ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPMP029

DESIGN STUDY OF A COMPACT SUPERCONDUCTING CYCLOTRON SC240 FOR PROTON THERAPY *

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Abstract

Superconducting cyclotron becomes an optimum choice for delivering high quality proton beam due to its compactness, low power consuming and high stability. We have developed a 200 MeV superconducting proton cyclotron for radiotherapy. For diversifying products, the goal of development is to produce a 240 MeV proton beam by superconducting cyclotron (SC240) for medical use. The magnet system is composed of one set of NbTi/Cu superconducting coils and four spiral sectors with a yoke. The hill angular widths, hill gaps, and spiral angles with radius have been designed for the isochronous magnetic field. The design and technical considerations on spiral hill, betatron oscillation optimization, and precession extraction have been presented.

INTRODUCTION

It is well known that particle therapy is one of the most effective methods for cancer treatment. Compared to traditional X-ray beam, proton beam has a unique depth-dose distribution with 'Bragg peak' located at the end of the radiation range, which is related to the proton energy. 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. According to PTCOG's report [1], the number of patients treated with particle therapy is 84,492 by 2010, and more than 85% is treated with proton beams.

For 25 cm depth of human tissues, 200 MeV energy for proton is required. Considering the price and compactness, a 200 MeV superconducting proton cyclotron is under construction for radiotherapy [2-5]. Compared to room-temperature magnet, 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 [6]. For diversifying products, a 240 MeV superconducting proton cyclotron (SC240) should be designed by ASIPP to treat deeper tumors.

At the world, the proton cyclotrons with 200-250 MeV energy range were provided by several suppliers for medical use, such as IBA [7], Varian [8], Mevion [9], etc. Recently, more organizations are actively in development of superconducting proton therapy system, such as Sumitomo [10], HUST [11], CIEA [12], Pronova [13], etc. The compactness, low power consumption and high stability of low temperature superconducting (LTS) magnet make this scheme very attractive for hospital application.

The SC240 cyclotron will accelerate protons from a few eV to 240 MeV. It is focused on high intensity beam, high extraction efficiency, and low current density in superconducting coils for long-time running. In this paper, the magnetic field distribution in mid-plane of a magnet has been designed for stable beam acceleration. We used FEM software to simulate a 3-D magnetic field and used self-writing code to analyze beam characteristics for the magnetic field distribution.

GENERALLY DESCRIPTION

SC240 proton cyclotron used an internal positive penning ion source (PIG) for obtaining the required beam intensity in proton therapy, which simplifies the injection structure. A set of NbTi / Cu superconducting coils is used to produce a high magnetic field. Precession beam extraction was employed in SC240. This extraction method can increased from < 1mm to ≈ 7.5mm at the last turn separation by introducing a 1[st] harmonic field bump near the resonance crossing line $\nu_r = 1.0$. The extraction efficiency is expected higher than 80%.

The superconducting magnet for SC240 proton cyclotron is consists of an iron yoke, four spiral hills, and a superconducting coil system (Figure 1). The general specifications of SC240 are listed in Table 1.

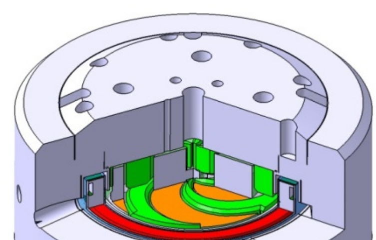

Figure 1: The superconducting magnet system of SC240.

The yoke and spiral hills are made of low-carbon steel. To achieve adequate axial focusing, the sector structure is four-fold rotational symmetric and is shaped in spiral. In addition, to maintain stable vertical focusing to avoid dangerous resonance crossing, the spiral angle need to be modulated along the radius. There are 8 holes in the yoke for RF cavities, 12 holes for support links of the super-

* Work supported by National Natural Science Foundation of China under grant No. 11775258 & 11575237, International Scientific and Technological Cooperation Project of Anhui grant No. 1704e1002207.
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conducting coil system, and 4 holes for lifting an upper yoke plate.

The superconducting coils of SC240 are made of rectangular NbTi / Cu wire. Two superconducting coils are connected in serial. The coils are directly cooled by liquid helium that is re-condensed by GM cryocoolers. The cryostat for the coils is composed of 4.2 K shield, 70 K thermal shield, vacuum shield, 2 high-temperature superconducting current leads and superconducting feeder.

Table 1: Specifications of SC240

Parameters	**Values**
Extraction energy	240 MeV
Ion source	Internal P.I.G. source
Beam intensity	500nA
Extraction radius	81.0 cm
Average magnet field	2.3 / 3.0 T
RF frequency	70.10 MHz (h = 2)
Number of cavities	4
Number of sectors	4
Pole radius	84 cm
Spiral angel (maximum)	71°
Hill / valley gap	5 cm / 60 cm
Coil diameter	2.28 m / 2.44 m
Coil height	115mm
Extraction scheme	Precession extraction
Magnet weight	≈ 90 tons

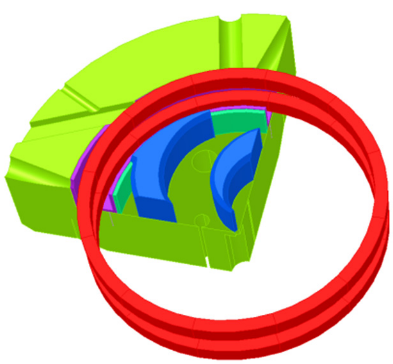

Figure 2: The 1/8 model of SC240 for magnetic field simulation.

MAGNET DESIGN

According to the geometry of magnet is reflection symmetric in x-y plane and is four-fold rotational symmetric in z-axis, 1/8 numerical model of SC240 was used in magnetic field simulation by FEM software for less CPU time (Figure 2).

The main design parameters are the sector geometries, such as radius, angular width, spiral angle, gap of hill. For magnet using superconducting coils, the induced field possesses dominant part. The flutter of SC240 is much lower than room-temperature magnet, which is contributed by pole hill and valley structure. Since vertical and radial focusing approximation is respectively given by:

$$\nu_z^2 \approx -k + \frac{N^2}{N^2-1} F\left(1+2\tan^2\varsigma\right). \quad (1)$$

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

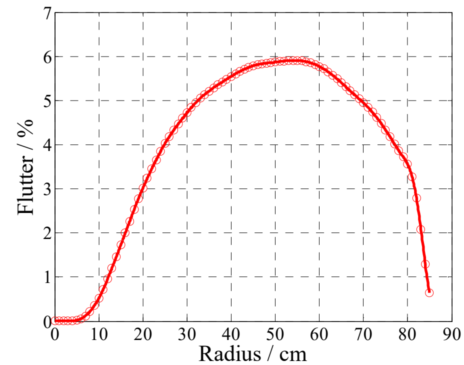

Figure 3: The flutter of SC240.

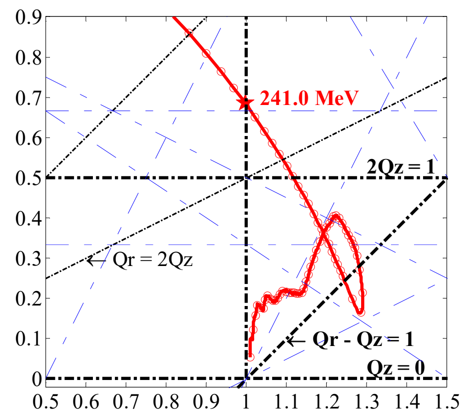

Figure 4: Betatron diagram during acceleration.

A spiral angle must be introduced to compensate the field index $k=\gamma^2-1$. For established extraction energy, the maximum spiral angle depends on the flutter at the extraction area, as shown in Eq. (1). Enhancing the flutter at this area could increase the spiral angle for obtaining higher RF voltage (Figure 3). According to the design requirement, the maximum of spiral angle should be controlled less than 70°.

Radial focusing will be smoothly changed by energy, as shown in Eq. (2). For maintaining stable vertical focusing, the spiral angle need be adjusted along the radius. Finally, a well-controlled betatron diagram was obtained (Figure 4).

To decrease the number of turns and the beam losses, we need to minimize magnetic field errors. This error should be less than 10 Gs before ν_r = 1. But if the field error is too small, the RF phase shift is sensitive to the field. We set the criteria of RF phase shift to ±20° (Figure 5).

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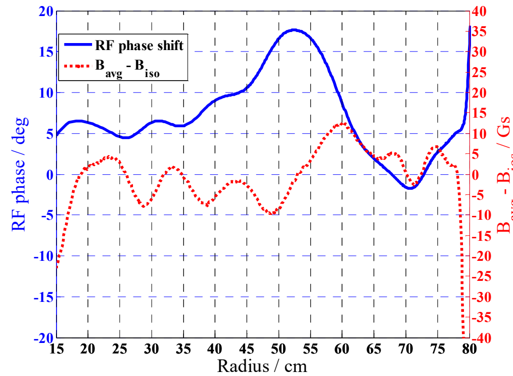

Figure 5: RF phase shift and difference between average and isochronous fields.

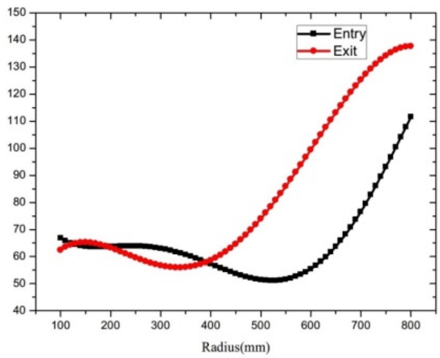

Figure 6: Voltage distribution of dee.

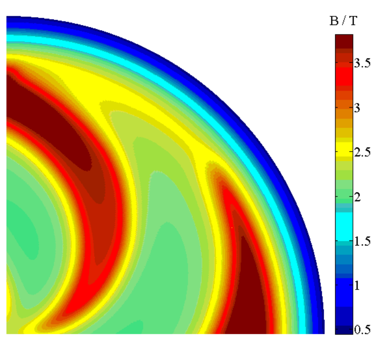

Figure 7: Cloud of magnet field in mid-plane.

As the hill shape changes, the acceleration gap also moves. When calculating the beam track, the spiral dee gap and its voltage were applied. The acceleration gap of dee has constant angle of 7 and the dee voltage varies from 65 kV to 140 kV with the radius (Figure 6).

DESIGN RESULT

The current density of the superconducting coil is 75 A/mm^2. The hill gap is 5 cm and the valley gap is 60 cm. At the extraction area, we designed a 2mm bulge and a skirt structure at valley to obtain better isochronous field approximation. The overall spiral angle is increased from 0 to 71 linearly. To adjust vertical betatron oscillation around outer region of the hill, the spiral angle was decreased in that region.

The range of the magnetic field distribution in mid-plane is 0.45– 3.81 T and that of the azimuthally averaged field is 2.30 T–3.01 T (Figure 7).

We have verified the central magnetic field, field errors, and beam tunes from equilibrium orbit calculation that was done in every 0.5 MeV from 1 MeV to 245 MeV. The RF frequency is 72.80 MHz with 2nd harmonic. The calculated average fields are within 10 Gs compare to the isochronous field with the radius, i.e. the field error is less than 0.1%.

We also obtained the characteristics of beam acceleration from beam tracking calculation. There are 522 times revolutions from 1 MeV to 240 MeV.

For high magnetic field around 3T at the extraction, the turn separation due to energy gain is less than 1mm, which brings significant beam loss if extracting by the septum in the electronic deflector. Single turn precession extraction can be employed to increase the turn separation. By generating a 1st harmonic field bump $B_1(r,\theta)=B_1(r)\cos(\theta-\theta_0)$, 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

$$\Delta R = \pi R\, \Delta\tau\left(B_1 / \overline{B}(r)\right). \quad (3)$$

In SC240, The bump field is generated by trim rod. The simulation result of turn separation is 7.58 mm with a 1st harmonic field B_1= 12 Gs, θ_0= 83°, $\triangle\tau$=7 (Figure 8). The theoretical turn separation $\triangle R$ = 6.95 mm agrees well with simulation.

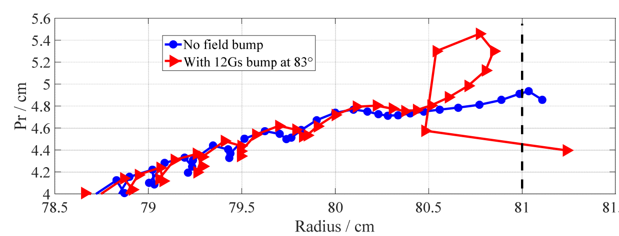

Figure 8: Precession extraction with a 12 Gs bump at 83°.

CONCLUSION

We have designed the superconducting magnet system for SC240. The overall structure of the superconducting magnet, detailed shape of the spiral hill, and extraction scheme has been presented. Other system, such as, RF cavity, the superconducting Dewar, central region and extraction structure are under design progress and not presented. We are also developing measurement system and shimming method for manufacture.

ACKNOWLEDGEMENT

Authors want to thank Dr. Evgeny Samsonov and Dr. Nikolay Morozov for the constructive discussion on the design of magnet.

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