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Spontaneous Quenches of a High Temperature Superconducting Pancake Coil

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Abstract — A double-pancake coil made of Bi-2223/Ag high temperature superconducting (HTS) tape was constructed with an embedded heater and graded conductors to study the stability and quench propagation in HTS coils. The experiments were performed with liquid nitrogen and gaseous helium cooling in temperatures ranging from 5 to 77 K. The coil was very stable, and no "normal" zone was sustained or propagated with local pulsed heating. However, spontaneous quenches of the coil were experienced. This was found to be the result of having the coil current higher than that of the lower I_c sections of the coil for a long time. This quench process took minutes to develop — much longer than would be expected in a low temperature superconducting coil. The quench behaved more like a spreading and continuous heating of an increasingly larger partially resistive section of the coil than like a sequential "normal" front propagation.

I. INTRODUCTION

As an ongoing effort to develop high temperature superconducting (HTS) coils for power applications, a double-pancake coil made of Bi-2223/Ag tape was constructed to study the stability and quench propagation in HTS coils. An embedded heater inside the winding and voltage taps on successive turns surrounding the heater were used for these experiments.

Since the current-carrying capability of a superconductor is a function of magnetic field, a common practice is to grade the conductor in a low temperature superconducting (LTS) coil so that fewer superconductors are used in lower field sections of a coil. Because HTS tapes are still very expensive to make, it would be advantageous if a similar grading technique can be used in a HTS coil. This task was attempted in the current work by winding a two-tape conductor bundle for the inner turns and grading to a single-tape conductor for the outer turns of the coil. This approach also provided built-in lower I_c sections to study the effect on the quench protection of an HTS coil of the often seen nonuniform HTS tapes in long lengths.¹

II. COIL CONSTRUCTION AND INSTRUMENTATION

The double-pancake coil was built with Bi-2223/Ag tape made by a metallic precursor process.² The 0.16-mm thick by 5.33-mm

wide tape was reacted before winding onto a 25.4-mm bobbin. A continuous 22-m length of a 2-tape conductor bundle was used to wind the inner 70 turns on each pie of the double-pancake. It was then graded to a 1-tape conductor, and another 32 turns (8-m long) were wound for the rest of each of the pies. Thus, the total length of the conductor for the double-pancake was 38 m. The turns were insulated with 0.0635-mm thick, epoxy impregnated paper. The finished double-pancake has a winding OD of 87 mm.

Fig. 1 shows the instrumentation used to study the stability and quench behavior of the coil. A 51-mm long (5 Ω) foil heater was sandwiched between the 2-tape conductor bundle at the crossover section of the two pancakes. Voltage taps (QA1 - QA5 and QB1 - QB3) on the successive turns next to the heater were applied to monitor the "normal" voltages of the conductor. The length of the crossover section QA1-QB1 is 243 mm and that between successive turns is about 84 mm each. The entire winding was enclosed in a G-10 casing.

III. STABILITY MEASUREMENTS

Stability of the coil was measured in LN₂ at 77 K and with helium gas cooling at 20 to 40 K in a variable temperature cryostat. The coil was charged to a specified current and held while a heating pulse was applied to the resistive heater and the voltages surrounding the heated zone were monitored. Fig. 2 shows an example of the conductor voltage responses for a shot at 20 K with the coil current held at 40 A. The heated zone QA1-QB1 voltage went up to 3.3 mV (as compared to 0.024 mV @ I_c , defined by the 1- μ V/cm criterion) during the heating and disappeared in less than 1 s after the heat was removed. The voltage over QA5-QB3, which covered several additional turns, showed

Fig. 1 The double-pancake coil and its instrumentation layout. Voltage taps for the stability measurements were labeled with "Q" and at the grading points were labeled with "G".

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B. Delayed Quench at a Given Current

The preceding observation seems to indicate that if an HTS coil is charged and held for a sufficiently long time at a current higher than the critical currents of weak spots, a quench could develop. This thought is investigated further during this series of experiments. Fig. 5(a) shows the coil current and voltage traces for a test run at 6 K. The coil was charged to 50 A in about 210 s and held at that current. According to Fig. 4, this current is lower than the critical current of the inner turns but higher than that of the outer turns of 1-tape conductor. Little coil voltage change was seen for the next 160 s. Then it increased rapidly, reaching a level of about 5.5 V in another 15 s. The coil current dropped to about 20 A at the same time. No operator action was taken during this period of time. The coil quenched spontaneously and its voltage rise was limited only by the 6-V power supply compliance limitation. This action caused the coil voltage to stop at 5.7 V and the coil current to drop. Manual discharge of the coil was finally implemented after 530 s.

Fig. 5 Coil current, voltage, and temperature traces of a current charge that started at a coil temperature of 6 K. Thermometer T_0 is located at the ID of the coil, and T_1 is located at the grading point.

Fig. 5(b) shows the thermometer readings of the coil. A small and steady temperature rise (about 0.15 K/s) was seen on both thermometers after the current reached 50 A. Surprisingly, only a very small temperature difference existed between the ID and the grading point of the coil. The temperature at the grading point, T_1 , was about 8 K higher than that at ID T_0 by 370 s, the time at which the coil voltage began to rise sharply. The average coil temperature was then about 35 K. At this temperature, the coil current had far exceeded the critical current of even the inner 2-tape conductor turns. The coil temperature also began to rise sharply at this time. Thus, we saw a gradual temperature rise followed by a rapid voltage and temperature rise of the coil when it quenched. Maximum temperatures of 188 K at the ID and of 168 K at the grading point were recorded. The poorer cooling condition at the ID was probably the main reason for the higher temperature that was reached there after the coil quenched. Note that the coil temperature continued to rise rapidly even after the current had dropped below 20 A — a result of the 110 W of heating still generated in the coil at this current.

Similar delayed quench behavior were observed at other test runs with coil starting temperatures ranging from 20 to 77 K.

C. Quench Development

To find out the source of the heat and the nature of the quench, let us examine the voltage signals of different sections of the coil. Fig. 6(a) shows the voltage excursions of the five different sections of the coil. At about 150 s, when the coil current reached 38 A, voltages on the two 1-tape conductor sections, (+)-GA and GB-(-), began to increase. They continued to increase after the current reached and was held at 50 A. The rate of increase accelerated with time. The voltages of these two sections saturated the amplifier at 0.1 V at about 350 s. No noticeable voltages were seen in the 2-tape conductor sections (GA-QA5, QA5-QB3, and QB3-GB) during this time. Thus, up to this point the temperature rise of the coil shown in Fig. 5(b) was due entirely to the joule heating in the 1-tape conductor sections. Apparently, the heat had been spread throughout the whole coil. Assuming that the joule heating of the 1-tape section was adiabatically and radially (neglecting the much longer path along the conductor) conducted toward the ID, the temperature difference observed in Fig. 5(b) between T_1 and T_0 indicated an effective radial thermal conductivity of about 0.3 W/cm-K for the current winding pack, which is about 1/10 of that for silver at this temperature range.

The 2-tape conductor sections began to show appreciable voltages only at about 350 s, after the coil temperature had reached 30 K. The voltage increase accelerated and the coil was quenched shortly. When the coil voltage reached the power supply compliance limit, the current started to decrease and the inductive voltage dipped at 385 s. We saw no distinctive and successive propagation of the "normal" front from the 1-tape section to the 2-tape section in this quench development process.

Fig. 2 Conductor voltage responses to a heating pulse at 20 K with the coil current holding at 40 A. Coil current was discharged at 13 s.

that a small voltage that expanded to the adjacent turns also disappeared after the heat was removed. The negative voltages at 13-13.5 s was due to the inductive voltage when the coil current was discharged. In all of the pulse heating shots, no resistive voltage was sustained or expanded with up to 18 J of heating applied in up to 0.6 s. Thus, the coil was stable against local heating of more than 200 J/cm^3 — 2 to 3 orders of magnitude higher than in a LTS coil. This result is similar to that measured and reported in more detail on a 1-T HTS magnet.³

IV. SPONTANEOUS QUENCHES

The coil, however, experienced spontaneous quenches, first unexpectedly in a critical current measurement at 20 K. During this series of experiments, only the voltages near the inner turns, which received the highest self-fields, were being monitored (and because T_0 was broken at the time, the temperature was monitored

Fig. 3 Coil current and inner turns voltage traces in an I_c measurement at 20 K. The coil suffered a spontaneous quench at 46 A, after it was charged to 48 A.

by a thermometer attached to the outside of the coil case). Fig. 3 shows that the coil was charged to 48 A in about 420 s and developed $260 \mu\text{V}$ in section QA5-QB3 (as compared to $75 \mu\text{V}$ @ I_c for this section). When the current was being ramped down to about 46 A, it dropped sharply and the voltage went negative. The coil had quenched spontaneously. Also the voltage in section QA5-QB3 was decreasing smoothly before the quench. Thus, the quench did not start from the inner high field turns. Then, the quench was thought to originate from the 1-tape conductor section. Similar spontaneous quenches were experienced at other temperatures from 5 to 40 K.

V. INVESTIGATION OF THE QUENCH BEHAVIOR

Additional voltage taps, GA and GB, were added to the conductor grading points of the double pancake. As is shown in Fig. 1, an RO_2 -thermometer was placed at the winding ID (T_0), and another one (T_1) was added at the grading point of the lower pie. A second series of experiments was performed to pinpoint the source of the spontaneous quench and to investigate the quench propagation behavior of the coil.

A. Critical Currents

Since the coil generates significant self-fields (64 G/A at the ID) and there is conductor grading, the critical current of the conductor can be quite different at different sections of the coil. Using the $1\text{-}\mu\text{V/cm}$ criterion, the critical currents of the coil, the inner-turns section, QA5-QB3, and the 1-tape conductor section of the lower pie, (+)-GA, were measured and plotted in Fig. 4 as a function of temperature. Although the inner turns conductor had 2-tape thickness, because of the higher self-field, its I_c was only 40% to 50 % higher than the outer turns. In the run that led to a spontaneous quench, shown in Fig. 3, the coil was charged above the I_c of both (+)-GA (32 A) and QA5-QB3 (44 A), although it stayed much longer above the I_c of (+)-GA.

Fig. 4 Critical currents of different sections of the coil and the whole coil as a function of temperature determined by the $1 \mu\text{V/cm}$ criterion.

Fig. 6 Voltage excursions of the five different sections of the coil in the same test run as is shown in Fig. 5. The flat top of 0.1 V was due to amplifier saturation. Also shown in (b) is a closer look of the voltage over the innermost turn, QA1-QB1.

It has now been widely accepted that the resistive transition of an HTS conductor is very broad, i.e., the n -value in the V - I power law is very low (often less than 10).⁴ Thus, when an HTS conductor is charged above its I_c , it enters into a partially resistive state rather than a true normal state as in an LTS conductor. A significant amount of current remains in the HTS core instead of flowing out to the matrix. Therefore, the joule heating in a partially resistive "normal" zone in an HTS conductor is much reduced. As this heat was spread throughout the coil, it heated up and drove more conductors into a partially resistive state, although their voltages could be too small to be measured. Thus, the coil quench was developed through the spreading of the joule heat, creating more low-resistance, partially resistive zones, and accelerated when most of the coil was far into the partially resistive state.

Thus, the development of a quench from a "normal zone" in an HTS coil would be much slower than in an LTS coil. At the tested conductor current density of up to 3 kA/cm² (in the 2-tape

conductor bundle), it took about 3 min to develop. Note that in the current change shown in Fig. 3, the coil current was above the I_c of the 1-tape section for about 200 s before the coil quenched.

Although the current test coil has a built-in lower I_c (1-tape conductor) section, lower I_c sections are unavoidable in a superconducting coil. It exists at regions with intrinsically lower I_c in the conductor, at regions of higher field, or at regions where the field is predominantly perpendicular to the face of the HTS tape. As heat is generated in a "normal zone" and is conducted throughout the coil, one can expect other "normal zones" to nucleate. Fig. 6(b) shows that the innermost turn of the coil, QA1-QB1, also went into "normal" state 20 s after the single-tape outer turns section, (+)-GA. However, neither "normal" front made a distinctive propagation into the middle GA-QA5 section for the next 120 s.

VI. CONCLUSION

Stability and normal zone propagation experiments were performed on a double-pancake coil made of Bi-2223/Ag high temperature superconducting tape. The HTS coil was very stable against local pulse heating. As a matter of fact, no "normal" zone was sustained or propagated with up to 18 J of pulse heating.

However, spontaneous quenches of the coil occurred because the coil current was higher than that of the lower I_c sections of the coil for a sufficiently long time. No sequential and distinctive "normal" front propagation was observed in the quench developing process. Rather, the quench behaved more like a spreading and continuous heating of an increasingly larger partially resistive section of the coil than like a "normal" front propagation.

Because of the high stability margin, one can expect an HTS coil not to suffer quenches from sudden heat release of wire motion or epoxy cracking as is often seen in an LTS coil. However, a delayed quench not common in an LTS coil may develop in an HTS coil that has undetected local weak spots. At a conductor current density of up to 3 kA/cm², this process may take minutes to develop. Thus, a different quench detection technique and protection system may be needed for HTS coils.

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