Remarkable difference in thermal runaway behavior between a Ni-alloy reinforced Bi-2223 coil and a REBCO coil

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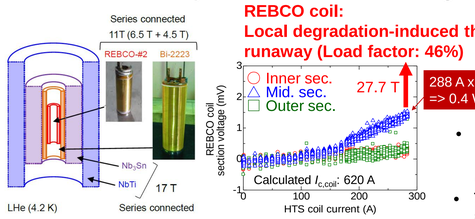
1. Introduction

■ Thermal runaway of the HTS coil in high field

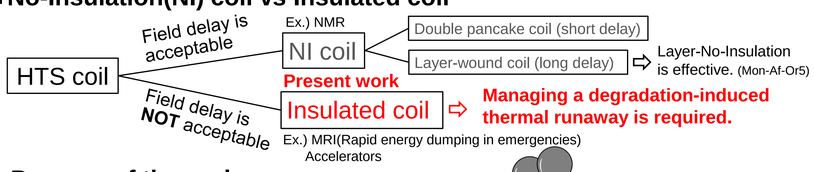


Yanagisawa et al. *IEEE/CSC & ESAS Superconductivity News Forum*, July 2016

The REBCO coil was burned out.

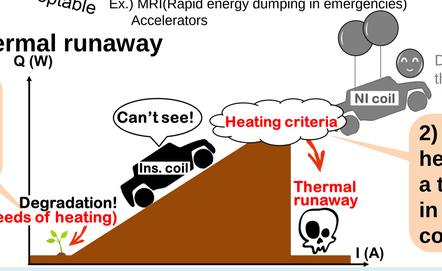
- REBCO coils suffer from thermal runaway at a current below the coil I_c due to local degradations.
- Thermal runaway occurs more frequently in REBCO coils than Bi-2223 coils.

■ No-Insulation(NI) coil vs Insulated coil



■ Process of thermal runaway

1) What kinds of degradation occur in high-field HTS coils ?



2) What are heating criteria for a thermal runaway in high-field HTS coils ?

Objective of this study

- To clarify the seeds of heating, i.e. local degradations, of actual HTS coils.
- To systematize heating criteria for a thermal runaway due to joule heating from degraded part to get safe indicators for insulated HTS coils through numerical simulations.

2. Types of degradation & thermal runaway in high field HTS coils

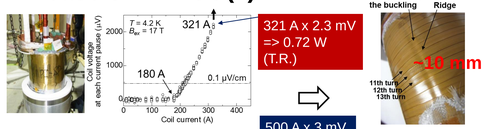
■ Actual cases of thermal runaway (T.R.)

・LHe (4.2 K) ・Insulated ・Layer-wound

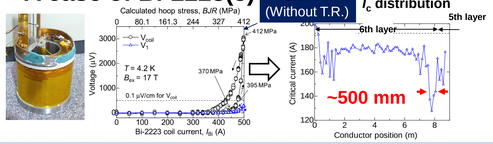
	Inner coil (Impregnated)	Number of layer	Central Magnetic field (T)	J_{cond} (A/mm²)	I_{op} (A) x V_{coil} (mV) => P_{coil} (W)	Thermal runaway or not	Degradation mode (Degraded length)	Degradation length
(1)	REBCO (SP) (Epoxy)	4	11.4	1025	410 x 0.9 => 0.37	None.	Composite stress (Several mm～several tens mm)	10 mm order
(2)	REBCO (SP) (Epoxy)	8	17 .7	803	321 x 2.3 => 0.72	T.R.	Buckling (Several mm)	
(3)	REBCO (Fujikura) (Paraffin)	74	25	284	210 x 2.2 => 0.46	None.	Cleavage・Peeling (Several tens mm)	
(4)	REBCO (Fujikura) (Paraffin)	76	27.6	389	288 x 1.4 => 0.4	T.R.	Missing	
(5)	Bi-2223 (SEI) (Paraffin)	6	17.7	383	500 x 3 => 1.5	None.	Over hoop strain (one turn order)	100 mm order

[1] T. Matsuda et al. *presented at ASC2016* 3LPo1G-11
[2] T. Matsuda et al. *Cryogenics and Superconductivity Society of Japan (2015)*, 1B-a04
[3] K. Kajita et al. *IEEE TAS* **26** (2016) 4301106
[4] Y. Yanagisawa et al. *IEEE/CSC & ESAS Superconductivity News Forum*, July 2016
[5] Y. Yanagisawa et al. *SuST* **28** (2015) 125005

■ A case of REBCO(2)



■ A case of Bi-2223(5)



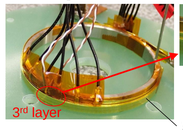
500 A x 3 mV
=> 1.5 W
(Without T.R.)

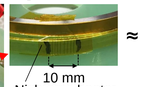
Short summary

- **REBCO** coils are **locally** degraded (10 mm order length) due to the stress concentration mode.
  Bi-2223 (Type HT-NX) coils are **widely** degraded (100 mm order length) due to homogeneous tensile stress mode. In high field **REBCO** coils,
- joule heating for a thermal runaway is **0.4 ~ 0.8 W**. On the other hand, a **Bi-2223 coil** did not show a thermal runaway with **>1.5 W**.

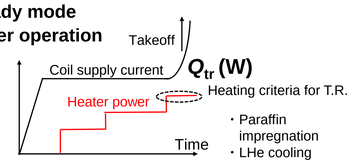
3. Heating criteria for thermal runaway

3-1 Experimental procedure



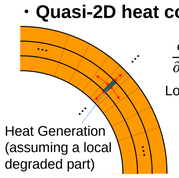


・**Steady mode heater operation**



3-2 Simulation model

・**Quasi-2D heat conduction FEM model**



$$\frac{\partial}{\partial x}\left(k(T)A\frac{\partial T}{\partial x}\right) - C(T)A\frac{\partial T}{\partial t} - \frac{k_{ins}(T)}{d_{ins}}(T - T_{outer})w$$

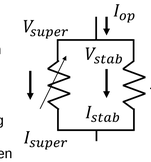
Longitudinal heat conduction | Combined heat capacity | Heat conduction with outer layer

$$-\frac{k_{ins}(T)}{d_{ins}}(T - T_{inner})w + g_j + g_c = 0$$

Heat conduction with inner layer | Joule heat generation | Cooling effect of cryogen

k_{ins} and g_c are determined by fitting simulation results to experimental results.

・**Parallel circuit model**



$$V_{super} = V_c\left(\frac{I_{super}}{I_c(T)}\right)^n$$
$$V_{stab} = I_{stab}R_{stab}(T)$$
$$V_{super} = V_{stab}$$
$$I_{op} = I_{super} + I_{stab}$$
$$I_c(T) = I_{c0}\left(\frac{T_c - T}{T_c - T_{op}}\right)$$

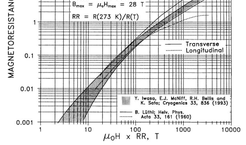
・**Assumed conductors**

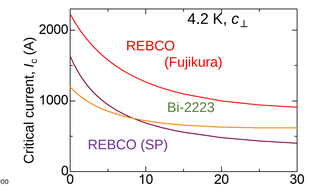
	REBCO (Fujikura)	REBCO (SuperPower)	Bi-2223 (SEI, Type HT-NX)
Width : Thickness (mm)	4 : 0.13	4 : 0.16	4.5 : 0.31
Stabilizer	Cu 50 μm	Cu 100 μm	Ag ratio 1.6
Stabilizer cross area / Conductor cross area	0.38	0.63	0.44
I_c (77K, self-field) (A)	200	100	180

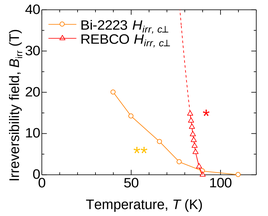
⇨ 5 layered coil

・**High field effects**

- $\rho_{stabilizer}$ (Cu, Ag)-B
- I_c-B
- B_{irr}-T (Field dependence of T_c)





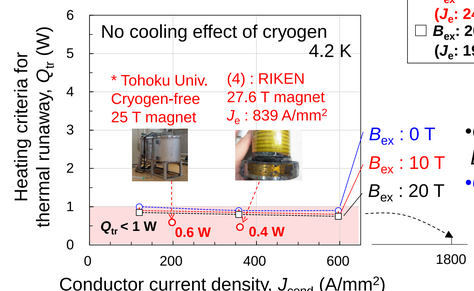


* Fuger et al. *IEEE TAS* **19** (2009) 1532-1535
** Ayai et al. *Physica C* **468** (2008) 1747–1752

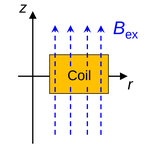
3-3 Results : Simulated criteria plot for thermal runaway

REBCO(Fujikura, Cu 50 μm)

Heating length: 10 mm $I_{c(77K, sf)}$: 200 A



○ B_{ex}: 0 T (J_e: 4292 A/mm², T_c: 90 K)
△ B_{ex}: 10 T (J_e: 2429 A/mm², T_c: 84.5 K)
□ B_{ex}: 20 T (J_e: 1921 A/mm², T_c: 80 K)

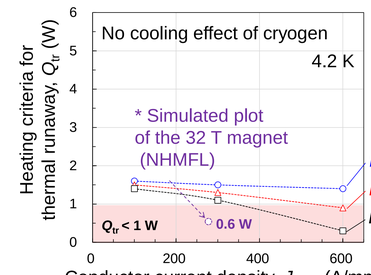


- Q_{tr} does not depend on J_{cond} and B_{ex} for $J_{cond} \leqq 600$ A/mm²
- Q_{tr} ~ 1 W or less

* Awaji et al. SuST 30 (2017) 065001 8pp

REBCO(SP, Cu 100 μm)

Heating length: 10 mm $I_{c(77K, sf)}$: 100 A



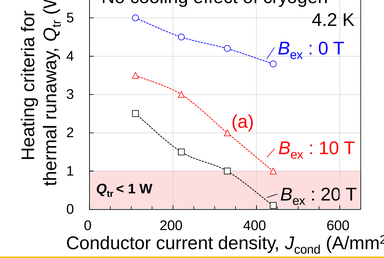
○ B_{ex}: 0 T (J_e: 2558 A/mm², T_c: 90 K)
△ B_{ex}: 10 T (J_e: 1075 A/mm², T_c: 84.5 K)
□ B_{ex}: 20 T (J_e: 750 A/mm², T_c: 80 K)

- In the case of high J_{cond} and high B_{ex}, Q_{tr} becomes very low, <0.5 W due to small margin.

* H. W. Weijers et al. *IEEE TAS* **26** (2016) 4300807

Bi-2223

Heating length: 100 mm $I_{c(77K, sf)}$: 180 A



○ B_{ex}: 0 T (J_e: 889 A/mm², T_c: 110 K)
△ B_{ex}: 10 T (J_e: 536 A/mm², T_c: 60 K)
□ B_{ex}: 20 T (J_e: 454 A/mm², T_c: 40 K)

- Q_{tr} substantially depends on B_{ex} (Effect of B_{irr}-T)
- In a low field, Q_{tr} > several W.
  ⇨Practically, no thermal runaway.
- In a high field (> 20 T), Q_{tr} ~1 W or less

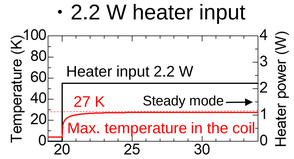
3-4 What determines the trigger of thermal runaway?

・Case of (a) on **Bi-2223**,
B_{ex} = 10 T
J_{cond} = 330 A/mm²
Without cooling effect of cryogen

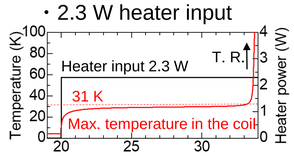
・T_{tr} :
Temperature at T. R.

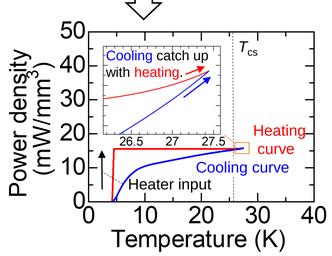
Heating curve = Heating from normal zone + Heater (assuming degraded parts)
Cooling curve = Radial heating conduction + Longitudinal heat conduction

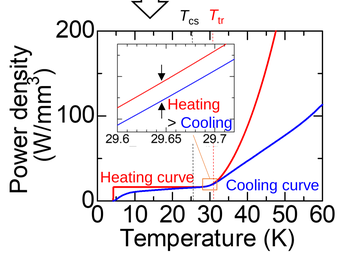
・2.2 W heater input



・2.3 W heater input







In local spot, Heating > Cooling ⇨ **Thermal runaway**

Short summary

- In the case of high field (20 T) and high J_{cond} (>300 A/mm²), heating criteria for a thermal runaway are **~1 W or less**, whether REBCO or Bi-2223.

Conclusions

- REBCO coils are **frequently** degraded with **several mm** length. Bi-2223 coils can be prevented from being degraded by making **a stress design**.
- In cases of practical operations (high field, high J_{cond}), heating criteria for a thermal runaway are <1 W. **0.2 W** for **REBCO** and **0.5 W** for **Bi-2223** may be safe on a thermal runaway.

Further standpoint

How to manage a thermal runaway of insulated HTS coils ?

Combination of **REBCO** **Bi-2223**

Technology to prevent degradations & **Heating criteria, Q_{tr}**

Stress design For insurance + **(Heating criteria, Q_{tr})**