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High Field Magnet R&D in the USA

Stephen A. Gourlay

Abstract-- **Accelerator magnet technology is currently dominated by the use of NbTi superconductor. New and more demanding applications for superconducting accelerator magnets require the use of alternative materials. Several programs in the US are taking advantage of recent improvements in Nb_3Sn to develop high field magnets for new applications. Highlights and challenges of the US R&D program are presented along with the status of conductor development. In addition, a new R&D focus, the US LHC Accelerator Research Program, will be discussed.**

***Index Terms*—Accelerator magnets, superconducting magnets**

I. INTRODUCTION

PERFORMANCE requirements of modern accelerators continue to press the limits of magnet technology. Parameters such as field or gradient and large beam-induced heat loads require the use of materials well beyond the capabilities of NbTi, that is the current basis of accelerator magnet technology. The magnets for the Large Hadron Collider (LHC) [1], soon to be commissioned at CERN, represent the ultimate application of NbTi. For applications requiring fields above 10 T, the focus of accelerator magnet programs in the US is based on Nb_3Sn, one of the A15 compounds. The preference of Nb_3Sn is based on a combination of performance and commercial availability. The material itself is over 4 decades old, however, the mechanical properties (brittleness and strain sensitivity) have kept it from active consideration for use in accelerator magnets until recently. While there are still many challenges to face, much progress has been made. Nb_3Sn has been a cornerstone of the magnet program at Lawrence Berkeley National Laboratory (LBNL) for over a decade. Other US magnet programs, at Fermi National Accelerator Laboratory (FNAL), Texas A&M University (TAMU) and Brookhaven National Laboratory (BNL) have more recently joined the effort. These programs are being given additional impetus by the newly launched US LHC Accelerator Research Program, a large fraction of which is devoted to developing technology for future upgrades of the LHC. For this application, Nb_3Sn is the only possible choice.

II. CONDUCTOR

It is well understood and appreciated by superconducting magnet builders that conductor properties ultimately determine the performance limits. Due to the increasing interest in Nb_3Sn for accelerator magnet applications, more effort has been put into conductor development.

A. US DOE Conductor Development Program

Recognizing the need to further the development of Nb_3Sn for future accelerator magnet applications, the High Energy Physics division of the US Department of Energy launched a Conductor Development Program (CDP) in 1999. The goal is to provide cost-effective, high-performance superconductor for the high-field magnets required for the next generation of high-energy physics colliders, as well as upgrades to existing colliders at Fermilab and CERN. Table I lists the target parameters.

TABLE I.
TARGET PARAMETERS FOR THE US CONDUCTOR DEVELOPMENT PROGRAM

J_c (non-copper, 12 T, 4.2 K)	3,000 A/mm^2
J_e (12 T, 4.2 K)	1,000 A/mm2
Effective filament diameter	< 40 microns
Process unit size	100 kg, average piece length > 10 km with diameters 0.3 mm – 1.0 mm
Wire cost	< $1.50/kA-m (12 T, 4.2 K)
Heat treatment time	Max 400 hrs; 50 hrs wind and react

The program, managed by LBNL and a committee consisting of representatives of US National Laboratories and Universities has made excellent progress in a very short time. The modestly funded program increased J_c by 50% in the first two years, reaching the goal of 3,000 A/mm^2. This conductor, manufactured by Oxford Superconducting Technology, uses the Restacked Rod Process (RRP). In this process, the raw Niobium is in the form of rods that are less expensive than expanded metal sheets used for Modified Jelly Roll (MJR) and is thus a better candidate for scale-up and cost reduction. Initial results for the RRP process, extrapolated to 12 T due to current testing limitations, were reported in [2]. Later testing at LBNL with improved sample mounting and testing procedures [3] gave a result of 3,016 A/mm^2 at a field (background + self-field) of 12.38 T. It is universally recognized that improvements in conductor characterization are necessary to support the Conductor Development Program. The programs at BNL [4] and FNAL [5] are also developing high current strand measurement techniques. These groups and others, from The University of Wisconsin

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and Ohio State University are actively engaged in investigating stability, magnetization, intra strand resistance measurements, strain sensitivity and other parameters related to magnet performance [6,7].

A paper on high field magnets must at least mention High Temperature Superconductor (HTS). Though there are several critical issues (irreversible strain degradation, filament diameter) that have not been sufficiently investigated, some progress has been made. The J_c of Bi-2212 continues to improve but J_e is still low compared to Nb_3Sn strands, Fig. 1. However, for fields above 17 - 18 T, there is no other choice. For this reason, programs at LBNL in HTS cable development [8] and the Wind and React program at BNL [9], continue at some level.

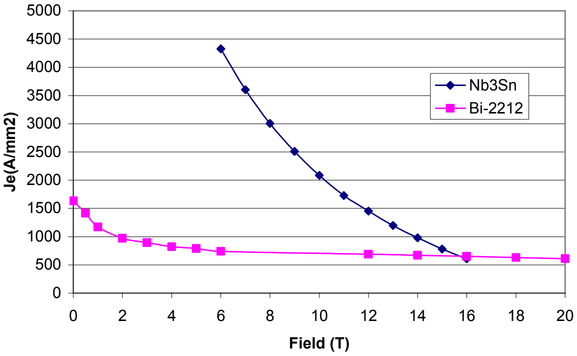

Fig.1. Comparison of J_e for Bi-2212 and Nb_3Sn

III. MAGNET ISSUES AND MYTHS

Nb_3Sn has many virtues related to high field magnets, but there are some issues associated with it. Notably, like all the A15 materials, it is brittle and strain sensitive. This impacts support structure design and fabrication techniques, and generates concern about thermally induced stress effects. Recent work by the U. S. program, has shown that Nb_3Sn is more robust than originally believed, particularly as applied to accelerator magnets. Field quality is a perpetual issue and there was some initial concern that Nb_3Sn magnets might present difficulty in achieving good field quality, but the D20 results at LBNL [10] and preliminary studies by Fermilab [11] indicate that geometric harmonics should be comparable to NbTi magnets. For Nb_3Sn however, high J_c comes at the price of large filaments; combined, this leads to large magnetization effects. Several groups have addressed this issue, although the effects will never be on the order of those seen with NbTi. High fields imply large stored energy and a concern for quench protection issues.

IV. US MAGNET PROGRAMS

The US magnet programs represent a diverse and complementary approach to developing technology for high field magnets. They are primarily focused on Nb_3Sn, but, as mentioned above, there is some HTS work as well. The US magnet programs combine to address the critical issues associated with the application of Nb_3Sn. A brief description of each of the programs along with selected highlights is given below.

A. Brookhaven National Laboratory

The BNL program has been involved with Nb_3Sn for many years. Their current high field magnet program is centered on the react and wind approach. Techniques for winding the brittle cable are studied using "10-turn coils", Fig. 2. Results so far have been mixed. Early tests using ITER strand performed very well. Subsequent tests using the newer, high performance strand have shown significant degradation.

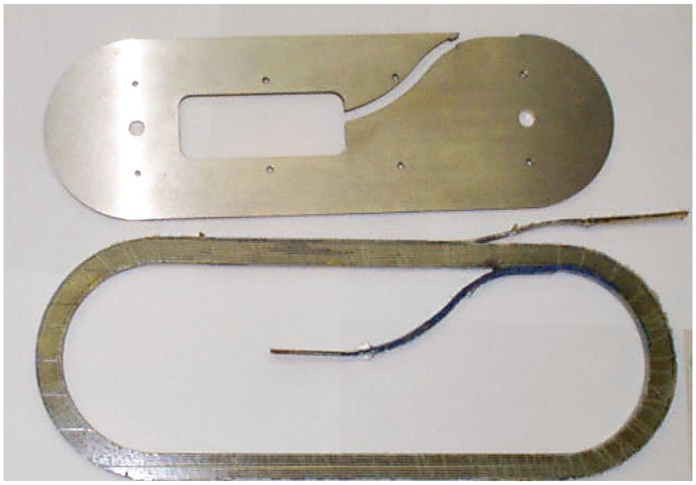

Fig. 2. BNL 10-Turn Coil

Methods to reduce the degradation, such as decreasing the strain by using smaller diameter strand and/or increasing the bending radius are being investigated [12]. BNL's method of conductor evaluation has been expanded to HTS Rutherford cable and given the challenge, has produced encouraging results [12]. For the near future they are planning the fabrication of 12 T background coils for high field insert tests.

B. Fermi National Accelerator Laboratory

The magnet program at FNAL is focused on the development of 10 – 12 T accelerator dipoles for future Hadron Colliders. The diverse program includes R&D approaches based on cos-theta and block coils using both wind and react and react and wind techniques. The program has produced three cos-theta dipole models. Although quench performance was limited, the magnets have contributed to a better understanding of field quality and control of magnetization effects [13, 14]. The quench performance of the cos-theta design is being studied using a magnetic "mirror" configuration. The react and wind program has produced three racetrack dipoles in the common coil configuration. Structural changes have been implemented on the third model in an attempt to improve the quench performance [15]. The last two model coils reached 75 and 78%, respectively, of the calculated short sample limit. The group has also built a react and wind common coil magnet [16], addressing field quality issues (Fig. 3).

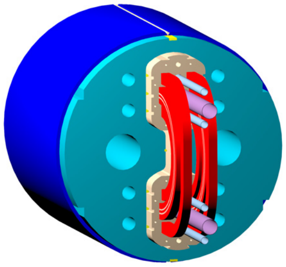

Fig. 3. FNAL React and Wind Common Coil Magnet

This magnet has a maximum field of 11 T with a 40 mm clear aperture. Test results for this magnet will be presented at this conference [17].

C. Lawrence Berkeley National Laboratory

The LBNL superconducting magnet program is directed towards advancing all aspects of the technological infrastructure for high field magnet development relevant to possible future accelerators. The program takes three parallel paths, each with its own series of magnets. The Racetrack Dipole (RD-series) is used to study collider magnet options in the common-coil configuration. With the subscale model (SM-series) we investigate new conductors and develop new technology. Finally, the Horizontal Dipole (HD-series) employs the simplest geometries to achieve high fields. In the past few years the program passed a number of key milestones in both magnet fabrication and materials development work. Recent efforts culminated in the successful test of HD-1, a record-breaking dipole that reached a field of 16 T [18, 19]. Table 2 is a list of prototype magnets and coil tests that have been used to study issues related to high field magnets, such as support structure mechanics, field quality, strain effects, and fabrication techniques.

TABLE II.
LBNL Nb_3Sn PROTOTYPES

Magnet/Coil	Year	Field	Type	Design Features
D20	1997	13.5	Cos-theta	50 mm clear bore, Field Quality
RD-2	1998	6	Common Coil	New coil configuration
RT-1	1999	12	Common Coil	High field coil test
RD-3b	2001	14.5	Common Coil	New structure, high stress
RD-3c	2002	10	Common Coil	35 mm bore, field quality fetures
HD-1	2003	16	Block	New "HD" configuration

The model magnet program is supported by conductor studies and work on sub-sized mechanical models. This program is now well underway, with five tests completed and several more planned for this year. Sub-sized models will be used to test support structure designs, new coil geometries and cable designs. The program has recently been used to investigate thermal stress effects relevant to long coil performance [20]. If new materials such as Nb_3Al, MgB_2 or Bi-2212 become available in sufficient quantity and with good properties, coils will be fabricated and tested in the sub-sized models.

D. Texas A&M University

The Texas A&M program is based on high field, high current density, wind and react coils using internal structures to limit coil stress [21]. The program was launched three years ago with the successful testing of TAMU1, a NbTi model in which a first test was done using many of the construction details of the high-field design. During this last year they built TAMU2, in which one of the three coil modules of a 12 T design (Fig. 4) is housed in the flux return structure designed for the whole dipole. This first Nb_3Sn model was built using ITER conductor, which has a lower current density than high-performance conductor of the final version but will enable them to evaluate reaction and impregnation procedures. TAMU2 is scheduled for testing at LBNL in fall 2003. Pending the results, they will continue the program with TAMU3, an identical single-module dipole using high-performance superconductor; then TAMU4, containing the double-pancake coil that forms the center section of the 12 T dipole; and ultimately TAMU5, the full implementation of the design, culminating in 12 T without stress concentration, minimal deflection at shear interfaces and a uniform preload, maintained through cool-down.. One of the magnetic features of the design is an inter-layer ferric plate, intended to significantly reduce snap-back.

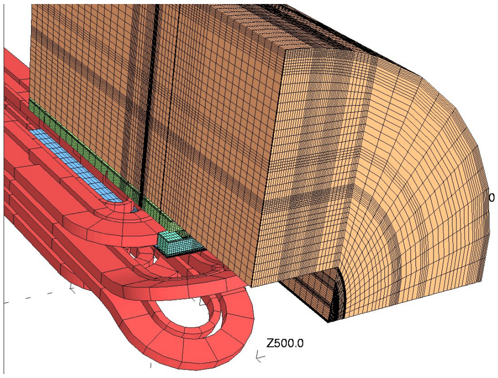

Fig. 4. Texas A&M 12 T design

V. LHC ACCELERATOR RESEARCH PROGRAM

Still several years from commissioning, there are already discussions on possible upgrades for the Large Hadron

Collider (LHC) [22]. The current LHC relies on pushing NbTi technology to the ultimate limit, revealing the magnet systems as the limiting components for improved machine performance and that any enhancements will require the use of new materials.

The U.S. LHC Accelerator Research Program (LARP) is a follow-on activity to the U.S. LHC Accelerator Construction Project, a collaboration of LBNL, BNL and FNAL [23]. Participation in this program will build on the previous investment in the construction project and ensure continued development of domestic accelerator science and technology, keeping the U.S. accelerator scientists at the forefront of the field. The multi-year program includes participation in commissioning the accelerator and U.S.-provided components, design and construction of state-of-the-art beam instrumentation, accelerator physics studies, and design and technology development required for an upgrade of the interaction region magnet systems to increase luminosity. The program was recommended for funding at a U.S. Department of Energy review earlier this year.

A. LARP Magnet R&D Program

The challenging requirements, along with recent progress, has led to the choice of Nb_3Sn as the conductor material for the proposed LHC upgrades. The LARP will be an important application of Nb_3Sn technology, helping to drive it well beyond state-of-the-art, significantly enhancing U.S. options in accelerator technology and providing opportunities for new applications.

Even the simplest upgrade configurations, in terms of magnet requirements, exceed the performance characteristics of NbTi and, in fact, push the limits of Nb_3Sn. The principal goal of the magnet program is to produce designs for Interaction Region (IR) upgrade quadrupoles and dipoles that utilize the full potential of the highest performance superconducting materials. The program will extend and quantify the limits on key performance parameters, providing accelerator physicists with IR options that most efficiently address the beam dynamics issues that limit machine operation.

Replacement of the existing inner triplets is a key step toward higher luminosity. There are two fundamental inner triplet design options [24]: a large-aperture, single-bore inner triplet followed by beam separation dipoles or double-bore inner triplet with separation dipoles first. The present inner triplet design is based on the first option. This approach and the magnet requirements are well understood. The second one needs a new layout of inner triplet optics with twin, large-aperture high gradient quadrupoles and correctors and very high field separation dipoles. This approach requires more study in terms of accelerator physics and magnet design.

Some preliminary work on a variety of quadrupole designs has been done by LBNL, FNAL and BNL [25-27]. Study of a reference design indicates that a 90 mm Nb_3Sn quadrupole with an operating gradient of 205 T/m, that would allow a factor of 2 decrease in β^*, is feasible with presently available material. With anticipated advances in Nb_3Sn performance and more aggressive magnet designs, even larger apertures are likely to be possible, permitting an even larger decrease in β^* and corresponding increase in luminosity. Several innovative options exist that could meet the operation requirements and will be studied as part of the program. These magnets can operate with energy deposition levels a factor of 10 (5) higher at 1.9 K (4.5 K) than the present NbTi-based system. Every design proposal requires pushing the limits of Nb_3Sn technology in several areas.

Recent progress in the development of Nb_3Sn has encouraged the prospects for use in accelerator magnets but the application for the LHC upgrade adds additional issues to the already formidable list. The magnets will operate in a high radiation environment, subject to unprecedented beam induced heat loads, that will require development of radiation hard materials for coil construction and understanding the heat transfer characteristics of composite coils. The design process will necessitate working closely with accelerator physicists to understand trade-offs between magnet performance limits and IR upgrade options.

A program to address the technological issues associated with high gradient, large aperture quadrupoles and high field dipoles, is necessary to realize the potential of this new regime and provide a variety of options.

After 4 – 5 years running at maximum luminosity, the LHC will need a major upgrade to the machine and detectors in order to realize the full physics potential. This implies that the magnet R&D must be completed around 2102 for installation of components in 2013 – 2014.

The program is comprised of two major phases; a beginning phase of technology development, focused on issues driven by the requirements of possible LHC upgrades, lasting 4 – 5 years, and a second, overlapping phase that takes that technology base and directs it to the chosen upgrade application. The program culminates in production-ready full-length prototypes.

The early stages of the program are dictated by slow turn-on of the funding profile (Fig. 5) and will rely initially on support from the base programs.

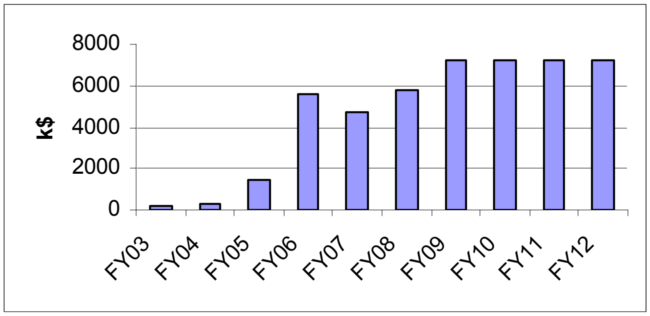

Fig. 5. LARP magnet program funding profile

The model is based on a well-coordinated, joint effort with national and international collaborators that is fully leveraged on the substantial existing infrastructure and intellectual resources of existing programs. General magnet issues will continue to be investigated through the existing base programs. The LARP will concentrate on issues specific to the needs and time-frame required for application to LHC upgrades.

Initially, the program will focus on integrating the three U. S. national laboratories and incorporating their technological strengths into the overall program. The LARP offers an excellent opportunity to strengthen the collaborative structure of not only the U.S. programs but internationally as well. The LARP can be used to extend and strengthen the environment developed in the framework of the current US/LHC Accelerator project. One of the beneficial consequences of the program will be the formation of a collaborative structure that makes efficient use of existing infrastructure in the labs and that will continue beyond the duration of the LARP.

1) FY04 Program

The FY04 LARP R&D plan was discussed at a recent collaboration meeting [28]. With a limited timeframe and a delayed funding profile, the emphasis of the meeting was to identify the most critical issues in magnet technology and accelerator physics and approach the task of narrowing the possible IR options. The R&D effort is broken down into three categories:

a) Technology Development

Technology development includes generic issues involving everything from investigations into new materials and fabrication techniques to complex model magnets for studying support structures and field quality. The FY04 program will study two quadrupole geometries. The bladder and key support structure developed by LBNL for dipoles [29, 30] will be applied to a cos-theta quadrupole. A racetrack geometry quadrupole (Figure 6), using existing coils from the LBNL sub-scale coil program will be built and tested. The racetrack quadrupole has the virtue that the conductor is removed from the highest radiation region of the aperture. The trade-off is that the design is less efficient.

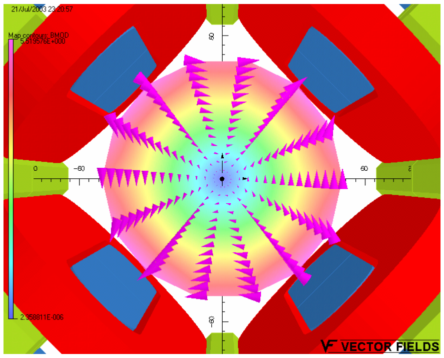

Fig. 6. Racetrack quadrupole geometry

b) Quadrupoles

One of the currently favored IR designs requires quadrupoles with closely spaced, non-parallel bores. The FY04 plan calls for a continuation of the recent work performed at FNAL to determine if this is a viable option.

c) Dipoles

The separation dipoles represent one of the greatest challenges for magnet designers. High field is a premium for any IR design option but one favored scenario places the dipole next to the interaction point, in an extreme radiation environment. FNAL [31] and BNL [32] have looked at a cos-theta and block geometry respectively. The original cos-theta design suffered unacceptable heat loads at the mid-plane. A modified design with the conductor removed at the mid-plane (Fig. 7) was created. The heat loads were significantly reduced but several other drawbacks were discovered; excessive stress at the mid-plane, large stored energy and large power dissipation in the cryogenic system. The open mid-plane design, with an aspect ratio more appropriate for the beam and no conductor or material on the mid-plane, looks much better in terms of reducing the heat load, Fig. 8. However, the challenge is to provide adequate support for this coil geometry. Therefore two issues will be studied this year; a mechanical design for the open mid-plane geometry and heat transfer analysis and studies using the LBNL sub-scale coils.

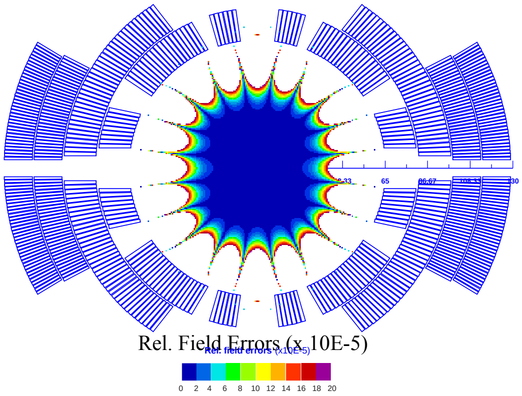

Fig. 7. FNAL dipole design with reduced heat load

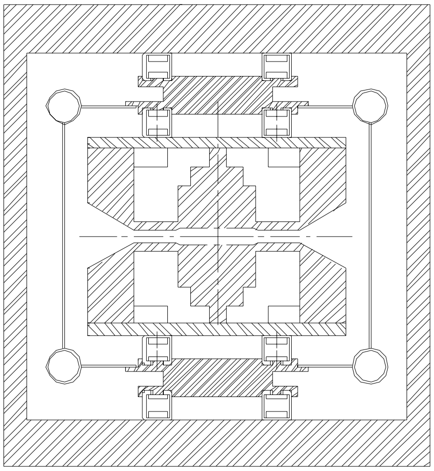

Fig. 8. BNL open mid-plane dipole design

VI. SUMMARY

The U.S. high field magnet program is making excellent progress. There have been some significant successes but there is still much work to be done in order to demonstrate the viability of magnet technology that reaches beyond the limits of NbTi. The LARP is an excellent opportunity to extend the expertise in high-field magnets, develop a strong technological base for future projects and add vitality and diversity to the overall US program. In addition to the technical aspects of the program, it will also serve to develop and strengthen collaborative ties between the US programs and international colleagues, laying a strong foundation for future endeavors.

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