YBCO CONDUCTOR TECHNOLOGY FOR HIGH FIELD MUON COOLING MAGNETS*

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Abstract

YBCO superconductors originally developed for high temperature operation carry significant current even in the presence of extremely high field when operated at low temperature. The final stage of phase space cooling for a muon collider uses a solenoid magnet with fields approaching 50 T. As part of an R&D effort we present measurements of mechanical and electromechanical properties of YBCO conductor. We describe a conceptual picture for a high field solenoid which incorporates the low temperature properties of YBCO conductor. We use critical current data as a function of magnetic field and field angle at 4.2°K to establish the operating current and design geometry to achieve 50 T.

INTRODUCTION

We describe an extremely high field solenoid that can be used to reduce the size of muon beam phase space for an energy frontier muon collider. A series of these magnets would have an application for the final stages of a muon cooling channel by providing a low beta region for a liquid H_2 absorber for the ionization cooling process. This series would contain solenoid magnets starting with 30 T and reaching 50 T at the end of the channel. As the transverse emittance is inversely proportional to the field, this extremely large magnetic field produces an extremely small transverse emittance.

Although we have chosen a 50 T solenoid as a goal, it is realized that there may be practical limits to achieving that field. There are several factors that affect the design of this magnet. These include the structural integrity of the magnet, the stored energy that would have to be removed in case of a quench and the modularity of the different parts in case it is necessary to replace or repair the magnet coils.

DESIGN CONFIGURATIONS

We have considered several approaches to the high field solenoid design which are illustrated in Figure 1. In the upper image the HTS conductor is wound into double pancakes without epoxy impregnation so that the conductor can slip slightly to accommodate differences in conductor strain within the pancake. Just enough epoxy is painted on the pancake face to hold it together during assembly. The two pancake halves are connected with a splice at the inner aperture of the coils. The pancake approach provides modularity to the magnet design since the pancakes are of the same design and can be replaced by a spare if necessary. The second approach segments the coils radially into cylindrical tubes as shown in the middle sketch. The radial variation of strain on the conductor would be limited in each conductor tube allowing the use of epoxy vacuum impregnation which would make the coils more structurally rigid. The lower sketch shows a variant of the radial cylinder scheme were the field is optimally shaped in the aperture. In all of these configurations the outer coils are wound with Nb_3Sn and NbTi conductor to produce 16 T.

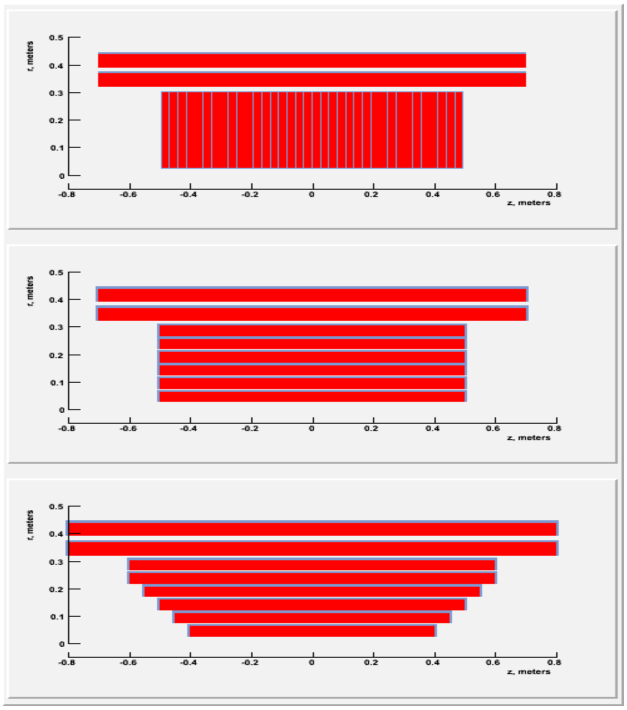

Figure 1: Possible configurations investigated for a high field solenoid design.

Table 1: Radial dimensions of solenoid magnet models for various fields.

Field	*HTS Inner Radius*	*HTS Outer Radius*	*Outsert Inner Radius*	*Outsert Outer Radius*
30 T	0.025 m	0.155 m	0.172 m	0.290 m
35 T	0.025 m	0.225 m	0.242 m	0.360 m
40 T	0.025 m	0.248 m	0.265 m	0.383 m
45 T	0.025 m	0.280 m	0.297 m	0.415 m
50 T	0.025 m	0.303 m	0.320 m	0.438 m

In this study magnets from 30 T to 50T were modelled. The radial dimensions of these models which are shown in Table 1 were obtained by keeping the field contributed

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by the outsert at 16 T and keeping the current density of the HTS coils constant. The length of the magnet was chosen to be 1 m long to provide a reasonably uniform field over the 70 cm long liquid H_2 absorber vessel needed for the muon cooling.

Selection of Conductor

HTS conductor is chosen for the inner part of the magnet because it has a significant current density in the presence of the large magnet fields, particularly above 20 T where conductors like Nb_3Sn are not viable. HTS conductor is commercially available from a number of vendors in reasonably large quantities which has stimulated this design study of a high field magnet that could be used for accelerator applications. We had previously examined a conceptual study of a similar solenoid using Bi-2223 conductor tape [1,2] which at the time was the lead HTS conductor in terms of commercial availability and knowledge of material properties. More recently YBCO conductors have shown significant improvement particularly in effective current density and mechanical strength which have made it an attractive alternative. The YBCO conductor is manufactured by depositing a thin 1 μm layer of the conductor onto a substrate of Hastelloy or stainless steel to provide mechanical strength which is needed to mitigate the large Lorentz stresses present in the magnet. Table 2 gives the specifications of YBCO conductors from several manufacturers' data sheets [3]. Other mechanical and electro- mechanical properties of these conductors are assembled from measurements [4,5,6] and are shown in Table 3. For the computations used in this paper we have used the parameters of the SuperPower SCS 4050 conductor.

Table 2: Nominal specifications of YBCO conductors.

Parameter	*SP SCS4050*	*AMSC 344C*	*Bruker*
Width	4 mm	4.4 mm	4 mm
Thickness	100 μm	200 μm	105 μm
Bend Radius	5.5 mm	12.5 mm	9 mm
Max Tensile Strain	0.45%	0.3%	NA
I_C	80 amp	90 amp	135 amp
J_E	200 amp/mm^2	102 amp/mm^2	320 amp/mm^2

Table 3: Mechanical and electro-mechanical properties of YBCO conductors measured at 77° K.

Parameter	*SP SCS4050*	*AMSC 344C*
Tensile Modulus, GPa	147	98
$\varepsilon_{95\%}$	0.45%	0.4%
ε_{irr}	0.7%	0.49%

Conductor Critical Current

Figure 2 shows the critical current as a function of field measured at 4.2°K for HTS conductors [7] oriented parallel and perpendicular to the field direction. The figure shows a significant reduction in current capacity for the YBCO conductor oriented perpendicular to the magnetic field when compared to the same conductor oriented parallel to the field. For the 50 T solenoid 32% of the HTS insert has a field angle greater than 10° from the conductor plane with a maximum field angle of 28.3° in the magnet end region. Figure 3 shows measurements of the angular dependence of the critical current density for YBCO conductor [8]. These measurements were parameterized with the following form for each value of the field:

$$J_C = J_C^{\perp} + (J_C^{\parallel} - J_C^{\perp})\exp\left(-\frac{|\theta|}{\theta_C}\right)$$

This formula has one free parameter, θ_C, which is determined by fitting the expression to the data for each field value. Figure 4 shows the critical current density for a 50 T solenoid as a function of the position in the HTS coils. If 1 mil stainless steel tape is used as insulation between conductor layers with epoxy to fill voids we would require 200 A/mm^2 to produce the desired field. Using a 70% operation factor the conductor will need to carry 286 A/mm^2. Figure 4 shows that this is satisfied through out the coils.

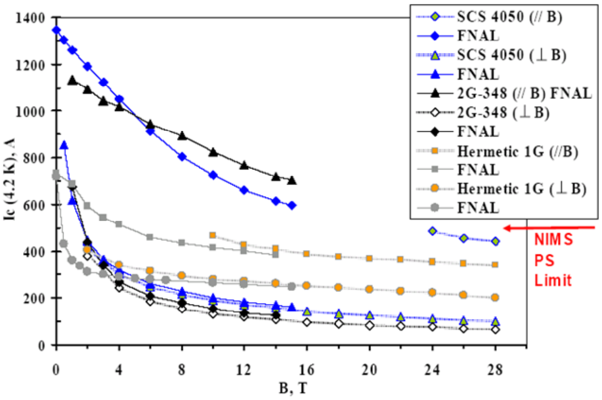

Figure 2: Critical current at 4.2° K as a function of field for YBCO conductors.

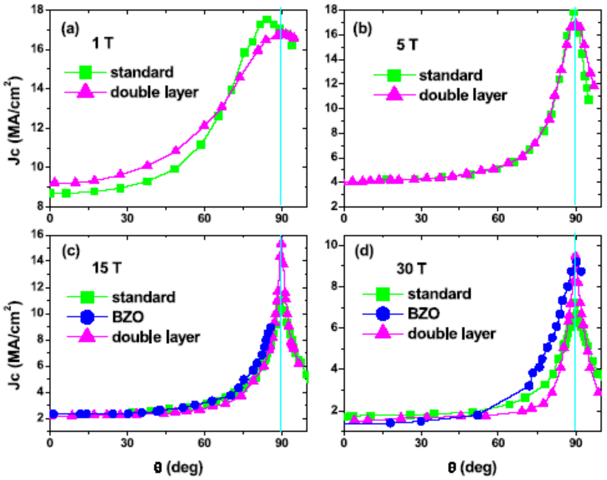

Figure 3: Angular dependence of J_C at 4.2°K for several values of the magnetic field. The figure comes from ref [8].

Magnetic Stresses and Strains

The large Lorentz forces in the magnet create a hoop stress on the coils which manifests itself as a tensile strain on the conductors. HTS conductors have intrinsic limitations when placed under strain. Table 3 shows the strain limit $\varepsilon_{95\%}$, above which the conductor J_E drops to 95% of its maximum capacity. Figure 5 shows the total tensile strain from Lorentz stress and conductor bending as a function of position in the HTS coils for the 50 T magnet. Maximum strains expected for 30 T to 50 T magnets are shown in Table 4.

Table 4: Maximum conductor strain, fraction of the insert with field angle greater than 10°, maximum field angle and minimum conductor J_E in HTS part of the magnet for field models.

Field	*Max Strain*	*Fraction > 10°*	*Max Angle*	*Min J_E*
30 T	0.196%	11%	13.2°	712 A/mm^2
35 T	0.245%	20%	18.5°	531 A/mm^2
40 T	0.302%	24%	21.9°	459 A/mm^2
45 T	0.388%	28%	25.3°	407 A/mm^2
50 T	0.421%	32%	28.3°	376 A/mm^2

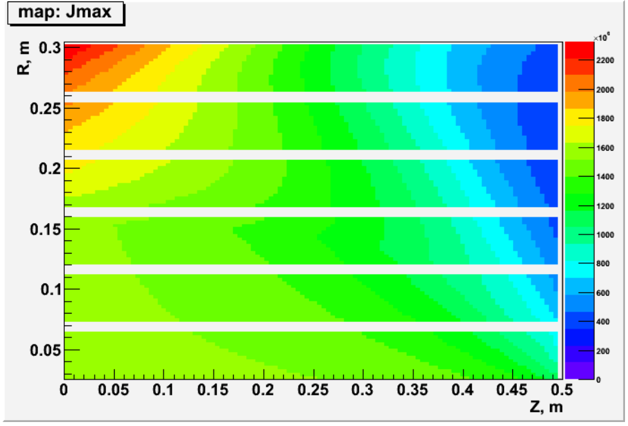

Figure 4: Maximum current density for the YBCO conductor as a function of position in the coils for the 50 T solenoid.

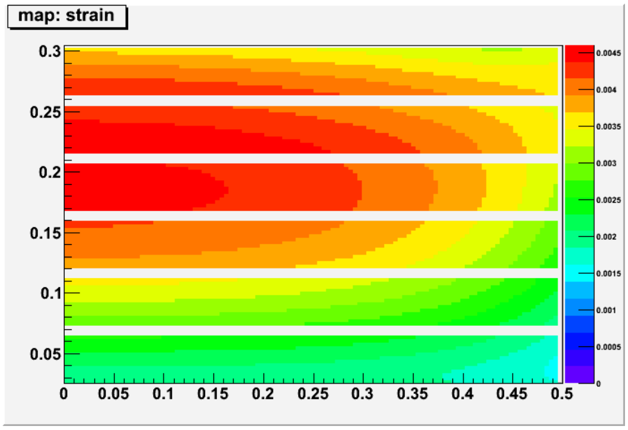

Figure 5: Tensile strain on the conductor as a function of position in the 50 T solenoid.

MAGNETIC PROPERTIES

The Opera2D finite element program [9] was used to analyze the magnetic properties of the different magnet models with fields varying from 30 T to 50 T. In these models 16 T is supplied by the Nb_3Sn and NbTi outer coils with the remaining field provided by the HTS inner coils. Table 5 shows the stored energy for these magnets. The stored energy is separated between the inner and outer coils using $U = \pi \int rA \cdot JdS$ where J distinguishes the different coils. The energy includes both the self energy and the energy from the mutual inductance of the other coil. The stored energy grows rapidly with field because of both the increased field and the larger magnet radius necessary to produce the larger field. The large stored energy can be a concern if there is a magnet quench because this energy would have to be removed in a manner that does not destroy the magnet itself. The stored energy of this high field solenoid magnet can be compared to the proposed 30 T COHMAG NMR magnet [10] which is 1.75 m long with a 0.55 m outer radius and is expected to have 90-96 MJ of stored energy.

Table 5: Stored energy for magnet designs of different fields.

Field	*Stored Energy from HTS*	*Stored Energy from Outsert*	*Total Stored Energy*
30 T	3.9 MJ	22.2 MJ	26.1 MJ
35 T	11.9 MJ	41.5 MJ	53.3 MJ
40 T	19.4 MJ	51.2 MJ	70.6 MJ
45 T	32.5 MJ	67.2 MJ	99.7 MJ
50 T	47.0 MJ	81.3 MJ	128.2 MJ

REFERENCES

[1] S.A. Kahn et al. "High Field Solenoid Magnets for Muon Cooling", Proc. of EPAC 2006, Edinburgh, p 2634

[2] S.A. Kahn at al., "High Field HTS Solenoid for Muon Cooling", Proc of PAC07, Albuquerque, p447.

[3] SuperPower,http://www.superpower-inc.com, AMSC http://www.amsuper.com, Bruker http://www.bruker-est.com/ybco-tapes.html.

[4] D.C. van der Lann and J.W. Ekin, "Dependence of the critical current of $YBa_2Cu_3O_{7-\delta}$ coated conductors…" Supercond. Sci Technol. 21, 115002.(2008) .

[5] K. Osamura et al., "Internal residual strain and critical current …", Supercond. Sci. Technol. 22, 065001. (2009)

[6] H-S. Shin et al., "The strain effect on critical current …", Supercond. Sci.Technol. 18, S364 (2005).

[7] D. Turrioni et al., "Study of HTS Wires at High Magnetic Fields", IEEE Trans on Appl Supercond. 19, No. 3, p 3057 (2009).

[8] A. Xu et al., "Angular dependence of J_C for YBCO coated conductors at low temperature and very …", Supercond. Sci. Technol. 23, 014002 (2009).

[9] Vector Fields Opera2D is provided by Cobham Technical Services. http://www.cobham.com

[10] W.D. Markiewicz et al., "Perspective on a Superconducting 30 T/1.3 GHz NMR Spectrometer Magnet", IEEE Trans. on Appl. Supercond. 16, No. 2, p1523 (2006)