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Two HTS options for a 600 MHz insert of a 1.3 GHz LTS/HTS NMR magnet: YBCO and BSCCO

S. Hahn^{a,*}, J. Bascuñán^a, W. Yao^a, and Y. Iwasa^a

^aFrancis Bitter Magnet Laboratory, Massachusetts Institute of Technology, 170 Albany Street, Cambridge, MA 02139, U.S.A.

Abstract

In 2008, the Phase 3 program to complete a 1.3 GHz (30.5 T) NMR magnet started at the Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology. It comprises two sub-phases, 3A and 3B. In Phase 3A, a 600 MHz high temperature superconductor (HTS) insert magnet (H600) will be designed, constructed, and operated in the bore of a 500 MHz low temperature superconductor (LTS) background magnet. This will be followed by Phase 3B, in which the H600 will be combined with a 700 MHz LTS background magnet to complete a 1.3 GHz NMR LTS/HTS magnet. This paper presents and discusses design issues for two conductor options for H600: BiSCCO-2223 (Bi2223) and coated-YBCO or its variants, here designated as YBCO. For each conductor option, we focused on the following issues: 1) elastic and thermal properties; 2) critical current vs. field performance; 3) splice and index heat dissipations; 4) mechanical and thermal stresses; and 5) protection.

Keywords

1.3 GHz; Bi2223; HTS insert magnet; LTS/HTS NMR magnet; YBCO

1. Introduction

In 2000, a 3-Phase program to build a 1-GHz- (23.5 T) NMR magnet began at the Francis Bitter Magnet Laboratory (FBML), Massachusetts Institute of Technology. The Phase 1 program was completed in 2002 and the Phase 2 program in 2007, achieving, respectively, NMR frequencies of 350 MHz and 700 MHz [1–3]. At the outset of the program we adopted two principal approaches to a magnet to be completed in each phase: 1) an LTS/HTS magnet, combining a low-temperature superconducting (LTS) background NMR magnet and a high-temperature superconducting (HTS) insert; and 2) an HTS insert as a stack of double-pancake (DP) coils. Although a 1.0 GHz all-LTS NMR magnet operated at 1.8 K is feasible [4] and indeed one was recently completed [5], we strongly believe that for a >1 GHz NMR

*Corresponding author Dr. Seungyong Hahn, Postal address: MIT-FBML NW14-3111, 170 Albany Street, Cambridge, MA 02139, U.S.A., Phone: +1-617-253-4161, Fax: +1-617-253-5405, syhahn@mit.edu.

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magnet it is the HTS magnet that will play an increasingly prominent role. This is because critical current densities of LTS, even at 1.8 K, become less than $\sim 100 \text{ A/mm}^2$, a practical lower limit for magnets, above $\sim 25 \text{ T}$.

The Phase 3 program, with the ultimate goal of completing a 1.3-GHz LTS/HTS NMR magnet, upgraded from the original (2000) target frequency of 1.0 GHz, comprises two sub-phases, 3A and 3B. In Phase 3A, which began in 2008, our goal is to reach 1.1 GHz in 2012; in Phase 3B a 1.3 GHz will be reached, expected in 2017. For this last phase, that is, Phase 3, a new 600 MHz HTS insert magnet (H600) will be designed, constructed, and operated at the FBML. This paper presents design issues of the H600 based on two HTS conductor options: BiSCCO-2223 (Bi2223) and coated-YBCO (YBCO) or its variants, here designated as YBCO. For each option key design issues include: 1) elastic and thermal properties; 2) critical current vs. field performance; 3) splice and index heat dissipations; 4) mechanical and thermal stresses; and 5) protection.

2. Phase 3 Overview: Phases 3A and 3B

In Phase 3A, the H600 will be combined with a 500 MHz LTS background magnet (L500) already available at the FBML. After successful completion of Phase 3A, in Phase 3B, a 700 MHz LTS magnet will be purchased and together with the H600 the final goal of 1.3 GHz will be achieved. Figure 1 shows to-scale drawings of the LTS/HTS NMR magnets, completed in Phases 1 and 2, and those to be completed in Phases 3A and 3B, all at the FBML.

Table I summarizes key parameters of the four LTS/HTS NMR magnets in Fig. 1. Note that for both Phases 3A and 3B magnets, the HTS insert frequency and LTS cold bore size are kept identical, i.e., respectively, 600 MHz and 236 mm. Since the H600 will be ultimately operated with an L700 in the Phase 3B system, H600, though operated first with L500 in Phase 3A, it must be designed to fulfill the operating requirements of the Phase 3B magnet.

3. HTS Conductor: YBCO vs. Bi2223

In Phase 1 and 2, BSCCO-2223/Ag (Bi2223) stainless steel reinforced tape was our choice of conductor. However, the recent progress in YBCO conductors, particularly in mechanical performance and overall current density, has broadened our conductor options. To date, our extensive design study of H600 has shown that neither tape, YBCO or Bi2223 as it is now available from commercial vendors, is suitable for H600. With YBCO, for example, its normal conductive metal component is insufficient to meet a protection criterion of H600. Similarly, with Bi2223 its reinforcement element is insufficient to meet mechanical requirements of H600. In this section, elastic and thermal expansion properties of each conductor with various additional layers are evaluated by a finite element method and a mixture model with measured data of each component. Protection-related properties will be discussed in section 5.

3.1 Equivalent model

Figure 2 presents to-scale equivalent models of a single turn in a DP coil module for finite element analysis to obtain equivalent elastic and thermal expansion properties: Figure 2-(a) is for Bi2223 conductor with a turn-to-turn insulator and a G10 pancake-to-pancake insulator; while Figure 2-(b) for YBCO conductor with additional copper stabilizer and a turn-to-turn insulator as in Bi2223. For simplicity of calculation, a half model with symmetry is adopted as seen in Fig. 2.

3.2 Equivalent elastic and thermal expansion properties

Table II summarizes elastic and thermal properties of base materials indicated in Fig. 2 [6–12]. Two options of a turn-to-turn insulator are: 1) stainless steel (SS) and 2) Nomex; Young's modulus of SS is about 60 times larger than that of Nomex, i.e., the SS layer essentially works as a mechanical reinforcement as well as an insulator in a DP coil. Recent tests, conducted at the FBML and to be reported later, have demonstrated that, at least for double-pancake coils, it may be possible to substitute an *uninsulated* resistive normal metal strip for an organic strip as a turn-to-turn insulator. In Table II, note that Bi2223 tape and copper yield with 0.4% strain close to the peak hoop strain in H600, while the YBCO tape is still under elastic elongation. The thicknesses of copper and insulator layers of Bi2223 and YBCO in Table II were determined to provide the best mechanical integrity while keeping the overall coil dimension below 236 mm, the cold bore size of the Phase 3A and 3B LTS background magnets.

Table II also presents calculation results from the equivalent models in Fig. 2. When combined with Nomex, equivalent orthotropic Young's moduli of both YBCO and Bi2223 mixtures were calculated to be less than 70% of those with SS. Note that the equivalent Young's moduli of the YBCO mixture are similar to those of Bi2223 because of copper yielding.

3. Coil configuration

3.1 Coil parameters

With the two options of conductors in Table II, two versions of the H600, YH600 (YBCO) and BH600 (Bi2223) have been designed and their key magnet parameters are summarized in Table III. Each version has two nested coils, each a stack of 56 DP coils, and produces a total field of 30.5 T in an LTS background field of 16.4 T (700 MHz). YH600 and BH600 both operate at currents nearly equal to 280 A. However, the overall current density of YH600 is about 8% larger than that of BH600. As a consequence, total conductor length, inductance, as well as overall coil sizes of the YH600 becomes smaller than those of BH600.

3.2 Critical currents vs. fields

To estimate an approximate ratio of the critical current at 4.2 K and a given perpendicular field (B_{prep}) over that at 77 K in self-field, empirical Eqs. (1) and (2) were used [13]. Figure 3 presents a graphical representation of those equations. YBCO:

$$\frac{I_c(4.2K, B_{\text{perp}})}{I_c(77K, \text{sf})} = 8.68117e^{(-B_{\text{perp}}/4.01932)} + 1.23055 \quad (1)$$

Bi2223:

$$\frac{I_c(4.2K, B_{\text{perp}})}{I_c(77K, \text{sf})} = 3.46755e^{(-B_{\text{perp}}/2.36666)} + 1.72936 \quad (2)$$

As seen in Fig. 3, at lower field the ratio for YBCO is better than that of Bi2223, particularly at <4 T, which is close to the peak perpendicular field in the H600. At a perpendicular field of 4 T, the ratio of YBCO is 4.1 and that of Bi2223 2.0. With conductors providing the 77 K-critical current stated in Table III, both options will meet the field vs. I_c requirement of the H600.

3.3 Splice resistance

We have set an upper limit of 100 mW for the total Joule dissipation from 110 splices in the H600. This limit translates, on average, 0.9 mW per splice. With the operating current of ~280 A, this implies each splice should have a resistance less than 12 nΩ, well within the range achieved with the splices made at FBML in Phase 1 and Phase 2 [14,15].

In each coil assembly, a 5-mm thick stainless steel overband (Table III) blocks the splices from direct exposure to liquid helium present in a narrow vertical cooling channel, 5-mm wide in YH600 and 2 mm in BH600, outside the coil assembly. The Joule dissipation in each splice must thus be thermally conducted through this overband before it is discharged to the liquid helium in the cooling channel.

To roughly estimate a cooling capacity in the narrow channel, we use Eq. 3

$$q_{\text{pk}} = \frac{10w}{1.19 + 0.37z} [\text{W}/\text{cm}^2] \quad (3)$$

where q_{pk} is a peak nucleate heat transfer and w and z are the channel width and length, respectively [16]. With the 0.2 cm channel width and the 52 cm axial length in the BH600, the q_{pk} is calculated as ~0.1 W/cm². Note that because a typical length of each splice is 10 cm long with ~1 cm wide, the maximum Joule dissipation flux per each splice is 0.09 mW/cm² (=0.9 mW/10 cm²), which is well below a cooling flux of ~0.1 W/cm² per each splice. Of course to dispose this splice Joule dissipation flux into the liquid helium in the cooling channel, it must be conducted radially out through the overbanding medium. Our rough thermal conduction analysis indicates the each splice, though not directly exposed to liquid helium, will not be heated no greater than 0.1 K from its operating temperature of 4.2 K.

3.4 Index dissipation

Using an Index model from [17], index heat dissipation in the H600, e_{index} may be expressed by

$$e_{\text{index}} = \int_{\text{total}} I_c(B) E_c \left(\frac{I_{\text{op}}}{I_c(B)} \right)^{n+1} dl \quad [\text{W}] \quad (4)$$

where E_c is an electric field criterion, e.g., of 1 $\mu\text{V}/\text{cm}$ to define critical current, I_c , and I_{op} and n are, respectively, operating current and the index of HTS. A typical index number of HTS under an operating condition of the H600, i.e., peak parallel and normal fields of 30 T and 4.5 T at 4.2 K, ranges from 15 to 20 [6]. Table IV summarizes estimated index dissipation of the YH600 with an I_c of 110 A at 77 K, self field, and that of the BH600 with 160 A. The overall index dissipation of YH600 is smaller than that of BH600 because in a low perpendicular field, < 4 T, the ratio of YBCO in Fig. 3 is relatively larger than that of Bi2223.

4. Stress

In stress analyses, elastic and thermal expansion properties of the equivalent model in Table II were used. Two types of stress are considered: 1) magnetic stress from Lorentz force in the HTS coils; 2) thermal stress during cool-down. Note that HTS properties in Table II are based on measured data at 77 K. In conclusion, for the thermal stress analyses, only the cool-down from 77 to 4.2 K is considered in a conservative way. Also, a structure to provide axial pre-load compression to the H600 is also included in the stress analyses.

4.1 Structure analysis

Figure 4 presents von-Mises stress distributions of a) YH600 and b) BH600. For calculation easiness, only the upper half of each H600 was analyzed. Also, stainless steel is selected for the pre-load structure material as well as for overband. In general, the von Mises stress of YH600 is larger than that of BH600 by about 10%. The peak von-Mises stress occurred in the SS overband in both cases: 530 MPa for YH600 and 490 MPa for BH600. Note that the ultimate and yield stresses of SS can be as larger than 1600 and 800 MPa at 77 K, respectively [18]. At the operating temperature of H600 at 4.2 K, SS bands keep the stress levels below its yield point.

Fig. 5 shows a detailed view of hoop strain distributions along the radial direction at the center of the BH600 where stress and strain values are maximum; red squares indicate only magnetic stress distribution without SS overband and thermal contraction taken into consideration; black circles adding the effect of SS overbanding (SSOB); and blue triangles including SSOB and thermal contraction from 77 to 4.2 K (TC). Red dashed line indicates the 95% I_c retention strain of 0.4% in Bi2223 at 77 K. In the actual operation of H600, the SS overbanding will be very important to keep the peak hoop strain level below 0.4% though the thermal contraction from 77 to 4.2 K may reduce the peak strain further.

4.2 Insulator: Nomex vs. Stainless Steel

We now consider two material options for a turn-to-turn insulating strip in the DP coils of H600: 1) SS; and 2) Nomex. Figure 6 presents a summary of the stress analyses along the H600 center plane; a) hoop strain; b) hoop stress; c) radial stress; and d) radial strain. In each figure, the blue and black data are, respectively, for YBCO and Bi2223, while solid and open circles indicate SS and Nomex, respectively.

As discussed in [19], the Nomex insulator is “spongy” and contributes to increase overall strains. With a Nomex insulator, the peak hoop strain becomes much larger than the 95% I_c criteria of YBCO and BSCCO as indicated by the black and blue dashed lines in Fig. 6 (a). As a consequence, the hoop stress is increased, the effect shown in Fig. 6 (b). Note that the Nomex choice is also unprofitable in radial stress as seen in Figs. 6 (c) and 6 (d).

In general, the overall stress level of BH600 is slightly smaller than that of YH600 in absolute values. However, the YBCO has better strain limit, 0.45%, compared with that of Bi2223, 0.4% at 77 K [6, 20]. Note that, in all cases, the radial stress in a portion of Coil 1 winding is larger than 5 MPa, which was reported as a source of premature quench in a wet winding of LTS magnets [21]. However, the radial strain is still negative in the region of positive radial stress because of the large hoop stress.

5. Protection

To estimate protection performances of YH600 and BH600 at 4.2 K, the Z -function as defined in Eq. (5) is adopted where C_m and ρ_m are respectively specific heat and electrical resistivity of conductor matrix, and T_f is a final temperature.

$$Z(4.2K, T_f) \equiv \int_{4.2}^{T_f} \frac{C_m(T)}{\rho_m(T)} dT \quad (5)$$

Using the equivalent model in Fig. 2 and measured base material properties, a Z -function of four combinations of YBCO-Bi2223 and SS-Nomex is presented in Figure 7. According to [22], Cu-laminated YBCO and Bi2223-Ag started a slight I_c degradation at 370 and 800 K, respectively. A characteristic current-decay time constant, t_{300} defined as a time to reach 300 K, may be calculated by equation (6) under the assumption of adiabatic winding, where J_e is the overall current density stated in Table III. The calculation results are summarized in Table VI; the time constant of YBCO is slightly better than that of Bi2223 but still too small compared with that of a typical LTS magnet, > 15 s. So, the protection will be a very challenging task for either option, YH600 or BH600. Currently, a bare stainless steel strip is being studied for H600 as an insulator and a reinforcement layer but also as a protection element in a detect-and-activate-heater scheme.

$$t_{300} = \frac{1}{J_e^2} \int_{4.2}^{300} \frac{C_m(T)}{\rho_m(T)} dT \quad (6)$$

6. Conclusion

The Phase 3 program to ultimately complete a 1.3 GHz NMR magnet, currently on-going at the Francis Bitter Magnet Laboratory at MIT, comprises both high-field LTS background NMR magnet and a high-field HTS insert, specifically in our case of 700 MHz (LTS) and 600 MHz (H600). Two designs of H600 were presented based on conductor choices, YH600 with coated-YBCO (or its variants) and BH600 with Bi2223. Each insert composes of 2 nested coils to keep stresses within each coil below the stress limits of respective conductor. Based on design analysis, we may conclude as follows.

- Both YBCO and Bi2223 conductors, combined with additional stabilizer and reinforcement layers suitably selected to each conductor, are usable to wind H600 that will be operated with L500 and L700.
- For H600, YBCO requires additional stabilizer layers such as of copper, which will yield at a stress of 400 MPa with a strain close to 0.4%. As a consequence, the elastic properties of the equivalent YBCO conductor mixture in YH600 are estimated to become similar to those of Bi2223 in BH600.
- The two insert options, YH600 and BH600 meet key specifications of the H600 that include: 1) $< 0.35\%$ tensile conductor strain under full operating conditions at 1.3 GHz; 2) 280 A operating current; 3) < 100 mW Joule dissipation for 110 splices in H600 at 280 A; and 4) < 100 mW of total index heat dissipation.
- For H600 insulator, Nomex is inadequate. A bare SS strip, with potential benefits for coil protection, is an alternative to Nomex and it is currently under consideration.

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Fig. 1. To-scale drawings of the LTS/HTS NMR magnets in the FBML-MIT: a) Phase 1 (350 MHz, completed); b) Phase 2 (700 MHz completed); 3) Phase 3A (1.1 GHz, to be completed in 2012); and 4) Phase 3B (1.3 GHz, to be completed in 2017).

Fig. 2.

To-scale equivalent models of a single turn in a DP coil module for finite element analysis to obtain equivalent elastic and thermal expansion properties: a) Bi2223 conductor with a turn-to-turn insulator and G10 pancake-to-pancake insulator; b) YBCO conductor with copper stabilizer as well as insulators.

Fig. 3.
Critical current ratios vs. perpendicular fields at 4.2 K from equations (1) and (2) for YBCO (black squares) and Bi2223 (blue circles).

Fig. 4. von Mises stress distribution in: a) YH600 and b) BH600. A pre-load structure is included in the analysis. For calculation easiness, only the upper half of each H600 was considered.

Fig. 5.

Hoop strain distributions along the radial direction at the center of the BH600 where stress and strain values are maximum; red squares: magnetic stress without SS overband and thermal contraction; black circles: including SS overbanding (SSOB); and blue triangles: including SSOB and thermal contraction from 77 to 4.2 K (TC). Red dashed line indicates the 95% I_c retention strain in Bi2223 at 77 K [6].

Fig. 6. Summary of the stress distributions along the H600 center plane; a) hoop strain; b) hoop stress; c) radial stress; and d) radial strain; blue: YBCO; black: Bi2223; solid: SS; vacant: Nomex.

Fig. 7.
Z functions, defined in Eq. (6) with four combinations of YBCO-Bi2223 and SS-Nomex.

TABLE I

Magnet parameters of the LTS/HTS NMR magnets from Phase 1 to Phase 3B

	Phase 1	Phase 2	Phase 3A	Phase 3B
Period	2000–2002	2003–2007	2008–2012	2012–2017
Total frequency	350	700	1100	1300
(LTS/HTS)	(300/50)	(600/100)	(500/600)	(700/600)
Center field	8.22	16.4	25.8	30.5
	[T]			
Operating temperature [K]	4.2	4.2	4.2	4.2
RT bore	55	55	55	55
	[mm]			
LTS cold bore	130	140	236	236
	[mm]			
Overall height	488	700	950	1240
	[mm]			
Overall width	202	452	635	1009
	[mm]			
Inductance	70.0	97.4	194	1202
	[H]			
Stored energy	0.25	2.6	7.15	33.2
	[MJ]			

TABLE II

Elastic and thermal expansion properties of base materials and the equivalent model

		Bi2223 [6]	YBCO [7]	Copper [8]	Insulator [9,10]		G10* [11]
					SS	Nomex	
Width		[mm]	4.5	4.0	4.5	4.5	0.0635
Thickness		[mm]	0.3	0.055	0.05	0.05	Tape T.
Young's Modulus, E		[GPa]	99	197	206	3.5	n:22.3 p:35.9
Young's Modulus @0.4% strain[GPa]		68**	197**	40**	206	3.5	n:22.3 p:35.9
Thermal expansion (4-300 K),TE[mm]		0.37	0.28 [12]	0.32	0.30	0.59	n:0.71 p:0.24

YBCO+Cu+Ins+G10				Bi2223+Ins+G10			
Insulation	Nomex	SS	SS	Nomex	SS	SS	SS
$E_t^{\dagger}$ [GPa]	17.21	51.49	18.82	73.75			
$E_h^{\dagger}$ [GPa]	58.13	85.69	57.79	85.91			
$E_z^{\dagger}$ [GPa]	58.22	83.97	57.78	84.37			
$\nu_{th}^{\dagger\dagger}$ [null]	0.430	0.386	0.429	0.349			
$\nu_{hz}^{\dagger\dagger}$ [null]	0.330	0.340	0.331	0.340			
$\nu_{tz}^{\dagger\dagger}$ [null]	0.101	0.201	0.107	0.284			
$\alpha_r^{\dagger}$ [%]	0.327	0.312	0.308	0.363			
$\alpha_h^{\dagger}$ [%]	0.331	0.313	0.377	0.359			
$\alpha_z^{\dagger}$ [%]	0.331	0.312	0.377	0.358			

* n: normal; p: parallel.

** measured at 77 K.

† Young's modulus;

†† Poisson ratio;

Thermal expansion (4 – 300 K)
 α_{L}

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TABLE III

Key magnet parameters of YH600 and BH600.

	YH600		BH600	
	Coil #1	Coil #2	Coil #1	Coil #2
Frequency	347	253	294	306
Field contribution	[MHz]			
	8.14	5.95	6.91	7.18
Max. radial field	[T]			
	4.1	4.3	4.1	4.2
I_c @ 77 K, sf	[A]	80 – 110	110 – 160	
I_c (4 T, 4.2 K)/ I_{c0} (sf, 77K)	[null]	4.1	2.0	
Operating Current	[A]	279.4	283.1	
Overall current density	[kA/cm ²]	19.1	17.5	
# of DP coils	56	56	56	56
# of turn per pancake	94	80	92	99
Inner diameter	[mm]	74.0	160.8	74.0
				152.4
Outer diameter	[mm]	140.8	217.6	138.4
				221.8
Height	[mm]	462.2	462.2	518.1
SS overband thickness	[mm]	5.0	5.0	5.0
Conductor length/DP	[m]	64	96	62
				116
Conductor length	[km]	3.56	5.33	3.44
				6.52
Total conductor length	[km]	8.89	9.96	
Self inductance	[H]	2.01	4.64	1.71
				6.17
Total inductance	[H]	10.6	12.15	

TABLE IV

Calculated index heat dissipation

		YH600		BH600	
		Coil #1	Coil #2	Coil #1	Coil #2
n=15	[mW]	0.36	0.55	23.6	61.5
n=20	[mW]	0.016	0.025	3.96	11.2

TABLE V

Characteristic time constant of yh600 and bh600 in protection

		YH600	BH600
SS	[s]	2.88	1.47
Nomex	[s]	2.63	1.30

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