Beam steering correction of the quarter wave resonator in the HISCL *

LIU Shu-Hui(刘淑会)[1)] WANG Zhi-Jun(王志军)[2)] ZHANG Cong(张聪) HE Yuan(何源)[3)]
Insititution of Modern Physics, the Chinese Academy of Sciences, Lanzhou 730000, China

Abstract: The Intensity Heavy Ion Superconducting Linear Accelerator as the injector of the High Intensity Heavy-Ion Accelerator Facility, which is a new project proposed in China has been designed. One of the design options in the low energy part is based on Quarter Wave Resonators (QWRs). However, because of the unsymmetrical geometry of the cavity, there are dipole fields near the beam hole, which may steer the beam vertically, thus leading to emittance growth and beam loss. The effect of the dipole mode field is analyzed, and a method to overcome the beam steering effect by placing QWRs with opposite orientation is proposed in this paper. The simulation results show that the beam steering effect is reduced effectively by this method, and the deviation of the beam centroid is decreased from 2.87 mm to 0.1 mm. The emittance growth is also smaller.

Key words: QWR, lattice structural layout, beam steering

PACS: 29.27.Bd, 52.65.Rr, 41.20.cv **DOI:** 10.1088/1674-1137/38/10/107007

1 Introduction

The High Intensity Heavy Ion Accelerator Facility (HIAF) is a multi-function, full ion species, national user accelerator facility, and it is proposed by the Institute of Modern Physics (IMP). The High Intensive Heavy Ion Superconducting Linear Accelerator (HISCL) as the injector of HIAF contains the Electron Cyclotron Resonance Ion Source (ECRIS), the Low Energy Beam Transport (LEBT), the Radio Frequency Quadrupole (RFQ) and the superconducting (SC) section [1].

The low-β Quarter Wave Resonators (QWRs) are applied extensively by existing and under construction heavy ion accelerators to accelerate ions in the low energy part, such as Facility for Rare Isotope Beam (FRIB) [2], spiral2 [3] and so on. The wide application of superconducting QWRs is due to its excellent properties, such as the high accelerating gradient, high efficiency, small volume and the possibility of accelerating particles with different q/A in the same linac [4]. However, due to the asymmetrical structure of the resonator with respect to the beam axis, both asymmetrical magnetic and transverse electric fields are produced and they have a net vertical steering effect on particles, which will deviate the beam centroid from the centre of the accelerator beam axis, and the beam quality will be destroyed. Some solutions have been proposed to compensate the steering effect by some laboratories, for example, a compensation method by tilting the drift tube face with a small angle proposed in the Argon National Laboratory [5]. This compensation method can effectively reduce the beam orbit deviation, but the structure is complex which will bring some difficulty for manufacturing.

In this paper, another solution of the compensation steering effect is proposed, which suggests alternatively placing the QWRs positively and negatively with each other. The single cryomodule layouts of the common lattice in which the cavities are placed with the same direction, and the new lattice in which the QWRs are placed with opposite direction are depicted in Fig. 1. Based on the design of the SC section of the HISCL, in

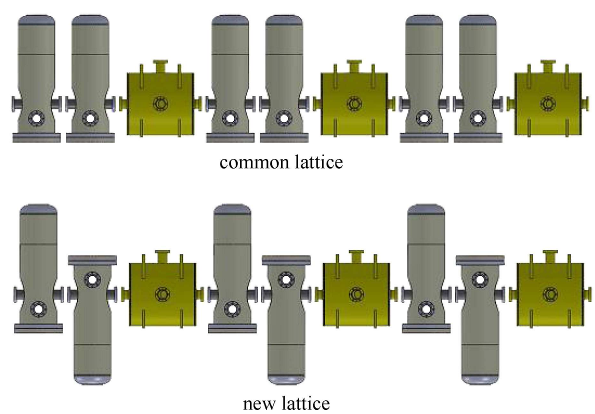

Fig. 1. (color online)Layouts of common and new lattices.

Received 6 November 2013
∗ Supported by National Science Foundation of China (11079001)
1) E-mail: liush@impcas.ac.cn
2) E-mail: wangzj@impcas.ac.cn
3) E-mail: hey@impcas.ac.cn

which the QWRs are adopted as accelerating elements to accelerate the U^{34+} from 1.3 MeV/u to about 5 MeV/u with a 2 mA beam current. The beam dynamic simulation with the TRACEWIN [6] code, which is a design and tracking code, has been performed. The simulation results will be presented in the following sections.

2 Analysis of beam steering in QWR

QWR with a 81.25 MHz frequency and 0.085 optimal beta is used in the design of the SC section of the HISCL. The QWR geometric structure and field map are shown in Fig. 2. As can be seen, it is asymmetric with respect to the x-z plane and which will cause dipole component fields. Both transverse magnetic and electric fields will produce the steering effect in the y direction [7] which has an impact on beam transport. An analytical formula of the beam steering caused by transverse field components, based on the homogeneous gap and constant velocity approximations, is shown in Eq. (1).

$$\Delta y' = -\frac{\Delta U}{\gamma mc^2\beta}\tan\phi\frac{\cos\left(\frac{\pi d_y}{\beta\lambda}\right)}{\beta\sin\left(\frac{\pi d}{\beta\lambda}\right)}K_{EY(y)} - \frac{\Delta U}{\gamma mc^2\beta}(\tan\phi)cK_{BX(y)}\Bigg\}, \qquad (1)$$

where ΔU is the particle energy gain; $\Delta y'$ presents the deflection angle; m is the rest mass; ϕ is the rf phase; d is the gap-to-gap (centre) distance; d_y is an effective gap-to-gap distance for the transverse electric field E_y; $K_{EY(y)}$ and $K_{BX(y)}$ are the average values calculated in one accelerating gap and normalized to the accelerating field on the beam axis respectively. As can be seen from Eq. (1), the deflection effect of the dipole mode field on the beam includes the electric deflection and the magnetic deflection. There are several factors that impact the steering angle. First, when the beam velocity and the energy are low, the beam steering effect becomes more serious. So, in the low energy part, the beam steering effect must be resolved to avoid bad beam quality. Second, the deviation angle will become large when the rest mass of m is small, so, QWR is not fit for light particles. Third, we can observe that the deflection angle strongly depends on the rf phase ϕ. When ϕ=0 there is maximum acceleration and no steering, while at $\phi=-90°$ (bunching) there is no acceleration and maximum steering. In addition, it is noticeable that the magnetic deflection is the dominant.

Figure 2 shows the field distribution of QWR. The yellow line presents the longitudinal electric field E_z along the cavity axis, the blue line presents the magnetic field B_x, and the red line presents the electric field E_y.

Compared with the accelerating component E_z, the transverse magnetic field B_x is shifted by 90° in the rf phase and has a similar antisymmetric distribution; the distribution of B_x is symmetric. All components act to the beam with different strengths as a function of beam velocity and rf phase.

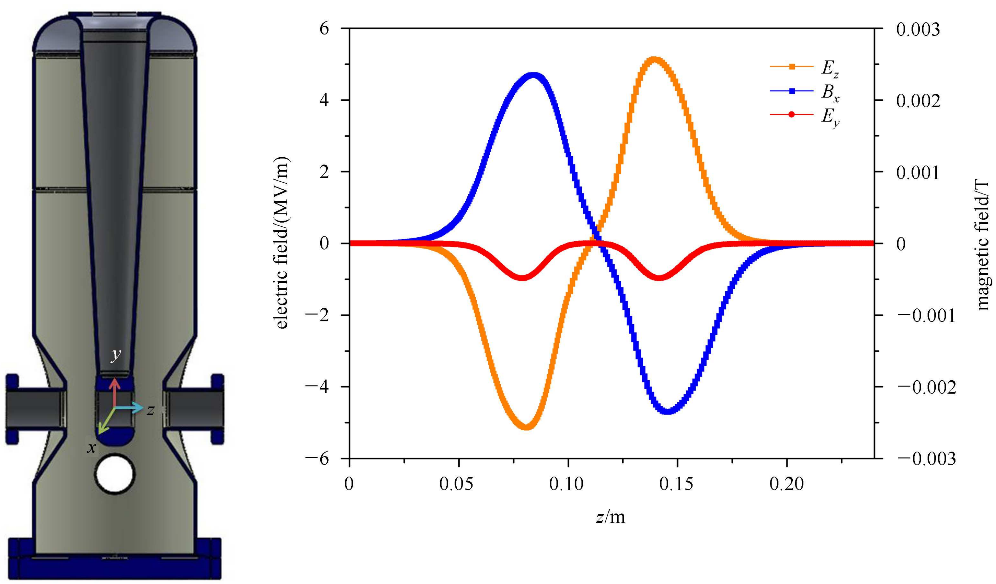

Fig. 2. (color online) Structure map and cavity Field distribution of QWR. The upper picture: The structure of QWR; the lower picture: The field distribution.

3 Beam dynamic simulation

The dynamic analysis is carried out based on the simulation results of the superconducting section of the HISCL. Table 1 shows the basic parameters of the superconducting section.

TRACEWIN is used for the beam dynamics simulation. The initial parameters for simulation are presented in Table 1, where ε_{xy} and ε_z are the initial normalized RMS emittances in the transverse direction and longitudinal direction. Fig. 3 shows the comparison of the beam centroid deviation between two types of structure whose cavities are alternatively placed positively and negatively and placed in the same direction. It can be seen that the new structure is good for cancelling out the steering effect, and the maximum centroid deviation is less than 0.1 mm. However, the maximum centroid deviation of the common design is about 2.87 mm. We can observe that the method of overcoming the steering effect is effective. To some extant, the bad influence on the beam centre orbit is eliminated.

Table 1. The main parameters of the design results.

parameter	value
frequency/MHz	81.25
ion species	U^{34+}
input energy/(MeV/u)	1.3
output energy/(MeV/u)	5
beam current/mA	2
ε_{xy}/mm·mard	0.2
ε_z/mm·mard	0.17

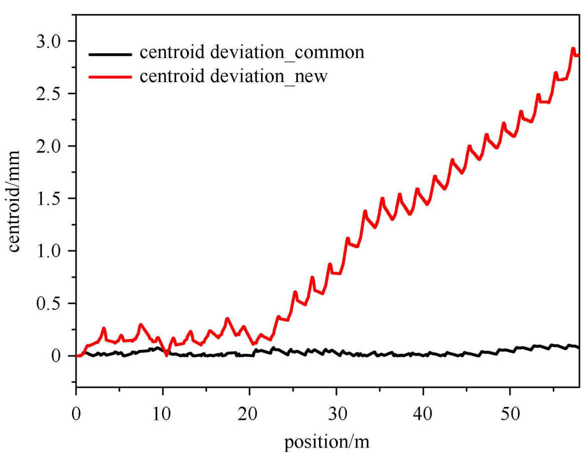

Fig. 3. (color online) Comparison of beam centroid deviation. The red line stands for the cavities placed in the same direction; the black line stands for the cavities alternatively placed positively and negatively.

Figure 4 shows the beam envelopes of the two types of lattice structural layout in vertical plane. More obvious evidence indicates that, for the common layout of QWRs, the beam largely suffers the steering effect of the dipole mode field, and the beam deviates from the reference orbit, and the beam envelope inclines upwards as shown in the simulation results. For the new layout of QWRs, the steering effects of QWRs are very weak, the envelope is smooth, and the beam size is uniform along the whole lattice.

The emittance growth is a very important criterion for a lattice design. The comparison of the transverse RMS emittance growths between the two types of lattice layout are given in Fig. 5. The transverse RMS emittance growth of the common lattice structural layout is larger than that of the new lattice structural layout. In this situation, the beam quality will become worse with the increase of the number of the period. The details of the emittance growth are listed in Table 2.

As it follows from the results of the beam dynamics simulation, the deviation of beam centroid of the new

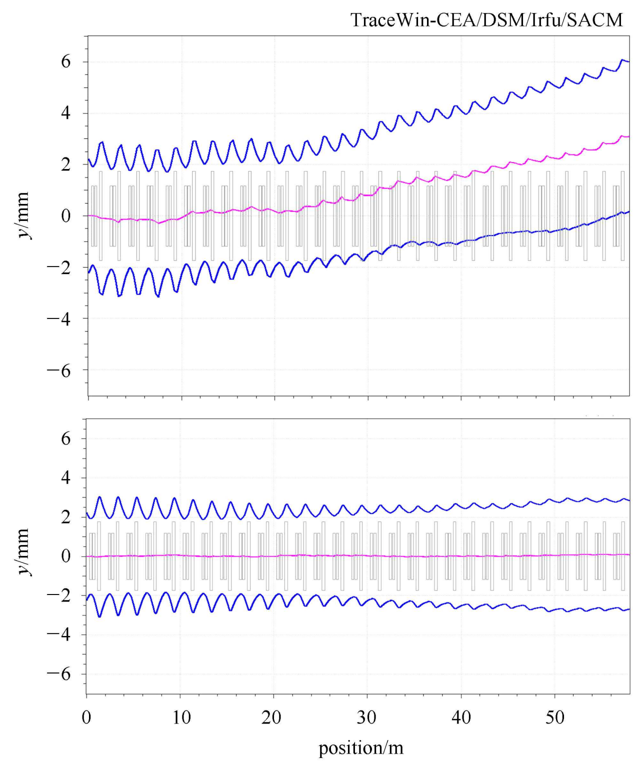

Fig. 4. (color online)Beam envelope of the superconducting section in the vertical plane. The upper picture: the common lattice layout; the lower picture: the new lattice layout.

Table 2. The main parameters of the design results.

parameter	common design	new design
deviation of centroid/mm	2.87	0.1
RMS emittance x growth(%)	6	0.8
RMS emittance y growth(%)	3	0.8

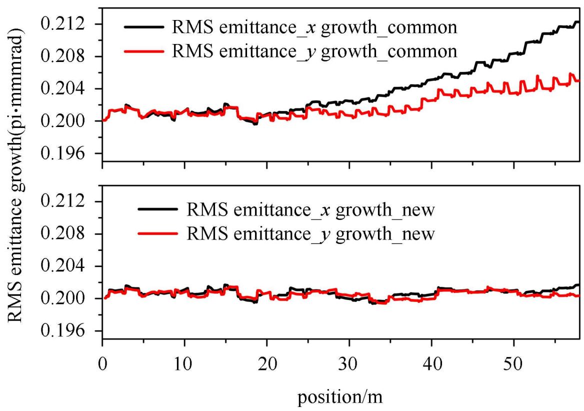

Fig. 5. (color online)The RMS emittance growths for both two types of lattice structural layout.

lattice structural layout, in which QWRs are alternatively placed positively and negatively, can be decreased to less than 0.1 mm. Namely, this method is effective to cancel out the steering effect from the dipole mode field of QWRs, and it can meet the requirement of accelerating ions almost without beam steering. For the HISCL project, this new lattice structural layout will be a good option for beam acceleration in the low energy part.

4 Conclusion

In this paper, a new lattice structural layout with QWRs which are alternatively placed positively and negatively is proposed. The beam dynamics results show that this lattice structural layout can eliminate the inherent steering effect of the QWRs, almost without centroid deviation of the beam. The RMS emittance growth is also lower than that of the common lattice structural layout in which QWRs are placed in the same direction.

References

1 Conceptual Physical Design on the HISCL Accelerators

2 York R C. A New Accelerator Facility for the Production and Experiments with Rare Isotope Beams. Proceedings of PAC09

3 Devanz G. SPIRAL 2 resonators, Physica C, 2006, **441**: 173–178

4 Kakutani N, Nakayama K, Tanabe Y et al. Study on Superconducting Quarter Wave Resonator for CW Intense Ion Linac. Proceedings of the 6th European Particle Accelerator conference. Stockholm:Stockholm City Congress Centre, 1998. 1858–1860

5 Mustapha B, Ostroumov P N. Electro-Magnetic Optimization of a Quarter-Wave Resonator. Proceedings of LINAC,2010

6 http://irfu.cea.fr/Sacm/en/logiciels/index3.php

7 ZHANG Cong, ZHAO Hong-wei, HE Yuan. Nuclear Physics Review, 2010, **27**(4): 436