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Beam Dynamics Study of the IH-DTL New Injector for HIRFL-CSR

QIAO Jian[1,2], YIN Xuejun[1,†], YUAN Youjin[1], YANG Jiancheng[1], MAO Lijun[1], YIN Dayu[1], ZHANG Xiaohu[1], DU Heng[1,2], LI Xiaoni[1], LI Zhongshan[1,2], WU Bo[1,2], ZHAO He[1,2], TANG Meitang[1], QIN Yuanshuai[1,2], SHI Jian[1], SHENG Lina[1], CHAI Weiping[1], SHEN Guodong[1], RUAN Shuang[1,2], WANG Geng[1,2], LIU Jie[1,2], QIN Zhiming[1,2], WANG Kedong[1,2], DONG Ziqiang[1,2], CAI Fucheng[1,2], CHEN Xiaoqiang[1,2], KONG Qiyu[1,2]

(*1. Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China;*
2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: In order to improve the operation efficiency of the Cooling Storage Ring of Heavy Ion Research Facility in Lanzhou (HIRFL-CSR), a heavy ion linac (linear accelerator) was proposed and designed as a new injector for HIRFL-CSR. Following the 108.48 MHz Radio-Frequency Quadrupole (RFQ), three tanks in total with Interdigital H-mode drift tube linac (IH-DTL) structure are installed to boost the beam energy from 0.3 to 3.71 MeV/u, and the beam current of ions with charge-to-mass ratio from 1/8.5 to 1/3 can reach to 3 mA. The first tank operatesat the same frequency as the RFQ, and the rest two operate at 216.96 MHz. The "Combined Zero-Degree Synchronous Particle Structure" (KONUS) beam dynamics was used in the beam dynamics design. The overview of the physics design on the main accelerating components, including RF design and beam dynamics design are introduced in this paper. The optimized structure design, fabrication status and simulation results are presented in this contribution. It shows that under the condition of assurance of 95.3% transmission efficiency, the normalized rms emittance is about 25%. When the beam current is up to 3 mA, owing to the space charge effect, the increase of longitudinal phase spread and transverse envelope are about 25% and 16.3%, respectively.

Key words: Injector; beam dynamics design; IH-DTL; KONUS, MEBT; parameter analysis

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1 Introduction

HIRFL-CSR[1], a multi-purpose cooling storage ring complex, is the post-acceleration of the Heavy Ion Research Facility in Lanzhou (HIRFL) which consists of a main ring (CSRm) and an experimental ring (CSRe). Besides the researches on the nuclear physics, atomic physics, irradiative in material and biology, the researches on the cancer therapy, hadron physics and high energy density are developing at HIRFL[1−3]. In order to meet the new requirements of physical experiments, many upgrading works need to be done such as the improvement of the beam quality and transmission efficiency. Furthermore, building a new heavy ion linac as the injector for the HIRFL-CSR is the most effective initiative in these upgrading works. Therefore, a heavy ion linac was designed and the layout of the main accelerating section of the new injector is shown in Fig. 1. It can accelerate most kinds of heavy ions with the charge-to-mass ratio ranging from 1/8.5 to 1/3, such as $^{12}C^{4+}$, $^{40}Ar^{12+}$, $^{208}Pb^{35+}$and $^{238}U^{28+}$. The beam energy can reach to 3.71 MeV/u.

The first IH-cavity operates at the same frequency as the RFQ (108.48 MHz) to capture the low energy ions from RFQ. The particle scan be accelerated to 1.85 MeV/u at the exit of the first cavity. In order to maintain the high efficiency of acceleration and shrink the length of the cavities, the next two cavities work at 216.96 MHz twice that of the RFQ frequency. The main parameters of the IH-DTL are listed in Table 1.

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Foundation item: National Natural Science Foundation of China(11375243)
Biography: QIAO Jian(1988–), male, Xinzhou, ShanXi, Master/Student, working on accelerator physics; E-mail: qiaojian@impcas.ac.cn
† **Corresponding author:** YIN Xuejun, E-mail: yinxj@impcas.ac.cn.

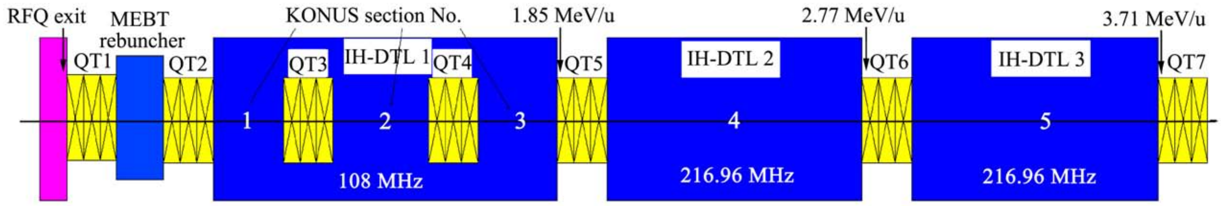

Fig. 1 (color online) Layout of CSR IH-DTL section.

Table 1 CSR-IH-DTL Parameters.

Parameter	Value
Input energy/(MeV/u)	0.3
Output energy/(MeV/u)	3.71
Charge to mass ratio (q/A)	1/8.5～1/3
Operating frequency/MHz	108.48/216.96
Beam pulse/ms	10
Duty factor/%	3
Output momentum-spread/%	< ±0.15
Beam transmission/%	> 90

The IH-DTL structure[2] has outstanding efficiency and high shunt impedance in the low energy with β ranging from 0.02 to 0.3[3−5] for hadron accelerators. A 'Combined Zero-Degree Synchronous Particle Structure' (KONUS)-period consists of three sections with separated functions respectively, as Fig. 2[4−6] shows. The first section is the main acceleration section in which the beam is injected with a certain energy spread compared with a "synchronous" particle. Following the main section, some triplet transport systems are used for the transverse focusing. Afterwards, the beam is injected into a longitudinal bunching section consisting of a few gaps with a negative synchronous phase shift typically from −25° to −35°.

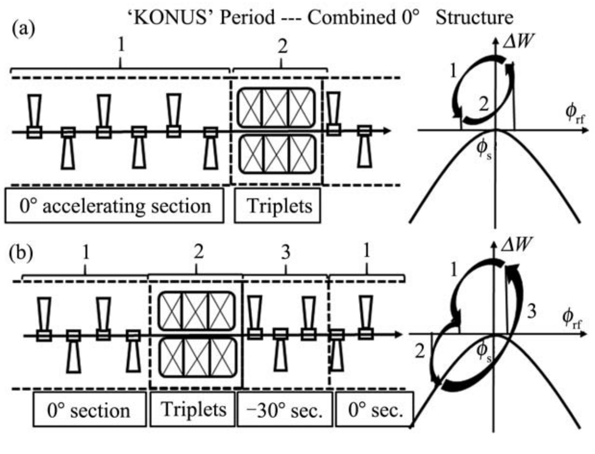

Fig. 2 The KONUS period and the principle of KONUS beam dynamics [4].

The LORASR code [7] was specifically used for the KONUS beam dynamics design of IH-DTL. In this paper, the beam dynamics has been designed and simulated for the IH-DTL part by LORASR code. In addition, the TraceWin code[8], which is used for linear (matrix) and non-linear calculations for 2D or 3D electrons or ions beam, was used to match the beam from the exit of RFQ to the DTL section. And the electric field distribution was calculated by CST Microwave Studio[9].

The main difficulties in designing the heavy ion linac are as follows:

(1) Beam matching between the RFQ and the first DTL tank;

(2) Determining the longitudinal phase shift and the energy difference between two sections;

(3) Optimizing the field distribution in the gap, that should smoothly change in order to inhibit the induced dipole field;

(4) Matching the acceptance and Twiss parameters of CSR, reducing the beam loss and limiting the transverse emittance to a reasonable range.

2 Beam matching and parameter analysis

2.1 The beam matching of the medium energy beam transport

The Medium Energy Beam Transport line (MEBT) plays an important role in matching the beam to the acceptance of the DTL. It mainly consists of two groups of triplets, a4-gap re-buncher working at 108.48 MHz and a diagnostic box.

It is important to minimize the growth of beam transverse emittance and beam halo formation in the DTL sections, because the large beam emittance and the formation of beam halo will cause beam loss. The total length of the MEBT is about 100 cm. The specific parameters are listed in Table 2.

Table 2 The specific parameters of the MEBT.

Parameter	Value
Total length/cm	100
Energy/(keV/u)	300
Effective voltage/kV	140
Frequency/MHz	108.48

Table 3 gives the beam parameters at the exit of the 108.48 MHz RFQ for U^{28+} ion beam with the current 0 mA and 3 mA. Downstream of the re-buncher, a triplet is applied to match the transverse phase space to the acceptance of the IH-DTL.

Table 3 The parameters atRFQ exit for 0 mA and 3 mA $^{238}U^{28+}$ ion beam.

RFQ Beam Parameter Lists	Parameters with 0 mA	Parameters with 3 mA
Frequency/MHz	108.48	108.48
Output energy/(keV/u)	300	300
Transmission efficiency/%	95.3	95.3
$\varepsilon_{x,\mathrm{out,rms}}/(\pi\mathrm{mm{\cdot}mrad})$	0.1	0.1
$\varepsilon_{y,\mathrm{out,rms}}/(\pi\mathrm{mm{\cdot}mrad})$	0.1	0.1
$\alpha_{x,\mathrm{out}}/\beta_{x,\mathrm{out}}/(\mathrm{mm/mrad})$	−1.39/0.22	−1.56/0.25
$\gamma_{x,\mathrm{out}}$	13.3	13.89
$\alpha_{y,\mathrm{out}}/\beta_{y,\mathrm{out}}/(\mathrm{mm/mrad})$	1.67/0.285	1.77/0.3
$\gamma_{y,\mathrm{out}}$	12.1	13.8
$\alpha_{z,\mathrm{out}}/\beta_{z,\mathrm{out}}/(\mathrm{mm/mrad})$	0.0/0.087	−0.145/0.125
$\gamma_{z,\mathrm{out}}$	11.4	8.17

Fig. 3 shows beam envelope of the MEBT calculated by TraceWin code. The red line represents the limitation of vacuum pipe. Pink and blue lines are the vertical and horizontal envelope, respectively. Considering that it should have a certain margin, the aperture of the vacuum pipe is set to 40 mm. The reason of using a triplet rather than a doublet after the re-buncher is that the triplet system is more effective in matching the beam as to the complexity in actual situation and obtaining a better quality beam in the future commissioning and operation. The beam Twiss parameters and the normalized emittance at the exit of the MEBT are listed in Table 4.

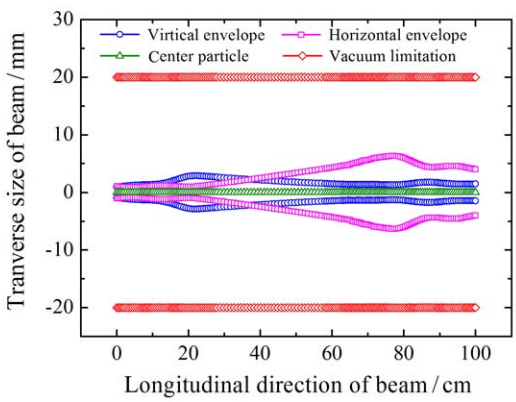

Fig. 3 (color online) The beam envelope of the MEBT.

The lattice parameters and normalized rms. beam emittance at the exit of MEBT are given in Table 4. About 99.99% of the particles of the main bunch are transmitted through the MEBT. The beam emittance remains the same, except some tiny variations of the horizontal emittance.

Table 4 The lattice parameters and beam emittance at the exit of the MEBT.

Space	α	β	εrms.norm
x-p$_x$	−0.2638	0.9820 mm/πmrad	0.1252 πmm·mrad
y-p$_y$	1.8397	0.7275 mm/πmrad	0.1689 πmm·mrad
z-p$_z$	−6.8002	45.2951 mm/π%	0.2126 πmm%

According to the results of simulation by TraceWin, only about 0.01% of the particles are lost after pass through the MEBT, and there is almost no emittance growth both in the transverse and the longitudinal planes. The injection Twiss parameters at the exit of the MEBT are close to the optimal values.

2.2 Discussions of the principal parameters of the IH-DTL

Because of the higher shunt impedance, the room temperature H-mode DTL cavity, based on the KONUS beam dynamics, is adopted. KONUS beam dynamics[4, 5] can keep the balance among the transverse defocusing, longitudinal bunching and RF acceleration.

In the KONUS beam dynamics, the key parameters are as follows:

(1) the effective accelerating electric field distribution of multi-gap;

(2) the initial beam parameters such as the phase width and energy spread at the first gap for each zero degree sections (the energy spread is the energy difference between bunch center W_c and synchronous particle W_s, while the phase width is the phase difference);

(3) the transverse focusing strength of the Quadrupole Triplets.

The IH structure operates at π-mode, which means the distance between the center of two adjacent gaps equals to $\beta\lambda/2$, where the β is the velocity of the synchronous particle and λ is the wave-length of electromagnetic field at corresponding frequency. The effective accelerating voltage is a comprehensive parameter that should consider the RF frequency, cell length, gap length, tube aperture, RF structure size and RF efficiency, and it has strong influence on acceleration efficiency and the value of Transit Time Factor (TTF). At the operation frequency, the gap length within the first tank is about 18 ∼ 25 mm. The ratio of gap length to cell length is varied to flatten the electric field distribution, but it's typically set to about 0.5. As the ratio of gap length to the aperture of drift tube decreases, the field magnitude in the drift tube increases and the ratio of the voltage on axis to voltage on drift tube decreases correspondingly. Generally, the value of TTF is larger than 0.8 which is the criterion for the geometry optimization. The control variable method is adopted to study the relationship between the geometry parameters, such as gap length and the tube aperture.

The peak electric field limit is determined by the gap length, tube radius and the resonance frequency. In order to obtain a stable operating state for a long time, the maximum axis field should be lower than the peak electric field limit. And the practical peak electric filed in the DTL should be lower than the corresponding peak electric field limit. The reasonable effective accelerating voltage is adjusted according to the peak electric field.

Fig. 4 shows the effective voltage of each accelerating gap. The maximum effective accelerating voltage is 0.375 8 MV. And the maximum axis field is about 14.45 MV/m, while the reasonable surface breakdown electric field is about 21.05 MV/m for 108.48 MHz and 27.38 MV/m for 216.96 MHz, whose K_p value is about 1.7, according to the Kilpatrick empirical Eq. (1):

$$f_r[\mathrm{MeV}] = 1.64 \times E_k^2 \mathrm{e}^{-8.5/E_k} \ , \qquad (1)$$

where f_r is the operation frequency and E_k is the Kilpatrick breakdown field, whose units are MHz and MV/m, respectively.

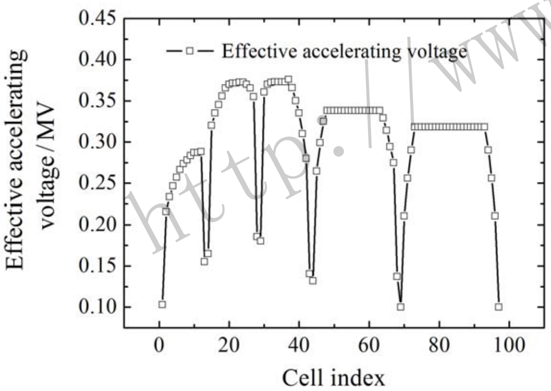

Fig. 4　The effective accelerating voltage.

In the KONUS sections, the transition cell from rebunching gap to the 0° accelerating gap belongs to the same resonator. The geometrical length of the transition cell can be adjusted by a drift tube whose length L_{shift} is determined by

$$L_{\text{shift}} = \left(1 + \frac{\Delta\phi}{180}\right) \times \frac{\beta\lambda}{2} \ , \qquad (2)$$

where $\Delta\phi$ is the phase shift between two adjacent sections.

The RF phases can be chosen independently when the transition gaps belong to different cavities. In the 0°section, the initial energy and phase should be adjusted to meet the requirements of the desired beam quality. The final re-bunching phase depends on the cell number in the 0° section. Well-balanced ratio of the number of re-bunching gap to the 0° accelerating gap is typically between 1:2 and 1:4. Meanwhile, the initial energy difference and phase offset mainly depend on the longitudinal phase space distribution.

As for the quadrupole triplets (QT), the parameters are shown in Table 5. Among them, QT3 and QT4 are the two quadrupole triplets installed in the first tank, while QT1 and QT2 will be installed in the MEBT, and QT5, QT6, QT7 will be installed in the appropriate space between two adjacent cavities. In the longitudinal direction, the quadrupole acts like a drift tube. Powerful short quadrupole triplets are needed to provide sufficient transverse focusing and minimum longitudinal defocusing. The maximum quadrupole field gradient is 88 T/m, corresponding to a pole tip magnetic field of 1.15 T for the triplet with aperture diameter of 40 mm. More details about the longitudinal parameters will be illustrated in the following longitudinal beam dynamic section.

Table 5　The quadrupole parameters of the MEBT and the IH-DTL sections.

Trip	Drift length/mm	Eff. length/mm	Field grad/(T/m)
QT1	238/22/22/456	77/138/77	56/53.5/56
QT2	187/22/22/22	77/138/77	63/62/63
QT3	26/22/22/26	77/138/77	76/73.5/76
QT4	26/22/22/26	77/138/77	70.5/71/70.5
QT5	56/22/22/56	77/138/77	86/88/86
QT6	67/22/22/67	77/138/77	82/84/82
QT7	67/22/22/67	77/138/77	82/84/82

3　Longitudinal KONUS beam dynamics simulation

Fig. 5 shows the longitudinal envelope in the first IH-DTL cavity. It mainly illustrates the evolution of phase spread and energy spread of 98% of the particles, with respect to the synchronous particle. The motions of bunch center with respect to the synchronous phase are also presented.

At the entrance of the 0° section, the bunch is focused in the longitudinal plane. During passing through the 0° section the bunch is defocused in the longitudinal direction due to closing to 0° rf(radiofrequency) phase. This effect can be partly compensated by the last two gaps No.16&17 that with negative rf phases. At the exit of the 0° section, the energy spread shows symmetric characteristic and the bunch is focused slightly. Each 0° section is followed by a quadrupole triplet performing transverse focusing. Afterwards the bunch is injected into the gap

No.18 which is the first re-bunching gap working at $\phi_s = -35°$. Note that by the redefinition of ϕ_s and W_s for the new synchronous particle, the bunch center and the synchronous particle are identical and the particle motions like in conventional beam dynamics designs.

Fig. 6 illustrates that the bunch center motion

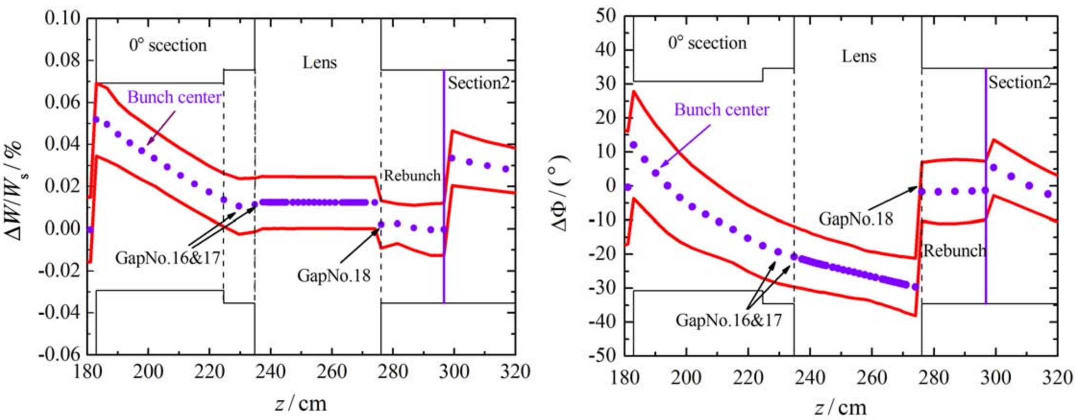

Fig. 5 (color online) The phase envelope and energy spread in the first CSR-IH-DTL cavity and the bunch center motion with respect to the synchronous phase.

for the five different sections along the longitudinal KOUNS period in the three cavities. The corresponding bucket of the gap No.18 is also presented. As the above analysis, the trajectory of the bunch center performs a quarter phase oscillation with initial surplus injection energy. And the bunch motion becomes stable after experiencing main acceleration.

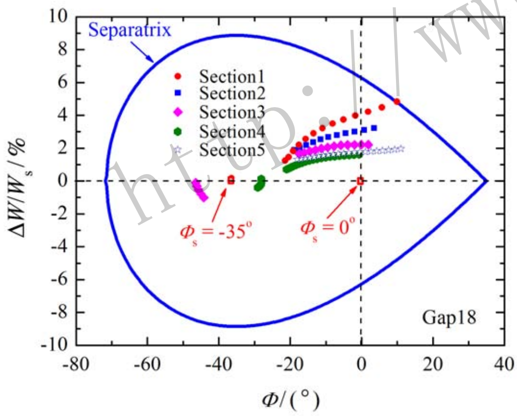

Fig. 6 (color online) The bunch center motion along the longitudinal KOUNS period for five sections and the first $\phi_s = -35°$ separatrix bucket at the 18th gap.

Fig. 7 shows the longitudinal phase envelopes against the structure defined by the synchronous particles. The energy of the central particles is traditionally higher than that of the synchronous particle in the zero degree sections. For this reason, both phase envelopes and particle energy are asymmetrically moving down in the zero degree sections. The phase spread of the ion beam with current of 3 mA at the exit is larger than that of zero current about 25% mainly due to space charge effect. The large width at the exit will be used to reduce the length of the drift section before the de-bunching cavity reducing the facility cost.

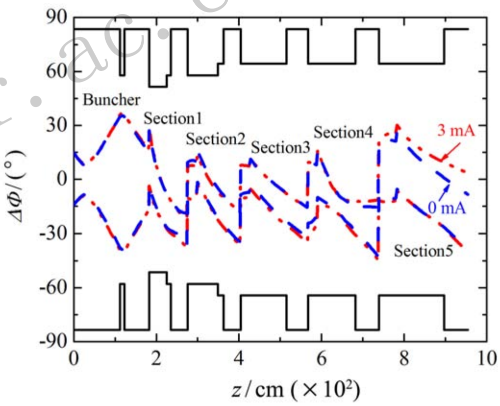

Fig. 7 (color online) Phase envelopes for 98% of the particles along IH structure.

Fig. 8 shows the evolution of energy spread of the beam along the DTL. As can be seen, the bunch center motion has a good coincidence of the synchronous particle along all re-bunching sections, as well as the

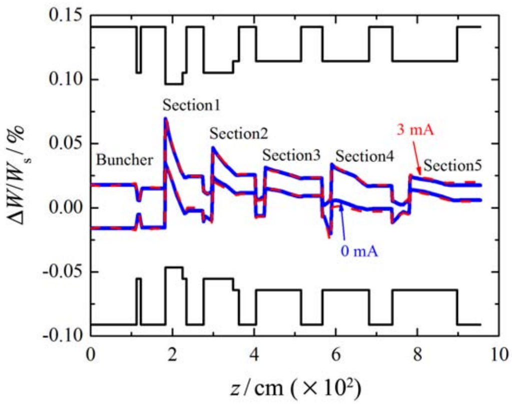

Fig. 8 (color online) Energy spread for 98% of the particle along IH Structure.

extra energy of the bunch along the five zero degree sections.

Fig. 9 illustrates the longitudinal phase distribution at the two ends of the CSR-IH-DTL. It shows that the ion beam almost locates in the center of the bucket both at the entrance and exit of the DTL. And it occupies approximate 18% of the bucket area at the exit, so the particle motion is stable enough.

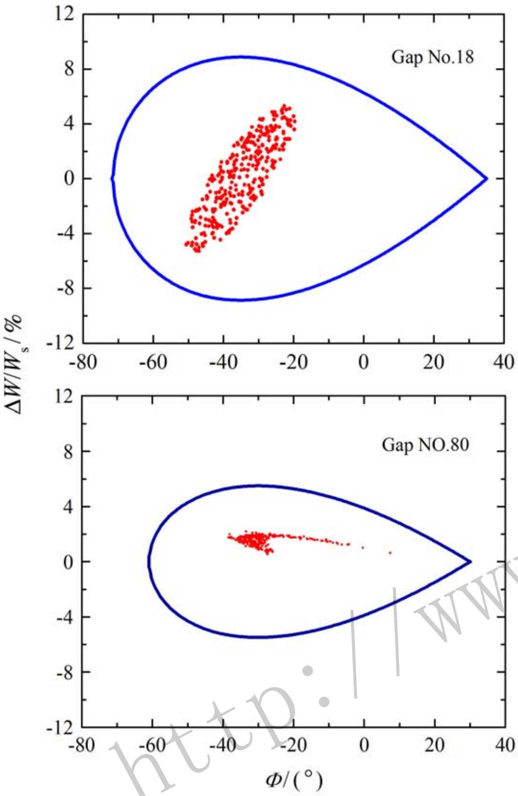

Fig. 9 (color online) The longitudinal phase distribution at the two ends of the CSR-IH-DTL.

4 Transverse KONUS beam dynamics simulation

The stable particle motion in transverse plane for KONUS is obtained by using the quadrupole triplets. Fig. 10 shows the transverse envelopes of 98% of the particles for the beam current of 3 mA and 0 mA which determines the minimum aperture diameters.

From Fig. 10, one can see that the transverse envelopes of full current occupy less than 50% area of the aperture and locally up to 70% which is mainly due to space charge effect. One can also see the maximum beam size (9.1 mm) occurs at the quadruple triplets between cavity 2 and cavity 3 in x-z plane. Although the inner radius (about 13 mm) of the matching quadruple triplets can cover the actual beam size at these positions, the quadrupole gradient and aperture should be optimized carefully to get enough safe margins. Additionally, more simulations have to be performed with more particles to investigate the tolerances effects. And errors like misalignment, gradient errors, RF field errors and phase shift should be taken into considerations.

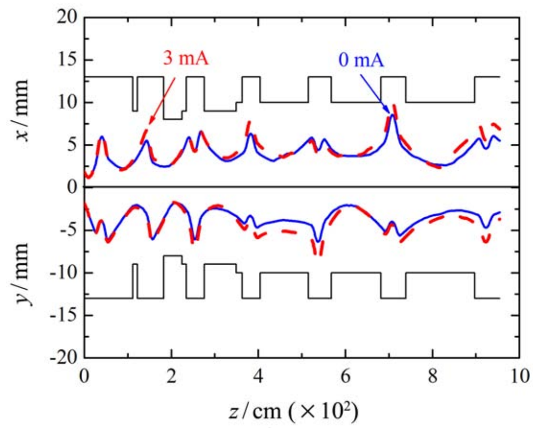

Fig. 10 (color online) Transverse beam envelopes of the CSR-IH-DTL.

Fig. 11 shows the ratio of the RMS emittance growth comparing with the initial value. In the calculation, 1 000 macro-particles were used to represent the input beam and the total RMS emittance growth is about 55%, but there is no beam loss during simulation.

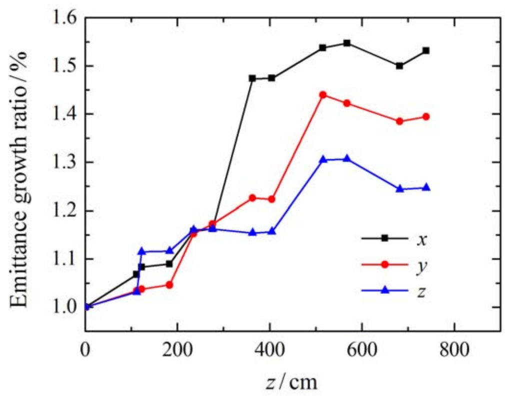

Fig. 11 (color online) RMS emittance growth ratio.

In the simulation, the structure parameters have been adjusted and optimized for the beam with the current of 3 mA. However, if the beam current is set to 0 mA, some mismatching phenomenon occurred in both transverse and longitudinal directions, although 100% transmission is kept. For this reason, a modified profile of magnetic field gradients as well as cavity voltages has been found especially at 0 mA. The effective gap voltage of the re-buncher in the MEBT is reduced from 145 to 130 kV for 0 mA case.

5 Conclusions

A powerful IH-DTL linac working at 108.48 MHz and 216.96 MHz as the new injector for HIRFL-CSR has been proposed. KONUS beam dynamics for the IH-DTL has been investigated and the beam dynamics simulated by LORASR code has been performed based on the present design. The efficiency of transmission can reach 100%. The optimized structure design, fabrication status and simulation results are presented in this contribution. It shows that under the condition of assurance of 95.3% transmission efficiency, the normalized rms emittance is about 25%. When the beam current is up to 3 mA, owing to the space charge effect, the increase of longitudinal phase spread and transverse envelope are about 25% and 16.3%, respectively.

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IH型漂移管直线加速器的束流动力学研究

乔 舰[1,2]，殷学军[1,†]，原有进[1]，杨建成[1]，冒立军[1]，殷达钰[1]，张小虎[1]，杜 衡[1,2]，李小妮[1]，李钟汕[1,2]，吴 波[1,2]，赵 贺[1,2]，汤梅堂[1]，秦元帅[1,2]，石 健[1]，盛丽娜[1]，柴伟平[1]，申国栋[1]，阮 爽[1,2]，王 耿[1,2]，刘 杰[1,2]，秦志明[1,2]，王科栋[1,2]，董自强[1,2]，蔡付成[1,2]，陈孝强[1,2]，孔启宇[1,2]

(1. 中国科学院近代物理研究所，兰州 730000；
2. 中国科学院大学，北京 100049)

摘要： 为了提高兰州重离子加速器冷却储存环 (HIRFL-CSR) 的运行效率、改善加速器输出束流品质，并实现几个加速装置分时供束，提高整个重离子加速装置的利用率，特为 (HIRFL-CSR) 增建一台新的注入器——CSR-LINAC。在 108.48 MHz 的 RFQ 之后的 CSR-LINAC 主加速段，主要由一台 108.48 MHz 和两台 216.96 MHz 的 IH 型漂移管直线加速器组成，用于加速荷质比为 1/8.5～1/3之间的重离子，其最大的束流流强为 3 mA，并将粒子从 0.3 MeV/u 加速到 3.71 MeV/u。运用 KONUS 动力学原理，在满足设计指标的情况下，首先利用 TraceWin 程序进行中能束线 MEBT 设计，后针对高频腔体设计和束流匹配的基本参数的系列讨论，特别是对 CSR-LINAC 的中能束流匹配线、参数选择和 IH 型 KONUS 结构的漂移管直线加速器进行设计模拟优化。最终得出，在保证腔体设计指标和 95.3% 的传输效率的情况下，该紧凑型直线加速结构经过三个腔体的加速后，束流的纵向归一化均方根发射度增长仅有 25%；同时发现，当流强达到 3 mA 时，存在空间电荷效应，导致其纵向相宽增长约 25%，最大横向包络也存在 16.5% 的涨落。

关键词： 直线注入器；动力学设计；IH型DTL ；KONUS；中能束线

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† **通信作者：** 殷学军，E-mail: yinxj@impcas.ac.cn。