DESIGN STUDY OF A 250MeV SUPERCONDUCTING ISOCHRONOUS CYCLOTRON FOR PROTON THERAPY*

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Abstract

Proton therapy is recognized as the most effective radiation therapy method for cancers with very high cure rate of 80%. Superconducting cyclotron becomes an optimum choice for delivering high quality proton beam due to its compactness, low power consuming and high stability. A 250MeV/500nA isochronous superconducting cyclotron was proposed in HUST, and the design and technical considerations on the spiral magnet, the tune optimization, and the beam extraction in high field will be introduces.

INTRODUCTION

The cancer is a leading cause of death worldwide. According to WHO's report, the number of new cancer cases and deaths will reach 15 million and 10 million in 2020. In China, the survival and cure rate for cancer patients is lower than 15%.

For methods of radiation therapy, compared to traditional X-ray beam, proton beam has a unique depth-dose distribution with the famous 'Bragg peak' located at the end of the radiation range, which is related to the proton energy. Hence, protons are more preferable for most types of tumors due to accurate local dose control and minimum damage to the healthy tissues surrounding at the target tumor. Since 1951, more than 50,000 patients were treated using proton beams, and 80% cure rate is achieved [1].

For 25cm penetration depth of human tissues, 200 MeV energy for proton is required; this is the reason that most proton therapy accelerators cover 210-250 MeV energy. For accelerators delivering proton beams, synchrotrons and cyclotrons are two main categories. In China, Zibo Hospital in Shandong Province established the first proton therapy center in 2004 and has treated more than 900 patients. IHEP proposed to build a proton therapy center in Shanghai using synchrotron scheme [2]. CIAE also initiated a project using superconducting synchro-cyclotron scheme [3].

In recent years, cyclotrons with room-temperature magnet and superconducting magnet are more adopted due to compactness and system simplicity. From a survey in 2009 [1], 9 planed proton therapy center all used cyclotrons, and among these proposals, 4 centers plan to use superconducting cyclotrons.

Compared to room-temperature magnet scheme, the radius of cyclotrons using superconducting magnet can be decreased to 50%, due to much higher average magnetic field which is easy to reach 3T. The compactness, low power consumption and high stability of low temperature superconducting magnet make this scheme very attractive for hospital application.

There are two main schemes for superconducting isochronous cyclotrons: MSU/PSI/Accel scheme [4] original designed by Dr. H. Blosser, with internal ion source; and INFN-LNS scheme with high intensity external ion source [5]. Since for proton therapy, 500 nA beam intensity can meet radiation dosage for 3 gantries, which is easy achieved with internal PIG source, we adopt the former conceptual design. This paper give a description of design considerations on a 250 MeV, 500 nA superconducting cyclotron used for proton therapy.

OVERALL DESCRIPTION

The main features of the machine are described as following, and overall parameters are listed in Table 1.

- For magnet using superconducting coils, the flutter is much lower than than of normal conducting magnet, which is below 0.1. To achieve sufficient axial focusing, spiral shape pole has to be employed. In addition, to maintain stable vertical focusing to avoid dangerous resonance crossing, the spiral angle need to be modulated along the radius.
- For the extraction magnetic field, it was balanced between the achievable value by using superconducting coils and realistic considerations for beam extraction and isochronous field formation. It is not difficult to reach 4-5 T at extraction, but this will make extraction design more challenging.
- An internal positive penning ion source (PIG) is used for moderate beam intensity required by proton therapy, which simplifies the injection structure.
- Superconducting magnet: NbTi/Cu composite superconductor with liquid Helium cooling will be used for producing maximum average field of 3.2 T in the median plane, with stored energy 3 MJ.
- Precessional beam extraction: The last turn separation due to acceleration is less than 1mm, which can be increased to 5mm by introducing a first harmonic field bump near the resonance crossing line $\nu_r = 1.0$, with the precessional extraction method.

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Table 1: Overall Parameters

Extraction energy	250 MeV
Ion source	Internal P.I.G. source
Beam intensity	≈ 500nA
Emmittance	5πmm · mrad
Injection / extraction field	2.45 / 3.1 T
Spiral angel (maximum)	66 degrees
Pole gap at hill	5 cm
Pole radius	84 cm
Total ampere turns	1.2MA · T
RF frequency	74MHz (harmonic mode=2)
Energy gain per turn	≈ 400keV
Extraction scheme	Precessional extraction

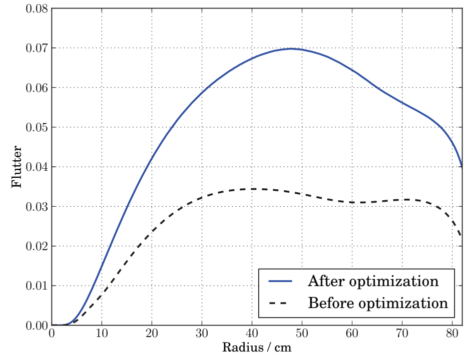

Figure 2: Optimization of the flutter.

MAGNET DESIGN AND TUNE OPTIMIZATION

Optimization Of the Flutter and the Piral Angle

The magnet model built by TOSCA [6] is shown in Fig. 1. Compared to room temperature magnet, the superconducting coil induced field possesses dominant part, and the field flutter contributed by pole hill and valley structure is much lower. Since $\nu_z^2 \approx -k + F \cdot (1 + 2\tan^2\zeta)$, and the field index $k = \gamma^2 - 1$ is pre-determined to maintain isochronous condition, a spiral angle must be introduced to compensate the instability of $-k$.

For a given extraction energy γ_{ext}, the maximum spiral angle has a strong relation to the flutter at the extraction area. To reduce this spiral angle for achieving higher rf voltage, the flutter is optimized by choosing a suitable ratio of hill / valley gaps. Also, the coil field need be controlled to avoid decreasing the flutter. Figure 2 shows the optimization of the flutter and the final flutter is beyond 0.05 for main acceleration area.

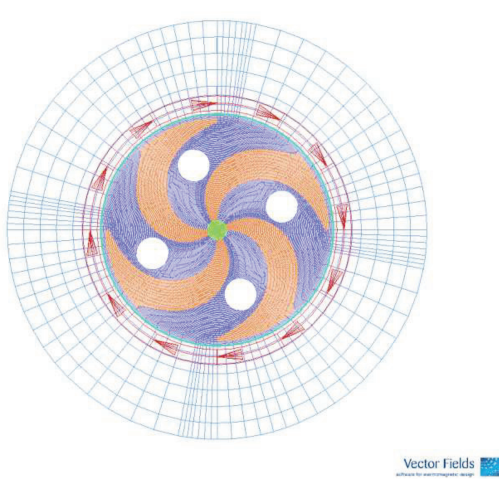

Figure 1: Magnet model.

Normally $\nu_r^2 \approx 1 + k = \gamma^2$ is smoothly changed by beam energy, but, to maintain a stable vertical tune, the spiral angle need be adjusted along the radius. A python script was developed to modify the spiral angel in the tosca model, according to the calculated tune variation. Finally, a well controlled tune shift was obtained, as shown in Fig. 3.

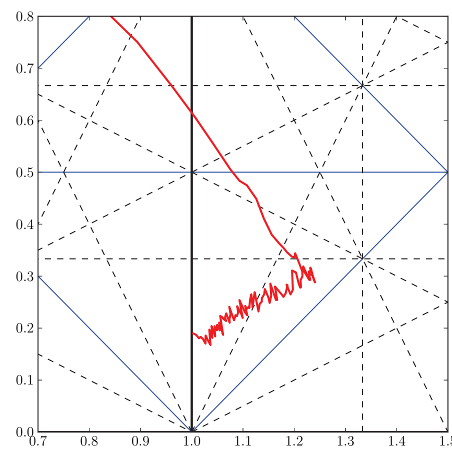

Figure 3: Tune diagram during acceleration, only third resonances drawn.

Isochronous Field Shimming with Trim Rods

For cyclotrons with room-temperature magnet, the isochronous field can be achieved by pole shaping precisely [7]. However, as addressed, the field component produced by the superconducting coils and iron pole saturation makes pole shaping not so efficient.

Two steps are used for field isochronism: 1) For meeting initial isochronous field condition, the hill pole width is increased from the central region to the pole end, with an iterative process by evaluating the field generated by TOSCA model. As shown in Fig. 4, the isochronous field error can be limited within 150 Gs. 2) Fine shimming by using trim rods. As shown in Fig. 5, 29 trim rods are located at the center line of the spiral pole, and the independent field shimming effect when removing these rods are shown in Fig. 6. For the trim rods with same surface area, the shimming effect will decrease along the pole radius due to the increasing

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circumference. To compensate this, two rod radius are used, with inner part 1cm and outer part 2cm. For consideration on technical issues, two vertical positions of the trim rods (2cm / 1cm to the pole surface) are used, and a code was written to get the combination the rods positions by adjusting the result from least square fit.

By combining these two methods, 0.05% local field error and ±15° total phase slip can be achieved.

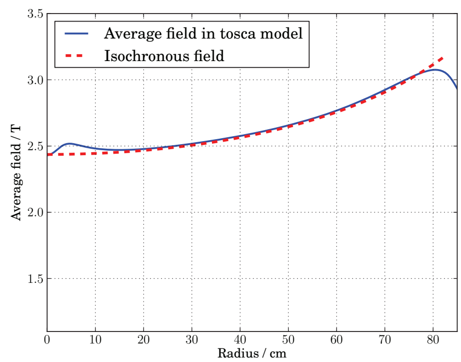

Figure 4: Average field with initial isochronous shaping.

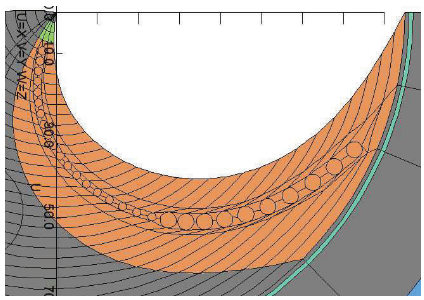

Figure 5: Trim rods located at the center of spiral pole, for fine shimming of the isochronous field.

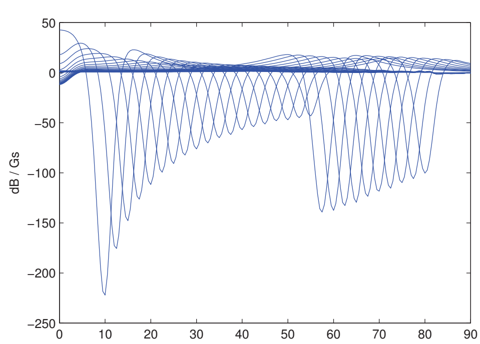

Figure 6: Independent field shimming effect with 2cm depth.

PRECESSIONAL EXTRACTION

For high magnetic field around 3T at the extraction, the turn separation due to energy gain is lower than 1mm, which brings significant beam loss when "cutting" by the septum in the electronic deflector. Meantime the energy spread will be enlarged. A mature method, single turn precessional extraction [8] can be employed to increase the turn separation.

By generating a first harmonic field bump $b1(r, \theta) = b1(r) \cdot \cos(\theta - \theta_0)$, before the $\nu_r = 1$ resonance crossing, at a given azimuthal angle θ_0, a coherent oscillation is created and the resulting radial displacement is:

$$\Delta R_{pre} = \pi R \cdot \Delta\tau (b1/\overline{B}(R)) \quad (1)$$

The bump field can be generate either by harmonic coils or trim rod. Figure 7 shows the simulation on tracing the beam envelope using $b1 = 6Gs$, $\theta_0 = 30°$, the effective turns during coherent oscillation $\Delta\tau = 9$. The final turn separation was enlarged to $\Delta R = 5.3mm$ including the acceleration component, which is coincident with the theoretical value $\Delta R_{pre} = 4.5mm$. In simulation, the beam is pre-centered by using the accelerating equilibrium orbit(A.E.O.).

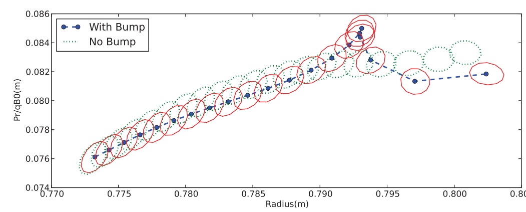

Figure 7: Precession extraction, using a 6Gs harmonic bump.

CONCLUSION AND DISCUSSION

Preliminary design considerations on an isochronous superconducting cyclotron aiming at proton therapy are described, mainly focusing on overall design, magnet, and extraction scheme. Some other system, important as well, such as the rf cavity, the superconducting coil / Dewar, the central region and the extraction structure are under design progress and not presented.

Considering the target patients for asian people, 235MeV extraction energy is also a choice.

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