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An 800-MHz all-REBCO Insert for the 1.3-GHz LTS/HTS NMR Magnet Program—A Progress Report

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Abstract

A critical component of the 1.3-GHz nuclear magnetic resonance magnet (1.3 G) program, currently ongoing at the Francis Bitter Magnet Laboratory, Plasma Science and Fusion Center, Massachusetts Institute of Technology, and now approaching its final stage, is the all high-temperature superconductor 800-MHz insert (H800). The insert consists of three nested double-pancake (DP) coils fabricated with 6-mm-wide REBCO conductor. Coil 1, the innermost coil of H800, has already been fabricated and tested at 77 and 4.2 K. In addition, one third of the DPs for Coil 2 have been wound and each DP individually fully tested. Work described here includes details of Coil 1 fabrication: DP winding, DP testing, assembling, joint performance, overbanding, and coil testing; winding details of DPs for Coil 2 and their testing are also included.

Keywords

High-temperature super (HTS); low temperature superconducting (LTS); magnet; nuclear magnetic resonance (NMR); superconducting

I. INTRODUCTION

THE Magnet Technology Division of the Francis Bitter Magnet Laboratory, Plasma Science and Fusion Center at MIT is in the home stretch of a high-resolution 1.3-GHz NMR magnet (1.3 G). The magnet system is a combination of a 500-MHz LTS (Low Temperature Superconducting) NMR magnet (L500) and an 800-MHz all-HTS insert (H800). A general overview of the 1.3-GHz/54-mm LTS/HTS NMR magnet system has been published elsewhere [1]. The current phase main goals are to: 1) complete the H800, which, as described in previous publications [2], consists of three nested stacks of DP coils wound with 6-mm-wide REBCO conductor; 2) generate a magnetic field of 30.53 T at 4.2 K; 3) map the 30.53 T field to establish spatial field properties; and 4) continue developing HTS shims and shaking-field techniques to finally bring the 30.53-T L500/H800 magnet to a high-resolution 1.3-GHz NMR magnet. To date, the innermost coil, Coil 1 has been fabricated and fully tested. Also individual DPs for Coil 2 have been wound and fully characterized in terms of current carrying capabilities. All three coils of the H800 are wound with REBCO conductor. Currently, we are in the process of continuing winding DPs for Coils 2 and 3. We are also continuing our efforts in developing field shimming techniques to transform a 30.5-T field to a high-resolution 1.3-GHz NMR magnet, in particular developing the so-called shaking-field magnet to minimize the effect of the screening currents.

II. H800 INSERT MAGNET (COIL 1)

Here, and for a general overview of the H800, Table I has the key parameters of the H800 in L500 at 4.2 K and operating at 251.3 A.

A. REBCO Conductor

The Coils 1 and 2 conductor, whose parameters and properties are listed in Table II is SuperPower 2G HTS wire type SCS6050-AP in tape form 6-mm wide. The REBCO based conductor was chosen over other HTS conductors because of two superior properties: mechanical strength and engineering current density. The chosen tape, 6-mm wide and 75- μm thick, has a 50- μm thick Hastelloy substrate with room temperature 0.2% yield stress and strain of 970 MPa and 0.95% [3], respectively. As compared with the 4-mm width conductor, the 6-mm wide conductor will induce a greater screening-current field (SCF), i.e., magnetization; this effect has been considered in our design. In Section III we describe a technique to reduce SCF-induced error fields.

B. Coil 1—General Aspects

Coil 1 consists of 26 DPs, 6 of which have an inside notch. DPs are dry wound with no turn-to-turn insulation (NI) but with a 178- μm thick G-10 inter-pancake insulation. The same G-10 insulation is installed between each DP during assembling. All DPs were wound with a

50-N winding tension. Details of our winding table have been presented in an earlier publication [6].

The no-insulation technique, proposed by our laboratory in 2011 [7], offers three beneficial features that are exactly needed and viable to H800: 1) Self-Protecting: a key feature of which, validated by other groups [8]–[10], is to allow, upon creation of a normal zone, the azimuthal current rapidly jump to adjacent turns preventing thus the hot spot from overheating; 2) Mechanical Integrity: elimination of mechanically weak organic insulation results in a very robust metallic entity; and 3) Compactness: self-protecting feature also leads to high field/ampere-turn efficiency.

C1) DP Winding: At the beginning of the winding phase for Coil 1, it was found that upon removal of the winding mandrel the innermost layers of the DP, including the cross-over from upper to lower pancake, would collapse. Considering the innermost layer of the DP (or of a single pancake) as a pressure vessel under external pressure, a simple calculation showed that indeed the pressure developed during winding would exceed the collapsing pressure of a thin walled pressure vessel. The remedy was to install a properly sized internal, nonmagnetic stainless steel, ring that now would be an integral part of the DP. For each DP of Coil 1 the ring is 12 mm wide and 0.5 mm thick.

Fig. 1(a) shows a DP with its collapsed innermost turns, while Fig. 1(b) shows a DP with its internal SS supporting ring.

C2) Coil 1 Assembling: All 26 DPs were assembled into Coil 1 by 25 splices that can be considered as double lap-joints. Splices were made using the 12-mm wide REBCO tape from SuperPower. A sample test joint is shown in Fig. 2. In order to minimize the splice resistance joints were made using three sections 60 mm long of the 12 mm wide tape.

At 4.2 K the average of the measured value of the joint resistances was $26.3 \mu\Omega$, about half of what was expected [11], meaning that at operating current the total dissipation from Coil 1 due to its 25 joints is ~ 50 mW.

The 26 DPs of Coil 1 are contained in a mechanical structure consisting of a central nonmagnetic stainless steel tube bounded by end flanges. The structure allows for the preload, necessary to maintain the integrity of the assembly during cooldown and energizing of the magnet. Preload is applied via jacking screws and Belleville washers (spring washers). Fig. 3 presents Coil 1 fully assembled and contained in its support structure.

C3) Coil 1 Testing: Once assembled and with its 25 splices done but without overbanding, Coil 1 was tested, first in LN₂ (77 K) and then in LHe (4.2 K). Coil 1 successfully generated a center field of 8.65 T at 253 A. Fig. 4 shows center $B(t)$ and current $I(t)$ traces. Field lags current by approximately 10 minutes, an NI effect. The coil reached the design field in one try; no training sequence. Coil was energized via an Oxford Instruments IPS 125–9 power supply manually controlled; magnetic field was measured with a Lakeshore HGCA-3020 Hall sensor.

C4) Coil 1 Overbanding: A stress analysis of the H800 operating in conjunction with the L500, published elsewhere [2], indicated that the H800 should not only consists of three nested coils, but that each coil should be overbanded. Its purpose is to limit the coil hoop stresses and hoop strains by making all the radial stresses compressive. Although the REBCO conductor allows a maximum hoop strain of 0.6%, we have limited it at 0.45% that occurs at the innermost turn in Coil 1.

The overbanding is done with nonmagnetic stainless steel tape 6-mm wide, 76- μ m thick. It is applied to each pancake to a predetermined build at a 50-N winding tension. Overbanding of Coil 1 is 7-mm thick. After applying 21 layers of overbanding to each of the 52 pancakes of Coil 1, we tested the coil at 77 K in LN₂. Purpose of the test was to verify if any of the splices had been damaged by the external pressure imposed by the overbanding. No damage or degradation of splices was found. For comparison, Fig. 5 shows $B_z(t)$ traces of Coil 1 at 77 K energized to 20 A; before and after 21-layer overband. The observed difference can be attributed to the re-positioning of the Hall sensor.

C5) Coil 2 Status: Ten DP coils have been wound and each individually tested for its 77-K critical current and charging delay time constant. Fig. 6 depicts plots of measured magnet time constants (center field/current) versus power supply current for all ten DPs wound. The design value of 1.885 mT/A for Coil 2 is indicated in the figure by a black horizontal line.

III. SHAKING COIL MAGNET

High-resolution, > 1-GHz NMR magnets, such as our 1.3-GHz NMR, must have an all-HTS insert; however one of the nuisances of REBCO coils is the effect of the screening current field (SCF). The SCF not only causes the central magnetic field to drift with time but it has also been demonstrated that SCF-induced error fields degrade spatial field homogeneity [12]–[15]. It has also been demonstrated that SCF reduces the central magnetic field [16]–[18].

Our approach to minimize the SCF error fields was to adopt a remedy proposed in 1982 for LTS magnets [19]–[21]. Recently, it has also been shown to be applicable to HTS magnet [22]–[27]. The basic idea is to apply a small time-varying $\pm$ axial field, and repeatedly (“shake”) force the screening current in the $\pm$ radial directions, thus gradually de-pinning and remove the SCF. We began a series of experiments, still on-going, with a test magnet, a stack of 3 NI DP coils, each wound with the same 6-mm wide REBCO tape for H800. The test magnet had a measured charging-delay time constant, τ_m , of 31 s. Each DP of the test coil has an ID = 78.0 mm and OD = 94.0 mm.

In this experiment the test magnet, immersed in a bath of LN₂ at 77 K, was self-magnetized through a charge-and-discharge sequence. A 5-T/300-mm RT bore superconducting magnet supplied a shaking field, $B_{sk}(t)$. Fig. 7 presents a graph, with an initial field due to the screening current (B_{SCF}) of 8.5 mT, of measured B_{SCF}/B_{SCFo} versus B_{sk} cycle plots. Data were taken with a $B_{sk}(t)$ ramp rate of 60 mT/min. The field amplitude, B_{sko} , ranged 100–600 mT. $B_{sk}(t)$, as indicated in insets, was of trapezoids, both flat field-on and quiescent periods

of ~5 min. The results show: 1) a precipitous drop in B_{SCF} at Cycle 1, down to $B_{SCF}/B_{SCFo} = 0.4$ for $B_{sko} = 600$ mT; 2) B_{SCF}/B_{SCFo} at cycle 1 is proportional to B_{sko} , though it begins to saturate at 500 mT; 3) a much more gradual drop rate after Cycle 1. This suggests that it may be possible to require only one shaking-field cycle to significantly reduce B_{SCF} in an NI coil.

IV. GAS HELIUM BUBBLE IN A HIGH MAGNETIC FIELD

Because the H800 will be always operated in the driven mode, there will be Joule heating in Coil 1 of ~50 mW generated by the DP-DP joints, dissipation that is removed by LHe nucleate boiling heat transfer. Boiling heat transfer relies on formation of helium gas bubbles that rise to and leave from the LHe bath surface. However, it has been reported that due to the diamagnetic susceptibility of helium [28], above a certain field the helium bubbles will be trapped over the joint surface, possibly heating the joint. McNiff et al. in 1988 demonstrated that the bubble trapping anomaly occurs in a region where $B_z (B_z/\mu_0) > -21$ T²/cm [29], which has more recently corroborated by at the NHMFL [30].

At $B_z (B_z/\mu_0) \approx -21$ T²/cm the buoyancy and the diamagnetic displacement forces are balanced. For $B_z (B_z/\mu_0) < -21$ T²/cm, the bubbles can rise and at $B_z (B_z/\mu_0) > -21$ T²/cm they are trapped. The result of our analysis, as applied to the H800, is presented in Fig. 8. The figure shows to scale the upper quadrant of H800 Coils 1 to 3 and the regions where $B_z (B_z/\mu_0) < -21$ T²/cm. It can be seen that only in a small region, at the entrance of the H800 bore, we note that $B_z (B_z/\mu_0) < -21$ T²/cm; however, since the area is very close to the LHe free surface, we believe that it does not pose any cooling problem to our system.

V. CONCLUSION

Of the three coils composing H800, Coil 1 has been wound and fully tested. At 4.2 K and 253 A the coil performed as expected. Testing in LN2 after overbanding shows that DP-DP splices are not damaged by overbanding. We have also examined the possibility of a gas helium bubble being trapped during system operation and found it not to be of concern for liquid helium cooling of the H800.

One of the shimming techniques, briefly described here, relies on a shaking-field magnet that reduces most of the SCF-induced error fields. It is possible that by applying just one cycle of the shaking-field, to reduce the effect of the screening currents by ~40%.

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Fig. 1.
(a) DP showing collapsed inner turns. (b) DP with supporting inner stainless steel ring.

Fig. 2.
Sample splice showing a before and after double lap-joint, such as the splices used to assemble Coil 1.

Fig. 3.
Fully assembled view of Coil 1 showing preload scheme (jacking screws, Belleville washers).

Fig. 4.
Measured Coil 1 center $B_z(t)$ and $I_{op}(t)$.

Fig. 5. Comparison of measured center $B_z(t)$ of Coil 1 as tested in LN2, before and after 21 layers of overbanding.

Fig. 6. Measured magnet constant (center field/current) versus power supply current for the ten DPs of Coil 2.

Fig. 7.
Measured B_{SCF}/B_{SCF0} versus B_{sk} cycle plots.

Fig. 8.
 $B_z \left(\frac{\partial B_z}{\partial z} \right) < -21 \text{ T}^2/\text{cm}$ regions in the 1.3-GHz NMR magnet. Only upper quarter of the H800 shown.

TABLE IDESIGNED H800 IN L500 AT 4.2 K AND $I_{OP} = 251.3$ A PARAMETER

Parameter		Coil 1	Coil 2	Coil 3
Frequency	[MHz]	369	242	189
Field contribution	[T]	8.66	5.68	4.44
$B_{\perp}$	[T]	4.8	4.6	3.8
$I_c(B_{\perp} 4.2 \text{ K})/I_c(77 \text{ K, sf})$		>2.3	>2.3	>2.7
Overall current density	[MA/m ²]		546.9	
Total # DP coils		26	32	38
# Notched DP coils		6	10	8
# turns/pancake		185	121	95
# turns/notched pancake		177	118	93
Inner diameter (ID)	[mm]	91.0	150.75	196.90
ID (notch)	[mm]	92.35	151.20	197.20
OD (without overhand)	[mm]	119.12	168.90	211.15
Overall height	[mm]	323.65	392.13	465.65
Notched section height	[mm]	74.65	122.54	98.03
SS overhand radial build	[mm]	7	5	3
REBCO length/DP coil	[m]	121.9	121.5	121.8
REBCO length/notch DP	[m]	116.7	118.7	119.3
Total length/coil	[km]	3.14	3.84	4.61
Inductance	[H]	2.43	3.08	3.71
Peak bending strain (σ_b)	[%]	0.060	0.0364	0.0279
Peak magnetic hoop strain (σ_m)	[%]	0.41	0.35	0.32
$\sigma_b + \sigma_m$	[%]	0.47	0.39	0.35

TABLE II

REBCO TAPE: PARAMETERS AND PROPERTIES

Parameter	REBCO Tape	
Non-REBCO material	Hastelloy	Cu et al.
Width, [mm]	6.0	
Thickness, [mm]	50	25
I_c @ 77 K, self-field, [A]	>160	
Young's modulus (E), [MPa]	197	33
$a_{\parallel}$ (77 K 4.2 K [%])	0.03 [4]	0.02 [3]
E_r, E_{θ}, E_z , [GPa]	73; 142; 134	
$n_{\theta}, n_{\phi}, n_z$	0.40; 0.35; 0.18	
a_r, a_{θ}, a_z (77K $\rightarrow$ 4.2K), [%]	0.026; 0.026; 0.030	
95-% I_c strain @ 77 K, [%]	0.6 [5]	
95-% I_c stress @ 77 K, [%]	>700	

Pancake to Pancake 127 μ m thick G-10 spacer

$n=0.33$; $E_r=E_{\theta}=36$ GPa; $E_z=22$ GPa

$a_r = a_{\theta} = 0.03$; $a_z = 0.07$