The 40 T Superconducting Magnet Project at the National High Magnetic Field Laboratory

H. Bai, M. D. Bird, *Senior Member, IEEE*, L. D. Cooley, *Senior Member, IEEE*, I. R. Dixon, *Member, IEEE*, K. L. Kim, D. C. Larbalestier, *Fellow, IEEE*, W. S. Marshall, *Member, IEEE,* U. P. Trociewitz, and H. W. Weijers, *Member, IEEE,* D. V. Abraimov, G. S. Boebinger

***Abstract*—The National High Magnetic Field Laboratory has launched an innovative project to develop a 40 T all superconducting user magnet. The first year funding was awarded by the National Science Foundation in September 2018. Consideration of a 40 T superconducting user magnet sets target specifications of a cold bore of 34 mm with a homogeneity of 500 ppm over a 1 cm diameter of spherical volume, a better than 0.01 T set-ability and stability, and with an ability to ramp up to full field 50,000 times over its 20 years design lifetime. It will be a fully superconducting magnet that can withstand quenches at its full 40T field and provide a very low noise environment for experimentalists. These capabilities will enable the 40 T SC magnet to support higher-sensitivity measurements than possible in present-day resistive and hybrid magnets; high-magnetic-field measurements that will be uniquely capable of addressing physics questions on a number of expanding frontiers in condensed matter physics. A 40 T SC magnet would enable more users to run long experiments at peak field with much less power consumption compared with resistive and hybrid magnets. However, realization of such a 40 T SC magnet requires magnet technology well beyond the present state-of-the-art. Initial analysis of different HTS magnet designs, based upon the three presently viable HTS conductors: REBCO, Bi-2212, and Bi-2223, has determined that each technology faces significant challenges. Hence, we decided that four HTS magnet technologies consisting of Insulated REBCO, No-Insulation REBCO, Bi-2212, and Bi-2223 would be developed in parallel and technology gaps based on major risks will be closed in the R&D phase. The candidate technologies will be narrowed down at the decision points. The objective and R&D activities of the 40 T all superconducting user magnet project are presented.**

***Index Terms*—High Field Magnet, High-temperature superconductors, Superconductor, Superconducting Magnet**

I. Introduction

The National High Magnetic Field Laboratory (NHMFL) is a user facility to develop, maintain, and operate advanced high field magnetic systems for a diverse user community to promote advances in physics, material, energy and life sciences. The DC magnet facility currently runs several world record magnets including the 45 T hybrid magnet [1], the 36 T hybrid magnet [2], and the 41.5 T resistive magnet [3]. Each of them requires 14 – 30 MW of power to operate the resistive coils. Superconducting (SC) magnets require much less electrical energy for around-the-clock operation. They also provide a very low noise environment for users' experiments. The maximum field reached by conventional Low Temperature Superconducting (LTS) magnets is not more than 23.5 T to date. The reasons are that the upper critical field of LTS superconductors are 15 T and 30 T for Nb-Ti and Nb_3Sn respectively and the critical current density falls off rapidly when the field is close to the upper critical field [4]. The high upper critical field and high critical current density of available High Temperature Superconductor (HTS) conductors can greatly extend the magnetic field beyond the limits of LTS conductors. Three commercial HTS conductors are available for high field magnet application: Bi-2212 ($Bi_2Sr_2CaCu_2O_{8+x}$), Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10+x}$), and REBCO (Rare Earth $Ba_2Cu_3O_x$) conductors. Fig. 1 shows the irreversibility field of the LTS and HTS superconductors. Note that the irreversibility fields for HTS superconductors are all well above 40 T at an operating temperature of 4.2 K [4].

The NHMFL started to pursue high field HTS superconducting magnet technology in the early 1990s [5], [6]. Most recently, the 32 T all-superconducting magnet reached full field in December, 2017 [7] after more than eight years of development, providing a field leap of 8 T over the previous record for superconducting magnets [8]. The success of the 32 T all-superconducting magnet and the great progress recently made on the performance of HTS conductors including REBCO, Bi-2212 and Bi-2223 enabled the NHMFL's proposal to the National Science Foundation (NSF) to launch a project to develop a 40 T all superconducting user magnet.

II. HTS Magnet Technology

HTS magnet technology development could not be advanced without progress on the HTS conductor performance. The commercial availability of REBCO conductors in long piece lengths brought up strong interests in the application of high field magnets because of the high upper critical field, high strength, and high critical current density in high magnetic field [9]. Currently the manufacturers can supply a length of hundreds of meters and a tape width of 2 mm to 12 mm. As such,

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H. Bai, M.D. Bird, L.D. Cooley, I.R. Dixon, K.L. Kim, D.C. Larbalestier, W.S. Marshall, U.P Trociewitz, H.W. Weijers, D. A. Abraimov, and G. S. Boebinger, are with the National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310, USA (e-mail: bai@magnet.fsu.edu).

REBCO has been the main candidate conductor for many high field magnets projects. W. D. Markiewicz *et al.* tested a solenoid made of REBCO conductor and reached a record 33.8 T in a 31 T background field in 2009 using the 4 mm width conductor [10]. Then the 32 T all superconducting user magnet project was funded by the NSF in 2009. It uses insulated stainless steel tapes as the co-wind for the HTS windings and a 250 mm bore LTS magnet as the outset to provide a background field of 15 T. It reached full field in the end of 2017 [7], [11], [12]. This represents the highest field user magnet and a key milestone reached by an all-superconducting magnet.

No-Insulation (NI) REBCO magnet design was introduced and demonstrated much higher current densities in the winding, and self-quench protection compared to insulated REBCO magnets [13]. A 26 T NI-REBCO standalone magnet was tested up to 26.4 T, which represented a record of magnetic field increase contributed by HTS conductor alone [14] although this magnet later showed damage [15]. Hahn *et al.* tested a No-Insulation REBCO coil in a 31 T background field and it reached 45.5 T in 2017 [16]. The inner diameter of this NI test coil winding is only 14 mm, too small for a user magnet; however it demonstrated that a REBCO coil can reach a field well above 40 T. A detailed *post mortem* of the coil showed conductor damage, probably due to both the high stress caused by induced screening currents and also overstress to some pancakes during quench. Many other groups are also working on NI-REBCO technology. Song *et al.* reached a field of 32.5 T by a metal-insulation REBCO coil in a background field of 18 T provided by a resistive magnet [17], [18]. A 1.3-GHz LTS/HTS NMR Magnet under development at MIT was damaged due to coil force interactions produced in a quench at 18 T [19], [20]. The failure of numerous REBCO coils indicates there are still significant challenges for high field REBCO magnets when the stored energy and stresses increase as the size and field of the magnets increases.

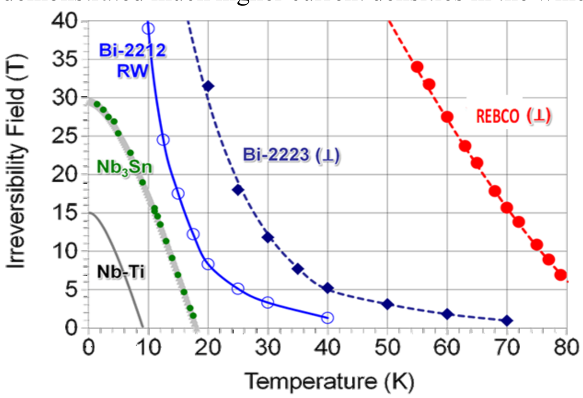

Fig. 1. Irreversibility field of the superconducting conductors. Each of the three HTS conductors (Bi-2212, Bi-2223 and REBCO) has an irreversibility field well above the limit that LTS conductors (Nb-Ti and Nb_3Sn) can reach [4].

Bi-2212 conductor is the only HTS conductor currently manufactured in round wire form. Round wire is favorable for magnet fabrication (the flexible architecture easily allows a diameter range of 0.8 to 1.5 mm). It needs to be reacted after winding at a high pressure ranging from 2 MPa to 10 MPa and at a temperature of about 880 °C [4], [21], a unique challenge among HTS conductors and significantly higher temperature than LTS Nb_3Sn. The highest field of 33.8 T has been reached by a Bi-2212 coil in a 31.2 T background at the NHMFL in 2014 [4]. The critical current density has continued to improve in the past few years and the engineering current density J_e reached 930 A/mm^2 at 4.2 K and 30 T in 2018 [21], [22].

In 2015, Bi2223 conductor with a high-strength nickel alloy lamination became available from Sumitomo Electric Industries, LTD. Like the REBCO conductor, it is delivered in a superconducting form without need of heat treatment. A Bi-2223 magnet reached 24.6 T in a background field of 14 T in Tohoku university in 2016 [8] and is now routinely operated to 24.0 T. At the NHMFL, a Bi-2223 coil was tested up to 19.5 T in a 14 T background field in 2017 [23], [24].

All three of the HTS conductors have been successfully used in HTS test coils or user magnets, but each of them faces significant technical challenges to construct a 40 T user magnet. As such, it is premature to fix a design and start construction of a 40 T superconducting magnet at this stage. Thus, during the first year R&D phase, the project focused on developing four HTS magnet technologies: Insulated REBCO (I-REBCO), No-Insulation REBCO (NI-REBCO), Bi-2212 and Bi-2223. The major challenges of the four technologies at the start of the 40 T project are listed in Table I.

III. R&D Activities

The 40 T superconducting magnet is expected to be installed in the NHMFL's DC Field facility. The expectation is that the magnet will operate in a similar manner to the LTS superconducting magnets presently installed. Requirements include: a central field of 40 T in a cold bore of not less than 34 mm with a homogeneity of 500 ppm over a 1 cm diameter of spherical volume, a better than 0.01 T set-ability and stability, and an ability to ramp up to full field 50,000 times over its 20 years design lifetime, with a ramping up time of about one hour to full field. To meet these requirements, the scope of work was planned to tackle the major technical challenges listed in Table I in the R&D phase.

A. Conductor Characterization and Quality Control

The mechanical and transport properties of HTS conductors are critical for the high field magnet design [25], [26]. In the 32 T project, tremendous effort was made on characterization of REBCO conductors manufactured by SuperPower. The REBCO conductor kept improving in recent years, mainly on the transport current. Due to high demand for REBCO conductor from the fusion community, the delivery time of conductors has recently become much longer. To qualify alternative conductor vendors seems necessary to mitigate schedule and budget risks. We have ordered conductors from various vendors to characterize their critical current, critical current uniformity, and mechanical properties. Fig. 2 shows the recent test results of REBCO conductors from these vendors. It shows that the I_c varies over quite a wide range among vendors.

The properties of Bi-2212 conductors and Bi-2223 conductors were also measured recently and details are reported in

TABLE I
COMPARISON OF THE FOUR HTS MAGNET TECHNOLOGIES

TECHNOLOGY	STATUS	MAJOR CHALLENGES
I-REBCO	Conductors available from multiple commercial vendors; Demonstrated in the 32 T all superconducting magnet at the NHMFL.	1. Quench protection in a large scale magnet; 2. High stress due to screening current; 3. Fatigue degradation of conductor due to cyclic operation.
NI-REBCO	45.5 T total field was achieved in a small test coil in a background field of 31 T; 26 T was reached in a standalone NI magnet.	1. High stress due to screening current and transient over-currents during quench; 2. Fatigue degradation of conductor due to cyclic operation; 3. Quench protection of a large coil; 4. Field ramping delay.
Bi-2212	33.8 T total field was reached in a small test coil in a background field of 31 T; Current density in the conductor reached 930 A/mm^2 in 30 T at 4.2 K.	1. Heat treatment of large coils at high temperature and high pressure; 2. High stress in the high field magnet and fatigue degradation; 3. Quench protection of a large coil.
Bi-2223	Bi-2223 coil reached a field of 24.5 T; Conductor of high-strength nickel alloy lamination is available.	1.Relatively low conductor current density requires a large size magnet; 2. Fabrication of large coils including coil winding and splices has not been demonstrated; 3. High stress in the high field magnet and fatigue degradation; 4. Quench protection.

[22], [27]. The Bi-2223 tapes have anisotropic transport properties, similar to the REBCO tapes. By contrast, Bi-2212 round wire is macroscopically isotropic.

The 40 T project will characterize the transport properties of the conductors up to a field of above 30 T, as well as electromechanical properties including fatigue life. For the REBCO magnet technologies, we also plan to use I_c graded REBCO tapes in the coil design to reduce the I_c margin, the required quench protection energy and deleterious screening current effects. These will build a knowledge base for the design of the 40 T SC magnet.

B. Coil Design and Simulation

The initial 40 T SC magnet designs require an HTS coil with a stored energy at least six times larger than the highest field HTS magnets ever achieved around the world to date. Initial designs aim to limit the peak stress and strain in the high field coils, which are driving factors for the size of a 40 T SC magnet.

Rippling along the edge of tape conductors was seen in Nb_3Sn coils from the 1970s as well as test coils in the 32 T project and, more recently, in NI-REBCO test coils at the NHMFL[16]. An example is shown in Fig. 3. We believe yielding of the tape substrate is due to high stress created by screening currents interacting with the high axial field.

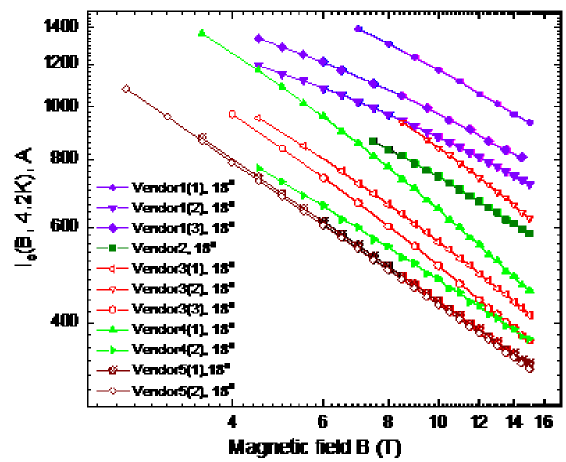

Fig. 2. Characterization of REBCO tapes (4 mm width) from various vendors. The I_c was measured at various magnetic fields, field angles and temperatures. This plot shows the I_c up to 15 T at 4.2 K and an angle of 18 degree from the tape plane. The tape characterization is necessary to identify potential vendors for high field magnets conductors and to provide I_c data for 40 T SC magnet designs. The I_c variation of vendor 3 is due to intentional grading.

During our 32 T SC magnet project, we partnered with the National Autonomous University of Mexico (UNAM), the Karlsruhe Institute of Technology, and Lanzhou University to compute screening currents in REBCO tape magnets [28], [29]. At that time the algorithms were too slow to allow computation of strain. We also started to perform fatigue testing of coils but schedule and budget constraints required us to press forward. More recently the algorithm for computing screening currents was accelerated, allowing real-time computation of the charging of a magnet [30] which could be used for field controlling. Strain due to screening currents has now been computed [30]-[32]. Fig. 4 shows the comparison of peak stress in a pancake coil with and without consideration of the screening current. Note that including the screening current yields much higher calculated peak stress.

We are also advancing quench simulation technologies to simulate the quench propagation [33][34]. We are actively developing Coupling Loss Induced Quench (CLIQ) method for Bi-2212 and Bi-2223 coils [35]. Compared with insulated superconducting coils, the quench simulation for an NI coil is relatively new. An NI coil was demonstrated self-protecting in small test coils [36]. As an NI coil becomes larger, it might not be self-protect [34]. The quench codes will be benchmarked against the coil test results shown in the next section.

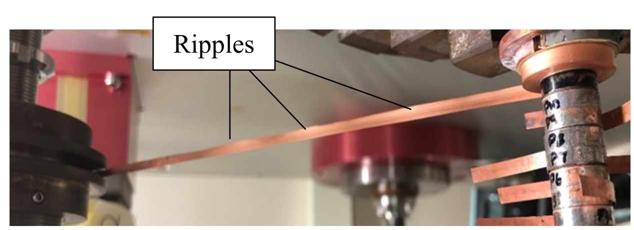

Fig. 3. The edges of the REBCO conductor are rippled after test in a test coil

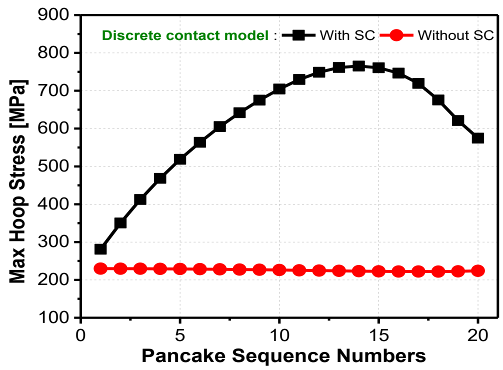

Fig. 4. Simulated maximum hoop stress in a pancake REBCO coil: with and without consideration of screening current (SC). They are calculated using COMSOL with discrete contact elements [32].

During the R&D phase, conceptual designs of 40 T SC magnets based on each of the technologies described above will be evaluated and the most promising design will be selected in the proposal for the construction of the 40 T SC magnet.

C. Coil Testing from Sub-scale to Mid-scale

Development of HTS coil technology at the NHMFL has typically been demonstrated in small-scale coils (<500 m length of conductors) before moving to mid-scale coils (< 2 km). The full-scale coils for 32 T included ~ 10 km of tape. For 40 T, we are again starting at the small scale for NI-REBCO while I-REBCO, being based on 32 T experience, will continue mid-scale testing. A series of test coils are planned to demonstrate effective stress management, fatigue life, quench detection and quench protection, and field control for each technology.

During the first year, two Bi-2212 small coils and four NI-REBCO small coils have been tested. Fig. 5 shows the quench propagation in a NI coil with 6 double pancakes (DP). The coil was designed to investigate fatigue life and quench propagation of a REBCO coil, especially considering the stress caused by screening current. The coil was cyclically operated for 2000 cycles and it is currently under inspection [37]. The fatigue test of another coil is still on-going. There is a large transient current in the pancakes during quench which was anticipated by quench simulation. The contact resistance is a critical parameter to be controlled in an NI magnet and efforts will be made to improve

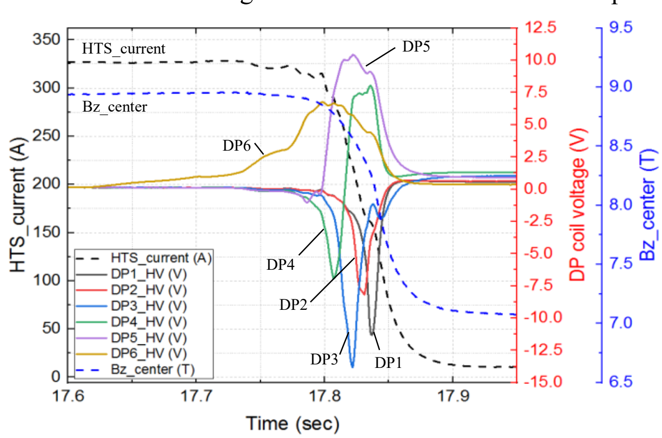

Fig. 5. Quench transient process of an NI test coil. This coil was tested in a background field of 6.9 T to investigate the fatigue life of a REBCO coil. The quench initiated in Double-Pancake 6 (DP6)

the charging time delay and reduce the transient current during quench [33], [34], [38]. For success, the contact resistance shall not degrade during quench and cyclic operation.

Two Bi-2212 coils were tested to develop reinforcement technology needed for high field magnets. Fig. 6 shows one of the test coils [39]. The coil was successfully ramped up to 345 A in a background field of 14 T with a maximum strain of 0.39%.

Although I-REBCO technology was successful in the 32 T SC magnet, it still requires significant further development to assess suitability at 40 T, especially for stress and fatigue management, as well as quench protection. The next I-REBCO test coil will use conductor with I_c grading, a new challenge for conductor manufacturer.

We will also continue to develop and improve magnet fabrication technologies in the R&D phase.

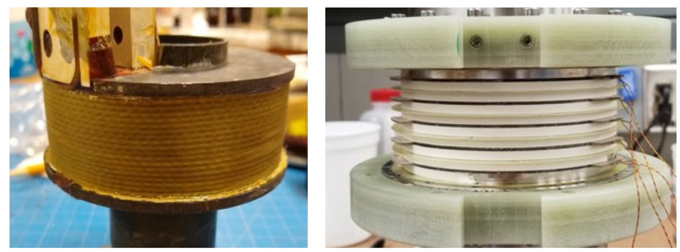

Fig. 6. A Bi-2212 test coil (left) and an NI-REBCO test coil. The Bi-2212 coil was tested in a 14 T LTS magnet. The NI-REBCO was tested in a 6.9 T background field.

IV. Conclusion

The NHMFL has launched the multi-faceted R&D program necessary for a 40 T all-superconducting user magnet. The 40 T SC project will advance the application of HTS in high field magnets and also benefit magnet technologies to advance ultra-high field NMR, neutron sand X-ray scattering, as well as high energy physics including axion detection. The 40 T SC project has been developing four promising HTS coil technologies in parallel (Bi-2212, Bi-2223, NI-REBCO, I-REBCO) to enable magnet technology beyond 32 T. Each of the four technologies has its own challenges, which are being tackled in the R&D phase of the 40 T SC project. One magnet design of one technology or more of these technologies will be selected to proceed a final design and construction. A successful 40 T SC magnet will enable users to run long experiments at peak field, with better field stability and homogeneity than those provided by resistive magnets.

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