WEPO007

The design of superconducting dipole magnet based on tilted solenoids

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Abstract:

As a core component of proton therapy equipment, the gantry can project the proton beam onto a tumor from different angles. The weight of the gantry with normal conducting magnets(mainly normal dipole magnets and quadrupole magnets) is usually more than 150 tons, which puts forward high requirements for the design, processing and fabrication. Thus, for the realization of light-weight gantry, this article puts forward a design of Canted-Cosine-Theta(CCT) superconducting magnet used on superconducting gantry. Since the superconducting CCT magnet can produce higher magnetic field, for the proton beam with the same magnetic stiffness, the deflection radius of the magnet can be significantly reduced, thus reducing the radius and volume of the gantry.

The finite element analysis software and Biot-Savart principle were adopted in this article to establish the method of magnetic field calculation for CCT superconducting magnet, and MATLAB was used to simulation and validation of particle path, which finally realize the design of CCT superconducting magnet that is applied in gantry.

1.Introduction

Table 1.1 Physical requirements for the deflected CCT magnet

Parameters	Value	Units
Maximum proton energy	280	MeV
Bending Angle	58.5	°
Bending Radius	0.9	m
Magnetic field intensity	2.8	T
Effective length	918.9	mm
Good field radius	>30	mm
Magnetic field homogeneity	1×10^{-3}	-

2.Theoretical model of bending CCT superconducting magnet

Bending CCT superconducting magnet trajectory equation can be established through two ways: one is in the cylindrical coordinates through linear CCT magnet trajectory equation is set up, another is in the toroidal coordinates.

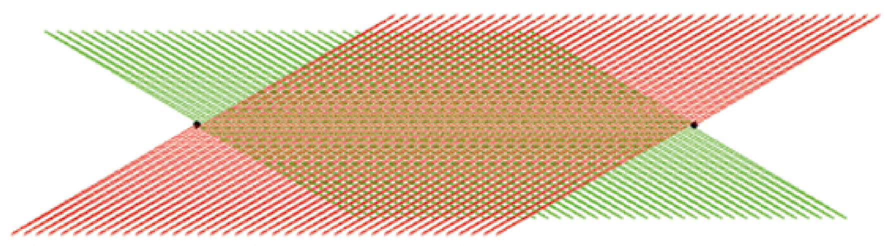

Fig. 2.1 Coil trajectory of a linear CCT superconducting magnet

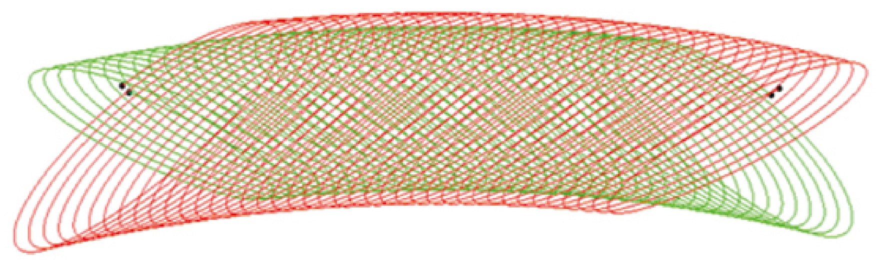

Fig 2.2 Coil trajectory of a bending CCT superconducting magnet

The trajectory equation of the linear CCT superconducting magnet in the Cartesian Coordinates is shown in Equation (1), where the origin of coordinates is at the center of the cylindrical surface:

$$\begin{cases} x=(R+r\cos\theta)\cos\varphi \\ y=(R+r\cos\theta)\sin\varphi \\ z=r\sin\theta \\ \varphi=\sum\left[\dfrac{r}{n\tan\alpha}\sin(n\theta)+\dfrac{\omega}{2\pi}\theta\right]\times\dfrac{1}{R} \end{cases} \quad (2)$$

$$\begin{cases} \eta=\eta_0 \\ \zeta=\zeta \\ \phi(\zeta)=\sum\left[\dfrac{\cot\alpha}{n\sinh\eta_0}\sin(n\zeta)+\dfrac{\phi_0}{2\pi}\zeta\right] \end{cases} \quad (3)$$

3.Structural model of bending CCT superconducting magnet

(1) Angle spacing solution

The analysis shows that the turn spacing is the smallest at the inner side of the deflect CCT coil, that is, at . On the outside of the coil, i.e. , the spacing between turns is the largest. The extreme value of turn spacing can be obtained as follows:

$$\begin{cases} \min(\delta)\big|_{\zeta=\pi}=a\phi_0\sin\alpha\tanh(\eta_0/2) \\ \max(\delta)\big|_{\zeta=0}=a\phi_0\sin\alpha\coth(\eta_0/2) \end{cases} \quad (7)$$

$$\phi_0=\frac{\delta_0+\mathrm{wd}}{a\sin\alpha\tanh(\eta_0/2)} \quad (8)$$

$$\begin{cases} a=\sqrt{R^2-r^2} \\ \eta_0=\dfrac{1}{2}\ln\dfrac{R+a}{R-a} \end{cases} \quad (9)$$

Table 3.1.

Table 3.1 Parameters of bending CCT superconducting magnets

Parameters	Value	Units
Pore size at room temperature	40	mm
Number of coil layers	2	layer
Bending Radius	900	mm
Coil tilt Angle	30	°
Number of coil turns	120	t
Inner coil radius	56	mm
Outer coil radius	66	mm
Minimum interturn rib thickness①	0.4	mm
Maximum interturn rib thickness	(3.9/4)②	mm
Inter-turn angular distance	0.0085	rad
Current value of a single superconducting wire	<1000	A

注：①The rib thickness is the wall thickness of the skeleton groove; ②3.9mm is the maximum interturn rib thickness of the inner coil and 4mm is the maximum inter-turn rib thickness of the outer coil.

Fig 3.4 Opera-3D CCT model

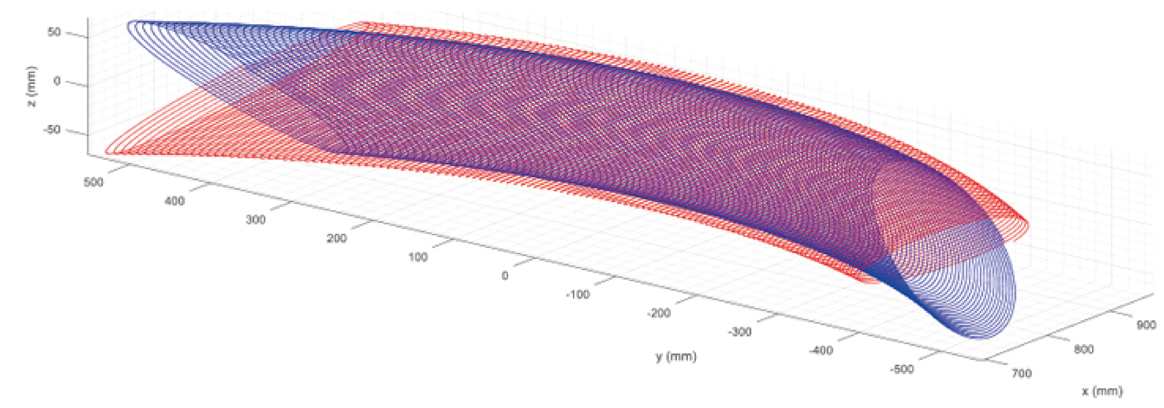

Fig 3.5 Center trajectory model

4.Magnetic field optimization and beam trajectory verification

(1)Magnetic field optimization

Adjustment coefficient				Magnetic field value	Harmonic component					
K1	K2	K3	K4	By/T	1	2	3	4	5	6
1	0	0	0	2.875	8.44E-02	1.78E-03	3.99E-05	8.97E-07	1.97E-08	3.94E-10
1	0.055	0.004	0	2.885	6.36E-04	9.91E-04	1.33E-04	7.46E-06	3.09E-07	1.08E-08
1	0.0548	0.003	0	2.885	1.92E-04	1.74E-04	7.36E-05	4.72E-06	2.06E-07	7.40E-09

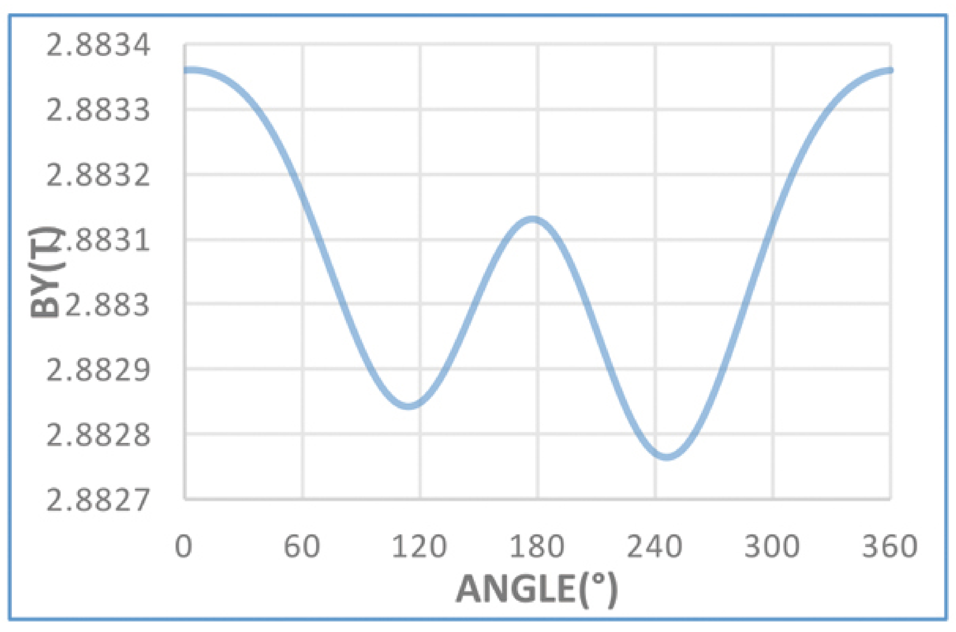

Fig. 4.3 Magnetic field distribution on the cross-section circumference(r=35mm)

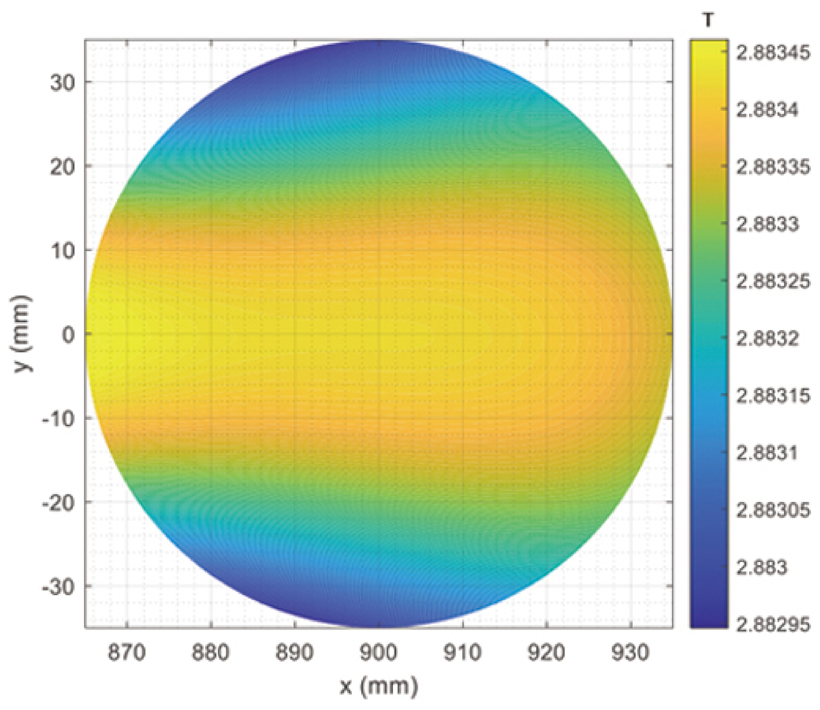

Fig. 4.4 Magnetic field distribution in the circumferential section(r≤35mm)

After reducing the harmonics, the transverse field uniformity and the integral field uniformity of the magnet are improved, as shown in Figures 4.5 and 4.6, which are in the range of ±1e-3 and meet the design requirements. After calculation, the polar plane deflection Angle is 4 degrees.

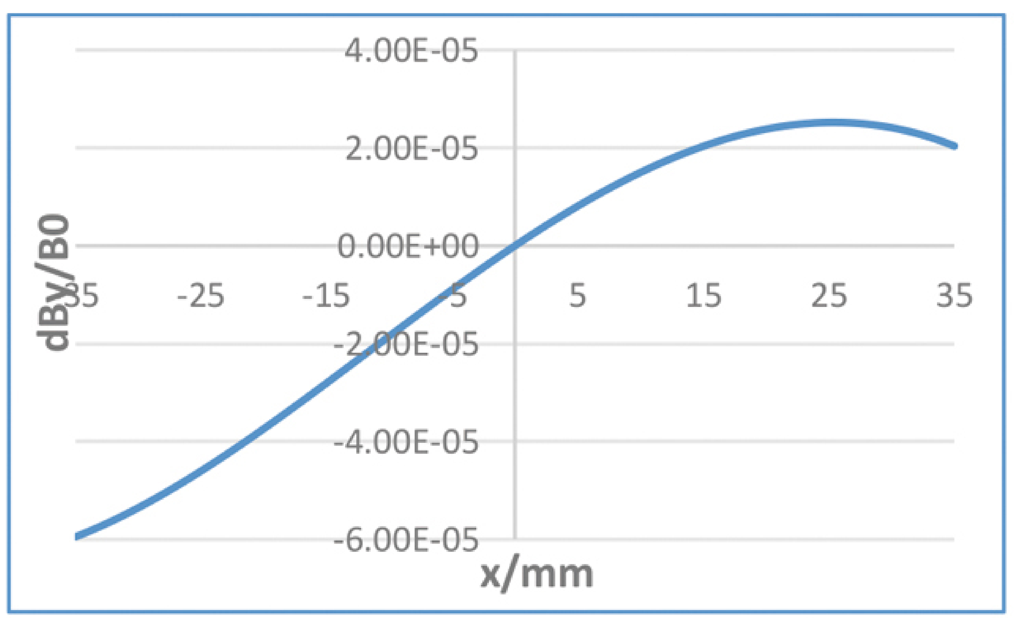

Fig 4.5 Transverse field uniformity (r=±35mm，y=0，z=0)

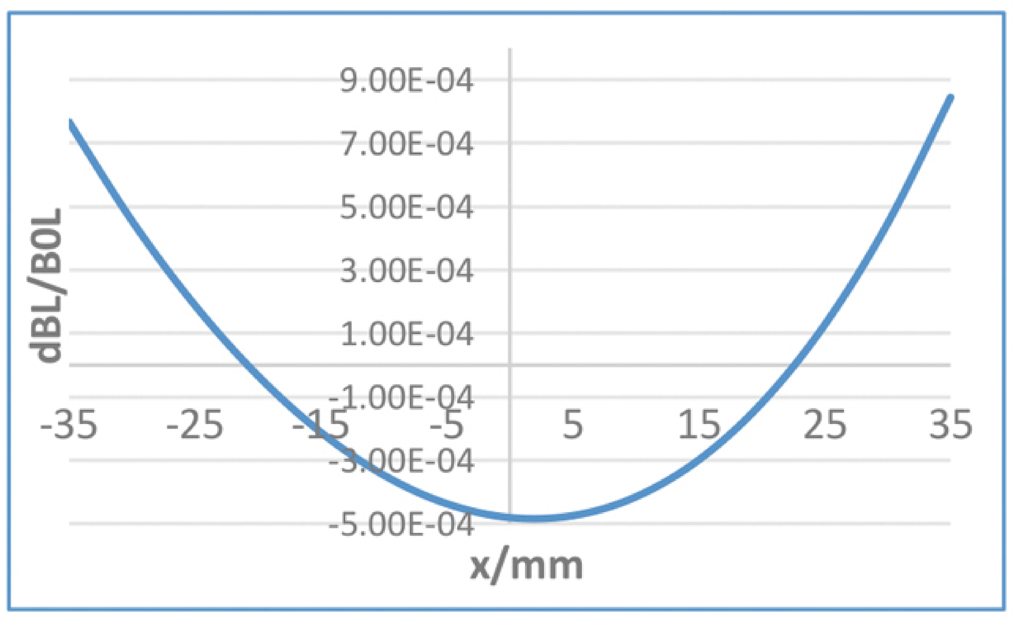

Fig 4.6 Integral field uniformity (r≤±35mm，y=0)