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# Development of an intra-Layer No-insulation (LNI) REBCO Coil Implemented with a Resistance-Controlled (RC) Interface

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***Abstract*— The intra-Layer No-Insulation (LNI) method achieves self-protection characteristics against quenching in a layer-wound REBCO coil, owing to a current bypass function associated with the copper sheet inserted in each layer. The self-protection is strongly influenced by the electrical contact resistivity ($\rho_{ct}$) of the interface between conductors and copper sheets. In particular, a coil requires a high $\rho_{ct}$ value, typically of the 100 mΩcm$^2$-class. However, the $\rho_{ct}$ value of a coil substantially changes due to external disturbances such as thermal cycles and electromagnetic forces. Therefore, it is vital to develop a technology to form an interface that provides a desired $\rho_{ct}$ value and that is stable against external disturbances. In the present work, we developed a basic method to form a resistance-controlled (RC) interface with a layer thickness as thin as ~30 µm, using epoxy resin mixed with conductive and insulating fillers, which respectively act as current bypassing paths and spacers. A certain value of the mixing ratio of the conductive fillers provides a target $\rho_{ct}$ value from a wide range from 1 mΩcm$^2$ to 1,000 mΩcm$^2$. An RC interface-implemented LNI-REBCO coil exhibits a stable $\rho_{ct}$ value under thermal cycles and self-protection against an overcurrent quench in liquid nitrogen.**

***Index Terms*— Epoxy resin, contact resistivity, intra-Layer No-insulation (LNI) REBCO coil, quench-protection.**

## I. Introduction

The layer winding method is suitable for high-temperature superconducting (HTS) magnet applications that need stable and homogeneous magnetic fields such as NMR and MRI systems. The intra-Layer No-Insulation (LNI) method [1] is a promising method that provides self-protectiveness to a coil against quenching at a high current density. This is a simple winding method where a one-sided insulated copper sheet is inserted layer by layer, as a current bypassing circuit, when winding uninsulated HTS conductors. The effectiveness of the method was demonstrated by a small LNI-REBCO coil surviving from quenching at a conductor current density of 723 A/mm$^2$ under 31.4 T [2].

As is the case for turn-to-turn contact resistance (or resistivity) of a no-insulation (NI)-REBCO pancake coil [3–7] the contact resistivity $\rho_{ct}$ between the conductors and the inter-layer copper sheets is a key parameter of an LNI-REBCO coil. The $\rho_{ct}$ value greatly influences the self-protection characteristics of an LNI-REBCO coil [2]. When the $\rho_{ct}$ value is too high, the coil suffers from localized overheating, leading to burnout. On the contrary, when the $\rho_{ct}$ value is too low, high-speed quench propagation with an inductive current exchange between turns gives a high induced current and excessive electromagnetic forces, resulting in mechanical damage. Therefore, the appropriate $\rho_{ct}$ value for a coil must be implemented in the winding. For example, in a previous work, we showed that a stand-alone LNI-REBCO coil for a 900 MHz (21.1 T) NMR magnet we aim to develop requires a 100 mΩcm$^2$-class ultra-high $\rho_{ct}$ value [8].

However, it is difficult to obtain a desired $\rho_{ct}$ value in a dry-wound LNI-REBCO coil, and the situation is complicated by a further problem that the $\rho_{ct}$ value of a coil increases by an order of magnitude from the initial value as a result of external disturbances such as thermal cycles and charge/discharge processes [2, 9].

For these reasons, for an LNI-REBCO coil, it is vital to develop a current bypassing interface technology that (i) allows the selection of a $\rho_{ct}$ value from a wide range of several orders of magnitude, including an ultra-high value of 100 mΩcm$^2$-class, and (ii) retains the coils contact state and the $\rho_{ct}$ value even while it experiences thermal cycles and electromagnetic forces. It is also important that (iii) the interface is thin and does not harm the packing factor, or the coil current density.

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To achieve these properties, we focused on epoxy resin recently used for no-insulation pancake REBCO coils [10–12]. The selection of the filler material and mixing ratio possibly provide controllability of the $\rho_{ct}$ value of an LNI-REBCO coil although a 100 μΩcm$^2$-class ultra-high value has not been reported in previous works.

Thus, in the present work, we developed a method to form a resistance-controlled (RC) interface between the REBCO conductors and the copper sheets using filler-impregnated epoxy resin, and demonstrated an RC interface-implemented LNI-REBCO coil (RC-LNI-RECO coil). Fig. 1(a) shows a schematic cross-section of an RC-LNI-REBCO coil. One-sided polyimide-laminated copper sheets are electrically connected to the surface of the REBCO conductors through the RC interface. We conducted (1) short sample interface model experiments to investigate the effects of the type and mixing ratio of the filler on the $\rho_{ct}$ value and (2) experiments on an RC-LNI-REBCO coil in liquid nitrogen.

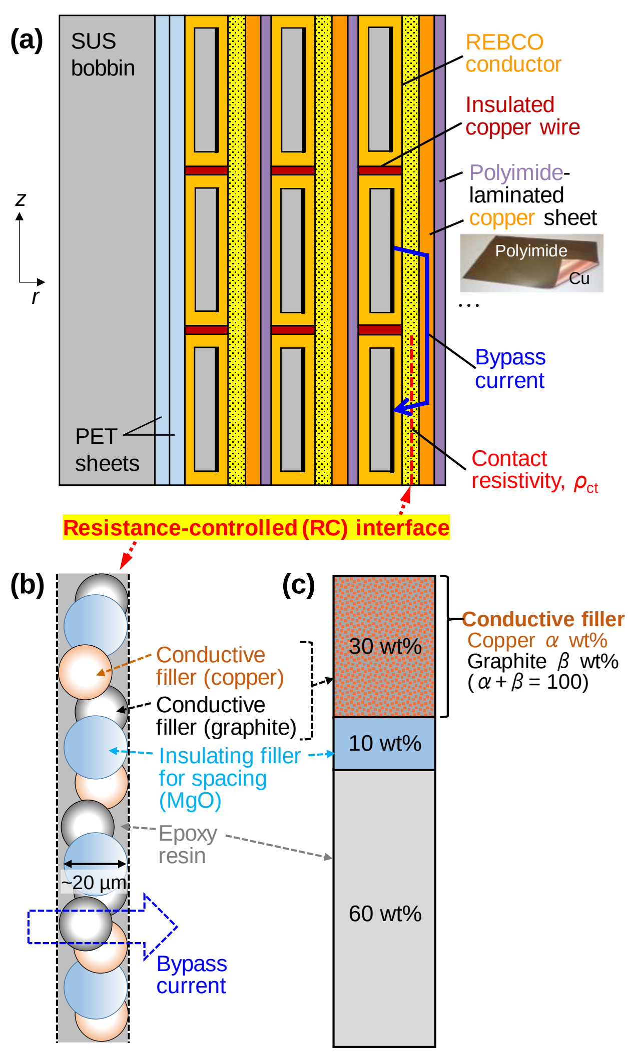


Fig. 1(a) Schematic of the cross-section of a resistance-controlled (RC) interface-implemented LNI-REBCO coil (RC-LNI-REBCO coil) proposed in the present work. (b) Schematic of a cross-section of the RC interface. (c) A component mixing ratio of the filler-impregnated epoxy resin for the RC interface.

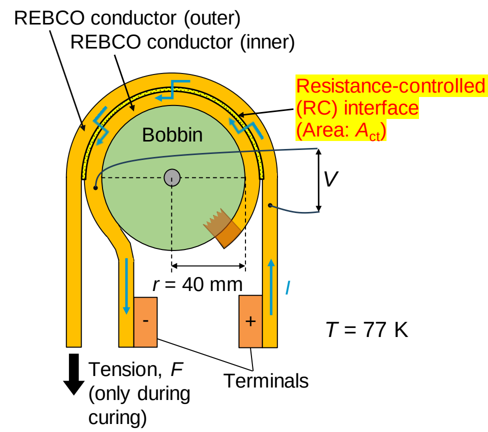


Fig. 2 Schematic of the short sample interface model experiment for current bypassing.

## II. Short Sample Interface Model Experiment

### A. Experimental

Fig. 2 shows a schematic of the short sample interface model for current bypassing. Although the interface in an actual coil is formed between the conductors and the copper sheets (see Fig. 1(a)), here we employed a conductor-to-conductor model to measure $\rho_{ct}$ values with high accuracy without being affected by the in-plane resistance of the copper sheet. Two REBCO conductors (SuperPower Inc. SCS4050-AP, 4.03 mm-width, 0.097 mm-thick) were wound half-turn over the GFRP bobbin (80 mm diameter) and each of the REBCO layers faced the outer direction. One end of the inner conductor was soldered to the negative terminal and the other was taped on the bobbin. For the outer conductor, one end was soldered to the positive terminal, and the other end was soldered to a weight (1.0 kg) to add a tension $F$.

After mounting the samples, we cleaned the surface of the REBCO conductors with ethanol and painted the epoxy. We prepared two types of filler-impregnated epoxy and their compositions are described in the following section. The filler-impregnated epoxy did not show electrical conductivity in a bulk state unlike typical conductive epoxy due to the small amount of the conductive filler mixed in. This epoxy adhesive provided electrical conductivity when it became a thin layer sandwiched by conductors, in which situation a pressure by the conductors made current paths of conductor-fillers-conductor. The samples were heat-treated at 80°C for 3 hours [13] in an electric furnace to cure the epoxy with the outer conductor tensioned.

After the heat treatment, we measured the voltage across the resistive interface $V$ (see Fig. 2) in liquid nitrogen with a test current of $I = 2$ A. The $\rho_{ct}$ value was determined by the following equation.

$$\rho_{ct} = \frac{V}{I} A_{ct} = \frac{V}{I} \pi r w \qquad (1)$$

Here, $A_{ct}$, $r$ and $w$ are the area of the interface, the radius of the bobbin and the width of the conductor.

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*B. Sample I (conductive filler)*

At first, we prepared epoxy resin with a single type of conductive filler. Epoxy resin CTD-521 (Composite Technology Development Inc.) was used as binder, which has a long pot-life and low thermal contraction coefficient [14]. For this sample, we employed 5 μm small diameter powders for conductive filler to pursue the thinness of the interface. We made two samples for each preparation condition.

Fig. 3 (a) shows the $\rho_{ct}$ value of the formed RC interface versus the percentage of conductive filler content. We could obtain 100 mΩcm$^2$-class $\rho_{ct}$ values with graphite filler and thin RC interface of 11–18 μm-thickness measured from cross-section pictures by an optical microscope. However, there is no dependence of the conductive filler content on the $\rho_{ct}$ values in any cases of copper or graphite filler in Fig. 3(a). In addition, in the case of graphite filler, the $\rho_{ct}$ value deviates by several orders of magnitude between two samples even under the same preparation condition. Cross-sectional observations on several samples showed that there were areas where the opposing conductors were in proximity to each other and we supposed that random direct contacts caused the large deviation of the $\rho_{ct}$ value.

*C. Sample II (conductive and insulating fillers)*

With reference to the results of Sample I, we came up with the idea of introducing spacing fillers with a relatively larger diameter, which occupy a certain thickness in the interface at the slight expense of thinness. Fig. 1(b) shows a schematic of the RC interface of the samples. It is composed of 60 wt% epoxy resin (CTD-521) as binder, 30 wt% conductive fillers, and 10 wt% insulating filler for spacers as shown in Fig. 1(c). We used a mixture of copper and graphite powders with a relatively larger particle size of about 20 μm, as the conductive fillers, and the insulating filler (MgO) with a particle size of ~20 μm as the spacing filler. This MgO filler especially plays the role to form an epoxy resin layer with a uniform thickness and prevents direct contacts between the conductors (or the conductors and the copper sheets in a coil).

Fig. 3(b) shows the results on the measurement of the samples. The vertical axis shows the contact resistivity ($\rho_{ct}$) and the horizontal axis shows $\alpha$, the percentage of copper content in the total conductive fillers of copper and graphite (see Fig. 1(c)). Each point is the average value of six samples using the same preparation conditions. The $\rho_{ct}$ value decreases as $\alpha$ increases. The maximum $\rho_{ct}$ value is 1,455 mΩcm$^2$ for $\alpha = 0$ wt% (copper 0% / graphite 100%) and the minimum value is 0.81 mΩcm$^2$ for $\alpha = 100$ wt% (copper 100% / graphite 0%). The data demonstrate that the $\rho_{ct}$ value can be controlled by changing the mixing ratio in the conductive filler over a wide value range of orders of magnitude including the 100 mΩcm$^2$-class high value. The micrograph in Fig. 4 shows a cross-section of a sample with $\alpha = 5$ wt%, showing the thickness of the resistive interface is as thin as ~30 μm. Although it is thicker than Sample I, it is still thinner than the conventional Kapton wrapping insulation.

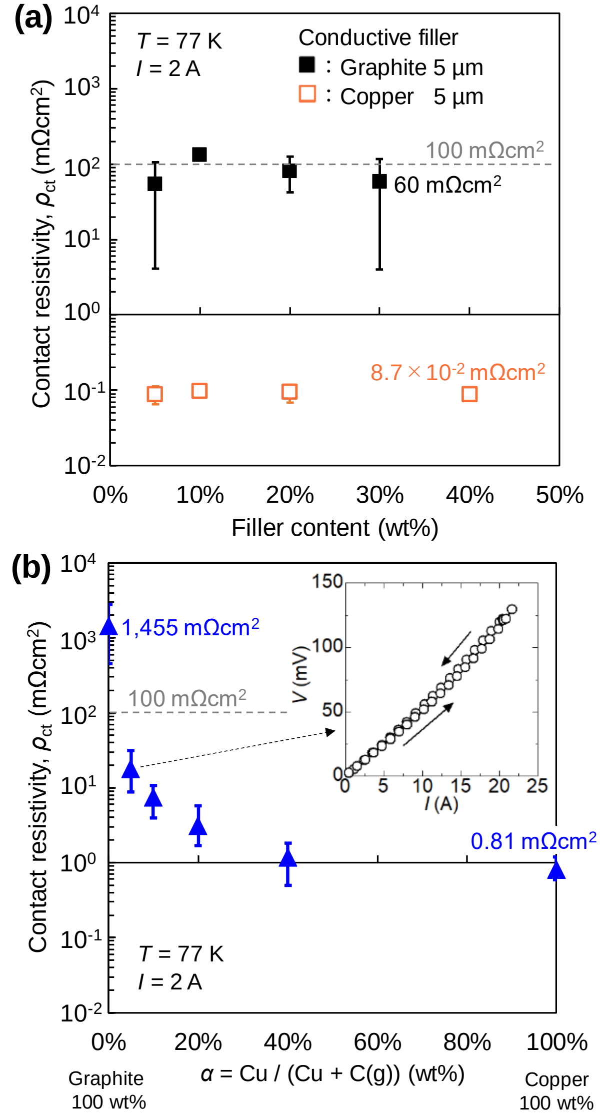


Fig. 3 Measured contact resistivity $\rho_{ct}$ values for the current bypassing interface model experiment at 77 K obtained under a test current of 2 A. Each point and error bar respectively show the average value and the maximum/minimum values. (a) $\rho_{ct}$ values for interfaces with epoxy resin with a single type of conductive filler without insulating filler. The horizontal axis shows the conductive filler content ratio in the overall resin. (b) $\rho_{ct}$ values for the resistance-controlled (RC) interface as a function of the copper content in the total conductive fillers, $\alpha$ (see the definition in Fig. 1(c)).

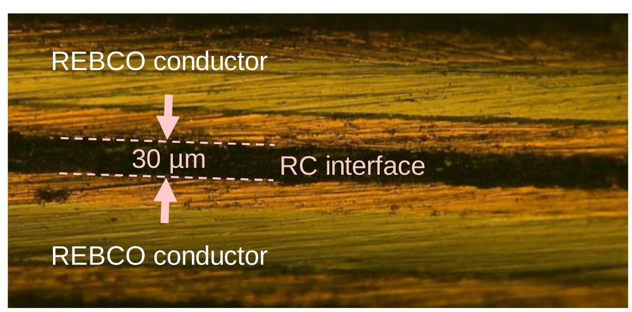


Fig. 4 Cross-section of a sample for the RC interface model with $\alpha$ = 5% (copper 5% / graphite 95%).

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## III. Coil Experiment

We fabricated an RC-LNI-REBCO coil and tested it in liquid nitrogen to investigate the behavior of the $\rho_{ct}$ value under conditions of thermal cycling and over-current quenching.

### A. Experimental

Table I shows the specifications of the RC-LNI-REBCO coil. The winding tension $F_w$ was 1.0 kgf and the conductor was wound with the REBCO layer facing the outer direction to obtain similar conditions as the model experiment. The ratio of the insulating (MgO) filler was 10 wt% and that of the conductive filler was 30 wt% in which $\alpha$ = 5 wt%. We painted the epoxy resin on the copper side of a polyimide-laminated copper sheet and inserted into every layer as shown in Fig. 1(a). In addition, we co-wound a polyimide-coated copper wire (0.039 mm-width, 0.139 mm-thick) as inter-turn insulation in each layer, preventing direct contacts between turns. The averaged thickness of the epoxy adhesive layer was estimated to 29 µm; it was obtained from the outer diameter of each layer measured during winding and the nominal thicknesses of the conductor and the polyimide-laminated copper sheet. The value is almost equals to the thickness directly observed for the short sample shown in Fig. 4. After winding, the coil was kept at room temperature for three days to cure the epoxy resin inside the winding [13].

A Hall sensor was installed at the coil center to measure the magnetic field ($B_{center}$). A pair of voltage taps were attached to the ends of the winding to measure the coil voltage ($V_{coil}$).

The sequence of (i) cooling to 77 K by immersing in liquid nitrogen, (ii) charging to 2 A and power supply shutdown, (iii) coil $I_c$ measurement, and (iv) warming up to room temperature was repeated six times. A $\rho_{ct}$ value was obtained by fitting a simulated $B_{center}$ curve to a measured one obtained from the power supply shutdown. For this fitting, we used an equivalent circuit model of an LNI coil [1], in which the $\rho_{ct}$ value is uniform over the winding.

Table I
Parameters of an RC interface- implemented LNI-REBCO coil

| | Unit | Values |
|---|---|---|
| REBCO conductor | – | SuperPower SCS4050-AP |
| Conductor Width/Thickness | mm | 4.03 / 0.094 |
| Conductor critical current at 77 K | A | 97 |
| Inner diameter | mm | 50.15 |
| Outer diameter | mm | 52.60 |
| Coil height | mm | 36.54 |
| Number of turns | – | 72 (9 turns × 8 layers) |
| Winding tension, $F_w$ | kgf | 1.0 |
| Coil constant | mT A$^{-1}$ | 1.51 |
| Coil critical current, $I_c$, at 77 K | A | 72.4 |
| Self-inductance | mH | 0.227 |

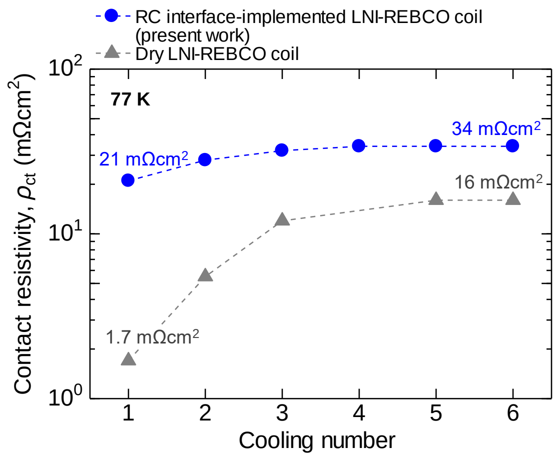


Fig. 5 Change in the contact resistivity, $\rho_{ct}$ values of LNI-REBCO coils at 77 K under repeated thermal cycles. Closed circles: data obtained in the present work for the RC-LNI-REBCO coil in Table I. Closed triangles: data from ref [9]. for a dry-wound LNI-REBCO coil (ID: 50 mm, 10 turns × 8 layers, winding tension: 2.0 kgf).

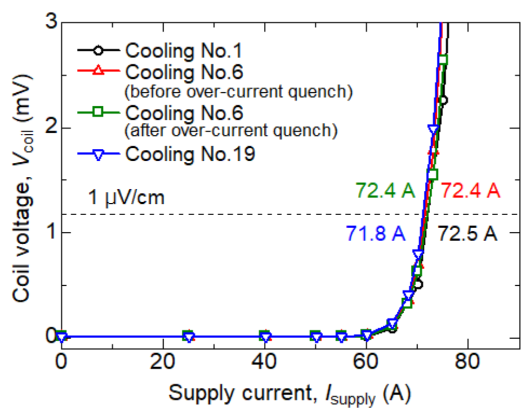


Fig. 6 Thermal cycle dependency of the voltage-current characteristics of the RC-LNI-REBCO coil.

### B. The values of $\rho_{ct}$ and $I_c$ under thermal cycles

Fig. 5 shows the history of the $\rho_{ct}$ values of LNI-REBCO coils under repeated thermal cycles. The result obtained in the present coil is indicated by the closed circles. For comparison, the result of a dry-wound LNI-REBCO coil [9] is also shown by the closed triangles, which will be discussed later. The initial $\rho_{ct}$ value of the present coil of 21 mΩcm$^2$ is close to the average value of 18 mΩcm$^2$ for the short sample interface model samples of $\alpha$ = 5 wt%. The $\rho_{ct}$ value increased with the thermal cycles and saturated at 34 mΩcm$^2$, which is 1.62 times higher than the initial value.

Fig. 6 shows voltage-current curves of the present coil along with thermal cycling data. The voltage-current curve for the 6th cooling cycle agrees with the initial curve of the 1st cooling cycle, showing no degradation in the coil performance.

### C. Over-current quench experiment

After the measurements described above, we turned to conduct an over-current quench experiment in liquid nitrogen. Fig. 7(a) shows the power supply current $I_{supply}$ (solid line), the coil voltage $V_{coil}$ (open circle) and central magnetic field $B_{center}$

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(dashed line) versus time during the experiment. Fig. 7(b) shows an enlarged window for the quenching process. $V_{coil}$ sharply increased and $B_{center}$ decreased at $t$ = 129 s ($I_{supply}$ = 87.5 A: 120% of the coil $I_c$) while $I_{supply}$ continually ramped up. This behavior shows that the current in quenching turns is bypassing into the facing copper sheets through the RC interface and the current bypassing zone is propagating. Subsequently, $V_{coil}$ is increasing to power supply shut down due to overvoltage. After the quench, we charged the coil again without any warming up to obtain the $\rho_{ct}$ value and the voltage-current curve. The voltage-current curve agreed with that before the quench, which demonstrates that current bypassing through the RC interface protected the coil. On the other hand, the $\rho_{ct}$ value dropped to 6 mΩcm$^2$ from 34 mΩcm$^2$.

We further continued to repeat $\rho_{ct}$ measurements along with thermal cycles and an over-current quench (see Fig. 8: cooling numbers 6-10). The $\rho_{ct}$ value, which dropped to 6 mΩcm$^2$ after

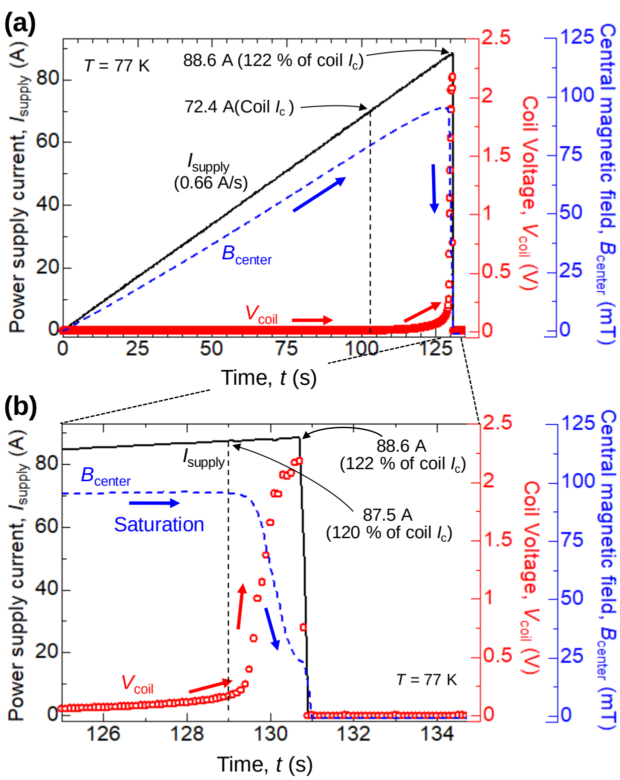


Fig. 7 Results of an over-current-induced quench in liquid nitrogen on the RC-LNI-REBCO coil: (a) overall results and (b) quenching process.

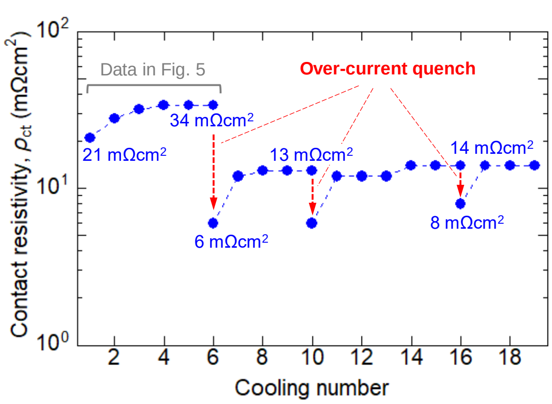


Fig. 8 Change in the RC-LNI-REBCO coil $\rho_{ct}$ value caused by thermal cycles and over-current-induced quenches.

the quench, increased to 13 mΩcm$^2$ and saturated. Again, the $\rho_{ct}$ value dropped by the second quench and increased along with thermal cycles and then saturated. These drops, increases, and saturations of the $\rho_{ct}$ value repeatedly occurred along with thermal cycles and quenches. Thus, except for the drop in the $\rho_{ct}$ value after the initial quench, the subsequent changes in the $\rho_{ct}$ value are reversible.

## IV. Discussions

### A. Current transport characteristics of the RC interface

For designing the protection scheme of an LNI-REBCO coil, it is important that the $\rho_{ct}$ value is constant with respect to the bypassing current i.e. the voltage-current characteristics are ohmic.

Fig. 9 shows voltage-current characteristics obtained for a simple direct contact model between REBCO conductors by using an experimental setup similar to that in Fig. 2. In this model, the interface between the conductors was not bonded and just mechanically contacted. The current was increased/decreased at a rate of 2.6 A/s and the voltage between the conductors was measured with the tension kept at 6.0 kgf. The current was not held during each process. The voltage increased linearly with the current up to 5 A. For a higher current, however, the voltage did not increase monotonically with the current and saturated. When the current was ramping down from 80 A after ramping up, the voltage was showing lower values compared to the ramping process, i.e. the voltage-current characteristics showed hysteresis, and therefore the $\rho_{ct}$ value was not constant (or not ohmic). Although we cannot completely explain the mechanism, a $Cu_2O$ film on the copper surface of the conductor might dominate this peculiar behavior. A $Cu_2O$ film has nonlinear voltage-current characteristics independent of its thickness, and its resistance decreases as the current increases [15] which can cause the characteristics seen in Fig. 9. With such characteristics, a high inductive current is induced during a coil quenching and the risk of overstressed damage on a coil increases. It makes it difficult to design a protection scheme that considers such complicated voltage-current characteristics including nonlinearity and hysteresis.

On the other hand, as seen in the inset in Fig. 3(a), the current-voltage characteristics up to 20 A of the RC interface with $\alpha$ = 5% show a linear relationship, i.e. the resistive interface behaves ohmic. In the RC interface, the copper surfaces of the conductors are covered by epoxy resin and the resistances of the conductive fillers dominate the voltage-current characteristics or resistance. This characteristic is effective in suppressing an induced current during quenching and is useful when designing a coil protection scheme.

### B. Effect of thermal cycles on the $I_c$ and $\rho_{ct}$ values of coils

A previous work [9] showed that the $\rho_{ct}$ value of a dry-wound LNI-REBCO coil gradually increases by about 10 times from the initial value and saturates along with repeated cooling–warming up cycles (see the closed triangles in Fig. 5).

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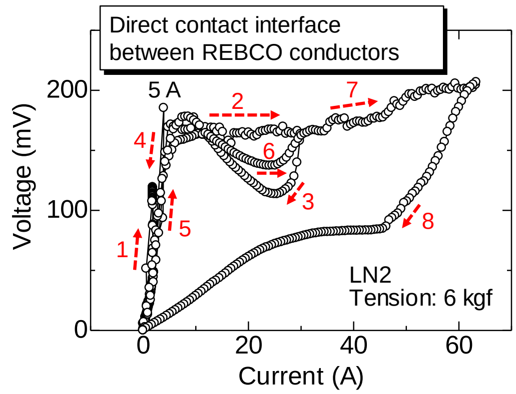


Fig. 9 Voltage-current characteristics of a direct contact interface between REBCO conductors in liquid nitrogen under charging up and down cycles. The measurement was made on a model experiment similar to that in Fig. 2.

This behavior was assumed due to irreversible deformations of the interlayer copper/polyimide sheets in gaps between the layers.

On the other hand, although the RC-LNI-REBCO coil (see the closed circles in Fig. 5) showed a slight increasing trend, the change rate was as low as ×1.62 (from 21 mΩcm$^2$ to 34 mΩcm$^2$). This stability is probably provided by the steady interface condition in which the conductors and the copper sheets are bonded by epoxy resin. A slight increase in the $\rho_{ct}$ value might be due to cracks in the epoxy resin formed during cooling. Thermal contraction from room temperature to 77 K for copper and Hastelloy are 0.31 % [16] and 0.25 % [17], respectively. In contrast, thermal contraction for the epoxy resin including the fillers is 0.82 % estimated from the densities and the thermal contractions of each component [13, 18, 19, 20], approximately three times larger than those for the components of the conductor. The mismatch of the contractions might cause cracks in the epoxy resin and reduce the $\rho_{ct}$ value.

Through the thermal cycles and over-current quenches, we did not observe any significant change in the voltage-current curves of the present coil (see Fig. 6). It is known that an epoxy-impregnated REBCO coil shows degradation in its performance due to delamination of a conductor from thermal contraction stresses during cooling [21,22]. An RC-LNI-REBCO coil, as proposed in the present work, does not show such degradation since each layer is mechanically decoupled by the interlayer sheet although the turns in each layer are bonded by epoxy resin.

### *C. Issues to be addressed for the present method for applying to HTS magnet at high current densities*

In the present paper, we have demonstrated results for a resistance-controlled (RC) interface with a layer thickness of ~30 µm and a selectable $\rho_{ct}$ value from a range of 1–1,000 mΩcm$^2$, which provides a current bypassing function for a LNI-REBCO coil. A stable and controlled $\rho_{ct}$ in an LNI-REBCO coil can be obtained by using the RC interface developed in this study. The $\rho_{ct}$ value can be selected from a wide range of orders of magnitude by changing the mixing ratio in the conductive fillers. This enables us to control quench propagation, temperature rise and induced currents by selecting the appropriate $\rho_{ct}$ value for each part inside a coil [23]. This is similar to composing a protection circuit by selecting a protection resistor for each coil section in the conventional superconducting magnet technology [24,25]. Based on these results, here we will discuss the issues to be addressed for the present method to be applied to a HTS magnet operated at a high current density.

In the present work, the experiments were conducted only in liquid nitrogen at 77 K. However, the operating temperature of a magnet can be 4–20 K for a high current density operation. Since the temperature of the coil rises from the operating temperature during quenching, we need to obtain a wide range temperature dependence of the $\rho_{ct}$ value of the RC interface for designing protection schemes.

The coil current density during an over-current quench for the present coil was as low as 141 A/mm$^2$. However, a coil has to be operated at a much higher current density >300 A/mm$^2$ to make the magnet reasonably compact. Therefore, the verification of the self-protectiveness against a quench at a high current density in liquid helium or conductive cooling must be conducted in combination with a numerical analysis.

In addition, such high current density operation imposes high compressive and hoop stresses under rotation forces by screening currents [26–28]. Stress analysis and coil tests are also important development items.

For shorter cooling time in the case of conduction cooling, thermal conductance between the conductors and the inter-layer sheets is important. For the RC interface, bonding by epoxy resin, including thermal conductive fillers, is expected to provide high thermal conductance. In particular, MgO has a high thermal conductivity, typically >1,000 W/mK in the range of 10–50 K [29]. In this regard, we will investigate the effect of the interface on the cooling speed of a coil.

## V. Conclusions

An intra-Layer No-Insulation (LNI) REBCO coil requires appropriate technology to control the contact resistivity, $\rho_{ct}$, inside a winding since the $\rho_{ct}$ value dominates the current bypassing function and self-protection characteristics from quenches. From this perspective, we developed a method to form a resistance-controlled (RC) interface between the conductors and the copper sheets, using an epoxy resin mixed with conductive and insulating fillers. Conclusions are as follows:

1) The present method provides an RC interface with a layer thickness as thin as 30 µm and a selectable value of $\rho_{ct}$ from a wide range of 1–1,000, in which interface copper/graphite fillers and MgO filler play the roles of electric conduction and spacer, respectively.
2) The RC interface shows a simple ohmic behavior and for an LNI-REBCO coil implemented with this interface, the $\rho_{ct}$ value is stable under external disturbances such as thermal cycles, unlike a conventional dry-wound LNI-

REBCO coil. These characteristics are useful for designing the quench protection scheme of a coil.

3) Thus, we demonstrated the required properties of selectivity and stability of $\rho_{ct}$ values along with the thinness of the interface. The method can be applied for NI pancake coils as well as LNI coils and is promising for a basic technology on HTS magnet applications. We need to work on further understanding of the physical properties of the interface and demonstrate its functions through coil experiments.

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