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ELECTRON COOLER OF THE NICA BOOSTER AND ITS APPLICATIONS

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Abstract

The report presents the results obtained during the commissioning the Electron Cooling System (ECS) of the Booster, the first in the chain of three synchrotrons of the NICA accelerator complex. The work was performed with a circulating ion beams $^{4}He^{1+}$ and $^{56}Fe^{14+}$ at ion injection energy of 3.2 MeV/u. In the first experiment (December 2020) with a circulating $^{4}He^{1+}$ ion beam, the effect of reducing the lifetime of the circulating ions was observed when the velocities of the cooling electrons and the cooled ions coincide. In second experiment (September 2021) the effect of electron cooling of $^{56}Fe^{14+}$ ion beam was registered both for longitudinal and transverse degrees of freedom using Schottky noise spectrometer and ionization profilometer.

INTRODUCTION

The main tasks of the Booster synchrotron of heavy ions are the accumulation of gold ions or other low-charged heavy ions and their acceleration to the maximum energy 578 MeV/u for gold ions, which is sufficient for their subsequent stripping to the state of bare nuclei. The application of electron cooling in a Booster at ion energy up to 65 MeV/u makes it possible to significantly reduce the 6D emittance of the beam.

NICA BOOSTER ELECTRON COOLING SYSTEM (ECS)

The Booster ECS (Fig. 1) was constructed according to the classical scheme proposed and implemented in 1970 in the Institute of Nuclear Physics (Novosibirsk) [1]. Its present version is significantly developed by the team of V. V. Parkhomchuk in the same Institute named after the founder academician G.I.Budker. In electron cooling set-up, an electron beam passes from the cathode of the electron gun to the collector in a uniform longitudinal magnetic field. In the ECS, the homogeneity of the magnetic field of this solenoid is made at the level of $3\cdot10^{-5}$ (straightness of the magnetic field line) that provides the design value of the cooling time. The energy of the ECS electrons variates in this range from 1.0 to 50.0 keV. The main Booster ECS parameters are shown in the Table 1.

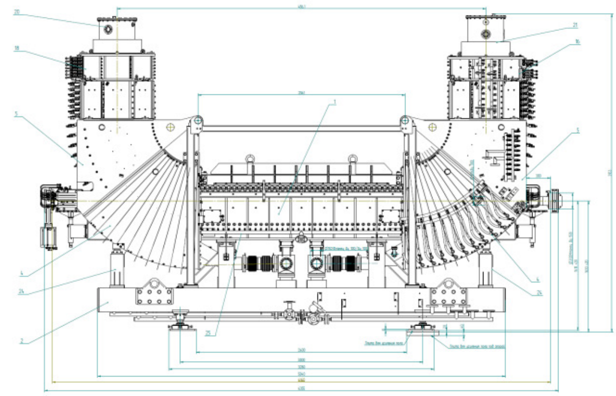

Figure 1: The Booster ECS scheme.

Table 1: The main Booster Electron Cooling System Parameters

Parameter	Value
Electron energy E, keV	≤ 1
Accuracy of energy adjustment and its stability, ΔE/E	$\leq 1\cdot10^{-5}$
Beam current stability, ΔI/I	$\leq 1\cdot10^{-4}$
Electron beam loss current, δI/I	$\leq 3\cdot10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, ΔB/B	≤ 3·10-5 on the length 15 cm
Transverse temperature of electrons in the cooling section (in the particle system), eV	≤ 0.3
Correction of the ion orbit at the input and output of ECS	offset, mm ≤ 1,0 angular deviation, mrad ≤ 1,0

FIRST ION ELECTRON COOLING EXPERIMENT

During the first Booster session in December 2020, an experiment was conducted to commission the ECS with a circulating $^{4}He^{1+}$ helium ion beam with an energy of 3.2 MeV/u (injection energy into the Booster) (Table 2). In this experiment the only diagnostic devices that allowed observing the cooling effect were used: a parametric current transformer (PCT) measuring ion beam current and the A. A. Baldin ionization profilometer [2], that was operated in summing mode the counting rate of all the MCP channels

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registering the vertical distribution of the beam density (relative counts – RC), and the time dependence RC(t) was measured. Then the results were summed over several injection cycles ⟨RC(t)⟩ (Fig. 2).

Table 2: First Ion Electron Cooling Experiment Parameters

Parameter	Value
Ion type	$^{4}He^{1+}$
Ion energy, MeV/u	3.2
Electron energy, keV	1.73 – 1.8
Electron beam current, A	0.1 – 0.2
Electron beam diameter, mm	28

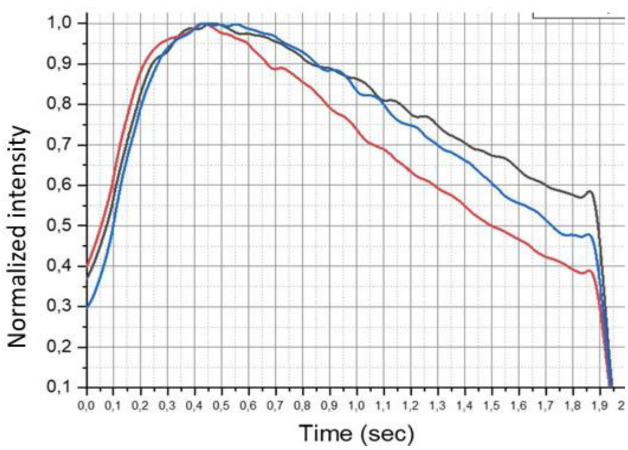

Figure 2: Normalized intensity for different electron energy. Black curve – 1.82 keV, blue curve – 1.72 keV, red curve – 1.76 keV.

As can be seen from figure 2, the strong decrease in the lifetime of the ion beam occurs at the energy 1.76 keV, which is in good agreement with the theoretical value. The optimal (theoretical) value of the electron energy is equal to $E_e = \frac{m_e}{m_n} E_{ion}$. For E_{ion}=3.2 MeV it gives E_e=1.754 keV, what is different from 1.76 keV by the ≈5.7 V, or 0.3%.

SECOND ION ELECTRON COOLING EXPERIMENT

During the second run of the Booster in September 2021, an experiment was conducted to electron cooling of iron ion $^{56}Fe^{14+}$ beam circulating at injection energy of 3.2 MeV/u (Table 3). A Schottky spectrometer was used as the device detecting beam momentum spread, as well as a horizontal and vertical profilometers used during first experiment.

Table 3: Second Ion Electron Cooling Experiment Parameters

Parameter	Value
Ion type	$^{56}Fe^{14+}$
Ion energy, MeV/u	3.2
Electron energy, keV	1.73 – 1.93
Electron beam current, A	0.02 – 0.13
Electron beam diameter, mm	28

Unfortunately, at high intensities of the ion beam the channels of the profilometer were overloaded and the signal could not be received from it. On the other hand, at low intensities the signal from the Schottky spectrometer was too weak. Also, it is possible to register the signal from the pickup stations in the Electron Cooling System about the position of the ion beam only when the RF is turned on. The cooling itself took place on a continuous beam. Therefore, the experiment was carried out as follows: the ion beam was injected at maximum intensity when the RF was turned on, and the beams were exposed in parallel and as close as possible to each other, after this the RF was turned off and the signal was registered from the Schottky spectrometer. Then the intensity was lowered, and the transverse sizes of the beam were measured from a profilometer.

Longitudinal Cooling Measurements

Spectrum measurements were carried out using a Schottky spectrometer at the 4th harmonic of the revolution frequency. The frames received from the detector were digitized and linearized (Fig. 3) for further processing.

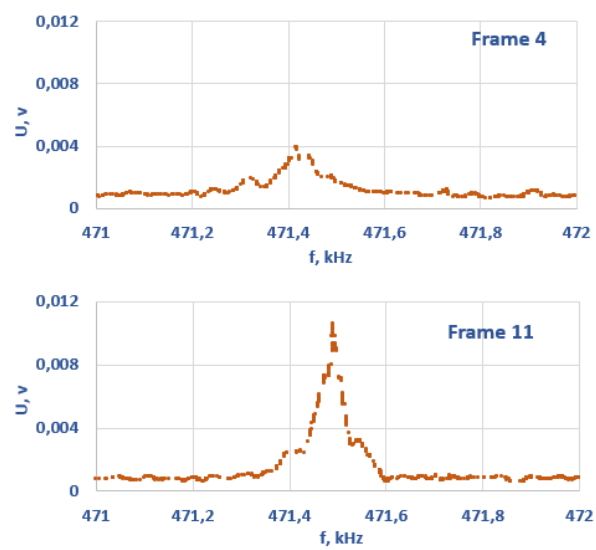

Figure 3: Schottky spectrometer signal. Frame 4 shows the signal at a time of 0.6 sec from the beginning of injection, frame 11 – 2 sec from the beginning of injection.

As can be seen from Fig. 3 and Fig. 4 the frequency of spectrum maximum during one injection and circulation cycle is changing and increasing with time, which indicates the compression of the beam orbit, which will also be shown on the data from the ionization profilometer.

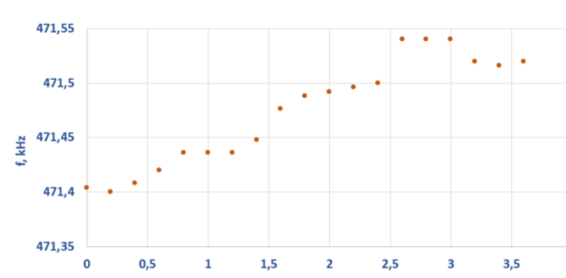

Figure 4: Spectrum maximum versus time.

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For the resulting set of frames, the full width of the signal at half its magnitude was measured, after that the values were converted to the values of the momentum spread (Fig. 5).

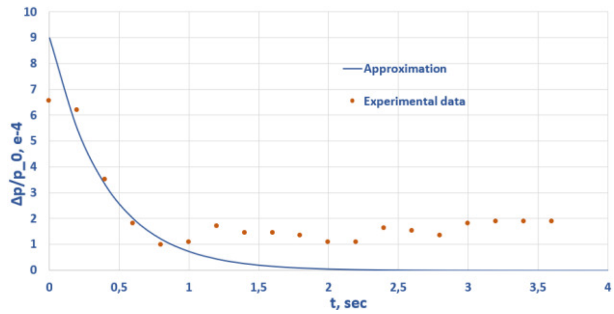

Figure 5: Momentum spread versus time.

Here, the dots show experimental data that were approximated by an exponential function, from which the characteristic cooling time of the ion beam momentum spread rms value, equal to 200 milliseconds, was obtained.

Transversal Cooling Measurements

After receiving the signal from the Schottky spectrometer, the intensity of the ion beam was reduced, which made it possible to receive a signal from the ionization profilometer. As can be seen from Fig. 6, initial transvers dimensions of the ion beam (one sigma) with the electron beam turned off equal to 9 mm and 10.5 mm for horizontal and vertical degrees of freedom, respectively. In addition, it is important to note that in the horizontal direction the ion beam is strongly shifted to the outer edge of the beam tube.

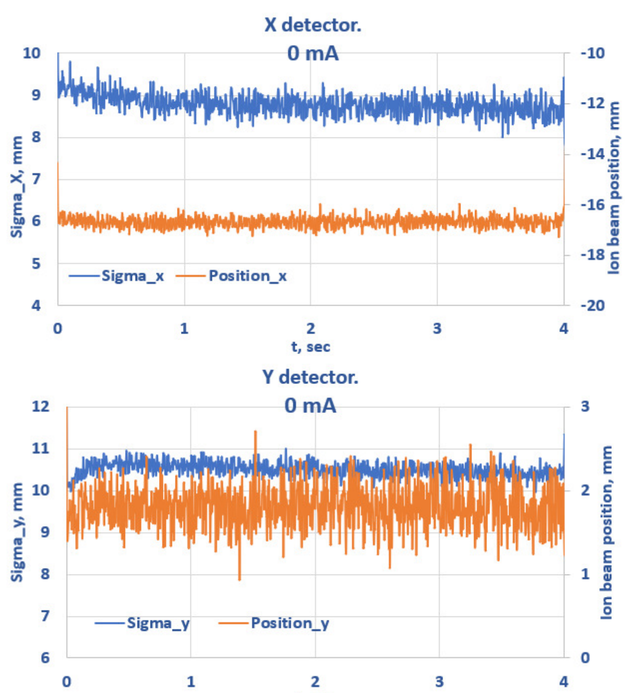

Figure 6: Ion beam transvers dimensions (blue curve) and ion beam axis coordinates (orange curve) in the profilometer with the electron beam turned off.

At first, the electron beam energy values were set close to the optimal theoretical value of 1.75 keV at an electron current of 46 mA (Fig. 7).

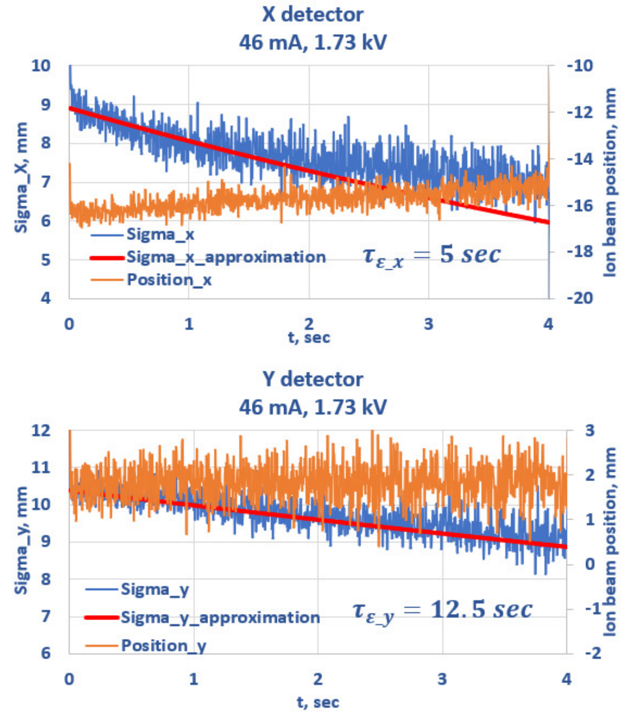

Figure 7: Ion beam transvers dimensions (blue curve) and ion beam axis coordinates (orange curve) in the profilometer with the electron beam current 46 mA and energy 1.73 keV.

According to the Fig 7, it can be noticed that the cooling time is very long both horizontally and vertically (5 sec and 12.5 sec respectively). This was because the fact that the beams were not aligned, and they were separated from each other by some distance, and, accordingly, there was a sagging of the electron beam potential along the radius (Fig. 8).

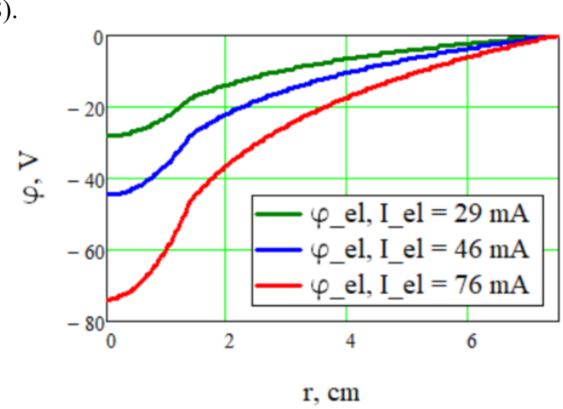

Figure 8: Electron beam potential sagging along the radius (electron beam radius equal to 1.4 cm) for different currents.

So long as RF was turned off and it was not possible to correct the orbit of the ion beam in the cooling section, it was decided to adjust the energy of the electron beam. The main problem here was that the potential change at the cathode is possible only in steps of 10 volts, which is a very

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large value for an energy of 3.2 MeV/u. Therefore, in addition to changing the cathode potential, the current also was changed.

The best results for a current of 46 mA were obtained at an energy of 1.83 keV (Fig. 9) – cooling time for horizontal degree of freedom varies from 2 to 4 sec and for vertical, equal to 5 sec, thus the difference between experimental and theoretical values amounted to 80 volts.

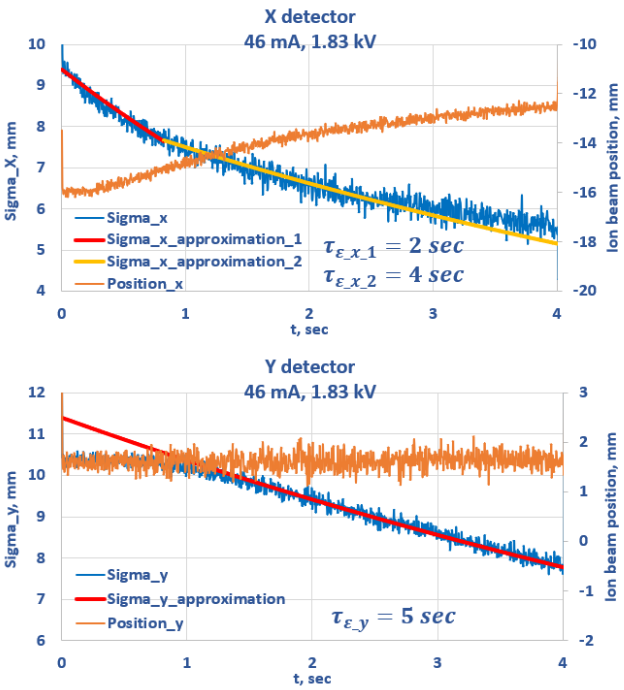

Figure 9: Ion beam transvers dimensions (blue curve) and ion beam axis coordinates (orange curve) in the profilometer with the electron beam current 46 mA and energy 1.83 keV.

This energy difference is approximately preserved at other electron beam currents. The best cooling times obtained for other values of the electron beam are shown in the Table 4.

Table 4: Transversal Cooling Times for Different Values of Electron Beam

I, mA	W, keV	τ_x, sec	τ_y, sec
29	1.81	4	14
46	1.83	2	5
76	1.86	3	4

Hence, it can be concluded that the electron and ion beams axes were far enough apart from each other, therefore the ion beam moved under action of electron cooling force.

DEVELOPMENT OF THE PARKHOMCHUK FORMULA

Due to the strong discrepancy between the theoretical and optimal experimental energy of the electron beam, it was decided to add to the classical Parkhomchuk formula for the friction force dependence on:

- sagging of the electron beam potential resulting in increase of the difference of electron and ion velocities, which significantly exceeds the velocity spread due to flattened distribution;
- effect of the drift velocity in the crossed longitudinal magnetic field and electric field of the electron beam

$$v_d(I_{el},\, r) = \gamma \cdot c\, \frac{E_{el}(I_{el}, r)_{\left[\frac{V}{cm}\right]}}{300 \cdot B_{[G]}}. \quad (1)$$

Considering these corrections, the total transverse and longitudinal velocities are now determined by the expressions

$$V_{x,y}(I_{el}, r) = \\ = \sqrt{V^2_{Ion_{x,y}} + \Delta^2_{el_{x,y}} + \frac{v_d(I_{el},\, r)^2}{2} + (\gamma V_0 \vartheta_B)^2} \\ V_s\left(\frac{dp}{p}, I_{el}, r\right) = \sqrt{V^2_{Ion_s}\left(\frac{dp}{p}\right) + \Delta v^2_{el_s}(I_{el},\, r)}, \quad (2)$$

where Δv_{el_s} – difference between the longitudinal velocities of the ions and the electrons, determined by the expression

$$\Delta v_{el_s} = \left(\sqrt{2\frac{U_{cath} - U(I_{el}, r)}{m_{el}}} - \beta_{ion}\right) c. \quad (3)$$

Expression under the root is the longitudinal electron velocity, which depends on the voltage at the cathode and on the potential sagging along the electron beam radius. The friction force can now be written as follows

$$F_{x,y}\left(\frac{dp}{p}, I_{el}, r\right) = q_{el} V_{Ion_{x,y}} \cdot \Big[\big(V_x(I_{el}, r) + \\ \gamma V_0 \vartheta_B\big)^2 + \big(V_y(I_{el}, r) + \gamma V_0 \vartheta_B\big)^2 + \\ V_s\left(\frac{dp}{p}, I_{el}, r\right)^2\Big]^{-\frac{3}{2}} \cdot \ln\left(1 + \frac{\rho_{max\left(\frac{dp}{p}, I_{el} r\right)}}{\rho_L + \rho_{min\left(\frac{dp}{p}, I_{el} r\right)}}\right). \quad (4)$$

Then the formulas for the cooling decrement and the corresponding emittance cooling time will take the form

$$D_{x,y}\left(\frac{dp}{p}, I_{el}, r\right) = \frac{F_{x,y}\left(\frac{dp}{p}, I_{el}, r\right) \cdot c^2}{A m V_{Ion_{x,y}}}; \quad (5)$$

$$\tau_{emit_{x,y}} = \frac{1}{2}\frac{\gamma}{\eta} D_{x,y}\left(\frac{dp}{p}, I_{el}, r\right)^{-1}. \quad (6)$$

Since the electron beam is magnetized, the collision of an electron with an ion can be considered as an absolutely elastic collision. For this reason, the transverse temperature of the electrons was chosen to be zero.

With an increasing in the electron current, a competition of micro and macro interactions can be observed:

- increasing in the sagging potential, which leads to an increase in the difference in the longitudinal velocities of ions and electrons, as a result decreasing of the friction force (Fig. 10).
- increasing in the electron density, which leads to an increase in the friction force (Fig. 11).

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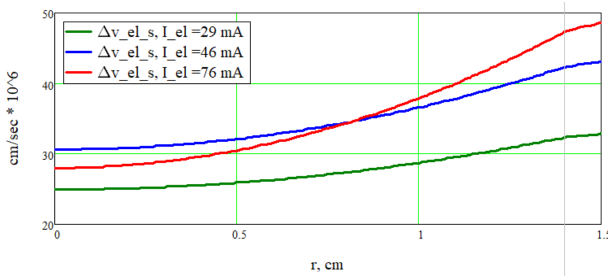

Figure 10: The difference between the longitudinal velocity of electrons and ions vs radial coordinate.

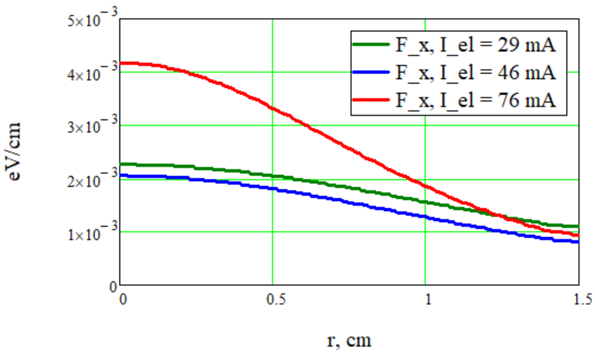

Figure 11: Horizontal friction force vs radial coordinate for dp/p=6e-4.

As the electron current increases, the influence of the space charge increases as well, and the cooling time increases first (Fig. 12, green and blue curves). But with a further increase of the current, the influence of the friction force growth begins to prevail over the influence of the longitudinal velocity spread. Therefore, cooling time decreases significantly (blue and red curves).

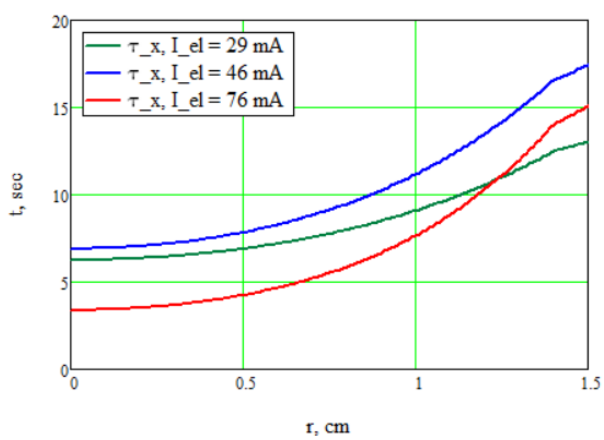

Figure 12: Horizontal emittance cooling time vs radial coordinate for dp/p = 6e-4.

CONCLISIONS

Electron cooling of heavy ions at injection energy (3.2 MeV/u) is of practical interest, because it makes it possible to use multi-turn or multiple injection. The peculiarity of low energy electron cooling is strongly influenced by the space charge of the electron beam. In this case well known Parkhomchuk formula needs appropriate correction.

REFERENCES

[1] V.I.Kudelainen, I. N. Meshkov, and R.A.Salimov., "Commissioning of the set-up for electron cooling experiment", Preprint of G.I.Budker INP, Novosibirsk, USSR, vol. 72-70, 1970.

[2] A. A. Baldin *et al.*, "Non-destructive diagnostics of accelerated ion beam with MCP-based detectors at the NICA accelerator complex. Experimental results and prospects", in *Proc. 27th Russian Particle Accelerator Conf. (RuPAC'21)*, Alushta, Russia, Sep. 2021, paper WED05.