HTS DEVELOPMENT FOR 30-50 T FINAL MUON COOLING SOLENOIDS*

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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 conductor parameters which are still under development and not yet well-defined. The HTS is being developed for accelerator use by concentrating on the design of solenoid magnet that will have a useful role in cooling muon beam phase space. A conceptual design of a high field solenoid using YBCO conductor is being analyzed. Mechanical properties of the HTS conductors will be measured along with engineering current densities (J_E) as a function of temperature and strain to extend the HTS specifications to conditions needed for low temperature applications. HTS quench properties are proposed to be measured and quench protection schemes developed for the solenoid magnet.

IDENTIFICATION OF THE PROBLEM

Extremely high field magnets will play important roles in future high-energy accelerators. Nb_3Sn, the superconductor used in today's highest field accelerator magnets is limited to maximum fields below 20 T. To create superconducting magnets that generated fields of 25 T and above, HTS will be required, because 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 as high as 45 T have been reported [1]. These measurements were not limited by the behavior of the HTS materials, but rather by the background magnetic field available for testing. Thus as new conductor technologies emerge, the limit to maximum achievable field may not be limited by J_E. In the high field magnets envisioned the very large electromagnetic forces and very large stored energy may be the limiting features. To fully take advantage of the high field properties, magnet designs must address these issues, which in turn require more thorough understanding of conductor behavior in extreme conditions which at this moment are not well defined.

As an application of choice, this paper will examine the design of a 45 T solenoid magnet to 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 where the magnet aperture would contain a vessel filled with liquid H_2 to act as an absorber for the beam cooling process [2]. 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.

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MAGNET DESCRIPTION

The choice of he 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 H_2 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 necessary insulation.

Table 1: Specifications of selected HTS wire available from vendor data sheets. J_E is the effective current density averaged over the material geometry at 77º K.

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	550
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	Yes

Conductor Choice

HTS conductors such as Bi2212, Bi2223 and YBCO are preferable to Nb_3Sn or NbTi because only HTS can carry significant J_E in the presence of high fields, particularly over 20 T. The commercial availability of HTS conductors has increased and reasonably large quantities are now available; this progress has stimulated this magnet design study. In a previous study [3,4] we examined a conceptual picture of a high field solenoid for muon cooling using Bi2223 conductor tape, which at that time was the leading conductor in terms of commercial availability and knowledge of material properties and because the tape conductor was easier to support mechanically. Since then there has been significant improvement in the J_E and tensile strength of the commercially available HTS conductors. Table 1 displays the properties of AMSC Bi2223 tape [5], along with the AMSC and SuperPower versions of YBCO conductor [5, 6]. This table shows significant improvement of the YBCO conductor over the Bi2223 conductor, particularly in J_E and mechanical strength. The Bi2212 conductor has the unique feature that it is available in a round wire, has a higher J_E than Bi2223 and has isotropic electromagnetic properties. However Bi2212 conductor is less robust against mechanical strain which is a serious concern for high field magnets. In order to effectively use Bi2212 conductor the magnet would need to be wound first and then reacted at 890ºC in pure oxygen, which poses significant challenges. In this report we will concentrate on using YBCO conductors.

The YBCO tape is composed of the superconductor deposited on a substrate. American Superconductor uses stainless steel, copper or bronze as a stabilizer and provides structural strength. SuperPower deposits the superconductor on a strong Hastelloy® substrate. Because the actual conductor is quite thin, the bending strain is minimal. The J_E quoted in Table 1 are averaged over the total cross section area and are given for 77ºK in self field. Figure 1 shows J_E at 4.2ºK for both YBCO conductors along with Bi2212 conductor in the presence of high magnetic fields [7]. The YBCO conductors show a strong anisotropic J_E dependence with respect to the field orientation. The J_E with the field in the plane of the YBCO conductor can be 2-4 times greater than when the field is perpendicular to the plane. Figure 2 shows this angular dependence as a function of angle normal to the conductor plane for various magnetic fields [7]. The dependence of current to field direction is an important consideration for the design of the solenoid ends.

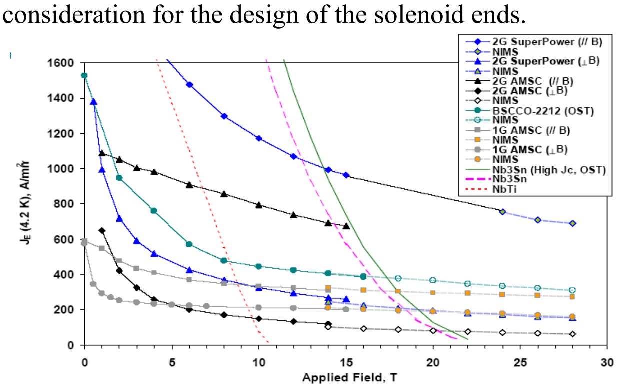

Figure 1: J_E vs. B for various HTS superconductors. The figure includes recent measurements from the FNAL-NIST collaboration.

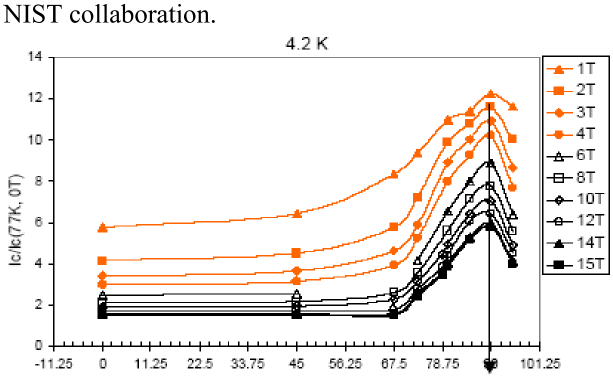

Figure 2: The I_C(4.2º) is shown as a function of the angle normal to the plane of the YBCO tape. The I_C is normalized to the I_C at 77ºK with no applied field.

Conceptual Design of a Magnet

We have previously looked at a configuration for a 45 T solenoid using AMSC High Strength Plus Bi2223 tape (shown in Table 1) where the conductor was interleaved with stainless steel tape for structural reinforcement. The interleaved stainless steel prevents the HTS conductor from exceeding the its maximum tensile strain limit. It is believed that significantly exceeding the conductor strain limit may cause micro cracking in the material that would cause irreversible degradation to the critical current limit. The current study uses a hybrid design where an outer magnet using Nb_3Sn and NbTi conductor and supplies 15 T of the field. An insert using SuperPower YBCO conductor will provide the remainder of the field. The Hastelloy substrate provides significant strength to the conductor and its large modulus protects the YBCO layer from excessive tensile strain. The larger J_E of the YBCO permits the magnet to be operated at 50% of I_c. Table 2 shows parameters describing the physical properties of the magnet configurations used in the study.

Table 2: Parameters describing the physical properties of the 30 T and 45 T magnet configurations.

Parameter	30 T Configuration	45 T Configuration	45 T Configuration
Conductor	YBCO	YBCO	Bi-2223
Length, m	1	1	1
Inner Radius, mm	30	25	25
Outer HTS Radius, mm	100	250	390
Total Outer Radius, mm	190	430	570
HTS Conductor Length, km	24	335	146
HTS Current, mega-amp-turns	12.5	24	24

Constraining the large Lorentz forces is an essential design concern for very high field magnets. The magnet design should keep the maximum tensile strain below the allowable limit. The maximum allowable strain includes contributions from the Lorentz hoop stress and the bending strain due to coil winding. The bending strain of the YBCO conductor is minimal because of the thin YBCO layer positioned at the center of the conductor. Figure 3 shows the tensile strain as a function of radius for 30 T and 45 T solenoid magnets using SuperPower conductor. Also shown is the strain vs. radius for a 45 T magnet using the AMSC Bi2223 conductor, where the conductor is co-wound with stainless steel tape to keep the tensile strain below the allowable limit. Adding the stainless steel interleaving increases the outer radius of the magnet, which increases the magnet's stored energy.

Other issues in the design that need to be addressed include:

- Lower current densities in the conductor where the local field is not oriented along the preferred direction
- Add insulation to each conductor tape to prevent the large voltage drops between adjacent layers.
- Separate the HTS part of the magnet into radial blocks to provide support for the build up of radial stresses. This will also provide room for support and cooling services.

Extend the Nb_3Sn/NbTi outer magnet beyond the HTS inner magnet to reduce the B_r in the end regions.

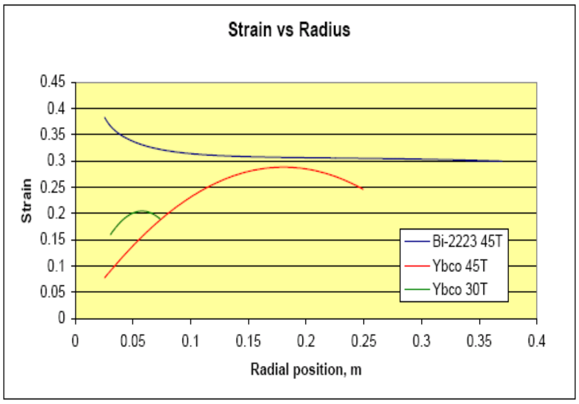

Figure 3: Strain vs. radius for a high field solenoid for different configurations. The red(green) curves show the strain with SuperPower YBCO conductor for a 45 T (30 T) magnet. The blue curve shows the strain for AMSC High Strength Plus Bi2223 conductor reinforced with stainless steel tape.

MAGNETIC PROPERTIES

This magnet was modeled using the OPERA-2D finite element program [8]. Table 3 shows the magnetic properties from the analysis. The table separates the stored energy between the HTS insert and the Nb_3Sn/NbTi parts of the magnet by assuming that $U = \pi \int r\, A \cdot J\, dS$. The stored energy increases rapidly with field since it is dependent on both the aperture field and the outer radius of the magnet. This large stored energy would have to be removed safely if a quench should occur. This is a serious issue since the quench velocity in HTS is considerably slower than in conventional superconductors.

Table 3: Parameters describing the magnetic properties of the YBCO models.

	30 T Configuration			45 T Configuration		
Parameter	*Whole Magnet*	*HTS Insert*	*Nb_3Sn Magnet*	*Whole Magnet*	*HTS Insert*	*Nb_3Sn Magnet*
B_0, Tesla	30.4	16.1	14.3	45.9	30.0	14.8
$\int B \cdot dl$, T-m	37.5	16.2	21.2	55.2	32.0	22.8
Stored Energy, Mega-joules	11.3	2.3	9.0	75	27.6	47.4
Axial Force MN	-8.3	-1.1	-7.1	-61.9	-18.6	-43.3
Total Radial Force, MN	206	107	98	726	533	193.4

Figure 4 shows a contour plot of the modulus of the field inside the coils along with field lines showing the field direction. As expected, the table shows large radial forces, which are mitigated locally so they do not accumulate. There are also compressive axial forces present from the radial fields at the ends of the magnet. The allowable compressive strain that the HTS tape can tolerate in less than 0.15%. As mentioned, the outer magnet will be designed to reduce the radial component of the field in the magnet end region. In addition it may be necessary to wind the end region of the magnet as separate *pancakes* with stainless steel support to prevent the compressive force build up. Addressing the end forces will be an important issue in the magnet design.

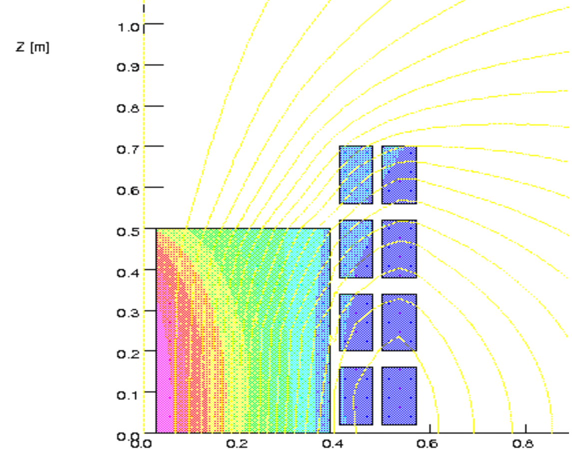

Figure 4: The contour plot of modulus of the field in the coils. The yellow contour lines indicate the field direction.

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[8] OPERA-2D is a product of Vector Fields, ltd.