Experimental and Numerical Studies on a Method to Mitigate Screening 
Current-Induced Field for No-Insulation REBCO Coils

Jiho Lee, Dongkeun Park, Yi Li, Yoon Hyuck Choi, Philip C. Michael, 
Juan Bascuñán, Yukikazu Iwasa

October 2018

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

This study was supported by the National Institute of General Medical Sciences of the National Institutes of Health under award R01GM114834. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Submitted to IEEE Transactions on Applied Superconductivity
Experimental and Numerical Studies on a Method to Mitigate Screening Current-Induced Field for No-Insulation REBCO Coil

Jiho Lee, Dongkeun Park, Yi Li, Yoon Hyuck Choi, Philip C. Michael, Juan Bascuñán, and Yukikazu Iwasa

Abstract—We present experimental and numerical studies on a method to mitigate screening current-induced field (SCF) for the MIT 1.3-GHz LTS/HTS NMR magnet (1.3G). The 1.3G consists of an 800-MHz REBCO insert magnet (H800) and a 500-MHz LTS background magnet (L500). The H800, a 3-nested-coil assembly of 96 no-insulation (Ni) REBCO double-pancake (DP) coils, is the main source of the SCF in the 1.3G. For our 1.3G, we have chosen a “field-shaking” technique, one of the proven methods to mitigate the SCF in tape wound magnets. In this technique, we propose to apply an axial shaking field to the H800, in the direction parallel to the 6-mm wide REBCO tape surface. Considering the length of H800 and L500 and the room inside the cryostat, we believe L500 is the only practical source of the shaking field for the 1.3G. To simulate the field-shaking using L500 and the behavior of H800 during the field-shaking, which magnetically coupled during 1.3G operation, we use an Ni REBCO coil to examine the proposed field-shaking SCF mitigation technique. The Ni REBCO coil was inserted into and magnetically coupled to the 5-T LTS background magnet. The Ni REBCO coil also has nano-ohm scale end-turn joint which makes the coil closed-loop and a PCS heater to make the coil open-loop. In this paper, we present the effectiveness of the field-shaking in some conditions for the Ni REBCO coil such as the open-loop coil, the closed-loop coil, the coil with the transport current. We expect that the field-shaking using L500 may be the successful SCF mitigating technique under certain conditions.

Index Terms— Field-shaking, HTS insert, nuclear magnetic resonance (NMR) spectrometer magnet, screening current-induced field (SCF)

I. INTRODUCTION

In this paper, we discuss the screening current-induced field (SCF) mitigation method for no-insulation (Ni) REBCO coil, which will help to construct the SCF mitigation scenario for the MIT 1.3-GHz LTS/HTS NMR magnet (1.3G). For our 1.3G, we have chosen a “field-shaking” technique, one of the proven methods to mitigate the SCF in REBCO tape wound magnets. The 1.3G consists of an 800-MHz REBCO insert magnet (H800) and a 500-MHz LTS background magnet (L500) [1, 2]. L500 is so longer than H800 that it can generate mostly axial field to H800 region. Considering the geometry of the 1.3G, we believe that L500 is the only practical source of the shaking field and going to be used as a shaking magnet to mitigate SCF of H800 in 1.3G operation. In previous study, the dedicated shaking coil transporting 60 Hz alternating current mitigated the significant amount of the SCF in the HTS insert with ~80 shaking iterations [3]. However, in 1.3G operation, if we use L500 as a shaking magnet, the number of the shaking iteration can be limited by the power dissipation and the liquid helium consumption from L500. Therefore, for 1.3G, the trapezoidal field-shaking using L500 is going to be conducted to mitigate the SCF of H800 [4]. In this paper, we

![Fig. 1. Positions of the Ni REBCO coil and the LTS background magnet and the measurement method of magnetic field $B_R$ to quantify and compare the SCF. Blue arrows mean the measurement point of $B_R$.](image1)

![Fig. 2. Circuit diagram of three tests in this study.](image2)
TABLE 1
TESTS PERFORMED IN THIS STUDY

<table>
<thead>
<tr>
<th></th>
<th>SCF induction</th>
<th>Field-shaking intensity [mT]</th>
<th>PCS heater</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Field-cooling</td>
<td>100 and 200</td>
<td>On*</td>
<td>No transport current</td>
</tr>
<tr>
<td>2</td>
<td>Field-cooling</td>
<td>100 and 200</td>
<td>Off</td>
<td>No transport current</td>
</tr>
<tr>
<td>3</td>
<td>Self-field*</td>
<td>50 and 100</td>
<td>On*</td>
<td>Transport current of 5 A</td>
</tr>
</tbody>
</table>

*To induce only the SCF without transport current, the field-cooling was used same as previous study [4].

REBCO coil excitation means that the coil was charged by external power supply.

PCS heater “on” means the NI REBCO coil is open loop. Therefore, during the field-shaking, the induced current of the coil is minimized and almost negligible. In the same way, “off” means the NI REBCO coil is closed loop.

Fig. 3. The result of test set1 when the shaking-field is 100 mT. The field mapping along the z-axis was measured at the inside of REBCO coil support ring, \( r=74.5 \) mm. ‘nth’ mapping means the mapping data after ‘nth’ field-shaking.

Fig. 4. The result of test set1 when the shaking-field is 200 mT. The field mapping along the z-axis was measured at the inside of REBCO coil support ring, \( r=74.5 \) mm.

deal with the field-shaking to mitigate the SCF in the strength of relatively high magnetic field with relatively a smaller

II. EXPERIMENTAL ANALYSIS ON MITIGATION OF SCF BY FIELD-SHAKING

In the previous study, we induced the SCF by the field-cooling of REBCO coils without any transportation current and analyzed the effect of field-shaking [4]. In this study, for a better understanding of field-shaking technique to mitigate the SCF in NI REBCO coil and better simulation of NI REBCO coil’s behavior with LTS background magnet, we conducted three tests to simulate the field-shaking of the NI REBCO coil in 1.3G. Fig. 1 and 2 show the experimental configuration of three tests in this study. Table 1 describes the conditions of each test. In all three tests, the ramp rate of the LTS background magnet was 1 A/min. The NI REBCO coil has a PCS switch at the end turn of upper pancake tape, and a nano-ohm scale bridge joint between both pancakes’ tape ends.
Fig. 7. Estimated engineering current density based on crude Bean’s critical state model.

Fig. 8. Comparison between the measurement data and the calculated data using estimated engineering current density.

A. Test-1: SCF induction by field-cooling and field-shaking of ‘open-loop’ REBCO coil

In 1.3G operation, magnetic field near the end-plane of H800 contains significant radial field component. In this test-1, to induce the SCF in the NI REBCO coil, we used the field-cooling method to make the SCF same as the previous study [4]; charging the LTS background magnet, placing the NI REBCO coil inside its bore in certain axial location, \( z = -175 \) mm, filling the nitrogen inside the cryostat bore to make the coil superconducting, and ramping down the LTS background magnet. After inducing the SCF and mapping the radial field, \( B_r \), along with the \( z \)-axis at the coil’s inner most turn, the NI REBCO coil was relocated to the center which has almost zero radial field, for field-shaking. During the field-shaking in the strength of 100 and 200 mT, we turned on the PCS heater installed in the NI REBCO coil to minimize the induced current in the azimuthal path in the NI REBCO coil. Considering the PCS resistance, \( R_{PC} \) of \(-1 \) m\( \Omega \), the characteristic resistance, \( R_c \) (NI coil’s feature [5]) of 322.1 \( \mu \Omega \), and the inductance, \( L_{II} \) of \(~18 \) mH, the induced current during the field-shaking is \(<1\) A which is almost negligible.

Fig. 3 and 4 show the test results in the trapezoidal field-shaking strength of 100 and 200 mT, respectively. Like many other previous studies [3, 6], the higher strength of field-shaking made the more mitigation of the SCF. Fig. 5 shows the comparison of the normalized SCF of each test according to the field-shaking iteration. With 13 iterations of the field-shaking, 100 mT field-shaking can reduce the SCF to \(~65\%\) of its initial values and 200 mT one can reduce it to \(~30\%\). Fig. 6 shows the property of SuperPower’s M4 tape used in the NI REBCO coil, \( J/I_{J0} \) at the field angle of \( 0^\circ \) (parallel to the tape surface) according to the applied field up to 1 T. At 100 and 200 mT, \( J/I_{J0} \) values are 0.962 and 0.926, respectively. These values are quite higher than the SCF mitigation values of the test results. Therefore, we may conclude that the mitigation of the SCF around \(~35\%\) and \(~70\%\) mostly came from the effect of the field-shaking.

In addition to the normalized SCF comparison in Fig. 5, to compare the effect of the SCF mitigation in the unit of the current, we estimated the engineering current density of test-1’s \( B_r \) mapping data. For this estimation, we assumed that every
turn of the NI REBCO coil has same current distribution as one-turn coil. We also assumed that the screening currents are generated based on the crude Bean-Slab model [7]. which means the current distribution in each single pancake consists of two regions; 3-mm high $J_z$ region and 3-mm high $+J_z$ region. We divided each region into 5 sections and numerically calculated the current density of each section by nonlinear regression method. Fig. 7 shows the estimated engineering current density of each part’s current loop, based on the crude Bean-Slab model. Though this calculation is not based on the scientific model, but based on the practical fitting model, we can observe the effect of the repeated field-shaking on the SCF.

B. Test-2: SCF induction by field-cooling and field-shaking of ‘closed-loop’ REBCO coil

In this test-2, we initially induced the SCF in the same way as test-1. Because the NI REBCO coil and the LTS background magnet are magnetically coupled, the change of the current in the background magnet induces the current in the inner NI REBCO coil. Therefore, unlike the test-1, we turned off the PCS heater to make the NI REBCO coil closed-loop to generate more induced current in the azimuthal path of the coil, during field-shaking. Considering the $R_c$ and $L_{R}$, the induced current during the 100 and 200 mT field-shaking are ~10 A. Fig. 9 and 10 show the results of test-2. In both tests, regardless of the initial induced SCF, the field-shaking did not make the SCF mitigation, but the other shape because of the relatively higher magnitude of the induced current in the azimuthal path in the NI REBCO coil than the initial induced screening current. This can be explained by that the magnitude of the penetration field, $B_p$ equals ~121.6 mT which is higher than 100 mT and lower than 200 mT. In the trapezoidal field-shaking, when the applied field is 100 mT and back to 0 T, then only the residual field remains in each turn of the NI REBCO coil. However, when the applied field is 200 mT which is higher than $B_p$ of the REBCO tape, there may be no more induced current at the field higher than $B_p$, and when the applied field is back to zero, there may be inversely induced current from its initial state.

C. SCF induction by self-transport and field-shaking of ‘open-loop’ REBCO coil

In test-3, unlike tests-1 and -2, we transported the current in the NI REBCO coil. As shown in Fig. 11, the field-shaking in the strength of 50 and 100 mT shifted the magnetic field peak point toward the center position in the $z$-axis. Because the magnitude of the induced current of 100 mT is larger than that of 50 mT, the peak shift of 100 mT field-shaking is more than that of 50 mT field-shaking. This phenomenon, peak shift towards inside corresponds to the effect of the current sweep reversal method [8]. Therefore, this peak shift means the screening current moved from the edge of the tape to center.

III. Conclusion

The effect of the field-shaking on the NI REBCO coil by LTS background magnet has been analyzed by experiments and its numerical analysis. The screening current-induced field (SCF) is the major field error to incorporate a REBCO insert for a high field LTS/HTS magnet. The field-shaking technique is going to be used to mitigate the SCF of 800-MHz REBCO insert magnet (H800) for MIT 1.3-GHz LTS/HTS NMR magnet (1.3G). Considering the effectiveness of the field-shaking, 500-MHz LTS background magnet (L500) is the only practical source of the field-shaking to mitigate SCF of H800 in 1.3G operation. However, due to the huge self- and mutual-inductance of H800 and L500, conventional relatively fast field-shaking studies which can be observed in the case using the dedicated copper (or BSCCO) shaking coil operated by high-frequency alternating current cannot be applied to our 1.3G. If the ramp rate of the field-shaking is sufficiently fast to induce a high current in H800 composed of no-insulation REBCO coils, the induced current from the field-shaking can be added to the transport current and cause more critical and dangerous operating situation for H800 such as an over-strain situation or quench of the whole 1.3G magnets. Though the ramp rate of L500 can be limited by the power dissipation and liquid helium consumption, if we can minimize the induced current during the field-shaking, we can expect that the effective mitigation of the SCF as shown in test-1.

**REFERENCES**


Screening Currents Induced in HTS Insert Coils for NMR Magnet,


