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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We present design and test results of a superconducting persistent current switch (PCS) for pancake coils of rare-earth-barium-copper-oxide, REBCO, high-temperature superconductor (HTS). Here, a REBCO double-pancake (DP) coil, 152-mm ID, 168-mm OD, 12-mm high, was wound with a no-insulation technique. We converted a ~ 10 -cm long section in the outermost layer of each pancake to a PCS. The 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 field decayed with a time constant of 100 h, which would have been nearly infinite, i.e., persistent-mode operation, were the joint across the coil terminals superconducting. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4961622>]

A high-field NMR (nuclear magnetic resonance) superconducting magnet composed of a low-temperature superconducting (LTS) magnet and a high-temperature superconducting (HTS) insert, e.g., the MIT 1.3-GHz LTS/HTS NMR magnet,¹ should ideally be operated in persistent mode. Although most all-LTS MRI and NMR magnets are operated in persistent mode, rare-earth-barium-copper-oxide (REBCO) magnets are still operated in driven mode. Note that it is impossible to energize a *superconducting loop*, e.g., a coil or magnet, with a power supply connected across the loop;² to energize such a shorted coil, a persistent current switch (PCS) is required. The HTS PCS has been developed for magnets of Bi2212,³ Bi2223,^{4–6} YBCO,^{7,8} and MgB₂.⁹ Note that YBCO is the first so-called coated conductor now generally designated as REBCO to highlight the possible substitution of other rare earth elements for Y in the coating. If a high-field insert magnet composed of REBCO double-pancake (DP) coils, e.g., 98 in the MIT insert,¹ were to operate in persistent mode, such an insert would need at least one PCS, preferably of REBCO. Thus, we have begun developing a REBCO PCS specifically for REBCO pancake coils.¹⁰ In this paper, we report a design and preliminary experimental results of a REBCO PCS.

For this experiment, using the no-insulation (NI) winding technique,¹¹ we wound an NI DP coil with SuperPower REBCO tape, 125-m long, 6-mm wide, 75- μ m thick of which 50- μ m thick Hastelloy and 2×10 - μ m thick electroplated

copper layers. Table I lists the coil key parameters, including L_{dp} , inductance, and R_m , an effective resistance¹² of the radial-flow current of an NI DP coil. A photo of the DP coil is shown in Fig. 1.

Figure 2 presents a coil circuit diagram that includes other key components. The terminals of the top and bottom pancakes form a *resistive* (R_j) pancake-pancake (P-P) joint, made by the same soldering technique used in our HTS insert.^{1,13} In each pancake, a ~ 10 -cm long section was converted to 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. Note that there is one PCS in each pancake; the figure does not include the PCS heaters. In charging mode (dashed arrows), current enters the outermost turn of the top pancake, spirals in to the innermost turn, continues through a crossover to the innermost turn of the bottom pancake, spirals out to the outermost turn, and leaves the coil. In persistent mode (solid arrows), with both switches

TABLE I. NI DP coil parameters.

Parameter name	Values
Winding dimensions:	
ID; OD($2a_2$); height (mm)	151.0; 171.6; 12.1
Total # turns	251
Field constant (mT/A)	1.91
L_{dp} ^a (mH)	18.5
R_m ^a (m Ω)	0.27

^aDeduced from experiment.

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

superconducting the current in the outermost turn of the bottom pancake, via a P-P joint, comes full circle to the top pancake. Here, because the P-P joint is *resistive* (R_j), the current is expected to decay with a time constant of $\tau_{dp} = L_{dp}/R_j$.

Figure 4 shows photos of two REBCO NI DP coils prepared in this experiment: (a) a 2-turn coil with 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.

For each PCS located near the terminals of this coil setup, we set two requirements: (1) a normal-state resistance of $1 \text{ m}\Omega$, $\sim 4 \times R_m = 0.25 \text{ m}\Omega$ (computed and $0.27 \text{ m}\Omega$, deduced from experiment), and (2) a power requirement of $\leq 1 \text{ W}$. Each 10-cm long heater section was of an insulated ϕ 0.1-mm Manganin wire sandwiched by 5-mm thick Styrofoam insulating layers—both switches are indicated in Fig. 4(b) photo.

Figure 5 shows the DP coil $V(I)$ traces at 77 K (solid), 65 K (dash) both in LN_2 , 59.9 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 at 50 A of $25.4 \mu\text{V}$, quite less than $125 \mu\text{V}$, a critical voltage (a $0.1\text{--}\mu\text{V/cm}$ criterion) for this DP coil.

With the coil energized and both switches superconducting, the current decayed with a time constant of L_{dp}/R_{cir} ,

FIG. 2. Circuit diagram.

FIG. 3. Schematically drawn panoramic view of the DP coil. Dimensions are in mm.

(a)

(b)

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.

FIG. 5. $V(I)$ traces at 77 K (solid), 65 K (dash), in SN_2 at 59.9 K (dash-dot-dot-dash), 57.3 K (dash-dot-dash).

FIG. 6. Normalized field vs. time plots at 77 K and at 59.8 K (SN_2).

where R_{cir} is the total resistance of this circuit. Figure 6 shows normalized (to initial value) center field 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 a decay time constant of $\simeq 100$ h. For these initial currents, we compute, with $L_{dp} = 18.5$ mH, $R_{cir} \simeq 50$ n Ω , which is identical with R_j directly measured with the voltage taps placed across the P-P joint. This and “zero” voltage measured across each PCS—within the limit of experimental resolution, the “zero” voltage translates to a P-P joint resistance uncertainty of ± 2.5 n Ω —make us conclude that $R_{cir} = R_j$ and thus each PCS was indeed in the superconducting state during a slow decay period. R_j also

agreed well with that of a 2-turn coil and those of our previous splice results.¹³ At a 50-A initial current at 77 K, the field decayed with a time constant of 8 h 53 min. This is because the coil has an index resistance, R_n , of 508 n Ω ($= 25.4 \mu\text{V}/50\text{ A}$). From $L_{dp}/R_{cir} = 8\text{ h } 53\text{ min}$, we measured $R_{cir} = R_n + R_j = 563$ n Ω , pretty close to a sum of 508 n Ω and 50 n Ω .

In conclusion, we have designed, built, and experimentally demonstrated a PCS design for HTS magnets assembled with REBCO DP 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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