Nb_3Sn MAGNETS FOR A MUON COLLIDER*

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Abstract

High field dipole and quadrupole magnet designs with racetrack coils are investigated. The design option is particularly attractive for a muon collider dipole magnet using the Nb_3Sn superconductor. A conceptual design of ~ 15 T single aperture dipole magnet is presented where the coils maintain a simple 2-d structure through the ends. The use of racetrack coils in quadrupole magnets is also discussed. It appears that the racetrack coils are less attractive for high gradient quadrupole magnets.

1 INTRODUCTION

The proposed muon collider [1] will use a number of superconducting dipole and quadrupole magnets. The magnet designs of ~9 T using either NbTi or Nb_3Sn in a cosine theta geometry have been presented earlier [2]. However, higher field magnets offer a significant improvement in the luminosity performance [2]. Nb_3Sn is the only commercially available conductor today that can generate fields well over 10 tesla in accelerator magnets. It also provides a high temperature margin over the operating field. Experiments at the Lawrence Berkeley National Laboratory (LBNL) in the 13.5 T, D20 magnet [3] have shown that the epoxy impregnated coils built with Nb_3Sn material are quite tolerant to heating. The magnet did not quench at 12 T when subjected to a 20 W heat load. Being brittle in nature and being sensitive to bending and other stresses, Nb_3Sn presents a number of engineering challenges. These problems are partly overcome in the proposed "conductor friendly" dipole design with all flat racetrack coils with straight ends. The design and program fits well with the racetrack coil base program [4] underway at the LBNL.

2 HIGH FIELD DIPOLE DESIGN

The concept and a cross-section of the proposed dipole magnet are shown in Fig. 1. In this design, the stress levels in the conductor are reduced by the use of rectangular coil block geometry and keeping the coils flat reduces the end support problems. In the more conventional "cosine theta" designs, the conductors are distributed around a cylinder and the azimuthal forces in the body of the magnet add up towards the mid-plane. Moreover, the end turns, as they arc over the cylinder while bending and stretching, are relatively hard to support.

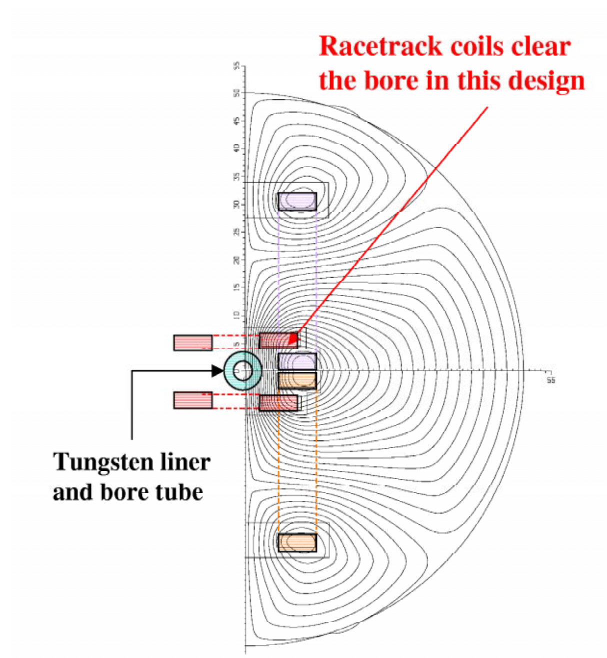

Figure 1: The cross section, field lines and the design concept of the proposed high field Nb3Sn design for muon collider.

As shown in Fig. 1, each quadrant of the magnet aperture has two blocks of conductors. The block at the pole, the pole block, in the first quadrant has a return block in the second quadrant, as that in a conventional design. The vertical position of this block (height) is such that it completely clears the bore. In a conventional design, the second block, the midplane block, would also have a return block in second quadrant. That would, however, require it to be lifted up in the ends to clear the bore and thus would lose the simple 2-D coil geometry. In the proposed design, the return block retains the 2-D coil geometry as it is returned on the same side (see Fig. 1) and naturally clears the bore. Due to a large bend radius in the ends, the "react and wind" technology may be used here. Some basic parameters and the expected performance of this design are given in table 1. The computed short sample value does not include the

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degradation in cable performance due to stresses. Each block is graded horizontally in two equal sizes to obtain a higher value of bore field at quench.

Table 1: Basic design parameters and the expected performance of the proposed high field Nb_3Sn dipole.

Total number of blocks in magnet	6
Total number of blocks in each quadrant of aperture (+ in yoke)	2 (+1)
Vertical location of the midplane block (from the coil midplane)	5 mm
Vertical location of the pole block (from the coil midplane)	45 mm
Block dimensions	25 mm X 70 mm (graded in 2 parts)
Size of each graded block	25 mm X 35 mm
Expected short sample	14.7 T (at 4.2 K)
Peak fields on conductors	16 T and 12.5 T
Overall current densities (at peak fields)	370 A/mm^2 and 600 A/mm^2
Max. current density in copper	1500 A/mm^2
Field harmonics at 10 mm	10^{-5} or less, all terms
Yoke outer radius	500 mm

Since the return turns of midplane block do not contribute to field, this design uses 50% more conductors than the conventional block design. Moreover, since the block designs in general use more conductor volume than the conventional cosine theta magnets, the total penalty may be about a factor of two. However, savings come from the simplicity of coil geometry and magnet construction. A cost penalty (as compared to cosine θ designs) may be acceptable for these magnets where the performance, not the cost, is the major issue.

3 HIGH GRADIENT QUADRUPOLES

The racetrack (or block) coil geometry is also investigated here for high gradient quadrupoles. Three types of designs have been examined. From these investigations and based on the explanations given below, it appears that such designs are not efficient for generating a high gradient in large aperture quadrupoles. The efficiency is defined here as the gradient in the useful aperture compared to the maximum field (peak field) on the conductor, rather than the quantity of conductor used. This determines the ultimate gradient performance of the magnet rather than the cost of it. The situation is different for quadrupoles made with high temperature superconductors where the critical current density (J_c) does not fall significantly with the field.

The first model (see Fig. 2) is similar to the one investigated by Morgan [5]. Morgan also included iron at the pole. Although the model has four fold symmetry, the coils do not. To fill the space at the midplane with rectangular cables, the racetrack coils in two opposite quadrants must be bigger than the other two by a cable width. All coils are flat. The distance of coil inner side from the magnet center (equivalent to aperture) varies with angle. It is minimum at the pole (45^o) and maximum at the midplane. This makes the field on the conductor drop rapidly in going from the pole turn to the midplane turn. This generates a situation (unless the coil is graded within itself) where the conductors at midplane have much larger margin and their current carrying capacity not fully utilized. Moreover, the conductors at the midplane are also those that contribute most to the field gradient. This implies that this is not an efficient geometry for generating the maximum gradient in a high gradient quadrupoles. The extra space at midplane may be, however, used for shielding.

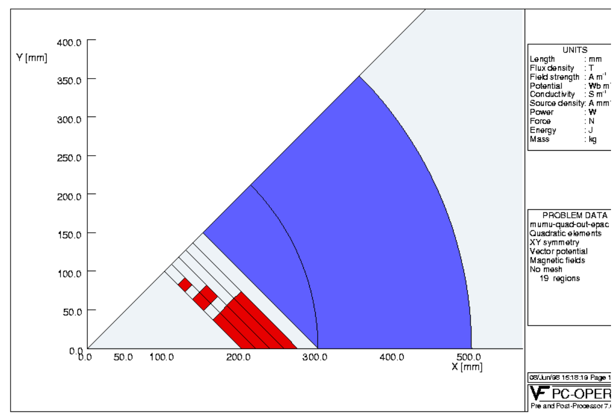

Figure 2: An octant of a quadrupole in model No. 1. This uses all flat racetrack coils through the ends.

The situation is better in the geometry proposed here (model No. 2, Fig. 3). In this geometry the coils with smaller pole angles make inner layers rather than outer. This is opposite to the conventional geometry including the one shown in Fig. 2. This allows conductors at the midplane come closer to center and hence contribute more to the field gradient. However, since the pole of all layers is at the same radius, the peak field is also similar in all layers. This means that the usual grading of conductors between different layers due to different peak fields cannot be utilized to increase the field gradient. Moreover, the conductors in the inner layers must be lifted up at the ends to clear the bore.

The third model (see Fig. 4) cannot be made with racetrack coils since the conductors on the two sides of the coils are at an angle. However, in the body of the magnet, it is still a block geometry design with the conductors in the ends bending over as in a conventional cosine theta magnet. This design also suffers from the same disadvantage (of case 1) that the ratio of the field between the conductors at the pole block and the conductors in the midplane block is large and unfavorable.

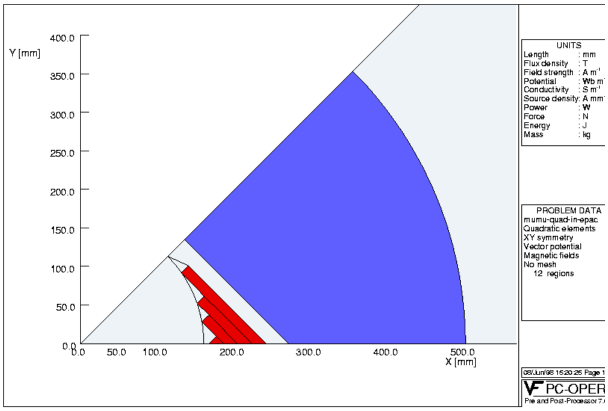

Figure 3: An octant of a quadrupole in model No. 2. The inner layers have smaller pole angle that brings turns at the midplane closer to the center and makes design more efficient.

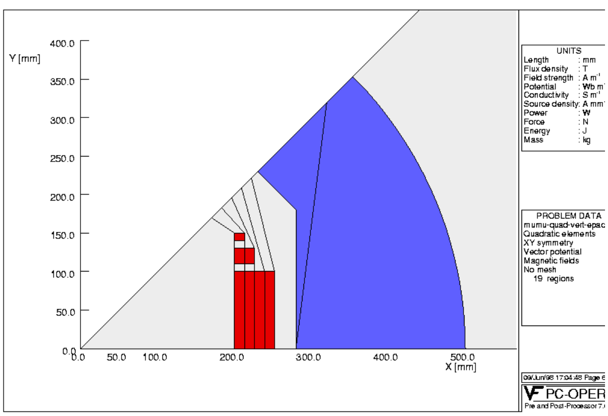

Figure 4: An octant of a quadrupole in model No. 3. This shows the conventional block design where the conductors must bend over the ends.

4 LBNL RACETRACK COIL PROGRAM

LBNL is developing a 2-in-1 common coil design [6] for high field Nb_3Sn dipole magnets [4]. The coil geometry of that design is similar to the geometry of pole block in the muon collider single aperture dipole (compare Fig. 1 and 5). This offers a unique low additional cost magnet R&D opportunity for the muon collider. As proposed in Fig. 5, in the first phase only the coils have to be powered differently to make the pole block geometry. To make the midplane block geometry, the vertical separation between the coils may be reduced in the next phase. This will also increase the bore field. It is noted that the actual coil in the proposed design (Fig. 1) has larger horizontal separation (aperture). This lower separation will generate a higher field if these coils are put together with the pole block coils. However, without the pole blocks, the midplane block configuration by itself will generate a field that is in between the pole block configuration and complete magnet configuration.

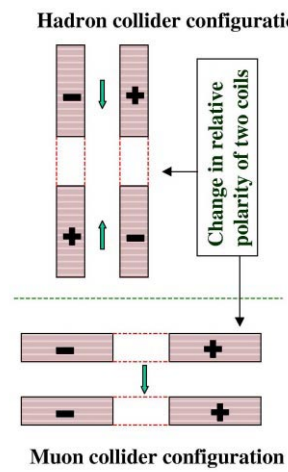

Figure 5: A change in relative polarity of two coils changes the 2-in-1 common coil dipole configuration to single aperture muon collider dipole configuration.

The two configurations discussed here are variations in the coil packaging of the magnet under construction at LBNL. Although, by themselves they do not constitute a complete magnet, nevertheless these tests address the critical technical issues of the proposed design and high field Nb_3Sn magnet technology, in general. These include high stresses in the coils, the mechanical support structure and other magnet design, engineering and construction issues. These designs are also amenable to stress management/reduction strategies, if required. In the third phase, one could build the complete dipole magnet with all six blocks of coils with a proper geometry.

5 CONCLUSIONS

A conceptual design of a high field (~15 T) Nb_3Sn magnet is presented which will allow a significant improvement in the luminosity performance of the proposed muon collider. The LBNL racetrack coil program offers an attractive path to achieving this goal.

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