Conceptional design of a heavy ion linac injector for HIRFL-CSRm *

ZHANG Xiao-Hu(张小虎)[1,2;1)] YUAN You-Jin(原有进)[1] XIA Jia-Wen(夏佳文)[1]
YIN Xue-Jun(殷学军)[1] DU Heng(杜衡)[1,2] LI Zhong-Shan(李钟汕)[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: A room temperature heavy ion linac has been proposed as a new injector of the main Cooler Storage Ring (CSRm) at the Heavy Ion Research Facility in Lanzhou (HIRFL), which is expected to improve the performance of HIRFL. The linac injector can supply heavy ions with a maximum mass to charge ratio of 7 and an injection kinetic energy of 7.272 MeV/u for CSRm; the pulsed beam intensity is 3 emA with the duty factor of 3%. Compared with the present cyclotron injector, the Sector Focusing Cyclotron (SFC), the beam current from linac can be improved by 10–100 times. As the pre-accelerator of the linac, the 108.48 MHz 4-rod Radio Frequency Quadrupole (RFQ) accelerates the ion beam from 4 keV/u to 300 keV/u, which achieves the transmission efficiency of 95.3% with a 3.07 m long vane. The phase advance has been taken into account in the analysis of the error tolerance, and parametric resonances have been carefully avoided by adjusting the structure parameters. Kombinierte Null Grad Struktur Interdigital H-mode Drift Tube Linacs (KONUS IH-DTLs), which follow the RFQ, accelerate ions up to the energy of 7.272 MeV/u for CSRm. The resonance frequency is 108.48 MHz for the first two cavities and 216.96 MHz for the last 5 Drift Tube Linacs (DTLs). The maximum accelerating gradient can reach 4.95 MV/m in a DTL section with the length of 17.066 m, and the total pulsed RF power is 2.8 MW. A new strategy, for the determination of resonance frequency, RFQ vane voltage and DTL effective accelerating voltage, is described in detail. The beam dynamics design of the linac will be presented in this paper.

Key words: linac injector, heavy ion, RFQ, parametric resonances, KONUS, IH-DTL, new strategy

PACS: 29.20.-c, 29.20.Ej **DOI:** 10.1088/1674-1137/38/10/107002

1 Introduction

The Heavy Ion Research Facility in Lanzhou (HIRFL) has been successfully upgraded with a multi-functional Cooler Storage Ring (CSR) at the end of 2007 [1]. As the only injector of HIRFL, the Sector Focusing Cyclotron (SFC), which has served for nearly 60 years, can provide a beam to the experimental terminals directly as well as acting as the injector of the Separated Sector Cyclotron (SSC) or the main Cooler Storage Ring (CSRm). In order to bring full functions of HIRFL-CSR into play, it is essential to construct an additional injector for CSR in the present facility.

In recent years, the linear accelerator has gradually taken the place of the cyclotron as the injector in the large scale scientific facility, such as GSI-UNLINAC [2], TRIUMF-ISAC [3] and RIKEN-RILAC [4]. Compared with the cyclotrons, the linacs have larger acceptance, higher transmission and a higher accelerating gradient. So the heavy ion linac called CSR-LINAC is proposed as the injector of CSRm in HIRFL, shown in Fig. 1. As can be seen, the SFC works for the SSC or one of the experimental terminals downstream at a time. Meanwhile, the CSR-LINAC, as the full-time injector, can supply a beam to CSR independently. Consequently, the double

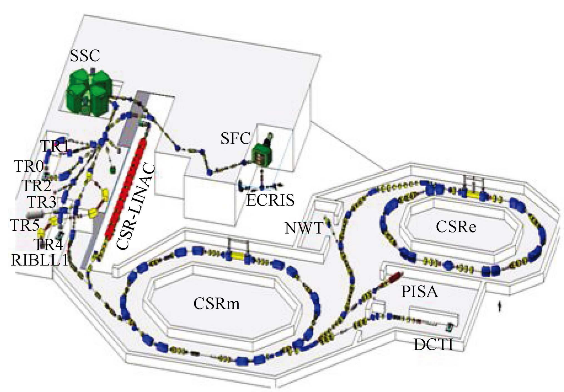

Fig. 1. (color online) Layout of HIRFL-CSR with CSR-LINAC.

Received 15 November 2013

∗ Supported by National Fund Committee Innovation Group (11221064) and National Basic Research Program of China (2014CB845500)

1) E-mail: zhangxiaohu@impcas.ac.cn

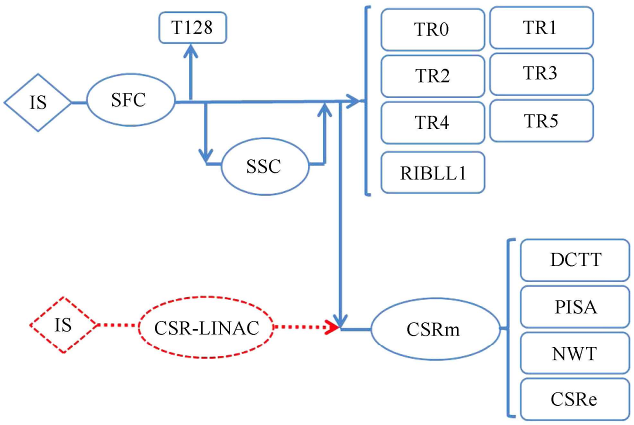

Fig. 2. (color online) New operation scheme in HIRFL-CSR.

injector parallel mode (DIPM) can be achieved in HIRFL, which doubles the beam time of HIRFL. The new operation scheme is illustrated in Fig. 2.

CSR-LINAC accelerates all kinds of heavy ions from carbon to uranium at the resonance frequencies of 108.48 MHz and 216.96 MHz and the duty factor of 3%. The pulsed beam current is set to 3 emA, which keeps spare space for updating the ECR ion source in the future. The main parameters of CSR-LINAC are listed in Table 1. Fig. 3 shows the layout of the whole linac with the resonance frequencies for tanks respectively. The linac injector mainly includes the following components: (1) an Electron Cyclotron Resonance Ion Source (ECRIS) that generates 0.004 MeV/u heavy ions; (2) a Radio-Frequency Quadrupole (RFQ) accelerator to bunch and pre-accelerate the ions to 0.3 MeV/u; and (3) a Drift Tube Linac (DTL), which is composed of 6 Interdigital H-type (IH) resonators, for the main acceleration up to 7.272 MeV/u.

Table 1. Main parameters of the CSR-LINAC.

parameters	value
A/q	3–7
emittance(norm, 99%)/π mm·mrad	0.88
frequency/MHz	108.48/216.96
pulsed beam current/emA	3
duration/ms	3
repetition/Hz	10
RFQ input energy/(MeV/u)	0.004
RFQ output energy/(MeV/u)	0.3
DTL input energy/(MeV/u)	0.3
DTL output energy/(MeV/u)	7.272
transmission(design)(%)	>90

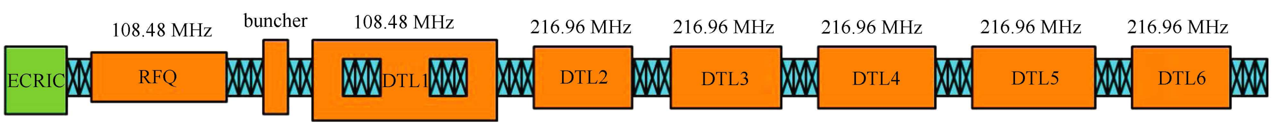

Fig. 3. Layout of CSR-LINAC.

2 The improvement of HIRFL-CSR

Because of larger acceptance and higher transmission, the beam current of a carbon ion from CSR-LINAC can reach nearly 150 euA and the uranium beam current approaches 60 euA, which is larger than that delivered by SFC. Suppose that the multi-turn-injection scheme is adopted with electron cooling, the maximum beam intensity stored in CSRm is as much as 100 times that at the injection. The maximum stored particle number comparison between SFC and CSR-LINAC as the injector of CSRm is shown in Fig. 4. As can be seen, the maximum stored particle number of the carbon ion has reached the space charge limit, 5.15×10^{10}, which is as nearly 11 times that as in the case of SFC as the injector of CSRm. Even for uranium, the maximum stored particle number can reach 4.85×10^{9}.

The maximum magnetic rigidity is the characteristic parameter related to the accelerating capability of synchrotron. The formula which calculates the magnetic rigidity is followed by:

$$B\rho=\frac{A\sqrt{2E_{\rm r}E_{\rm k}+{E_{\rm k}}^2}}{300Z}, \tag{1}$$

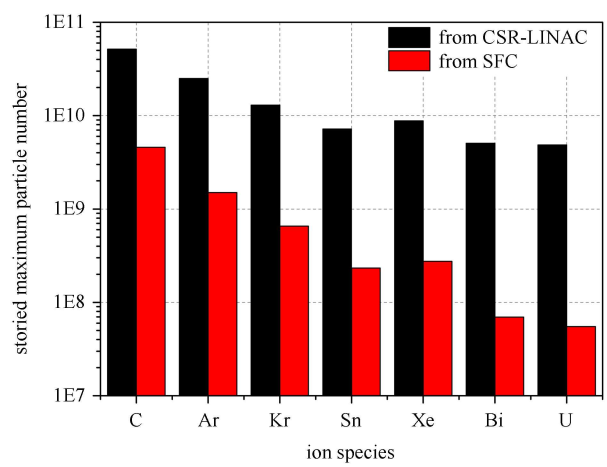

Fig. 4. The maximum stored particle number comparison for SFC and CSR-LINAC as the injector of CSRm.

for CSRm, the maximum magnetic rigidity is a constant value, 11.5 T·m. The final extraction energy can be improved by increasing the charge state of super-heavy ions. However, the heavier ion corresponds to the lower stripping efficiency [5]. Fig. 5 shows the equilibrium charge state distribution of the uranium ion with the energy of 7.272 MeV/u. As can be seen, the stripping efficiency of $^{238}U^{34+}$ to $^{238}U^{67+}$ is only 18.27%, which makes it essential to supply enough beam intensity before stripping. According to Formula (1), the CSRm can accelerate the stripped $^{238}U^{67+}$ to 414.22 MeV/u but for $^{238}U^{34+}$ only to 122.3 MeV/u.

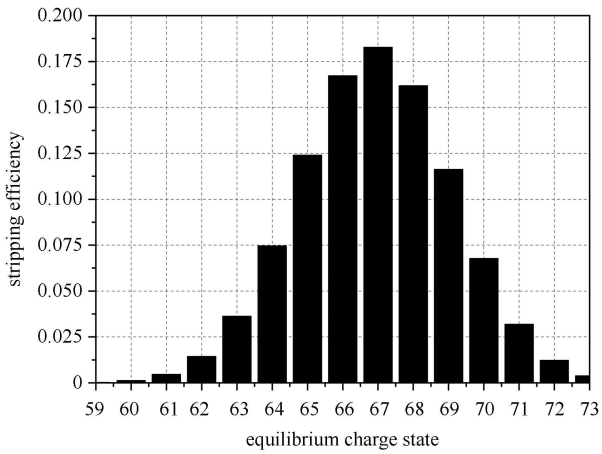

Fig. 5. The equilibrium charge state distribution of 7.272 MeV/u $^{238}U^{34+}$ after stripping.

3 RFQ beam dynamics

For a large linac complex, the RFQ accelerator at the front end has to change the continuous input beam to suitable bunches with an expected energy gain for the DTL accelerating structure downstream. According to the RFQ principle [6], the key parameter Br is introduced to determine a reasonable resonance frequency (f_r):

$$Br = \frac{ZeE_s}{Am_0 {f_r}^2 \kappa}, \tag{2}$$

where B is the transverse focusing strength, r is the average aperture radius, E_s is the maximum surface electric field on the pole and κ is set to 1.36, which is reasonable in the RFQ structure. According to Formula (2), Br is only proportional to Z/A and inversely proportional to the square of f_r for a given maximum surface electric field (E_s, 2 times the kilpatrick limit), illustrated in Fig. 6. As can be seen, a Br value corresponds to a sole f_r at a certain designed particle and therefore to choose a reasonable resonance frequency means to choose a reasonable Br. There are some considerations about Br as follows:

1) a higher accelerating gradient at a higher resonance frequency, which is helpful to realize a compact RFQ structure, requires a smaller Br parameter;

2) a larger Br parameter supplies a larger beam acceptance of the RFQ channel, which means a better transmission performance;

3) a larger Br parameter corresponds to a freer selection of structure parameters.

Figure 6 shows different kinds of RFQs in international large scale scientific facilities. As can be seen, HSI-RFQ (14.6), HLI-RFQ (15.93) and HIT-RFQ (15.2) in German represent the lower limit value of Br, which are nearly the highest level of RFQ design today. So Br of 20.15 is reasonable for an RFQ which accelerates heavy ions with a minimum charge to mass of 1/7 in CSR-LINAC and correspondingly 108.48 MHz is set as the resonance frequency of RFQ.

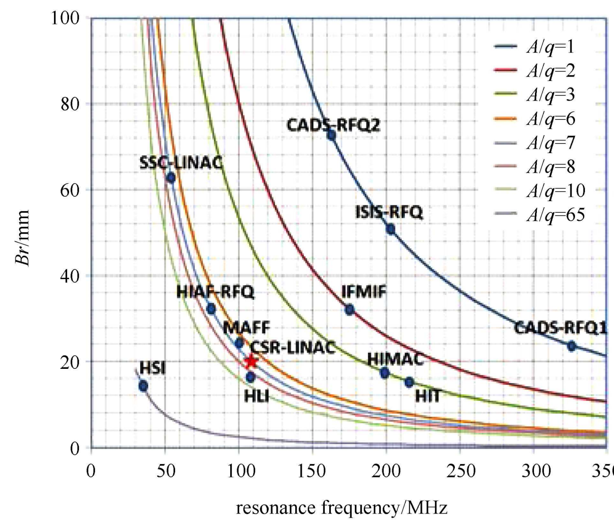

Fig. 6. (color online) Br as a function of frequency and A/q.

Table 2. Main Parameters of the RFQ.

parameters	value
ions	$^{12}C^{4+}$, $^{86}Kr^{18+}$, $^{129}Xe^{27+}$, $^{209}Bi^{32+}$, $^{238}U^{34+}$
A/q	3–7
beam current/emA	3
f_r/MHz	108.48
V_{vane}/kV	68.8
modulation	2.124
a_{min}/mm	2.623
L_{vane}/m	3.07
$P_{dissipation}$/kW	140
(E_{in}/E_{out})/(MeV/u)	0.004/0.3
transmission(%)	95.3

Usually the focusing parameter $B>4.5$, which supplies a large enough transverse phase advance, is helpful for good beam transmission, and therefore 68.8 kV is set as the vane voltage of RFQ through $U=\dfrac{E_{\mathrm{s}}r}{\kappa}$. The RFQ input energy of 0.004 MeV/u, which brings a fast bunch in RFQ, is reasonable and correspondingly the ECRIS extraction voltage is in an acceptable range of 12 kV to 28 kV according to the present performance of the ECR source in HIRFL. The RFQ output energy of 0.3 MeV/u, generally 2 q/A MeV/u [7], can be well matched for the DTLs downstream. The main parameters of RFQ in CSR-LINAC are exhibited in Table 2.

To accomplish an efficient bunching process for the CSR-LINAC RFQ, an unconventional design approach, the so-called New Four-Section Procedure (NFSP) [8] has been employed. Abandoning the unreasonable constant-B law and inefficient evolution manners of dynamics parameters adopted by the classic LANL Four-Section Procedure (FSP) [9], the NFSP strategy deals with the accelerating beam for high transmission, small emittance growth and large error tolerance. Variable-B is adjusted to avoid the parametric resonance [10], especially in the case of $\sigma_{0\mathrm{t}}=\sigma_{0\mathrm{l}}$. The zero current phase advances are given by:

$$\sigma_{0\mathrm{t}}^2 = \frac{B^2}{8\pi^2}+\varDelta_{\mathrm{rf}}, \tag{3}$$

$$\sigma_{0\mathrm{l}}^2 = -\frac{Z\pi^2TU_0\sin(\phi_{\mathrm{s}})}{AE_{\mathrm{r}}\beta^2}, \tag{4}$$

where B is the transverse focusing strength, the RF transverse defocusing factor $\varDelta_{\mathrm{rf}}=-\dfrac{1}{2}\sigma_{0\mathrm{l}}^2$, T is the accelerating efficiency, E_{r} is the rest mass per nuclei and ϕ_{s} is the synchronous phase, which directly influences the longitudinal capture efficiency. The beam non-resonant stable region requires $B>2\sqrt{3}\pi\sigma_{0\mathrm{l}}$ and the larger B corresponds to a larger error tolerance. However, the maximum surface electric field goes up to the spark value when B increases. In the gentle bunching (GB) section, B increases to balance the stronger growing transverse defocusing effect, so that the bunching speed can increase safely. When the acceleration (AC) section starts, the quickly increased beam velocity weakens the transverse defocusing effect, and B should accordingly fall down to avoid longitudinal emittance growth and to allow a large bore aperture. Fig. 7 exhibits RFQ parameters as a function of the position z and the maximum surface electric field (23.2 MV/m) appears at 80 cm, where the longitudinal phase advance is closest to the transverse phase advance. The minimum aperture is 2.623 mm at the AC section. Fig. 8 shows the transverse beam envelope and the longitudinal phase space evolution along the RFQ. Beam loss occurs mainly at the end of the GB section and the AC section. Fig. 9 lists the phase space distributions at the entrance and exit of RFQ. The FWHM energy spread at the exit of the RFQ is approximately 2.4%.

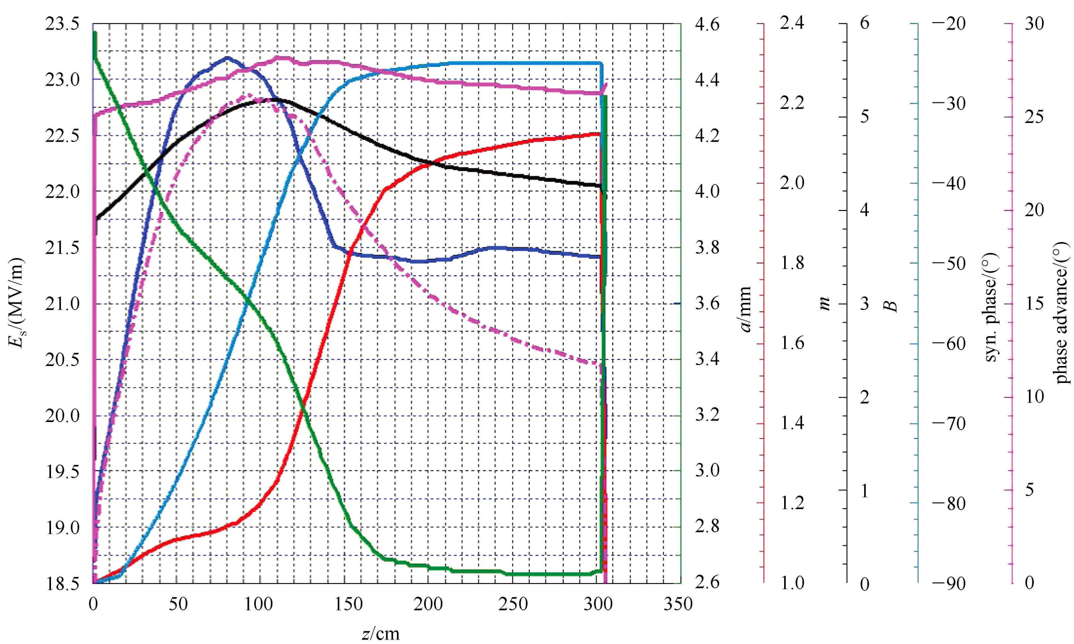

Fig. 7. (color online) The RFQ beam dynamics parameters as a function of position z.

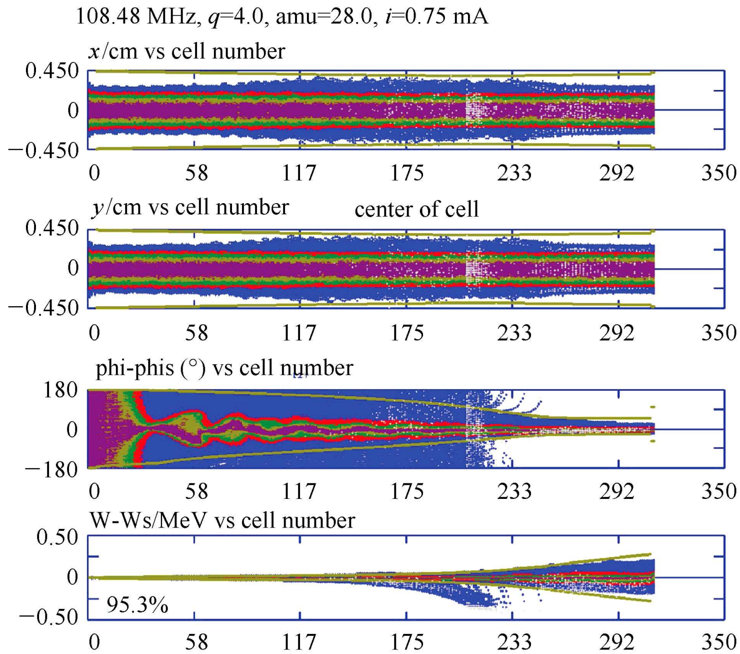

Fig. 8. (color online) Beam transmission along the RFQ. Plots from top to bottom are the beam profiles in x and y planes, phase and energy spectrums respectively.

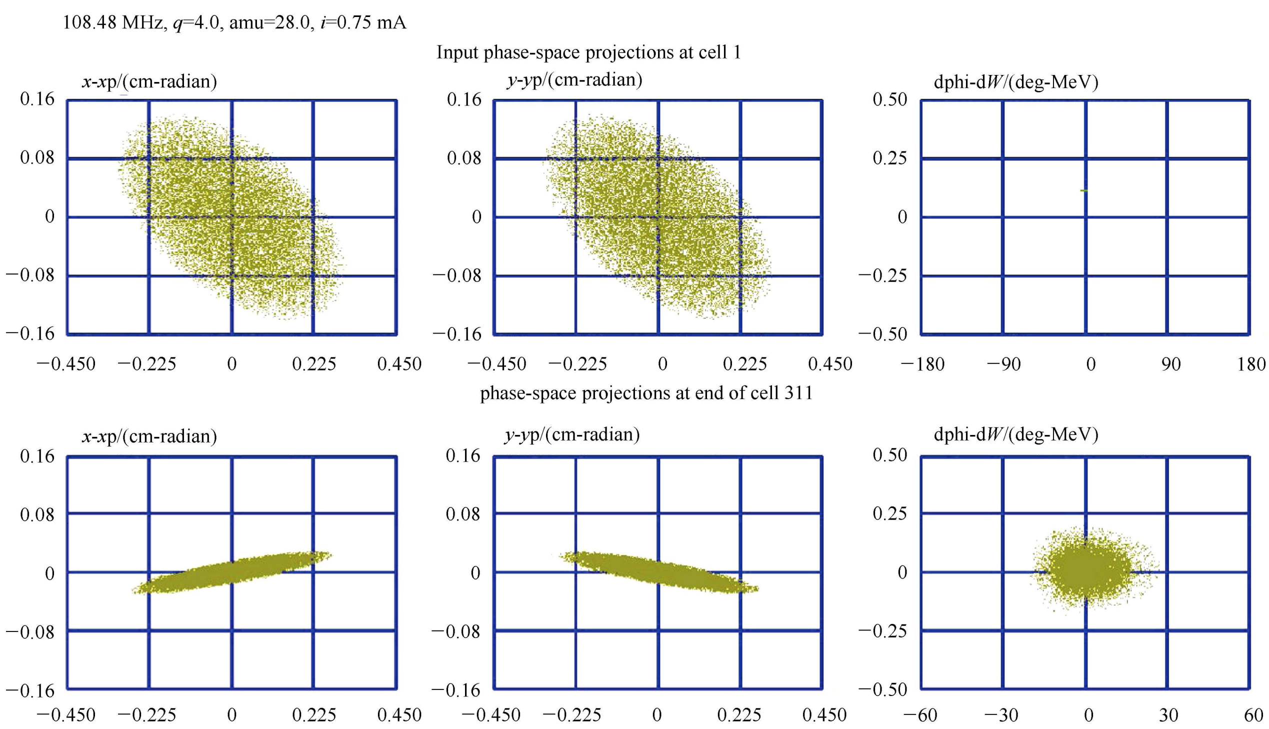

Fig. 9. (color online) Transverse phase space projection at the entrance (upper) and exit (lower) of the RFQ.

4 DTL beam dynamics

The Interdigital H-mode Drift Tube Linacs (IH-DTL), which consists of 6 DTL tanks and a rebuncher, accelerates the ions from 0.3 MeV/u to 7.272 MeV/u at the resonance frequency of 108.48 and 216.96 MHz. Its total effective accelerating voltage is 58.6 MV and the total pulsed RF power is 2.8 MW in the linac. The maximum accelerating gradient can reach 4.95 MV/m at the last cavity with the resonance frequency of 216.96 MHz. Table 3 exhibits the main parameters of the DTL section in CSR-LINAC.

Table 3. Main parameters of the DTL sections.

parameters	value
tanks	7 (including rebuncher)
A/q	3–7
beam current/emA	3
f_{r}/MHz	108.48/216.96
L_{total}/m	17.066
$Gradient_{\mathrm{max}}$/(MV/m)	4.95
P_{rf}(total)/MW	2.8
$(E_{\mathrm{in}}/E_{\mathrm{out}})$/(MeV/u)	0.3/7.275
transmission(%)	⩾95

Kombinierte Null Grad Struktur (KONUS) beam dynamics are applied to the drift tube linac in CSR-LINAC [11], and an Interdigital H-mode (IH) structure is adopted because of high shunt impedance [12]. The LORASR code is applied to the beam dynamics design of KONUS DTL. The period structure concept is proposed in the KONUS beam dynamics design. A KONUS period is composed of three sections with separated functions. The first section consists of a few gaps with a negative synchronous phase of typically from $-25°$ to $-35°$ and acts as a rebuncher. Then the beam is injected into the main accelerating section with surplus energy and phase compared with a synchronous particle. Finally, the multi-gap section is followed by the transverse focusing elements, such as the magnetic quadrupole triplets. In the beam dynamics design of the KONUS period structure, the key parameters to be chosen are as follows [13]: (1) effective accelerating voltage distribution, (2) cell number per section, and (3) starting phase and energy in 0° section.

For a given geometry, the relation of the peak electric field E_{p} on the axis to the maximum surface electric field E_{s} is illustrated by:

$$E_{\mathrm{p}}=\kappa_{\mathrm{opt}}(g,d)E_{\mathrm{s}}, \tag{5}$$

where $\kappa_{\mathrm{opt}}(g,d)$ depends on the accelerating gap length g, the tube diameter d and the tube pole geometry, which is independent to the resonance frequency when the cell size is much smaller than the RF wave length. The database of $\kappa_{\mathrm{opt}}(g,d)$, simulated and calculated by the CST Microwave Studio, shows the corresponding relation of E_{s} to E_{p}. The peak electric field limit $E_{\mathrm{p,limit}}$ on the axis is obtained by:

$$E_{\mathrm{p,limit}}=\kappa_{\mathrm{opt}}(g,d)E_{\mathrm{spark}}, \tag{6}$$

where E_{spark} is the maximum surface electric field for the spark, which is 21.05 MV/m for 108.48 MHz and 27.38 MV/m for 216.96 MHz. The variation of $E_{\mathrm{p,limit}}$ with a gap length at a different tube radii and resonance frequency, and the peak electric field distribution per cavity are presented in Fig. 10. As can be seen, the peak electric fields in the first DTL with a tube radius of 10 mm are lower than the corresponding peak electric field limit (black line) at the resonance frequency of 108.48 MHz; the peak electric fields of the first 15 cells in the DTL2 with a tube radius of 10 mm are lower than the corresponding peak electric field limit (red line) at the resonance frequency of 216.96 MHz; and the peak electric fields of the others downstream with a tube radius of 11 mm are lower than the corresponding peak electric field limit (green line) at the resonance frequency of 216.96 MHz.

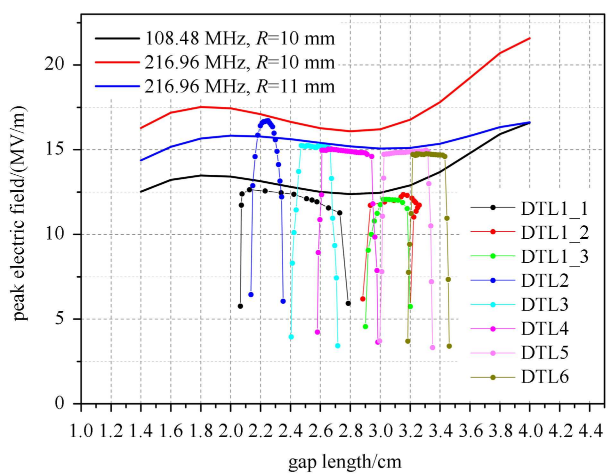

Fig. 10. (color online) The dot-lines stand for the peak electric field distribution per cavity. The lines mean the peak electric field limit as the function of the gap length, at different tube radii.

In the LORASR code, the peak electric field (E_{p}) on the axis is calculated from the given effective accelerating voltage, and the reasonable effective voltage distribution is adjusted according to the peak electric field in Fig. 10. Fig. 11 shows the effective accelerating voltage distribution along the DTL section, and the maximum effective accelerating voltage is 0.561 MV, which keeps in a safe region.

Concerning the phase shift (for example at the transition $\phi_{\mathrm{sec1}}\rightarrow\phi_{\mathrm{sec2}}$) in the same cavity, the geometry length of the transition cell is adjusted by:

$$L_{\mathrm{shift}}=\left(n+\frac{\phi_{\mathrm{sec2}}-\phi_{\mathrm{sec1}}}{180}\right)\frac{\beta\lambda}{2}, \tag{7}$$

where n=1 at the transition to the 0° section and n depends on the length of the quadrupole triplet where the 0° section transfers to the negative phase section. The tank RF phases can be chosen independently when the transition gaps belong to different cavities. In the 0° section, the starting energy and phase are adjusted to get the desired beam parameters, which match the needs of the following sections. Generally, the final bunch center phase is in the range of −20° to −30° (seen in Fig. 12), and also depends on the cell number in the 0° section.

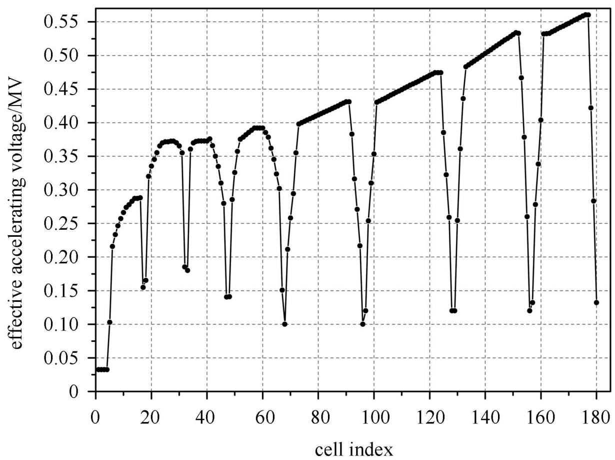

Fig. 11. The effective accelerating voltage distribution per cell along the DTLs.

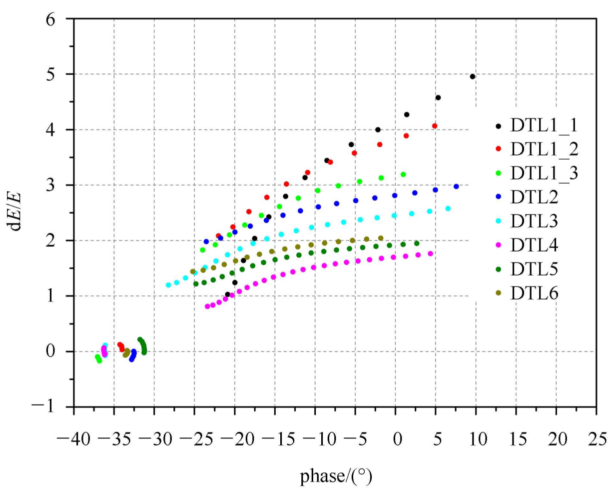

Fig. 12. (color online) The evolution of the reference particle in the longitudinal phase space.

A pole tip field up to $B_{\max}$=1.3 T is available with conventional technology. At a lower beam energy section, quadrupole triplets must be installed within the resonator for the shortest possible drifts (QT3, QT4) between the sections, which make the mechanical design and RF tuning more complicated. With increasing beam energy, external lenses (QT5-QT10) are preferably used. A triplet section consists of four drift spaces and three magnetic quadrupoles, and parameters of magnetic quadruple triplets are listed in Table 4. The maximum quadrupole field gradient is 90 T/m, corresponding to a pole tip magnetic field of 1.17 T for the triplet aperture diameter of 26 mm, which keeps the 10% margin of the magnetic field limit, 1.3 T. Fig. 13 shows the transverse envelope evolution along the position z. The beam envelope is smaller than 12 mm in the drift tube section with aperture diameters of 20–22 mm. Fig. 14 exhibits the relative longitudinal energy spread and phase spread as a function of the position z. The 95% relative energy spread is smaller than 0.5% at the end of the DTL section, which can fill in the longitudinal acceptance of CSRm.

Table 4. Quadruple triplets parameter.

triplets	L_{drift}/mm	$L_{\text{eff,Q}}$/mm	field/(T/m)
QT1	328/22/22/455.7	77/138/77	60/50/44
QT2	127/22/22/142	77/138/77	58/51.5/57
QT3	34.7/22/22/34.7	77/138/77	81/74.5/81
QT4	35.5/22/22/35.5	77/138/77	80/78/78.5
QT5	94/22/22/94	77/138/77	79/79.8/79
QT6	94/22/22/94	92/162/92	79.1/82/82
QT7	94/22/22/94	92/162/92	85/88.5/84.5
QT8	109/22/22/109	92/162/92	80/85/80
QT9	119/22/22/119	92/162/92	83/90/83
QT10	119/22/22/-	92/162/92	84/90/85

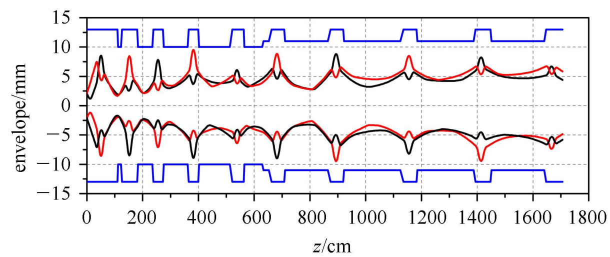

Fig. 13. The x (red) and y (black) transverse envelopes as a function of the position z.

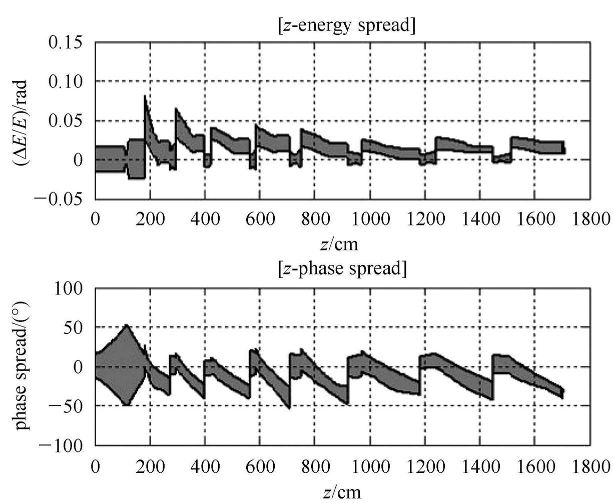

Fig. 14. The longitudinal relative energy spread (upper) and phase spread (lower) as a function of the position z.

5 Summary

The CSR-LINAC is proposed as the injector of CSRm, which is beneficial to the capability improvement of HIRFL-CSR, and DIPM is achieved to double the operation time of the whole facility. The new linac injector can supply heavy ions with maximum mass to a charge ratio of 7 and an energy of 7.272 MeV/u for CSRm. The beam current is as much as 10–100 times as that from SFC, which makes it possible to get higher charge state super-heavy ions by stripping and extracting a higher energy beam from CSRm.

A new strategy, which is used for the determination of the main parameters (resonance frequency, RFQ vane voltage and DTL effective accelerating voltage) in heavy ion linac, is described in detail. 108.48 MHz, as the basic resonance frequency of CSR-LINAC, is relatively high but brings a high accelerating gradient for a compact injector. Taking advantage of the efficient NFSP strategy, a new beam dynamics design has been realized for CSR-LINAC RFQ. The H-mode structure suitable for the low and medium β range, as well as the KONUS beam dynamics concept for a high gradient DTL, is applied to the main accelerating section in CSR-LINAC. The detail error study of CSR-LINAC will be presented systematically in the next paper. The CSR-LINAC project has been listed in the next 5-year plan of the Institute of Modern Physics (IMP).

The authors want to give special thanks to Prof. Lu Yuanrong of Peking University for providing the LANL RFQ code, to Prof. U.Ratzinger for providing the LORASR code, and to the members of the CSR-LINAC work group for many discussions.

References

1 XIA J W, ZHAN W L, WEI B W et al. Nucl. Instrum. Methods A, 2002, **488**(1): 11–25
2 Barth W. arXiv preprint physics/0008087, 2000
3 Hutcheon D A, Bishop S, Buchmann L et al. Nucl. Instrum. Methods A, 2003, **498**(1): 190–210
4 Yano Y. Nucl. Instrum. Methods B, 2007, **261**(1): 1009–1013
5 Wittkower A B, Betz H D. Atomic Data and Nuclear Data Tables, 1973, **5**(2): 113–166
6 Wangler T P. RF Linear accelerators. http://as.wiley.com/, 2008
7 Staples J W. AIP Conference Proceedings, 1992, **249**: 1483
8 ZHANG C, Schempp A. Nucl. Instrum. Methods A, 2008, **586**: 153–159
9 Crandall K R, Stokes R H, Wangler T P. Proceedings of the 1979 Linac Accelerator Conference. USA, 1979. 205–216
10 Ilija M. Kapchinsky, LA-UR-93-4192. Los Alamos, 1993
11 Ratzinger U. Record of the 1991 IEEE PAC. San Francisco. 1991, **91**: 3038-7
12 Bres M, Chabert A, Foret F et al. Proceedings of the 1971 Particle accelerators. Chicago, 1971, **2**: 17
13 Tiede R, Ratzinger U, Podlech H et al. Hadron Beam, USA, 2008, **1**: 2013