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SUPERCONDUCTING DIPOLE DESIGN FOR A PROTON COMPUTED TOMOGRAPHY GANTRY

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Abstract

Proton computed tomography aims to increase the accuracy of proton treatment planning by directly measuring proton stopping power. This imaging technique requires a proton beam of 330 MeV incident kinetic energy for adult patients. Employing superconducting technology in the beam delivery system allows it to be of comparable size to a conventional proton therapy gantry. A superconducting bending magnet design for a proton computed tomography gantry is proposed in this paper. The 30 deg, 3.9 T canted-cosine-theta dipole wound with NbTi wires is used to steer 330 MeV protons in an isocentric beam delivery system which rotates around the patient. Two methods of magnetic field shielding are compared in the context of proton therapy facility requirements; traditional passive shielding with an iron yoke placed around the magnet and an active shielding option utilising extra layers of the superconducting coil.

INTRODUCTION

The main goal of employing superconductivity (SC) in particle therapy gantry design is the reduction of overall size and mass. In carbon-ion systems where the beam rigidity to be transported can be as much as 6.6 Tm, significant reductions in size and mass are obtained from using SC magnets; however for proton therapy up to 250 MeV (around 2.4 Tm) the gantry size reduction is limited by such things as maintaining a minimum nozzle length, so that SC magnets have limited benefits. Gantries capable of transporting protons up to 350 MeV for computed tomography (2.9 Tm) may benefit from SC fields, and we show here a design of such a gantry suitable for retrofitting to a 250 MeV normal-conducting treatment room. Several groups have developed realistic designs of dipoles with sufficient aperture for beam scanning at fields above 3 T. Our present design examines the use of canted-cosine-theta (CCT) dipoles to be used in a for a proton computed tomography gantry [1]; an NbTi-based CCT dipole delivering up to 4.6 T bore field was tested at LBNL [2] and a Toshiba-manufactured superconducting gantry for carbon ion therapy has been in operation at NIRS since 2017 using 2.8 T dipoles [3].

CANTED COSINE THETA

A canted-cosine-theta magnet consists of a pair of concentric, nested conductor coils oppositely skewed such that the solenoidal field is cancelled and the transverse field components sum. In recent years several groups have shown interest in this concept; such magnets have been designed for such applications as ion therapy [4, 5] and high energy physics [6]. CCT magnets offer good field quality suppression of the higher harmonics, and may be constructed to deliver dipole, quadrupole and higher-order fields by superposition of appropriately-wound coils. As each conductor is located in a separate channel, the Lorentz forces are intercepted by the ribs and the spar. Because the forces are not accumulated, little or no pre-stress is required. In our downstream-scanning gantry optics design [1] we have determined dipole requirements as given in Table 1.

Table 1: Superconducting Dipole Requirements for 350 MeV Gantry (with spot scanning downstream of the final dipole [1])

Parameter	Value
Magnetic length	0.52 m
Bending angle	30 deg
Integrated field	1.46 Tm
Clear bore radius	33 mm

The obtained efficiency of a CCT magnet is limited because of the non-zero rib thickness at the midplane [4] and as a result of the cancelling solenoidal components. Although more conductor is required for a CCT when compared with a conventional magnet of the same field, the overall cost is approximately 20% less expensive [7] due to much lower total number of components required [2].

CCT magnets conventionally employ an iron yoke that provides good passive shielding; however, active shielding might also be used. An actively-shielded magnet replaces the iron yoke with additional CCT dipole windings surrounding the main coils, but with opposite polarity to the main coils to cancel the stray fields. Removing the iron yoke eliminates its contribution to the magnet mass, particularly the cold mass if a cold yoke is used. An active-shielded magnet may also be more reliably modelled as the fields are only determined by the Biot-Savart contributions.

CCT DIPOLE DESIGN

General Assumptions

In this work a NbTi strand was assumed of 0.825 mm diameter and non-Cu/Cu ratio of 0.51; the operating current and number of strands were chosen such that the operating point of the magnet stay below 80% of the superconductor load line. The skew angle of the main coils was optimised for the required total length of the magnet. The chosen midplane rib thickness was the minimum value possible to withstand forces created in the strand winding process. In the

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active-shielded case, the tilt angle of the shielding coils was optimised using Field 1.9.1 code developed at CERN, which is based on Biot-Savart calculations (see Table 2). Magnetic fields in both cases (passive and active) were modelled using Opera-3D version 19 [8].

Table 2: CCT Dipole Parameters Common for both Passive and Active Designs

Parameter	Value
Tilt angle of the main coil	31.8 deg
Min. midplane rib thickness	0.3 mm
Strand diameter	0.825 mm

Passive Shielding Design

A conventional design of a double-layer CCT dipole with iron yoke is presented in Fig. 1 and its basic properties in Table 3. The field quality in the good field region is better than 10^{-4}. The superconductor operating point at 4.5 K is 64% makes it a robust magnet and therefore likely safe to operate in clinical use. The maximum bore field in the dipole is 3.9 T (Fig. 2); the iron yoke enhances the central field by approximately 0.8 T whilst shielding the stray flux. Stray fields of 0.5 mT extend up to 0.45 m in longitudinal direction (see Fig. 3).

Table 3: Design Parameters of the Passively-shielded CCT Dipole Case

Parameter	Value
Engineering current	268 A
Peak field in the conductor	4.2 T
Number of strands	8x2
Inner radius of the yoke	74 mm
Approximate yoke weight	270 kg
Total length of the SC strand	1.14 km

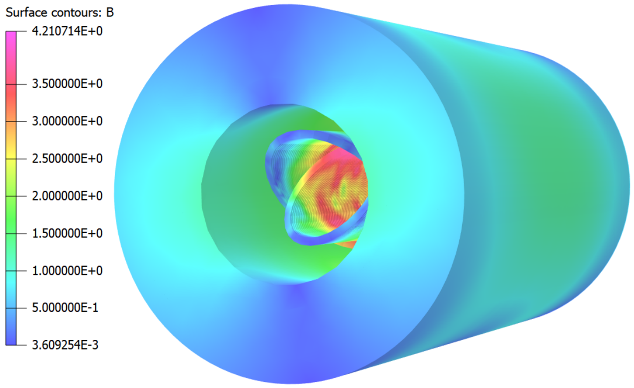

Figure 1: Layout of CCT double-layer (passive) dipole with iron yoke, modelled in OPERA; magnetic flux in Tesla.

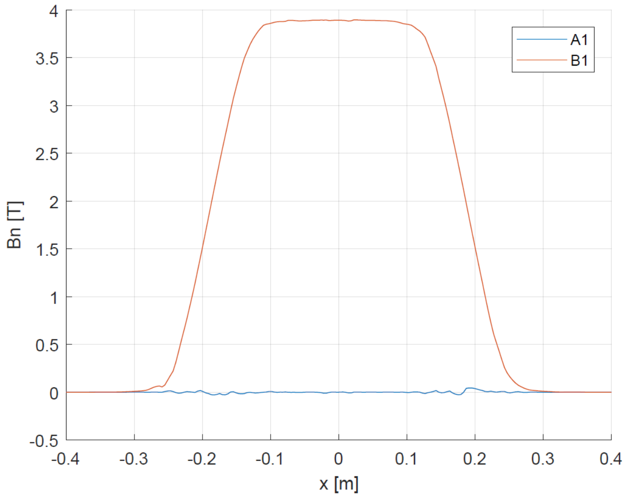

Figure 2: Dipole (normal $B1$ and skew $A1$) field components along the passive magnet design, modelled in OPERA.

Active Shielding Design

In the actively-shielded case, the yoke is removed and replaced with additional cancellation coils; this solution is found to require more than 2.5 times more superconducting wire. Parameters are shown in Table 4. To perform acceptable field cancellation we find that the outer coils must be located at a large radius (Fig. 4), thereby requiring a relatively-large cryostat. Using an active shield winding consisting of one superconducting strand in each layer, we find that the field cancellation is not as good as can be achieved in the passive case; the 0.5 mT isosurface extends more than 1 m from the magnet centre, which is clearly not acceptable.

Table 4: Design Parameters of the Actively-shielded CCT Dipole Case

Parameter	Value
Engineering current	283 A
Peak field in the conductor	5.0 T
Number of strands	11x2
Tilt angle of the shielding coil	62.17 deg
Inner radius of the shielding coil	220 mm
Total length of the SC strand	2.74 m

DISCUSSION

We find that a conventional passively-shielded design offers better reduction of the stray field than an actively-shielded design of a 3.9 T dipole. Whilst the yoke weight of the passive design is obviously larger it may sit outside the cryostat and therefore allow a relatively small cold volume. In contrast, the rather large diameter of the outer coils in the active case would require a much larger cryostat, increasing the cold volume and thereby possibly also cancelling out the weight advantage compared to the passive design. Overall, it

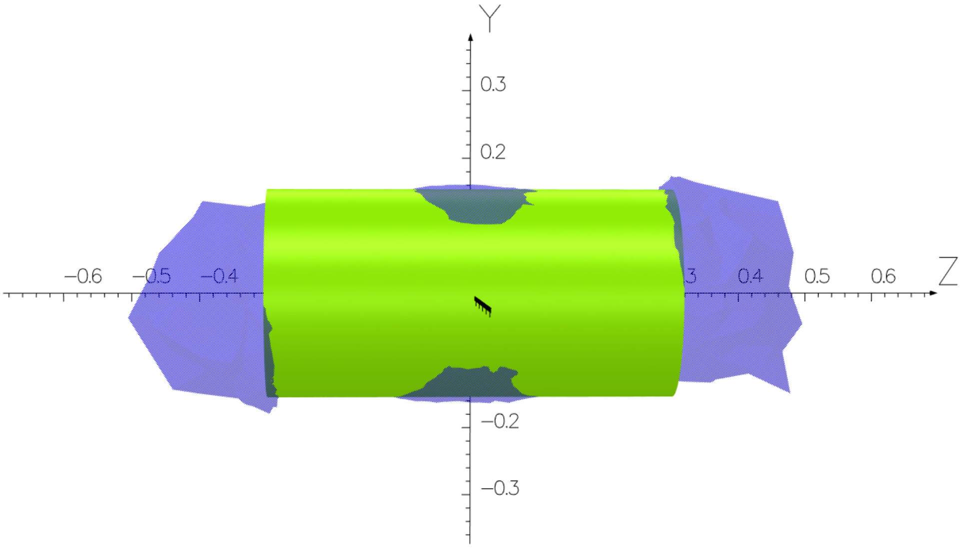

Figure 3: Stray fields (blue) extending beyond the iron yoke (green): 0.5 mT iso-valued surface (modelled in OPERA). The fields extend an acceptably-small distance from the magnet (much less than 5 Gauss at a distance of 1 m). Axes scale shown in meters.

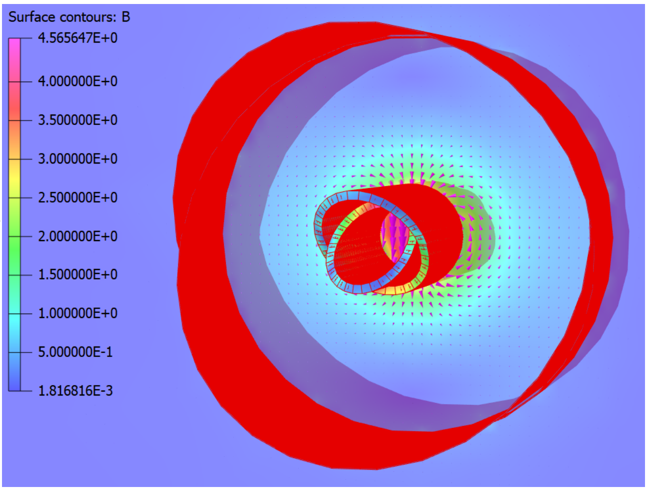

Figure 4: Layout and field strength in the actively-shielded magnet option, modelled in OPERA; the shielding coil lies around 220 mm from the central beam axis; field strength is indicated by colour in Tesla.

appears the use of extra coils for shielding purposes is more complex and less efficient than just using a yoke. However, one could further examine the active shielding coil to try to improve its efficiency, for example by utilising more complex winding geometries. If the cold mass is not such a factor, it might also be possible to utilise a hybrid solution where a thinner yoke is used outside the outer active coils to suppress the remainder of the stray field.

Because of its simplicity and likely lower cost, we have chosen the passive shielding option for use in our proton CT gantry design. The total cold mass and dimensions of the cryostat are significantly smaller in the passive shielding case, particularly if warm yoke is considered. More detailed cryogenics solutions, forces and thermal analysis for this bending magnet are the next steps to be undertaken.

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