Published in final edited form as:

IEEE Trans Appl Supercond. 2018 April ; 28(3): . doi:10.1109/TASC.2018.2799182.

HTS Shim Coils Energized by a Flux Pump for the MIT 1.3-GHz LTS/HTS NMR magnet: Design, Construction, and Results of a Proof-of-Concept Prototype

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Abstract

In this paper we present design, construction, and preliminary results of a proof-of-concept prototype of high-temperature superconductor (HTS) shim coils operated at 77 K and energized, for the first time among all shim coils, by a flux pump, here called digital flux injector (DFI). Although the prototype shims were wound with 2-mm wide REBCO tape, and DFI with Bi2223 and REBCO tapes, the HTS Z1 and Z2 shims to be installed in the MIT 1.3-GHz LTS/HTS NMR magnet (1.3G) currently under construction and operated at 4.2 K will be wound with reinforced Bi2212 wire and DFI with Nb₃Sn tape. The paper concludes with two sets of Bi2212 Z1 and Z2 shims for 1.3G.

Index Terms

Axial (Z1 and Z2) shim coils; digital flux injector (DFI); high-temperature superconductor (HTS) shim coils; screening-current field (SCF)

I. Introduction

FOR a high-resolution NMR the field must be uniform with an error field of 0.01 ppm over a sample volume, making *field shimming* a must in the NMR magnet. Currently all shim coils are of NbTi. Because of their field limitations (<12 T even at 1.8 K) and size (15–30 mm radial build), NbTi shims have always been located outside the magnet assembly, i.e., radially furthest away from the magnet center where the field homogeneity matters.

For a shim coil placed outside the magnet assembly, there are two inherent technical disadvantages: 1) at a great distance each coil must work *harder* to generate a required shim field, i.e., a greater ampere (current)-turns (coil size); and 2) the shim fields are *attenuated* by the “diamagnetic” walls of the magnet assembly comprising many coils as the shim fields reach the center; worse, field attenuation is axially asymmetric [1]. In contrast, an HTS shim

coil, operable even in a >12-T field and slim (~1-mm radial build), can be placed inside the magnet assembly, eliminating the inherent disadvantages of the NbTi coil.

One prominent source of field error is the screening-current field (SCF), i.e., a diamagnetic field, generated by each coil in the superconducting magnet [2]–[10]. The “diamagnetic wall” is proportional to the superconductor size and critical current density [11]. The NbTi shim field generated outside of the magnet, cannot avoid the diamagnetic walls, while a shim field from *inside* is free of the detrimental effects of the diamagnetic wall [1].

Diamagnetic Wall

Fig. 1 shows a profile of the axial shim field through a cylindrical “diamagnetic wall,” a manifestation of a screening current induced by a field impinging on the cylinder [11]. Here, the diamagnetic wall is a solid superconductor cylinder, thick, inner diameter $2R$, and infinite in the z -axis, i.e., a “Bean” tube [11]. A shimming field of axial (z) amplitude H_{shm} , generated outside the Bean cylinder, is decreased by $H_{dw}=J_c$ [11], where J_c is the superconductor critical current density.

All LTS coils are now wound with a wire of superconducting multifilaments (each typically of $100\text{ }\mu\text{m}$ size) embedded in copper. In contrast, most high-field HTS coils are wound with REBCO or Bi2223 of typically millimeters in size. Although neither of these sizes can be equated to , LTS coils have much less *attenuating* and *distorting* effects of the diamagnetic walls than HTS coils. The MIT 1.3-GHz LTS/HTS NMR magnet (1.3G) is composed of an LTS 500-MHz NMR magnet (L500) and an HTS 800-MHz insert (H800) currently under construction at FBML, of which the H800 embodies a menacing diamagnetic wall.

Our HTS Z1 and Z2 shim coils, to be installed in the 1.3G, are pertinent for two reasons: 1) being axial, they can easily be accommodated in a narrow annular space inside the H800 bore; and 2) Z1 and Z2 harmonic error field has been shown to be prominent in REBCO coils due to SCF [12].

Z1 and Z2 Shims

The axial component of magnetic field within a spherical volume with no current source, B_z , can be expressed in the spherical and cartesian coordinates as in (1):

$$\begin{aligned} B_z &= \sum_{n=0}^{\infty} \sum_{m=0}^n r^n P_n^m(\cos\theta) \times (a_{nm} \cos m\phi + b_{nm} \sin m\phi) \\ &= a_{00} + a_{10}z + a_{11}x + b_{11}y + \frac{1}{2}a_{20}[2z^2 - (x^2 + y^2)] + 3a_{21}zx + 3b_{21}zy + 3a_{22}(x^2 - y^2) \\ &\quad + 6b_{22}xy + \dots \end{aligned} \quad (1)$$

where a_{nm} and b_{nm} are the harmonic coefficients, and $P_n^m(\cos\theta)$ is associate Legendre polynomial of order n and degree m . The Z1 and Z2 shim coils are used to minimize the

axial error field in diameter of spherical volume (DSV), respectively, linear (1st) a_{10} and curvature (2nd) a_{20} harmonics. For both HTS Z1 and Z2 shim coils to be installed in the 1.3G we have tentatively chosen reinforced Bi2212 wire [13].

Fig. 2 shows ideal Z1 coil and two Z2 coils, Z2₁ and Z2₂, each a pair of loops of $2a$ diameter. When each pair is separated by a gap shown in Fig. 2, Z1 generates *zero* 3rd harmonic term [11], while each Z2 shim *zero* 4th term. At the same current in the two Z2 coils, Z2₁ generates the 0th term (center field) and the 6th term 3.297 times and -11.04 times those of Z2₂ [14]: it is thus theoretically possible to eliminate the 6th term zero by having Z2₁ carry 1/11.04th of Z2₂ current.

Digital Flux Injector (DFI)

Both Z1 and Z2 shim coils will be energized with a digital flux injector (DFI) [15]–[19]. We developed the DFI, then called a flux pump, to inject at an interval a metered (i.e., “digital”) amount of flux to a 1-GHz LTS/HTS NMR magnet, a project that began in 2000 [20]. Fig. 3 shows a CAD image of a composed of four double-pancake (DP) coils, placed 90° apart. To minimize the DFI field at the magnet center, the nested DFI primary and secondary coils are toroids [15]. Both coils were wound with Nb₃Sn tape, 3 mm×0.24 mm, manufactured by GE. We plan to use a similar configuration with the same type of conductor for the DFI primary and secondary coils for 1.3G.

Overall System

Fig. 4 shows a schematic drawing of a cross section of the 1.3G housed in a cryostat. It indicates the locations of L500, H800, Z1 and Z2 shim coils, and DFI. The Z1 and Z2 shim coils are in a 5-mm annular space in the H800 cold bore, immersed as L500 in 4.2-K liquid helium (LHe). The DFI is placed in the 65-mm high cold space, above the LHe level, and thermally attached to the top radiation shield at ~50 K, anchored to the 1st-stage of a 3 W@4.2 K cryocooler. Note that the cryocooler’s primary function is to recondense the effluent He vapor and thus to minimize LHe consumption.

II. Proof-of-Concept Prototype

A. A Prototype Z2 Shim and DFI Coils

As a precursor to a flux-pump-energized set of Z1 and Z2 shim coils to be installed in our 1.3G, we have built and operated at 77 K a prototype comprising a set of Z2 shim coils and a DFI. Table I lists key parameters of the prototype. For operation at 77 K, we used 2-mm wide, 65- μ m thick REBCO tape to wind both the Z2 shim coils and the DFI secondary coil, and 4.5-mm wide Bi-2223 tape for the DFI primary coil. The Z2 shim set is composed of 2 pairs of Z2 coils, Z2₁ and Z2₂, wound in the opposite directions from each other. Fig. 5 shows, respectively, (a) a circuit diagram and (b) a photo of the prototype system.

The Z2 shim set is operated in quasi-persistent mode after persistent-current switch (PCS), S1, closed, having a Z2 shim coil inductance, L_{Z2} , and two resistive (for this prototype) joints ($J1_{Shim}$ & $J2_{Shim}$) at terminals of Z2 shim set to a S1. To make the field decaying time constant as large as possible for this Z2 shim set, Z2₁ and Z2₂ were wound with a single

continuous length of conductor to minimize the number of resistive joints. The DFI was placed 45-cm away from the Z2 shim coil center in the orthogonal direction to the main Z2 field to minimize the field interference generated by DFI. Each PCS of REBCO tape had a 350-Ω strain gauge heater and surrounded by a 5-mm wall expanded polystyrene foam sealed with Epoxy [22]–[24]. About 0.3-W of heater power was required to open the PCS within 10 s.

B. Test Results at 77 K in Liquid Nitrogen

Following the operation procedure described in [15], we induced the current, I_s , in the DFI upper loop in Fig. 5(a) ideally given by $(M_{ps}/L_s)I_p$, where M_{ps} and L_s are the mutual and the secondary inductances, respectively; and I_p is the DFI primary current. Then, opened S1 PCS to increase a Z2 shim current, I_{op} , by I_{op} theoretically expressed as [15]:

$$L_{Z2}I_{op} + L_sI_s = (L_{Z2} + L_s)(I_{op} + \Delta I_{op}) \quad (2)$$

Solving (2) for I_{op} with $I_s = (M_{ps}/L_s)I_p$, we have:

$$\Delta I_{op} = \frac{M_{ps}I_p - L_sI_{op}}{L_{Z2} + L_s} \quad (3)$$

where we assume that the resistive joints are negligibly small for a short time period estimation. Experimentally, I_{op} was inferred from the peak axial Z2 field with the Hall sensor. Fig. 6 shows selected results for two flux pumping events. I_{op} increased as S1 was opened but dropped quickly when the DFI primary coil current reached $I_p = 5$ A, until S1 was closed. DFI-injected current by pumping iterations, I_{op} , was 0.6 A, only $\sim 1/15^{th}$ of an expected I_{op} of 9 A, according to (3) at $I_{op} = 1.5$ A. This unexpected poor performance may indicate that the REBCO tape might have been damaged, e.g. a kink inflicted to REBCO tape during assembly. After 10 flux injections, we achieved $I_{op} = 3$ A and mapped the axial field of the Z2 shim: Fig. 7 shows measured (blue crosses) and computed (red line) field distributions. Data fitting gives a 2nd order strength of 880 Hz/cm²/A. A discrepancy from the computed 794 Hz/cm²/A have been caused by both a small difference (<1 mm) in the winding dimensions and an additional turn in the Z2 coils introduced as the entire set was wound with one continuous length of tape. Next, in order to investigate the location of an unexpected damaged part, we increased I_{op} to 17 A by increasing I_p to 30 A with a ramp rate of 1 A/s while S1 was opened during ramping and by closing S1 to isolate the Z2 coil loop. Fig. 8 shows that I_{op} dropped quickly as it did during flux pumping iteration with the field decaying time constant by the Z2 shim inductance, L_{Z2} , of 111 μH and the equivalent circuit resistance of ~ 5 μΩ that we suspect the kink, but once S1 was closed I_{op} started decaying slowly with a time-constant-equivalent circuit resistance of 60 nΩ, mostly from two 8-cm long, 2-mm wide REBCO-REBCO lap joints, J_{shim} and J_{shim} , resulting ~ 50 nΩ cm², between S1 and the Z2 shim set. This result may indicate the ~ 5 -μΩ kink exists in either the DFI secondary coil or PCS S2.

III. Designs of Z1 and Z2 Shim Coils for 1.3G

Unlike the ideal Z1 and Z2 shim coils in Fig. 2, they consist of many turns, as in the prototype Z2 shim coil, to maximize the shim strength under the confined size and the operable current. The 1st-cut design with a two-pair Z2 coils was used for the prototype Z2 shim without considering an inductive coupling with 1.3G. However, one of the key requirements for the *axial* shim coils to be installed in 1.3G is to limit changes in Z1 and Z2 operating currents, I_{Z1} and I_{Z2} , induced by $I_{1.3G}$, a change in the 1.3G operating current $I_{1.3G}$: $I_{Z1} = (M_{Z1}/L_{Z1}) I_{1.3G} \ll I_{Z1}$ and $I_{Z2} = (M_{Z2}/L_{Z2}) I_{1.3G} \ll I_{Z2}$, where $M_{Z1,Z2}$ and $L_{Z1,Z2}$ are mutual to 1.3G and self inductances of Z1 and Z2 shim coils, respectively. We designed a Z1 and Z2 shim coil sets to maximize the target shim strength while minimizing the other harmonic error terms and the mutual inductance with 1.3G. The Z1 shim coil set inherently has no inductive coupling with 1.3G, i.e., $M_{Z1} = 0$. For this new designed Z2 shim coil set composed of series-connected three pairs of Z2 coils, Z2₁, Z2₂, and Z2₃, we compute $I_{Z2} \sim 0.03 I_{1.3G}$. Thus even if $I_{1.3G} = 250 \text{ A} \rightarrow 0 \text{ A}$, i.e., $I_{1.3G} = 250 \text{ A}$, $I_{Z2} < 10 \text{ A}$, which is less than 10% of the maximum operating current of 100 A, clearly safe enough change for this Z2 shim coils. Table II presents key parameters of one-layer Z1, Z2₁, Z2₂, and Z2₃ coil pairs, based on inductive coupling consideration. As indicated in the table, each coil pair is wound with 1.25 mm×0.6 mm reinforced Bi2212 wire on a stainless steel tube, $\phi 80$ -mm and 0.5-mm wall thickness (δ). As may be inferred from Table II, in the top and bottom Z1 coils, as well as in Z2₂ coils, “-” turns are wound in the opposite direction, i.e., the current flows in the opposite directions.

IV. Conclusions

We have designed a set of HTS Z1 and Z2 shim coils for installation within a 5-mm annular space in the cold bore of the H800 that together with the L500 forms the MIT 1.3-GHz LTS/HTS NMR magnet currently under construction at FBML. In addition to an innovative idea of placing these persistent-mode shim coils in a close proximity to the magnet center, i.e., at the highest field region of the magnet, possible only with HTS, we are also introducing another innovative idea of powering the HTS shim coils with a DFI. In our first attempt, we designed, built, and operated at 77 K a prototype composed of two pairs of Z2 coils, both wound with a continuous length of 2-mm wide, 65- μm thick REBCO tape and powered by a DFI, which also operated at 77 K. Although below our expectation, most likely because of a kink (in the REBCO tape in the DFI loop) that prevented the DFI to operate at full capacity, the preliminary results have validated the viability of “thin” HTS shim coils and operation principle of an HTS DFI. For 1.3G, we plan to use reinforced Bi2212 wire for the Z1 and Z2 shim coils, the designs of which are presented here, and the GE Nb₃Sn tape for the DFI primary and secondary coils.

Acknowledgments

The authors thank the project technician Peter Allen for making parts; the Wentworth Institute of Technology coop student, Jad Hanna, for their technical assistance.

Research reported in this publication was supported by the National Institute of General Medical Sciences of the National Institutes of Health under award number R01GM114834.

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Fig. 1. Schematic profile of the axial magnetic field (green) with a diamagnetic wall (blue), thick and $2R$ ID.

Fig. 2.

Ideal Z1, Z2₁, and Z2₂ shim coils, each a pair of loops of $2a$ diameter. Note that distances separating coil pairs are not scaled.

Fig. 3.
CAD image of a DFI [19].

Fig. 4.
Schematic drawing of 1.3G cross section. Dimensions in mm.

Fig. 5. Prototype DFI-Z2 system, constructed and operated at 77K. (a) circuit diagram; (b) photo.

Fig. 6. Measured S1, S2 temperatures, I_p and I_{op} signals vs. time resulting from 2 sequential flux injections.

Fig. 7.
Z2 axial field distributions at 3 A; measured (blue crosses) and computed (red line).

Fig. 8.
Z2 shim I_{op} induced by DFI with $I_p = 30$ A.

TABLE I

Key Parameters of Prototype Z2 Shim Set & DFI

<i>Shim Set ($z = 0$ plane symmetry)</i>		Z2₁	Z2₂
Conductor; dimensions	[mm]	REBCO; 2×0.065	
I_c in self-field @77 K	[A]	<60	
Winding ID ($2a_1$) / OD ($2a_2$)	[mm]	76.0/76.1	
Bottom z positions (b_1)	[mm]	6.2	36.9
Top z positions (b_2)	[mm]	16.7	102
# of turns		2×-5	2×31
Total conductor	[m]	2.4	15
Self inductance, L_{Z2}	[μ H]	110.9	
0 th ; 2 nd ; 4 th ; 6 th [Hz/cm	n A]	-8; 794; 1; 2	

<i>Digital Flux Injector</i>		Primary	Secondary
Conductor (tape)		Bi2223	REBCO
Winding ID ($2a_1$) / OD ($2a_2$)	[mm]	76.2/90.0	92.5/92.6
Winding height ($2b$)	[mm]	36.9	30.0
Total # of turns		224	14
Total conductor length	[m]	58	4
Self inductances, L_p & L_s	[μ H]	3913	23.3
Mutual inductance, M_{ps}	[μ H]	250.8	

TABLE IIKey Parameters of 1-Layer Z1 and Z2 ($Z2_1$, $Z2_2$ & $Z2_3$) Shim Coils for 1.3G

	Z1	Z2 ₁	Z2 ₂	Z2 ₃
<i>SS Coil form</i> : OD; Wall (δ)	[mm]	80; 1.5		
<i>Bi2212 wire</i> : Dimensions	[mm]	1.25 $\times$ 0.60		
I_c in 30.5 T @ 4.2 K	[A]	250		
Tolerable stress limit	[MPa]	>250		
Winding ID ($2a_1$) / OD ($2a_2$)	[mm]	80.0/81.2		
Bottom z positions (b_1)	[mm]	30.4	7.0	41.0
Top z positions (b_2)	[mm]	40.4	15.5	88.8
# of turns		± 8	2×-38	2×34
Operating currents, I_{Z1} & I_{Z2}	[A]	100		
Total conductor	[m]	4	3	19
Inductances				
Self, L_{Z1} , L_{Z2}	[μ H]	17	219	
Mutual to 1.3G, M_{Z1} , M_{Z2}	[μ H]	0	6.0	
0 th term	[Hz/A]	0	4.7	
1 st term	[Hz/cm A]	1663	0	
2 nd term	[Hz/cm ² A]	0	-893	
3 rd term	[Hz/cm ³ A]	0.3	0	
4 th term	[Hz/cm ⁴ A]	0	-0.5	