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FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2021

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19-21 OCTOBER, 2021

TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

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ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ

UNIVERSITY „GOCE DELCHEV” - SHTIP
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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA.***
ETIMA has a goal to gather the scientists, professors, experts and professionals from the field of technical sciences in one place as a forum for exchange of ideas, to strengthen the multidisciplinary research and cooperation and to promote the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.
Conference ETIMA was held as online conference where contributed more than sixty colleagues, from six different countries with forty papers.
We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA’21 by presenting the results of their current research activities and by launching the new ideas through many fruitful discussions.
We invite you and your colleagues also to attend ETIMA Conference in the future. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information in direct contact, as well as to enjoy the social events together.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот Гоце Делчев.
ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живееењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.
Конференцијата ЕТИМА се одржа online и на неа дадоа свој допринос повеќе од шеесет автори од шест различни земји со четириесет труда.
Сакаме да ја искажеме нашата благодарност до сите колеги кои допринесоа за успехот на ЕТИМА’21 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Ве покануваме Вие и Вашите колеги да земете учество на ЕТИМА и во иднина. Веруваме дека следниот пат ќе имаме можност да се сретнеме, да размениме идеи, знаење и корисни информации во директен контакт, но исто така да уживаме заедно и во друштвените настани.

Организационен одбор на конференцијата

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PROGRESS OF NO-INSULATION HTS MAGNET DEVELOPMENT TOWARDS ULTRA-HIGH MAGNETIC FIELD GENERATION

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Abstract

In this paper, we present the progress of the development of a No-Insulation (NI) winding technique. The NI technique is recognized as a technology necessary for the ultra-high magnetic field generation, because the NI technology drastically improves the thermal stability of High Temperature Superconducting (HTS) magnets. Many researchers have presented several types of the NI coils, such as Metal-as-Insulation (MI), Conductive-Epoxy-Resin-Covered (CERC), and intra-Layer No-Insulation (LNI) coils. However, the thermal stabilities of these coils are not clarified nor compared. Hence, in this paper, we systematically investigate the thermal stabilities and conduct the thermal stability comparison among these coils.

Key words
HTS magnets, No-insulation winding technique, thermal-stability, ultra-high field.

Introduction

High Temperature Superconducting (HTS) magnets have a potential to revolutionize high field applications; such as Magnetic Resonance Imaging (MRI) **Error! Reference source not found.**, Nuclear Magnetic Resonance (NMR) **Error! Reference source not found.**, and particle accelerators **Error! Reference source not found.**. Rare-Earth Barium Copper Oxide (REBCO) coated conductor, which is one promising high temperature superconducting wire, has the higher critical current and critical magnetic field than other superconductors.

In general, superconducting magnets have any electrical insulation between turns and layers. One well problem of turn-insulated REBCO coils is a high possibility to be burned-out or mechanically damaged at an event of “quench” **Error! Reference source not found.**. However, in 2011, a breakthrough winding technique has been proposed, which is called No-Insulation (NI) winding technique **Error! Reference source not found.**. The NI winding technique dramatically improves the thermal stability of REBCO pancake coils, because the operating currents can bypass a local hot spot through turn-to-turn contacts to reduce Joule heating. At National High Magnetic Field Laboratory of US, on 2017, an NI REBCO pancake coil showed its great potential by generating a world-record highest DC magnetic field of 45.5 T **Error! Reference source not found.**.

Towards higher magnetic field generation, the thermal stability improvement is more important. To date, many researchers have proposed several different types of the NI winding technology, such as Metal-as-Insulation (MI) **Error! Reference source not found.**, Conductive-Epoxy-Resin-Covered **Error! Reference source not found.**, and intra-Layer No-Insulation (LNI) **Error! Reference source not found.**. These coils are simply categorized into two groups from the viewpoint of the electrical equivalent circuit: 1) *conventional-based NI* including conventional NI and MI and 2) *supplementary-based NI (SNI-)* including CERC and LNI. For the conventional-based NI REBCO coils, the thermal stability has been well investigated in experiments and simulations. Meanwhile, for the SNI REBCO coils, the thermal stability has not been investigated well, although the different thermal stabilities and electrical behaviors have been reported **Error! Reference source not found.**. Towards further i mprovements in thermal stability, it is necessary to clarify the thermal stability dependence on the characteristic parameters of SNI REBCO coils. In this paper, we investigated the thermal stabilities of SNI HTS coils systematically in simulations. The simulation results are compared with that of the conventional-based NI REBCO coils.

1. Electrical equivalent circuit of conventional-based NI REBCO coils

Fig. 1 shows the schematic view of the conventional NI and the MI REBCO pancake coils, which are categorized to the conventional-based NI REBCO pancake coils. In the case of the conventional NI REBCO pancake coil, an insulator between turns is removed. In a normal operation, the operating current flows through a REBCO layer in the circumferential direction without electrical resistance, because the turn-to-turn contact resistance is much higher than the superconducting zero resistance. When a local hot spot appears, the current escapes into the radial direction to reduce the Joule heating, as shown in Fig. 1 (a). If a current keeps passing through a normal-transitioned REBCO layer, a REBCO pancake coil would be burned out due to its high electrical resistance. For the MI REBCO pancake coils, although the REBCO tape is cowound with stainless steel tapes, a current can also bypass a local hot spot as shown in Fig. 1 (b). The current shortcut-paths of NI and MI REBCO pancake coils are identical despite their different structures.

The electrical equivalent circuit of the conventional-based NI REBCO pancake coils are shown in Fig. 2 [8]. The azimuthally directional elements are composed of the inductance L, the REBCO layer resistance Rre, and the copper matrix resistance Rmt. The REBCO layer resistance Rre exhibits a strong nonlinearity and the calculation model given in [13] is adopted. The radially directional element consisting of the radial turn-to-turn contact resistance Rr is connected in parallel to the azimuthally directional elements. It is well known that the radially directional turn-to-turn contact resistance characterizes the thermal stability of the conventional

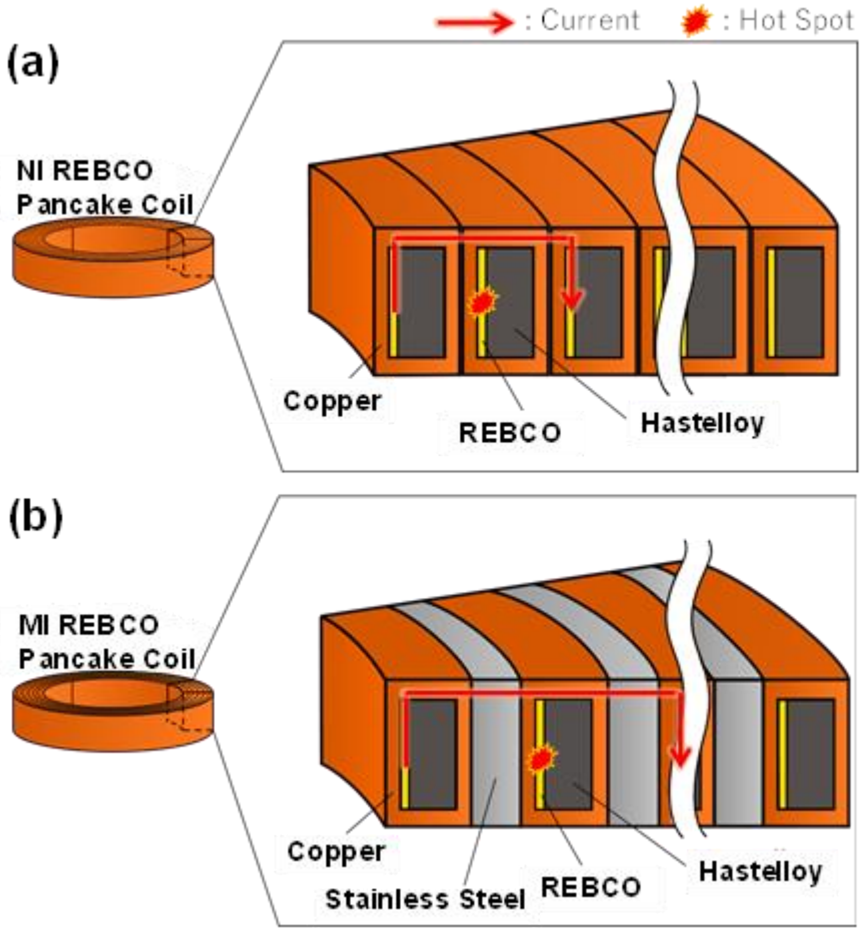

Fig. 1 Schematic views of (a) NI REBCO pancake coil and (b) MI REBCO pancake coil.

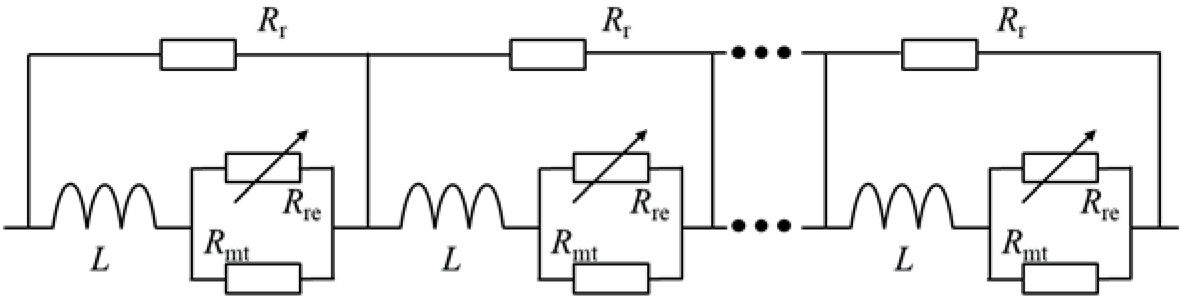

Fig. 2 Electrical equivalent circuit of conventional-based NI REBCO pancake coils. Radial turn-to-turn contact resistance R_r determines thermal characteristics.

NI REBCO pancake coil **Error! Reference source not found.**. It is noted that each coil turn is modeled as an element circuit of Fig. 2.

2. Electrical equivalent circuit of SNI REBCO coils

The schematic views of the LNI and the CERC REBCO pancake coils are shown in Fig. 3. The LNI REBCO coil, as shown in Fig. 3 (a), is composed of a solenoid coil embedding supplementary copper sheets and insulators between layers. For the CERC REBCO pancake coil, the REBCO coated conductor is wound with insulator, and conductive epoxy is coated onto the top surface as a supplementary conductor. These coils are categorized into SNI REBCO coils, based on its bypassing current paths. For instance, in the case of the CERC REBCO pancake coil, a bypassing current flows into conductive epoxy when a local hot spot appears, and the bypassing current flows back into the adjacent turn.

Fig. 4 shows the electrical equivalent circuit for the supplementary-based NI coils. The azimuthal elements are the same as these of the conventional NI coils. The radially directional elements, which are connected in parallel to the azimuthal elements, represent the supplementary conductor resistance Rsp. The supplementary conductor resistance is obtained based on the volume and resistivity of the supplementary conductor such as copper and conductive epoxy. The contact resistance Rcn between the REBCO coated conductor and the supplementary conductor is also modeled based on the contact area. The supplementary conductor resistance and the turn-to-turn contact resistance are the parameters to characterize the thermal stability of the SNI REBCO coils.

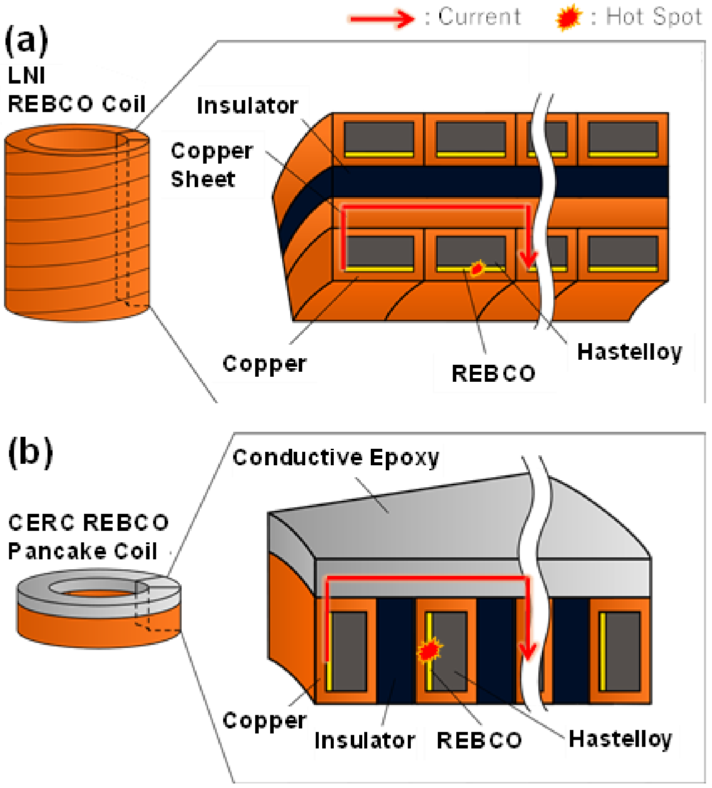

Fig. 3 Schematic views of (a) LNI REBCO coil and (b) CERC REBCO pancake coil.

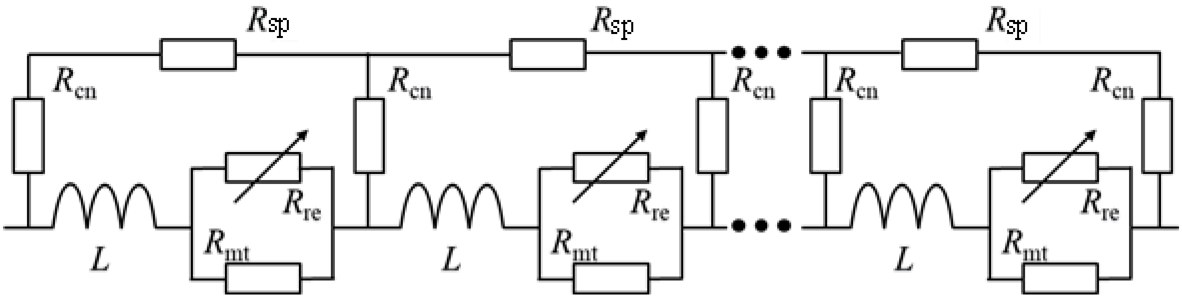

Fig. 4 Electrical Equivalent Circuit of Supplementary-Based NI REBCO Coils. Each Coil Turn Is Modeled as an Element Circuit.

From the equivalent circuit, the electrical behavior is easily simulated. The heat diffusion along the radial direction is also simulated with a finite element method to correctly grasp the quench phenomenon. In this simulation, the heat generation on the contact surface between the supplementary conductor and the REBCO coated conductor is assumed to be equivalently divided to the supplementary conductor and the REBCO coated conductor.

3. Simulation Results

To compare the thermal stability of the conventional NI and the CERC REBCO pancake coils, the temperature rise was investigated when whole one turn of the REBCO coils turns from superconducting to normal state at t = 0. The simulation conditions are listed in Table 1.

Fig. 5 shows the temperature rise in 2 s after the occurrence of the local normal state transition. The nonlinear dependence of the temperature rise against the different supplementary conductor resistances is depicted (red, blue and green line). The high supplementary conductor resistance or contact resistance results in high temperature rise. Whereas, in the case of the conventional-based NI REBCO pancake coils (black line), the temperature linearly rises with the turn-to-turn contact resistance. It is noted that the temperature rise of the SNI REBCO coil in the dashed red-circle is lower than that of the conventional NI REBCO pancake coil. That is, the SNI REBCO coils with sufficiently small contact resistance are thermally more stable than the NI REBCO pancake coils.

The actual resistances gained in experiences are also plotted in Fig. 5, for the conventional NI [14], the MI [5], the LNI [12], and the CERC coils [6]. The high temperature rises of the CERC and the LNI REBCO pancake coils are observed. Whereas the temperature rise of the conventional NI RBECO pancake coils is much smaller than the others. Thus, the thermally most stable coil is the conventional NI REBCO pancake coil. To achieve the development of

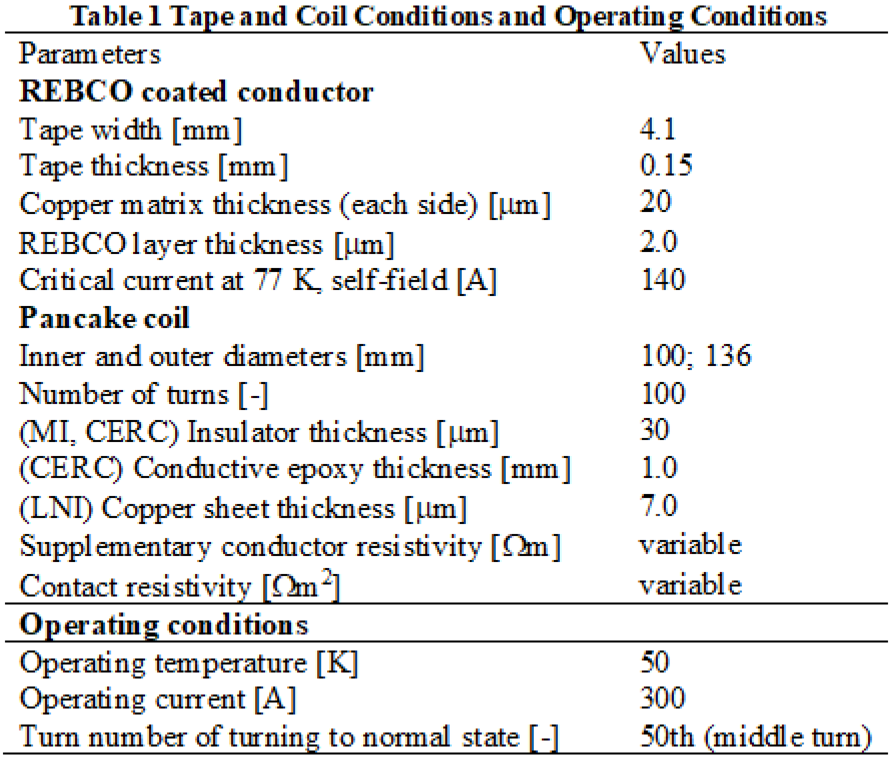

Table 1 Tape and Coil Conditions and Operating Conditions

Parameters	Values
REBCO coated conductor	
Tape width [mm]	4.1
Tape thickness [mm]	0.15
Copper matrix thickness (each side) [μm]	20
REBCO layer thickness [μm]	2.0
Critical current at 77 K, self-field [A]	140
Pancake coil	
Inner and outer diameters [mm]	100; 136
Number of turns [-]	100
(MI, CERC) Insulator thickness [μm]	30
(CERC) Conductive epoxy thickness [mm]	1.0
(LNI) Copper sheet thickness [μm]	7.0
Supplementary conductor resistivity [Ωm]	variable
Contact resistivity [Ωm^2]	variable
Operating conditions	
Operating temperature [K]	50
Operating current [A]	300
Turn number of turning to normal state [-]	50th (middle turn)

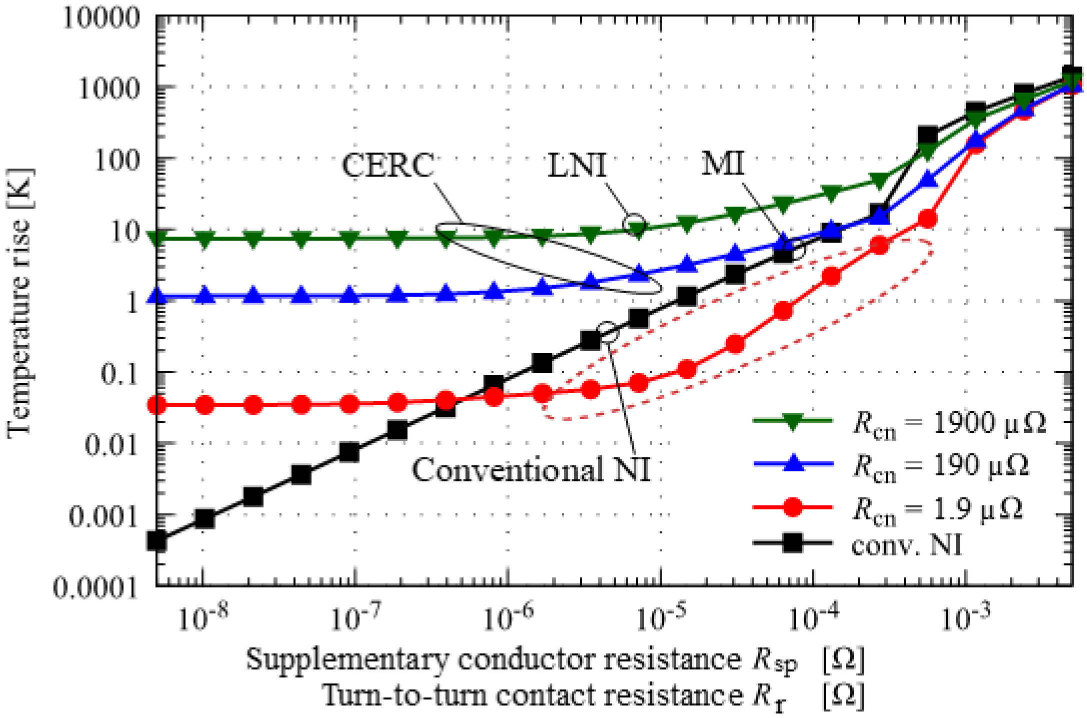

Fig. 5 Temperature rise in 2 s after local normal state appearance as function of supplementary conductor R_{sp} or turn-to-turn contact resistance R_r. Red, blue and green line shows in case SNI REBCO coils for different contact resistance, and black line shows conventional-based NI REBCO pancake coils.

thermally more stable NI REBCO coils for ultra-high magnetic field generation, the important task is to decrease the contact resistance.

Conclusions

In this paper, we investigated the thermal stability of several No-Insulation (NI) Rare-Earth Barium Copper Oxide (REBCO) coils, such as the conventional NI [1], the Metal-as-Insulation [5], the intra-Layer NI (LNI) REBCO [12], and the Conductive-Epoxy-Resin-Covered (CERC) REBCO coil [6]. We modeled the electrical equivalent circuit of these coils and categorized them based on the equivalent circuit; 1) the conventional-based NI for the conventional NI and the MI REBCO coils, and 2) the supplementary-based NI (SNI) for the CERC and the LNI REBCO coils. The thermal stability dependences on the supplementary conductor resistance and the contact resistance together with the radial turn-to-turn contact resistance are systematically investigated. As the result, the SNI REBCO coil exhibits the nonlinear thermal stability, whereas the conventional-based NI REBCO pancake coil shows linear dependence. Also, it is found that the SNI REBCO coils are thermally more stable than the conventional-based NI REBCO pancake coils when the contact resistance is sufficiently small. The thermal stability comparison among the four types of NI REBCO coils was also conducted. The conventional NI REBCO pancake coils are the best in the thermal point of view. However, the CERC and the LNI REBCO coils are thermally unstable due to their large contact resistivity, compared to the conventional NI REBCO pancake coil. A technology to reduce the contact resistivity is required.

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