Temporal Enhancement of Trapped Field in Compact NMR Magnet Comprising YBCO Annuli

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Abstract—The temporal “enhancement” of trapped fields around the center of a compact NMR magnet comprising a stack of 2800 YBCO “square” annuli (YP2800) was observed at 4.2 K. This paper presents a computational approach to simulate the trapped field enhancement in YP2800. Firstly, based on the inverse calculation technique, the current distributions in the 560 5-plate modules of YP2800 were estimated. Then, YP2800 was modelled as “three magnetically-coupled subcoils”: the “bottom” coil (C_B, 140 modules); the “middle” coil (C_M, 280 modules); and the “top” coil (C_T, 140 modules). Using an equivalent circuit model with the index resistance of each coil included, the current in C_M was calculated to increase “slowly”, due to the magnetic induction by the “fast” decay of the C_B and C_T currents. As a result, the center field in YP2800, which is dominated by the currents in C_M, increases in time, which agrees well to the measured temporal enhancement of trapped fields.

Index Terms—Compact NMR magnet, trapped field, temporal enhancement, YBCO annuli

I. INTRODUCTION

SINCE 2009, the MIT Francis Bitter Magnet Laboratory has conducted a 2-phase program to develop a compact desktop NMR (nuclear magnetic resonance) magnet comprising YBCO annuli [1]–[6]. In Phase 1, the main target is to design and construct a 100-200 MHz NMR magnet having a 9-mm room temperature (RT) bore, and operate it in solid nitrogen (SN2) at 10 - 15 K. The magnet, named YP2800, has been constructed with 2800 YBCO “square” annuli [4], [5]; each square annulus is 40- or 46-mm wide, 0.08-mm thick, and has a machined inner hole of φ26 mm. Recently, trapped field tests of YP2800 in a bath of liquid helium at 4.2 K have been completed. Currently, a customized NMR probe is being constructed, which will fit into the 9-mm RT bore of YP2800.

While testing YP2800 at 4.2 K, we observed temporal “enhancement” of trapped fields at and near the center of YP2800. We reported a similar field enhancement in YP1070 [6], an earlier model of YP2800. Patel et al. also reports a similar trapped field enhancement in a stack of high temperature superconductor (HTS) plates operated at “low (<20 K)” temperatures [7]. To date, the field enhancement, either in YP1070 or YP2800, has not been observed in any tests performed in a bath of liquid nitrogen (LN2) at 77 K [2]–[5]. The temporal behavior of magnetic field is particularly important for NMR magnets to obtain high-quality NMR signals [8]–[14].

This paper presents the 4.2-K trapped field test results focusing on the trapped field enhancement around the YP2800 center. A computational approach is proposed to simulate the temporal behavior of trapped fields in YP2800 at 4.2 K. The simulation results agreed reasonably well with the measured data, which demonstrates the validity of the proposed approach.
the top and bottom of the stack. The construction details of YP2800 were previously reported in a separate paper [4]. Fig. I summarizes key parameters of YP2800.

B. Test Setup and Field-Cooling Procedure

Fig. 1 shows a schematic drawing of the setup for the 4.2-K “field-cooling [3], [15]” experiments. A 5-T/300-mm (RT bore) magnet [2] provides a target background field, 3.5 T in this experiment, during the field cooling. After YP2800 is “fully” cooled at 4.2 K, the background field was discharged at 1.0 mT/sec.

C. Field Measurement Accuracy

To measure an axial distribution of trapped fields along the 9-mm RT bore, a search coil is used (Fig. 1), of which i.d., o.d., height, numbers of turns, and moving speed are, respectively, 6.0 mm, 8.38 mm, 2.54 mm, 120 and 33.4 mm/s. To investigate the measurement accuracy of the search coil approach, a magnetic center field from the 5-T background magnet was repeatedly measured at a given operating current of the background magnet. Table II summarizes the search coil accuracy test results; the measurement error of the search coil approach is estimated to be ≤ 0.1 %.

D. Test Results

Fig. 2 shows measured axial field distributions around the center of YP2800 (z \leq 30 mm); z is defined as axial displacement from the YP2800 center. The t=0 is set to 5 minutes after the background magnet is completely discharged. In Fig. 2, the trapped field at the center (z=0) “increases” from 3.5115 T at t=0 to 3.5302 T at t=4 hrs. In contrast, Fig. 3 shows measured axial field “decay” at 80 mm \leq z \leq 100 mm. The trapped field enhancement in YP2800 is similar to that in YP1070 [6]. Note that the enhancement was not observed in any tests at 77 K, either for YP2800 or YP1070 [2]–[4].

Fig. 2. Temporal “increase” of trapped fields at and near the YP2800 center.

Fig. 3. Temporal decay of trapped fields at 80 mm \leq z \leq 100 mm along the YP2800 axis.

III. SIMULATION OF TEMPORAL BEHAVIOR OF TRAPPED FIELDS IN YP2800 AT 4.2 K

A. Estimation of J_{ce} at 77 K

Fig 4 shows measured axial trapped field distribution of YP2800 (black squares) in a separate LN2 test at 77 K. For the field cooling, the background field was 2 T, \geq 3 times larger than the measured peak trapped field of 0.65 T. This implies that the 0.65 T is practically the maximum trapped field of YP2800 at 77 K and thus all the plates in YP2800 are “saturated” in terms of current carrying capacity. We may define an average critical engineering current density, J_{ce} for each 5-plate module as the maximum current of a module divided by its overall cross section area (A_{4}).

Using the “inverse calculation technique [16]”, J_{ce} of the 560 modules at 77 K (red triangles in Fig. 5) can be estimated to minimize the object function of (1), where J_{ce}, B_{z|ins}, B_{z|cal}, and 2z_{1} are, respectively, average critical engineering current density of the i-th module, measured axial fields, calculated axial fields with a give J_{ce} distribution, and the target axial space (here, z_{1} is set to 100 mm). Fig. 4 presents good agreement between the measured (black squares) and calculated (red circles) axial field distributions at 77 K; Fig. 5 shows the estimated J_{ce} of the 560 modules at 77 K by the

TABLE I
KEY PARAMETERS OF YP2800

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square width</td>
<td>[mm] 40 or 46</td>
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<tr>
<td>Inner hole diameter</td>
<td>[mm] 26</td>
</tr>
<tr>
<td>Thickness of each plate</td>
<td>[mm] 0.08 ± 0.005</td>
</tr>
<tr>
<td>Total number of plates</td>
<td>2800</td>
</tr>
<tr>
<td>Number of 5-plate modules</td>
<td>560</td>
</tr>
<tr>
<td>Overall height</td>
<td>[mm] 234</td>
</tr>
<tr>
<td>Peak trapped field at center at 77 K [T]</td>
<td>0.65</td>
</tr>
</tbody>
</table>

TABLE II
MEASUREMENT ACCURACY OF SEARCH COIL (UNIT: T)

<table>
<thead>
<tr>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Mean</th>
<th>SD [%]</th>
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</thead>
<tbody>
<tr>
<td>3.0497</td>
<td>3.0487</td>
<td>3.0497</td>
<td>3.0487</td>
<td>3.0488</td>
<td>0.065</td>
</tr>
<tr>
<td>3.2483</td>
<td>3.2485</td>
<td>3.2463</td>
<td>3.2452</td>
<td>3.2471</td>
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<tr>
<td>3.4933</td>
<td>3.4949</td>
<td>3.4968</td>
<td>3.4937</td>
<td>3.4947</td>
<td>0.10</td>
</tr>
</tbody>
</table>
inverse technique for the calculated axial fields (red circles) in Fig. 4.

\[ f(J_{ce}^i) = \int_{-z_1}^{z_1} \left\{ B_z|m - B_{z|cal}(J_{ce}^i) \right\}^2 dz, \quad i = 1, \ldots, 560 \]

(1)

B. Estimation of \( J_{ce} \) and \( J_{ce} \) at 4.2 K

Black diamonds in Fig. 4 show the measured axial trapped fields at \(|z| < 100\) mm from the LHe experiment. The “plateau” of the measured distribution at 4.2 K in Fig. 4, not observed those from the LN2 test (black squares), indicates that a number of YBCO plates around the YP2800 center are “not saturated”, i.e., the average engineering current density, \( J_e \) in each plate is smaller than its \( J_{ce} \). Thus, using the measured fields at 4.2 K (black diamonds) in Fig. 4, the same inverse calculation technique was applied to the estimation of \( J_{ce} \) of each module at 4.2 K, black squares in Fig. 5, not the \( J_{ce} \).

In our previous report [6], the maximum trapped field of YP1070, the earlier model of YP2800, at 4.2 K is 4.3 T, ~10 times larger than that of 0.43 T at 77 K. Since the maximum trapped field of YP2800 at 77 K is 0.65 T, that at 4.2 K may be estimated to be \( \sim 6.5 \) T. Thus, \( J_{ce} \) at 4.2 K (blue circles in Fig. 5) was calculated by \( J_{ce} \) at 77 K multiplied by 10.

C. Equivalent Circuit Analysis with “Three Coil Model”

The 560 modules in YP2800 may be grouped into “three magnetically-coupled subcoils” (Fig. 6a): the first coil (C_B) consists of the “bottom” 140 saturated (\( J_e \sim J_{ce} \)) modules; the second coil (C_M) the “middle” 280 unsaturated (\( J_e < J_{ce} \)) modules; and the last coil (C_T) the “top” 140 saturated modules. The total turns of a “coil” is assumed to be the number of modules; the coil current is defined as \( J_e \) multiplied by the module cross section area, \( A_M \).

Fig. 6b presents an equivalent circuit model for the three coils, of which the circuit equations can be expressed by (2), where \( L \) and \( M \) are self and mutual inductances, respectively. The \( R \) is a resistance due to the “index loss” in (3), where \( V_c \) and \( n \) are, respectively, voltage criterion for critical current (1 \( \mu \)N x coil conductor length) and index value of ReBCO conductor, typically ranged 10 - 40 [17]-[20], that is set to 30 for 4.2 K Table III summarizes key parameters of the “three coils”.

\[
\begin{bmatrix}
L_T & M_{TM} & M_{TB} \\
M_{TM} & L_M & M_{MB} \\
M_{TB} & M_{MB} & L_B
\end{bmatrix}
\begin{bmatrix}
\frac{dI_T}{dt} \\
\frac{dI_M}{dt} \\
\frac{dI_B}{dt}
\end{bmatrix}
= 
\begin{bmatrix}
R_T I_T \\
R_M I_M \\
R_B I_B
\end{bmatrix}
\]
The field constant at \( z = 100 \) mm, measured (black squares) and calculated (blue circles). From Table III, the field decays in Fig. 7.

**IV. CONCLUSION**

The temporal “enhancement” of trapped fields at and near the axial center of a compact NMR magnet comprising a stack of 2800 YBCO “square” annuli (YP2800) was observed during long-term field cooling tests in a bath of liquid helium at 4.2 K. We analyzed the 4.2-K axial trapped field distributions in YP2800, 234-mm long, with a focus on the field enhancement around the YP2800 center (\(|z| < 30\) mm) and the field decay at \(|z| > 80\) mm. Then, a computational approach was proposed to simulate both enhancement and decay of trapped fields in YP2800. Firstly, based on the inverse calculation technique, the current distributions in the 560 5-plate modules of YP2800 were estimated. The results showed that the 140 modules at the top and bottom of the YP2800 stack were “saturated” in terms of current-carrying capacity, while the 280 modules in the middle of YP2800 were “unsaturated”. Then, YP2800 was modelled as “three magnetically-coupled subcoils”: the first coil (C\(_B\)) consists of the bottom 140 modules; the second coil (C\(_M\)) the middle 280 modules; and the third coil (C\(_T\)) the top 140 modules. With the index resistance of each “coil” taken into consideration, the average current in C\(_M\) was “slowly” increased due to the “fast” decay of currents in C\(_B\) and C\(_T\). As a result, the center field, which is dominated by the currents in C\(_M\), increases while the field at \( z = 100 \) mm decays, which agrees well to the measured temporal behavior, both trapped field enhancement and decay.

**REFERENCES**


