DESIGN STUDY OF THE 250 MeV ISOCHRONOUS SUPERCONDUCTING CYCLOTRON MAGNET*

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Abstract

Superconducting cyclotron is an optimum choice to deliver high quality continuous wave (CW) proton beams for proton therapy with its compactness and power saving. Field isochronism and tune optimization are the two crucial factors of cyclotrons during the magnet design. This paper is concentrated on the superconducting magnet design, mainly including the spiral magnet, isochronous field and the tune optimization. The main parameters and some features of the machine will be presented.

INTRODUCTION

Today, cancer is a leading cause of death worldwide especially in industrial countries. Its treatment still presents a real challenge. In China, the survival and cure rate for cancer patients is lower than 15%. It is reported that the number of new cancer cases and deaths will reach 15 million or even more in 2020 [1].

As a method of radiation therapy, proton therapy has attracted widespread attention in recent years. Proton beams have the characteristic Bragg peak in their depth-dose distribution compared to traditional X-ray. Hence, proton therapy is preferable for most types of tumors due to accurate local dose control and minimum damage to the healthy tissues surrounding at the target tumor. Approximately more than 50,000 cancer patients have been treated with proton beams and Proton therapy is recognized as the most effective radiation therapy method for cancers with very high cure rate of 80% [2][3].

There are two main categories of accelerators that are currently used for proton therapy, synchrotrons and cyclotrons, which can accelerate protons up to energies of 230-250 MeV. With the Superconducting technology developed, a superconducting isochronous cyclotron is the best choice for it has great advantages of compactness and economy, saving costs for construction and operation.

For isochronous cyclotrons with fixed RF frequency, the field isochronism is important, which means the azimuthal average magnetic field should be increased to keep the same gyration frequency of the accelerating beam when the beam energy changes. What is more, the axial beam tune due to the field changes is also important and difficult to avoid the axial instabilities, especially the vertical tune is very low. The sectors should be shaped with a suitable geometry which can meet both the two requirements. It is an iterative procedure by matching the sector angle width and the spiral angle to find the shape of the magnet that provides the required magnetic field.

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A 250 MeV isochronous superconducting cyclotron (SCC-250) was proposed in HUST for the purpose of proton therapy [4]. This paper mainly focused on the superconducting magnet design ignoring the central region design, including the spiral magnet, isochronous field, and tune optimization. Some special extraction considerations in the demonstrated model are discussed. The main parameters and some features of the machine are presented.

OVERALL DESIGN OF THE MAGNET

A fourfold symmetric compact magnetic structure has been chosen to produce the required azimuthal varying magnetic field. The superconducting coils can product much higher magnetic field and the magnet radius can be much smaller. It is not difficult to reach 4-5 T, but this will make extraction design more challenging due to a smaller accelerated turn separation. Meanwhile, the formation of the isochronous field using a flat pole gap becomes challenging. In our case, the maximum magnetic field flux intensity is about 3.9 T, with the azimuthal average field 3.1 T.

Based on the parameters of extraction energy (250 MeV) and the extraction field *Bext*, the other main parameters, like: the pole diameter, injection field, total ampere turns, hill and valley gap can be determined using simple analytical calculation [5], which define the initial layout of the cyclotron magnet.

In order to ensure the axial stability of the beam during acceleration, it is necessary to shape the edges of the sectors as spirals. The matrix method was applied for approximate description of the dynamic of the beam inside the cyclotron to define the initial spiral angle, and the initial maximum spiral angle in the extraction is about 70 degrees.

The design of the yoke is performed taking account of two parameters: 1) the avoidance of saturation in the yoke; 2) the fringing field shape near the cyclotron. A value of the yoke radius $Ryoke = 2 \cdot Rpole$ should be a conservative choice. Based on the considerations above, the main parameters of the magnet can be determined and are listed in Table 1. Based on the parameters in Table 1, the 1/4 magnet model simulated by TOSCA [6] is shown in Figure 1.

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Table 1: Main Parameters of the Magnet

Design parameter	Value
Extraction energy	250 MeV
Injection field	2.4 T
Extraction field	3.1 T
Spiral angle (maximum)	66 degrees
Pole gap at hill	5 cm
Valley gap	64 cm
Pole radius	84 cm

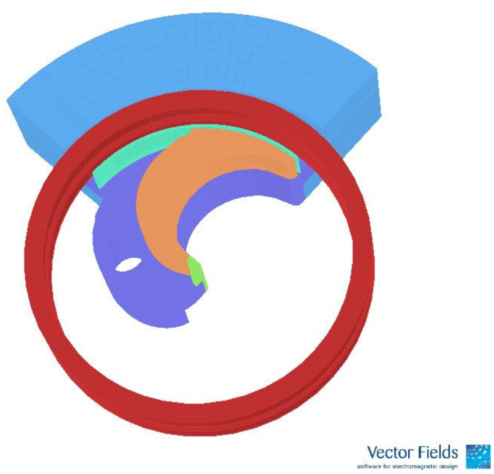

Figure 1: 1/4 model of the magnet in OPERA-3D.

MAGNETIC FIELD DESIGN METHOD

The magnetic field in the acceleration region has to guide the protons on isochronous trajectories and provide the required focusing in order to maintain good internal beam characteristics. These two properties are the result of two effects: 1) The spatial field variations due to the shape of four spiral sectors; 2) the positive radial gradient for the isochronous field is obtained by increasing the angular span of the sectors. The corresponding optimal magnetic field was achieved by shaping the sector geometry according to the two effects.

Magnet Design Process

From the analytical approach we have designed the preliminary model of the machine, assuming the width angle of the sectors to be constant along the radius. Once the dimensions of the structure were fixed, the simulations with 3D code (TOSCA) were carried out, to refine the magnetic field. The sector width and the spiral angle are the two main variables in the model to optimize the magnetic field design and the optimization process is shown in Figure 2. The hill-edge points with the radial step being 2.5 cm are parameterized to modify the sector width and spiral angle in the TOSCA model during the optimization process.

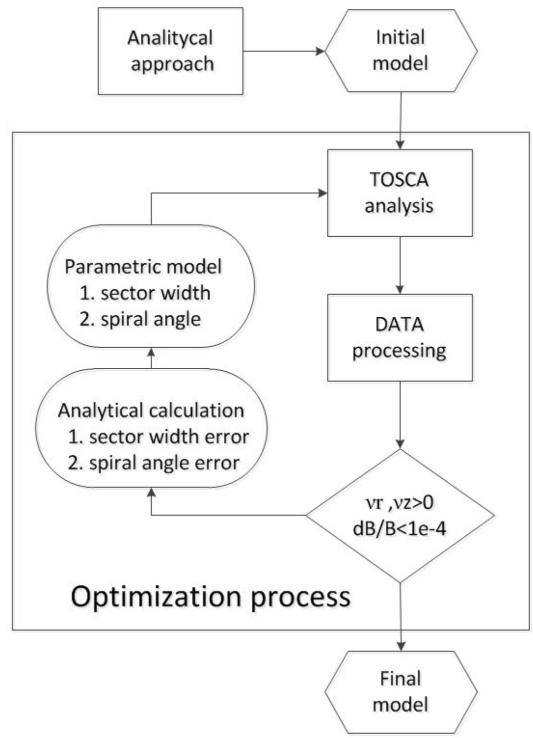

Figure 2: Magnetic field design optimization.

Field Isochronism

For a given magnetic field distribution in the mid-plane, one can compute the gyration frequency $f_p(r)$ of the particles as a function of the pole radius r either from simulated field maps or measured data. $f_p(r)$ can be calculated with equilibrium orbit codes which are based on the numerical integration on particle motion16. Then the isochronous field error $\Delta B(r)$ can be evaluated with Eq. (1) [7].

$$\Delta B(r) = B(r) - B_{iso}(r) = B_{iso}(r)\gamma^2(r)\Delta f(r) = B(r)\frac{\gamma^2(r)\Delta f(r)}{1+\gamma^2(r)\Delta f(r)} \quad (1)$$

Where $B_{iso}(r)$ is the ideal isochronous field at radius r; $B(r)$ is the calculated or measured azimuthal average field at radius r; $\gamma(r) = 1 + E\mathrm{k}(r)/E0$; $\Delta f(r)$ is the gyration frequency error defined by $\Delta f(r) \equiv (fp(r) - f0)/f0$ and $f0$ is the designed ion orbital frequency. For transforming the calculated isochronous field error $\Delta B(r)$ to the sector shape change $\Delta\theta(r)$,the hard edge approximation method[7] was adopt to calculate the sector width error, while maintaining convergence of the field isochronism.

$$\Delta\theta(r) \approx \frac{\Delta B(r)(2\pi/N)}{B_H(r)-B_V(r)} \quad (2)$$

Tune Optimization

Beyond the requirement of isochronism condition, the magnetic field distribution of compact cyclotrons should provide sufficient transversal focusing of the beam, as well as avoid dangerous resonance crossing during beam acceleration, or at least pass through quickly.

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The horizontal tune ν_r and vertical tune ν_z of beam depend on multiple parameters of the magnet, which can be approximately expressed by Eq. (3) and Eq. (4) [7].

$$\nu_r^2 = 1 + k + \frac{3N^2}{\left(N^2-1\right)\left(N^2-4\right)} F\left(1+\tan^2\zeta\right) \quad (3)$$

$$\nu_z^2 = -k + \frac{N^2}{\left(N^2-1\right)} F\left(1+2\tan^2\zeta\right) \quad (4)$$

where $k = \frac{r}{\overline{B}} \cdot \frac{\partial \overline{B}}{\partial r}$ is the radial field index; $B(r)$ is the azimuthal average field at radius r; ξ is the spiral angle; $F = \left(\overline{B^2} - \overline{B}^2\right) / \overline{B}^2$ is the field flutter which represents the azimuthal variation of the magnetic field, is very small with value less than 0.1 due to the highly saturated iron pole. Since $k > 0$ for the condition of field isochronism, the spiral angle of the magnet pole has to be introduced to compensate $-k$. So, the spiral angle should be modulated along the radius and we can calculate the required spiral angle with Eq. (4) during the tune optimization.

THE MAGNET DESIGN RESULT

The main considerations and methods in the superconducting cyclotron magnet design have been introduced. A good agreement between the isochronous field and the average field was achieved without the help of any correction system (trim coils or trim rods). Just with sector shaping and some shims in the extraction, we can get the fine magnetic field.

Figure 3 shows the average magnetic field in the TOSCA model after sectors shaping. The maximum spiral angle is 66◦ and the maximum sector width angle is 45◦ after shaped. Finally, 0.05% local field error and ±20◦ total phase slip during the main acceleration region was achieved as shown in Figure 4. As shown in Figure 5, a well-controlled tune shift was obtained and the $\nu_r = 1$ resonance crossing happened at the energy of 248.4 MeV.

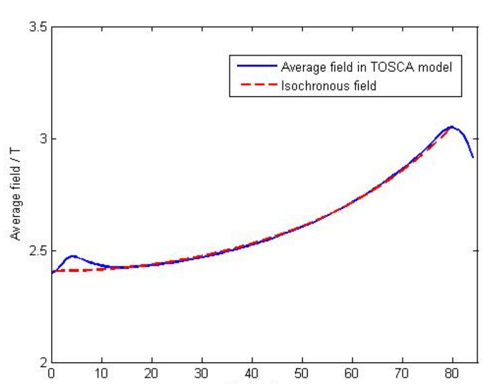

Figure 3: The average magnetic field in TOSCA model after sectors shaping.

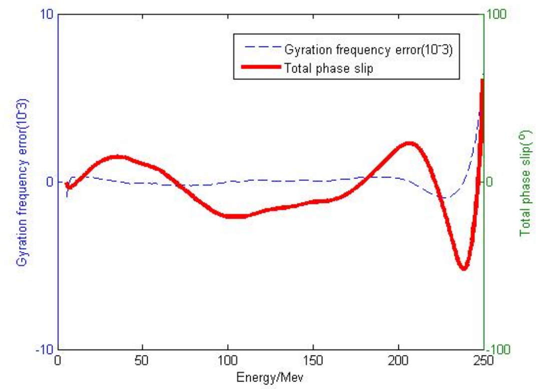

Figure 4: The final gyration frequency and the total phase slip with the change of energy.

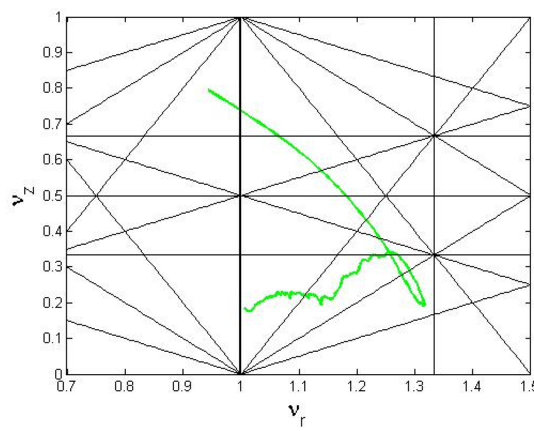

Figure 5: Tune diagram during acceleration.

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