STUDY OF CHARGE EXCHANGE INJECTION IN HITFiL*

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Abstract

A new accelerator complex dedicated to hadron cancer therapy, Heavy-Ion Therapy Facility in Lanzhou (HITFiL), is proposed and designed. Based on the operating experience and existing technology on HIRFL-CSR, a heavy-ion cyclotron is used as an injector instead of a linac. A heavy-ion synchrotron as main component is designed with special attention paid to compact structure, high reliability and low cost. HITFiL is designed to accommodate both proton and carbon-ion using the same injecting channel but different injecting points. Charge exchange injection scheme, which is more efficient compared with single-turn injection but less costly compared with multiple multi-turn injection aided by electron-cooling, is adopted. H_2^+ or C^{5+} beams, pre-accelerated by the cyclotron, are stripped into H^+ or C^{6+} by a carbon foil at injection point, then injected and merged into synchrotron central orbit. The design of the injection system is presented in this paper. The whole injection process is simulated, optimization of parameters on injecting efficiency, painting scheme and emittance growth are performed. The resulting beam distribution in phase space after injection is achieved.

Instruction

A new heavy ion therapy facility HITFiL is proposed, designed and shall be constructed at Lanzhou, China for producing of both proton and carbon ion beam. For the complementarity of proton and carbon ions in performance in cancer therapy, HITFiL is designed to accommodate both proton and carbon ions. It consists of a ECR ion source, a Sector Focusing Cyclotron, a Mean Energy Beam Line, a synchrotron, a High Energy Beam Line and four treating terminals. Hydrogen molecule or carbon ions, generated in ECR source, are pre-accelerated to 7MeV/u, transferred and injected into synchrotron to be re-accelerated to higher energy, then extracted and transferred to treating terminal for cancer therapy. A schematic layout of the synchrotron is shown in Figure 1.

Lattice of HITFiL-ring

The design of the HITFiL-ring aims at minimizing structure for low cost. The circumference of the ring is determined to be 56.17m after suppressing and superposing the component as many as possible. A relatively small but reasonable aperture is designed to reduce power consumption of the magnet component without lessening essential beam intensity. The main design parameters of the ring are listed in Table 1.

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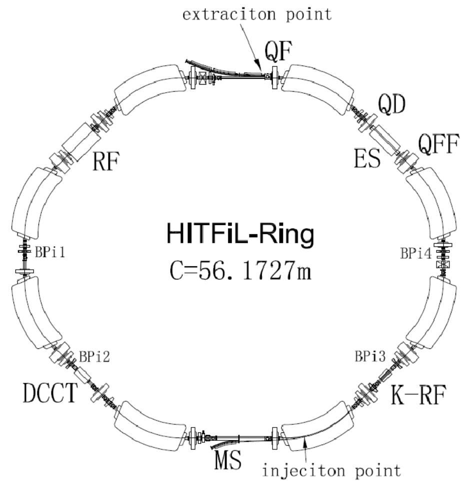

Figure 1: Schematic layout of the HITFiL synchrotron

Table 1: Main Parameters of HITFiL-ring

Particle Species	H^+/C^{6+}
Circumference	56.1727m
Super Periodicity	2
Transition energy	1.7388
Maximum Extraction Energy	400MeV/u(C^{6+})
Magnetic Rigidity	0.7627~6.6197T.m
Operation Period	3.2~13.2s
Tune Q_x/Q_y	1.68/1.23
Max. β_x/Max. β_y	9.97m/15.16m
Acceptance(Horizontal)	200π.mm.mrad ($\Delta P/P$=+4‰~-5‰)
Acceptance(Vertical)	50π.mm.mrad
Acceptance($\Delta P/P$)	+1% ~ -1.1% (ε_h=20π.mm.mrad)
Dipole Field	0.18~1.66(ρ=4m)
Quadrupole gradient	0.5~7.5T/m

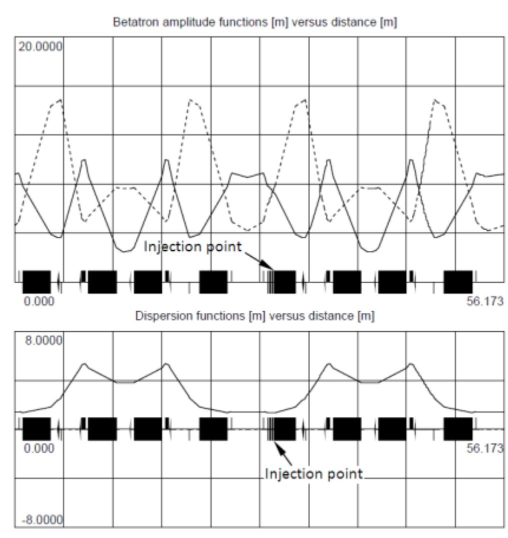

Figure 2: Betatron amplitude and dispersion function of the HITFiL synchrotron ring

The betatron amplitude of the ring is shown in upper part of Figure 2, in which the solid line shows horizontal β function and dashed line shows vertical one. The β function is designed as small as possible (below 16m) with an average of 6.2m in horizontal and 8.6m in vertical direction. The dispersion function is shown in lower part of Figure 2. It can be seen that the dispersion at injecting point is relatively small for injection and extraction. Aiming at compact structure, it is difficult to fit the dispersion to zero, but it is small enough for injection.

Injection Orbit

Charge exchange injection scheme is adopted in HITFiL. This scheme allows injecting a beam at the point of phase space already occupied by previously injected beam. Therefore an intense beam can be accumulated into the ring without largely increasing the beam emittance as well as the physical aperture of the ring. In addition, it is more desirable to incorporate the phase space painting into this scheme to reduce the hitting probability at the stripping foil then increase injecting efficiency.

$H_2^+(C^{5+})$ beams with energy 7MeV/u from a cyclotron injector is deflected by a magnetic septum to quasi-parallel to circulating beam orbit in synchrotron(the resulting separation angle is 1.85deg) and then reach the stripping foil in a main dipole, by which they are stripped to $H^+(C^{6+})$. Due to the difference in charge to mass ratio of them, their magnetic rigidities are different. This difference is used to separate the injecting and circulating beam in the dipole magnet.

Injection Parameters

Twiss parameters at injection point and injected beam matching parameters are listed in Table 2.

Table 2: Injection Parameters

	Horizontal		Vertical	
	Inj. point	Matching	Inj. point	Matching
α	0.527039	0.257872	-1.072051	-1.072051
β(m)	7.153319	3.500000	7.947982	7.947982
D(m)	1.327439	1.327439	0	0
D’	0.046542	0.046542	0	0
ε_{rms}	25π.mm.mrad		25π.mm.mrad	
Injecting position	X(mm)	X’(mrad)	Y(mm)	Y’(mrad)
	37.53	-4.88	0	0
Kinetic Energy	7 MeV/u			
$\Delta P/P_{rms}$	±5‰			

In vertical direction, twiss parameters of the injection line and the ring match at injection point. However, in order to reduce the foil dimension, twiss parameters do not match in horizontal direction but the following condition is met.

$$\frac{\beta_i}{\beta_m} = \frac{\alpha_i}{\alpha_m}$$

where i and m indicates the parameters of injection line and ring at injection point respectively. This condition ensures the injected beam optimally positioned within the desired beam acceptance in the ring, i.e. the injected beam lays upright in normalized phase space[1].

6D-Simulation of Charge Exchange Injection

The injecting orbit is shown in Figure 3, where the green colour shows H_2^+ beam envelope with emittance 25 π.mm.mrad and momentum deviation ±5‰, the deep green colour shows injected H^+ envelope, the blue, red and cyan colour shows circulating beam with emittance 25, 100 and 100π.mm.mrad and momentum deviation ±5‰, +7‰ and -7.5‰ respectively distorted by the bump magnet.

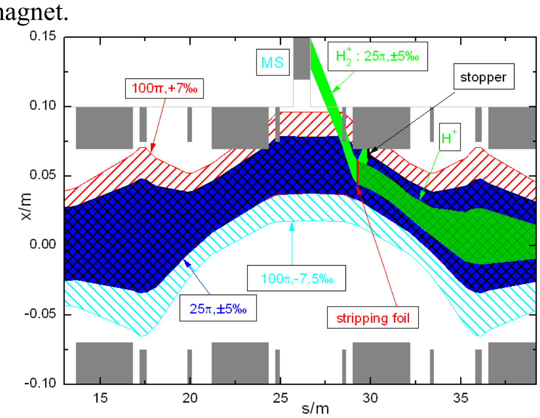

Figure 3: Injecting and coasting beam envelope

The bumped closed orbit at the injecting point is: x=37.5mm, x’=-4.88mrad, which is symmetric with respect to the global axis of symmetry, i.e. x’=0 at the straight section before injecting point. The injection painting takes place only in horizontal direction. Bump strength falls linearly as injection goes on. Closed orbit located at 37.5mm initially and vanishes at turn 30. The foil parameters are listed in Table 3.

Table 3: Foil Parameters

Material	C			
Atomic number	6			
Atomic weight	12			
Foil dimension (mm)	Lower -X 27.5	Upper -X 57.5	Lower -Y -15	Upper-Y 15
density	$2.265 g/cm^3$			
thickness	$15 \mu g/cm^2$			
Mean ionization potential	79eV			

The injection process in the synchrotron is studied using the code Accsim[2]. The simulation is 6-dimensional, with tracking of a number of representative particles through the lattice. Coulomb scattering and energy loss in the foil are modelled by Accsim using Monte Carlo method.

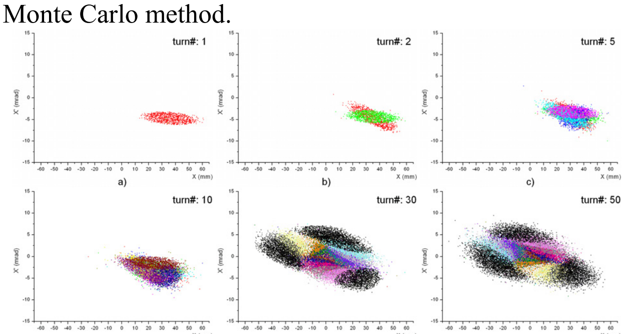

Figure 4: X-X’ phase space evolution during injection

Figure 4 shows the injecting process, where the scatters represent the particles coordinates in X-X' phase space with different colour indicates particles injected during different turn. Since there are only 24 colours in colour set of the graph-processing program, the colour wrap around if turn number exceed 24. a) shows particles injected during the 1st turn, b) shows particles injected during 1st and 2nd turn, c) shows particles injected from beginning of injection to the 5th turn, d) the 10th turn, e) the 30th turn, i.e. the end of injection, f) the 50th turn(20 turns' revolution after injection). 1000 macro particles are injected per turn with uniform distribution in both horizontal and vertical phase space, and in longitudinal phase space: uniform in phase and Gaussian in energy.

Figure 5 shows the emittance growth during injection without defining the upper number limit of injected macro particles, it can be seen that horizontal emittance reaches the acceptance limit (200π.mm.mrad) at 31th turn, which proves that a 30 turns of injection is rational. Vertical emittance is well below vertical acceptance(50 π.mm.mrad).

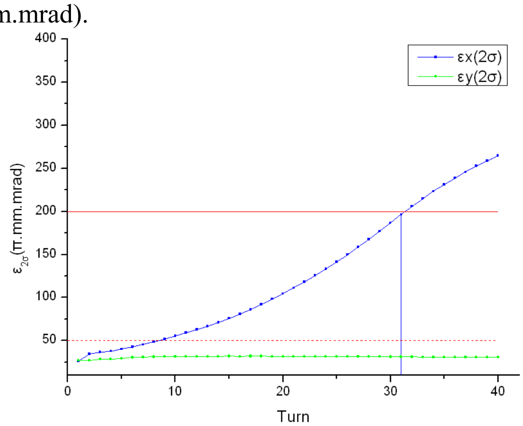

Figure 5: Horizontal emittance growth during injection

Tracking proves that particle loss after 1000 turns are negligible. Based on this point of view, the lost particles are counted versus turn number during which they were injected. The statistical injection efficiency is shown in Figure 6, it can be seen that the injection efficiency drops rapidly from the 14th turn and drops to 72.5% at the 17th turn.

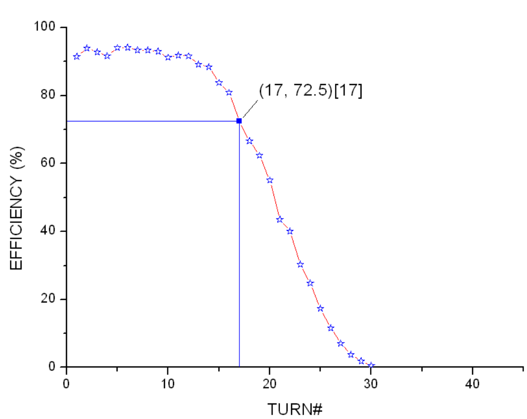

Figure 6: Injection efficiency during the injecting process

The loss occerance and fraction are shown in Figure 7, where the blue color indicates a dipole, the red color represents a quadrupole ant magenta color shows the stripping foil. The total loss is normalized to be 100%. It shows that the most particles loss occurs at the final dipole(the injecting point is defined the very beginning of the ring). The second most significant loss is at the dipole near the extraction point. However, the apture of this dipole have been enlarged considerably for extration of the beams, so it is less important. The other losses occurs at quadrupoles around the ring, which is all less than 10%.

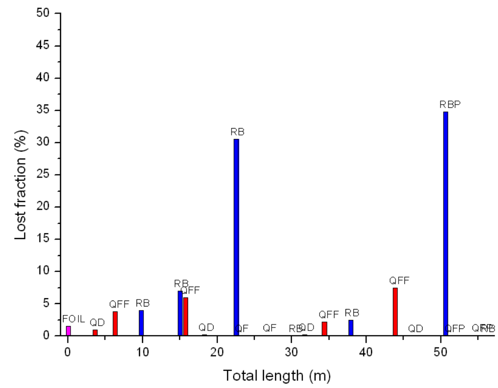

Figure 7: Particles lost position around the ring

Conclusion and Discussion

The injection system of HITFiL cancer therapy facility is designed and the whole injecting process is simulated using the macro particle tracking code Accsim. The emittance growth and the injection efficiency is obtained. The loss factor is presented, which provided a theoretical basis for the vacuum chamber design. In this papar: 1)The stripping efficiency is not included for the lack of basic cross section data of molecular ion H_2^+ interacting with materials. 2)A more carefully designed bump function should found to increase the injeciton efficiency as high as possible. 3)Since the Accsim code did not support interactions of carbon ions in matter, the injecting process of carbon ions into the ring is not included. All the three issues will be studied later.

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