Magnetization and screening current in an 800 MHz (18.8 T) REBCO nuclear magnetic resonance insert magnet: experimental results and numerical analysis

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Magnetization and screening current in an 800-MHz (18.8-T) REBCO NMR insert magnet: experimental results and numerical analysis

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Abstract. The nonuniform superconducting current distribution in REBCO coated conductor, including a varying-field-induced screening current, is responsible for a significant magnetization effect that not only degrades the field quality of REBCO magnets, but also introduces risks of over stressing conductor. This paper presents our experimental and simulation studies on the screening current effect on an 800-MHz (18.8-T) REBCO insert (H800) that together with a 500-MHz LTS NMR magnet (L500) constitutes the MIT 1.3-GHz LTS/HTS NMR magnet (1.3G). To develop our simulation model, which subsequently validated by a good agreement between simulation and experiment, we chose H800, Coil 1 of the 3-coil assembly operated alone and the entire H800, for the sources of experimental data, specifically their remnant fields after current discharge and diminished axial fields during operation. Armed with this valid model, we examined in detail the negative effects of screening current on H800, an important 1.3G component. Our simulation indicates that the screening current, nonuniformly distributed in the REBCO conductor, not only deteriorates H800 field, both strength and homogeneity, thus that of 1.3G, but also may overstress the REBCO conductor.

1. Introduction

High magnetic fields provide irreplaceable extreme conditions for biomedical research, life science, fusion technology and high energy physics. In nuclear magnetic resonance...
(NMR) applications, the high magnetic field, i.e., high resonance frequency (having a relationship of 42.5775 MHz/T for proton), leads to improved spectral resolution and sensitivity, which allows the determination of large and complex molecular structures [1–3]. Although resistive magnets can successfully achieve strong magnetic fields above 30 T [4–6], their huge energy consumption and cooling requirement make superconducting magnets enabling for high-field applications. Efforts have been ongoing to make high-temperature superconducting (HTS) magnets viable to generate high field, including a 26-T no-insulation REBCO magnet [7], a 32-T all-superconducting magnet [8], a 14.4-T HTS insert under 31.1-T background field [9], and an 800-MHz (18.8-T) HTS insert (H800) to be nested in a 500-MHz (11.7-T) LTS magnet (L500) for the 1.3-GHz (30.5-T) NMR magnet project underway at the Francis Bitter Magnet Laboratory (FBML), MIT.

REBCO coated conductor is considered as one of the most promising HTS for high-field magnets due to its outstanding critical current performance in high fields and excellent mechanical strength. However, the geometry of coated conductor introduces a non-negligible magnetization effect [10, 11] that causes a REBCO magnet to produce a magnetic field distribution different from its design. Meanwhile, the complex hysteresis loop and flux motion also makes a history-dependent and time-varying field error [12]. These disadvantages could make REBCO coated conductor challenging for magnets such as magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), and high-energy physics (HEP) that require spatial field homogeneity and temporal stability [13, 14].

The nonuniform superconducting current distribution, including a varying-field-induced persistent screening current (SC), is responsible for the complex magnetization of an HTS magnet. Many studies have developed numerical methods that accurately compute the screening-current-induced field error and estimate hysteresis losses [15–22]. Gu et al. observed a remnant magnetic field in a de-energized Bi-2223 coil and established a numerical model to explain this phenomenon [15]. This model was also applied to a 700-MHz NMR magnet composed of a 600-MHz LTS NMR magnet and a 100-MHz Bi-2223 insert and successfully described its remnant field pattern [18]. Amemiya et al. evaluated the screening current field (SCF) for a conceptual design of 1.3-GHz NMR magnet with an 8-T REBCO insert using T-formulation. His result indicated a field error unacceptable to the NMR magnet [16]. Yanagisawa et al. calculated the SCF in a large magnet and revealed its dependence on magnet and conductor geometry [17]. Pardo proposed a model using continuous approximation for a large magnet containing up to 40000 turns [21]. Ueda et al. developed a 3D simulation code to compute an SCF and its temporal behavior applicable to a large, layer-wound magnets [22]. However, all these works were achieved with in-house closed source programs. Without advanced programming skills, it is still very challenging to simulate the screening current in a large-scale HTS magnet with over 10⁴ turns, not to mention analyzing other adverse effects, such as its mechanical issue [23, 24].

For the MIT 1.3-GHz NMR magnet project, although we recognized, as early as
in 2006 [18], an important role SCF plays in field homogeneity, it was not until 2013 we began paying more attention to this subject. Both numerical models for simulating the screening current and experimental methods for eliminating an SC-induced field errors [25, 26] have been developed. This paper presents our latest results on our 800-MHz REBCO insert (H800). We have studied the SC-caused magnetization through two measurements on H800: remnant field after H800 Coil1 was discharged and axial during H800 operation. We have developed a finite element method (FEM) model based on the $T$-$A$ formulation [16, 27]. To achieve a good accuracy with low computing resources, we have adopted the continuous approximation model [28–32] to take the coupling between the screening currents in different pancake coils into account. The model has been validated by experimental data. With this model, we have analyzed H800 for its screening current, which in turn generates a field error and affects stress distribution.

2. The MIT 800-MHz REBCO magnet

The 800-MHz HTS insert (H800) [2, 33] and illustrated in figure 1, is designed to produce 18.78 T at an operating current ($I_{op}$) of 251.3 A, 8.66 T, 5.68 T, and 4.44 T, respectively, by Coil1 (inside), Coil2, and Coil3 (outside). Each coil is a stack of double-pancake (DP) coils wound with 6-mm wide SuperPower REBCO conductor and over-banded with stainless-steel tape. A photograph of Coils1–3 is shown in figure 2. With no-insulation (NI) winding technique [34] and stainless-steel over-band [35, 36], H800 is compact, mechanically robust and self-protecting against overheating [2, 37].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coil 1</th>
<th>Coil 2</th>
<th>Coil 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total # of DP coils</td>
<td>26</td>
<td>32</td>
<td>38</td>
</tr>
<tr>
<td>Winding overall height [mm]</td>
<td>323.65</td>
<td>392.13</td>
<td>465.65</td>
</tr>
<tr>
<td>Winding outer diameter [mm]</td>
<td>119.10</td>
<td>168.90</td>
<td>211.15</td>
</tr>
<tr>
<td># of regular DP coils</td>
<td>20</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>inner diameter [mm]</td>
<td>91.00</td>
<td>150.75</td>
<td>196.90</td>
</tr>
<tr>
<td># of turns of single pancake</td>
<td>185</td>
<td>121</td>
<td>95</td>
</tr>
<tr>
<td>Notched section</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of notched DP coils</td>
<td>6</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>inner diameter [mm]</td>
<td>92.35</td>
<td>151.20</td>
<td>197.20</td>
</tr>
<tr>
<td># of turns of single pancake</td>
<td>177</td>
<td>118</td>
<td>93</td>
</tr>
<tr>
<td>Rated operating current [A]</td>
<td></td>
<td>251.3</td>
<td></td>
</tr>
<tr>
<td>Designed field contribution [T]</td>
<td>8.66</td>
<td>5.68</td>
<td>4.44</td>
</tr>
</tbody>
</table>

After Coils1–3 passed their independent electromagnetic performance tests at both 77 K and 4.2 K [38, 39], H800 was assembled and tested in March 2018 [40, 41]. In this
paper, we focus, experimental and numerical, on the H800-SC effects. Our numerical analysis uses the design parameters listed in table 1. To simplify computation of field distribution, we use a 2D symmetric model.

3. Numerical model

3.1. Basic equations and assumptions

In this study, we use the $T$-$A$ formulation [16, 27], a magnetofquasistatic approximation of Maxwell’s equations specifically for conductor with 2D-film geometry, to model the
current penetration into the REBCO magnet.

The superconducting current density distribution is analyzed by the $T$-formulation

$$J = \nabla \times T$$

(1)

which is widely used in eddy current calculation [42, 43]. The HTS is defined by the $E$-$J$ relationship

$$E(J) = E_0 \left| \frac{J}{J_c} \right|^n \frac{J}{|J|}$$

(2)

where $E$ is the electric field and $J$ the current density; $E_0$ is an electric field criterion to define $J_c$ the critical current density and $n$ the index—1 $\mu$V/cm is often chosen for $E_0$. The current density $J$ is coupled with magnetic field $B$ according to Faraday’s Law

$$\nabla \times E(J) = -\frac{\partial B}{\partial t}$$

(3)

where $B$ can be calculated by magnetic vector potential $A$ using either analytical way [16] or FEM [27].

Because the thickness of REBCO layer is much smaller than the tape width (our H800 REBCO tape, 1–2 $\mu$m vs. 6 mm), we consider REBCO coated conductor as a 2D material, in which the vector potential $T$ is reduced to a scalar potential $T$. For an axially symmetric solenoid magnet with its axis in the $z$ direction, made of 2D HTS conductor with thickness $\delta$, the current density has only $\phi$ component with a simple
form of $dT/dz$

$$J = J_\phi = \frac{dT}{dz}$$

(4)

The current in a 2D conductor only responds to the normal component of magnetic field $B_r$, therefore

$$\frac{d}{dz}E_\phi(J) = -\frac{\partial B_r}{\partial t}$$

(5)

The total current flows in the conductor is applied through the boundary condition of the scalar potential $T$:

$$I_t = (T_1 - T_2) \cdot \delta$$

(6)

With the boundary condition (6), it is convenient to adopt the continuous-approximation model [28–32], which treats the REBCO-coated-conductor windings as anisotropy bulks. The boundary conditions are illustrated and compared in figure 3. To make them identical, different values are assigned for thickness $\delta$: the total tape thickness for continuous model; and real thickness of the HTS layer for thin-tape model.

Figure 3. Boundary conditions of the $T$-formulation: an evolution from the thin-tape model on the left, to the “continuous” model on the right. The scalar potential $T$ is valid on the conductors, and $T = T_1$ and $T = T_2$ are the Dirichlet boundary condition.

The continuous-approximation model is suitable for the REBCO pancake coil, which has a real “continuous” geometry: wound by a tape with its radial position continuously increasing along its longitude. The altered thickness $\delta$ and the removal of non-superconducting gaps in the continuous-approximation model, however, causes minor difference in magnetization behavior, specifically, it slightly changes the current penetration depth into the superconductor [44]. The error is proven very small [28, 32, 44], and therefore ignored in our simulation.
In this study, we solve the $T-A$ formulation in the FEM approach. Unlike the “homogenization” technique in the $H$-formulation model [29, 31], which requires special meshing and complex current constraints, the boundary condition (6) of the “continuous” $T-A$ model (shown in the rightmost of figure 3) ensures that each conductor carries the same total current, independent of the meshing. As a result, the $T-A$ formulation with the continuous approximation allows us to model a large-scale magnet in 2D with a much simpler geometry and more flexible meshing.

3.2. In-field performance of REBCO tapes

The simulation result of current distribution could be sensitive to the input field dependence of critical current density $J_c$. In this study, we determine the $J_c$ of each conductor in H800 according to its $I_c(77 \, \text{K}, \text{self-field})$ provided by SuperPower, and lift factors in external field at selected operating temperatures. The $J_c-B$ relationship, given by equation (7), is based on field-dependent critical current data,

$$J_c(B, \theta) = J_{c0} \cdot \left\{ \frac{A_1(B) - A_2(B)}{1 + \exp \left[ \frac{-\theta}{\theta_0(B)} \right]^k(B)} + A_2(B) \right\}$$

where $B$ is the field strength, $\theta$ the angle between field and the $a$-$b$ plane, $J_{c0}$ the critical current at 77 K in self field. Parameters $A_1$, $A_2$, $\theta_0$ and $k$ are determined by nonlinear fits of the critical current data. To simplify equation (7), we use a unified $J_{c0}$ expression

$$J_{c0} = \frac{I_{c0}}{w \cdot \delta}$$

for both “continuous” model and thin-tape model, where $w$ is the width of HTS conductor, and thickness $\delta$ is chosen following the same rule as equation (6).

A set of lift factors, $J_c(B, \theta)/J_{c0}$ at 77 K [45] is plotted in figure 4. The 4-K $J_c(B, \theta)/J_{c0}$, as given by equation (7) is based on the previous reports [46–48]. The dimensionless parameters, except $\theta_0$ given [°], $A_1$, $A_2$, and $k$ for 77 K and 4.2 K are plotted in figure 5 (a) and (b), respectively. In order to plot all parameters for 77 K in one figure 5 (a), as indicated in the left-hand side y-axis label, $k$ is given as $k/3$; for 4.2 K, using a 77-K average value, we fix a relatively insensitive parameter $k$ at 1.6.
Figure 4. Angular dependence at selected external fields at 77 K of SuperPower REBCO tape.
Figure 5. Parameters of in-field performance of REBCO tapes described by equation (7): (a) 77 K: note that $k/3$; (b) 4.2 K: $k = 1.6$. 
4. Experimental details

4.1. Measurement of H800 Coil 1 remnant field at 77 K

In the 77-K test of the standalone H800 Coil 1, to minimize extraneous fields, we characterize the magnetization effect by measuring remnant field on the coil axis. We assumed that Coil 1 at its quiescent state would generate zero field; any non-zero field would thus be by a screening current.

Because a superconductor magnetization depends on charging sequence, we operated Coil 1 in a series of charge-hold-discharge-hold time functions with a 10-A increment up to 30 A. The ramping rates during charge/discharge were respectively at $\pm 2$ A/min. To reach a stable current distribution in this NI Coil 1, we held the current at each step for $> 10\tau$, where $\tau = L_m/R_m$. $L_m$ is the Coil 1 inductance and $R_m$ is the radial resistance determined by an equivalent circuit model [49]. The axial screening-current-induced remnant fields, plotted in figure 6, were measured with a movable Hall probe after Coil 1 had been discharged from 3 holding currents, 10 A, 20 A, and 30 A at 77 K.

4.2. Stand-alone test of H800 at 4.2 K

After each H800 coil was built and tested separately, Coils 1–3 were assembled into H800. The H800 was first operated in liquid nitrogen at 77 K, and then in liquid helium [40, 41].

According to our equivalent circuit model of NI coil [49], the power supply current, during excitation, splits between the azimuthal current flowing along conductor turns and the radial current flowing from turn-to-turn. Because the radial current generates power dissipation which not only raises the winding temperature but also increases helium consumption, H800 magnet was charged with a ramp rate of as low as 0.01 A/s in the liquid helium test to limit the peak power dissipation in each coil to below 3 W [40]. The power supply current was held at 190 A and 217.5 A, because voltage spikes were observed. During these hold-current periods, after the radial current became almost zero, we mapped the on-axis field with a Hall sensor.

About 5 min after the power supply current, $I_{ps}$, had reached 251.3 A, the magnet operating current, H800 unexpectedly quenched. Later examination revealed that the quench incident damaged H800 severely. We have neither H800’s measured on-axis field distribution at $I_{ps} = 251.3$ A nor its remnant field. Therefore, we use the results of at 10 A and 20 A measured at 77 K and at 190 A and 217.5 A at 4.2 K to estimate respective SCF’s and compare them with our simulation results.
5. Results and discussions

5.1. Remnant on-axis field of Coil 1

Figure 6 presents experimental and simulated remnant field vs. axial position plots for discharge currents at 77 K of 10 A, 20 A and 30 A. Our simulation assumed a simplified charging sequence, with a period of 10 s for both ramping and holding. The 77-K $I_c(B, \theta)$ relationship presented in figure 4 is used for this simulation.

![Figure 6](image)

**Figure 6.** Coil 1 on-axis remnant field vs. axial position plots, after Coil 1 was discharged from 10 A, 20 A, and 30 A at 77 K

As can be seen in figure 6, simulation matches measurement quite well for on-axis remnant fields at in the top half of Coil 1. However, in the bottom half, although simulation obviously gives an axially symmetric remnant field distribution about the midpoint, the 30-A data show otherwise. We believe that this distortion is caused by a slightly magnetic laboratory floor. To further confirm our belief, we plot in figure 7 computed magnetic field lines, (a) at 20 A, (b) at 30 A, and (c) after discharged from 30 A to 0, with the distribution of both normalized current density $J/J_c$ and engineering current density $J_e$, each Coil 1 top half.

From figures 7 (a) and (b) it is evident that deeper field penetration and greater screening currents occur in the pancake coils towards the coil end, where the conductor is exposed to the strongest perpendicular field. In most pancake coils, the induced azimuthal-directed screening current is large enough to make the azimuthal current negative in the tape bottom half. Especially at 30 A, the end pancake coil is fully penetrated by the radial field, causing a saturation of screening current, whereas the
Figure 7. The current distribution in Coil 1 at (a) energized state with $I_{op} = 20$ A; (b) energized state with $I_{op} = 30$ A; and (c) remnant state that discharged from $I_{op} = 30$ A. Only half of Coil 1 is shown due to the symmetry.
pancake coils near the midplane show very little screening current.

Since the total current in the conductor is zero in the remnant state, a remnant field, mainly trapped by the DPs near the coil end, is completely produced by a screening current. By comparing figure 7 (c) with (b), we can see that the screening current is induced in the opposite directions during charge and discharge to oppose a field change. Because the critical current densities are less suppressed by a decreasing field, a reversed screening current induced in the discharge concentrates on the conductor edges and generates a stronger magnetic field that overcomes the original field. As a result, the remnant field, dominated by the reversed screening current induced in discharge, has different directions at the coil center and coil ends.

It is worth noting that the remnant magnetic field in the bottom half is nearly proportional to the applied current, implying a low saturation of screening currents in the bottom half pancake coils. However, the pancake coils close to the top end were obviously saturated at the energized state of $I_{op} = 30$ A. Since the pancake coils at both ends of Coil 1, wound with REBCO tape with similar performance, were supposed to experience similar current penetration and saturation, we believe that it was the magnetized floor that attracted the field lines and reduced the radial fields in pancake coils close to the floor.

5.2. Field reduction in H800 assembly

![Figure 8. As-designed, measured, and simulated 77-K on-axis H800 fields vs. axial position plots with left- and right-hand y-axes for $I_{op}$ respectively 10 A and 20 A. The gray line corresponds to both as-designed magnetic fields at their respective y-axis scales.](image)
On-axis H800 field mapping was performed at stable transport currents of 10 A and 20 A at 77 K, with results plotted in figure 8; and 190 A and 217.5 A at 4.2 K with results plotted in figure 9. For comparison, calculated field distributions with measurement-based 77-K $I_c(B, \theta)$ data and 4.2-K $I_c(B, \theta)$ formulated from SuperPower standard-AP conductor are included in figures 8 (77 K) and 9 (4.2 K).

![Figure 9](image)

**Figure 9.** As-designed, measured, and simulated 4.2-K on-axis H800 field vs. axial position plots: (a) $y$-axis with one scale; (b) left- and right-hand $y$-axes for $I_{op}$ respectively 190 A and 217.5 A. The gray line in figure (b) corresponds to the as-designed magnetic fields for both 190 A and 217.5 A at their respective $y$-axis scales.

As can be seen from results shown in figures 8 and 9, measured fields are reduced considerably from designed fields. Our simulated on-axis field distributions match the...
experimental data quite well.

Specifically, in the 77-K test (figure 8), the designed central fields are 0.747 T and 1.495 T for $I_{op} = 10$ A and 20 A, respectively, while measured values, reduced by a screening current, are 0.718 T (reduction by 3.9%) and 1.470 T (by 1.8%). The field reduction in the center is much greater than those at two sides. Our simulated on-axis field distribution matches the experimental data quite well, with a standard error of 1.4 mT (0.19%) for $I_{op} = 10$ A, and 4.8 mT (0.32%) for $I_{op} = 20$ A along axial $\pm 100$ mm, validating our numerical method.

With the 4.2-K test (figure 9), the designed central fields are 14.20 T and 16.26 T for $I_{op} = 190$ A and 217.5 A, respectively; measurement gave 13.76 T (reduction by 3.1%) and 15.79 T (by 2.9%). It is worth noting that after the magnet was cooled down from 77 K to 4 K, the field gradient $dB/dz$ at the center turned from positive to negative, shown in figure 10. Since screening current is a major source of field degradation, there apparently are significant differences on $J_c(B)$ relationship among the REBCO pancake coils. The standard errors between simulated and measured fields along axial $\pm 100$ mm are 33 mT (0.24%) at 190 A, and 66 mT (0.42%) at 217.5 A. The simulation agreed with measurement well in the central area, and less in the area away from the center. We believe that these differences are mainly due to the difference between real and formulated $J_c(B)$.

![Normalized on-axis H800 field $B/B_0$ vs. axial position plots: where $B$ is the measured on-axis field, and $B_0$ the center field.](image)

**Figure 10.** Normalized on-axis H800 field $B/B_0$ vs. axial position plots: where $B$ is the measured on-axis field, and $B_0$ the center field.
6. Simulation of H800 at 251.3 A

6.1. The on-axis field

Based on our validated model, we carried out a screening current analysis of H800 at its rated current of 251.3 A. Only magnetization generated by screening current is considered in this analysis. Intractable uncertainty sources that affect the magnetic field distribution in each of Coils 1–3 are beyond the scope of this model and therefore not considered in our analysis. Of these sources most obvious is geometric, i.e., coil form dimensions, 3-coil alignment, conductor dimensions and locations.

![Image](image.png)

**Figure 11.** As-designed, measured, and simulated on-axis H800 field vs. axial position plots at $I_{op} = 251.3$ A.

**Table 2.** Simulated magnetic field harmonic error components of as-designed H800* at 251.3 A

<table>
<thead>
<tr>
<th></th>
<th>$Z_0$</th>
<th>$Z_1$</th>
<th>$Z_2$</th>
<th>$Z_3$</th>
<th>$Z_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total field</td>
<td>18.30</td>
<td>100</td>
<td>4.0</td>
<td>-43</td>
<td>-0.19</td>
</tr>
<tr>
<td>SCF term</td>
<td>-0.484</td>
<td>-2.6</td>
<td>4.0</td>
<td>23</td>
<td>-0.19</td>
</tr>
</tbody>
</table>

*H800 parameters listed in table 1.

As plotted in figure 11, a simulation center field of 18.30 T is 0.48 T lower than expected. Since the field reduction, due to screening current, is only 2.6%, the center field may be simply corrected with a minor adjustment in operating current. We
also performed a harmonic analysis based on this simulation result. The harmonic components of both total magnetic field and screening current field error are listed in table 2. Both field plot and harmonic analysis indicate a rather uniform screening current field distribution in the central area. We believe that the field error terms $Z_1$ and $Z_2$ due to screening current are within the compensation range of our HTS shim coils [50, 51].

6.2. Current Density

Figure 12 shows the normalized current density $J/J_c$ distributions in H800 at 251.3 A. More detailed current distribution and potential $T$ contours in selected DPs from the top half of Coil 1 are presented in figure 13, with the DP numbers ascending order from top to bottom, i.e., DP01 at the top end and DP13 closest to the midplane. The red $T$ contours, having adjacent spacing inversely proportional to the current density, indicate a rather uniform current distribution in the DPs close to midplane. In each pancake, the turns around the central area, shielded by each other, share a similar current distribution pattern; however, deeper penetration occurs in the turns close to inner or outer radius.

The screening current in each pancake trapping a magnetic moment forms an antisymmetric field error with an axial field gradient at its center. Figure 14 shows the computed SCF by selected Coils 1–3 DPs. The fields represent the trapped magnetic moments. Although both end DPs in each coil are exposed to the largest radial field in the coil, because screening currents are limited by the suppressed $J_c$ and have reached saturation condition, their error fields at the coil center are not the largest.

6.3. Magnetic moment and hoop stress analysis

The screening current-induced magnetic field in a pancake coil generates a torque on its conductor. We express the average torque $m$ per unit conductor length (m), $[(N\cdot m)/m]$, acting on the conductor, i.e., each turn, by

$$m = \frac{1}{N_{sp}} \int_{S_{sp}} [J_\phi \cdot B_z \cdot (z - \bar{z})] dS$$

(9)

where $N_{sp}$ is the turn number of the single-pancake coil, $S_{sp}$ its cross section, and $\bar{z}$ the axial position of the its center. Figure 15 presents the average magnetic torque on each H800 single-pancake coil. Note that average torques/(length) are largest in Coil 1 with a peak value of 11.7 (N·m)/m. Their impact on Coil 1 is discussed below.

A simple mechanical analysis on selected pancakes is performed to evaluate the influence of the magnetic torque on hoop stress distribution based on the simulated current distribution. As illustrated in figure 16, a pancake coil, with its innermost winding supported by a rigid center tube (bobbin inner diameter in figure 16) and the winding axially held by rigid boundaries, may expand only radially. Compared with the Lorentz forces that result from the axial magnetic field and coil current, winding tension, and differential thermal forces have less impacts on conductor hoop stress. In
Figure 12. Normalized current density $J/J_c$ distribution in H800 at 251.3 A. Each rectangle schematically represents, only in the axial direction, REBCO tape 6-mm wide.
**Figure 13.** The detailed current distribution in selected double-pancakes from Coil 1. The contours of potential \( T \) are plotted in red to show the uniformity of current distribution. Coil 1 consists of 26 DP coils, and the DP numbers counts from top to bottom, e.g., DP01 at the top end and DP13 closest to the midplane.

In this analysis, we only calculate the Lorentz force inducing hoop stress and compare the maximum hoop stresses with and without screening current effect.

We modeled every single turn of the H800, including that of the stainless steel over-band wrapped around each pancake coil. Three key mechanical properties of REBCO conductor (derived from [52]) and stainless steel at 4.2 K are listed in table 3; both materials are treated elastic in our model. For ease of modeling, we ignore the REBCO tape constituents and consider the tape as an orthotropic solid material with uniform mechanical properties. The Lorentz forces are applied to the tape entire cross-section rather than only on the REBCO layer. The model focuses on the hoop stress on macroscale, under which the \( I_c \) degradation of REBCO tape is measurable [53], to determine whether the REBCO tape is under a risk of being overstressed. However, the potential damages inside the coated conductor due to the concentration of Lorentz force
and difference in mechanical properties between layers, such as delamination [54–56], are not within the scope of this analysis.

We assumed a free turn-to-turn contact without friction, which maximizes the
influence of magnetic torque. However, the friction between adjacent pancake coils, enhanced by the axial forces on H800 coils, can partially counteract the magnetic torque. In this analysis, we considered two extreme conditions of interaction between adjacent pancake coils: one with friction-free contact; and one with strong interaction assuming a friction proportional to the axial clamping pressure, as shown in figure 16

\[ f = \lambda \cdot (P_m + P_p) \]  

(10)

where \( f \) is the friction force per unit area; \( \lambda \) the coefficient of friction; \( P_m \) the clamping pressure due to the axial Lorentz force; \( P_p \) the axial pre-load pressure, fixed at 3.6 MPa. Because the H800 coils were over-banded, after pre-loading, with 5.9-mm wide, 76-µm thick stainless steel tapes slightly narrower than the REBCO conductor over a radial build of 7 mm, we consider the axial clamping force were applied on the REBCO conductor only.

Figure 17 shows the simulated hoop stress, \( \sigma_{\text{hoop}} \), results for three pancakes from
Table 3. 4.2-K mechanical properties for pancake coil [52]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stainless Steel</th>
<th>REBCO conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isotropic</td>
<td>r</td>
</tr>
<tr>
<td>Young's modulus [GPa]</td>
<td>212</td>
<td>133</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
<td>0.286</td>
</tr>
<tr>
<td>Shear modulus [GPa]</td>
<td>83</td>
<td>83</td>
</tr>
</tbody>
</table>

H800 Coil 1, which suffers the highest Lorentz force and magnetic torque among three nested coils, in the case of $\lambda = 0.2$ (left) and $\lambda = 0$ (right). We selected three Coil 1 pancakes as follows: DP01 at the top; DP13 near midplane; and DP03, which is subjected to largest magnetic torques according to the average torque results shown in figure 15. As can be seen in figure 17, the Lorentz forces have a strong impact on the hoop stresses. According to our previous estimate based on a homogeneous current distribution, the maximum hoop stresses in Coils 1 is 310 MPa. However, this simulation, based on no turn-to-turn friction assumption, gives peak hoop stress concentration that reach up to 680 MPa with $\lambda = 0.2$, and 940 MPa with $\lambda = 0$, both occurring on the innermost turn. The comparison between two $\lambda$ conditions indicates that interaction between adjacent pancake coils can play an important role in reducing the effects of magnetic torque.

A quantitative comparison is shown in figure 18 with simulated hoop stresses plotted vs. coil radius of selected Coil 1 pancakes. Unlike a general view that the closer the pancake coils are to the magnet midplane, the greater hoop stresses they are subjected to, DP13 lower pancake, exposed to the strongest axial field, is under a uniformly low hoop stress. However, in a pancake with a large screening current, magnetic torque dominates the stress distribution. Compared with the case that assumes a homogeneous current, this nonuniform-current-distribution model gives, because of the concentration of outward Lorentz force produced by transport current, a high tensile hoop stress. Meanwhile, the screening current-induced inward Lorentz force may also cause a compressive azimuthal stress in the HTS winding.

Although the absence of turn-to-turn friction in our model overestimates hoop stress, this preliminary study indicates that screening current in H800 may increase the peak stress to a level close to the stress limit [53]. Specifically, it has highlighted the importance of screening current evaluation in designing a REBCO magnet to avoid overstressing REBCO conductor in the magnet.
Figure 17. Hoop stress ($\sigma_{\text{hoop}}$) distribution with nonuniform current density considered and zero turn-to-turn friction, where “IR” and “OR” are the inner and outer radius of HTS winding, and “ES” the external surface of the over-band. 3 single pancakes are selected from Coil 1: one at the end of coil, one near the midplane, and one affected by maximum magnetic torque.
Figure 18. Hoop stress vs. radius plots for selected pancakes from Coil 1 with $\lambda = 0.2$. The hoop stress plots in (b) are along the dash lines shown in (a).
7. Conclusion

We have presented results of experimental and numerical studies on screening-current induced field error in the 800-MHz HTS insert (H800) of the MIT 1.3-GHz LTS/HTS NMR Magnet (1.3G). The HTS magnetization was measured and simulated in two cases: standalone Coil 1 remnant field; and field reduction in H800 due to screening current.

To calculate the screening-current induced field error, we developed a simple model based on T-A formulation and continuous approximation for HTS magnet assembled from pancake coils. We validated our model through a good agreement between experiment (H800) and simulation.

With the validated simulation model, we analyzed in detail the magnetization of H800 at 251.3 A, the target operating current. According to our simulation, a screening current reduces a designed center field of 18.78 T by 0.48 T to 18.30 T, though a field distortion uniformly distributed. We believe that by adjusting the operating current and applying shimming techniques, screening-current-induced field errors are manageable in H800 and thus 1.3G.

The REBCO conductor magnetization, i.e., nonuniform superconducting current distribution along the tape width, can introduce a risk of overstressing REBCO conductor. This screening-current-induced overstressing may become an important mechanical issue for ultra-high-field NMR magnets that must include an HTS magnet.

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