Published in final edited form as:

IEEE Trans Appl Supercond. 2013 June ; 23(3): . doi:10.1109/tasc.2012.2234812.

A New High-Temperature Superconducting (HTS) 700-MHz Insert Magnet for a 1.3-GHz LTS/HTS NMR Magnet

J. Bascuñán, S. Hahn, Y. Kim, Y. Iwasa

The MIT Francis Bitter Magnet Laboratory, Magnet Technology Division, Cambridge, MA 02139 USA

Abstract

Upon the totally unexpected theft of the original 600 MHz HTS insert that occurred in December 2011, we were forced to examine our entire 1.3 GHz NMR Magnet program anew and determined that a combination of a 600 MHz LTS magnet and a 700 MHz HTS insert (H700) would yield a 1.3 GHz LTS/HTS magnet that meets the technical specifications consistent with economic constraints. Although this new 700 MHz HTS insert still comprises, as H600, a YBCO inner coil and a Bi2223 outer coil, it incorporates innovative design features. In addition to presenting the major design parameters of the new H700, we discuss here its key electromagnetic and mechanical issues.

Index Terms

Bi2223; double pancake coils; NMR; superconducting magnet; YBCO

I. Introduction

THE PROGRESS of our 1.3 GHz LTS/HTS NMR magnet program [1] has been abruptly interrupted by the theft, in December 2011, of all 112 double pancakes (DP) ready to be assembled as the inner and outer coils of the 600 MHz all HTS insert of our 1.3 GHz NMR magnet [2]. The incident forced us to re-examine the entire electromagnetic and mechanical design of the 1.3 GHz magnet, making use of the latest advances in magnet technology. The original version of the 1.3 GHz was to be comprised of a 700 MHz all LTS (L700) background magnet and a 600 MHz (H600) all HTS insert.

The new design presented here, has the magnet roles reversed, that is the LTS background magnet now provides 600 MHz (L600) while the all-HTS insert generates 700 MHz (H700). Fig. 1 has a schematic to-scale representation of the original and new HTS inserts in the bore of their respective background LTS magnets.

The main reason to proceed in our 1.3 GHz NMR program as a combination of L600 + H700 rather than L700 + H600 comes chiefly from the economics constrains.

The cost of an all-LTS NMR magnet is nearly directly proportional to the magnet stored energy [3], e.g., the stored energy of a 700 MHz LTS magnet is ~24 MJ, while that of a 600 MHz LTS magnet is ~15 MJ. This means that an L700 is approximately 60% more costly than an L600. On the other hand, conductor replacement cost for the original H600 is approximately equal to the conductor cost for the *innovative* H700 described in this paper.

II. New All HTS 700 MHz Insert

A. General

The new HTS 700 MHz (H700) insert will comprise, as the original 600 MHz was, two nested stacks of double-pancake coils (DPs), the arrangement necessitated by the high stresses that the insert will withstand during operation.

The new inner coil will be wound with 6-mm wide “YBCO” tape from SuperPower, while the outer coil will, once again, be wound with reinforced Bi2223 Type HT-SS tape from Sumitomo Electric Industries. The effect of an increase, although not substantial, of the screening currents introduced by a wider YBCO tape (6 mm as opposed to the original 4 mm wide tape), has been considered in our design.

Conductor specifications, as provided by the manufacturers and which meet our specifications, are listed in Table I. The key parameters of the new YBCO and Bi2223 insert coils that constitute H700 are listed in Table II.

Compared with the original design of the H600, in which the inner YBCO coil was co-wound with a copper strip insulated in one side, the new H700 incorporates two innovative features: 1) the inner YBCO coil having no turn-to-turn insulation [4],[5]; 2) “inside”-notch DPs, introduced for those at and near the midplane, for field homogeneity enhancement. This no-insulation (NI) winding technique results in a compact coil of a high overall current density, robust winding, and improved stability/protection.

Fig. 2 illustrates compactness of a NI-wound YBCO coil, the technique of which is adopted for the new YBCO coil, against a copper/insulation YBCO coil, the technique used in the original YBCO coil. Both coils have the same inner diameter and generate the same central field. (The NI technique and its design issues are discussed in a paper elsewhere in this conference [6].)

Notched coils, the standard presence in NMR and MRI magnets [7], [8], are deployed to enhance the magnet field homogeneity. To enhance the field homogeneity of a “short” coil such as the new YBCO and Bi2223 coils, each comprising a stack of DPs, the “notching” is introduced in each stack in the form of “inside-notch” DPs placed at and near the midplane, 8 and 2 notched DPs, respectively, in the YBCO and Bi2223 coils, as indicated in Table II. Notching is further discussed below.

B. Design A and Design B for H700

Designs A and B were considered for H700. In Design A, both YBCO and Bi2223 coils comprise 56 DPs, wound with tapes of respective “standard” widths (4 mm for YBCO and

4.3 mm for Bi2223) as are those of H600. In Design A, YBCO coil is 462.2 mm high, while the Bi2223 coil is 518.2 mm high, requiring total conductor lengths, respectively, of 6.3 km and 8.8 km. In Design B, the YBCO coil of 26 (8 of notched) NI DPs, each wound with 6-mm wide tape, is 318.6 mm and requires a total conductor length of 3.3 km; similarly, the Bi2223 coil of 40 (2 of notched) DPs, each of 4.3-mm wide tape, is 370.2-mm high and requires a total conductor length of 5.3 km. Fig. 3 presents to-scale schematics of the two designs.

In Design A, the calculated field homogeneity over a 3-cm DSV is 170 ppm. In Design B, it is 15 ppm, enhanced remarkably from 1200 ppm of no notched DPs in both coils.

C. Coils Assembly

The coils will be wound with the winding machine which was designed and constructed at FBML for H600, the machine fully described elsewhere [1]. As in the original H600, each DP in the YBCO coil, as stated before, will be wound with no turn-to-turn insulation, while that in the Bi2223 coil will be co-wound with 50- μ m thick stainless steel strip. As with the original H600, a thin layer of insulating G-10 is inserted between each pancake in H700. The same insulation layer will be used between each DP in each coil.

Once that all the DPs have been wound and fully characterized by testing in LN₂, their stacking order will be determined to produce the best field profile possible. The stack of DPs will be then placed in a supporting structure consisting of a central stainless steel (SS) tube and end flanges. The central SS tube acts as a centering component and also prevents radial motion of individual DPs. A set of jacking screws for each coil, acting upon Belleville (spring) washers, will provide the axial preload required by the system. The preload guarantees that no relative motion, in the azimuthal direction between pancakes during the energizing of the H700, will occur and also it transforms the entire assembly into a single structural entity. During cooldown, the Belleville washers maintain the integrity of the assembly. After stacking and axially preloading each coil, we will electrically connect adjacent DPs in each coil, i.e., the bottom pancake of one DP with the top pancake of the DP below. Once all inter-DP connections are made, each coil will have a SS wire overbanding, layer-wound over the outermost assembly. The overbanding will maintain the radial stresses within each coil of H700, whether H700 is operated itself or in a background field of a 600-MHz LTS magnet. We are presently conducting test to refine the overbanding technique, specifically targeted to H700. See [6], this same conference. The assembly structure in H700 incorporates a set of bottom screws that serves to allow fine alignment of the magnetic centers of the two coils. Fig. 4 shows a sketch of the complete assembly of H700. Not shown in the figure are bumpers installed to prevent lateral movement and therefore misalignment. Fig. 5 shows a sketch of the complete assembly. Also not shown is a top interface that fully integrates the inner and outer coils into H700.

D. Splices

The electrical connections are splices of the lap-joint type that will be made directly on the coils, in the curved configuration, thus eliminating a potential damage to the splice that could occur if the splice is made straight and then bend to conform to the coil shape. Fig. 5

shows schematically the splice configuration. The H700 has two types of splices: YBCO-YBCO for the inner coil, and Bi2223-YBCO-Bi2223 splices for the outer coil. In developing a joining technique that would yield consistent low splice resistance values, particular attention has been paid to the cleaning process of the splice components, since it has shown to influence the contact resistivity. The splices are made with the side that has the YBCO layer closer to the surface facing each other, thus ensuring that the current path in going through the splice involves, for instance in the case of YBCO, only low resistance superconductor components, such as the 10- μm copper stabilizer and the 2- μm silver overlayer and not high resistivity components, namely the 50- μm Hastelloy in this case.

All splices will be approximately 100 mm long. A complete detailed discussion of the splices is presented in a companion paper (this conference [9]).

As indicated in Table II, the inner YBCO coil consists of 26 DPs, requiring 25 inter-DP connections. On the other hand the outer Bi2223 coil having 40 DPs will have 39 such connections. Based on experimental results [9] an average resistivity value for a splice is taken as 100 n Ω – cm²; noting that the operating currents of both coils is 257 A (Table II), the 25 10-cm long, 6-mm wide YBCO lap-joints will generate a dissipation of 27 mW, while the 39 Bi2223 splices of the same length will dissipate ~57 mW. The total dissipation of 84 mW due to the 64 splices translates into a LHe consumption of ~100 cc/hr.

III. Conclusion

A new design for the all-HTS insert component of the 1.3 GHz NMR magnet, forced upon us due to the loss, by theft, of the original H600, is described. Two design options for a 700 MHz HTS insert (H700) are discussed that meet not only the electromagnetic but also economic requirements. The new H700 incorporates two innovative design features: i) no-insulation winding; and ii) inside notch DP coils.

Acknowledgments

This work was supported by the National Center for Research Sources, National Institute of Biomedical Imaging and Bioengineering, and National Institute of General Medical Sciences of the National Institutes of Health (NIH).

References

- [1]. Bascuñán J, Hahn S, Park D, and Iwasa Y, “A 1.3 GHz LTS/HTS NMR magnet—A progress report,” *IEEE Trans. Appl. Supercond*, vol. 21, no. 3, p. 2092, 6 2011. [PubMed: 22081752]
- [2]. Bascuñán J, Hahn S, Park D, Kim Y, and Iwasa Y, “On the 600 Mhz HTS insert for a 1.3 GHz NMR magnet,” *IEEE Trans. Appl. Supercond*, vol. 22, no. 3, p. 4302104, 6 2012. [PubMed: 31171896]
- [3]. Yushikawa M, private communication, 2011.
- [4]. Hahn S, Park D, Bascuñán J, and Iwasa Y, “HTS pancake coils without turn-to-turn insulation,” *IEEE Trans. Appl. Supercond*, vol. 21, no. 3, p. 1592, 6 2011.
- [5]. Hahn S, Park DK, Voccio J, Bascuñán J, and Iwasa Y, “No-Insulation (NI) HTS inserts for > 1 GHz LTS/HTS NMR magnets,” *IEEE Trans. Appl. Supercond*, vol. 22, no. 3, p. 4302405, 6 2012. [PubMed: 31080326]
- [6]. Hahn S, Kim Y, Voccio J, Park D, Bascuñán J, Shin H, Lee H, and Iwasai Y, “No-insulation coil under time-varying conditions: Magnetic coupling with external coil,” *IEEE Trans. Appl. Supercond*, vol. 23, no. 3, p. 4601705, 6 2013.

- [7]. Montgomery B and Weggel R, Solenoid Magnet Design. Malabra, FL: Krieger, 1980.
- [8]. Wilson MN, Superconducting Magnets. Oxford, U.K.: Clarendon, 1986.
- [9]. Kim Y, Bascuñán J, Lecrevisse T, Hahn S, Voccio J, Park D, and Iwasa Y, “YBCO and Bi2223 coils for high field LTS/HTS NMR magnets HTS-HTS joint resistivity,” IEEE Trans. Appl. Supercond, vol. 23, no. 3, p. 6800704, 6 2013. [PubMed: 31130800]

Fig. 1. Each to-scale, schematics of the original 600 MHz and the new 700 MHz HTS inserts, installed in the bore of an all LTS background magnet.

Fig. 2. Compactness comparison of an insulated-wound coil and a NI-wound coil, both of the same inner diameter generating the same central field. Coils are wound with the same conductor.

Fig. 3.

Two design options considered for the new 700 MHz HTS insert: (a) inner and outer coils have 56 DPs, but inner YBCO coil wound with no inter-turn insulation; (b) outer coil with 40 DPs, inner coil with 26 DPs and no inter-turn insulation. Both coils in Design B with inside notch—notching is illustrated schematically.

Fig. 4.

Sketch, to-scale, showing the coil assembly. In red, the inner coil wound with YBCO conductor; in black, the outer coil wound with Bi2223 conductor. Also shown are the jacking screws/Belleville washers that provide the axial preload. Bottom screws allow for coil magnetic center alignment.

Fig. 5.
Schematics of the splice in the curved configuration.

TABLE I**Conductor Specifications (Manufacturers Provided)**

Superpower (RE)BCO Type SCS6050-AP Wire	
Width	6.1 mm (6.1 mm $\pm$ 0.15 mm)
Thickness	$\sim$ 0.075 mm + 0.025 mm/−0.01 mm
I _c (77 K, self field)	minimum value of 165 A
Copper stabilizer thickness	0.02 mm $\pm$ 0.01 mm (10 μ m per side)
Silver overlayer thickness	2.0 μ m $\pm$ 0.5 μ m
Hastelloy substrate thickness	0.05 mm
Critical tensile stress	> 550MPa
Sumitomo Bi2223/Ag, DI-BSCCO Type HT-SS	
Width (average)	4.5 mm $\pm$ 0.3 mm
Thickness (average per unit length)	0.31 mm
I _c (77 K, self field)	180 A
Configuration (reinforcement)	SS 304-H lamination, 20 μ m x 2
Tensile strength at 77 K	270 MPa

TABLE II

700 MHz HTS Insert Key Parameters (as Designed)

	Units	Inner Coil	Outer Coil
Conductor		YBCO	Bi2223
Field contribution	T	9.62	6.82
Operating temperature	K	4.2	4.2
Operating current	A	257.36	257.36
Current density	kA/cm ²	56.01	13.91
Total number of DPs		26	40
Turns per pancake		198	110
Inner/Outer diameter	mm	86.0/115.70	147.70/233.70
Height	mm	318.6	370.16
Notch ID	mm	87.5	147.3
Number of notched DPs		8	2
SS overbanding thickness	mm	5.0	5.0
Total conductor length	km	3.27	5.24