BOOSTER ELCTRON COOLING SYSTEM OF NICA PROJECT

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Abstract

Nuclotron-based Ion Collider fAcility (NICA) [1] is the new accelerator complex being constructed on the JINR site. A few cooling systems are considered for the NICA project – electron one for the Booster-synchrotron and for Collider rings – both electron and stochastic ones. The main goal of the Booster electron cooler is a decrease of the longitudinal emittance from the injection value to the necessary value for acceleration to Nuclotron. The designed electron cooling system for Collider rings have to prevent the emittance growth due to the intrabeam scattering and to keep the average luminosity on the constant value. The peculiarity of electron cooling systems is the using of superconducting solenoids to provide the beam transportation in cooling sections.

INTRODUCTION

The main goal of the Booster electron cooler is the decreasing of the longitudinal emittance from the injection value of about 7.5 eV·s to the necessary value of 2.5 eV·s. Cooling time is limited by the operation cycle of the Booster and can not exceed the value of 1 sec. For the transverse plane the cooling system has to keep the value of the normalized transverse emittances at the level of 1 π·mm·mrad (rms). For the stabilization of the transverse emittance the misalignment of electron and ion beam axes is proposed on the level of about 1 mrad in both transverse planes [2].

Ion energy in the Booster ranges from 6 MeV/u to 600 MeV/u that corresponds to the electron energy range 3.27 ÷ 330 keV. Choosing an optimal energy value for electron cooling one has to account the following effects:

1) beam lifetime limitation due to interaction with the rest gas ;
2) beam lifetime limitation due to recombination on the cooling electrons;
3) space charge effects appearing due to ion beam shrinking at cooling;
4) sufficiently short cooling time (≤1 sec);
5) space charge effect of electron beam on ion cooling;
6) an optimal use of the RF station;
7) cost of the electron cooler.

ELECTRON COOLER OPERATION

The maximum design ion energy of 4.5 GeV/u can be achieved in the Nuclotron with fully stripped ions only. To provide high efficiency of the ion stripping one has to accelerate them up to the energy of a few hundreds of MeV/u. For this purpose a new synchrotron ring – the Booster is planned to be used. Heavy ion injector-linac is designed for acceleration of Au^{32+} ions. The Booster has maximum magnetic rigidity of 25 T·m that corresponds to about 600 MeV/u of the ion energy, and the stripping efficiency is no less than 80%.

The Booster is equipped with an electron cooling system that allows providing an efficient cooling of the ions in the energy range from the injection energy up to 100 MeV/u.

The magnetic system of the Booster is superconducting. Its design is based on the experience of construction of the Nuclotron SC magnetic system [3] and SC magnetic system of SIS-100 developed later at FAIR project. Therefore to avoid connections between "warm" and "cold" sections in the ring the solenoids of the cooler located along the Booster circumference are designed in the SC version (Fig. 1). This is main difference of the Booster cooler from a conventional electron cooling systems.

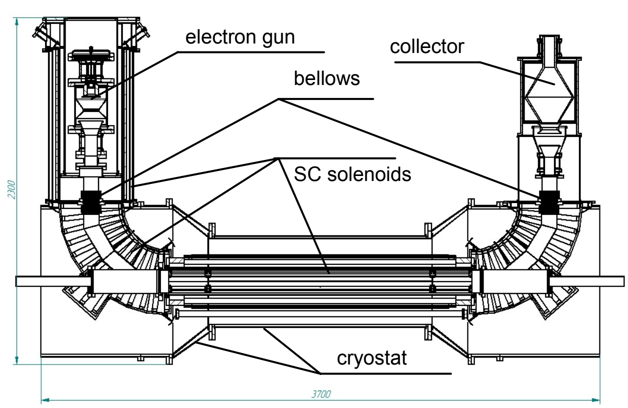

Figure 1: Booster electron cooler.

To cover total range of the ion energy in the Booster (600 MeV/u) the electron beam maximum energy has to be about 330 keV. However the cooling system at such energy is rather expensive, therefore the maximum electron energy (60 keV) is chosen as a compromise between the system price and its capability to fulfill the main project task – the ion colliding beams. A possibility to decrease the ion beam phase volume at injection energy is restricted by space charge limitations.

Another criterion for the electron energy choice is related to the frequency variation range of the Booster RF system. The ion acceleration in the Booster is proposed to be performed in two steps: on the 4^{th} harmonics of the revolution frequency up to the cooler energy and on the 1^{st} one after the cooling. If the cooling is performed at the ion kinetic energy ≥ 100 MeV/u, one can use the same RF system on both steps of the acceleration.

All other parameters of the Booster cooler (Table 1) are typical for conventional electron cooling systems. Design of the cooler is performed by JINR electron cooling group and its construction is planned to be done at JINR workshop. Test of the cooler elements will be performed at existing test bench.

Table 1: Basic Parameters of the Booster and its Electron Cooling System

Ions	$^{197}Au^{32+}$
Booster circumference, m	211.2
Injection/extraction energy, MeV/u	6.2/600
Max. dipole field, T	1.8
Ion number	2×10^{9}
Beta functions in cooling section, m	8 / 8
Dispersion function in cooling section, m	0.6
Maximum electron energy, keV	60.0
Electron beam current, A	0 ÷ 1.0
Cooler overall length, m	4.0
Effective length of the cooling section, m	2.0
Magnetic field in the cooling section, kG	1.5
Magnetic field inhomogeneity in the cooling section, ΔB/B	$1\cdot10^{-4}$
Electron beam radius in the cooling section, cm	2.5
Transverse electron temperature, meV	200
Longitudinal electron temperature, meV	0.5
Cooling time, s	1
Residual gas pressure, Torr	10^{-11}

At the electron cooling of heavy ions one of the serious problems is the recombination - i.e. capture of cooling electrons by ions - resulting in loss of the ions due to change of their charge and deformation of the ion closed orbit. The recombination rate of Au^{32+} ions in the Booster cooler was extrapolated from the experimental data obtained at GSI and CERN. The estimation has shown that during 1 s of cooling the ion losses will be less than 10%. In any case the use of SC solenoid in the cooling section gives a possibility to provide the electron beam compression in order to suppress the recombination by increase of the temperature of transverse degree of freedom of the electron beam.

ELECTRON GUN AND COLLECTOR

All elements of the electron cooling system have the cryogenic temperature except the electron gun and collector which have the standard design for electron coolers (Fig.2).

The superconductive solenoids of electron gun and collector are used for the formation of the longitudinal magnetic fields The electron gun and collector are placed inside the anti cryostats and have a special bellows between “warm” and “cold” vacuum chambers (Fig.1).

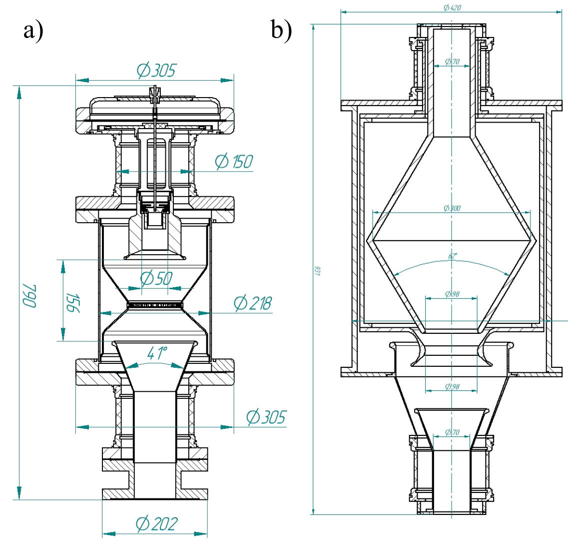

Figure 2: Electron gun(a) and collector (b) design.

For simulation of the optics of the electron guns and electron collectors both BINP and JINR electron cooling groups use mostly the special code SAM [4]. The code allows to simulate the electron trajectories taking into account the geometry of electrodes, the longitudinal magnetic field and the field of the electron beam space charge. As result of a simulation (Fig. 3) one can obtain distribution of the electron beam density and variation of the electron transverse velocity across and along the beam.

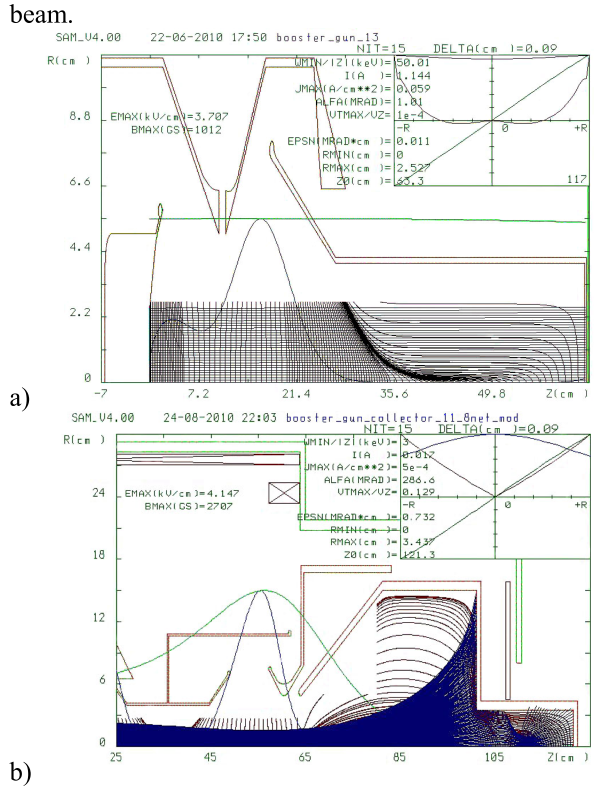

Figure 3: Simulation of electron trajectories in the gun (a) and collector (b).

SIMULATION OF COOLING PROCESS WITH BETACOOL

Main goal of the cooling of heavy ion beam is to decrease its longitudinal emittance to the value required for effective injection and acceleration in the Nuclotron and for the bunch compression in the Nuclotron before injection into the collider. Transverse beam emittance has to be stabilized at relatively large value to avoid space charge limitations in the Nuclotron and collider rings. To avoid overcooling of the transverse degree of freedom the electron beam misalignment in respect to the ion orbit can be used. Simulations of such a regime of the cooler operation performed with BETACOOL [5] code showed that during 1 second of the cooling one can decrease the longitudinal beam emittance by about 3 times at practically constant transverse emittance. That is sufficient for our goal.

The simulation of the electron cooling of $^{197}Au^{32+}$ ions in the Booster does demonstrate the effect of misalignment of the electron beam (Fig. 4-5).

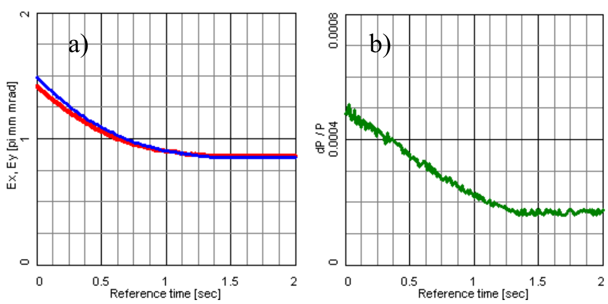

Figure 4: Evolution of the bunched ion beam parameters during the cooling process with misalignment angle of 5×10-4. a) horizontal (red) and vertical (blue) emittances, b) ion momentum spread.

One can see that after 1 sec of cooling the transverse emittance (Fig. 4a) and momentum spread (Fig. 4b) reach the equilibrium between the cooling and IBS heating. The necessary longitudinal emittance of about 2.5 eV·s can be reached in less than 1 sec of the cooling process.

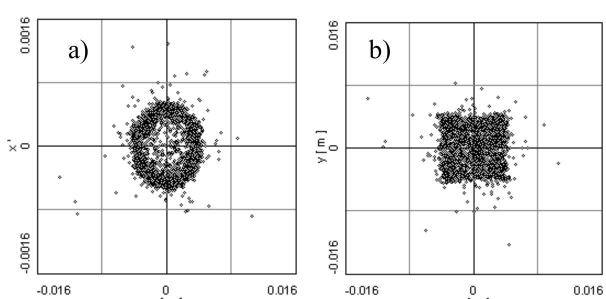

Figure 5: Ion beam density distribution after 2 seconds of the cooling: a) transverse plane and b) horizontal transverse phase space of the cooled ion beam

The beam profile at cooling with misaligned electron beam has a well pronounced double peak structure and most of the particles oscillate with equal amplitudes in the horizontal plane. (Fig.5a). Due to misalignment the transverse cross-section of the cooled ion beam has a rectangular form (Fig.5b).

The optimum regime can be found from the dependence of the cooling time on misalignment angle when the longitudinal emittance decreases from 7.5 eV·s to necessary value of 2.5 eV·s (Fig.6). The cooling time has to be less than 1 sec and the transverse emittance has to be about 1 π mm mrad. For the misalignment angle 0.5 mrad the cooling time does not decrease too much and the transverse emittance is sufficiently large to avoid a tune shift resonance.

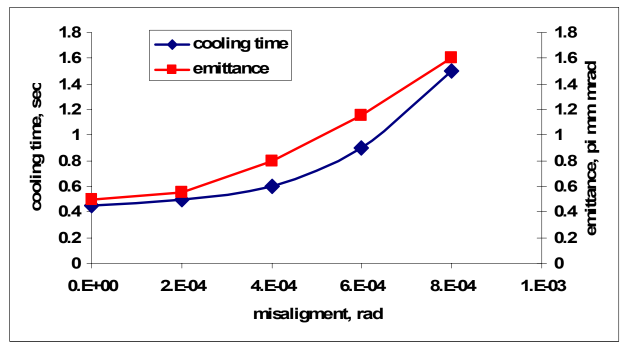

Figure 6: The dependence of the cooling time and transverse emittance after the cooling process on the misalignment angle between electron and ion beams axes; cooling time is defined as time interval when longitudinal emittance decreases from 7.5 eV·s to 2.5 eV·s.

REFERENCES

[1] G. Trubnikov, et.al., Project of the Nuclotron-based ion collider facility (NICA) at JINR, Proceedings of EPAC08, Genoa, Italy. http://www.jacow.org

[2] Design and Construction of Nuclotron-based Ion Collider fAcility (NICA). Conceptual Design Report, Dubna 2008. http://nica.jinr.ru/files/NICA_CDR.pdf

[3] H.G.Khodzhibagiyan, A.A.Smirnov. The concept of a superconducting magnet system for the Nuclotron, *Proc. of the 12th Int. Cryogen. Eng. Conf.*, 1988, pp. 841–844.

[4] Fomel B.M., Tiunov M.A., Yakovlev V.P. SAM – an Interactive Code for Evaluation of Electron Guns: Preprint № 89-159, INP, Novosibirsk, 1989.

[5] I. Meshkov, A. Sidorin, A. Smirnov, E. Syresin, G.Trubnikov, P. Zenkevich, Numerical Simulation of Particle Dynamics in Storage Rings Using Betacool Code. Proceedings of RuPAC XIX, Dubna 2004. http://betacool.jinr.ru