TRANSFER CHANNEL FROM BOOSTER TO NUCLOTRON AT THE NICA FACILITY

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Abstract

In the last years the Nuclotron-based Ion Collider fAcility (NICA) project is developed at Joint Institute for Nuclear Research (JINR), Dubna, Russia. Important elements of the NICA are two synchrotrons: Booster and Nuclotron. Connection between these synchrotrons is provided with the transfer channel for heavy ions at energy of 600 MeV/u. The transfer channel includes a stripping station and charge separation system. General goal of the optic design is to minimize emittance at the exit of the channel. Magnetic system of the channel will be constructed using magnets of the Nuclotron type.

INTRODUCTION

The NICA project [1] aims to construct the new accelerator facility for colliding beam experiments. The first stage of the project is experiments on heavy ion beams particularly gold ions. Goals of the transfer channel between Booster synchrotron and existing Nuclotron are the following: the beam transport with minimum ion losses and minimum increase of the beam emittance; ion stripping to a maximum charge state (the goal charge of the beam) and the separation of parasitic charge states. The design parameters of the ion beam are given in Table 1.

Table 1: Design parameters of the beam

Sort of ions	
before stripping station	Au^{31+}, Au^{52+}, Au^{65+}
after stripping station	Au^{79+}
Maximum energy of ions, MeV/u	685
Maximum magnetic rigidity of ions, T m:	
before stripping station	25
after stripping station	11
Ion number	$2{\cdot}10^9$

The channel has some features considered in the physical design of the channel:

- complex 3D geometry which proposes the installation of tilt bending magnets;
- presence of the striping station and the necessity of the separation of parasitic charge states;
- different magnetic rigidities of ions before and after the striping station;
- wide ranges of momentum spread values, horizontal and vertical emittances at the entry of the channel;
- increase of the beam emittance in the channel because of ion stripping and betatron coupling;
- mismatch of the beam parameters with lattice functions of Nuclotron.

Old version of physical design of the channel has been presented in early works [2, 3]. New schemes of the beam extraction from Booster and the beam injection into Nuclotron are applied that impact on the channel geometry. Also, the new lattice of the channel is designed considering minimization of transverse emittances after the beam injection into Nuclotron.

LATTICE OF THE TRANSFER CHANNEL

The geometry and the magnetic system of the channel are mainly defined by the mutual position of Booster and Nuclotron. These synchrotrons have different radii and vertical positions of their median planes. The vertical distance between median planes of the synchrotrons is 3.76 m. The beam is extracted from Booster in both directions. The horizontal extraction angle is 120 mrad, the vertical extraction angle is 30 mrad. The beam is injected into Nuclotron in the vertical plane at an angle of 350 mrad. The beam in the channel is transported in the horizontal and vertical directions simultaneously. The total length of the channel is 23.2 m. Its azimuthal size is 45°, which corresponds to the beam injection through one Nuclotron octant from the point of extraction from Booster.

The channel consists of 5°tilt sector bending magnets and 7°quadrupoles, 2 of which are tilt ones. Magnetic elements of the beam are superconductive with an iron yoke. One quadrupole has the opportunity to reverse a polarity. Vacuum chamber of the channel has a circle cross section with a diameter of 60 mm.

The stripper station is situated inside the Booster yoke. Parasitic charge states after stripping is separated by the optical system of the channel and then a superconductive Lambertson magnet.

General view of the Booster-Nuclotron channel and a view from above are given in Fig. 1, 2. Vertical profile of the channel is shown in Fig. 3 (the profile means a side view of the linearized channel so it differs from any lateral view of the channel itself). Lattice of the channel is presented in Fig. 4, where BM1-BM5 — bending magnets, Q1-Q7 — quadrupoles, LM — Lambertson magnet, Str — stripping station. Main parameters of the magnetic elements are given in Table 2.

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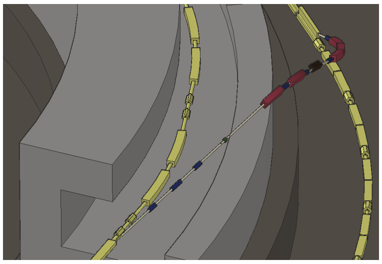

Figure 1: General view of Booster-Nuclotron channel.

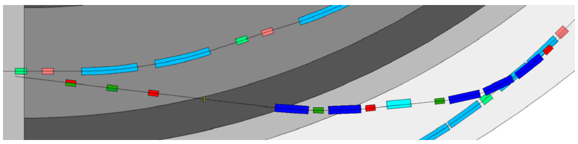

Figure 2: A view of the channel from above.

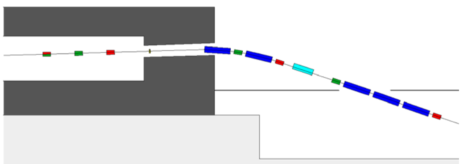

Figure 3: Vertical profile of the channel.

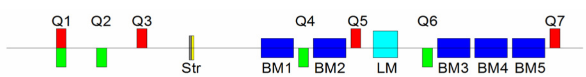

Figure 4: Lattice of the channel.

Table 2: Main parameters of the magnetic elements

Magnetic element	**Effective length, м**	**Max. magnetic field (gradient), T (T/m)**
BM1-BM5	1,312	1,8
LM	1	1,5
Q1, Q3	0,4	27
Q2	0,6	27
Q4-Q7	0,4	12

OPTIMIZATION OF OPTICAL SYSTEM OF THE CHANNEL

The beam is transported from Booster to Nuclotron with increase of longitudinal and transverse emittances. The main reasons behind the growth are the following:

- multiple scattering and energy straggling of the beam ions at the stripping target;
- a coupled motion in tilt bending magnets;
- a mismatch of the beam at the exit of the channel with lattice functions of Nuclotron.

Significant growth of the beam emittance causes decrease of NICA collider's luminosity, so minimization of the emittance growth in the channel is a necessary requirement for parameter definition of the channel optical system.

The optical system of the channel has to provide separation of parasitic charge states appearing after stripping and their extraction to a dump system because of high beam intensity.

So, criteria of optimality for a tuning of the channel optical system are:

1) minimality of horizontal and vertical emittances of the beam after their dilution by filamentation in Nuclotron (longitudinal emittance growth depends only on properties of the stripping target and is not taken into account in the optimization);

2) full separation of Au^{78+} ions from the Au^{79+} beam.

The values of the beam emittance at the entry of the channel may vary over a wide range because Booster has features such as: 1) different methods of the beam injection, and 2) the electron cooler system. Optical system of the channel must satisfy the criteria of optimality defined above for all the possible initial values of momentum spread, horizontal and vertical emittances.

The optimization of the optical system of the channel is the minimization of the corresponding objective function, arguments of which are gradients of magnetic field in quadrupoles. Minimization is performed by numerical methods.

Simulations have been carried out for initial values of momentum spread, horizontal and vertical emittances in the following ranges: from 0.01 to 1.8 π·mm·mrad for horizontal emittance $\varepsilon_{x,0}$; from 0.01 to 0.14 π·mm·mrad for vertical emittance $\varepsilon_{y,0}$; from $7\cdot10^{-5}$ to $3\cdot10^{-4}$ for momentum spread $\sigma_{p,0}$. 125 µm Carbon film was considered as the stripping target. The simulation results are shown that longitudinal emittance growth is not greater than 10%, that is acceptable. Values of horizontal and vertical emittances after their dilution in Nuclotron ($\varepsilon_{x,Nucl}$ and $\varepsilon_{y,Nucl}$) are less than 1.5π·mm·mrad and 0.9 π·mm·mrad, respectively. It should be noted that vertical emittance of the beam increases for any values of $\varepsilon_{x,0}$ and $\varepsilon_{y,0}$ while horizontal emittance decreases for $\varepsilon_{x,0}$ > 0,5 π·mm·mrad. It is explained by betatron coupling in the channel. Variation of initial momentum spread does not influence essentially on transverse emittances.

Ranges of optimal gradients in the channel quadrupoles are given in Table 3. Contour plots of horizontal and vertical emittances $\varepsilon_{x,Nucl}$ and $\varepsilon_{y,Nucl}$ depending on initial values are presented in Fig. 5.

Table 3: Parameters of quadrupoles in the channel.

Quadrupole	**Gradients (min/max), T/m**
Q1	-11.8 / 22
Q2	-26.5 / -9.7
Q3	20.8 / 25.2
Q4	-10.1 / -6.4
Q5	5.3 / 9.5
Q6	-8 / -5.1
Q7	5 / 6.8

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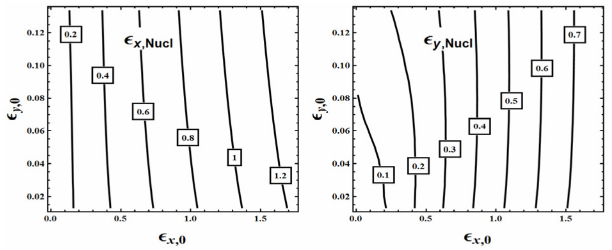

Figure 5: Contour plots of horizontal (left) и vertical (right) emittances after their dilution in Nuclotron. All values are given in π·mm·mrad.

BEAM DYNAMICS SIMULATION

Simulation of the beam dynamics in the channel has been fulfilled for different initial values of the beam emittances. Results have shown that the chosen aperture of the vacuum chamber allows transporting the ion beam with 100% efficiency.

The results of the beam dynamics simulation for $\varepsilon_{x,0}$ = 1.8 π·mm·mrad, $\varepsilon_{y,0}$ = 0.14 π·mm·mrad and $\sigma_{p,0} = 3 \cdot 10^{-4}$ are given in Fig. 6-8. The optical functions of the beam $\beta_{x,y}$ and $D_{x,y}$ are shown in Fig. 6. Envelopes of the beam $a_{x,y} = 2.45\sigma_{x,y}$ are in Fig. 7. Fig. 8 shows evolution of the RMS beam emittances $\varepsilon_{x,y}$ along the channel (including the beam emittance growth due to the injection of the mismatched beam into Nuclotron that is shown as a leap at the plot end).

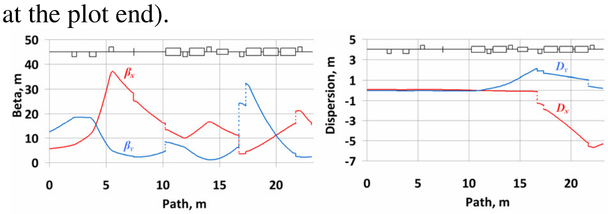

Figure 6: The optical functions of the beam.

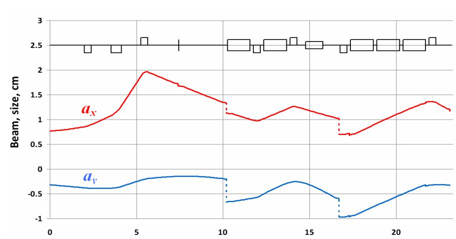

Figure 7: The beam envelops along the channel.

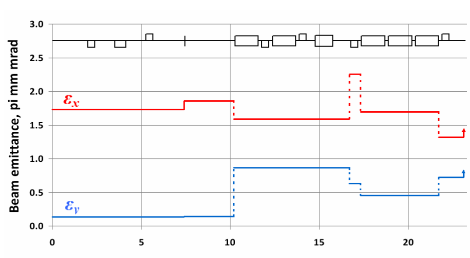

Figure 8: Evolution of the beam emittances.

As the channel does not lie in one plane, coordinates x and y means transverse coordinates of local reference system spanned by the accompanying tripod of the reference trajectory of the beam. Ox is an axis directed at a minimal angle to the horizontal plane. Rotations of the local reference system are used in the beam dynamics simulations because magnetic elements are installed at different angles to the horizontal plane. The rotations are shown as dashed gaps of the plot in Fig. 6-8.

CHARGE STATE SEPARATION

A composition of the ion beam after the stripping station is defined by its stripping efficiency. The stripping efficiency for Au^{31+} at the energy of 580 MeV/u (that corresponds to the Booster maximum magnetic rigidity) is estimated to be not less than 80%, so ions of parasitic charge states (mainly Au^{78+}) after stripping can reach about 20% of the beam intensity.

A section of the channel with bending magnets BM1-BM2 and quadrupoles Q4-Q5 is used for the separation of the parasitic charge states. Lambertson magnet carries out a final extraction of Au^{78+} ion beam.

The trajectories and envelops of Au^{79+} and Au^{78+} beams in the separation section are given in Fig. 9.

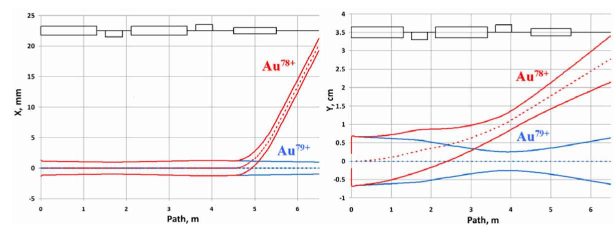

Figure 9: The separation of Au^{78+}ion beam.

CONCLUSION

The geometry and the lattice have been chosen in frame of the conceptual project of the Booster-Nuclotron channel. The optical system parameters have been optimized to provide the ion beam transport with a minimal emittance growth and full separation of parasitic charge states. Requirements for the aperture of the vacuum chamber and the magnetic elements of the channel are defined by means of the beam dynamics simulations. Design and parameters of the magnets are similar to the Booster ones, which prototypes were constructed and tested at JINR.

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