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On the 600 MHz HTS Insert for a 1.3 GHz NMR Magnet

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Abstract

We update here on the status of one of the main components of a 1.3 GHz NMR magnet currently being developed at the MIT Francis Bitter Magnet Laboratory (FBML): the 600 MHz HTS insert coil. Started in 2000 as a 3-phase program and currently in its final phase (Phase 3A), the HTS insert will first be installed in the bore of a 500 MHz all LTS magnet, generating a field of 25.8 T (1.1 GHz). In Phase 3B, we will place the HTS insert in the bore of a 700 MHz LTS magnet, achieving our ultimate goal of completing a high-resolution 1.3 GHz magnet.

The HTS insert, built as a stack of double pancakes (DP), consists of two concentric stack of coils, the inner coil wound with YBCO tape and the outer coil with Bi2223/Ag tape. The series-connected coils, immersed in a bath of liquid helium at atmospheric pressure, will be operated in driven mode.

The paper describes detailed aspects of: 1) design and fabrication of both coils, 2) testing of individual DPs at 77 K to characterize the current carrying capabilities and magnetic performance of each DP coil, 3) techniques and elements utilized in the DP-to-DP splice procedure and, 4) splice dissipation.

Keywords

Bi2223/Ag tape; HTS insert magnet; LTS/HTS NMR magnet; YBCO coated conductor; 1.3 GHz

I. INTRODUCTION

THE completion of a 1.3 GHz NMR magnet is the ultimate goal of a 3-phase program started in 2000 at the MIT Francis Bitter Magnet Laboratory (FBML). Phase 1 and 2 saw the successful completion of a 350 MHz system (in 2002) [1] and of a 700 MHz system (in 2007) [2]. For the final phase, we are building an all high-temperature superconducting (HTS) insert, which initially, and as an intermediate step, will be coupled to an all low-temperature superconducting (LTS) 500 MHz magnet to achieve 1.1 GHz (Phase 3A). The HTS insert will subsequently be combined with an LTS 700 MHz magnet to achieve an NMR-quality frequency of 1.3 GHz.

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II. HTS 600 MHZ INSERT

A. General

Our 600 MHz HTS insert consists of two nested coils, arrangement necessary due to the high stresses that the insert will experience during operation. Each coil is built as a stack of 56 Double Pancakes wound with high-temperature superconductor in tape form. Key parameters (based on design) of the two coils are given in Table I.

B. Conductor

“YBCO,” actually Zr(GdY)BCO, for Inner Coil, Type SCS4050-AP, from SuperPower, and Bi2223/Ag for Outer Coil, Type HT manufactured by Sumitomo, were the conductors of choice for the fabrication of the insert. However, since neither of the two conductors met the stress/strain and protection requirements of the coil, it was necessary to co-wind the YBCO for Inner Coil with additional copper for protection, and the Bi2223/Ag for Outer Coil with stainless steel for reinforcement [3]. Manufacturer specifications for the conductors are listed in Table II.

C. Winding

The double-pancake (DP) coils for Inner and Outer Coils were wound on a winding table designed and fabricated at the FBML, details of which have been reported earlier [4]. The winding tension on both coils was approximately 70 N and provided by permanent magnet clutches. The YBCO Inner Coil was co-wound with 4 mm $\times$ 0.2 mm copper, insulated on one side with polyester 0.023-mm thick. The Bi2223/Ag Outer Coil was co-wound with stainless steel 4 mm $\times$ 50 μ m. The coils were not epoxy impregnated, but while winding a drop of Super Glue was placed in a few places every 10 turns. In order to ensure that all the DP coils would have the same final outer diameter, co-winding material was added or removed in the outer turns as required. Fig. 1 shows a photograph of a finished DP for: a) YBCO Inner Coil and, b) Bi2223/Ag Outer Coil.

III. DOUBLE PANCAKES TESTING

To date, all 56 Bi2223/Ag DP coils for Outer Coil and 52 YBCO DPs for Inner Coil have been wound.

The DP coils instrumented with voltage taps and a Hall sensor (Toshiba THS118) located at the center of the DP coil are individually tested in a Styrofoam box filled with liquid nitrogen (LN₂) for their current carrying capacity and field.

Transport current, provided at a rate of 10 A/min by an Oxford Instruments IPS 125–9 power supply, and voltage drop across the entire coil were recorded simultaneously via a 16-bit National Instruments DAQ board through isolated amplifiers (system accuracy $\pm 0.4327\%$, stated by the manufacturer) with all data read and written to a computer by LabView. Center field versus current of a representative Bi2223/Ag and YBCO DP coil are presented in Fig. 2. A typical V-I curve generated from the data for an YBCO coil and that for a Bi2223/Ag DP coil are shown in Fig. 3.

From the V-I curves and with the $1 \mu\text{V}/\text{cm}$ criteria, the I_c and also the n -values of the coils were calculated; n -values were calculated between $0.1 \mu\text{V}/\text{cm}$ and $1 \mu\text{V}/\text{cm}$ with an estimated accuracy of $\pm 1 \sim 2\%$. The calculated values are presented in Fig. 4 for the YBCO DP coils and in Fig. 5 for the Bi2223/Ag DP coils. The average I_c and n -value for the YBCO DP coils the values are 47.8 A and 20.9, while for the Bi2223/Ag DP coils are 69.6 A and 11.5, respectively.

IV. SPLICES

Joint resistance at the splices need to be minimized in order to avoid excessive LHe boil-off caused by the joule heating, here $\sim 10 \text{ n}\Omega/\text{joint}$. Another important concern is the potential reduction in I_c at the splice section due to this heating. When assembled, our 600 MHz HTS insert will have 110 “bridge” type splices 10-cm long, 0.8-cm wide. Our aim is to have not only low resistivity splices but also to have all of them of a similar value. With a total of 224 splices (2 splices at each DP-coil-to-DP-coil joint), a $10 \text{ n}\Omega$ resistance generates a total Joule heating of 150 mW at an operating current of 251 A.

Since even the Bi-2223/Ag DPs for the outer coil will be connected by splices in which the bridge element is a piece of SuperPower’s 12-mm wide YBCO tape, our efforts have been directed to perform tests on YBCO-YBCO splices. Effectively, and since in our case, the bridge splice is a double lap joint, the splices tested were all in the lap joint configuration and the tests performed in a bath of LN₂ in self-field. Fig. 6 presents a schematic drawing of the configuration tested, in it the red dots indicate the locations of voltage taps, SUB side refers to the Substrate side of the YBCO tape. The (+) and (−) signs in the figure indicate the direction of the current. In making a splice, the HTS side of one part is always placed to face the HTS side of the other part (see Fig. 6).

A. Sample Preparation

To ensure consistency in the fabrication of the lap joints, samples were cleaned first by a light scrub with 3M No. 96 Scotchbrite and then washed with methyl alcohol or acetone. Most sample pieces were cut from remnants of the YBCO conductor used to wind our Inner Coil, that is, 4-mm wide samples with a $5 \text{ } \mu\text{m}$ thick copper stabilizer per side.

B. Solders and Fluxes

Four type of solders were used in the tests: i) Tix Solder: an indium based solder developed for the jewelry manufacturer in 1947. It comes only in wire form of about 2 mm diam. and contains no silver or bismuth. Its melting point is 135, has a specific gravity of 8.6 and a bonding strength of $\sim 30 \text{ MPa}$.

The measured solder resistivity, at 77 K, is $163.4 \text{ n}\Omega \text{ } \text{m}$; ii) Solder paste Formosa 63Sn/37Pb from Shinmao Technology, an eutectic alloy with a melting point of 183°C . The resistivity of a standard 63Sn/37Pb eutectic solder at 77 K is $36 \text{ n}\Omega \text{ } \text{m}$ [5]; iii) 80In/15Pb/5Ag solder in ribbon form from Indium Corporation, solder is $51 \text{ } \mu\text{m}$ thick, has a liquidus melting temperature of 154°C and a solidus melting temperature of 149°C ; iv) 63Sn/37Pb eutectic solder in ribbon form from Indium Corporation. Solder is also $51 \text{ } \mu\text{m}$ thick and has a liquidus/solidus melting temperature of 183°C . Also, two types of fluxes

were used: i) Tix Flux, a liquid which is water soluble and can be easily neutralized by a solution of bicarbonate of soda, and ii) Oatey No. 5 lead-free solder paste, which contains zinc chloride and ammonium chloride.

C. Testing

Although the splices joining two adjacent DP coils are on a curved surface that spans a circular segment of $\sim 90^\circ$, in this preliminary stage the lap joints are straight on a flat surface, chiefly to identify the parameters that would consistently result in a splice resistivity of $< 50 \text{ n}\Omega - \text{cm}^2$. These parameters include surface preparation, pressure, temperature, solder/flux.

The lap joints were made using the fixture shown in Fig. 7. Samples, either pre-tinned with Tix solder or covered with 63Sn/37Pb solder paste, are placed in the fixture and a transverse load is applied. After the soldering temperature is reached, as indicated by monitoring thermocouples, a cartridge heater is turned off and the sample cooled down in air still under load. Once removed from the soldering fixture, the sample is tested in a bath of LN2 to determine its resistance and I_c . Testing is performed with the same equipment used for the DP coils.

D. Results

All samples were tested at least three times to ensure reproducibility of results. Transport current rate, applied either at 1 A/s or 0.5 A/s did not affect the measurements. Effect of transverse load variation on solder thickness appears to be minimal, on average the thickness was about $20 \mu\text{m}$. The results are all for a 7-cm long, 4-mm wide (superconductor width) splice, although some 10-cm long splices were also made with no obvious improvement in contact resistivity, given in $\text{n}\Omega - \text{cm}^2$. For all the splices done with the same type of conductor used in our inner coil, that is, 4-mm wide with a $5 - \mu\text{m}$ thick copper layer on each side, a wide range in resistivity, $40\text{--}400 \text{ n}\Omega\text{--cm}^2$, was measured regardless of the type of solder used.

More consistent results were found in splices made with tapes with the standard stabilizer thickness of the SuperPower conductor, that is, $20 \mu\text{m}$ of copper per side.

Two splices 7-cm long were made for each of three YBCO conductor widths, 4-mm, 6-mm, and 12-mm, all having $20 \mu\text{m}$ of Cu per side. The results are presented in Table III.

Retested Splice 6 contact resistivity was $100 \text{ n}\Omega - \text{cm}^2$. This deterioration is likely to be caused by strain effects, e.g., differential contractions, on the splice upon thermal cycles, because the same deterioration was not observed in the other samples.

Ultimately, the splices will have to be done on the pre-assembled coil, i.e., instead of on a flat surface as were these test splices but on a curved surface. A proposed fixture for splicing real DP coils is shown in Fig. 8. Here, the heating element is a strip of stainless steel of $\sim 250 \mu\text{m}$ thick. The length of the heating element can be adjusted, even beyond 90° circular segment (see Fig. 8) to meet a required splice length. To test the setup, a single lap joint 7

cm long was made using YBCO conductor. Parts were pre-tinned with Tix solder. An encouraging value of $\sim 62 \text{ n}\Omega - \text{cm}^2$ was obtained.

V. CONCLUSION

All 56 Bi2223/Ag double-pancake (DP) coils for Outer Coil of a 600 MHz HTS insert have been wound and individually tested in an open bath of LN₂, while 52 of a total of 56 YBCO DP coils for Inner Coil have gone through the same process.

Efforts are still continuing to determine splice parameters required to consistently achieve a contact resistivity of $< 50 \text{ n}\Omega - \text{cm}^2$. This limit is set forth to minimize a total 4.2 K splice dissipation at an operating current of 251 A. To date, test results from splices, made in the lap joint configuration and with SuperPower YBCO tape conductor, indicate that the contact resistivity of the splice does not depend on: i) contact pressure during splicing; ii) splice active length.

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(a)

(b)

Fig. 1. Photograph of finished Double Pancake coils for: (a) YBCO Inner Coil (i.d.: 74 mm; o.d.: 142.3 mm) and (b) Bi2223/Ag Outer Coil (i.d.: 158.3 mm; o.d.: 221.3 mm).

Fig. 2.
Center field vs. current for representative YBCO and Bi2223/Ag DP coils.

Fig. 3.
Typical V-I plot of a Bi2223/Ag DP coil and a YBCO DP coil.

Fig. 4.
 I_c and n -value variation of 52 YBCO DP coils.

Fig. 5.
 I_c and n -value variation of 56 Bi2223/Ag DP coils.

Fig. 6.
Splice test configuration. Red dots indicate voltage tap locations.

Fig. 7.
Lap joint soldering fixture.

Fig. 8.
Curved splice soldering fixture.

TABLE I

AS DESIGNED 600 MHZ HTS INSERT PARAMETERS

		Inner Coil	Outer Coil
Conductor		Zr(GdY)BCO	Bi2223/Ag
Frequency	[MHz]	354.8	245.3
Operating temperature	[K]	4.2	4.2
Operating current	[A]	251.0	251.0
Overall current density	[kA/cm ²]	19.94	15.50
# of DP coils		56	56
# of turns per pancake		112	90
Inner/Outer diameter	[mm]	74.0/142.3	158.3/222
Height	[mm]	462.2	518.2
SS over banding thickness	[mm]	5.0	5.0
Conductor length/DP	[m]	77.6	107.4
Total conductor length	[km]	4.35	6.02
Co-winding material		Insulated Copper	Stainless Steel

TABLE II

CONDUCTOR SPECIFICATIONS

SUPER POWER TYPE SCS4040-AP – INNER COIL	
Width	4.1 mm $\pm$ 0.15 mm
Thickness	$\sim$ 0.065 mm +0.025 mm/–0.01 mm
Critical Current (I_c) @ 77 K, s.f.	> 100 A
Copper Stabilizer Thickness	10 μ m (5 μ m per side) $\pm$ 1 μ m
Silver Overlay Thickness	2.0 μ m $\pm$ 0.5 μ m
Hastelloy Substrate Thickness	50 μ m
Critical Tensile Stress	>550 MPa
SUMITOMO DI-BSCCO TYPE HT-SS – OUTER COIL	
Width	4.5 mm $\pm$ 0.3 mm
Thickness	0.30 mm $\pm$ 0.04 mm
Critical Current (I_c) @ 77 K, s.f.	160 A
N value (index)	N 15 @ 0.1–1 μ V/cm, 77 K, self field
Configuration	Stainless steel lamination (20 μ m $\times$ 2)
Critical Tensile Stress	210 MPa

TABLE IIISPICES MADE WITH YBCO CONDUCTOR WITH 20 μM CU LATER IN EACH SIDE

Splice #	Length [cm]	Width [mm]	Contact Resistivity [$\text{n}\Omega\text{-cm}^2$]	Solder
1	7	4	336	Sn63/Pb37 paste
2	7	4	344	Sn63/Pb37 paste
3	7	6	92	Sn63/Pb37 paste
4	7	6	88	Sn63/Pb37 paste
5	7	12	92	Sn63/Pb37 paste
6	7	12	50 (100 [*])	Sn63/Pb37 paste
7	7	12	311	Tix solder
8	7	12	1428	Tix solder
9	2.5	12	152	80In/15Pb/5Ag ribbon
10	2.5	12	122	63Sn/37Pb ribbon

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See text