Test results of a REBCO superconducting switch for reducing temporal fluctuations in driven-mode

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Abstract. High-temperature superconducting magnets are generally driven by a power supply (driven mode), and temporal fluctuations of the power supply unit, such as ripple noise, directly affect the magnetic field stability. A method of suppressing such temporal instability by short-circuiting both ends of the coil with finite low-resistance joints, somewhat similar to a persistent current switch, has been proposed in order to form a closed loop having a large time constant, \(L/R\). In this research, we developed two types of REBCO superconducting switches (type-A and type-B). To obtain a high resistance during excitation, the type-A prototype switch was constructed with a non-inductive winding using mainly ordinary copper-coated REBCO tapes, and type-B switch used uncoated REBCO tapes toward application to emergency shutdown. For the type-B switch, at the end of the winding, copper-coated REBCO tapes were jointed to prevent degradation by exposure to moisture. The \(R-T\) and \(V-I\) characteristics of each switch when cooled with liquid nitrogen were tested. The type-A switch was applied to a test REBCO magnet, and the temporal stability of the magnetic field was evaluated under a conduction cooling configuration in the driven mode.

1. Introduction
A persistent current mode with a closed loop composed of a superconducting coil and a persistent current switch connected to both ends of the coil can improve the temporal stability of the coil's magnetic field. The temporal stability of the magnetic field depends on the time constant, \(L/R\), of the closed loop. The superconducting joint technique [1, 2], which has an extremely low resistance of about \(10^{-10}\) to \(10^{-12}\) \(\Omega\) or less between the low-temperature superconducting (LTS) wires such as NbTi and Nb3Sn, is already well established, and this technique enables a large time constant, \(L/R\), and has been widely applied to various LTS magnets, including NMR and MRI magnets that require extremely high temporal stability.

For REBCO high-temperature superconducting (HTS) magnets, superconducting joint techniques using REBCO tape wires have been studied extensively in recent years, and low-resistance joints have been successfully achieved by some research groups [3-5]; however, a joint technique that can achieve sufficient critical current and mechanical strength has not been established yet. The typical driven mode that constantly supplies the operating current to superconducting coils does not require these superconducting joints, but temporal instability of the current supplied from the power supply directly affects the temporal stability of the magnetic field. In particular, short-time fluctuations such as ripple noise are troublesome obstacles to achieving clear imaging in NMR and MRI. Therefore, various
countermeasures have been studied, such as highly stable power supplies, auxiliary power supplies, flux pumps, and secondary coil units [6].

Another method of suppressing such temporal instabilities by short-circuiting both ends of a coil with finite low-resistance joints, somewhat similar to a persistent current switch, has been proposed in order to form a closed loop, thereby resulting in a long time constant, \( L/R \), in superconducting magnets [7-9]. In this study, we developed two types of REBCO superconducting switches (type-A and type-B). To obtain high off-resistance during excitation, like a persistent current switch, a prototype of the type-A switch was constructed of a non-inductive winding formed of ordinary copper-coated REBCO tapes in a single-pancake coil shape. The off-resistance was 1 \( \Omega \) at 100 K, which was two-times higher than the protection resistance of 0.5 \( \Omega \) in the test described in Section 3. However, for user safety, practical magnets must be capable of emergency shutdown and degaussing immediately. In order to adapt to a superconducting switch to emergency shutdown, the superconducting switch needs a higher off-resistance because, if the off-resistance is of a similar order of magnitude to the protection resistance, part of the stored magnetic energy is consumed in almost the same manner as the protection resistance, so that a switch having a smaller heat capacity than the main coil has a high risk of burning out. Therefore, the type-B REBCO superconducting switch was mainly constructed of a non-inductive winding formed of uncoated REBCO tapes to further increase the resistance without increasing the size toward application to emergency shutdown. At the end of the winding, copper-coated REBCO tapes were jointed to prevent degradation by exposure to moisture. The off-resistance of the type-B switch was 8 \( \Omega \) at 100 K, which was about eight-times higher than the resistance of the type-A switch, and the outer diameter was reduced to about 0.8-times smaller than that of the type-A switch.

The \( R-T \) and \( V-I \) characteristics of each switch when cooled with liquid nitrogen were tested. The type-A switch was applied to a test REBCO magnet, which was developed in 2015 in a project supported by the Japan Agency for Medical Research and Development (AMED). This magnet had MRI model coils, a room-temperature bore diameter of 500 mm, and a rated magnetic field of 1.5 T [10] and was tested under a conduction cooling configuration so as to verify whether or not the switch could reduce short-time fluctuations of the magnet in the driven mode.

2. Type-A switch for prototype: specifications and test results with liquid nitrogen cooling

2.1. Specifications

The specifications of the type-A REBCO superconducting switch are shown in Table 1. Even if the off-resistance is 1 \( \Omega \), the required tape length is 38 m, assuming that the resistance per unit length of the coated copper is about 26.3 m\( \Omega \)/m at 100 K. Since it is difficult to place 38 m long REBCO tapes in a cryostat, the two REBCO tapes were non-inductively wound in a single-pancake coil shape, as shown in Figure 1. The two REBCO tapes were lap-jointed with solder at the innermost part of the single-pancake coil. The length of the lap joint was 100 mm. Polyimide insulation tape was co-wound with the two tapes, and the switch was impregnated with epoxy resin for filling the gaps acting as cooling paths. In an impregnated single-pancake coil, the radial thermal stress due to the cooling process degrades the REBCO coated conductor [11, 12], which has a very low delamination strength [13-16], and therefore, the polyimide insulation was coated with fluorine resin, which had a low adhesive strength to the epoxy resin [17].

2.2. Test results with liquid nitrogen cooling

The prototype type-A switch was slowly cooled by the cold nitrogen gas evaporating from liquid nitrogen until immersed in the liquid nitrogen. During the cooling process from room temperature, a constant current of 5 mA was supplied, and the \( R-T \) characteristics were measured to check the off-resistance. After that, the \( V-I \) characteristics were measured at 77 K to check the on-resistance and the degradation.

Figure 2 shows the \( R-T \) characteristics of the type-A switch. The resistance was 4.4 \( \Omega \) at room temperature, and the off-resistance was 1 \( \Omega \) at 100 K. From about 92 K, the resistance dropped rapidly,
and the switch transitioned to a superconducting (on) state. The $V$-$I$ characteristics at 77 K are shown in Figure 3 (a) and (b). Figure 3 (a) shows a linear plot below 0.005 mV, where the flux flow resistance was negligibly small compared to the off-resistance. The on-resistance in this low-current region was 4.2 nΩ from 0 A to 100 A. Figure 3 (b) shows a logarithmic plot above 115 A, where the voltage was divided by the tape length of 38 m. The $n$-value of the type-A switch was sufficiently high at 29 [16], which indicates that the windings of the switch had no degraded areas.

After the test with liquid nitrogen, a high-purity aluminum plate (thickness, 0.25 mm) was bonded to one side of the pancake with epoxy resin for conduction cooling, and a heater was attached to the aluminum plate near the pancake.

Table 1. Specifications of type-A REBCO superconducting switch.

| Parameter                  | unit | Value |
|----------------------------|------|-------|
| Tape type                  |      | Copper-coated REBCO tapes |
| Tape width                 | mm   | 4     |
| Tape thickness             | mm   | 0.1   |
| Coated copper thickness    | mm   | 0.02  |
| Insulation tape thickness  | mm   | 0.06  |
| Number of bundles          |      | 2     |
| Inner diameter             | mm   | 50    |
| Outer diameter             | mm   | 100   |
| Number of turns            |      | 80×2  |
| Tape length                | m    | 19×2  |
| On resistance at 77 K      | nΩ   | 4.2   |
| Off resistance at 100 K    | Ω    | 1     |

Figure 1. Type-A superconducting switch composed of a non-inductive winding formed of copper-coated REBCO conductors.

Figure 2. $R$-$T$ characteristics of the type-A switch at 5 mA.
3. Design of the experimental circuit and test results in driven-mode

3.1. Design of the experimental circuit

The type-A switch was applied to the test REBCO magnet, and the temporal stability of the magnetic field was evaluated under a conduction cooling configuration to verify whether or not the switch could reduce short-time fluctuations of the magnet. The test REBCO magnet was developed in 2015 in a project supported by the Japan Agency for Medical Research and Development (AMED), and had MRI model coils, a room temperature bore diameter of 500 mm, and a rated magnetic field of 1.5 T at 192 A [10].

Prior to the test, we designed a closed-loop circuit formed by short-circuiting both ends of the main coil of the test magnet with the type-A switch. Figure 4 shows a schematic diagram of the experimental circuit. The temporal stability of the magnetic field is dependent on the time constant, \( L/R \), of the closed loop formed by the main coil and the switch, where \( L \) is the inductance of the main coil and \( R \) is the sum of the resistances of the main coil, \( R_{\text{coil}} \), the bus-bar, \( R_{\text{bus}} \) and the switch, \( R_{\text{switch}} \). The main coil was composed of six units using 60 single pancake coils in total, and had an inductance of 12.4 H. The resistances of the six units were 4.6 \( \mu \Omega \), and the joint resistances between the units were 1.3 \( \mu \Omega \), so that the total resistance of the main coil \( R_{\text{coil}} \) was 5.9 \( \mu \Omega \). These resistances easily change with the main coil temperature under the conduction cooling configuration, and therefore, the main coil temperature was stabilized at 8.5 K with heater as shown in figure 4 [9]. Also, the resistance of the bus-bar \( R_{\text{bus}} \) was 1.1 \( \mu \Omega \). On the other hand, the on-resistance of the switch \( R_{\text{switch}} \) was 4.2 n\( \Omega \) even at 77 K. In this case, the total resistance value of the closed loop, \( R \), was 7.0 \( \mu \Omega \), and the time constant \( L/R \) was quite long, at 492 hours. However, when the operating current was supplied, since the current distribution of the coil side and the switch side is determined by the inverse ratio of \( R_{\text{switch}} \) to \( R_{\text{coil}} \) and \( R_{\text{bus}} \), the current flowing through the coil side was assumed to be only 192 A \( \times \) 4.2 n\( \Omega \)/7.0 \( \mu \Omega \) \( \approx \) 0.12 A.

Therefore, a stainless-steel 650 \( \mu \Omega \) auxiliary resistance, \( R_{\text{aux}} \), was added in series to the switch side as a finite resistance having close to 100-times the resistance on the coil side. In this case, the current flowing through the coil side was assumed to be 192 A \( \times \) 650 \( \mu \Omega \)/657 \( \mu \Omega \) \( \approx \) 190 A, and the time constant of the closed loop circuit, \( L/R \), was 5.2 hours, which is still longer than the short-term fluctuations of the power supply unit, such as ripple noise. Although the supplied current from the power supply can be increased to adjust the current flowing through the coil side to 192 A, this was not done in this experiment.
3.2. Operation procedure
The operation procedure is shown in Figure 5. Similar to the operation with the persistent current switch, a heater was put on the REBCO superconducting switch, and the temperature of the switch was raised to about 100 K to turn it off. Then, the main coil was energized and overshoot to 195 A in order to reduce the screening-current-induced magnetic field and held in this state for 1 hour. After that, the main coil was de-energized to the rated 192 A, the heater was turned off, and the switch was allowed to cool down to the on state. The magnetic field was measured with an NMR probe placed at the center of the main coil. The temporal stability of the magnetic field was evaluated after 56 hours, which was the total of 4 hours for energization and overshooting, and 52 hours, that is, about 10-times the time constant of the closed loop circuit, until the current distribution was balanced.

3.3. Evaluation of the temporal stability of the magnetic field
Figure 6 shows the time variation of the change in magnetic field. For comparison, the experimental data obtained without the short-circuiting using the REBCO superconducting switch (type-A) is also shown in Figure 6. Without the short-circuiting, the short-time fluctuation was about 0.5 ppm, whereas with the short-circuiting, it was reduced to 40%, that is, to 0.2 ppm. From this result, it was verified that the closed-loop formed by the short-circuiting using the REBCO superconducting switch was effective to improve the temporal magnetic field stability of the REBCO magnet.
Figure 6. Time variation of the magnetic field change with/without the short-circuiting using the REBCO superconducting switch.

4. Type-B switch for higher off-resistance: specifications and test results with liquid nitrogen cooling

4.1. Specifications
Practical magnets must be capable of emergency shutdown and degaussing immediately for user safety. In order to adapt a superconducting switch to emergency shutdown, it needs to have a higher off-resistance because, if the off-resistance is close to the order of the protection resistance, part of the stored magnetic energy is consumed in almost the same manner as the protection resistance, so that a switch having a smaller heat capacity than the main coil has a high risk of burning out. A simple solution is to increase the tape length according to the designed off-resistance, but this increases the size of the switch, so that it takes a longer time or higher heater output to turn off the switch. If the designed off-resistance is $8\, \Omega$, the length of copper-coated REBCO tapes used for the type-A switch becomes about 304 m and the outer diameter of the switch increases to about 251 mm.

Therefore, the type-B switch was mainly constructed by uncoated REBCO tapes which had a high off-resistance per unit length of about $0.93\, \Omega/m$ at 100 K, which was almost 35-times higher than the off-resistance of the copper-coated REBCO tapes. However, at the end of the winding, which means the outermost 12 turns in the winding, copper-coated REBCO tapes were jointed to prevent degradation by exposure to moisture, where the length of each lap joint between the uncoated and copper-coated REBCO tapes was 90 mm. Table 2 shows the specifications of the type-B switch, and Figure 7 shows a photograph of the switch. Similarly to the type-A switch, the two REBCO tapes were jointed with solder at the innermost part of the single-pancake coil, and the length of the lap joint between the copper-coated REBCO tapes was 90 mm.

4.2. Test results with liquid nitrogen cooling
The type-B switch for higher off-resistance was slowly cooled down and tested in the same way as the type-A switch. The $R$-$T$ characteristics were measured to check the off-resistance, and the $V$-$I$ characteristics were measured at 77 K to check the on-resistance and the degradation.

Figure 8 shows the $R$-$T$ characteristics of the type-B switch. The resistance was 20 $\Omega$ at room temperature, and the off-resistance was 8 $\Omega$ at 100 K, which was about 8-times greater than the resistance of the type-A switch while the outer diameter was reduced to about 0.8-times. From about 92 K, the resistance dropped rapidly, and the switch transitioned to a superconducting (on) state. The $V$-$I$ characteristics at 77 K are shown in Figure 9 (a) and (b). Figure 9 (a) shows a linear plot below
0.005 mV, where the flux flow resistance was negligibly small compared to the off-resistance. The on-
resistance in this low-current region was 130 nΩ from 0 A to 80 A. Figure 3 (b) shows a logarithmic
plot above 90 A, where the voltage was divided by the tape length of 21 m. Also the linear component
derived from the on-resistance was subtracted to check the n-value. The n-value of the type-B switch
was sufficiently high at 32, which indicates that the windings of the switch had no degraded areas,
even though uncoated REBCO tapes were used.

| Parameter                     | Unit | Value       |
|-------------------------------|------|-------------|
| Tape type                     |      | uncoated REBCO tapes and copper-coated REBCO tapes (outermost 12 turns) |
| Tape width                    | mm   | 4           |
| Tape thickness                | mm   | 0.55        |
| Silver layer thickness        | mm   | 0.003       |
| Insulation tape thickness     | mm   | 0.06        |
| Number of bundles             |      | 2           |
| Inner diameter                | mm   | 50          |
| Outer diameter                | mm   | 77          |
| Number of turns               |      | 41×2 (uncoated tapes) and 12×2 (copper-coated tapes) |
| Tape length                   | m    | 7.8×2 (uncoated tapes) and 2.7×2 (copper-coated tapes) |
| On resistance at 77 K         | nΩ   | 130         |
| Off resistance at 100 K       | Ω    | 8           |

Figure 7. Type-B superconducting switch composed of a non-inductive winding with REBCO coated-conductors.

Figure 8. R-T characteristics of the type-B switch at 10 mA.
Figure 9. $V$-$I$ characteristics of the type-B switch: (a) linear plot below 0.005 mV, and (b) logarithmic plot above 90 A where the voltage was divided by the tape length of 21 m. Also, the linear component derived from the on-resistance was subtracted to check the n-value.

5. Conclusion
Two types of REBCO superconducting switches (type-A and type-B) were developed. The prototype type-A switch was constructed of a non-inductive winding using ordinary copper-coated REBCO tapes and the type-B switch was constructed using uncoated REBCO tapes toward application to emergency shutdown.

The $R$-$T$ and $V$-$I$ characteristics of each switch with liquid nitrogen cooling were tested. It was confirmed that both the type-A and type-B switches achieved the designed off-resistance. The off-resistance of the type-B switch was 8 $\Omega$ at 100 K, which was about 8-times greater than the resistance of the type-A switch, and the outer diameter was reduced to about 0.8-times. Also, the n-values were sufficiently high, confirming that the switches had no degraded areas.

The type-A switch was applied to a test REBCO magnet, and the temporal stability of the magnetic field was evaluated under a conduction cooling configuration in the driven mode. The short-time fluctuation was reduced to 40%, that is, to 0.2 ppm, compared to the case without the short-circuiting using the switch. This indicates that the closed loop formed by the short-circuiting using the REBCO superconducting switch was effective to improve the temporal magnetic field stability of the REBCO magnet.

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