SUMITOMO ELECTRIC

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Quench (Thermal Runaway) Protection of Bi2223 (DI-BSCCO) Magnets

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DI-BSCCO production shift plan

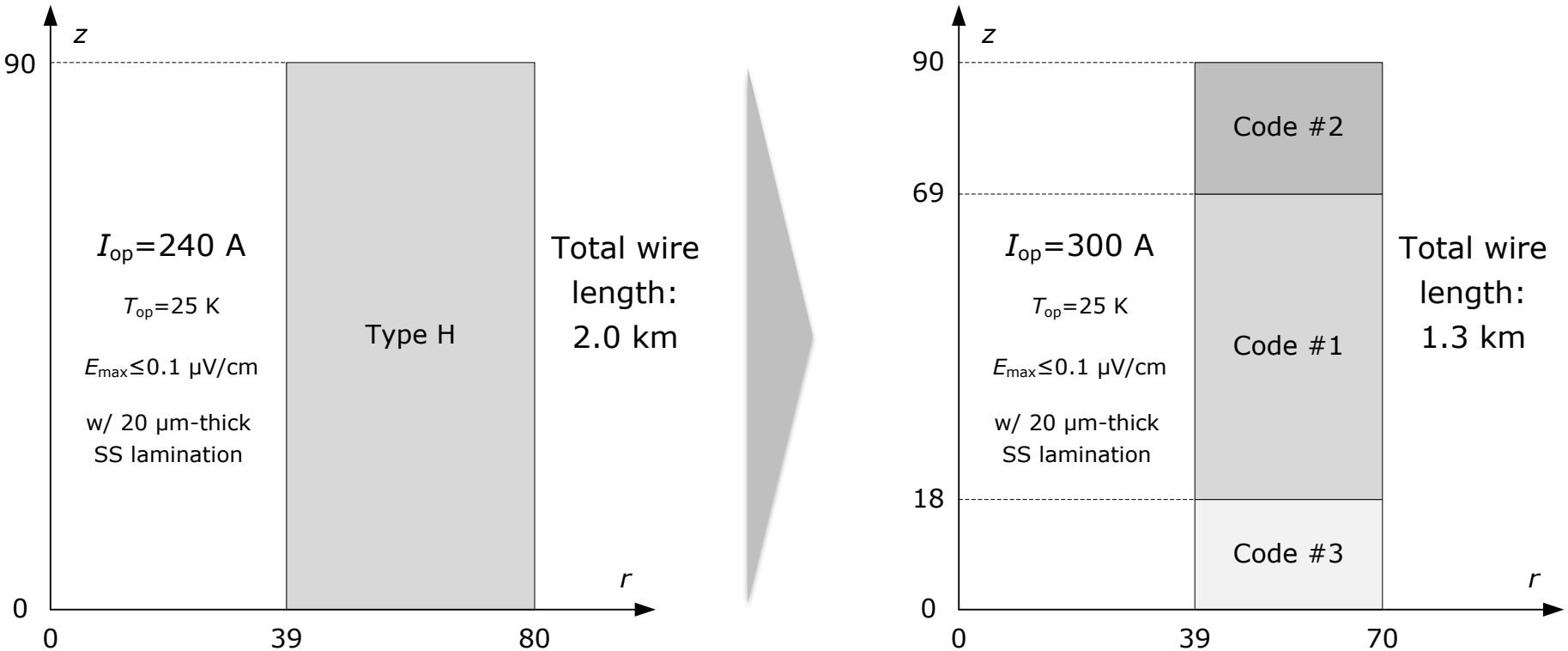
Type H	0.99 mm^2 (4.3×0.23)	180-200 A

Code #2	1.13 mm^2 (4.9×0.23)	220-240 A
Code #1	0.86 mm^2 (4.3×0.20)	180-200 A
Code #3	0.72 mm^2 (3.8×0.19)	140-160 A

sectional area (width × thickness) I_c(77 K, s. f.)

- Sumitomo Electric is going to shift the wire production from one to three types because of their advantages of J_e and cost.
- The new three types have different cross-sectional areas and thereby critical currents.

Design study on coil grading



The center field, inner diameter, and magnet length refer the following article:

Hahn, S. et al. (2014), 'A 78-mm/7-T multi-width no-insulation ReBCO magnet: Key concept and magnet design', *IEEE Trans. Appl. Supercond.* **24**(3), 1--5.

- The coil grading can increase the operating current and reduce the total wire length by approx. 35 %.

Background of quench protection

- "The technological problems for HTS coils thus far encountered [...] the difficulty in protecting the magnet in the case of an abrupt thermal runaway."

  Maeda, H. & Yanagisawa, Y. (2014), 'Recent developments in high-temperature superconducting magnet technology', *IEEE Trans. Appl. Supercond.* **24**(3), 1--12.

- Quench (thermal runaway) protection might be a problem generally for HTS magnets due to small NZP velocity.

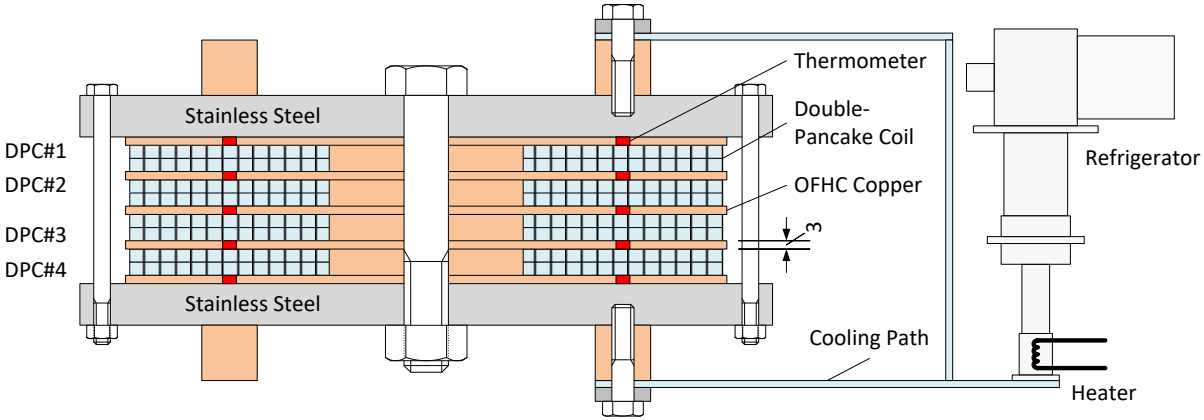
- A NHMFL group has been successfully developing quench heaters for REBCO magnets.

  Weijers, H. W. et al. (2016), 'Progress in the development and construction of a 32-T superconducting magnet', *IEEE Trans. Appl. Supercond.* **26**(4), 1--7.

- Sumitomo Electric confirmed that a bridge circuit with a dump resistor can protect Bi2223 magnets, and investigated its limits.

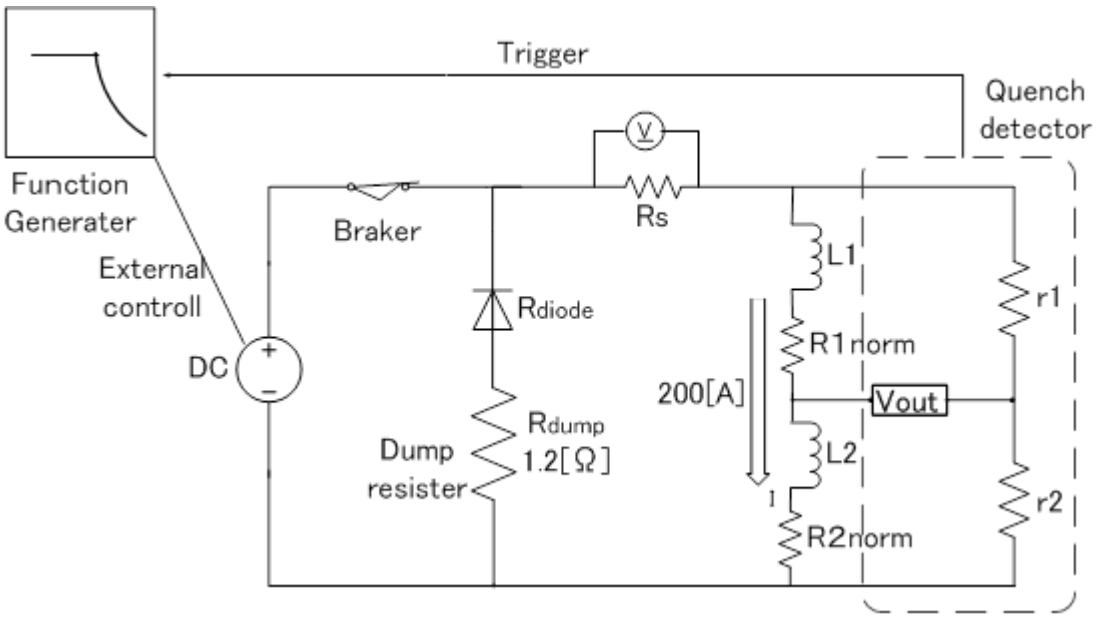
Coil for quench protection tests

Wire	DI-BSCCO Type Hi
I_c of wire (77 K, s. f.)	approx. 180 A
Coil	epoxy-impregnated double-pancake coils
Number of DP coils	4
Total wire length	880 m
Number of turns	2000 turns (500 turns×4)
Peak $B_\perp$	2.0 T
Peak $B_\parallel$	4.2 T
Inductance	0.4 H
Stored energy	8.2 kJ at 200 A



This study was supported by Japan Science and Technology Agency (JST) of Japan.

Experimental methodology

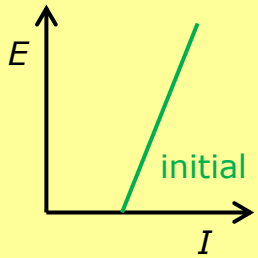


$$V_{\mathrm{out}} = \frac{1}{2} I (R1_{\mathrm{norm}} - R2_{\mathrm{norm}}) = \frac{1}{2}(V_1 - V_2)$$

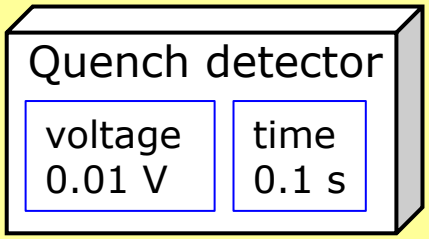
Operating current	200 A
Quench detection	Detecting voltage is a parameter. Detecting time is 0.1 s.
Quench generation	Raise the coil temperature from 35 K
Current decay	External control with wave form generation $I(t)$=200 A×exp（$-t/\tau$） τ = 4, 10, 20, 60 s

This study was supported by Japan Science and Technology Agency (JST) of Japan.

Experimental methodology

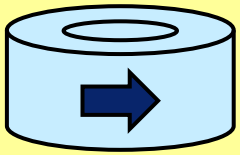


Measurement of initial *I-E*

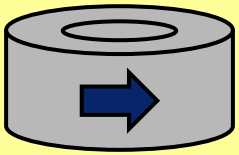


Setting the detecting voltage

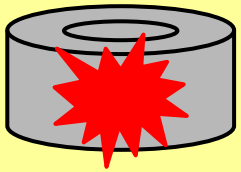
Temperature raised by a heater



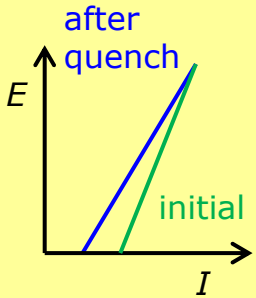
35 K
200 A



38 K or more
200 A



quench
200 A→0 A

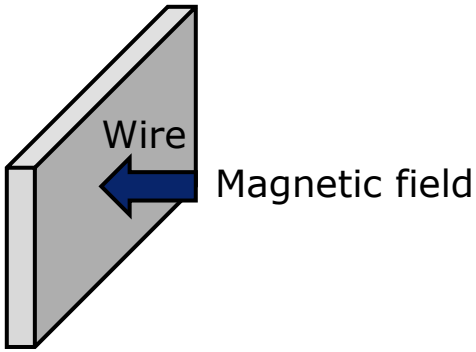


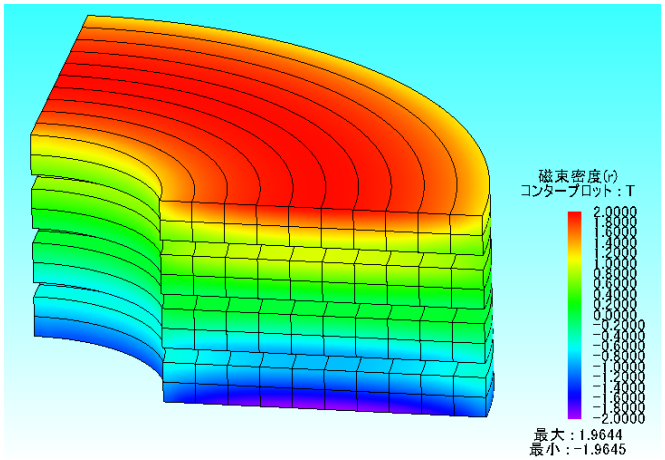
Measurement of *I-E*
Comparison with initial *I-E*

Has a degradation been observed?
→Yes. The experiment has finished and τ will be changed in the next experiment.

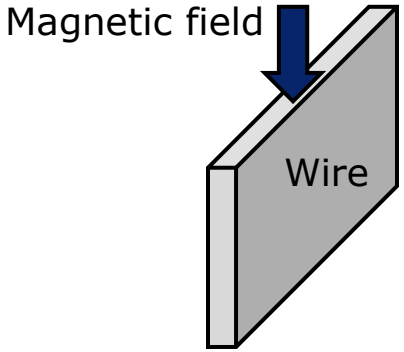
→No. The detecting voltage will be raised.

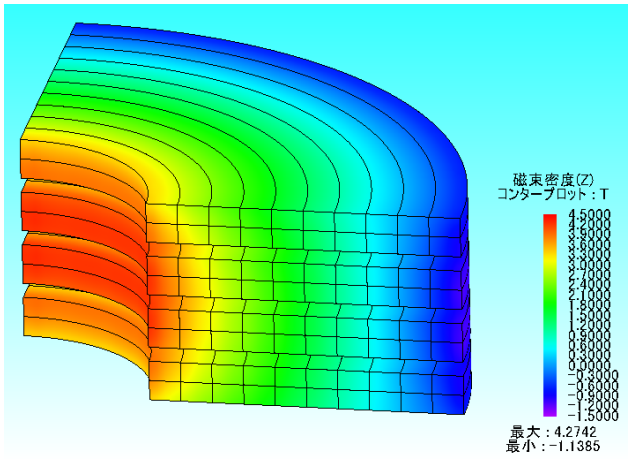
Magnetic field distribution in the coil applying 200 A





Peak $B_{\perp}$ 2.0 T



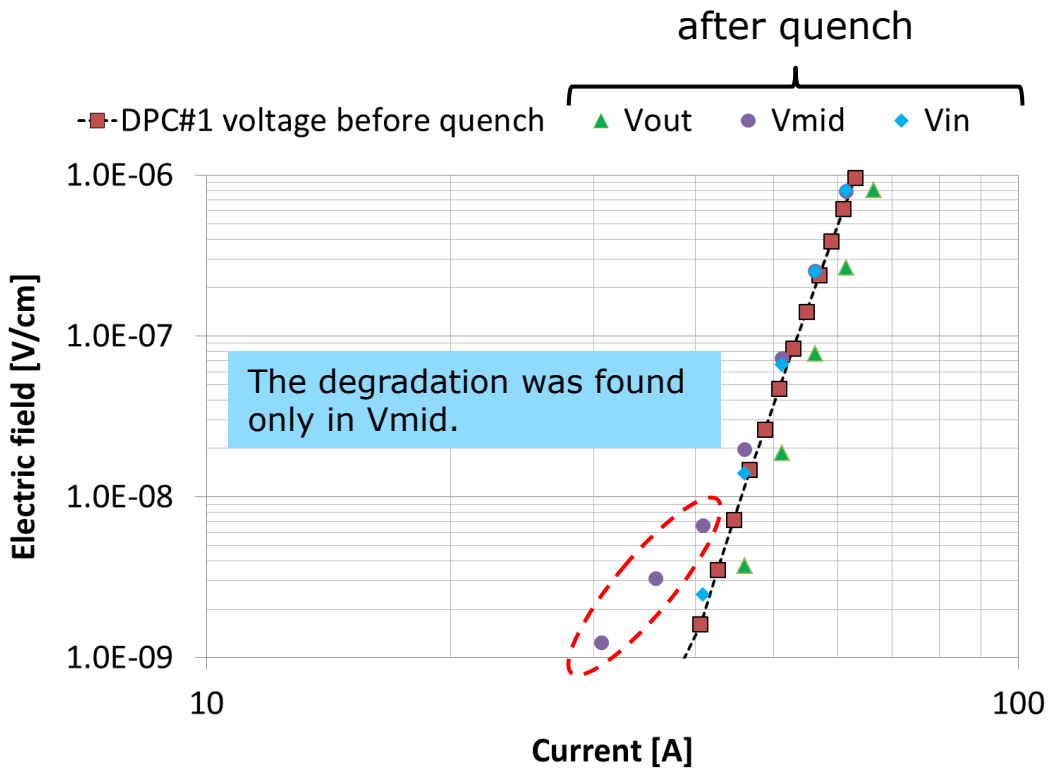


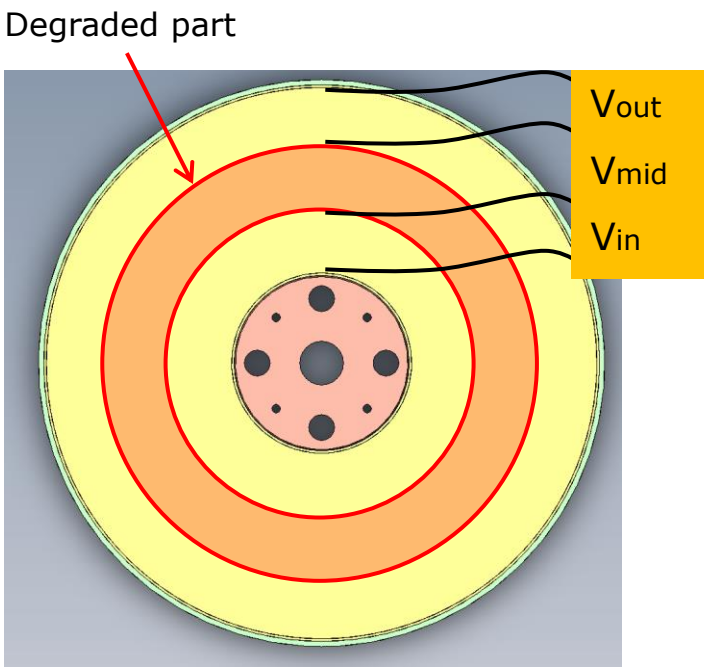
Peak $B_{\parallel}$ 4.3 T

- $B_{\perp}$ peaks around the middle in the radial direction.
- Since the I_c decreases there, the heat generation increases, and a hot spot tends to arise and result in a degradation.

Investigation into the degraded part

The coil was not burned out but degraded.





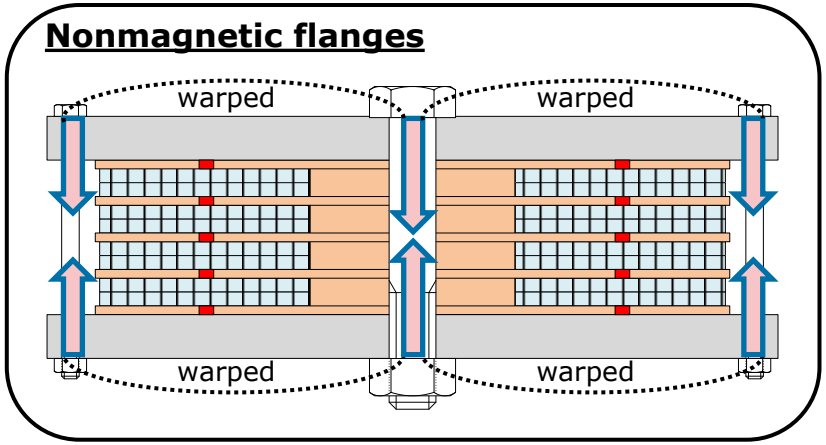
It is considered that the degraded part is the area surrounded by the red circles.

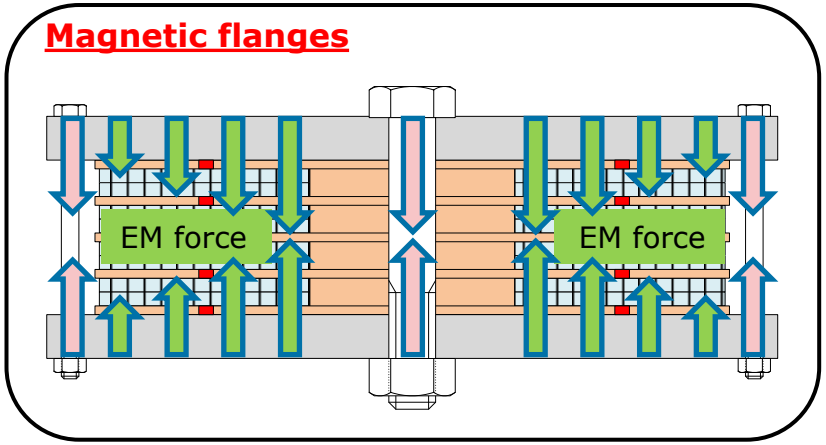
A method for increasing thermal conductivity

Ideal state
The flanges uniformly press the cooling plates so that heat at a hotspot spreads via them.

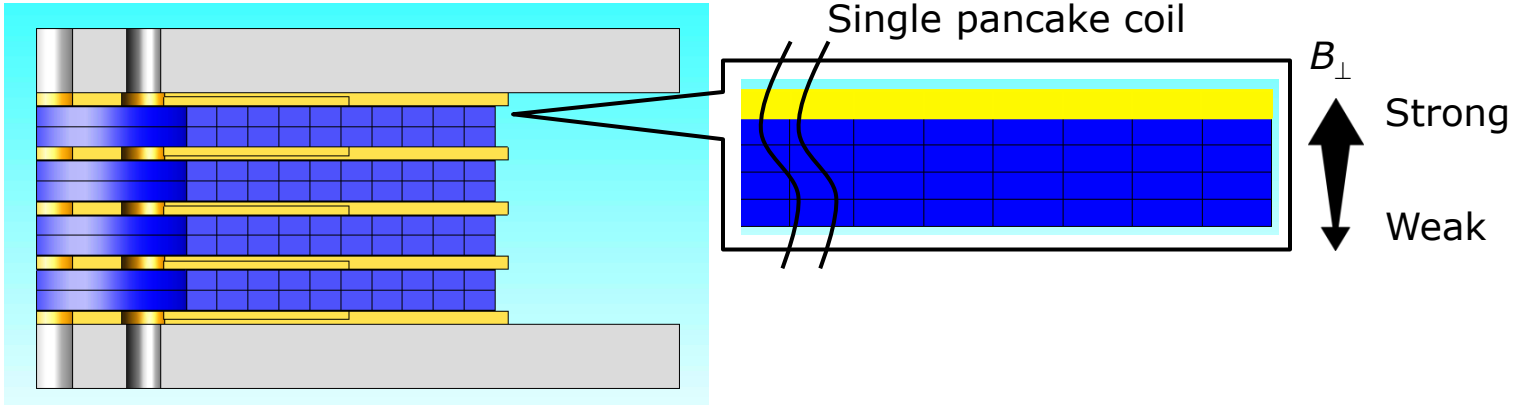
Previous study
The flanges were warped by bolt fastening.
The contact pressure between them was not uniform.

Present study
Magnetic flanges are attracted by electromagnetic force.
It is considered that they are not warped and the contact pressure is uniform.
A higher thermal conductivity should be achieved.



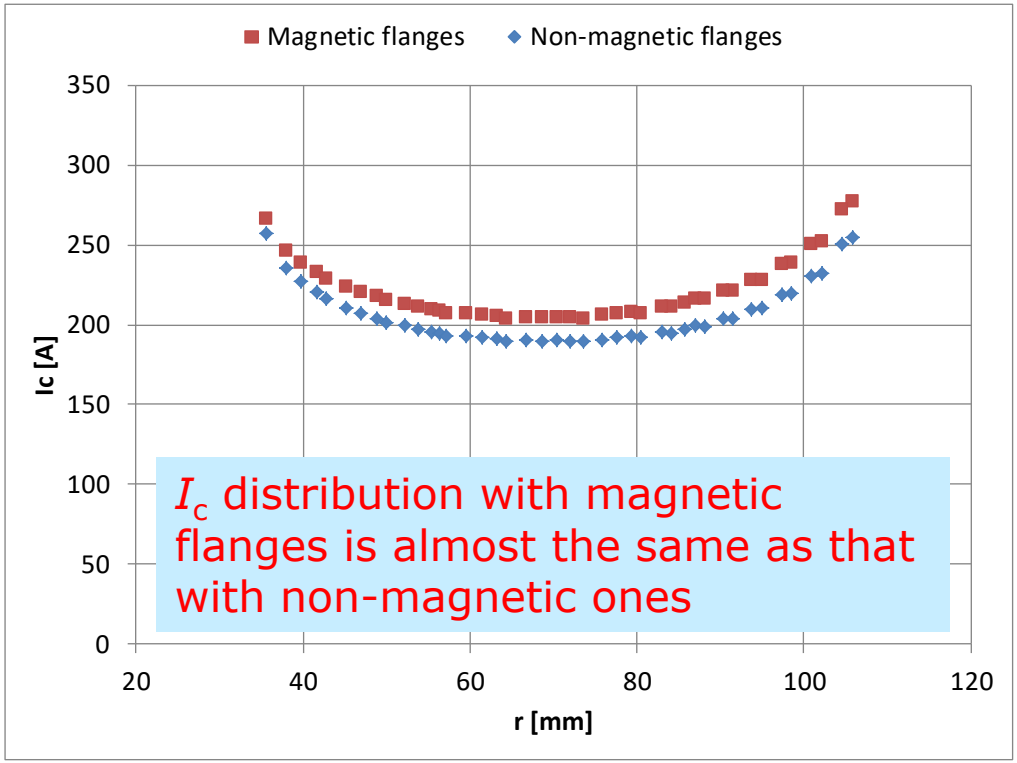


I_c with magnetic and non-magnetic flanges

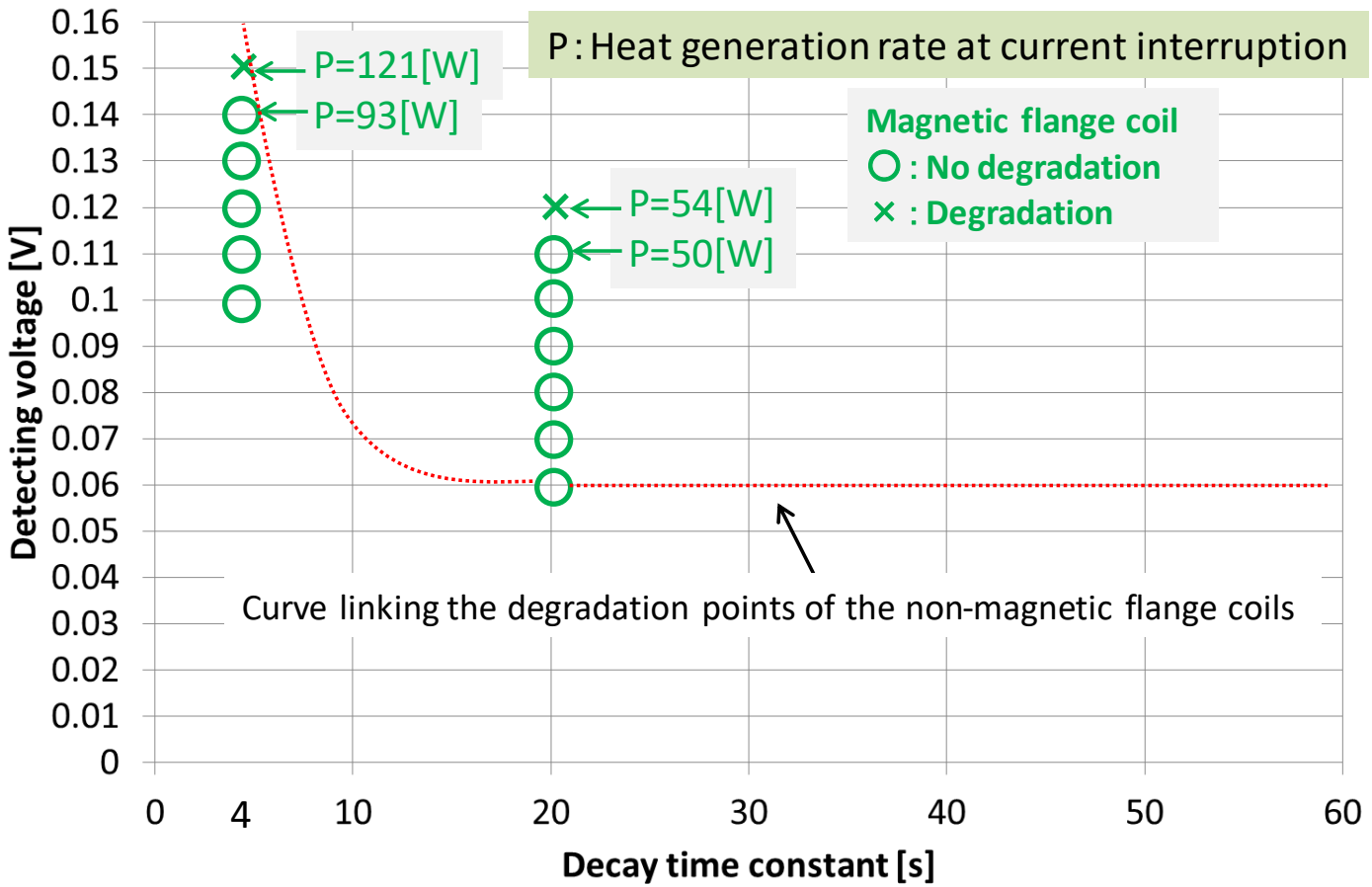


Conditions of field calculation	
I_{op}	200 A
Calculation points	The peak $B_\perp$ points among each 5 points dividing a single pancake in coil axis direction

Conditions of I_c calculation	
I_c (77 K, s. f.)	180 A
T	35 K



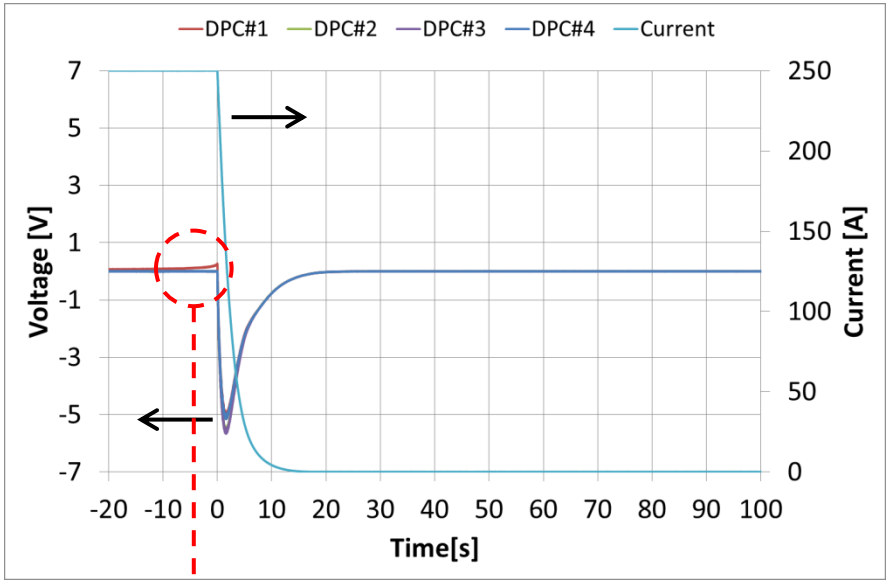
Results | Magnetic flange coil

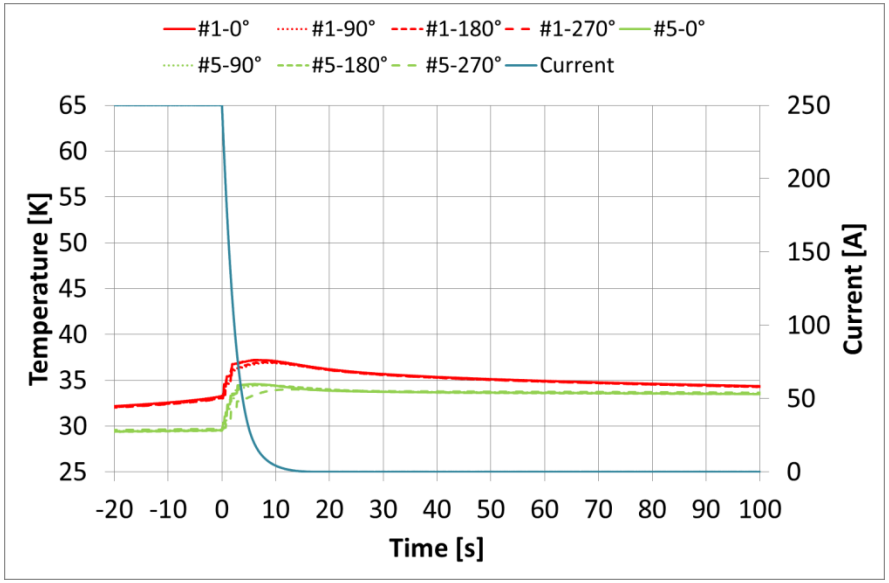


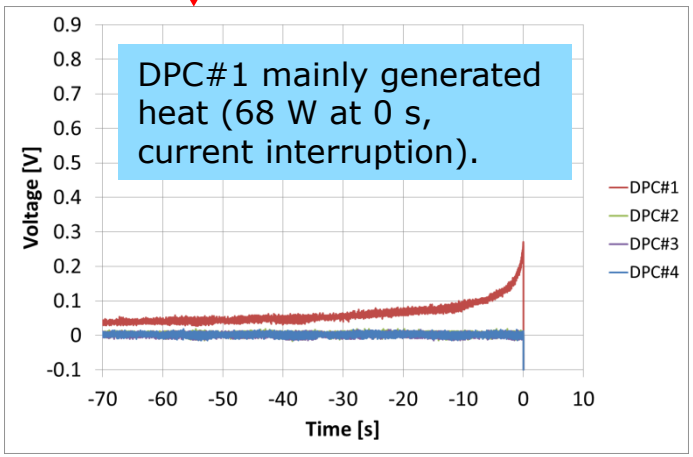
I_{op} = 200 A

When the decay time constant was 20 s, an effect of the magnetic flanges was found. In the below experiments, the flanges are magnetic.

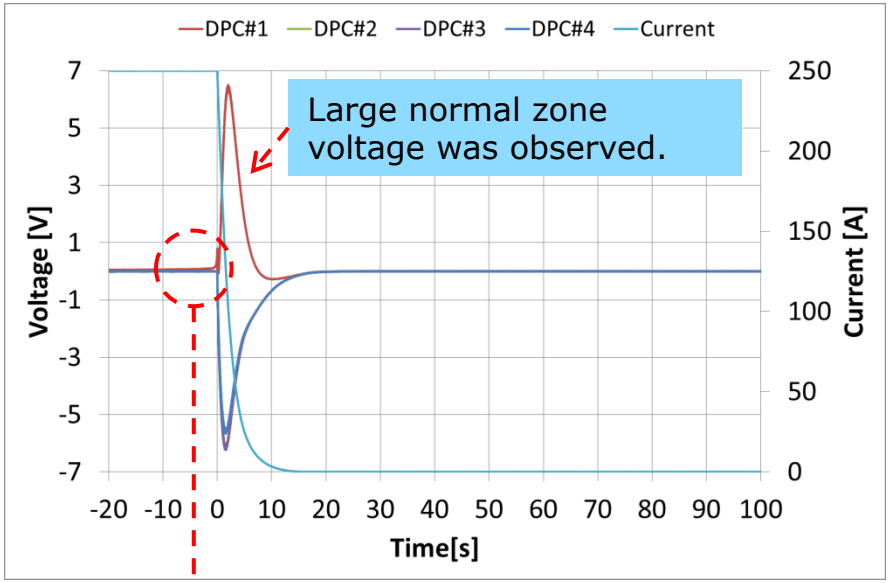
250 A-2 s-120 mV (No degradation)

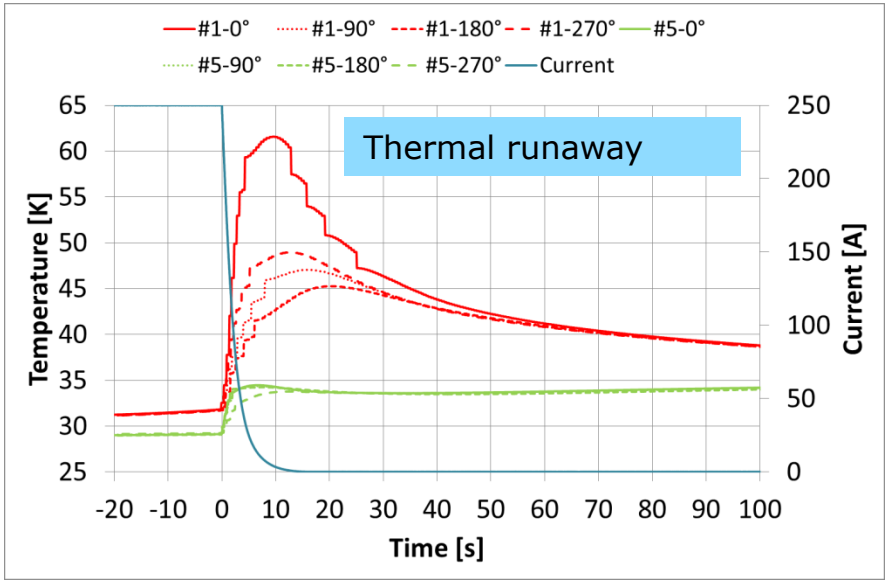


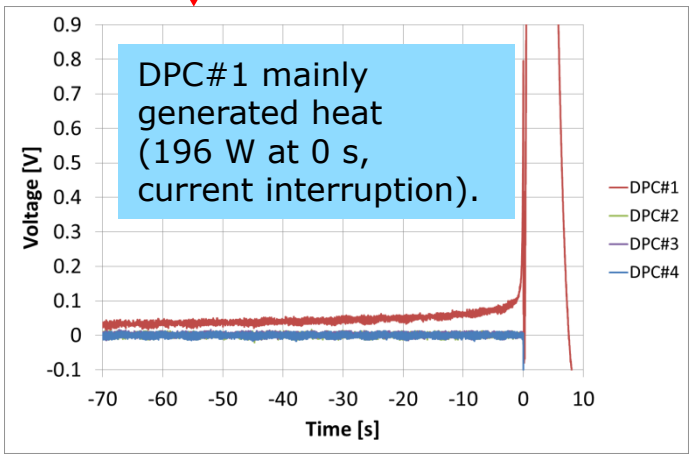




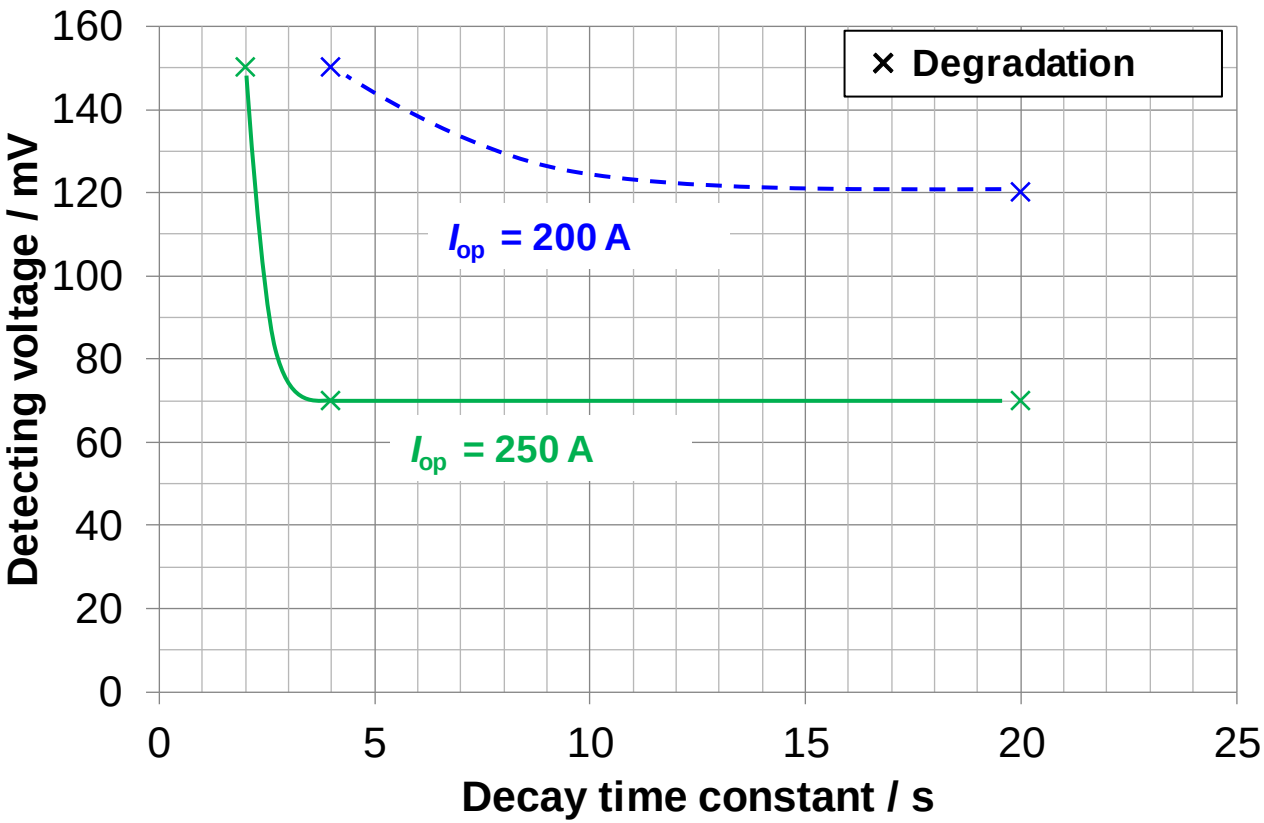
250 A-2 s-150 mV (Degradation)







Results | Operating current 250 A



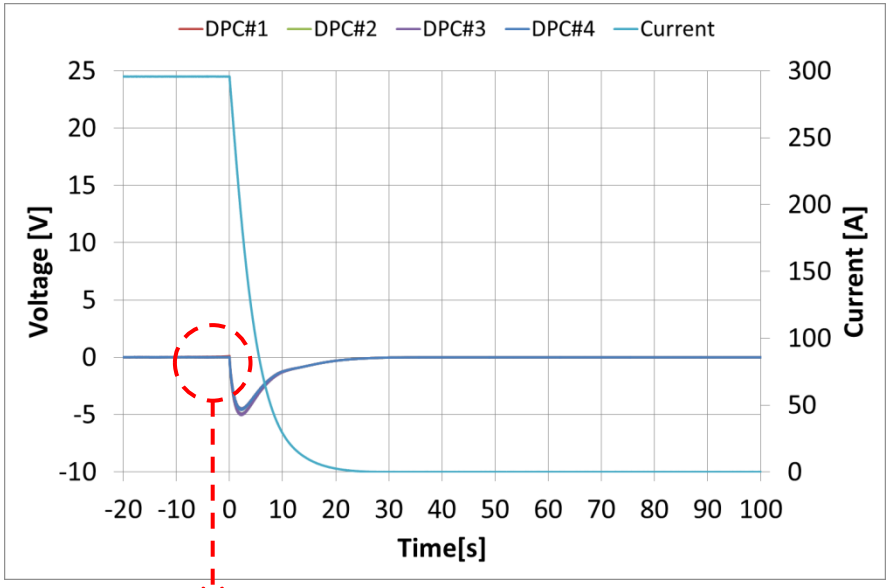
- The coils operated at 250 A were successfully protected with a detecting voltage at least 60 mV.
- The increase of I_{op} from 200 A to 250 A greatly lowered the protectable detecting voltages.

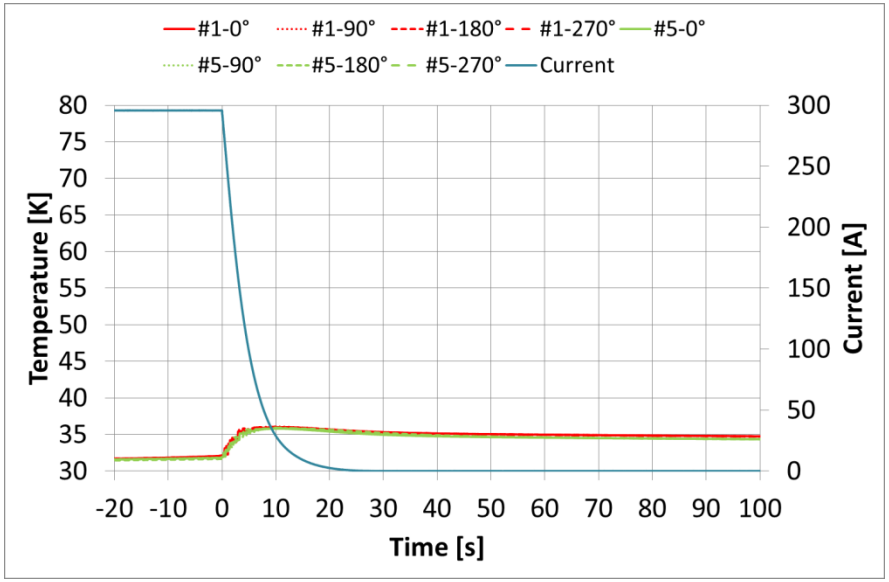
Key parameters of the coils

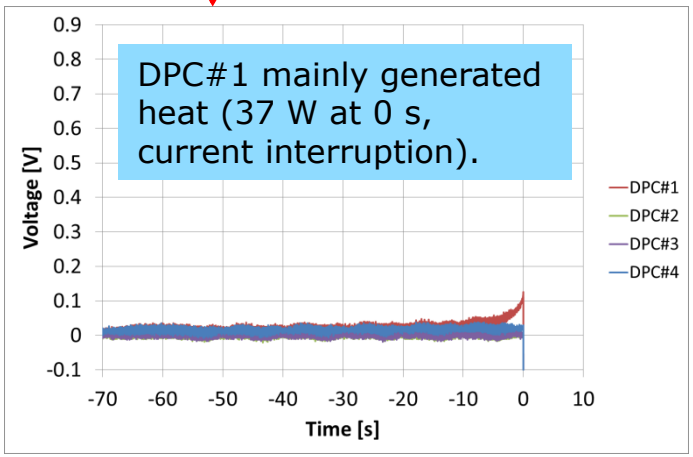
	I_{op} 200 A, 250 A	I_{op} 300 A
Wire	DI-BSCCO Type Hi	Code #2
Wire insulation	overlapped 12.5 μm-thick polyimide films	overlapped 5 μm-thick polyimide films
I_c of wire (77 K, s. f.)	approx. 180 A	approx. 230 A
DP coil i. d.	70 mm	89 mm
DP coil o. d.	214 mm	214 mm
DP coil height	9.7 mm	10.9 mm
Number of DP coils	4	4
Number of turns	2000 turns (500 turns×4)	2000 turns (500 turns×4)
Peak $B_{\perp}$	1.7 T@200 A, 2.2 T@250 A	2.9 T
Peak $B_{\parallel}$	4.8 T@200 A, 5.9 T@250 A	6.8 T
Flanges	Magnetic	Magnetic

- If Sumitomo Electric designs a coil with I_{op} over 250 A, Code #2 wire will be used as in the design study at the beginning.
- I_{op} 300 A experiments were conducted with coils of Code #2 wire, keeping the number of turns the same.

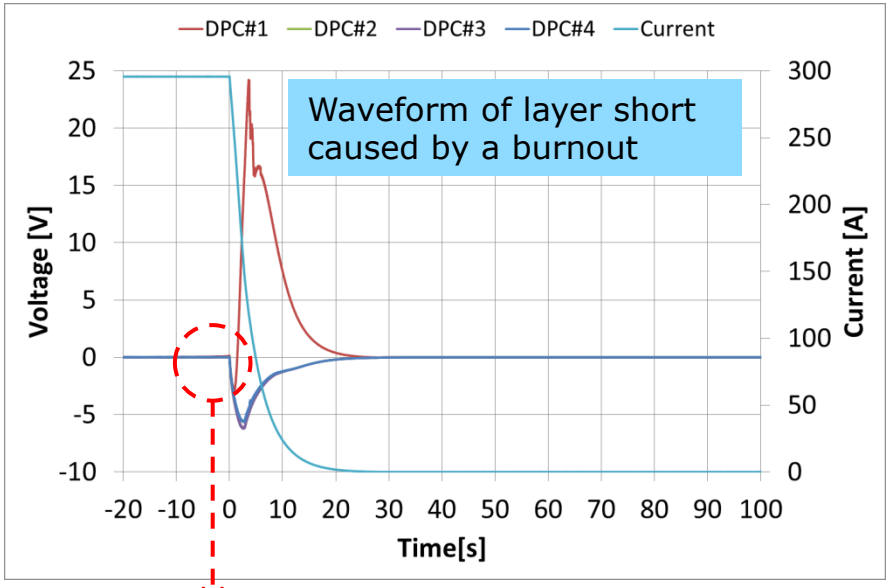
300 A-4 s-40 mV (No degradation)

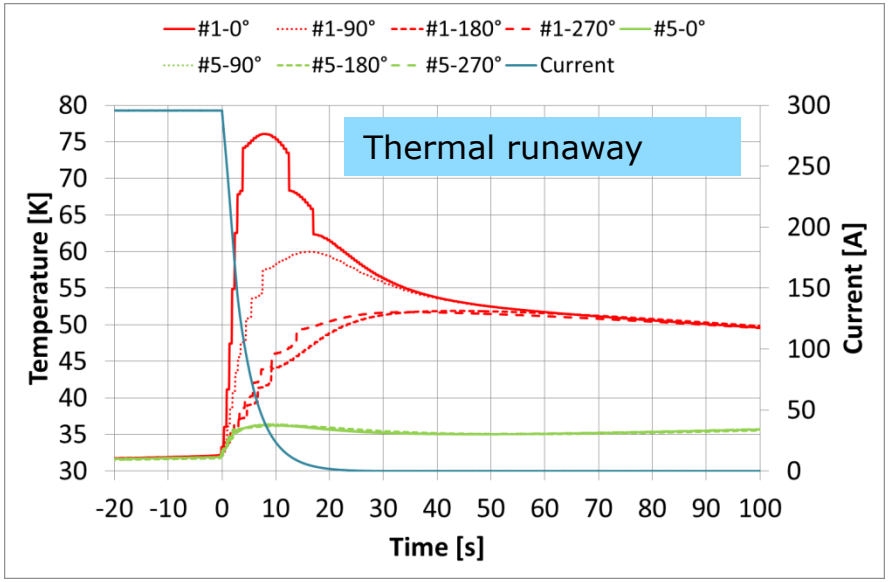


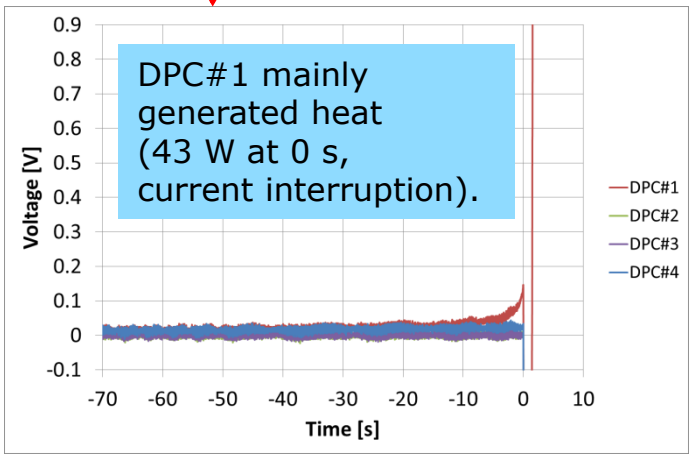




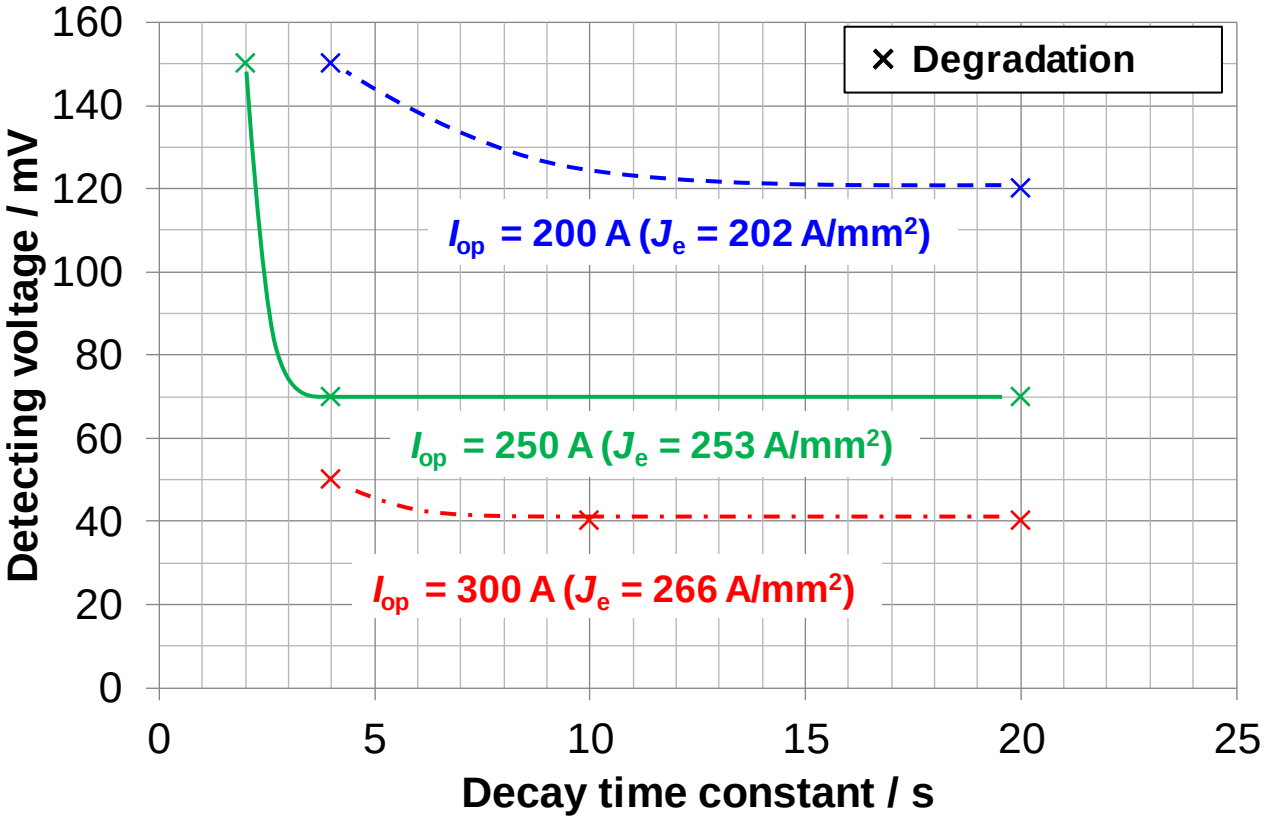
300 A-4 s-50 mV (Degradation)







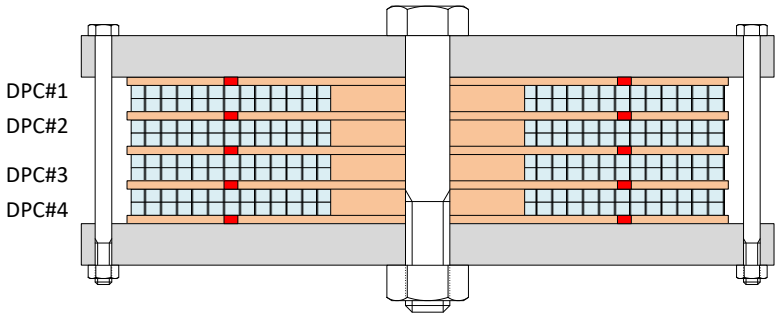
Results | Operating current 300 A



- The coils of Code #2 wire operated at 300 A were successfully protected with a detecting voltage at least 30 mV.

Discussion

- The two DP coils in the magnet center region (#2 and #3) have never thermally run away. Degraded coils were always at the magnet ends (#1 or #4).
- The infield I_cs of DP coil #2 and #3 are higher than those of DP coil #1 and #4.



- In a DP stack, unless the infield I_c is lower than those of the Code #2 wire at the magnet ends, it is considered that Code #1 or Code #3 wire, which has a smaller cross-sectional area, can be used for the rest of the stack.

Bi2223 coil grading is now feasible.

Summary

- A DI-BSCCO production shift plan was introduced.

  Code #2 (1.13 mm^2) 220-240 A

  Type H (0.99 mm^2) 180-200 A →Code #1 (0.86 mm^2) 180-200 A

  Code #3 (0.72 mm^2) 140-160 A

- Coils of Type H operated at 250 A can be protected with a detecting voltage at least 60 mV.

- Coils of Code #2 operated at 300 A can be protected with a detecting voltage at least 30 mV.