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Design of an Alternating Gradient Canted-Cosine-Theta superconducting magnet applied to proton therapy

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Abstract

Canted-Cosine-Theta(CCT) magnet has demonstrated advantages of superior field quality and structure compactness in superconducting magnet schemes. Combining with Alternating-Gradient (AG) field feature, CCT magnets can be applied to proton therapy gantries with a significantly increased momentum acceptance. This paper will introduce design considerations of a 67.5-degree AG-CCT magnet for proton therapy gantry, including design and optimization of magnetic field with AG combined function. The calculation method of magnetic field for simulating Canted-Cosine-Theta coil entity with multiple lines based on B-S law is discussed in details. Technical issues covering the choice of superconducting coils, layer scheme will also be discussed.

INTRODUCTION

For proton therapy(PT) facilities, the gantry plays an important role for projecting the proton beam onto a tumor at various angles, normally in range of ±180°. Since the weight of the gantry is mainly contributed from dipole magnets in the gantry beamline, employing superconducting magnets becomes very attractive to decrease both the weight and footprint of the gantries[1].

The CCT(Canted-Cosine-Theta) concept was firstly proposed in 1970[2], but it's applications were postponed to the early 2000's. By combining alternating-gradient (AG) features, CCT magnet provided a feasible and attractive scheme for light-weight superconducting gantries applied to proton therapy[3, 4].

A light-weight superconducting gantry with downstream scanning using AG-CCT magnets was proposed at HUST[5]. This paper introduces the magnetic field calculation and optimization of a 67.5 degree four-layer AG-CCT applied to the above scheme. In section II, the calculation method of the CCT magnetic field based on the Biot-Savart Law with multiple-line model is introduced. In section III, the design and optimization result of the specific AG-CCT is presented.

AG-CCT Superconducting Magnet Scheme

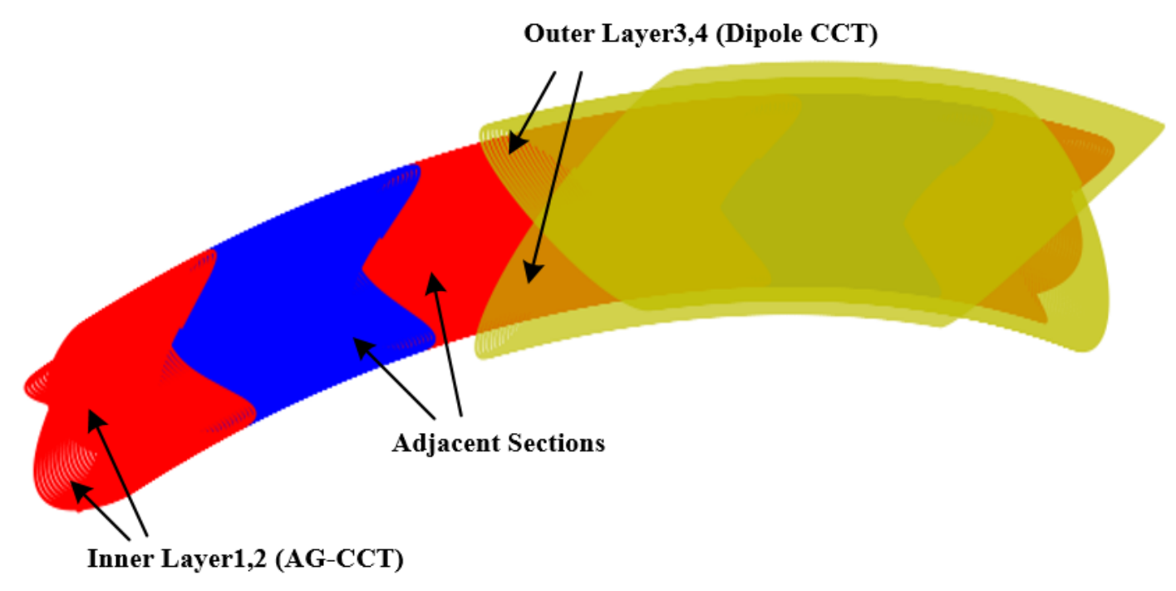

Figure 1:The layout of the four-layer AG-CCT magnets

Fig.1 shows the layout of the AG-CCT magnet. The AG-CCT magnet consists of several CCT quadrupole sections placed in sequence from left to right so that the excitation current direction can be reversed between adjacent sections. This will produce alternating quadrupole fields along the bending path.

By combining with the main dipole CCT field, AG-CCT can provide strong focusing and very small dispersion for an independent bending section of the gantry beamline. In consequence, with a large momentum acceptance, frequently field ramping in superconducting coils can be avoided during energy modulation procedures in PT. In this scheme, the AG-CCT magnets are divided into five sections(FDFDF) to realize the purpose of locally achromatic[6].

Method of high-precision calculation by multi-line model

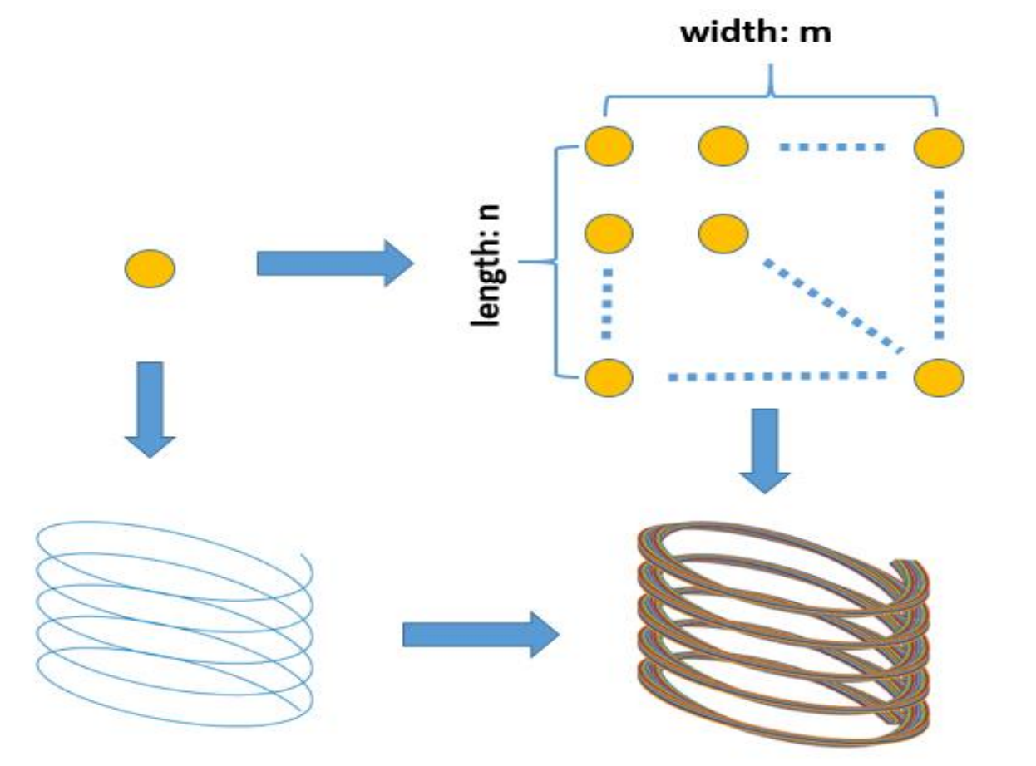

Figure 2: Diagram of single-line model and multi-line model

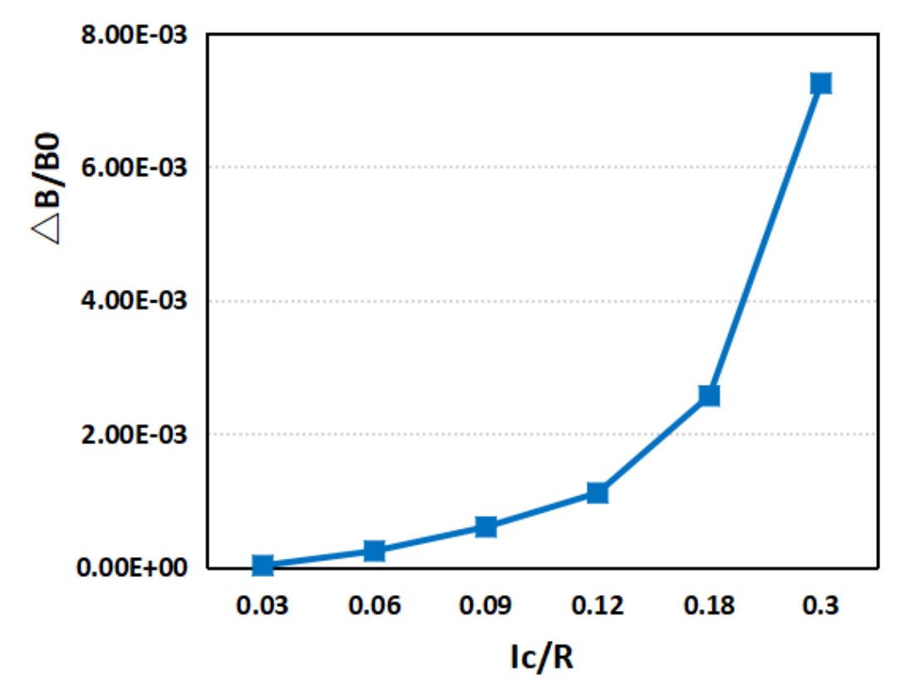

Figure 3: The relationship between field relative error of single-line model and the ratio of coil size to aperture

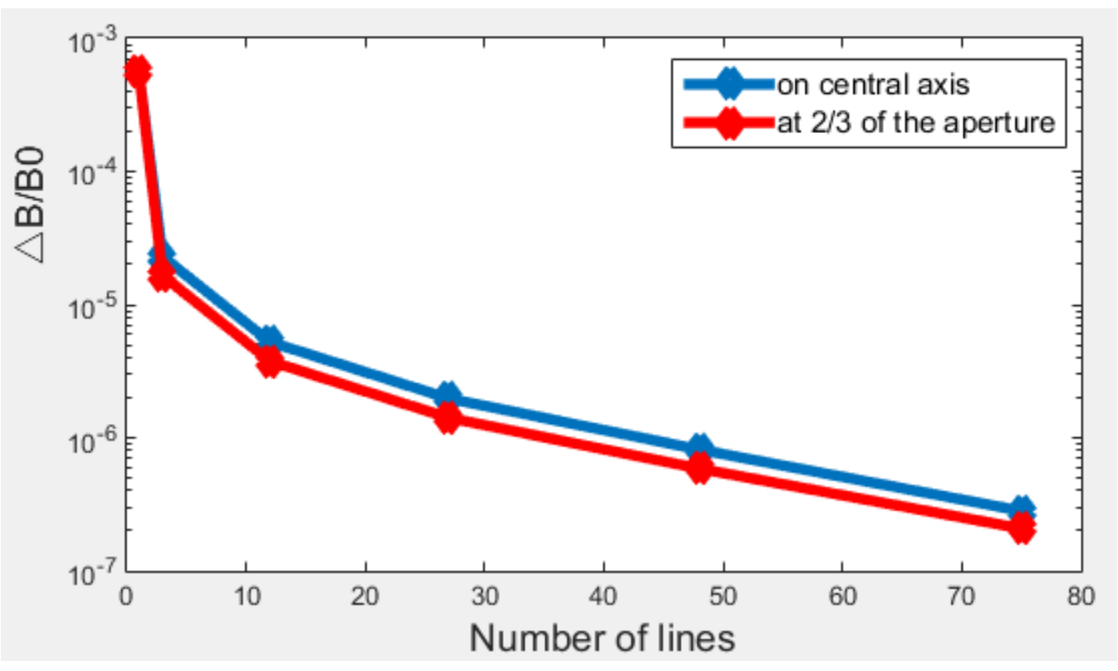

Figure 4: Magnetic field relative error of multi-line models on central axis and at 2/3 of the aperture

The magnetic field in CCT magnets is usually calculated by finite element softwares. However, this method is quite time-consuming for a complex CCT structure with high precision requirement. In this paper, the method of vector line approximate simulation based on Bio-savart's law is adopted to calculate the magnetic field of CCT magnets. As shown in Fig.2, one yellow dot represents a single-line model. The multi-line model consists of many single-line models uniformly distributed in the coil according to the length-width ratio of coil cross section.

The error of magnetic field is related to the ratio of the coil thickness to the CCT aperture as shown in Fig.3. The advantage of the multi-line model is more obvious with the increase of the ratio. We calculated the magnetic field of the different multi-line models on the center axis and edge of good field region. It can be seen from Fig.5 that the accuracy of the multi-line model is improved rapidly at first and then saturated with the increase of lines. Compared with single-line model, multi-line model can improve the accuracy of field calculation by two or more orders. We can choose the number of lines according to the accuracy we need.

DESIGN OF THE AG-CCT MAGNETS

Table 1 Design parameters of the AG-CCT magnets

Constant dipole field	2.43T
Bending Radius	1m
Aperture	D>=80mm
Good field region	+/-30mm
Total bending angle	67.5 deg
9 deg, Focus	G=43T/m
12.9 deg, Defocus	G=-43T/m
23.8 deg, Focus	G=43T/m
12.9 deg, Defocus	G=-43T/m
9 deg, Focus	G=43T/m

The AG-CCT magnets consist of two pairs. The inner pairs are quadrupoles divided into five sections. The outer pairs are dipoles which generate a dipole field along the bending path to deflect the beam.

The detailed physical requirements of the AG-CCT magnets are listed in Table 1: (1) The bending radius of the whole AG-CCT magnet system is 1m; (2) The system has a good field with a radius of 30mm and the bore diameter is at least 80mm; (3) The constant dipole field is 2.43T; (4)The total bending angle of the AG-CCT system is 67.5 degree and each bending angle of the five quadrupoles is shown respectively in Table1. The alternating gradient of the quarupoles is 43T/m.

Table 2 Winding Mandrel Geometry (in mm)

type	Ri	Ro	Wall	Channel
AG-CCT	40	50	10	2/7
AG-CCT	50	60	10	2/7
Dipole CCT	60	69	9	2/6
Dipole CCT	69	78	9	2/6

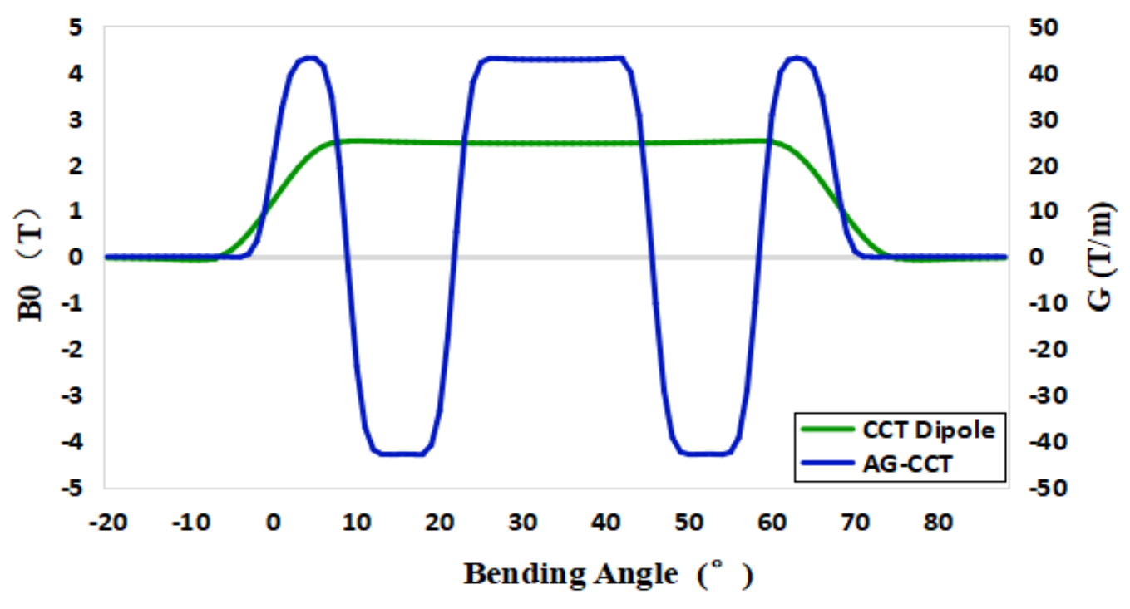

Fig.6. Dipole and alternating gradient distributions of the AG-CCT magnets

The winding mandrel geometry parameters are shown in Table 2. The depth of channel depends on the number of strands in each layer. The distribution of magnetic field along the bending path of the AG-CCT magnets is shown in Fig.6. As designed, there is a constant dipole field and an alternating gradient field along the bending path.

Optimization of Magnetic Field Uniformity and Type Selection

The curved CCT magnet presents asymmetry in the transverse direction different from the straight CCT magnet. Combined function CCT magnet is used to compensate the quadrupole field component introduced by bending process. The quadrupole field component can be introduced to offset the redundant quadrupole field component by adjusting the ratio of quadrupole field component to dipole field component.

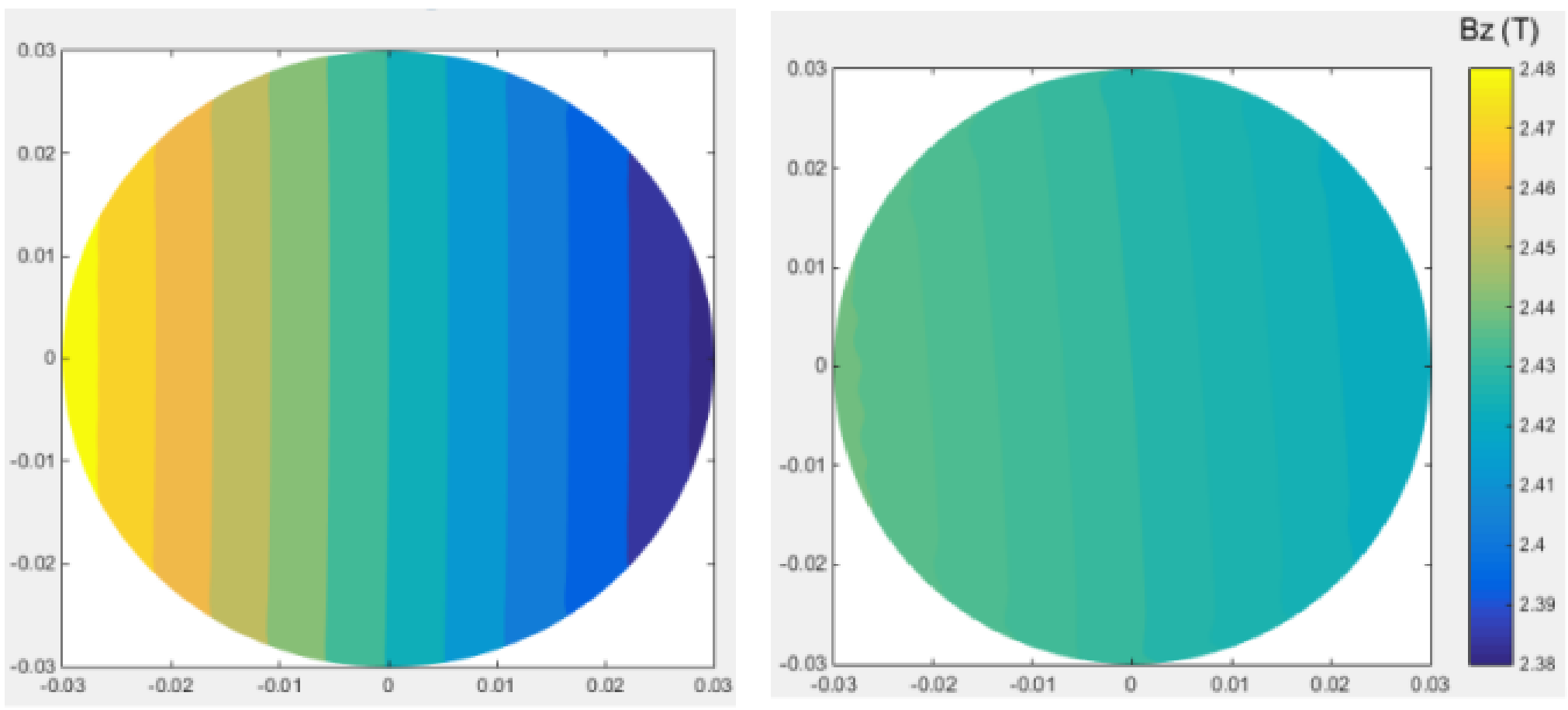

Figure 7: Magnetic field distribution on the cross section at center position of the curved CCT before and after optimization

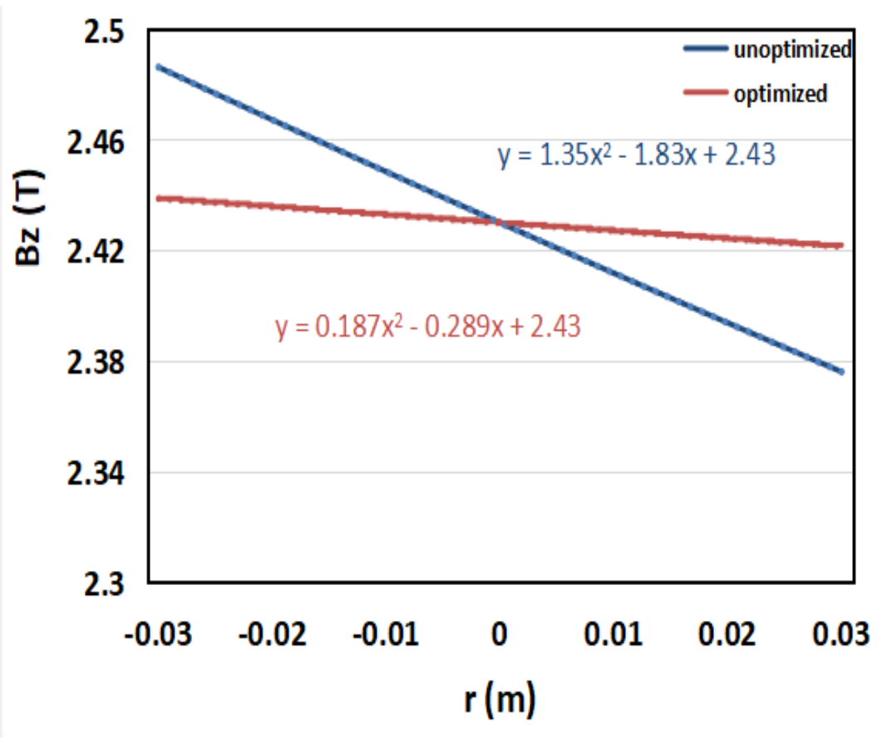

Figure 7: The profile of the magnetic field on the mid-plane

Fig.9 shows the contrast diagram of the magnetic field on the cross section at center position of the curved CCT before and after optimizing. The uniformity of optimized model is obviously improved.

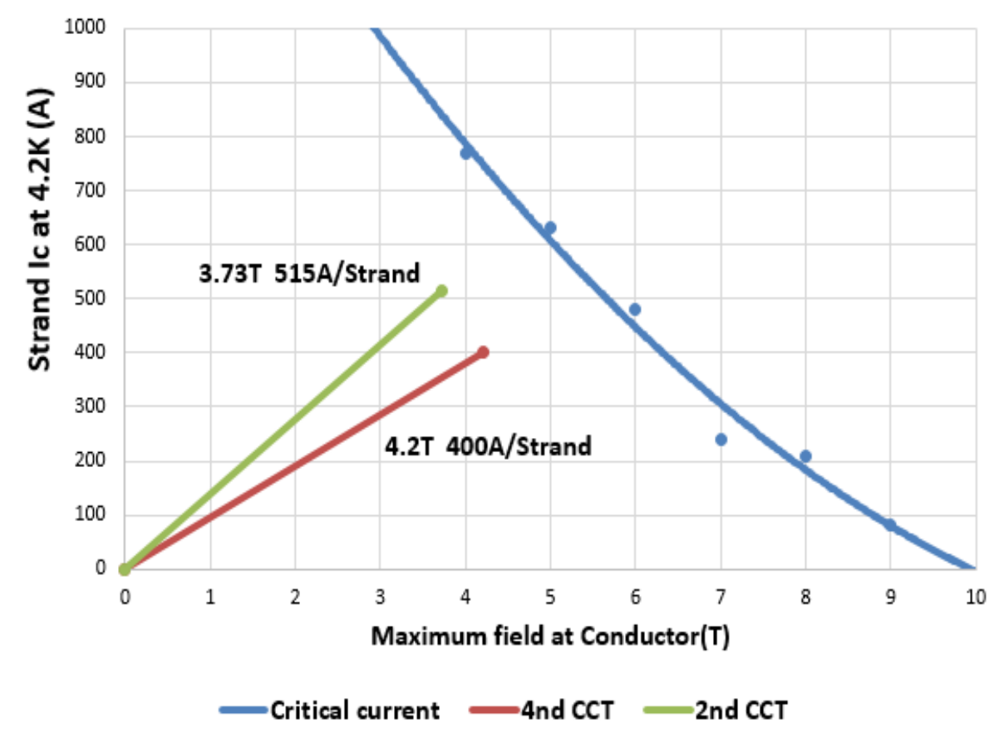

Figure 7: Characteristic line of monolith NbTi superconducting materials and maximum operating points of CCT

Monolith NbTi wire produced by Western Superconducting Technologies Co.,Ltd in Xi'an of China is chosen as the superconducting wire.

Fig.11 shows the critical current line of monolith NbTi superconducting materials and maximum operating points of the dipole CCT and AG-CCT layers. In this design we ensure at least 20% current margin.

CONCLUSIONS

Method of high-precision calculation by multi-line model has been discussed in this paper. The preliminary electromagnetic design of the AG-CCT system has been completed, and the method and result of magnetic field optimization have been given. Stress analysis and support structure design of the AG-CCT system are in progress.

REFERENCE

[1] A. Gerbershagen et al. A novel beam optics concept in a particle therapy gantry utilizing the advantages of superconducting magnets. Z. Med. Phys. 26(2016) 224-237.

[2] Meyer DI et al. A new configuration for a dipole magnet for use in high energy physics applications[J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment: 1970, 80:339-341.

[3] Weishi Wan et al. Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries, Phys. Rev. ST Accel. Beams 18, 103501 (2015).

[4] L. Brouwer et al. Canted-Cosine-Theta Superconducting Accelerator Magnets for High Energy Physics and Ion Beam Cancer Therapy, Ph. D Dissertation, University of California, Berkeley, 2015.

[5] B. Qin et al. Design considerations of a superconducting gantry with alternating-gradient combined-function magnets, International Conference on Medical Accelerators and Particle Therapy, Seville, Spain, September 2019, https://indico.cern.ch/event/803528/timetable/#20190904