Applied Physics Express

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To cite this article: Yasuaki Takeda *et al* 2023 *Appl. Phys. Express* **16** 093002

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OPEN ACCESS

Applied Physics Express **16**, 093002 (2023) **LETTER**

https://doi.org/10.35848/1882-0786/acf7a9

Interpretation of time-dependent current and resistance of HTS closed loop with superconducting joint considering flux creep

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Received July 3, 2023; revised August 10, 2023; accepted September 6, 2023; published online September 19, 2023

A low circuit resistance is required for a superconducting magnet operated in persistent mode using superconducting joints. We performed current decay measurements on a high-temperature superconducting (HTS) closed loop with a superconducting joint to evaluate the time dependence of the current and resistance. The results have been quantitatively explained by considering current sharing and flux creep. After the elapse of 10^5 s, current sharing was suppressed and a circuit resistance of less than 10^{-13} Ω was observed. The main finding is that joint resistance of an HTS closed loop is inversely proportional to time, contributing to low circuit resistance.

NMR spectroscopy requires a temporally stable magnetic field. A 400 MHz (9.4 T) NMR magnet exhibits field stability of less than 10 ppb h^{-1}. Such a stable field is typically generated by a superconducting magnet operated in persistent mode. Because a magnet consists of a dozen or more superconducting coils, a corresponding number of inter-coil joints are expected to be present. Assuming self-inductance (L) of several tens of Henry, the resistance of the joints should be less than 10^{-13} Ω to achieve stability of less than 10 ppb h^{-1}. A joint between superconducting wires/tapes that exhibits such a low joint resistance (R_j) is called a superconducting (or persistent) joint.[1,2)]

This low R_j value is too small to be evaluated using transport measurements. It is typically evaluated by the current decay method, i.e. by measuring the time (t) dependence of the current flowing in a closed loop (I_{loop}) made of a superconducting wire/tape with a superconducting joint.[1–6)] The following equation is used to deduce the circuit resistance (R) of the closed loop:

$$I_{loop}(t) = I_{loop}(0)\exp\left(-\frac{R}{L}t\right). \tag{1}$$

In current decay measurements, an initial fast decay is usually observed after the introduction of the I_{loop}. This is due to current sharing, i.e. an inhomogeneous current distribution in the superconducting wire/tape or joint.[1,3,4,6)] After settling the fast decay, a subsequent slow decay can be observed. Assuming that R_j is equivalent to the circuit resistance R and is constant during slow decay, R_j value is obtained by fitting the data points to Eq. (1).

With recent developments in superconducting joint technology for high-temperature superconducting (HTS) tapes/wires,[2,7–13)] studies have been published on the evaluation of R_j for an HTS closed loop using the current decay method. However, the time dependence of I_{loop} (or the magnetic field trapped in the loop) in these studies did not fit well to Eq. (1).[8,9,12–15)] This implies that R_j for an HTS closed loop is time dependent and not uniquely determined using Eq. (1).

It is well known that an electric field is generated inside a superconductor by flux creep.[16–21)] This causes a decay in the magnetization current, which is experimentally observed as magnetic relaxation. Ohki et al. reported that a logarithmic current decay was observed in a $REBa_2Cu_3O_y$ HTS closed-loop sample, which suggested voltage generation by flux creep at the joint.[8)] Even though other studies have also mentioned the flux-creep effect to explain the decay of the current flowing in a closed loop,[1,4,5)] the flux-creep effect has not yet been clarified sufficiently.

In this study, we propose an interpretation of the time-dependent current and resistance of an HTS closed loop with a superconducting joint observed in current decay measurements. This interpretation, which considers current sharing and flux creep, quantitatively explains the time dependence of I_{loop} and R_j.

Current decay measurements were performed on a three-turn closed-loop sample with a superconducting joint, as shown in Fig. 1. The sample was made of a commercially available Ag-sheathed multifilamentary $(Bi,Pb)_2Sr_2Ca_2Cu_3O_y$ (Bi-2223) HTS tape (DI-BSCCO® Type H).[22,23)] Both ends of the 1.6 m long Bi-2223 tape were joined by a hot-pressing process developed by us to form a praying-hands-type superconducting joint.[12,24)] The procedure involved the synthesis of a Bi-2223 intermediate layer of the joint. The diameter of each loop was 100 mm. The self-inductance L of the sample was estimated to be about 1.4 μH.

Measurements at a temperature (T) of 4.2 K were made using the developed joint resistance evaluation system.[25)] I_{loop} was induced by magnetic induction using a copper coil located at the center of the loop. The measurements were carried out using a current transformer consisting of a split core made of laminated electromagnetic steel and a Hall sensor.[15)] A magnetic field (B) of 1 T was applied to the joint, as shown in Fig. 1. Inside the joint, the I_{loop} has a component orthogonal to the direction of B, which causes flux creep at the joint.

The time dependence of I_{loop} obtained from the experiment, I_{loop}–t, is shown in Fig. 2. We defined $t = 0$ when the induced I_{loop} reached its maximum value, as indicated in the inset. A fast decay until about $t = 10^3$ s and subsequent slow decay was observed. A decay in I_{loop} was observed even for $t > 2 \times 10^5$ s and the slope of I_{loop}–t gradually approached

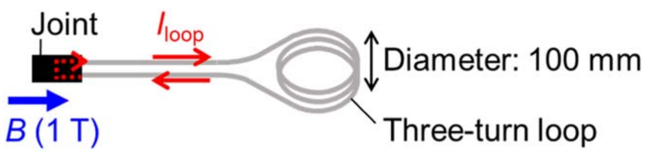

Fig. 1. Schematic of three-turn closed-loop sample with superconducting joint. Both ends of Bi-2223 tape were joined by a praying-hands-type superconducting joint. Directions of I_{loop} and B in current decay measurements are also shown.

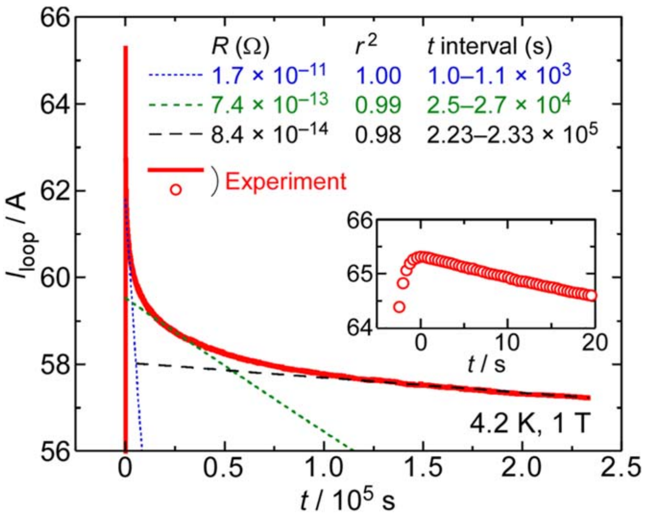

Fig. 2. I_{loop}–t obtained by current decay measurements at 4.2 K and 1 T. Inset shows magnified view at approximately $t = 0$. Three dashed lines were deduced by fitting data points with different time intervals to Eq. (1). Equation (1) can only fit small portion of I_{loop}–t and not entire region, suggesting that circuit resistance R is time dependent.

zero. The three dashed lines were obtained by fitting the experimentally obtained data points at different time intervals to Eq. (1). The three lines indicate that Eq. (1) can only fit a small portion of I_{loop}–t and not the entire region. This suggests that circuit resistance R is time dependent.

Figure 3 shows the time dependence of R. The value of R was obtained by dividing the data points of I_{loop}–t into time intervals and fitting each interval to Eq. (1) using the least squares method. Each interval was chosen such that the

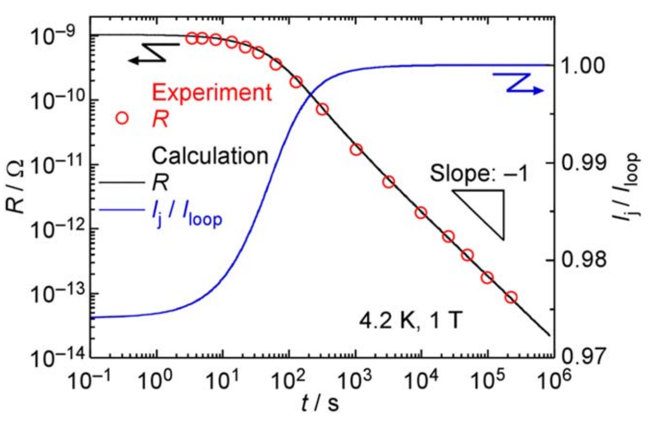

Fig. 3. Time dependence of experimentally obtained circuit resistance R in current decay measurements at 4.2 K and 1 T. Value of R was obtained by fitting data points to Eq. (1). R–t and I_j/I_{loop}–t curves obtained by calculation are also displayed. Calculated R–t curve agrees well with experimentally obtained R–t plots. At $t > 10^4$ s, I_j/I_{loop}–t shows that current sharing is almost completely suppressed, and R is inversely proportional to time.

coefficient of determination (r^2) was higher than 0.96, as shown in Fig. 2. Up to $t = 10^2$ s, the time variation of R was small, decreasing in the same order of magnitude ranging from 9 to 2×10^{-10} Ω. At $t > 10^2$ s, R decreases significantly with increasing t. At $t = 2.3 \times 10^5$ s, R reached the lowest value of 8.4×10^{-14} Ω within the measurement time.

Let us interpret the time dependence of I_{loop} and R by considering flux creep at the joint. Assuming flux creep under the conditions of $T = 4.2$ K and $B = 1$ T, we used the Anderson-Kim model.[16,17] From this model, the generation of an electric field (E) by flux creep is described as

$$E \propto B \exp\left(-\frac{U_0}{k_B T}\left(1 - \frac{J}{J_{c0}}\right)\right), \tag{2}$$

where J, U_0, and J_{c0} are the current density, pinning potential (U) at $J = 0$, and critical current density at $U = 0$, respectively.[20] Based on Eq. (2), the voltage generated at the joint $V_j(t)$ can be expressed as follows:

$$V_j(t) = V_j(0) \exp\left(-\frac{U_0}{k_B T}\left(1 - \frac{I_j(t)}{I_{cj0}}\right)\right), \tag{3}$$

where $I_j(t)$ and I_{cj0} are the current and characteristic critical current (I_c) of the joint, respectively.

We also considered current sharing at the joint. The equivalent circuit model of the closed-loop sample shown in Fig. 4 was used. We assumed a constant resistance (R_0) parallel to the joint. R_0 probably corresponds to the normal resistance of Ag around the joint. We adopted the variable resistance of the joint, $R_j(I_j) = V_j/I_j$. The resistance of the loop is neglected owing to the significantly higher I_c of the superconducting tape than that of the joint,[22,23] which leads to the generation of a negligibly small E by the flux creep at the loop.

$V_j(t)$ can also be described as follows:

$$V_j(t) = R_0(I_{loop}(t) - I_j(t)). \tag{4}$$

$$V_j(t) = -L\frac{dI_{loop}(t)}{dt}. \tag{5}$$

Using Eqs. (3)–(5), the time development of I_{loop}, V_j, and R are calculated. The calculated R–t and I_{loop}–t curves are shown in Figs. 3 and 5, respectively. The parameters U_0, I_{cj0}, and R_0 used for the calculation were 412 K (35.5 meV),

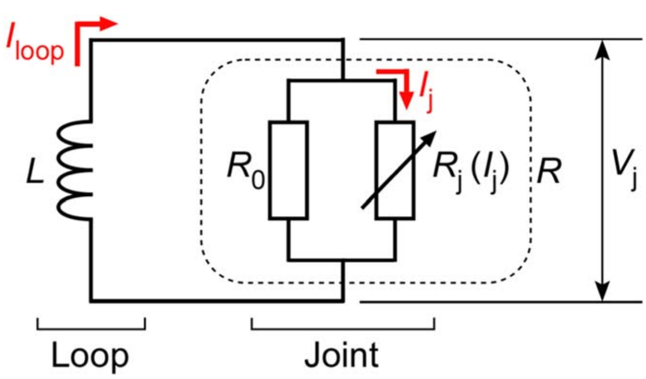

Fig. 4. Schematic of an equivalent circuit model of closed loop sample with superconducting joint. We assumed constant resistance (R_0) in parallel to the joint. We adopted variable resistance of joint, $R_j(I_j) = V_j/I_j$.

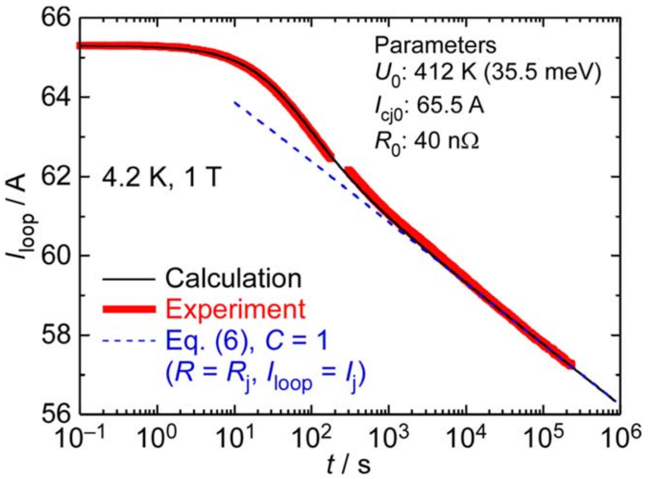

Fig. 5. I_{loop} as a function of time obtained by calculation and current decay measurements at 4.2 K and 1 T. Calculated I_{loop}–t curve agrees well with experimentally obtained I_{loop}–t data. The missing data points at $t = 2$–3×10^2 s is due to the fact that voltage measurement device used to evaluate I_{loop} was changed during that time period. I_{loop}–t using Eq. (6) with $C = 1$ also agrees well with experimentally obtained data at $t > 10^4$ s.

65.5 A, and 40 nΩ, respectively. The experimentally obtained I_{loop}–t, shown in Fig. 2, is also displayed in Fig. 5. The calculated R–t and I_{loop}–t curves agreed well with the experimental results.

The time dependence of I_j/I_{loop} was calculated, as shown in Fig. 3. I_j/I_{loop} is ranging from 0.97 to 0.99 at $t < 10^2$ s and higher than 0.9999 at $t > 10^4$ s. Up to $t = 10^2$ s, current sharing with R_0 ranging from 3% to 1% is estimated, which leads to the small variation of R shown in Fig. 3. In contrast, current sharing was almost completely suppressed at $t > 10^4$ s. This means that the current decay is dominated by flux creep at the joint. Thus, the time dependence of I_{loop} and R can be quantitatively explained by considering current sharing and flux creep at the joint.

As noted above, the current sharing is negligible at $t > 10^4$ s. This indicates that R and I_{loop} are equivalent to R_j and I_j, respectively, as R_j becomes considerably lower than R_0 ($R_j \ll R_0$). By assuming $R = R_j$ and $I_{loop} = I_j$ and from Eqs. (3) and (5), we obtain

$$I_{loop}(t) = I_{cj0} - \frac{k_B T I_{cj0}}{U_0} \ln\left(\frac{t}{t_0} + C\right), \tag{6}$$

where $t_0 = L I_{cj0} k_B T / U_0 V_j(0)$, and C is a constant. An I_{loop}–t corresponding to Eq. (6) with $C = 1$ and $t > 10^1$ s is shown in Fig. 5, which agrees well with the experimentally obtained data at $t > 10^4$ s. This approximation provides an analytical solution for the current decay dominated by flux creep at the joint. The decrease in the I_{loop} was proportional to the logarithm of time.

From Eq. (4) and the calculation results, $V_j(0)$ is estimated to be 6.6×10^{-8} V, thereby resulting in t_0 of 1.4×10^1 s. At $t > 10^4$ s, where the current decay is dominated by flux creep, C will be neglected compared with t/t_0 ($>7.1 \times 10^2$). Under the assumption that $t/t_0 + C \cong t/t_0$, we obtain the approximation of an analytical solution for R_j using Eqs. (5) and (6) as follows:

$$R_j \cong \frac{L}{(U_0/k_B T - \ln(t/t_0))t}. \tag{7}$$

Here, we show that the circuit resistance R is inversely proportional to time at $t > 10^4$ s, which is suggested in Fig. 3. Using Eq. (7), we obtain

$$\frac{d(\ln R_j)}{d(\ln t)} = -1 + \left[\frac{U_0}{k_B T} - \ln\left(\frac{t}{t_0}\right)\right]^{-1}. \tag{8}$$

$[U_0/k_B T - \ln(t/t_0)]^{-1}$, which increases with increasing t, was less than 1.1×10^{-2} until $t = 10^6$ s. This implies that the right side of Eq. (8) is nearly equivalent to -1, resulting in $R = R_j \propto t^{-1}$. Thus, assuming $R = R_j$ and $I_{loop} = I_j$ owing to negligible current sharing, we demonstrated that circuit resistance R is inversely proportional to time. This implies that a low R can be achieved after a sufficiently long time.

Let us now discuss the appropriateness of parameters U_0, I_{cj0}, and R_0 used for the calculation. U_0 of a sintered Bi-2223 monofilament tape was reported to be 4.2×10^2 K (3.6×10^{-2} eV) at 5 K and magnetic field of 1 T parallel to the ab-plane.[26] Because Bi-2223 grains in the intermediate layer of the superconducting joint used in this study are weakly c-axis-aligned,[24,27] magnetic field (B = 1 T) is applied parallel to the ab-plane mainly. Thus, U_0 at 412 K (35.5 meV) is similar to that reported in 26). Considering that I_{loop} decayed from 65.3 A, I_{cj0} of 65.5 A would have a similar value. The R_0 of 40 nΩ is comparable to the normal resistance of about 3×10^{-8} Ω observed in our previous transport measurements at 4.2 K and 1 T using a Bi-2223 superconducting joint sample.[12]

V_j can be obtained by multiplying I_{loop} and R. Experimentally obtained and calculated V_j–I_{loop} are shown in Fig. 6.[28] In general, the current dependence of voltage (V–I) can be approximated by the power law model with an exponent n ($V \propto I^n$). It is known that this approximation is applicable to V–I dominated by flux creep.[19,20,29] The experimentally obtained V_j–I_{loop} ranging from 10^{-12} to 10^{-10} V, corresponding to $t > 10^4$ s where the decay of I_{loop} is dominated by flux creep, is well fitted to the power law model with $n = 84$. This n value is significantly higher

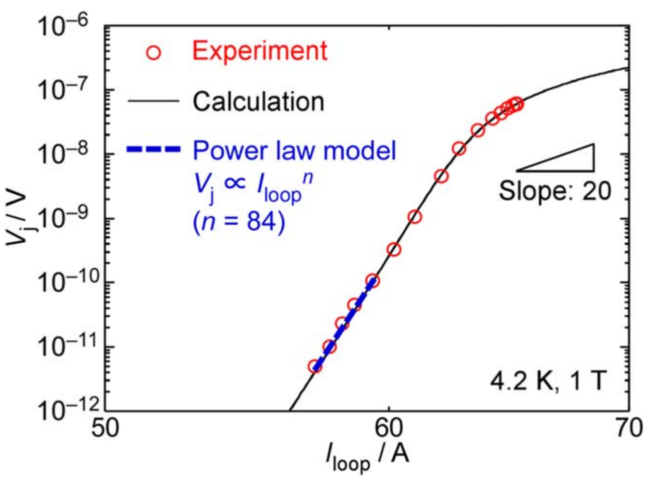

Fig. 6. I_{loop} dependence of V_j obtained by multiplying I_{loop} and R. Experimentally obtained V_j–I_{loop} ranging from 10^{-12} to 10^{-10} V corresponding to $t > 10^4$ s is well fitted to power law model with $n = 84$. n value of calculated V_j–I_{loop} is estimated to be 20 at approximately 10^{-7} V.

than that observed in our previous transport measurements described above, which was approximately 20 at V_j ranging from 10^{-8} to 10^{-7} V.[12] As shown in Fig. 6, the n value of the calculated V_j–I_{loop} is estimated to be 20 at approximately 10^{-7} V. This implies that a low n value is observed at high V_j owing to current sharing, whereas an intrinsic and high n value is observed at low V_j owing to flux creep.

Equations (6) and (7) imply that persistent-mode operation using superconducting joints at high temperatures is challenging. This is because relatively fast current decay and high R_j will be observed at high temperatures. In contrast, enhancing J_{c0} of a superconducting joint contributes to increasing U_0.[30,31] This may be effective in achieving a slower current decay and a lower R_j value. It has been reported that a high n value in the power law model provides a large $U_0/k_B T$.[19,20,29] An increase in the n value of a superconducting joint may also be effective.

In cases with a low I_{loop} or $T > 20$ K, the Anderson-Kim model is insufficient for describing the current decay phenomena. When I_{loop} value is lower than the maximum persistent current, which corresponds to I_c of the joint determined by a low criterion of V_j or R_j, Eq. (3) does not correctly describe V_j. This is because the relationship of $J \cong J_{c0}$ is usually assumed in flux creep described by Eq. (2). To describe E under conditions of $T > 20$ K, the collective flux creep model is generally used.[18–21] This model needs to be applied to interpret the current decay at high T. However, the current decay and time-dependent R_j will be described quantitatively considering the flux motion, including flux creep.

In summary, the time-dependent current and resistance of the Bi-2223 closed loop with the superconducting joint have been interpreted considering current sharing and flux creep at the joint. An approximation of the analytical solutions of the current and resistance after a sufficiently long time was obtained owing to the suppression of current sharing. It has also been demonstrated that the joint resistance is inversely proportional to the elapsed time, resulting in a low circuit resistance.

Acknowledgments This work was partly supported by the JST-Mirai Program Grant Number JPMJMI17A2 and JSPS KAKENHI Grant Numbers JP22K14482 and JP22H01522, Japan.

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