LETTER

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Letter

26T 35mm all-GdBa$_2$Cu$_3$O$_{7-x}$ multi-width no-insulation superconducting magnet

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Abstract

A 26 T 35 mm winding diameter all-GdBa$_2$Cu$_3$O$_{7-x}$ (GdBCO) magnet was designed by the MIT Francis Bitter Magnet Laboratory, and constructed and tested by the SuNAM Co., Ltd. With the multi-width (MW) no-insulation (NI) high temperature superconductor (HTS) winding technique incorporated, the magnet is highly compact; its overall diameter and height are 172 and 327 mm, respectively. It consists of a stack of 26 NI double pancake coils wound with MW GdBCO tapes in five different widths ranged 4.1–8.1 mm. In a bath of liquid nitrogen at 77 K, the magnet had a charging time constant of 16 min due to the intrinsic NI characteristics. In liquid helium at 4.2 K, the magnet generated a 26.4 T field at the center, a record high in magnetic fields from all-HTS magnets. The results demonstrate a strong potential of MW-NI GdBCO magnets for direct current high-field applications.

Keywords: multi-width, no-insulation, REBCO magnet

(Some figures may appear in colour only in the online journal)

1. Introduction

Since the discovery of high temperature superconductor (HTS) in 1986, substantial progress has been made for ‘magnet-grade’ HTS wires including Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212), Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ (Bi2223), MgB$_2$, REBa$_2$Cu$_3$O$_{7-x}$(REBCO, RE = rare Earth) [1–5]. REBCO tapes are one of the viable HTS options for high-field (>23 T) magnets, mainly owing to their strong mechanical properties and large in-field current-carrying capacities [6–15]. Recent progress in REBCO tapes is notable. Most commercial REBCO tapes now have >550 MPa and >0.5% for the respective 95% $I_c$ retention stress and strain [16–18]. Selvamanickam et al, recently achieved a critical current ($I_c$) of 3963 A with a 12 mm wide tape, i.e. 15 MA cm$^{-2}$ in a 2.2 $\mu$m thick film, at 30 K under a 3 T perpendicular (parallel to c-axis) field [8]. The latest CORC cable, where five layers of three 4 mm wide SuperPower REBCO tapes were wound around a 5.5 mm diameter former, reached >1600 A at 77 K [16]. SuNAM has now routinely provided REBCO tapes having a minimum critical current of 150 A/4 mm at 77 K and self-field.

In spite of the large current-carrying capacities of REBCO tapes, conventional REBCO magnets have been designed with a relatively low coil current density, typically <200 A mm$^{-2}$ even at 4.2 K, mainly due to difficulty in protection. In 2011, the no-insulation (NI) HTS winding technique was introduced to enable an NI HTS magnet to be essentially self-protecting [19]. Combined with the multi-width (MW) technique [20], essentially a ‘conductor grading’ approach commonly adopted in superconducting magnet design [21], an MW-NI HTS magnet was demonstrated,
2. Design and construction

2.1. Magnet design and double-pancake (DP) coil construction

Table 1 shows key parameters of the MW GdBCO tapes having five different widths—4.1, 5.1, 6.1, 7.1, and 8.1 mm. For fabrication of the MW tapes, 12 mm tapes with GdBCO deposition completed were slit to have a target width before copper electroplating. Minimum critical current ($I_c$) of each MW tape was essentially proportional to their width. Except the difference in width, all the GdBCO tapes are identical, i.e., having the same stainless steel substrate, 0.11 mm thick, and the copper stabilizer, 15 μm per each tape side.

A total of 26 Ni DP coils were wound with the MW GdBCO tapes, of which key parameters are summarized in Table 2. Here, a ‘module (M)’ is defined as a set of DP coils having the same tape width. Thus, the magnet consists of five different modules, M1–M5. M1 consists of ten DP coils wound with 4.1 mm tapes, while M2–M5 have been wound with four DP per module with tape widths of 5.1, 6.1, 7.1, and 8.1 mm, respectively. The GdBCO tapes for each module were taken from different batches and consequently have different thicknesses ranged 0.135–0.146 mm as summarized in Table 2. Figure 1 shows a picture of the 26 MW-NI DP coils grouped in the five different modules. To make the outer diameter of each DP coil identical for ease of DP–DP splices, the turn per each DP coil was adjusted as summarized in Table 2. The tape length per DP ranges 297–320 m; the total ‘4.1 mm equivalent’ tape length for the 26 MW-NI DP coils is 11.2 km. In average, four lap joints were made for the spool-to-spool splices per each DP.

2.2. $I_c$ test of MW NI DP coils at 77 K

Critical current ($I_c$) of each DP coil with a 0.1 μV cm$^{-1}$ criterion was measured in a bath of liquid nitrogen (LN$_2$) at 77 K and is presented in Figure 2. The dashed line indicates an average DP $I_c$ of each module; due to the self-field effect, it is not linearly proportional to the tape width. $I_c$ values of DP 14 and DP 24 are substantially larger than those of the other DPs in the same module, mainly because DP14 and DP24 were wound with 600 A/12 mm GdBCO tapes, while the rest with 500 A/12 mm. The DP coil numbers on the $x$-axis in Figure 2 represent the actual stacking order of the 26 DP coils; ‘1’ for the bottom DP coil, while ‘26’ for the top.

2.3. DP coil assembly and DP–DP splicing

Figure 3 shows: (a) a picture of the completed magnet after the final assembly; and (b) a to-scale schematic drawing of the DP assembly in accordance with the stacking order in Figure 2. For the stack of M1 coils, DP14 having the largest $I_c$ was placed at the axial center of the stack, where the field strength is at its peak, and those having the progressively lower $I_c$ toward the top and bottom of the M1 stack. For stacks of the other module DP coils, a pair of DP coils having the largest $I_c$ in each module were placed at the top and bottom of the respective stack, where the perpendicular field (parallel to $c$-axis) is the largest in each module (Figure 2).

After all the 26 DP coils were stacked, DP–DP splices were made using a fixture that has two 10 kg weights to...
3. Operation

3.1. Magnet test in LN2 at 77 K

After the magnet construction completed, it was firstly energized in LN2 at 77 K with a power supply ramping rate of 10 mA s⁻¹. Figure 5 shows test results: circles, squares, and triangles stand for power supply currents, magnet terminal voltages, and magnet center fields, respectively. The charging time constant of the NI magnet was measured to be 947 s; from the magnet inductance of 12.8 H, the characteristic resistance of the magnet (Rᵣ), an intrinsic property of an NI coil [25, 26], can be estimated to be 13.5 mΩ that corresponds to a surface contact resistance [25] of 9.6 μΩ cm².

The magnet has a total resistive splice resistance of 9.9 μΩ: (1) 8.3 μΩ for the 25 DP-to-DP splices; and (2) 1.6 μΩ for the 104 spool-to-spool lap joints (average four joints per each DP). At 15 A, the overall magnet terminal voltage was estimated to be 0.2 mV, while the measured one was ~0.4 mV; the discrepancy may imply that the NI magnet was not fully in a steady-state mode, though, due to the resolution limit of the voltage measurement system, the measured value of 0.4 mV may not be precisely accurate.

3.2. 26 T operation in LHe at 4.2 K

Finally, the magnet was tested in a bath of liquid helium at 4.2 K and the results were presented in figure 6. The charging was occasionally halted to check the magnet status and some field measurements at a constant power supply current. When the magnet was being energized, the power supply current was ramped at a constant rate of 0.01 A s⁻¹. At 207 A, axial fields along the magnet axis were measured using a Hall sensor, which agreed well with the calculated ones (figure 7). When the center field reached 26.4 T at a power supply current of 242 A, 2.5 mV was measured as the terminal voltage of DP18 (figure 3(b)), the topmost DP coil of the M1 stack wound with 4.1 mm tapes, and then the magnet was discharged; with a 0.1 μV cm⁻¹ criterion, the critical voltage of DP18 wound with 297 m long GdBCO tapes (table 2) was calculated to be 3 mV. At 26.4 T, the overall terminal voltage of the magnet was measured to be 12 mV, smaller than the critical voltage of the magnet, 81 mV with the 0.1 μV cm⁻¹ criterion, wound with a total of 8.1 km GdBCO tapes. The peak magnetic hoop stress at 26.4 T was estimated to be 286 MPa, half of the 95% Iᵣ retention stress of the GdBCO tape, 550 MPa, at 77 K [16–18]. For the hoop stress estimation, the coil current density of each DP, summarized in table 2, was obtained from the power supply current divided by each DP cross-section.
4. Discussion

4.1. Record high field in all-HTS magnet

26.4 T is a record high in magnetic fields from all-HTS magnets. In 2011, Trociewitz, et al, with the National High Magnetic Field Laboratory, reported a 35.4 T field generated by a 4.4 T REBCO insert placed in a cold bore of a 31 T background magnet [31].

4.2. Compactness of the magnet

At 26.4 T, the current density of the M1 DP coils, wound with the narrowest (4.1 mm) GdBCO tapes and placed at and near the magnet center, was 404 A mm$^{-2}$, significantly larger than that of the conventional insulated HTS magnets, typically <200 A mm$^{-2}$ at 4.2 K. As a result, the magnet is highly compact; the overall magnet diameter and height are 172 and 327 mm, respectively.
Figure 6. Test results in LHe at 4.2 K. Ramping was occasionally halted to check the magnet status. The axial field mapping was done at a power supply current of 207 A. The magnet reached 26.4 T at a power supply current of 242 A.

Figure 7. Axial fields along the magnet axis. The graph shows that the measured field profiles (circles) coincide with the calculated ones (triangles).

4.3. Charging delay and average surface contact resistance ($R_{ct}$)

The charging delay of an NI magnet may be characterized by a charging time constant, $\tau_c = L/R_{ct}$, where $L$ and $R_{ct}$ are the respective inductance and characteristic resistance of the NI magnet [25]. The average surface contact resistance, $R_{ct}$ (MKS unit: $\Omega$ m$^2$), is a key parameter to determine $R_c$ of an NI magnet, essentially a sum of the turn-to-turn contact resistance of each turn divided by its contact surface area [25, 26]. $R_{ct}$ of the 26 T magnet was measured to be 9.6 $\mu$Ω cm$^2$, while ~70 $\mu$Ω cm$^2$ was reported previously with small-scale REBCO NI test coils [25]. This ‘broad’ range of $R_{ct}$ and the consequent difficulty in the charging time estimation are one of the major challenges for design of an NI magnet.

5. Conclusion

A 26 T 35 mm winding diameter all-REBCO magnet was designed, constructed, and successfully operated. With the NI MW winding technique incorporated, the magnet consisted of 26 DP coils wound with REBCO tapes of five different widths—4.1, 5.1, 6.1, 7.1, and 8.1 mm. The average DP–DP joint contact resistance was measured to be 190 nΩ cm$^2$ in LN$_2$ at 77 K and 160 nΩ cm$^2$ in LHe at 4.2 K. Each DP has an average of 4 spool-to-spool splices, of which the total resistance was measured to be 1.6 $\mu$Ω in LHe. Due to the intrinsic NI charging delay, the magnet charging time constant of 947 s was measured in LN$_2$ at 77 K, which corresponds to an average surface contact resistance ($R_{ct}$) of 9.6 $\mu$Ω cm$^2$. The magnet generated 26.4 T at a power supply current of 242 A, a record high in magnetic fields from all-HTS magnets. At 26.4 T, the coil current density of the central DP coils wound with the narrowest 4.1 mm GdBCO tapes was 404 A mm$^{-2}$, significantly larger than that of the conventional insulated HTS magnets, typically <200 A mm$^{-2}$ at 4.2 K. As a result, the magnet is highly compact; the overall magnet diameter and height are 172 and 327 mm, respectively. The results show a strong potential of the MW-NI REBCO magnet for future high-field DC magnets, yet more researches are required, particularly on the charging delay issues.

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