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Experimental and theoretical JINR studies on the development of stochastic cooling of charged particle beams

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Contents

Abstract. **In 2010, based on the superconducting heavy-ion synchrotron Nuclotron, a new accelerating complex NICA (Nuclotron-based Ion Collider fAcility) started to be constructed at the Laboratory of High Energy Physics of the Joint Institute for Nuclear Research, its key facility being the 1.0 – 4.5 GeV per nucleon heavy ion collider. For the purpose of effectively collecting statistics, an average collider luminosity of 10^{27} cm^{-2} s^{-1} is required. With this collider energy, the cooling of the beam both in the process of storage and during the experiment is mandatory to ensure the required parameters. In this paper, a possible new regime of stochastic cooling is examined.**

Keywords: hadron collider, beam cooling, stochastic cooling

1. Introduction

Stochastic cooling was proposed by Simon van der Meer in 1968 for the storage of antiprotons and the provision of high proton–antiproton collider luminosity [1]. Stochastic cooling is a process of reducing betatron oscillation amplitudes or the energy spread of beam particles (hence, the respective cooling of transverse and longitudinal degrees of freedom) with the help of a broadband feedback system. The method is essentially as follows. The transverse coordinate or the particle energy deviation from a nominal value is measured at a given ring point using so-called pickup electrodes. Then, the signal is processed, amplified, and reproduced by a kicker (momentum-correction device) located at a distance from the pickup along the beam path. The signal propagation delay time in transmitting cables and electronic devices is chosen to be equal to the time of flight of a particle with nominal energy from the pickup to the kicker. Stochastic cooling, just like electron cooling, finds wide application for the storage of rare particles (antiprotons, ions of radioactive isotopes, etc.) and the maintenance of luminosity in internal target experiments.

However, stochastic cooling has not until recently been applied in high-energy colliders because, on the one hand, the required luminosity can be achieved without beam cooling, and, on the other hand, due to technical difficulties related to the high beam bunching factor. A bunched beam was first cooled in the high-energy hadron collider RHIC (Relativistic Heavy Ion Collider) at the Brookhaven National Laboratory, USA, where systems for the cooling of transverse, vertical, and longitudinal degrees of freedom were commissioned successively between 2007 and 2012 [2].

The idea of creating a heavy-ion collider with an ultralow energy of the colliding beams was brought up at the Joint Institute for Nuclear Research (JINR) in 2008. Analysis of the ion dynamics in such a facility offered the necessity of beam cooling in the process of ion storage and during the experiment, with both stochastic and electron cooling being indispensable for its efficient operation in a wide range of energies. A wealth of experience has been gained in designing and developing electron cooling systems at the Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences. Similar studies have been carried out for many years at the Electron Cooling Sector of JINR. At the same time, Russian researchers have practically no experience in the development of stochastic cooling systems. This gap began to be filled in 2009 by the development of a project of

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building a stochastic cooling system prototype for the Nuclotron accelerator then in operation. This article is designed to consider peculiar features of the stochastic cooling system in a low-energy collider and report results of experimental studies on the cooling process obtained at JINR.

2. Peculiar features of NICA. Cooling in the process of ion storage

In 2010, based on the superconducting heavy-ion synchrotron Nuclotron, construction began on a new accelerator complex NICA (Nuclotron-based Ion Collider fAcility) at the Laboratory of High Energy Physics [3] with a view to putting JINR into leading positions in the fields of relativistic nuclear physics and spin physics. The plan of relativistic nuclear physics research includes exploration of colliding beams of heavy ions with a kinetic energy of 1.0–4.5 GeV per nucleon. For the purpose of effectively collecting statistics, an average collider luminosity of 10^{27} cm^{-2} s^{-1} is required, which is an unprecedented task to be fulfilled in the said energy range. The NICA project appears to be the world's first experience in designing hadron colliders with such a low energy and high luminosity.

At the RHIC facility, gold ions collide at a kinetic energy of 100 GeV per nucleon. The peak luminosity of 10^{28} m^{-2} s^{-1} is limited from above by beam collision effects. The luminosity lifetime prior to commissioning the cooling system amounted to approximately 4 h and was restricted by an increase in the bunch phase volume. Stochastic cooling in the gold ion collision regime slightly prolonged the lifetime of luminosity, while integral luminosity increased roughly twofold. For a smaller bunch intensity, e.g., in uranium nuclei collisions, the application of stochastic cooling at RHIC markedly enhanced both the lifetime and the peak value of luminosity. As a result, integral luminosity increased roughly fivefold [4].

In the regime of heavy-ion collisions at the Large Hadron Collider (LHC) in CERN, Switzerland, the maximum kinetic energy of lead nuclei amounts to approximately 3.7 TeV per nucleon. The mean expected luminosity of 10^{27} cm^{-2} s^{-1} is limited by the maximally attainable event count rate in the detector rather than by the accelerator capabilities. The luminosity lifetime depends on the particle loss due to high-order betatron oscillation resonances and, on the optimal choice of the working point, it can be increased to 10 h. In the present LHC configuration, the beams are not cooled, but successful application of stochastic cooling at RHIC promoted the development of an analogous system for heavy-ion cooling in LHC, too [5].

In both presently working heavy-ion colliders, the shift of betatron oscillation frequencies under the effect of the bunch eigenfield is negligibly small, and luminosity does not depend on the perimeter of the accelerator; it can be enhanced by increasing the number of colliding bunches. Particles are accumulated in colliders as the orbits are filled up by successive injections of bunches (or bunch trains) prepared in an injection chain. In so doing, active methods for the formation of the phase volume of the injected beam in the collider itself are not employed. Transverse beam emittance (due to kinematic reduction associated with acceleration) at the energy of a given experiment is a few orders of magnitude lower than the collider acceptance.

At a mean beam kinetic energy of a few GeV per nucleon, the main effect limiting the achievable luminosity in a colliding beam experiment is the shift of betatron oscillation frequencies under the effect of the bunch eigenfield. The frequency shift is proportional to the accelerator perimeter; therefore, luminosity is inversely proportional to the square of the perimeter at the same limiting shift. For example, luminosity in the RHIC program of scanning in a low-energy range is roughly 10^{25} cm^{-2} s^{-1} due to frequency shift limitations. The RHIC perimeter is around 3.8 km; therefore, decreasing it by about an order of magnitude is likely to increase luminosity to 10^{27} cm^{-2} s^{-1}.

It turned out in the course of developing the NICA conceptual project that peak luminosity close to 10^{27} cm^{-2} s^{-1} can be reached using the same bunch accumulation scheme at injected bunch parameters analogous to those in RHIC and a perimeter of about 250 m (the composition and the expected characteristics of the injection chain in NICA being similar to the RHIC injection chain) [6]. In this case, however, the luminosity lifetime is limited by the effect of increasing longitudinal phase volume due to intrabeam scattering (IBS), which varies from 10 to 100 s. For this reason, it is impossible to reach the design value of luminosity without beam cooling during the experiment. In this case, application of the beam stochastic cooling with technically realistic parameters seems to be problematic due to a high peak linear particle density in short bunches.

Such a short luminosity lifetime in this regime is attributable to two factors. First, the collider acceptance is incompletely utilized at a fixed bunch intensity as implied by the storage scheme under consideration. Second, a bunch prepared in the injection chain is far from thermodynamic equilibrium between longitudinal and transverse degrees of freedom. Therefore, the heating rate depends largely on the energy redistribution between longitudinal and transverse oscillations.

A detailed analysis of the size of the technological equipment to be placed inside the collider for the purpose of experiment showed that the minimum perimeter of the facility should be about 500 m. Standard approaches to the storage and formation of bunches in the collider cannot, in principle, ensure the required level of luminosity.

To increase luminosity, it is necessary to optimize bunch parameters, making the best of the collider structure regardless of the injection chain properties. In this case, a flexible scheme of beam storage in the collider is needed to enable formation of beams with any required parameters. The most universal storage device of this type is the Recycler Ring, successfully applied in the Fermi National Accelerator Laboratory (Batavia, USA) for the formation of an antiproton beam to be injected into the Tevatron collider. This scheme is based on the use of the so-called barrier radiofrequency system. The storable beam then occupies roughly half of the perimeter of the accelerator, while new batches of particles are successively added to it. This process is combined with the cooling of the stored beam. Both stochastic cooling and electron cooling are used in the Recycler Storage Ring [7]. When the required intensity is reached, the necessary number of bunches are formed.

A similar scheme was proposed to store heavy ions in HESR (High Energy Storage Ring) of the FAIR project (Facility for Antiproton and Ion Research), Darmstadt, Germany [8]. The feasibility of using such a storage scheme in NICA was theoretically investigated in Ref. [9], and possibility of its realization with the use of stochastic cooling was confirmed in studies on ESR (Experimental Storage

Ring) at the GSI Helmholtz Centre for Heavy Ion Research (Darmstadt) [10].

3. Stochastic cooling strategy for the maintenance of low-energy collider luminosity

The application of stochastic cooling also seems practicable in a collider experiment with heavy ions, because it does not lead to an additional loss of particles and the formation of a dense beam core that may provoke the development of a variety of beam instabilities. However, the working regime of the cooling system differs from operating modes of all earlier facilities.

Beam cooling systems with a high bunching factor, unlike those used in low-energy storage devices, are needed. Given the realistic technical parameters of the NICA cooling system, there is every reason to expect characteristic cooling times of around 1000 s. Accordingly, parameters of the collider structure and the bunches can be chosen such that characteristic times of emittance growth due to IBS are not smaller than the above-mentioned value. This problem was addressed by examining several optical structures that revealed a variant optimal in terms of IBS rate [11]. The ratio of transverse-to-longitudinal phase volumes of the bunches was chosen to be close to that at thermodynamic equilibrium to avoid fast processes associated with the bunch relaxation.

At equal luminosities, the minimal IBS rate corresponds to the maximum phase volume of the bunch; therefore, the maximally possible acceptance of the collider must be ensured. The transverse acceptance of the NICA facility was brought up to 40 π mm mrad by the correct choice of the vacuum chamber aperture and the use of a correction system, while the acceptance of relative momentum spread was about 1%. In doing so, the root-mean-square emittance of the beam taking account of technical reserves can be up to 1.1 π mm mrad, and the root-mean-square relative momentum spread up to 1.5×10^{-3}. In the case of a maximum use of acceptance, characteristic IBS times at a highest energy of 4.5 GeV per nucleon can be above 2000 s (see the table) [12].

Table. Beam parameters and luminosity records for gold-gold collisions.*

Parameter	Value		
Ring perimeter, m	503.04		
Number of bunches	22		
Root-mean-square bunch length, m	0.6		
Beta function at the collision point, m	0.35		
Ring acceptance, π mm mrad	40		
Longitudinal acceptance, $\Delta p/p$	± 0.01		
Critical gamma factor γ_{tr}	7.091		
Ion energy, GeV per nucleon	1.0	3.0	4.5
Number of ions in a bunch	2.75×10^8	2.4×10^9	2.2×10^9
Root-mean-square momentum spread, 10^{-3}	0.62	1.25	1.65
Root-mean-square horizontal/vertical emittance of the beam, unnormalized, π mm mrad	1.1/1.01	1.1/0.89	1.1/0.76
Luminosity, 10^{27} cm^{-2} s^{-1}	0.011	1	1
Characteristic IBS times, s	186	702	2540

* Maximum admissible integral betatron oscillation frequency shift caused by the bunch eigenfield and the counterpropagating bunch field at collision points is assumed to be 0.05.

The possibility of effecting the stochastic cooling of a beam with a high bunching factor (close to that needed for the NICA project) was demonstrated on RHIC. However, the NICA collider, unlike RHIC, will be operated at energies close to critical. Under these conditions, the efficiency of cooling will greatly depend on the beam energy. It requires meeting additional conditions as regards both collider structure and the arrangement of various elements around its perimeter to enable energy scanning.

The essence of these additional requirements may be illustrated by simple analytical estimates. The stochastic cooling system constitutes a broadband feedback system. A beam-induced signal measured by a pickup is processed, amplified, and fed after a proper delay to the kicker (a device acting on the beam). Given that the system has an optimal amplification coefficient (and the amplifier intrinsic noise is disregarded), the stochastic cooling rate for all three degrees of freedom can be estimated from the well-known formula [13]

$$\frac{1}{\tau} = \frac{W}{N_{\rm eq}} \frac{(1 - 1/M_{\rm pk}^2)^2}{M_{\rm kp}} , \tag{1}$$

where $W = f_{\max} - f_{\min}$ is the transmission bandwidth of the feedback system, $N_{\rm eq}$ is the equivalent number of particles, and $M_{\rm pk}$ and $M_{\rm kp}$ are the mixing coefficients of the particles traveling from the pickup to the kicker and back, respectively.

For a bunched beam, the equivalent number of particles $N_{\rm eq}$ is calculated from formula for the bunching factor:

$$N_{\rm eq} = N \frac{C}{\sqrt{2\pi}\sigma_{\rm s}} , \tag{2}$$

where N is the number of particles in the bunch, C is the ring perimeter, and $\sigma_{\rm s}$ is the root-mean-square bunch length. To reduce cooling time, the system's transmission bandwidth W should be as large as possible. It is, however, limited not only by the technical capabilities of powerful electronics but also by the accelerator parameters and momentum spread in the beam being cooled. The time of flight from pickup to kicker increases (or decreases) if the particle momentum differs from the nominal value. Cooling fails if the difference between the particle's time of flight and signal transmission is greater than the pulse length applied to the kicker. The undesirable mixing coefficient of the particles traveling from the pickup to the kicker, namely

$$M_{\rm pk} = \frac{1}{2(f_{\max} + f_{\min})\, \eta_{\rm pk} T_{\rm pk}\, \Delta p/p} , \tag{3}$$

determines the upper frequency limit $f_{\max}$ of the system's band that can be estimated as

$$f_{\max} \leqslant \frac{1}{2\eta_{\rm pk} T_{\rm pk}\, \Delta p/p} . \tag{4}$$

The 'useful' mixing coefficient of particles traveling from the kicker to the pickup can be calculated as

$$M_{\rm kp} = \frac{1}{2(f_{\max} - f_{\min})\, \eta_{\rm kp} T_{\rm kp}\, \Delta p/p} . \tag{5}$$

In the ideal case, it must be highest and close to unity. Here, η_{pk}, η_{kp}, T_{pk}, T_{kp} are partial slip factors and times of flight from the pickup to the kicker and back, respectively. Usually, the root-mean-square value σ_p ($\Delta p/p \sim 2\sigma_p$) is taken instead of momentum spread when calculating the characteristic cooling rate.

In a ring-shaped storage device, partial slip factors are similar and determined by the particle energy and the storage ring critical energy:

$$\eta_{\text{pk}} = \eta_{\text{kp}} = \frac{1}{\gamma^2} - \frac{1}{\gamma_{\text{tr}}^2}\,. \tag{6}$$

For example, to ensure efficient operation of stochastic cooling in high-energy colliders with $\gamma \gg \gamma_{\text{tr}}$, it is sufficient to choose an optimal value of the critical energy. In such a case, cooling efficiency is practically independent of particle energy. Reduced energy in low-energy colliders is responsible for a rapid increase in the slip factor that leads to the lowering of the admissible upper frequency of the system and cooling efficiency.

In the course of the NICA project elaboration, this problem was addressed by studying the possibility of using a collider with critical energy tuning [11]. However, such a regime does not ensure large acceptance over the entire energy range of interest.

Another solution consists in taking into account the concrete orbit geometry of the collider and the specific dynamics of longitudinal particle movements. The NICA project considers beam collision at two points, the natural ring shape with a minimal perimeter making a racetrack: two turning sections are linked together by two straight sections in which collision points are located. In an energy range above approximately 3 GeV per nucleon, the character of longitudinal particle movement through the turning and straight sections is different. Thus, for a particle with a momentum higher than the equilibrium value, the time of flight through the turning section is shorter than for an equilibrium particle, whereas in the straight section the nonequilibrium particle overtakes the equilibrium one. The choice of the pickup position at the entrance to the turning section permits such a kicker position to be found in the subsequent straight section that makes the time of pickup-to-kicker flight at a certain energy independent of the particle momentum. This approach ensures efficient stochastic cooling in a wide enough energy range.

For the chosen optical structure of the collider, the optimal arrangement of stochastic cooling equipment ensures efficient beam cooling in the energy range from 3 to 4.5 GeV per nucleon [12]. For example, pickup and kicker positions for cooling the longitudinal degree of freedom are chosen such that the partial slip factor between the pickup and the kicker has a small negative value, $\eta_{\text{pk}} = -2 \times 10^{-3}$, at a maximum energy of 4.5 GeV per nucleon, and a small positive value, $\eta_{\text{pk}} = 5 \times 10^{-3}$, at a minimal energy of 3 GeV per nucleon (Fig. 1). In this case, the undesirable mixing of particles is practically suppressed within the entire energy range, while useful mixing of particles flying between the kicker and the pickup is enhanced. The possibility of using such an operating mode of stochastic cooling has been discussed with regard to other projects, i.e., in connection with designing storage devices for the beams of short-lived ions of radioactive isotopes for which maximum cooling rates are needed. However, none of the proposed options materialized into a concrete technological project due to the difficulties in achieving the required acceptance of a storage ring. The ion energy range and ring geometry of the NICA collider proved most suitable for the realization of this beautiful idea.

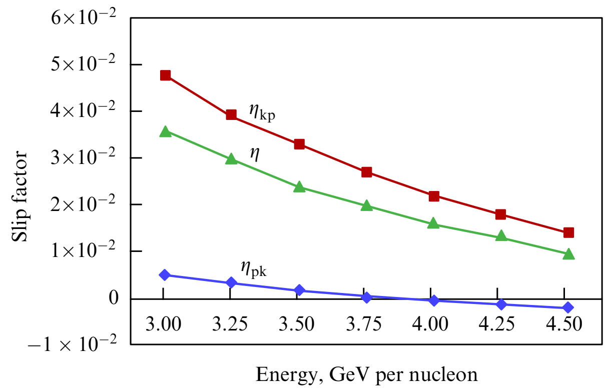

Figure 1. Calculated energy dependences of the total slip factor (η), partial slip factor between pickup and kicker (η_{pk}), and partial slip factor between kicker and pickup (η_{kp}).

With the chosen mutual arrangement of the kicker and the pickup, condition (4) gives an estimate of 20 GHz for the acceptable value of the upper frequency band of the system (taking into account that momentum spread equals the dynamic longitudinal aperture of the ring reaching ± 0.01). This actually means that the choice of the system's frequency band for the optical structure under consideration is limited only by technical capabilities. In our concrete case, luminosity at the level of 10^{27} cm^{-2} s^{-1} is possible if the number of ions in the bunch amounts to 2.3×10^9, which corresponds to the effective number of 8×10^{11} ions. Evidently, the frequency bandwidth of the stochastic cooling system can be chosen within 2–4 GHz to ensure characteristic cooling times one half (to have a technical reserve) the characteristic heating times due to IBS. This is consistent with the range used extensively in global practice, as posing no serious radio-technical difficulties.

Taking account of geometric restrictions and additional requirements for oscillation phase advance imposed on transverse cooling systems, the optimal mutual arrangement of the components of the stochastic cooling system for all three degrees of freedom was found in the framework of the NICA technical project (Fig. 2 [12]).

The electron cooling system was decided to be employed in an energy range of 3 GeV per nucleon to ensure maximum luminosity.

4. Numerical simulation of stochastic cooling dynamics

Requirements for parameters of the stochastic cooling system and characteristics of its components were determined based on the results of numerical simulations of beam dynamics in the storage facility. Special software programs for the calculation of stochastic cooling systems being unavailable, we created a computer code to simulate the evolution of the particle distribution function by solving the Fokker–Planck equation for the technical project of the NICA cooling system.

For example, cooling the beam's longitudinal degree of freedom was analyzed by numerical simulation of the

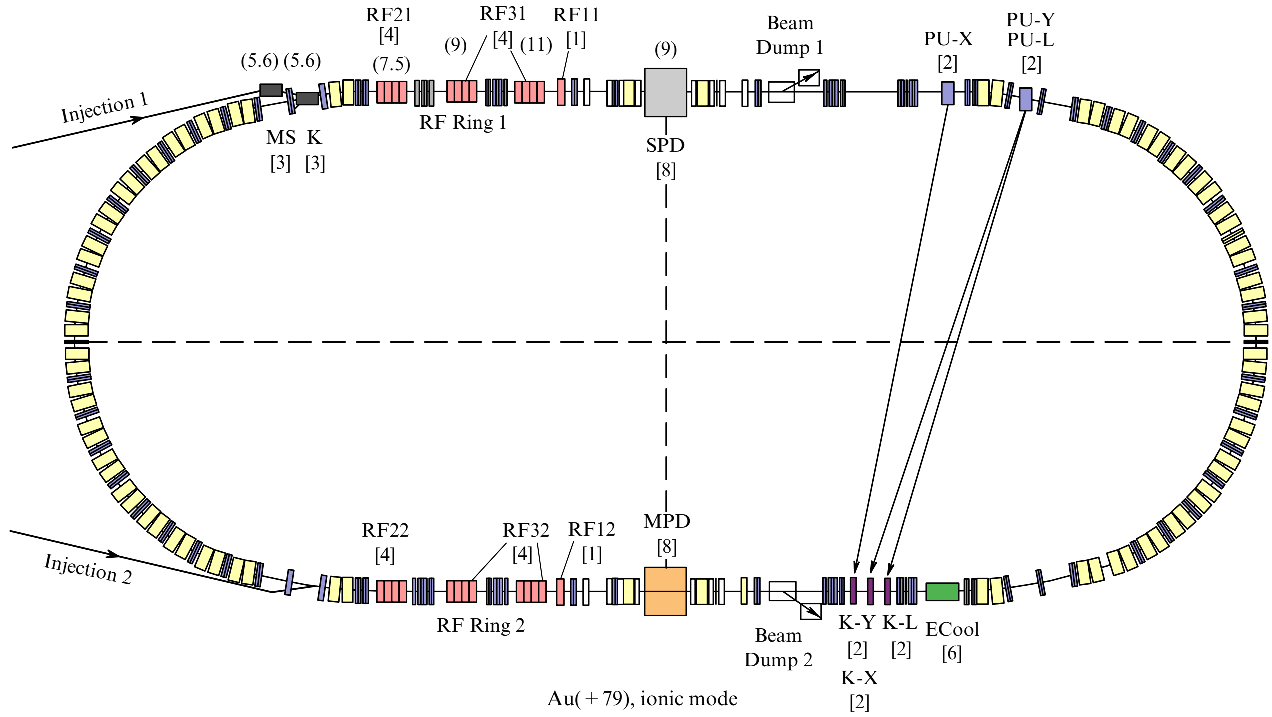

Figure 2. Schematic arrangement of equipment around the perimeter of NICA: RF — elements of the radio-frequency system; MS and K — magnetic septum and kicker of the beam injection system; MPD — multipurpose detector; SPD — spin physics detector; Beam Dump — beam dumping system; PU-X, PU-Y, PU-L — horizontal, vertical, and longitudinal pickups of the stochastic cooling system; K-X, K-Y, K-L — respective kickers, and ECool — electron cooling section.

temporal evolution of the particle energy distribution function $\Psi(E,t) = \mathrm{d}N/\mathrm{d}E$. The main factors responsible for cooling efficiency can be described as 'drift', $F(E) = f_0 \Delta E_{\mathrm{c}}$, and 'diffusion', $D(E,t) = 1/2 f_0 \langle \Delta E_{\mathrm{ic}}^2 \rangle$, terms of the Fokker–Planck equation

$$\frac{\partial \Psi(E,t)}{\partial t} + \frac{\partial}{\partial E}\left(F(E)\,\Psi(E,t) - D(E,t)\,\frac{\partial \Psi(E,t)}{\partial E}\right) = 0\,, \tag{7}$$

where $\Delta E_{\mathrm{c}}(E)$ is the useful energy part of the correction signal per revolution, ΔE_{ic} is part of the energy related to the incoherent noise effects, and f_0 is the particle revolution frequency.

The drift term, or the drag force, describes the cooling of a single particle, and the diffusion term describes all effects responsible for beam 'heating'. In our code, the diffusion term takes account of the beam Schottky noise, and thermal noise of radiotechnical elements of the system.

Coefficients of the Fokker–Planck equation are derived from parameters of radiotechnical elements of the system by successive multiplication of the respective transfer functions [14, 15]. Simulation of the cooling process envisages the possibility of using both theoretical expressions for transfer functions and the results of their bench test measurement.

The reliability of the code was verified by comparing our calculated results with those obtained with the employment of analogous programs developed at CERN, Forschungszentrum Jülich GmbH (FZJ, Germany), and GSI based on the same models of radiotechnical elements entering the system.

The proposed code made it possible to determine the optimal composition and required characteristics of the elements of the NICA cooling system. The working frequency band was chosen to be 2–4 GHz. Systems of slot-couplers developed at FZJ for the HESR (High-Energy Storage Ring) cooling system and possessing the best characteristics for the desired frequency range served as the pickup and the kicker [16]. The maximum power output of the main amplifier needed to ensure the required cooling times did not exceed 1 kW. The full set of equipment includes six cooling channels (for three degrees of freedom in each of the two rings of the collider); the estimated overall cost of the project, including requisite test benches, and research and development of individual elements, amounts to several million US dollars.

The stochastic cooling system is crucial for reaching the projected luminosity of NICA. To recall, Russian researchers have practically no experience in designing or operating such systems (there has been practically no research and development activities in this field over the past 30 years, since the pioneering studies on proton cooling in an antiproton storage device at the Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences). Also, peculiarities of the operating modes of the system being developed forbid using the experience of foreign research centers. Therefore, main engineering solutions for the cooling system of NICA and testing the proposed code are sought based on the methods of experimental studies on beam stochastic cooling used in research on the operating Nuclotron synchrotron at JINR [15, 18].

5. Method of experimental studies on stochastic cooling at the Nuclotron

The Nuclotron is a superconducting synchrotron with a perimeter of 251.5 m and magnetic rigidity up to 45 T m,

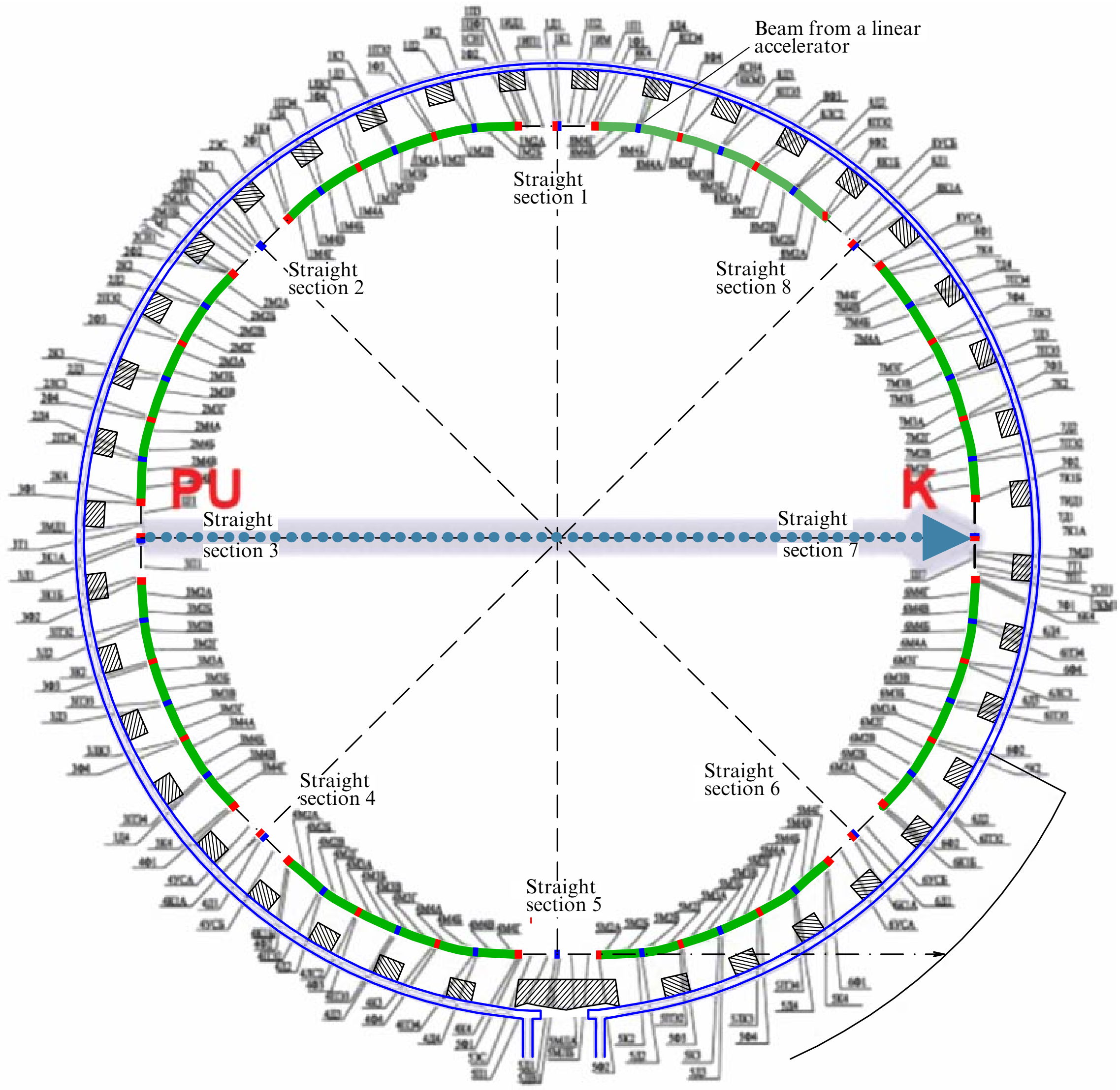

Figure 3. Schematic of the Nuclotron ring (optical structure) with the proposed arrangement of elements of the stochastic cooling system for the pickup station and the kicker.

operated by the Laboratory of High Energy Physics (JINR) since 1993. It was designed to accelerate heavy multicharged ions with an energy up to 6 GeV per nucleon (for the charge-to-mass ratio $z/A = 1/2$), and proton and polarized deuteron beams. The magnetic structure consists of eight superperiods, each containing three regular FODO type periods and one period without dipole magnets (large straight section). The regular period includes focusing (F) and defocusing (D) quadrupole lenses, four dipole magnets, and two small free sections for siting multipole correctors and beam diagnostic devices. The wide straight sections serve to place the beam injection and extraction systems, radio-frequency (RF) accelerating stations, diagnostic devices, etc. At the onset of development of the stochastic cooling system, there were a few free sites around the perimeter of the ring inside the magnetic cryostat system and a single long straight section (the seventh one along the beam path starting from the injection point) suitable for the arrangement of equipment in which the vacuum chamber was at room temperature.

Rather high thermal power is released in the kicker of the stochastic cooling system. Therefore, it should be installed in the 'hot' section, whereas the optimal place for the pickup is the third section located diametrically opposite the seventh one (Fig. 3). This section has a cryogenic temperature (from 4 to 15 K), which allows the thermal power noise produced by the pickup to be decreased. The Lorentz factor corresponding to the critical energy of the Nuclotron at the commonly used working point is about 9.16. The maximum relative momentum spread of the accelerated beam does not exceed 10^{-3} (which roughly corresponds to the separatrix height upon acceleration). At an upper frequency of 4 GHz of the transmission band, condition (4) is fulfilled at energies above 2.5 GeV per nucleon. The cooling time calculated by using formula (1) has a flat minimum in an energy range of 3–4 GeV per nucleon.

In other words, the parameters of the Nuclotron and the existing possibility of arranging equipment in this facility taken together provide a basis for the creation of a beam stochastic cooling system with characteristics close to those envisaged by the NICA project.

The time available for cooling an unbunched beam is determined by the potential of the electric power supply system of Nuclotron magnets and lenses. Moreover, the duration of circulation of a bunched beam depends on the thermal regime of accelerating RF stations under conditions of quasicontinuous operation. Before the onset of development of the stochastic cooling system, we had no experience working at the Nuclotron with the length of the magnetic field plateau in excess of 10 s. Therefore, the program of creation of the stochastic cooling system envisaged measures for the maintenance of the long-term beam circulation regime necessary for adjusting elements of the system.

Cooling the longitudinal degree of freedom by the time-of-flight method and the rejector filter technique places no additional requirements on the ring optical structure. Palmer cooling of the longitudinal degree of freedom implies dispersion at the pickup point. At the Nuclotron, dispersion is present at practically all ring points and becomes maximum in the center of the long straight section. It varies from 2 to 4 m, depending on accelerator adjustment, which turns to be reasonable for testing the system.

Cooling the transverse degrees of freedom requires optimal betatron oscillation phase advance in the ring section between the pickup and the kicker located in the corresponding superperiods on different sides of the quadrupole lens. Due to this, the phase advance required in the transverse plane can be reached at the respective betatron number somewhat lower than 7.5. The possibility of accelerating a beam in the vicinity of such a working point was demonstrated in Nuclotron experiments. Optimal adjustment in each transverse plane requires an electric power supply system to ensure current modulation in the chains with focusing and defocusing lenses.

The pickup and the kicker chosen for the NICA project (Fig. 4) possess the universality needed to test various cooling methods, and comprise the assembly of 16 rings with a 90-mm internal aperture. Each ring of the structure has eight short-circuited gold-plated electrodes uniformly arranged over the azimuth (Fig. 5 [19]).

Signals from the electrodes located beneath one azimuth on different rings are collected by connecting plates with strictly adjusted delays for different rings, so that the signal propagates in the plate synchronously with the beam. Thus, the structure has eight outlets, the signals from which can be extracted from the vacuum chamber (or cryostat) and then combined to obtain a beam signal corresponding to the longitudinal, vertical, or horizontal degree of freedom.

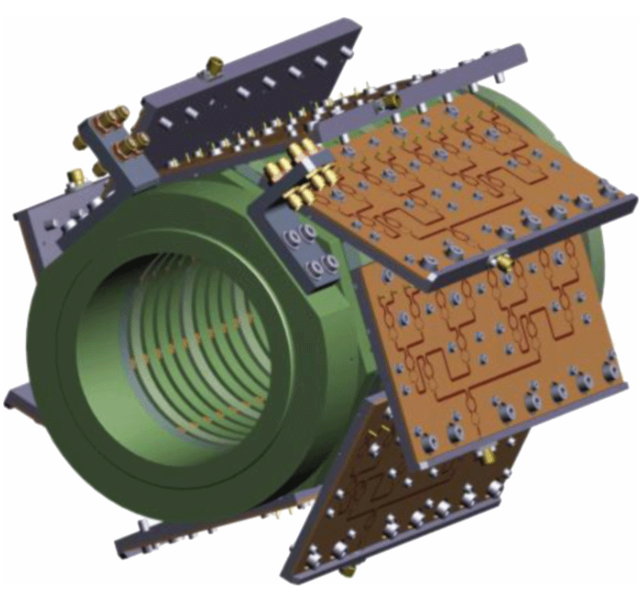

Figure 4. Pickup/kicker design.

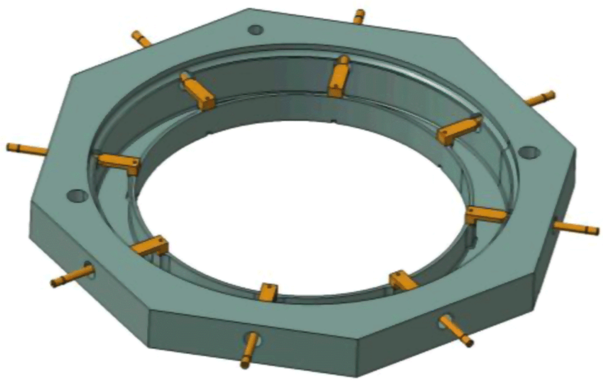

Figure 5. One of the 16 pickup rings.

Such a peculiarity of the design makes it possible to successively test all known cooling methods from the simplest to more complicated ones, without replacing elements installed on the ring in the course of development of the respective Nuclotron systems.

At the first stage of the work, rejector filter method of cooling the longitudinal degree of freedom was investigated [15]. This method is rather simple from the standpoint of its technical realization, and imposes no strict requirements on the choice of the Nuclotron working point. Moreover, it is better suited for cooling a bunched beam, because it permits cutting out the peak of the pickup signal corresponding to coherent particle movement.

6. Nuclotron stochastic cooling system

The Nuclotron stochastic cooling system was initially designed for cooling the longitudinal degree of freedom by the rejector filter (the so-called notch filter) technique [14, 15, 19]. In this method, a radiotechnical filter is introduced into the feedback loop (Fig. 6) that transmits the signal from pickup to kicker; the filter cuts out the harmonics of the circulation frequencies of an equilibrium particle from the main signal and inverts the signal phase. As a result, the correction signal does not affect equilibrium particles but additionally accelerates slow particles and slows down fast ones, i.e., decreases momentum spread of the longitudinal component.

Apart from the signal induced at the pickup by an equilibrium particle, signals brought in with other beam particles are also detected. This incoherent effect depending on the shot noise power of the beam (Schottky noise) is responsible for a diffuse increase in momentum spread. One

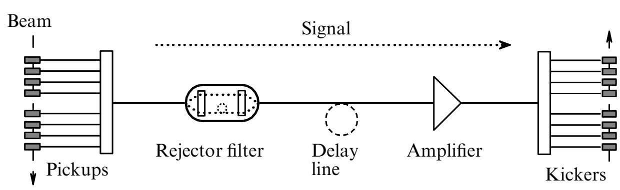

Figure 6. Schematic of a signal transmission from pickup to kicker with the use of a periodic rejector filter, amplifier, and delay line.

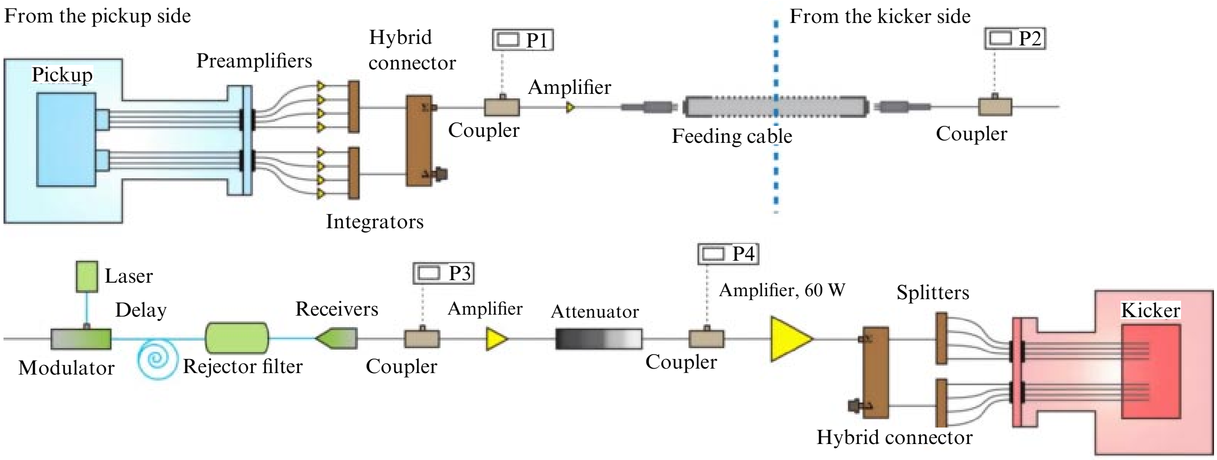

Figure 7. Schematic of the longitudinal stochastic cooling channel for the Nuclotron; P1–P4 are the sites for connecting diagnostic equipment: vector spectrum analyzers are connected at P1–P3, and the network analyzer at P4.

more source of beam 'heating', associated with the cooling system operation, is a thermal noise produced by radio-technical elements applied to the kicker.

A complete schematic of the cooling channel for the Nuclotron is presented in Fig. 7. To enable cooling of the longitudinal degree of freedom, the pickup signal must be proportional to the total current. Therefore, eight signals from pickup plates that passed through preamplifiers are joined together into one via ultrahigh frequency integrators and a hybrid connector. To allow diagnostics of the radio-technical line and observation of the cooling effect, the setup includes at different sites couplers separating a small part of the total signal for measurements with the help of a network analyzer. The first coupler (P1 in Fig. 7) is connected in the stationary mode to the spectrum analyzer for the observation of a beam shot noise (Schottky noise) from which the cooling effect is evaluated.

After the signal passes the coupler, it is amplified again by a 34-dB preamplifier and transferred through a feeding cable along a tunnel to the diametrically opposite point of the Nuclotron, where a rejector filter with optical delay is placed. After the optical delay and passage of the signal through the rejector filter, the signal is amplified once more to compensate for losses. A variable attenuator serves thereafter to adjust the entire amplification system. The signal that passed through the attenuator enters the main amplifier with an output power up to 60 W. Then, the correction signal is divided into eight components in the hybrid connector and splitters, and finally induces voltage at the kicker plates, which corrects beam particle momentum spread.

A peculiar feature of this setup is realization of a delay system on the optical cable. Such a system has a number of advantages over the delay system realized on the coaxial cable: it is much more compact, while adjustment becomes precise and simple. The delay system consists here of a number of fiber-optic cables of different lengths. The precise adjustment of the delay is achieved by using precision variable delay in a range of 0–560 ps.

The rejector filter scheme was developed based on the optical delay line (see the right part of Fig. 8). The operating principle of the filter consists in modulation of the laser beam by the input RF signal from the pickup and its division into halves by a splitter. The long branch of the filter has a delay roughly equaling the circulation period and an additional regulated precision delay (0–330 ps) for finer tuning. The short branch of the filter has a regulated attenuator for leveling the signal amplitude. Thereafter, the optical signal in each arm is converted back into the RF signal with the help of receivers. The resulting signals are subtracted by the hybrid connector. The subtracted signal amplitudes being exactly identical, the amplitude of the output signal at the hybrid connector depends on frequency f as $\sin(\pi f T_0)$, where T_0 is the temporal delay in the long branch of the filter. It turns into zero at frequencies that are multiples of $1/T_0$. When the

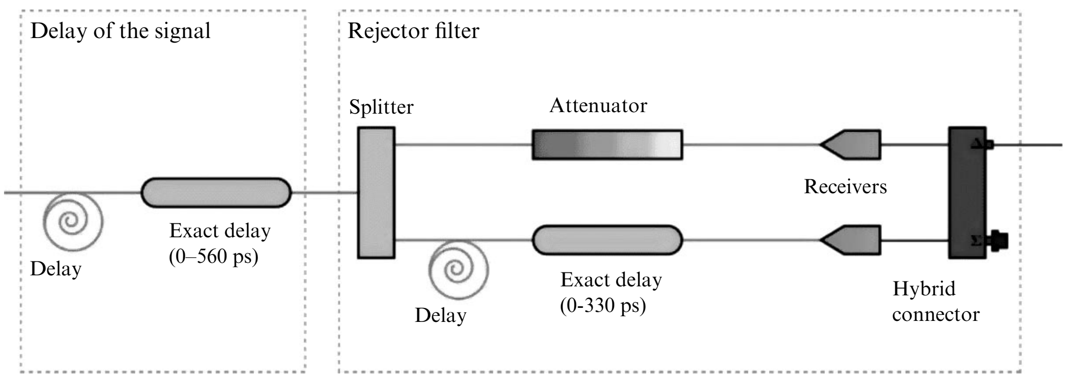

Figure 8. Schematic of the optical delay and rejector filter.

amplitude passes through zero, the signal phase changes jumpwise by π. The quality of the filter depends on characteristics of the attenuator in its short branch and signal dispersion in the long branch. The optical delay system in front of the splitter regulates the total time of the signal passage over the feedback loop.

The pickup and the kicker for the stochastic cooling system of the Nuclotron were fabricated at Forschungszentrum Jülich GmbH.

In the period from 2009 to 2011, engineering development of alternate designs was undertook for the arrangement of the radiotechnical structure of the pickup station in the Nuclotron with due regard for cryogenic requirements for the magnetic cryostat system. Heat inputs were calculated and an optimal configuration was chosen for the cooling of the vacuum chamber by two-phase helium from the Nuclotron direct helium collector at the site of the pickup station. A special high-vacuum housing and a cryostat were designed and manufactured for the pickup station (Figs 9 and 10).

Eight output signals from connecting plates of the pickup were removed from the cryostat through a special low-loss UHF cable and two high-vacuum flanges with SMA (SubMiniature version A) type connectors welded into a ceramic feed through insulator (four per flange). The design of the cryostat and the vacuum housing permits placing in the vacuum space not only the pickup station but also the additional beam diagnostic system — equipment with a linear size up to 600 mm, and diameter up to 250 mm. Fabrication and assembling of the pickup cryostat were completed in September 2011 (Fig. 10).

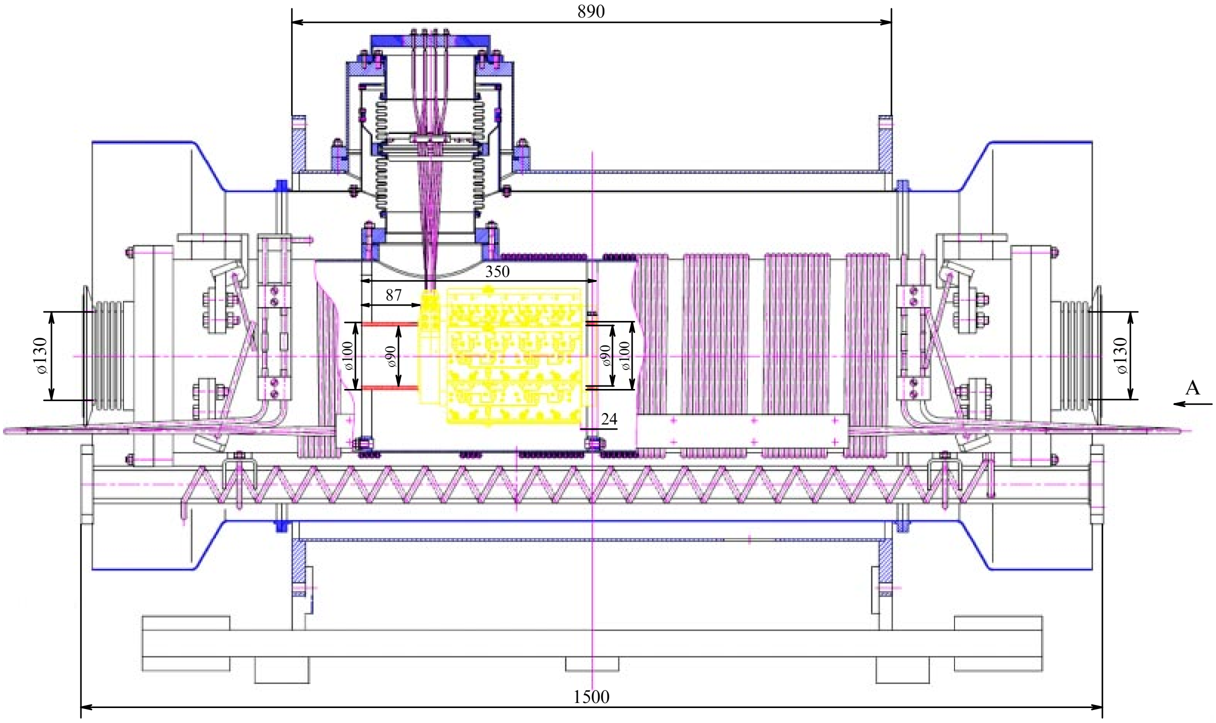

Figure 9. Construction of a cryostat for the placement of the pickup station in the magnetic cryostat system (MCS) of the Nuclotron.

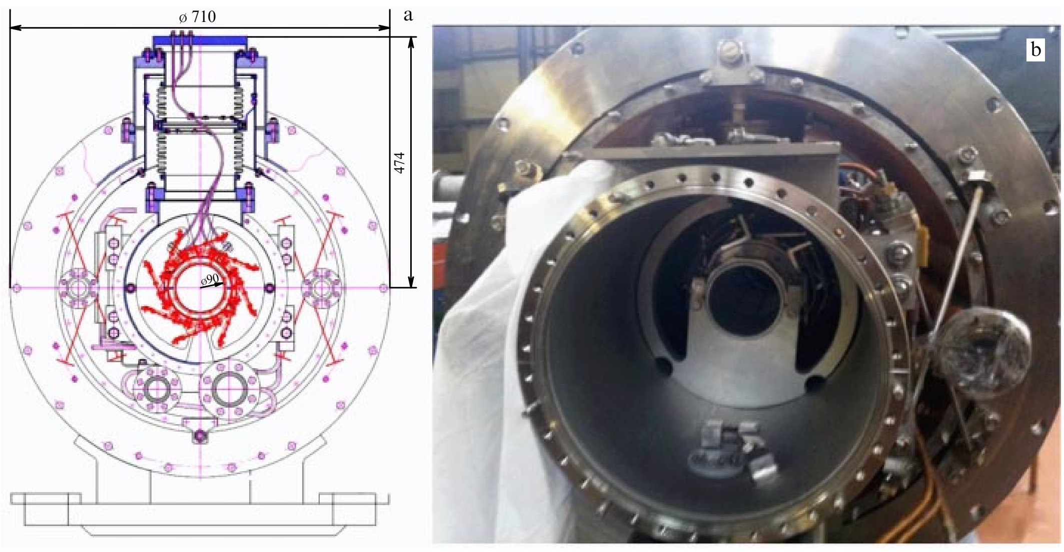

Figure 10. (a) Cross section of the cryostat with the pickup station installed inside. (b) Cryostat assembly with the pickup station placed inside.

The cryostat was installed in the Nuclotron ring after successful vacuum and cryogenic bench testing of the entire assembly and measurement of high-frequency characteristics of the pickup station at the liquid-helium temperature (4.5 K) (Fig. 11).

In 2010, the Laboratory of High Energy Physics developed a vacuum box for the placement of the kicker in the 'warm' section of the Nuclotron. The special high-vacuum chamber was manufactured jointly with Vacuum-Praha Co. After assembling and vacuum testing of the chamber, all the construction was built into the magnetic cryostat system of the Nuclotron instead of the former box type electrostatic pickup module (Fig. 12).

A feeding cable with high-speed signal propagation, short group delay time, and small loss factor (0.07 dB m^{-1}) was laid across the building from the pickup to the kicker. A stabilized power supply unit, an industrial computer, electronic equipment, an optical comb filter, and a powerful broadband amplifier were arranged on a special post near the 'warm' section of the Nuclotron.

Thus, in a year and a half, all elements of the cooling system were designed, manufactured, and installed on the ring by the onset of the 44th working session of the Nuclotron (November 2011). The course of work and the potential of the system for testing elements of the cooling system of the collider are described in Refs [20–23]. During the 44th working session of the Nuclotron, testing of its equipment in the presence of the beam was started along with the study of methods to adjust parameters of the feedback system.

7. Bench testing and adjustment of elements of the stochastic cooling system

A special UHF Laboratory equipped with a spectrum analyzer and network analyzer with an appropriate auxiliary equipment was set up to test and adjust elements of the stochastic cooling system being developed. The multiple application platform (JDSU MAP-200) was also used for testing and measuring fiber-optic networks. It included a distributed Bragg reflector laser that allowed fine tuning of the emitted light frequency (at a wavelength of 1550 nm) and regulation of the output radiation power in a range from 7 to 13 dBm.

The main activities of UHF Laboratory include optimization of the rejector filter design and the development of a method for its automatic adjustment. The amplitude–frequency dependence must have similar minima and low dispersion over the entire frequency band to ensure efficient

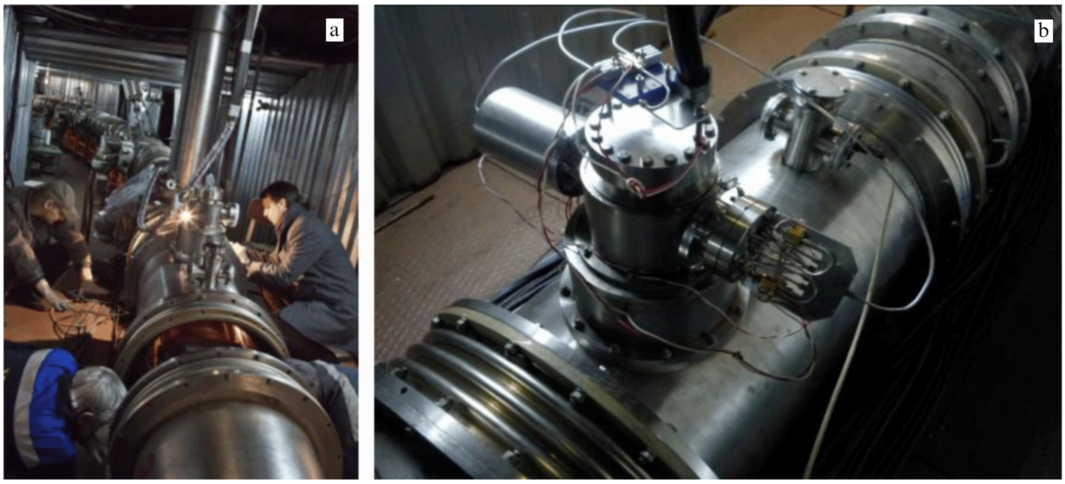

Figure 11. (a) Instaling cryostat with the pickup in the third straight section of the Nuclotron. (b) Cryostat with the pickup assembled and installed on the Nuclotron ring. Special assemblies of amplifiers and hybrid connectors of the signals can be seen in the outlet flange.

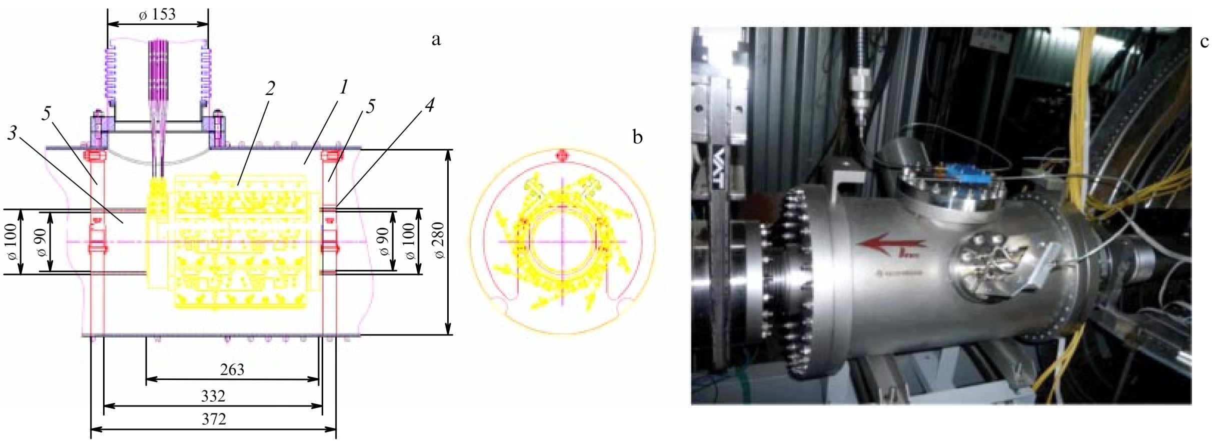

Figure 12. (a) Vacuum kicker-station assembly: *1* — vacuum housing, *2* — radiotechnical assembly (kicker) of mounting plates, *3* — vacuum chamber, *4* — attachment and adjustment unit of the structure inside the vacuum housing, and *5* — adjustment ferrule; sizes are in millimeters. (b) Cross section through the structure. (c) Kicker installed on the Nuclotron ring (arrow shows beam direction in the vacuum chamber).

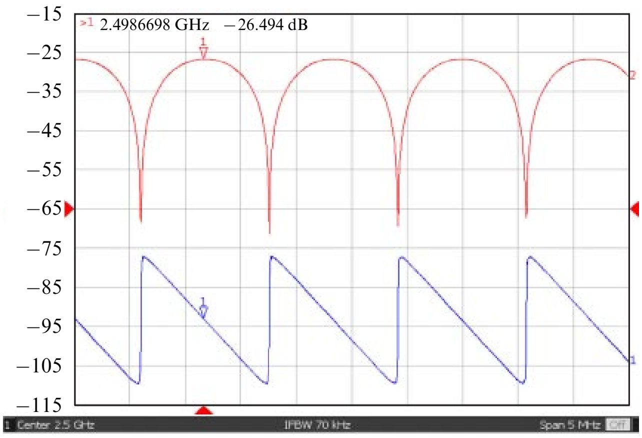

Figure 13. Display of the network analyzer with the results of measurements of amplitude–frequency (top curve) and phase–frequency (bottom curve) characteristics of the filter. Frequency is plotted on the horizontal axis. The center of the scale corresponds to a frequency of 2.5 GHz, and full range of the scale is 2.5 MHz. Attenuation in decibels is plotted along the vertical axis. As the amplitude–frequency characteristic passes through the minimum, the phase makes a jumpwise 180° change.

cooling. Carefully choosing the filter elements made it possible to reach mean attenuation in the minima of more than 40 dB. This parameter for coaxial and coaxial–optical filters is on the order of 25 and about 35 dB, respectively. The largest deviation of minimum positions for the amplitude–frequency dependence from harmonics of the beam circulation frequency (dispersion) was ensured at the level below 10 Hz (Fig. 13) [24]. For the most precise coaxial–optical filters, the dispersion is roughly 25 Hz.

When adjusting the filter, it is necessary that minimum positions on its amplitude–frequency characteristic coincide with the harmonics of a certain given frequency over the entire working frequency band. The frequency band usually contains several thousands of harmonics, and a large number of measurements are needed to finely adjust the filter. The manual adjustment is a labor-intensive process that cannot be performed remotely and which accounts for the large amount of nonproductive time during a Nuclotron session. This problem was addressed developing software for the adjustment in the totally autonomous regime for 5–10 min, depending on the quality of the initial adjustment. The adjustment is performed in two steps: filter frequency adjustment, and adjustment of straight branch attenuation realized with the aid of the successive iteration algorithm.

Another time-consuming procedure for adjusting the stochastic cooling system reduces to the adjustment of the system's delay in the feedback loop. Original software was developed to facilitate adjustment of the stochastic cooling system, which allowed it to be performed remotely in a semi-automatic regime. This software was tested and validated at the UHF Laboratory. As a result, the adjustment time of the stochastic cooling system decreased to 1–2 hours, depending on the acceleration cycle-repetition period. Adjustment of an analogous system in other acceleration centers takes 1–2 operation shifts.

The precision of adjustment thus achieved and the working characteristics of the system's elements measured at the UHF Laboratory were used in numerical simulations of the cooling process and comparing the calculated results with experimental data.

8. Development of Nuclotron systems

Partial modernization of certain Nuclotron systems was needed to implement the program of experimental studies into stochastic cooling. One part of this work was done in the framework of routine preparation of the accelerator for operation as a component of the NICA injection chain, while the other was immediately oriented toward maintaining the Nuclotron regimes needed for stochastic cooling experiments.

The primary goal was to ensure the possibility of prolonged circulation of unbunched and bunched beams at the magnetic field 'plateau', which required finishing off the control subsystem for the field of the cycle specifying equipment, improvement of the cooling regime of accelerating RF stations, and elaboration of the system relating the frequency of accelerating RF voltage to the field of dipole magnets.

Before the onset of work on stochastic cooling, the main source of the power supply for the magnetic system was driven by an B-series signal generated in the B-timer of the cycle-specifying equipment based on the measurement of the time derivative of the field in the measuring magnet. When the cycle duration was short, such a scheme ensured the desired faithfulness of optimization of specified fields. In the long 'plateau' regime, an uncontrollable drift of the magnetic field took place due to the B-timer drifts and noises in the measuring circuits. The constant field in the magnets was maintained by operating the source in the mode corresponding to a current stabilization. To do so, an oil shunt-based current sensor was introduced in the power circuit. We developed schemes for secondary commutation of shunt protections and their matching with operating schemes of power source control. An electronic unit of a precision halvanically isolated operational amplifier was created for regulation circuits. The new scheme of work of the Nuclotron magnetic system was preliminarily checked without beam acceleration at a relatively small field value of 8 kHs, and a 'plateau' length up to 500 s [25].

In the course of the 45th Nuclotron session (March 2012), circulation regimes of the accelerated beam were investigated as the 'plateau' length was successively increased from 30 s. The beam lifetimes on the 'plateau' were compared during operation of the main power source in the current stabilization and field stabilization regimes. In the latter case, the drift of the B-timer accounts for the orbit going away a distance equal to a full chamber aperture for approximately 30 s, which results in the beam loss. In the current stabilization regime on a 1.2-T 'plateau' (corresponding to an energy about 3 GeV per nucleon), the lifetime of the beam is much longer than 1000 s (Fig. 14) [25]. To measure the beam current for a long period, the software for the current transformer was improved.

The above results are of importance not only for the stochastic cooling research alone, but they also provide a basis for further developing the correction software to monitor B-timer drifts. Relative field instability on the 'plateau' in the current stabilization regime was reduced to approximately 6×10^{-5}, which is important, in particular, for upgrading the quality of slow beam ejection.

The problem of B-timer drifts had to be addressed for the maintenance of the long-term circulation of a bunched beam. The frequency of accelerating RF voltage in the acceleration regime is controlled by the magnitude of the magnetic field derivative, which practically excludes particle losses. In

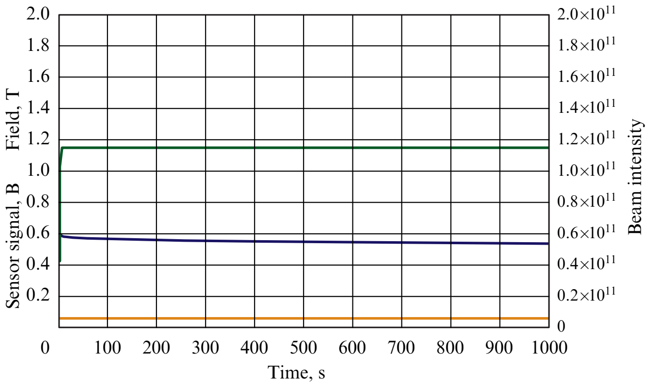

Figure 14. Results displayed in the client application window of the current transformer control system during deuteron beam circulation on the field 'plateau' 1000 s in length. The upper curve shows the signal from the magnetic field sensor (left scale in teslas), the two lower curves are signals of the accelerated deuteron beams from current transformers — direct (left scale in volts) and recalculated per number of circulating ions (right scale).

circulation on the 'plateau', hardware-specific frequency drift causes a beam orbit shift by the aperture for roughly 15 s. To solve this problem, the system of control of the master generator was modified, the frequency control circuit was interrupted in response to the signal of 'plateau' initiation, and the frequency remained unaltered till the arrival of the signal to restore reference to the field. This procedure, initially developed for stochastic cooling experiments, was later employed to implement the Nuclotron working regime for two users. In doing so, it required circulation of the unbunched beam on the first 'plateau' of the field, where an internal target experiment was carried out; then, the beam had to be bunched and its remaining part trapped in the acceleration regime. On the second 'plateau' a slow extraction was realized for the experiment on a fixed target. 'Freezing' the master generator frequency on the first 'plateau' allowed the highest efficiency of retrapping to be reached to the acceleration regime.

The possibility of working with long 'plateaus' and high current of the magnetic system energizing was realized by optimizing operational conditions of the cryogenic complex. The safety of these studies was ensured by the new system of sensors of transition to the normal conducting phase that began to be put into operation in November 2011 [25].

The critical energy of the accelerator and the dispersion function at the pickup and kicker points of the stochastic cooling channel had to be known to analyze shot noise spectra of the beam and the cooling process, respectively. Such measurements with the Nuclotron were made for the first time in December 2011 with the aid of the digital master generator of the RF-accelerating system and digital system for measuring orbit position, which were put into operation during modernization of the accelerating complex. The measuring technique consisted in determining the orbit position of the bunched beam circulating on the 'plateau' of the magnetic field as a function of the particle circulation frequency specified by the RF-accelerating system. Measurements made at energies of 2 and 3.5 GeV per nucleon and a relative change in the frequency of the RF-accelerating system on the order of 10^{-4} gave the Lorentz-factor value of $\gamma_{\rm cr} = 6.71$ corresponding to the critical energy; it is consistent with the value of the orbit compaction coefficient $\alpha = 0.022$. The value of dispersion measured at the beginning of the superperiod was $D \approx 1.1$ m. These results are in judicious agreement with calculated Nuclotron parameters. The measurements were made for the Nuclotron working point $Q_x/Q_z = 7.3/7.35$ that is slightly higher than the design value [18, 25].

Before the installation of elements of the stochastic cooling channel during a Nuclotron session in March 2011, the first experimental observations of beam shot noise were made. During their running, the signal from one of the standard beam position sensors was recorded [18].

At present, preparation for an experimental study on stochastic cooling of transverse degrees of freedom of a beam is underway. A source of current of imbalance between focusing and defocusing lenses, needed to gain the necessary oscillation phase incursion from pickup to kicker, was created and tested. Transverse cooling requires precise positioning of the beam in both pickup and kicker. This problem was solved in a series of sessions by applying the method for the correction of the equilibrium orbit based on the singular value decomposition of the response matrix. The work of correcting magnets was tested in the field growth regime (orbit correction on injection energy alone is sufficient to accelerate the beam in the Nuclotron).

Thus, preparation of stochastic cooling experiments stimulated the development of various accelerator systems, while the experiments themselves provided conditions for the comprehensive evaluation of the functional state of the Nuclotron. The methods for its adjustment and regimes of operation used in these studies also found application in the implementation of physical research programs involving Nuclotron beams.

9. Experimental studies of the stochastic cooling process

The onset of experimental studies with the use of the proposed system of stochastic cooling dates to December 2011. First and foremost, we measured shot noise of the beam over the entire transmission bandwidth of the system with successive connecting of a spectrum analyzer to different points of the UHF tract. Also measured was the momentum spread of a deuteron beam (d) and carbon ions (C^{6+}) over a wide energy range. Characteristic intensity of the carbon ion beam in the courseofmeasurementswasontheorderof$(1-2) \times 10^9$ particles per pulse, and that of the deuteron beam varied from 5×10^9 to 2×10^{10} particles per pulse. Characteristic peak width corresponded to relative momentum spread $\Delta p/p \sim 8.1 \times 10^{-4}$ for deuterons, and $\Delta p/p \sim 9.5 \times 10^{-4}$ for carbon ions.

In the experiments that followed, the focus was on the adjustment of the cooling channel by the rejector filter technique. The adjustment procedure itself included two relatively independent operations: tuning the rejector filter to the beam circulation frequency, and precision adjustment of the delay in the feedback loop.

The precision adjustment of the signal temporal delay in the feedback loop was reached by measuring the beam transfer function, as shown in Fig. 15 [25]. The feedback line was interrupted, ahead of the entrance to the main amplifier, and the network analyzer was placed at this point. The output signal of the frequency sweep generator of the network analyzer was fed to the inlet of a powerful amplifier and then applied to the kicker acting on the beam. The beam signal measured by the pickup is transmitted through the feedback line to the inlet of the network analyzer that

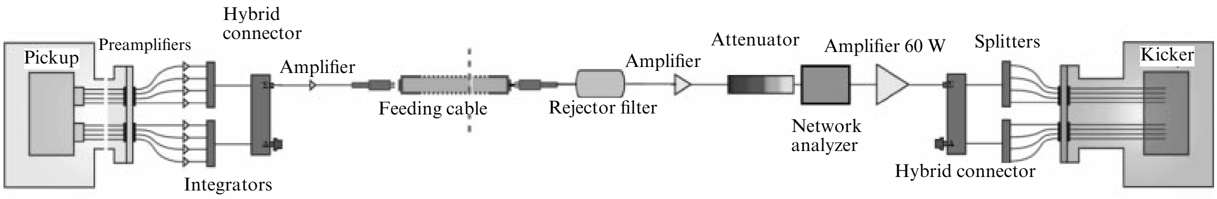

Figure 15. Schematic of the adjustment of temporal delay in the feedback loop.

measures the ratio of amplitudes of the output and input signals and the phase shift between them.

The network analyzer was utilized to preliminarily measure delays of all elements of the radiotechnical circuit; particle propagation times from pickup to kicker were calculated at the energy of the experiment on the assumption that the exact 'ring' length between the centers of the pickup and the kicker is 127,120 mm. These results were used to choose the length of the fiber-optic cable in the delay line. Further adjustment consisted in the correction of the signal propagation time by means of controlled precision delay at the inlet of the rejector filter.

The adjustment procedure started from the assumption that the signal is transmitted from kicker to pickup at beam velocity. If the signal propagation time in the feedback line equals the time of flight of the beam from the pickup to the kicker, the difference between signal phases at the outlet and inlet of the network analyzer at all harmonics of the beam circulation frequency is the same with an accuracy up to $2\pi n$, where n is an integer. Measurements are made using an unbunched beam; therefore, the network analyzer is triggered on the 'plateau' of the magnetic field with a certain delay after the accelerating RF voltage is turned off. Modulation of particle longitudinal density recorded by the pickup is performed by the kicker only at the frequencies present in the particle circulation frequency spectrum. For this reason, the ratio of amplitudes of output and input signals near the circulation frequency harmonic has the same shape as the beam shot noise spectrum (Fig. 16).

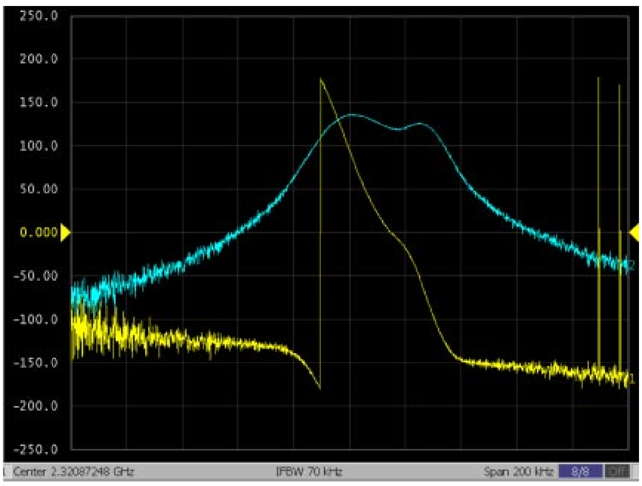

Figure 16. Display of the network analyzer during measurements with an open circuit on the 2004th circulation frequency harmonic. Upper (lower) curve — amplitude (phase) response. The frequency is plotted on the horizontal axis; the center of the scale corresponds to 2.3207248 GHz, full range of the scale is 200 kHz, and vertical axis is the phase shift in degrees.

The amplitude of the signal from the sweep frequency generator of the network analyzer is chosen so as to enable reliable recording of the phase shift between output and input signals. The phase shift corresponding to the maximum of the input signal amplitude is measured successively at all circulation frequency harmonics of the system's transmission bandwidth. Then, regulated precision delay is given such that the phase shift has the same value for a maximum possible number of harmonics. The maximally achievable accuracy of adjustment depends on phase–frequency characteristics of the feedback line elements.

In the course of the 46th Nuclotron session (December 2012), the first precision adjustment of the rejector filter created was undertaken [26]. The influence of the filter on the characteristics of the beam noise signal is illustrated in Fig. 17. During the same session, the complete system adjustment procedure was realized, which required almost two accelerating shifts; moreover, the beam response to the action of the feedback circuit was recorded.

In preparing the 47th Nuclotron session (February–March 2013), to speed up the adjustment procedure, software was developed to automate filter adjustment and perform it remotely. In the course of the 47th session, one working shift was spent to adjust the system, optimize feedback parameters, and observe the effect of decreasing momentum spread of particles in an unbunched beam (Fig. 18). The root-mean-square momentum spread was lowered approximately 2.2-fold for 480 s. To make the effect even more apparent, the initial relative spread was artificially increased to 0.55×10^{-3} by jumplike switching off the accelerating voltage as the field 'plateau' was reached. The final spread amounted to 0.25×10^{-3} [26–29].

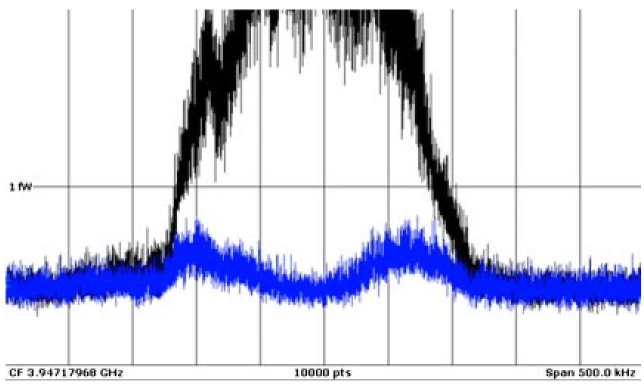

Figure 17. (Color online). Display of the spectrum analyzer during measurements of beam shot noise (Schottky noise) on the 3048th harmonic of the beam circulation frequency: the signal with the filter switched on (black) and off (blue). The center of the scale corresponds to 3.9471968 GHz, full range of the scale is 500 kHz, and vertical axis is the noise power in fW units.

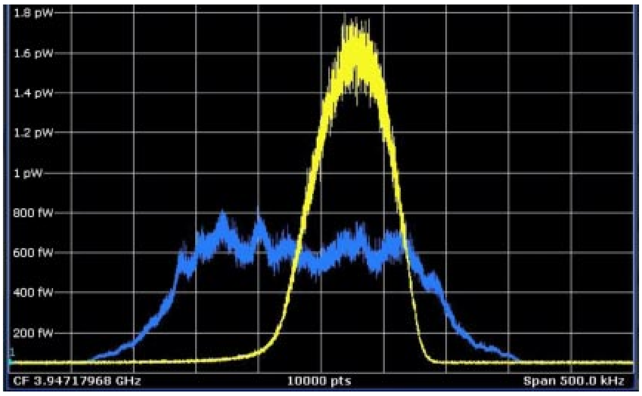

Figure 18. (Color online). Results displayed in the client application window for remote spectral analysis during the cooling of a deuteron beam with an energy of 1 GeV per nucleon. Number of particles in the beam is $\sim 10^9$. The spectrum of longitudinal shot noise of the beam on the 3048th harmonic of circulation frequency: lower curve (blue) — immediately after injection, and yellow curve — after 8 min of cooling. The frequency is plotted on the horizontal axis; the center of the scale corresponds to 3.947196 GHz, and full range of the scale is 500 kHz, and vertical axis is the noise power in pW units.

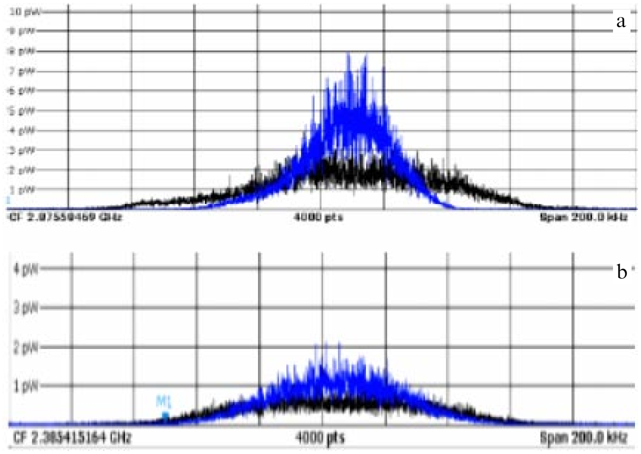

Figure 20. (Color online). Results of experimental cooling of unbunched (a) and bunched (b) beams of $^{12}C^{6+}$ ions. The beam shot noise spectrum: black curve — initial distribution, and blue curve — after cooling. The frequency is plotted on the horizontal axis (scale division value of 20 kHz). The center of the scale corresponds to 2.07550469 GHz in figure a, and 2.385415264 GHz in figure b; vertical axis shows noise power in pW units.

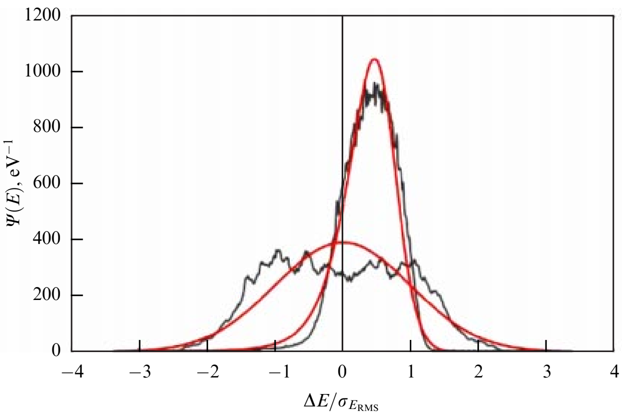

Figure 19. Results of simulation of the cooling process in the case of 110 dB amplification in the feedback circuit, 20-ps error in the signal delay, and 10-ps error in the filter delay. Experimental (crooked curves) and theoretical (smooth curves) initial and final distributions are plotted. $\sigma_{E_{\mathrm{RMS}}}$ is the root-mean-square spread of beam particles in energies.

This result was interpreted based on the simulation of the evolution of the energy distribution function $\Psi(E)$ of the particles by means of numerical solution of the Fokker–Planck equation. The rate of stochastic cooling weakly depended on the patterns of particle distribution over energies. Therefore, experimental distribution was approximated by normal distribution to simplify calculations. The main amplifier of the system was operated in a close-to-saturation regime, and the net amplification in the feedback loop could be estimated roughly at 110 dB. Errors associated with the adjustment of the feedback system are quite realistic and fairly well consistent with the results of simulations based on experimental data (Fig. 19) [30].

Once the session was completed, revision of all elements of the cooling system and the scheme optimization were undertaken to reduce the characteristic cooling time necessary to carry out a bunched beam cooling experiment (because the maximum length of RF voltage pulse on the field 'plateau' currently being assumed to be shorter than 25 s).

In the 48th session (December 2013), the stochastic cooling effect was successfully demonstrated for both unbunched and bunched beams of carbon nuclei (Fig. 20) [31, 32]. The voltage of the accelerating RF station on the field 'plateau' reached 2 kV. The bunching factor (the ratio of peak current of the bunch to the mean beam current) estimated from the measured value of the momentum spread was approximately 5. The ion energy in the experiment was 2.5 GeV per nucleon, and their number roughly amounted to 2×10^9. Momentum spread of the unbunched beam decreased under cooling from 0.15×10^{-3} to 0.07×10^{-3} and became consistent with the characteristic cooling time of approximately 27 s. The momentum spread of the bunched beam was lowered from 0.2×10^{-3} to 0.13×10^{-3}, while characteristic time equaled roughly 64 s.

These results are in good agreement with those predicted based on numerical simulation.

In March 2014, a series of measurements of the beam transfer function in the horizontal plane were carried out in the framework of preparing to experiments on the stochastic cooling of transverse degrees of freedom. The Nuclotron sessions immediately following will be devoted to the study of cooling the longitudinal degree of freedom with the application of the time-of-flight method.

The current state of the project work, its role in the progress of the NICA project, and prospects for its further development are discussed in reviews [33, 34].

10. Conclusion

The results of numerical simulation of particle dynamics and experimental studies on the Nuclotron were utilized to substantiate the strategy for achieving the design value of luminosity of the NICA facility in the range of kinetic energies of colliding heavy-ion beams from 3 to 4.5 GeV per nucleon. The main technological characteristics of the cooling system necessary for this purpose have been determined, and the reliability of the code designed for calculations in experiments has been confirmed.

A new method for experimental studies of the stochastic cooling process on the synchrotron Nuclotron (JINR) has been proposed, and the original system of stochastic cooling for the realization of this method has been developed.

Experiments on cooling the unbunched and bunched beams of light ions were performed in our Institute for the first time in Russia.

Nuclotron experiments not only contribute to the progress of the NICA project but also are of special value for the development of the international FAIR project. For example, the kicker created by Forschungszentrum Jülich GmbH for the cooling system of the High-Energy Storage Ring (HESR) of the FAIR project was tested for the first time in Nuclotron experiments designed to elucidate its influence on the particle beam (it has parameters similar to those of the NICA cooling system but is designed for a different purpose).

Acknowledgments

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