Normal zone propagation in superconducting thin-film fault current limiting elements with Au-Ag alloy shunt layers

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Abstract. We have been developing a superconducting fault current limiter (FCL), in which YBCO superconducting thin films with Au-Ag alloy shunt layers are used. We have already achieved high electric fields (>40 V_{peak}/cm), which enable the total length of FCL elements to be reduced drastically, thus greatly reducing the cost of FCLs. In this paper, we report the normal zone propagation velocity in our films when over-current was applied to the films at 50 Hz for 100 ms. The velocity plotted against the root-mean square values of the normalized film current showed a common curve or curves. The data were also discussed using the adiabatic theory. As the normal zone propagation velocity was not so fast, we divided one unit film of 120 mm length into two portions, to each of which an external resistance was attached. The test result showed that a high electric field of 45 V_{peak}/cm and total voltage of 450 V_{peak} were achieved in the first cycle after quenching, and the film withstood the voltage for five cycles. The temperature distribution along the length of the film was also shown.

1. Introduction
Fault current limiters (FCLs) are a useful solution when fault currents exceed the set values of various electrical equipment due to the connection of newly-introduced distributed power sources in a power system. Among various FCLs, the resistive superconducting FCLs using high-temperature superconducting thin films are the most promising because of their compactness and self-triggered, rapid switching operation [1], [2]. However, a major drawback is the high cost of large-area superconducting thin films, so we have proposed FCLs using Au-Ag alloy shunt layers on YBCO superconducting thin films to prevent the “hot-spots” problem, and achieved high electric fields of >40 V_{peak}/cm [3]-[6]. This value is much higher than the electrical field of <10 V_{peak}/cm attained in conventional devices using Au shunt layers [1]. Our new approach thus offers a way to greatly reduce the cost of FCLs.

In this study, we examine the normal zone propagation velocity in our films because the normal zone propagation in the films is an important subject for the design of FCLs. Based on the results, a unit film of 120 mm length was divided into two portions in order to develop voltages in the film rapidly by multi-initiation of quenching.

2. Experimental Set-up
Table 1 shows the specifications of Specimens S1 to S5 of our Au-Ag/YBCO composite films. All specimens had a layer structure of Au-Ag/YBCO/CeO₂ on a sapphire substrate. Composites of
YBCO/CeO$_2$/Al$_2$O$_3$ for Specimens S1, S2, S3 and S5 were purchased from THEVA Ltd. Specimen S4 was prepared by fluorine-free metal organic deposition (MOD) in our institute [7]. The Au-Ag layers for all specimens were formed by a sputtering process using an Au-23wt% Ag alloy target. There were gold or silver electrodes at both ends of each specimen.

Figure 1 shows the circuit diagram used for over-current tests. The external resistance $R$, a non-inductively wound manganin wire, was connected in parallel to the specimen to protect the superconducting films from the “hot-spots” problem during quenching. Both the specimen and the external resistance were immersed in liquid nitrogen. Four voltage taps 1 to 4 were attached to Specimens S1 to S4, respectively. Each space between the voltage taps, 1-2, 2-3 and 3-4 was 20 mm, respectively, for Specimens S1, S2 and S4. For Specimen S3, the space was 16.7 mm. Switching experiments were carried out by applying sinusoidal over-currents to the parallel-connected specimen and the external resistance, with an over-current duration of 100 ms, for five cycles at 50 Hz.

The AC power supply was operated in current-control mode for the tests of Specimens S1 and S2 or in voltage-control mode for Specimens S3 to S5. In voltage-control mode, the power supply induces the output voltage $V_{\text{power}}$ which is proportional to the voltage applied to the power supply, where a resistance $r$ of 0.2 Ω was connected to the power supply as shown in figure 1. In current-control mode, the power supply induces the output current $I_{\text{total}}$ which is proportional to the voltage applied to the power supply, where $r = 0$ Ω.

3. Test results and discussion

3.1. Over-current test
One of the test results of Specimen S2 is shown in figure 2 as a typical test result. Quenching initiated at $t = 135.6$ ms between voltage taps 3 and 4, and voltages $V_{34}$, $V_{23}$ and $V_{12}$ started to rise in this order,

![Figure 1. Experimental set-up for the switching experiments.](image1)

In liquid nitrogen

![Figure 2. Test result for Specimen S2.](image2)

Table 1. Specifications of the tested specimens.

| Specimen | Thickness of YBCO (nm) | Average $J_c$ (MA/cm$^2$) | Thickness of Au-Ag (nm) | Thickness of substrate (mm) | Width × effective length of YBCO (mm) | Length of electrodes (mm) | External resistance $R$ (Ω) |
|----------|------------------------|---------------------------|--------------------------|-----------------------------|----------------------------------------|--------------------------|-----------------------------|
| S1       | 300                    | 3                         | 50                       | 1                           | 10 × 60                                | 10                       | 2.0                         |
| S2       | 300                    | 3                         | 50                       | 0.7                         | 10 × 60                                | 10                       | 2.0                         |
| S3       | 300                    | 3                         | 60                       | 0.7                         | 20 × 50                                | 5                        | 0.5                         |
| S4       | 195                    | 2.1                       | 60                       | 1                           | 40 × 60 $^a$                           | 10                       | 0.7                         |
| S5 $^b$  | 300                    | 3                         | 60                       | 0.7                         | 10 × 100 $^b$                          | 5                        | 1.0, 1.0 $^b$               |

$^a$ In Specimen S4, the width of sapphire substrate is 50 mm, which is wider than the YBCO width. In other specimens, the widths of the YBCO film and the sapphire substrate are the same in each specimen.

$^b$ Details of Specimen S5 are shown in figure 4.

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corresponding to the expansion of the normal zone. $V_{\text{film}}$, the voltage between voltage taps 1 and 4, represents the total voltage along the effective length of the specimen.

3.2. Temperature distribution

Temperatures $T_{12}$, $T_{23}$, $T_{34}$ and $T_{\text{film}}$, which were derived from the resistance calculated from the film current $I_{\text{film}}$ and the voltages $V_{12}$, $V_{23}$, $V_{34}$ and $V_{\text{film}}$, respectively, are also indicated in figure 2 [5]. $T_{12}$, $T_{23}$ and $T_{34}$ correspond to the average temperature between each of the voltage taps. Data of $T_{\text{film}}$ indicating the average temperature along the total effective length of the film overlapped with the data of $T_{23}$ after $t = 155$ ms which had the middle level among $T_{12}$, $T_{23}$ and $T_{34}$.

The temperature difference between $T_{12}$ and $T_{34}$ at $t = 158$ ms was approximately 100 K and the difference slightly decreased with elapse of time as shown in figure 2. The data show that the non-uniformity of temperature was almost kept for the short period of ~100 ms [8].

3.3. Normal zone propagation velocity

From figure 2, we can calculate the normal zone propagation velocity of 2.45 m/s from the difference in rise time of $V_{23}$ and $V_{12}$, 8.17 ms, and the space of 20 mm between voltage taps 2 and 3. When this velocity was obtained, the root-mean square (RMS) of current $I_{\text{film}}$ was 24.8 A from the data of $I_{\text{film}}$ between the time of voltage rises of $V_{23}$ and $V_{12}$. In this way, we measured the normal zone propagation velocity and RMS values of $I_{\text{film}}$, $I_{\text{film}}$, RMS, for Specimens S1 to S4, where various levels of over-current were applied at 50 Hz for 100 ms.

The test results are shown in figure 3(a) with solid lines. In figure 3(b), we plot the same data against $I_{\text{film}}$, RMS/w, where w is the substrate width of each specimen. In figure 3(b), the experimental data would be represented by a common curve or curves if the normalized horizontal axis was used. The data of Specimens S1 and S4 whose substrate thickness was 1 mm overlapped. The data of Specimens S2 and S3 also seem to form one common curve, where both specimens had the same substrate thickness of 0.7 mm. The normal zone propagation velocity of the former group was slower than that of the latter because the thicker substrate had the larger heat capacity, leading to the lower temperature rise and the lower velocity. In figure 3(b), it can also be seen that the experimental data show almost straight lines in the low current density region ($I_{\text{film}}$, RMS/w < 27 A).
The dashed lines in figure 3(a) indicate theoretical values of the normal zone propagation velocity $v_n$ calculated by the following equation based on the adiabatic theory [9], [10]:

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

(1)

where $A$ is the cross-sectional area of each sample, and $C_p$, $\kappa$ and $\rho$ are the specific heat, the thermal conductivity and the resistivity of the sample, respectively. $I_{mp}$ is the minimum propagating current, $T_c$ is the critical temperature (88 K), and $T_0$ is the initial temperature, which is the boiling point of liquid nitrogen (77 K). As we measured the normal zone propagation velocity by AC at 50 Hz, $I_{film, RMS}$ is used as $I$ in equation (1).

For calculating the theoretical data, the resistivity at the temperature just above the critical temperature was used, where the $\rho$ values were $9.76 \times 10^{-4}$, $6.29 \times 10^{-4}$, $5.40 \times 10^{-4}$ and $9.70 \times 10^{-4}$ $\Omega$m for Specimens S1 to S4, respectively. The $I_{mp}$ values for Specimens S1 to S4 were 7.86, 6.73, 6.78 and 16.1 A, respectively, which were obtained by linear extrapolation using the experimental data in figure 3(a). In this extrapolation, $I_{mp}$ for Specimen S2 was calculated using the data of $I_{film, RMS} < 25$ A, and $I_{mp}$ for Specimen S4 was calculated using the data of $I_{film, RMS} < 134$ A in order to use the almost straight parts in each low current region.

In the analysis, we tried to find $C_p$ and $\kappa$ so that the theoretical values using equation (1) agreed with the experimental data. For Specimens S1 and S2, the theoretical values agreed well with experimental data when the constants of sapphire substrate at 80 K, that is $C_p = 0.27 \times 10^6$ J/m$^3$-K and $\kappa = 1200$ W/m-K, were used [11], [12]. These two specimens had the substrate width of 10 mm. However, in the case of Specimen S3 whose substrate width was 20 mm, the experimental data agreed with the theoretical values using the constants of sapphire at 85 K, that is $C_p = 0.33 \times 10^6$ J/m$^3$-K and $\kappa = 909$ W/m-K. These results suggest that the average temperature in the front region of the normal zone in Specimens S1 and S2 was lower than that in Specimen S3. For Specimen S4 which had the
wide substrate width of 50 mm, the experimental data in its low current region ($I_{\text{film, RMS}} < 134$ A) are close to the dashed line using the constants at 85 K rather than that at 80 K.

3.4. Switching test of Specimen S5 with high voltages

We plan to use rectangular Au-Ag/YBCO composite films whose effective length is 100–200 mm for the production of a FCL. Because the normal zone propagation velocity was as low as 2–5 m/s for one direction even in the cases of high film current as shown in figure 3(b), it takes 10–50 ms (0.5–2.5 cycles at 50 Hz) to propagate along the whole length of 10 cm, which means that a large temperature inhomogeneity would occur in some cases. Thus, we divided Specimen S5 whose total length was 120 mm into two portions as shown in figure 4, in order to achieve simultaneous quenches [13]. One

![Figure 4](image)

**Figure 4.** Specimen S5 connected with two external manganin resistances. Gray areas indicate electrodes covered with Au layers.

Figure 5. Over-current test result of Specimen S5. $V_{\text{power}}$ means the output voltage of the power source.
portion had the effective length of 50 mm with one external resistance of 1 Ω.

The result of the high-voltage test is shown in figure 5. $V_{\text{film1}}$ emerged approximately 0.7 ms later than $V_{\text{film2}}$. These simultaneous voltage rises led to a rapid increase of voltage along Specimen S5, where voltage $V_{\text{film}}$ of 450 $V_{\text{peak}}$ along the effective length of 100 mm was achieved at $t = 135$ ms. This voltage corresponds to a high electric field of 45 $V_{\text{peak}}$/cm. These results confirm that the design with one film divided using external resistances is appropriate [13]. Total current $I_{\text{total}}$ would reach approximately 2.5 kA$_{\text{peak}}$ if this set of specimen and resistance was not connected. By using our films, $I_{\text{total}}$ was limited to 268 A at the initial peak immediately after quenching, and this $I_{\text{total}}$ was lower than the $3 \times I_c$, 270 A.

4. Conclusions

The normal zone propagation velocity in YBCO thin-films with Au-Ag alloy shunt layers was measured at 50 Hz and discussed. The normal zone propagation velocity from 0.5 to 5.5 m/s was obtained by changing the over-current level at 50 Hz for 100 ms in switching experiments for various specimens. For low film current density, the normal zone propagation velocity versus root-mean square of the film current showed straight lines, obeying the adiabatic theory.

We divided a unit film into two portions with two external resistances in order to induce simultaneous quenching to develop voltages in the film rapidly. The test result showed that a high voltage of 450 $V_{\text{peak}}$ and high electric field of 45 $V_{\text{peak}}$/cm along the effective length in the film can be achieved in the first cycle after quenching.

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