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STATUS OF THE ELECTRON COOLER FOR NICA BOOSTER AND RESULTS OF ITS COMMISSIONING

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Abstract

The electron cooling system of the NICA booster is intended for accumulation of the ion beam at the injection energy and for cooling at some intermediate energy value before acceleration to the extraction energy. The system was produced in BINP (Novosibirsk, Russia) and commissioned in the JINR (Dubna, Russia) in 2019. The current status of the electron cooler and the results of its tests are presented in the article.

INTRODUCTION

In order to achieve needed parameters of the ion beam in the NICA booster the ring will be equipped with low energy electron cooling system, which provides accumulation of ions on injection energy (3.2 MeV/u) and on some intermediate energy (60-100 MeV/u) to prepare the beam for acceleration to the extraction energy.

The electron cooling system was developed and commissioned in the BINP in 2016. In 2017 it was assembled and commissioned in the JINR. Its main parameters are shown in the Table 1.

Table 1: Main Parameters of the Cooler

Parameter	Value
Ion type	$^{197}Au^{31+}$
Electron energy, E	1.5÷60 keV
Electron beam current, I	0.2÷1.0 A
Energy stability, ΔE/E	$<10^{-5}$
Electron current stability, ΔI/I	$<10^{-4}$
Longitudinal magnetic field, B	0.1÷0.2 T
Electron current loses, I_{leak}/I	$<3\cdot10^{-5}$
Vacuum pressure, Pa	$\approx10^{-11}$ mbar

Important feature of the system is possibility of work on different energies in one cycle of booster ring (ramp regime). Since length of booster cycle is several seconds, regime of the cooler have to be changed from injection to intermediate energy in period of about 0.5-1 sec.

CONSTRUCTION

The cooler is produced with the classical scheme (Fig. 1). The DC electron beam is formed in the gun and then it is accelerated to work energy. After acceleration it moves through the toroid magnet to the cooling section, where it interacts with ion beam. After that the electrons move though another toroid to the electron collector where them are decelerated and absorbed on collector surface. Deceleration before collector is made to recuperate electron energy.

On whole way from gun to collector the beam moves in longitudinal magnetic field. There are two reasons for it: the field provides transverse focusing of the beam; in the cooling section the field allows to make, so called, fast electron cooling [1]. In order to reach high homogeneity of longitudinal magnetic field in the cooling section, the solenoid is made of separate coils with possibility to rotate each coil around two transverse axes [2].

To compensate centrifugal force in toroid magnets special electrostatic plates, which produce transverse electric field, are used. Use of electric filed instead of magnetic to compensate centrifugal force allows to increase recuperation efficiency without improving of collector efficiency [3,4].

The gun and the collector are based on constructions used in previous coolers produced in BINP. The collector consists of two parts: main massive, oil cooled, electrode and ceramic insertion before it, which contains suppressor and pre-collector electrodes. The suppressor allows to produce potential barrier on the collector entrance in order to lock secondary electron in the collector, to increase its efficiency. The pre-collector electrode has the same voltage as the collector and provides symmetry of the potential in suppressor region. The electrostatic barrier in the collector is supplemented by magnetic plug, which is produced by special shape of the magnetic filed.

The main gun feature is four sector control electrode that provides measure not only beam position (with the help of beam position monitors, by modulation of voltage on all four sectors simultaneously) but also beam size (by modulation of voltage on every sector separately) [5].

Solenoids of the magnetic system are powered with 4 independent high current power supplies (PS, IST type). Nominal value of the longitudinal field in the system is 1-2 kG.

Besides high current supplies the system contains set of low current power supplies (5 and 20 A), which power magnetic correctors of the cooler.

In order to work in ramp regime, correctors and HV system must have capability to change output parameters for a period of 0.5-1 sec. It was decided, that high current PS (IST) will not change output current during ramp, because

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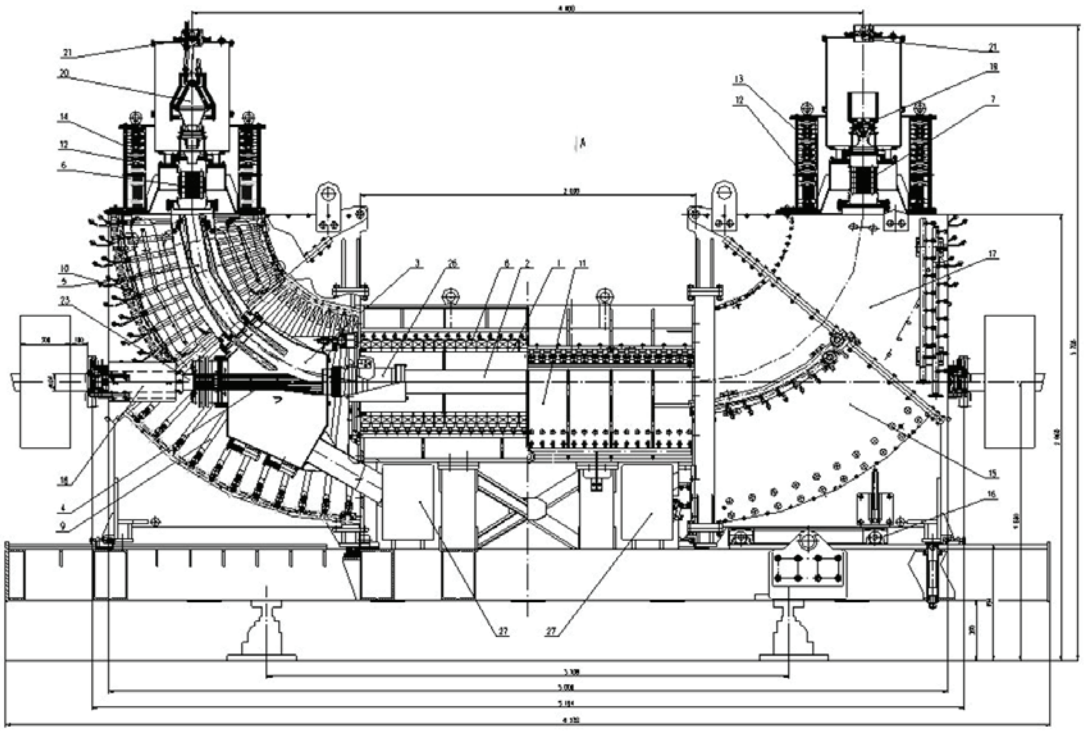

Figure 1: Drawing of the electron cooling system for the NICA booster.

such type of PS are too slow, and there is possibility to make ramp regime without them.

Since synchronous change of electron beam energy with currents in magnetic correctors is difficult task (because it needs fast online measurements) and there is no necessity to cool beam during acceleration, it was decided to turn off the beam before change of its energy and turn it on after energy reaches another value. To turn off the beam anode voltage will be set to 0 and control electrode voltage will be set to -2÷-3 kV. Synchronization of all systems is done with the help of special electronic block (CGTI).

TEST RESULTS

After the cooler was commissioned some additional works with electronics and experiments with electron beam were carried out. Results of some experiments are presented below.

High Voltage Tests

Results of high voltage tests are shown in Fig. 2. Here one can see dependence of leakage current on voltage of the main power supply.

In Fig. 3 dependence of voltage and vacuum pressure on time for the same measurements are shown. Abrupt increase of pressure on high voltage (higher then 40 kV) means that some discharge processes occurs in vacuum chamber of the cooler.

Beam Tests

During tests with electron beam in JINR current up to 500 mA was achieved. Figure 4 shows dependences of main beam current and leakage current on time. Electron energy here is 10 keV.

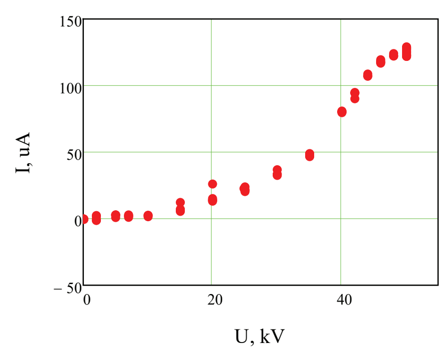

Figure 2: Dependence of leakage current on voltage of main PS

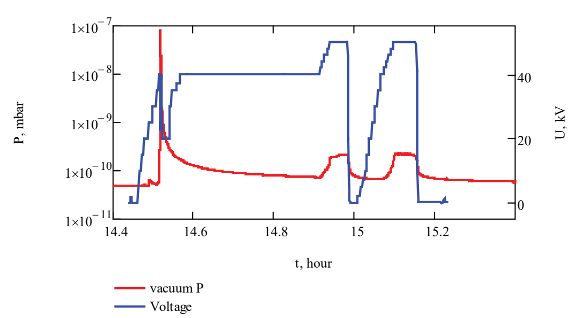

Figure 3: Dependence of voltage of main PS and vacuum pressure on time during high voltage test.

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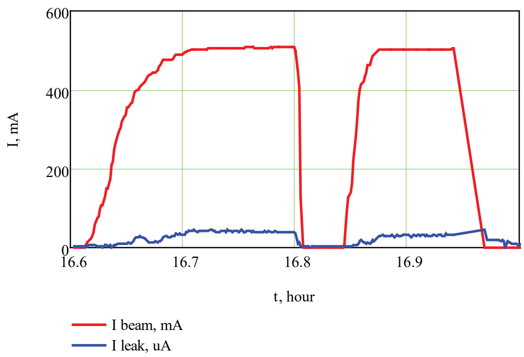

Figure 4: Results of tests with beam.

An interesting effect, which was observed during commissioning in JINR is vacuum pumping by the electron beam (during commissioning in BINP it was observer too). In Fig. 5 dependences of beam current, leakage current and vacuum pressure on time are shown. One can see, that when the beam is turned off vacuum pressure increases.

Design of the electron collector of the cooler supposes, that space charge of electron beam forms additional potential barrier in the collector entrance, improving collector efficiency. It means that on high values of current of main beam increase of beam current can lead to decrease of leakage current [6]. Since absorption of leaked electrons by walls of vacuum chamber, can cause desorption of neutral molecules and increase vacuum pressure, decrease of leakage current (while increase beam current) will decrease vacuum pressure. But in Fig. 5 one can see, that the leakage current decreases almost to zero value during turn off of the beam, that means the effect doesn't related with leakage current.

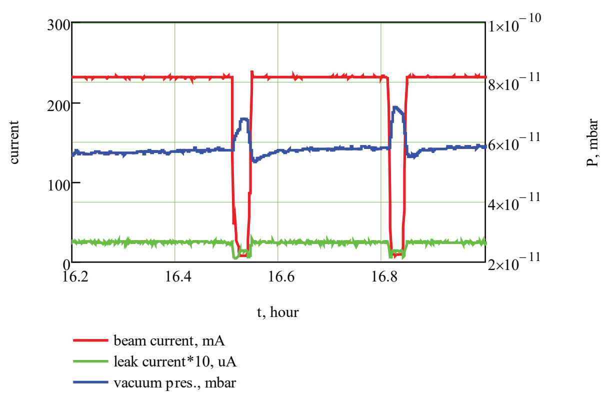

Figure 5: Dependence of the main beam current, leakage current and vacuum pressure on time.

Such dependence of vacuum pressure on beam current can be explained by ionization of rest gas by main electron beam. Produced positive ions of gas can move along the beam to gun or collector, where they are absorbed on walls of vacuum chamber. This effect was observed on previous electron coolers [7].

If electron trajectory length from gun to collector is L and ionization cross-section is σ, then one electron moving from gun to collector ionizes all atoms in volume v_1:

$$v_1 = \sigma L \,. \tag{1}$$

Assuming that all ions later die on walls of the vacuum chamber, the volume v_1 is equal to volume, evacuated by one electron. Number of electrons per second can be calculated from electron current:

$$\frac{dN}{dt} = \frac{I}{e} \,. \tag{2}$$

Resulting pump speed (evacuated volume per second) is equal to volume evacuated by one electron multiplied by number of electrons per second

$$\frac{dv}{dt} = v_1 \frac{dN}{dt} = \frac{\sigma L I}{e} \,. \tag{3}$$

For good vacuum conditions rest gas mainly consists of hydrogen molecules. Estimations of pump speed for electron current 230 mA give pumping speed about 5 l/s, that is close to observed results.

Space Charge Effect

As it was said before, the electron gun has four sector control electrode, which allows to measure not only beam position, but also beam size. On Fig. 6 four pictures, showing results of the beam size measurements on different BPMs with different current values are shown.

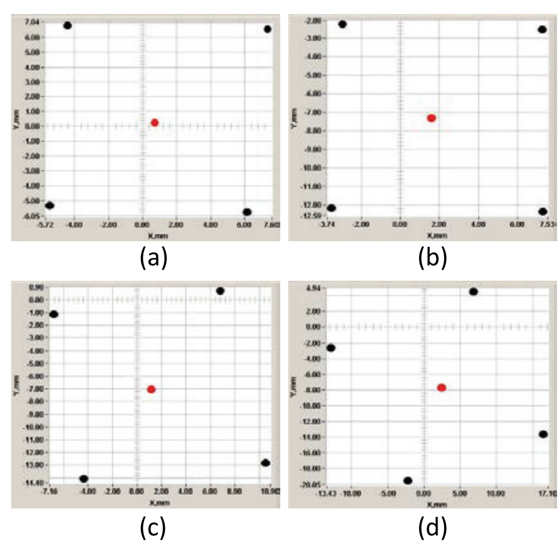

Figure 6: Electron beam size on different BPMs for different current of the beam: a) 1-st BPM with 30 mA beam, b) 3-rd BPM with 30 mA, c) 3-rd BPM with 115 mA, d) 3-rd BPM with 200 mA.

The first picture shows 30 mA beam on the 1-st BPM. The BPM is installed right after the electron gun and only beam size can be changed here. This picture can be considered as a reference for other pictures. Other pictures show

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measurements from 3-rd BPM, which is installed in the end of the cooling section (about 4 m farther). One can see, that the picture depends on beam current value. Beam rotation can be observed here, which depends on beam current value. For small current (30 mA) there is almost no rotation, but for higher current the rotation (counterclock-wise) is stronger. This is result of the transverse drift of electrons in field of beam's space charge and longitudinal magnetic field.

In axial symmetric system the electric field E_r from the electron beam in radius R can be calculated with formula:

$$E_r = \frac{4\pi}{RV_0}\int_0^R rj(r)dr\,, \qquad (4)$$

where V_0 – electron velocity, $j(r)$ – beam current density.

Assuming, that transverse beam size is constant, one can estimate angle of beam rotation along system

$$\Delta\varphi = \omega_{DR}\tau = c\frac{E_r}{B_{\parallel}R}\frac{L}{V} = \frac{4\pi cL}{B_{\parallel}R^2V_0^2}\int_0^R rj(r)dr\,, \qquad (5)$$

here L – distance, which beam passes, τ – time of flight, R – radius of electron, c – speed of light, $B_{\parallel}$ – longitudinal magnetic field.

For 10 kV beam with current 200 mA the equation (5) gives angle 15-20º, that is close to measured value.

CONCLUSSION

The electron cooling system was commissioned in the JINR in 2017 and tested during last years. Electron beam current up to 500 mA and voltage up to 50 kV were obtained.

Results of measurements obtained in JINR (such as vacuum pressure and vacuum pumping by electron beam) show that quality of beam and vacuum conditions are good enough for system work in the booster.

Despite some additional work with electronics of the cooler is needed, the system is ready for work with ion beam.

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