Persistent-current switch for pancake coils of rare earth-barium-copper-oxide high-temperature superconductor: Design and test results of a double-pancake coil operated in liquid nitrogen (77–65 K) and in solid nitrogen (60–57 K)

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Persistent-current switch for high-temperature superconducting pancake coils: design and test results of a coil operated in liquid nitrogen (77–65 K) and in solid nitrogen (60–57 K)

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Abstract
We present design and test results of a superconducting persistent current switch (PCS) for persistent-mode operation of high-temperature superconducting (HTS) double-pancake (DP) coils. We placed a PCS to each pancake of a DP coil, 152-mm ID, 168-mm OD, of REBCO (Rare Earth Barium Copper Oxide) tape, 6-mm wide and an overall thickness of 75 \(\mu\)m, wound with a no-insulation (NI) winding technique. The REBCO NI DP coil was operated in liquid nitrogen (77–65 K) and in solid nitrogen (60–57 K). Over the operating temperature ranges of this experiment, the normal-state PCS enabled the DP coil to be energized; thereupon the PCS resumed the superconducting state and the DP coil operated in semi-persistent mode with a field decay time constant of 100 hr.

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A high-field NMR (nuclear magnetic resonance) superconducting magnet composed of a low-temperature superconducting (LTS) magnet and an HTS insert, e.g., the MIT 1.3-GHz LTS/HTS NMR magnet,\(^1\) should ideally be operated in persistent mode. Although persistent-mode operation is routine with all-LTS NMR magnets, most HTS magnets, particularly those of REBCO tape, must still be operated in driven mode. This despite the fact that a technique to make superconducting splices with REBCO tapes has been reported.\(^2\) Note that it is not possible to energize a superconducting coil, terminated with a superconducting splice, with a power supply connected across its terminals;\(^3\) to energize such a shorted coil, a persistent-current switch (PCS) is required. When a technique to make superconducting splices with REBCO tapes is developed, readily applicable to an HTS insert composed of REBCO double-pancake (DP) coils, e.g., 98 in the MIT insert,\(^4\) such an HTS insert will need a PCS to operate in persistent mode. Thus, we have begun developing a PCS for HTS pancake coils. In this paper we report a design and preliminary experimental results of a PCS applied to a REBCO DP coil.

Table 1: NI DP Coil Parameters

<table>
<thead>
<tr>
<th>Winding dimensions:</th>
<th></th>
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<tbody>
<tr>
<td>ID; OD (2a2); height [mm]</td>
<td>151.0; 171.6; 12.1</td>
</tr>
<tr>
<td>Total # turns</td>
<td>251</td>
</tr>
<tr>
<td>Field constant [mT/A]</td>
<td>1.91</td>
</tr>
<tr>
<td>(L_{dp})* [mH]</td>
<td>18.5</td>
</tr>
<tr>
<td>(R_m)* [m(\Omega)]</td>
<td>0.27</td>
</tr>
</tbody>
</table>

* Deduced from experiment.

For this experiment, using the no-insulation (NI) winding technique,\(^4\) we wound an NI DP coil with REBCO tape, 6-mm wide, 75-\(\mu\)m thick, and 125-m long. Table 1 lists the coil key parameters, including \(L_{dp}\), inductance, and \(R_m\), an effective resistance\(^5\) of the radial-flow current of an NI DP coil. A photo of the REBCO NI DP coil is shown in Fig. 1.

Figure 2 presents a circuit diagram of the coil that includes other key components. Note that the terminals (last turns) of the top and bottom pancakes are spliced, for now resistively \((R_j)\), which for persistent-mode operation must be superconducting. In each pancake a \(~\)10-cm long REBCO tape section of the last turn also serves as a PCS with the normal-state resistance of \(R_{pcs}\). A power supply, shown at the far left in Fig. 2, was used to energize the NI DP coil.

Figure 3 gives a schematically drawn panoramic view of the DP coil with the key components. In charging mode (dashed arrows), current enters the outermost turn of the top pancake, spirals down to the innermost turn, continues though a crossover to the innermost turn of the bottom pancake, spirals up to the outermost turn, and leaves the coil. In semi-persistent mode (solid arrows), with both switches superconducting the current in the outermost turn of the bottom pancake, via a resistive, \(R_j\), pancake-to-pancake (P-P) joint, comes full circle to the top pancake, decaying with a time constant of \(L_{dp}/R_j\). Note that there is one PCS in each pancake. The figure does not include the PCS heaters.

Fig. 1 Photo of the NI DP coil used in the experiment.

Fig. 2 Circuit diagram.
Fig. 3 Schematically drawn panoramic view of the DP coil. Dimensions are in mm.

Fig. 4 Photos of two REBCO NI DP coils prepared in the experiment: (a) 2-turn coil to test a P-P joint (foreground); (b) full-test coil—one PCS is visible in each side.

Figure 4 shows photos of two REBCO NI DP coils prepared in this experiment: (a) 2-turn coil to test, at 77 K, a ~8-cm long P-P joint (foreground), replicated in the full-test coil of (b), in which one PCS is visible in each side of the coil. The center field was measured by a Hall sensor. For 77-K operation in liquid nitrogen (LN$_2$), we placed the coil setup in a Styrofoam container; for operation at 65 K (LN$_2$) and in solid nitrogen (SN$_2$), we used a cryostat filled with LN$_2$, pumped out to lower the temperature, eventually reaching 63 K (SN$_2$) and down to 57.3 K.

The top and bottom pancakes were joined with the same REBCO tape ~10-cm long but 12-mm wide, the same as the first practice coil (Fig. 4a) and those of our REBCO DP coils.$^{1,6}$ For this coil setup, each PCS, placed near the terminal, we set two goals: 1) a resistive zone of ~1-mΩ, ~4 times $R_m = 0.25$ mΩ (computed and 0.27 mΩ, deduced from experiment); and 2) a power requirement of $\leq 1$ W. Each 10-cm long heater section was of an insulated φ1-mm Manganin wire sandwiched by 5-mm thick Styrofoam insulating layers—both switches are indicated in Fig. 4b photo.

Figure 5 shows the DP coil $V(I)$ traces at 77 K (solid); 65 K (dash) both in LN$_2$; 59.5 K (dash-dot-dot-dash) and 57.3 K (dash-dot-dash) in SN$_2$. At 77 K the coil was resistive at a measured voltage of 25.4 µV at 50 A, still
quite less than 125 µV, a critical voltage (a 0.1-µV/cm criterion) for the NI DP coil wound with 125-m long REBCO tape.

With the coil energized and both switches superconducting, the current decayed with a time constant $\tau_{dp} = L_{dp}/R_{cir}$, where $R_{cir}$ is the total resistance of the semi-persistent circuit. Figure 6 shows normalized (to initial value) center field in semi-persistent mode vs. time plots for initial currents of 20 A (circles), 30 A (squares), and 50 A (blue line) at 77 K in LN$_2$ and 100 A (triangles) at 59.8 K in SN$_2$. From these plots, except the solid line corresponding to 50 A at 77 K, we determine $\tau_{dp} \sim 100$ hr. For these initial currents, we compute, with $L_{dp} = 18$ mH, $R_{cir} = R_j \approx 50$ nΩ, which was identical with $R_j$ directly measured with the voltage taps placed across the P-P joint. $R_j$ also agreed well with that of a 2-turn coil and those of our previous splice results.\textsuperscript{6} At a 50-A initial current, the field decayed with $\tau_{dp} \sim 8$ hr 53 min. This is because the coil has an index resistance, $R_n$, of 508 nΩ (= 25.4 µV/50 A). From $\tau_{dp} \sim 8$ hr 53 min, we compute $R_{cir} = R_n + R_j = 563$ nΩ, pretty close to a sum of 508 nΩ and 50 nΩ.

In conclusion, we have designed, built, and experimentally demonstrated a new persistent-current switch (PCS) design for HTS magnets assembled with REBCO double-pancake coils. Once REBCO DP coils can be terminated with superconducting joints, we believe that a PCS based on this design will become an essential and enabling component for an REBCO magnet to operate in persistent mode.

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References


