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Presentation SA-17 was given at ISS 2014, Tokyo, November 25 - 27, 2014.

DI-BSCCO

Quench protection of DI-BSCCO coil

Sumitomo Electric Industries, Ltd.

2014/11/26 ISS2014

T. Yamaguchi*, E. Ueno, T. Kato, K. Hayashi

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Outline

- Background
- Our work
- Experiment
  - test coil
  - full-scale pole coil
- Summary

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Background

Premise

HTS wires have very slow normal zone propagation velocity.

⇒Hotspot easily occurs, resulting in the degradation.

To prevent this, it is important to quickly reduce an operating current.

Issue1

A large superconducting motor in the 20 MW range will have a large inductance, so the coil and the wiring to have a huge withstand voltage.

Issue2

It is necessary to detect a quench at a higher voltage than an environmental noise without a degradation.

↓

Purpose

It is needed that the relation between the current decay time constant and the quench detecting voltage without a degradation.

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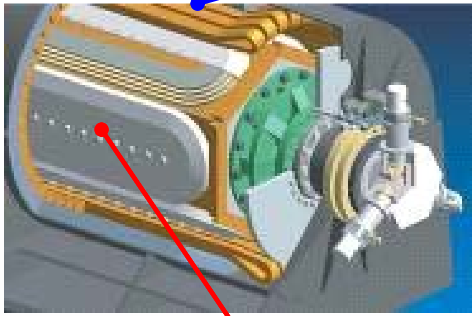
Our work

First, we made the test coil and investigated the condition without a degradation.

Second, we made the full-scale pole coil for a 20MW motor and investigated the condition without a degradation.



An image of 20MW motor

Rated output	20 MW
Rotating speed	90 rpm
Efficiency	99%
Torque density	56 kNm/m^3

Number of HTS field coils	96 coils / 24 poles
Amount of DI-BSCCO wire	307 km / 96 coils
Number of total turns	96,000 turns
Rated current	200 A at 37 Kelvin
Cooling system	Helium-neon gas mixture thermosyphon cooling and Conduction cooling

[Courtesy of Kawasaki Heavy Industries, Ltd.]

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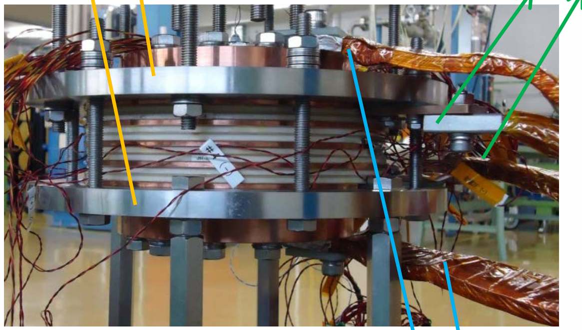
DI-BSCCO

Specifications of test coil

Type of DI-BSCCO wire	Type H
Critical current of wire	about 180 A
Coil	Circular double pancake (Epoxy impregnated)
Number of stacked coil	4
Number of total turns	2000 turns
Maximum parallel magnetic field	4.2 T
Maximum perpendicular magnetic field	2.0 T
Inductance	0.4 H
Stored energy	8.2 kJ at 200A



The coil was cooled by a refrigerator.

Coils for experiment

Coil No	Ic of wire @77K s.f	n value @77K s.f
DPC#1	180.9	17.5
DPC#2	174.6	17.9
DPC#3	174.8	17.2
DPC#4	181.3	17.5

The upper and lower ends are as symmetric as possible

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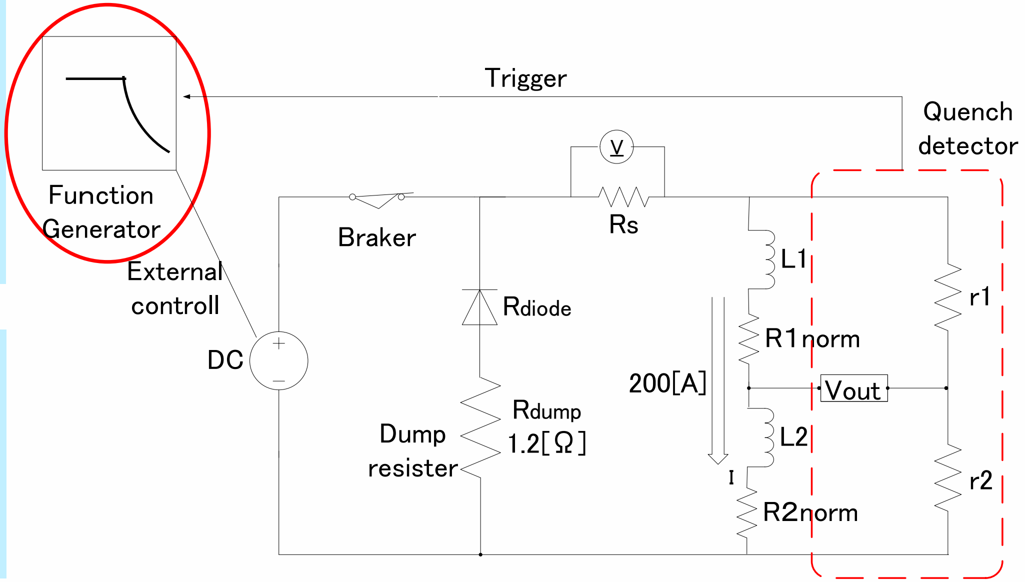
Experimental circuit for the test coil

We cannot reduce exponentially the operating current due to coil's small inductance.

Exponential reduction of the operating current by a function generator.



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

- Detection of a quench by a balance circuit
- Detection time is 0.1 sec
- Decay time constant are 4sec, 10sec, 20sec and 60sec.

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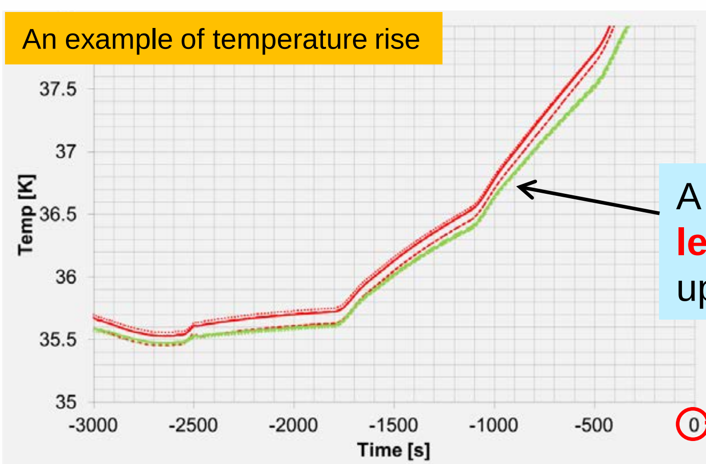
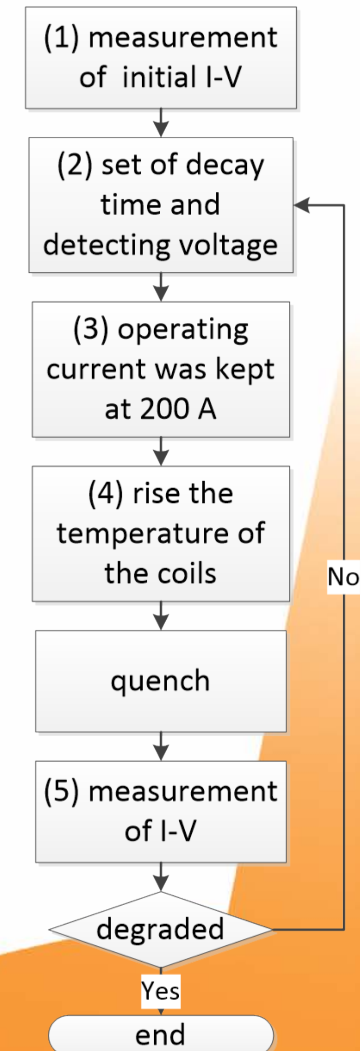
Experimental method of the test coil

(1)Measurement of initial I-V curve at 33 K
(2)Set of the current decay time constant and quench detecting voltage
(3)The operating current is kept at 200 A at 35 K.
(4)The temperature of the coils is gradually raised to initiate quench.
(5)Measurement of I-V curve at 33 K and comparison with initial I-V curve. If the coil has no degradation, we rise the quench detecting voltage and carry out (2)~(5).
It was repeated until the coil had degradation.



A temperature difference of **less than 0.3 K** between the upper and lower ends

When the current was broken, time was 0.



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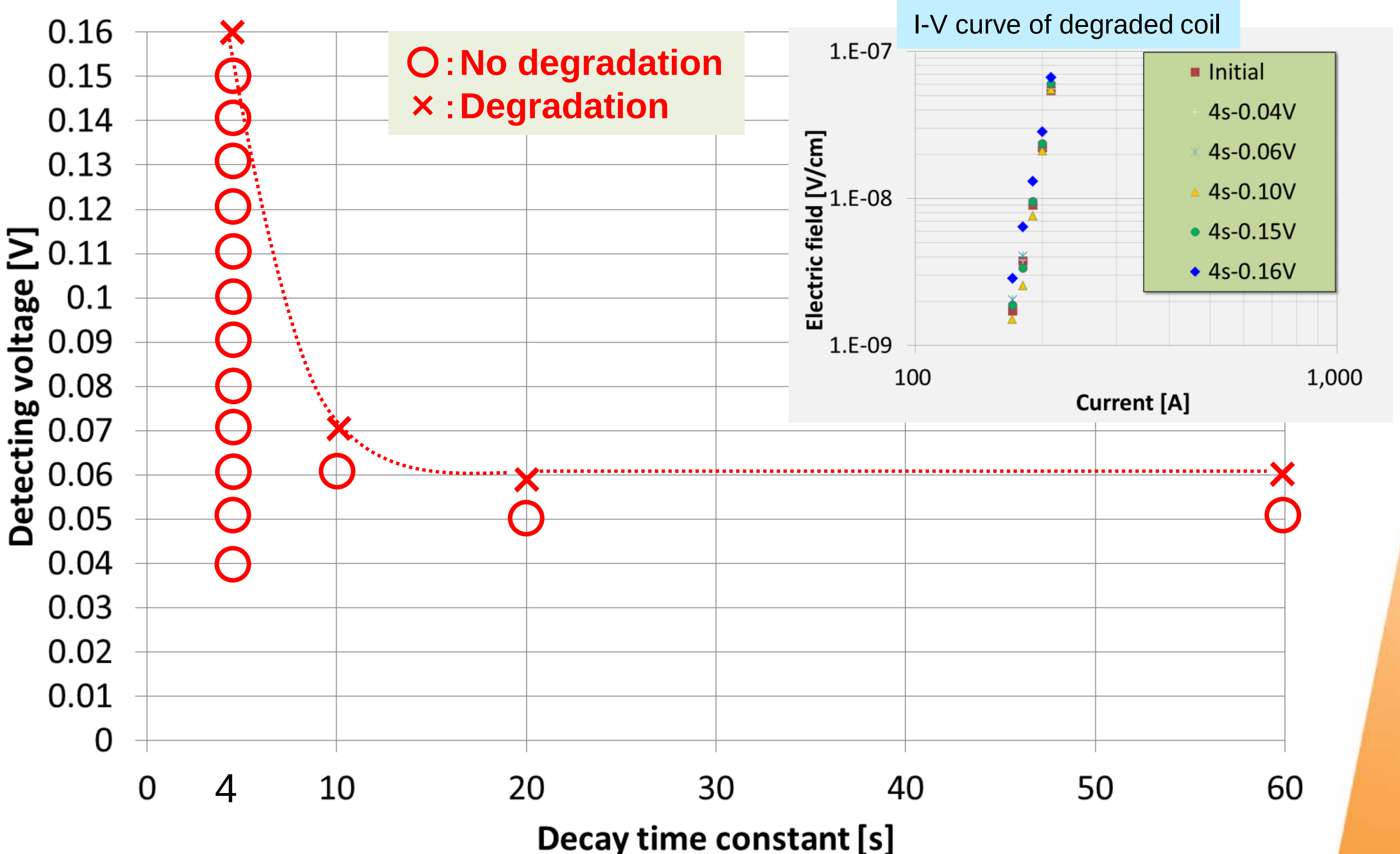
Results of test coil



Here, we shall show the temperature and the voltage of 0.04 V, 0.06V, 0.15 V and 0.16V.

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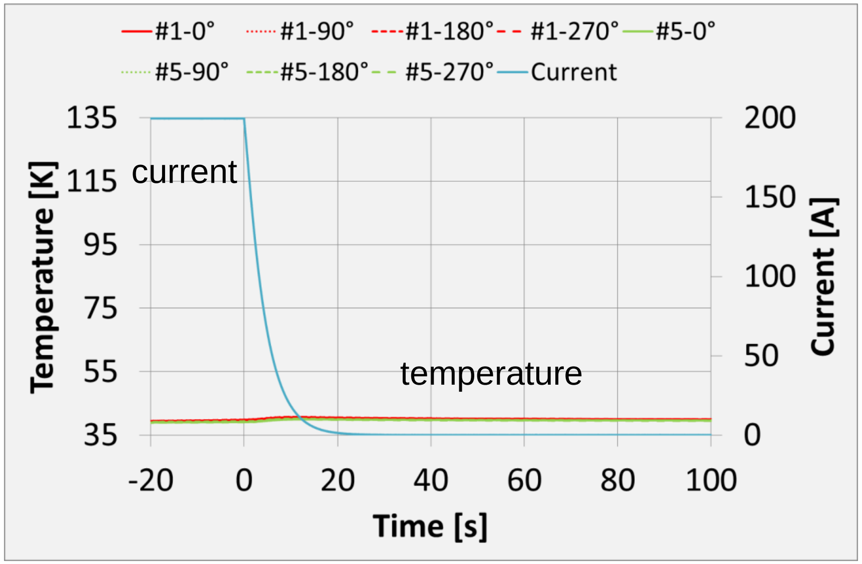
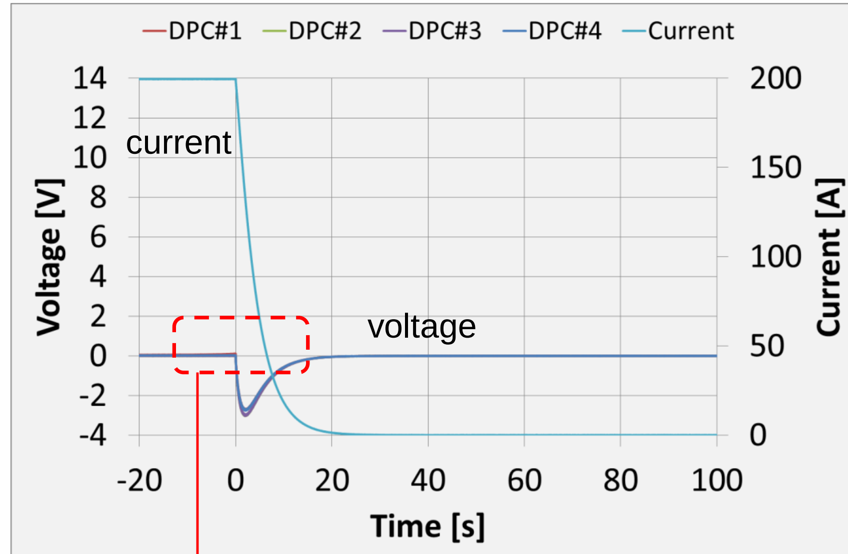
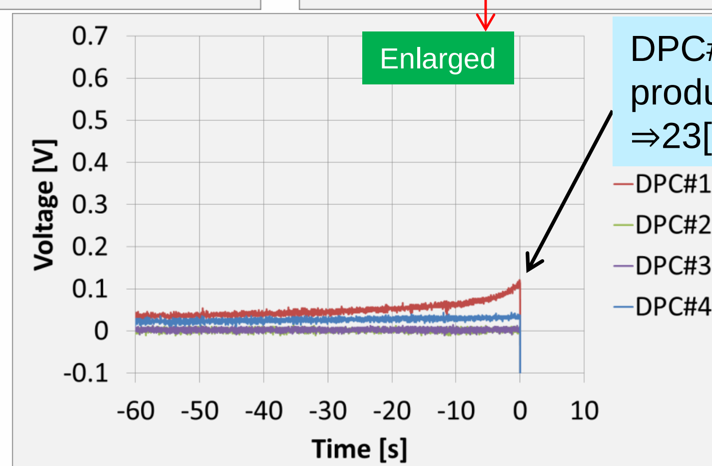
4s-0.04V (No degradation)

Current & Temperature



Current & Voltage





DPC#1 generated heat production rate mainly.
⇒23[W]

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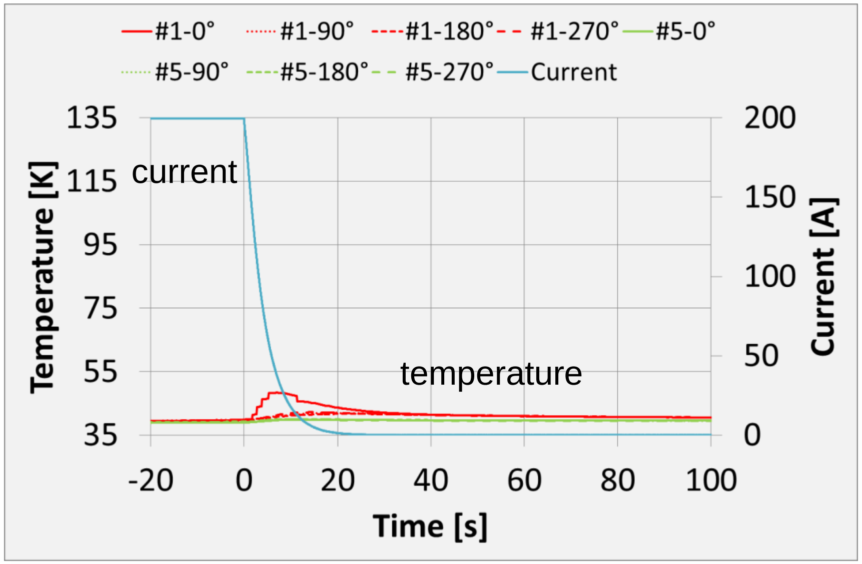
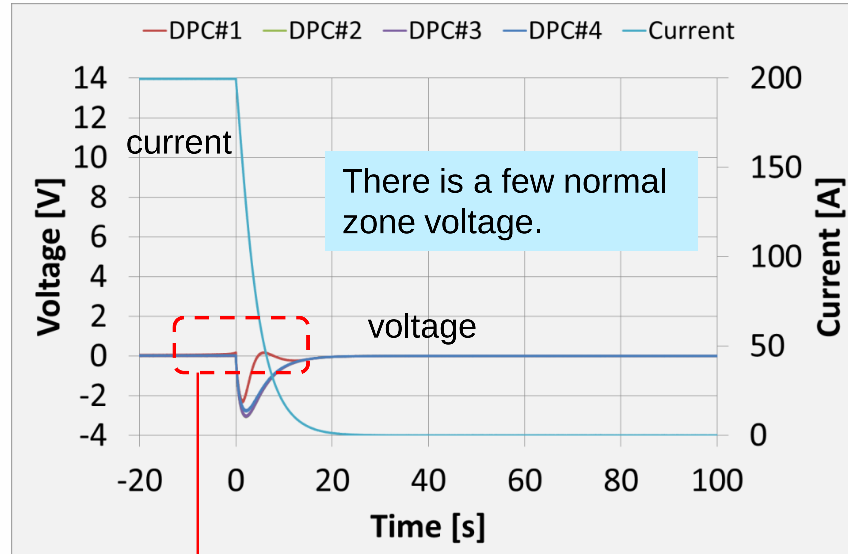
DI-BSCCO

4s-0.06V (No degradation)

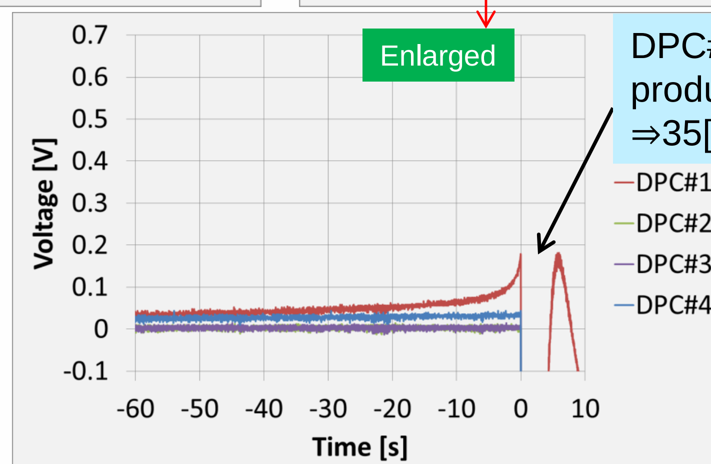
Current & Temperature



Current & Voltage



There is a few normal zone voltage.



DPC#1 generated heat production rate mainly.
⇒35[W]

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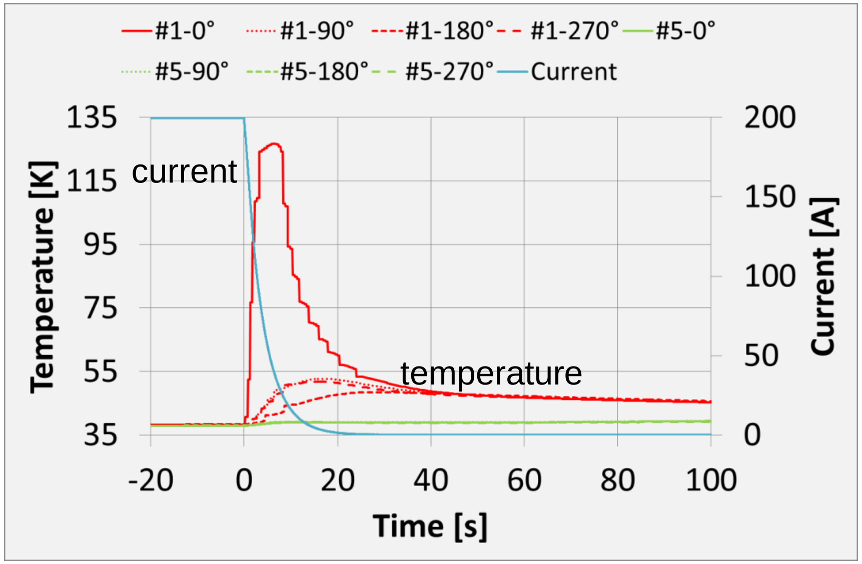
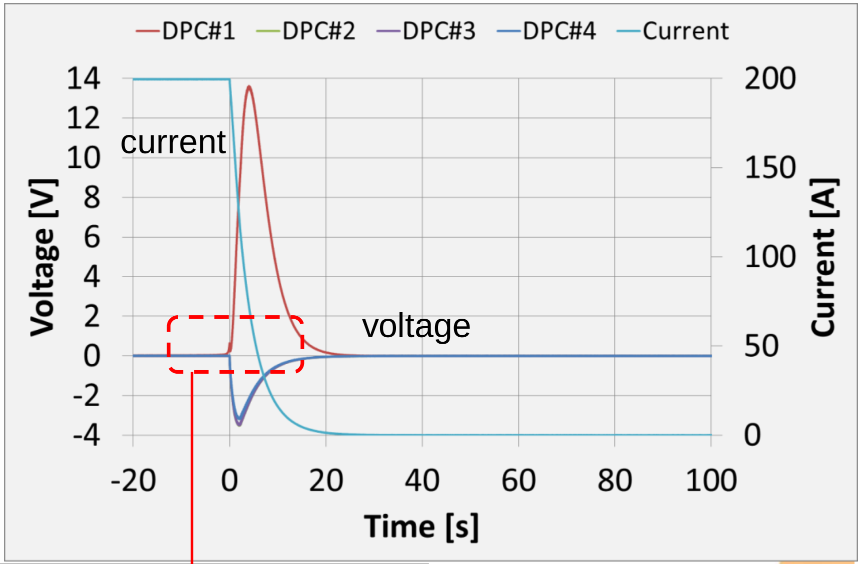
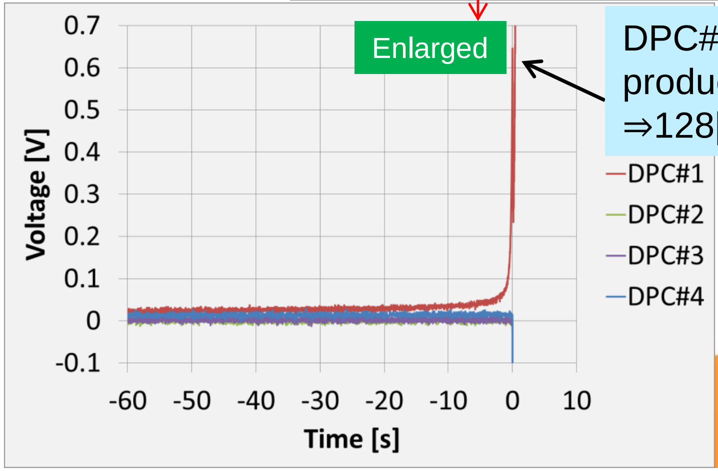
4s-0.15V (No degradation)

Current & Temperature



Current & Voltage





DPC#1 generated heat production rate mainly.
⇒128[W]

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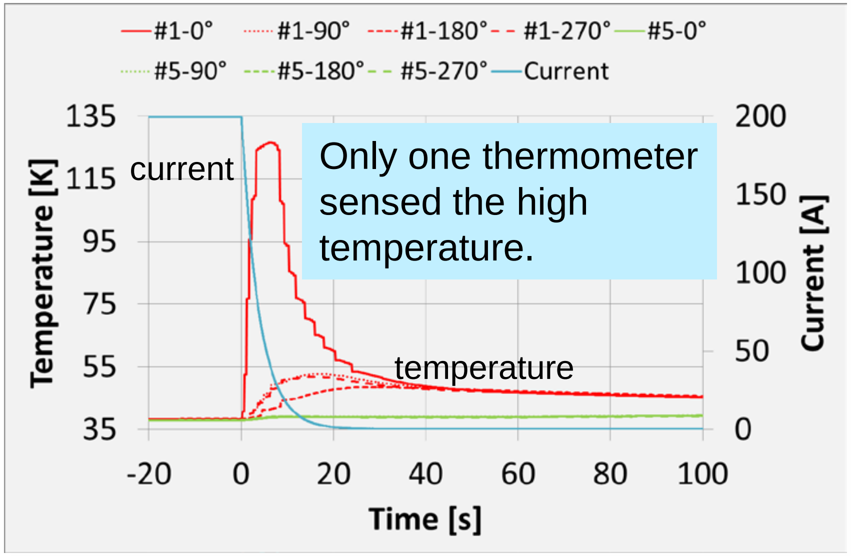
DI-BSCCO

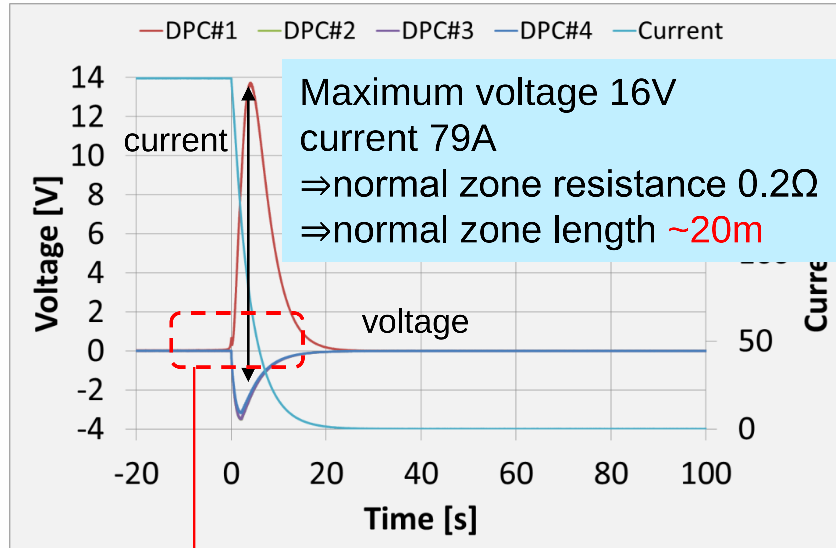
4s-0.16V (Degradation)

Current & Temperature

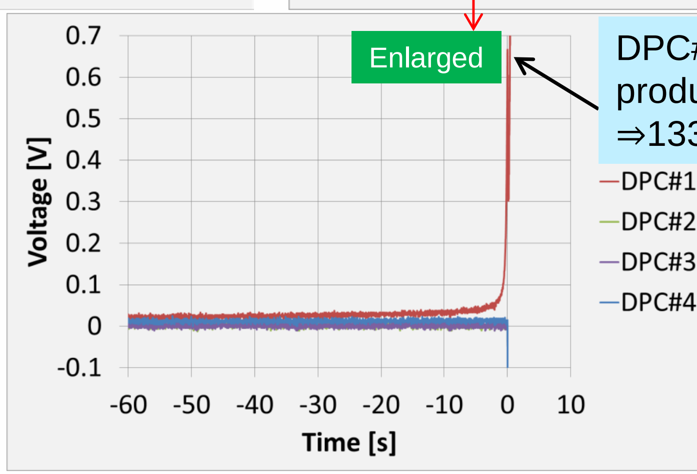


Only one thermometer sensed the high temperature.

Current & Voltage



Maximum voltage 16V
current 79A
⇒normal zone resistance 0.2Ω
⇒normal zone length ~20m



DPC#1 generated heat production rate mainly.
⇒133[W]

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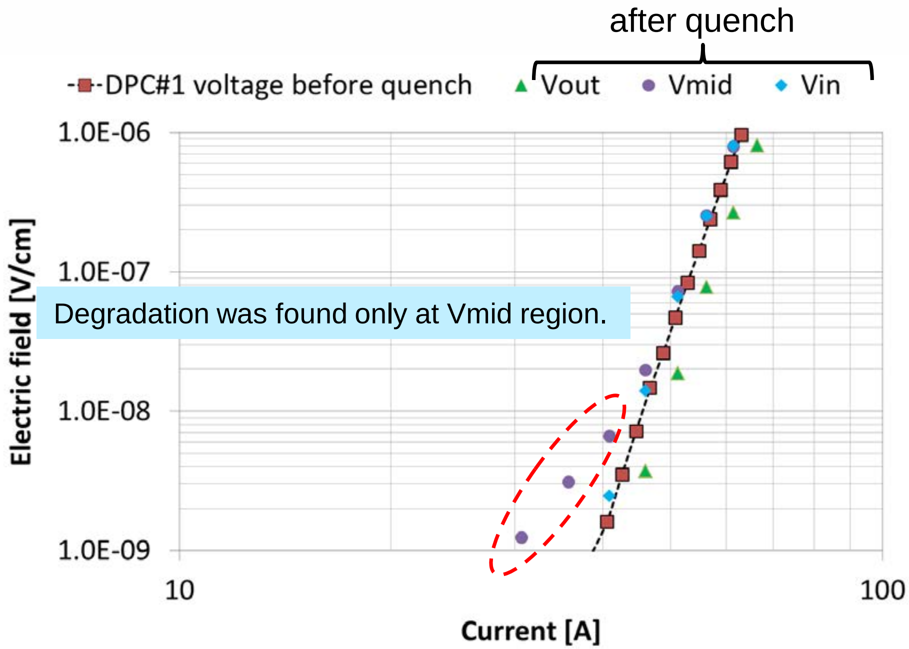
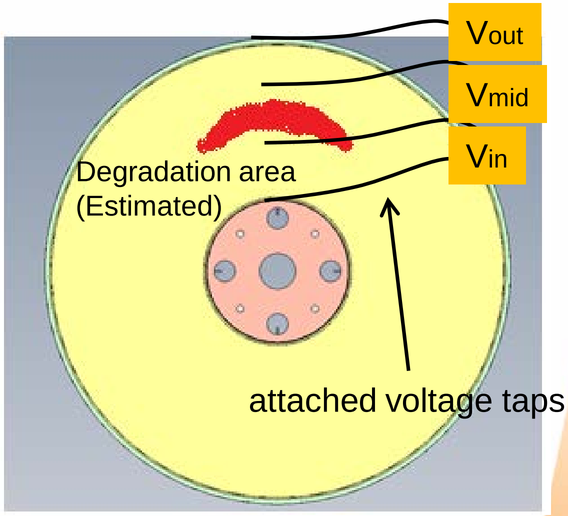
DI-BSCCO

Investigation of degraded part





- Only one thermometer sensed the high temperature. (previous page).
- The normal zone length was about 20m. (previous page)
- Degradation was found only at Vmid region.

It is estimated that degradation area resembled the painted area in above figure.

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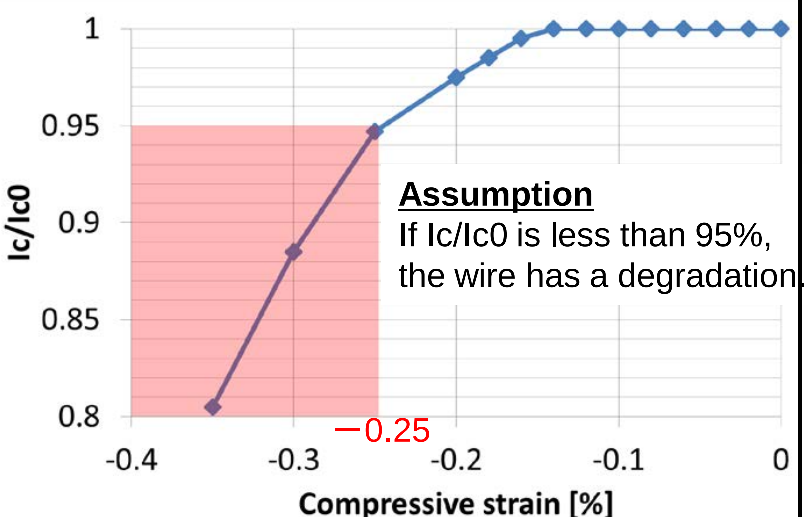
DI-BSCCO

Discussion of degradation

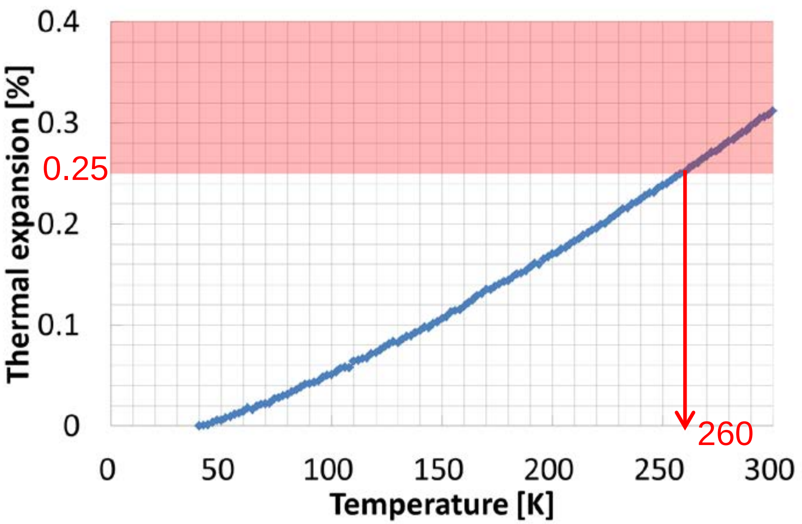
A degradation of the wire was caused by stress induced by change in the thermal expansion coefficient as the temperature increased.

Compression characteristics of DI-BSCCO wire (Type H) by Dr.Osamura



When the compressive strain is more than -0.25%, Ic/Ic0 is less than 95%.

Thermal expansion characteristics of DI-BSCCO wire (Type H)



When the thermal expansion is more than 0.25 %, the temperature is more than 260 K.
⇒hotspot's temperature is more than 260 K, we estimate.

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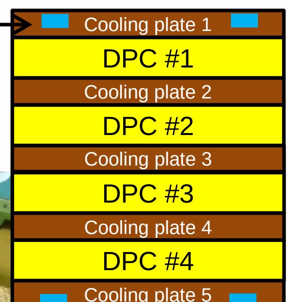
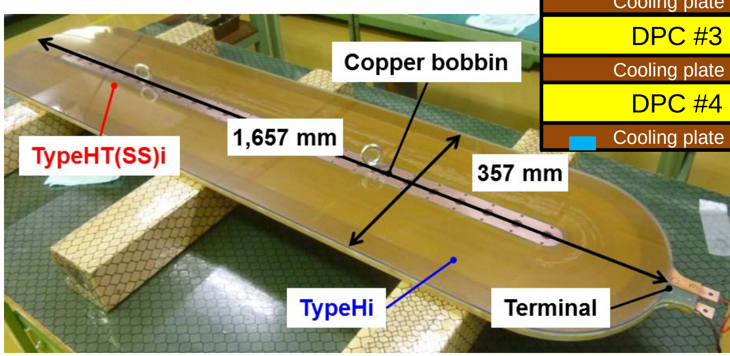
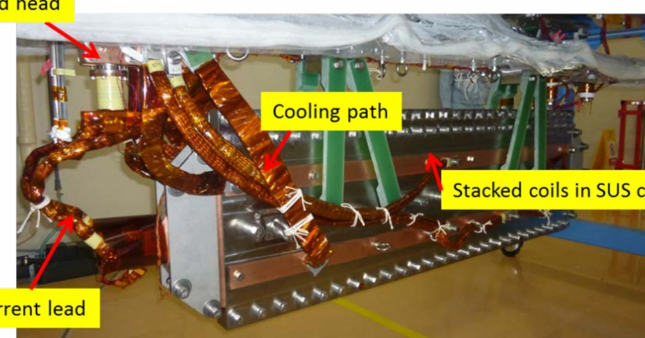
Specifications of the full-scale pole coil

Type of DI-BSCCO wire	TypeHTi、TypeHi
Critical current of wire	about 180A
Coil	Racetrack double pancake (Epoxy impregnated)
Number of stacked coil	4
Number of total turns	4000 turns
Maximum parallel magnetic field	5.7 T
Maximum perpendicular magnetic field	2.5 T (Round part)
	3.0 T (Straight part)
Inductance	15H
Stored energy	300kJ at 200A



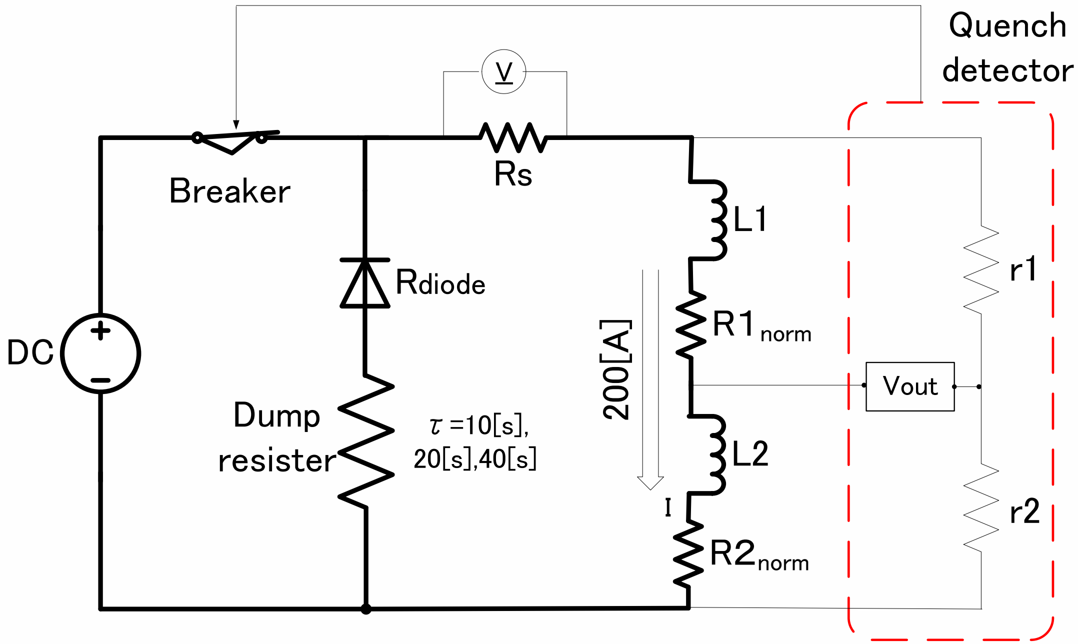


The coil was cooled by a refrigerator.



DI-BSCCO

Experimental circuit for the full-scale pole coil



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

- Detection of a quench by a balance circuit
- Detection time is 0.1 sec
- Reduction of the current by a dump resister
- Decay time constant is 10sec, 20sec and 40sec

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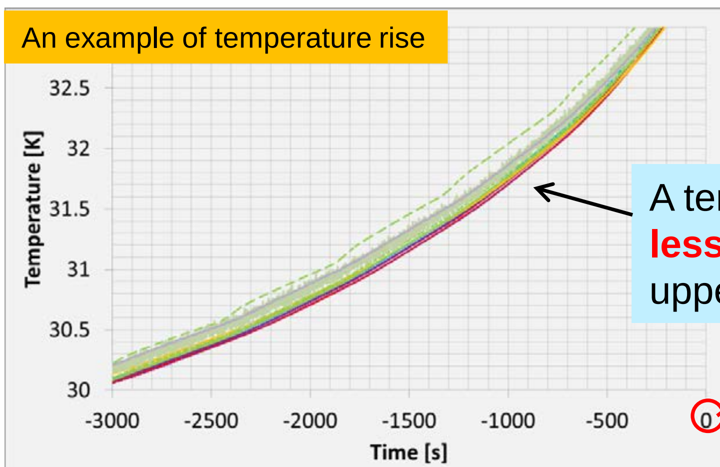
DI-BSCCO

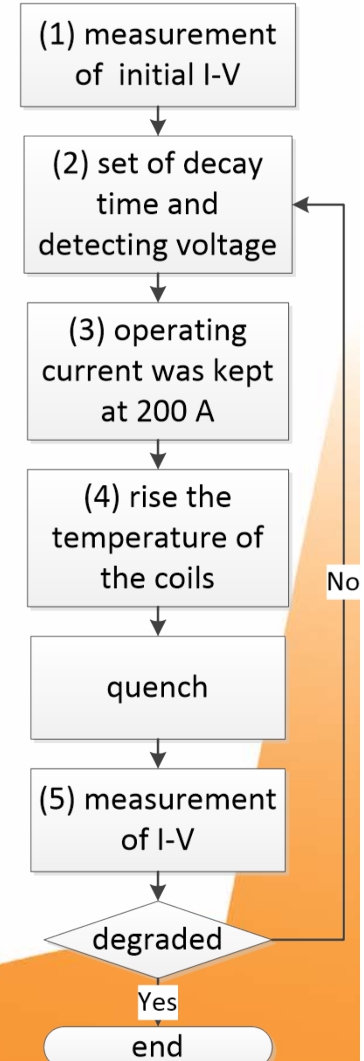
Experimental method of the full-scale pole coil

(1)Measurement of initial I-V curve at 27 K
(2)Set of the current decay time constant and quench detecting voltage
(3)The operating current is kept at 200 A.
(4)The temperature of the coils is gradually raised to initiate quench.
(5)Measurement of I-V curve at 27 K and comparison with initial I-V curve. If the coil has no degradation, we carry out (2)~(5).
It was repeated until the coil had degradation.



A temperature difference of **less than 0.3 K** between the upper and lower ends

When the current was broken, time was 0.



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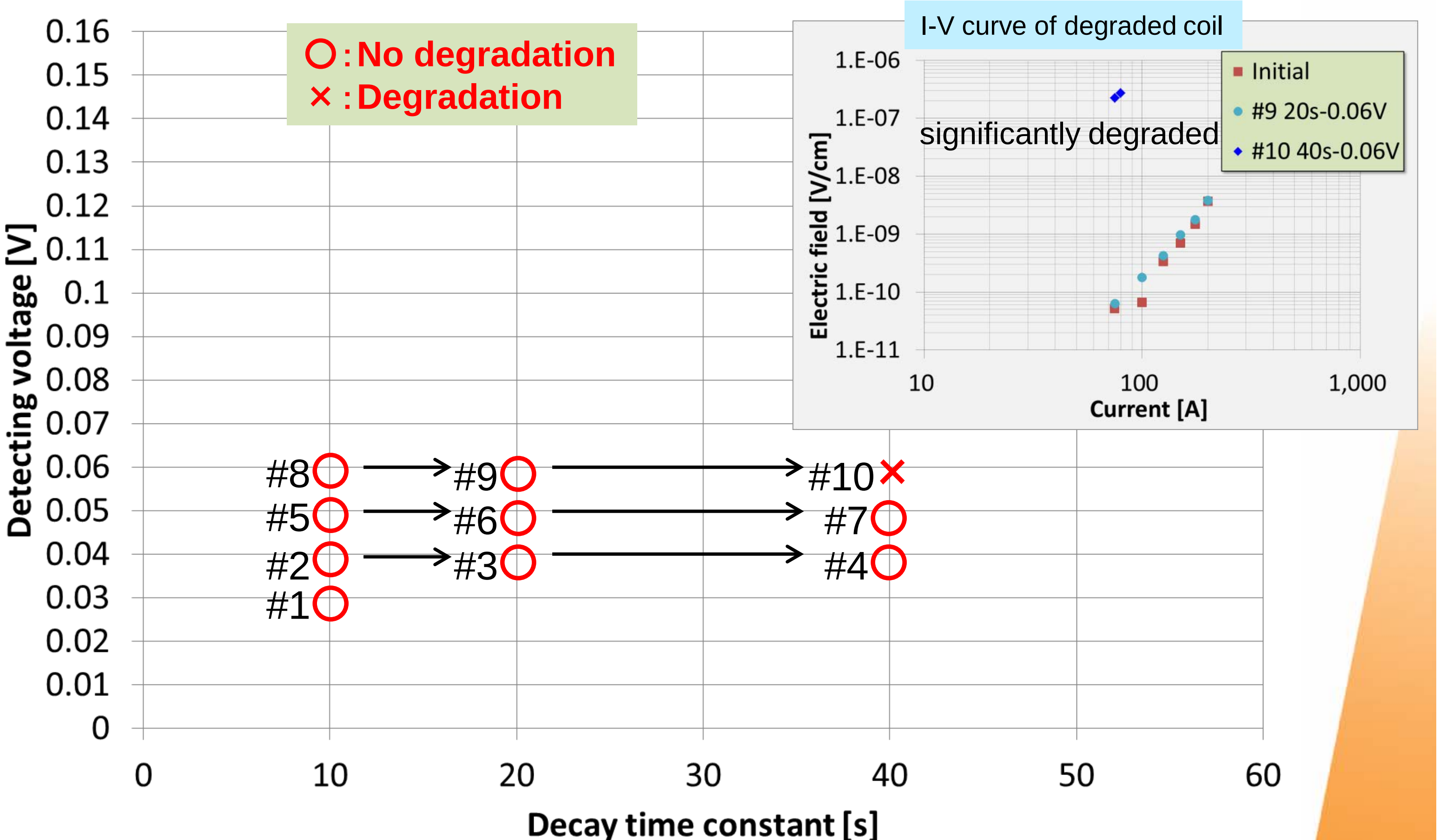
Results of full-scale pole coil



Here, we shall show the temperature and the voltage of #9 and #10.

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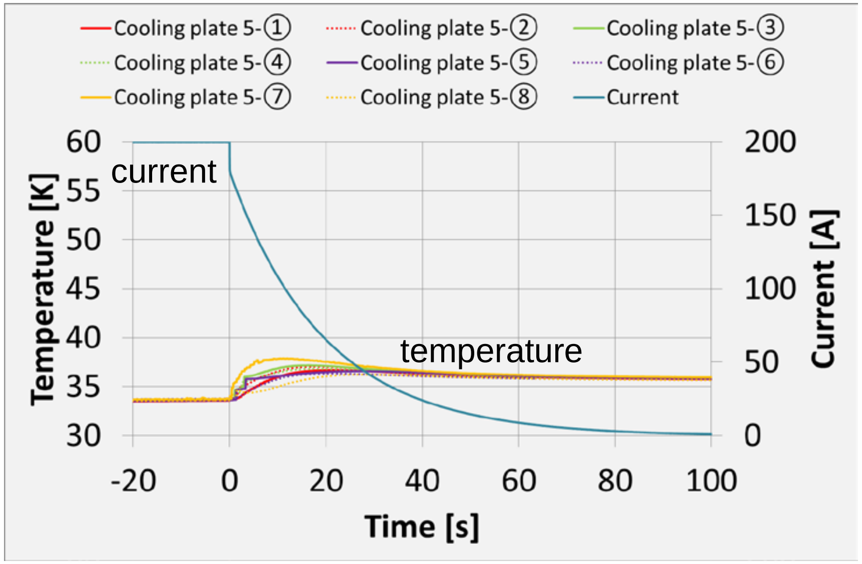
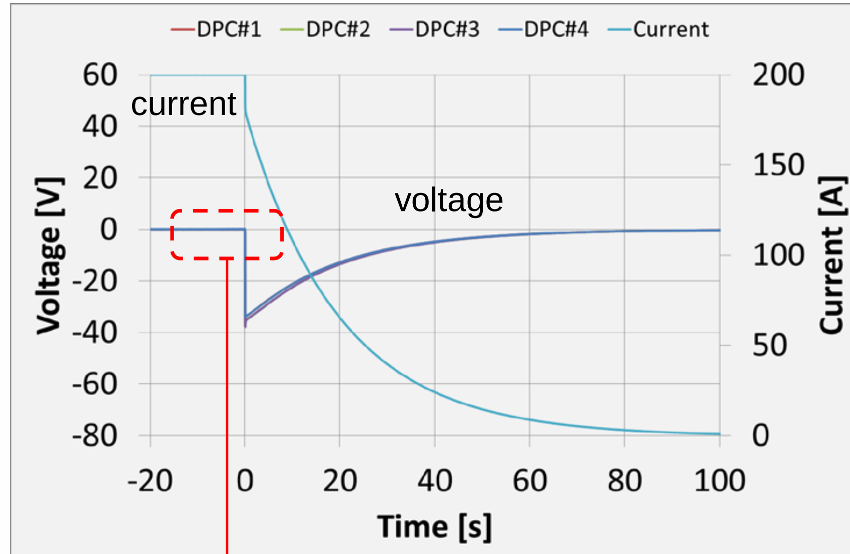
DI-BSCCO

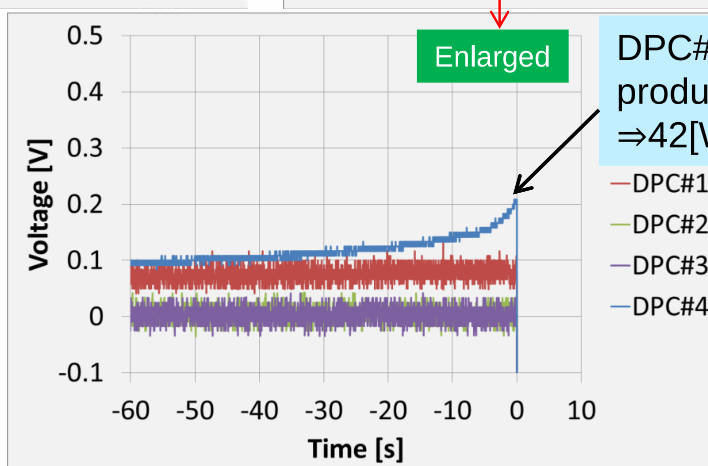
20s-0.06V (No degradation)

Current & Temperature



Current & Voltage





DPC#1 generated heat production rate mainly.
⇒42[W]

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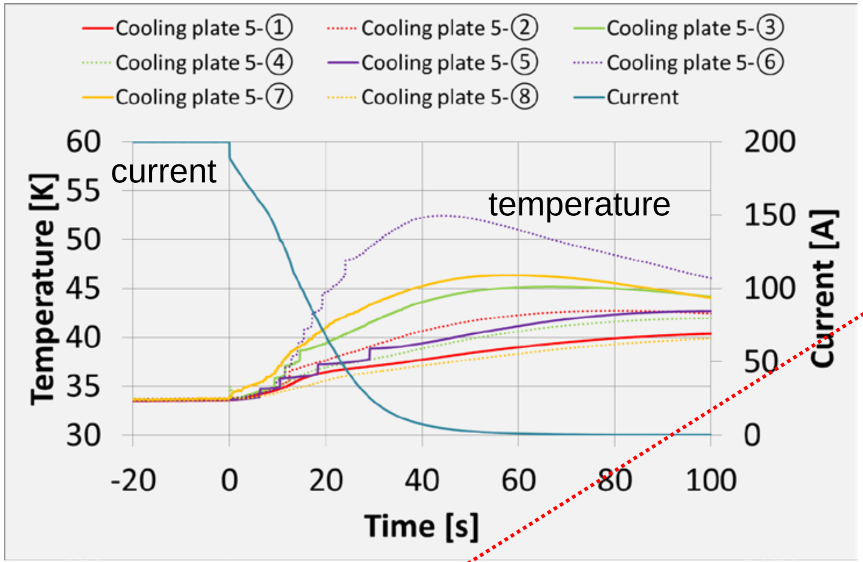
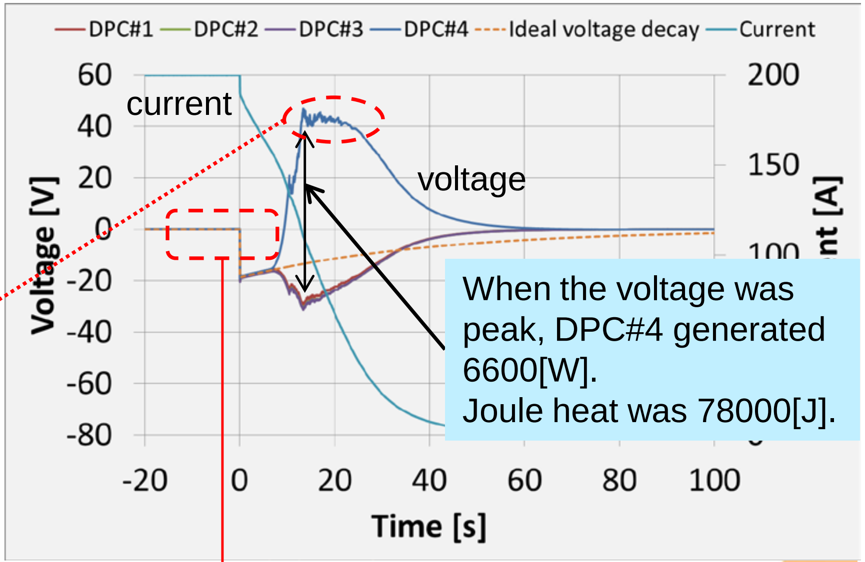
40s-0.06V (Degradation)

Current & Temperature

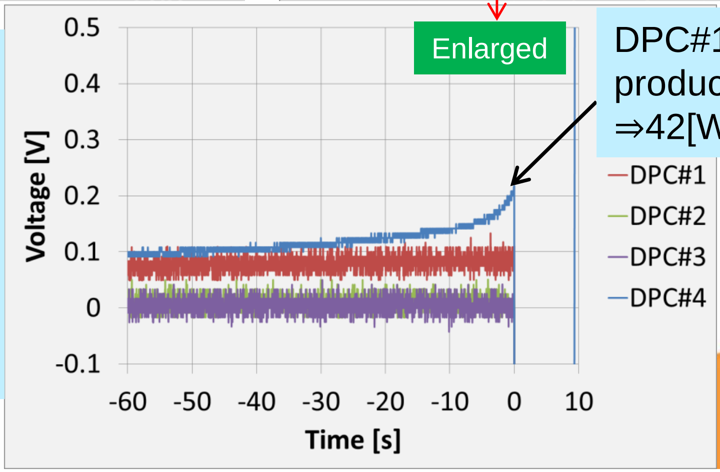


Current & Voltage



When the voltage was peak, DPC#4 generated 6600[W].
Joule heat was 78000[J].

●Hypothesis
Fluctuation of voltage
⇒Change of inductance
⇒Short circuited between adjacent some turns
We estimated that the temperature of hotspot exceeded 800 K at minimum, which pyrolysis polyimide.



DPC#1 generated heat production rate mainly.
⇒42[W]

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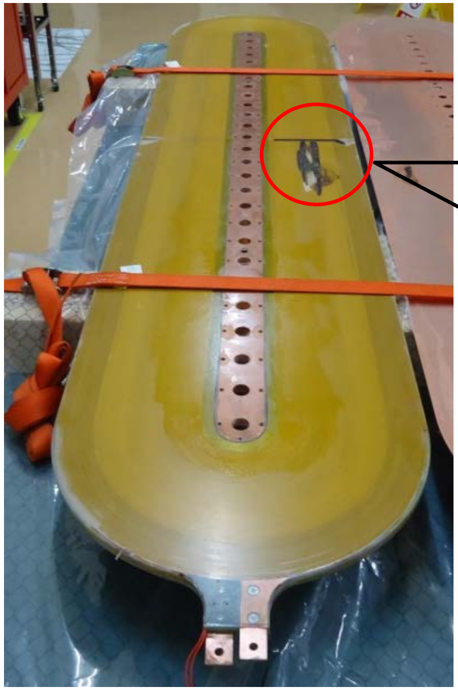
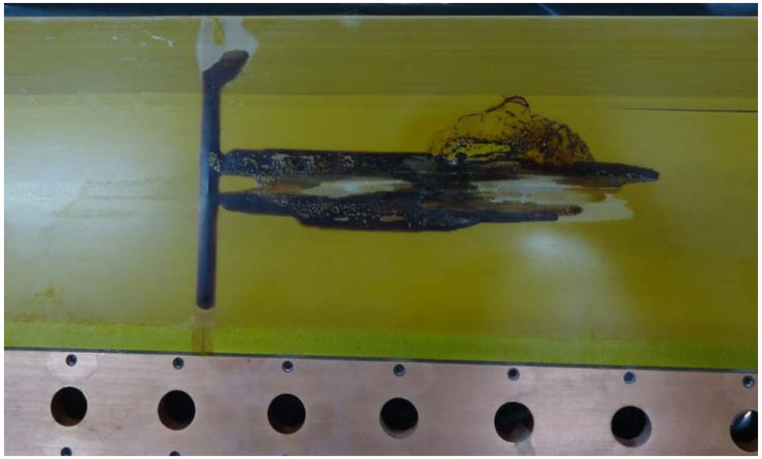
DI-BSCCO

Photograph after quench





We found the burnout in the part where perpendicular magnetic field was maximum.

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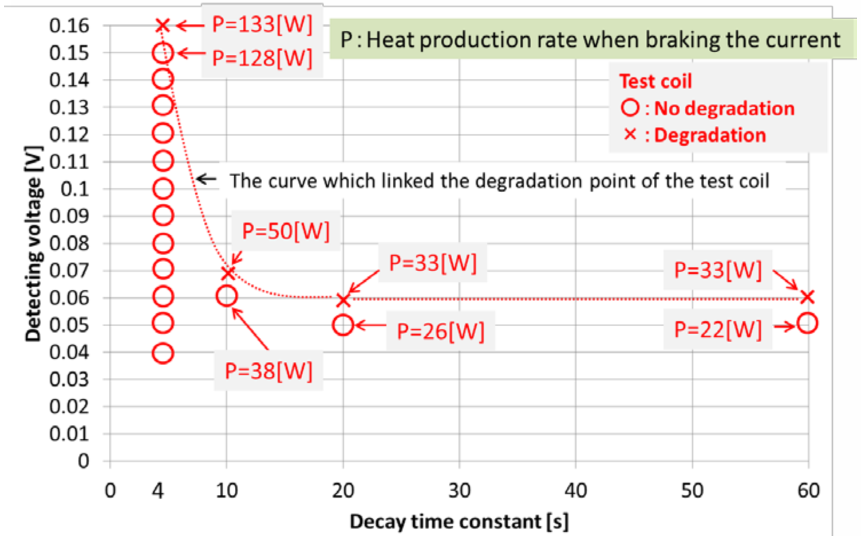
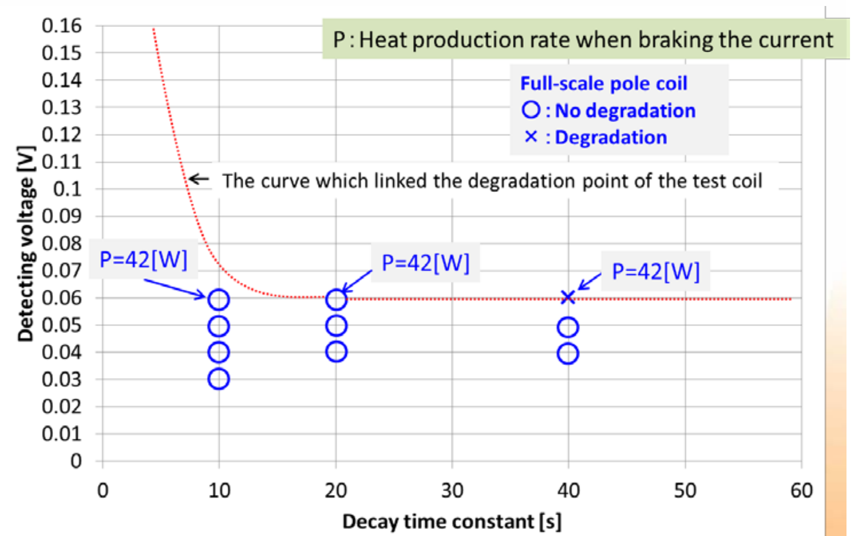
DI-BSCCO

Comparison of the results of test coil and those of full-scale pole coil



Results of the test coil



Results of the full-scale pole coil

There is not great difference between the results of the test coil and those of the full-scale pole coil.

⇒This means that **heat production rate in hotspot are similar.**

⇒Quench protection for coil depends on **heat production rate in the hotspot, but not on the size of coil.**

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DI-BSCCO

Summary

We investigated quench protection of DI-BSCCO coils (test coil and full-scale pole coil), and found the required relation between the detecting voltage and the decay time constant for coil protection.

- The experiment of the test coil

  When the current decay time constant was 4 sec, it can be protected even with a detecting voltage of 0.15 V, despite a significant heat production rate of 128 W.

  ⬇

Even when the heat production rate was high, DI-BSCCO coils showed very stable operation because of their homogeneity with respect to critical current and the good heat transfer between adjacent turns.

- The experiment of the full-scale pole coil

  The full-scale pole coil can be protected by conditions similar to those that protected the test coil.

  ⬇

This means that heat production rate in hotspot are similar.

Coil protection depended on the heat production rate in the hotspot, but not on the size of coil.