COMPARATIVE RESEARCH OF LOW ENERGY BEAM TRANSPORT SYSTEMS FOR H-MINUS ION BEAM

B.A.Frolov, National Research Centre “Kurchatov Institute” State Research Center of Russian Federation – Institute for High Energy Physics, Protvino, Moscow Region, Russia
V.S.Klenov, Institute for Nuclear Research, Russian Academy of Science, Moscow, Russia

Abstract

The source of H-minus ions for the injection in LU-30 accelerator is constructed in IHEP. A three-dimensional simulation code IBSimu (Ion Beam Simulation) has been utilized for modeling of the transport and matching system of beam from the H-minus ion source into RFQ. A magnetic low energy beam transport (LEBT) line consisting of two solenoids and LEBT consisting of six magnetic quadrupole lenses were analyzed. The particle data from the 50 mA 100 keV ion beam extraction system simulations were taken as the starting data for the LEBT simulations. The final aim of calculations was to achieve the required Twiss parameters and to minimize emittance growth of beam at RFQ entrance. LEBT consisting of two solenoids is more convenient in adjustment and as simulation results have shown this system offers more acceptable beam characteristics at the match point in comparison with LEBT composed of quadrupole lenses.

INTRODUCTION

The collaboration of IHEP and INR is developing the source of H-minus ions for injection in the linear accelerator LU-30. The implementation of the negative ion source as the linear accelerator injector and the organization of multi-turn charge-exchange injection at the circular accelerator exit U-1.5 (buster) will allow to several times raise the intense of the IHEP acceleration complex. This will provide new possibilities for fundamental research and applied studies. For charge-exchange injection implementation the source generating H-minus ion beams with the following parameters: current ≥ 50 mA, pulse duration – 25 µs, repetition rate - 25 Hz, energy of ions -100 keV, normalized rms emittance ≤ 0.25 π mm·mrad, e/H^- ratio < 5 is being developed. The surface-plasma source with the Penning gas-discharge chamber with axially symmetric emission aperture at the ion source exit was chosen as a source of H-minus ions. The three-electrode ion-optical system (IOS) was simulated with 3D code IBSimu [1] to extract H-minus ions from plasma, form beam and accelerate it up to the energy of 100 keV in [2].

At the LU-30 accelerator entrance the ion beam with the energy of 100 keV should have the following parameters: normalized 4•rms emittance (for the 50 mA beam current) $\varepsilon \leq 1\pi$ mm·mrad and Twiss parameters of phase ellipse α=2.3, β=0.14. In [2] as a first approximation the beam transportation through the two solenoid matching channel to the RFQ entrance was simulated with by code TRACE-2D. Matching channel calculations done with the help of TRACE-2D do not take into consideration the fields distribution and space charge and do not allow to evaluate the beam emittance growth at its transportation to RFQ. In the current work the 3D modelling of the whole system including three-electrode IOS and two-solenoid LEBT with consideration of real field distribution for the 50 mA beam current was done with the help of code IBSimu. The matching channel consisting of the magnetic quadrupole lenses was examined. For the quadrupole lenses channel it resulted hard to provide the beam matching with the accelerator entrance because of considerable angle divergence which the beam acquires at the drift length before the channel entrance. IOS consisting of five electrodes was projected to reduce the radius and the beam divergence angle at the matching channel entrance.

IOS OF BEAM EXTRACTION AND ACCELERATION TO 100 KEV

The three-electrode IOS of H-minus ions extraction is formed by plasma, extraction and acceleration electrodes. Plasma electrode works as gas discharge anode and is at the impulse potential of 100 kV. The extraction electrode potential is +20 kV relative to the plasma electrode, acceleration electrode is ground. Emission aperture with 3 mm diameter was selected upon analog of the version of the penning source developed in BINP SB RAS [3]. The selection of the three-electrode IOS optimal geometry (radii of extraction (2 mm) and acceleration (2 mm) electrodes and lengths of extracting (3.3 mm) and accelerating (7.5 mm) gaps) was done [1] basing on a series of detailed calculation under the condition of getting minimal emittance at the matching channel entrance. 3D modeling and IOS optimization was carried out with the help of code IBSimu taking into account scattered transverse magnetic field of penning discharge for the H-minus beam current of 50 mA with the co-extracted electrons current of 150 mA.

IOS variants with additional electrodes with accelerating or decelerating potential were investigated to reduce the radius and divergence angle of the beam at matching channel entrance and to extend IOS focusing capacities. The optimal variant which ensured minimal emittance growth in such a system consisting of five electrodes with the potential of 0 kV - 20 kV - 100 kV - 50 kV – 100 kV (in the line of beam) is demonstrated in fig.1. The first three electrodes have the same geometry (diameters and gaps) as those in the 3-electrode IOS. The radius of the forth electrode is 2.5 mm and the distance from it to the third and fifth electrodes is 4 mm. The ion source magnetic field with the induction of around 0.1-

ISBN 978-3-95450-181-6

0.15 T protrudes to the beam extraction and acceleration area and deflects the negative ions off-axis in the extraction and acceleration gaps. Two corrector dipoles with the opposed fields are used to return the beam back to axis with the null angle deflection. SmCo (10×20×10 mm^3) dipole-antidipole magnet configuration (with magnetic yoke and auxiliary winding) is located in the drift gap between the acceleration electrode and LEBT.

In simulation the ions and electrons transverse temperature was set to 2 eV, plasma potential to 10 eV, the initial energy of particles to 5 eV, number of each sign particles to 25 000. The source, dipoles, solenoids and quadrupoles magnetic fields were calculated with ANSYS and the magnetic field data were imported in IBSimu. Figure 1 shows the ions (red) and electrons (yellow) trajectories in IOS considering the source and dipoles magnetic fields. The residual magnetic field of source quite properly separates the electron flux from ion beam and deflect electrons on the extraction electrode. The simulation has been carried out with gas-discharge chamber peak magnetic field of 0.1 T.

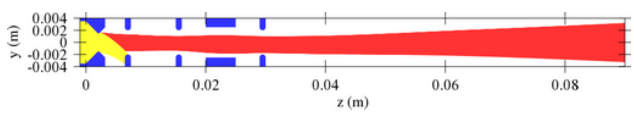

Figure 1: Trajectories of H-minus ions (red) and electrons (yellow) from 3D simulation of the five-electrode IOS.

The Einzel lens composed of the electrodes with 100-50-100 kV potentials reduces the beam radius and divergence angle at LEBT entrance for the 5-electrode IOS in comparison with the 3-electrode IOS (see below the Twiss-parameters in the table 1 and table 2). Additionally the lens makes possible tuning these parameters. Figure 2 shows the beam phase space distribution in horizontal x-plane and vertical y-plane at z = 90 mm.

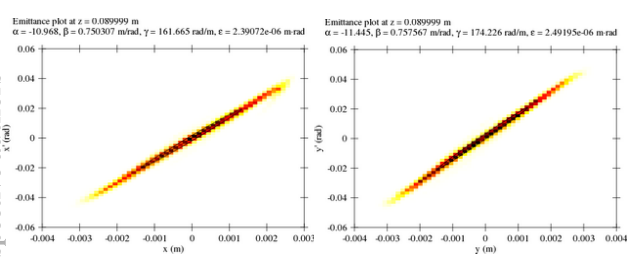

Figure 2: Calculation transverse emittance plot in xx'-plane (left) and in yy'-plane (right) from 3D simulation shown in the fig. 1 at z=90 mm.

BEAM SIMULATIONS FOR TWO-SOLENOID MAGNETIC LEBT

Constant step mesh is used for calculations in the code IBSimu. For this reason 3D simulations of IOS and LEBT were carried out in two stages. IOS was calculated with the small step ($5 \cdot 10^{-2}$ mm) of mesh, which is needed for extraction beam process simulations in the emission electrode area. LEBT simulations were carried out on a mesh with bigger step. The LEBT was simulated starting with the phase coordinates of particles from the three-electrode IOS simulation. The matching channel consisted of two solenoids, that were located at z=0.08 m and z=0.805 m respectively. The length of each solenoid with magnetic yoke is 255 mm, the aperture radius is 60 mm. The distance of 470 mm between solenoids is meant for gas evacuation and diagnostic device allocation. The whole length of two-solenoid magnetic LEBT up to RFQ entrance is 1250 mm. As a result of simulations the peak magnetic field on the axis equals 0.524 T and 0.496 T in the first and second solenoids for achieving the required Twiss parameters with minimal beam emittance growth at RFQ entrance. Figure 3 shows the H-minus ions trajectories through the LEBT for 50 mA beam current. The beam phase portraits in xx'-plane and yy'-plane at the LEBT exit are shown in figure 4.

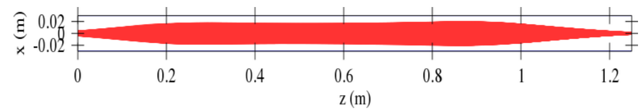

Figure 3: Trajectories of H-minus ions through two-solenoid LEBT for 50 mA beam current.

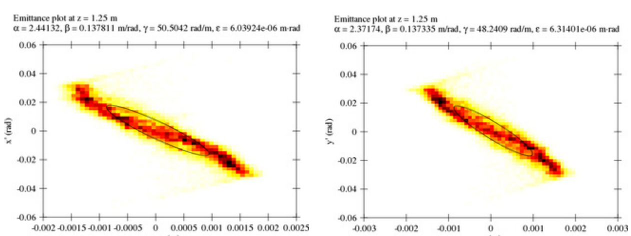

Figure 4: Calculation transverse emittance plot in xx'-plane (left) and in yy'-plane (right) at the two-solenoid LEBT exit.

Twiss-parameters and rms emittances at the two-solenoid LEBT entrance and exit are listed in the table 1. Twiss-parameters at the matching channel exit are closed to required at the RFQ entrance. Exact matching is not possible because of beam deviations at the LEBT entrance from xy-symmetry. The beam emittance value increased in 2.4 times in both planes at the LEBT exit. The normalized 4•rms emittance equals 0.35 π mm·mrad in xx'-plane and 0.37 π mm·mrad in yy'-plane at the matching point.

Table 1. Twiss-parameters and rms emittances at the two-solenoid LEBT entrance (top line) and exit (bottom line).

α_x	β_x m/rad	E_{rms}•10^{-6} m•rad	α_y	β_y m/rad	E_{rms}•10^{-6} m•rad
-19.5	1.43	2.55	-18.4	1.34	2.63
2.44	0.138	6.04	2.37	0.137	6.31

ISBN 978-3-95450-181-6

BEAM SIMULATIONS FOR QUADRUPOLE LENS MAGNETIC LEBT

The quadrupole lenses LEBT utilization instead of the two-solenoids LEBT decreases the equipment and exploitation costs. The five-electrodes IOS allows to use the system consisting of six quadrupole lenses (at reasonable lengths and diameters), bunched two triplet, for beam matching with RFQ. The phase coordinates of particles at the LEBT entrance corresponded to phase coordinates received on the five-electrode IOS exit at z=90mm. The quadrupole lenses LEBT variants with various geometry (length and diameter) and various distance between lenses were investigated. Quadrupole lenses geometry was chosen from the compromise between reasonable gradients requirement and the necessity of intensive beam transportation.

As a result of simulation and magnetic field optimization only approximate values of required Twiss parameters at the quadrupole LEBT exit were received. Figure 5 shows the H-minus ions trajectories for one of the most optimal variant of the matching channel in the xz-plane and yz-plane for 50 mA beam current. The aperture channel diameter is 80 mm, the poles length is 90 mm. The whole length of the quadrupole lenses LEBT is 1350 mm. Z coordinates of lenses are 0.07-0.16, 0.2-0.29, 0.33-0.42, 0.9-0.99, 1.03-1.12, 1.16-1.25 m. The corresponding magnetic field gradients of lenses equal ±4.156 T/m, ±5.226 T/m, ±2.731 T/m, ±2.797 T/m , ± 5.062 T/m, ±3.559 T/m (the upper sign is assigned to xz-plane, the lower sign to xy-plane). The beam phase portraits in xx'-plane and yy'-plane at the LEBT exit are shown in figure 6.

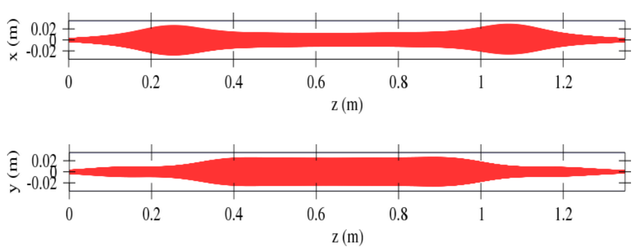

Figure 5: Trajectories of H-minus ions through quadrupole LEBT for 50 mA beam current in the xz-plane (at the top) and yz-plane (at the bottom).

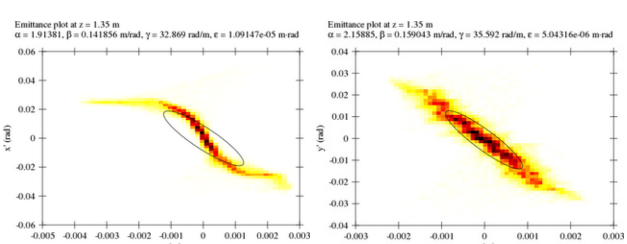

Figure 6: Calculation transverse emittance plot in xx'-plane (left) and in yy'-plane (right) at the quadrupole lenses LEBT exit.

Twiss-parameters and rms emittances at the six quadrupole lenses LEBT entrance and exit are listed in the table 2. The calculation data demonstrate noticeable aberration of the beam phase portrait and bigger growth of the emittance in xx'-plane (in 4.6 times) in comparison with yy'-plane (in 2 times) at the LEBT exit.

Table 2. Twiss-parameters and rms emittances at the six quadrupole lenses LEBT entrance (top line) and exit (bottom line).

β_x m/rad	α_x	E_{rms}•10^{-6} m•rad	α_y	β_y m/rad	E_{rms}•10^{-6} m•rad
-11.0	0.75	2.35	-11.4	0.758	2.49
1.91	0.142	10.9	2.16	0.159	5.04

CONCLUSIONS

The magnetic two-solenoid LEBT structure allows to get the beam with the close to optimal Twiss-parameters at the RFQ entrance for 50 mA beam current. In the same time the beam emittance grows in 2.4 times, which is absolutely acceptable. The magnetic quadrupole lenses LEBT allows to reach less satisfactory beam matching with bigger emittance growth in one of the planes. Let's notice that the matching channel of two solenoids is easy in tuning (by adjusting the two solenoid currents) in comparison with the six quadrupole lenses LEBT.

REFERENCES

[1] T. Kalvas, O. Tarvainen, T. Ropponen, O. Steczkiewicz, J. Ärje et.al., "IBSIMU: A three-dimensional simulation software for charged particle Optics", Rev. Sci. Instrum., **81**, 02B703 (2010).

[2] B.A. Frolov, V.S. Klenov, V.N. Mihailov, O.M. Volodkevich, "Simulation and Optimization of Ion Optical Extraction, Acceleration and H^-Ion Beam Mathing Systems", RuPAC2014-THPSC46, Obninsk, Russia, pp.429-431, (2014).

[3] Yu.I. Belchenko, A.I. Gorbovsky, A.A. Ivanov et.al., "Upgrade of CW Negative Hydrogen Ion Source" , AIP Conf. Proc.,1515, 448-455 (2013).

ISBN 978-3-95450-181-6