SIMULATION AND OPTIMIZATION OF ION OPTICAL EXTRACTION, ACCELERATION AND H$^-$ ION BEAM MATCHING SYSTEMS

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Abstract

The source of negative hydrogen ions for the implementation of multiturn charge-exchange injection to increase the intensity of IHEP buster is developed. Surface-plasma ion source with Penning discharge is selected as a source of H-minus ions. A high-current extraction system with downstream electron dumping has been designed. A three-dimensional ion optical code IBSimu has been utilized for simulation and optimization the extraction system and ion beam acceleration to energy of 100 keV. A magnetic low energy beam transport line consisting of two solenoids has been designed to match the beam with RFQ. TRACE 2D code was used to optimize LEBT. A deflecting magnet with small angular deflection (10^0) has been installed between solenoids to eliminate forward tracing of neutral atoms from ions source to RFQ.

INTRODUCTION

The beam intensity increase is one of the main tasks of modern proton accelerators' development. In the leading acceleration centers of the world the charge-exchange injection H-minus (H$^-$) ions to accelerators is being used for this purpose. Such methodology is planned to be used in the IHEP booster storage ring which will allow to several times raise the intensity of U-70 complex acceleration (up to 10^{13} protons per cycle). It will be necessary to develop the highly effective and reliable source of H-minus ions. The collaboration of IHEP and INR is developing the H-minus ions source which should produce the H- beam with the following parameters: H-minus current ≥ 50 mA, pulse duration – 25 µs, repetition rate -25 Hz, energy of ions -100 keV, normalized rms emittance $\leq 0.25\ \pi$ mm·mrad, e/H$^-$ ratio < 5. Basing on the experience of working with the negative ions source in INR RAS [1] and BINP SB RAS [2], and also on the analysis of publications about the work of negative ions sources in BNL [3] , ISIS [4], FNAL [5], CERN [6] the surface-plasma source with the Penning gas-discharge chamber with axially symmetric emission aperture at the ion source output was chosen as a source of H-minus (H$^-$) ions. To extract ions from plasma, accelerate and form the beam with minimal aberrations and match the optical parameters of ion beam with the RFQ entrance the high effective ion-optical system (IOS) and low energy beam transportation system (LEBT) are needed. The numeric modeling results of IOS of extraction, acceleration and H$^-$ beam matching are described below.

EXTRACTION AND ACCELERATION SYSTEM

The three-electrode IOS is used to extract ions from plasma and accelerate to the energy of 100 keV. It is formed by plasma, extraction and acceleration electrodes. Plasma electrode works as gas discharge anode and the gas-discharge chamber of source itself is under potential of 100 kV. Emission aperture diameter equals to 3 mm. Extraction voltage is 20 kV, extracting electrode diameter is 4 mm. The acceleration of negative hydrogen ions up to energy of 100 keV happens in the second gap. The lengths of extracting and accelerating gaps were chosen basing on the detailed calculation series on the condition of getting minimal rms emittance at the matching line entrance. The drift space of 140 mm before the matching line entrance is provided after the accelerating electrode. It is meant for gas evacuation, magnet corrector and diagnostic device allocation. Penning gas-discharge chamber is located in the magnetic field with the induction of around 0.1-0.15 T. The ion source magnetic field protrudes to the extraction and acceleration area. The negative ions are deflected from the axis by the gas-discharge chamber magnetic field in the extraction and acceleration gaps. Therefore the corrector is required to compensate the H$^-$ beam deflection.

The three-dimensional code IBSimu (Ion Beam Simulation) was used for the H$^-$ beam extracting, focusing and accelerating simulation [7]. Self-consistent procedure of plasma sheath calculation takes into account fast and thermal positive ions, negative ions and electrons. IBSimu is used in several acceleration centers (like CERN, SNS , etc.) for modeling of negative ions extraction from plasma and beam transportation processes. IBSimu describes the experimental results with good accuracy [8].

The extraction system was simulated with ion source producing H- beam current of 50 mA and co-extracted electrons current of 150 mA. 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 30 000. The electron component was deflected from the ion beam on the extraction electrode by the source residual magnetic field. The simulation has been carried out with gas-discharge

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chamber peak magnetic field of 0.1 T The dipole field was used to correct the H^- beam deflection. Two SmCo permanent magnets ($10\times20\times10$ mm^3) with the axis peak induction of 0.098 T for vertical x-direction are situated at z=35 mm and create the corrector dipole field. The source and the corrector magnetic fields were calculated with ANSYS and the magnetic field data were imported in IBSimu.

The Figure 1 shows the ions (red) and electrons (yellow) trajectories in IOS considering the source and corrector magnetic fields. The gas-discharge chamber magnetic field quite properly separates the electron flux from ion beam. Setting the corrector before the beam matching line helps to minimize the ion beam deflection angle. The corrector magnetic field almost returns the H^- beam back to axis (the beam horizontal deflection from axis is in order of 0.3 mm). Second dipole is needed to achieve the beam near-zero off-axis displacement and near-zero angular deflection.

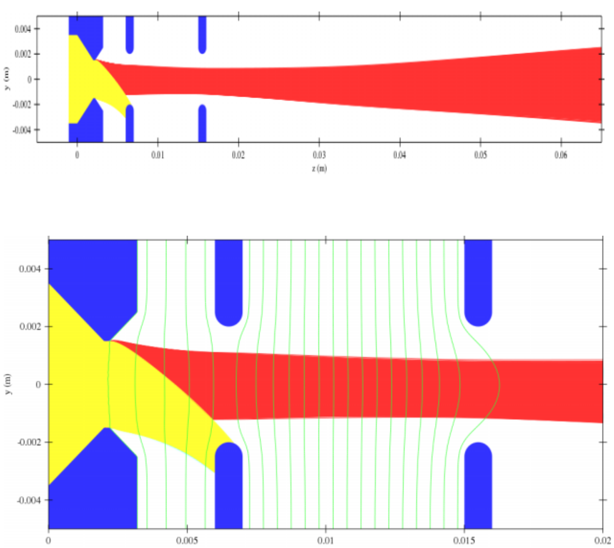

Figure 1. Trajectories of H^- ions (red) and electrons (yellow) from 3D simulation of the IOS. The co-extracted electron beam with the energy of 20 keV is deflected on the extraction electrode by a source magnetic field.

Fig.2 and Fig.3 show the beam phase space distribution in horizontal y- plane and vertical x-plane at z = 65 mm. The simulation of IOS showed that the beam emittance varies only slightly in the drift space after the acceleration electrode (ε_y = 2.50 π mm·mrad and ε_x = 2.433 π mm·mrad at z= 2 mm and ε_y= 2.466 π mm·mrad and ε_x = 2.463 π mm·mrad at z = 65 mm). The calculated normalized 4*rms emittance of ε = 0.14 π mm·mrad is approximately close in magnitude to the experimentally measured Penning source emittance in the operating mode without fluctuations of discharge parameters ("noiseless" operating mode) [9]. Source adjustment to get such operating mode should be done by optimizing hydrogen and cesium supply and the source magnetic field value.

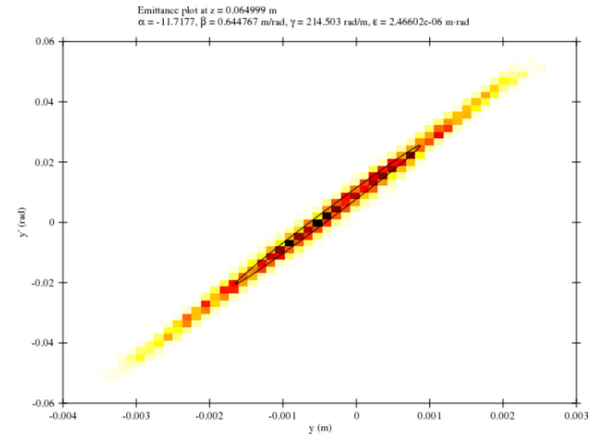

Figure 2.Transverse emittance plot in y-plane from 3D simulation shown on figure 1.

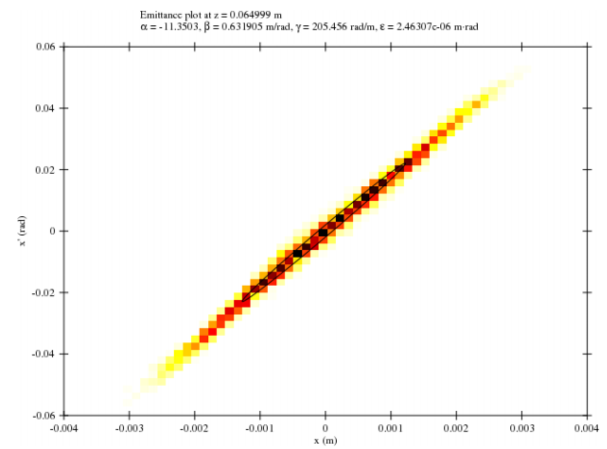

Figure 3.Transverse emittance plot in x-plane from 3D simulation shown on figure 1.

TWO-SOLENOID MAGNETIC LEBT

The emittance requirements at the entrance of the RFQ are the Twiss parameters A=2.3 and B=0.14 and 4*rms normalized emittance $\varepsilon \le 1\pi$ mm·mrad at an injection energy of 100 keV. As a first step to select set of LEBT elements, the ion beam transportation through the matching channel up to RFQ entrance was simulated by code TRACE-2D. [10]

As the forward tracing of neutral cesium atoms from the emission aperture of ions source to RFQ entrance should be eliminated, the beam-bending magnet should be added in matching channel. Several variants of arrangement for matching channel of beam with the linear accelerator LU-30 entrance were investigated, including the channel with the quadrupole lenses, with two or one solenoid lens and with beam-bending magnet in different allocations and with different parameters of deflection angles, radius and field index. For the matching channel with quadrupole lenses it resulted hard to provide the beam matching with the accelerator entrance at sensible channel geometry (length and diameter) due to quite serious angle difference which the beam acquires at the drift space before the channel entrance.

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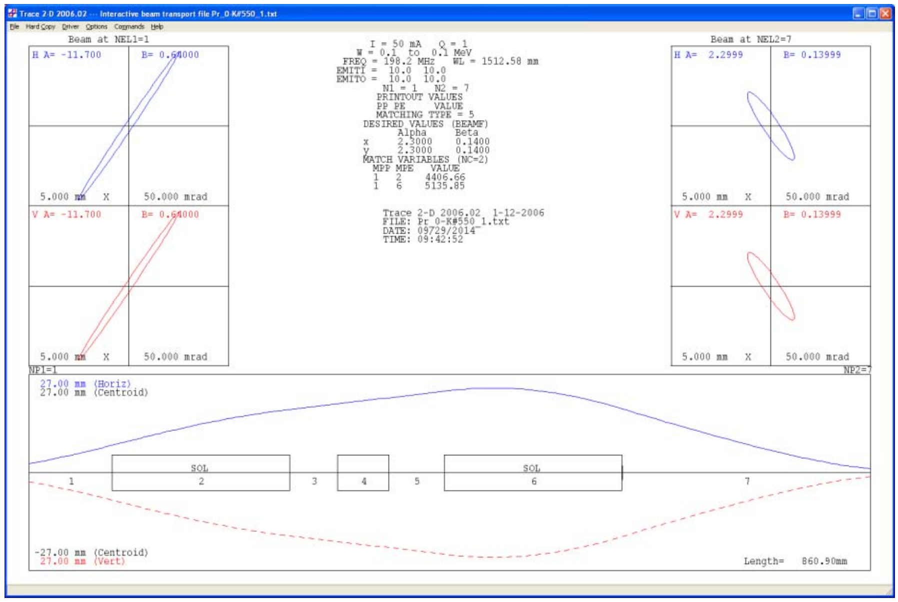

Figure 4. The beam envelope profile for two-solenoid magnetic LEBT (2, 6) with beam-bending magnet (4).

The channel of two solenoids is more convenient in adjustment and beam matching. Basing on the several parameters the variant with two solenoid lenses and beam-bending magnet with small deflection angle of 10^0 was chosen. Two correctors also included in the channel. Such LEBT structure helps to get the beam with the required parameters at the RFQ entrance and allows you to have a sufficiently large drift space before the RFQ entrance for gas evacuation and diagnostic device allocation. The Figure 4 shows the beam envelope for "noiseless" operating mode in horizontal and vertical planes. The Twiss parameters and emittance were taken from the IOS simulating at z=65 mm. The magnetic field induction on the lenses axis is around 0.441 T and 0.514 T in the first and second lenses accordingly, the channel diameter does not exceed 55 mm for the beam passing with no losses.

CONCLUSION

Simulation of IOS has been carried out with source peak magnetic field of 0.1 T. The adjustment of source magnetic field will be needed to generate ion beam in "noiseless" operating mode. Therefore the second dipole with auxiliary winding is required to compensate the beam deflection caused by the change of the source magnetic field. In the future IOS simulation will be carried out by taking into account the second dipole and with various values of the source magnetic field. LEBT will be also simulated using the large particles method and the complete IOS and LEBT modeling will be carried out by using IBSimu code.

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