Quench Experiments of Conduction-Cooled Coated Conductors with Various Copper-Stabilizer Thicknesses

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***Abstract*—We experimentally studied the quench properties of $REBa_2Cu_3O_y$ (RE-123) coated conductors with various plated-copper thicknesses (20 and 40 μm). A short sample of coated conductors was conduction-cooled to 45 K, a magnetic field ($\mu_0 H$, up to 2 T) was applied perpendicular to its wide face to control the critical current, an operating current was supplied, and subsequently quench was initiated using a small heater. Normal zone propagation velocities (NZPVs) were measured at various operating currents, and the NZPVs of coated conductors with various copper thicknesses were compared with each other. To understand the impact of the copper stabilizer on quench protection, hot-spot temperatures were measured during the processes that simulate quench detection using voltage taps and protection using dump resistor. The maximum hot-spot temperatures were plotted against the operating current as well as the overall current density, and the impact of the thickness of the copper stabilizer on hot-spot temperature was examined. The impact of the initial temperature on hot-spot temperature was also studied.**

***Index Terms*—Coated conductor, conduction-cooled, copper stabilizer, protection, quench.**

I. Introduction

The amount of copper stabilizer in the cross section of a superconductor is a significant parameter in the context of quench protection because it directly impacts the Joule heating in the quench process [1]. In the early stage of the development of $REBa_2Cu_3O_y$ (RE-123) coated conductors, their superconductor layers were covered only with several-micrometer-thick silver layers [2]. Recently, attaching copper stabilizer has become common in commercially available coated conductors, but their cross sections are still relatively small [3]–[4]. For example, in the case of a 4-mm-wide coated conductor plated with 20-μm-thick copper carrying 200 A of current, its copper current density in the event of quench is 1250 A/mm^2.

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Several studies have been conducted on the normal zone propagation velocity (NZPV), focusing on the copper stabilizer in coated conductors numerically [5] and experimentally (at 77 K) [6]. In this study, we particularly measured the NZPV of conduction-cooled coated conductors with plated-copper stabilizers of various thicknesses.

To understand the impact of copper stabilizer on quench protection, we performed quench detection and protection experiments at various operating currents using the conventional quench detection and protection scheme, *i.e.*, detecting quench using voltage and dumping the stored energy in an external dump resistor, because of the simplicity and well-established hardware for a real magnet.

II. Experimental Method

The specifications of the samples used in this study are listed in Table I. The thicknesses of the Hastelloy substrates in FYSC-SCH04 and FYSC-SCH04(40) are the same, but the copper stabilizer in FYSC-SCH04(40) is thicker. The plated-copper thicknesses of FYSC-SCH04 and SCS4050 are the same, but the Hastelloy substrate in FYSC-CSH04 is thicker. The critical currents of the samples were measured at various temperatures and are depicted in Fig. 1. The positions of the voltage taps and temperature sensors are depicted in Fig. 2. The entire length of a sample, including the length attached to the copper current terminals (25 mm each), was 230 mm. The temperature of the sample was PID-controlled at 45 K (in most experiments) using the temperature measured by CX1 and CX2 as well as heaters (not shown in Fig. 2) near the copper terminals. One side of sample faces vacuum and the other side is attached to a GFRP sample holder through epoxy resin and polyimide tape.

In this study, hot-spot temperature during the quench process was calculated from $v_{5\text{-}6}$ based on the current sharing model and the temperature dependence of the resistivity of plated copper, which was introduced in a previous study [7].

Fig. 3(a) depicts the voltage and current waveforms in an example of NZPV measurement. We used the time when $v_{4\text{-}5}$ (voltage between VT4 and VT5) and $v_{3\text{-}4}$ (voltage between VT3 and VT4) reach 1 mV as well as $d_{4\text{-}5}$ (distance between VT4 and VT5: 15 mm) to estimate the NZPV. Fig. 3(b) depicts the typical data of quench detection and protection shot.

TABLE I
SPECIFICATIONS OF SAMPLE

Properties	FYSC-SCH04 (Fujikura)	FYSC-SCH04(40) (Fujikura)	SCS4050 (SuperPower)
Width	4 mm	4 mm	4 mm
Entire thickness	0.13 mm	0.17 mm	0.1 mm
Plated-copper thickness	20 μm	40 μm	20 μm
Thickness of Hastelloy substrate	75 μm	75 μm	50 μm
Critical current	~ 320 A (45 K, 2 T)	~ 320 A (45 K, 2 T)	~ 320 A (45 K, 0.4 T)

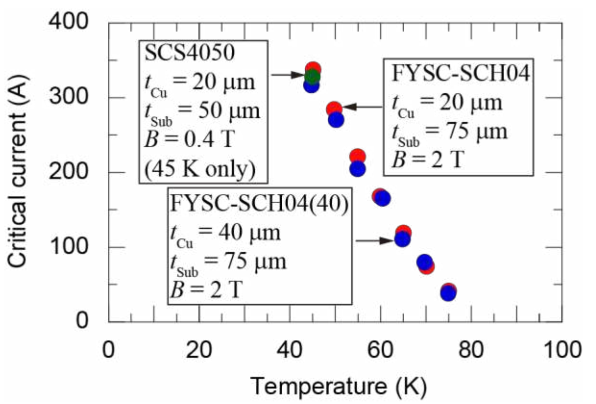

Fig. 1. Critical current of samples measured at various temperatures (E_0 = 100 μV/m)

A field-programmable gate array (FPGA) was used to monitor the voltage and control the output of power supply. Once the monitored voltage of the entire sample ($v_{1\text{-}10}$) reached a detection voltage (simulating quench detection), after a period of delay (simulating the time required for detection in a real coil and for activating the circuit breaker), the sample current was decreased exponentially (simulating current decay by the dump resistor while neglecting the normal resistance). The critical currents and n values of a sample before and after quench are used to determine whether there is degradation or not. In all the quench detection and protection experiments in this study, the threshold voltage was set to 100 mV and the delay time was set to 100 ms.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Normal Zone Propagation Velocity

The NZPVs of coated conductors with various plated-copper thicknesses (FYSC-SCH04, FYSC-SCH04(40)) at various operating currents were measured at 45 K, 2 T, as depicted in Fig. 4. Ignoring the transverse thermal diffusion, the NZPV could be calculated using the following equation [8]:

$$v = \frac{J}{\gamma C}\left\{\frac{L_0\left(T_g + T_c\right)}{T_g + T_c - 2T_0}\right\}^{\frac{1}{2}} \tag{1}$$

where J represents the overall current density, L_0 is the Lorentz number (2.45 × 10^{-8} W·Ω·K^{-2}) from the Wiedemann–Franz–Lorentz law, T_g is the temperature at which heat is generated, T_c is the critical temperature (assumed as 82 K, based on the measured data in Fig. 1), and T_0 is the initial temperature (45 K). The parameter T_g is expressed as follows:

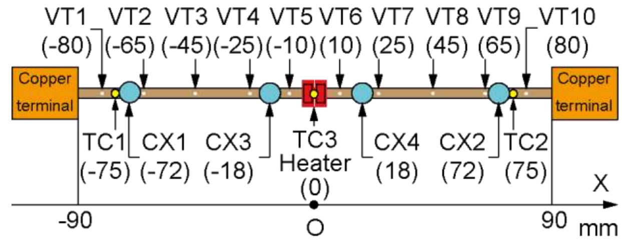

Fig. 2. Positions of voltage taps and temperature sensors (VT: voltage tap, TC: thermocouple, CX: Cernox temperature sensor). Numbers in brackets indicate relative positions (in mm) to sample center in longitude direction.

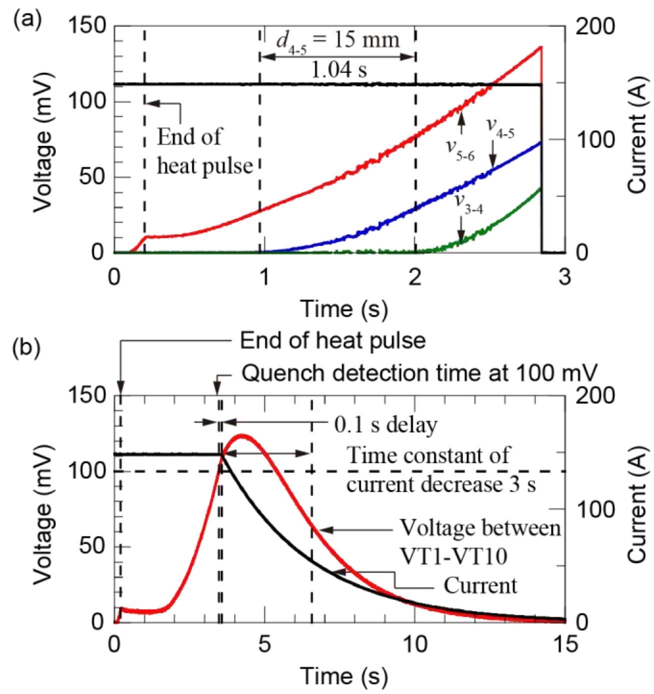

Fig. 3. The example of NZPV measurement, quench detection, and protection experiment (T_i = 45 K, B = 2 T, I_{op} = 150 A, FYSC-SCH04(40), $v_{m\text{-}n}$: voltage between VTm and VTn, $d_{m\text{-}n}$: distance between VTm and VTn): (a) voltage and current in NZPV measurement, (b) voltage and current in quench detection and protection experiment.

$$T_g = T_c - \left(T_c - T_0\right)\frac{J}{J_{c0}} \tag{2}$$

where J_{c0} is the overall critical current density at the initial temperature (672 A/mm^2 in FYSC-SCH04 and 503 A/mm^2 in FYSC-SCH04(40)). The heat capacity γC is calculated by considering the mean over the temperature range of the transition.

$$\gamma C = \left\{\frac{T_c^4 - T_0^4}{4T_0^3\left(T_c - T_0\right)}\right\}\sum_n \lambda_n \gamma_n C_{0n} \tag{3}$$

where λ_n is the proportion of the nth component, γ_n is its density, C_{0n} is its specific heat at T_0, and it is assumed that C varies as T^3. γC = 1.84 × 10^6 J/m^3·K in FYSC-SCH04 and γC = 1.86 × 10^6 J/m^3·K in FYSC-SCH04(40). The calculated NZPVs are represented as dashed lines in Fig. 4. The measured NZPVs were lower as compared to the calculated results, which might be attributed to transverse thermal diffusion in

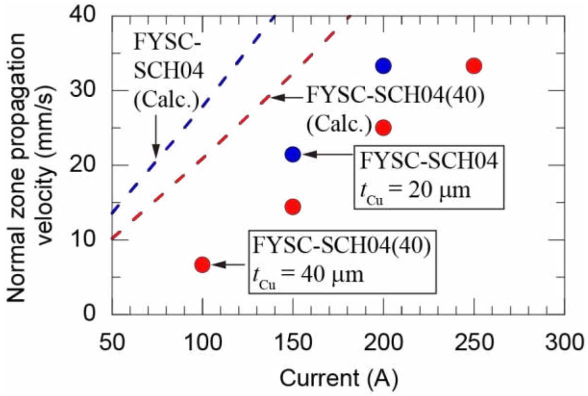

Fig. 4. NZPV vs current in coated conductors with different copper thicknesses ($T_i = 45$ K, $B = 2$ T, $I_c \sim 320$ A).

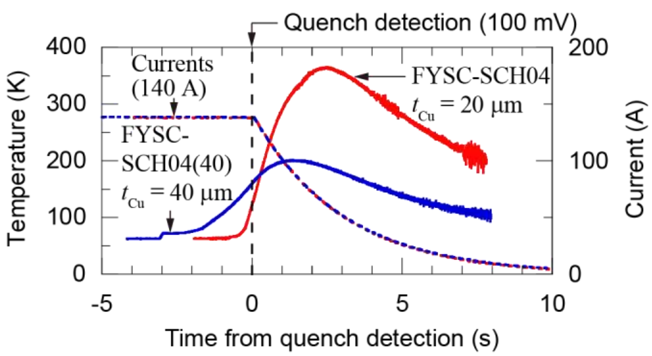

Fig. 5. Hot-spot temperature and current waveforms of samples with different copper thicknesses ($T_i = 45$ K, $B = 2$ T, $I_c \sim 320$ A, $I_{op} = 140$ A, $v_{th} = 100$ mV, $t_d = 100$ ms, $\tau = 3$ s)

the experiments. Also some assuming on physical properties (C varies as T^3, ignoring the effect of magnetic field) might have some influences on such differences between calculated and measured results. Both the calculated and experimental results indicate that increasing the thickness of plated copper in a coated conductor causes a decrease in the propagation velocity. In previous study, it was reported that the increasing of heat capacity is the main reason for the decrease in NZPV when increasing copper thickness [6]. However, based on (1), as these two samples have nearly the same values of T_g, T_c, and T_0, and there is not too much of difference in the heat capacity γC between these two coated conductors, it is considered that the decrease in the overall current density J (by increasing the thickness of the copper stabilizer) is the main reason for this decrease in NZPV.

B. Hot-spot Temperature During Quench Detection and Protection Process

Fig. 5 illustrates an example of hot-spot temperature and current waveforms during the quench detection and protection process using samples with various copper thicknesses. The figure suggests that increasing the copper thickness decreases the maximum hot-spot temperature during the quench detection and protection process. Such experiments were conducted with various operating currents and time constants. As depicted in Fig. 6(a), at first, the experiments were performed using FYSC-SCH04 and FYSC-SCH04(40), setting the time constant of current decrease as 1 s, and the current at the first shot was 100 A and was raised incrementally. It is clear that at the same operating current, the maximum hot-spot temperature

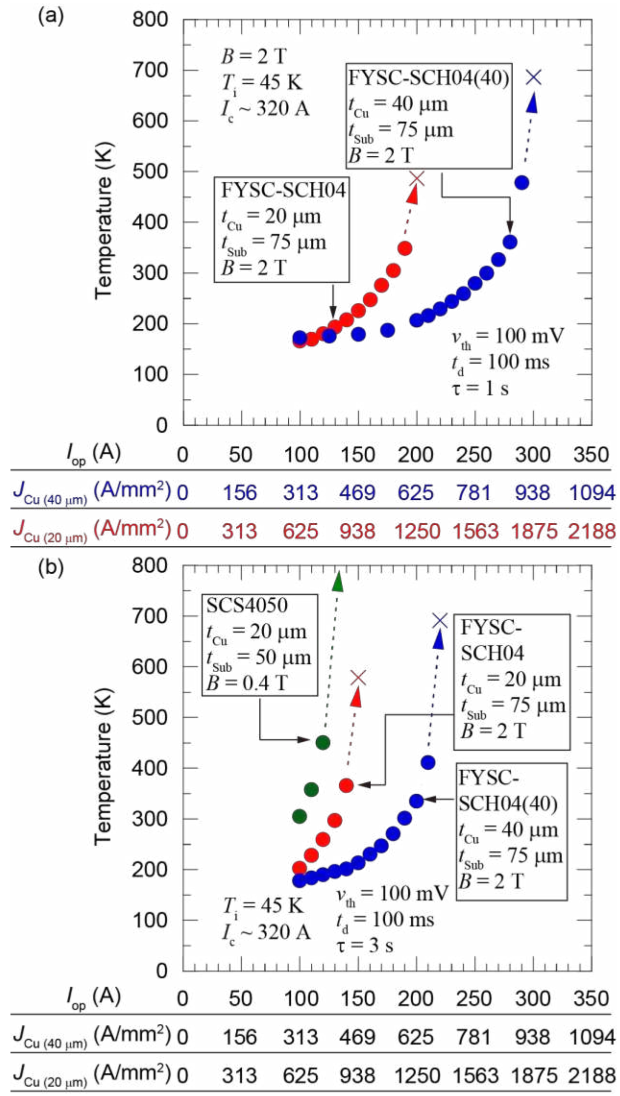

Fig. 6. Maximum hot-spot temperature vs operating current/current density ($T_i = 45$ K, $t_d = 100$ ms): (a) $\tau = 1$ s; (b) $\tau = 3$ s.

was lower in FYSC-SCH04(40). For example, at 150 A, the maximum hot-spot temperature in FYSC-SCH04 was 225 K (J_{Cu} = 938 A/mm^2), whereas the maximum hot-spot temperature in FYSC-SCH04(40) was 179 K (J_{Cu} = 469 A/mm^2). As depicted in Fig. 6(b), similar experiments were conducted when the time constant was set to 3 s using FYSC-SCH04, FYSC-SCH04(40), and SCS4050. It should be noted that in the experiments using SCS4050, the magnetic field was set to 0.4 T to let the critical current be close to the other two types of coated conductors. In both Fig. 6(a) and Fig. 6(b), the experimental results of FYSC-SCH04 and FYSC-SCH04(40) demonstrated the impact of increasing the copper thickness on decreasing the maximum hot-spot temperature owing to the decrease in copper current density as well as the increase in the heat capacity. Further, the experimental results of FYSC-SCH04 and SCS4050 suggest that increasing the Hastelloy substrate thickness impacts the maximum hot-spot temperature remarkably (e.g., it was 202 K in FYSC-SCH04 but 305 K in SCS4050 at 100 A) owing to the increase in the heat capacity.

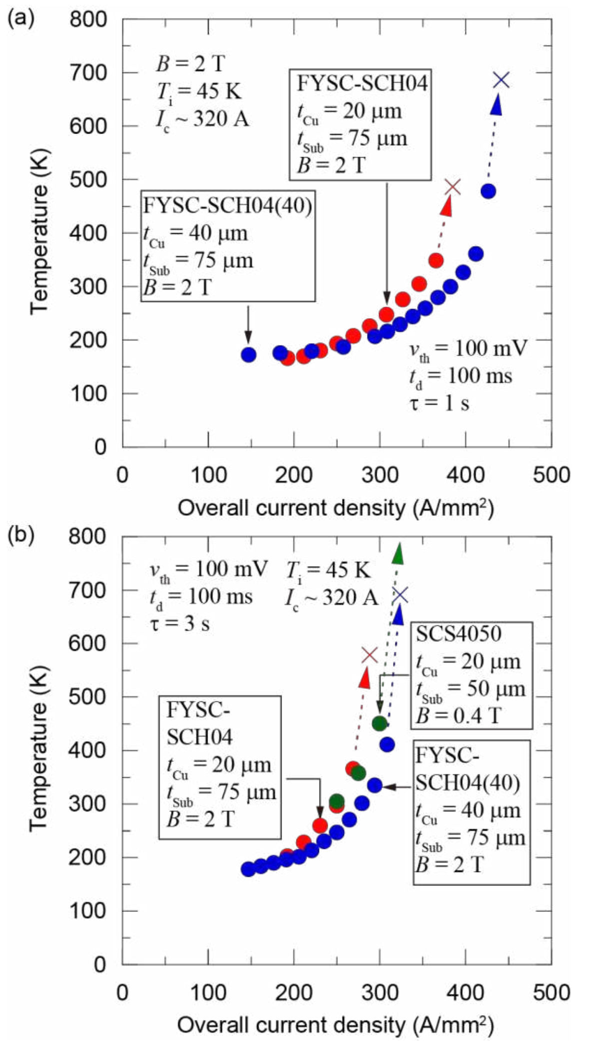

Fig. 7. Maximum hot-spot temperature vs copper current density (T_i = 45 K, t_d = 100 ms): (a) $\tau = 1$ s, (b) $\tau = 3$ s.

Fig. 6 depicts that increasing the copper thickness of a coated conductor reduces the copper current density and the maximum hot-spot temperature. However, increasing the copper thickness of a coated conductor could also reduce the overall current density, which is required to be high in a real magnet. To understand whether it is beneficial to increase the copper thickness, considering the overall current density, we compared the maximum hot-spot temperature at various overall current densities using various samples, as depicted in Fig. 7. The experimental results for FYSC-SCH04 and FYSC-SCH04(40), depicted in Fig. 7, suggest that at the same overall current density, the hotspot temperature of a coated conductor with a thicker copper stabilizer (40 µm) could be rather lower. However, as depicted in Fig. 7(b), the results of FYSC-SCH04 and SCS4050 suggest that the relation between the hot-spot temperature and overall current density does not change substantially by changing the thickness of the Hastelloy substrate.

C. *Impact of Initial Temperatures*

Fig. 8 displays the waveforms of the hot-spot temperature and current of FYSC-SCH04(40) when the initial temperature was varied. The experiments were performed at 150 A with

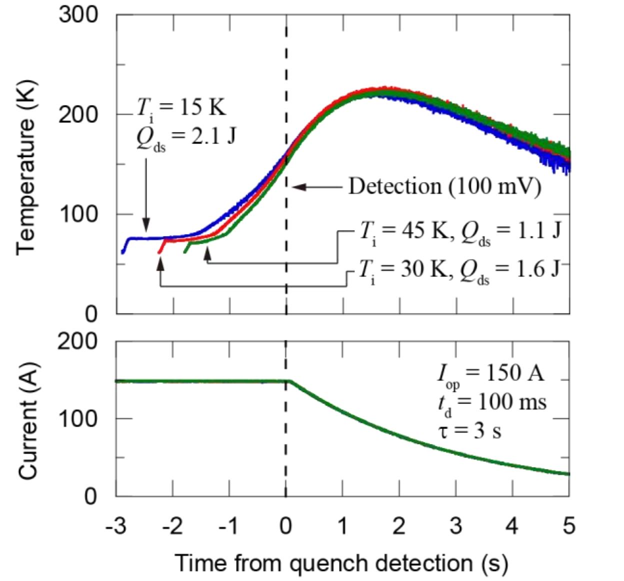

Fig. 8. Hot spot temperature and current at various initial temperatures (FYSC-SCH04(40), I_{op} = 150 A, v_{th} = 100 mV, t_d = 100 ms, $\tau = 3$ s).

the same time constant of current decrease (3 s). No significant difference was observed among the hot-spot temperatures after quench detection, which suggests that the initial temperature has little impact on quench detection and protection.

In Fig. 8, the energies of thermal disturbance causing quench were 2.1 J at 15 K, 1.6 J at 30 K, and 1.1 J at 45 K. Ignoring thermal conduction, the enthalpy margin can be calculated at various temperatures using the following equation [9]:

$$H(T_0) = \int_{T_0}^{T_i} \gamma C(T) dT \qquad (4)$$

where T_i is the temperature at which the electric field reaches 100 µV/m, which is 62 K in this case, and $\gamma C(T)$ is the volumetric specific heat of the conductor averaged over its cross section. The calculated enthalpy margins are as follows: 2.3×10^7 J/m^3 at 15 K, 2.1×10^7 J/m^3 at 30 K, and 1.5×10^7 J/m^3 at 45 K. The energies of thermal disturbance causing quench in the experiments as well as the enthalpy margin suggest that the initial temperature does not considerably impact the energy that induces a quench at low temperature.

IV. Summary

Using conduction-cooled coated conductors, we experimentally confirmed that increasing the thickness of plated copper decreases the propagation velocity and suppresses hot-spot temperature. Decreasing the overall current density could cause the former and decreasing the copper current density could cause the latter. The heat capacity of the substrate has a remarkable impact on the hot-spot temperature. Essentially, the hot-spot temperatures of the coated conductor with 40-µm-thick plated copper were lower than those of the coated conductor with 20-µm-thick plated copper at the same overall current densities. The initial temperature hardly impacts the hot-spot temperature.

References

[1] Y. Fu, O. Tsukamoto, and M. Furuse, "Copper stabilization of YBCO coated conductor for quench protection," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1780–1783, Jun. 2003.

[2] A. P. Malozemoff, S. Annavarapu, L. Fritzemeier, Q. Li, V. Prunier, M. Rupich, C. Thieme, W. Zhang, A. Goyal, M. Paranthaman, and D. F. Lee, "Low-cost YBCO coated conductor technology," *Supercond. Sci. Technol.*, vol. 13, no. 5, pp. 473–476, May 2000.

[3] A. P. Malozemoff, S. Fleshler, M. Rumpich, C. Thieme, X. Li, W. Zhang, A. Otto, J. Maguire, D. Folts, J. Yuan, H-P. Kraemer, W. Schmidt, M. Wohlfart, and H- W. Neumueller, "Progress in high temperature superconductor coated conductors and their applications," *Supercond. Sci. Technol.*, vol. 21, no. 3, Mar. 2008, Art. no. 034005.

[4] M. W. Rupich, X. Li, S. Sathyamurthy, C. L. H. Thieme, K. DeMoranville, J. Gannon, and S. Fleshler, "Second generation wire development at AMSC," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. no. 6601205.

[5] C. Lacroix, F. Sirois, and J-H. F. Lupien, "Engineering of second generation HTS coated conductor architecture to enhance the normal zone propagation velocity in various operating conditions," *Supercond. Sci. Technol.*, vol. 30, no. 6, Jun. 2017, Art no. 064004.

[6] M. Daibo, S. Fujita, M. Haraguchi, Y. Iijima, and T. Saitoh, "Evaluation of the normal-zone propagation characteristics of REBCO coated conductors with laminated Cu tape," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2428–2431, Jun. 2011.

[7] X. Luo, S. Inoue, N. Amemiya, "Experimental study on quench detection and protection conditions of copper-stabilized coated conductors using short samples," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 8, Dec. 2019, Art. no. 4703511.

[8] M. N. Wilson, "Propagation velocities," in *Superconducting Magnets*, Oxford, U.K.: Clarendon, 1983, pp. 204–208.

[9] K. Takahashi, N. Amemiya, T. Nakamura, T. Ogitsu, T. Kurusu, T. Yoshiyuki, K. Noda, and S. Awaji, "Magnetic field design of dipole magnet wound with coated conductor considering its current transport characteristics," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1833–1837, Jun. 2011.