Published in final edited form as:

IEEE Trans Appl Supercond. 2018 April ; 28(3): . doi:10.1109/TASC.2018.2803801.

A Field-Shaking System to Reduce the Screening Current-Induced Field in the 800-MHz HTS Insert of the MIT 1.3-GHz LTS/HTS NMR Magnet: A Small-Model Study

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Abstract

In this paper, we present experimental results, of a small-model study, from which we plan to develop and apply a full-scale field-shaking system to reduce the screening current-induced field (SCF) in the 800-MHz HTS Insert (H800) of the MIT 1.3-GHz LTS/HTS NMR magnet (1.3G) currently under construction—the H800 is composed of 3 nested coils, each a stack of no-insulation (NI) REBCO double-pancakes. In 1.3G, H800 is the chief source of a large error field generated by its own SCF. To study the effectiveness of the field-shaking technique, we used two NI REBCO double-pancakes, one from Coil 2 (HCoil2) and one from Coil 3 (HCoil3) of the 3 H800 coils, and placed them in the bore of a 5-T/300-mm room-temperature bore low-temperature superconducting (LTS) background magnet. The background magnet is used not only to induce the SCF in the double-pancakes but also to reduce it by the field-shaking technique. For each run, we

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induced the SCF in the double-pancakes at an axial location where the external radial field $B_r > 0$, then for the field-shaking, moved them to another location where the external axial field $B_z \gg B_r$. Due to the geometry of H800 and L500, top double-pancakes of 3 H800 coils will experience the considerable radial magnetic field perpendicular to the REBCO tape surface. To examine the effect of the field-shaking on the SCF, we tested each NI REBCO DP in the absence or presence of a radial field. In this paper, we report 77-K experimental results and analysis of the effect and a few significant remarks of the field-shaking.

Index Terms

Field-shaking; High field magnet; HTS insert; REBCO; SCF; Screening current

I. Introduction

For the development of >1 GHz NMR spectrometer system, with LTS outsert coil, an HTS insert coil must be used owing to its large in-field current-carrying capacities [1]. For a high-resolution NMR spectrometer system, its magnetic 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. The screening current-induced field (SCF), a diamagnetic field generated by each turn of HTS coil, is the major field error to incorporate an HTS insert for a high field LTS/HTS magnet. The magnitude of the diamagnetic field, the SCF is directly proportional to the superconductor size and critical current density [2]. Various studies have reported the screening current-induced field (SCF) generated by HTS coils [3–5].

Although the SCF in LTS magnets is much less severe than the one in HTS magnets, the so-called field-shaking technique to minimize the SCF error fields was proposed in 1986 for LTS magnets [6–8]. This technique has since been demonstrated, theoretically and experimentally to apply to HTS magnet [9–15]. Since the SCF by an HTS insert magnet can be >100 times greater than those typical by an LTS outsert magnet, it is critical to reduce or even eliminate the SCF-generated error field.

Francis Bitter Magnet Laboratory (FBML) of Massachusetts Institute of Technology (MIT) has developed a high-resolution 1.3-GHz/54-mm LTS/HTS NMR magnet (1.3G). The 1.3G consists of the 800-MHz HTS insert (H800) composed of 3 nested coils, each a stack of no-insulation (NI) REBCO double-pancakes (DPs), and the 500-MHz LTS outsert (L500). In 1.3G, H800 is the primary source of a large error field generated by its own SCF. Though L500 has adequately long length, the end-plane DPs of three H800 coils will experience the considerable radial magnetic field perpendicular to the REBCO tape surface. To examine the effect of the field-shaking on the SCF, we tested each NI REBCO DP in the absence or presence of a radial field. Based on our earlier field-shaking works [9–11], the experiment presented in this paper will help us to design a field-shaking system most suitable for our 1.3G. Unlike our previous field-shaking experiments in which we used either a stack of 3 REBCO 94mm OD NI DPs [10, 16] or a pile of 12-mm×12-mm square NI REBCO strips [11], we use 2 NI REBCO DPs, one from each of two H800 coils (HCoil2 and HCoil3) for our new experiment.

By a 5-T/300-mm room-temperature bore LTS background magnet, we induced the screening current at DP coils. The 5-T background magnet also reduces the SCF generated by the screening current by the trapezoidal field-shaking patterns, confirmed as effective for reduction of the SCF [16]. Considering the geometry of the LTS/HTS combination and the magnetic field within the HTS tape, the largest SCF error field occurs in the top and bottom end regions of a magnet, where the radial fields, applied- and self-field, are greatest. Therefore, we induced the SCF in the presence of the maximum external radial field and then, attempt to reduce it by the field-shaking technique in absence or presence of the external radial field.

II. Test Coils and Experimental Procedure

In this study, for the SCF induction and field-shaking tests, we used 2 NI REBCO DP coils, one from each of 2 H800 coils (Coils 2 and 3). Separate tests were used to characterize the field-shaking behavior of the HCoil2 DP and the HCoil3 DP, respectively. Specifications of 2 REBCO DPs are shown in Table I.

The magnetic field near the ends of the H800 contains significant radial field component. To examine the effect of the field-shaking on the SCF, we tested each NI REBCO DP in the absence or presence of a radial field. This can be achieved by testing each NI REBCO DP at a selected position above or below the mid-plane of the 5-T LTS background magnet. From the geometry of the coil winding of the LTS background magnet, both Coil 2 and Coil 3 NI REBCO DPs will experience the maximum radial field at $z = \pm 175 \text{ mm}$ by the shape of the background magnet. Fig. 1 shows the position of the LTS background magnet and the tested DPs. The SCF was induced at $z = -175 \text{ mm}$, and the field-shaking was done at the midplane. Dashed arrow lines mean that the DP attached to the flange plate is movable.

The procedures to induce the SCF and later to reduce the SCF by the field-shaking are as below:

1. Place a single NI REBCO DP, at room temperature, at an axial location, $z = -175 \text{ mm}$, below the mid-plane of the LTS background magnet.
2. Apply the magnetic field of 5 T to the single NI REBCO DP. The coil experiences the external radial field of 0.73-0.82 T, perpendicular to the tape surface, at this location.
3. Turn the NI REBCO DP into the superconducting state by cooling in a bath of liquid nitrogen, ready for inducing an SCF by flux trapping
4. Reduce the external magnetic field to zero, the process of which induces the SCF in the DP.
5. Relocate the DP to the mid-plane of the LTS background magnet for the field-shaking in the absence of the radial field; or stay at $z = -175 \text{ mm}$, for the field-shaking in the presence of the radial field.
6. Apply a shaking field with the LTS background magnet using 0.6-1.6 T trapezoidal field injection, confirmed as effective for reduction of the SCF [16].

7. Map the radial field along the z -axis at the DP's inner-most turn.

III. Induction of SCF and Field-Shaking Test

A. Field-shaking of HCoil2 DP: with and without radially shaking field

Following the above-noted procedure, we induced the SCF of HCoil2 DP at $z = -175 \text{ mm}$ and later positioned the DP to certain locations, $z = 0 \text{ mm}$ or -175 mm to reduce its SCF by field-shaking with or without the radial field. At $z = 0 \text{ mm}$, the DPs experienced the axial component of the shaking field, B_{sk-Z} and almost zero radial component of the shaking field, B_{sk-R} . However, at $z = -175 \text{ mm}$, both certain B_{sk-Z} and B_{sk-R} were applied to the DPs. The measurements of magnetic flux density distribution along the z -axis were repeated after every fieldshaking experiment.

Fig. 2 and 3 show B_R , the measured radial field at the innermost turn of HCoil2 DP before and after field-shaking when the DP was located at $z = 0 \text{ mm}$ and -175 mm , respectively. To quantify and compare the effect of B_{sk-R} on the field-shaking for the reduction of the SCF, we calculated the line integrals of the measured magnetic flux density along the z -axis, $\int |B_{scf}| dz$ which has the unit of Wb/m and compare their normalization values. Fig. 4 shows the normalization value of that line integral for HCoil2 DP's field-shaking tests.

When the field-shaking was performed at $z = 0 \text{ mm}$ with the absence of B_{sk-R} , six field-shaking applications of B_{sk-Z} of 0.6 T lowered the SCF to 20.9-23.2% of its originally induced SCF. After a precipitous drop to 22.8% at its first field-shaking application, the SCF was saturated at ~22% with more applications.

However, when the field-shaking was performed at $z = -175 \text{ mm}$ with B_{sk-R} of 0.14 T, three field-shaking applications of B_{sk-Z} of 0.6 T showed the saturation of the SCF reduction, at 89.1-91.1%. Because the SCF reduction showed the tendency of saturation, the additional tests were performed at $z = 0 \text{ mm}$. Without B_{sk-R} , the first application of field-shaking reduced the SCF to 15.0% and two more applications reduced the SCF to 13.9% and 15.0%, respectively.

B. Field-shaking of HCoil3 DP

Similar to HCoil2 DP's tests, we induced the SCF of HCoil3 DP at $z = -175 \text{ mm}$ and later moved the DP to $z = 0 \text{ mm}$. In this test, when the SCF reduction showed the tendency of the saturation, B_{sk-Z} was increased.

Fig. 5 shows the B_R of HCoil3 DP before and after field-shakings. Fig. 6 shows the comparison the field-shaking effect on HCoil3 DP with various B_{sk-Z} . It shows that five field-shaking applications of $B_{sk-Z} = 0.6 \text{ T}$ lowered the SCF to 54-51% of its originally induced SCF. Moreover, each four more field-shaking applications of $B_{sk-Z} = 0.8 \text{ T}$ and 1.2 T reduced the SCF to 48-42% and 32-28%, respectively. Moreover, three more field-shaking applications of $B_{sk-Z} = 1.6 \text{ T}$ reduced the SCF to 24-21%.

C. Test summary and Discussion

Two tests on HCoil2 DP and a test on HCoil3 DP successfully reduced the SCF to approximately 20% of their initially induced values. Once the reduction of the SCF shows the tendency of saturation, unless the shaking-field was increased, the repetition of the field-shaking did not reduce the SCF anymore. The field-shaking of 0.6 T with the radial field of 0.14 T makes the field-shaking significantly less effective which shows only 11% reduction ($100 \rightarrow 89\%$), compared with the field-shaking of purely axial 0.6 T which shows 80% reduction ($100 \rightarrow 20\%$). Therefore, we may conclude that for 1.3G operation, the field-shaking for the reduction of SCF in H800 should be performed with the almost pure axial field.

In addition to the SCF reduction, though any current was not supplied to each DP, we observed the superconducting-to-normal transition in an HCoil3 DP test from the electromotive force between the background magnet and the NI DP coil. Fig. 7 shows this phenomenon during the test. Due to the existence of the turn-to-turn contact, NI coil can be expressed as a closed-loop RL circuit which can be charged by the external varying magnetic field in this test. The electromotive force from the background magnet is directly proportional to the current sweep rate of the background magnet. Therefore, for NI HTS magnets, the electromotive force is also directly proportional to the frequency of the field-shaking.

IV. Conclusion

The measurement of the SCF and the effect on the field-shaking for its reduction was studied experimentally. Two NI REBCO DPs, one from each of two H800 coils (Coils 2–3) were tested. The field-shaking tests were performed at various amplitudes of shaking-field and DPs axial location. The experiment presented in this paper will help us to design a field-shaking system most suitable for our 1.3G. Based on the experimental results and analyses to date, we may conclude that:

- The field-shaking technique successfully reduces the initial amount of the SCF even after one field-shaking application.
- The higher shaking field is more effective on the reduction of the SCF than the lower.
- Presence of the radial field during field-shaking made field-shaking significantly less effective than in the absence of one.
- For the field-shaking of the HTS magnets adapting NI winding technique, the frequency of the field-shaking can be restricted within a certain limit due to the induced current by the electromotive force.

Acknowledgments

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. Position of HCoil2 DP (blue), and HCoil3 (red) in the 5-T/300-mm LTS background magnet (black).

Fig. 2. Measured radial magnetic flux density, B_R , at innermost turn region of HCoil2 DP along the z-axis axis when the DP was located at $z = 0 \text{ mm}$.

Fig. 3.

Measured radial magnetic flux density, B_R , at innermost turn region of HCoil2 DP along the z-axis when the DP was located at $z = -175$ mm.

Fig. 4.
Comparison of the field-shaking effect on HCoil2 DP with and without B_{sk-R}

Fig. 5. Measured radial magnetic flux density, B_R , at innermost turn region of HCoil3 DP along the z-axis when the DP was located at $z = 0$ mm.

Fig. 6.
Comparison of the field-shaking effect on HCoil3 DP with various B_{sk-Z} .

Fig. 7.
Coil induced voltage and the axial component of the magnetic flux density at $z = -175 \text{ mm}$ during the SCF induction of HCoil3 DP

Table I

Specifications of Tested HTS Double Pancake Coils

Parameters	HCoil2 DP	HCoil3 DP
Conductor (REBCO)		
Width; thickness [mm; μm]	6.02; 76	6.04; 75
Cu stabilizer thickness [mm]	0.02	0.02
I_c @ 77 K [A]	188	190
NI Double pancake Coil		
ID [mm]	151.04	196.90
OD [mm]	169.18	211.50
Height [mm]	12.198	12.200
Turn per pancake	120	96
Self-inductance [mH]	18.06	16.60
Characteristic resistance, R_c [$\mu\Omega$]	322.1	491.9
Time constant, τ [s]	56.07	33.75
I_c @ 77 K, self-field [A]	42.81	67.41

Table II

Specifications of the 5-T/300-mm Room-Temperature Bore LTS Background Magnet

Parameters	Values
Cooling method	Conduction cooling by 4 K GM refrigerator
Overall i.d.; o.d.; height [mm]	327; 415; 338
RT bore size; length [mm]	300; 780
Magnet constant [mT/A]	61.52
Center field at I_{op} of 81.268 A [T]	5.0
Self-inductance [H]	143