A COUPLED CYCLOTRON SOLUTION FOR CARBON IONS ACCELERATION

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Abstract

A concept of coupled cyclotrons for acceleration of carbon ions (charge 6+) to 400 MeV/nucleon by a separated sector cyclotron consisting of six sector magnets with superconducting coils is proposed. Injection to the machine will be provided by a compact 70 MeV/nucleon cyclotron. The accelerator complex is intended for setting up a radiation therapy facility employing carbon ions. The advantages of the dual cyclotron design are typical of cyclotron-based solutions. The first design studies of the sector magnet of the main cyclotron (magnetic field increases from 4.2 T to 6.5 T, RF frequency 73.56 MHz, RF mode 6) show that it is feasible with acceptable beam dynamics. The accelerator has a relatively compact size (outer diameter of 8 m) and can be an alternative to synchrotrons.

INTRODUCTION

Development of accelerators for producing carbon beams with the energy of 400–450 MeV/nucleon for hadron therapy appears to be an increasingly important issue today. The existing facilities for producing these beams are mainly based on synchrotrons. It seems interesting to use isochronous cyclotrons instead, as is the case in proton therapy. However, the developed designs of compact superconducting cyclotrons have some disadvantages in addition to their advantages [1]. An alternative solution can be a facility based on a superconducting sector cyclotron justified in detail in [2]. The design of this facility should comply with a number of conditions. First, the size and weight of the accelerator must be as small as possible, which makes it expedient to use the maximum high magnetic field. Second, the injection energy should be low enough for the injector to be of tolerable size. Third, the magnetic system design should be feasible, that is, the parameters of the superconducting coil (engineering current density, acting forces) should be adequate and the space between the sectors should be large enough to accommodate accelerating elements, inject a beam, etc. [3]. A separate task is to develop a system such that both maintains isochronism of the magnetic field and allows beam acceleration with a minimum number of resonance crossings.

INJECTION SYSTEM

The injection energy is chosen to be 70 MeV/nucleon because the accelerator with this final energy can be also used to accelerate H_2^+ ions. Their subsequent stripping allows obtaining protons of the appropriate energy suitable for medical applications. This cyclotron can be used for treating eye melanomas and also for producing radioisotopes.

A compact superconducting cyclotron seems to be the most optimal option. The magnetic rigidity of 70-MeV/nucleon C^{6+} ions is about that of 250-MeV protons in the Varian cyclotron [4]. So, some technical solutions of the Varian machine can be applicable to the injector. The use of an external carbon ion source limits the central magnetic field to a maximum of 3.0 T because of performing injection through a spiral inflector. Another constraint comes from the necessity to have the same RF frequency in the injector and in the booster machines, which also governs the central magnetic field in the injector. The optimum solution is a cyclotron with a central field of 2.4 T operating at the fourth harmonic of the accelerating field. The magnetic field is formed by four spiral sector shims. With an acceptable spiral angle of 50°, the external diameter of the accelerator will be no larger than 3 m and the weight will be about 90 t.

The system for injection in the main cyclotron consists of four magnetic channels and an electrostatic deflector (Fig. 1).

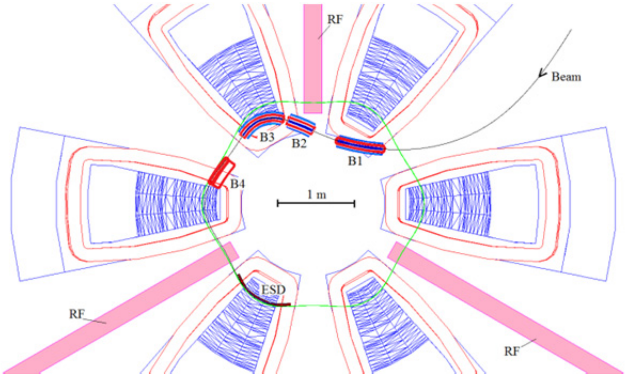

Figure 1: Injection system

The central fields in the channels are 1.2, 1.4, 1.4, and 0.8 T. The fourth magnetic channel comprises a septum. The strength of the electric field on the electrostatic deflector (ESD) is 80–90 kV/cm and can be slightly varied to ensure good beam centering.

As far as possible, the channels are arranged in the region of the magnetic field with a large gradient. The channel structure made such as to provide increasing or decreasing magnetic fields allows compensating for the negative effect of the main field on the transverse emittance of the beam. The axial distance between the coils with their cryostats in the beam injection region is

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~400 mm, which is enough to house the magnetic channels. In addition, the distance between the pole tips of the sector magnet in the area intended for the third magnetic channel is large enough to install this channel. No problem arises with the formation of the required isochronous field since the major contribution to the cyclotron magnetic field can be from the superconducting coils. The negative magnetic induction in the valley is the highest at medium radii, amounting to 1.4 T. At the center of the accelerator it is also high, being 1.2 T. The beam path in the valley is not linear. Passing through the valley, the beam moves alternately in the increasing and decreasing magnetic field, which leads to the alternating ion focusing.

For injection, the beam should be shaped at the entrance to the valley so as to have the smallest spread in angles. The following parameters of the beam at the entrance to the valley near the final radius were chosen for the dynamics analysis: transverse emittances 2 π mm mrad, transverse size 5 mm, and the Twiss parameter $\alpha = 0$. The spread in angles is below ±1 mrad. The orbit separation at the location of the electrostatic deflector is ~4 mm. The beam losses on the ESD septum are only ~15% with the septum thickness increasing along its length from 0.2 to 0.5 mm. During the beam tracing, the transverse size of the injected beam is no larger than ±6 mm. The size of the beam passing through the ESD is acceptable (±4 mm). With the deflector aperture of 10 mm, there should be no beam guiding problems.

MAIN CYCLOTRON

The magnetic rigidity of the carbon ions extracted from the main cyclotron with energy 400 MeV/nucleon is about 2.4 times that at injection. Therefore, the accelerator cascade could have an external size of about 12 m (Fig. 2), noticeably smaller than that of the synchrotron-based facilities currently used for hadron therapy.

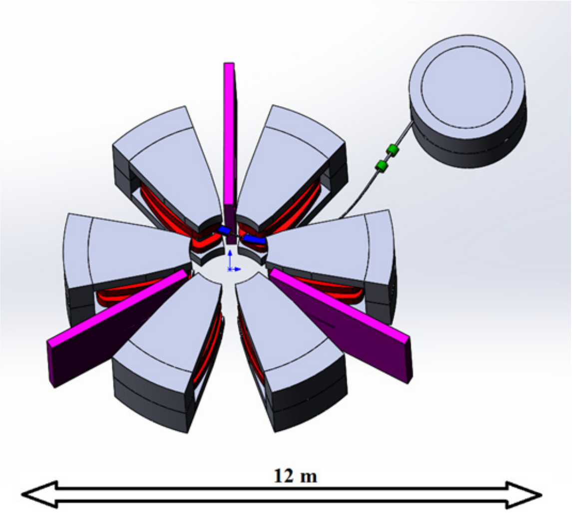

Figure 2: Acceleration complex including injector.

Injection at a relatively low energy leads to a considerable decrease in the magnetic field flutter from the initial to the final radius, which makes the working point to cross dangerous resonances. To increase the flutter near the final radius, the axial distance between the upper and lower coils in this region should be decreased. This coil arrangement causes a decrease in the mean field at small radii. An increase in the azimuthal size of the sectors can compensate for the missing magnetic field. The space between the neighboring sectors should be large enough to accommodate cryostats with coils and accelerating systems. According to some data, the critical engineering current density can be brought up to 150 A/mm^2. However, the operational value is considered to be 50–70 A/mm^2.

The following requirements were imposed on the magnet design: a) space for the installation of the coil cryostat 50–70 mm; b) axial distance between the coils no smaller than 120 mm; c) avoiding concave parts of the coil wherever possible.

All the magnetic field calculations were performed on a three-dimensional basis using the Opera3D code. It was found out from a series of calculations that for the above requirements to be fulfilled, the central magnetic field that governs the particle circulation frequency should be no higher than 1.6 T. With this field, the extraction radius of ions with the energy of 400 MeV/nucleon is 278 cm, and the external diameter of the cyclotron is as large as 8 m. Desired minimization of the variation in the frequency of axial free oscillations entails a necessary increase in the magnetic field flutter at medium radii, where the superconducting coil must thus be convex. This shape allows avoiding additional problems with forces acting on the coil. The magnetic induction in the region of the coil is as high as 7.2 T. The maximum field is 7 T in the hills, 2.7 T in the yoke, and 8 T in the pole tips. The main parameters of the accelerator are presented in Table 1.

Table 1: Basic Cyclotron Parameters

Parameter	**Value**
Ion type	$^{12}C^{6+}$
Number of sectors	6
RF system	3 × 200 kV
RF frequency	73.56 MHz
RF mode	6
Average magnetic field: injection/extraction	1.64/2.11 T
Maximal magnetic field: injection/extraction	4.22/6.40 T
Energy: injection/extraction	70/400 MeV/u
Radius: injection/extraction	143/278 cm
Air gap between sectors	88-135 mm
Dimensions: diameter × height	8 m × 2.2 m
Total weight (sectors + coils)	310 t

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The yoke of a sector externally measures 3.2 × 2.0 × 2.2 m^3. The sector weighs 50 t. The operational engineering current density in the superconducting coil is 62 A/mm^2, and its cross section is 170 × 330 mm^2. The coils are tilted with respect to the median plane at angles of ±4°. Axial profiling of both the pole tip and the pole itself is used to shape the isochronous field (Fig. 3).

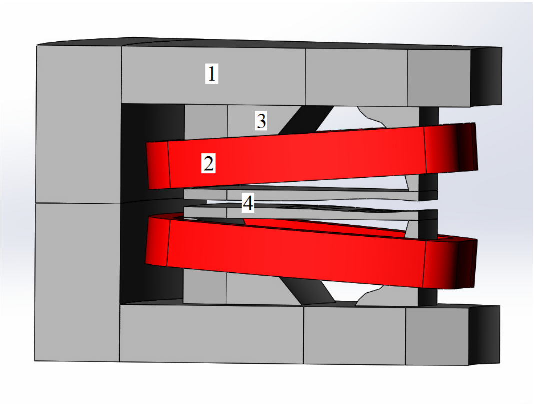

Figure 3: Magnet sector: 1 – yoke, 2 – superconducting coil, 3 – pole, 4 – pole tip.

Additional space between the neighboring sectors allows the azimuthal size of the sector to be varied, which combined with variation of the position of the coil permits producing the required field shape. Thus, it is possible to select a structure in which flutter increases with the radius and the variation range of the frequency Qz is the smallest (Fig. 4). A change in the azimuthal size of the coil leads to a shift of the frequency in the entire range of radii, and it becomes possible to prevent the working point from crossing dangerous resonances associated with the axial frequency of betatron oscillations (Qz = 1, 2Qz = 3, Qr − Qz = 0). Unfortunately, the crossing of the 2Qz − Qr = 1 and 2Qr − Qz = 2 resonances cannot be avoided. Their danger is to be investigated later.

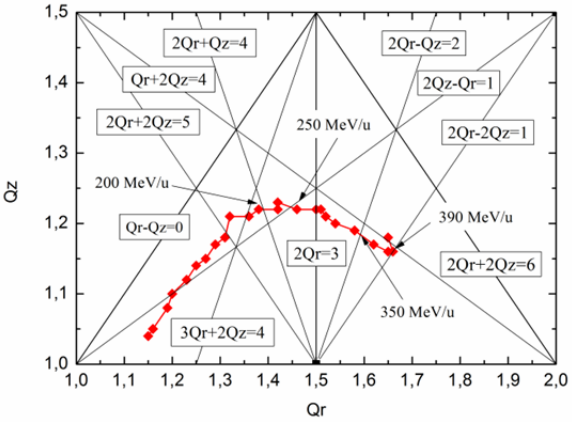

Figure 4: Tune diagram.

Isochronization of the calculated field was performed as follows. First, dependence of the mean magnetic field on the radius is calculated by the analytical formula:

$$B(r) = b \cdot \left[1 - \left(\frac{r}{a} \right)^2 \right]^{-1/2}, \tag{1}$$

$$a = c / \omega_0,\ b = m \cdot \omega_0 / q.$$

Here m is the ion mass, q is the ion charge, and ω_0 is the particle circulation frequency.

Next, when the initial configuration of the magnet is obtained and the data on the magnetic field parameters (flutter, maximal spiral angle) are available, the dependence of the mean field on the radius is calculated using the Gordon algorithm [5]. Then the closed orbit is calculated for the given ion energy using one of the particle tracing codes. The magnetic field is multiplied by the scaling factor so that the particle circulation frequency in this orbit coincides with the isochronous frequency. The calculated correction is then registered at the crossing of the orbit with the sector central line for subsequent shimming. The above procedure is repeated for all ion energies. The ultimate result is the correction to the available magnetic field calculated along the central line of the sector. Calculations show that two or three iterations are enough to obtain the ultimate result.

Using the above magnetic field isochronization algorithm, we managed to keep the deviation of the beam phase from the optimum value within ±30°. The deviation of the magnetic induction from the required one along the central line of the sector varies within ±20 Gs. The 3D calculations of the field revealed that in order to keep the beam phase within the given limits, the axial profiles of the pole shim and the pole must be manufactured with the respective accuracy of ±0.2 mm and ±1 mm. In the beam phase calculations, the energy gain was given analytically in accordance with the accelerating voltage and the particle phase during the crossing of the accelerating gap. The acceleration is supposed to be performed by the RF field of three cavities located in the valleys with the accelerating voltage amplitude of 200 kV. In this case, the central particle makes 1240 revolutions to reach the final energy.

CONCLUSION

This design study has been carried out to show that a coupled superconducting cyclotron complex is a serious candidate for a light-ion medical facility. The cyclotron is more compact than the synchrotron and simpler to operate. The cyclotron elements specified in the current design are realistically achievable. The short-term activity on the project development includes:

- Concept of beam extraction from the cyclotron.
- Configuration of the accelerating system.
- Calculation of forces acting on the superconducting coil.
- Injector design and beam transport to the injection point of the separated sector cyclotron.

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