# Numerical Simulation of REBCO Pancake Coil with No-Insulation Technique

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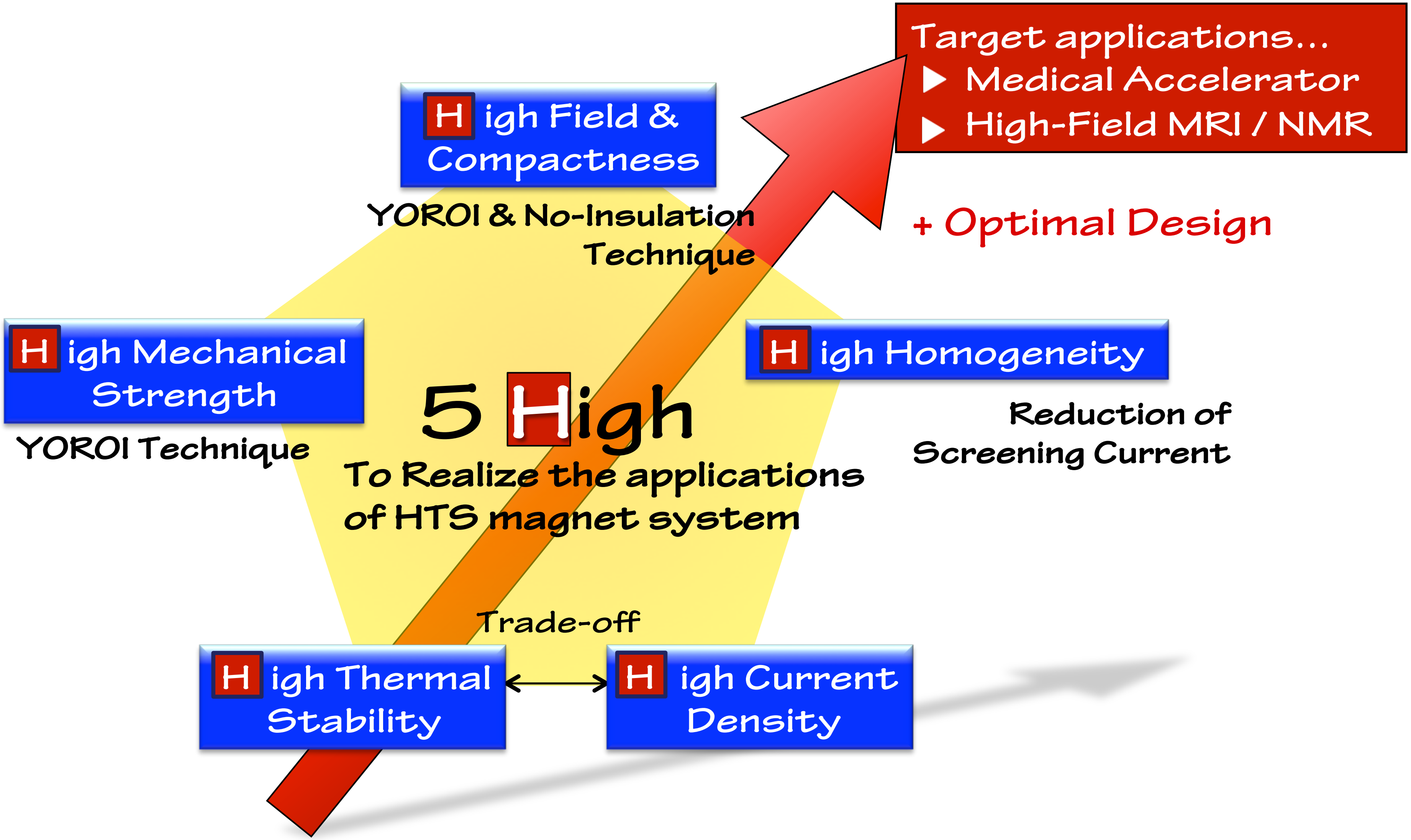
# Contents

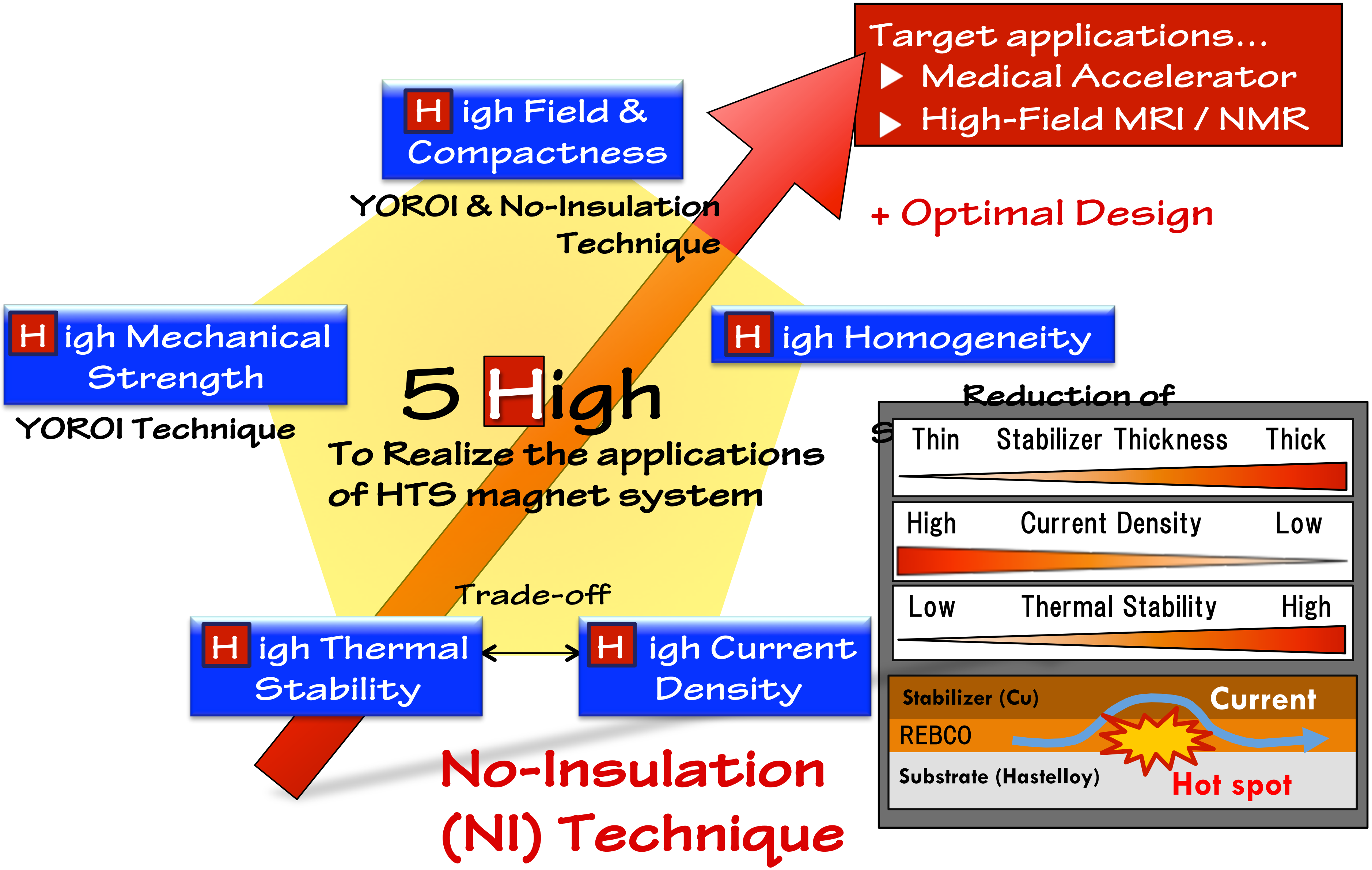
# Contents

- ◆ NI winding technique & PEEC model
- ◆ Discharging/charging test
- ◆ Over-current test
- ◆ Current flow on cross section
- ◆ Conclusion

# 5-Hs REBCO pancake coil



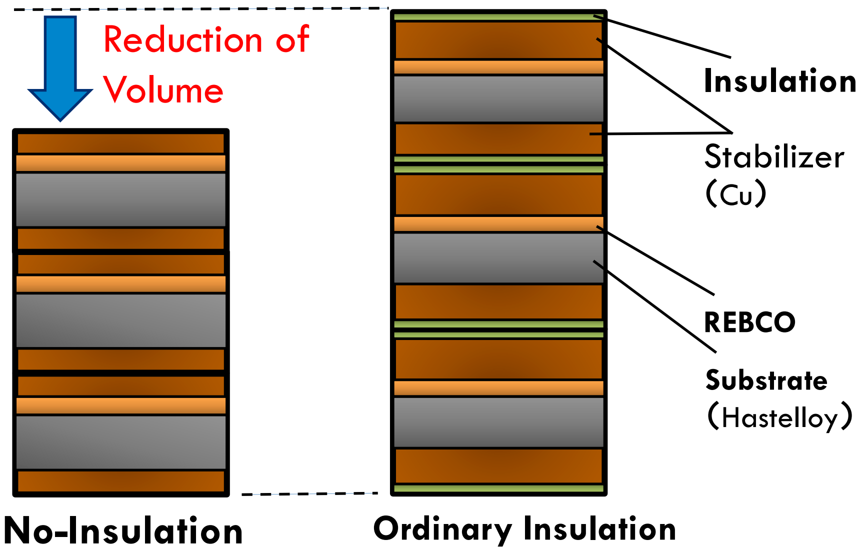
# 5-Hs REBCO pancake coil



# Advantages of NI Technique

## High Current Density

▪To Enhance Engineering Current Density Je

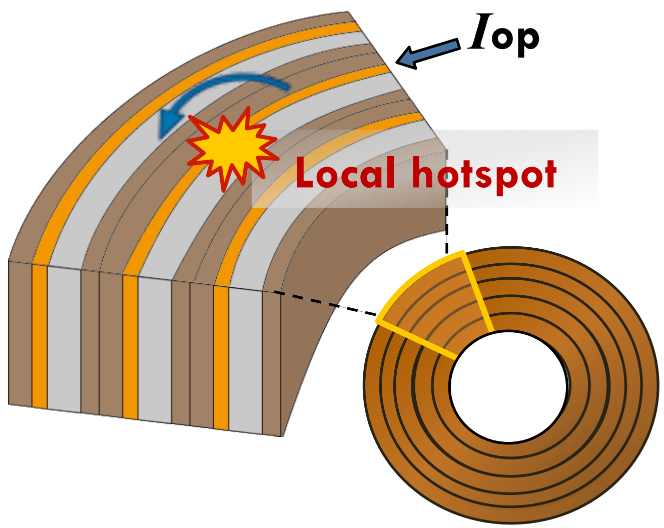



▪Winding with no-insulated REBCO tape
▪Decrease of stabilizer by sharing it

➡ **Possible to enhance current density?**

## High Thermal Stability

▪Self-protection




▪Current avoiding a local hotspot
▪Dissipating magnetic energy into thermal capacity of a whole coil

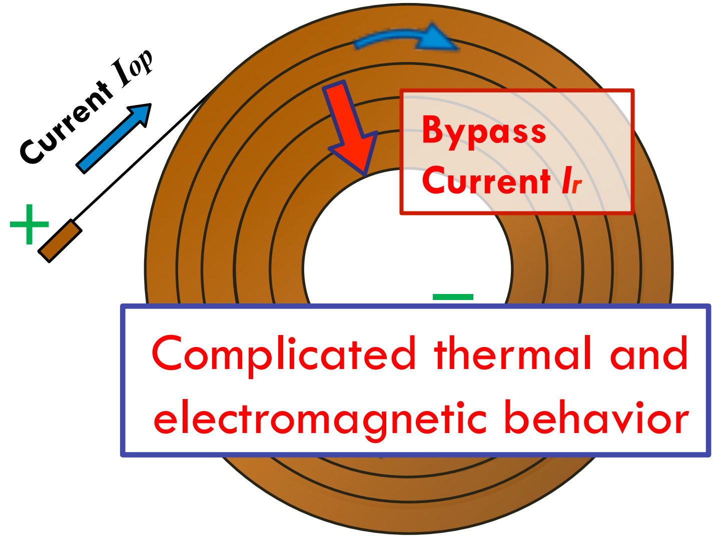
➡ **Possible to protect coil from burning-out?**

# For Evaluation of NI pancake coil

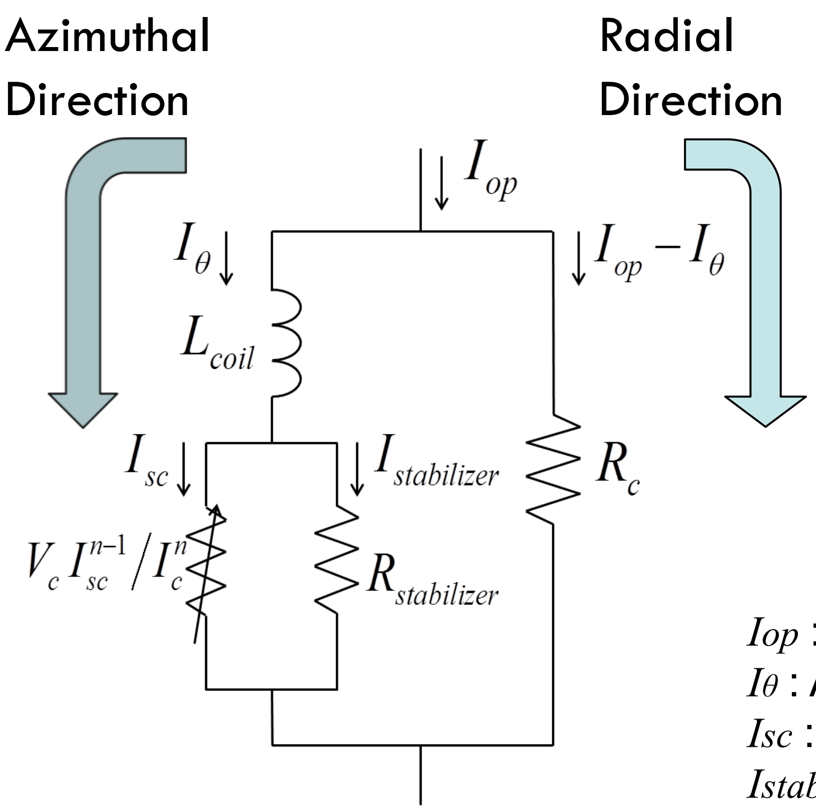
**To evaluate NI coil performances**

1. Thermal & electromagnetic behavior
2. Transient behavior at bypassing
3. Charging/discharging delay

To investigate these performances, we have developed the PEEC (Partial Element Equivalent Circuit) analysis with the thermal FEA (Finite Element Analysis).



# Simple Parallel Equivalent Circuit (SPEC)




$$L_{coil}\frac{dI_\theta}{dt}+R_{stabilizer}I_{stabilizer}=R_c\left(I_{op}-I_\theta\right)$$

$$R_{stabilizer}I_{stabilizer}=V_c\left(\frac{I_{sc}}{I_c}\right)^n$$

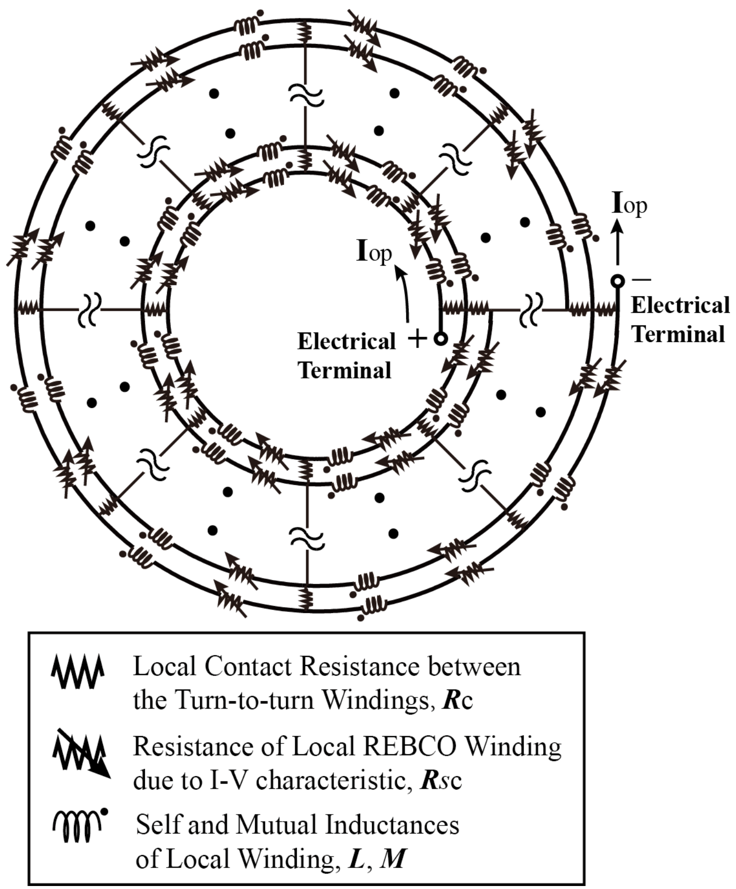
$$I_{stabilizer}+I_{sc}=I_\theta$$

*Iop* : Transport current
*Iθ* : Azimuthal current
*Isc* : Current in REBCO
*Istabilizer* : Current in Stabilizer
*Lcoil* : Coil Inductance
*Rc* : Resistance at contact
*Rstabilizer* : Resistance at Stabilizer

➢ Features of the circuit

- ➢ Simplifying azimuthal and radial direction of current path
- ➢ Employing n-power model as nonlinear V-I characteristic
- ➢ Impossible to investigate the detailed behavior inside the coil

# PEEC model




## ➢ Features of PEEC model

- ➢ Azimuthally dividing the coil into 72 elements
- ➢ Considering the followings:

1. Electric resistance of winding

(The REBCO resistance, based on n-power law, is dominant.)

2. Turn-to-turn contact resistance

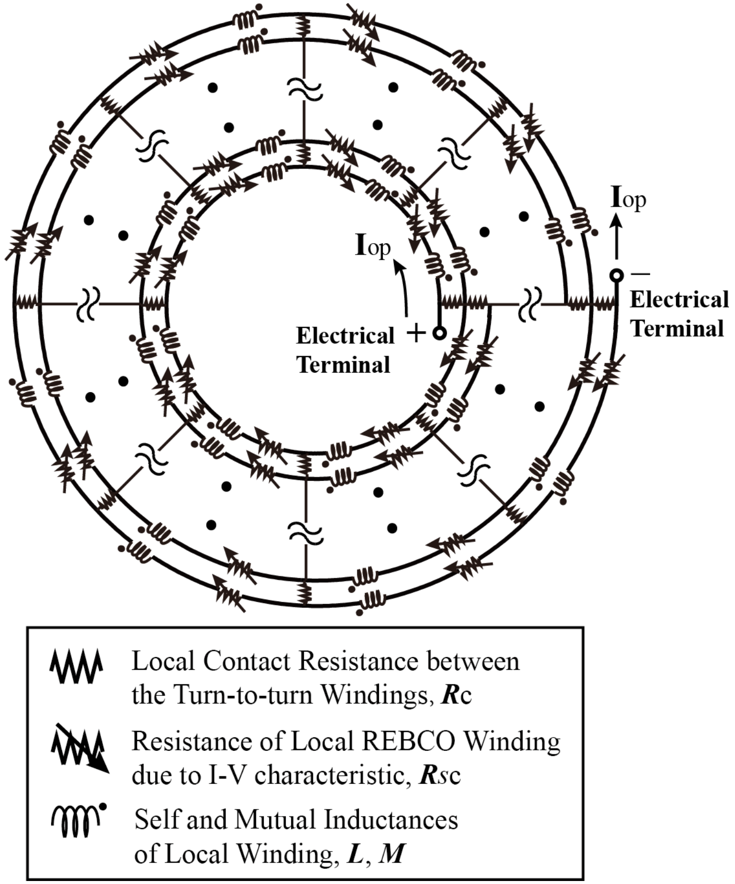
(As the priori study, it is estimated to be **70 μΩ・cm²**)

3. Self- and mutual-inductances of every element

(It strongly affects a local behavior)

➢ Possible to, in detail, investigate the complicated current distribution inside NI pancake coil

# PEEC model




## Equations on PEEC

$$R_\theta^{(i)} I_\theta^{(i)} + \sum_{j=1}^{N} M_{ij} \frac{\mathrm{d}I_\theta^{(j)}}{\mathrm{d}t} + R_r^{(i+1)} I_r^{(i+1)} = R_\theta^{(i+Div\theta)} I_\theta^{(i+Div\theta)} + \sum_{j=1}^{N} M_{(i+Div\theta)j} \frac{\mathrm{d}I_\theta^{(j)}}{\mathrm{d}t} + R_r^{(i)} I_r^{(i)}$$

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

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

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

$R_\theta$ : Azimuthal resistance (parallel circuit of Cu and REBCO)
$R_r$ : Radial resistance (70 μΩ•cm$^2$)
$I_\theta$ : Azimuthal current
$I_r$ : Radial current
M : Self- and mutual-inductances

# PEEC model with thermal analysis

## Partial Element Equivalent Circuit

$$R_\theta^{(i)} I_\theta^{(i)} + \sum_{j=1}^{N} M_{ij} \frac{dI_\theta^{(j)}}{dt} + R_r^{(i)} I_r^{(i)}$$

$$= R_\theta^{(i+Div_\theta)} I_\theta^{(i+Div_\theta)} + \sum_{j=1}^{N} M_{(i+Div_\theta)j} \frac{dI_\theta^{(j)}}{dt} + R_r^{(i+1)} I_r^{(i+1)}$$

$$I_\theta^{(i)} + I_r^{(i)} = I_\theta^{(i-1)} + I_r^{(i-Div_\theta)}$$

$R_\theta$: Resistance in rotational direction
$I_\theta$: Current in rotational direction
$R_r$: Resistance in radial direction
$I_r$: Current in radial direction
$M$: Inductance matrix including self and mutual inductance

Import Rsc

## Superconductive Behavior

- Formula of Biot-Savart

$$B = \frac{\mu_0 J}{4\pi} \int_0^{2\pi} \frac{n_J \times R}{R^3} dv$$

- Percolation Model

$for\ T < T_{GL}$

$$E(J) = \frac{\rho_{FF}}{m+1} J \left(\frac{J}{J_0(T,B)}\right)^m \left(1 - \frac{J_{CM}(T,B)}{J}\right)^{m+1}$$

$for\ T = T_{GL}$

$$E(J) = \frac{\rho_{FF}}{m+1} J \left(\frac{J}{J_0(T,B)}\right)^m$$

$for\ T > T_{GL}$

$$E(J) = \frac{\rho_{FF}}{m+1} |J_{CM}(T,B)| \left(\frac{|J_{CM}(T,B)|}{J_0(T,B)}\right)^m \cdot \left\{\left(1 + \frac{J}{|J_{CM}(T,B)|}\right)^{m+1} - 1\right\}$$

Export T

## Partial Element Equivalent Circuit

- Formula of 2D Thermal Conduction Analysis:

$$\rho c(T) \frac{\partial T}{\partial t} = \lambda_x(T) \frac{\partial T}{\partial x^2} + \lambda_y(T) \frac{\partial T}{\partial y^2} + Q_J + Q_c$$

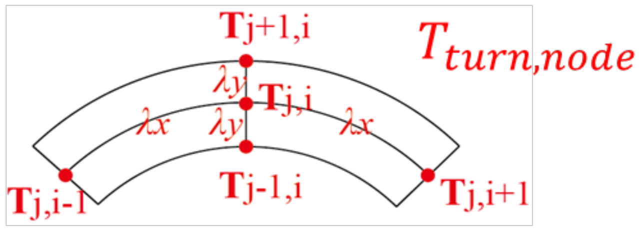
- Cooling Effert:

$$Q_c = h(T)(T_{LN_2} - T_i)$$

- Heat Generation:

$$Q_J = I^2 R(T) \Delta t$$

$\rho$: Density
$c(T)$: Specific heat
$\lambda_x(T), \lambda_y(T)$: Thermal conductivity in horizontal and vertical direction




$$\lambda_y = \frac{1}{20} \lambda_x$$

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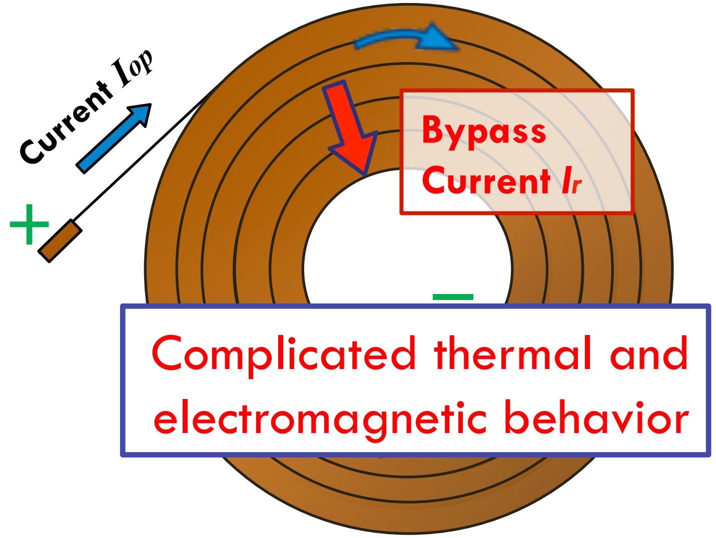
# For Evaluation of NI pancake coil

**To evaluate NI coil performances**

1. Thermal & electromagnetic behavior
2. Transient behavior at bypassing
3. Charging/discharging delay

To investigate these performances, we have developed the PEEC (Partial Element Equivalent Circuit) analysis ~~with the thermal FEA (Finite Element Analysis)~~.



# Discharging test

No-Insulation REBCO pancake coil

| Parameter | NI-20 | NI-40 | NI-60 |
|---|---|---|---|
| **REBCO conductor** | | | |
| Overall width; thickness(mm) | 4.0; 0.063 | | |
| Copper stabilizer thickness(μm) | 10(5 per each side) | | |
| $I_c$@77K,self-field(A) | ＞100 | | |
| **Coil** | | | |
| i.d.; o.d.; Height(mm) | 60; 62.5; 4 | 60; 65.0; 4 | 60; 67.6; 4 |
| Turns | 20 | 40 | 60 |
| $I_c$@77K,self-field(A) | 54 | 47 | 43 |
| $B_z$ per amp at center(mT/A) | 0.41 | 0.80 | 1.17 |

- The coils of 20 and 40 turns are made by unwinding 60-turn cool.
- The coil is suddenly discharged from 30 A.
- The center magnetic field Bz is measured.
- From the time constant of Bz decay,
  the turn-to-turn contact resistance is estimated.

$$R_c = \frac{L_{coil}}{\tau}$$

# Discharging test (time constant)

No-Insulation REBCO pancake coil

| Parameter | NI-20 | NI-40 | NI-60 |
|---|---|---|---|
| REBCO conductor | | | |
| Overall width; thickness(mm) | 4.0; 0.063 | | |
| Copper stabilizer thickness(μm) | 10(5 per each side) | | |
| $I_c$@77K,self-field(A) | ＞100 | | |
| Coil | | | |
| i.d.; o.d.; Height(mm) | 60; 62.5; 4 | 60; 65.0; 4 | 60; 67.6; 4 |
| Turns | 20 | 40 | 60 |
| $I_c$@77K,self-field(A) | 54 | 47 | 43 |
| $B_z$ per amp at center(mT/A) | 0.41 | 0.80 | 1.17 |

| | Parameters | | Results | | |
|---|---|---|---|---|---|
| | $L_{coil}$(μH) | $R_{ct}$(μΩ･cm$^2$) | Experiment $\tau$ (ms) | PEEC $\tau$ (ms) | SPEC $\tau$ (ms) |
| **NI-20** | 51.4 | 75.3 | 277 | 350 | 383 |
| **NI-40** | 197.8 | 72.4 | 552 | 627 | 654 |
| **NI-60** | 431.6 | 72.4 | 810 | 854 | 911 |

# Discharging test (comparison)

No-Insulation REBCO pancake coil

| Parameter | NI-20 | NI-40 | NI-60 |
|---|---|---|---|
| **REBCO conductor** | | | |
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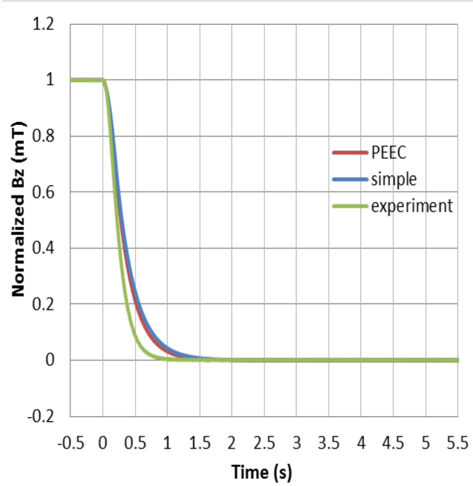
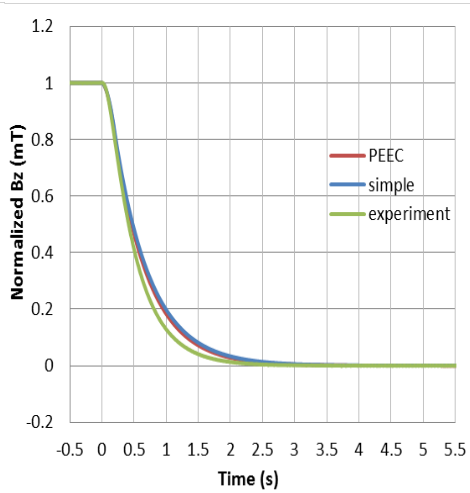
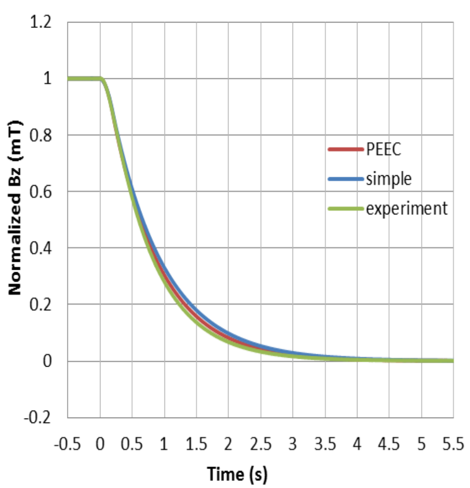



NI-20




NI-40




NI-60

# Charging test

No-Insulation REBCO pancake coil

Parameters of NI HTS pancake coil

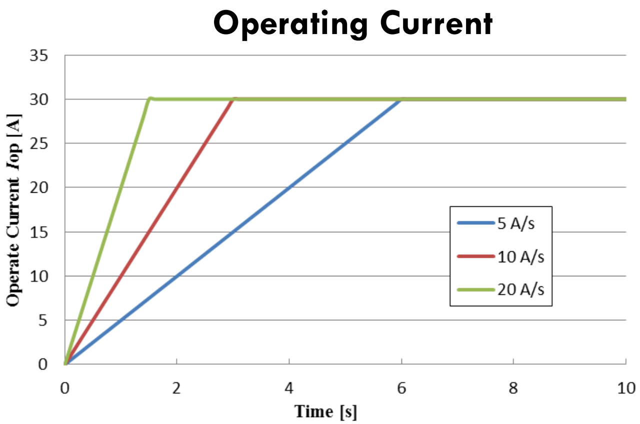
| | | |
|---|---|---|
| REBCO wire | Overall width; thickness (mm) | 4.0; 0.063 |
| | Copper stabilizer thickness | 10 (5 per each side) |
| Coil | Inner diameter (mm)<br>Outer diameter (mm)<br>Height (mm) | 60.0<br>67.6<br>4.0 |
| | Turns | 60 |
| | $I_c$ at 77 K, self-field (A) | 43 |
| | $B_z$ per amp at coil center (mT/A) | 1.17 |
| | Inductance (μH) | 432.3 |
| Turn-to-turn contact resistance, $R_c$ (μΩ) | | 534 |
| Contact surface resistivity, $R_{ct}$ (μΩ•cm $^2$) | | 71.3 |

## Operating Current

Charging Speed

- **Sweep rate 5 A/s**
- **Sweep rate 10 A/s**
- **Sweep rate 20 A/s**

(max. 30A)

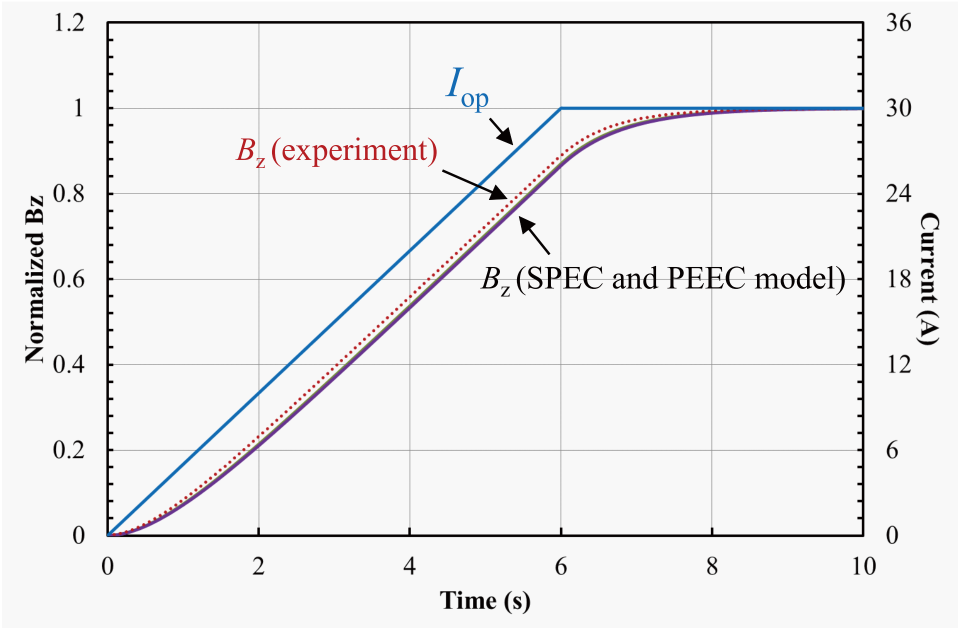


# Charging test (comparison)

Charging Delay

| Ramp rate (A/s) | Experiment | SPEC | PEEC |
|---|---|---|---|
| **5** | 1.11 s | 1.62 s | 1.52 s |
| **10** | 2.20 s | 2.68 s | 2.58 s |
| **20** | 2.61 s | 3.12 s | 3.02 s |

## 5 A/s



# Charging test (comparison)

Charging Delay

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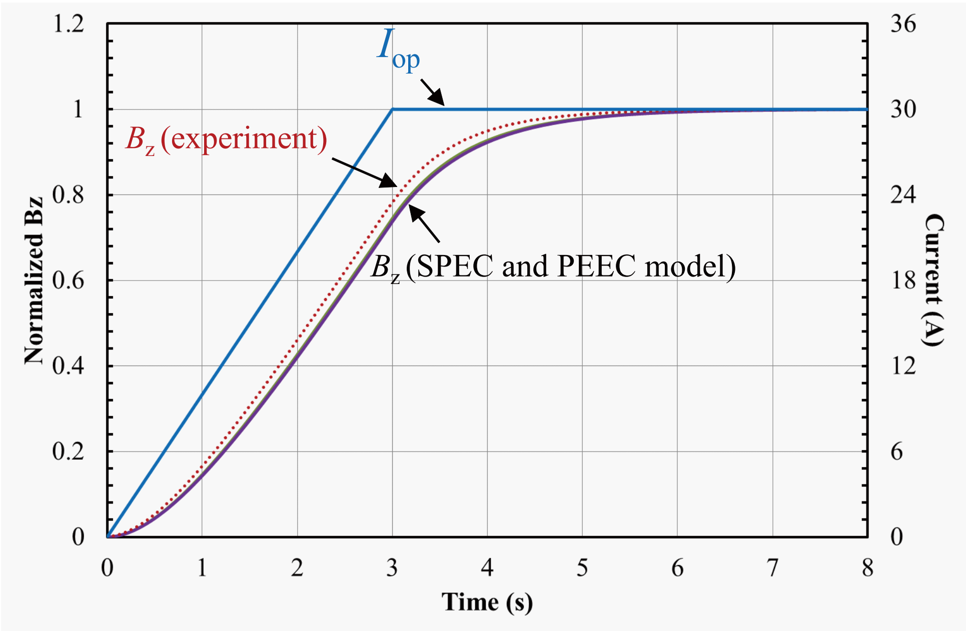
## 10 A/s

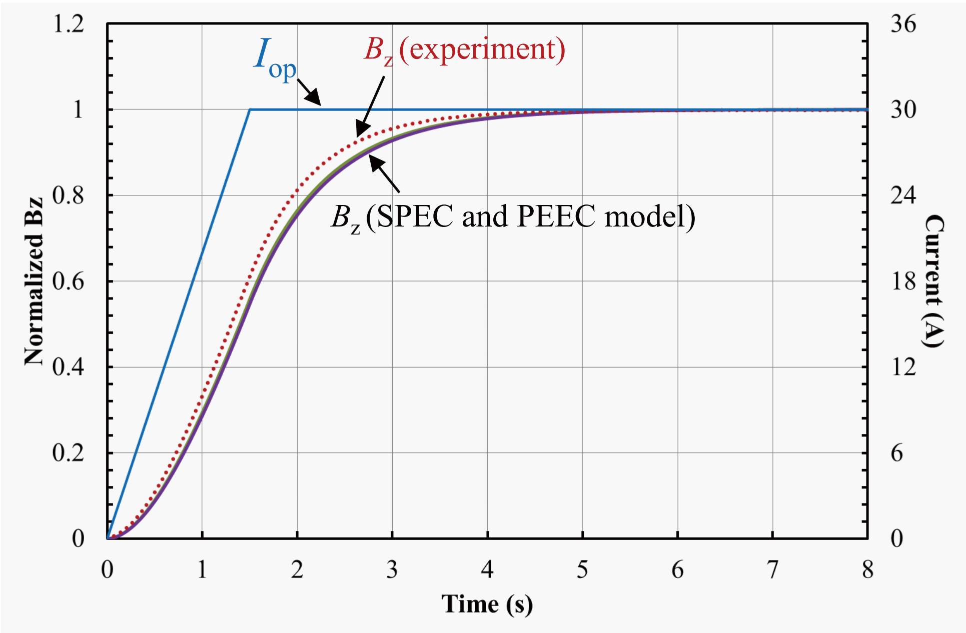


# Charging test (comparison)

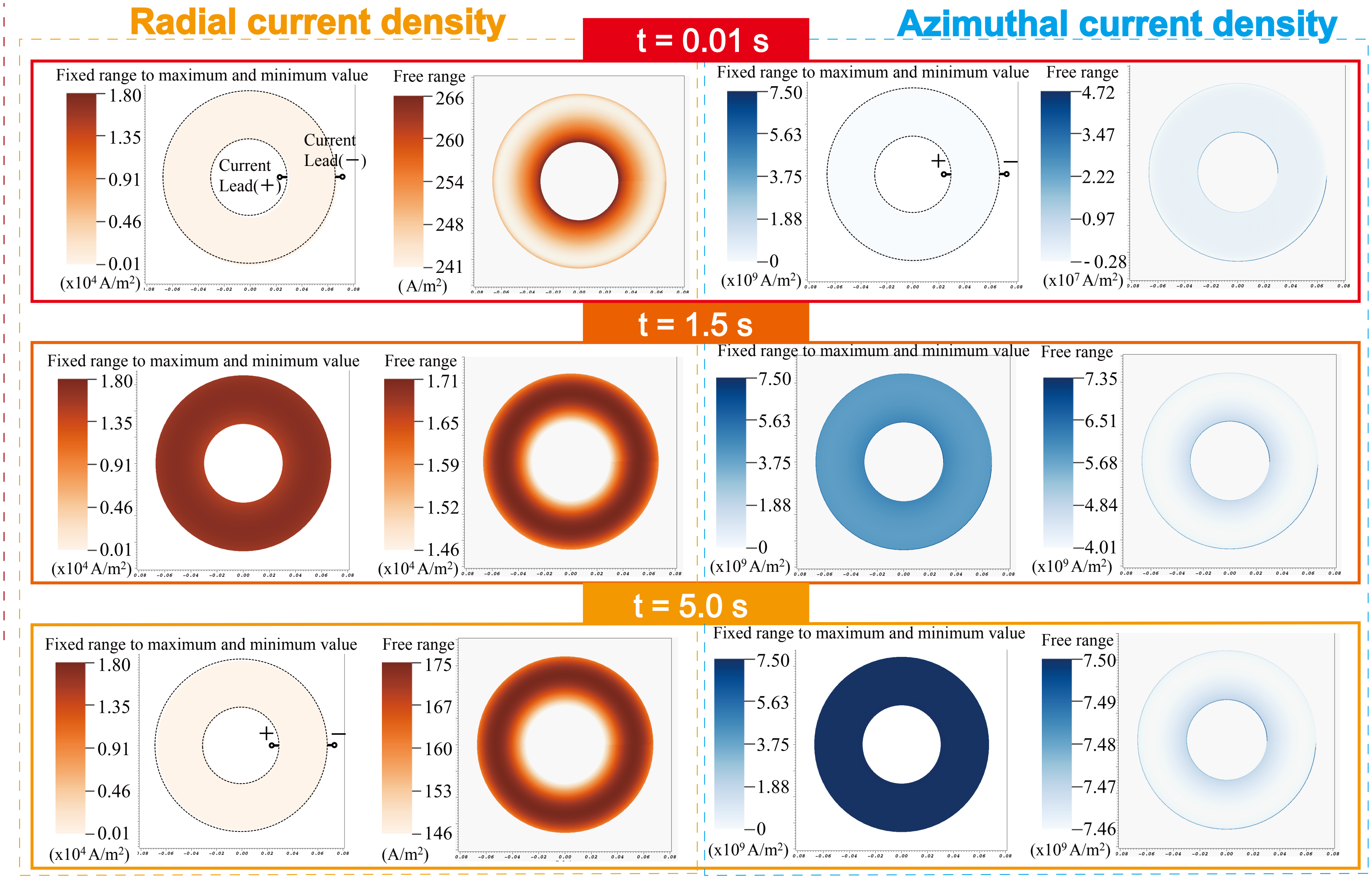
Charging Delay

| Ramp rate (A/s) | Experiment | SPEC | PEEC |
|---|---|---|---|
| **5** | 1.11 s | 1.62 s | 1.52 s |
| **10** | 2.20 s | 2.68 s | 2.58 s |
| **20** | 2.61 s | 3.12 s | 3.02 s |

## 20 A/s



# Charging test (current distribution)



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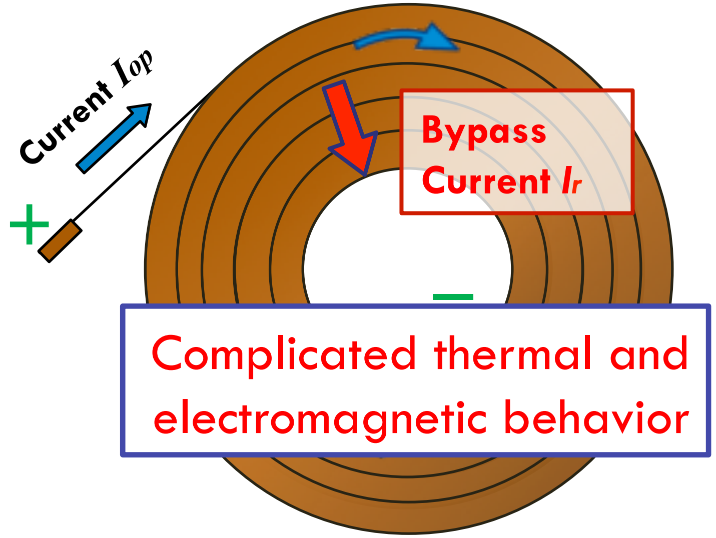
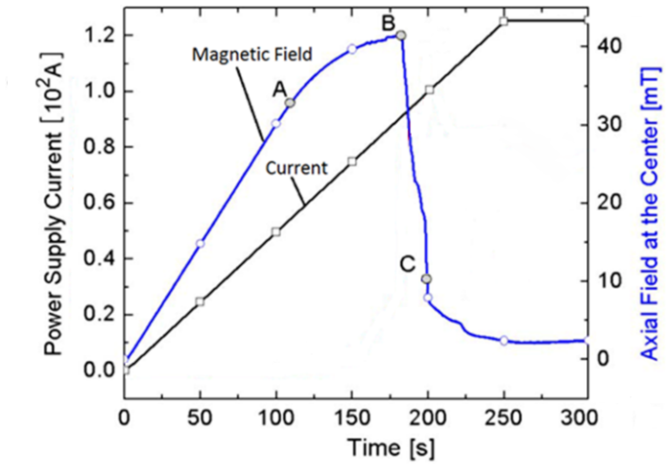



To investigate these performances, we have developed the PEEC (Partial Element Equivalent Circuit) analysis with the thermal FEA (Finite Element Analysis).

Over-current test of NI pancake coil

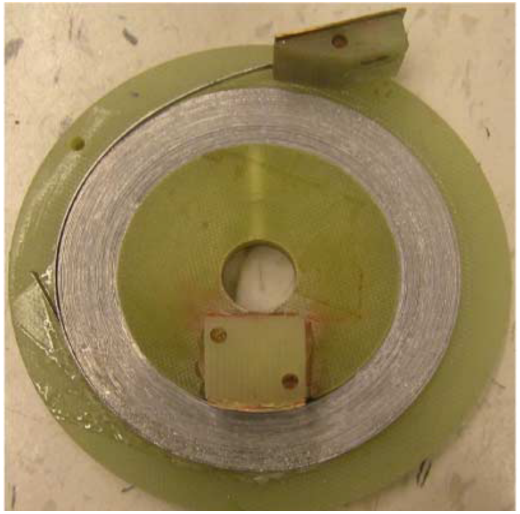



[1] S.Hahn, Y.Iwasa et al.:, "HTS Pancake Coils Without Turn-to-Turn Insulation", IEEE Trans. On Appl. Supercond., Vol. 21 (2011) 1592-1595

# Over-current test (experiment)

## Specifications of NI REBCO single pancake

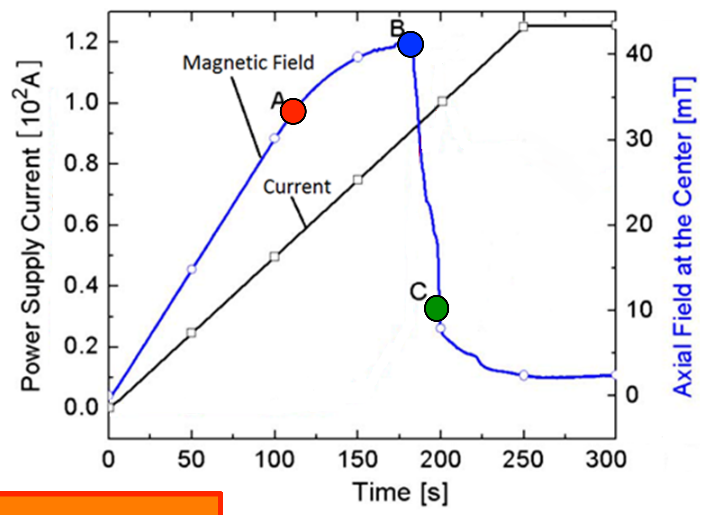
| Parameters | Values |
|---|---|
| HTS Conductor | SuperPower® SCS4050 |
| Conductor width; thickness [mm] | 4.0; 0.1 |
| Copper stabilizer thickness [mm] | 0.04 |
| Ic @ 77K, self-field [A] | 85 |
| Ic @77K, coil [A] | 54 |
| n-Value @ 77K | 30 |
| Insulation | Bare (no insulation) |
| Number of turns | 30 |
| i.d.; o.d.; height [mm] | 60; 66; 4.0 |
| Sweep Rate [A/s] | 0.5 |
| Inductance [μH] | 110.0 |



NI Coil made at MIT

[1] S.Hahn, Y.Iwasa et al.:, "HTS Pancake Coils Without Turn-to-Turn Insulation", IEEE Trans. On Appl. Supercond., Vol. 21 (2011) 1592-1595

# Over-current test (comparison)




Experiment

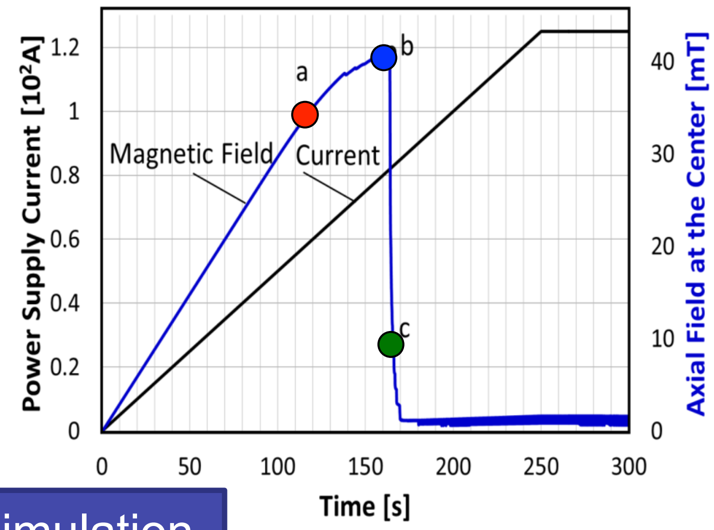
**Current Sweep Rate: 0.5 A/s**

Center field linearly increases to **Point A** close to Ic.

Slowly increasing from **A** to **B**.

Reaching to 40 mT at **B**, and then drastically dropping.

At **Point C** (12 s after **B**), reducing to10 mT.




Simulation

Center field linearly increases to Point a close to Ic.

Slowly increasing from **a** to **b**.

At **Point b**, reaching to 41 mT, and then drastically droping.

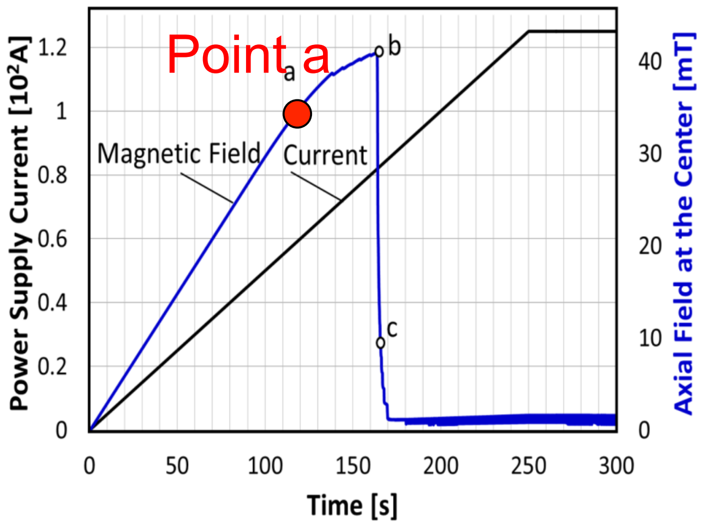
At **Point c** (6 s after **b**), dropping to 10 mT.

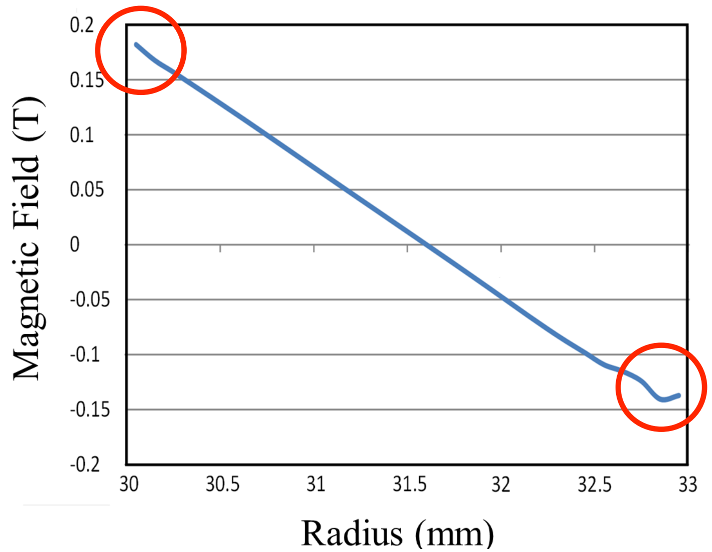
Beyond **Point c**, keeping 0.60 mT.

[1] S.Hahn, Y.Iwasa et al.: "HTS Pancake Coils Without Turn-to-Turn Insulation", IEEE Trans. On Appl. Supercond., Vol. 21 (2011) 1592-1595

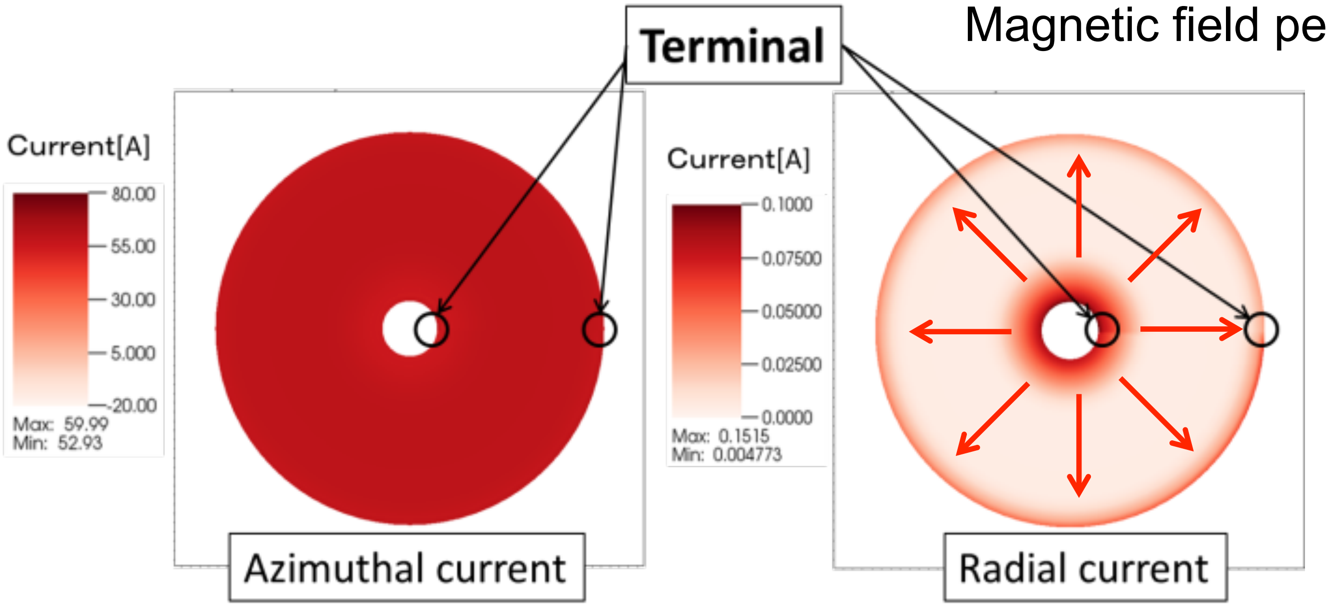
Simulation result agrees with Experiment well.

# Over-current test (current distribution)



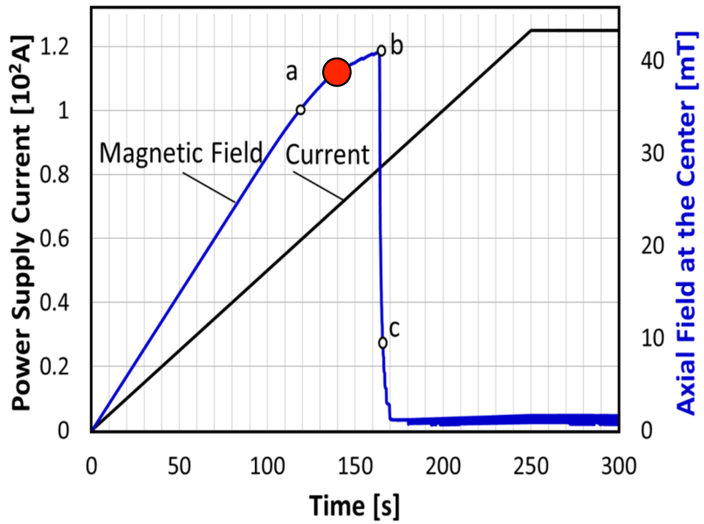

Magnetic field perpendicular to coil, Bz




Time : 120 s

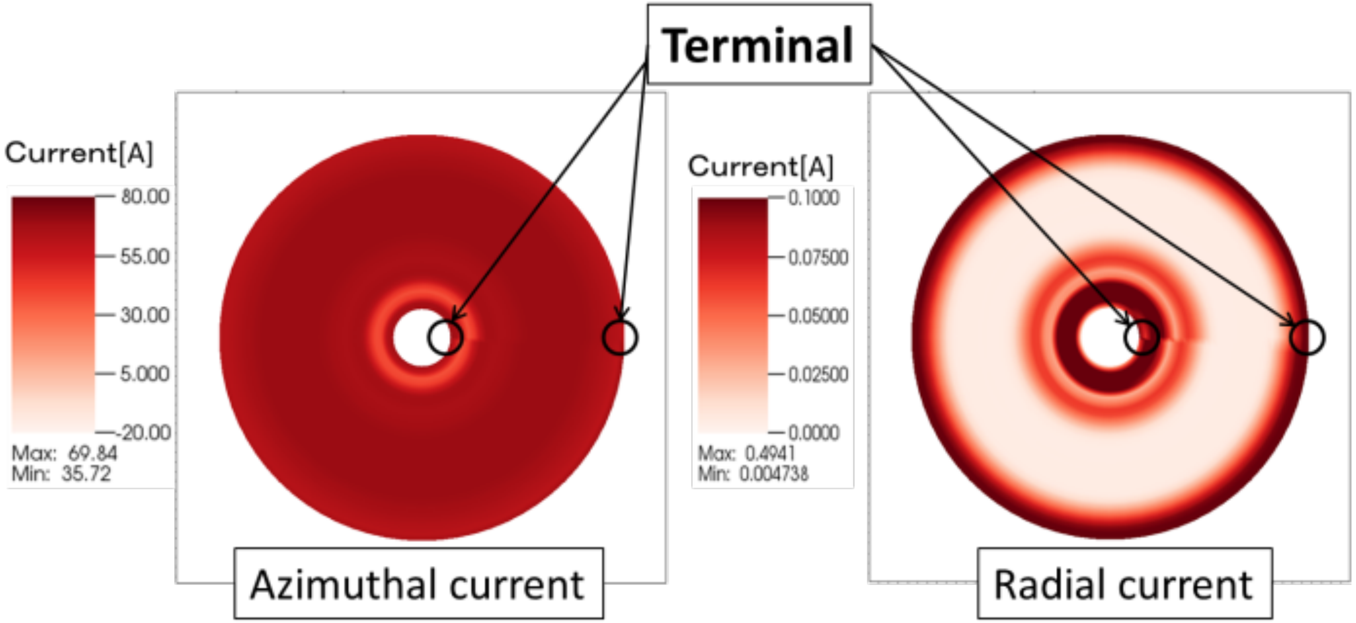
Current : 60 A

# Over-current test (current distribution)

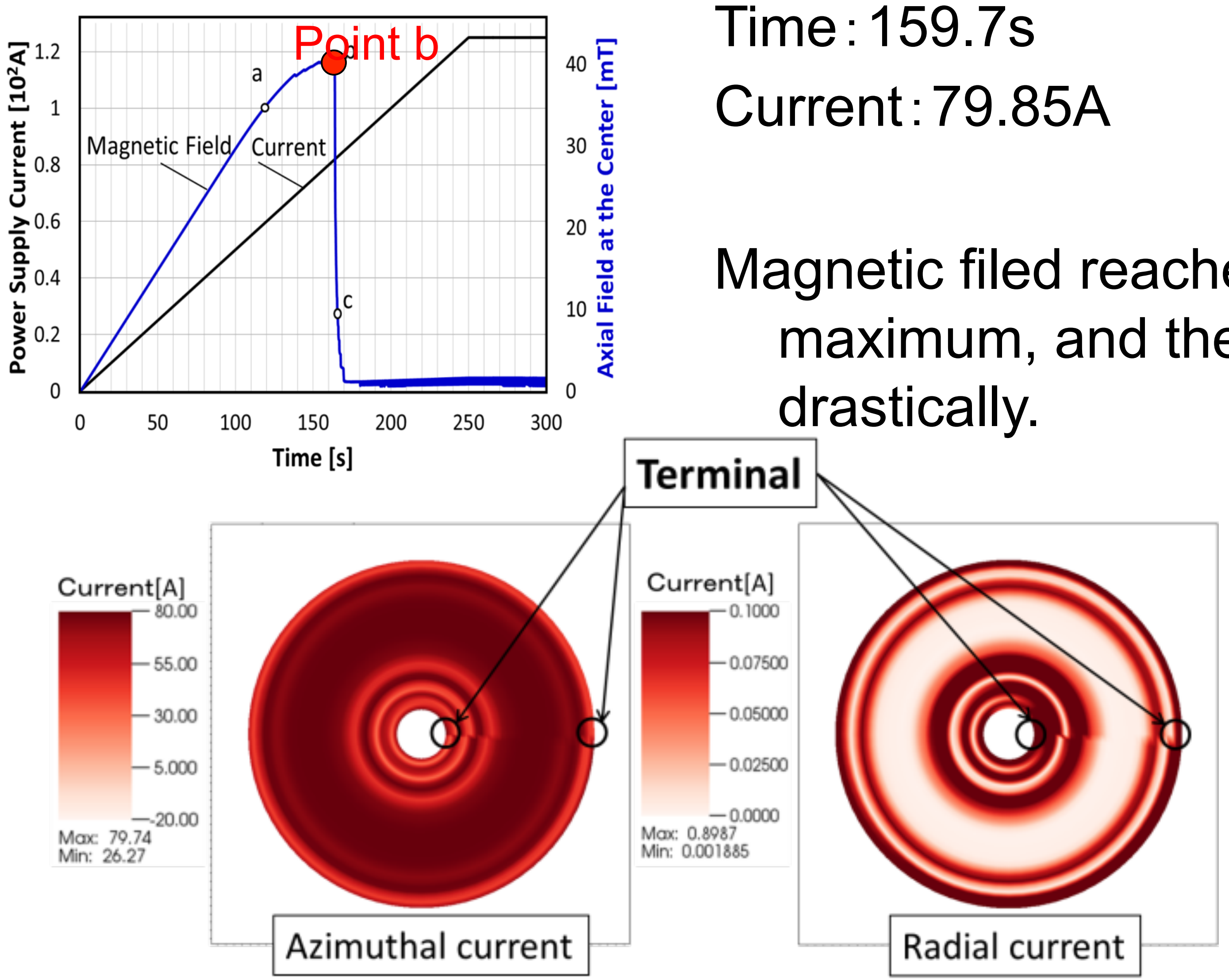



- Time：140 s
- Current：70 A

- From a to b, magnetic field slowly increases.
- Radial Current gradually increases inside and outside coil.



# Over-current test (current distribution)

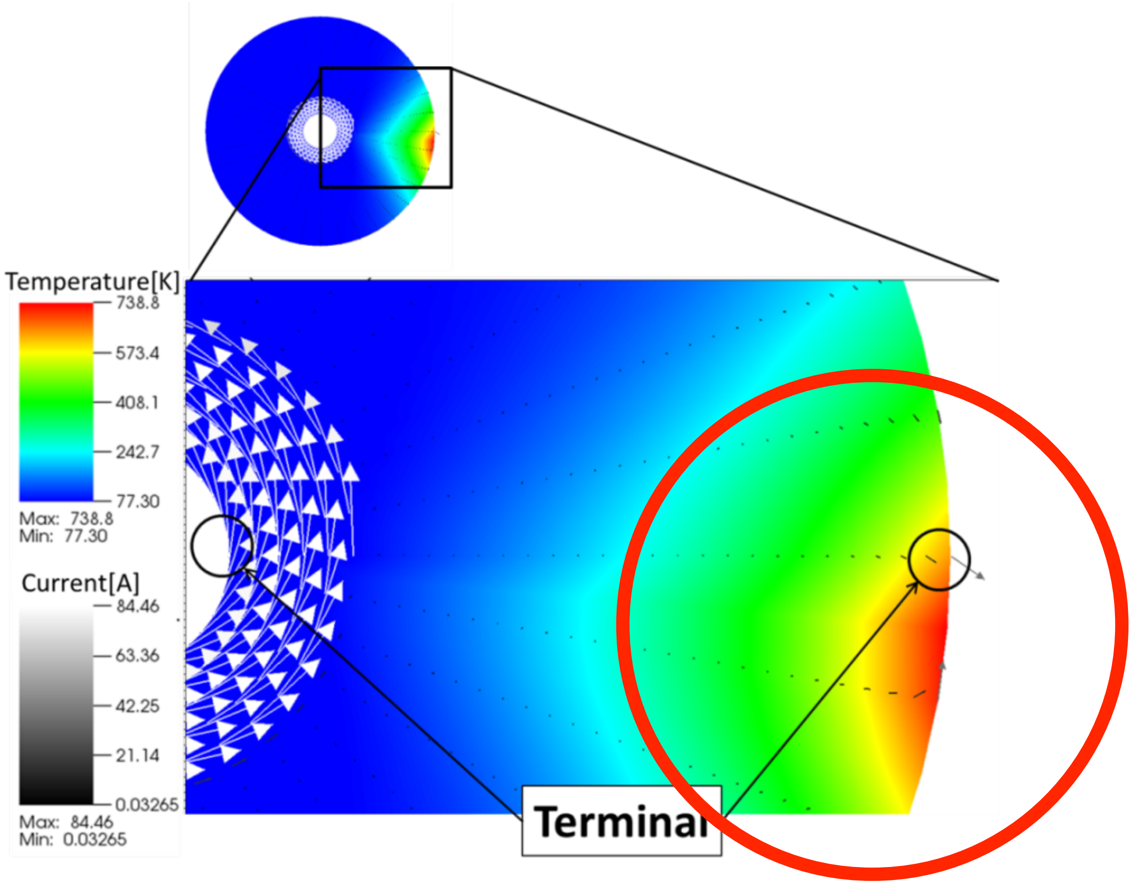



Time : 159.7s

Current : 79.85A

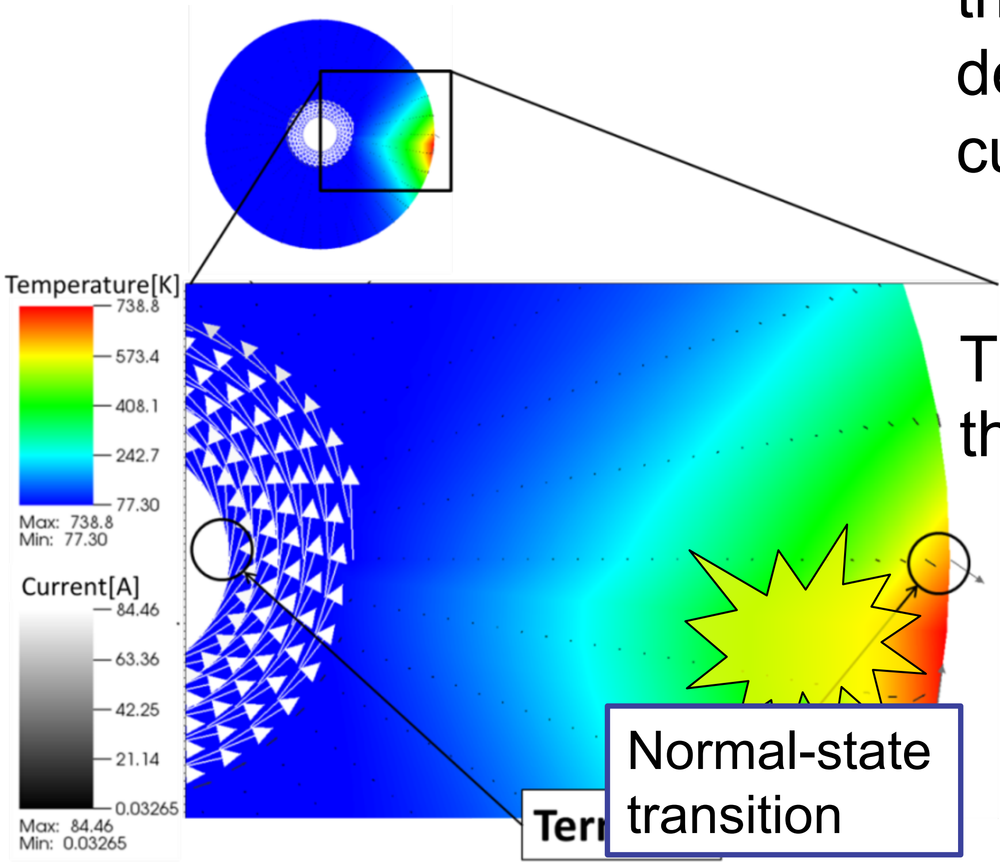
Magnetic filed reaches to maximum, and then drop drastically.

# Over-current test (current distribution)




Heating near the outer electric terminal

# Over-current test (current distribution)



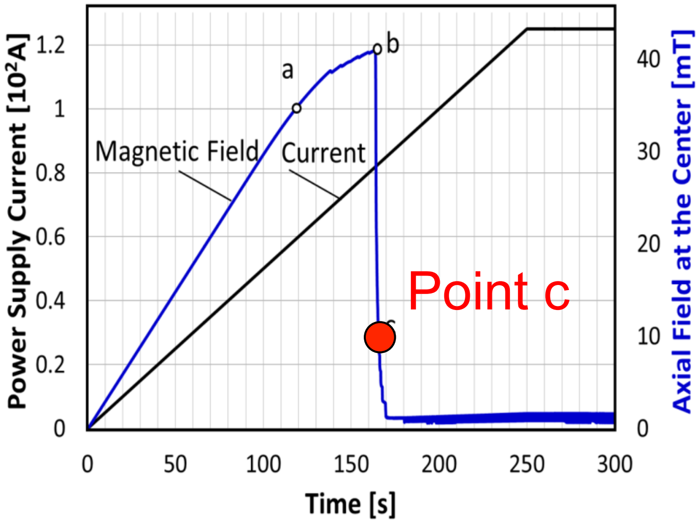

On the outermost turn, the critical current deteriorates, so the radial current extremely increases.

The current concentrates into the outer terminal.

Heating near the outer terminal

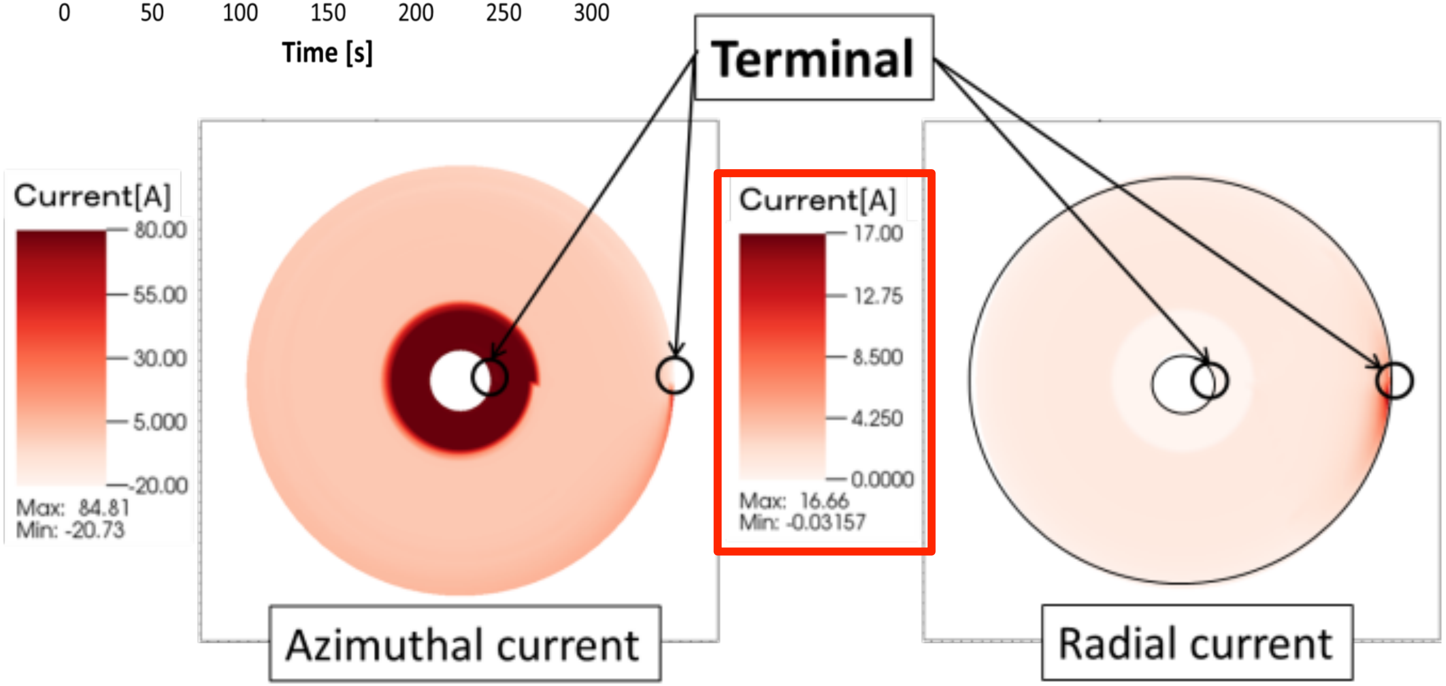
Normal state propagates into the inside of coil

# Over-current test (current distribution)




- Time：165.5s
- Current：82.75A

- The azimuthal current hardly flows except the inside of coil.
- The radial current increases.



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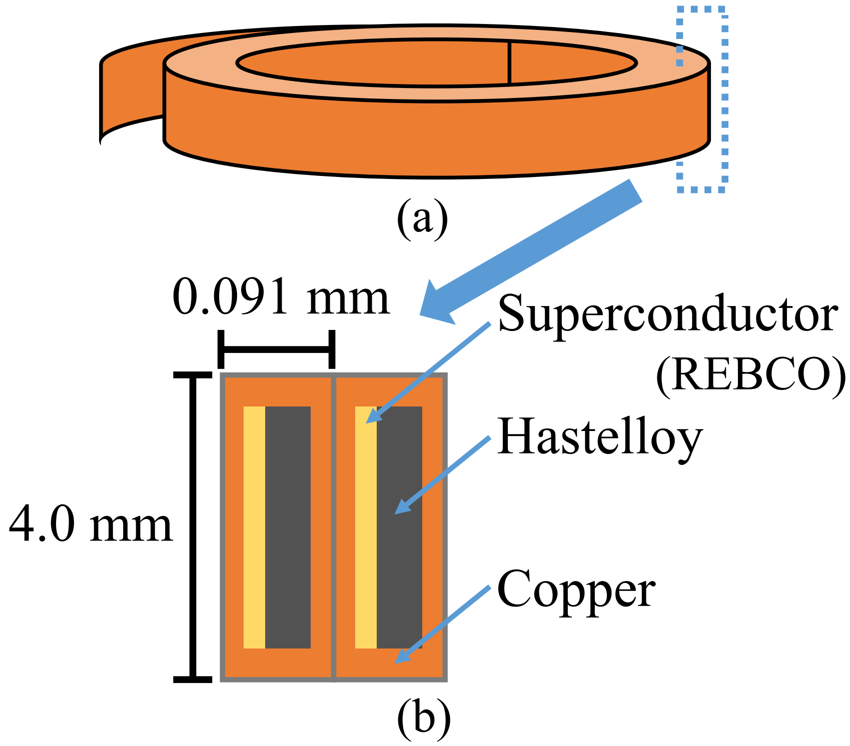
# Simulation of current flow on cross section




Specifications of REBCO Tape

| Parameters | | Values |
|---|---|---|
| Tape width | [mm] | 4 |
| Copper stabilizer thickness | [mm] | 0.02 |
| Superconductor thickness | [μm] | 1.0 |
| Superconductor width | [mm] | 3.96 |
| Hastelloy thickness | [μm] | 50 |

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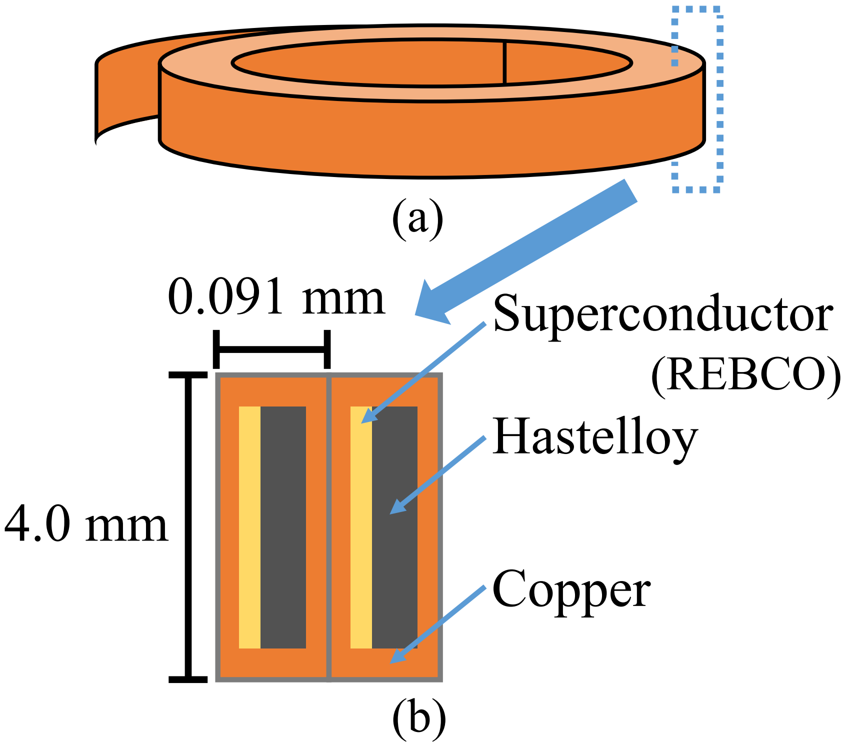


2D-FEM
with double-nodes technique

Governing Equation

$$\nabla \cdot \sigma \nabla \phi = 0$$

Turn-to-turn contact surface condition

$$\phi_i - \phi_j = \rho_{\mathrm{ct}} J_{\mathrm{ct}}$$

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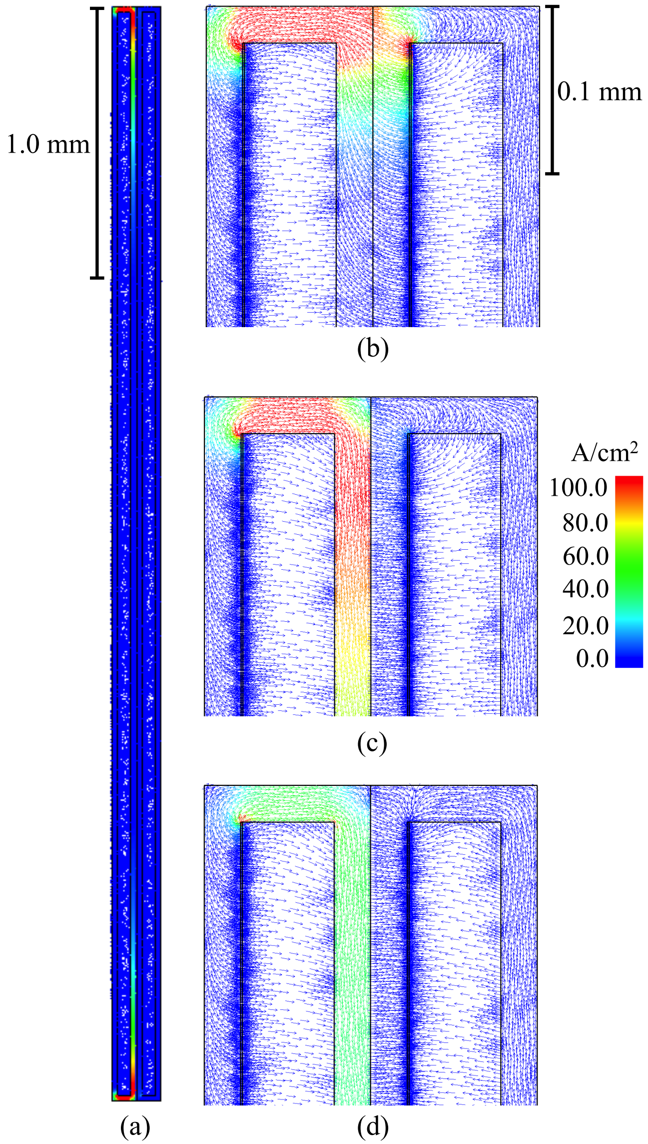
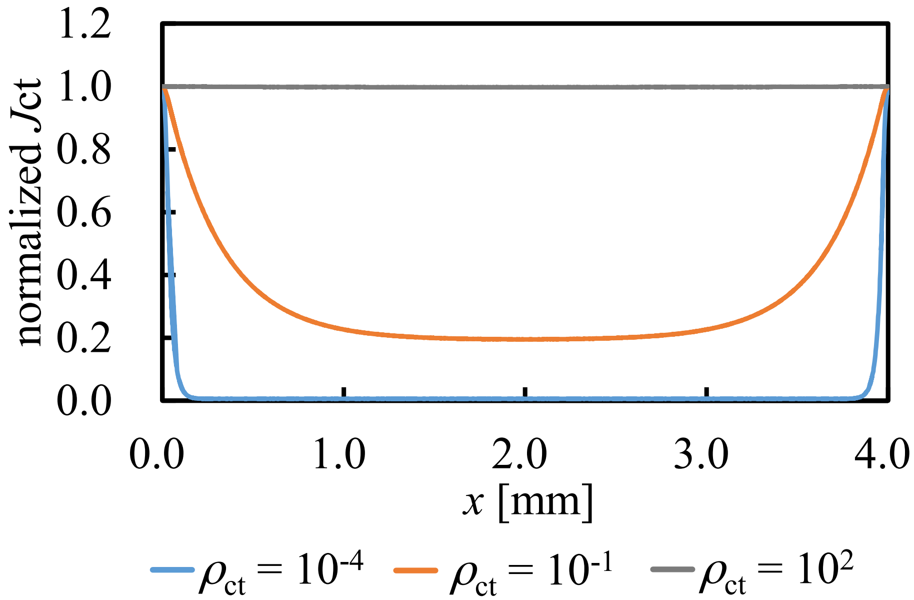



Current density distribution on two cross sections of NI REBCO tapes at $\rho_{ct}$ = (a) $10^{-1}$ $\mu\Omega\cdot cm^2$. (b)-(d) current density distributions on the top of cross section in NI REBCO tape when $\rho_{ct}$ = (b) $10^{-4}$, (c) $10^{-1}$, and (d) $10^2$ $\mu\Omega\cdot cm^2$, respectively.



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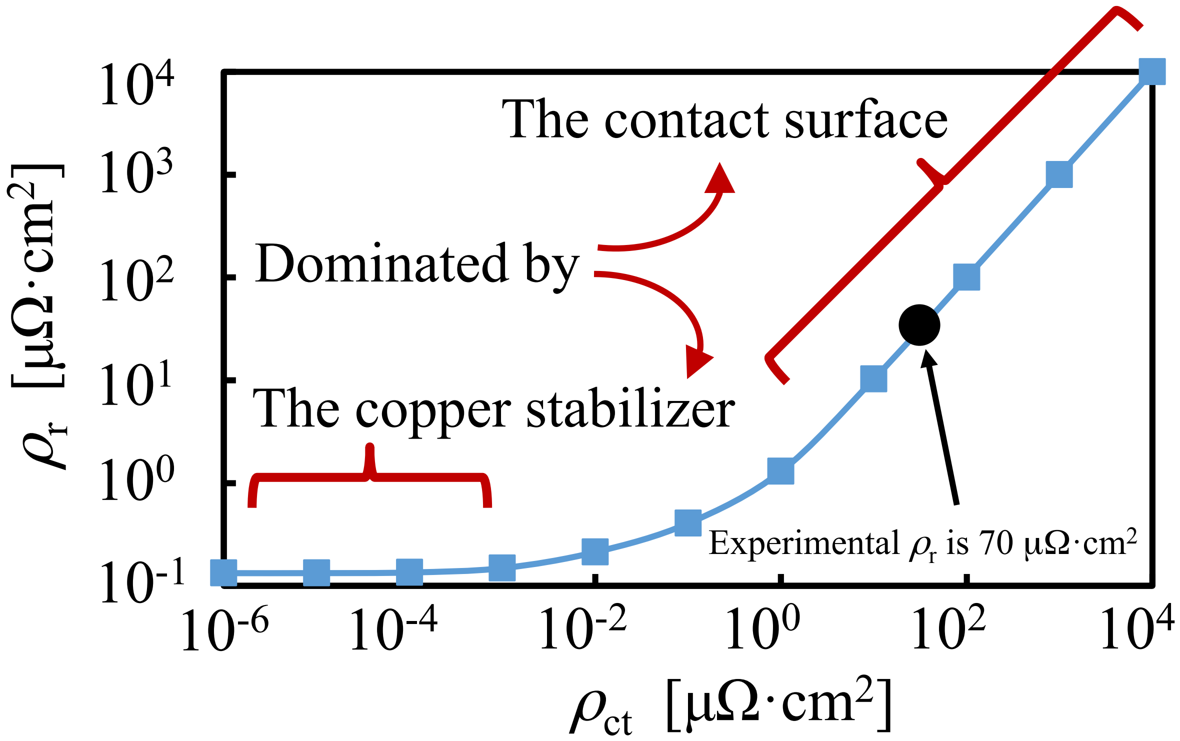

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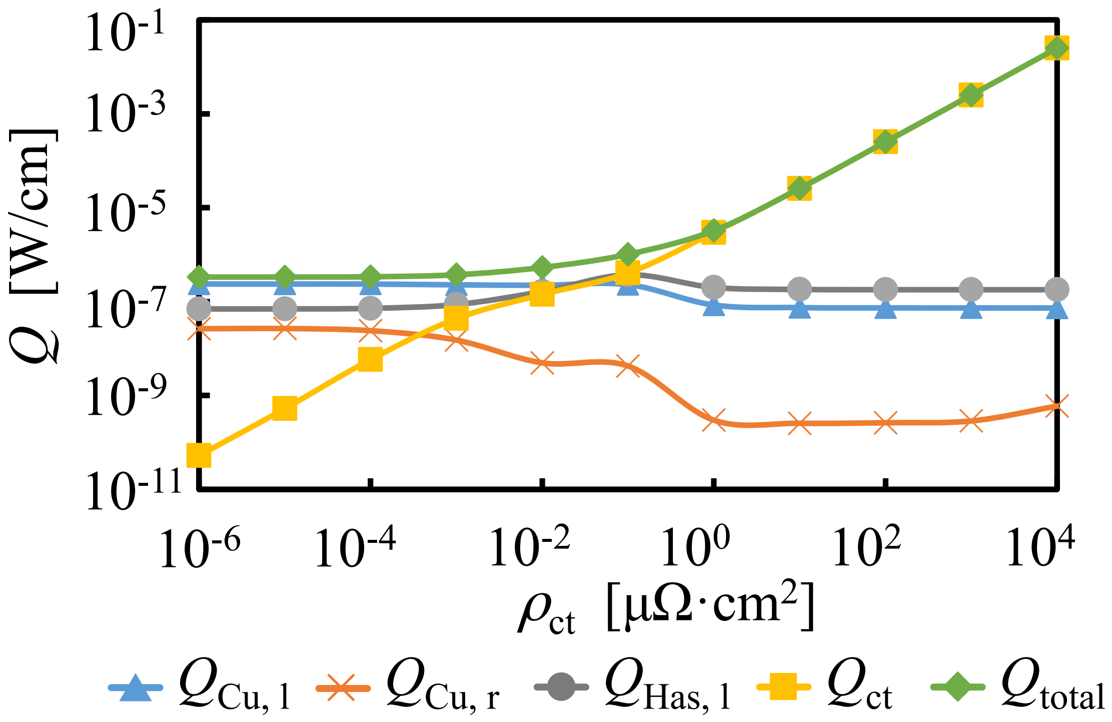

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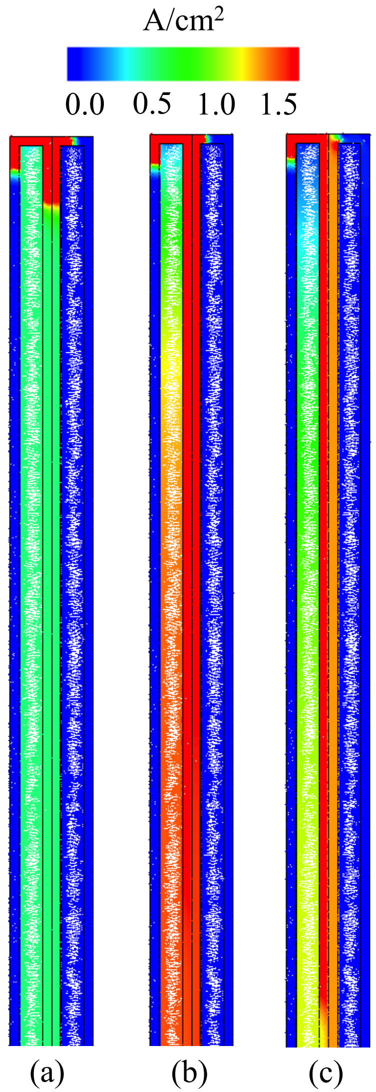
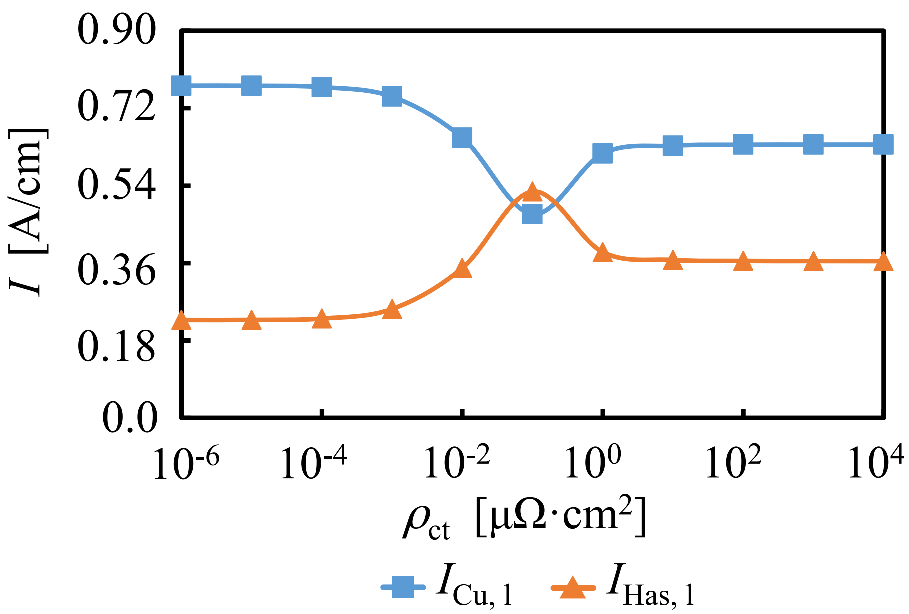



Current distribution in the Hastelloy substrate at (a) $\rho_{ct}$ = $10^{-4}$, (b) $10^{-1}$, and (c) $10^{2}$ μΩ·cm$^2$, respectively.



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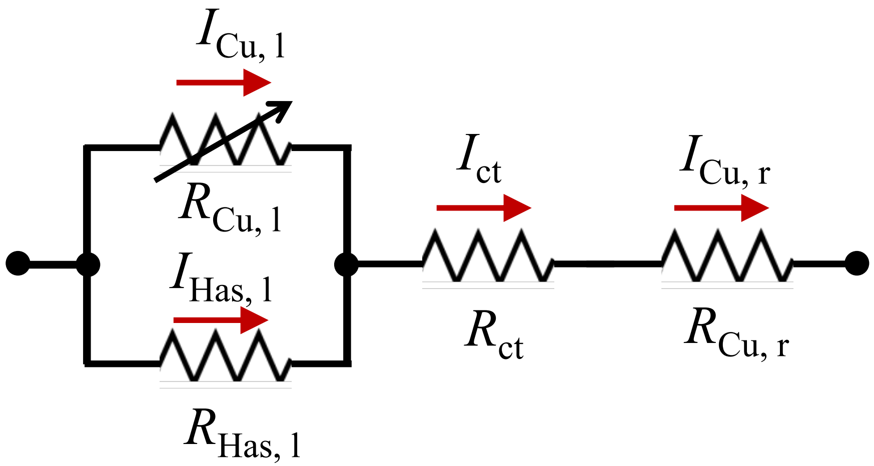


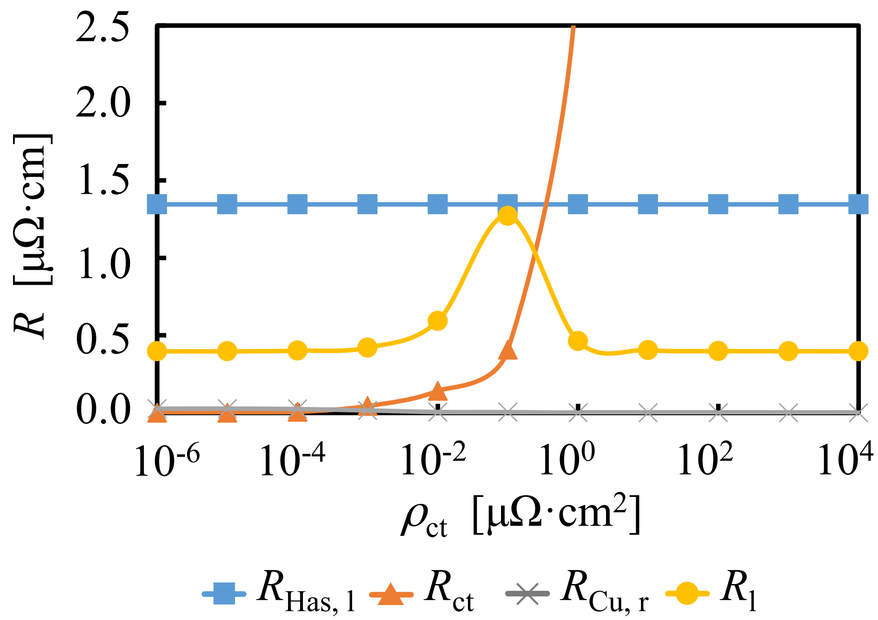

## Contents

# Conclusion

- The PEEC model is applied to No-Insulation REBCO pancake coil.
- Simulation of discharging/charging test agrees with experiments well.
- Simulation of over-current test agrees with experiments well.
- We can know the electromagnetic and thermal behavior inside NI coils using the PEEC model.
- We can know the electromagnetic behavior on the cross section between turns of NI coils.

## In future

- We'd like to develop the simulation tools more, to design the coil and wire configuration.