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# *The actual quenches of HTS coils*


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# Contents

1. ***Various kinds of actual quenches of HTS (REBCO) coils***

2. ***Protection of high current density coils***

   ***Pancake-winding vs. layer-winding***

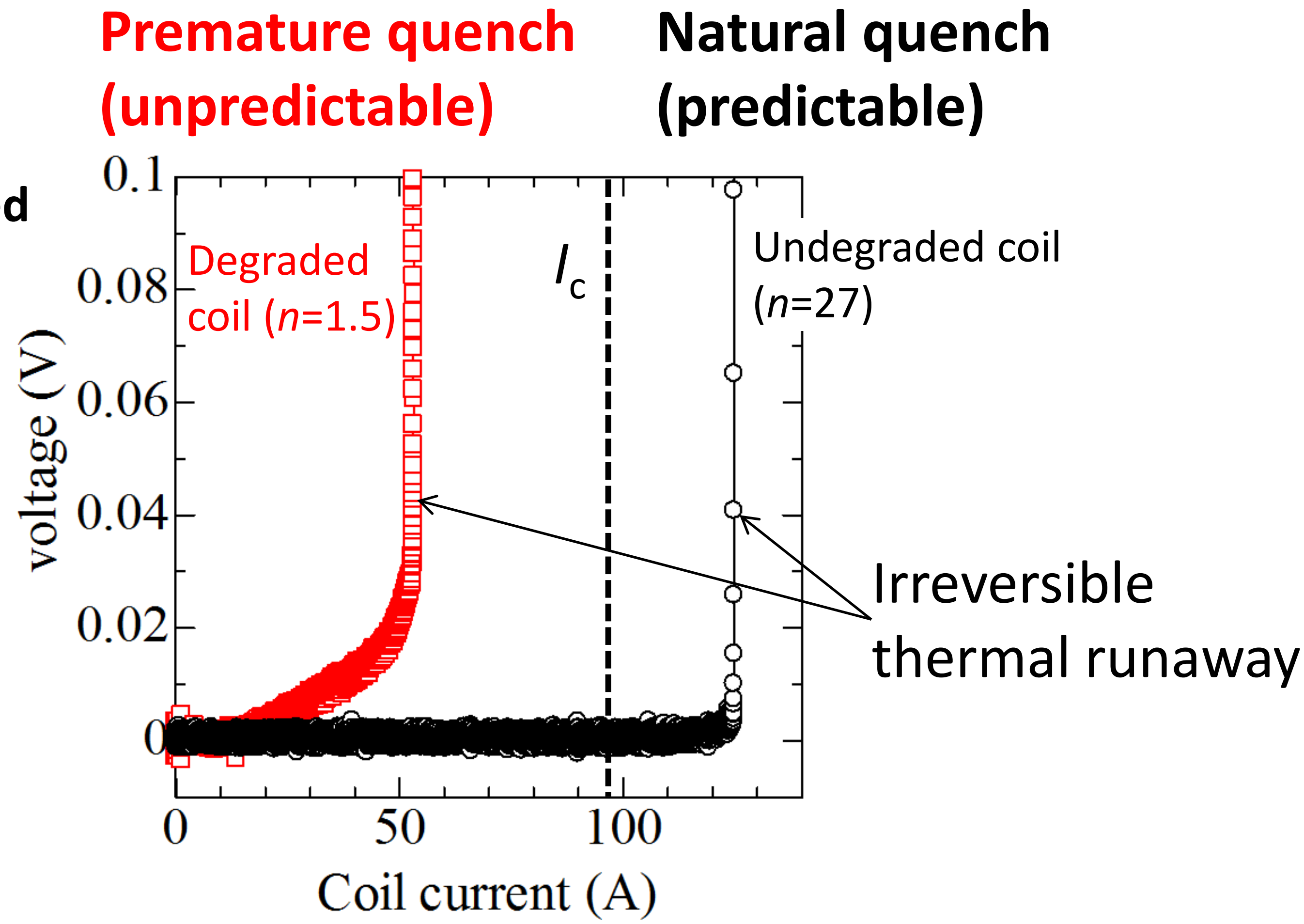
3. ***Overview of winding methods:***

   ***Trade-off between degradation and protection***

# Two basic patterns of quench for REBCO coils

**Paraffin-impregnated REBCO coils at 77K**

Maeda and Yanagisawa, *IEEE TAS*, **24**, 4602462, 2014.

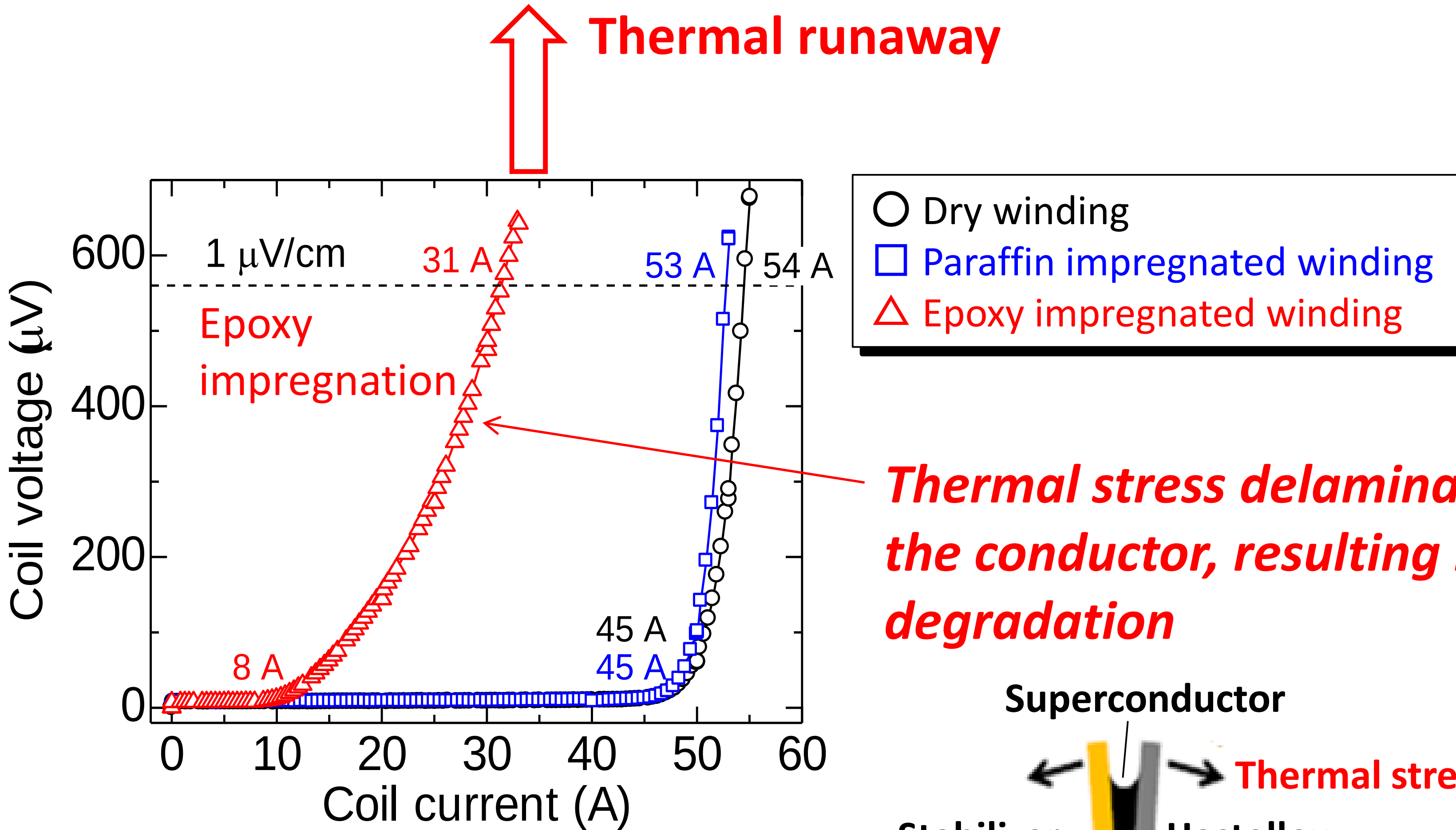



***Systematic investigation and the remedies for the degradation are the essential for stability and protection of REBCO coils.***

# Premature quenches

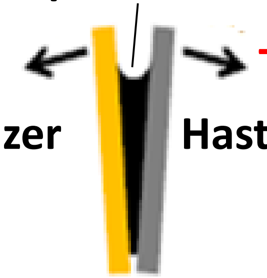
*The premature quenches in REBCO coils are caused by local heating due to degradation owning to thermal stress and electromagnetic force.*

# 1) Degradation due to thermal stress

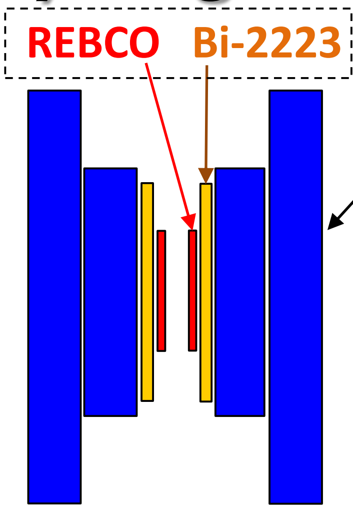



Takematsu et al., *Physica C*, **470**, 674-677, 2010

***Thermal stress delaminates the conductor, resulting in degradation***



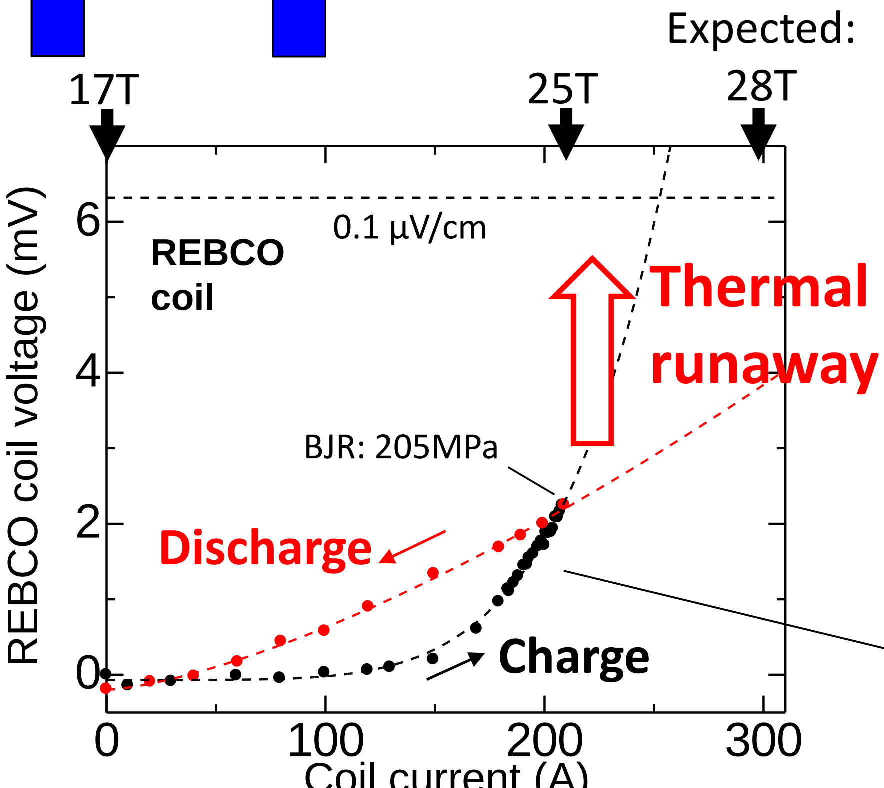
# 2) Degradation due to an electromagnetic force



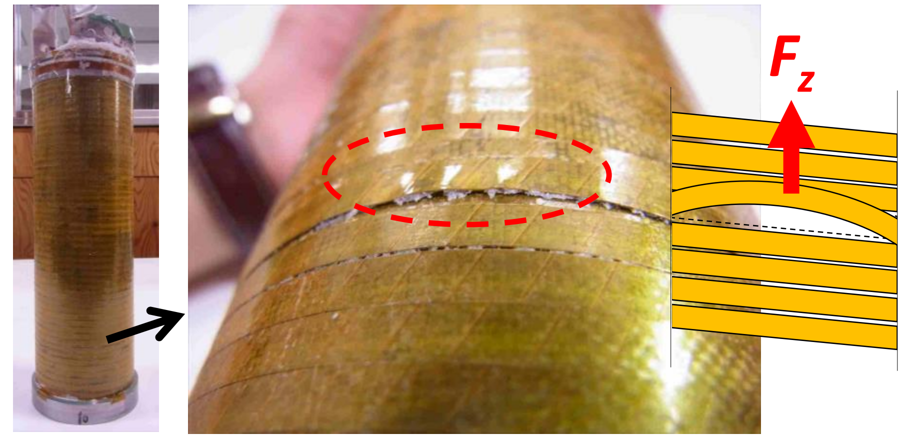

> Series-connected
> Layer-wound
> Paraffin impregnation

17T LTS coils (NIMS)

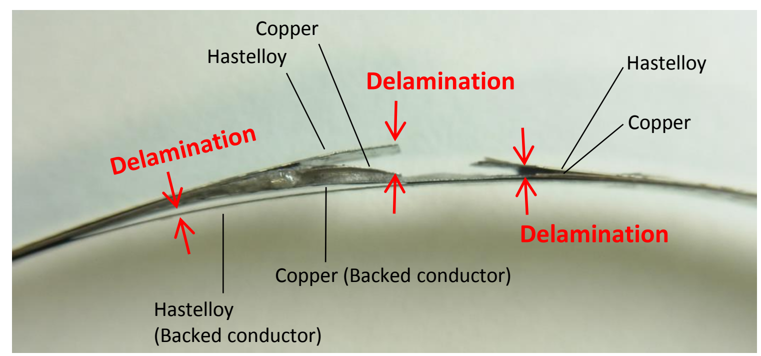
**Designed to generate 28T (LTS 17T + HTS 11T)**




**REBCO (layer-wound, paraffin-impregnation)**




***Edgewise bent*** due to the axial force




***Delamination*** in the solder bridge joint due to the hoop stress

**Electromagnetic force proceeds the degradation during charging**

# Natural quenches

*Natural quenches sometimes appear due to over current caused by mutual inductance between coils.*

# A worst case of a natural quench

**<u>3T Bi-2223 MRI</u>**
(Kyoto University, NIMS, Kobe Steel, and Sumitomo Electric)

Terao et al. *IEEE TAS*, **23**, 4400904, 2013.

Courtesy of Prof. Fukuyama and Dr. Urayama


Terao et al. *IEEE TAS*, **24**, 4401105, 2013.

***Thermal runaway in one coil causes an unbalance of the axial magnetic force, resulting in the mechanical breakdown of the terminal and the catastrophic arching.***

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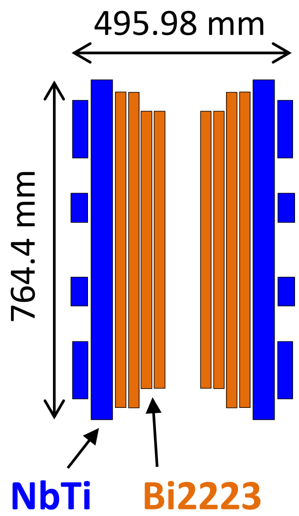
# Example: 1.2 GHz (28.2T) LTS/HTS NMR magnet

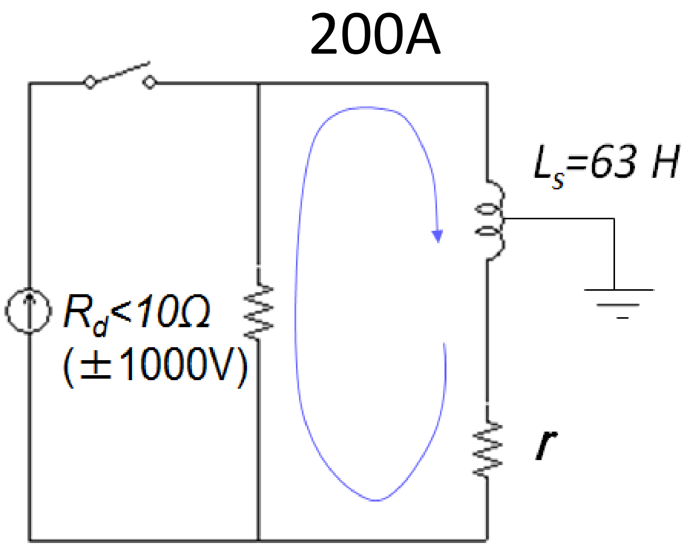
**1.2 GHz LTS/HTS NMR**




$BJR$ < 371 MPa

$J_e$ < 220 A/mm$^2$

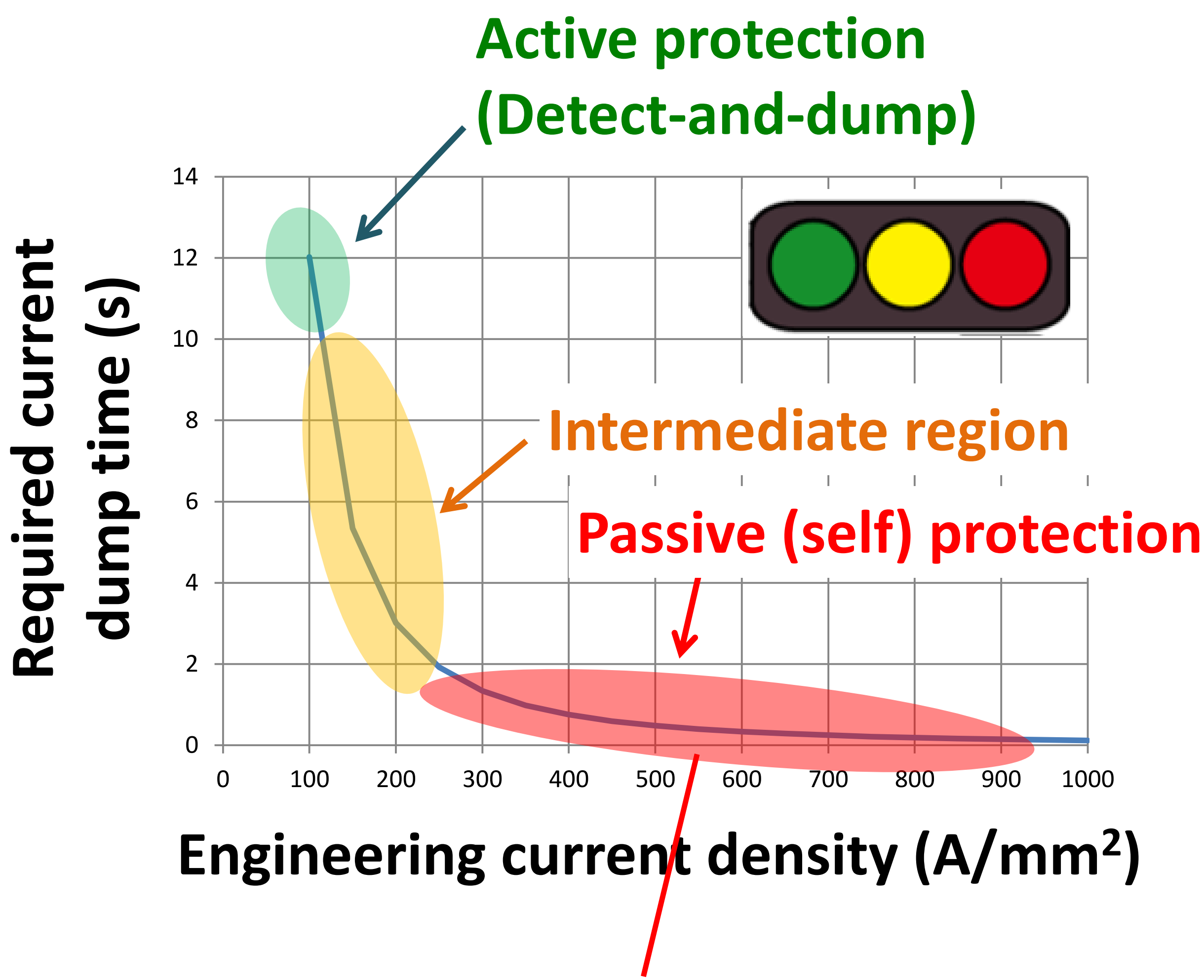
Detect and dump circuit for the Bi-2223 NMR magnet




$$\tau = \frac{L}{R_d + r} = \frac{63}{10} = 6.3s$$

($r$~10-100 mΩ)

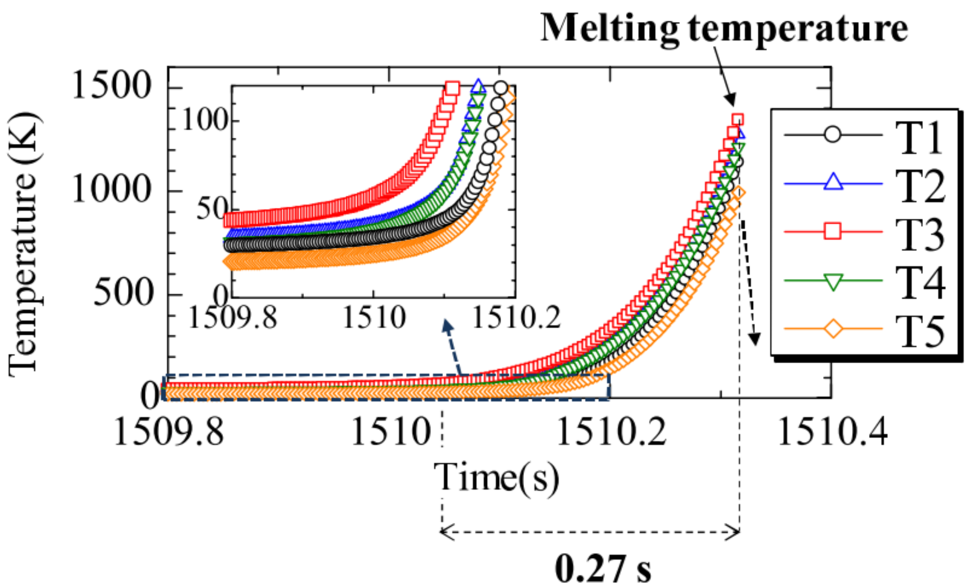
# Protection of HTS coils



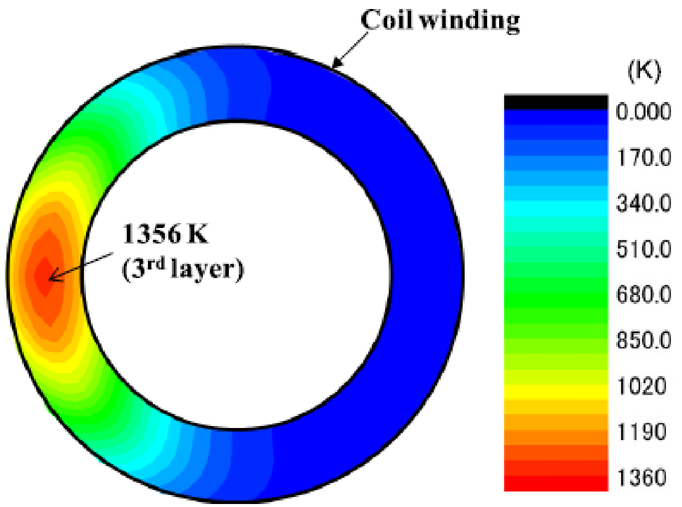

For LTS coils, 3D-quench propagation gives a sufficiently short current dump

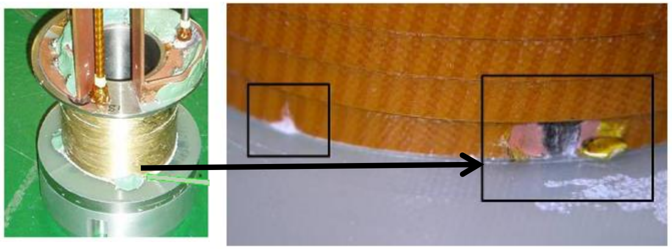
# Premature quench for high-current density operation

Premature quench at 258A (645A/mm$^2$) under 10T;
52% of the coil critical current (simulation)



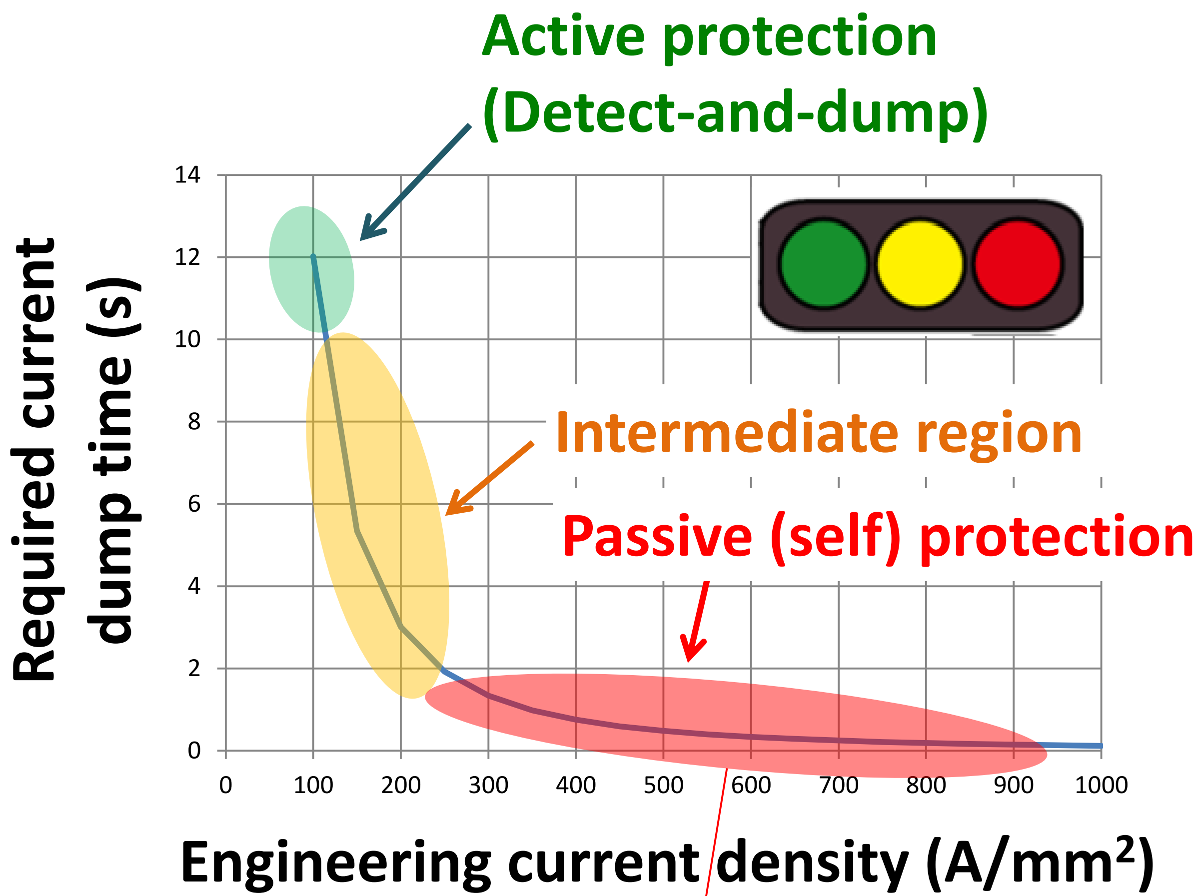

Yanagisawa et al., *SuST*, **25**, 075014, 2012.



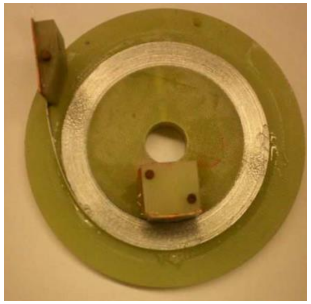



Matsumoto et al., *IEEE TAS,* **22**, 9501604, 2012

# Protection of REBCO coils




Hahn et al., *IEEE Trans. Appl. Supercond.*, **21**, 1592-1595, 2011.



***No-insulation (NI) method is a solution for REBCO coils → current spills along the radial direction***

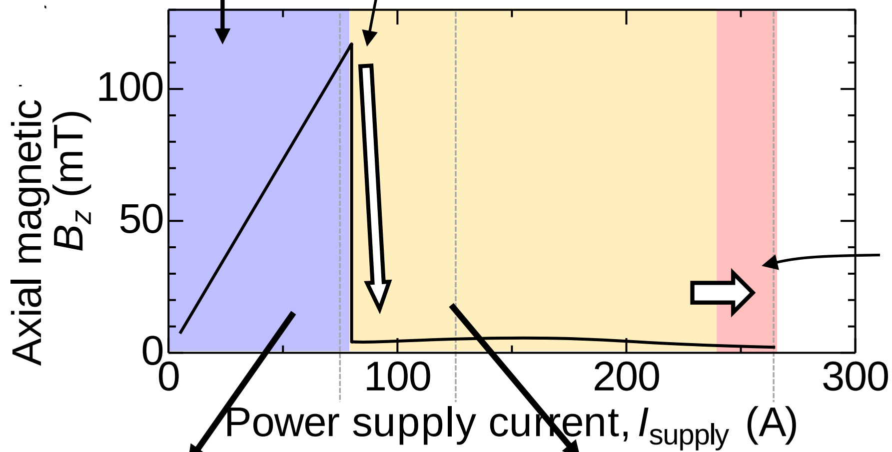
**For LTS coils, 3D-quench propagation is necessary to get sufficient internal resistance.**

# Basic operation modes of a NI coil

Yanagisawa et al., *Physica C*, **499**, 40-44, 2014.

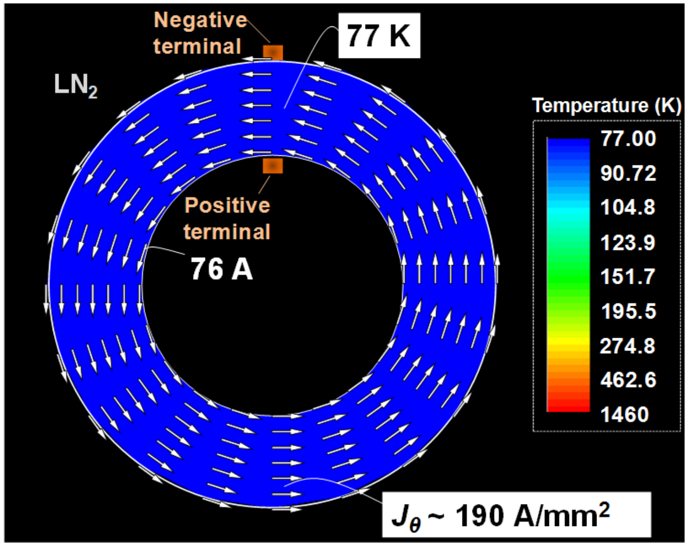
**Normal operation below the critical current.**

*Self-protected from quench (thermal runaway)*
*Similar to high NZPV of LTS coils*

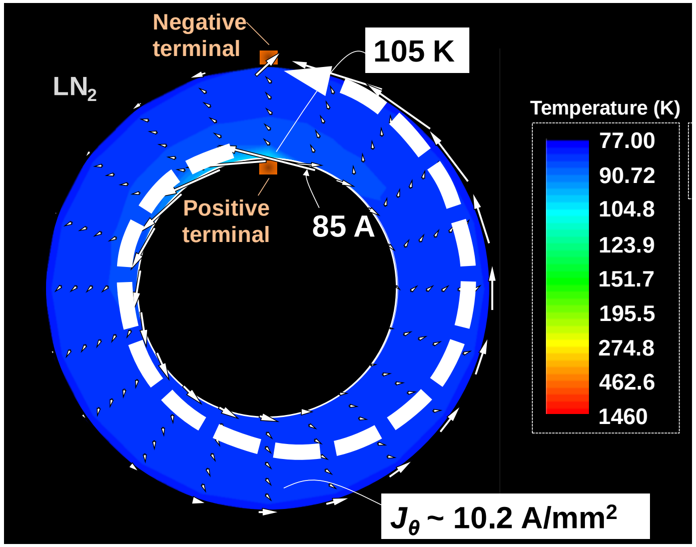



**Catastrophic overheating**

**(I) Multi-turn**




**(II) Single-turn (Safe)**

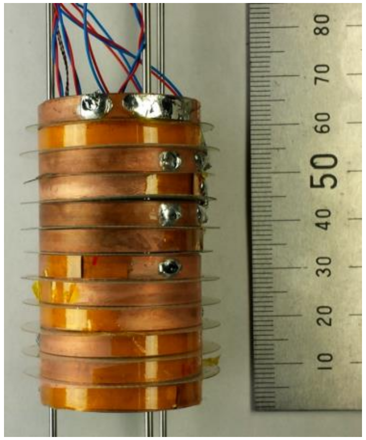


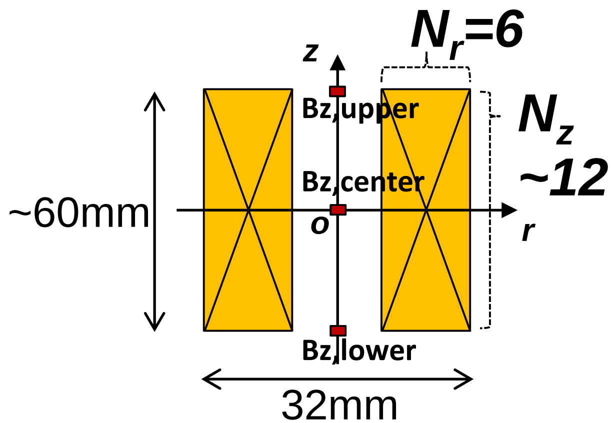

- ■“Self protection” versus “Charge delay”
- ■“Pancake winding” versus “Layer winding”

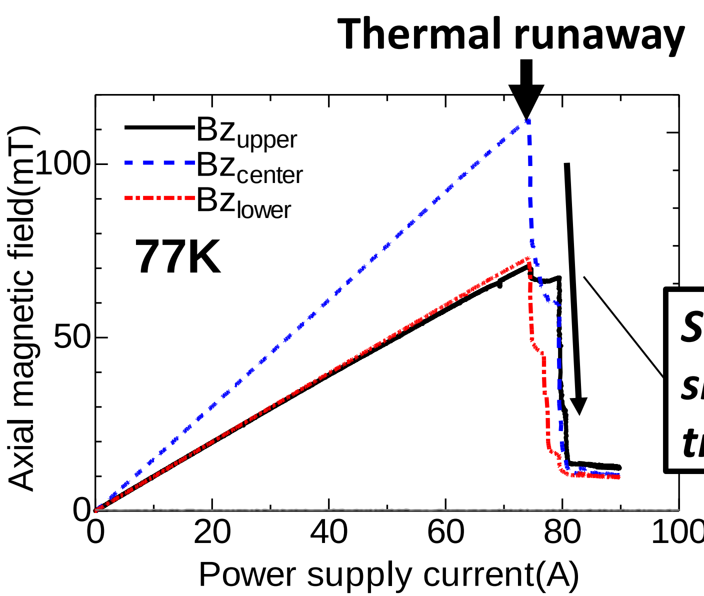
# Self-protection

## *Double pancake*

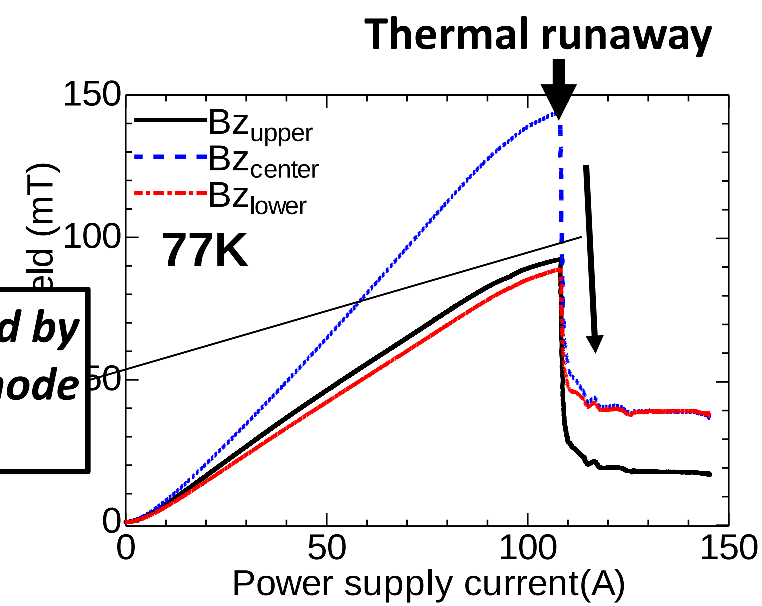
## *Layer*





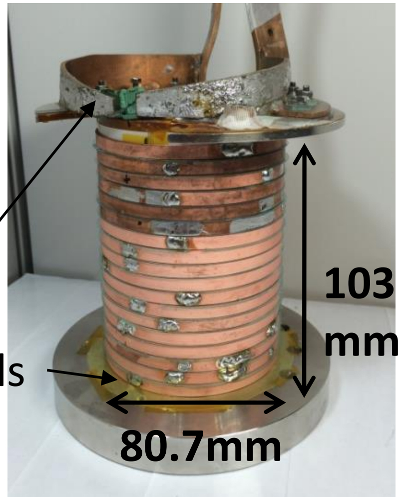



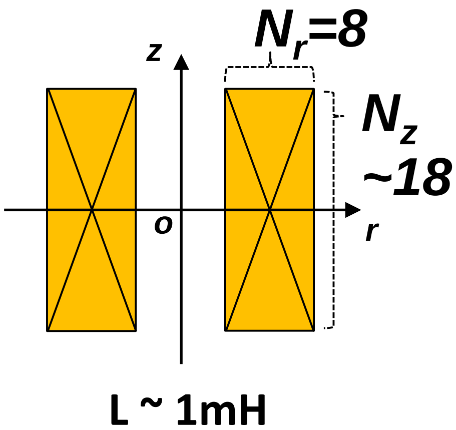

***Self-protected by single-turn mode transition***



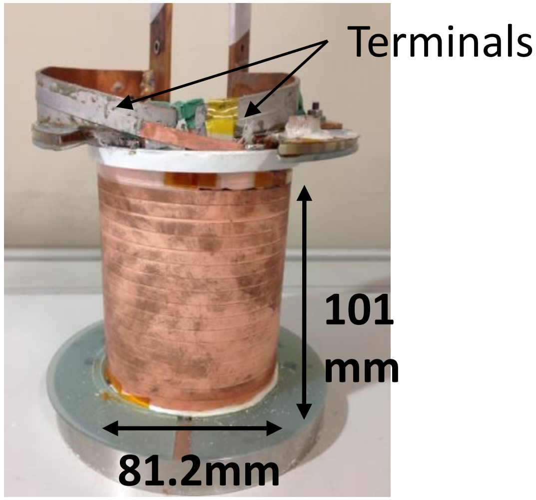
# Charging delay

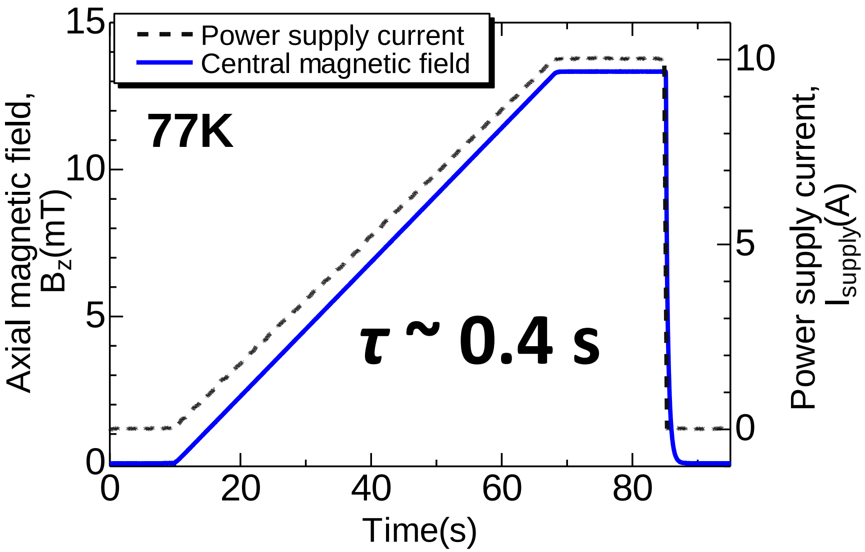
## *Double pancake*

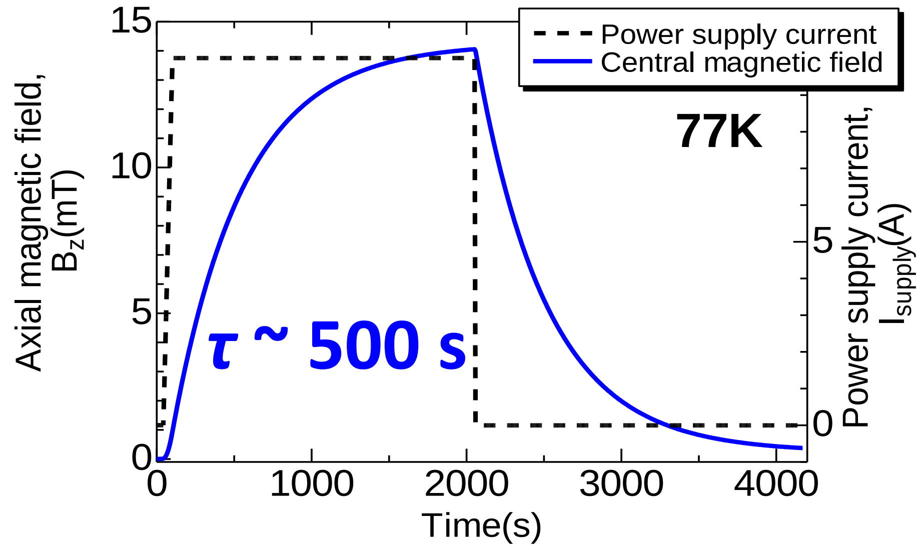



## *Layer*



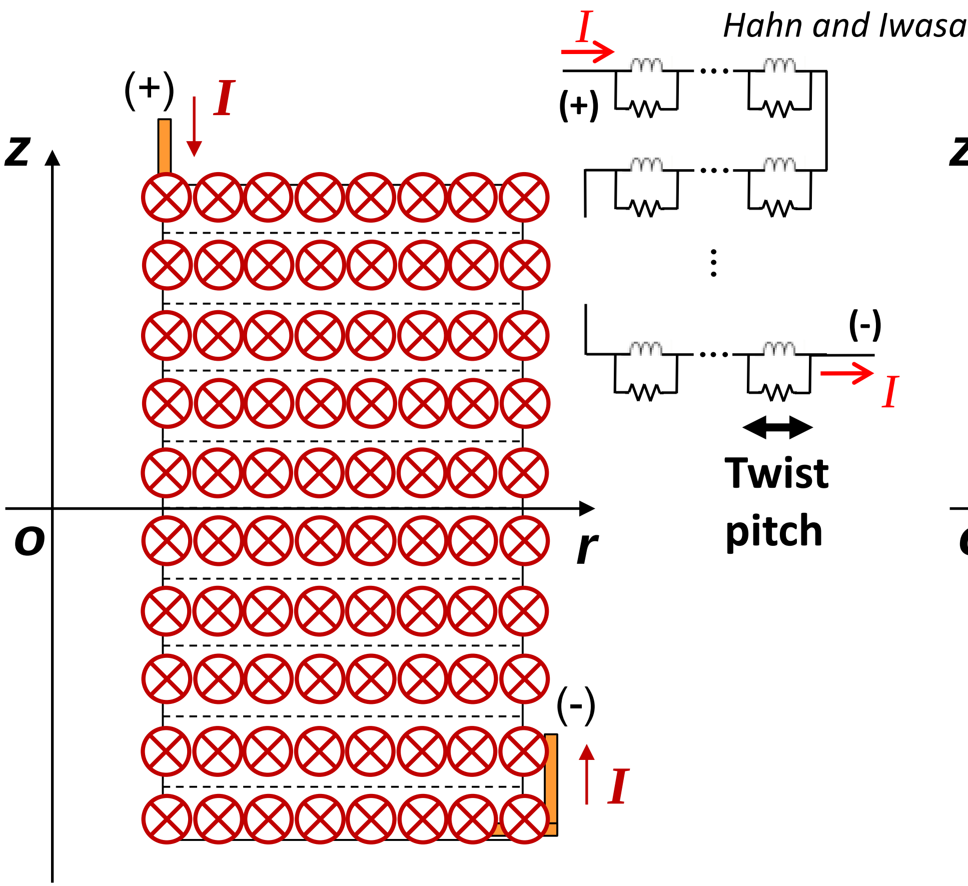



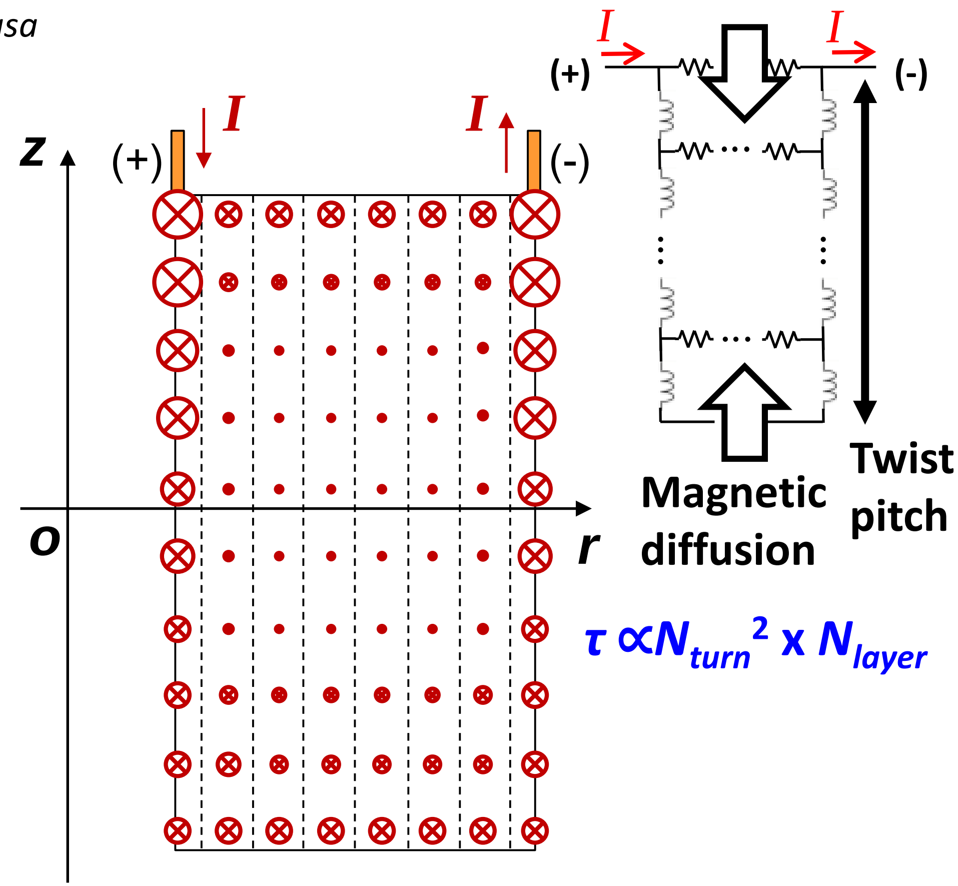

***Charging delay for the layer-winding is ~2000 times longer***

# Simulated current distribution

## Double pancake

## Layer




$\tau \propto N_{turn}^2 \times N_{layer}$

***Pancake*: Twisted => Short charging delay**

***Layer*: Untwisted => Impractically long charging delay**

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# High current density REBCO coil winding methods from a view point of degradation and protection

| | ✓: OK<br>X : NG | Preventing degradation | Self-protect | NMR |
|---|---|---|---|---|
| **Pancake**<br> | **Insulated**<br>(Example: NHMFL 32T) | ✓ *Epoxy + polyimide coating, dry, or paraffin* | X | > Inhomogeneous field<br>> Driven mode |
| | **NI**<br>(Example: MIT/NHMFL/ SuNAM 26T) | ✓ *Dry* | ✓ | |
| **Layer**<br> | **Insulated**<br>(Example: RIKEN NMR) | ✓ *Epoxy + polyimide coating*<br>Yanagisawa et al. *Physica C*, **476**, 19-22, 2012.<br> | X | > Homogeneous field<br>> Possibility of persistent mode<br>(ultimate goal) |
| | **NI** | X *Dry: Conductor movement due to electromagnetic force* | X *Long charging delay* | |

# Summary

- ***Major origin of quench for REBCO coils is conductor degradation***
  - *Thermal stress*
  - *Electromagnetic force*

- ***NI self-protection for high current density coil***
  - *Pancake: Twisted, compatible with charging delay*
  - *Layer: Untwisted, extraordinary long charging delay*

- ***NMR:***
  - *Layer-wound, polyimide coating + epoxy impregnation*
  - *To be actively protected.*