FERMILAB SUPERCONDUCTING Nb$_3$Sn HIGH FIELD MAGNET R&D PROGRAM

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Abstract

Magnets based on the modern Nb$_3$Sn conductor are the main candidates for future high-energy hadron colliders. Fermilab as part of the U.S. MDP executes an extensive R&D program on these high-field magnets. This program includes basic conductor and material R&D, quench performance studies, and building a meter-long high-field demonstrator. This paper summarizes the current status of the program including its recent results.

INTRODUCTION

Fermilab superconducting Nb$_3$Sn high field magnet research and development (R&D) is an integral part of the U.S. Magnet Development Program (MDP) [1]. The main goal of this program is the development of advanced superconducting (SC) magnets, materials and baseline technologies for present and future particle accelerators. The near-term program focuses on small- and large-aperture accelerator magnets based on the Nb$_3$Sn superconductor with a possible insert based on high temperature superconductors (HTS) and associated technologies. These Nb$_3$Sn magnets are designed for operation fields up to 15-17 T. In the longer term, the program will move toward development of accelerator magnet technology at the limits of low temperature superconductor (LTS) and HTS materials. The ultimate goal is to design and test 20+ T hybrid dipoles. This goal will continue to evolve and align with the priorities of the future program.

The current program has four interconnected aspects: conductor R&D, materials and technology R&D, Nb$_3$Sn, and HTS magnets. This paper will discuss only the Nb$_3$Sn aspect of the program as well as a new test facility needed to perform high field magnet R&D. The HTS aspect is presented in a separate paper in this conference [2].

CONDUCTOR R&D

Fermilab’s conductor R&D effort is currently focused on improving strand characteristics of Nb$_3$Sn. In collaboration with Ohio State University and Hyper Tech Research Incorporated, we have been developing wires with Artificial Pinning Centers (APCs) [3]. This is a potentially novel breakthrough technology in which the precursors of Nb$_3$Sn conductors are modified: the commonly used Nb is replaced by Nb-1%Zr, and oxide powder (SnO$_2$) is added to the Sn source of subelements to supply oxygen to the Nb-1%Zr. Zirconium has a much stronger affinity for oxygen than Nb and as a result during heat treatment the Zr atoms are oxidized to form ZrO$_2$ nanoparticles. These nanoparticles serve as grain refiners capable of reducing the Nb$_3$Sn grain size from 110–150 nm in present conductors to 35–70 nm, which leads to improved pinning. The potential gain in the critical current density ($J_c$) of Nb$_3$Sn can be a factor of 2–3 depending on whether the conductor is a binary or ternary APC conductor. Figure 1 shows the current result [3] obtained on the prototype APC wires. The dashed line represents the $J_c$ specification for a Future Circular Collider (FCC). One can conclude that APC wires meet or exceed the conductor specifications for FCC at a field above 16 T. The tested wires have 50% more critical current density as compared to the state-of-the-art Nb$_3$Sn conductor currently produced, which is shown in the lower left corner of Fig. 1. In the next several years, the main goal is to optimize the internal wire geometry and material content, and to design a stable conductor (at low field) that can be drawn in long batches.

The recent Nb$_3$Sn magnet built in the U.S.A. and Europe (CERN) [4, 5] showed that these magnets need a long training, about 20-30 quenches, to reach operational currents. A primary reason for these quenches is the low specific heat of the Nb$_3$Sn superconductor at temperatures below 5 K. Due to this low specific heat, a small heat perturbation can cause a large temperature increase in Nb$_3$Sn superconductors and a resulting magnet quench.

The next important modification to Nb$_3$Sn has the potential to eliminate or decrease quench training of Nb$_3$Sn magnets. Increasing the specific heat (C) of Nb$_3$Sn wires can be a promising way to suppress their instability and also reduce magnet training. To achieve this effect, a high-C material is added to Nb$_3$Sn wires, replacing some Nb$_3$Sn or...
Cu filaments with Cu tubes filled with a mixture of Cu plus high-C powders. In the first prototype wire, Gd$_2$O$_3$ was used as a high-C component [6]. Several wires with different percentages of Gd$_2$O$_3$ were drawn by Hyper Tech Research Incorporated [7]. Figure 2 shows the comparison between wires with and without the Gd$_2$O$_3$ additive. A tripling of minimum quench energy (MQE) is observed in the case of doped wires.

**MATERIALS AND TECHNOLOGY**

The goal of this R&D is to increase the training rate and reduce the margin of operation (ultimately to 90-93%) in the Nb$_3$Sn magnets. The ultimate current of “ideally-built” magnets is generally limited by magnetic field and Lorentz forces in the conductor and how these forces are handled in a magnet. The coils are epoxy impregnated to allow their pre-stressing to reduce their motion. When approaching these high operational limits, the MQE required to initiate a quench converges to zero. With a low MQE, small disturbances from the release of heat (cracking, slip-sticks, or flux jumps in the conductor) will initiate a quench. It is believed that slip-sticks in the epoxy create mechanical disturbances which are the main contributors to quenching that approaches the short sample limit of the magnet conductor [8].

There are several possible technical solutions. One of these includes improved resins or epoxies with the following characteristics: fracture resistant (fewer cracks, see Ref. [9]), a high modulus (less strain energy) and ability to sustain heat fluctuations, thermal conductivity, and increased specific heat (similar to what was discussed in the section above on conductors). Another possible improvement is to find a way to prepare clean Nb$_3$Sn conductor surfaces and use insulation with better bonding capabilities.

The standard “test-bed” to investigate or measure the properties of the new materials or coil technologies is the so called 10-stack experiment [10]. This technique imitates a portion of the coil by using 10 short-length, fully insulated cables (samples) which are subjected to all the steps of fabrication–curing, reaction, and epoxy impregnation. These samples can be tested under compression along different directions in a calibrated loader at room and cryogenic temperatures (Fig. 3 shows a test sample). Thermal contraction and electrical measurements can be tested as well. Furthermore, using acoustic sensors during the compression provides information about the processes that release heat and possibilities of comparing the signals from real magnet quenches.

**NB$_3$SN MAGNET R&D**

As was mentioned above, the near-term program focuses on small-aperture accelerator magnets based on the Nb$_3$Sn superconductor with nominal operation fields of 15+ T and technologies associated with these magnets. In the longer term, the program will move toward development of accelerator magnet technology at the limits of Nb$_3$Sn materials.

The current effort is concentrated in the 15 T Nb$_3$Sn dipole demonstrator, which is the flagship of the MDP LTS program. This magnet is a step toward dipole development for a 100 TeV proton-proton collider. It is a shell-type dipole, with 4-layer graded coils forming a field in a 60-mm aperture. The coils were optimized for conductor stresses, field quality, and efficiency. The coils are made of two Rutherford cables with the same 15 mm width with an average thickness of 1.87 mm in the inner layers and 1.32 mm in the outer layers. The 1.0 mm and 0.7 mm Nb$_3$Sn strands are used in the inner and outer coil layers, respectively.

The magnet cold mass is approximately 1 m long. The cold mass transverse size was kept below 610 mm, a
NEW MAGNET TEST FACILITY

One of the goals of MDP is to develop 16+T Nb₃Sn or 20+ T hybrid accelerator dipole magnets. This program will require additional test facility infrastructure to accommodate magnets of much larger diameter, as well as to provide options for multiple power and energy extraction systems that would allow use of the facility to perform HTS conductor testing for magnet inserts. A possible upgrade to support HTS cable tests for the U.S. fusion community is under investigation. Initial plans are to locate a new High Field Vertical Magnet Test Facility (HFVMTF) at Fermilab near the existing infrastructure which would utilize the existing 1.9 K liquid helium supply, the 30 kA power supplies, and other infrastructure.

The parameters of such a facility are summarized in Table 1. The minimum operating temperature is set to 1.9 K for the Nb₃Sn test magnet or for the magnet providing the background field HTS samples. For the latter, it is assumed that there should be a variable cooling ability in the vicinity of 4.3 to 45-55 K. The test facility cryostat should be able to accommodate a dipole cold mass with a maximum diameter of 1.3 m and length of approximately 3.0 m.

Two independent power supply (PS) and quench protection (QP) systems are needed to operate the hybrid magnets. The main PS system will provide 24 kA for the LTS coils, while the HTS coils will be powered by a 15 kA PS. The QP systems will be tuned specifically for the LTS or HTS coils of the magnet.

The major requirements for the facility are defined based on safe and efficient operation, minimizing the time for the preparation of test objects, and no helium gas losses after quenches. The operation life span of this facility will be 20 years or longer, depending on the future test demands.

The large-aperture Nb₃Sn magnet providing background field for HTS samples will be designed and manufactured in a collaboration between the U.S. MDP and Fusion Science. It is expected to have similar or better parameters than FRESCA2 [13] of the EDIPO magnet substitute [14]. Layouts, facility structural analysis, and cost estimates have been completed, and financial approval to begin the civil construction is expected.

CONCLUSION

Fermilab’s Nb₃Sn R&D program is an integral part of the U.S. MDP. The program is vibrant and covers a full spectrum of tasks from conductor to magnet technology and to building a 15 T dipole demonstrator. In this short paper, we summarize only the major efforts to be undertaken, especially in conductor and magnet R&D. We have also included a description of a new Fermilab Magnet TEST Facility.

REFERENCES


Table 1: HFVMTF Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>Operating temperatures, [K]</td>
<td>1.9-4.5</td>
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<td>Max. energy of the cold mass, [MJ]</td>
<td>15</td>
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<td>Max. magnet diameter and length, [m]</td>
<td>1.4/3.0</td>
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<tr>
<td>Max. weight of the cold mass, [t]</td>
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<td>Max. number of quenches</td>
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<td>Max. number of thermal cycles</td>
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<td>Cool down and warm up speed</td>
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<td>Magnet test position</td>
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<td>Life span</td>
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MC7: Accelerator Technology
T10 Superconducting Magnets
