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FEATURES OF THE ELECTRON COOLING SYSTEM OF THE NICA BOOSTER

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Abstract

The report presents the results obtained during the commissioning the Electron Cooling System (ECS) of the Booster (Fig. 1), the first in the chain of three synchrotrons of the NICA accelerator complex. The work was performed without an ion beam and with a circulating ion beam He^{1+} and $^{56}Fe^{14+}$. In the work with a circulating ion beam He^{1+}, the effect of reducing the lifetime of the circulating ions was observed when the velocities of the cooling electrons and the cooled ions coincide. The dependences of the electron beam current on the ECS parameters for different electron energy values were experimentally obtained. The specific features of operation of electron gun of the NICA Booster are hollow beam formation and the phenomenon of virtual cathode creation confirmed both experiments and by numerical simulation. In conclusion section the results of first experiments on electron cooling of $^{56}Fe^{14+}$ ion electron cooling are presented.

INTRODUCTION

The main tasks of the Booster synchrotron of heavy ions are the accumulation of $2{\cdot}10^9$ gold ions $^{197}Au^{31}+$ or other low-charged heavy ions and their acceleration to the maximum energy (578 MeV/u for $^{197}Au^{31+}$), which is sufficient for their subsequent stripping to the state of bare nuclei. The use of electron cooling in a Booster at ion energy of 65 MeV/u makes it possible to significantly reduce the 6D emittance of the beam.

SCHEME OF THE ELECTRON COOLING SYSTEM OF THE NICA BOOSTER

The ECS is constructed according to the classical scheme proposed and implemented in the early 1970s in the Institute of Nuclear Physics of SB of USSR Academy of Science [1].

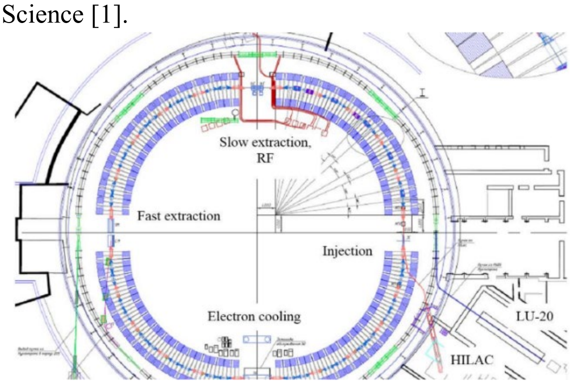

Figure 1: Booster Scheme with Built-in ECS.

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In electron cooling set-up (Fig. 2), an electron beam passes from the cathode of the electron gun to the collector in a uniform longitudinal magnetic field. A short rectilinear solenoid allows one to form an electron beam with the necessary parameters in a gun with special optics. The toroidal sections of the Cooler magnetic system are used to transport the beam to straight solenoid – the cooling section.

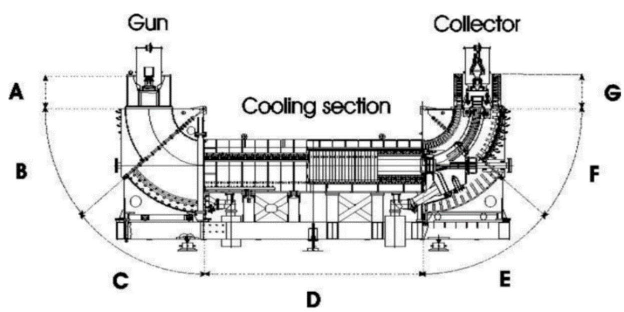

Figure 2: A, G–the solenoids of the gun and the collector, B, C, E, F - the sections of the toroidal solenoids, D-the cooling section solenoid.

In the ECS of the NICA Booster (Table 1), the homogeneity of the magnetic field of this solenoid is made at the level of $3{\cdot}10^{-5}$ (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 of 1.0 – 50.0 keV.

Table 1: Parameters of the Booster ECS

Electron energy E, keV	1.5 – 50
Electron beam current I, A	≤ 1
Accuracy of energy adjustment and its stability, ΔE/E	$\le 1{\cdot}10^{-5}$
Beam current stability, ΔI/I	$\le 1{\cdot}10^{-4}$
Electron beam loss current, δI/I	$\le 3{\cdot}10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, ΔB/B	$\le 3{\cdot}10^{-5}$ 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

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PARKHOMCHUK'S ELECTRON GUN

The ECS electron gun invented by V. V. Parkhomchuk, (Fig. 3) consists of three-electrode [2], which are cathode (1), a cathode electrode ("grid") (2) and an anode (3). The grid potential relative to the cathode can vary from -1 to +2 kV. The electrons from the cathode of the gun to the collector move in a longitudinal homogeneous magnetic field of a strength up to 1000 Gs. The cathode of a diameter of Ø 30 mm has a convex shape. The grid is necessary for the formation of a hollow electron beam (see below).

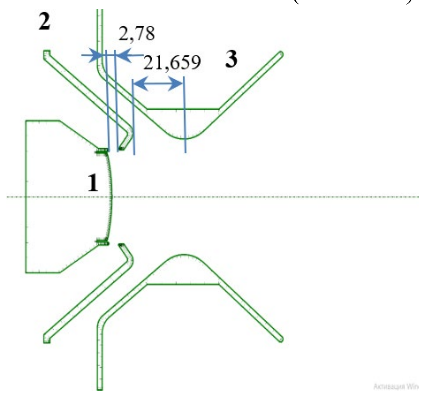

Figure 3: The Booster ECS gun scheme.

TESTING THE ECS

Experiments without a circulating ion beam in the Booster were performed at the ECS installation in the period from June 2019 to November 2020. During this time, the maximum design current values (1.0 A) were obtained for various values of the beam energy, the current-voltage functions of the gun were obtained (Fig. 4), and the formation of a virtual cathode (hollow beam) was investigated. These dependencies were verified by numerical modeling with help of SAM code (BINP of SB of RAS.

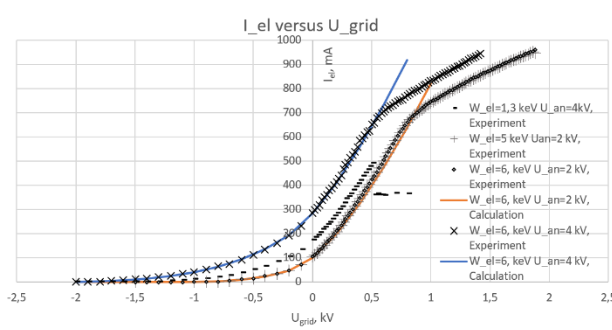

Figure 4: The volt-ampere characteristics of the gun for the electron beam energy of 5 and 6 keV. The potential difference between the cathode and the anode is 2 and 4 kV. Calculations were fulfilled for electron energy 6 keV and potential difference between the cathode and the anode was 2 and 4 kV (red and blue curves respectively) and are in a good agreement with the experimental values.

As follows from Fig. 4, influence of electron energy outside the gun (the gun cathode potential relatively to ground) on electron beam current is very weak – «+» curve (5 keV) and «•» curve (6 keV) coincide practically. At the same time, influence of anode potential is rather significant.

It can be seen from the volt-ampere characteristic that the beam current begins to grow at the ratio |Ugrid/Uan| = 0.5. At current values (≈ 0.7 A), the field of the space charge of the beam forms a "sag" of the potential, which in turn leads to deceleration of the beam and some part of them that comes to zero (relatively to the cathode) potential area is reflected back to the cathode. As result, the perveance of the gun decreases (the bend of the curves in Fig. 4) and a region free of electrons appears. This is so-called "hollow electron beam" based on virtual cathode formation (Fig. 5). This mode of cooling electron beam operation is preferable when ion recombination with cooling electrons is significant.

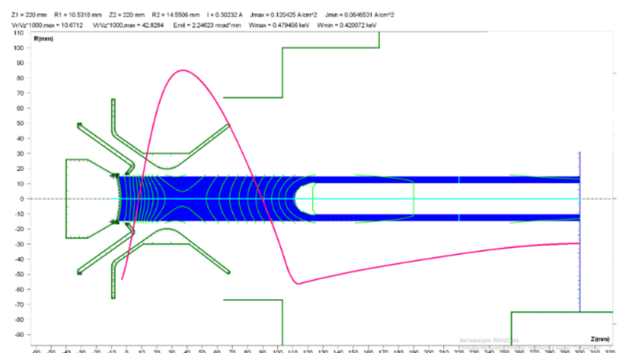

Figure 5: Formation of the hollow beam Potential values: φ_{cath} = -1.3 kV, U_{an}=4 kV, U_{grid} = 0.5 kV. Longitudinal magnetic field is equal to 0.1 T. The red curve gives the electron beam potential distribution at the axis relatively to ground.

FIRST ION ELECTRON COOLING EXPERIMENT

During the first Booster session in December 2020, an experiment was conducted to commission the ECS with a circulating 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: the A. A. Baldin ionization profilometer [3] and a parametric current transformer (PCT) measuring ion beam current.

Table 2: Experiment Parameters

Ion type	He1+
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

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During the experiment, the electron beam was not hollow, which was confirmed by further numerical modeling, as well as the results of measuring the beam profile on an electron gun similar to the one in the Booster ECS [2]. Therefore, during the experiment, a significant decrease in the lifetime of the circulating beam was observed, due to, probably, strong recombination.

The ion beam profile was also recorded by an ionization profilometer that was operated in summing mode the counting rate of all the MCP channels 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. 6).

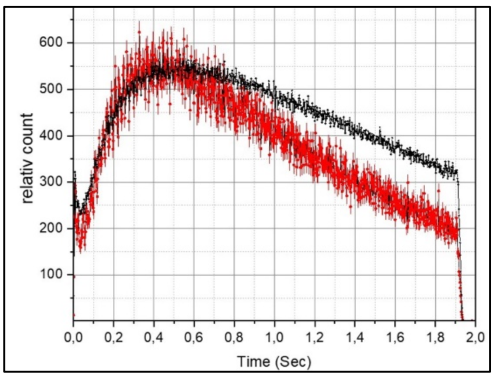

Figure 6: ⟨RC(t)⟩ with the electron current off (black curve) and on (red curve). The electron energy is 1.78 keV, the electron beam current 150 mA. The latter is the optimum electron energy for electron cooling equal to $(E_e)_{opt} = (m_e/m_{nucleon})\times E_{ion}$, where E_e is electron energy (not corrected to electron beam space charge potential!), E_{ion} is the ion energy per nucleon.

SECOND ION ELECTRON COOLING EXPERIMENT

During the second run of the Booster in September 2021, an experiment was conducted to electron cooling of ions $^{56}Fe^{14+}$ beam circulating at injection energy of 3.2 MeV/u. A Schottky spectrometer was used as the main detecting device (Fig. 7), as well as a profilometer used during first experiment.

After the appearance of a wide signal of the ion beam injected into the Booster (Fig. 7a) with a large frequency spread Δf/f0, the signal narrows, its amplitude increases but its area insignificantly decreases in accordance with the beam life time. Thus, there is a decrease in the peak width, i.e decrease of the ion momentum spread of the beam. Such a signal behavior demonstrates definitely effect of electron cooling.

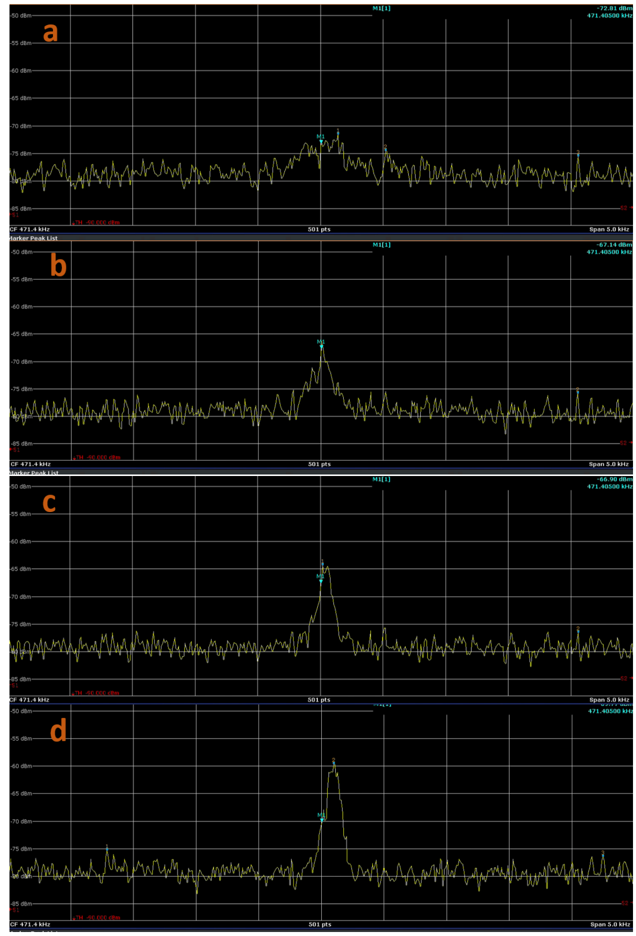

Figure 7: The signal from the Schottky spectrometer. a) is the signal of injection of an ion $^{56}Fe^{14+}$ beam into the Booster ring, b), c), d) are the cooling of the ion beam by an electron beam.

Thus, we can say that the first electron cooling of a heavy ion beam was observed in the Russian Federation.

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