PROGRESS IN THE DESIGN OF A CURVED SUPERCONDUCTING DIPOLE FOR A THERAPY GANTRY*

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Abstract

A compact curved superconducting magnet for a proton gantry requires a large bore and a high magnetic field. In this paper we report on a combined function 3.5 T superconducting dipole magnet for a proton gantry. The coil is curved 90 degrees at a radius of 634mm and places two layers around 130mm bore of oppositely wound and skewed solenoids (scanted) that are energized in a way that nulls the solenoid field and doubles the dipole field. Furthermore, the combined architecture of the windings can create a selection of field terms that are off the near-pure dipole field. In this paper we report on the design of a two layers curved coil and the production of the winding mandrel. Some details on the magnet assembly are included.

INTRODUCTION

Ion beam cancer therapy is the use of ion beams to treat cancer tumours. Larger accelerators and rotatable gantries are needed to direct the beam towards a patient at any arbitrary angle without having to tilt the patient [1-3]. Using magnets to direct and focus the beam have dominated the size and weight of such gantries for both proton and carbon gantries.

Studies have shown that high-field superconducting magnets can be used to reduce the over-all size and weight of proton and carbon gantries and suggested that using canted coils, especially for curved magnet, offer an advantage [4]. Although our initial interest has focused on magnets for a carbon beams, as a first step we have scaled down the magnet size closer to that suitable for proton beams. In this paper we describe a design of a curved superconducting dipole magnet with a nominal field of 3.5T that is also a combined function.

A COMBINED FUNCTION CANTED MAGNET

A Large Aperture Final Bend

A combined function dipole field, with additional quadrupole and sextupole terms is needed to focus and bend the beam around a curve. Scaling down the magnet closer to ½ the size needed for carbon [5-6], reduces the bore, field and bending radius to 130mm, 3.5T and 634mm respectively and puts this magnet closer to that of a proton gantry magnet. The conceptual design remains the same; two solenoid-like windings that are oppositely canted (tilted) with respect to the torus bore axis with a combined current density on the surface that generates a cosine-theta like dipole and additional combined terms that focus and keep the beam parallel [7-13]. The desired field and its quality can be achieved by optimizing the winding position while undesired end-harmonics naturally tend to integrate to zero.

The overall design approach strongly depends on the winding path and conductor size. We have selected to use an Aluminum mandrel with machined slots to guide and retain a NbTi Rutherford cable. Our plan is to use E2 glass fibers to insulate the cable and impregnate the coil. Two such layers will nest to complete the magnet coils. Mechanical support will be provided by two none-magnetic pads placed between the coils and an iron yoke and surrounded by an Aluminum shell. Insertion of loading keys between the pads and yoke locks the coils and insures they pre-compressed unable to move under Lorentz forces [14].

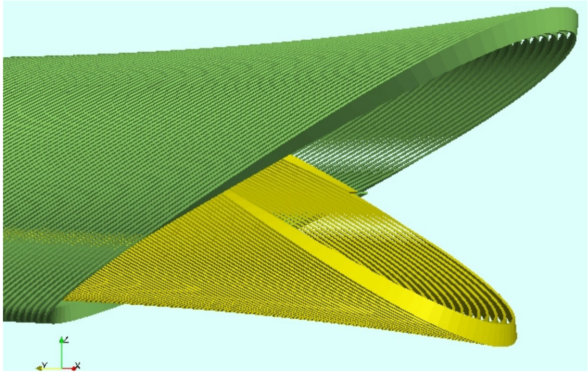

Figure 1: Two nested tilted coils wound onto a torus can generate a desired combined function field.

WINDINGS

Rutherford cables made of twisted superconducting strands are typically used in superconducting accelerator magnets in part thanks to their flexibility when bent the "hard" way, because their size is easily adjustable by tuning the number of strands, and because they are usually readily available from industry. Placing and guiding the cable around a bore requires predetermine passages that are typically channels or grooves. Here, fitting and winding a cable into channels was first studied with a 23 strand wide cable and subsequently followed with a smaller 8 strand cable. Both cables were tried with channels that were made from parts made on a Rapid-

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Prototype (RP) machine. That process was proven to be less time consuming and more cost effective

A 23 Strand Cable

We placed an insulated 23 strand cable into RP channels of 1.68x10.2 mm. The channel size was tilted 49 degrees (with respect to a normal) to reduce the hard-way bend and maintain the winding close to a "constant perimeter". Although with some effort the winding could be pushed into the channels, cable swelling and deformation would have required an even wider channels (beyond the present generous tolerance), further reducing the compactness of the windings. It was therefore decided to try a 8 strand cable with a smaller strand diameter.

An 8 Strand Cable

The width of RP channel size was increased to 12.09mm in order to accommodate 4 small size cables wound on top of each other inside the channel. Winding and stacking a small size cable into the channels was proven to be easier despite the fact that the channels were not tilted anymore and no consideration was given to "constant perimeter" winding.

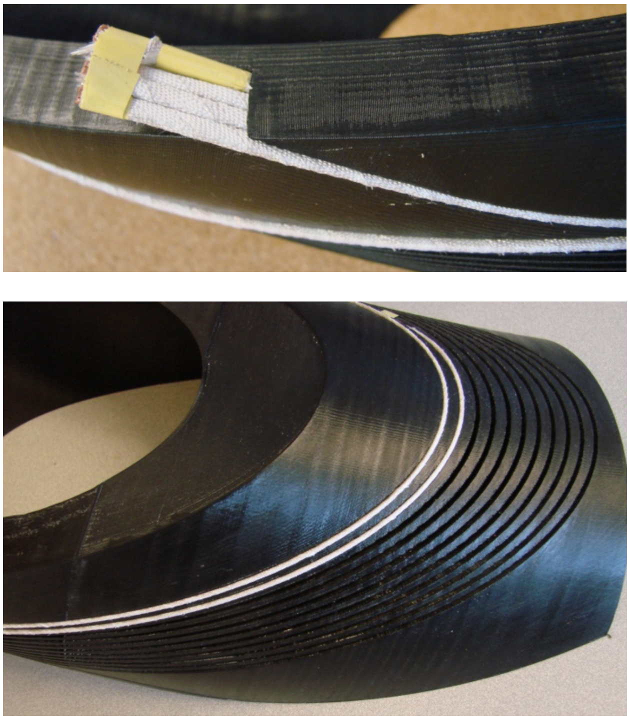

Figure 2: Four turns of a small 8 strand cable are wound into a single RP channel (top) and windings around the torus inner layer (bottom).

Table 1: Magnet Geometry

Torus curvature radius	mm	634
Clear bore diameter	mm	130
Layer 1 inner diameter	mm	140
Layer 2 outer diameter	mm	198.77
Bare cable width	mm	2.723
Bare cable thickness	mm	1.072
Cable insulation thickness	mm	0.150
Iron inner diameter	mm	290
Iron outer diameter	mm	590
Aluminium shell thickness	mm	10

MAGNET AND FIELD

A magnetic analysis was done using Biot-Savart (no-iron) and the Tosca program for calculations that included real iron (Fig. 3). Both models used a large number of elements for the coils and long run-times, up to a week, were required for the analysis.

Tables 1 and 2 summarize the geometry and calculated results. According to the load line (Fig. 4) the magnet central field will reach 3.5T at 1320A having a 67% margin. At 3.3T the central dipole field on the mid-plane has a gradient of -3.17T/m and a sextupole of 1.84 T/m^2. Figure 4 is a plot of the dipole field in the bore for a case without iron.

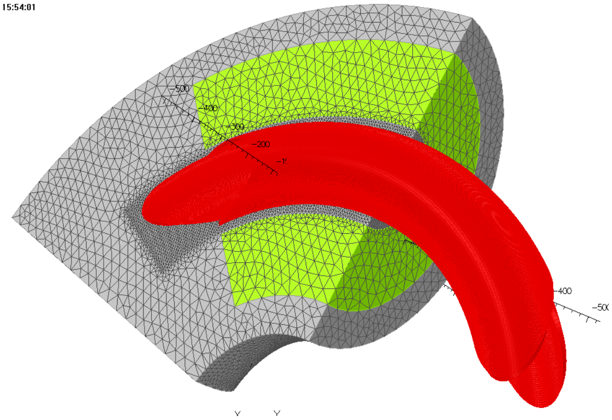

Figure 3: TOSCA model showing coils yoke and mesh.

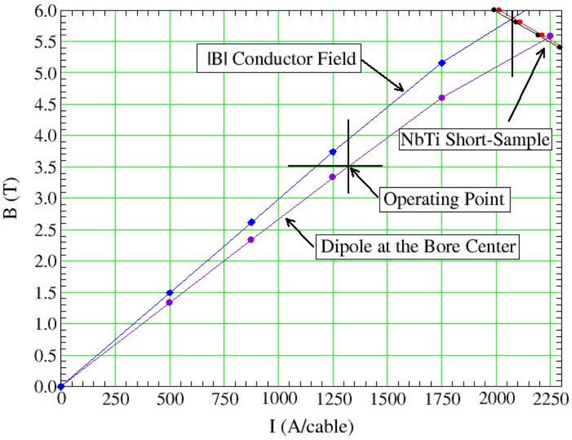

Figure 4: Load lines of the central and conductor field.

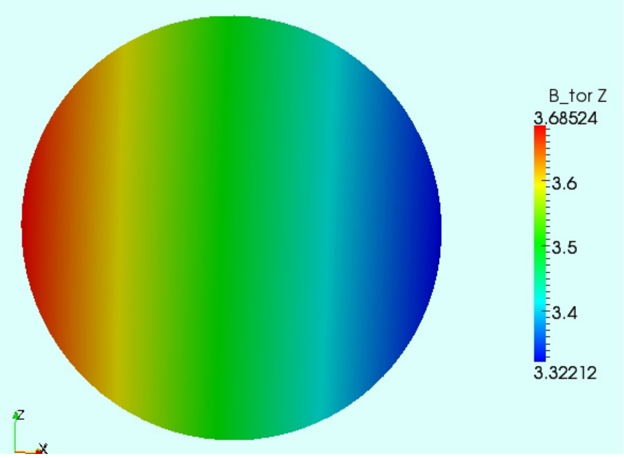

Figure 5: Dipole and gradient across the bore (no surrounding iron).

Table 2: Magnetic Parameters

Strand diameter	mm	0.648
Strand type and Cu:Sc ratio	SSC outer	1.8:1
Number of strands per cable	#	8
Central dipole field\current at target	T\A	3.5\1320
Central dipole field\current at SS	T\A	5.25\2076
Conductor field\current at SS	T\A	5.86\2076
Margin at target	%	67
Stored energy at target	kJ	134
Stored energy at SS	kJ	300
Coil tangential stress at SS	MPa	-77
Coil tangential stress at target	MPa	-31
Aluminium shell stress at SS	MPa	220

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