Assembly and Test of a 3-Nested-Coil 800-MHz REBCO Insert (H800) for the MIT 1.3 GHz LTS/HTS NMR Magnet

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Assembly and Test of a 3-Nested-Coil 800-MHz REBCO Insert (H800) for the MIT 1.3 GHz LTS/HTS NMR Magnet

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Abstract—We present assembly and test results of a 3-nested-coil 800-MHz (18.8 T) REBCO insert (H800) for the MIT 1.3 GHz LTS/HTS NMR magnet currently under completion. Each of the three H800 coils is a stack of no-insulation (NI) REBCO double-pancake coils (DP’s). The innermost 8.7-T Coil 1 (26 DP’s) was completed by mid-2016; the middle 5.6-T Coil 2 (32 DP’s) was completed in mid-2017; while the outermost 4.5-T Coil 3 (38 DP’s) was completed in early 2018.

Coils 1, 2 & 3 were assembled together in early 2018 as a 3-nested-coil, the H800, and tested, first in liquid nitrogen to a power supply current of 20 A, followed by testing in liquid helium to a power supply current of 251 A, the H800’s design operating current. After roughly five minutes settling time at 251 A, the H800 quenched. In this paper we examine probable sources of quench initiation and simulate ensuing quench behavior. Remedial efforts to minimize the tendency towards quenching in the H800 are presented and discussed.

Index Terms—High-temperature superconductors, nuclear magnetic resonance, superconducting magnets,

I. INTRODUCTION

This paper summarizes results from final test of the MIT H800 insert coil. The H800 is the first, high-field insert coil designed using no-insulation (NI) double-pancake (DP) windings to generate a central magnetic flux intensity of 18.8 T. This was to have been the final test of the H800 prior to integration with the large-bore, 500-MHz NMR-quality magnet (the L500) to complete the 30.5 T combined central magnetic flux density.

The complete engineering design for the H800 was presented previously [1]–[3]. Engineering development in support of H800 construction was also presented [4]–[9]. Construction and test results for the H800 coils were presented sequentially following the completion of each coil [2], [3], [10]–[11].

In section II of this paper we briefly summarize assembly of the H800. Section III presents results obtained from test of the H800 in liquid helium, during which the magnet quenched. Section IV summarizes post-quench examination of the magnet. Section V includes preliminary assessment of the cause of the quench and proposes methods to reduce the tendency towards quench in future high-field magnets built from NI DP.

II. H800 ASSEMBLY

A schematic cross-section of the as-built H800 is shown in Fig. 1. The H800 was radially sub-divided into three coils to limit peak strain in its REBCO conductor. Table I summarizes key parameters for the coils during operation at the H800’s 251.3 A design current.

The outermost coil, Coil 3, was wound in the opposite direction from Coils 1 and 2 to simplify the lead arrangement. Current enters at the bottom of Coil 2, passes from the top of Coil 2 to the top of Coil 3, from the bottom of Coil 3 to the

![Fig. 1. Schematic cross-section of the H800 showing current lead routing.](image-url)
TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Coil 1</th>
<th>Coil 2</th>
<th>Coil 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of double-pancakes</td>
<td></td>
<td>26</td>
<td>32</td>
<td>38</td>
</tr>
<tr>
<td>Winding inner diameter (without inside notch)</td>
<td>[mm]</td>
<td>91.0</td>
<td>150.8</td>
<td>169.9</td>
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<tr>
<td>Winding outer diameter</td>
<td>[mm]</td>
<td>119.1</td>
<td>169.2</td>
<td>211.3</td>
</tr>
<tr>
<td>Winding height</td>
<td>[mm]</td>
<td>323.65</td>
<td>393.8</td>
<td>465.8</td>
</tr>
<tr>
<td>Over-banding thickness</td>
<td>[mm]</td>
<td>7</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Magnetic field contribution</td>
<td>[T]</td>
<td>8.67</td>
<td>5.64</td>
<td>4.46</td>
</tr>
<tr>
<td>Stored magnetic energy</td>
<td>[kJ]</td>
<td>178</td>
<td>233</td>
<td>245</td>
</tr>
</tbody>
</table>

Charging of the H800 proceeded smoothly up to about 190 A, when small upticks in both Coil 2 and Coil 3 voltage were observed, suggesting possible increase to their series resistances. At this point, $I_{PS}$ was held steady at 190 A for 240 min to permit the coil voltages to settle and to perform initial mapping of on-axis field. By the end of the hold period, the measured series resistances for the coils were in the range from 18 $\mu$Ω to 25 $\mu$Ω, slightly more than, but consistent with the sum of DP-DP splices in each coil.

B. Voltage spikes

The current ramp from 190 A to 251.3 A was briefly interrupted twice, at 217.5 A and again at 235.2 A, each time following a large voltage spike in one of the coils, accompanied by abrupt, transient increase in the helium boil-off rate.

Fig. 2 shows the Coil 2 double-pancake voltages and the power supply current vs. elapsed time as the power supply current was ramped from 235.2 A to 251.3 A. Because of our limited number of data acquisition channels, the Coil 2 and Coil 3 double pancakes were measured in groups of three to four. As an example, the C2_DP1-4 designation refers to the lowest four DP in Coil 2. Fig. 2 shows the occurrence of three large voltage spikes superposed on the characteristic upward exponential voltage rise in the DP voltage during current upramp and decaying exponential voltage during settling at constant current.

Voltage spike heights up to 20 mV were occasionally observed. The locations of the spikes in the H800 varied. Typically one end of the H800 would see spikes while the other would not. Large spikes were only observed in Coils 2 and 3. For instance, the largest spikes in Fig. 2 appeared in C2_DP1-4. Upward directed spikes for DP in one coil were generally accompanied by simultaneous downward directed spikes in DP at the same vertical elevation in the other coils.

C. Quench event

Fig. 3 shows signals recorded during quench of the H800. Fig. 3a shows central magnetic flux density and power supply current vs. time, while Fig. 3b shows the individual coil voltages and power supply current vs. time. Data was sampled at 10 Hz due to the large numbers of signals and total test duration.

![Fig. 2.](image-url)
tion; unfortunately, this slow sampling rate precludes high resolution examination of quench dynamics. The data record was similarly broken into several “small” files. Although the elapsed time axis in Fig. 3 says 1930.2 s the quench actually occurred about 18.5 hr after the start of initial current ramp.

Fig. 3b shows that Coil 2 quenched first, approximately 5 min. after the power supply current reached the H800’s 251 A design current (1600 s in Fig. 2). Approximately 0.3 s later Coil 1 quenched, followed another 0.1 s later by quench in Coil 3. Quench in Coil 2 began in the lower most pancakes, C2_DPI-4. The power supply current remained constant until the quench reached Coil 3, decaying rapidly to zero by 1931.1 s elapsed time. The power supply interlock didn’t work properly, allowing the magnet current to increase slightly following the quench. Collapse of the central magnetic flux density lagged behind the current discharge by roughly 0.1 s, with the entire field decay lasting roughly 0.4 s.

Based on the extremely short duration of the event, the H800 clearly fits the model developed for high current density NI coils where quench propagation occurs via electromagnetic coupling rather than by thermal diffusion [13]–[15]. NI coils effectively maintain near constant magnetic flux. Disappearance of azimuthal current in a quenching DP, causes simultaneous current increase in its near neighbors via electromagnetic induction, ending when the induced azimuthal currents in the neighbors also reach critical current, Ic. The central magnetic flux density collapses as magnetic energy is dissipated and azimuthal current in all DP drops to zero.

IV. POST-QUENCH EXAMINATION

A. Inspection and Disassembly

Following a few days warm-up, the H800 was removed from its test cryostat for inspection and disassembly. The disassembly followed the assembly procedure in reverse order. The coils were separated from one another. The overbanding, DP-DP splices and preload were removed. The DP were separated from one another for re-characterization in liquid nitrogen. Finally all DP were unwound for reel-reel Ic measurement, performed for a limited number of tapes on the Tapes-tar® equipment at SuperPower, and for all conductors using our own in-house system, which is based on the MCorder technique developed at Tsinghua University [16].

B. Visual Observations

When the H800 from its cryostat we saw that although the top half of the outermost coil, Coil 3, appeared unharmed nearly all DP below the mid-plane were noticeably deformed. The outer surface of the over-banding for the lower half of the coil was bulged and rippled, and a 9 mm to 14 mm gap had opened between the lowest DP and the coil’s end flange. After disassembly of Coil 3 to individual DP we observed that several of the DP were compressed axially, with sufficient pressure to emboss the glass weave from the G-10 spacers into the DP surface; this effect in shown in Fig. 4a. Other DP showing characteristic ripple pattern associate with overstraining in hoop direction were also observed; as shown in Fig. 4b.

Coil 2 initially appeared unaffected. However as the DP were removed from the stack, several were found with the ripple pattern shown in Fig. 4b. Then, as DP were unwound, a few (including the lowest DP, C2_DPI1) showed signs of crumpling at the cross-over between pancakes, similar to that shown in Fig. 3b.
shown in Fig. 4c for a Coil 1 DP.

Coil 1 showed completely different behavior, in which all but the lowest pancake had rotated as a unit by 10° while shifting vertically upward by 6 mm, simultaneously breaking all six of its ¼-20 preload bolts in the process. Fig. 5 shows a close-up of a broken pre-load bolt with recess hole in the pre-load plate shifted laterally beneath. During unwinding, we found several DP where the ends of the cross-over didn’t crumple, but rather, they cut partway into each other.

C. Re-characterization of Individual DP

The x-axis in Fig. 6 shows the ratio of DP critical current measured following the quench to that before the quench, while y-axis shows DP axial position in each of the three coils. Although there is no obvious variation in $I_c$ with vertical position, nearly all DP showed reduced $I_c$ following the quench. Typically, $I_c$ for the Coil 1 and Coil 2 DPs remained within 80% of their initial values, while some DP in Coil 3 approach 90% reduction in measured post-quench $I_c$.

D. Reel-to-reel Determination of Tape $I_c$

Fig. 7 shows the variation in $I_c$ vs. position along the conductor unwound from the lowest DP in Coil 2, C2_DP1, using our reel-to-reel system. The measured $I_c$ along most tapes remains close to the as-received value, except at the location of cross-over turn between pancakes. The most severely degraded DP show multiple, periodic drop-outs, centered either about the cross-over location, or concentrated towards the ends of the tape, following a similar pattern to that reported in [17]. The more severely degraded tapes come from DP showing the Fig. 4b ripple pattern. We believe this pattern results from over-straining in the hoop direction caused by azimuthal current overload (explained in more detail in section V.C.). Although we cannot prove it, we believe that the damage to the cross-over turn occurred prior to, and contributed to the quench, rather than as a result.

V. ANALYTICAL MODELLING

A. Voltage spikes

Fig. 8 shows results, using (1), to simulate typical DP voltage spikes seen in Fig. 2. Only the largest simulated spikes are shown. To match both rise time and spike height for the C2_DP1-4 spike (occurring at 665.5 s elapsed time in Fig. 2) we introduced series resistances, $R_s$, with 1.1 mΩ peak values into each of the four DP. The applied $R_s$ rose abruptly to peak value was held constant for 0.1 s and decayed to zero with 0.04 s time constant. Following the spike, the DP voltages recovered to their initial distribution following the H800 characteristic time constants. During recovery, the DP were subjected to turn-turn losses as the induced azimuthal and radial DP currents relaxed back toward their initial state.

The peak $R_s$ is consistent with normal-state conductor length of roughly 0.4 m at 3x10⁻¹⁰ W-m copper resistivity; this matches the length of a Coil 2 DP inner turn cross-over. The similar appearance of these spikes to those attributed to conductor-motion in LTS magnets [18]–[19], combined with the estimated length of involved conductor leads us to attribute the spikes to abrupt vertical motion of the cross-over turns. The tendency towards motion increase with coil current; as increasing electromagnetic loads relieve radial pressure while simultaneously increasing the axial forces at the winding ID and frictional restraining forces relax [20].

We believe this is the first observation of conductor motion induced spikes in an NI-wound REBCO magnet. We also believe that the current bypass feature present in NI coils generally precludes direct transition from voltage spike to quench. Magnet currents simply avoid any section with locally high resistance, allowing rapid recovery from transient disturbances.
lize thick-sectioned, low-temperature superconductors (LTS) launch/axially compressive loads. Visual observation of both flux. The proposed current pattern at start of quench produces both a torque on the lowest DP in both coils as well as vertical motion during winding is ineffective for two reasons; the conductor’s finite tensile strength is better used to support electromagnetic loads during operation, while manufacturing tolerances always leaves some portion of conductor length less well supported than expected [20].

We have previously devised means to effectively immobilize thick-sectioned, low-temperature superconductors (LTS) as a means to suppress conductor motion induced quenching in both DP [18] and layer [20] dry-wound magnets. We are pursuing similar strategies to support the cross-over turn in thin HTS tape-wound DP. Simply increasing conductor tension during winding is ineffective for two reasons; the conductor’s finite tensile strength is better used to support electromagnetic loads during operation, while manufacturing tolerances always leaves some portion of conductor length less well supported than expected [20].

We designed, constructed, and tested a three-nested, 18.8 T high-field insert coil (the H800) using REBCO tape conductor wound into NI DP. The H800 quenched and suffered significant damaged during testing in March 2018. Although the cause of the quench is not conclusively determined, based on the coil behavior during charging and visual examination following quench, we suspect that abrupt movement of the cross-over turns in the end most DP in Coils 2 and 3 locally degraded conductor performance sufficiently to initiate the quench. We are presently working on a revised, single-coil HTS insert design, called the H800N, with an eye towards eliminating structural weaknesses and enhancing its quench handling characteristics.

VI. CONCLUSION

Our voltage spike simulation shows that DP at same axial elevation in the H800 are electromagnetically tightly coupled. Sudden disappearance of azimuthal current in C2_DP1-4 during quench initiation, is expected to produce corresponding increases in the radial and azimuthal currents for the lowest DP in both Coil 1 and Coil 3 as they strive to preserve magnetic flux. The proposed current pattern at start of quench produces both a torque on the lowest DP in both coils as well as vertical launch/axially compressive loads. Visual observation of both coils following quench are qualitatively consistent with the proposed scenario.

Detailed finite element modeling the H800 shows critical currents in excess of 1000 A for the DP nearest the mid-plane of Coil 3 immediately preceding quench, using same critical current scaling for all three coils. However, the conductors for the H800 were acquired between 2014 (for Coil1) and 2018 (for Coil 3). If our conductor performance evolved similarly over time to those for the NHMF 32-T [21], then the Coil 3 conductors should have higher than average lift factors in the H800 due to more recent delivery.

Note that the central magnetic flux density in Fig. 3a remains constant even after Coil 3 has started to quench. For Coil 3 alone to sustain 18 T central magnetic flux density at this point, requires azimuthal currents on order of 1 kA in the DP, resulting in average mid-plane pressure on order of 900 MPa, consistent with the compressive strength of both the G-10 spacers and NI DP windings, as well as the observed damage to both.

We are presently using the physical observations outlined in this paper to guide the analytical modeling of the H800 during its final current ramp and quench [22]–[23]. Results from these on-going analyses will be presented in appropriate journals as the match between simulation and observation improves.

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REFERENCES


