GOCE DELCEV UNIVERSITY, SHTIP, NORTH MACEDONIA
FACULTY OF ELECTRICAL ENGINEERING

# ETIMA 2021

## FIRST INTERNATIONAL CONFERENCE

19-21 OCTOBER, 2021

## TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

УНИВЕРЗИТЕТ „ГОЦЕ ДЕЛЧЕВ" - ШТИП
ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ

UNIVERSITY „GOCE DELCHEV" - SHTIP
FACULTY OF ELECTRICAL ENGINEERING

ПРВА МЕЃУНАРОДНА КОНФЕРЕНЦИЈА
FIRST INTERNATIONAL CONFERENCE

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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 живеењето. 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*

## Содржина / Table of Contents

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# INVESTIGATION ON STABILITY OF PANCAKE COILS WOUND WITH BUNDLED MULTIPLE REBCO CONDUCTORS

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## Abstract

*REBCO (Rare-Earth Barium Copper Oxide) pancake coils without turn-to-turn insulation, called no-insulation (NI) winding technique, have shown a high thermal stability against normal state transition. REBCO is the 2nd-generation high-temperature superconductor (HTS) with great properties. In recent years, NI REBCO coils have been desired for practical ultra-high magnetic field applications. It has been reported, as an experimental result, that the excitation delay, which is a problem of the conventional NI REBCO pancake coils, is improved by coils wound with multi-bundled REBCO conductor (MB NI REBCO coils). As an operating current may not be evenly distributed in each bundled tape due to the different inductances, the current distribution in MB NI coils is complicated. Therefore, we must clarify the excitation characteristics and the current and thermal stability of MB NI REBCO pancake coils using numerical simulation. We also compared the cases with and without insulation between turns. For a current simulation, an MB NI REBCO coil is modeled using a Partial Element Equivalent Circuit (PEEC) method. From the simulation results, it was confirmed that the excitation delay was improved by a multi-bundled REBCO conductor. Furthermore, we found that the MB NI REBCO coil without turn-to-turn insulation was the most stable because the current could be distributed widely, not concentrated.*

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

## Introduction

2nd-generation (2G) high-temperature superconducting (HTS) magnets can generate very high magnetic fields, because they can carry large currents with small cross-sectional area at extremely low temperatures [1]. 2G HTS magnets are expected to be applied to high filed applications; magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), and particle accelerators. These applications need high magnetic fields for high performances. REBCO (Rare-Earth Barium Copper Oxide) which is 2G HTS has a high critical field and excellent electrical properties. However, conventional REBCO pancake coils have a serious problem against quench protection [2].

To solve this problem, a no-insulation (NI) winding method was proposed by Hahn, *et al.* [3],[4]. It enables to drastically enhance the thermal stability of HTS magnets due to eliminating turn-to-turn insulation and allowing currents to radially bypass a local normal-state region through the turn-to-turn contacts. Also, the NI winding method makes HTS magnets more compact with the higher engineering current density than ever. In these recent years, because of these advantages, NI REBCO pancake coils have been strongly desired for practical ultra-high magnetic field (>30 T) applications.

Although NI REBCO coils have these above-mentioned merits, no turn-to-turn insulation causes a charging delay. This is a major issue for a long time [5],[6]. To overcome this issue, a few different methods have been proposed [7],[8],[9]. One of them is a multi-bundled

REBCO tape winding method, where a pancake coil is wound with multi-bundled REBCO conductors without insulation between bundled tapes. It was reported, as an experimental result, a charging delay was improved because the inductance per one tape of the NI pancake coils wound with multi-bundled REBCO conductors (MB NI REBCO pancake coils) is smaller than that of a conventional NI pancake coils wound with a single REBCO conductor [10]. In addition, the high current density of the MB NI coil is expected. However, as the current behavior of MB NI coil is complicated, the stability has not yet been investigated in detail. For example, an operating current may not be evenly distributed in each bundled tape due to their different inductances. The purpose of this study is to clarify the charging characteristics and the stability of MB NI REBCO pancake coils based on the current and thermal distributions obtained by numerical simulation. We will also compare the cases with and without insulation between turn-to-turn.

## 1. Simulation method

To obtain the detailed current distribution, an MB NI REBCO pancake coil is modeled using a Partial Element Equivalent Circuit (PEEC) method [5]. Since, in the PEEC model, the equivalent circuit is built by dividing the MB NI REBCO coil in the circumferential and radial directions, it is possible to observe the local phenomena inside the coil. The electrical resistance of the REBCO layer is approximated by an *n*-index model [11], and the critical current density required for the *n*-index model is calculated using approximate equations obtained from experiments. Since the *n*-index model involves a strong nonlinearity, the Newton-Raphson method is introduced as a nonlinear solver. The heat generation in each resistance component is computed from the obtained current distribution, and the thermal distribution is obtained using a Finite Element Method (FEM).

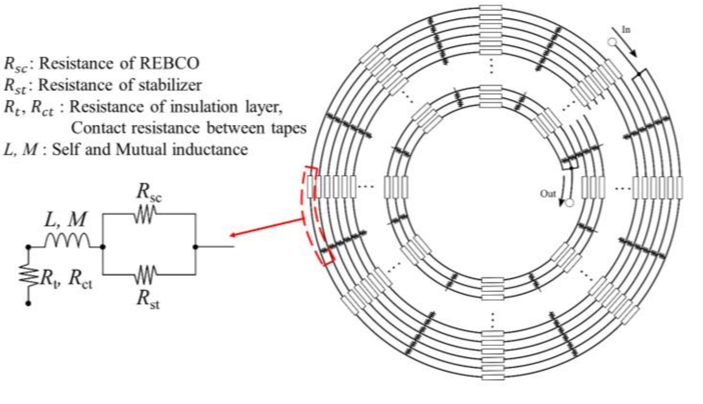


**Fig. 1 PEEC model of MB NI coil (3 tapes bundled).**

## 2. Analysis models

The coil models and the specifications of REBCO tape and coils used in this study are shown in Fig. 2 and Table 1. It is supposed that all the coils are wound with SuperPower 2G-HTS tape wires and the contact resistivity between bundled tapes is 70 $\mu\Omega \cdot \mathrm{cm}^2$ based on experimental results [12]. To investigate the effect of turn-to-turn resistance on the stability of MB NI REBCO coils, 3 coils with different values of turn-to-turn resistance are compared. All the 3 coils are wound with 3-bundled REBCO conductors. The turn-to-turn resistivity of each coil is equal to the no-insulation (1 times), 10 times (10×70 $\mu\Omega \cdot \mathrm{cm}^2$), and infinity (insulated). These 3 coils are called A, B, and C, respectively, also the bundled tapes are called Tapes 1, 2 and 3 from the outside of the coils in this paper.

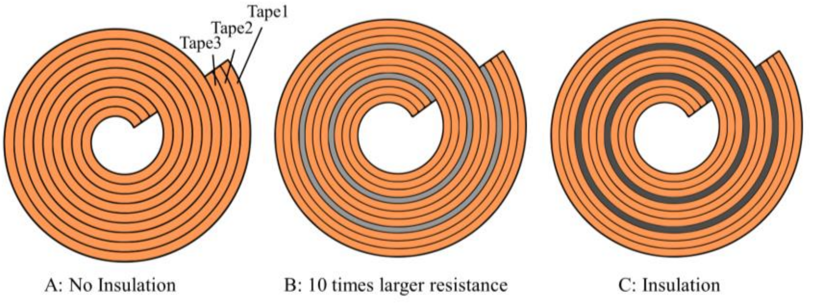


**Fig. 2 3 MB NI coil models with different turn-to-turn resistance.**

**Table 1 Specifications of REBCO tape and coils**

| **Parameters** | **Value** | | |
|---|---|---|---|
| **Coil model** | A | B | C |
| **REBCO tape** | | | |
| **Tape width [mm]** | | 4.0 | |
| **Tape thickness [mm]** | | 0.1 | |
| **Insulation layer thickness [mm]** | | 0.03 | |
| **REBCO layer thickness [μm]** | | 2.0 | |
| **Copper stabilizer thickness [μm]** | | 20.0 | |
| **Critical current at 77K, self-field [A]** | | 120.0 | |
| **Pancake coil** | | | |
| **Coil i.d., o.d. [mm]** | 120.0, 144.0 | 120.0, 146.4 | 120.0, 146.4 |
| **Number of bundle tapes** | | 3 | |
| **Number of turns** | | 40 | |
| **Azimuthal division** | | 8 | |
| **Contact resistivity (Tape-to-Tape) [$\mu\Omega \cdot cm^2$]** | | 70.0 | |
| **Contact resistivity (Turn-to- Turn) [$\mu\Omega \cdot cm^2$]** | 70.0 | 700.0 | Insulation |
| **Inductance [mH]** | 3.524 | 3.485 | 3.485 |

## 3. Charging simulations

Experimental results showed that MB NI REBCO coils could reduce the charging delay compared to a conventional NI coil [10]. However, there is a possibility that the operating current is not evenly distributed in bundled tapes during charging due to the variety of tape inductances. The detailed current phenomenon has not yet been known. Therefore, we simulated the current and temperature distributions inside the MB NI REBCO coils during charging, and then investigated the stability of the charging.

The simulation conditions for the charging test are shown in Table 2. The operating current is increased for all three coils at 1 A/s per tapes and stays for 50 s after reaching 450 A. Here, the operating current is indicated as the sum of the currents flowing in all three bundled conductors.

**Table 2 Simulation condition of charging test**

| **Simulation Condition** | |
|---|---|
| Time step [s] | 0.1 |
| Simulation time [s] | 200.0 |
| Operating temperature [K] | 20.0 |
| Operating current [A] | 0 to 450 |
| Charging speed [A/s] | 1.0 |

Fig. 3 shows the time variation of the operating current and the axial magnetic field for the MB NI coil and the conventional NI coil. From the results, multi-bundled coils are confirmed to improve the excitation delay caused by the NI winding technique. Fig. 4 shows the azimuthal current distribution during the coil excitation. We found that there were some current differences between the tapes. However, these differences are not expected to have a significant impact on the operating conditions or the magnet stability. In addition, no current differences are observed immediately after the end of excitation. Thus, the MB NI coil is effective against the charging delay, and has the high stability during charging.

## 4. Quench simulations

The sudden normal-state transition in NI pancake coils is called “quench.” When a quench occurs in a conventional NI coil (single tape), the current is diverted via the turn-to-turn low resistance path, thereby preventing a pessimistic temperature rise. At a quench event of an NI coil, currents are induced in the adjacent tape wires to compensate the magnetic field, which results in unbalance currents between tapes. In the MB NI coil, the current distribution would be complicated in each bundled tape during quench.

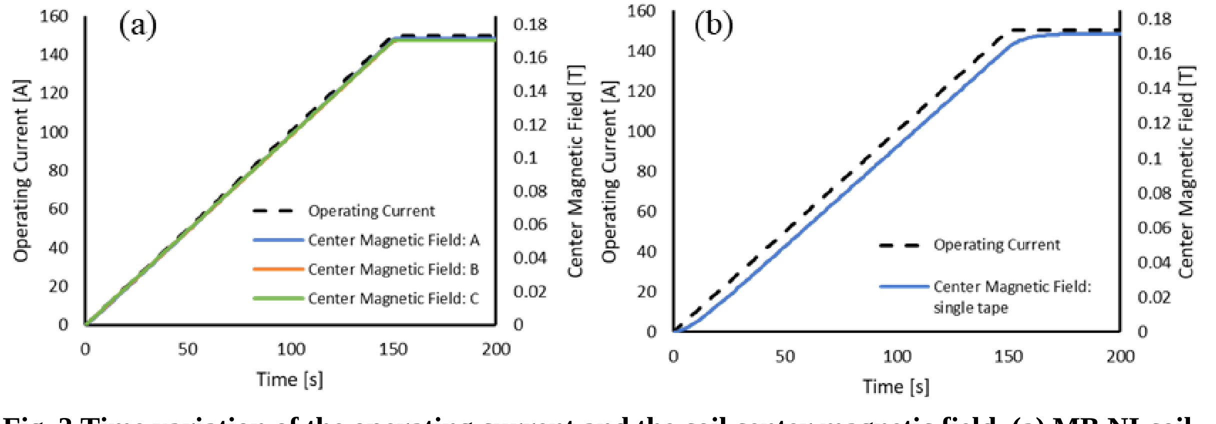


**Fig. 3 Time variation of the operating current and the coil center magnetic field, (a) MB NI coil, (b) single tape NI coil.**

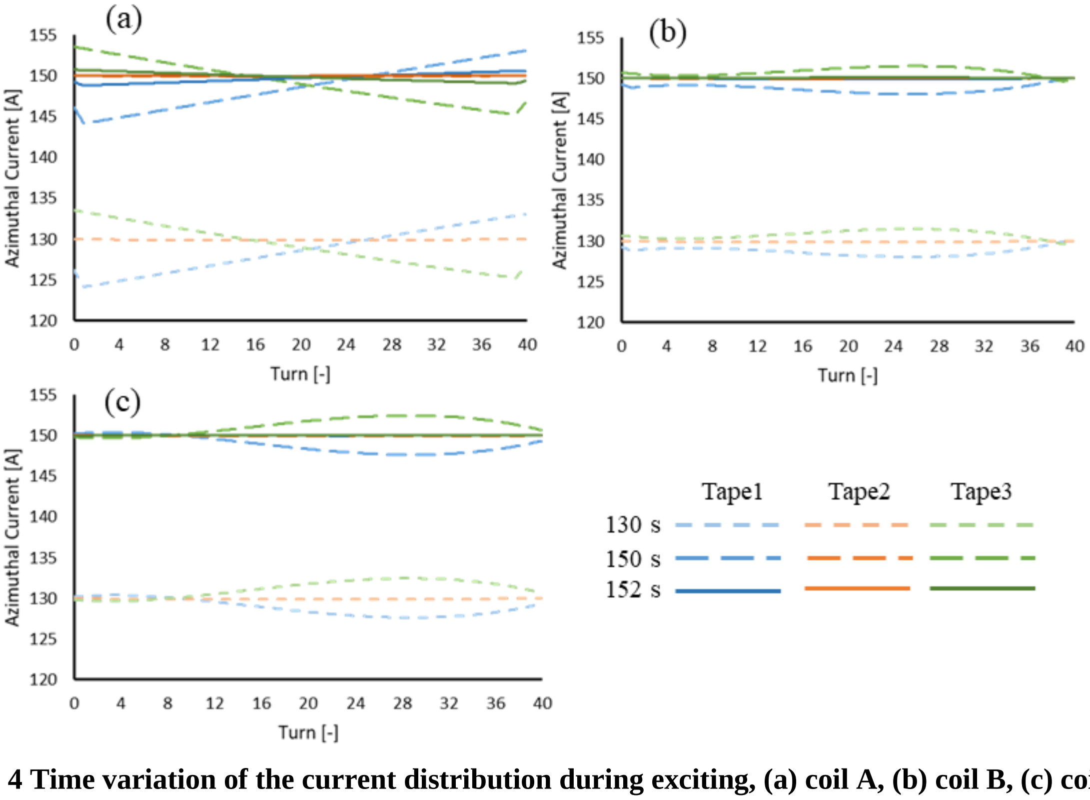


**Fig. 4 Time variation of the current distribution during exciting, (a) coil A, (b) coil B, (c) coil C.**

The quench simulations were conducted to verify the stability of the MB NI REBCO coil against quench. For MB NI coils A, B, and C, with a steady state current of 450 A, the one turn (mid-turn) of the outer tape (Tape 1) is quenched at 0 s. The operating current remained constant after quench. The simulation conditions for the quench simulations are listed in Table 3.

Fig. 5 shows the results of the quench simulations. In all the coils, it can be seen that when the quench occurs, the current at the quench region in Tape1 is transferred to the other tapes. The current of Tape 2 reaches to the maximum value near the normal-state element, with the smallest value in coil A, which has no insulation, and the largest value in coil C, which has turn-to-turn insulation. This is because the insulation layer between the turns prevents the current from passing from Tape 1 to 3, and the current concentrates on Tape 2. Furthermore, in coils B and C, the current in Tape 3 is also transferred to Tape 2 at 0.01 s after the quench. It is considered that this is due to the strong influence of the inductances.

From these results, it is considered that the MB NI coil has a high thermal stability against the normal-state transition, but there is a possibility that the current may concentrate on one tape and reach the critical current depending on the operating current. However, no temperature rise is observed in all the coils, as shown in Fig. 6.

**Table 3 Simulation condition of quench test**

| Simulation Condition | |
|---|---|
| Time step [s] | 0.001 |
| Simulation time [s] | 1.0 |
| Operating temperature [K] | 20.0 |
| Operating current [A] | 450 |

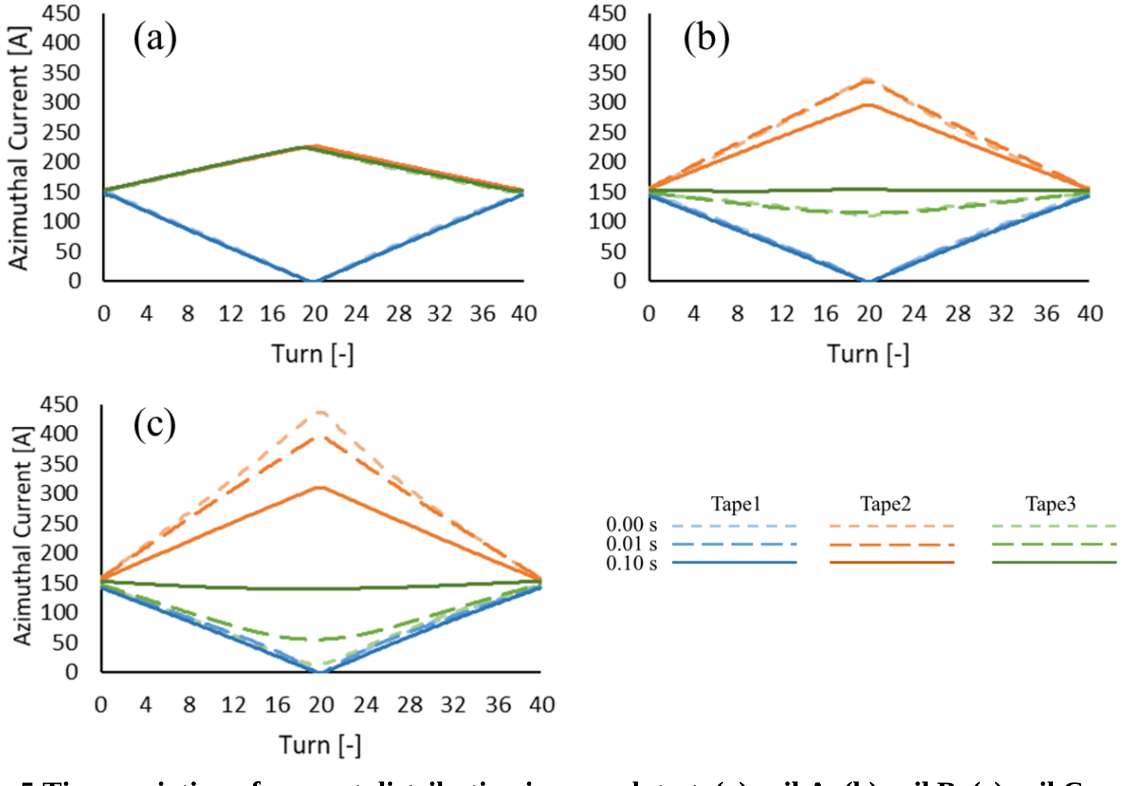


**Fig. 5 Time variation of current distribution in quench test, (a) coil A, (b) coil B, (c) coil C.**

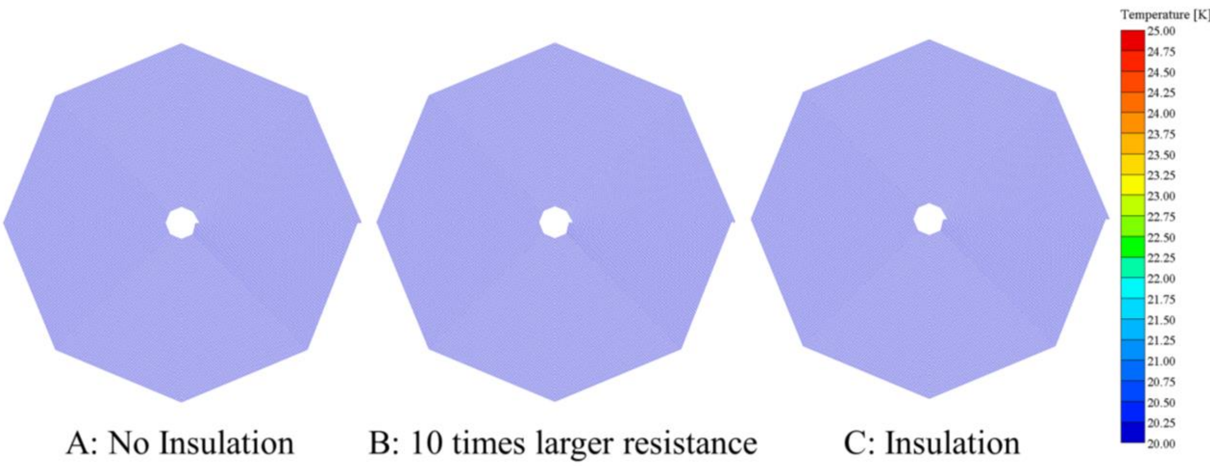

**Fig. 6 Temperature distribution at 0.1 s after the quench.**

## Conclusions

For the practical use of REBCO magnets, NI coils are expected to have both the high current density and the high thermal stability, but an excitation delay is an issue to be solved. The proposed MB NI coil was reported to be able to improve the charging delay. Nevertheless, the distribution of the current flowing in the coil has not been clarified, and the stability against the normal-state transition has not been confirmed. In this study, we investigated the current and temperature distributions of the MB NI coil by numerical simulation using the PEEC method and the thermal finite element method.

From the excitation test results, it was confirmed that the MB NI coils could improve the charging delay. During the excitation of the MB NI coils, there is no large current difference between the tapes, and a stable excitation is expected to be possible.

From the quench simulation results, the MB NI coil is thermally stable with no pessimistic temperature rise even when a quench occurs. However, we found that current differences occur between bundled tapes, and if the turn-to-turn are insulated, there is a threat that almost all of the operating current would flow to one tape. Therefore, no-insulation between turn-to-turn of MB NI coils seems to be desirable.

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