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A REBCO Persistent-Current Switch (PCS): Test Results and Switch Heater Performance

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Abstract

In this paper, we report preliminary results of our on-going effort to develop a superconducting persistent-current switch (PCS) for REBCO pancake coils that will be operated in liquid helium. In the first part of this paper, we briefly describe experimental results of our PCS operated in the temperature range 77–57 K, i.e., liquid-and solid-nitrogen environments. The rest we devote to a new PCS heater design in which we target a heating power of < 1 W in liquid helium.

Keywords

Persistent-current-switch (PCS) heater; persistent-mode operation; REBCO double-pancake (DP) coils

I. Introduction

IDEALLY all NMR (nuclear magnetic resonance) and MRI (magnetic resonance imaging) superconducting magnets should operate in persistent mode, primarily to satisfy their stringent temporal stability requirement, generally ~0.1 ppm/hr. Although persistent-mode

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operation is standard with all LTS (low-temperature superconducting) NMR and MRI magnets, this is not the case with magnets that include high-field HTS (high-temperature superconducting) coils, particularly of Bi2223 and/or REBCO conductors. This is because a technique to make a superconducting joint with Bi2223 and REBCO conductors has not yet been adopted in making these HTS coils, this despite a report that such a joining technique has been developed [1]. It is impossible to energize a *superconducting loop*, e.g., a coil or magnet, using only a power supply connected across the loop [2]; to energize such a shorted coil, a persistent-current switch (PCS) is also 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. If a high-field insert magnet composed of REBCO double-pancake (DP) coils, e.g., 98 in the MIT insert [10], 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 [11]. Because we have already reported a design and preliminary experimental results of a REBCO PCS [12], here we focus on performance results of our latest switch heater.

II. PCS

To test our PCS design we wound a double-pancake (DP) coil with SuperPower REBCO tape, 125-m long, 6-mm wide, 75- μm thick of which 50- μm thick Hastelloy and $2 \times 10\text{-}\mu\text{m}$ thick electroplated copper layers. For this REBCO DP coil we applied a non-insulation (NI) winding technique[13]. A photo of the DP coil is shown in Fig. 1. Table I lists the NI DP key parameters, including L_{dp} , inductance, and R_m , an effective resistance[14] of the radial-flow current of an NI DP coil.

Fig. 2 presents a circuit diagram of the coil that includes other key components. Note that the terminals of the top and bottom pancakes are spliced; here the joint is *resistive*, R_j , made by the same technique used in our HTS insert [10], [15]. In each pancake a $\sim 10\text{-cm}$ 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.

Fig. 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 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 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.

III. PCS Heater

For each PCS located near the terminals of this coil setup, we set two requirements: 1) a normal-state resistance of $\sim 1\text{-m}\Omega$, $\sim 4 \times R_m = 0.25\text{ m}\Omega$ (computed and $0.27\text{ m}\Omega$, deduced from experiment); and 2) a power requirement of $\sim 1\text{W}$, both of which were met by each

PCS. A 10-cm long heater section of each switch was of an insulated $\phi 0.1$ -mm Manganin wire sandwiched by 5-mm thick Styrofoam insulating layers. However, although a switch heater requirement of 1 W is satisfactory in the range 77–57 K, it would translate to ~ 10 W in the LHe temperature range. Later in this paper, we present a new switch heater designed for <1 W operation at LHe temperatures and its preliminary results.

IV. PCS OPERATION & RESULTS

For 77-K operation in liquid nitrogen (LN₂), we placed the coil setup in a Styrofoam container; for operation at 65 K (LN₂) and in solid nitrogen (SN₂), we used a cryostat filled with LN₂, pumped out to lower the temperature, eventually reaching 63 K (SN₂) and down to 57.3 K. The center field was measured by a Hall sensor.

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. Fig. 4 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 LN₂ and 100 A (triangles) at 59.8 K in SN₂. From these plots we determine $\tau_{dp} \approx 100$ hr.

For these initial currents, we compute, with $L_{dp} = 18$ mH, $R_{cir} = R_j \approx 50$ n Ω , 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 [15].

V. PCS Development

A. Prototype PCS Sample

There are two main sources of heat leak from our PCS. One is axial conduction along the REBCO tapes high conductivity copper stabilizer, the other is transverse conduction through the low-conductivity insulation. We built and tested a number of PCS prototypes, such as the one schematically illustrated in Fig. 5 to better understand the relative importance of these two mechanisms.

The prototype PCS in Fig. 5 contains a 250-mm long RE-BCO tape used in the DP shown in Fig. 1. The REBCO tape was mounted to a 1.5-mm thick by 9.5-mm wide G-10 strip to facilitate handling. Two 350- Ω strain gauges, each 6-mm wide by 12-mm long, were epoxy-bonded to the REBCO tape to serve as low-power heaters, Heater 1 (H1) was located 22.2 mm to the left of center, while Heater 2 (H2) was located 14.3 mm to the right of center. The REBCO tape was instrumented with two type E thermocouples (TC). The measurement junction for TC1 was attached 3.2 mm to the left of center, while that for TC2 was attached 34.9 mm to the right of center. The reference junction for each TC was fastened near the end of the G-10 support to permit differential temperature measurement with respect to the surrounding cryogen bath. A copper wire twisted pair was used to bring each TC measurement from the cryogenic environment to our data acquisition equipment.

The instrumented tape section was suspended near the center of a 120-mm long G-10 tube, 35-mm OD and 1.5-mm thick wall. The space surrounding that section was filled with Loctite Tite Foam expanding polyurethane foam as a means to tightly seal the insulation

around the assembly [16]. A pair of current leads (–CL and +CL) and voltage taps (–VT and +VT) were installed near the ends of the REBCO tape to monitor the tape resistance during heating experiments. Fig. 6 shows a photo of a prototype PCS. Loctite Tite Foam is visible protruding from the right end of the G10.

B. Thermal Modeling

Heat leak from our prototype PCS was modeled by analogy to a cooling fin [17], with convection at the fin surface replaced by radial conduction through the insulation. Axial conduction, $Q_a(x)$, along the REBCO tape was computed using (1), while the incremental radial conduction, $dQ_r(x)$, at each location, x , was computed using (2).

$$Q_a(x) = k_{Cu} A_{Cu} \frac{dT(x)}{dx} \quad (1)$$

$$dQ_r(x) = \frac{2\pi k_i}{\ln(d_i/d_e)} T(x) dx \quad (2)$$

where, k_{Cu} is the average thermal conductivity of copper over the anticipate range of PCS operation, k_i the average thermal conductivity of the insulation, A_{Cu} , the cross-section area of the copper stabilizer, d_i outer diameter of the insulation, d_e , effective diameter of the tape (equal to the geometric mean of width, w , times thickness, t), while $T(x)$, is the temperature rise at location x above the ambient cryogen bath temperature. We assumed isothermal boundary at the insulation surface equal to the cryogen bath temperature, and effective heat transfer coefficient, h , near the ends of the PCS equal to 20 kW/m² K, which was approximated from the slope of the nucleate boiling curve for LN2. For the PCS tests in LN2 we set k_{Cu} to 780 W/m K (assuming operation between 77 K and 100K). To match experiment and measurement, we needed to set k to 0.06 W/m-K, significantly above the commonly reported value of 0.01 W/m-K for polyurethane foam [18]. We believe that the elevated k value needed to fit our data occurred because our prototype heater was operated in liquid nitrogen bath whereas the reference [18] value was measured in vacuum at cryogenic temperatures. In fact, the k value deduced for in-field applications can often be up to an order of magnitude higher than that obtained under ideal laboratory conditions [19]. The k value for foamed polymers strongly depends on the conductivity of gas contained in the pores [18], [20], thus, the elevated value observed during our heater tests was most likely caused by permeation of atmospheric nitrogen vapor into the pores of our heater insulation during testing.

C. Comparison With Experiment

Measurement and calculation both show that we need to apply at least 65 mW to H2 to partially open the PCS (attainment of 0.1-mΩ resistance) and 110 mW to achieve our target resistance of 1 mΩ. The same heating power is needed to achieve 1 mΩ resistance whether heating is confined to H2 or divided equally between H1 and H2. If we assume 50 RRR for

the copper stabilizer, then the 1 m Ω target resistance can be achieved by heating a 35-mm long REBCO tape to just over its 93 K transition temperature (16-K temperature rise).

Fig. 7 shows transient response of the prototype PCS with heater immersed in LN2 and 0.25-W heating power applied to H2. These high heating power tests were used in preparation for subsequent PCS tests at LHe temperatures. During the test, the asymptotic temperature rise measured by TC1 was 28.5 K, the rise measured by TC2 was 22.2 K. The tape resistance with 0.5 A current applied, increased to roughly 2.7 m Ω . If we assume that the tape remains fully superconducting at temperature rise below 16 K in our simulation and integrate the stabilizer resistivity over the remaining tape section we obtain a resistance of 2.4 m Ω , which is reasonably close to the measured value.

Fig. 8 compares measured temperature rise at TC1 and TC2 to simulated results with the PCS immersed in LN2, with 0.25-W heating applied to H1 only, 0.25-W heating applied to H2 only, and 0.25-W heating applied to each of H1 and H2 (0.5 W total). For simplicity, the heaters were modeled as point sources, which accounts for the high peak temperatures at the heater locations. The dotted vertical lines in Fig. 7 show the heater locations, while the dotted horizontal line at a 16-K temperature rise corresponds to REBCO transition temperature of 93 K. Agreement is reasonable, giving some confidence in the predictive capability of the model.

VI. PCS DEVELOPMENT FOR LOW TEMPERATURE USE

We expect the thermophysical properties of our PCS to change markedly when operated in LHe bath. At the same time, the minimum temperature rise needed to open the switch will increase to at least 89 K.

Fig. 9 shows the results of a “worst case” low-temperature PCS simulation, with k_{Cu} increased to 850 W/m K (assuming operation between 4 K and 100 K), k_f equal to 0.06 W/m K, and h increased to an artificially high value of 250 kW/m² K, to keep the ends of the REBCO tape to within 1 K of the LHe bath temperatures. Although we expect k to decrease markedly at low temperature, we conservatively retained the value deduced from the LN2 tests in our low-temperature simulations. To reduce the space required to install the PCS we also reduced d_f to 20 mm in this simulation. The simulation in Fig. 9 indicates that we will need a total heating power of at least 0.88 W to achieve our desired 1-m Ω switch resistance for coils operated in LHe environment. This will likely require the use of four strain gauge heaters to limit the peak heating power on each to below 0.25 W.

VII. Conclusion

We have designed, built, and experimentally demonstrated a persistent-current switch (PCS) design for HTS magnets assembled with REBCO double-pancake coils. The preliminary performance results of a new switch heater targeted for operation in the LHe temperatures indicate that our PCS will perform efficiently in the LHe range too. Once REBCO DP coils can be terminated with superconducting joints, we believe that our PCS will become an essential and enabling component for an REBCO magnet to operate in persistent mode.

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Fig. 1.
Photo of the NI REBCO DP coil of 151.0-mm ID.

Fig. 2.
Circuit diagram.

Fig. 3.

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

Fig. 4.
Normalized field vs. time plots at 77K and at 59.8K (SN₂).

Fig. 5.
Illustration of prototype PCS.

Fig. 6.
Photo of a prototype PCS. G10 tube is 120-mm long

Fig. 7.

Transient response of the prototype heater to application of 0.25 W heating power to heater H2, showing the temperature rise measured by thermocouples TC1 and TC2 vs. elapsed time, along with HTS tape resistance and heating power.

Fig. 8.

Temperature rise vs. axial position along the PCS prototype, showing measured results at TC1 and TC2 along with calculated results. The plot shows three conditions, with 0.25 W power applied to: H1 only, H2 only, and to each of H1 and H2.

Fig. 9.

Temperature rise vs. axial position along a low-temperature PCS. The plot shows three conditions, with 0.44-W power applied to: H1 only, H2 only, and to both H1 and H2 (0.88 W total). The heaters are spaced close enough to achieve relatively flat temperature profile over the roughly 35-mm length needed to achieve our desired 1-m Ω switch resistance.

TABLE I**NI DP COIL PARAMETERS**

<i>Winding ID; OD (2a_2) [mm]</i>	151.0; 171.6; 12.1
<i>Total # turns</i>	251
<i>Field constant [mT/A]</i>	1.91
<i>L_{dp} (deduced from experiment) [mH]</i>	18.5
<i>R_m (deduced from experiment) [mΩ]</i>	0.27