HIGH FIELD SUPERCONDUCTOR FOR MUON COOLING*

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Abstract

High temperature superconductors (HTS) have been shown to carry significant current density in the presence of extremely high magnetic fields when operated at low temperature. The successful design of magnets needed for high energy physics applications using such high field superconductor depends critically on the detailed wire or tape parameters which are still under development and not yet well defined. In the project reported here, we are developing HTS for accelerator use by concentrating on the design of an innovative magnet that will have a useful role in muon beam cooling. Measurements of available materials and a conceptual design of a high field solenoid using YBCO superconductor are being analyzed with the goal of providing useful guidance to superconductor manufacturers for materials well suited to accelerator applications.

INTRODUCTION

Extremely high field magnets will play important roles in future high-energy accelerators. In our example of choice, an energy-frontier muon collider, high field solenoid magnets will be used to reduce size of the muon beam phase-space. The superconductor used in today's highest field superconducting magnets, Nb_3Sn, is limited to a maximum magnetic field of around 24 T. Thus to create superconducting magnets that generate magnetic fields of 25 T and above, HTS will be required. In addition to having very high critical temperatures, HTS materials have very high values H_{c2}, the critical field beyond which the superconductor becomes normal conducting. High critical current densities at 4.2ºK in magnetic fields as high as 45 T have been reported. These measurements were limited by the available magnetic field, not by the HTS material itself.

This paper will examine the design of a 45 T solenoid magnet using HTS conductor that is currently commercially available. This magnet would have an application for the final stages of a muon cooling channel where the magnetic aperture would contain a vessel filled with liquid H_2 to act as an absorber for the beam cooling process [1]. The extremely high field is required to produce an extremely small transverse emittance, which is inversely proportional to the magnetic field. A major design consideration of such a high field magnet is how to contain the large Lorentz force associated to the high field. The successful design of high field magnets for high energy physics applications using HTS depend critically on the wire or tape parameters which are still under development and well defined.

MAGNET DESCRIPTION

The choice of the physical dimensions of the solenoid is determined by the muon cooling requirements. The magnet is 1 m long, which provides a reasonably uniform field over the 70 cm long liquid hydrogen absorber vessel needed for the muon cooling. The inner radius of the solenoid is determined by the minimum bending radius of the HTS conductor, but allows for the radial size of the vessel, radiation shielding, and the necessary insulation.

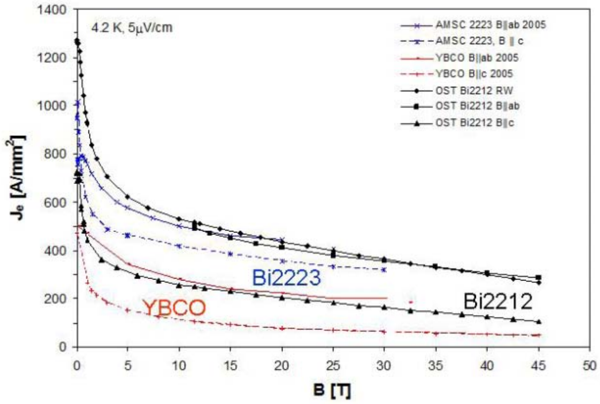

Figure 1: J_E for HTS conductors at 4.2ºK, circa 2005. Note that J_E for YBCO has since improved by a factor of 5 and Bi-2212 has improved by a factor of 2.

Conductor Choice

HTS conductor is chosen over Nb_3Sn or NbTi superconductor because it can carry significant current in the presence of high fields. For fields over 20 T only HTS conductors have significant current carrying capacity. In a preliminary study [2,3] we examined a conceptual picture of a high field solenoid for muon cooling using Bi-2223 HTS tape. Since then there has been a significant improvement in the J_E and tensile strength of the commercially available HTS conductors. Table 1 displays the properties AMSC Bi-2223 tape [4] along with the AMSC and SuperPower versions of YBCO conductor [5,6]. The table shows a significant improvement of the YBCO conductor over the Bi-2223 conductor. The table does not show the characteristics of the Bi-2212 HTS conductor. Bi-2212 is the only HTS conductor with high J_C that is available in an isotropic round wire, which we shall see is an important advantage. The mechanical tensile strain limit of the Bi-2212 conductor is not as high as the YBCO conductor. If the Bi-2212 conductor is wound on a radius as tight as 2.5 cm, the entire allowable strain limit would be exceeded by the bending strain. Under such conditions the Bi-2212 coils would have to be wound first and then reacted at 890ºC in pure oxygen, which poses significant challenges.

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Table 1: Specifications of selected high temperature superconducting wire available from vendor data sheets, J_E, is the engineering critical current density, which is the critical current divided by the entire conductor cross-section. These values are reported at 77ºK.

Parameter	AMSC High Strength Plus Tape	AMSC 344S	SuperPower 2G HTS
Chemistry	Bi-2223	YBCO	YBCO
J_E, amp/mm^2	133	136*	250
Thickness, mm	0.27	0.15	0.095
Width, mm	4.2	4.4	4.0
Max Tensile Strength, (77 K), MPa	250	250	1200
Max Tensile Strain (77 K)	0.4%	0.3%	0.45%
Min Bend Radius, mm	19	25	5.5
Max Length, m	400	100*	600
Spliceable	yes	yes	not stated

The YBCO tape is manufactured using a thin film deposition of YBCO conductor on a Hastelloy substrate surrounded by a Cu stabilizer. The YBCO conductors have significantly better mechanical properties than the Bi-2212 conductor primarily due to the strong Hastelloy substrate. Because the actual conductor is quite thin the bending stress on the conductor is minimized. The YBCO conductors can only be manufactured as thin tapes which have significant anisotropic response to field. This is particularly true at 4.2ºK as is shown in figure 1. This figure shows the engineering current density, J_E, for various HTS conductors. Although the YBCO has a very high critical current, its J_E is comparable to the other HTS conductors, since the conducting fraction is small.

Conceptual Design of a Magnet

We have examined how different HTS conductors could be used to make a high field solenoid. The magnet is a hybrid design with the outer magnet using Nb_3Sn conductor and supplying 15 T of the field. The insert part of the magnet uses HTS conductor. For the calculations in this paper the properties of the AMSC *high strength plus* tape shown in table 1 were used, however the YBCO conductor would be preferred. We have assumed that the magnet will be operating at 85% of its maximum critical current.

Constraining the large Lorentz forces is a major concern in the design of this magnet. In this study we propose to mitigate the build-up of Lorentz forces by interleaving stainless steel tape under tension between the layers of HTS tape. The interleaved stainless steel tape prevents the HTS tape from exceeding its maximum tensile strain. The conductor chosen has a maximum allowable strain of 0.4%, which is the strain at which the critical current is degraded by 5%. There is concern that some irreversible damage may occur to the superconductor at high strain by introducing some micro cracking into the material.

The thickness of the stainless steel interleaving is varied to give the maximum allowable strain at each turn to minimize the amount of superconductor required. This also minimizes the outer radius of the magnet, which reduces the amount of both Nb_3Sn and HTS superconductor required and the total stored energy of the system. The maximum allowable tensile strain includes both the component from the Lorentz hoop stress and that from the bending strain due to winding the HTS tape to a radius. Figure 2 shows the required thickness of stainless steel interleaving as a function of radius for a 50 T solenoid. The average current density varies as a function of radius because of the varying stainless steel thickness. To avoid spring-back during the winding of stainless steel layers thicker than 2 mils, it will be necessary to wind these as multiple layers. Table 2 lists the physical properties of the solenoid magnet described.

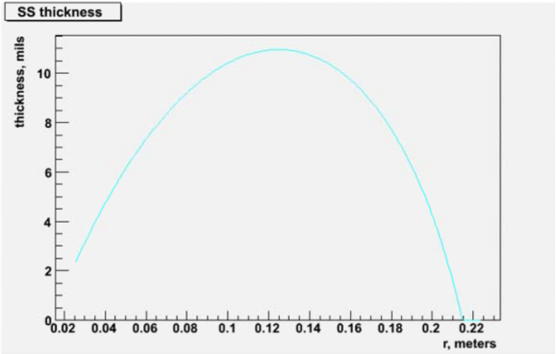

Figure 2: Thickness of stainless steel interleaving not to exceed the maximum allowable strain for a 50 T solenoid.

Table 2: Parameters Describing the Physical Properties of the Magnet

Parameter	Value
Length, m	1
Inner Radius, mm	25
Outer HTS Radius, mm	390
Total Outer Radius, mm	570
HTS Conductor Length, km	137
Current, mega-amp-turns	47.5

The magnet design includes the following features:

- Require that the sum of the bending and tensile strains remain below the conductors maximum strain
- Add 25 µm insulation to each tape to prevent large voltage drops between adjacent layers.
- Use Bi-2212 round cable in the end region where there is a significant radial component to the field.
- Separate the HTS insert into seven radial blocks with 1 cm gaps between the blocks. This will provide radial support for the build-up of radial stresses. This also allows room for support and cooling of the coils.
- Wind the outer part of the magnet with Nb_3Sn blocks. This would be wound as pancakes. The Nb_3Sn blocks extend axially beyond the end of the HTS insert to reduce the radial component of the field seen in the HTS end region.

These features increase the radius of the magnet. The HTS insert has an outer radius or 39 cm and the outer magnet has a radial extent of 57 cm.

MAGNETIC PROPERTIES

This magnet was modeled using the OPERA-2D finite element program [7]. Figure 3 shows a contour plot of the field in the coils. Also shown superimposed are the field direction lines through out the magnet. Table 3 shows the magnetic properties from the analysis. The table separates the stored energy between the HTS insert and the outer Nb_3Sn outer part of the magnet using $U = \pi\int r\, A\cdot J\, dS$. The HTS insert magnet provides 2/3 of the 45 T field seen in the aperture. This magnet has a considerable amount of stored energy. A quench protection system specific to the HTS magnet will be necessary to dissipate the energy safely in case of an incident. The quench protection of an HTS magnet is a serious challenge because the quench propagation velocity is significantly slower with HTS conductors.

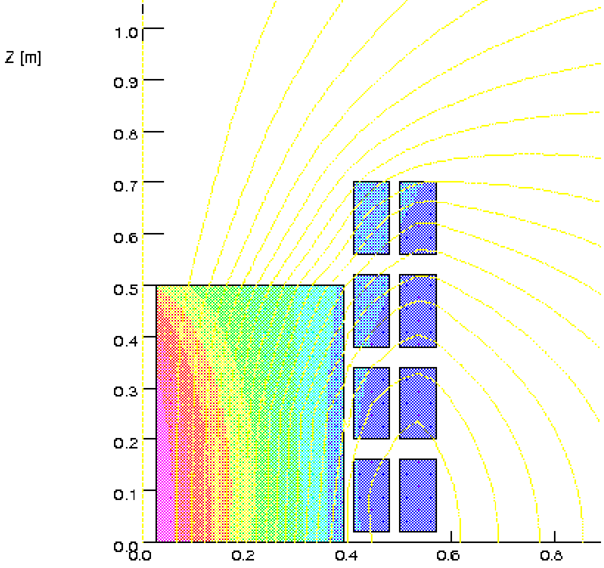

Figure 3: The contour plot shows the modulus of the field through the coils. The yellow lines illustrate the field direction.

Table 3: Parameters Describing the Magnetic Properties.

Parameter	Whole Magnet	HTS Magnet	Nb_3Sn Magnet
B_0, Tesla	45.9	30.0	15.9
$\int B\cdot dl$	59.7	32.0	26.7
Stored Energy, Mega-joule	182	57.7	124.6
Axial Force, Mega-newtons	-151	-42	-109
Total Radial Force, Mega-newtons	532	375	157

In addition to the large radial forces, which the design attempts to mitigate locally so that they do not accumulate, there are compressive axial forces present from the radial field components at the ends of the magnet. Figure 4 shows the axial force density along the magnet length for the radius where the force density is maximal. Also shown in figure 4 is the accumulated force obtained by integrating the force density, which is maximal at the center of the magnet. The compressive strain that the HTS tape can tolerate is less than 0.15%. It may be necessary to wind the end region of the magnet as separate pancakes with stainless steel support to prevent this compressive force from building up. This will be a design issue for this magnet.

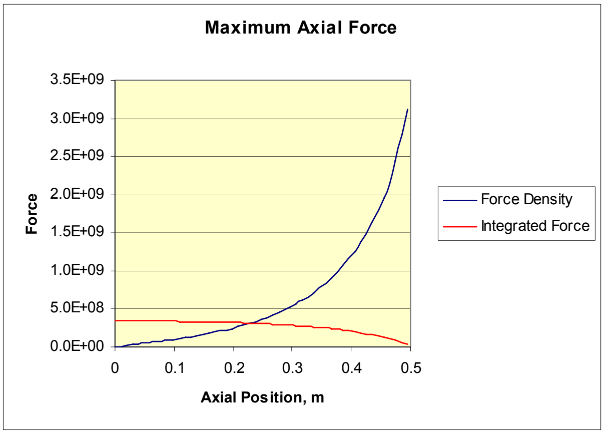

Figure 4: The blue curve shows the axial force density at the radius where the force density is maximal for this design. The units are nt/m^2. The red curve is the accumulated force density at the same radius. The units are nt/m.

CONCLUSIONS

Very high field solenoid magnets up to 50 T will have an important role in the final stages of cooling for a muon collider. In this paper, we present a conceptual picture for such a high field magnet using HTS conductor that is available commercially.

REFERENCES

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[4] American Superconductor specification sheet for Bi-2223 HTS tape, http://www.amsc.com/products/htswire/1gHSP.html

[5] American Superconductor specification sheet for YBCO 344S tape. http://www.amsc.com/products/htswire/344SS.html

[6] SuperPower 2G HTS wire specification sheet http://www.superpower-inc.com

[7] OPERA-2D is a finite-element suite of programs for electromagnetic design analysis. It is a product of Vector Fields, ltd.