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# Particle-in-cell mode beam dynamics simulation of the low energy beam transport for the SSC-linac injector*

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**Abstract:** A new SSC-linac system (injector into separated sector cyclotron) is being designed in the HIRFL (heavy ion research facility of Lanzhou). As part of SSC-Linac, the LEBT (low energy beam transport) consists of seven solenoids, four quadrupoles, a bending magnet and an extra multi-harmonic buncher. The total length of this segment is about 7 meters. The beam dynamics in this LEBT has been studied using three-dimensional PIC (particle-in-cell) code BEAMPATH. The simulation results show that the continuous beam from the ion source is first well analyzed by a charge-to-mass selection system, and the beam of the selected charge-to-mass ratio is then efficiently pre-bunched by a multi-harmonic buncher and optimally matched into the RFQ (radio frequency quadrupole) for further acceleration. The principles and effects of the solenoid collimation channel are discussed, and it could limit the beam emittance by changing the aperture size.

**Key words:** SSC-linac, LEBT, PIC mode, optimal injection, collimation

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## 1 Introduction

To meet the requirements of SHE (super heavy elements) experiments [1], a linear accelerator is designed to add to the HIRFL system to supply middle and heavy ions. From calcium to uranium, high intensity and low emittance beams are required from the ECR (electron cyclotron resonance) ion source, which is still very challenging, especially for heavy ions. Research and development directed towards improved ECR performance is currently conducted at the institute of modern physics to circumvent the ion source limitations to the beam current for heavier ions.

To avoid beam loss in the following superconducting linac and cyclotron, a solenoid collimation channel is designed to limit the beam emittance in transverse phase space. A pre-buncher before the RFQ aims to bunch the beam efficiently before injection. As part of the SSC-linac, the LEBT has been designed and extensively simulated by the TRACE-3D code [2], and crosschecked by the BEAMPATH code [3], which has been developed based on the PIC method.

## 2 The arrangement of LEBT

The layout of LEBT is shown in Fig. 1. Transport of the heaviest ion beams is the most challenging task. Therefore, the LEBT simulation primarily focuses on the uranium beam. Due to the space-charge effects, a high current beam diverges quickly after extraction from the ion source. Therefore, a solenoid right after the source is located to control the beam envelope and limit the emittance growth. The following bending magnet plays a valuable role in separating the different charge states [4].

After the charge selection, the four magnetic quadrupoles are used to convert an asymmetric beam from the upstream analysis section to a symmetric beam and further to the solenoid collimation chan-

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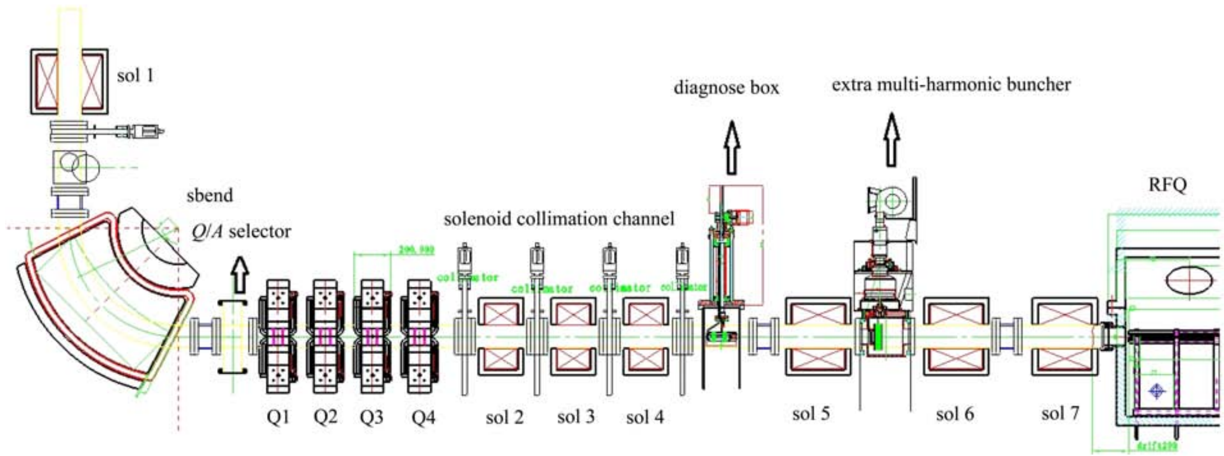


Fig. 1. The layout of LEBT in SSC-linac.

nel, they provide a large tuning range to accommodate the beams with different Twiss parameters. The three subsequent solenoids with the same length and strength are used to carry out the phase space rotation and the multiple-stage collimation [5].

The continuous beam can be efficiently prebunched by an external multi-harmonic buncher before injection into the RFQ. A beam waist is produced by sol5 and the multi-harmonic buncher is placed at this focal point to bunch beam. From this point, sol6 and sol7 focus the beam to match the RFQ acceptance. A pair of steering magnets is located between sol6 and sol7 to enable the possibility of a position and angle correction at the entrance of the RFQ.

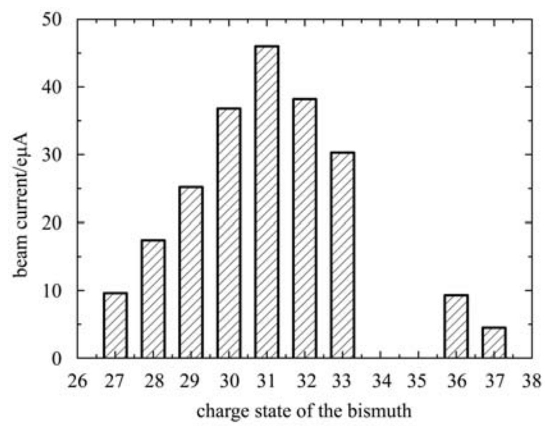


Fig. 2. The charge state distribution of bismuth after selection.

## 3 The ion source conditions

To perform beam simulations for LEBT, it is essential to have reasonable initial beam parameters from the ion source. However, there are no experimental data available for uranium beam.

Bismuth beam was systematically tested in recent commissioning. A normalized emittance of 0.062 πcm·mrad was obtained in the measurement after the charge selection for the 46 eμA $Bi^{31+}$ beam, with the total extracted current of 220 eμA for a platform voltage of 20 kV. The charge state distribution of different bismuth ions is shown in Fig. 2.

Simulations are performed using the experimental setting and measured data to obtain the initial beam parameters. An initial normalized emittance of 0.06 πcm · mrad is obtained from the beam simulations for the 46 eμA $Bi^{31+}$ and the Twiss parameters at the LEBT entrance are $\alpha_x=\alpha_y=-1$ and $\beta_x=\beta_y=$ 16.233 cm/rad.

It is assumed that uranium has a charge-state distribution similar to bismuth and all ion species have the same Twiss parameters at the exit of the ion source. An intrinsic momentum spread of ±0.2% is included for all charge-state particles. These particles are initially distributed in a four dimensional waterbag transverse hyperspace with uniform distribution in phase and momentum spread.

## 4 The beam dynamics calculation

### 4.1 The beam dynamics calculation from the ion source to the $Q/A$ selector

To limit the impact of the space-charge effects and to ease the beam transport, a higher ion source extraction voltage is preferred. Based on the commissioning experience, an extraction voltage of 25 kV for uranium beam is chosen. A 90 degree bend angle is selected for charge selection. The bending radius and pole-face angle are selected to be 60 cm and 27.5 degrees, respectively, providing double focusing. The transport of multi-charge state beams is calculated to verify the analyzing ability of the bending magnet.

The particle distributions of different charge state beams at the selection point in real space and in phase space are shown in Fig. 3. The separation of different charge states at the selection point is checked, including space-charge effects calculation, showing perfect separation of the five charge states.

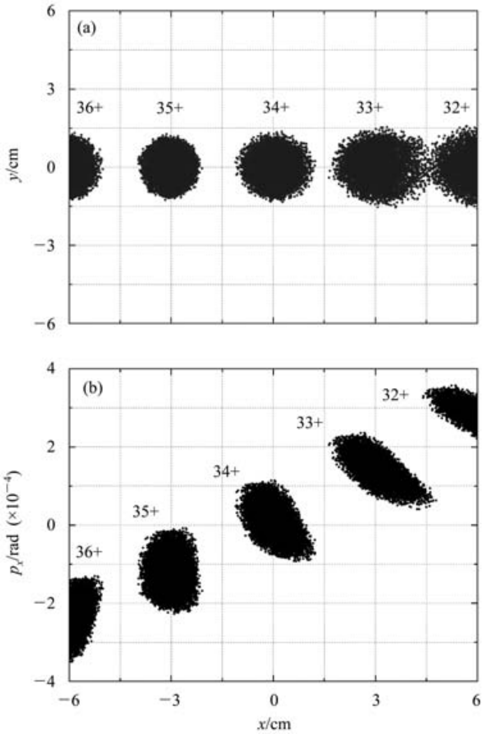


Fig. 3. (a) Particle distribution in real space. (b) Particle distribution in phase space.

### 4.2 The beam dynamics calculation from the $Q/A$ selector to the entrance of RFQ

The beam intensity for heavy ions after the selection is typically low and the space-charge effects are inconspicuous. Based on the simulation without space-charge effects, the Twiss parameters at the $Q/A$ selector are listed in Table 1 and the beam dynamics simulation is shown in Fig. 4.

Table 1. Beam parameters at the $Q/A$ selector.

| | $\alpha$ | $\beta$/(cm/rad) | $\varepsilon_n$/($\pi$cm·mrad) |
|---|---|---|---|
| horizontal | 0.487 | 28.0 | 0.06278 |
| vertical | 0.447 | 59.5 | 0.06014 |

The maximum envelope in this section is less than 4 cm and the space-charge effects are not strong behind the bending magnet, therefore the inner radius of the vacuum pipe is chosen to be 6 cm, which provides a safety margin to cope with the misalignments and mismatch of the ion source.

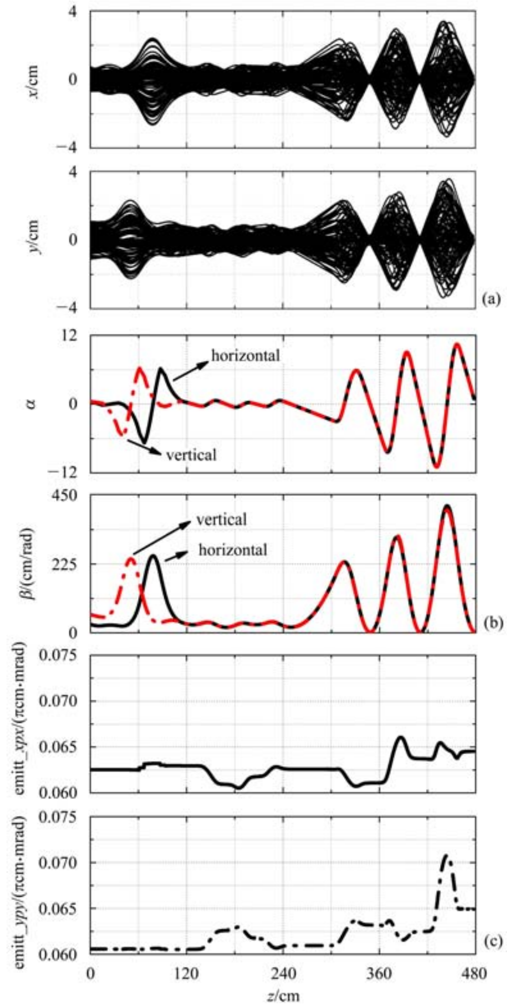


Fig. 4. (a) The multi-particle trajectories. (b) The oscillation of Twiss parameters. (c) The beam emittance growth.

Due to the edge focusing effects, the beam from the bending magnet becomes asymmetrical in horizontal and vertical phase space, but the solenoid collimation channel needs a symmetrical ellipse for injection. Four magnetic quadrupoles are used to match the beam from the bending magnet to the downstream collimation channel. The last two solenoids adapt the beam to the RFQ acceptance.

The two-dimensional magnetic fields in the solenoid are calculated as

$$B_z(z,r) = B_z(z,0) - \frac{r^2}{4}\frac{\mathrm{d}^2 B_z(z,0)}{\mathrm{d}z^2}, \quad (1)$$

$$B_r(z,r) = -\frac{r}{2}\left[\frac{\mathrm{d}B_z(z,0)}{\mathrm{d}z} - \frac{\mathrm{d}^3 B_z(z,0)}{\mathrm{d}z^3}\right]. \quad (2)$$

In order to match the RFQ injection, the large envelope has to be formed in the last two solenoids. If the particle deviates from the center of the solenoid, the particle feels a non-linear force. The non-linear force causes emittence growth in the solenoid. In the course of LEBT transmission, the beam emittance increases obviously in the last two solenoids (no more than 10%). However, the beam emittance still stays within the RFQ acceptance.

### 4.3 The pre-buncher simulation

To increase the longitudinal capture efficiency of the RFQ before injection into the cyclotron, a pre-buncher in the LEBT is required. After charge selection, the beam current is low enough, so the continuous beam can be efficiently pre-bunched before injection.

The RFQ can produce a smaller longitudinal output emittance with a pre-bunched beam. The buncher can be a single gridded gap applied by a saw-tooth wave form or resonant cavities operating at the fundamental and multiple harmonic. The particle distributions in longitudinal phase space at the $Q/A$ selector and at the exit of the LEBT are shown in Fig. 5. The pre-buncher is installed 130 cm before the entrance of the RFQ, and its voltage is about 0.8 kV.

The continuous beam from the ion source is pre-bunched at 13.4 MHz, the fourth sub-harmonic of the RFQ frequency. Nearly 80% of the input particles are captured within 90 degree RF-phase at 13.4 MHz, and these particles could be captured by the following RFQ. Since the bunching only reduces but does not cancel the beam between the main bunches, there is a small quantity of particles emerging on either side of the main bunch at the exit of the RFQ. In order to avoid the unnecessary beam loss in the following super-conducting drift-tube-linac and cyclotron, a chopper must be installed somewhere in the accelerator chain [6].

### 4.4 Perfect injection of the RFQ

The acceptance of the RFQ is calculated to be 0.12 πcm·mrad through the PARMTEQ-M code, and the momentum spread acceptance is ±3% via BEAMPATH code [7]. The injection into the RFQ must ensure a phase space smaller than the RFQ acceptance ellipse. To obtain a wanted phase space in the horizontal and vertical directions, two solenoids are necessary. The particle distributions in transverse phase space and the RFQ acceptance are shown in Fig. 6.

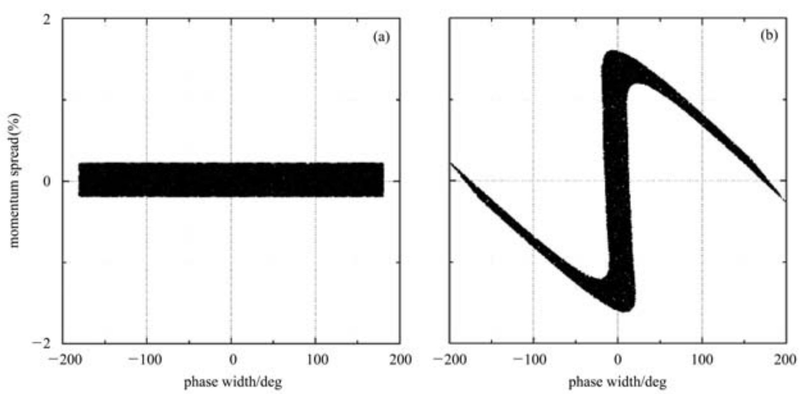


Fig. 5. (a) The longitudinal particle distribution at $Q/A$ selector. (b) The longitudinal particle distribution at the exit of the LEBT.

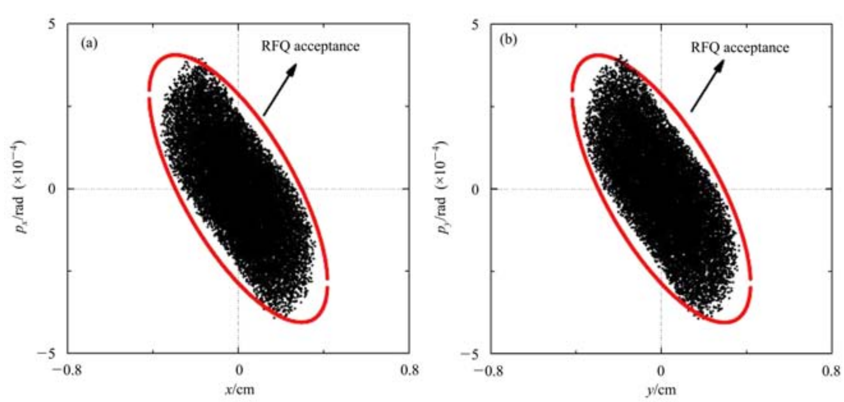


Fig. 6. (a) The horizontal particle distribution at the RFQ entrance. (b) The vertical particle distribution at the RFQ entrance.

It could be observed that the particle distributions in both phase spaces at the exit of the LEBT fit very well to the RFQ acceptance ellipses.

### 4.5 The solenoid collimation channel

The beam emittance from the ion source is generally larger than the cyclotron acceptance. The utilization of collimators to remove unwanted particles has been a well-known method to maintain beam quality since the 1970s. This channel has three cells, including three identical solenoids and four apertures (drift-solenoid-drift). Each solenoid is set to have a phase space rotation of 60 degrees. Four apertures are used to get the multi-stage collimation with the phase space rotation in between.

$$\sigma=\frac{B}{2B\rho}\sqrt{SL};\ \bar{\beta}=\frac{S}{\sigma}=\frac{2B\rho}{B}\sqrt{\frac{L}{S}};\ \varepsilon=\frac{a^2}{4\bar{\beta}}. \quad (3)$$

In the above formulas, $\sigma$ is the phase advance, $B$ is the magnetic field in the solenoid, $B\rho$ is the magnetic rigidity of the beam, $L$ is the length of the solenoid, $S$ is the length of the cell, $\bar{\beta}$ is the eigen Twiss parameter (for $\alpha$=0), $\varepsilon$ is the desired emittance and $a$ is the aperture width. Fig. 7 illustrates the particle distribution at the exit of the last collimator without and with the four successive collimators ($a$=0.5 cm).

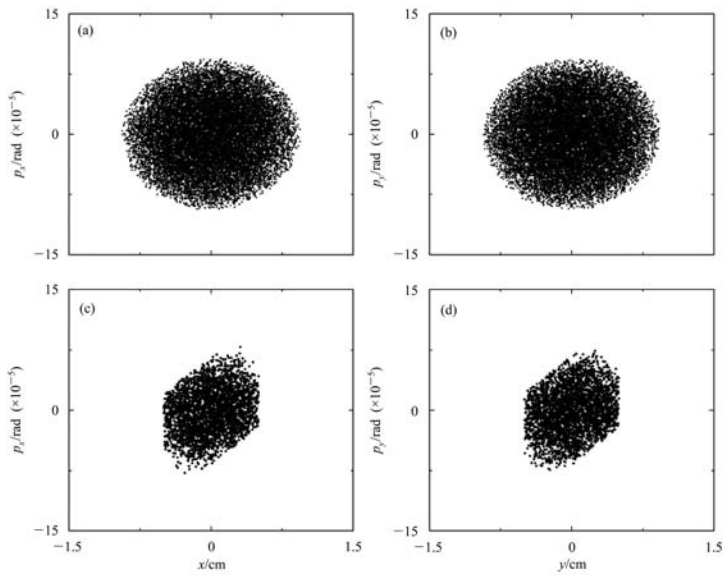


Fig. 7. (a) and (b) are the particle distributions without collimation; (c) and (d) are the particle distributions with collimation

The unwanted particles are dumped onto the collimators, and the particles with better quality are still retained. Utilization of the collimators could limit the beam emittance at the expense of decreasing the transmission efficiency, and using collimators of smaller radii could result in smaller beam emittance [8].

## 5 Conclusion

The beam simulation results show that the LEBT design for the SSC-Linac provides adequate matching and bunching for the desired charge state beam. Small transverse and longitudinal emittance can be achieved at the entrance of the RFQ for acceleration. Further beam simulations in the LEBT will include experimentally based initial beam phase spaces and parameters for uranium. Other codes will also be used in future beam simulations.

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