RF knock-out extraction in HITFiL*

SHI Jian(石健)[1,2] YANG Jian-Cheng(杨建成)[1;1)] XIA Jia-Wen(夏佳文)[1]
YUAN You-Jin(原有进)[1] LI Jie(李杰)[1,2] CHAI Wei-Ping(柴伟平)[1,2]
SONG Ming-Tao(宋明涛)[1] ZHANG Xiao-Hu(张小虎)[1,2]

[1] Institution of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: A compact facility for cancer therapy has been designed and is presently under construction. A slow beam extraction system using the RF-Knock Out method and 3rd-order resonance is adopted in the synchrotron of this facility. Eight sextupoles are used, four of them are for correcting the chromaticity and the rest for driving the 3rd-order resonance. In order to save the aperture of vacuum chamber, a 3-magnet bump is adopted during the extraction process. The extraction phase space map and the last 3 turns' particle trajectory before extraction are given. The matching betatron functions with HEBT (high energy beam transport) are also presented.

Key words: RF-knock out slow extraction, 3rd order resonance, cancer therapy

PACS: 29.20.-c, 87.56.bd, 29.20.dk **DOI:** 10.1088/1674-1137/36/10/016

1 Introduction

Cancer therapy with protons and light ions [1] has developed considerably in recent years. Several facilities have already been built or are under construction world-wide. The HITFiL (Heavy Ion Therapy Facility in Lanzhou) is the first carbon ion cancer therapy facility in China. The project is supported by the Lanzhou municipal government, funded by the SHENGDA Company, and designed and constructed by the Institute of Modern Physics. The facility has been designed based on the experience of the construction and operation of the HIRFL-CSR [2, 3].

Figure 1 shows the layout of the HITFiL. An ECR ion source is put under the cyclotron, which produces the C^{5+} beam. The beam will be injected into the cyclotron from the axis direction, and be accelerated from 29 keV/u to 7 MeV/u, then injected into the

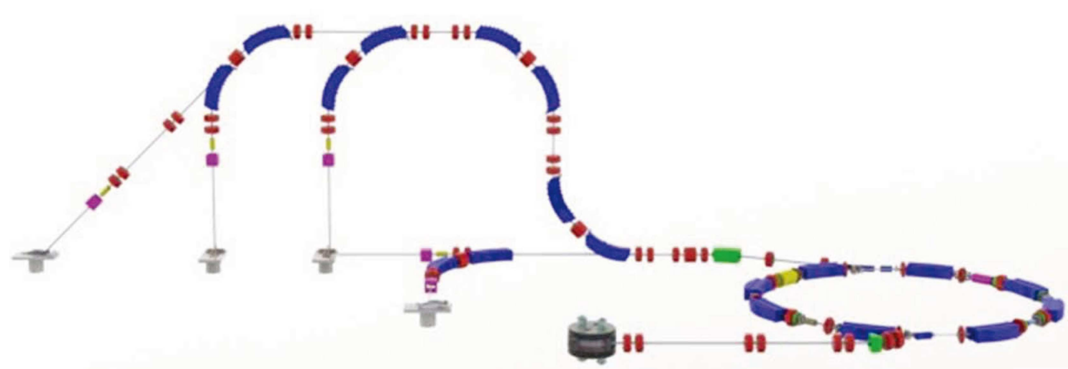

Fig. 1. (color online) General layout of the HITFiL.

Received 23 December 2011
* Supported by State Key Development Program of Basic Research of China (2010CB834204)
1) E-mail: yangjch@impcas.ac.cn

synchrotron by the charge exchange injection method. There are four treatment rooms with one shown in the figure. The energy of the beam delivered to the treatment room can be changed from 80 MeV/u to 400 MeV/u in a step length of 1.5 MeV/u.

2 Design of the RF-knock out extraction

2.1 Lattice of synchrotron

The synchrotron has a circumference of 56.2 m, and has a two-fold symmetry structure which is composed of 8 dipoles and 12 quadrupoles, as seen in Fig. 2.

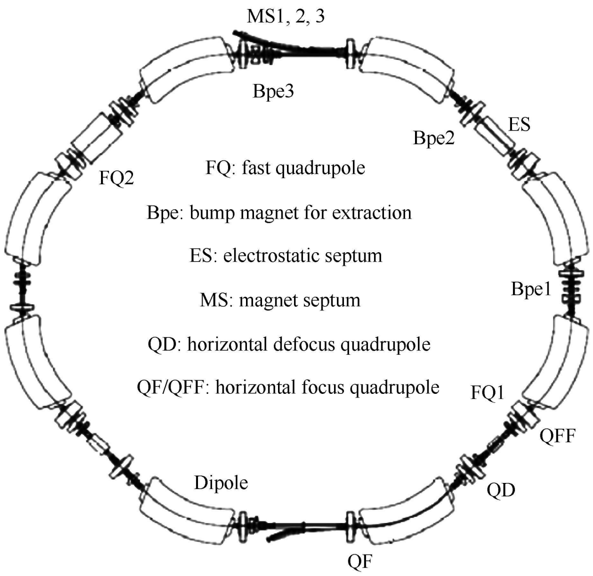

Fig. 2. (color online) Layout of the HITFiL synchrotron.

Table 1 lists the parameters of the synchrotron and Fig. 3 shows the twiss functions. In order to fulfill the Hardt condition [4], the electrostatic septum (ES) is put in the descending part of the dispersion bump.

2.2 Distribution of the sextupole

The normalised sextupole strength is given by [5]:

$$S=\frac{1}{2}\beta_x^{\frac{3}{2}}\frac{l_{\rm s}}{B\rho}\left(\frac{{\rm d}^2B_z}{{\rm d}x^2}\right)_0=\frac{1}{2}\beta_x^{\frac{3}{2}}l_{\rm s}k', \qquad (1)$$

where k' is the normalized sextupole gradient,

$$k'=\frac{1}{B\rho}\left(\frac{{\rm d}^2B_z}{{\rm d}x^2}\right),$$

and $l_{\rm s}$ is the length of the sextupole, β_x is the horizontal beta function in the sextupole. For several sextupoles distributed in a machine, the combined effect can be described by [6]:

$$S_{\rm virt}^2=\left(\sum_n S_n\cos(3\mu_{x,n})\right)^2+\left(\sum_n S_n\sin(3\mu_{x,n})\right)^2,$$

$$n=1,2,3,... \qquad (2)$$

where the $S_{\rm virt}$ is called virtual sextupole strength, S_n and $\mu_{x,n}$ are the strength and phase displacement of the single sextupole, respectively.

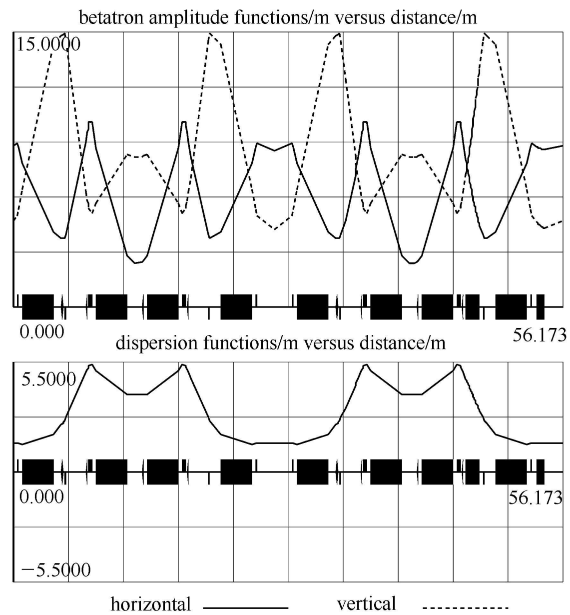

Fig. 3. Twiss parameters. The last dipole in the figure is the magnet septum (MS1 in Fig. 2), and the last third dipole is the electrostatic septum. The phase advance between the two septa is 75 degrees.

Since the horizontal work point has been chosen as 1.68 just near the even number, and the super-period is 2, the chromaticity and the resonance driving function can be achieved separately from Eq. (2). Therefore the 8 sextupoles are distributed

Table 1. Parameters of the synchrotron.

C/m	$B\rho$/(T·m)	$\beta_{x\max}/\beta_{y\max}$/m	$D_{\max}$/m	Q_x/Q_y	super period	$\gamma_{\rm t}$
56.2	0.76–6.62	10/15	5.4	1.68/1.23	2	1.74

symmetrically in the ring; 4 of them are used to control the resonance excitation and the others are used to adjust the chromaticity. The dynamic aperture will be considerablely reduced when the sextupoles are working, but it is still large enough for the beam operations.

2.3 Extraction state at the ES

Similar to the CSRm, the RF-KO method [7] has been proposed, which has many advantages compared with other methods, such as responding fast to beam-on/off [8], producing static target beam spots during extraction, keeping the lattice of the synchrotron constant, changing the spill intensity easily [9], etc.

Figure 4 shows the phase space simulated by MAD-X [10] at the entrance of the electrostatic septum. The blue dots describe the maximum stable area, and the red dot is the same as the blue dot but the transverse RF is switched on. The dashed line represents the position of the ES wires, which are positioned at 60 mm from the center of the vacuum chamber. The emittance in the stable area is about 40 π·mm·mrad, and the spiral step is about 10 mm (it also can be seen from Fig. 7).

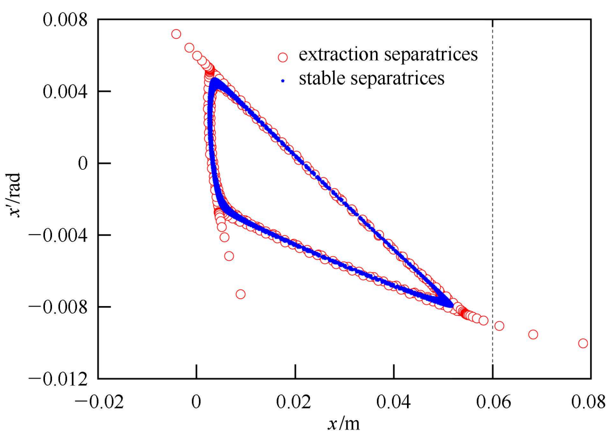

Fig. 4. The separatrices and outgoing trajectories at the entrance of ES.

Figure 5 shows the limiting trajectories of the separatrices over the last three turns before they are extracted and the extracted beam segment between the electrostatic and magnetic septa. The angle of the electrostatic septum is −8 mrad; just parallel with the extraction spill. The extraction orbit has been bumped by a 3-magnet bump (Bpe1, Bpe2, and Bpe3 in Fig. 2), which raised a height of 20 mm at the entrance of ES during extraction.

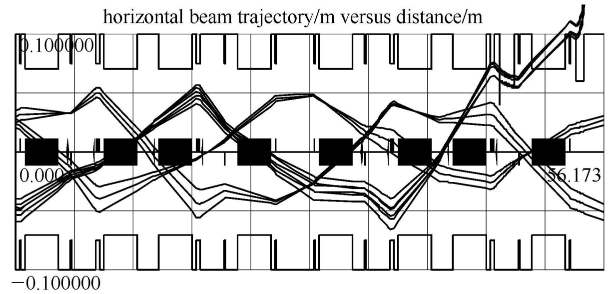

Fig. 5. The trajectory of the last three turns before extraction and the extracted segment between ES and MS.

2.4 Spill feedback

The spill feedback controlled by fast quadrupoles has been successfully realized in CSRm, the amplitude of the spill ripple within 1000 Hz can be reduced to 1/10 times [11] from the conventional mode. The power supply ripple of the quadrupole in HITFiL is similar to CSRm. In order to suppress the spill ripple, a group of fast quadrupoles is adopted, which are distributed symmetrically in the synchrotron. The fast quadrupoles are positioned near the horizontal focus quadrupoles, which produces a large horizontal betatron amplitude function (see FQ in Fig. 2). The parameters of the fast quadrupoles are listed in Table 2.

Table 2. Parameters of fast quadrupole.

number	2
$\text{strength}_{\max}$/(T/m)	2
effective length/mm	150
aperture	150 mm×80 mm
response time/ms	0.2

2.5 Electrostatic septum

Since the beam enters the ES with a negative angle relative to the synchrotron chamber, and the ES is placed at the same angle as the extraction beam, the effective aperture for the storage beam will be decreased at the injection process. In order to reduce the voltage of the ES and keep the aperture effective, a new design of electrostatic septum has been created. The septum wall formed by tungsten wires has been bent into a curve from a straight line, and the radius of the curve is 400 meters. 3 mm horizontal aperture will be saved in this situation, and the voltage of the ES will be reduced by 20%. Fig. 6 shows the spill trajectory and electrostatic channel, the yellow part in the figure represents the spill which enters the ES, and the dotted region represents the ES channel. The effective length of the electrostatic septum is 1.4 m, the diameter of the wires is 0.1 mm, and the maximum tolerance voltage is 160 kV.

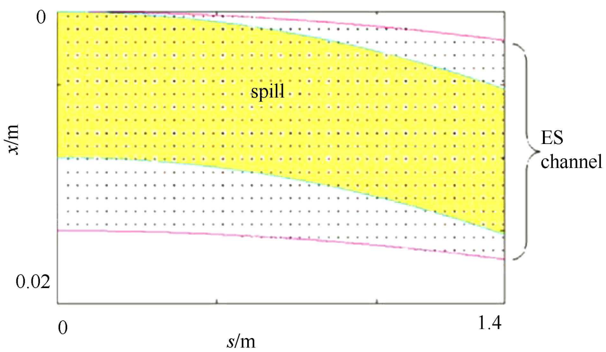

Fig. 6. The spill orbit vs. the ES channel.

2.6 Matching to the HEBT

In the horizontal phase-space, the extracted particles are distributed, for all practical purposes, in a long and thin rectangle, referred to as the "bar" of charge, which is the part of the extraction separatrix cut by the electrostatic septum. However, the extracted beam in the vertical phase-space has the same betatron functions as the synchrotron. The horizontal emittance will change its shape due to the unavoidable variations in the closed orbit or other relevant parameters such as the ripple of the power supply. The change of the shape in the phase space requires a new matching of the beam lines. So an unfilled ellipse is chosen such that the "bar" of charge is nearly a diameter of the ellipse, and the whole ellipse will be treated as the matching emittance, as seen in Fig. 7.

The match parameters are listed in Table 3 after using the matching ellipse. Taking into account the uncertainties such as the close orbit and power supply ripple, the dispersion function has a range, which means the position of the ellipse shakes with the uncertainties, and will be considered in the design of the HEBT.

Figure 8 shows the twiss parameters from ES to MS. Since the extracted particles do not pass the quadurpoles in the center line, the quadrupoles are treated as dipoles but contain a quadrupole component. The last three dipoles represent the three extract magnet septa: MS1, MS2, and MS3.

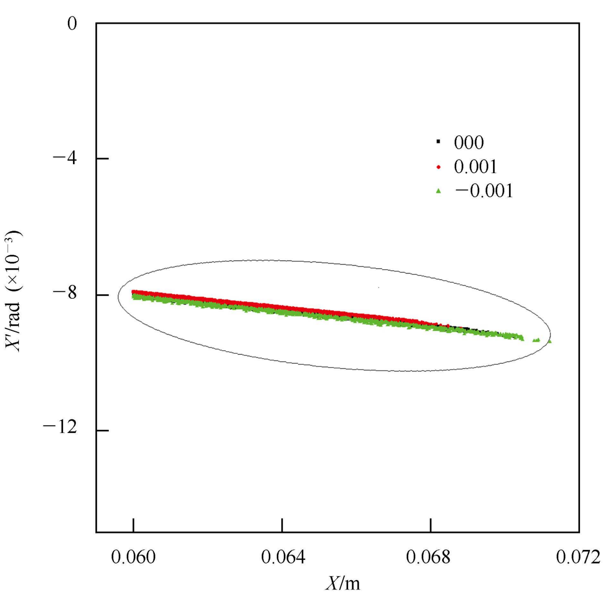

Fig. 7. The ellipse and the extraction bar in the phase-space at the electrostatic septum. The red and green dots represent the extraction beams, which have a momentum spread of 1‰ and −1‰, respectively. The result is simulated by using WinAgile [12], which is slightly different from Fig. 4 (simulated by MAD-X).

Table 3. The matching parameters at ES.

β_x/m	4.0
α_x	0.49
D/m	−0.45–−0.75
D'	0.05–0.25
β_y/m	7.24
α_y	−1.69

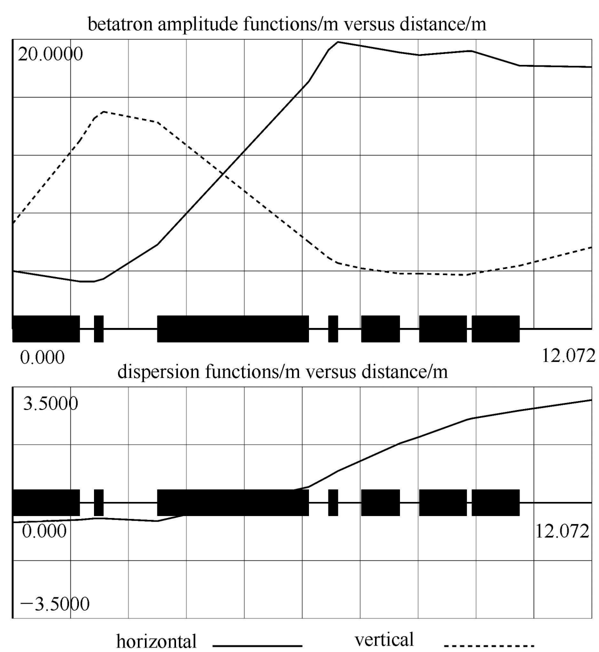

Fig. 8. Twiss parameters from ES to MS.

3 Conclusion

The 3rd resonance slow extraction of the HIT-FiL has been described. The extraction simulation is done with the accelerator codes MAD-X and WinAgile. To save enough vacuum chamber space for beam injection, the 3-bump orbit has been adopted in the extraction process, and a new electrostatic septum has been proposed. The spill matching to the HEBT has also been taken into account.

The authors want to thank Dr. S. Y. Lee from Indiana University for his discussions and help.

References

1 Daniela Schulz-Ertner, MD, Oliver Jakel et al. Semin Radiat Oncol, 2006, **16**: 249–259
2 XIA J W, ZHAN W L, WEI B W et al. Nucl. Instrum. Methods A, 2002, **488**: 11–25
3 YUAN You-Jin, SONG Ming-Tao et al. High Power Laser And Particle Beams, 2005, **17**(2): 275–278
4 Hardt W. CERN, PS/DL/LEAR Note 81-6. 1981
5 Bryant P, Benedikt M, Badano L. CERN/PS 99-010 (DI). 1999
6 Guignard G. CERN, CERN-78-11
7 Noda K, Furukawa T, Shibuya S et al. Nucl. Instrum. Methods A, 2002, **492**: 241–252
8 Takuji Furukawa, Koji Noda. Nucl. Instrum. Methods A, 2002, **489**: 59–67
9 Furukawa T, Noda K, Uesugi T H et al. Nucl. Instrum. Methods B, 2005, **240**: 32–35
10 http://madx.web.cern.ch/madx/
11 MAO R S, LI P, MA L Z et al. Proceedings of ICALEPCS, 2011. 186–188
12 Bryant P J. AGILE, A Tool For Interactive Lattice. Design. CERN, Geneva, Switzerland