Influence of coil size and operating temperature on transient stability in multi-stacked no-insulation REBCO pancake coil system

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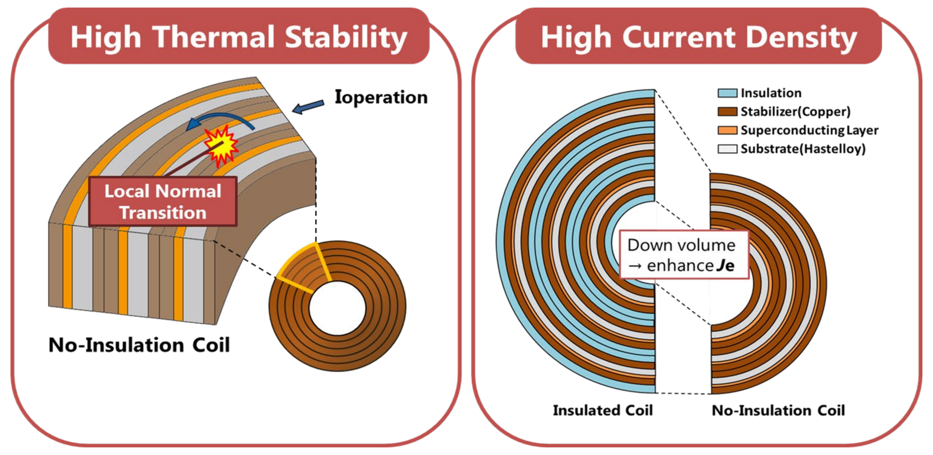
1. Introduction

★No-Insulation REBCO Pancake Coil Systems

The No-Insulation (NI) coil is a technology expected to realize both high current density and high thermal stability, which are essentially trade-off relationship in REBCO coil application. Because there is no electrical insulation layer in NI coils, the Cu stabilizer between turns in winding can be shared. Therefore, the stabilizer layer can be reduced, resulting in realizing higher overall current density. Furthermore, because the operating current can bypass the adjacent turns when a local normal transition occurs, it is possible that the thermal stability of the coil can be significantly enhanced.



No-Insulation Technology

★Motivation and Contents of this Study

NI-coil technique has been mainly studied for application to inner coils of NMR magnet exceeding 30T. In this case, the coil has a small diameter of several cm and is cooled by 4.2-K liquid He. We are developing an NI-REBCO coil system aimed at application to high-magnetic-field whole-body MRI and medical cyclotron to be used for cancer therapy. For these applications as well, the NI-coil technology is considered as an effective technology satisfying both high current density and high thermal stability. However, the REBCO coil which we aim for above development has a diameter of ~1 m, the generated magnetic field is ~10 T, and conduction cooling at ~30 K is assumed. Therefore, because size, operating temperature, and magnetic field differ from those of the NMR coil, it is possible that the electromagnetic, thermal and mechanical behaviors when adopting the NI-coil winding will be quite different. In this study, we numerically evaluate the transient behaviors when a local deterioration occurs in NI-REBCO double-pancake coil by adopting coil size, operating temperature, and magnetic field as parameters.

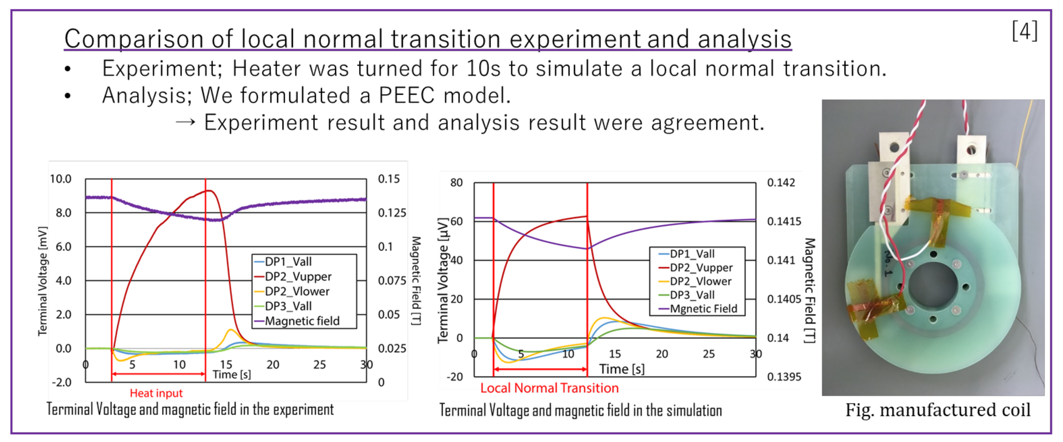
Specifications required for each application

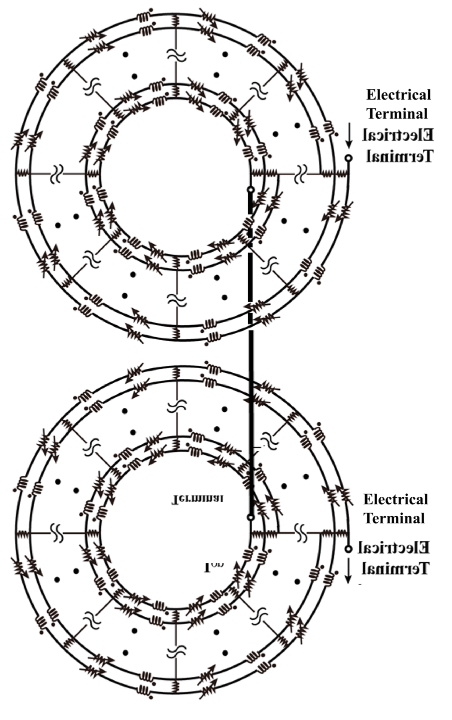
	MRI cycrotion	NMR
Magnetic field [T]	～10	>30 (>1.3GHz)
Current density [A/mm²]	200～500	>1000
Coil size (i.d.) [m]	～1	～0.02
Operating temperature [K]	>20	4.2
Winding type	Pancake	Pancake or layer

2. Numerical analysis

★Method

We conducted a numerical analysis that combines current distribution analysis based on the PEEC (Partial Element Equivalent Circuit) model with thermal analysis by 2-dimensional finite element method. The PEEC model can reproduce detailed current distribution by subdividing the coil into its radial and azimuthal directions [3]. The validity of this analysis has been confirmed by comparing its simulation results with the experiments on a small-diameter coil in [4].





$$\sum_{j=1}^{N}\sum_{i=1}^{N} M_{ij}\frac{dI_\theta^{(j)}}{dt} - R_r^{(k)} I_r^{(k)} = 0$$

$$I_\theta^{(i)} + I_r^{(i)} = \begin{cases} I_{OP} & (i=1) \\ I_\theta^{(i-1)} & (1<i\le Div\theta) \\ I_\theta^{(i-1)} + I_r^{(i-Div\theta)} & (N-Div\theta+1<i<N) \end{cases}$$

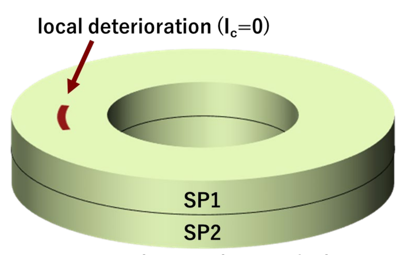
$$I_\theta^{(i)} + I_r^{(i-Div\theta+1)} = I_{OP} \qquad (i=N)$$

R_θ : azimuthal resistance(n-value model)
R_r : partial turn-to-turn contact resistance
I_θ : azimuthal current
I_r : radial current
M : inductance matrix of partial self and mutual inductances determined by the Neumann equation;

PEEC (Partial Element Equivalent Circuit) Model

★Condition

- It is assumed that a deterioration (I_c=0) occurs over 1/8 length of the circumference of one layer of the winding center of the upper coil, SP1.
- The operating current (I_{op}) is set so that load factor (I_{op}/I_c) is equal at 70% under all conditions shown in Tab.1, and is kept constant during the analysis.
- The test coil is exposed to a uniform and constant external magnetic field(B_{ex}), and self-magnetic field(B_{sf}).



Analytical model

Conditions for comparison

	60mmΦ		500mmΦ
	10T	30T	10T
4.2K	(i) 600A	(ii) 545A	
30K	(iii) 344A		(iv) 345A

I_{op} / I_c = 70%

Parameters and assumed values for analyses

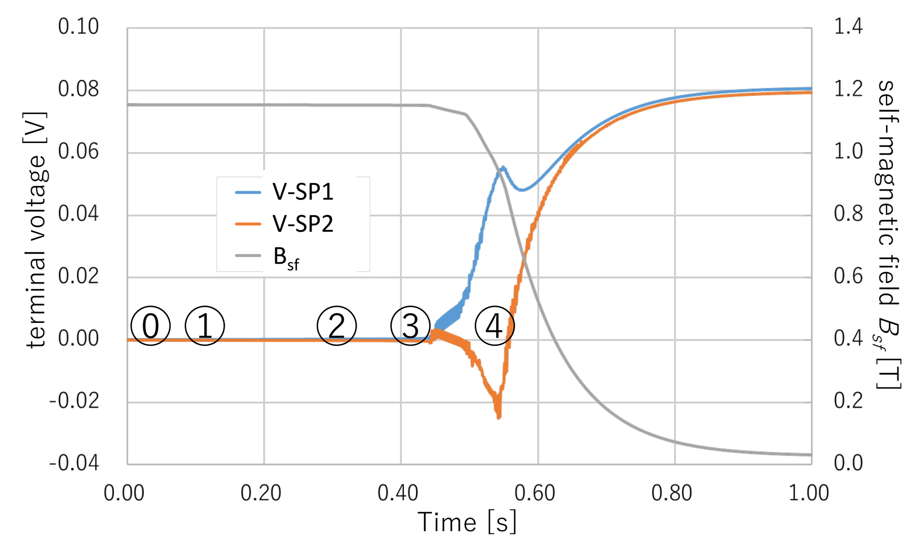
Parameters	Assumed Values
REBCO conductor	
Overall width [mm]	4.00
Copper stabilizer thickness [μm/side]	20
Tape Ic @77K, self-field [A]	115
Coil	
Turns per pancake	50
i.d [mm]	60, 500
Height [mm]	10
Turn-to-turn contact resistivity [Ω・cm²]	2.1 × 10^{-5}
Analysis	
I_{op} [A]	600, 545, 344, 345
I_{op} / I_c [%]	70
Initial operating Temperature [K]	4.2, 30
Cooling condition	Adiabatic
External magnetic field in the z- direction, B_{ex} [T]	10, 30

3. Results and Discussion

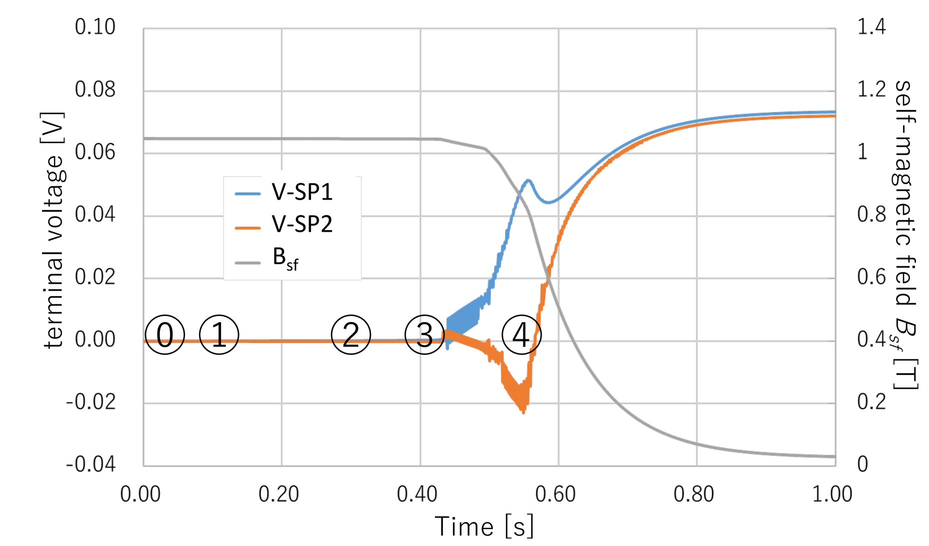
3-1 Central self-magnetic field of NI coil and terminal voltage traces

Electromagnetic and thermal behavior in cases of (i) and (ii)

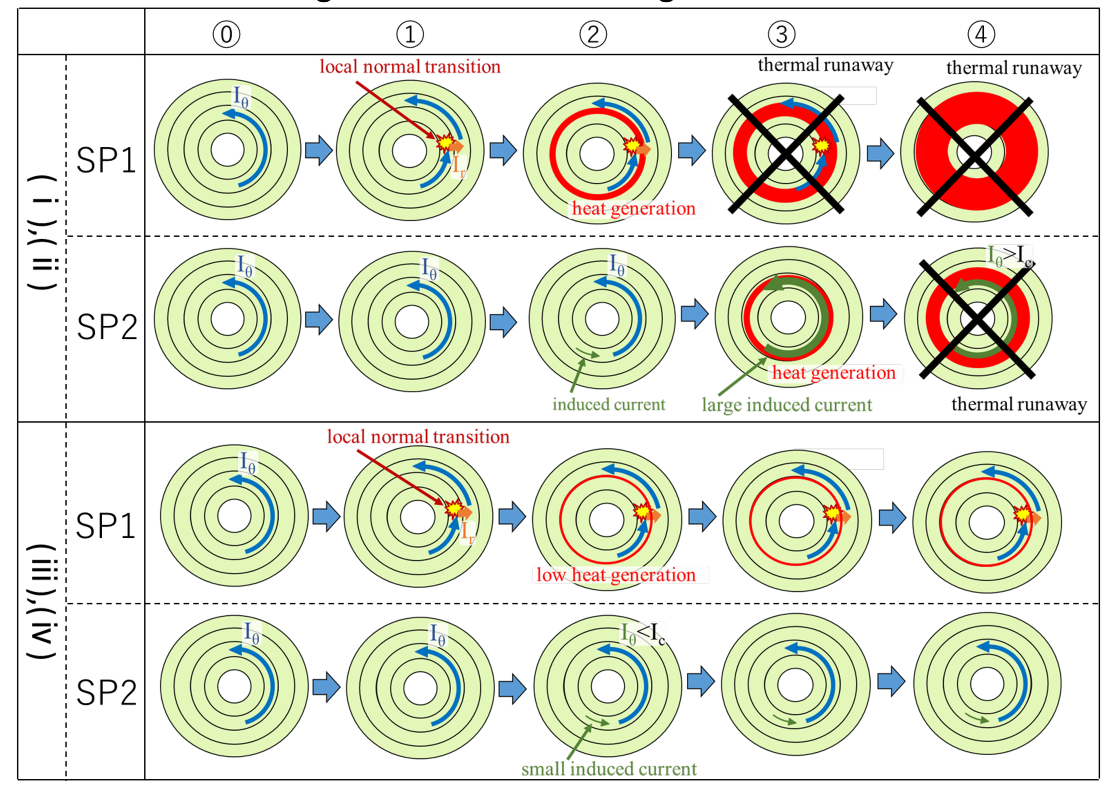
(i) 4.2K 10T 60mm 600A



(ii) 4.2K 30T 60mm 545A



Schematic drawings of Current and heat generation at each moment



<SP1 in Cases(1) and (2)>

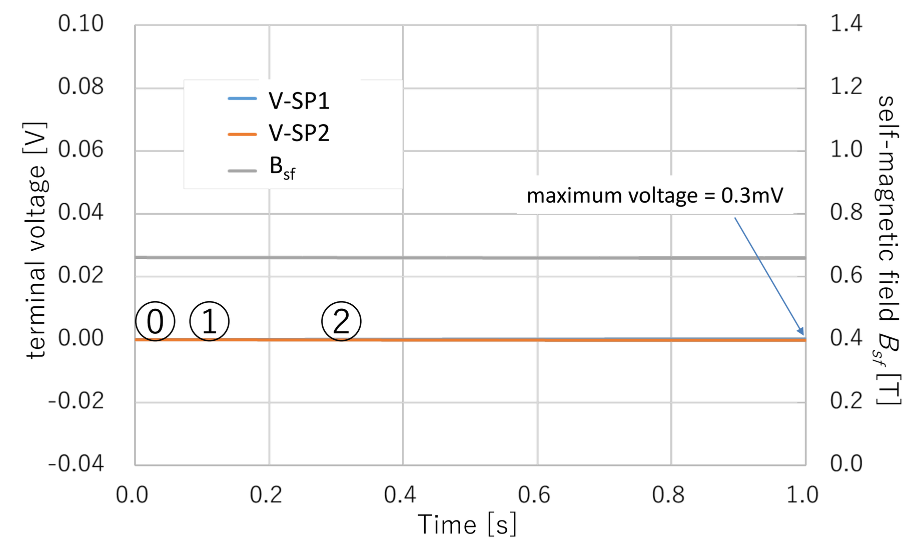
① A local deterioration occurs
① Current begins to flow toward adjacent layers in the radial direction
① Positive voltage begins to occur
② Joule heat is generated because current flows to the adjacent layers through the contact electrical resistance
③ As the temperature rises, the critical current, I_c, drops and the thermal runaway begins. Then the self-magnetic field, B_{sf}, decreases rapidly toward zero
④ Thermal runaway

<SP2 in Cases(1) and (2) >

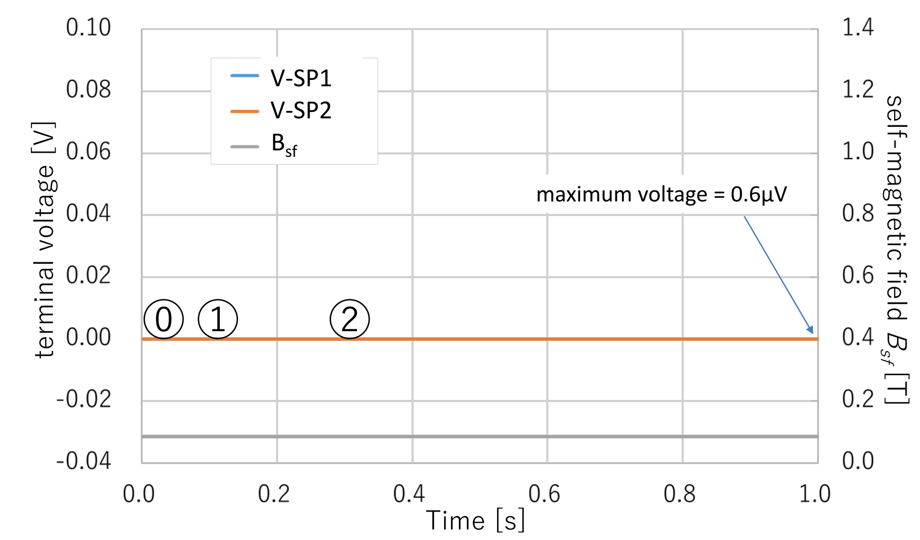
② Induced current flows to compensate for the decreasing magnetic field of SP1
③ A large induced current flows due to the continuous magnetic field decrease of SP1, and a negative voltage begins to occur
③ Heat generation caused by induced current also occurs
④ Azimuthal current exceeds the critical current I_c and begins thermal runaway
④ Voltage turns from negative to positive, eventually leading to thermal runaway

Electromagnetic and thermal behavior in cases of (iii) and (iv)

(iii) 30K 10T 60mm 344A



(iv) 30K 10T 500mm 345A



<SP1 in Cases(3) and (4) >

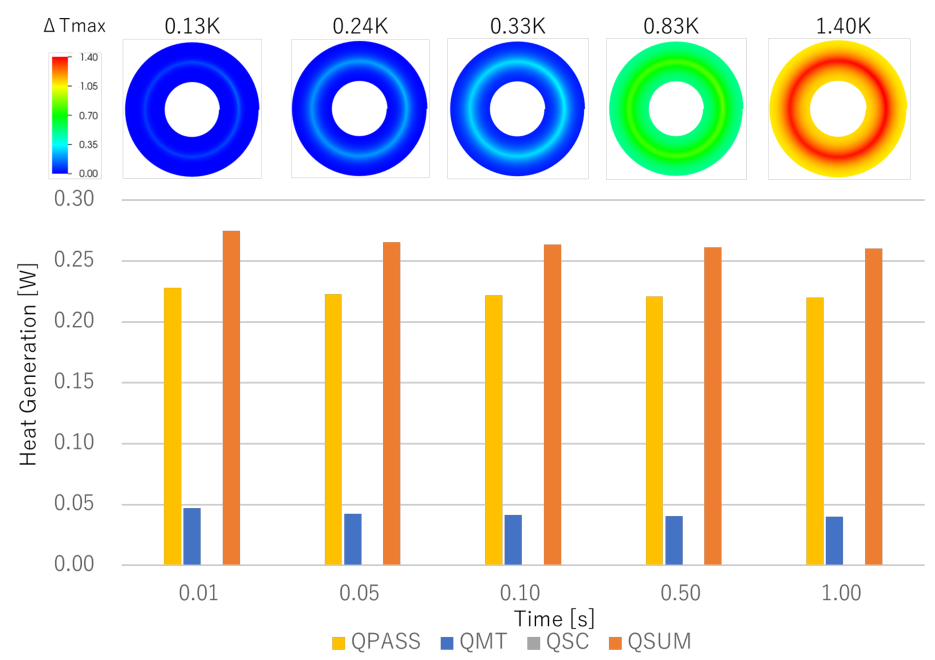
① A local deterioration occurs
① Current begins to flow in the radial direction toward adjacent layers
① Positive voltage begins to occur
② Joule heat generation, caused by current redistribution to adjacent turns, occurs. However, the changes of voltage and heat generation, and the decrease in central magnetic field are very small. Therefore, thermal runaway does not occur

<SP2 in Cases(3) and (4) >

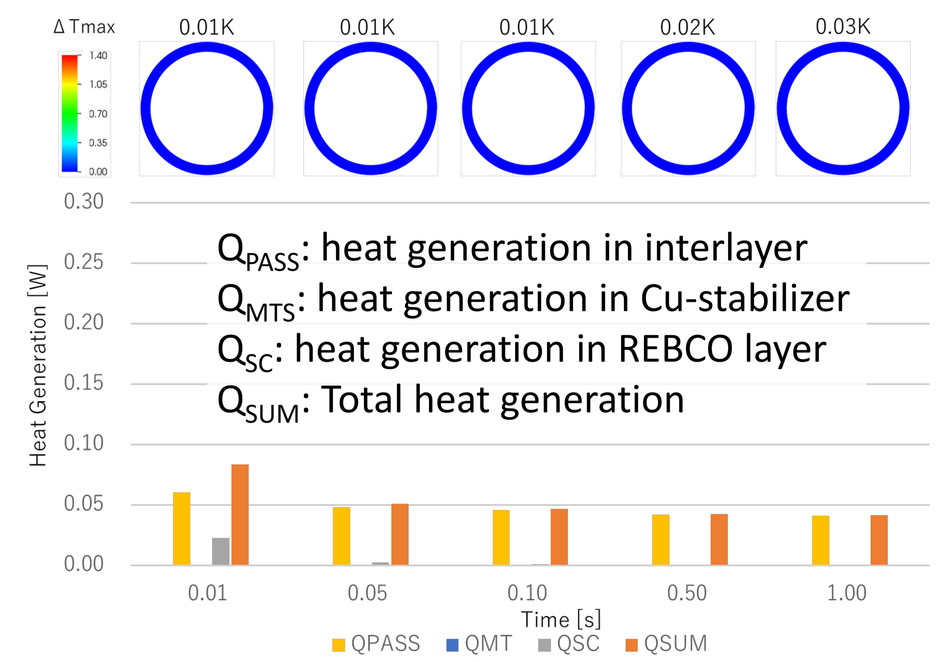
② Induced current in SP2 flows to compensate for the SP1 magnetic field decrease. However, because the decrease in magnetic field is quite small, there is almost no induced current and thermal runaway does not occur

3-2 Heat generation and Temperature distribution in SP1

(iii) 30K 10T 60mm 344A



(iv) 30K 10T 500mm 345A



(iii) and (iv)

- As shown in 3-1, there is almost no change in current and voltage. Furthermore, because the heat capacity is large at an operating temperature of 30 K, the temperature hardly increases
- In the case of (iv), the total heat generation and its density are much smaller than (iii), therefore the temperature rise even less, and the maximum temperature rise, ΔT, after 1s is only 0.03 K
- Comparing the points of heat generation, Q_{pass} is dominant in both (iii) and (iv). Q_{pass} is the Joule heat caused by current bypassing to adjacent layers through the contact electrical resistance
- Because the current bypass occurs over a wide area around the entire circumference, the heat generation density is smaller, particularly in large-diameter coil. As a result, the temperature rise is extremely small
- There is almost no heat generation in the Cu stabilizer, Q_{MT}. Thus, the stabilizer thickness can be drastically reduced, resulting in the overall current density being dramatically increased

4. Conclusions

- The electromagnetic and thermal behaviors were investigated when a local deterioration occurs in no-insulation (NI) REBCO double-pancake coils using numerical analysis considering coil size, operating temperature, and magnetic field as parameters.
- The Joule heat caused by current bypass to adjacent layers through the contact electrical resistance is dominant.
- There is almost no heat generation in the Cu stabilizer. Therefore, the stabilizer thickness can be reduced and the overall current density can be increased.
- As the operating temperature increases, the heat capacity increases and temperature rise decreases. Thus thermal runaway is less likely to occur.
- As the coil diameter increases, the heat generation and its density caused by current bypass through the contact electrical resistance, decreases. Therefore, there is a possibility that the temperature rise can be made even smaller.

[1] S.Hahn, et al., IEEE Trans. Appl. Supercond., Vol.21 (2011) pp.1592-1595
[2] S.Hahn, et al., Nature, Vol.570, pp.496-499, 2019
[3] H.Miyazaki, et al., IEEE Trans. Appl. Supercond., Vol.27 (2017) 4300805
[4] H.Ueda et al., IEEE Trans. Appl. Supercond., Vol.29 (2019) 4101105
[5] X.Wang, et al., Superconductor Science and Technology, Vol.26, no.3, 2013

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