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Injection system design for a hadron therapy synchrotron

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Abstract A synchrotron is designed for tumour therapy with C^{6+} ions or proton. Its injector is a cyclotron, which delivers C^{5+} or H_2^+ ions to the synchrotron. After comparing the methods of the single-turn injection, the multi-turn injection and the stripping injection, this paper chooses the stripping injection method. In addition, the concept design of the injection system is presented, in which the synchrotron lattice is optimized.

Key words injection mode, stripping injection, synchrotron, lattice

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1 Introduction

The hadron therapy center is a project of high investment, so the design of the clinic synchrotron is a compromise between the cost and the flexibility. Nowadays, the circumference of the heavy-ion therapy synchrotron is usually 60—80 m in the world.

A heavy-ion synchrotron facility for medical use is designed[1] and optimized later, with great attention paid to compactness, low cost and high reliability. The circumference of the synchrotron is about 63.1 m after optimization. It consists of four cells with three dipole magnets and four quadruples in each cell. The ring has two long straight sections (6.0 m) with zero dispersion and four short dispersive ones (2.1 m). In contrast to the initial design, it has been improved in three aspects:

(1) Short circumference,
(2) Large acceptance, and
(3) Low cost.

Usually, there are three injection methods for synchrotron, namely the single-turn injection, the multi-turn injection and the stripping injection. The multi-turn injection method has been used by three medical centers in Germany[2] and Japan[3, 4], utilizing carbon beam or proton beam from linac. From the commissioning experience of the Cooler Storage Ring (CSR) at the Institute of Modern Physics, the stripping injection method is proved to be reliable and efficient. To meet the requirements of low cost and high reliability of the therapy synchrotron, the stripping injection scheme is thereby adopted for the proposed therapy synchrotron. Two injection points are needed for the injecting beam C^{5+} and H_2^+ respectively. Compared with the injection scheme of the initial design, it has two advantages:

(1) Low cost due to using a cyclotron as its injector,
(2) High beam intensity due to its large acceptance and adoption of the stripping injection method.

2 Optimization of the lattice

The initially designed synchrotron consists of four cells with three dipole magnets and four quadruples in each cell. Its circumference is 70 m. It has two long straight sections with zero dispersion and four short sections with dispersion. The long ones are used to accommodate the devices for injection and extraction respectively. The short ones are used to install sextupoles for chromaticity correction, RF cavity, and the bump magnets of the injection system and the electrostatic septum of the extraction system. The multi-turn injection method is used for the design of the injection system, utilizing fully stripped carbon ions from a linac injector.

In order to further reduce the cost and obtain high intensity beam of the synchrotron, the linac injector

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is substituted by a cyclotron injector, and the multi-turn injection scheme is substituted by the stripping injection scheme.

According to the requirement of stripping injection and the characteristic of the injecting beam C^{5+} and H_2^+, the lattice of the synchrotron is improved and optimized. Fig. 1 shows the layout of the synchrotron after optimization. Two long straight sections with zero dispersion are extended from 4 m to 6 m. They are used to accommodate the devices of the stripping injection system, the third-order resonant extraction system and the RF acceleration system. Each quadruple originally located in the two sections is moved upstream or downstream to its new positions between two dipole magnets. Four straight sections with dispersion are reduced from 3.8 m to 2.1 m. They are used to install the chromaticity correction sextupoles, the bump magnets of the injection system and the electrostatic septum of the extraction system. The circumference is reduced from 70 m to 63.1 m. The horizontal acceptance increases from 100 πmm·mrad to 150 πmm·mrad ($\Delta p/p = \pm 0.25\%$), and the momentum acceptance increases from ±0.55% to ±0.75% (ε_x=20 πmm·mrad). Fig. 2 shows the betatron and dispersion functions. Table 1 shows the main parameters of the synchrotron after optimization.

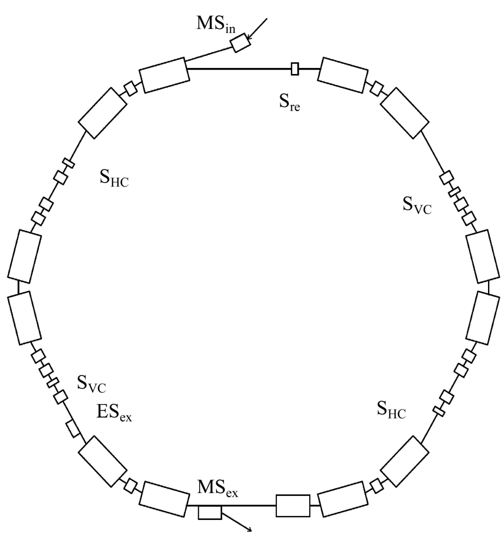

Fig. 1. Layout of the synchrotron.
MS_{in}: injection magnet septum, ES_{ex}: extraction electrostatic septum, MS_{ex}: extraction magnet septum, S_{re}: resonance sextupole, S_{HC}: Hor. chromaticity sextupole, S_{VC}: Vert. chromaticity sextupole.

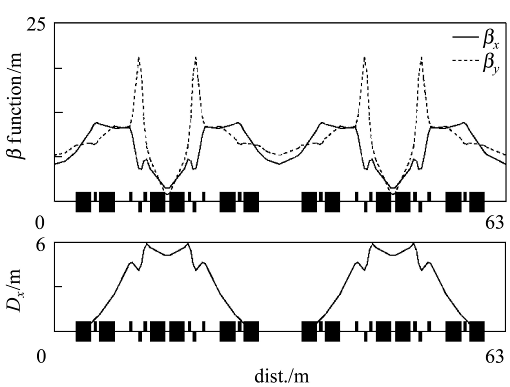

Fig. 2. Betatron and dispersion functions.

Table 1. Parameters of the synchrotron.

particles	p and C^{6+}
Max. energy	p: 250 MeV C: 430 MeV/u
circumference	63.1 m
super periodicity	2
H/V acceptance	150/60 πmm·mrad ($\Delta p/p = \pm 0.25\%$)
mom. acceptance	$\Delta p/p = \pm 0.75\%$ (ε_x=20 πmm·mrad)
beam intensity	C^{6+}: 4×10^8 ions/spill p: 10^9 ions/spill
injection energy	7 MeV/u
Max. dipole field	1.66 T
tune Q_x, Q_y	1.67, 1.72
Max. β_x, β_y	10.9, 20.2 m
natural chromaticity	−0.974/−2.989
Max. dispersion D_x	5.9 m

3 Injection system

Three injection methods are usually used for the injection system of the therapy synchrotron, namely single-turn injection, multi-injection and stripping injection.

In a synchrotron with single-turn injection, the beam intensity is usually limited. If high beam intensity is demanded, the beam from the injector has to increase greatly.

For the multi-turn injection, the intensity of accumulated beam is higher than that in the single-turn injection case. However, the injection turn numbers are limited by the acceptance of the synchrotron. And the resulting emittance ε_x in the ring increases because of the finite thickness of the electrostatic septum and the elliptical phase space contours of the injecting beam. If the injector emittance is ε_i, and the number of injected tunes is n, the resulting emittance ε_x in the ring, even in the absence of transverse space charge effects, is $\varepsilon_x > 1.5n\varepsilon_i$.

For the stripping injection, the constraints of Liouville's Theorem on multi-turn injection will not be applied to it since the stripping of ion occurs within the acceptance of the ring. Compared with the multi-turn injection, the stripping injection method has two advantages:

(1) The injection turn numbers are not limited by Liouville's Theorem,

(2) The filling of the phase space is more gradual than multi-turn injection without empty phase space and distinct boundaries between successive turns.

In a word, the injection turn numbers may increase greatly, so is the beam intensity. The experience of CSR commissioning shows that the stripping injection is reliable and convenient.

3.1 Design of the stripping injection[5—7] system

Based on the above analysis and comparison of three injection methods, the stripping injection scheme will be adopted for the injection system of the optimized therapy synchrotron. The hadron beam (C_{12}^{5+} or H_2^+) coming from the injector is injected into the synchrotron at a fixed angle. The carbon (proton) beam will circulate in the closed orbit of the synchrotron after crossing the stripping foil located at 6° (2°) in the first dipole magnet. The injection system of the synchrotron consists of four bump magnets and one magnetic septum. The closed orbit is bumped up to 45 mm (C_{12}^{5+}) or 50 mm (H_2^+) by the four bump magnets during injection. Fig. 3 shows the layout of stripping injection system. Fig. 4 is the sketch of the stripping injection.

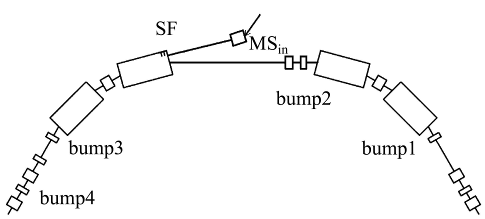

Fig. 3. Layout of the stripping injection system (SF: stripping foil).

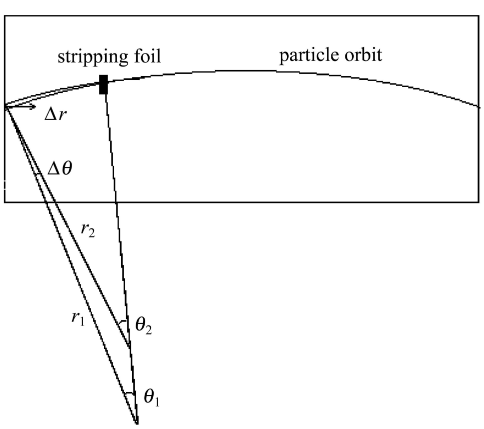

Fig. 4. Sketch of the stripping injection.

From the well-known formula of magnetic rigidity $r=p/Bq$, obviously,

$$r_1 q_1 = r_2 q_2 \ , \tag{1}$$

where, q_1 is the charge state of the injecting particle, and q_2 the charge state after stripping. From Fig. 4, one may find,

$$r_1\theta_1 \approx r_2\theta_2 \tag{2}$$

and

$$\Delta\theta = \theta_2 - \theta_1 \approx \left(1-\frac{q_1}{q_2}\right)\theta_2 \ . \tag{3}$$

Utilizing the geometrical relationship of the triangle, the gap ΔR between the injecting beam and the circulating beam at the exit of septum magnet can be obtained,

$$l_2 = r_2\cdot\sin(\theta_2)/\cos(\theta_2/2), \tag{4}$$

$$\Delta r = l_2\cdot\sin(\Delta\theta/2)/\cos(\theta_1/2), \tag{5}$$

$$\Delta R = \Delta r + L_1\cdot\tan(\Delta\theta), \tag{6}$$

where l_2 is the secant of θ_2, L_1 the length between the magnetic septum and the dipole magnet with the stripping foil.

By applying (6) and considering these principles listed below,

(1) the same injection channel used by the carbon and proton beam,

(2) sufficient gap between the injection beam and circulation beam at the exit of septum magnet,

(3) adequate distance between the injection beam line and the synchrotron at the entrance of the septum magnet.

The stripping foil is finally located at 6° (2°) from the entrance of the first dipole magnet for the $C_{12}^{5+}(H_2^+)$ beam due to large difference of charge ratio (q_2/q_1). As the height of the bump orbit is limited by the good-field region of the dipole magnets (±6.5 cm) and that of the quadruples (±7.0 cm), only those particles with $1.15 \leqslant q_2/q_1 \leqslant 1.30$ (6°) and $1.74 \leqslant q_2/q_1 \leqslant 2.86$ (2°) can be injected into the synchrotron. Assuming the emittance of injecting beam is 20 πmm·mrad, the momentum deviation of the injecting beam is ±0.25%, and the closed orbit is bumped up to 45 mm (50 mm) for $C_{12}^{5+}(H_2^+)$ beam during injection. The beam simulation is carried out by the program Winagile. It shows that all the injected ions have their orbits in the good-field region. Fig. 5 shows the beam track for H_2^+, the fractional relative momentum offset ($\Delta p_0/p$) from the central orbit is −0.3%. The horizontal and vertical emittances are 20 πmm·mrad. Fig. 6 shows the envelope of the carbon ion beam at injection. The full momentum spread of the beam ($\Delta p/p_0$) is 0.5%. The fractional relative momentum offset from the central orbit ($\Delta p_0/p_0$) is set to −0.3% so as to push the beam to the inside in the dispersion region. The horizontal emittance is 70 πmm·mrad. Table 2 lists the parameters of the injection elements.

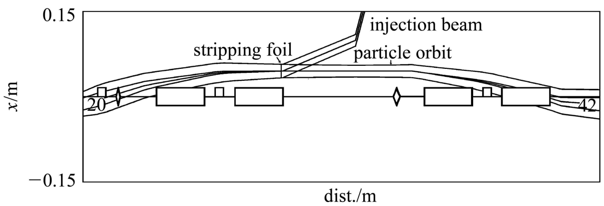

Fig. 5. Simulation of the stripping injection. (ε_x=20 πmm·mrad, $\Delta p_0/p_0$=−0.3%).

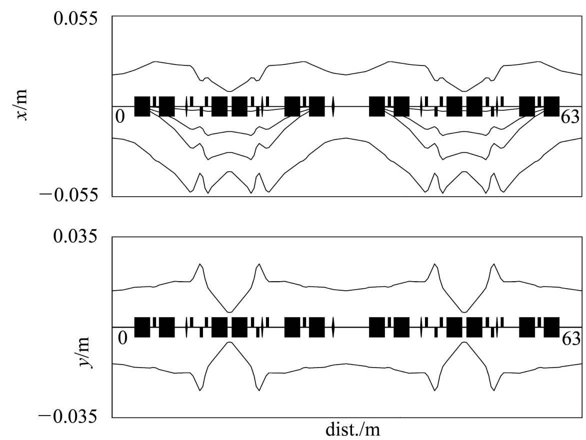

Fig. 6. Envelopes of the carbon ion beam at injection. (ε_x=70 πmm·mrad, $\Delta p_0/p_0$=−0.3%, $\Delta p/p_0$=0.5%).

Table 2. Parameters of the injection elements.

element name	length	Max. angle
bump1	0.3 m	10.0 mrad
bump2	0.3 m	−6.2 mrad
bump3	0.3 m	−4.8 mrad
bump4	0.3 m	14.7 mrad
magnetic septum	0.6 m	0.28 rad

4 Summary

A tumour therapy synchrotron is designed. In order to utilize the stripping injection scheme, the lattice of the synchrotron is optimized. Compared with the former design, the circumference of the synchrotron has reduced by 6.9 m, the beam acceptance has increased by 50 πmm·mrad and the momentum acceptance has increased by 0.4%. Based on the optimized lattice, the injection system is designed for C_{12}^{5+} and H_2^+. The injection system includes four bump magnets and one magnetic septum. Beam simulation shows that the designed injection system well meets the requirements for the injection of the $C_{12}^{5+}(H_2^+)$ beam. Besides, other particles with $1.15 \leqslant q_2/q_1 \leqslant 1.30$ (6°) or $1.74 \leqslant q_2/q_1 \leqslant 2.86$ (2°) can be also injected and accumulated in the tumour therapy synchrotron. Detailed design of the injection system is in progress.

The program Winagile[8] is used for all the lattice design and optimization of the tumour therapy synchrotron and its injection system.

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