QUENCH TESTS OF A 20-cm-LONG RABiTS YBCO TAPE

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ABSTRACT

A 20-cm-long YBCO tape fabricated by the Rolling Assisted Bi-axially Textured Substrate (RABiTS) technique was used to study the quench behavior of a second-generation high-temperature superconductor (HTS). Quench tests of the sample were performed in a conduction cooling condition with a cryocooler. The sample was subjected to a short overcurrent pulse to create normal zones, followed by a longer operating current up to the critical currents of the weaker zones of the tape. Distinctive normal zone propagation was observed for the first time on a YBCO tape. Propagation velocities of 1.4 to 8.3 mm/s were measured, which increase linearly with the current. Stability margins and a minimum propagation current were also observed. One-dimensional thermal modeling showed good agreement with the test results.

INTRODUCTION

High-temperature superconductors (HTSs) possess higher stability margins than low-temperature superconductors (LTSs). This primarily results from their higher critical temperatures and thus higher material specific heats at the higher operating temperatures. Stability margins on the order of 100 J/cm^3—2 to 3 orders of magnitude higher than LTS were measured on BSCCO-2223 HTS [1]. Normal zone propagation velocity on the order of only millimeters per second was predicted theoretically [2]. Delayed quenching without a distinctive normal-front propagation of an HTS coil made with this first-generation conductor was observed [3]. The development of a second-generation YBCO-coated conductor promises much higher critical current density while operating at higher magnetic

fields. A knowledge of whether similar stability margin and quench behavior exist in YBCO tape is essential for its use in superconducting magnets and power applications.

Preliminary quench tests were performed on several YBCO tapes fabricated by the Rolling Assisted Bi-axially Textured Substrate (RABiTS) technique [4]. The YBCO film was not coated with silver; only strips of silver film were provided for voltage contacts. The samples were tested in a liquid nitrogen bath. No normal zone propagation was observed. Negative transient voltages were also observed in several zones of the sample, indicating current paths to the nickel substrate and back to the YBCO. Thus, silver coating was requested to provide current shunts for weaker zones of the YBCO tape. Testing of a sample coated with 2 μm of silver showed no spurious negative voltages. Again no normal zone propagation or thermal runaway were observed when the test was performed in a liquid nitrogen bath. This sample and two others with silver coatings of up to 8 μm were also tested in a conduction-cooled condition to study the role of silver in the quench dynamics of the RABiTS-processed YBCO tapes [5]. This paper reports the quench tests of a new RABiTS YBCO tape that has significantly higher critical currents than the previous samples. Distinctive normal zone propagation was observed for the first time on a YBCO tape.

SAMPLE AND TEST PROCEDURE

The RABiTS YBCO sample tested has dimensions of 20 cm long by 1.25 cm wide. It has a nickel substrate of 50 μm, a CeO_2-YSZ barrier of 0.2 μm, a YBCO film thickness of 0.3 μm, and a silver coating of 1.5 μm, for a total thickness of about 52 μm. The sample was mounted between a Kapton-tape-insulated copper block and a G-10 block with nine bronze strips to monitor voltages of the sample in eight zones of 2-cm length. The two end zones 1 and 8 were also situated about 2 cm from the current leads.

The sample holder was affixed to the first-stage cold-head of a Cryomech GB-37 cryocooler for conduction cooling to about 54 K. TABLE 1 shows the measured critical current, I_c, distribution of 24 to 65 A for the eight different zones of the sample. It is clear that the sample has a weak spot in zone 5. The critical current density over the YBCO-film ranged from 0.64 to 1.7×10^6 A/cm^2.

Quench tests of the sample were performed with a short overcurrent pulse followed by a longer operating current. Because of the nonuniformity of the I_c of the sample, we expected an initial normal zone created at the weak spot to propagate to other zones of the sample. Overcurrent pulses of up to 72 A for up to 2 s were used to create the initial normal zone. This was followed by an operating current of up to 45 A for pulse lengths up to 30 s to monitor the recovery or quenching of the sample.

STABILITY MARGIN

By setting the operating current near the critical current of the weakest zone, the initial pulse energy was varied by changing the magnitude or the duration of the overcurrent

TABLE 1. Critical Current Distribution of the YBCO Sample

Zone	1	2	3	4	5	6	7	8
I_c (A)	30	53	43	42	24	44	65	60

pulse. Full recovery or quenching of the sample was observed with different initial pulses. FIGURE 1 shows that at an operating current of 30 A, the sample recovered from an initial pulse of 68 A for 1.75 s, but it had a propagating quench for a slightly longer 2-s pulse.

By integrating the VI product over the pulse time, one can find the initial heat input to each zone of the sample. In the shots shown in FIGURE 1, we found that the heat pulse to the weakest zone 5 was about 1 J for the 1.75-s pulse and 1.8 J for the 2-s pulse. Note that the voltage and thus the heat input increases rapidly after the zone voltage reached a certain level. Thus, a small increase in overcurrent or pulse duration can add significantly more input energy. The highest initial energy input that still led to full recovery of the sample was about 1 J in the present experiment. This is equivalent to 80 J/cm^3 over the whole conductor (including the nickel substrate). This energy would raise the conductor temperature to about 105 K adiabatically. Thus, similar to BSCCO, the YBCO conductor also has a stability margin on the order of 100 J/cm^3. It is stable against local heating that does not drive it above its critical temperature of about 80 K.

NORMAL ZONE PROPAGATION

Distinctive normal zone propagation from the weak spot of zone 5 to adjacent zones was measured at different operating currents.

Minimum Propagation Current

With an initial pulse higher than the stability margin, normal zone propagation was measured at different operating currents. A threshold operating current was found that no normal zone propagation was observed below that current, even if the initial pulse was increased substantially higher than the stability margin. FIGURE 2 shows that with an operating current of 15 A even the weakest zone recovered within 10 s after an overcurrent pulse of 72 A. The initial heat input to zone 5 in this shot was about 240 J/cm^3—more than twice the stability margin. This minimum propagation current of about 15 A corresponds to a current density of about 79 kA/cm^2 over the silver-coating cross section and about 2.3 kA/cm^2 over the whole sample cross section. The existence of a minimum propagation current implies that no distinctive normal zone propagation would be observed, if the I_c of the sample were lower than this current [5].

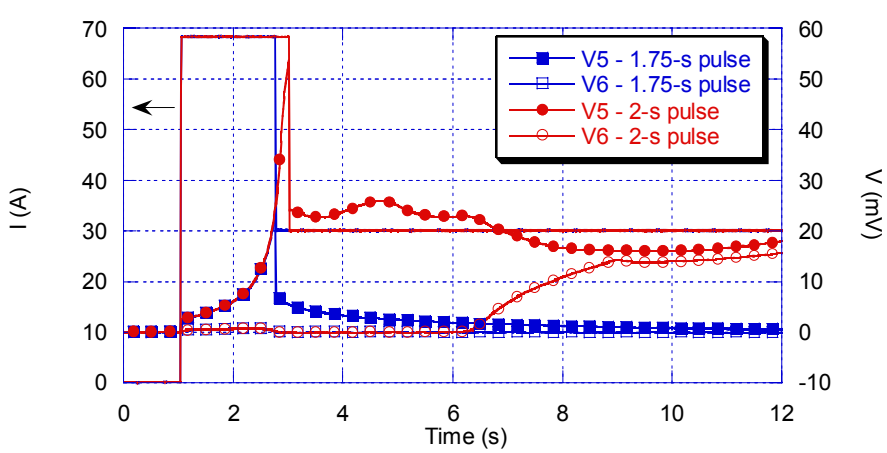

FIGURE 1. Full recovery was observed at a 68-A overcurrent pulse for 1.75 s and a quench propagation to adjacent zones for a 2-s pulse.

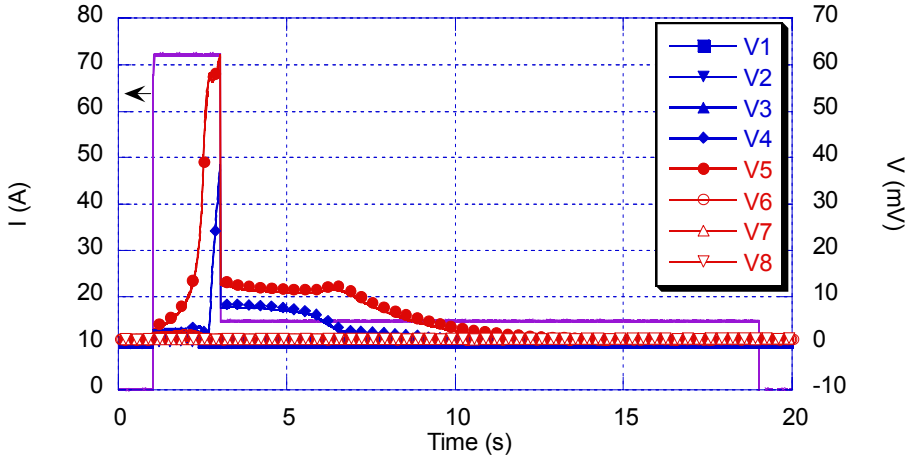

FIGURE 2. Full recovery was observed when the operating current was set at 15 A or lower.

Propagation Velocity

FIGURE 3 shows two examples of distinctive normal zone propagation of the sample at operating currents of (a) 20.5 A and (b) 30 A. The initial overcurrent was 72 A for 2 s in FIG. 3(a) and 68 A for 2 s in FIG. 3(b). For the 20.5-A shot, zones 4 and 5 stayed normal after the initial pulse and propagated through zones 6 and 7 on one side and zones 3

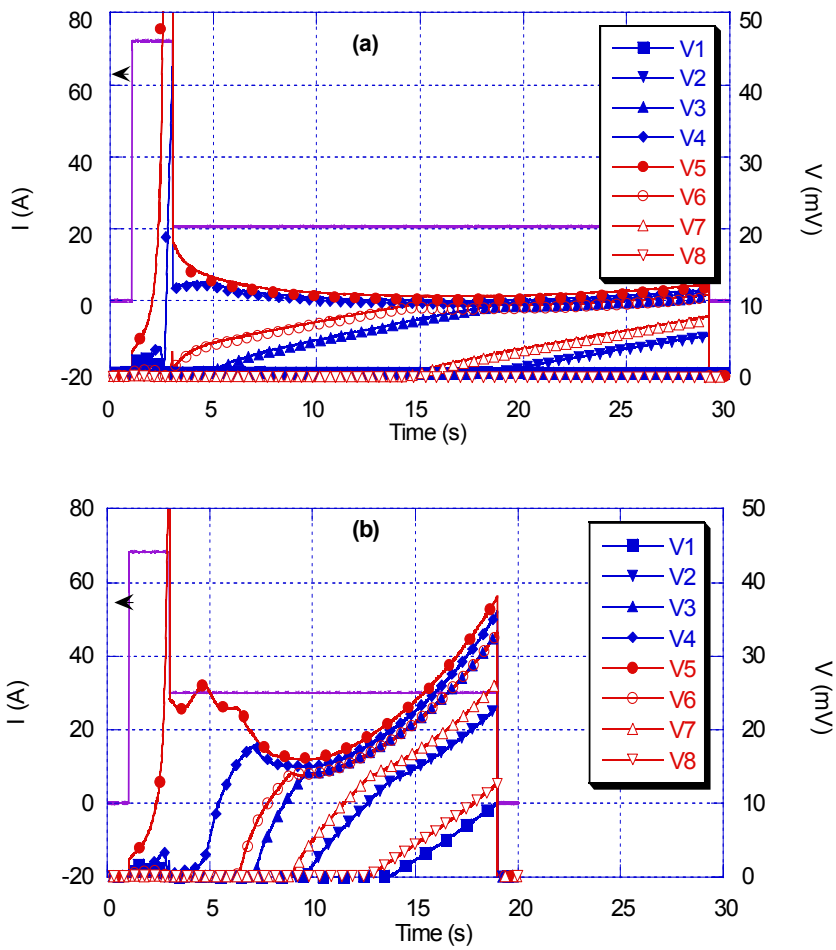

FIGURE 3. Normal zone propagation at operating currents of (a) 20.5 A and (b) 30 A.

and 2 on the other side. For the 30-A shot, which used a smaller initial overcurrent pulse, only zone 5 stayed normal after the pulse but propagated throughout all the zones on either side of this hot spot. Apparently the operating current dominates the dynamics of the normal zone propagation process. It is also noted these and other shots that away from the hot spot, the propagation velocity is insensitive to the initial heat pulse.

The propagation velocity, v, from one zone to the next was calculated by dividing the zone length of 20 mm by the time of flight of the normal front through that zone—the time between the start of rapid voltage rise of that zone and the next zone. Propagation velocities of 1.4 to 8.3 mm/s were measured for currents of up to 30 A. The results are shown in FIGURE 4. The velocities through the interior zones, $v6$, $v4$, and $v3$, follow a line, while those through the outer zones, $v2$ and $v7$, follow another line.

Comparison with the Adiabatic Theory

The YBCO sample was rested on a Kapton-tape-insulated copper block and was pressed by the bronze voltage strips from the top. The cooling condition approximates conduction cooling through the end lead connections only. The normal zone propagation velocity can be compared with that calculated by adiabatic theory [6]. Because a minimum propagation current, I_{mp}, existed in the experiment, the following equation for the propagation velocity is proposed:

$$\upsilon = \frac{\left(I - I_{mp}\right)}{A \cdot C_p} \cdot \left(\frac{k\rho}{\left(T_c - T_0\right)} \right)^{1/2} , \qquad (1)$$

where A is the cross-sectional area, C_p is the specific heat, k is the thermal conductivity, ρ is the resistivity, T_c is the critical temperature (80 K), and T_0 is the initial temperature of the sample. In the present experiment, the initial overcurrent pulse produced large heating in the weak zone and small but nonzero heating in other parts of the sample. An average T_0 of 65 K is chosen for the calculation. At this temperature the weighted values of the sample material properties were estimated to be C_p = 1.0 × 10^6 J/m^3-K, k = 370 W/m-K, and

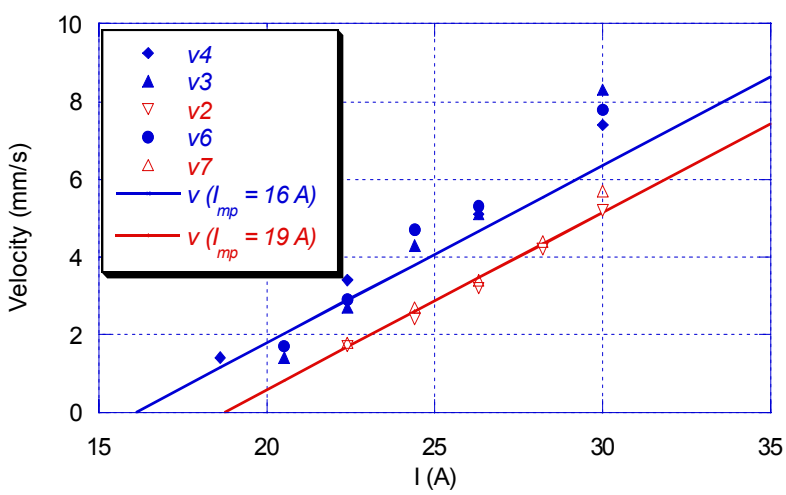

FIGURE 4. Measured normal zone propagation velocities as a function of current and the adiabatic theory calculations.

$\rho = 3.5 \times 10^{-9}$ Ω-m. With an I_{mp} of 16 A, very good agreement was found between the data of the interior zones and the modified adiabatic theory as shown in FIGURE 4. A slightly higher I_{mp} of 19 A also generates excellent agreement with the data of the outer zones. It is conceivable that the end conduction affected the outer zones and raised its minimum propagation current.

THERMAL ANALYSIS

The temperature history and profile of the sample during quench tests are valuable information. It was decided to use the resistance of the sample itself as the thermometer during the quenching of the sample. The resistance of the sample during the cooldown was measured and calibrated against a Cryogenic Linear Temperature Sensor (CLTS) thermometer. It was found that the resistance of the sample was equal to the parallel combination of the silver coating and the nickel substrate. They were shorted together and would share the current when the YBCO superconductor goes normal. Thus, the total cross section of silver and nickel was used in equation (1) to calculate the theoretical velocity and resulted in very good agreement with the data.

The resistance of the different zones of the sample vs the CLTS temperature between 100 to 200 K were fitted with linear equations. Assuming this calibration can be extended to the 60 K temperature range where the quench tests were taken, FIGURE 5 shows the temperature evolution of the different zones of the sample for the propagation shot at 30 A [FIG. 3(b)]. The initial overcurrent pulse heated the weak zone 5 to about 150 K. It was cooling down after the overcurrent pulse to about 120 K; but when the neighboring zones went normal, this zone and zone 4 heated above 200 K and toward a thermal runaway 15 s after the initial pulse. The temperatures of zones 1 and 8 that are only about 4 cm away were still lower than 100 K. Thus, the thermal conduction along the length of the sample was not sufficient to prevent localized heating. Burnout of a YBCO tape is a distinct possibility if there are weak zones in the conductor.

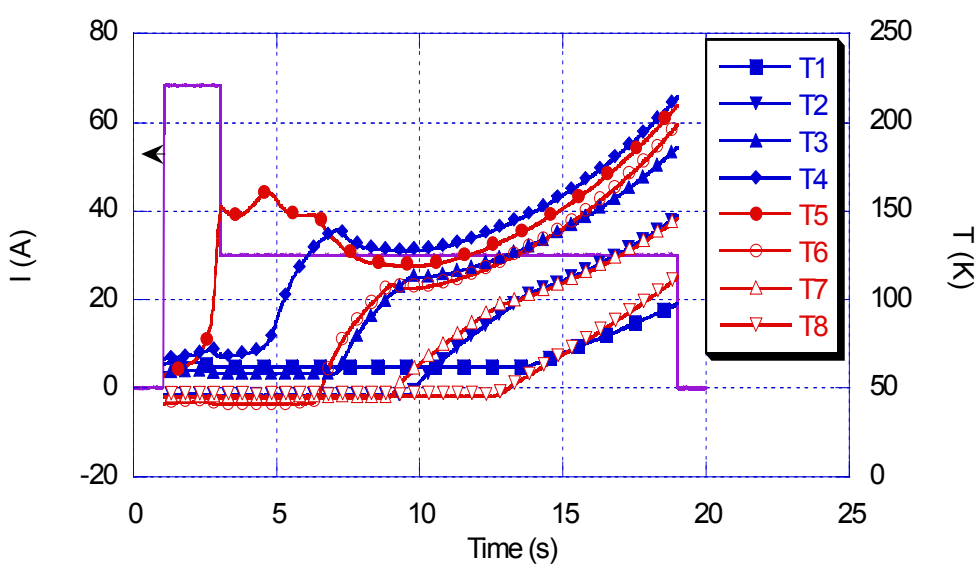

FIGURE 5. Temperature evolution of the different zones of the sample for the normal zone propagation at an operating current of 30 A [same shot as FIG. 3 (b)].

FINITE-ELEMENT MODELING

The experimental results presented above were modeled by a commercial finite-element (FE) code, FlexPDE, developed for the solution of partial differential equations (PDEs) [7]. It uses a Galerkin FE model with quadratic or cubic basis functions involving nodal values of the system variables.

The following time-dependent, nonlinear, one-dimensional PDE was solved:

$$C_p(T)\cdot\frac{dT}{dt}=\frac{d}{dx}\left(k(T)\cdot\frac{dT}{dx}\right)+\rho(T)\cdot J^2 \quad . \tag{2}$$

In this equation, the thermal conductivity k, specific heat C_p, and resistivity ρ are functions of the local temperature. A weighted average over the YBCO silver coating and nickel substrate was used for the thermal conductivity and specific heat. Additionally, a section of the tape has an enhanced resistivity around 12–13 cm (in zone 5 closer to zone 4) to simulate the lower critical current in this section as noted in TABLE 1. All the stability and quench phenomena such as stability margin, minimum propagation current, normal zone propagation, and thermal runaway can be predicted qualitatively by such FE modeling. Details of the analysis will be presented elsewhere. Two sample calculations are shown here.

The 20-cm-long YBCO tape was initially at ~50 K before the current pulse. The applied current waveform was 72 A for 2 s, followed by an operating current of 15 A for 16 s, corresponding to the shot shown in FIG. 2. FIGURE 6(a) shows the resulting voltage evolution at 1-cm intervals in response to this current waveform. It shows a full recovery, in good qualitative agreement with the data shown in FIG. 2.

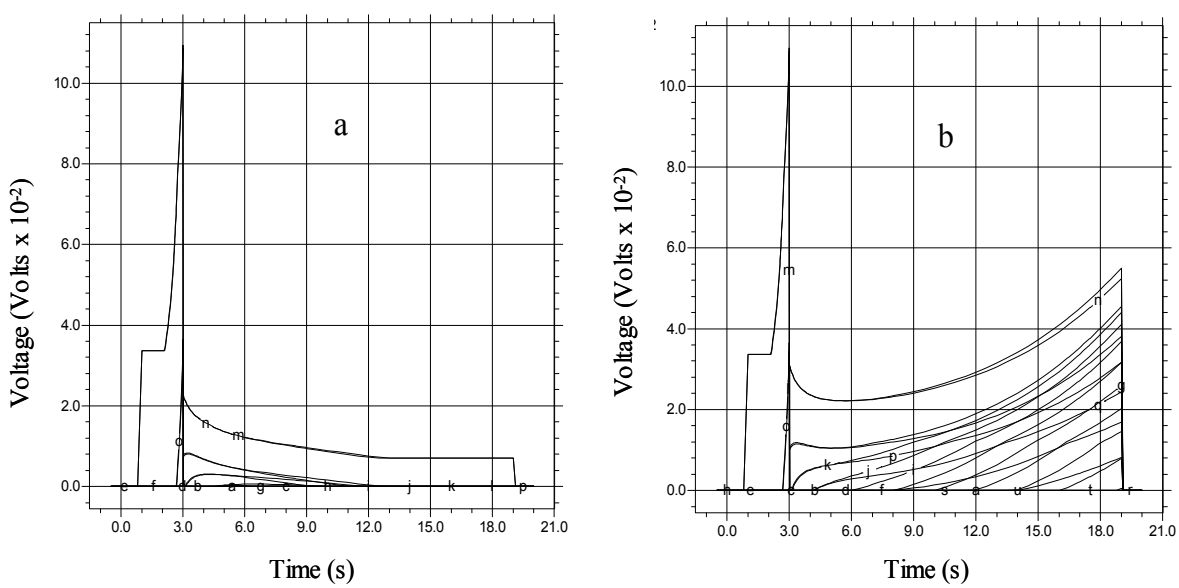

FIGURE 6. (a) Full recovery for input conditions of FIG. 2 and (b) normal zone propagation for conditions of FIG. 3(a).

FIGURE 6(b) shows the calculated voltage evolution for conditions of FIG. 3(a): a current waveform of 72 A for 2 s, followed by an operating current of 20.5 A for 16 s. Normal zone propagation is evident. It is again in good qualitative agreement with the data. In general, when normal zone propagation was observed in the experiment, the code also predicted normal zone propagation under the same test conditions.

CONCLUSION

Quench tests of a RABiTS YBCO superconductor were performed in a conduction cooling condition. Distinctive normal zone propagation was observed for the first time on a YBCO HTS tape. Stability margin and minimum propagation current were also observed. Normal zone propagation velocities of 1.4 to 8.3 mm/s were measured. The velocity increases linearly with the current, and it agrees quite well with a modified adiabatic theory that took into account the existence of a minimum propagation current. These low propagation velocities could result in local thermal runaway or burn-out of the HTS conductor. On the other hand, the stability margin of the YBCO tape was found to be very high, about 100 J/cm^3—similar to that of a BSCCO/silver HTS. It would be stable against any local heating that does not raise the conductor temperature above its critical temperature. One-dimensional finite-element thermal modeling showed good agreements with the test results. All the stability and quench phenomena observed in the experiment can be reproduced qualitatively by such analysis.

ACKNOWLEDGEMENT

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REFERENCES

1. Lue, J. W. et al., "Stability Measurements on a 1-T High Temperature Superconducting Magnet," *IEEE Trans. Applied Supercond*. **5**, pp. 230–233 (1995).
2. Dresner, L., "Stability and Protection of Ag/BSCCO Magnets Operated in the 20-40 K Range," *Cryogenics*, **33,** pp. 900–909 (1993).
3. Lue, J. W. et al., "Quenches in a High-Temperature Superconducting Tape and Pancake Coil," *Cryogenics*, **36,** pp. 379–389 (1996).
4. Goyal, A. et al., "Fabrication of Long Range, Biaxially Textured High Temperature Superconducting Tapes," *Appl. Phys. Letters*, **69**, pp. 1795–1798 (1996).
5. Duckworth, R. C. et al., "Quench Dynamics in Silver Coated YBCO Tapes," paper I-07A-03 presented at the 2001 CEC/ICMC joint Conference, Madison, Wisconsin, July 16–20, 2001.
6. Dresner, L., *Stability of Superconductors*, Plenum Publishing Corp. New York, 1995, pp. 110–113.
7. Backstrom, G., *Fields of Physics by Finite Element Analysis*, GB Publishing, Malmo, Sweden, 2000, pp. 198–206.