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BEAM TRANSFER SYSTEMS OF NICA FACILITY: FROM HILAC TO BOOSTER

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Abstract

New accelerator complex is being constructed by Joint Institute for Nuclear Research (Dubna, Russia) in frame of Nuclotron-based Ion Collider fAcility (NICA) project. The NICA layout includes new Booster and existing Nuclotron synchrotrons as parts of the heavy ion injection chain of the NICA Collider as well as beam transport lines which are the important link for the whole accelerator facility. Designs and current status of beam transfer systems in the beginning part of the NICA complex, which are partially commissioned, are presented in this paper.

INTRODUCTION

The Nuclotron-based Ion Collider fAcility (NICA) including new accelerator complex [1, 2] is constructed in Joint Institute for Nuclear Research (Dubna, Russia). In frame of the NICA project the existing superconducting synchrotron Nuclotron which is under operation since 1993 was modernized to match the project specifications [3, 4] and the new accelerators - the heavy ion linear accelerator (HILAC) and the superconducting Booster synchrotron [5] – as well as systems of beam transfer between these accelerators had been created and commissioned in 2016-2021 [6-9].

In the paper, design and current status of creation and commissioning of the first of connecting links of the heavy ion injection chain of the NICA Collider - beam transfer systems from the HILAC to the Booster - are given.

BEAM TRANSFER FROM HILAC TO BOOSTER

The beam transfer of heavy ions (Au^{31+} is chosen as reference ions) from the HILAC into the Booster ring at energy of 3.2 MeV/n is fulfilled by means of a beam transport channel and devices of a beam injection system of the synchrotron [10-13]. The ion-optical system of the beam transport channel and the beam injection system provide beam injection by several methods for accumulation of ions in the Booster with required intensity. Main methods of beam injection are single-turn, multi-turn (up to three turns) and multiple injections (twice or triple injection repetitions with rate of 10 Hz). Accumulation of ions is based on betatron stacking in the horizontal phase plane of the Booster synchrotron. To be able to inject beams by three given methods, the beam injection system of the Booster has a set of devices containing the electrostatic septum ESS and three electric kickers, or modules of inflector plates IP1 – IP3. The beam transport channel from HILAC to the Booster [14] contains 2 dipole and 7 quadrupole magnets, 6 steerers, a debuncher and extended set of beam diagnostics devices including Faraday cups, fast and AC current transformers, shoe-box and button pick-ups, a phase probe, multi-wire profile monitors (see Fig. 1). The ion-optical system of the channel provides beam debunching and betatron matching of ion beams of the target charge state with the Booster lattice functions as well as separation and collimation of neighbor parasitic charge states of ions. It is designed to be flexible enough to maintain required beam parameters at the channel exit for different working points of the Booster as well as for different initial beam parameters at the exit of the HILAC. The beam transfer systems also have options useful to fill more compact the phase space of the Booster by injected ions: rapid change of electric fields inside the kickers and variation of electric fields of the septum and magnetic fields of the channel's magnets in intervals between beam injections during multiple injection.

The HILAC-Booster beam transport channel is located in the median plane of the synchrotron and connected to the Booster at the entrance of the electrostatic septum ESS. The septum ESS and the kicker IP2 [15] are placed in the 1st straight section of the Booster ring (see Fig. 2) which is under room-temperature conditions. The kickers IP1 and IP3 are located in the vicinity of the 1st straight section and placed inside the Booster cryostat.

EQUIPMENT

Dipole, quadrupole and steering magnets of the channel are room-temperature. Dipoles and quadrupoles are powered in pulsed mode. Pulsed power supplies developed and assembled at JINR provide twice-triple repetitions of pulses to maintain multiple injection and also allow to realize dynamical retuning of the channel. 2D steerers have DC power supplies. Optional DC power supply is also used for the dipoles to obtain high stability of magnetic fields.

The 4-gap debuncher was produced as a part of Bevatech (Germany) project on design and creation of the HILAC. The debuncher is integrated into the HILAC RF system.

The electrostatic septum with length of 1.9 m is a pair of curved anode and cathode with curvature radii of 11.535 m and 11.5 m correspondingly installed inside a vacuum box. High voltage up to 130 kV is applied to the cathode while the anode is grounded. HV power supply maintains capability to vary the voltage in intervals between beam injections during multiple injection in the range to 10 kV.

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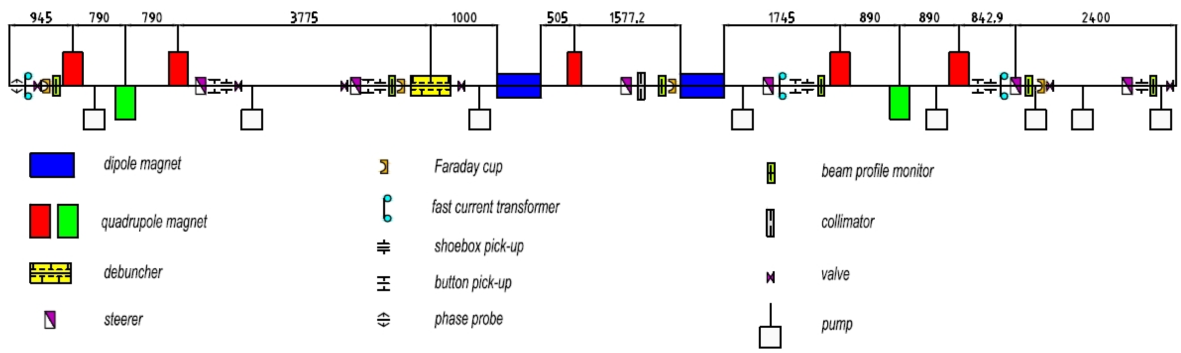

Figure 1: Layout of the HILAC-Booster beam transport channel. Beam direction is from left to right.

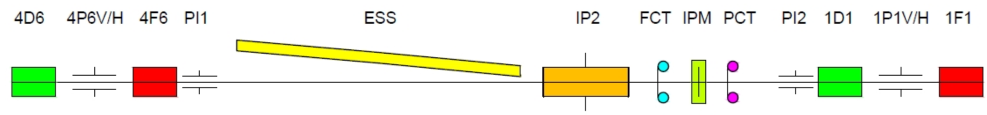

Figure 2: Layout of the 1st straight section of the Booster. Notation: 1D1, 1F1, 4D6, 4F6 – quadrupole lenses, FCT – fast current transformer, PCT – parametric (DC) current transformer, IPM – ionization profile monitor, 1P1V/H, 4P6V/H – lattice vertical/horizontal pick-ups, PI1, PI2 – additional vertical/horizontal pick-ups for beam injection tuning.

The electric kickers IP1 – IP3 are pairs of inflector plates installed vertically inside vacuum chambers parallel to the Booster axis. In turn the chambers of the cryogenic modules IP1 and IP3 are places inside cryostats. The IP1 and IP3 are designed on maximum voltage up to 65 kV while the module IP2 has maximum voltage of 50 kV. Five pulsed power supplies [16] provide independent unipolar charging/discharging of each of the inflector plates excluding one of the plates of the module IP1. Two modes of power supply system operation are maintained: the single-plateau pulse mode with charging of one plate of the kicker only and the double-plateau pulse mode with charging of both plates and asynchronous discharging of them which leads to rapid jump of electric field.

COMMISSIONING AND FIRST RUNS WITH BEAMS

At present all the beam transport channel equipment except one multi-wire profile monitor and a collimator of ions of parasitic charge states was manufactured and most of them is mounted (see Fig. 3) and tested on the channel during three stages of the channel mounting performed in 2019-2021.

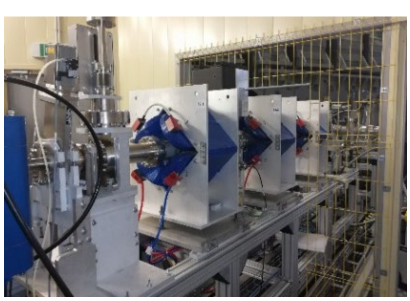

Figure 3: The beginning section of the HILAC-Booster beam transport channel.

Manufacturing of all the modules of inflector plates as well as the electrostatic septum is also finished and the start configuration of the beam injection system providing the single-turn injection of a beam is assembled on the Booster ring in 2020. It includes the module of inflector plates IP3 with one pulsed power supply feeding the primary plate of the module (see Fig. 4) and the electrostatic septum with the module of inflector plates IP2 (see Fig. 5).

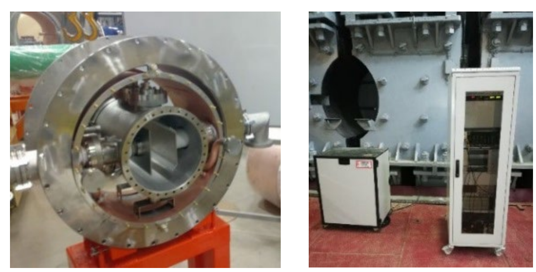

Figure 4: The module of inflector plates IP3 before mounting into the Booster (left) and racks of power supply and control of the IP3 near the Booster tunnel (right).

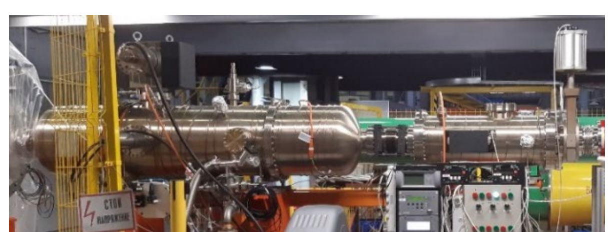

Figure 5: The electrostatic septum (left vacuum box) and the module of inflector plates IP2 (right vacuum box).

The first ion beam in the HILAC-Booster beam transport channel was transported during the short run of the HILAC on December 2019 after finish of the first stage of mounting when a beam had been observed in the last Faraday cup of the channel.

The first run of the Booster was hold on December 2020. At start of the run, after vacuum pumping of the insulating volume and beam pipes of the Booster, the equipment of the beam injection system had been tested and the septum

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has reached the design value of voltage 130 kV. On the IP3 the voltage of 62 kV which is close to the design one has been also obtained.

During the run the He^{1+} ion beam had been successfully transported in the channel with transmission efficiency of more than 90%, injected into the Booster ring and a beam circulation was obtained without activation of the closed orbit correction system of the Booster. Injection was achieved with the tuning of the beam injection system close to the designed one: voltage of the ESS - 74 kV vs. 72 kV, voltage of the IP3 - 38 kV vs. 40 kV.

During the runs on December 2020 and September 2021, tuning of a beam transmission through the final section of the channel and the beam injection devices ESS and IP2 was resulted in transmission efficiency about 90% and then the following methodic of fine tuning of beam injection was tested. The main idea of the methodic is that the closed orbit (CO) may be locally corrected (by means of steerers located in vicinity of the 1st straight section) in order to get intersection of the CO and a trajectory of the injecting beam in the center of the module IP3 that allows to inject a beam directly onto the corrected CO with minimal deviations from the Booster axis. The first step is to obtain a beam circulation during first several turns by tuning of the Booster magnetic field, the working point and the CO correction system. Then turn-by-turn measurement of the injected beam positions and angles at the septum exit during first N turns is performed by processing signals from two pick-ups neighbour to the 1st straight section: the pair PI1 and PI2 (at present these pick-ups are not installed yet into the Booster) or the pair 1P1 and 4P6 (which were used in the first Booster runs). Phase coordinates of the injected beam at the septum exit are calculated by solving the matrix equations [Eq. (1)].

$$\begin{cases} X_{2,i} = M_{sep\to 2} \cdot M_{1\to sep} \cdot X_{1,i} \\ X_{sep,i} = M_{1\to sep} \cdot X_{1,i} \end{cases} \qquad (1)$$

Here $X_{1/2/sep,i}$ – vectors of phase coordinates of a beam in the 1st or 2nd pick-up or the septum exit after i^{th} turn where $x_{1/2,i}$ and $y_{1/2,i}$ are measured beam positions in the pick-ups; $M_{1\to sep}$ and $M_{sep\to 2}$ – transfer matrices from the 1st pick-up to the septum exit and from the septum exit to the 2nd pick-up correspondingly.

As a result of the measurements, ellipse-shaped figures may be plotted representing coherent oscillations of a beam after injection (see Fig. 6) and parameters of the Booster ring at the septum exit such as phase coordinates of CO X_{CO} and lattice functions β_x, α_x as well as betatron tunes Q_x may be evaluated by processing the set of turn-by-turn measured phase coordinates (see [Eqs. (2-4)]). Brackets ⟨ ⟩ in [Eqs. (2-3)] mean averaging over turns.

$$X_{CO} = \langle X_{sep,i} \rangle, \qquad (2)$$

$$\begin{pmatrix} \beta_x & -\alpha_x \\ -\alpha_x & \gamma_x \end{pmatrix} = \frac{\langle (X_{sep,i}-X_{CO})\cdot(X_{sep,i}-X_{CO})^T \rangle}{\sqrt{\det\langle (X_{sep,i}-X_{CO})\cdot(X_{sep,i}-X_{CO})^T \rangle}} \qquad (3)$$

$$Q_x = \left\langle \arctan\left(\beta_x \frac{x'_{i-1}}{x_{i-1}} + \alpha_x\right) - \arctan\left(\beta_x \frac{x'_i}{x_i} + \alpha_x\right) \right\rangle \qquad (4)$$

The estimated parameters permits to find initial positions (x_0, x'_0) of the injected beam at start of the 1st turn which are calculated by [Eq. (5)] (analogously for y).

$$\varphi_0 = Q_x - \arctan\left(\beta_x \frac{x'_1}{x_1} + \alpha_x\right),$$

$$x_0 = \sqrt{2\,\beta_x\, I_x}\, cos\, \varphi_0,$$

$$x'_0 = \sqrt{\frac{2\, I_x}{\beta_x}}\,(sin\, \varphi_0 - \alpha_x\, cos\, \varphi_0). \qquad (5)$$

Knowing phase coordinates of both CO and the injected beam, one can firstly tune the septum and the IP3 to shift the initial position of the injected beam closer to the Booster axis and then correct the orbit by local bump to shift CO into the initial position of the injected beam. Iteration of these steps permits to tune the beam injection with minimal amplitudes of coherent oscillations.

During the run on September 2021 the beam injection with amplitude of coherent oscillations less than 4 mm was obtained. In Fig. 6 results of tuning of injection of Fe^{14+} beam are presented.

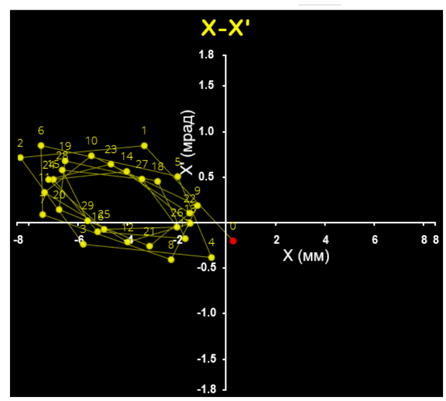

Figure 6: Phase trajectories of horizontal coherent oscillations of the injected Fe^{14+} beam at the exit of the electrostatic septum. Red point is the calculated initial position of the injected beam. Phase coordinates are given in mm and mrad.

CONCLUSION

Start configuration of the HILAC-Booster beam transfer systems has been manufactured and commissioned in 2019-2021. The first two runs of the Booster allow to test the systems with beams of He^{1+} and Fe^{14+} ions and beam transmission from HILAC to the Booster was achieved at level not less than 80%. Methodic of fine tuning of the beam injection providing minimization of coherent oscillations after injection has been proposed and successfully tried out.

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