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Thermal and Electrical Stabilities of Solid Nitrogen (SN₂) Cooled YBCO Coated Conductors for HTS Magnet Applications

J. B. Song, K. J. Kim, K. L. Kim, J. H. Lee, H. M. Kim, G. H. Lee, H. M. Chang, D. K. Park, T. K. Ko, and H. G. Lee

Abstract—Recently, a cooling system using a solid cryogen such as solid nitrogen (SN₂), was introduced for high temperature superconducting (HTS) magnet applications. In order to apply the SN₂ cooling system successfully to HTS applications, it is essential to obtain sufficient data regarding the characteristics of the SN₂-cooled YBCO-coated conductor (CC), including the thermal and electrical properties. Therefore, this study examined the effect of SN₂ on the thermal/electrical stability of YBCO CC tape. The SN₂ was produced by conduction cooling using a GM-cryocooler and cooled to 58 K. The voltages and temperatures of the YBCO CC tapes were measured while applying an over-current. The results showed that the thermal and electrical stability of the YBCO CC tape were improved considerably in the SN₂ cooling system compared to that in the conduction cooling system.

Index Terms—Over-current, solid nitrogen (SN₂), thermal/electrical stability, YBCO coated conductor (CC).

I. INTRODUCTION

HIGH- T_c superconducting (HTS) tapes are used widely in superconducting magnet applications, such as superconducting magnetic energy storage (SMES), motors, transformers, and inset coils for high-field nuclear magnetic resonance (NMR) magnets. In particular, the YBCO-coated conductor (CC), which is the second generation (2G) HTS tape, is one of the most attractive superconducting materials on account of its higher current density and better mechanical properties than those of the first generation (1G) HTS tape (i.e. BSCCO tapes). Therefore, the fabrication of HTS magnets using YBCO CC tape promises significant efficiency gains.

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In general, a cooling system for a HTS magnet is operated below 30 K, because the current transport characteristics of the HTS tape and its magnetic field dependency are improved by reducing the temperature. For this reason, considerable R&D on HTS magnet applications have been carried out by conduction cooling using a cryocooler which can easily cool down to ~ 10 K. However, in the case of a conduction cooling system, the thermal stability of the HTS magnet is poor against thermal or electrical disturbances. Solid nitrogen (SN₂) as a heat capacitor in the temperature range of 4.2 and 63 K may be an alternative choice for enhancing the thermal stability of HTS magnets under transient heating [1], [2]. In particular, since the enormous heat capacity of SN₂ enables the superconductor to maintain its temperature for a certain period without active cooling, the system can be designed to be either stand-alone or portable for a limited but reasonably long duration [3].

In recent years, pioneering studies have been carried out in the Francis Bitter Magnet Laboratory (FBML) at MIT and Kyoto University to evaluate the thermal stability of SN₂-cooled low temperature superconductors (LTS), YBCO bulks, and BSCCO tapes [4]–[7]. However, the stability of SN₂-cooled YBCO CC tape also needs to be examined before an optimal SN₂ cooling system can be developed for HTS magnet applications. Therefore, this study examined the thermal and electrical characteristics of the YBCO CC tapes in both SN₂ and conduction cooling systems through quench/recovery tests in order to confirm the cooling effects of SN₂ on the YBCO CC tapes, and compared them with the conduction cooling system. Furthermore, the thermal contact problem (i.e., dry-out phenomenon) between SN₂ and the YBCO CC tape was examined by repetitive quench/recovery tests.

II. EXPERIMENT DETAILS

A. Test Samples

In order to investigate the thermal stability of YBCO CC tapes in both SN₂ cooling and conduction cooling systems, YBCO CC tapes were prepared with a brass stabilizer (4 mm in width and 160 mm in length), which was manufactured by the American Superconductor Corporation (AMSC). The self-field critical currents (I_C) of the YBCO CC tape were measured at various temperatures < 77 K using the $1 \mu\text{V}/\text{cm}$ criterion. The distance between the voltage taps attached to each tape was 12 cm for the critical current measurement and quench/recovery tests. The resistance of the samples was measured using a four point probe while they were being cooling from 300 K to 60 K. The final approach temperatures were estimated from the results of

TABLE I
SPECIFICATIONS OF THE YBCO CC TAPE

Parameters	Specifications
Stabilizer	Brass
Length [mm]	160
Width [mm]	4
Thickness of YBCO CC tape [mm]	0.4
Thickness of stabilizer - both side [μm]	300
Thickness of YBCO Layer [μm]	1
Attachment of stabilizer	Soldering (PbSn)

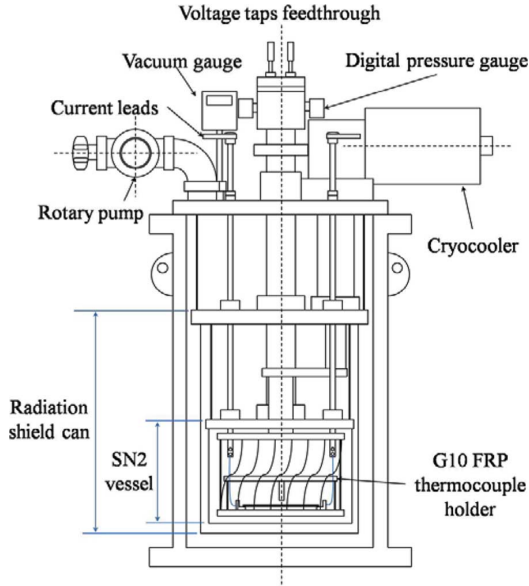


Fig. 1. Schematic drawing of the SN2 cooling system.

these R-T curves. Table I lists the specifications of the YBCO CC tape.

B. Solid Nitrogen (SN2) Cooling System

Fig. 1 shows a schematic diagram of a cross section of the SN2 cooling system. The SN2 cooling system consisted of a SN2 vessel, a radiation shield, two feedthroughs for the thermocouples and voltage taps, six current lead ports, one digital vacuum gauge, two digital pressure gauges and a two-stage GM cryocooler.

Fig. 2 shows a photograph of the sample holder in the SN2 cooling system. To improve thermal contact between the YBCO CC tape and bottom copper plate, thermal grease (N-grease) was spread onto each contact surface. The bottom copper plate was thermally connected to cold head of the cryocooler with oxygen free high thermal conductivity copper (OFHC) wires. The temperature variations during the quench/recovery tests were measured by E-type thermocouples, which were attached on the YBCO CC tape, bottom copper plate, cold head, and a thermocouple holder over the YBCO CC tape.

The SN2 vessel was sealed with aluminum wire and pre-cooled until the temperature reached 77 K, and then filled with LN2. In order to produce compact SN2 inside the vessel, the LN2 was solidified slowly to its operating temperature of 58 K using a GM cryocooler.

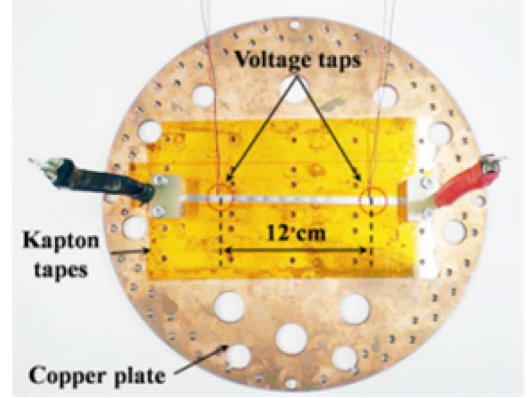


Fig. 2. Photograph of the sample holder in the SN2 cooling system.

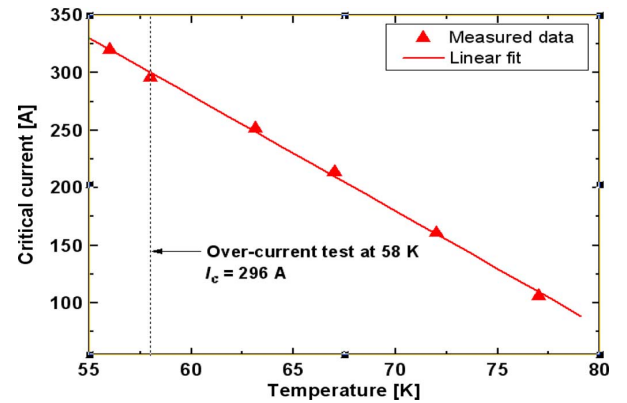


Fig. 3. I_C of the YBCO CC tape as a function of temperature.

C. Quench/Recovery Test

The quench/recovery tests were carried out at 58 K to compare the quench/recovery characteristics of the YBCO CC tape in both SN2 and conduction cooling systems. Three steps of the current pulse were applied to the YBCO CC tape in the following sequence: 1) operating currents (I_{op}) of 0.5 and 0.7 I_C (77 K) for 5 s, 2) over-current pulses (I_{over}) of 400 and 425 A for 0.5 s, and 3) I_{op} again for a few seconds until the YBCO had recovered completely. In addition, quench/recovery tests were repeated 10 times to discuss the change in thermal contact between the SN2 and YBCO CC tape. These were carried out at intervals with sufficient time so that after the tests, the temperature on the YBCO CC tape returned completely to its initial temperature (i.e., 58 K).

III. RESULTS AND DISCUSSION

Fig. 3 shows the measured I_C of the YBCO CC tape as a function of temperature. As expected, I_C increased linearly with decreasing temperature decreased from 77 to 56 K. The I_C values measured at 77 and 58 K were 108 and 296 A, respectively.

Fig. 4 shows the resistance of the YBCO CC tape as a function of temperature. The resistance per unit length of the YBCO CC tape at 300 K was 0.4 m Ω /cm.

Fig. 5 shows the voltage $V(t)$ traces of the YBCO CC tape measured at 58 K, and $I_{op} = 54$ A and $I_{over} = 400$ and 425 A in both the SN2 and conduction cooling systems. At $I_{over} = 400$ A, the peak joule heating flux (q_{peak}) measured in the SN2 ($V(t)$ traces 1) and conduction cooling system ($V(t)$ traces 2) were 60.7 and 60.8 W/cm², respectively. Although

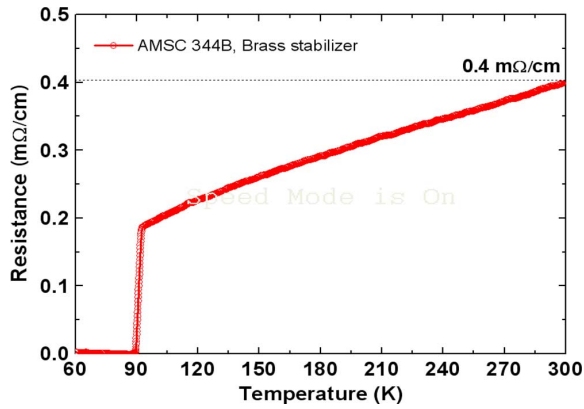


Fig. 4. Resistance of the YBCO CC tape as a function of temperature.

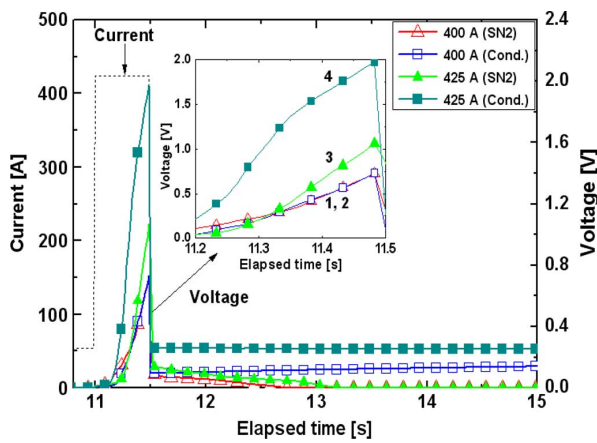


Fig. 5. Quench/recovery test results at $I_{op} = 54$ A, $I_{over} = 400$ and 425 A (at 58 K) in both SN2 and conduction cooling systems.

these two values were similar, the sample in the SN2 cooling system recovered fully within 1 s, whereas the $V(t)$ trace curve of the conduction cooling system increased gradually with time, which indicates that sample had not recovered even after the test was finished. At $I_{over} = 425$ A, the q_{peak} of the SN2 cooling system (94.4 W/cm²) was much smaller than that in the conduction cooling system (174.9 W/cm²). In addition, the SN2 cooled sample had fully recovered within 2 s, whereas the conduction cooled sample did not. Furthermore, the maximum resistance per unit length of the YBCO CC tapes in the SN2 and conduction cooling systems were 0.21 and 0.39 mΩ/cm, which corresponds to final approach temperatures of 109 and 288 K, respectively (see Fig. 4). These results can be explained by the YBCO CC tape in the SN2 cooling system being more stable against a thermal disturbance than in the conduction cooling system.

Fig. 6 shows the repetitive quench/recovery test results measured at $I_{op} = 54$ A and $I_{over} = 400$ A in both the SN2 and conduction cooling systems (at 58 K). In the case of the SN2 cooling system, the q_{peak} values were almost equal to 65.6 W/cm² until the 8th quench/recovery test, as shown in Fig. 6(a). The value of q_{peak} in the 9th and 10th quench/recovery tests increased slightly to 69.8 and 72.1 W/cm², respectively.

In the case of the conduction cooling system, the q_{peak} values (61.6 W/cm²) were similar to those in the SN2 cooling system (65.6 W/cm²) until the 6th quench/recovery test, whereas after the 7th quench/recovery test, the q_{peak} increased abruptly and

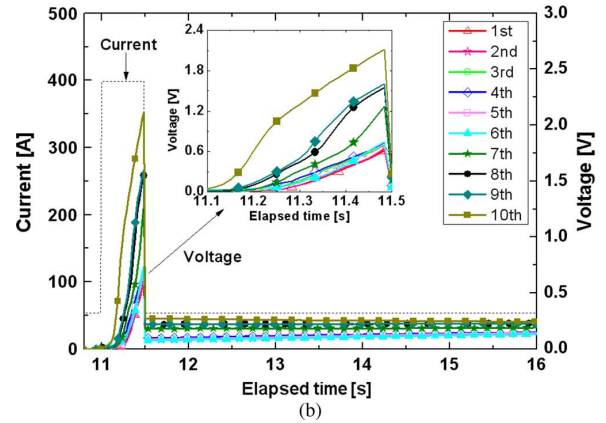
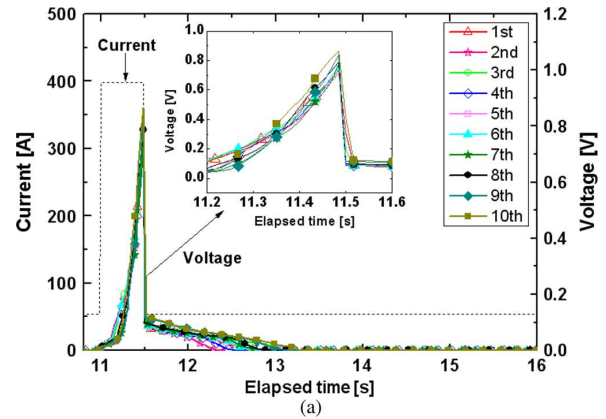


Fig. 6. Repetitive quench/recovery test results at $I_{op} = 54$ A and $I_{over} = 400$ A (at 58 K) in both SN2 (a) and conduction cooling systems (b).

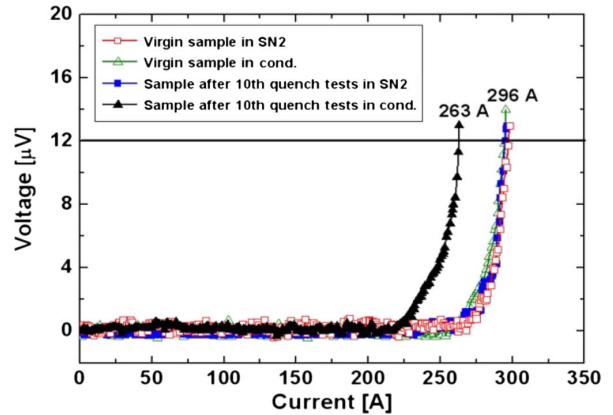


Fig. 7. $V-I$ curves of the virgin sample and the samples after the 10th quench/recovery tests at 58 K in both SN2 and conduction cooling systems.

reached 176.5 W/cm² at the 10th test. In addition, the recovery times for all samples in the SN2 cooling system were < 2 s [see Fig. 6(a)], while those in the conduction cooling system did not recover completely [see Fig. 6(b)].

Fig. 7 shows the $V-I$ curves of the YBCO CC tape before and after the repetitive quench/recovery tests in the SN2 and conduction cooling systems. The I_C value of the YBCO CC tape after the 10th quench/recovery test in the SN2 cooling system was 294 A, which is similar to that of the virgin YBCO CC tape (296 A). However, in the case of the conduction cooling system, the I_C value of the YBCO CC tape after the 10th quench/recovery test was 11.1% lower (263 A) than that of the virgin YBCO CC tape. This shows that the YBCO CC tape in the SN2 cooling

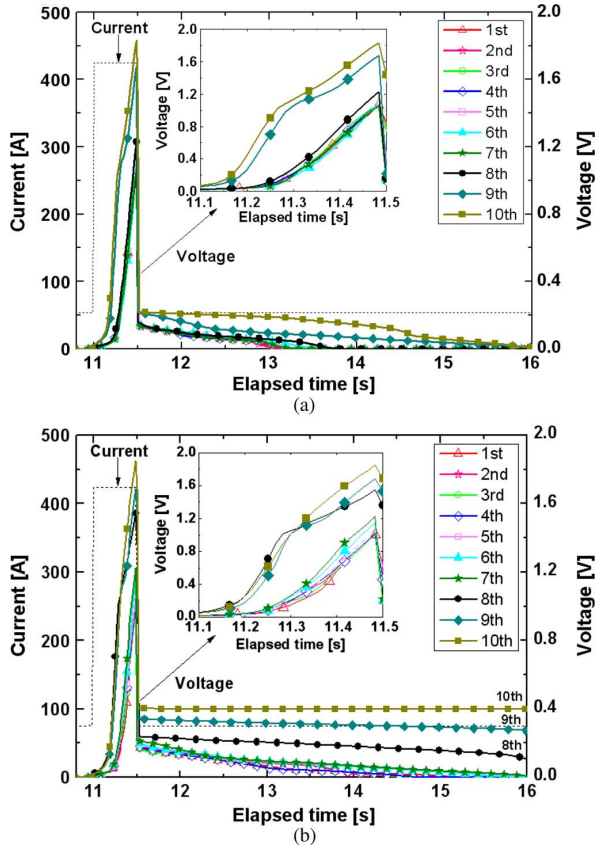


Fig. 8. Repetitive quench/recovery test results at $I_{over} = 425$ A and $I_{op} = 54$ A (a) and 76 A (b) in the SN2 cooling system (at 58 K).

TABLE II
RECOVERY TIMES WITH RESPECT TO THE NUMBER OF QUENCH/RECOVERY TESTS AT 58 K AND $I_{over} = 425$ A

I_{op} [A]	Recovery time [s]									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
54	1.8	1.7	1.8	1.8	1.9	2.1	1.8	2.2	4.8	4.8
76	3.3	3.3	3.1	3.3	3.4	4.5	4.8	-	-	-

system remained undamaged even after the 10th quench test, indicating that the SN2 cooling effect enables the YBCO CC tape to remain stable even in the event of a repetitive transient current.

The change in thermal contact between SN2 and the YBCO CC tape in the SN2 cooling system was examined by performing the repetitive quench/recovery tests at $I_{over} = 425$ A and $I_{op} = 54$ and 76 A. Fig. 8 shows the repetitive quench/recovery test results performed at 58 K. Table II summarizes the recovery times extracted from these results.

As shown in Fig. 8(a) and Table II, at $I_{op} = 54$ A, the values of q_{peak} (94.1 W/cm²) until after the 7th quench/recovery test were almost equal, and the recovery times were < 2.2 s. However, the value of q_{peak} after the 9th quench/recovery test increased abruptly to 148.7 W/cm², and the recovery time (4.8 s) also increased 2.2 times until the 8th quench/recovery test. At $I_{op} = 76$ A [see Fig. 8(b)], the q_{peak} values (92.5 W/cm²) were also similar until after the 5th quench/recovery test, and the recovery times were <3.5 s. After the 6th test,

the q_{peak} value (101.7 W/cm²) and recovery time (4.8 s) increased slightly until the 8th quench/recovery test, after which it increased abruptly to 136.8 W/cm². The sample did not recover completely even after the test was complete. These results suggest that, at $q_{peak} > 90$ W/cm², thermal contact between the SN2 and YBCO CC tape worsens gradually and they become separated at the inter-surface (i.e., dry-out phenomenon), which causes the YBCO CC tape to recover more slowly and finally run away [8]. In the case of $I_{op} = 54$ A, the YBCO CC tape recovered completely during the repetitive quench/recovery tests because relative small I_{op} was not enough to cause the SN2 to dry-out, or delayed the time for drying-out to occur.

IV. CONCLUSION

This study examined the thermal/electrical stabilities of YBCO CC tapes subjected to an over-current pulse in both conduction and SN2 cooling systems for HTS magnet applications. The thermal/electrical performance of the YBCO CC tape was enhanced in the SN2 cooling system compared to that in the conduction cooling system. The repetitive quench/recovery tests confirmed that the YBCO CC tape was more stable in the SN2 cooling system than in the conduction cooling system due to the SN2 cooling effect. In the case of the SN2 cooling system, the YBCO CC tape was stable under repetitive quenching with a q_{peak} value $< \sim 90$ W/cm². On the other hand, repetitive quenching with those > 90 W/cm² worsened the thermal contact between the SN2 and YBCO CC tape, which resulted in a ‘dry-out’ problem. Future studies should examine the thermal/electrical properties of SN2-cooled YBCO CC tapes with various stabilizers because YBCO CC tapes with various materials as a stabilizer might exhibit different thermal/electrical behaviors.

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