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A particle-in-cell mode beam dynamics simulation of medium energy beam transport for the SSC-Linac*

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Abstract: A new linear accelerator system, called the SSC-Linac injector, is being designed at HIRFL (the heavy ion research facility of Lanzhou). As part of the SSC-Linac, the medium energy beam transport (MEBT) consists of seven magnetic quadrupoles, a re-buncher and a diagnose box. The total length of this segment is about 1.75 m. The beam dynamics simulation in MEBT has been studied using the TRACK 3D particle-in-cell code, and the simulation result shows that the beam accelerated from the radio frequency quadrupole (RFQ) matches well with the acceptance of the following drift tube linac (DTL) in both the transverse and longitudinal phase spaces, and that most of the particles can be captured by the final sector focusing cyclotron for further acceleration. The longitudinal emittance of the RFQ and the longitudinal acceptance of the DTL was calculated in detail, and a multi-particle beam dynamics simulation from the ion source to the end of the DTL was done to verify the original design.

Key words: SSC-Linac, MEBT, PIC mode, acceptance, re-buncher

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1 Introduction

The current HIRFL (heavy ion research facility of Lanzhou) system is composed of two cyclotrons, SFC (sector focusing cyclotron) and SSC (sector focusing cyclotron), one CSRm (cooling storage ring main) synchrotron, and one CSRe (cooling storage ring experimental) storage ring. The SFC is the injector of the SSC. The SFC can be an injector of the CSRm for light ions, and the SFC and SSC can work together to be the injector of CSRm for heavy ions [1], which causes low efficient beam time of the whole facility. The design of the SSC-Linac injector is being considered in order to improve it.

As part of the SSC-Linac injector, the MEBT (medium energy beam transport) plays an important role in matching the beam to the acceptance of the DTL (drift tube linac). It is important to minimize the growth of the transverse emittance and beam-halo formation in the DTL section, which has been recognized as one of the major causes for beam loss in the final cyclotron. To maintain the beam quality in the following DTL, a re-buncher is designed in the MEBT to rotate the beam shape in the longitudinal phase space in order to match the beam with the DTL longitudinal acceptance. The lattice of the MEBT has been designed and extensively simulated by the TRACE-3D code [2], and crosschecked by the TRACK code [3], which has been developed based on the particle-in-cell (PIC) method.

2 The arrangement of the MEBT

Transport of the heaviest ion beam is the most challenging task. Therefore, the MEBT simulation

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primarily focuses on the uranium beam. The beam intensity for the heavy ions after the selection is typically low and the space charge effects are inconspicuous, thus in the MEBT simulation, the space charge effects are not considered [4].

According to previous studies, the phase ellipses are anti-symmetric in the horizontal and vertical directions at the exit of the RFQ (radio frequency quadrupole) [5]. For this reason, a triplet right after the RFQ is used to convert an anti-symmetric beam to a symmetric beam at the entrance of the re-buncher. The following re-buncher plays an important role in matching between the RFQ and DTL in the longitudinal phase space.

By changing the voltage of the re-buncher, the particle distribution at the entrance of the DTL in the longitudinal phase space can be modified to ensure that most of the particles can be captured by the following DTL. After the re-buncher, two doublets are used to match the optimal beam Twiss parameters ($\alpha = 1.60$, $\beta = 60.00$ cm/rad) at the entrance of the first tank. Four quadrupoles provide a large tuning range to accommodate the beams with different beam Twiss parameters. A diagnose box is placed between the two doublets to measure the beam parameters in the MEBT section.

3 The simulation from ion source to the end of RFQ

To perform beam dynamics simulation for the MEBT, it is essential to have reasonable initial beam parameters at the entrance of the MEBT. The particle motion in the realistic field is non-linear, and the most comprehensive beam dynamics simulation studies can be carried out by numerical simulation. The multi-particle dynamics simulation with the 3D field has been done with the TRACK code. Therefore, the front-to-end beam dynamics simulation from the ion source to the exit of the RFQ has been done, and the output particle distributions at the exit of the RFQ are selected to be the initial input particle distributions for the MEBT simulation. The beam Twiss parameters and the normalized emittance at the entrance of the LEBT (low energy beam transport) are listed in Table 1.

Table 1. The beam parameters at the LEBT entrance.

space	α	β/(cm/rad)	$4\varepsilon_{\rm rms}/(\pi\cdot{\rm mm}\cdot{\rm mrad})$
x-px	−0.491	15.09	0.1991
y-py	−0.506	15.07	0.2008

During the simulation, a 3D external field is employed in the TRACK code. In the LEBT section,

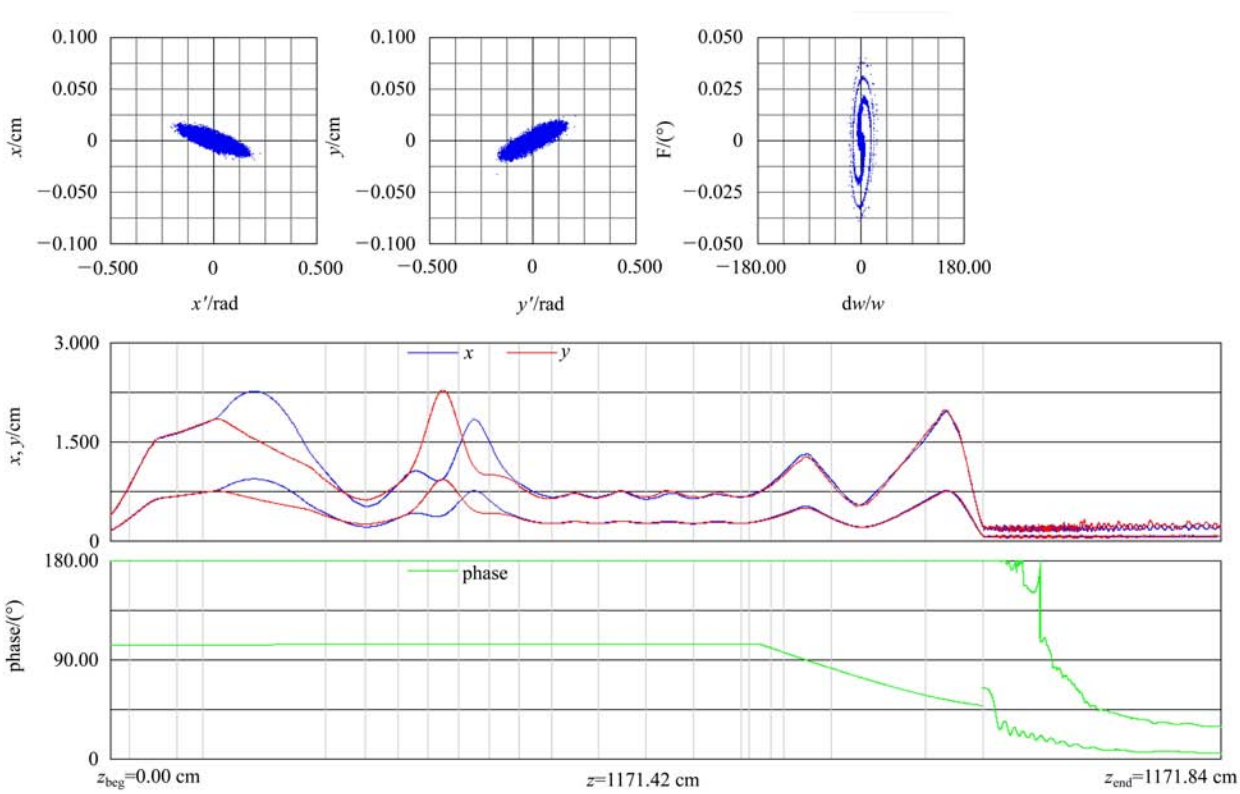

Fig. 1. (color online) The multi-particle beam dynamics simulation from the ion source to the end of the RFQ.

a 3D static magnetic field of the quadrupole and solenoid has been calculated by the OPERA-3D program [6], and the 3D rf electric field of the multi-harmonic buncher has been calculated by the CST program [7]. In the RFQ section, the 3D rf electric field in the regular cells has been presented by an eight-term Fourier-Bessel expansion, which is derived from the PARIOUT file generated by the PARMTEQ-M code [8].

The beam dynamics simulation via the TRACK code is demonstrated in Fig. 1. The simulation is performed with a beam represented as a collection of 20000 macro-particles. These particles are initially distributed in a 4D water-bag transverse hyperspace with uniform distribution in phase width and momentum spread.

In Fig. 1, the lower curves are the beam rms (root-mean-square) sizes and the upper curves are the beam envelopes. The transverse rms emittance growth does not exceed 10%. The output energy from the RFQ is 143.28 keV/u, slightly higher than the result calculated by the PARMTEQ-M code. The Twiss parameters and the normalized beam emittance at the exit of the RFQ are listed in Table 2.

The particle distributions in the phase spaces at the exit of the RFQ are shown in Fig. 2. At the entrance of the LEBT, one rf period (the fundamental frequency is 13.4167 MHz) bunched beam is assumed, and the value of the beam energy spread is chosen to be ±0.01%.

The frequencies of the RFQ and DTL are 53.667 MHz, four times that of the fundamental frequency. Due to the energy spread and the motion couple between the transverse and the longitudinal directions [9], one bunch is divided into five bunches in the RFQ and about 83.02% of the particles can be captured in the main bunch. The remaining satellite bunches can be accepted by the following DTL, but cannot be accepted by the final SSC (the fundamental frequency).

Table 2. Beam parameters at the exit of the RFQ.

space	α	β	$4\varepsilon_{\rm rms}$
x-px	1.359	19.83 cm/rad	0.2088 $\pi\cdot$mm$\cdot$mrad
y-py	−1.580	17.22 cm/rad	0.2210 $\pi\cdot$mm$\cdot$mrad
z-pz	−0.121	4.82 deg/(dw/w)	1.097 keV/u·ns

In Fig. 2, parts (a), (b), (c) and (d) illustrate the particle distributions in x-px, y-py, x-y and z-pz phase spaces at the end of the RFQ.

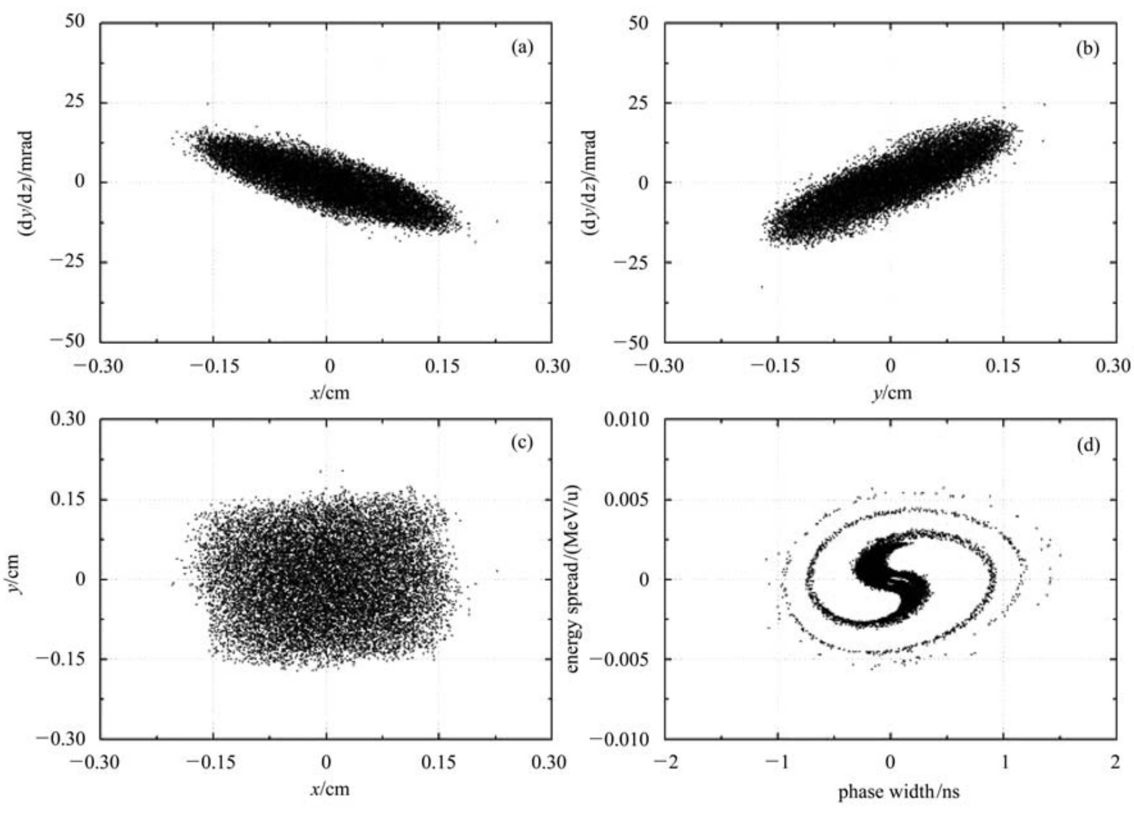

Fig. 2. The particle distributions at the exit of the RFQ.

4 The MEBT simulation

A new subroutine was developed for the particle tracking in the DTL tank in the TRACK code. Special attention should be paid to the initial phase of the DTL tank. In the DTL simulation using the TRACK code, each tank has two input files. One file is the geometry data of the cells and the other is the 2D electric field data.

The rf electric field, which is employed in the DTL simulation, is the 2D map calculated using the CST program. Fig. 3 is the 2D field in the first half cell of the re-buncher, Fig. 3(a) is the E_r field map and Fig. 3(b) is the E_z field map at t=0.

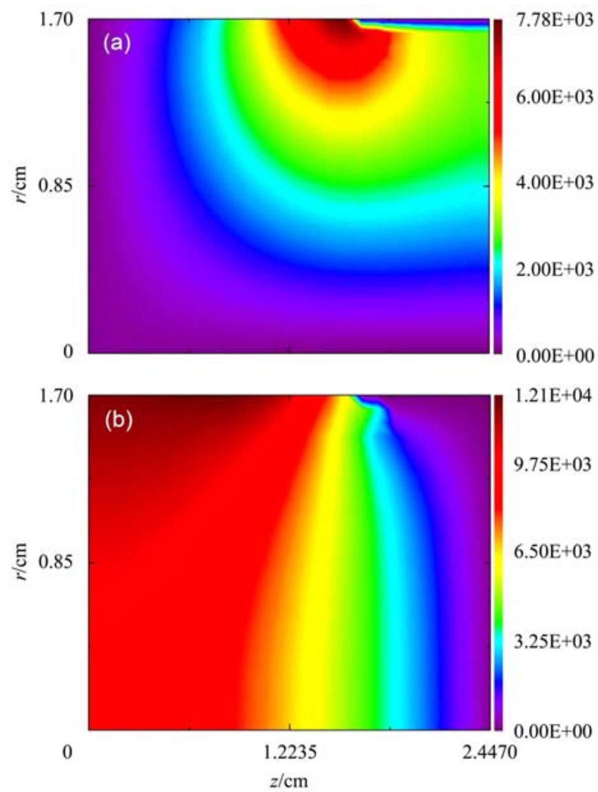

Fig. 3. (color online) (a) The radial electric field map. (b) The longitudinal electric field map.

In the following four tanks, the 2D field in every cell is calculated in the same way, and the shift of the geometry center between the gap center and the cell center is considered in every cell. The initial phases of the four tanks are given independently at the entrance of the tank. As the result of that, the beam dynamics simulation can be done cell by cell in the whole DTL structure. The magnetic field of the triplet between the tanks is generated by the OPERA-3D program mentioned above.

The final beam, with an energy spread of less than ±0.5% and a phase width of less than ±1.28 ns, is required at the exit of the last tank. These can match with the longitudinal acceptance of the SSC.

The strength of the re-buncher can be adjusted to guarantee that most of the particles are within the range of the DTL longitudinal acceptance. The longitudinal emittance of the main bunch and the longitudinal acceptance of the DTL at the entrance of the DTL are illustrated in Fig. 4, respectively.

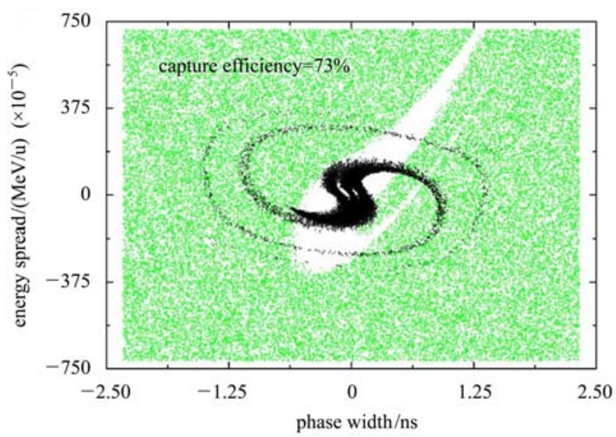

Fig. 4. (color online) The longitudinal acceptance of the DTL and the particle longitudinal distribution at the entrance of the DTL.

The hollow region is the acceptance of the whole DTL (including the four tanks and the triplets in between), and the area occupied by red dots is the matched longitudinal emittance at the entrance of the DTL. The acceptance looks narrow in the phase width. However, the core of the longitudinal emittance and the DTL acceptance are overlapped. According to the simulation result, there are still about 73.04% of the particles within the hollow region.

Downstream of the re-buncher, four quadrupoles are used to match to the transverse phase spaces to the acceptance of the DTL. The beam Twiss parameters and the normalized emittance at the exit of the MEBT are listed in Table 3 and the particle distributions are shown in Fig. 5.

Table 3. Beam parameters at the exit of the RFQ.

space	α	β	$4\varepsilon_{\rm rms}$
x-px	1.622	58.06 cm/rad	0.2075 $\pi\cdot$mm$\cdot$mrad
y-py	1.516	56.50 cm/rad	0.2201 $\pi\cdot$mm$\cdot$mrad
z-pz	−0.108	9.915 deg/(dw/w)	1.085 keV/u·ns

In Fig. 5, parts (a), (b), (c) and (d) illustrate the particle distributions in x-px, y-py, x-y and z-pz phase spaces at the exit of the MEBT. Only the particles of the main bunch are plotted in the above figure.

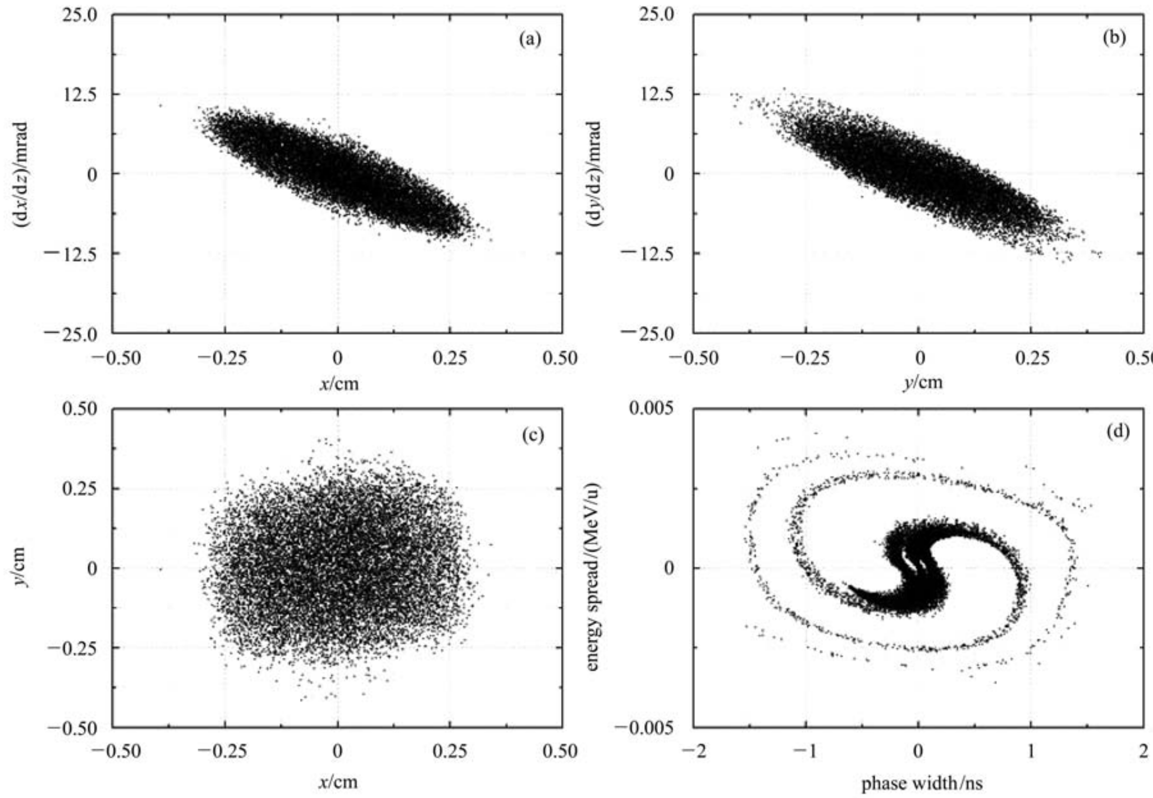

Fig. 5. The particle distributions at the exit of the MEBT.

According to the simulation result, only about 0.16% of the particles are lost in the transport of the MEBT, and there is no emittance growth in both the transverse and the longitudinal phase spaces. The injection Twiss parameters at the exit of the MEBT are close to the optimal values.

5 The simulation from the ion source to the end of the DTL

The IH (interdigital-H type) DTL structure is designed by the LINREV code [10], which is based on the matrix method. In the simulation from the entrance of the MEBT to the end of DTL, the external 3D magnetic static field (besides the dipole) map and the 2D rf electric field map of all the elements are used in the simulation. The initial phases of the multi-harmonic buncher, the re-buncher and the four tanks are given, respectively.

According to the data analysis, some particles in the tail of the bunch are beyond the longitudinal acceptance of the DTL. Therefore, only part of the particles (about 80.00%, five bunches, the energy spread is lower than $\pm 1.0\%$) can be accelerated to the desired energy at the end of the DTL. The layout of the SSC-Linac injector system is shown in Fig. 6. The front-to-end multi-particle beam dynamics simulation from the ion source to the end of the DTL has been done and the simulation result is shown in Fig. 7. The image shows the beam ellipse in all three phase spaces, the transverse envelopes (x and y, rms and peak) and the phase widths (rms and peak), respectively.

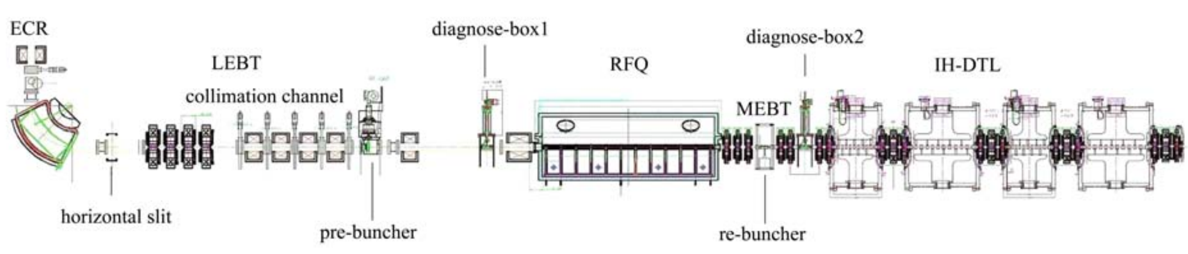

Fig. 6. The layout of the SSC-Linac injector.

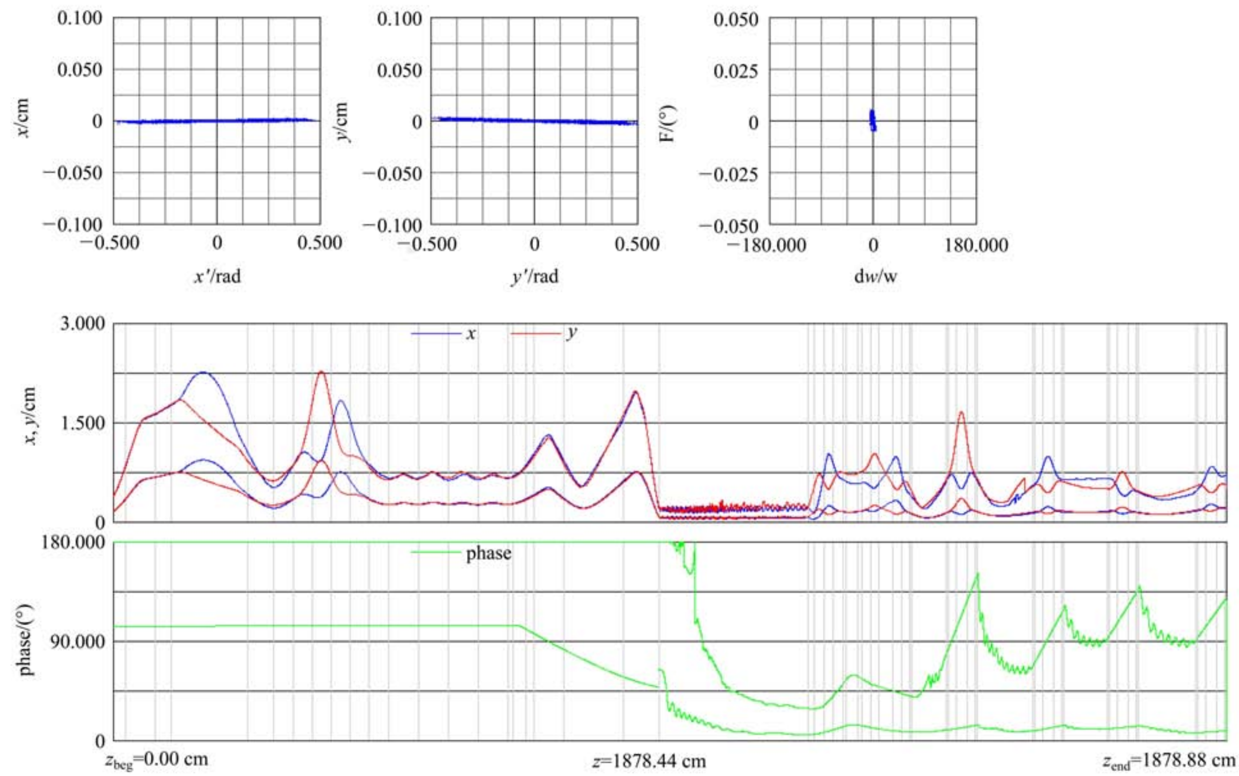

Fig. 7. (color online) The multi-particle beam dynamics simulation from the ion source to the end of the DTL.

The beam is pre-bunched in the LEBT at 13.667 MHz, the fourth sub-harmonic of the RFQ frequency. Since bunching only reduces but does not cancel the beam between bunches, there will be a small quantity of beam emerging from the RFQ in the three buckets on either side of the main bunch. Fig. 8 shows the distribution of the bunches at the exit of the RFQ.

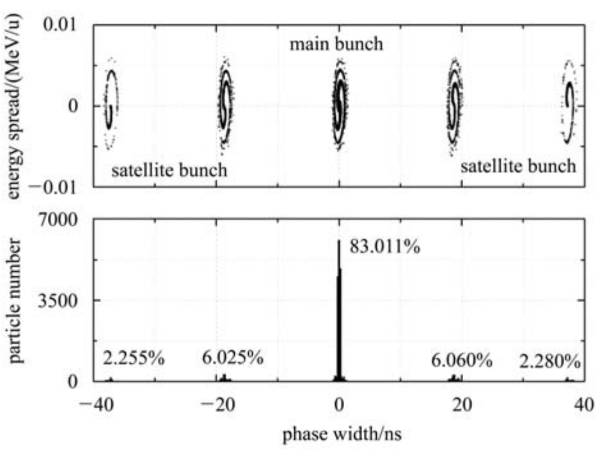

Fig. 8. The longitudinal distribution of the particles at the exit of the RFQ.

The total particle distribution, composed of one main bunch and four satellite bunches, is shown in Fig. 9(a), and the main bunch particle distribution in

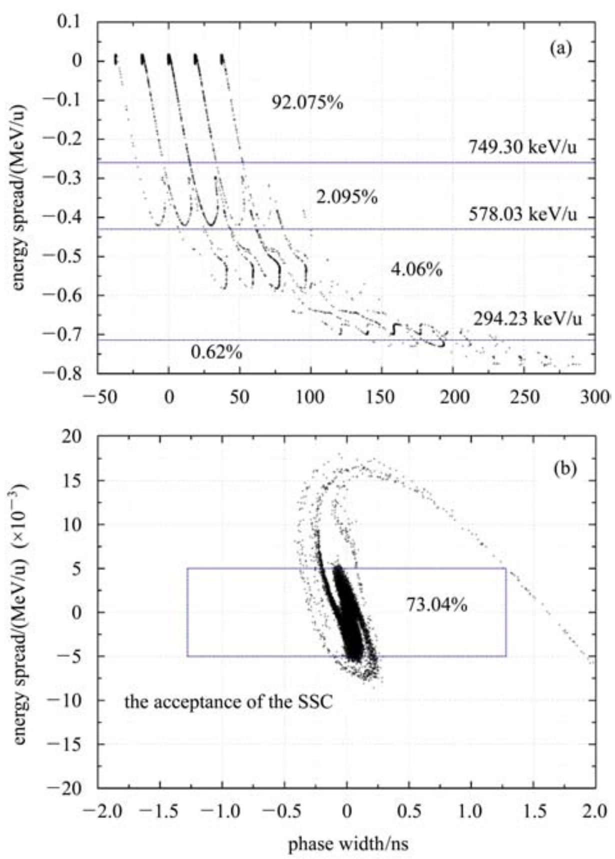

Fig. 9. The full particle longitudinal distribution (a), and the main bunch particle longitudinal distribution (b).

the longitudinal phase space is shown in Fig. 9(b).

About 73.04% of the particles are distributed in the main bunch, and these particles can be accepted by the final SSC. The input and output energies for each tank calculated by the TRACK code are listed in Table 4, and the input and output beam energies calculated by the LINREV code are also listed for comparison. The output energy at the exit of the RFQ is slightly higher than the result calculated by the PARMTEQ-M code.

Table 4. The input and output beam energies in the DTL section.

section	matrix (in/out)	PIC (in/out)	unit
MEBT	143.00/143.00	143.29/143.29	keV/u
Tank1	143.00/295.64	143.29/294.23	keV/u
Tank2	295.64/580.09	294.23/578.03	keV/u
Tank3	580.09/754.75	578.03/749.30	keV/u
Tank4	754.75/1025.35	749.30/1008.29	keV/u

In the PIC mode beam dynamics simulation of the DTL section, the beam energy gains in the four tanks are lower than the values calculated by the matrix mode. However, these minute differences can be reduced easily by changing the voltage of every tank.

6 Conclusion

Based on the previous matrix mode design, an MEBT with a re-buncher has been simulated, adopting the TRACK code. The multi-particle beam dynamics simulation result shows that this MEBT provides adequate matching in both the transverse and longitudinal phase spaces. Most of the particles can be rotated suitably to match the longitudinal acceptance of the DTL, and the acceleration efficiency is more than 70% at the exit of the DTL for the main bunch.

Further beam simulations in the MEBT will include the error analysis, and other codes will also be used in the next stage of beam dynamics simulations.

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