnitude below the Collider's requirements [3].

To address this, an initial strategy involved accumulating the beam in the Booster’s transverse plane using multiple injections and beam damping with electron cooling [7]. Given that the rate of longitudinal cooling is nearly three times faster than transverse cooling, the current plan focuses on longitudinal plane accumulation [8]. Note that transverse cooling is further suppressed for high-amplitude particles because the electron beam radius is approximately half the beam size at the acceptance

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† E-mail: tamashevich@jinr.ru

boundary. To achieve a tenfold accumulation (Fig. 1a), the Booster cools the stored bunch during the accumulation process, reducing its length to less than half of the ring circumference, while the remaining half is allocated for beam injection.

The beam pulse duration from the ion source was consequently reduced to 4 μs (Fig. 1b).

II. BOOSTER ELECTRON COOLING

The Booster electron cooling system [9−11], designed and manufactured by BINP SB RAS, features a maximum electron energy of 50 keV and a cooling length of 2.5 m [3] (see Table 1 and Fig. 2).

During Collider operations, this system will be employed at the injection energy of 3.2 MeV/u for beam accumulation and cooling. Although the Booster electron cooling system was tested with various ion species, it was not regularly used for beam delivery to users until near the end of Run IV.

Investigations of Booster electron cooling were conducted during the 2nd [4] and 4th [12] Runs. Measurements were carried out at the injection energy of 3.2 MeV/u using $^{56}Fe^{14+}$ [4] (Figs. 3 –4) and $^{124}Xe^{28+}$ ions. In the 4th Run, acceleration of $^{124}Xe^{28+}$ ions began 230 ms after beam injection. Although this interval is relatively short, it was sufficient to cool the ions, reducing the bunch length by a factor of 3 with an electron beam current of 50 mA (Fig. 5).

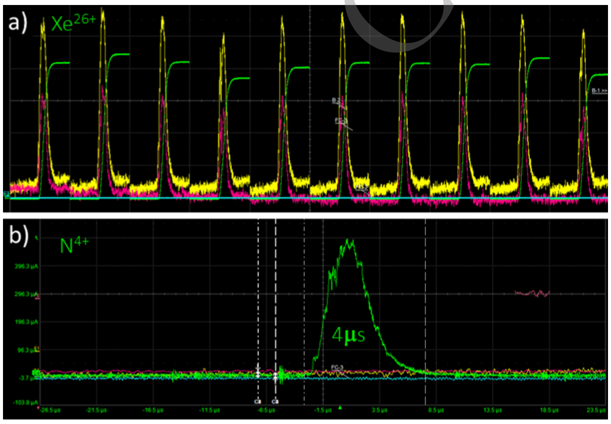

Fig. 1. (color online) (a) Multi-cycle injection with ten pulses from HILAC. (b) Dependence of nitrogen ion beam current intensity on time.

Table 1. Parameters of the Booster electron cooling system.

Maximal electron energy	50 keV
Electron beam current	0–1 A
Length of the cooling section	2.5 m
Electron beam radius	14 mm

Figure 6 compares the time evolution of bunch duration with cooling turned off (red circles) and on (blue stars). These experimentally measured rates indicate a longitudinal cooling time of approximately 70 ms.

The effects of transverse cooling were observed using a beam viewer installed in the Booster-Nuclotron transfer line. This allowed us imaging of the transverse intensity distribution after beam acceleration. As shown in Figs. 7 and 8, cooling reduced the full width at half maximum (FWHM) beam transverse sizes from 7.81 to 3.34 mm horizontally and from 5.38 to 1.63 mm vertically.

The reduction in beam emittances led to decreased beam losses in the course of acceleration and a subsequent doubling of the intensity of the beam extracted from the Nuclotron for the fixed-target BM@N experi-

Fig. 2. (color online) Image of the Booster electron cooling system with the 2.5 m cooling section designed for a maximum electron energy of 50 keV.

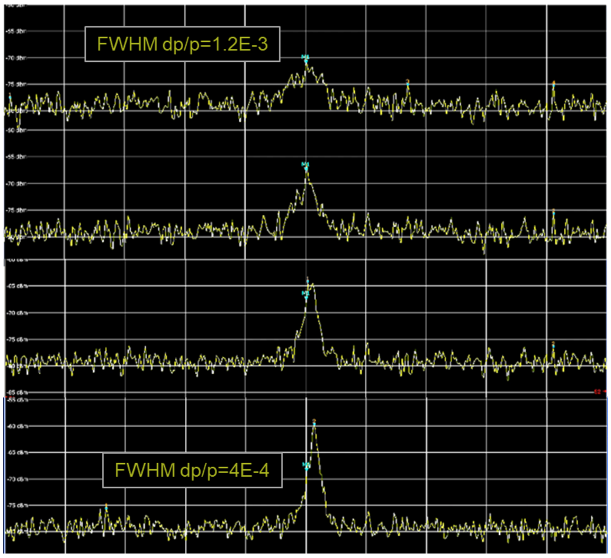

Fig. 3. (color online) Evolution of the Schottky noise signal at the 4th harmonic of the revolution frequency for $^{56}Fe^{14+}$ ions at 3.2 MeV/u. The top trace shows the signal without cooling, while the bottom trace illustrates the signal after cooling.

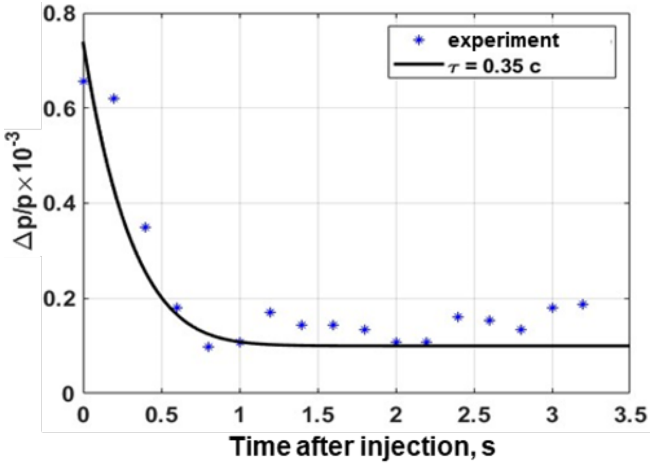

Fig. 4. (color online) Dependence of the momentum spread of the $^{56}Fe^{14+}$ ion beam on time at an ion energy of 3.2 MeV/u and an electron beam current of 76 mA. Measurements were performed for a continuous beam with Schottky noise.

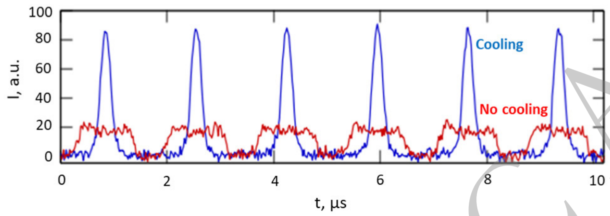

Fig. 5. (color online) Longitudinal bunch profiles of $^{124}Xe^{28+}$ ion beams without (red line) and with (blue line) electron cooling at an electron beam current of 50 mA. Measurements were obtained using a fast beam current monitor shortly before beam acceleration, in the presence of RF voltage.

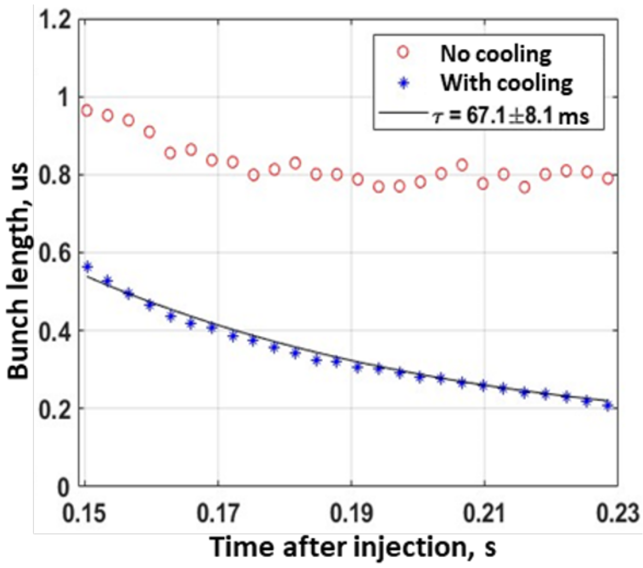

Fig. 6. (color online) Dependence of bunch duration on time with electron cooling enabled (blue stars) and disabled (red circles) for $^{124}Xe^{28+}$ ions, measured during Run IV.

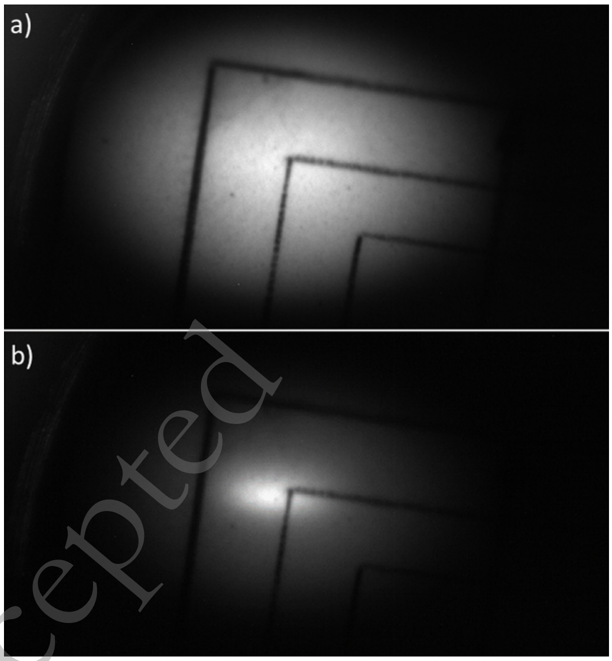

Fig. 7. (color online) Transverse profiles of the ion beam captured on the beam viewer (luminophore screen) without electron cooling (a) and with electron cooling (b). The beam intensity was reduced to prevent saturation of the screen.

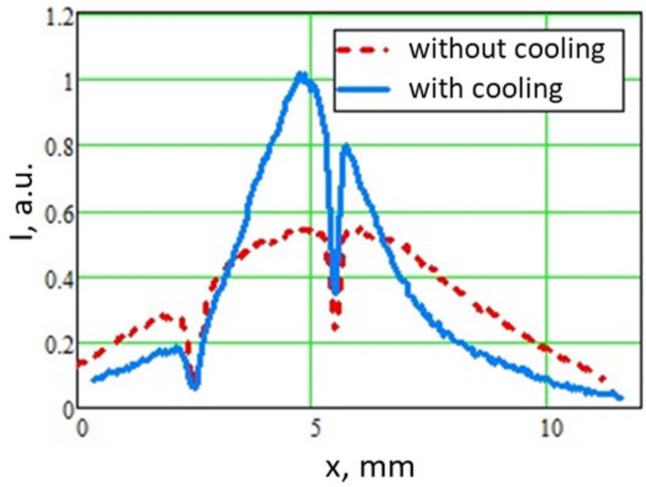

Fig. 8. (color online) Transverse beam profiles in the transfer channel without Booster electron cooling (red dotted line) and with electron cooling (blue solid line).

ment. As a result, the number of $^{124}Xe^{54+}$ nuclei reached 10^7 per pulse (Fig. 9).

III. BEAM ACCUMULATION IN BOOSTER

To provide Collider operations at designed parameters, the number of ions delivered from the injection chain to the Nuclotron at its top energy must be increased by a factor of about 30 compared to recent runs. This requirement arises from a 20-fold shortfall in ion source intens-

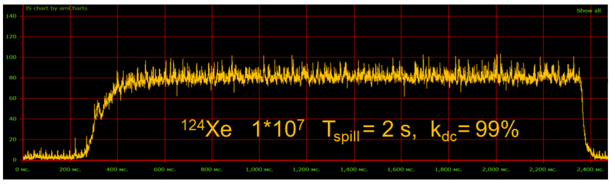

Fig. 9. (color online) Dependence of beam intensity on time for the $^{124}Xe^{54+}$ ion beam extracted from the Nuclotron. The extraction efficiency is approximately 30%, and the coefficient k_{dc} characterizes the time uniformity of the extracted beam intensity.

ity compared to the design specification. The shortfall will be addressed through ion accumulation in the Booster, facilitated by electron cooling, and by minimizing beam losses during acceleration and transfer.

Since longitudinal cooling is significantly faster than transverse cooling, accumulation will be performed in the longitudinal plane. Electron cooling will clear space for subsequent injections. Calculations, supported by experimental results on electron cooling, indicate an optimal stacking rate of ≈10 Hz. Between 10 and 15 injections will be needed to reach the space charge limit at the injection energy. Consequently, around 1 second of the 5-second acceleration cycle will be dedicated to beam accumulation in the Booster.

A 10 Hz operation of the Krion-6T ion source with 10 pulses was recently demonstrated for $^{124}Xe^{28+}$ ions (Fig. 1a). Optimizing the ion source tuning increased the total extracted charge from 2.4 to 3 nC. Further improvements included shortening the ion pulse duration from ≈15 μs to 4 μs (Fig. 1b) by reshaping the holding electrodes to produce a uniform electric field and implementing a specially programmed electrode power supply.

The low-energy beam transport, as well as the linac and transfer line quadrupole power supplies, have been configured to support 10 consecutive injection pulses at a repetition rate of 10 Hz from linac. Beam accumulation in the Booster will occur at the first RF harmonic, with a bucket height of $(\Delta p/p)_{max} = 1.8\times10^{-3}$, which maximizes the cooling rate. Achieving this requires an RF voltage of 200 V.

Half of the Booster ring will be used for injection, and the other half for accumulation (Fig. 10). Each new injection will take place only after the previous bunch is cooled to the core. The constant presence of the first RF harmonic will minimally affect particles with high synchrotron amplitudes. The total number of accumulated ions and the depth of cooling will be limited by the ion bunch space charge. It is expected that approximately 10^9 ions of $^{209}Bi^{35+}$ can be stored.

To minimize longitudinal emittance growth, rebunching during Booster acceleration will be avoided. Instead, the entire acceleration process will proceed at the first harmonic. Since the RF frequency at the start of the cycle

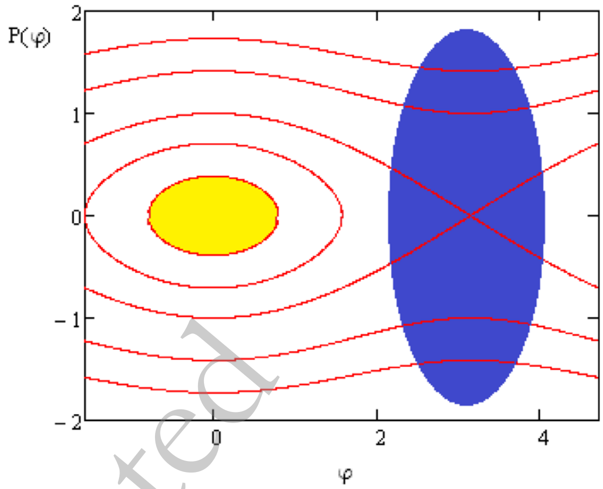

Fig. 10. (color online) Schematic representation of Booster ion accumulation in longitudinal phase plane, facilitated by electron cooling.

is outside the nominal operational range, the initial RF voltage will be reduced to approximately 1.5 kV. As the beam accelerates, the RF voltage gradually increases, reaching its nominal value of 10 kV at a beam energy of around 100 MeV/u. This approach will extend the acceleration cycle by 300 ms, equivalent to the time that would otherwise be required for rebunching.

IV. COLLIDER

The NICA Collider [1, 2, 3, 13] comprises two storage rings (Fig. 11) with two interaction points (IPs). The main operational parameters for fully stripped $^{209}Bi^{83+}$ ions are summarized in Table 2.

The electron cooling system [14] for the Collider will be operating at a maximum electron energy of 2.5 MeV. Main parameters of the system are listed in Table 3. It is designed for ion accumulation and bunch formation at kinetic energies ranging from 1.0 to 4.5 GeV/u. The system includes a 6 m solenoid cooling section with a magnetic field of 0.1 T and a maximum electron beam current of 1 A (Fig. 12). Construction of the cooling system began at BINP in 2016, with assembly work planned for 2025 and electron beam operation set to start in 2026.

The RF barrier bucket technique [3] facilitates efficient particle accumulation, enabling the achievement of high intensities. The Collider receives one bunch from the Nuclotron every four seconds, containing $(0.2 - 2) \times 10^9$ nuclei. Figure 13 illustrates the results of modeling calculations showing the dependence of the stored number of $^{209}Bi^{83+}$ ions in the Collider ring at an ion energy of 3 GeV/u. The cooling time for these ions is anticipated to be approximately 100 seconds at energies of 3–4.5 GeV/u.

At a cooling time of 300 s, the longitudinal accept-

Fig. 11. (color online) Assembly process of the Collider rings at the NICA facility.

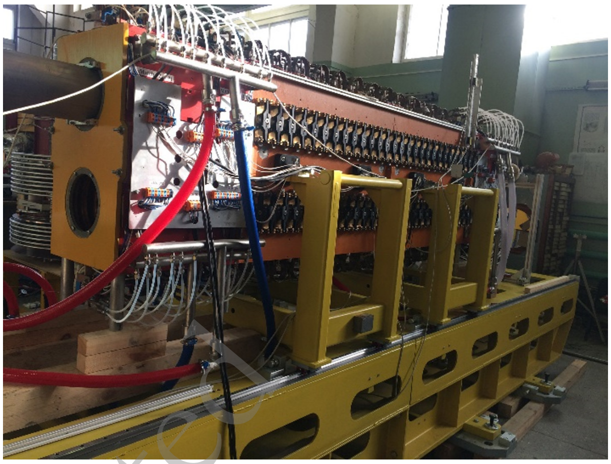

Fig. 12. (color online) Solenoidal section of the Collider electron cooling system.

Table 2. Key parameters of the NICA Collider.

Circumference	503.04 m
Maximal magnetic rigidity	45 T m
Average residual gas pressure	<1 × 10^{-8} Pa
Maximal dipole magnets field	1.8 T
Kinetic energy of gold nuclei	1–4.5 GeV/u
Luminosity at maximal energy	1 × 10^{27} cm^{-2} s^{-1}

Table 3. Main parameters of the Collider electron cooling system.

Electron energy	0.2–2.5 MeV
Energy stability, $\Delta E/E$	<1 × 10^{-4}
Electron beam current	0.1–1 A
Cooling section length	6 m
Solenoid magnetic field	0.05–0.2 T
Field homogeneity, $\Delta B/B$	<1 × 10^{-5}

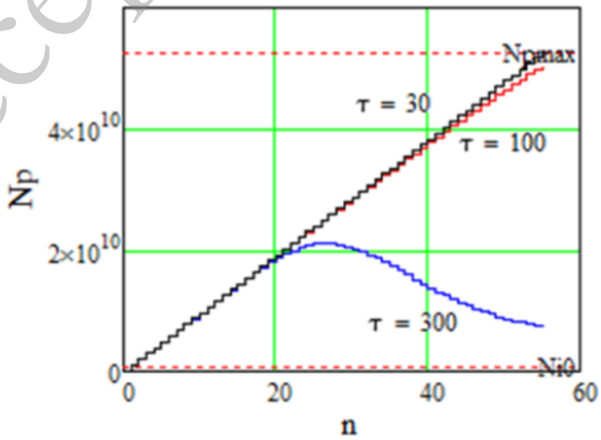

Fig. 13. (color online) Dependence of the number of stored ions (Np) on the number of injection cycles (n) for different cooling time constants (τ).

ance of RF1 barrier is fully utilized after 25 ion injection cycles. The observed reduction in stored intensity for injection cycles exceeding $n > 25$ (Figure 13) is attributed to ion losses caused by an increase in momentum spread due to intrabeam scattering.

Precooling in the Booster reduces the relative rms momentum spread ($\Delta p/p$) by a factor of 3 down to 4 × 10^{-4}, allowing ions to be stored for up to 75 injection cycles. Under these conditions, a cooling time (τ_{cool}) of 300 seconds allows stack storage with the required intensity.

The Collider electron cooling system plays a critical role in achieving an ion momentum spread of $\Delta p/p \approx 10^{-3}$ and a bunch length of 0.6 m (Fig. 14).

Achieving the design luminosity of 1 × 10^{27} cm^{-2} s^{-1} will require full-scale commissioning of the RF3 system,

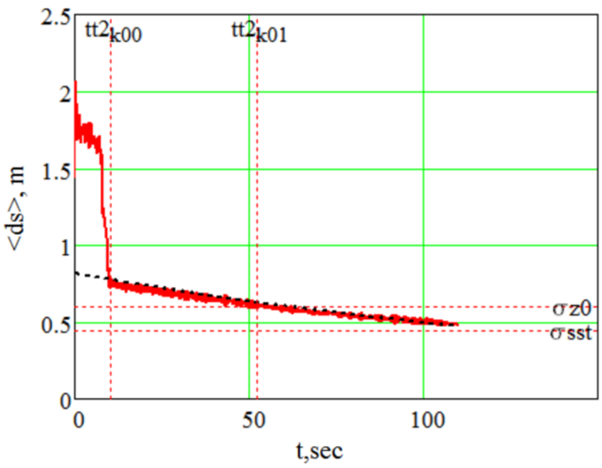

Fig. 14. (color online) Dependence of bunch length on time during RF3 bunching and electron cooling, with a cooling duration of 100 seconds.

Table 4. Main parameters of the Collider stochastic cooling system.

Ion energy for $^{209}Bi^{83+}$	2.5–4.5 GeV/u
Momentum cooling method	Filter
Full bandwidth	640–3240 MHz
Channel 1	640–960 MHz
Channel 2	960–1440 MHz
Channel 3	1440–2160 MHz
Channel 4	2160–3240 MHz
Cable distance Pickup-Kicker	≈120 m
Beam distance Pickup-Kicker	186 m (∥) 194 m (⊥)
Pickup shunt impedance	200 Ω (∥) 4 Ω/mm (⊥)
Kicker shunt impedance	800 Ω (∥) 16 Ω/mm (⊥)
Pickup temperature	300 K

electron cooling, and full energy extraction from the Nuclotron, which is expected by 2026.

In addition to electron cooling [14], the Collider will be equipped with a stochastic cooling system (SCS), capable of cooling all three degrees of freedom [3, 15]. Main parameters of the system are listed in Table 4. The SCS operates at ion energies of 2.5–4.5 GeV/u with a frequency range of 640–3200 MHz. It is designed to cool bunches containing up to 3.1×10^9 $^{209}Bi^{83+}$ ions.

The SCS employs pickup electrodes and kickers, along with signal delay system blocks, cascaded solid-state amplifiers and preamplifiers, and a comb filter system. A distinctive feature of the NICA SCS is an installation of pickups and kickers around ceramic vacuum chambers. Each cooling system is divided into four bands as shown in Table 4.

The SCS hardware will be installed in two stages. The first stage, covering ≈ 25% of the system and operating at frequencies of 960–1440 MHz, will be installed by the end of 2024 for longitudinal cooling. The final stage, incorporating the full system, will be implemented in 2026.

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