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FERMILAB SUPERCONDUCTING Nb_3Sn HIGH FIELD MAGNET R&D PROGRAM*

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Abstract

Magnets based on the modern Nb_3Sn 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_3Sn 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_3Sn superconductor with a possible insert based on high temperature superconductors (HTS) and associated technologies. These Nb_3Sn 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_3Sn, and HTS magnets. This paper will discuss only the Nb_3Sn 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_3Sn. 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_3Sn 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

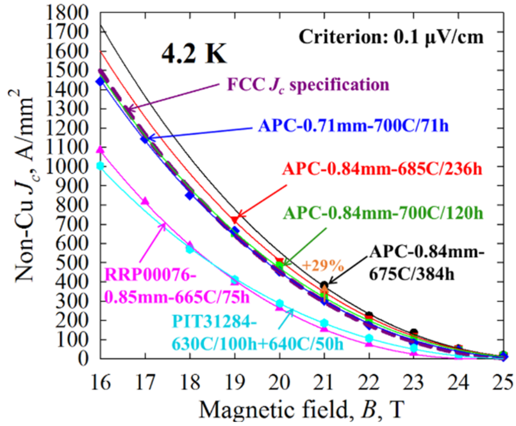

Figure 1: Non-Cu J_c of APC wires, the current state-of-the-art production wires for HL-LHC and FCC specifications (from Ref. [3]).

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_3Sn 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_3Sn 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_3Sn 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_3Sn 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_3Sn superconductor at temperatures below 5 K. Due to this low specific heat, a small heat perturbation can cause a large temperature increase in Nb_3Sn superconductors and a resulting magnet quench.

The next important modification to Nb_3Sn has the potential to eliminate or decrease quench training of Nb_3Sn magnets. Increasing the specific heat (C) of Nb_3Sn 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_3Sn wires, replacing some Nb_3Sn or

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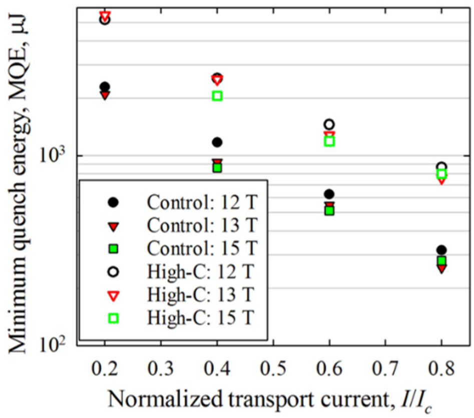

Figure 2: Minimal quench energy for wires with and without high C additives in relation to the I/I_c ratio (from Ref. [7]).

Cu filaments with Cu tubes filled with a mixture of Cu plus high-C powders. In the first prototype wire, Gd_2O_3 was used as a high-C component [6]. Several wires with different percentages of Gd_2O_3 were drawn by Hyper Tech Research Incorporated [7]. Figure 2 shows the comparison between wires with and without the Gd_2O_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_3Sn 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_3Sn 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.

NB3SN MAGNET R&D

As was mentioned above, the near-term program focuses on small-aperture accelerator magnets based on the Nb_3Sn 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_3Sn materials.

The current effort is concentrated in the 15 T Nb_3Sn 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_3Sn 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

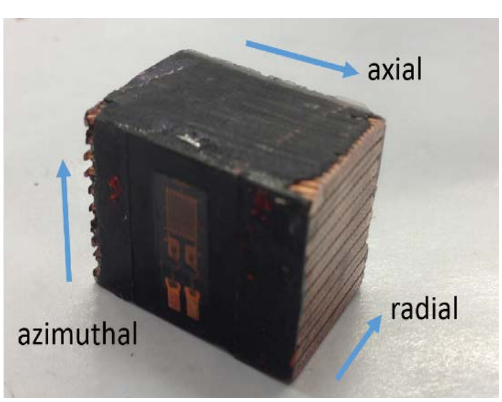

Figure 3: An example of a cable stack sample [10].

Figure 4: 15 T dipole demonstrator prepared for cold test.

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limitation necessitated by the inner diameter of Fermilab's test cryostat. Quench protection heaters made of stainless-steel strips are placed on the top of the outermost layer. The details of the magnetic and structural designs as well as the magnet parameters are described elsewhere [11, 12].

With contributions from LBNL and CERN, the magnet has been assembled and fully instrumented. The first cold test is expected in May–June 2019. Depending on the lessons learned from the first test, a second test is planned for late 2019. Figure 4 shows the 15 T cold mass in the preparation stage for insertion into the testing cryostat in the Fermilab Vertical Magnet Test Facility.

NEW MAGNET TEST FACILITY

One of the goals of MDP is to develop 16+T Nb_3Sn 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 Nb_3Sn 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.

Table 1: HFVMTF Parameters

Parameter	Requirement
Operating temperatures, [K]	1.9-4.5
Max. energy of the cold mass, [MJ]	15
Max. magnet diameter and length, [m]	1.4/3.0
Max. weight of the cold mass, [t]	15
Max. number of quenches	15000
Max. number of thermal cycles	2000
Cool down and warm up speed	Variable
Magnet test position	Vertical
Life span	25 years

The large-aperture Nb_3Sn 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 Nb_3Sn 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.

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