High Field Magnets with HTS Conductors

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***Abstract*—Development of high-field magnets using high temperature superconductors (HTS) is a core activity at the NHMFL. Magnet technology based on both YBCO-coated tape conductors and Bi-2212 round wires is being pursued. Two specific projects are underway. The first is a user magnet with a 17 T YBCO coil set which, inside an LTS outsert, will generate a combined field of 32 T. The second is a 7 T Bi2212 demonstration coil set to be operated in a large bore resistive magnet to generate a combined magnetic field of 25 T. Owing to the substantial technological differences of the two conductor types, each project faces different conductor and magnet technology challenges. Two small coils have been tested in a 38-mm cold bore cryostat inserted in a 31 T resistive magnet: a Bi2212 round-wire layer-wound insert coil that generated 1.1 T for a total of 32.1 T and a YBCO double-pancake insert that generated 2.8 T for a total central field of 33.8 T. Four larger layer-wound coils have been manufactured and tested in a 20 T, 186-mm cold bore resistive magnet: a sizeable Bi-2212 coil and three thin large-diameter YBCO coils. The test results are discussed. The current densities and stress levels that these coils tolerate underpin our conviction that > 30 T all-superconducting magnets are viable.**

***Index Terms*—BSCCO, YBCO, HTS, high-field magnet**

I. Introduction

APPLICATIONS for high-field magnets with HTS conductors include general purpose research magnets and NMR magnets. At its founding the NHMFL was charged with the development of a 900 MHz 21.1 T NMR magnet to be followed by a 25 T system [1]. In 2005 COHMAG threw down the challenge of a superconducting 1.3 GHz 30 T magnet [2]. Application of HTS is also proposed as replacement for the resistive magnet in the ZeEMANS scattering magnet [3] and now too for high-energy physics applications such as dipoles [4] and muon cooling magnets [5]. HTS coils are planned in conceptual designs of 55 T Hybrids to extend the magnetic field contribution of the superconducting coils beyond the range of Nb_3Sn, allowing replacement of the outer resistive coils that consume a disproportionate fraction of the power dissipated relative to their magnetic field contribution [6]. Development of high-current HTS cables is highly desirable for the latter applications. Here we will consider primarily solenoidal HTS research magnets with single-strand conductor, but many results are relevant to all high-field HTS magnets.

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Two of the primary demands on the windings of HTS coils are the ability to carry high current density at high magnetic field and tolerance for the resulting stress levels. Benchmark parameters for 25 T magnets are an average winding current density J_{ave} of 100 A/mm^2 and stress levels of order 200 MPa. A cold bore size on the order of 4 to 5 cm is implied. For compact 30 T magnets with similarly sized outsert LTS coils, a J_{ave} of ~200 A/mm^2 should suffice, but with more than double the stress levels [7]. The required current density averaged over the cross-section of the conductor J_e itself is higher than J_{ave} and depends on the superconductor fill-factor. At this early stage, insulation fill factor challenges are particularly obvious for wind-and-react Bi2212.

High field magnets are usually conceived as an assembly of Nb-Ti and Nb_3Sn outer coils (the “outsert”) and HTS inner coils (the “insert”). Preferably, the insert runs electrically in series with the outsert. However, during the development phase of an HTS insert magnet, it is common to power HTS coils under test independently of the outsert. The outsert can be either a superconducting, resistive or a hybrid magnet. Most HTS inserts to date have been demonstration magnets, intended to prove certain technology advances. High field capable conductors that are available in more or less long lengths include Bi-2223 tape conductor, Bi-2212 round wire and tape-form REBCO coated conductor. At this time REBCO conductor development is primarily driven by low field electric utility applications at 65-77 K. The implications of such a focus for high field applications at 4 K and high fields are not all yet obvious.

II. Recent developments

In the early 1990s, before long-length REBCO coated conductor became available, the development of HTS high-field magnets concentrated on react-and-wind tape Bi2212 and Bi2223 conductors. An early outstanding result was obtained in 1994 with a Bi2223 coil that generated a central field of 24 T in the MIT Hybrid [8]. By 2000 Hitachi had developed the first HTS coil that became part of a high-field user magnet [9]. With a Bi-2212 insert coil a new 50 mm bore 21.1 T LTS/HTS magnet was created that was operated for 1.5 years. Another Hitachi-developed HTS insert created a field increment of almost 2 T for a central field of 23.42 T [10], the magnetic field value required for 1 GHz NMR. In 2003 the NHMFL/OST 5T Bi2212 insert magnet, which used about 2 km of tape conductor, was the first to reach the 25 T central field benchmark [11]. Other sizeable insert coils using about 2 km length of Bi2223 tape conductor were built and tested [12]-[15], the latter three specifically targeting the application of HTS in NMR magnets. The trend in the above mentioned developments was for the central magnetic field to slowly approach and reach 25 T, while the average winding current density slightly decreased as the HTS inserts became larger.

This rather evolutionary and steady advance was decisively broken by the very first REBCO coils which generated larger magnetic field increments with far less conductor [16]-[17] than earlier BSCCO coils. These coils feature winding current densities at least double the highest values observed in BSCCO coils, despite a nearly non-existent development activity specific to REBCO coils. At the time of the first test of the SuperPower/NHMFL coil, even the most basic high field I_c data with which to reasonably predict coil performance was lacking, as were reliable coil construction procedures in this new high stress and high energy density domain. In fact this first SuperPower coil [17] had degraded conductor resulting from the overbanding applied during coil construction to protect the outer pancake joints. This damage did not however prevent the achievement of very high winding current densities of 275 A/mm^2 at almost 27 T. A subsequent GdBCO insert built by ISTEC [18] and operated in a narrow bore 28.3 T Hybrid magnet brought the maximum central field inside an HTS insert to 29.3 T; this too despite reported damage to the conductor during winding [19]. A comparably sized YBCO insert was then constructed at the NHMFL and operated in a 31 T resistive magnet generating an additional 2.8 T at a remarkable winding current density of 440 A/mm^2 and stress levels of up to 380 MPa [20]. A group at Tohoku University, Sendai, operated spirals of YBCO coated conductor at 4.2 K under hoop stress levels of about 1 GPa [21]. In summary, YBCO coated conductors grown on strong substrates have clearly shown that superconducting magnets in the domain above 30 T are possible.

Progress on Bi2212 conductor during the recent years is not less dramatic. Virtually leak free wind-and-react coils are now possible. Bi2212 round wire is magnetically isotropic, available in lengths up to 300 m with consistent performance thus offering additional versatility to HTS based applications.

Leakage, which is due to liquid flowing through the Ag sheath during the heat treatment, was a problem with the Bi-2212 flat tape used in the 25T coil [11] and until recently was a problem in round Bi-2212 wire fabricated by OST. LoSchiavo [22] traced some leakage in OST's round wire to cracks in the as-fabricated wire. In about mid-2007, OST modified their fabrication process. Heat treated wire now shows dramatically reduced leakage. Godeke et al. [4] also reported very few leaks in heat treated sub-scale coils wound from Rutherford cable made with OST's new Bi-2212 wire.

In 2008 Oxford Instruments achieved an additional 2.07 T field increment inside a 20 T LTS system using an HTS insert made from two concentric Bi2212 wire wound coils [23]. Several small test coils and two intermediate size Bi2212 coils have recently been built and tested at the NHMFL with one of coil generating an additional 1.1 T at 31 T background field. These most recent YBCO and Bi2212 coils are further discussed in this paper.

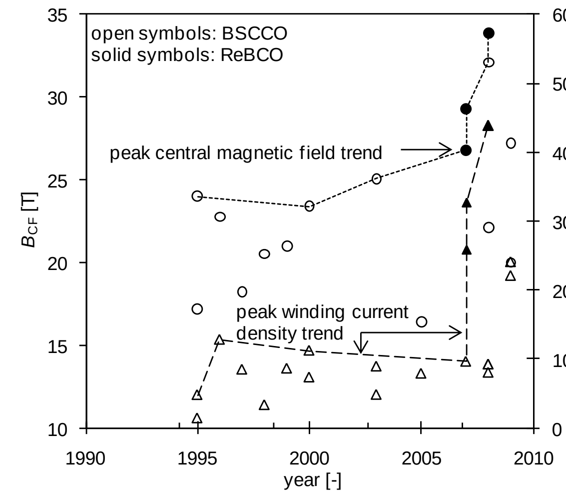

Fig. 1. Trends in the central field (circles) and winding current density (triangles) achieved in HTS coils. The breakthrough in winding current density and peak central magnetic field in HTS coils coincides with the emergence of practical rare-earth coated conductors.

The observed characteristics of recent HTS conductors clearly represent a breakthrough, while research and development specific to HTS inserts and particularly REBCO inserts have barely started.

III. NHMFL Projects and Programs

A. *32 T user magnet*

A 32 T YBCO research magnet construction project has funding by the NSF as of September 2009. The design calls for a 15 T contribution from the outer LTS coils and 17 T from the HTS coils. Target uniformity is 5x10^{-4} over 1cm diameter spherical volume (DSV) in a 32 mm cold bore. At an operating current of 186 A and with an inductance of 436 H, the resulting stored energy is 7.54 MJ. Quench protection will be accomplished with densely distributed heaters.

TABLE I. Properties of HTS Coils in the 32 T Magnet

Property	unit	Coil 1	Coil 2	Coil 3
Inner radius	mm	20	47	77
Outer radius	mm	42	71	101
Coil height	mm	144	240	340
Field increment	T	5.7	5.7	5.6
J_{ave}	A/mm^2	255	211	211
Current density copper	A/mm^2	426	426	426
Maximum stress	MPa	305	400	435
Conductor length	km	0.75	2.4	5.2

Pancake winding is planned for Coil 1 as shown in Table 1, to avoid excessive strain from in-plane bending. The remaining HTS coils may be layer wound. Some of the focal points for development are coil terminals, solder joints that can be embedded in the windings, mechanical and electrical properties of these joints, quench heaters, determination of the required amount of copper in the conductor and insulation.

Varnish insulation applied by dip coating has been used for a number of coils with a demonstrated ability to coat with a 25 μm build. However, varnish debonding was observed in epoxy impregnated coils at high conductor strain, as discussed in section V. C. Modifications of the varnish application are under development as well as alternative insulation techniques with coatings of ZnO or Al_2O_3.

Through a series of small coils, the technology will be established before fabrication of major prototype coils. The 32 T magnet will be installed with a new dilution refrigerator in the NHMFL milli-Kelvin building as a user facility.

B. 25 T Bi-2212 project

A 7 T insert magnet to reach 25 T combined field using Bi-2212 round wire is one of the goals of a research collaboration between industry and seven major research laboratories (BNL, FNAL, FSU-NHMFL, LBNL, NCSU, NIST and TAMU) in the US funded by the DOE. Bi-2212 round wire has the huge advantage of being magnetically isotropic and because of its geometry can be easily adapted to a variety of applications, *e.g.* Rutherford cables. The magnet design calls for a 7 T Bi-2212 layer-wound insert to operate in 18 T background field. The conductor is a 1.02-1.25 mm diameter Bi-2212/Ag-alloy multifilament wire with a 0.15 mm thick alumino-silicate braid insulation. The insert consists of four concentric shells with external stainless steel overbanding to serve as mechanical reinforcement. At an operating current of 221 A and a coil inductance of 240 mH, the stored energy of the coil is about 5.9 kJ. Coil parameters are shown in Table II. The insert magnet will be operated inside the large bore resistive magnet of the NHMFL with the goal of a stable field increment of 7 T in 18 T background. Protection of the coil will be accomplished using a parallel dump resistor circuit coupled with fast circuit breakers that are controlled by coil and coil section voltages through data acquisition software, as well as trip signals of the resistive outsert magnet in case of an outsert fault.

TABLE II. PROPERTIES OF THE 7 T INSERT MAGNET

	unit	Coil 1	Coil 2	Coil 3	Coil 4
Inner radius	mm	16.2	30.2	46.2	64.2
Outer radius	mm	28.2	42.2	58.2	76.2
Coil height	mm	160	160	160	160
ΔB	T	1.96	1.85	1.71	1.53
J_e	A/mm^2	270	270	270	270
J_{ave}	A/mm^2	135	135	135	135
Reinforcement	mm	0	2	4	6
Maximum stress	MPa	103	99	93	88
Conductor length	m	186	303	437	588

IV. CONDUCTOR PROPERTIES

YBCO tapes are undergoing enormous pinning enhancements that greatly enhance the J_c at higher temperatures and low fields. Here we consider three recent and representative SuperPower coated conductors fabricated using the metal-organic chemical vapor deposition (MOCVD) process on very strong Hastelloy substrate. The three samples were all doped with Gd. One (standard) was without other additions and was 2.17 μm thick. One (BZO) had Zr additions which produced $BaZrO_3$ (BZO) precipitates and was 1.5 μm thick. The third (double layer) contained two layers without BZO and was 2.15 μm thick [24]. Although the BZO sample had a distinct c-axis peak at 77K and 1 T, no sign of this remained at low temperatures where many other pinning centers operate.

Fig. 2 shows J_c as a function of external magnetic field up to 31 T at 4.2 K when the applied field is parallel and perpendicular to the ab-plane. In the H||c configuration, J_c strongly decreases with increasing magnetic field and the differences in J_c in the 3 different samples that are evident at low fields fade away at high fields. The BZO sample has the highest J_c along the c-axis and the lowest J_c in the ab plane at fields below 20 T. The really striking feature of the data is that J_c barely depends on magnetic field in the H||ab configuration up to ~20 T, while showing a reduction by ~30% at higher fields. However, this reduction is not an intrinsic property of the coated conductor, but rather a heating artifact. It is well established that diamagnetic helium is repelled from the center of the field, resulting in a helium gas bubble around the sample when the field-field gradient product $H \times \mathrm{d}H/\mathrm{d}z$ exceeds 21 T^2/cm [25], which in our system is reached at ~ 20 T. This bubble leads to measured sample temperature increases up to ~12 K. Assessment of narrow-track samples with much smaller I_c where much smaller heating occurs indicates that a linear extrapolation above 20 T in the H||ab configuration is justified. The in-plane I_c at 20 T for 4 mm wide CCs is 1205 A and 1387A for the double layer and standard samples, respectively, values quite high enough for magnet applications.

Results of the $J_c(\theta)$ measurements at 4.2 K and fields up to 30 T are striking as there is no c-axis peak for any sample at any magnetic field, quite in contrast to the 77 K data. At higher fields, the shape of $J_c(\theta)$ is same for all 3 samples and is shown for the standard samples in Fig. 3. This common cusp-like $J_c(\theta)$ strongly suggests a single dominant pinning mechanism at low temperature and high magnetic fields. At present we favor the interpretation that some of this enhanced pinning is due to the intrinsic pinning of the Cu-O planes and some to the extensive ab-plane twinning that occurs in all 3 samples.

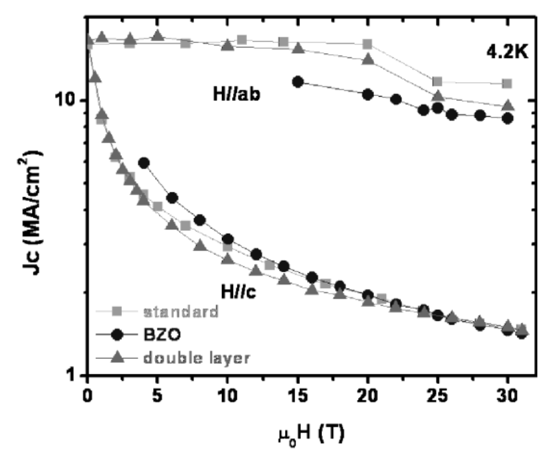

Fig. 2. Current density in the superconducting layer of three recent SuperPower conductors; one standard conductor and two samples with enhanced pinning. The reduction for H//ab above 20 T is mostly an artifact as explained in the text. Differences between conductors evident for H//c at low magnetic field disappear above 20 T.

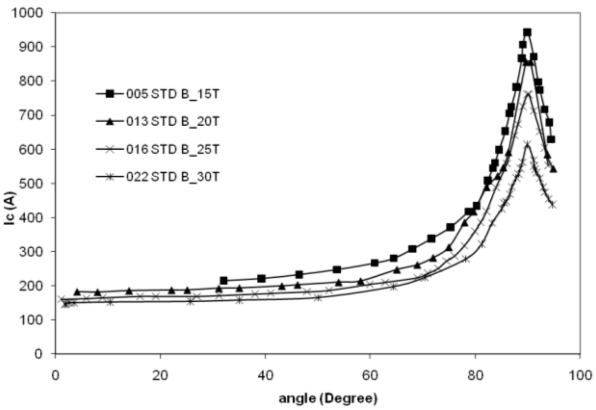

Fig. 3. Calculated I_c at 4 K of a sample of standard SuperPower SP4050 conductor. The width of the superconducting layer between the voltage taps is reduced from 4 to 1 mm to accommodate the limited amperage of the experimental setup. The measured I_c's are then multiplied by four. For reference, I_c(77 K, self-field) of the conductor as-received is around 120 A.

V. COIL RESULTS

A number of HTS insert coils have been built and tested with the intent of finding magnetic field and strain induced limitations of the conductor and to gain experience with the construction of YBCO and Bi-2212 coils. The main properties of the coils are listed in Tables III and IV. All coils were tested while submerged in liquid helium at atmospheric pressure at 4.2 K unless otherwise noted. Active quench detection was set up using a dump resistor parallel to the insert and contactors in the leads to the power supply. The contactors were activated when the voltage across one of multiple taps on the insert exceeded a preset threshold, usually around 50 mV. The delay between exceeding the trip voltage and opening of the contactors is <10 ms. A Hall –effect sensor placed in the bore of the inserts was used to measure the central magnetic field, which corresponded, in all cases, closely to the values based on the calculated field constants.

TABLE III. PROPERTIES OF THE PANCAKE MAGNET

Property	unit	Coil A
Superconductor	-	YBCO
Inner radius	mm	12.3
Outer radius	mm	18.3
Coil height	mm	46
Field constant	mT/A	8.6
Number of pancakes	-	10
Turns per pancake	-	38
Conductor length	m	36

TABLE IV. PROPERTIES OF THE LAYER WOUND MAGNETS

Property	unit	Coil B	Coil C	Coil D	Coil E	Coil F
Superconductor	-	----Bi-2212----		---------YBCO------------		
Inner radius	mm	15	32	79.9	79	79
Outer radius	mm	38	57	81.7	81	81
Coil height	mm	100	180	25	25	25
Field constant	mT/A	9.1	9.1	0.45	0.39	0.39
Layers	-	10	10	12	10	10
Turns/ layer		75	13.5	5	5	5
Conductor length	m	66	220	30.5	30.5	25.3
Impregnation	-	Vacuum		vacuum		wet-wound

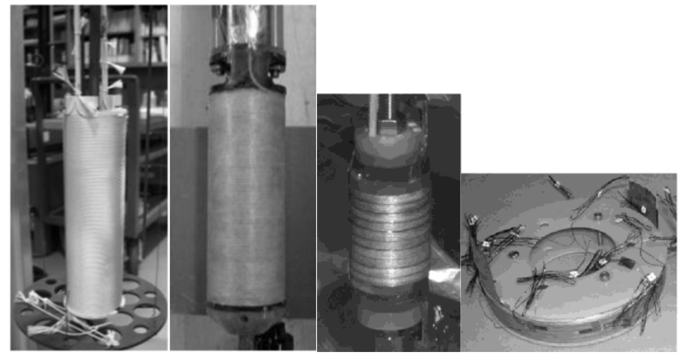

Fig. 4. From left to right: Coil B built following largely the design specification of the innermost coil of the 7 T insert magnet design; Coil C that generated 1.1 T in 31 T background field; Coil A that generated 2.8 T in 31 T background field; and Coil F that tolerated 760 MPa.

A. *YBCO coils in high magnetic field*

Coil A as described in Table III was built to explore the magnetic field induced limits of the current carrying capacity of YBCO coils above 30 T. The conductor is standard SuperPower SP4050 type with 20 μm Cu plating and a nominal cross-section of 4.04 mm by 0.095 mm. I_c(77 K, self-field) is 129 A. Based on a comparison with similar conductors (see Fig. 3), the I_c(4.2 K, 31 T) is expected to be ~ 600 A.

The coil is constructed from 10 single pancake units with soldered resistive joints at the inner and outer radius. Turn-turn insulation is provided by a varnish coating on the conductor while G-10 disks are used as insulation between the pancakes. The coil itself is not impregnated, but is overbanded with a 1 mm thick layer of epoxy-bonded glass fiber string, forming the structural backbone.

When operated in the 31 T background field from a resistive magnet a maximum current of 325 A was reached, corresponding to a record central magnetic field of 33.8 T. The average current density in the windings was around 440 A/mm^2, which is an exceptionally high value for any superconductor at high magnetic field. Estimating the stress in the outer turns as $J_e \cdot B \cdot$radius assuming independent turns and ignoring the effect of the overbanding yields 324 MPa.

There were two effects that limited the operating current in this insert. The first limiting effect was excessive Joule heating in the current lead connections to the coil in combination with the magnetic properties of helium gas. Helium gas can become trapped when the magnetic-field·field-gradient product exceeds 2100 T^2/m, leading to poor cooling of the coil. This threshold was exceeded by a factor of at least four. Readings of a temperature sensor located near the windings indicated that the coil temperature likely exceeded 12 K before thermal runaway and exceeded 50 K thereafter. For each subsequent test the background magnet was ramped below 20 T to release the gas. Pumping the bath to a temperature of 1.7 to 1.8 K to cool the coil with superfluid helium brought no effective relief from this effect. Significantly reducing Joule heating, which is certainly possible in this case, would likely result in adequate cooling.

The second limiting effect was mechanical in nature. Voltage taps indicated local degradation of the critical current, possibly because of axial forces within the coil or stress concentrations at the terminals. The coil was not impregnated so as to allow for replacement of pancakes and indeed one double pancake unit was replaced after the first test. A failed solder joint in the current lead connections near the coil terminals damaged the coil in a subsequent test so the effectiveness of the repair could not be assessed.

B. Bi-2212 in high magnetic field

In both coils B and C, see Fig. 4, alumino-silicate braided Bi2212 wire was used that was wound around mandrels made from a high strength, corrosion resistant Nickel-base alloy (Inconel600) [26]. Using the recent generation of Bi-2212 wire by Oxford Instruments the coils did not exhibit any observable leakage. After the heat treatment the coils were vacuum impregnated with STYCAST 1266 epoxy resin.

The specifications of Coil B are in Table IV. At 31 T background the coil generated a magnetic field increment of 1.1 T at 120 A and a winding current density J_{ave} of 80 A/mm^2 at a peak stress of about 86 MPa without any measurable degradation. These results make it the first HTS wire wound coil to successfully reach beyond 30 T.

Coil C was manufactured largely following the design specification of the innermost coil of the 7 T insert design. At 20 T background field this coil generated 1.2 T before the inner layer went into early quench at 105 A. The other layers and the terminals showed no voltage rise. Peak stress levels were around 72 MPa.

C. YBCO coils at high stress

Coils D, E, and F were built to explore the strain-induced limits of YBCO coils. The coil outer diameters are as large as practical for the available cryostat of the NHMFL 20 T Large Bore Resistive Magnet. The radial build of the coils was only about 1.5 mm and the coil height is 25 mm to ensure a homogeneous stress distribution in the windings. The conductor in two of the coils was varnish insulated with a glass fiber string as turn-to-turn insulation; a combination of paper and glass fiber string were used for layer-layer and turn-to-turn insulation respectively in coil F. Vacuum impregnation with STYCAST 1266 was used for the varnish-insulated coils and wet-winding for the paper insulated coil. The windings are self-supporting except for the turns near the terminals. The coils were loosely held in place to allow the windings to expand and contract unrestrained under the Lorentz-force.

The conductor is standard SP4050 type but with 30 μm Cu plating thickness instead of the usual 20 μm. The nominal thickness of 0.115 mm was used to calculate the cross-sectional area. The manufacturer reported an I_c at 77 K, self field that ranges from 94 A to 100 A for the conductor used.

Each coil is equipped with multiple voltage taps and several strain gauges to measure hoop strain as well as axial strain. Several voltage taps were used to monitor the whole coil, the outer layer, the inner layer, the hard bend at the transition between the inner and the next layer, the equivalent of the hard bend in the outer layer and two taps for the conductor near the terminals. Two strain gauges were mounted to measure circumferential strain on the inner diameter, two more on the outer diameter and one measuring axial strain.

Coil D was first operated in self-field to 190 A, followed by a run in a background magnetic field of 20 T. No degradation was observed up to a 204 A (corresponding to a calculated, single-turn unsupported stress value of 714 MPa) when a voltage rise was observed around the outer terminal. A quench occurred at 217 A (760 MPa) without a voltage rise in most voltage taps on the inner and outer layer, so the intrinsic irreversible strain limit of the conductor was not reached. Comparison of the first and last self-field runs shows that the coil performance was slightly degraded after 760 MPa, but the 20 T data clearly indicates that the damage is localized, not widespread.

The strain gages, which were applied with the manufacturer's recommended glue, showed an effective modulus of the winding pack of 165 GPa. But all strain gages failed between 0.05 and 0.3% strain by step-wise debonding. Visual inspection after warm-up of the inner and outer coil surface confirmed that the active area of some of the strain gages had separated from the conductor and also that the epoxy-varnish combination was cracked and occasionally flaking off. However, electrical shorts were not observed so turn-turn insulation was not affected.

Coil E is very similar to coil D except for the use of STYCAST 1266 epoxy for mounting the strain gages. At self-field the coil was ramped to the power supply limit of 620 A without observing any onset of a transition. When operated in a 3 T background field above 230 A (190 MPa) a sharp but reversible voltage rise was observed near the outer terminal. Localized damage has occurred that progressively became worse and limited the high-field quench current to around 200 A. After a quench at 16 T and 199 A (560 MPa) voltage taps on the outer layer showed significant degradation. Regardless, the absence of a transition in the other voltage taps indicated that the damage was again localized and indeed the coil could still be operated to 492 A at self-field.

The strain gages remained attached and functional. The highest recorded strains were 0.46 to 0.54% at 577 MPa. Data from one of the strain gauges is presented in Fig. 5. Visual inspection after warm up revealed that half a turn on the bottom of the outer layer had de-bonded from the underlying layers and had visibly yielded. Thus insulation debonding did limit coil performance.

Coil F is similar to coil E except for the use of paper and glass fiber string as insulation, which required a wet-wind procedure. The onset of a transition at self-field was observed above 615 A leading to a quench at 687 A. The quench protection malfunctioned at the end of the 1 T run, causing an unprotected quench. Resulting degradation was observed in the voltage tap that spans the outer terminal, including a small part of the solder joint with the current lead and one turn of the outer layer. After the unprotected quench, the coil critical current was reduced by 40%. It is not yet clear where the degradation occurred. At 465 MPa there was a sudden further degradation within this voltage tap, reducing I_c a further 4%. The coil was operated to 19.9 T and 217 A (760 MPa, J_{ave}~300 A/mm^2) without degradation anywhere except at or near the outer terminal, indicating that the irreversible strain level of the conductor was not reached. The sequence of maximum current per run versus background magnetic field is presented in Fig. 6.

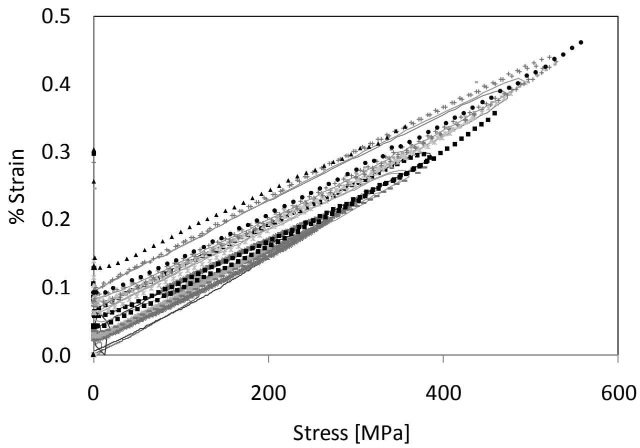

Fig. 5. Stress-strain curves as measured by a strain gage on the inner surface of Coil E. Other strain gauges gave very similar results. The current was cycled up and down numerous times at incrementally increased values of the background magnetic field, resulting in the above loading-unloading curves.

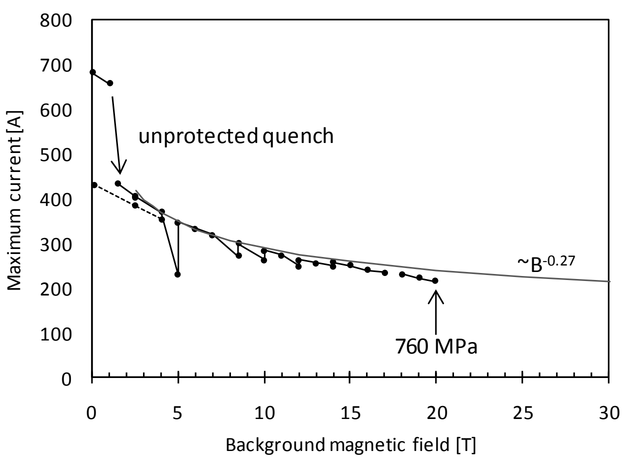

Fig. 6. History of maximum current versus background magnetic field for Coil F. The maximum current corresponds to either a sharp onset of a voltage rise or the quench current. After measuring the maximum current sequentially from 0 T to 20 T, the measurements at 0 T, 2.5 T and 4 T are repeated (dashed line). A power law curve is included (grey line) as a guide to the eye. The coil exhibited training as evidenced by the saw-tooth pattern

VI. Discussion

Bi-2212

Significant improvement has been achieved with Bi2212 round wire compared with Bi2212 tape conductor of a few years ago, which is surprising given the significantly lower level of funding for Bi2212 compared with its coated conductor counterpart. Bi2212 conductor is available in the most versatile round wire geometry in batch lengths of around 300 m. Nearly leak-free, wind-and-react coils are now possible showing fairly consistent performance and 25 T magnet systems appear possible. Due to the complexity of the Bi2212 phase formation in combination with the wind and react approach, however, there is still much understanding to be developed to process coils with even more consistent performance, as well as higher current densities [27],[28]. The presently observed winding current densities are sufficient for the design of 25 T magnets, although further improvement is needed to successfully approach the 30 T threshold.

YBCO

The operating current in a YBCO pancake coil tested in a 31 T background field is limited by poor cooling and mechanical effects. Both factors can be mitigated. The winding current density of 440 A/mm^2 is still well below the intrinsic limits of the conductor at 4 K, but more than sufficient for the design of 30 T magnets. It should be noted however, that the magnetic field angle in this coil is < ~2º, so anisotropy has only a minor effect. Field angles up to ~ 20 º can be expected at the top and bottom of the larger coils in magnets like the 32 T magnet. However, even at the most unfavorable angle, measured short sample performance (see Fig. 3) still matches the 32 T specifications.

A surprising and very positive result is that irreversible degradation did not occur even at 760 MPa in a conductor with a 50 μm Hastelloy substrate and a non-standard 30 μm Cu layer on all sides. The optimum amount of Cu is to be determined and may depend on the design of the quench protection. Coil operation at 20 T with J_{ave} ~ 300 A/mm^2 is stable and was limited by local damage, not the intrinsic properties of the conductor. Both J_{ave} and stress are well above the 32 T design specifications.

The terminals of the large-diameter YBCO coils sustained fairly high stress but still damaged before the main windings. Thus the terminal design can be further improved. It should be noted that the terminals for all high-stress coils were designed to minimize their reinforcing effect on the nearby turns and thus not as robust as possible.

The impregnated layer-wound coils were found to be insensitive to quenches, provided the quench protection worked. Paper and glass work well as insulation, as does varnish in un-impregnated coils. Debonding between conductor and varnish was observed in coils that were epoxy impregnated and subjected to high stress. Pieces of varnish and epoxy flaked off from the outer and inner layers and in one case half a turn let loose. The impregnating epoxy used (STYCAST 1266) is also suitable for mounting strain gages.

VII. Summary

The NHMFL is engaged in several HTS high-field magnet projects, including construction of a 7 T Bi2212 demonstration insert magnet for 25 T and an all-superconducting 32 T research magnet using YBCO. These projects are supported by a broader R&D effort to address magnet technology issues.

The observed winding current density and stress tolerance in test coils exceed the 32 T specifications. These results underpin our conviction that > 30 T all-superconducting magnets are viable.

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