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NICA SYNCHROTRONS AND THEIR COOLING SYSTEMS

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) is under construction at JINR. The NICA goal is to provide of colliding beams for studies of hot and dense strongly interacting baryonic matter and spin physics. The ion mode accelerator facility of the NICA Collider consists of the following accelerators: The new operating Heavy Ion Linac (HILAC) with RFQ and IH DTL sections at energy 3.2 MeV/u, new operating superconducting Booster synchrotron at energy up 600 MeV/u, operating superconducting synchrotron Nuclotron for the gold ion energy 3.9 GeV/u and two Collider storage rings with two interaction points. There is the electron cooling system in the Booster synchrotron, the Collider has electron and stochastic cooling systems. The status of the NICA acceleration complex and its cooling systems is presented. The application of the cooling systems to the operation of the NICA accelerators – the Booster and the Nuclotron are discussed.

NICA INJECTION COMPLEX

The NICA accelerator complex [1,2] is constructed and commissioned at JINR. NICA experiments will be aimed at searching of the mixed phase of baryonic matter and studying the nature of the nucleon/particle spin. The new NICA accelerator complex will permit implementing experiments in the following modes: with the Nuclotron ion beams extracted to a fixed target; with colliding ion beams in the Collider; with colliding ion-proton beams; with colliding beams of polarized protons and deuterons. The main elements of the NICA complex are an injection complex, which includes a set of ion sources and two linear accelerators, the superconducting operating Booster, the superconducting operating synchrotron Nuclotron, a Collider composed of two superconducting rings with two beam interaction points, a Multi-Purpose Detector (MPD) and a Spin Physics Detector (SPD) and the beam transfer lines.

The heavy ion injection chain consists from electron string ion source, the laser ion source, the plasma ion source, the operating HILAC, the transfer line HILAC-Booster, the superconducting operating synchrotron Booster, the transfer line Booster-Nuclotron and the operating superconducting synchrotron Nuclotron.

The HILAC constructed by the JINR-Bevatech collaboration is under exploitation since 2016. It is aimed to accelerate the heavy ions injected from KRION-6T, a superconducting electron-string heavy ion source. At the present time KRION-6T produces 5×10^8 $^{197}Au^{31+}$ and 2×10^8 $^{209}Bi^{27+}$ ions per pulse.

Especially for the test of the Booster [3] the plasma source generating a single component He^{1+} beam was created. The efficiency of the beam transportation through second and third IH sections was 78.5%. The maximal ion $^{4}He^{1+}$ beam current at HILAC entrance during first Booster runs corresponds to the project value of 10 mA. During second Booster run the $^{4}He^{1+}$ and $^{56}Fe^{14+}$ ions produced in the plasma and the laser ion sources were accelerated in HILAC and injected in Booster.

The transfer line from HILAC to Booster [1] consists of 2 dipole magnets, 7 quadrupole lenses, 6 stirrer magnets, debuncher, collimator, vacuum and diagnostic equipment. The assembling of transfer line was done in 2020. The achieved efficiency of the beam transportation during first Booster beam run was of 90% at the beam current at the HILAC exit of 4 mA, this value was sufficient for the first experiments.

The Booster [1-3] (Fig. 1) is a superconducting synchrotron intended for accelerating heavy ions to an energy of 600 MeV/u. The magnetic structure of the Booster with a 211-m-long circumference is mounted inside the yoke of the Synchrophasotron magnet.

Figure 1: Booster ring inside Synchrophasatron yoke.

The main goals of the Booster are accumulation of $2\cdot10^9$ $^{197}Au^{31+}$ ions, acceleration of the heavy ions up to the energy 578 MeV/u required for effective stripping, and forming of the required beam emittance with the electron cooling system. The Booster has a four-fold symmetry lattice with DFO periodic cells. Each quadrant of the Booster has ten dipole magnets, six focusing and six defocusing quadrupole lenses, and multipole corrector magnets. All Booster dipole magnets and quadrupole lenses were fabricated and tested at JINR.

The beam injection system of the Booster consists of an electrostatic septum and three pulsed electric kickers.

The Booster RF system designed and constructed by Budker Institute of Nuclear Physics (BINP), Siberian Branch, Russian Academy of Sciences, provides 10 kV of

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acceleration voltage. The operating frequency range of the stations is from 587 kHz to 2526 kHz.

The electron cooling system (Fig. 2) designed and manufactured by BINP SB RAS has the maximal electron energy of 60 keV. The Booster electron cooling will be used at first at an energy of 3.2 MeV/u for multiple or multiturn injection. The application of the electron cooling permits to increase in accordance to BETACOOL simulations the intensity of $^{197}Au^{31+}$ stored ion beam by factor of 5 (Fig. 3) at the cooling time of 150 ms, the injection repetition frequency of 10 Hz, the vacuum pressure life time of 5 s and the electron recombination life time of 2 s. A reduction of the beam emittance and the momentum spread will be done by the electron cooling at the ion energy of 65 MeV/u and the cooling time of 1 s. This allows to provide acceptable beam parameters after acceleration to 578 MeV/u and the stripping on a target at extraction from the Booster.


Figure 2: Booster electron cooling system.

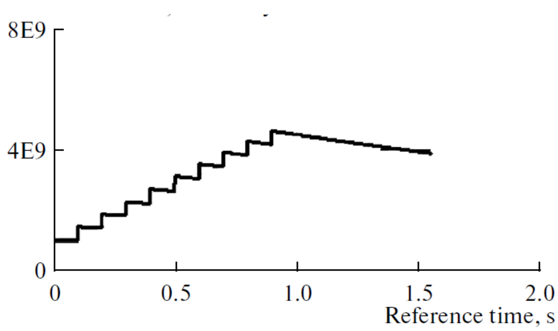

Figure 3: Dependence of stored Au^{31+}ion intensity on time at multiple injection with electron cooling.

The first technical Booster run was performed in November-December 2020. After the orbit correction and tuning of the injection system the intensity of the $^4He^{1+}$ circulating beam was increased up to 7×10^{10} ions. This is equivalent to the charge of 2×10^9 Au^{31+} ions. The lifetime of ions corresponds to 1.3 s at the equivalent average residual gas pressure 2×10^{-8} Pa.

During second run in September 2021 the beams of ions $^4He^{1+}$ and $^{56}Fe^{14+}$ (mass-to-charge ratio A/Z=4) and intensity up to 4×10^{10} and 4×10^9 respectively were injected in Booster, bunched on the injection plateau of the magnetic field on fifth RF harmonic and then accelerated up energy 65 MeV/u, where they were rebunched on the first RF harmonic and again accelerated. The $^{56}Fe^{14+}$ ions were accelerated in Booster up to the project energy of 578 MeV/u (Fig. 4).

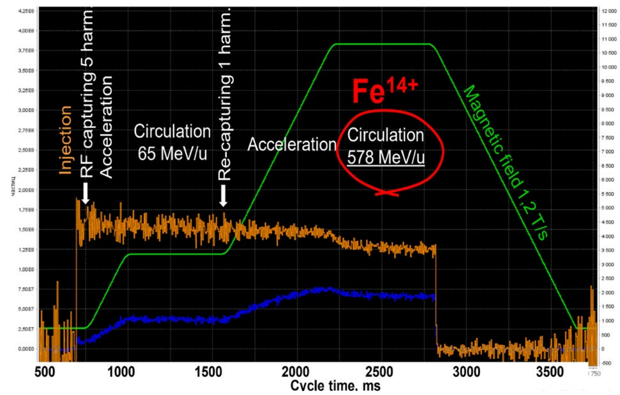

Figure 4: Beam current transformer signal at $^{56}Fe^{14+}$ ion acceleration.

The main results of the second Booster run are the following: the beam injection efficiency is larger than 95% with adiabatic capturing at 5th harmonic; acceleration up to the energy 65 MeV/u with recapturing from the 5th harmonic to the 1th one with efficiency close to 100%; acceleration up to energy of 578 MeV/u with dB/dt = 1.2 T/s; ultrahigh vacuum at $^4He^{+1}$ ion life-time longer than 10 s; the electron cooling of ions at energy of 3.2 MeV/u; the beam extraction in to the Booster-Nuclotron transfer line and the beam transportation in this transfer line with total efficiency of 70%.

The $^4He^{1+}$ ion lifetime (Fig. 5) during second Booster run corresponds to 10.8 s. The equivalent residual gas pressure is about 5×10^{-9} Pa.

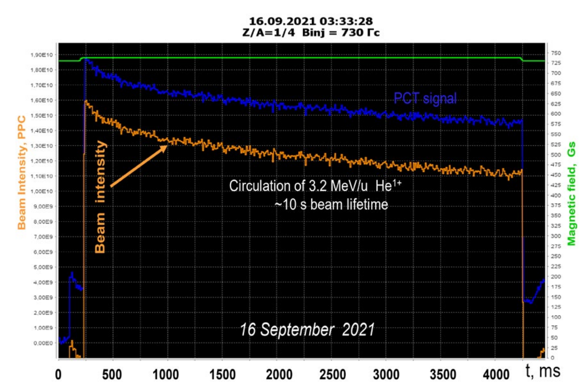

Figure 5: Parametric current transformer (PCT) signal at $^4He^{1+}$ ion energy 3.2 MeV/u.

The cryomagnetic and the power supply systems were tested at the design magnetic field cycle during first Booster run (Fig. 6). The magnetic cycle has three plateaus: for injection, electron cooling and beam extraction. The achieved magnetic field ramping rate of 1.2 T/s corresponds to the project value (Fig. 6). The achieved maximum magnetic field of 1.8 T is also equal to the project value.

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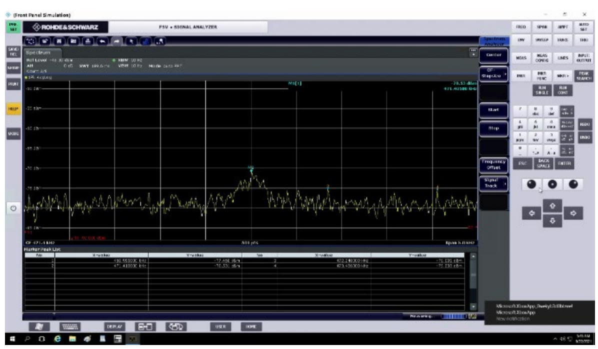
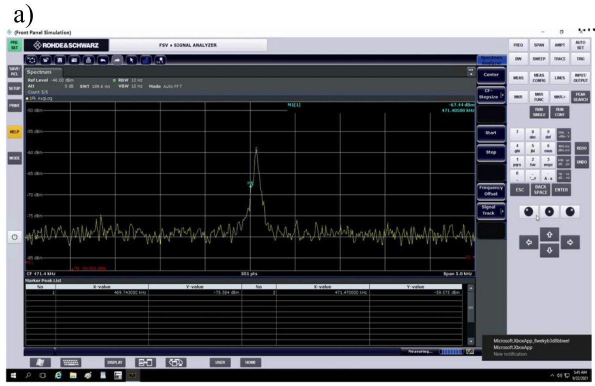
The electron cooling of $^{56}Fe^{14+}$ ions was first done during second Booster run. The ion beam circulation and acceleration were performed from injection energy 3.2 MeV/u up 65 MeV/u, corresponding to designed energy range of electron cooling system (ECS), at ECS solenoid magnetic field 0.7 kGs. Operation of ECS was done with an effective recuperation at the electron beam current range of 30 - 150 mA.

Figure 6: The Booster magnetic field cycle at design parameters.

The FWHM relative momentum spread of uncooled circulated beam corresponds to $1.2{\cdot}10^{-3}$ (Fig. 7a). The FWHM relative momentum spread of cooled ions is equal to $4{\times}10^{-4}$ (Fig. 7b).



a)

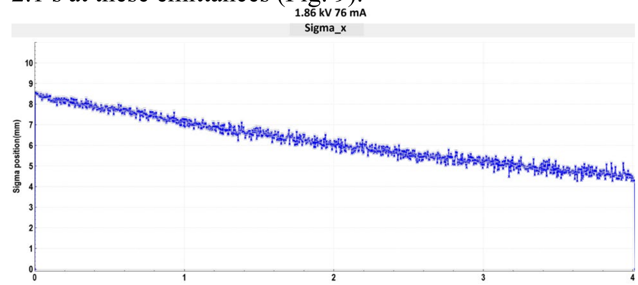


b)

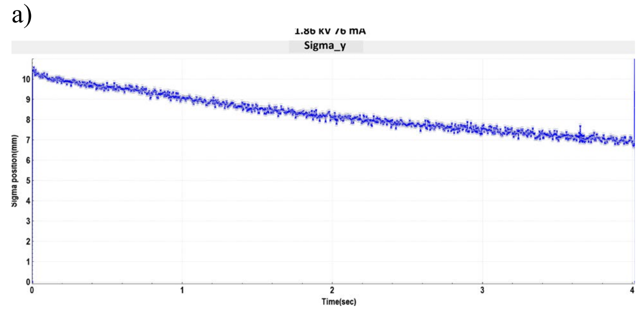
Figure 7: Schottky noise signal at 4 harmonic of revolution frequency and $^{56}Fe^{14+}$ ion energy of 3.2 MeV/u.

The horizontal and vertical beam profiles were measured by Micro Channel Plate ionization profilometer. The root-mean-square (rms) emittance of circulated beam was rather large $\varepsilon_x/\varepsilon_z$=14/8 π·mm·mrad at a mismatched and not optimized injection during first run with electron cooling. The horizontal cooling time corresponds to 3,1 s at the e-times reduction in the beam emittance (Fig. 8a).

The BETACOOL simulated horizontal cooling time is 2.1 s at these emittances (Fig. 9).



a)



b)

Figure 8: Dependence of MCP measured rms horizontal (a) and vertical (b) of $^{56}Fe^{14+}$ ion beam on time at ion energy 3.2 MeV/u and electron beam current of 76 mA.

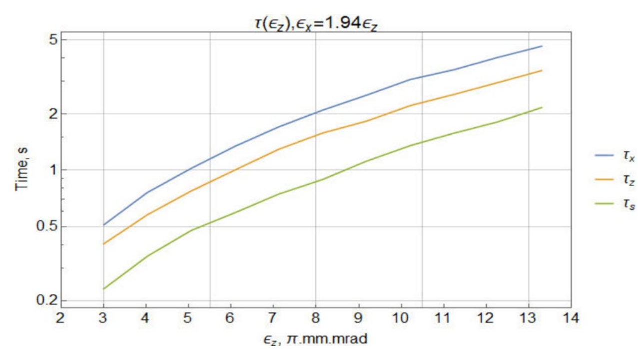


Figure 9: Dependence of horizontal, vertical and longitudinal cooling time on vertical emittance ε_z at horizontal emittance $\varepsilon_x=1.94\varepsilon_z$ and electron beam current of 76 mA.

The effects of electron heating were observed at an electron energy shifted from the corresponding ion energy related to the electron cooling. At a higher electron beam current and a high ion intensity the coherent longitudinal oscillations were observed (Fig. 10). The coherent oscillations disappeared at a threshold value of the electron beam current multiplied on the ion intensity $(I_e{\times}N_i)_{th}$ (Fig. 11). The $^{56}Fe^{14+}$ ion lifetime is reduced at switch on the electron beam current (Fig. 12). The $^{56}Fe^{14+}$ ion lifetime corresponds to 4.9 s at the intensity of $4{\cdot}10^9$ ions and zero electron beam current (Fig. 12a). It is reduced to the value of 1.35 s at the electron beam current of 100 mA (Fig. 12b).

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Figure 10: Signal of coherent longitudinal oscillations at 5th harmonic of revolution frequency and $^{56}Fe^{14+}$ ion energy 3.2 MeV/u.

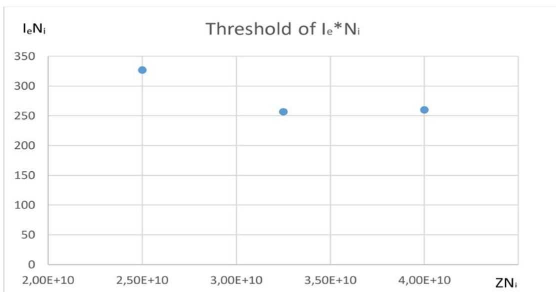
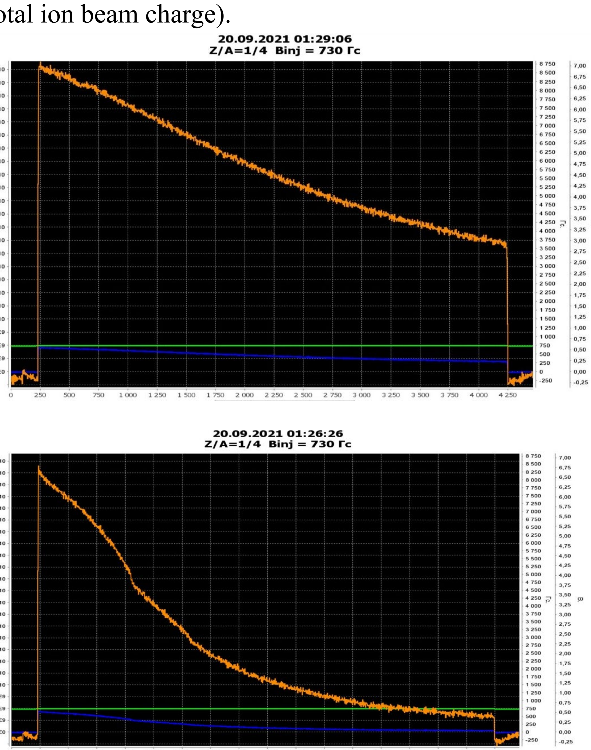


Figure 11: Dependence of threshold value $(I_e \times N_i)_{th}$ (relative units), at which coherent longitudinal oscillations disappeared, on the ion intensity multiplied by the ion charge (total ion beam charge).



a)

b)

Figure 12: PCT signal for $^{56}Fe^{14+}$ ions at electron beam current I=0 mA (a) and I=100 mA (b).

The Booster beam extraction system [1] consists of a magnetic kicker, two magnetic septa, a stripping station and a closed orbit bump subsystem including four lattice dipoles with five additional HTS current leads. The Booster beam extraction system together with the transfer line Booster-Nuclotron were fabricated by BINP. The first beam experiments with extracted $^{4}He^{1+}$ and $^{56}Fe^{14+}$ ion beams were performed during second Booster beam run.

The upgraded Nuclotron [4] accelerates protons, polarized deuterons and ions to a maximum energy depending of the sort of particles. The maximum ion energy corresponds to 5.2 GeV/n at present time.

The installation in the Nuclotron of the Booster beam injection system and the Collider fast extraction system are required for its operation as the main synchrotron of the NICA complex. The kicker and the Lambertson magnet should be installed in the injection section in end 2021 or in beginning 2022.

COLLIDER RINGS

The Collider [1,2,5] consists of two storage rings with two interaction points (IPs). Its main parameters are as follows: the magnetic rigidity is up to 45 T·m; the residual gas pressure in the beam chamber is not high than 10^{-10} Torr; the maximum field in dipole magnets is 1.8 T; the kinetic energy of gold nuclei ranges from 1 to 4.5 GeV/u; the beam axes coincide at the interaction section (zero intersection angle); the average luminosity is 10^{27} cm^{-2} s^{-1} for gold ions. The rings of the Collider are identical in shape to a racetrack — two arcs are connected by two long straight section (109 m each). The circumference of each ring is 503.04 m.

Methods for cooling charged particle beams represent the key accelerator technologies, which are critical for achieving the design parameters of the complex. The electron cooling system [1] for the NICA Collider at an electron energy of 2.5 MeV is intended for accumulation and bunch formation at the ion kinetic energies in the range of 1.0–4.5 GeV/u. The cooling time of Au^{79+} ions corresponds to 20-100 s at ion energy 3-4.5 GeV/u (Fig. 13). The solenoid cooling section has the length of 6 m, the magnetic field is of 1 kGs. The maximum electron beam current corresponds to 1 A. Construction of the electron cooling system was started in BINP in 2016. The commissioning of the cooling system in JINR will be in end of 2022.

The stochastic cooling system (SCS) [1] of the NICA Collider (Table 1) must provide ion cooling up to 3.1×10^{9} $^{197}Au^{79}$ ions in a bunch. To achieve the design cooling time, an SCS with the frequency bandwidth 0.7–3.2 GHz is necessary. The Collider SCS uses pickup electrodes and kickers. The main elements of the stochastic cooling system also include signal delay system blocks, solid-state amplifier and preamplifier cascades, and a rejector (comb) filter system.

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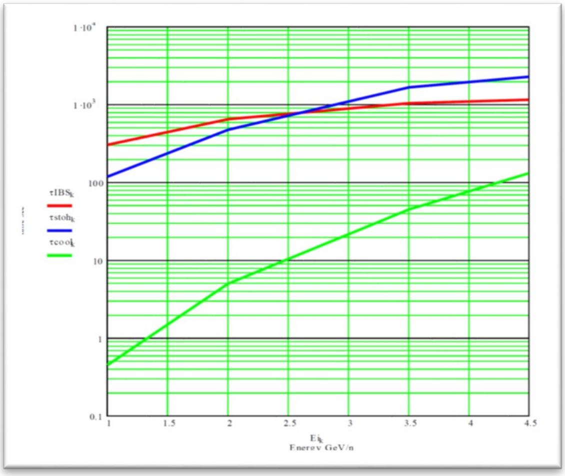

Figure 13: Dependence of electron, stochastic cooling time and IBS time on ion energy.

Table 1: Parameters of Stochastic Cooling System

Longitudinal cooling method	Filter
Passband, GHz	0,7 – 3,2
Beam distance pickup -kicker, m	183,5-191,5
Phase from pickup to kicker, deg	1340-1360
Ion Energy Au^{79+}, GeV/u	3,0
Slip-factor from pickup to kicker	0.0294
Revolution slip-factor	0.0362
Pickup/kicker coupling impedance, Ω	200/800
Gain, dB	75 – 79
Peak power at kicker, W	3×200
Pickup/noise temperature, K	300/40

Three RF systems with 26 cavities of the acceleration radio-frequency voltage will be applied for ion accumulation and formation of ion bunches [1,5]. Accumulation of the beam of the required intensity is planned to be realized in the longitudinal phase space with the use of the ‘technique of barrier RF1 voltages’ and of stochastic or electron cooling of the particles being accumulated. The barrier bucket technique also will be used for ion acceleration in the rings.

The rms longitudinal emittance of injected beam in the Booster corresponds to $\varepsilon_B=\beta_{inj}(\Delta p/p)_{inj}\sigma_{inj}=0{,}0048$ m, where $(\Delta p/p)_{inj}=10^{-3}$ is the relative momentum spread after the HILAC debuncher, $C_B=210$ m is the Booster circumference, $\sigma_{inj}=C_B/(2\times3^{1/2})=66$ m is the rms length of injected beam. The total longitudinal emittance of the ion beams corresponds to $\varepsilon_{inj}=n_{inj}\varepsilon_B=0.39$ m at $n_{inj}\approx80$ Collider injection cycles.

The longitudinal acceptance of RF barriers is equal to $\varepsilon_c=\gamma_c\beta_c(\Delta p/p)\sigma_c=0.06$ m at $\gamma_c=3$, $(\Delta p/p)_c=3\cdot10^{-4}$ is the relative rms momentum spread related to RF barrier acceptance, $\sigma_c=C_c/(4\times3^{1/2})=72$ m is the rms stack length. The ratio of total longitudinal rms beam emittances at $n_{inj}\approx80$ Collider injection cycles to acceptance of RF barriers corresponds to $\varepsilon_{inj}/\varepsilon_c=6.5$. The electron cooling time should be shorter $\tau_{cool}=\tau_{inj}\ \varepsilon_c/\varepsilon_B\approx100$ s, where $\tau_{inj}=8$ s is the repetition injection time in each Collider ring. The Booster ion precooling permits to reduce by a factor of 3 the relative rms momentum spread $dp/p\approx4\cdot10^{-4}$. In this case the cooling time of $\tau_{cool}=300$ s provides the stack storage with required intensity.

When the necessary intensity is achieved, the beam is bunched the RF2 system at voltage up to 25 kV of the 22nd harmonics of the rotation frequency with the subsequent takeover by the RF3 system of the 66th harmonics. This permits 22 short bunches with rms length of 0.6 m to be formed (Fig. 14), which is necessary for achieving high luminosity.

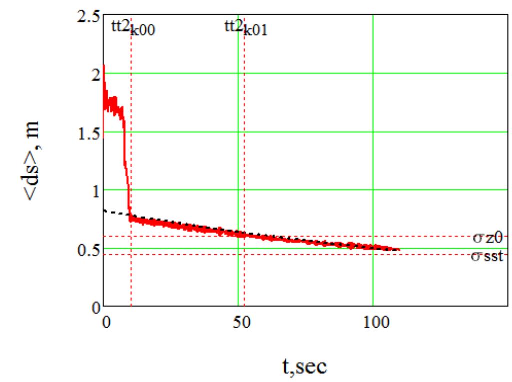

Figure 14: Dependence of bunch length on time at cooling time of 100 s.

The maximal RF3 voltage corresponds to 125 kV. The RF solid state amplifiers developed by Russian firm TRIADA are used for RF2 and RF3 cavities. The construction of three RF systems was started in 2016-2017 in BINP. Two RF1 stations, 8 RF2 and 16 RF3 cavities will be installed in Collider in 2022.

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