REVIEW OF SCIENTIFIC INSTRUMENTS **78**, 096104 (2007)

Strip injection for carbon ion synchrotrons

S. Y. Lee, W. M. Tam, and Z. Liu
Department of Physics, Indiana University, Bloomington, Indiana 47405, USA

(Received 6 June 2007; accepted 30 August 2007; published online 25 September 2007)

Requirements and effects of strip injection of C^{4+} at 6 MeV/u into carbon ion synchrotrons are studied. The setup is composed of three chicane dipoles, one Lambertson septum, and one carbon stripping foil at a thickness of 60 $\mu g/cm^2$. The required length of the injection section is about 4.1 m. The emittance growth due to multiple Coulomb scatterings is studied. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2786933]

Since the proposal of using fast protons for radiotherapy by Wilson in 1947,[1] protons and light ions have been used for clinical treatment during the past few decades. Due to its advantageous energy deposition (Bragg peak) in tissues, proton beam has been widely used for therapy and, in fact, over 40 000 patients have been treated (up to 2004).[2] Efforts have also been devoted to examine the suitability of different kinds of light ions for radiotherapy. The *relative biological effectiveness* (RBE) lying between lithium and carbon ions was found to be optimal for therapy. The convincing results from carbon ion therapy[3,4] encourage investment in building carbon machines. Since 1994, there are three carbon ion therapy facilities around the world, the Gesellschaft für Schwerion forschung (GSI) in Germany and the Heavy Ion Medical Accelerator (HIMAC) and the Heavy Ion Beam Medical Center (HIBMC) in Japan. They are all synchrotrons, but other types of accelerators, such as the fixed field alternating gradient (FFAG) accelerators,[5] have also been proposed.

At present all carbon ion facilities use an electron cyclotron resonance (ECR) ion source for injection,[6] where C^{4+} ions are produced by an ECR ion source. The ions are usually accelerated by a linac to around 6–7 MeV/u.[7] The C^{4+} ions are stripped to C^{6+} before being injected and accumulated into a synchrotron. Multiturn injection with phase space painting is adopted for accumulation up to a desired intensity. The injection intensity is thus limited by the aperture of the machine and the septum thickness; the injection efficiency is usually poor and high beam loss occurs at the septum magnet.[8]

In this article, we study and propose an innovative injection scheme for light ion medical synchrotrons, where the C^{4+} ions are injected into a synchrotron by electron stripping in a stripping foil. Due to the difference in charge to mass ratio of C^{4+} and C^{6+}, their magnetic rigidities are different. This difference will be utilized to separate the injecting and circulating beams in the middle chicane dipole magnet. We will use the C^{4+} beam extracted from either the FFAG low energy ring[5] or the linac[7] as the source for injection into the synchrotron.

When a beam of fast moving particles enters a matter, electrons of the particle can be stripped away or the particle can capture electrons from atoms in the matter. The fraction F_i of a charge state i of the beam particles is given by

$$\frac{dF_i}{dx} = \sum_{j\neq i} \sigma_{ji}F_j - \sum_{j\neq i} \sigma_{ij}F_i, \tag{1}$$

where σ_{ij} is the cross section from the charge states i to j and x is the target thickness.

When the projectile velocity is much larger than the Thomas-Fermi velocity $Z_T^{2/3}\alpha c$ of target atoms, where Z_T is the electron number of the target atoms, $\alpha \approx 1/137$ is the fine structure constant, and c is the speed of light, the capture cross section has a much smaller stripping cross section, i.e., $\sigma_{ji} \ll \sigma_{ij}$ where $j > i$. The stripping normally occurs in two body interaction, and thus $\sigma_{i,i+2} \ll \sigma_{i,i+1}$. With these approximations, the C^{4+} charge-stripping process becomes

$$\frac{dF_4}{dx} = -\sigma_{45}F_4,$$

$$\frac{dF_5}{dx} = \sigma_{45}F_4 - \sigma_{56}F_5,$$

$$\frac{dF_6}{dx} = \sigma_{56}F_5, \tag{2}$$

where F_4, F_5, and F_6 are fraction of charge states 4+, 5+, and 6+, respectively. Given an initial 100% C^{4+}, the population of C^{6+} is

$$F_6(x) = 1 - e^{-\sigma_{45}x} - \frac{\sigma_{45}}{\sigma_{45} - \sigma_{56}}(-e^{-\sigma_{45}x} + e^{-\sigma_{56}x}). \tag{3}$$

We use Gillespie's formula for the stripping cross section as follows:[9]

$$\sigma_{\text{stripping}} = 8\pi a_0^2(\alpha/\beta)^2 I, \tag{4}$$

where $a_0 = 5.29 \times 10^{-11}$ m is the Bohr radius, βc is the speed of the particle, and

$$I \approx \frac{1.24Z_T}{Z_p^2}(1 + 0.105Z_T - 5.4 \times 10^{-4}Z_T^2) \tag{5}$$

is the collision strength introduced to fit experimental data and Z_p is the charge state of the projectiles.

Since the multiple Coulomb scatterings can induce emittance growth, it is advantageous to use low Z materials for the stripping foil. Thus we choose carbon foil for electron-stripping medium. The foil thickness to reach 95% stripping

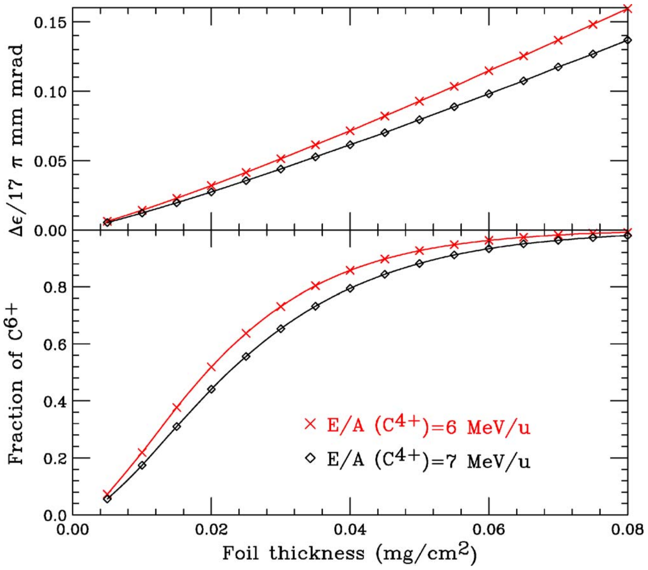

FIG. 1. (Color online) Bottom: fraction of C^{6+} vs the foil thickness (x) for injection energies of C^{4+}:6 and 7 MeV/u, respectively. Top: fractional increase of emittance, $\Delta\epsilon/(17\pi$ mm mrad), per passage of the stripping foil vs the stripping foil thickness.

efficiency is 60 μg/cm^2 for both 6 and 7 MeV/u injection beam energies, as shown in the bottom plot of Fig. 1.

For a multiturn stripping injection, the closed orbit of the circulating beam is bumped to near or on the stripping foil, where the injecting beam merges onto the bumped orbit. When the beam is accumulated in multiturn injection, the circulating particles in a synchrotron may pass through the stripping foil several times. Each time when the beam passes through the foil, small angle multiple Coulomb scatterings cause average beam size to increase. Using Moliére's formula[10] and assuming a typical betatron amplitude function of $\beta_x = 16$ m at the stripping foil, the fractional emittance growth in each foil hit is shown in the top plot of Fig. 1 for two candidates of C^{4+} injectors: the 6 MeV/u low energy FFAG accelerator[5] and the 7 MeV/u linac.[7]

The FFAG low energy accelerator can provide about 5.9×10^9 particles with emittance 8.8π mm mrad/pulse at 200 Hz. To accumulate 10^{11} particles with a rms emittance of 17π mm mrad, one needs 19 injection turns with a tolerable foil hit about 10, which can be achieved by proper beam manipulations.[11] The linac can deliver a beam current of 130 μA C^{4+} with emittance 6.4π mm mrad at 7 MeV/u, and thus we expect to accumulate 4×10^8 particles per injection turn. For the entire pulse length of 300 μs, one can accumulate 6×10^{10} carbon ions in 150 injection turns. At 7 MeV/u, the beam can tolerate about 12 foil hits, which is challenging but possible. If the horizontal and the vertical betatron amplitude functions are designed with smaller values at the stripping foil location, the effect of emittance dilution can also be reduced.

The ionization energy loss due to the passage of the carbon foil can result in energy loss and straggling. Particles passing through the stripping foil (thickness of 60 μg/cm^2) ten times will lose a total of 0.11 MeV/u. The momentum spread increment due to the stripping foil is small.

Exploiting the difference in magnetic rigidity of the C^{4+} and C^{6+}, we use chicane magnets in a straight section for stripping injection. Figure 2 shows a schematic drawing of key components in the injection straight section, where the chicane magnets (three dipoles) provide an orbit bump to merge the incoming beam. The kick angles of the middle chicane dipole are, respectively, $\theta_1 + \theta_2$ and $\frac{2}{3}(\theta_1 + \theta_2)$ for the circulating C^{6+} and the injecting C^{4+} beams. The angular divergence of these two beams at the entrance of the magnet is $\frac{1}{3}(\theta_1 + \theta_2)$. At a distance yL away from the middle chicane dipole, a Lambertson septum (or a current sheet septum) separates the injection beam line from the synchrotron.

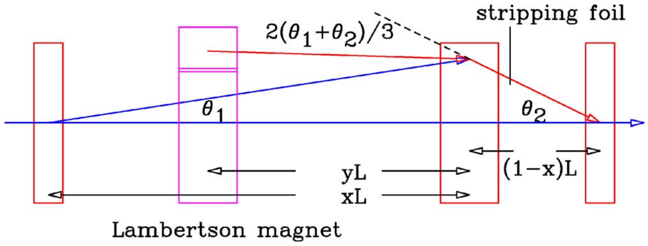

FIG. 2. (Color online) A schematic drawing of the injection scheme with a chicane. Three injection chicane dipoles have angular kick angles θ_1, $\theta_1 + \theta_2$, and θ_2, respectively.

The requirements for these injection components to fit into a straight section are

$$\frac{1}{3}(\theta_1 + \theta_2) yL \geqslant 3(\sigma_{\text{inj}} + \sigma_{\text{cir}}) + \Delta_{\text{septum}}, \tag{6}$$

$$(x - y) L \theta_{\text{septum}} \geqslant H, \tag{7}$$

$$(1 - x) L \geqslant 1 \text{ m}, \tag{8}$$

where σ_{inj} and σ_{cir} are the rms beam sizes of the injecting and the circulating beams, Δ_{septum} is the septum thickness, and H is the height of the nearest magnet to avoid. The first condition (6) shows that the beam should clear the Lambertson septum. Assuming the Lambertson septum thickness of 5 mm and using the $\beta_x \approx 16$ m with emittances of the injectors and the circulating beams, we find that $yL \geqslant 1.3$ m, where we use $\theta_1 + \theta_2 = 0.2$ rad; the angular deflection can be attained by a 15 cm dipole magnet at 1 T flux density. The bending radius of the middle chicane dipole is $\rho_0 = 0.75$ m.

The second condition (7) demands the injecting beam line to avoid the obstruction of the first chicane dipole. Assuming $H = 0.8$ m and $\theta_{\text{septum}} = 0.6$ rad, which can be obtained by a 0.5 m Lambertson magnet with field strength of 1.2 T, we find $xL \geqslant yL + 1.33 \approx 2.7$ m; and we find $L \geqslant 4.1$ m with $x = 2/3$. Finally, condition (8), intended to provide enough space for the stripping foil equipment, is naturally satisfied. Furthermore, the C^{4+} injection beam line is parallel to the circulating beams with the choice of $x = 2/3$ or $\theta_2 = 2\theta_1$.

We now examine the aperture requirement of the middle chicane dipole. Figure 3 shows the beam separation versus the dipole bending angle in a rectangular chicane magnet for carbon and oxygen ions, assuming that these ion beams merge at the exit. We note that the beam separation at the entrance is small in the case of $\rho_0 = 0.75$ m for chicane dipoles.

We can also use the main dipole to separate the injecting and circulating beams, where the bending radius is typically $\rho_0 \approx 4.23$ m, the beam separation shown in Fig. 3 becomes

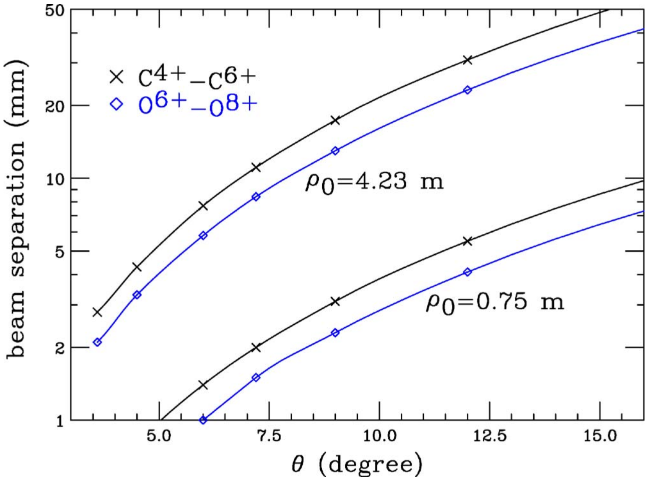

FIG. 3. (Color online) The beam separation of ions with different rigidity vs the bending angle of a magnet.

too large. It is difficult to use main dipole for beam separation, unless special magnets are made to accommodate the injecting beams.

Since the ratio of the magnetic rigidities of O^{6+} and O^{8+} is $\frac{4}{3}$, which substantially differs from that of carbon ions, the designed carbon channel cannot be used for the oxygen ion injection. This problem can be solved by using a large aperture Lambertson magnet. The beam separation between C^{4+} and O^{6+} is about 2 cm at the Lambertson magnet. A larger aperture (4 cm) Lambertson septum can accommodate both ions. Alternately, one may also use another straight section for other light ion injection.

In conclusion, we have studied the feasibility of the strip-injection scheme and proposed a realistic device design for injecting C^{4+} ions into light ion medical synchrotrons. Making use of the difference between magnetic rigidities of C^{4+} and C^{6+} beams, we design a chicane magnetic system to demonstrate the feasibility of this injection scheme. The required drift space length is about 4.1 m. The injection process should be able to maintain excellent beam emittance by carefully manipulating the injection process. Our injection scheme has advantage over the existing phase space painting accumulation scheme in higher efficiency and a smaller emittance. For example, one can get an emittance of 17π mm mrad for more than 20 injection turns, to be compared with a minimum of 100π mm mrad for the phase space painting scheme. This proposed injection scheme should greatly benefit future facilities.

This work is supported in part by grants from the US Department of Energy under Contract No. DE-FG0292ER40747 and the National Science Foundation NSF PHY-0552389. We thank Mark Ball for his comments and reading of this paper.

[1] R. Wilson, Radiology **47**, 487 (1946); Phys. Rev. **71**, 385 (1947).
[2] PTCOG, http://ptcog.mgh.harvard.edu/
[3] U. Amaldo and G. Kraft, Rep. Prog. Phys. **68**, 1861 (2005).
[4] T. Kamada, H. Tsujii, H. Tsuji, T. Yanagi, R. Imai, J. Mizoe, T. Miyamoto, H. Kato, S. Yamada, S. Kato, K. Yoshikawa, and S. Kandatsu, AIP Conf. Proc. **680**, 1142 (2003).
[5] T. Misu, Y. Iwata, A. Sugiura, S. Hojo, N. Miyahara, M. Kanazawa, T. Murakami, and S. Yamada, Phys. Rev. ST Accel. Beams **7**, 094701 (2004).
[6] R. Becker, Rev. Sci. Instrum. **77**, 03A903 (2006).
[7] B. Schlitt, R. Baer, W. Barth, T. G. Fleck, M. Hoerr, G. Hutter, C. M. Kleffner , M. T Maier, A. Peters, M. Schwickert, K. Tinschert, W. Vinzenz, H. Vormann, and D. Wilms, Proceedings of LINAC 2007 (unpublished), p. 148.
[8] T. H. Uesugi, T. Furukawa, T. Naruse, K. Noda, T. Fujimoto, and S. Shibuya, Proceedings of EPAC 2004 (unpublished), p. 2640.
[9] G. H. Gillespie, Phys. Rev. A **18**, 1967 (1978); **26**, 2421 (1982); see also K. Dennis, H. Akimune, G. P. A. Berg, S. Chang, B. Davis, M. Fujiwara, M. N. Harakeh, J. Jýýnecke, J. Liu, K. Pham, D. A. Roberts, and E. J. Stephenson, *ibid.* **50**, 3992 (1994).
[10] see http://pdg.lbl.gov/pdg.html
[11] S. Y. Lee, *Accelerator Physics*, 2nd ed. (World Scientific, Singapore, 2005), p. 115.