Self-healing effect from thermal runaway for No-Insulation (NI) REBCO coils

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High current density characteristics of REBCO

Limitation of LTS

HTS
High current density, >200A/mm², in a super-high field over 23.5 T

http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html
Thermal runaway for REBCO coils

Paraffin impregnated coil at 77K

Coil critical current

Premature thermal runaway

Natural thermal runaway

Take-off

Degraded coil; \( n = 1.5 \)

Undegraded coil; \( n = 27 \)

REBCO layer-wound coil
(17.2T at 4.2K)

Premature thermal runaway: 353A

Normal voltage due to conductor degradation

Damage on the coil

Matsumoto et al.  
IEEE 9501604 (2012)

Yanagisawa et al, SuST 2012

Normal voltage due to conductor degradation
No-insulation (NI) method


NI REBCO pancake coil

Critical current

Stable

Thermal runaway

Reduction in magnetic field

Self-healing from thermal runaway

=> Mystery of NI coils
Motivation:
Why is thermal runaway for a NI coil self-healed?

Goal:
Reveal the mechanism of the self-healing effect by experiments and using simulation
Mechanism of self-healing effect from thermal runaway for NI REBCO coils
Self-healing from thermal runaway

Coil parameters
>Conductor: SCS4050
>Winding: single pancake
>ID: 30, OD: 37.1mm, Length: 4.1mm
>Number of turns: 37
>Coil critical current: 55A

(77K, 1μV/cm)

Why?
Simulation model of NI pancake coil

1\textsuperscript{st} turn

2\textsuperscript{nd} turn

Nth turn

Thermal conduction along circumferential direction

Thermal conduction along radial direction

Circumferential current, \( I_\theta \)

Radial current, \( I_r \)

Normal resistance

Inductance

Turn-to-turn contact resistance

Positive electrode (Inner part)

Negative electrode (Outer part)

DC power supply

\( I_{\text{supply}} \)

Circuit equation

FEM
Process of current mode transition (simulation)

Magnetic field

Coil voltage

Coil temperature
"Multi-turn" mode

$I_{\text{supply}}$: 76 A

Negative electrode

Positive electrode

$76$ A

$J_\theta \sim 190$ A/mm$^2$

Temperature (K):

- 77.00
- 90.72
- 104.8
- 123.9
- 151.7
- 195.5
- 274.8
- 462.6
- 1460

Current

76 A
Process of current mode transition (simulation)

Magnetic field

Coil voltage

Coil temperature
Notable reduction in current density $J_\theta \sim 10.2 \text{ A/mm}^2$
Process of current mode transition (simulation)

Magnetic field

Coil voltage

Coil temperature
$I_{\text{supply}} = 265\text{A}$

Temperature (K):
- 77.00
- 90.72
- 104.8
- 123.9
- 151.7
- 195.5
- 274.8
- 462.6
- 1460

Current:
- 100 A

Terminal-to-terminal mode

$J_\theta \sim 4.39\text{A/mm}^2$

Positive electrode

Negative electrode

$T = 1460\text{K}$

$I = 171\text{A}$

$J = 173\text{K}$
Over heating due to terminal-to-terminal mode (190A)

Overheated area

Positive electrode

Negative electrode

Coil winding

Coil form
Operation of NI coil

- Normal operation below the critical current
- Margin
- Self-healing from thermal runaway. Helium will be evaporated.
- Catastrophic overheating

Diagram:

- Power supply current, $I_{\text{supply}}$ (A)
- Coil terminal voltage, $V_{\text{terminal}}$ (V)
- Axial magnetic field, $B_z$ (mT)
- Temperature (K)

- Illustrations:
  - (I) Multi-turn
  - (II) Single-turn (Safe)
  - (III) Terminal-to-terminal (Hazardous)

- Currents and Temperatures:
  - LN2
  - $J_\theta \sim 190$ A/mm$^2$
  - $77$ K
  - $J_\theta \sim 10.2$ A/mm$^2$
  - $105$ K
  - $J_\theta \sim 4.39$ A/mm$^2$
  - $1460$ K

- Notes:
  - Normal operation below the critical current
  - Margin
  - Self-healing from thermal runaway. Helium will be evaporated.
  - Catastrophic overheating
"Single-turn" mode lower current density

Reduction of current density

Reduction of heat

Thermal runaway is self-healed

Power supply current: 125 A
85 A
105 K
LN₂
Positive terminal
Negative terminal

\[ J_θ \sim 10.2 \text{ A/mm}^2 \]

Temperature (K)

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Current</th>
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<tbody>
<tr>
<td>77.00</td>
<td>100 A</td>
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Problem: Unbalanced electromagnetic force

Radial current can cause unbalanced electromagnetic force.

Unbalanced electromagnetic force can damage coils.
Summary

1. NI coils have 3 current mode phase.
   (I) Multi-turn (II) Single-turn (III) Terminal-to-terminal

2. "Single-turn" mode transition lower the current density, thermal runaway is self-healed.
   →This is the mechanism of NI coils.

3. There is a problem of unbalanced electromagnetic force, which can damage coils.
Thank you for your attention.