FUTURE EXPECTATIONS, LIMITS AND OPERATIONAL ISSUES FOR HIGH FIELD SUPERCONDUCTING ACCELERATOR DIPOLE MAGNETS*

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Abstract

Energy upgrades of existing accelerators require the use of the highest field magnets available. Steady improvement in the application of Nb_3Sn technology has been made over the last several years and it can now be considered a viable material for practical high field accelerator magnets. This paper presents a brief review of current work in this area and in particular discusses recent results from the LBNL High Field Dipole R&D Program and how they might apply to future accelerator magnet capabilities. A projection of limits and expectations for practical applications over the next 10 – 15 years will be discussed along with some of the operational issues associated with high field magnets.

1 INTRODUCTION

For almost a decade, the LBNL Superconducting Magnet Group has been engaged in the development of high field accelerator magnet technology. The first practical application of this technology could likely be for a luminosity and/or energy upgrade of the LHC. With commissioning only a few years away, it is not too early to begin thinking about upgrade scenarios. Indeed, such possibilities are already being considered [1]. In the case of upgrades, performance is the key issue and there is no debate over operational parameters such as field, thermal margin and radiation hardness. The goal is to push performance in these areas and others as far as practically possible. This report will try to identify some of the major issues, serving as a general guide for R&D and to examine the possibilities and prospects over the next 10 – 15 years.

2 CONDUCTOR

High performance superconductor is the key enabling technology for high field magnets. Reaching fields in excess of 10 Tesla requires the use of materials other than NbTi. Nb_3Sn, Nb_3Al and high temperature superconductors (HTS) are all possible candidates. Figure 1 shows the relative performance of NbTi, Nb_3Sn and Bi-2212. There has been steady progress in the development of Bi-2212. LBNL has successfully produced a Rutherford cable made from 0.8 mm strands [2], the current density continues to increase and the upper critical field ultimately gives it the potential to produce much higher fields if the engineering drawbacks of the material can be overcome. However, the engineering current density is a factor of two lower than Nb_3Sn strand, there is still an issue with strain sensitivity and the asymptotic cost does not look promising for large-scale applications. At this time, Nb_3Sn is the leading choice because of manufacturability, cost potential, critical current density and relatively favorable mechanical properties. The first phase of a modest conductor development program, initiated by the U.S. Department of Energy, has resulted in readily available conductor with critical current densities over 2,000 A/mm^2 @ 12 Tesla and 4.2 K in less than two years [3]. The target parameters are shown in Table 1. The cost is still high, and the second phase of the program will focus on scale-up and cost reduction with a goal of $1.50/kA-m (12T, 4.2k).

Table 1. Technical and cost performance goals of the US/HEP conductor development program.

Specification	Target value
Jc (noncopper,12T, 4.2K)	3000 A/mm^2
Effective filament size	Less than 40 microns
Minimum piece length	Greater than 10 km in dia. of 0.3 to 1.0 mm
Wire cost	Less than $1.50/kA-m (12T, 4.2K)
Heat treatment times	Less than 200 hrs

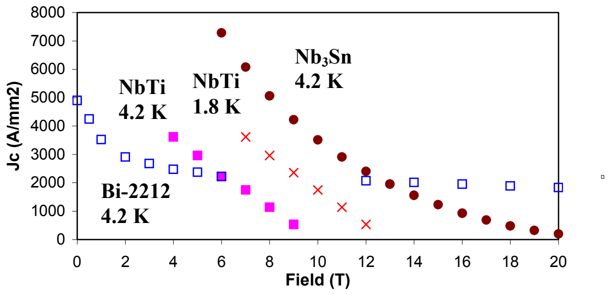

Figure 1: J_c vs B for 0.8 mm wire

3 LBNL MAGNET TECHNOLOGY

The recent work on Nb_3Sn-based magnets at LBNL began in 1997 with D20 [4], a 4-layer, cosine-theta geometry dipole that reached 12.8 Tesla at 4.2 K and 13.5 Tesla at 1.8 K. This was followed by RD2 [5], a 6 Tesla (4.2 K) common-coil geometry magnet using low J_c conductor from the ITER project. The common-coil design concept, proposed by Brookhaven National Laboratory [6,7], consists of a pair of racetrack coils shared between two apertures, producing fields in opposite directions. This geometry is intrinsically suited for a collider, but modifications can be used for single-aperture applications as well. Last year the group tested RD3-b, a 3-layer common-coil design that reached a field of 14.7 Tesla at 4.5 K [8]. This record-breaking success

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*This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. SAGourlay@lbl.gov depended on the availability of conductor with a J_c of 2,200 A/mm^2 @ 12 Tesla, a minimal coil spacing of 25 mm and development of a new support structure. The first test cycle of the next magnet, RD3-c, has just been completed [9]. Achieving a field of approximately 10 Tesla, this magnet focused on adding field quality to the basic common-coil configuration with a clear bore of 35 mm. The "RD" (Racetrack Dipole) program, based on common-coil magnets is supported by several other R&D activities. Last year a technology development program based on sub-scale model magnets was started. These sub-scale or SM-series magnets [10], have reached fields as high as 12 Tesla. They serve as tools for development of a wide variety of magnet related issues, from conductor and materials development to fabrication techniques and structural design. Another R&D route is based on racetrack coils in an "H-type" coil configuration. The main objective of the so-called "HD-series" is to achieve the highest fields possible while minimizing the amount of conductor, simplifying the structural requirements and reducing the stored energy of the magnet for more economical fabrication and testing. A schematic of the basic design is shown in Figure 2. The support structure and assembly concept, consisting of two flat, racetrack coils is the same as for the "RD-series" but there are notable differences. The forces are on the broad face of the cable, there is no central island or pole, there is a mid-plane gap and the bend radius is small compared to the common-coil.

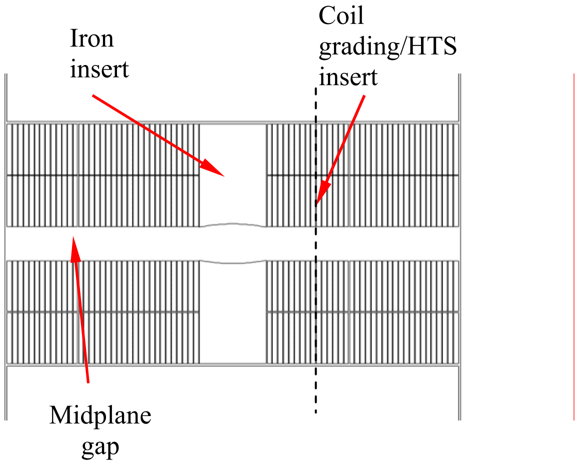

Figure 2: HD Coil Schematic

The first magnet in the series, HD1, is in the design stage and will be tested in the spring of 2003 (Figure 3). The predicted field is 15.3 Tesla at 10.1 kA and 4.2 K with a 10 X 20 mm bore. The open mid-plane of this design is not the most efficient in terms of conductor usage but offers some potential options for handling the high synchrotron radiation loads these magnets will encounter during operation. Table 2 illustrates how various modifications to the basic "HD" design affect the bore field. HD1 performance is based on the conductor used for RD3 (2,200 A/mm^2 at 12 Tesla and 4.2 K). An increase in critical current (I_c) by 50 % increases the bore field by almost a Tesla. I_c can be increased by using thinner insulation and by decreasing the amount of copper in the cross section. Insulation schemes now in use range in thickness from 200 to almost 500 micrometers. New methods are being pursued at LBNL to reduce the thickness to about 100 micrometers. Current superconducting strands contain about 50% copper. A series of sub-scale model tests at LBNL is investigating the operation of coils with high copper current density (J_{Cu}). A pair of coils has been successfully operated with a J_{Cu} of over 2,700 A/mm^2 at 12 Tesla without a heater-based quench protection system. This is a promising result but more work needs to be done to determine an acceptable limit for long magnets. High field magnets naturally allow the reduction of copper since J_{Cu} decreases as the field increases. In RD3, J_{Cu} reached 1150 A/mm^2 at 14.7 Tesla and the temperature did not exceed 200 K.

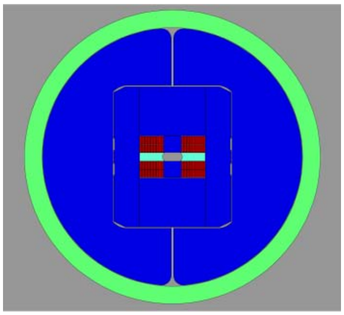

Figure 3: HD1 Cross Section

The high aspect ratio of the HD design benefits significantly from grading and the next magnet in this series, which is expected to exceed 16 Tesla, will incorporate a graded coil structure. As long as the aperture is kept small, field quality in this design can be achieved with relatively minor modifications to the basic geometry. At 4.2 K, Nb_3Sn reaches a practical limit at fields around 17 Tesla. Exceeding 17 Tesla will require mechanically robust materials with high critical fields.

Table 2. HD Design Options

Design features	Dipole field (T)	Iss (kA)
Reference: HDI (RD3B conductor	15.3	10.1
Ic increase 50%	16.1	10.9
No central iron insert	14.1	9.9
No iron insert and no midplane gap	15.1	9.0
Nb3Sn graded coil 10 turns ½ dens	16.8	13.3
HTS insert 7 turns 0.8 mm 361 A @ 18 T	18.6	13.0

4 R&D ISSUES

The successful application of high field magnets relies on optimization of several important issues involving performance, operation and cost. The primary challenges are discussed below.

4.1 Aperture

Along with field quality, which is related, aperture poses one of the most difficult parameters to determine. The choice of aperture has a huge impact on cost and performance. A smaller aperture has the advantages of using less conductor for a given field, lower stored energy and simplified support structures. In rectangular designs, the coil geometries required for larger aperture magnets are more complex. From the operational point of view, larger clear bores are preferred. Consideration of beam instabilities and space for beam screens and cooling channels call for increasing the bore diameter.

4.2 Synchrotron Radiation Loading

Any post-LHC collider will need to deal with increased heat loading due to synchrotron radiation. An elegant solution for the LHC is to use beam screens to absorb the radiation and maintain good vacuum. However, these systems are expensive and more importantly, occupy a significant fraction of the aperture. Photon stops, commonly used in electron machines have been proposed for use in hadron colliders [11]. The photon stops are placed in the magnet interconnects and remove the synchrotron radiation heat at room temperature. This approach limits the magnet length depending on the arc bending radius. High field magnet designs with a conductor-free mid-plane offer other options for placing absorbers and vacuum ports without compromising aperture size.

4.3 Magnet Length

By reducing the number of magnets and hence the number of expensive interfaces, increasing the magnet length has clear cost savings advantages. Aside from the issues of mechanical stability, alignment, transport and magnetic measurements, there is concern that the effects of differential thermal contraction during a quench could induce stresses that would degrade or damage the coil. The coldmass temperature can be as high as 300 – 400 K during a quench, while the surrounding support structure remains at 4 K. It is possible to mininize this effect through careful design and the R&D program should begin engineering studies as soon as possible.

4.4 Quench Protection

The large stored energy and high inductance of high field superconducting magnets requires active quench protection systems. Higher fields and the use of Nb_3Sn will require adaptation of the standard approach. The desire for redundancy limits heater coverage to 50%. However, there has been experimental evidence of a strong quench-back effect in the LBNL Nb_3Sn magnets [12]. It may be possible to integrate the quench-back effect along with other methods, such as inductive coupling, into the quench protection design, minimizing heater requirements and/or substantially reducing the peak coil temperatures. The addition of copper stabilizer is not necessarily the best way to lower temperatures. It has a limited effect on peak temperatures and results in a decrease in the overall current density in the coils. But, preliminary results of magnet tests at LBNL indicate that low RRR's can effectively reduce temperatures without adversely affecting stability [12]. Certainly, designs with higher currents (up to 30kA) and hence lower inductance have advantages for quench protection as well as reducing the amount of non-superconductor in the cross section.

5 SUMMARY

Development of dipole magnets with fields in excess of 15 Tesla will require an integrated approach, incorporating innovation from accelerator physicists and magnet designers. Current assumptions regarding design limits must be challenged every step of the way.

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