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PRELIMINARY DESIGN OF A LEBT FOR HIAF LINAC AT IMP

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Abstract

Heavy-Ion Advanced Research Facility (HIAF) is a new project proposed at Institute of Modern Physics (IMP) in China. HIAF project accelerator is composed of intense ion beam sources, injector superconducting LINAC, acceleration and accumulation storage ring, a collection ring and a collider ring. To achieve the ultimate project goal, HIAF accelerator requires the ion source to provide very high intensity of heavy ion beams, such as 1.7 emA $^{238}U^{34+}$ with a repetition rate of 5 Hz and pulse length of 0.5 ms. No state-of-the-art ion source can meet the needs. As a baseline of the project, a high performance superconducting ECR ion source, which is designed to be operational at the microwave frequency of 40-60 GHz will be adopted to produce the pulsed beam of interest for the HIAF accelerator. To transport and match the beams from ECR to the downstream RFQ, a low energy beam transport (LEBT) is needed. This paper presents a preliminary design of the LEBT and the beam dynamics in the LEBT.

INTRODUCTION

Heavy Ion Advanced Research Facility (HIAF) [1] is a new project in the twelfth five-year plan for heavy ion research at Institute of Modern Physics (IMP). This facility will be used for researches of precise mass measuring, quantum chromo-dynamics, high energy density physics, radioactive physics, super-heavy element synthesis, non-perturbation hadron physics and so on. The HIAF project accelerator consists of intense ion beam sources, injector superconducting LINAC, acceleration and accumulation storage ring, a collection ring and a collider ring. The HIAF project asks for very high requirement for beam intensity of high charged heavy ions, for example, it requires 1.7 emA $^{238}U^{34+}$ beam, which is very challenging for the ion source. For ECR ion source, the latest record of the uranium beam is of 0.4 emA $^{238}U^{34+}$ [2], which is still 4.25 times lower than needed current for HIAF. However, According to Geller's scaling law, the ECR type ion source performance can be greatly improved by the factor of frequency scaling. As a baseline of the project, a so called 4th Gen superconducting ECR ion source with 40-60 GHz microwave hearting will be employed to provide the required beams.

To deliver and match the beams from ECR to the downstream RFQ, a LEBT line is needed. The high current ion beams give rise to the difficulty of LEBT design to control the beam emittance blowup. Magnets with large apertures and small aberrations should be adopted to lower down the non-linear effects and improve the beam quality. Conceptual design and beam dynamics studies of the LEBT for HIAF LINAC have been done and are discussed in this paper. The baseline design has been primarily focused on $^{238}U^{34+}$, since it is the heaviest and most challenging ion beam to meet the HIAF requirements. TRACK [3], a well proven code using PIC method, is used to carry out the beam simulation.

PRELIMINARY DESIGN OF THE LEBT

Fig. 1 shows the conceptual design of the HIAF LEBT layout. As the driver LINAC for HIAF will provide a wide range of ion beams, from H_2^+ to uranium ion, only one ion source seems inadequate to satisfy the requirements for ion species and intensities, therefore, two superconducting ECR ion sources and one room-temperature 2.45 GHz microwave H_2^+ source are arranged and each is located on a high voltage platform. The production of H_2^+ beam is accompanied with contaminant ions, such as proton and H_3^+, which will be filtered out by using a 90-degree analyzing magnet behind the ion source. For highly charged heavy ion beams, the design of the Q/A selector becomes more complicated and challenging, because it has to be matched for a wide species of ion beams with different densities. Meanwhile, the serious space charge effect will reduce the momentum resolution of the Q/A selector by increasing the beam spots in the focal plane and degrading the beam quality. Besides the space charge effect, another major factor to intensify the beam emittance growth is the aberrations in the magnets, in particular, the second-order aberration in the analyzing magnet. Therefore, the Q/A selector system has to be designed from the beginning to handle high intensity ion beams and provide an adequate resolution. As shown in Fig. 1, the Q/A selector for the superconducting ECR ion source consists of a solenoid lens, which is directly attached on the extraction flange of the source body to control the size of the beam going into the analyzing magnet, a double focusing 110-degree analyzing magnet, a set of quadrupole triplet and two slits mounted on both the horizontal and the vertical directions. The analyzing magnet has a rather large "good-field" region of 35 cm in horizontal direction and vertical gap of 22 cm. Bending radius is of 60 cm and edge angle is of 41 degree. The quadrupole triplet is used to play a supplementary role to adjust the position of the beam waist to the separation point, especially for those high current heavy ion beams. Beam diagnosis apparatuses, such as faraday cup and emittance measurement unit, are placed just after the slit system to monitor the beam quality.

Due to the required energy of 14 keV/u by RFQ, heavy ion $^{238}U^{34+}$, for example, needs to be accelerated

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by a 98 kV high voltage (HV). However, the extraction voltage of the ion source is usually below 30 kV and can not reach the energy requirement because of the sparking risk, so a 100 kV accelerating tube will be employed and all upstream elements will be put on the HV platform.

After being analyzed and accelerated, the ion beam is delivered and matched to the vertical line to reach the RFQ, which is shared by all ions. Three quadrupoles and a dual 90-degree bending magnet are used as the transmission link, in which two quadrupoles are placed before the bending magnet and the other one is just behind it.

The last section of the LEBT, so called vertical line, is to correctly match the beam to the RFQ. This section is mainly composed of four quadrupoles, two solenoid lenses, one longitudinal buncher, diagnostics and a pre-chopper just before the RFQ entrance. The four quadrupoles are used to convert a non-axisymmetric beam to an axisymmetric beam and at the same time to produce a beam waist, at where the buncher is located to pre-bunch the beams so as to provide a relatively small longitudinal emittance.

Matching of the RFQ's acceptance requests two beam Twiss parameters of α and β. This is often achieved by having at least two independent lenses, for example, two solenoids or double quadrupole-doublet. We have compared a dual-solenoid-based matching section with a double quadrupole-doublet-based matching section via beam simulations, suggesting that if choosing the second scheme, it becomes very difficult and time-consuming to tune the system to match the input conditions of RFQ, because the quadrupole is a non-axisymmetric focusing element. In addition, tight matching conditions require a strong beam convergence at the RFQ entrance, resulting in a large diameter of the beam in the quadrupoles, which will lead to a remarkable phase space deformation. On the contrary, the dual-solenoid-based matching section is rather simple and robust to facilitate a variety of input conditions. However, the strong beam convergence at the RFQ entrance forces us to adopt superconducting solenoid to provide a large enough field strength of even up to a peak value of 1 Tesla.

Solenoid will produce a rotational matrix and a focusing matrix, leading to several coupling terms in the beam matrix. The 4*4 transfer matrix of a solenoid lens can be described as:

$$R_{sol} = \begin{bmatrix} \cos^2(kz) & \sin(2kz)/2k & \sin(2kz)/2 & \sin^2(kz)/k \\ -k\sin(2kz)/2 & \cos^2(kz) & -k\sin^2(kz) & \sin(2kz)/2 \\ -\sin(2kz)/2 & -\sin^2(kz)/k & \cos^2(kz) & \sin(2kz)/2k \\ k\sin^2(kz) & -\sin(2kz)/2 & -k\sin(2kz)/2 & \cos^2(kz) \end{bmatrix}$$

If two solenoids, having the same current values but in opposite directions, are combined. The so called paired solenoid [4] will have the transfer matrix as:

$$R_{ps} = R_{sol+} * R_{sol-} = \begin{bmatrix} \# & \# & 0 & 0 \\ \# & \# & 0 & 0 \\ 0 & 0 & \# & \# \\ 0 & 0 & \# & \# \end{bmatrix},$$

Which will not give rise to a correlation between horizontal and vertical directions. Based on the above-mentioned factors, a dual-paired solenoid-based matching section is finally chosen in our design.

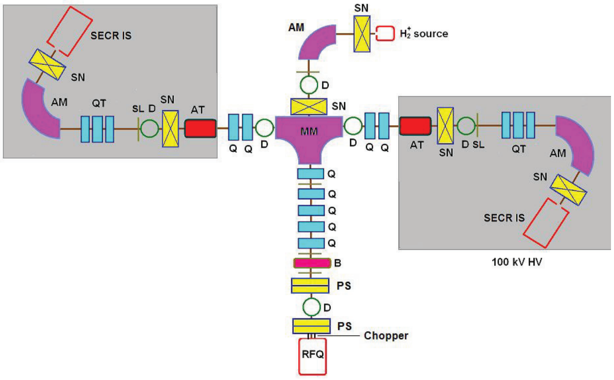

Figure 1: Conceptual design of HIAF LEBT. The abbreviations SCECR, SN, AM, SL, QT, D, AT, Q, MM, B and PS represent the super-conducting ECR, solenoid lens, analyzing magnet, slit, quadrupole triplet, diagnostics, accelerating tube, quadrupole, dual-90 degree bending magnet, buncher and paired solenoid.

BEAM SIMULATION

Q/A Selector System Simulation

Firstly, simulation was performed to verify the momentum resolution of the Q/A selector for highly charged ions. We choose $^{238}U^{34+}$ as the design ion, because it has the largest mass desired by HIAF and is most difficult to be analyzed. Multi-species ion beams tracking with TRACK code has taken space charge effect into account by assuming the total beam current of 20 emA, in which $^{238}U^{34+}$ beam current is of 2 emA. The huge self-electric field generated by the ion beams could be compensated with the secondary electrons that are generated by the ion beams either by collisions with residual gas atoms or by sputtering of ions at the beam tube. The space charge compensation (SCC) ratio was estimated to be of 90% in the simulation. Fig. 2 illustrates the analyzed beam particle distribution on the focal plane. Separation of different charge states at the resolution plane is demonstrated, showing sufficient resolution of the Q/A selector system.

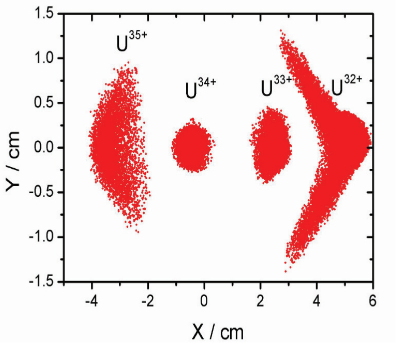

Figure 2: Simulated particle distribution on the focal plane.

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Front-to-End Dynamics Simulation

Front-to-end simulation of the LEBT requests initial beam condition at the ion source exit. However, to obtain it by experiment is challenging, because a variety of charge state ion beams are extracted from the ion source simultaneously. Ion beams extracted from ECR ion source always have a complicated structure both in real space and phase spaces. The magnetic confinement fields in the ion source will make the ion density distribution across the extraction aperture inhomogeneous and charge state dependent. In addition, a strong solenoidal field in the extraction area adds an angular momentum to the beam, resulting in a significant horizontal and vertical coupled beam. To simplify the simulation, an axially symmetric and uncoupled beam is assumed, with the initial parameters as: $\alpha_x=\alpha_y=-0.5$, $\beta_x=\beta_y=193$ mm/mrad, normalized RMS emittance $\varepsilon_x=\varepsilon_y=0.083\ \pi$ mm·mrad. Fig. 3 shows the calculated $^{238}U^{34+}$ beam envelope along the LEBT. Space charge effect is included by assuming a beam current of 2 emA and a compensation factor of 90%. However, in the accelerating tube, the SCC ratio is zero because the secondary electrons are deflected away by the electric field.

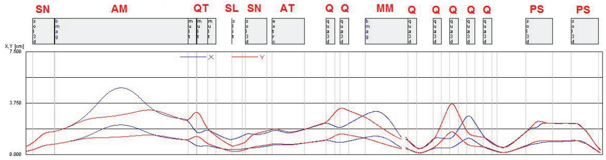

Figure 3: Calculated $^{238}U^{34+}$ beam envelope along the LEBT.

To verify the beam emittance growth along the LEBT, particle distributions in phase space at RFQ entrance are plotted in Fig. 4. The small distortions in the phase space distributions indicate the beam has a relatively small envelope when traveling through the magnetic and electric elements. The calculated normalized RMS emittances at the RFQ entrance is of $\varepsilon_x=0.12\ \pi$ mm·mrad and $\varepsilon_y=0.13\ \pi$.mm.mrad, which are within the RFQ's acceptance.

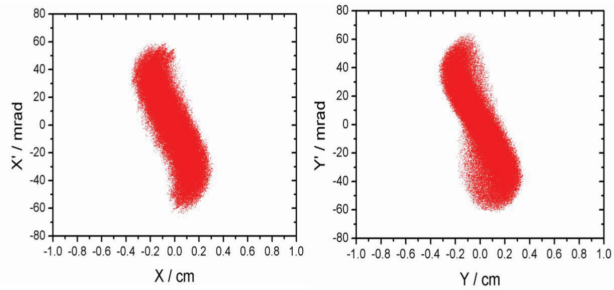

Figure 4: Simulated particle distribution in phase space at RFQ entrance.

CONCLUSION AND PERSPECTIVES

A conceptual design of a low energy beam line for HIAF LINAC has been presented and discussed. Uranium beam was tracked from the ion source exit to RFQ entrance with taking account of space charge effect. The beam dynamics simulations indicate that the emittance growth through the LEBT line is relatively slow, showing the design is reasonable and reliable to meet the RFQ demands. Detailed design and simulation will be carry out in the future, which should include more realistic conditions, such as experimental-based initial beam structure, particularly the transverse coupling feature of the beam.

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