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Conceptional design of the laser ion source based hadrontherapy facility

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Abstract: A laser ion source (LIS), which can provide a carbon beam with highly stripped state (C^{6+}) and high intensity (several tens mA), would significantly change the overall design of the hadrontherapy facility. The proposed LIS based hadrontherapy facility has the advantages of short linac length, simple injection scheme, and small synchrotron size. With the experience from the DPIS and HITFiL projects that have been conducted in IMP, a conceptional design of the LIS based hadrontherapy facility will be presented, with special attention given to APF type IH DTL design and simulation.

Key words: laser ion source, hadrontherapy, APF, DTL, design

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1 Introduction

Hadrontherapy with carbon ions is a frontier medical method in cancer therapy, as well as a very important development in accelerator technology [1–3]. Unfortunately, due to its high cost, hadrontherapy is still a very expensive and unaffordable medical method to most ordinary patients, even though it has a significant advantage in terms of cure rate. Consequently, a reduction in the cost of the hadrontherapy facility will become a very meaningful work.

During the construction of an accelerator facility, the ion source is a fundamental element that determines the overall structure of the accelerator and which decides the cost of the accelerator. With an ECR (Electron Cyclotron Resonance) ion source, which provides C^{4+} of several hundred μA, an accumulation process in the synchrotron is needed, which means that a multiturn injection or stripping injection scheme is necessary. Moreover, accumulation will enlarge the beam emittance in the ring, which means that a wider magnet gap is needed, this greatly increases the cost of the facility. Also, in order to ensure a high stripping efficiency, the linac injector usually needs to be long enough to accelerate the C^{4+} to a high enough energy (typically, 7 MeV/u). All these reasons will make the facility complex, as well as keep the cost solidly high.

A LIS ion source, which can provide C^{6+} of several tens mA, will solve the above problem. With its high current intensity, no accumulation in the ring is needed, which means that the injection scheme has been simplified and that the gap of the dipole magnets has been shortened, this greatly reduces the costs of the facility. Furthermore, the high charge state C^{6+} means that no stripping process is needed, which implies the linac injector could be relatively shortened.

With all of these advantages, a LIS based hadrontherapy facility is quite a good option. Consequently, this paper will present a conceptional design of the facility. The schematic layout of the facility is given in Fig. 1.

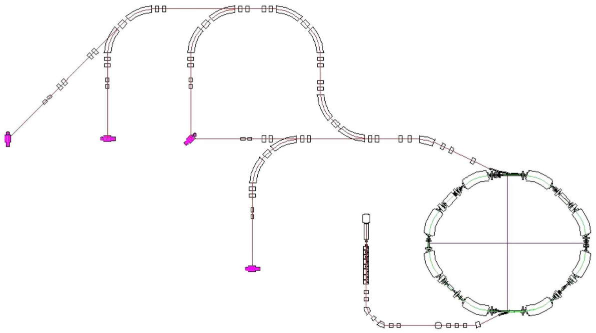

Fig. 1. (color online) The layout of the LIS based hadrontherapy facility.

2 General considerations

2.1 The LIS system

The existing laser ion source in the Institute of Modern Physics, Chinese Academy of Sciences (IMPCAS) uses a commercial Nd-YAG laser system and the extraction voltage is set to be 60 kV. The LIS can provide C^{6+}

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of 21.6 mA in pulse, with laser energy of 1.437 J, and an excitation time of 10.09 μs. Some of its main parameters are summarized in Table 1 [4].

Table 1. The main parameters of the LIS.

parameters	value
wavelength/nm	1064
max energy/J	3
pulse duration/ns	8–10
repetition/Hz	1
extraction energy/(keV/u)	30
focus length/mm	100
target dimension/mm	50×100×1
max power density/(W/cm^2)	8.4×10^{12}

2.2 The RFQ and direct plasma injection scheme (DPIS)

Since 2010, the IMPCAS has finished a series of tests and commissioning of the direct plasma injection scheme. An RFQ of 100 MHz, which accelerate the C^{6+} from 30 keV/u to 593 keV/u, is directly joined to the extraction end of the LIS. The design injection beam is 20 mA, with transversal normalized RMS emittance of 0.25 πmm·mrad, the extraction beam would be 6.5 mA, with transversal normalized RMS emittance of 0.35 πmm·mrad and momentum spread of ±1.4%. The main parameters of the DPIS RFQ are listed in Table 2 [5].

Table 2. The main parameters of the DPIS RFQ.

parameters	value
frequency/MHz	100
cells number	100
electrode length/m	2.0
inter-vane voltage/kV	120
minimum aperture/mm	7.07
modulation parameter	1 to 2.1
synchronous phase	−90° to −20°

2.3 The parameters of the DTL

2.3.1 The energy of the DTL

Using the experience from the ready-made DPIS RFQ and the Heavy Ion Therapy Facility in Lanzhou (HITFiL) project, which is now under construction, we will try to give the general parameters of the DTL linac. The lattice of the synchrotron, which is from the HITFiL, has a circumference of 56.173 meters and a total dipole magnet length of 25.138 meters. This means that when the C^{6+} is accelerated to 400 MeV/u, corresponding to a magnetic rigidity of 6.3654 T·m, the magnetic field of the dipole magnet is working on its highest end of 1.6 T. Similarly, the energy of the injection beam of the synchrotron, which is equal to the extraction energy of the DTL, is decided by the lowest end of the dipole magnet. Furthermore, the fully stripped C^{6+} from the LIS makes the stripping process no longer necessary and so, theoretically speaking, the extraction energy of the DTL could be as low as 2 MeV/u. However, when we are concerned about the ripples of the power source, we want the extraction energy to be 4 MeV/u, which corresponds to dipole magnetic field of 0.144 T.

2.3.2 The Intensity of the DTL

The 4 MeV/u C^{6+}, which corresponding to relativity β=0.0924, will circle the ring in 2.03 μs. If we can keep the intensity of the extraction beam from the DTL more than 5 mA, then there are 1.057×10^{10} ions being injected into the ring in a single turn. Because we consider the injection efficiency of 40%, capture efficiency of 80% and acceleration efficiency of 80%, the particle per pulse in the ring can easily achieve 2×10^9.

2.3.3 The emittance of the DTL

According to our study, the growth of the normalized RMS emittance is inevitable during the acceleration. We are trying to suppress the growth of the emittance in order to reduce the gap of the magnet. Considering that the transversal injection emittance of the DTL is 0.35 πmm·mrad, we expect to control the extraction emittance under 0.5 πmm·mrad. We have also tried to reduce the momentum spread from ±1.4% to ±0.5%.

After comparing the Alternating Phase Focusing (APF) and the Combined Zero Degree Structure (KONUS), we have decided to use APF because of its simplicity in structure, which makes it easy to be constructed and operated. Furthermore, the APF attracts us because of its high acceleration gradient as well as its adequate transmission efficiency in our intensity range.

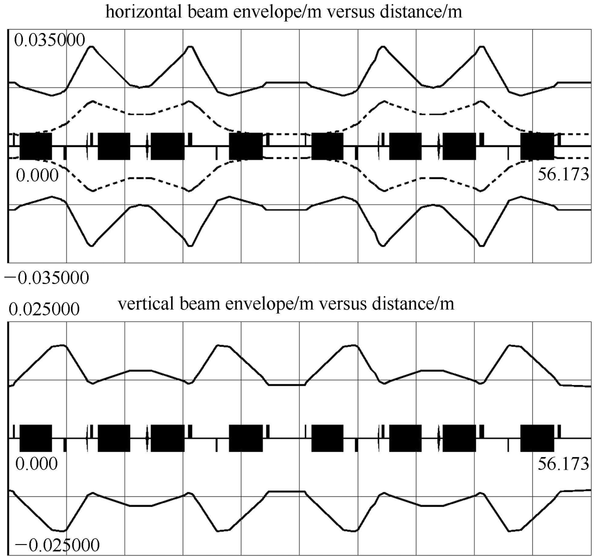


Fig. 2. The envelope of the synchrotron.

2.4 The modification of the synchrotron

Although the basic lattice structure of the synchrotron is the same as the HITFiL, we have made some modifications to meet the demand of LIS based scheme. Because the emittance of the injection beam is only 0.5 πmm·mrad, a 70 mm×50 mm magnet aperture is enough. A reduction of the aperture would exponentially reduce the cost of the magnet, which means that the primary goal of our design scheme will be achieved. Moreover, the stripping injection will be replaced by a single turn injection, which remarkably simplifies the injection system and cuts the costs. The envelope of the modified synchrotron is presented in Fig. 2.

3 Conceptional design of DTL linac

3.1 The aim of the DTL design

The aim of our DTL design is based on the following consideration. First is acceleration efficiency. The acceleration efficiency, also called the acceleration gradient, decides the length of the DTL, which will decide the cost of the accelerator and this, as we have noticed, is one of our primary considerations. Second is the transmission efficiency. As revealed above, we hope that more than 80% transmission efficiency will be achieved. Another aim is the emittance suppression, which decides the envelope of the beam as well as the aperture of the synchrotron.

3.2 The principle of the DTL design

When the particles pass through the RF gap, they will “feel” electromagnetic force. According to Laplace’s equation,

$$\frac{\partial^2 V}{\partial^2 x}+\frac{\partial^2 V}{\partial^2 y}+\frac{\partial^2 V}{\partial^2 z}=0, \tag{1}$$

where V is the potential and x, y, z represent three orthogonal axes.

If the synchronous phase is negative, then it will be focused in the longitudinal direction, which satisfies the stable acceleration condition. But at the same time, the longitudinal focusing field will bring the particles transversal defocusing effect [6].

$$\Delta(\gamma\beta r')=-\frac{\pi q E_0 T L \sin\phi}{mc^2\gamma_s^2\beta_s^2\lambda}r, \tag{2}$$

where β, γ are the relativity factor, q and mc^2 are the charge and mass of the particle, E_0TL is energy gain when the particle passing through the RF gap, ϕ and λ are synchronous phase and wavelength, respectively, r represent any of the three axes x, y or z, and the subscript s means synchronous particle.

Conventionally, this transversal defocusing force is compensated by quadrupole magnets, which obviously reduces the acceleration gradient. The APF theory provides another solution, which is to use a positive synchronous phase to provide transversal focusing force. Since the beam dynamics of the APF are exclusively decided by its synchronous phase arrangement, the setting of the phase array will be crucial. Several different types of APF have been designed and constructed, as shown in Fig. 3 [7–11].

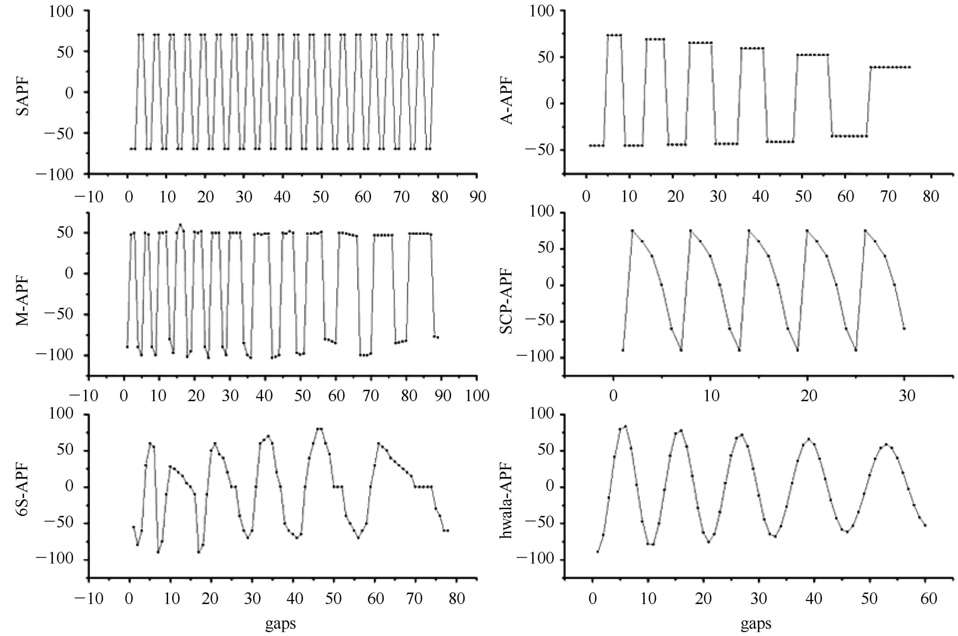


Fig. 3. (color online) Different types of APF DTL.

Due to its relative weak focusing strength, a simple FODO type APF would be unsuitable for us. Since we consider the transmission efficiency as well as emittance suppression, an Iwata type APF is the best choice.

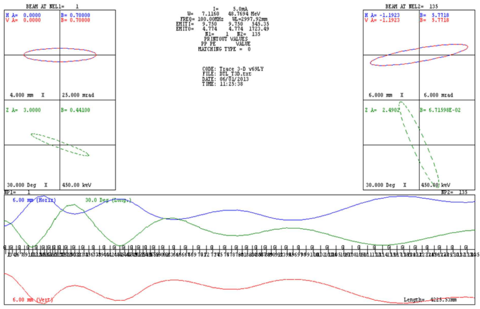
3.3 The DTL design

The first crucial parameter we encountered is the maximum surface electric field. Since we consider the 100 MHz operation frequency, which is the same as the RFQ, the Kilpatric limit would be 113 kV/cm. To avoid possible voltage breakdown, the gap voltage should be determined to insure that the maximum surface field will be kept under 1.6 $E_{\rm Kilpatric}$, which is 180 kV/cm.

The phase arrangement of the Iwata type APF is described in the following function [12]:

$$\phi_{\rm s}(n)=\phi_0\cdot{\rm e}^{-a\cdot n}\cdot\sin\left(\frac{n-n_0}{b\cdot{\rm e}^{c\cdot n}}\right), \qquad (3)$$

where n is the cell number and ϕ_0, n_0, a, b, c are adjustable parameters used in optimization search.



```
         I=      5.0mA
    W=   7.1160   48.7694 MeV
 FREQ= 100.00MHz   WL=2997.92mm
EMITI=   9.750    9.750   545.35
EMITO=   4.774    4.774  1723.49
        N1=    1   N2=  135
         PRINTOUT VALUES
        PP PE        VALUE
      MATCHING TYPE =  0

      CODE: Trace 3-D v69LY
      FILE: DTL_T3D.txt
      DATE: 06/01/2013
      TIME: 11:25:38
```

Fig. 4. (color online) The interface of the design process, with initial and terminal space phase, beam envelop and major parameters are included.

When both the synchronous phase and gap voltage have been determined, the whole structure of the DTL can be established. A self-developed code is used to calculate the parameters of the structure and TRACE 3D is used to simulate the beam dynamics. At the same time, an optimization search is conducted. The result is shown in Fig. 4.

3.4 The simulation

To verify our design, an end to end simulation is conduct by a particle in cell method code BEAMPATH [13]. During the simulation work, some modifications to the drift tube length were carried out to get a better transition time factor. The results are shown in the Fig. 5.

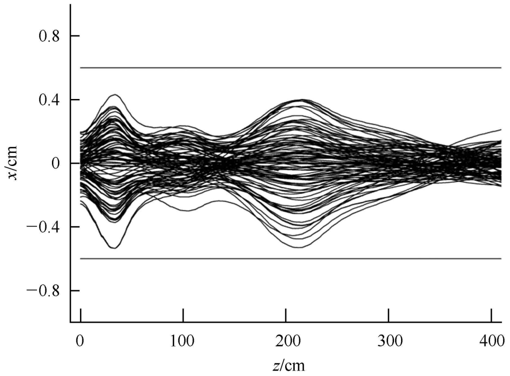


Fig. 5. (color online) The trajectory of the beam simulated by PIC method, 10000 macro-particles are used to simulate the acceleration precess. The transmission efficiency is 88.7%.

4 Conclusion

As can be seen in the above description, we have achieved an excellent design that can balance the transmission efficiency, emittance suppression and momentum spread control. Moreover, the acceleration gradient is also quite good. From the above study we can conclude that a LIS based hadron therapy facility with high intensity, simple injection scheme, low injection energy and short linac length would be an ideal for a low budget choice.

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