The 2014 Kyoto Workshop on HTS Magnet Technology for High Energy Physics
The 2nd Workshop on Accelerator Magnet in HTS (WAMHTS-2)
at Kyoto university, Japan, November 14, 2014

Recent progress in R&D of REBCO coated conductors and coils at Fujikura

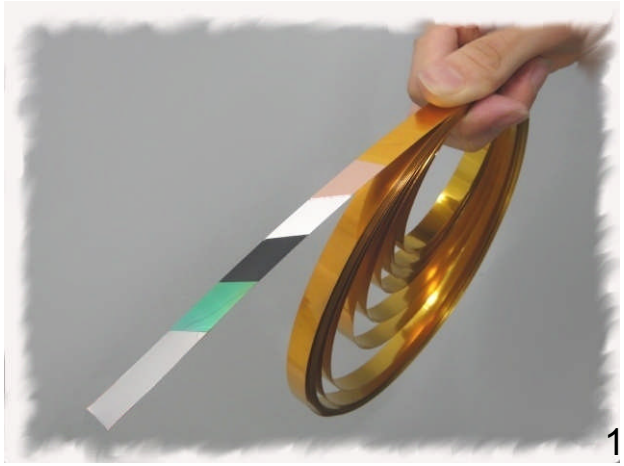
M. Daibo, S. Fujita, M. Igarashi, R. Kikutake, K. Kakimoto,
M. Nagata, Y. Iijima, F. Tateno

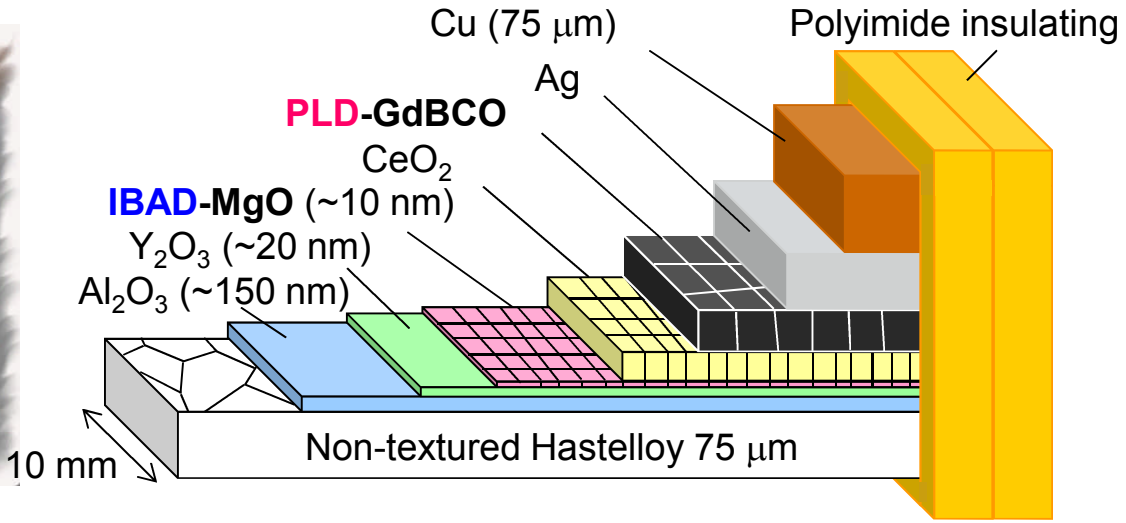
Fujikura

Outline

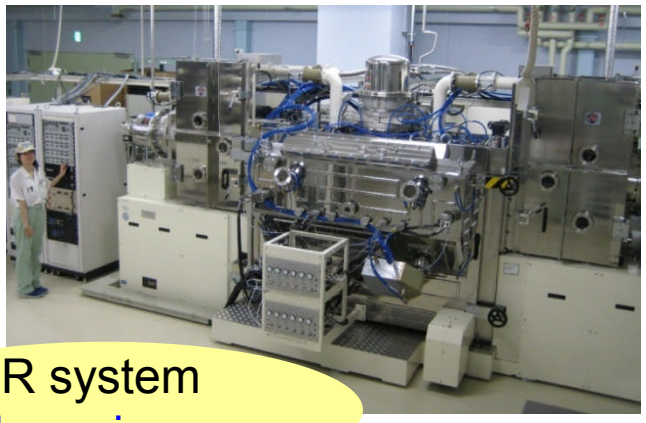
- Introduction
- Uniformity of REBCO coated conductors (c.c.) and In-field I_c properties
- Characteristics of REBCO coated conductors for 25 T Cryogen-free Superconducting Magnet
- Development of REBCO coils at Fujikura
  - Development of a 5 T 426 kJ REBCO magnet
  - Feasibility study for accelerator magnets
- Summary

Fujikura's REBCO coated conductor (IBAD / PLD)





Ion Beam Assisted Deposition (IBAD)



R-to-R system
with large ion source

Pulsed Laser Deposition (PLD)

R-to-R system
with hot-wall heating

Fujikura

Typical spec. of REBCO c.c. at Fujikura

Typical Specification

Products	Width (mm)	Thickness (mm)	Substrate (μm)	Stabilizer (μm)	Critical Current (A) (@77K, s.f.)
FYSC-S					> 250
FYSC-S					> 500
I_c >					

- ✓ **Fujikura will change original wire width from conventional 10 mm to new 12 mm wide.**
- ✓ **New products based on 4 mm wide will be released in the 1st quarter of fiscal year 2015.**

Schematic of Fujikura's REBCO coated conductors (c.c.)

Insulating tape [Polyimide] 12.5 μm x 2 layers (Non-adhesive film)

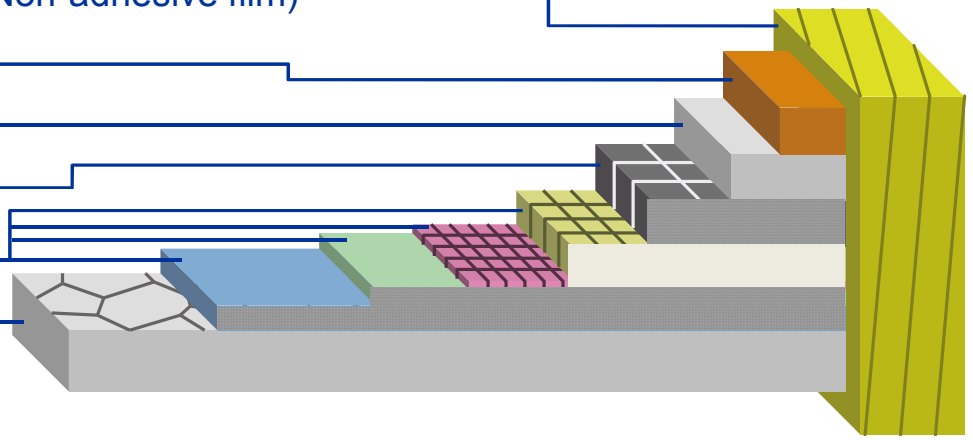
Stabilizer [Cu] 75 μm

Protection layer [Ag] 2~ μm

Superconducting layer [$GdBa_2Cu_3O_x$]

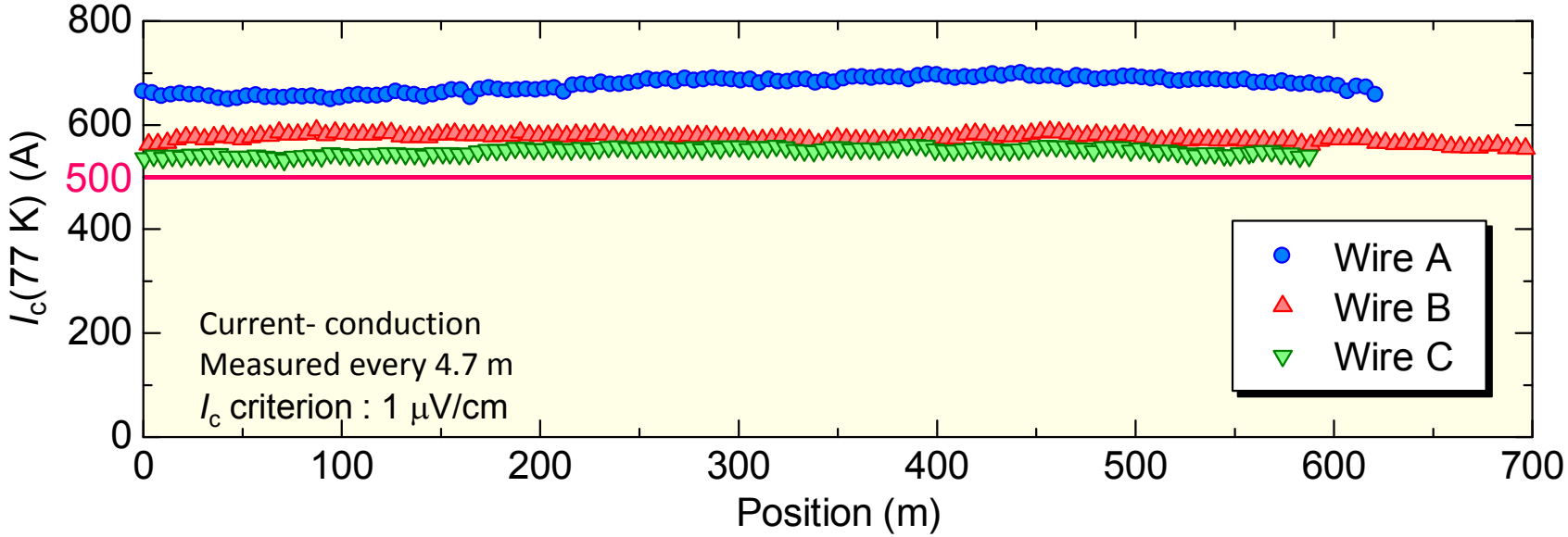
Buffer layer [AL_2O_3, Y_2O_3, MgO] ~0.7 μm

Substrate [Hastelloy®] 75 μm



Uniformity of production wires

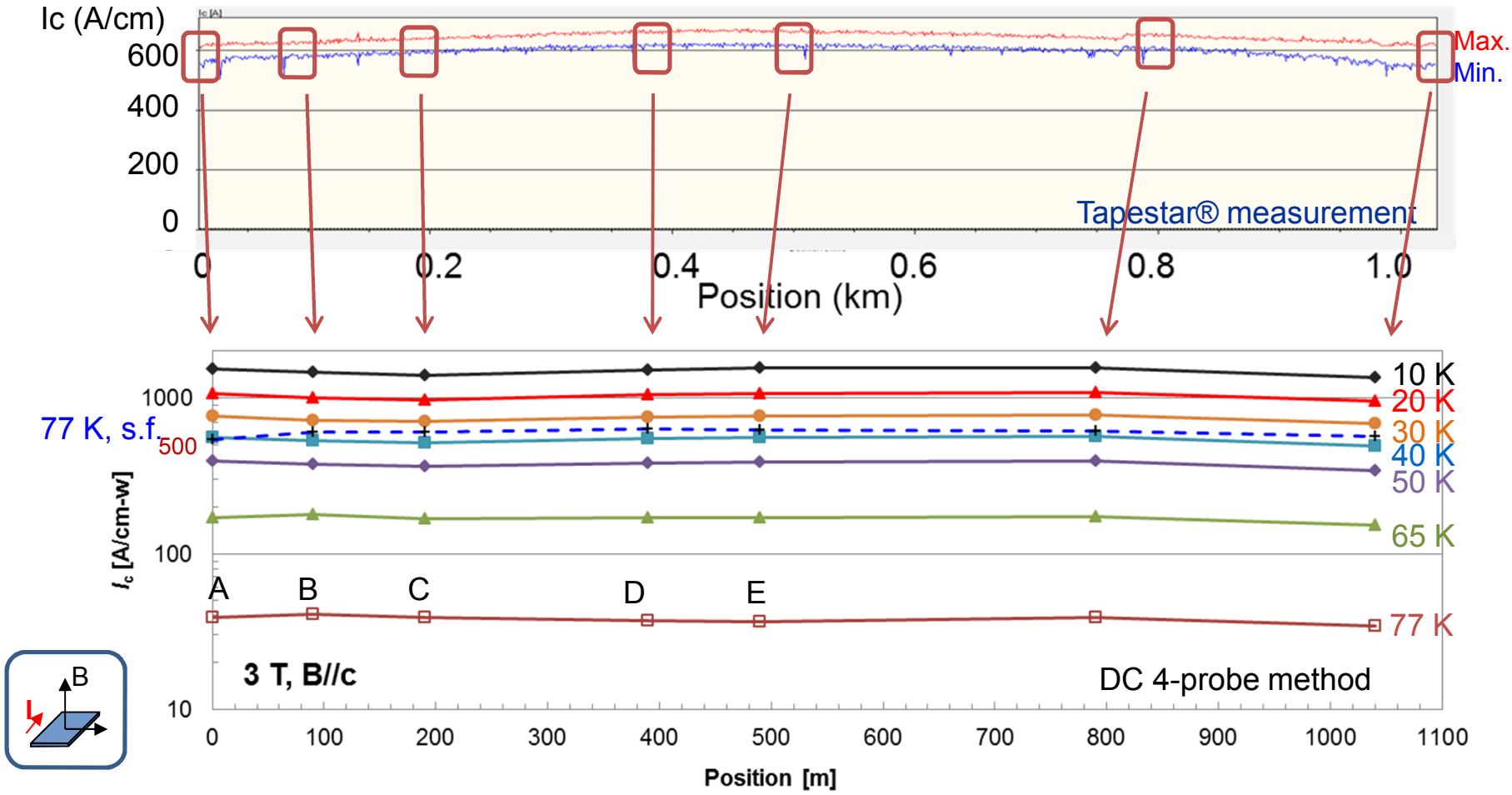
- Longitudinal I_c distribution **quite uniform I_c > 500 A/cm with L > 500 m obtained**



	Wire A	Wire B	Wire C
1. Piece length	621 m	700 m	587 m
2. I_c (max.)*	700 A	590 A	562 A
3. I_c (min.)*	649 A	555 A	533 A
4. I_c (avg.)*	677 A	575 A	550 A
5. Uniformity**	7.5 %	6.1 %	5.2 %

*10 mm-W **Uniformity : {I_c (max.) - I_c (min.)} / I_c (avg.) x 100

In-field I_c distribution in a 1 km long demo sample (10-77 K, 3 T)

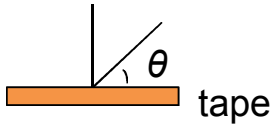


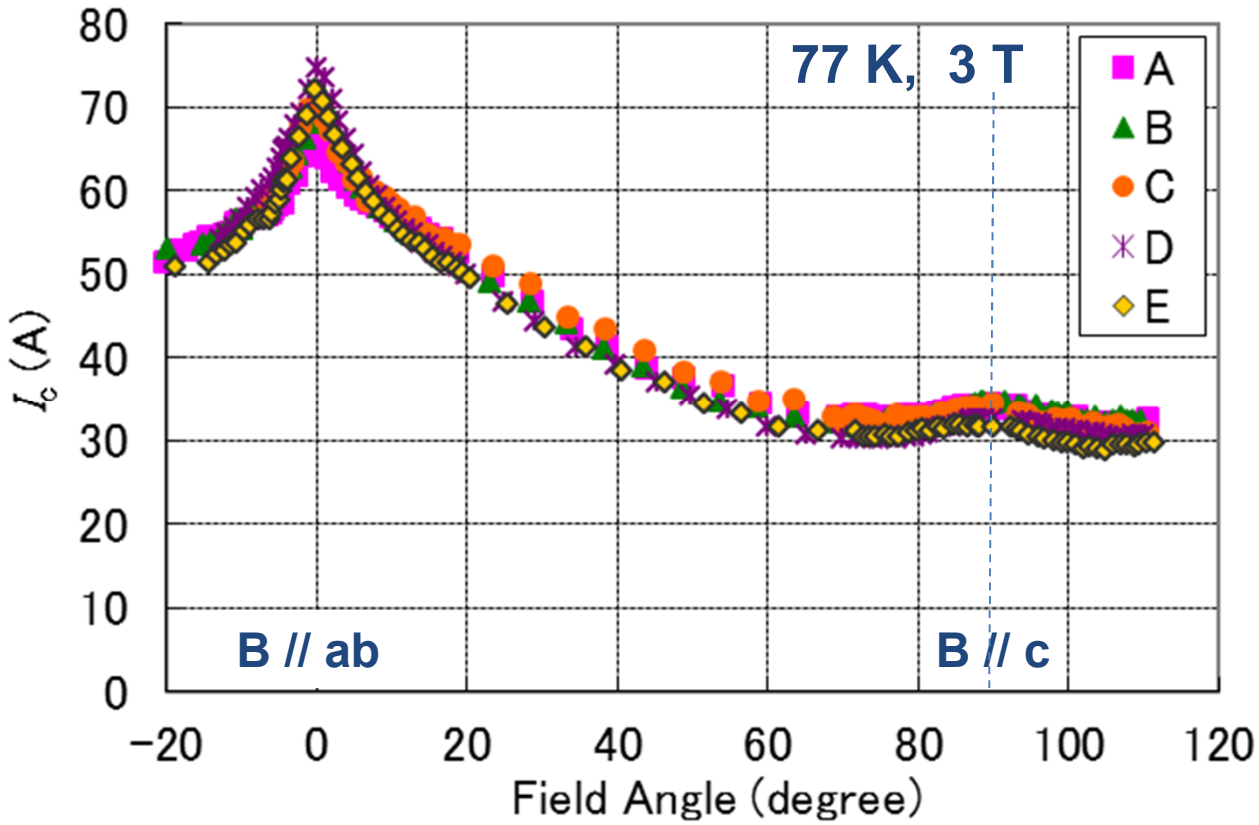
Uniform I_c >500 A(77K,s.f.) and in-field I_c in wide range of temperatures are observed

STDEV / average < 5.8%

Longitudinal I_c-θ characteristics at 77 K, 3T

Same samples shown in last page





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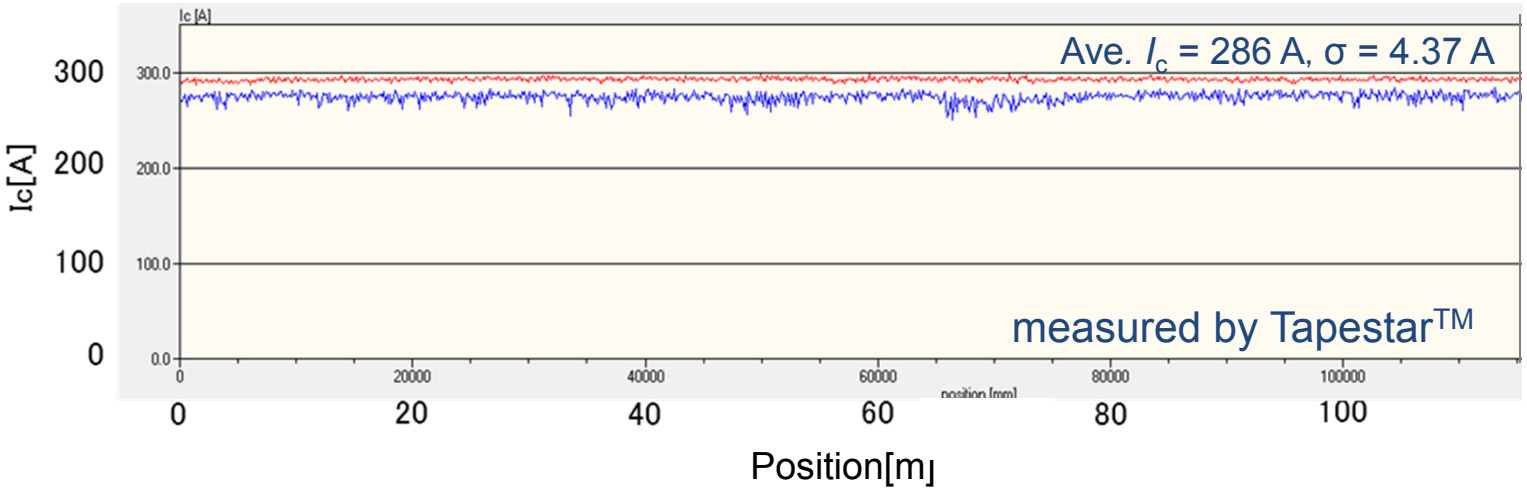
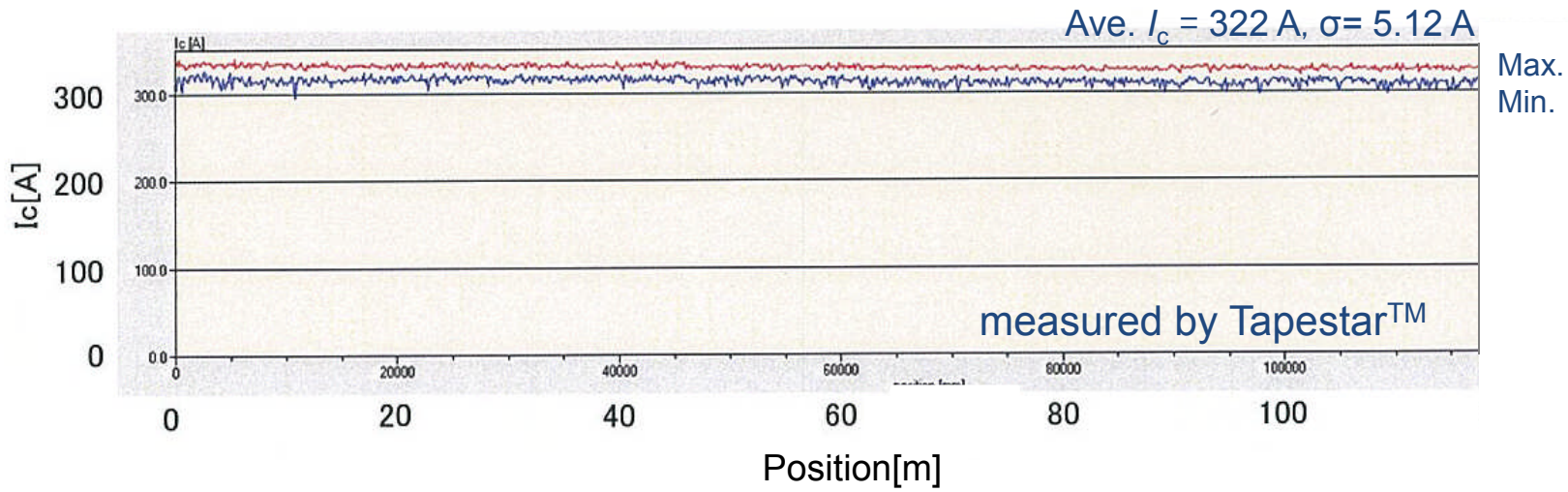
I_c distribution of typical c.c. for 25 T-CSM

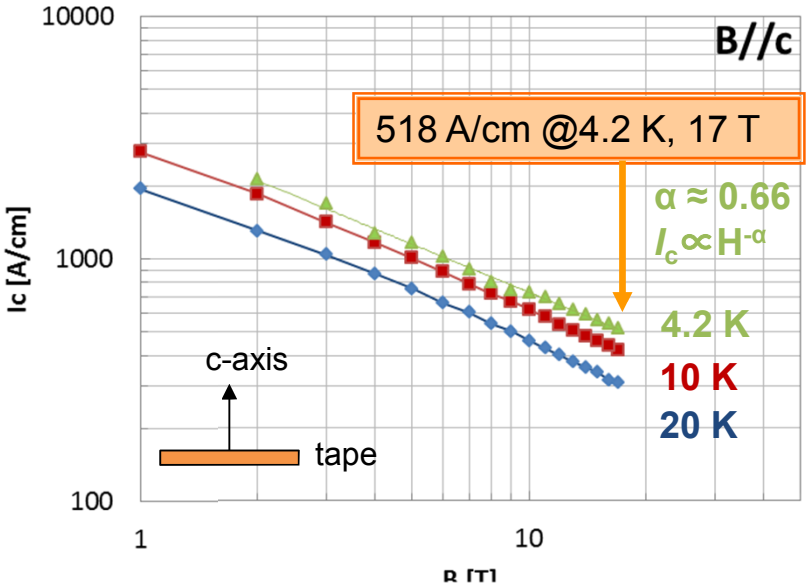


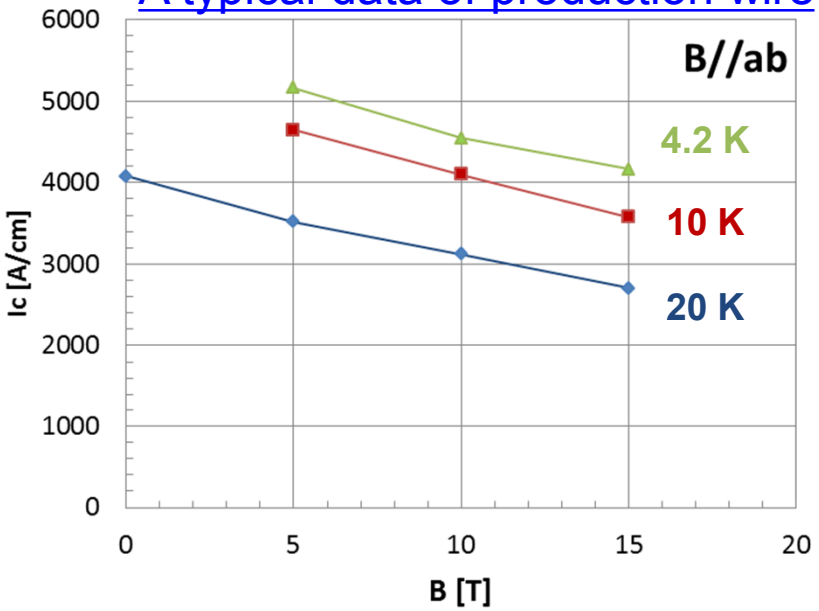


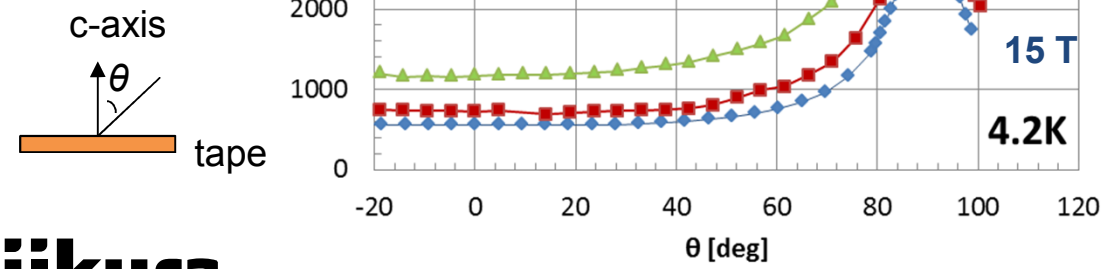
Standard deviation (σ) of 70 pieces of the mass-produced c.c.
→ Average (calculated) : 4.54 A

I_c-B-T, I_c-B-θ characteristics for high field magnet

A typical data of production wire





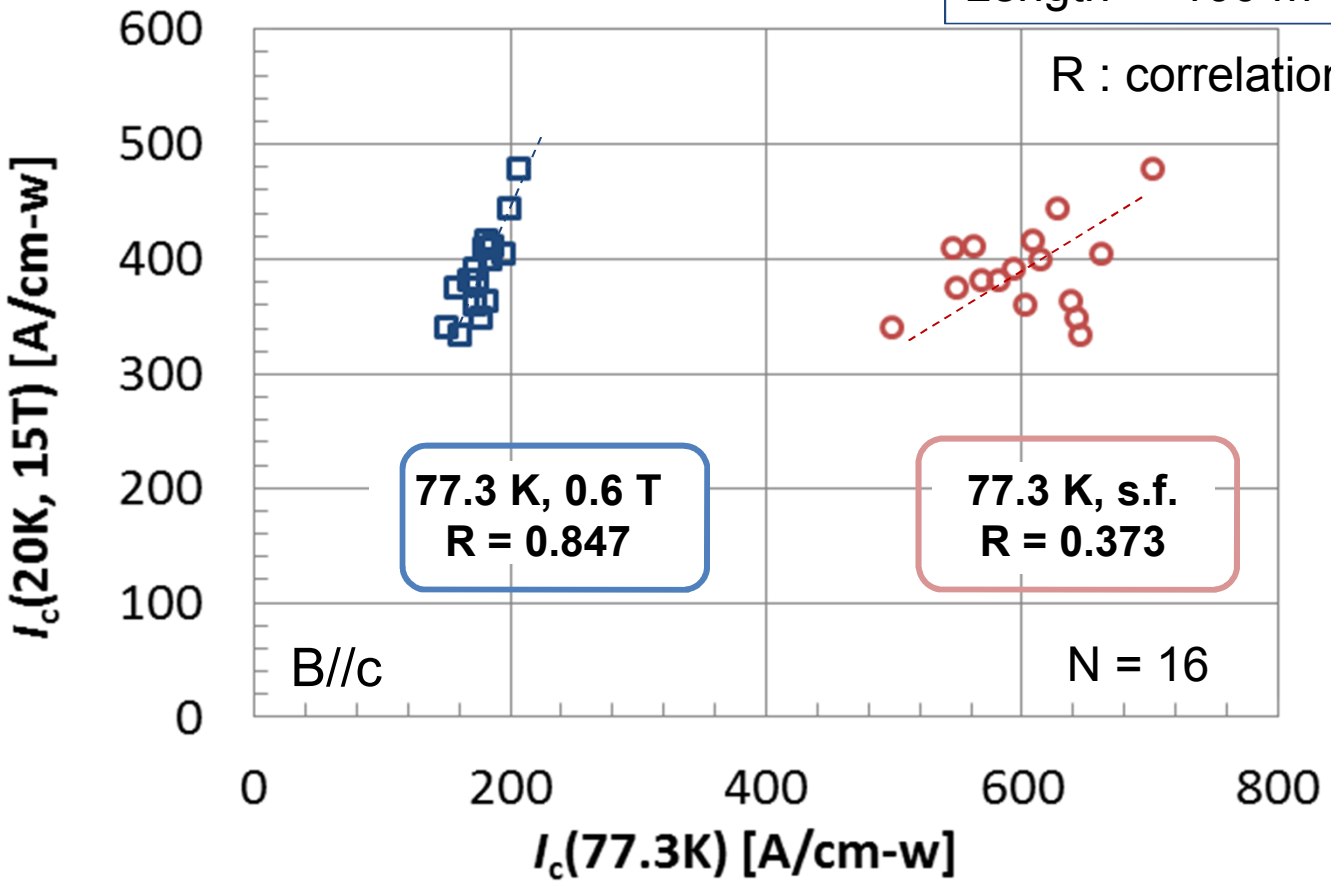


I_c = 498 A (77K, s.f.) (10 mm^w)

This work includes data measured at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

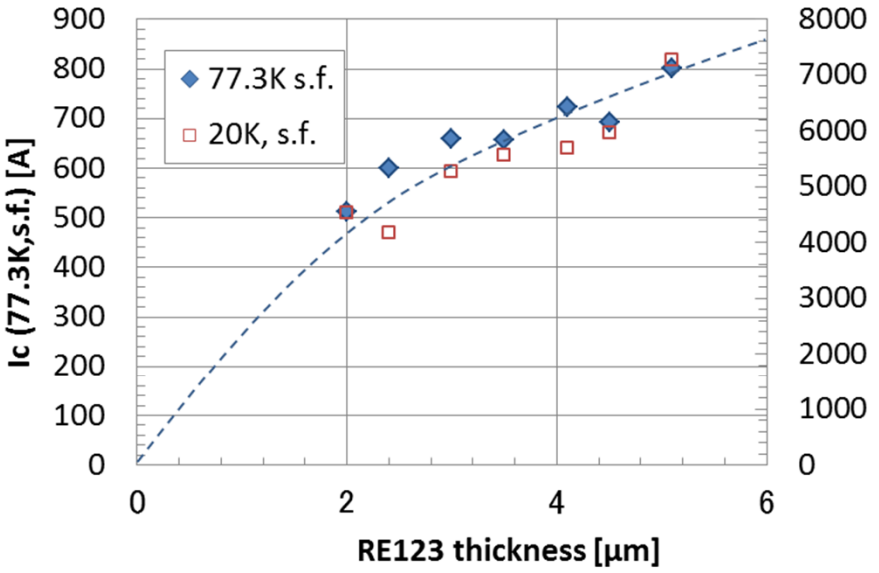
The correlation between I_c at 20 K and I_c at 77.3 K

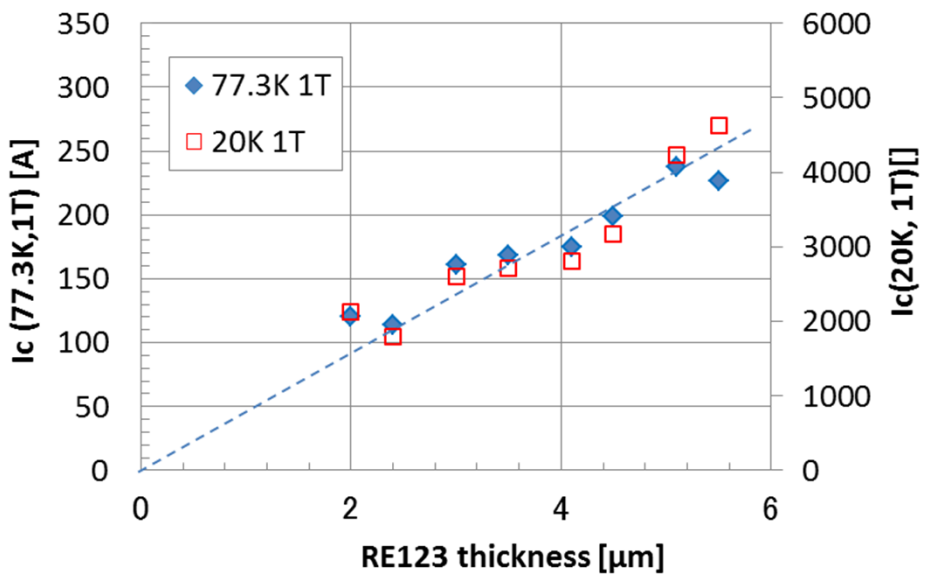
GdBCO layer : 1.9-3.5 μm
I_c(77 K, s.f.) 498-702 A
Length > 100 m



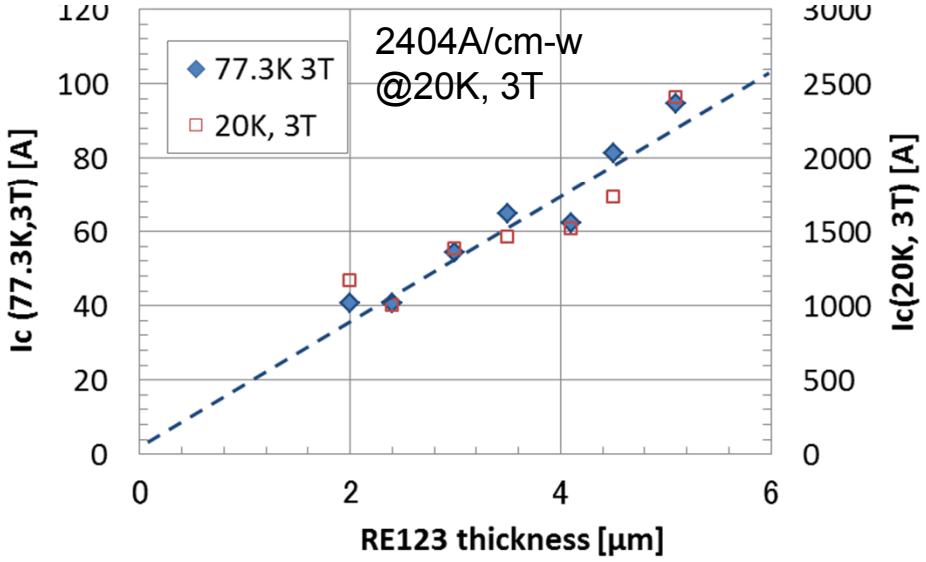
I_c (20 K, 15 T) have stronger correlation with I_c (77.3 K, 0.6 T) rather than I_c (77.3 K, s.f.)

Thickness dependence of I_c for self-field and in-field



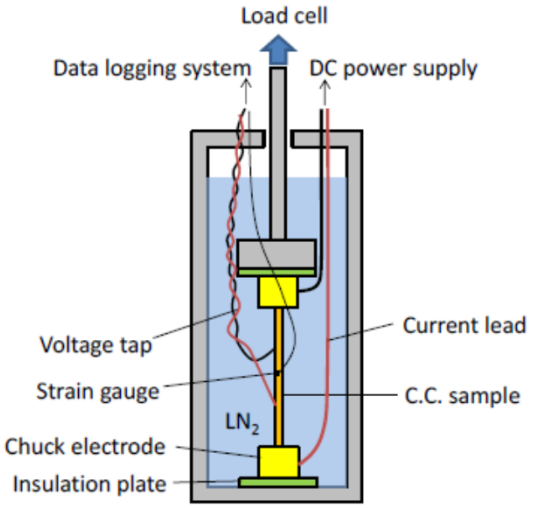


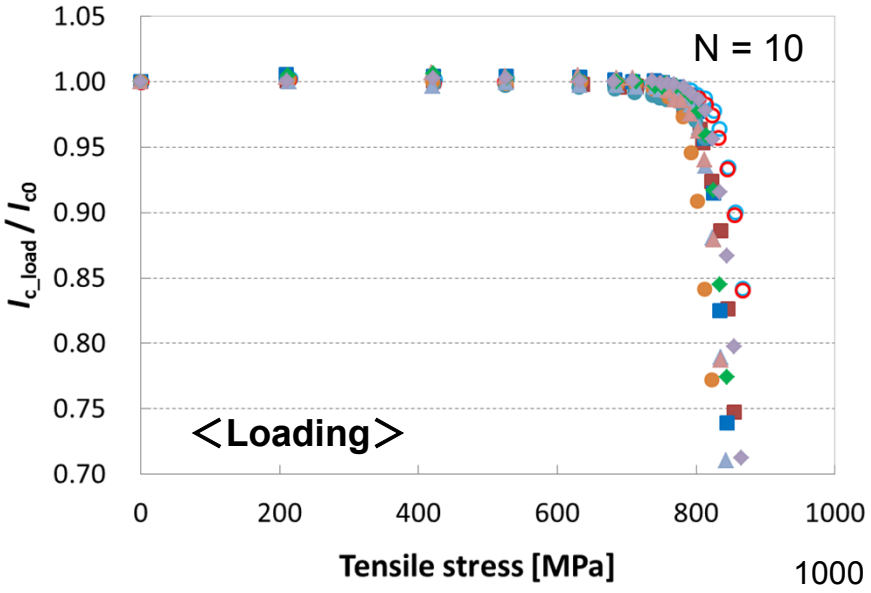
in-field I_c linearly increase with REBCO thickness in wide temperature range, where deviation observed in self-field

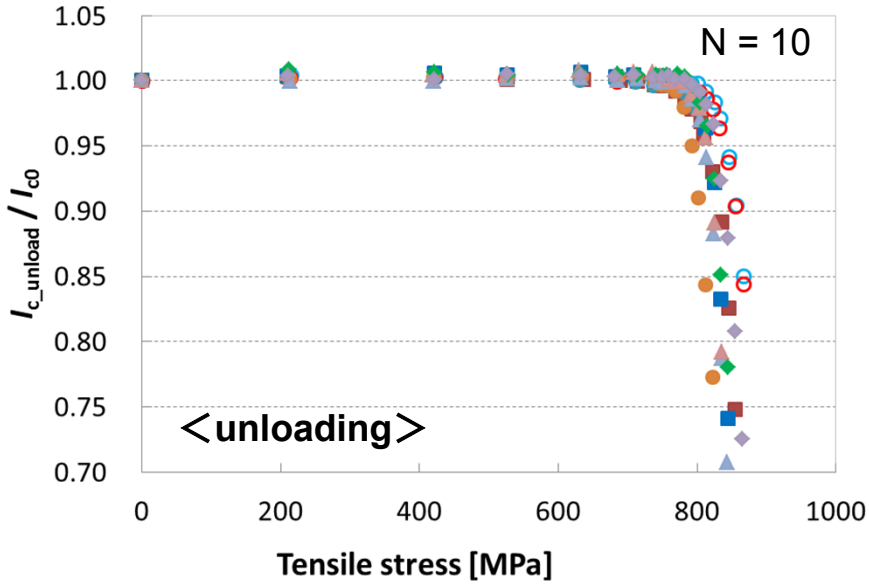


Typical tensile characteristics for the production c.c. at 77.3 K

- Sample : 5 mm-wide REBCO c.c.
- Grip distance : 160 mm
  Distance of voltage taps : 100 mm
- Procedure（in LN_2 ）
  1）Measure I_c before loading (I_{c0})
  2）Load tensile stress in LN_2 (tensile stroke ratio 4.8 mm/min)
  3）Measure I_c during loading (I_{c_load})
  4) Measure I_c after loading (I_{c_unload}) (unloading state)





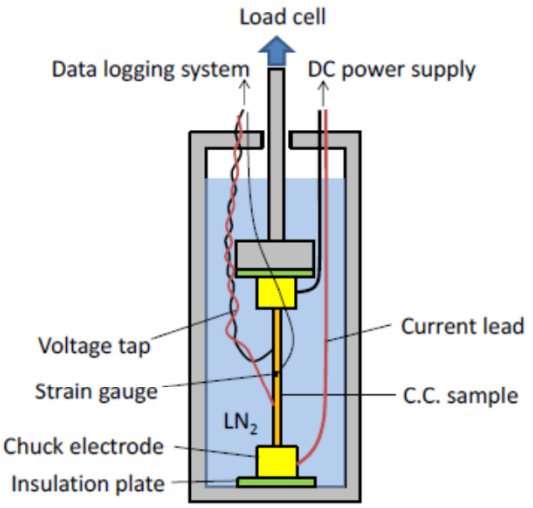


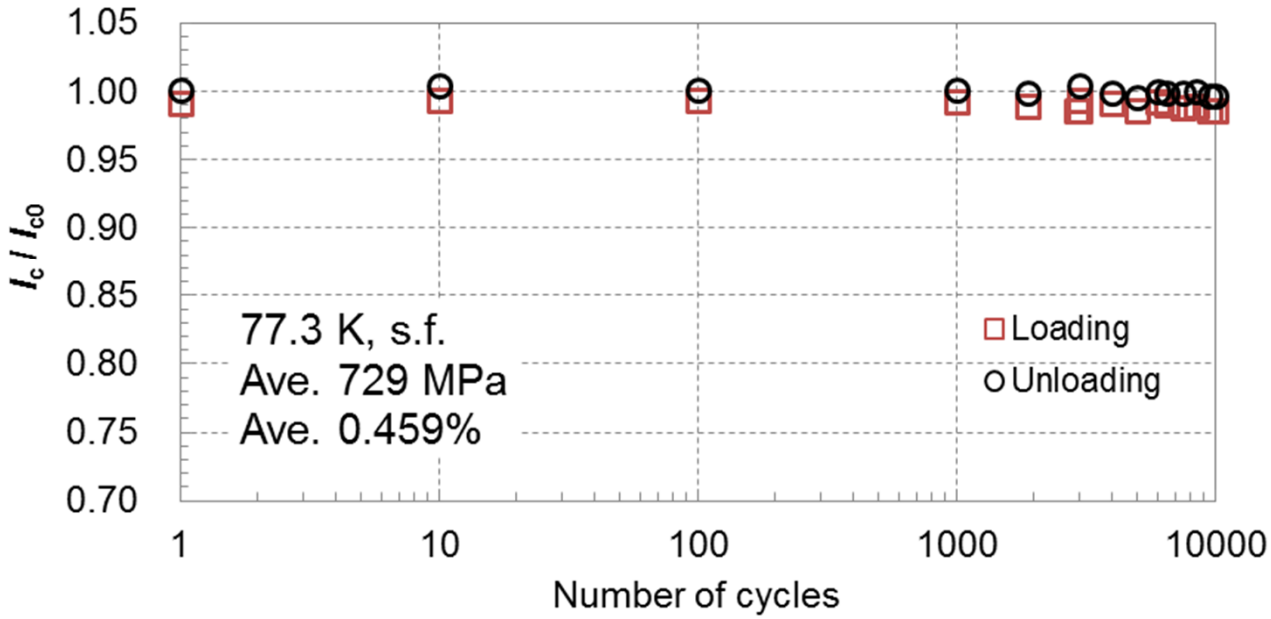
Ave. reversible tensile stress > 788 MPa, I_c/I_{c0} > 0.99 (N = 10)

Typical repeated tensile characteristics up to 10,000 cycles at 77.3 K

- Sample : 5 mm-wide REBCO c.c.
  (GdBCO layer 2.5 μm^t)

- Grip distance : 160 mm
  Distance of voltage taps : 100 mm





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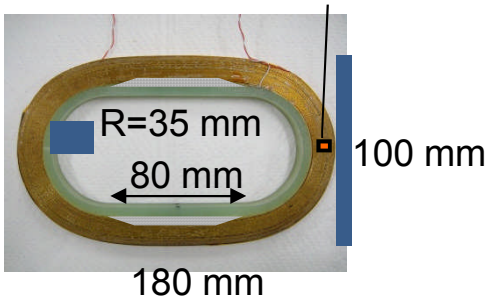
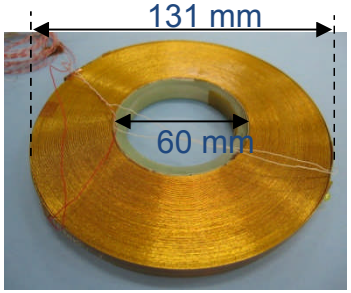
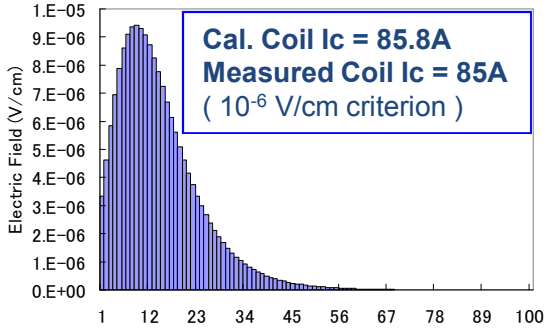
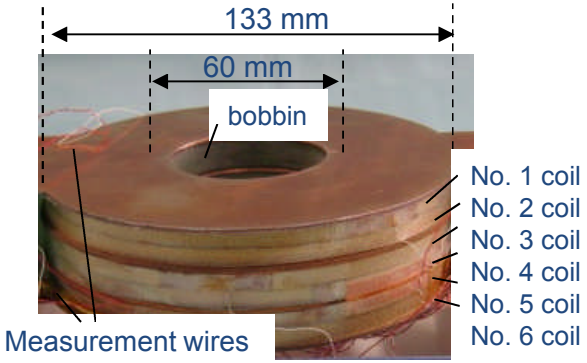
Development of REBCO impregnated coils

- Fujikura has developed several impregnated REBCO coils

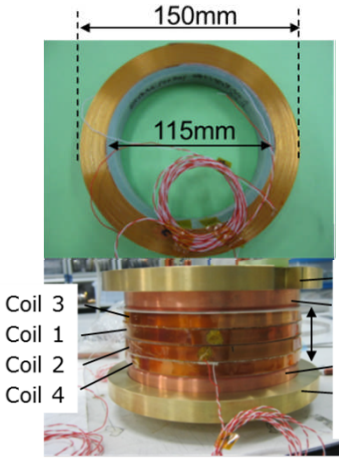


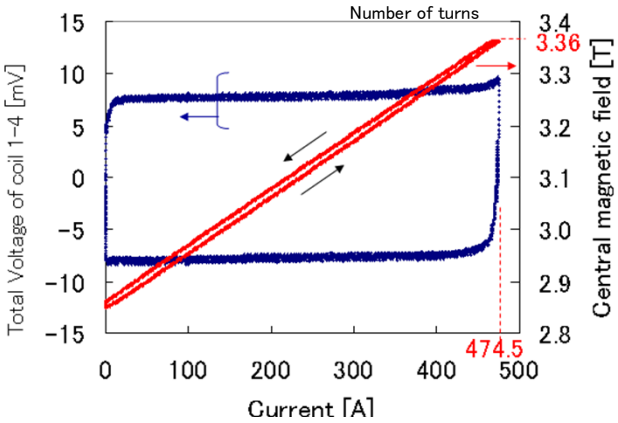






6-layer stacked coil using 200 m（600 turns）



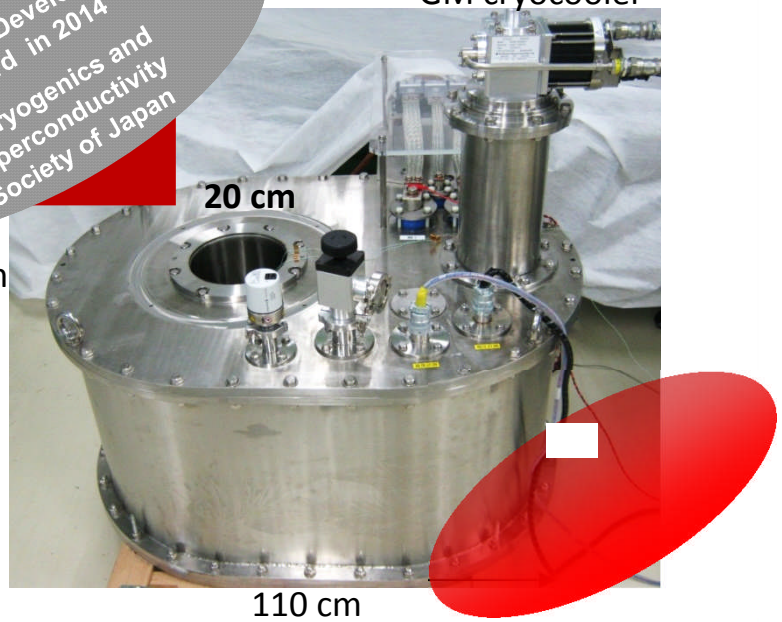


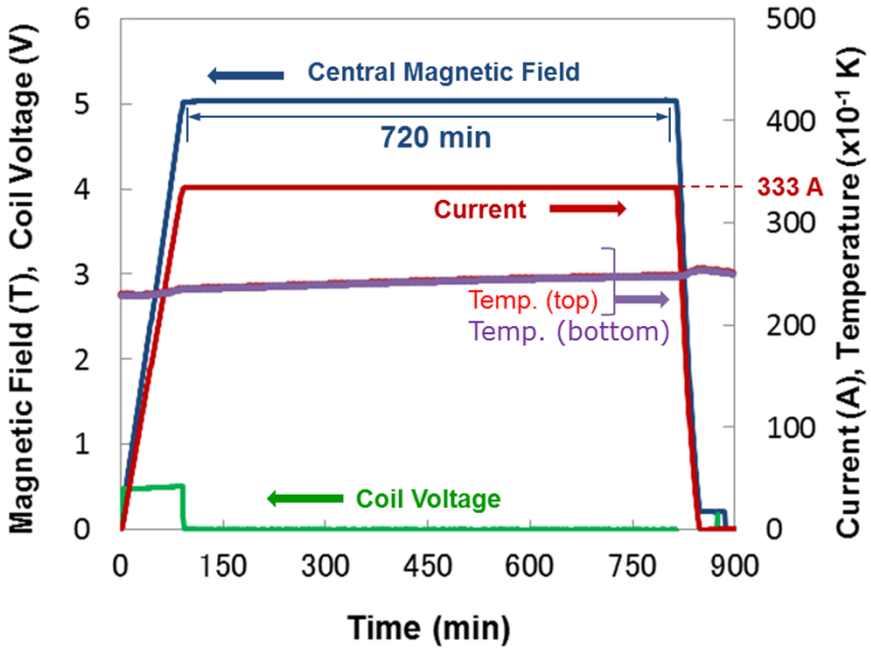
V-I characteristics in 2.85T back up field, at 20K

Development of 5 T REBCO magnet with 20 cm bore

- Fujikura's 10 mmw coated conductors
- Total tape length : 7.2 km (300 m x 24)
- Stored energy : 426 kJ
- Composed of 24 pancake coils
- Total number of turns : 5775
- Operating temperature : 25 K

Technical Development Award in 2014 of Cryogenics and Superconductivity Society of Japan





Fujikura Ltd. successfully developed a 5 T REBCO cryocooled magnet in 2012.

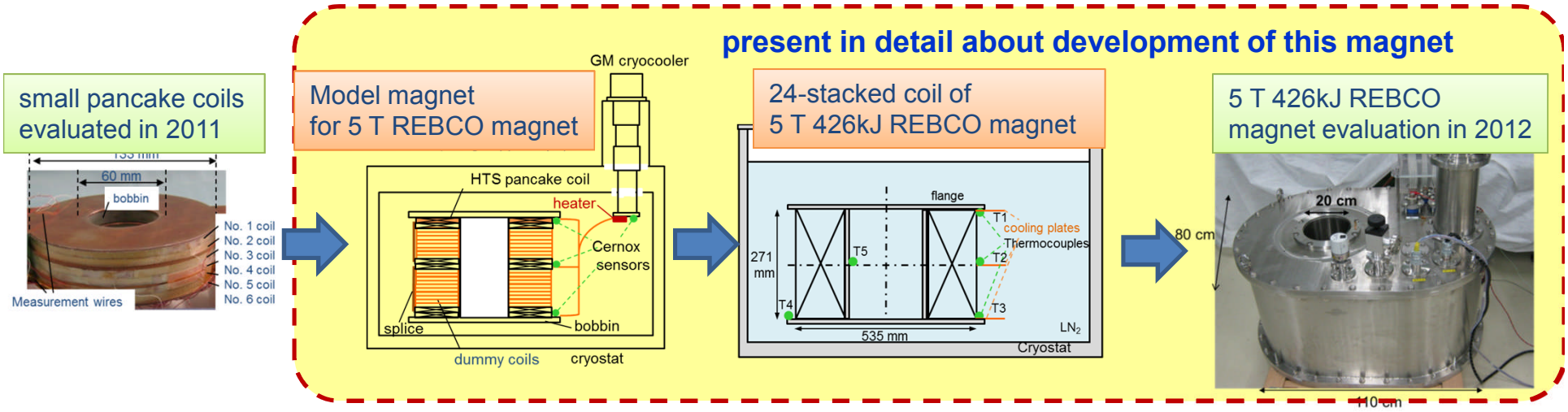
The magnet can be excited up to 5 T for 720 min after 2nd cooling

M. Daibo, et al., IEEE Trans. Appl. Supercond. 23-3 (2013) 4602004

Fujikura

Development process of 5 T 426 kJ REBCO magnet

- Fabricated a model magnet with dummy coils before the fabrication of the 5 T 426 kJ REBCO magnet
- Evaluated a model magnet with dummy coils including thermal runaway test under conduction-cooled conditions
- Fabricated the 24-stacked coil of 5 T 426 kJ REBCO magnet and evaluated the 24-stacked coil in LN_2
- In 2012, Fujikura Ltd. successfully developed a 5 T 426 kJ REBCO magnet with a 20-cm-diam. room temperature bore



Specifications of 5 T 426 kJ REBCO magnet

Parameters	Values
Inner diameter of coil	260 mm
Outer diameter of coil	535 mm
Coil height	271 mm
Number of pancake coils	24
Total tape length	7.2 km (300m x 24)
Total number of turns	5775
Operating temperature	25 K
Operating current	333 A
Central magnetic field	5.0 T
Inductance	7.68 H
Stored energy	426 kJ

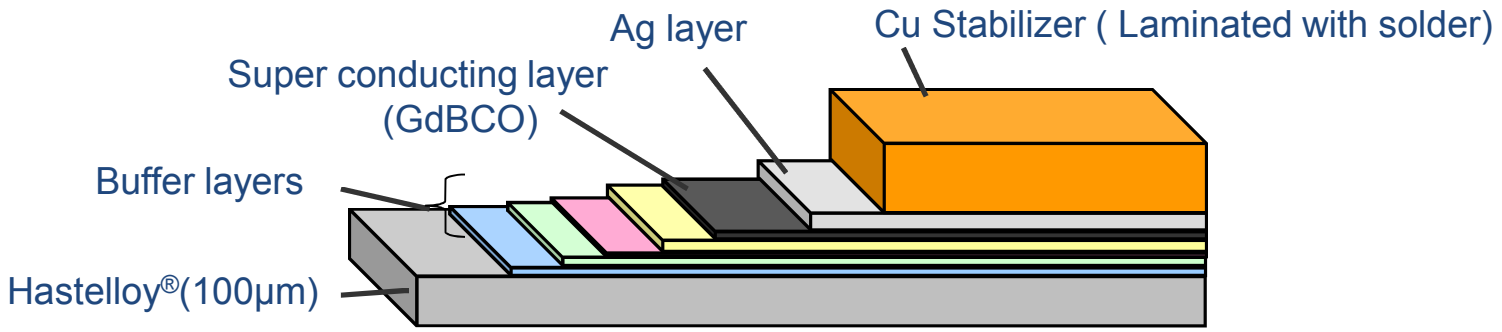
Specifications of a model magnet for 5 T REBCO magnet

Parameters	values
Inner diameter of coil	260 mm (same)
Outer diameter of coil	515 mm (535)
Coil height	271 mm (same)
Total number of pancake coils	24
- Number of REBCO pancake coils	6
- Number of "dummy coils" (pancake coils)	18
Total REBCO tape length	1646 m
Total number of turns of REBCO coils	1350
Operating temperature	41 - 77 K

"dummy coils" : epoxy-impregnated pancake coils using the same dimension copper tapes of REBCO c.c.

Specifications of REBCO c.c. of the model magnet

Parameters	values
Width of coated conductors	10 mm
Thickness of Substrate	0.1 mm
Superconducting layer	GdBCO
Thickness of Cu stabilizer	0.3 mm
Critical current (I_c) (77 K, s.f.) (10^{-7} V/cm criterion)	350 - 426A



Stabilizer thickness for protection of 426kJ REBCO magnet

The heat balance equations (under adiabatic conditions)

$$S_t C_t(T)\frac{\partial T}{\partial t} = S_{stab}\rho_{stab}(T)\cdot J_{stab}(t)^2$$

$$\int_{T_0}^{T_m}\frac{C_t(T)}{\rho_{stab}(T)}dT = \frac{S_{stab}}{S_t}\left(t_d + \frac{E}{V_m I_0}\right)J^2{}_{stab,0}$$

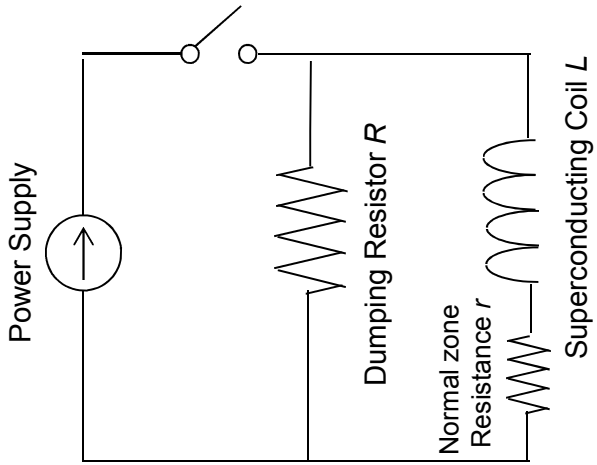


Fig. Protection circuit representing a quenching coil

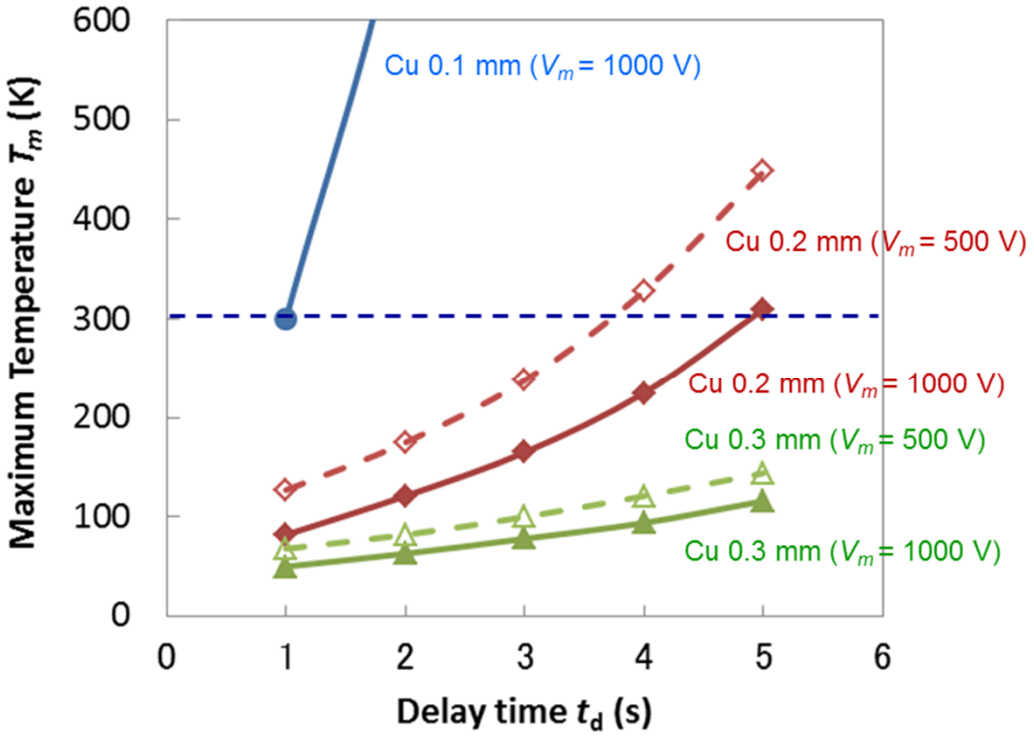
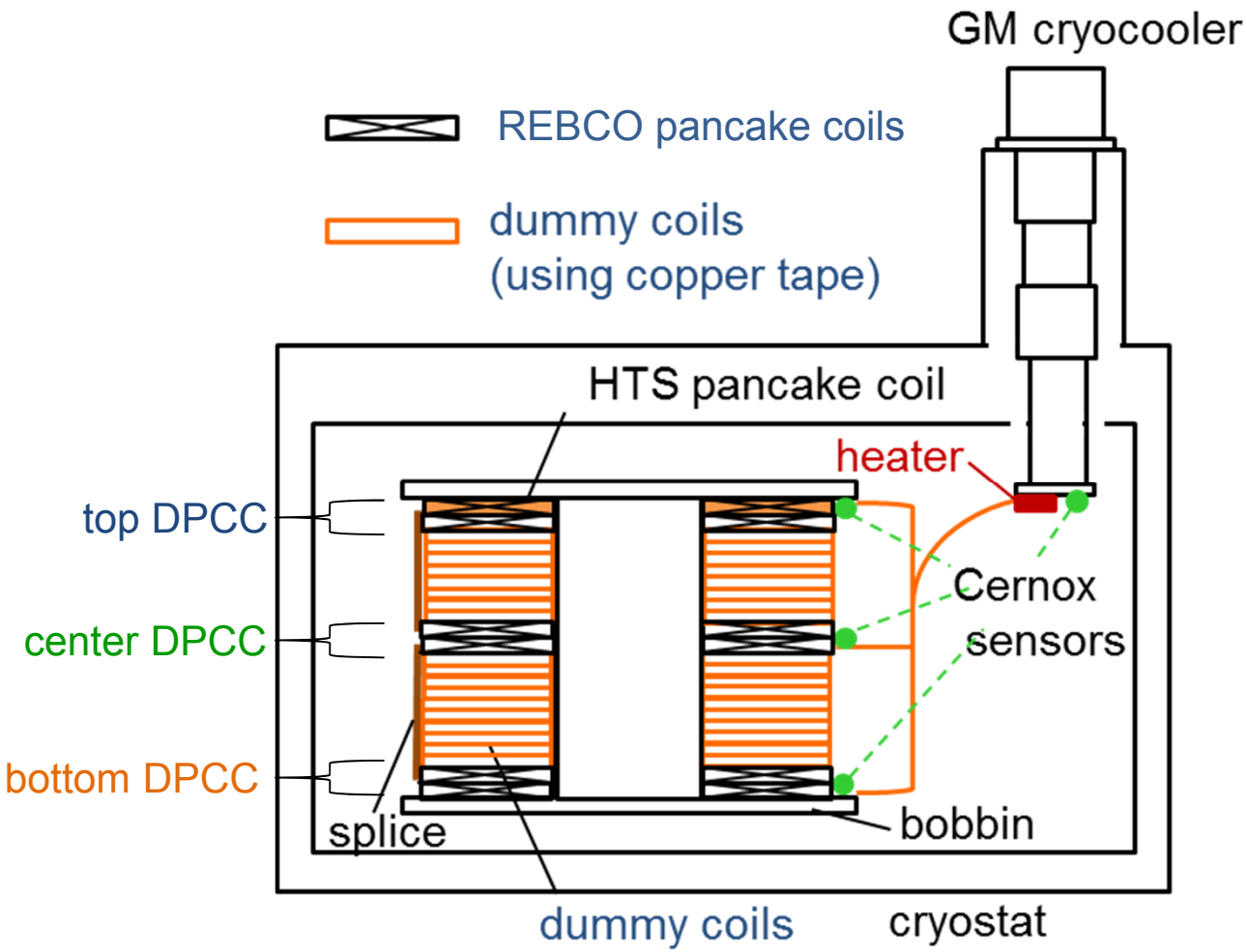


Fig. Calc. results of max. temperature after quenching as a function of delay time for Cu thickness : V_m = 1000 V (solid) and V_m = 500 V (dotted) (T_0 = 25 K, I_0 = 333 A, E = 426 kJ)

M. Daibo et al., IEEE Trans. Appl. Supercond. 23 (2013) 4602004.

Schematic of the model magnet

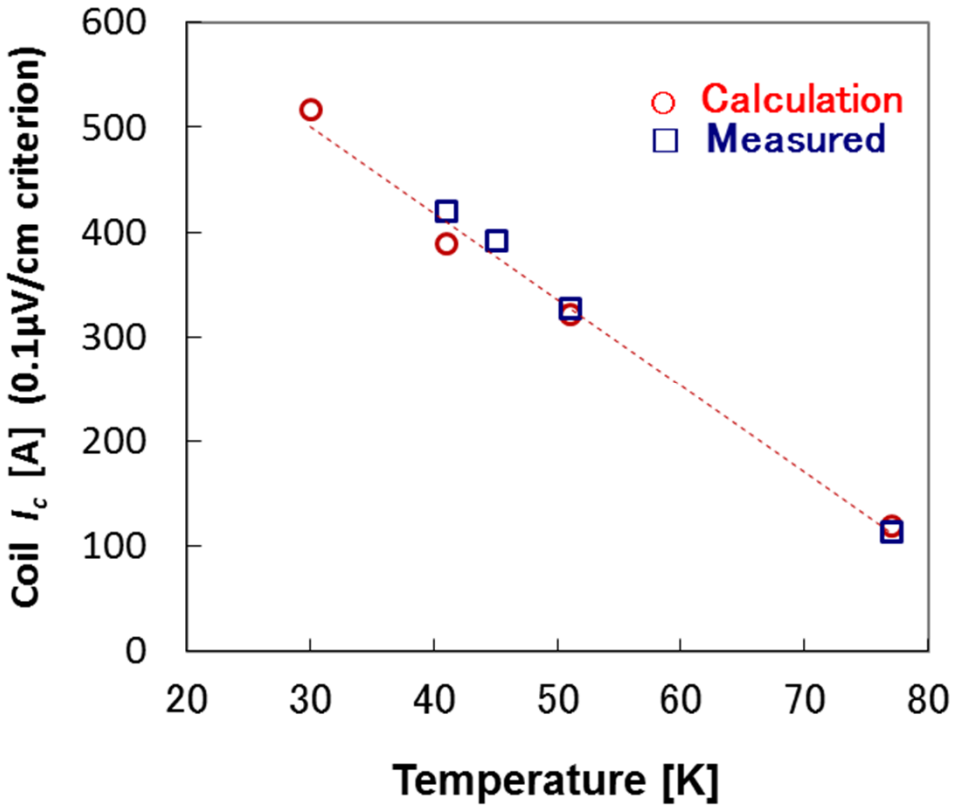


compared calculated and measured coil I_c of the top single pancake coil

Comparison of coil I_c of the top single pancake coil of the model magnet

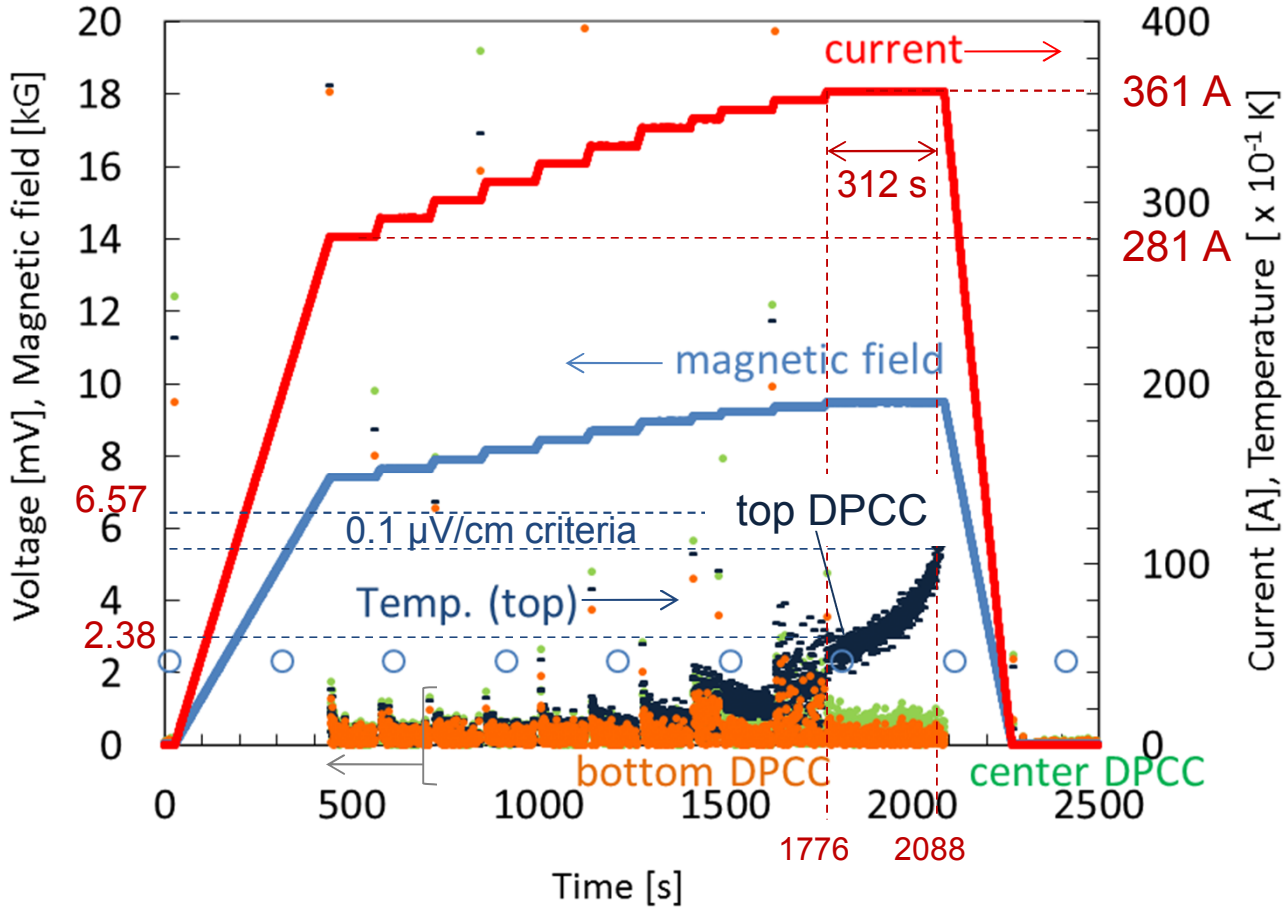
$$V = \sum 2\pi r \times 10^{-6} \left(\frac{I}{I_c(B,T,\theta)} \right)^{n(B,T,\theta)}$$

in the calc., I_c-B-θ characteristics of c.c. are obtained from the fit of the experimental results of short sample



the difference between calculated approximate expression and measured coil I_c at 30 - 77 K : **within 5%**

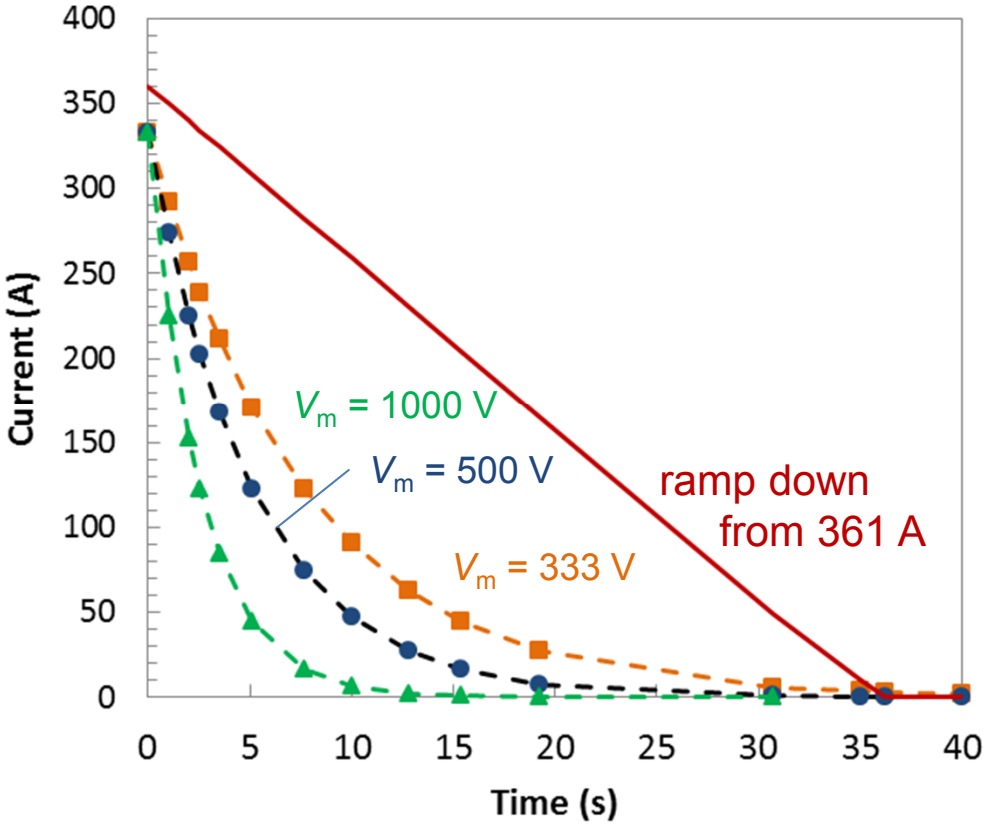
Thermal runaway test of model magnet at 46 K



I_t = 361 A at 1776 s : a slight increase of voltage of top DPCC is observed

After maintaining for 312 s, I_t is ramped down at 1.66 A/s ramp rate

Comparison of the ramped down current of the model coil and predicted current decay profiles of the 5 T 426 kJ REBCO magnet



the calculated current decay profiles of
5 T 426 kJ REBCO magnet
with a dump resistor

V_m = 1000 V : τ= 2.56 s

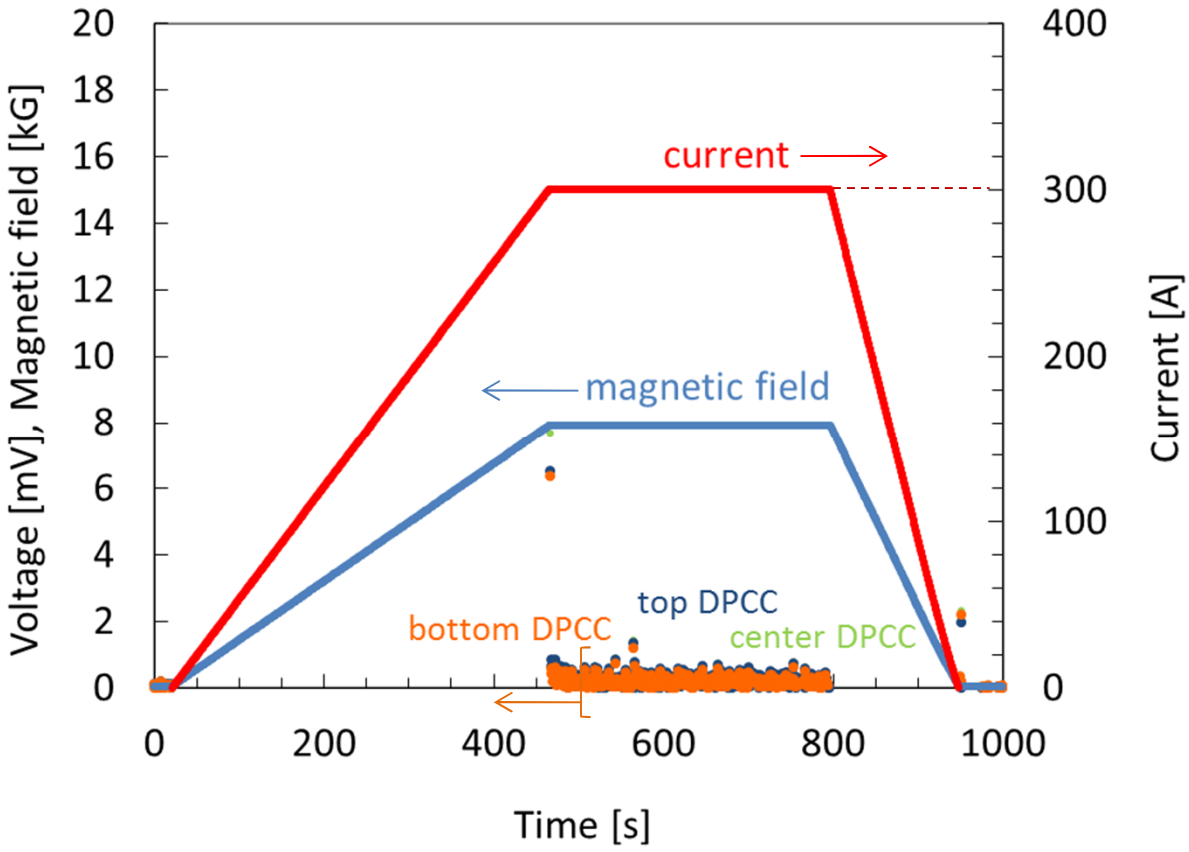
V_m = 500 V : τ= 5.12 s

V_m = 333 V : τ= 7.68 s

Shut down occurs at t=0.

Thermal runaway test was conducted
under stringent conditions of 5 T 426 kJ REBCO magnet

Excitation test results after thermal runaway test



Model magnet with a 0.3-mm-thick copper stabilizer was excited up to 300 A without degradation at 46 K after thermal runaway test

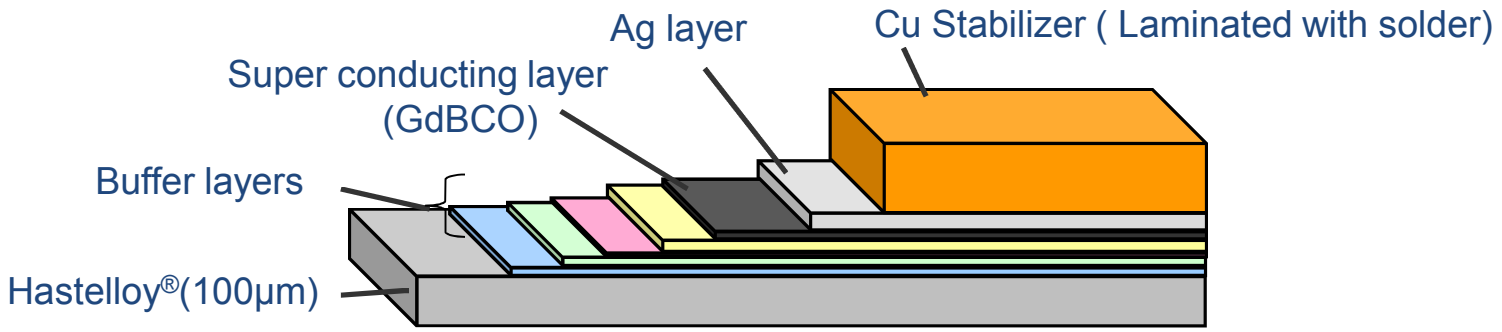
started to fabricate 5 T 426 kJ REBCO magnet in 2012

Specifications of 5 T 426 kJ REBCO magnet

Parameters	Values
Inner diameter of coil	260 mm
Outer diameter of coil	535 mm
Coil height	271 mm
Number of pancake coils	24
Total tape length	7.2 km (300m x 24)
Total number of turns	5775
Operating temperature	25 K
Operating current	333 A
Central magnetic field	5.0 T
Inductance	7.68 H
Stored energy	426 kJ

Specifications of REBCO c.c. of 5 T 426 kJ REBCO magnet

Parameters	values
Width of REBCO coated conductors	10 mm
Thickness of Substrate	0.1 mm
Superconducting layer	GdBCO
Thickness of Cu stabilizer	0.3 mm
Critical current (I_c) (77 K, s.f.) (10^{-7} V/cm criterion)	> 467 A
n-value (77 K, s.f.) (range from 10^{-8} to10^{-7} V/cm)	24～38



Calculated coil I_c of 5 T 426 kJ REBCO magnet at 25 - 77 K

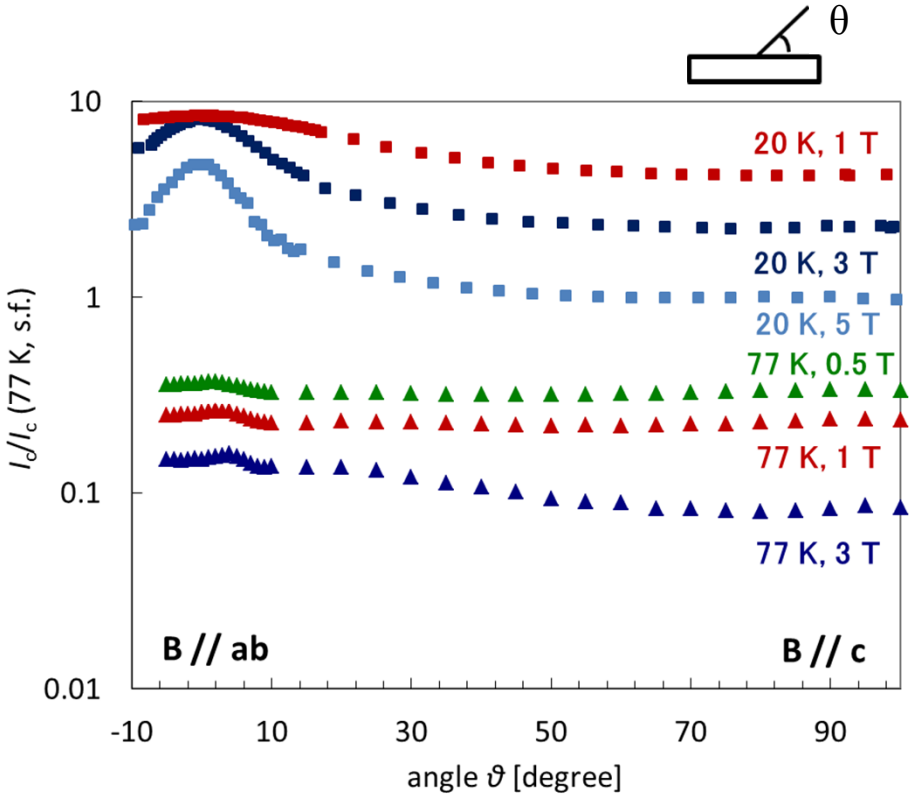
Measured I_c-B-θ characteristics

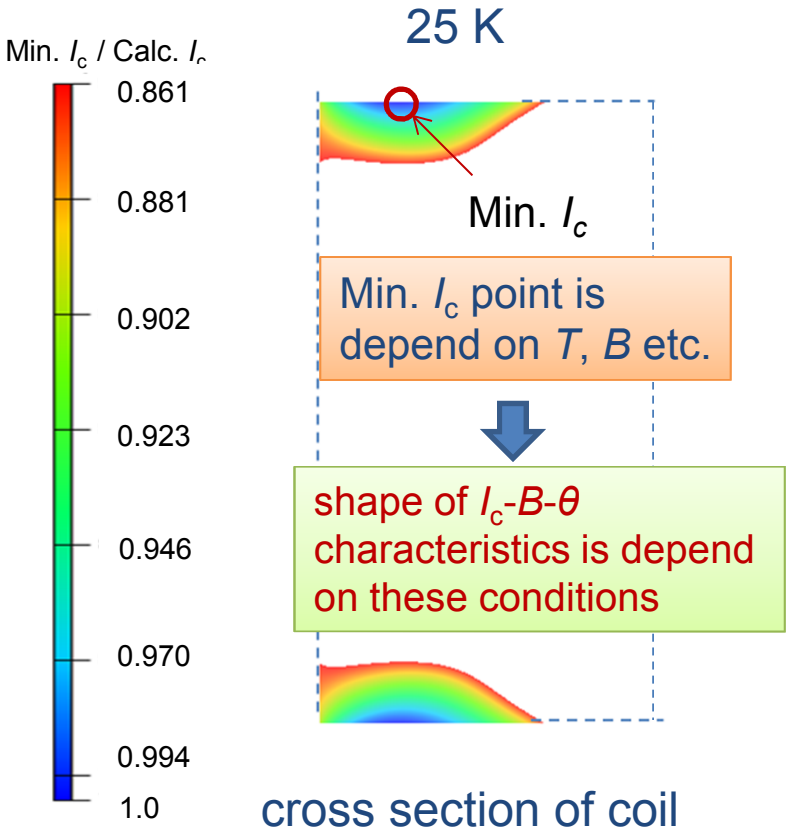
Calculated magnetic field of coil

→ Calculated coil I_c at 25 - 77 K

$$V = \sum 2\pi r \times 10^{-6} \left(\frac{I_t}{I_c(B,T,\theta)} \right)^{n(B,T,\theta)}$$

I_t : transport current (A)
r : radius
V : voltage
B : magnetic field
T : temperature

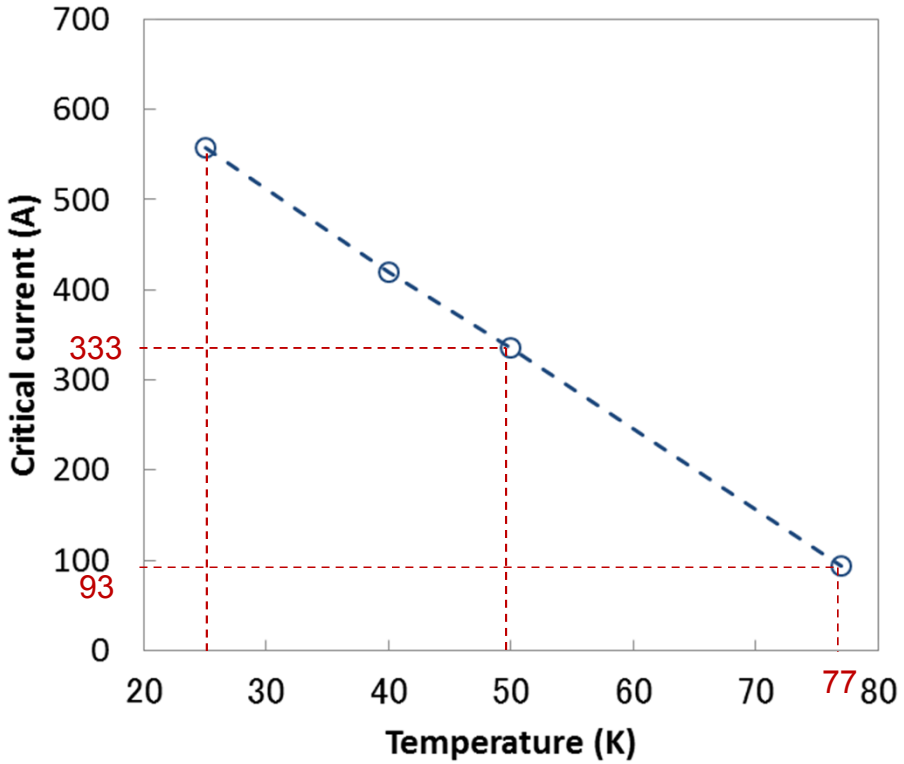




cross section of coil

Calculated coil I_c of 5 T 426 kJ REBCO magnet at 25 - 77 K

Calculated coil I_c at each temperature



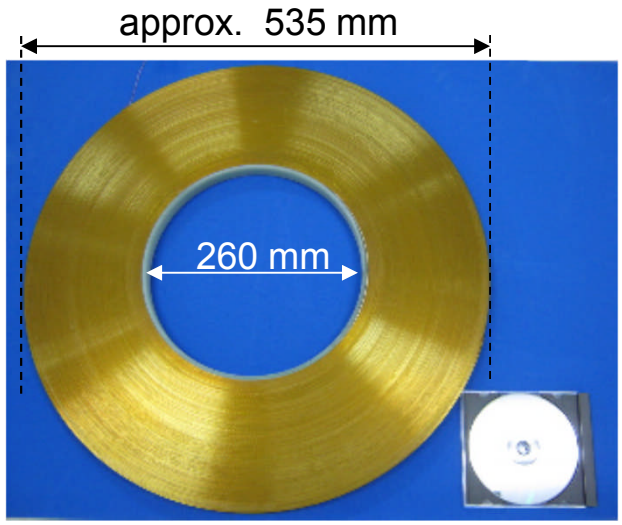
designed load factor at 25 K ≒ 0.6
calculated temperature margin ≒ 25 K

calculated coil I_c at 77 K = 93 A

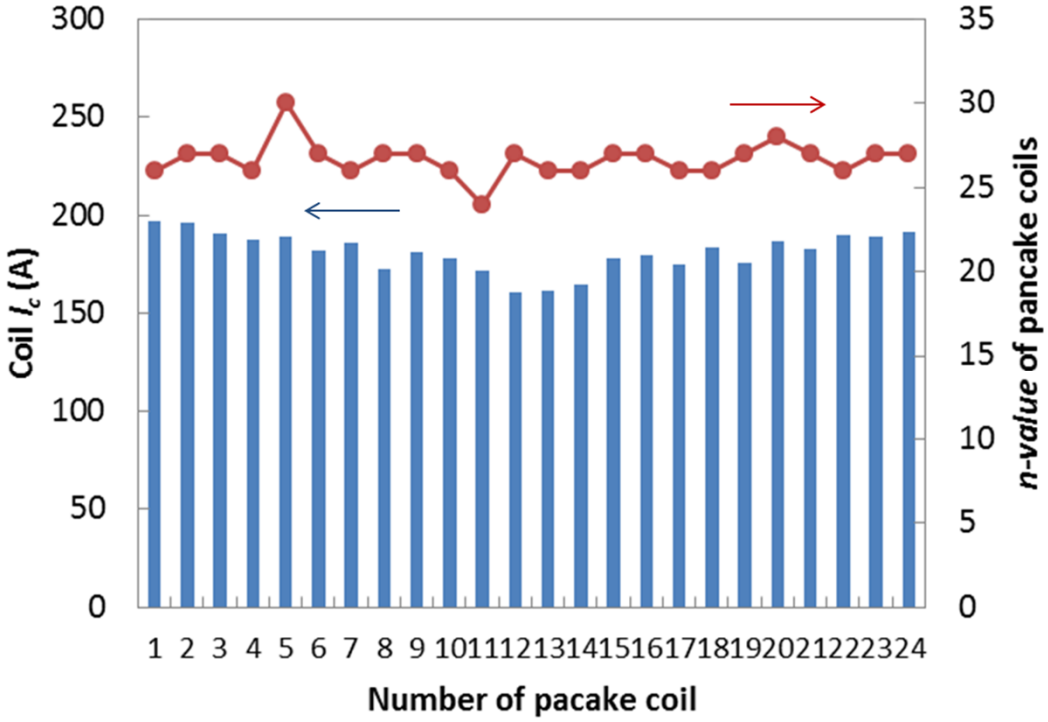
V-I characteristics of impregnated pancake coil

Fabricated and evaluated an impregnated pancake coil in LN_2

n-values of all pancake coils > 24 ➡ **No degradation**



Compact Disc

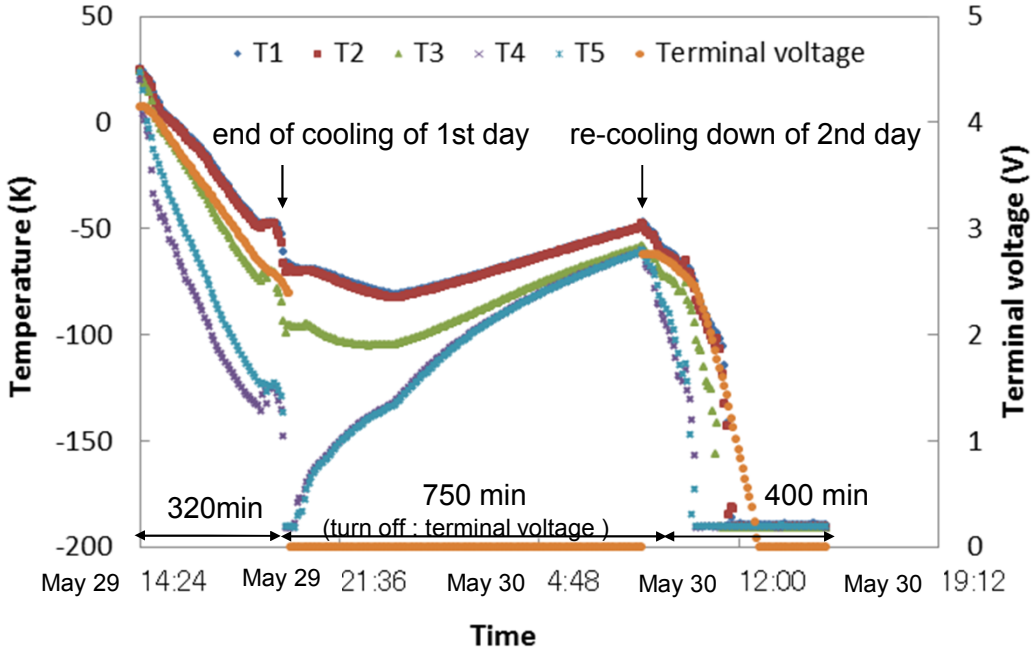


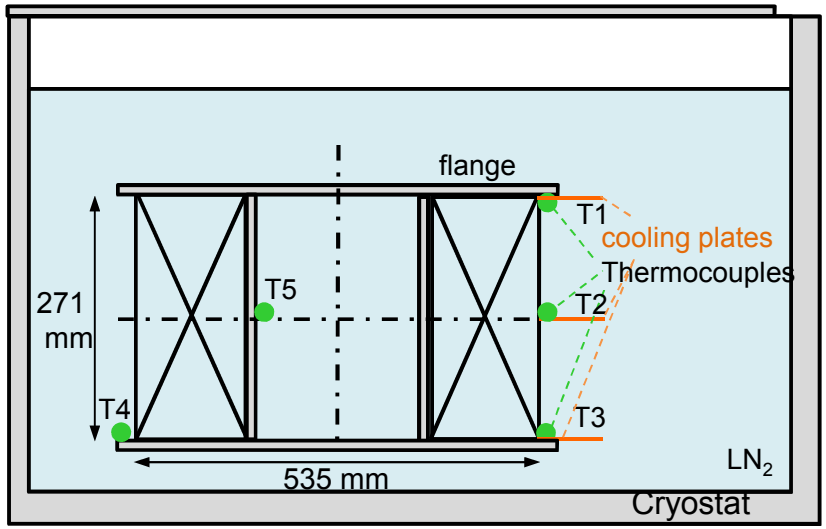
n-value : range from 10^{-8} to10^{-7} V/cm

I_c : 10^{-7} V/cm criterion

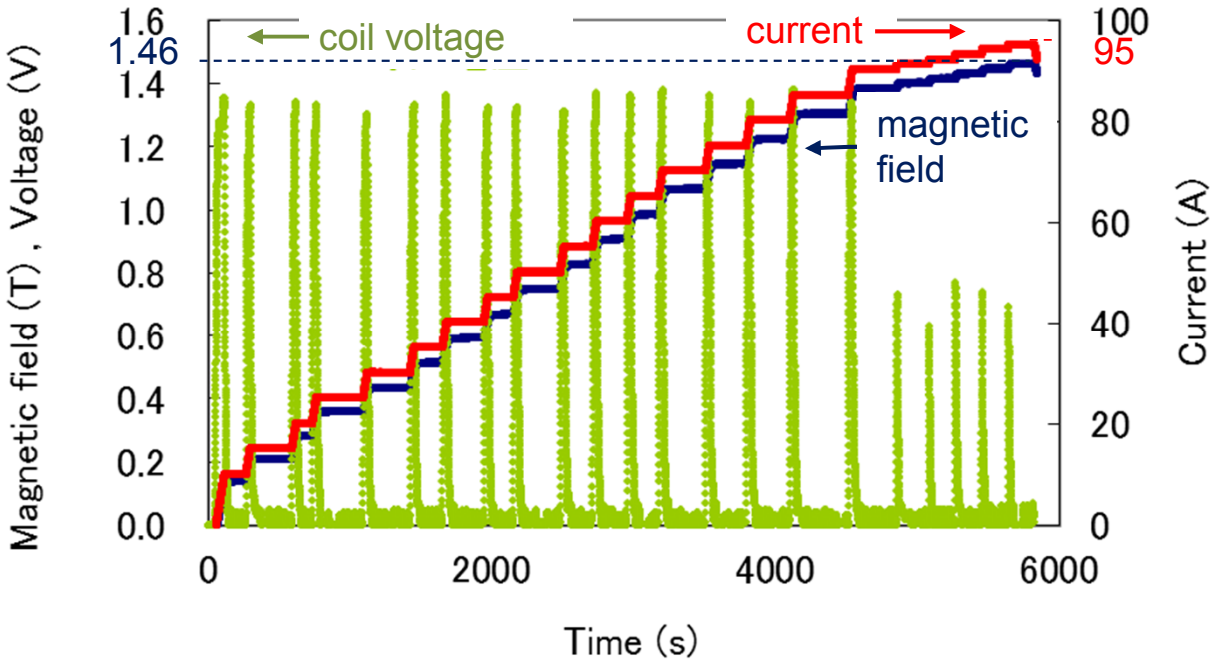
Cool down to 77 K of the 24-stacked coil

The 24-stacked coil was carefully cooled down for 1470 min with gas and liquid nitrogen after the fabrication





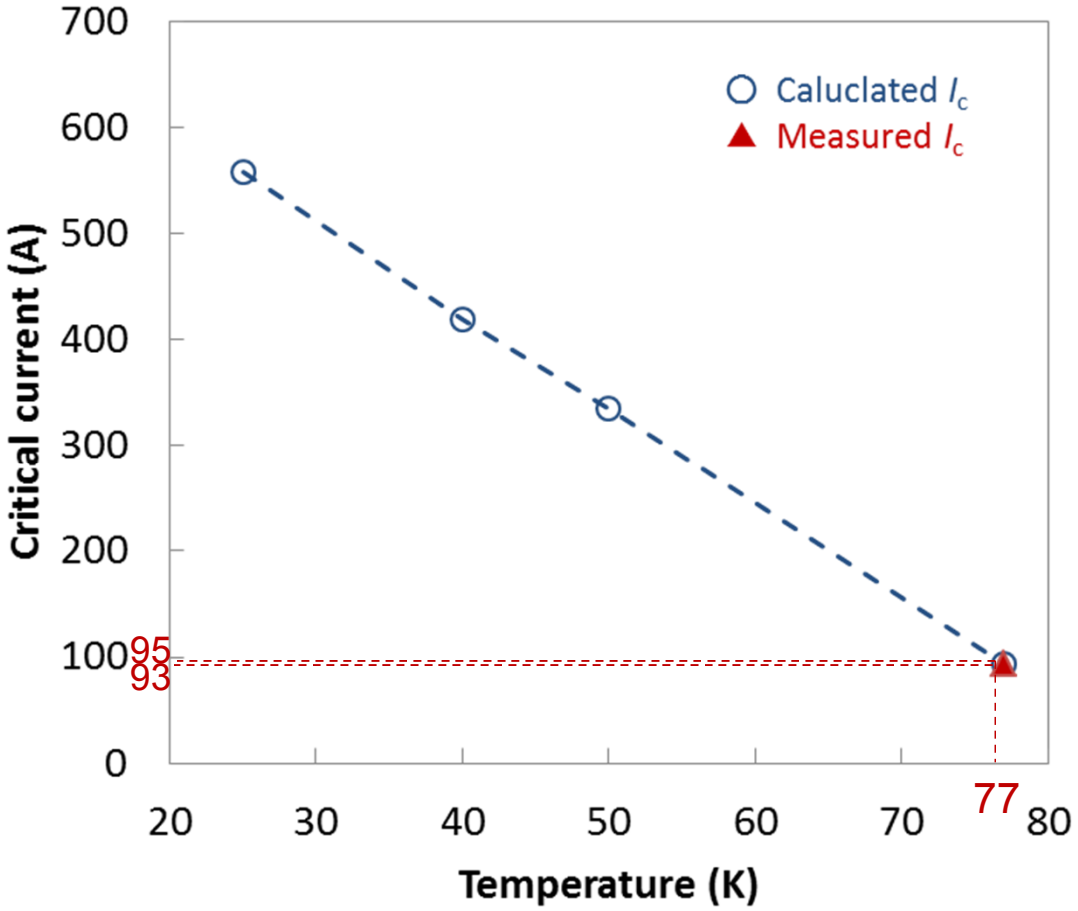
Measurement result of 24-stacked coil I_c in LN_2



Magnetic field of the 24-stacked coil was measured 1.46 T when the coil I_c reached at 95 A

24-stacked coil was successfully excited up without degradation

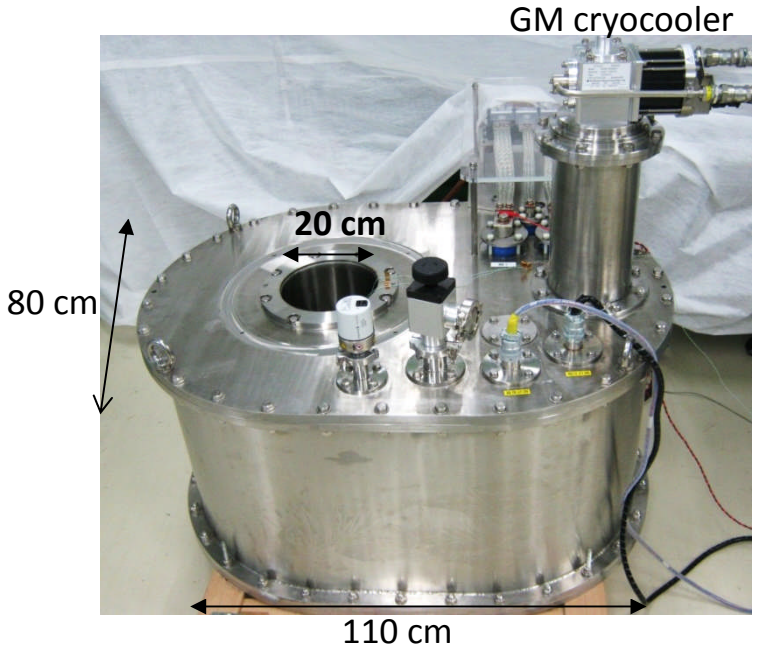
Comparison of calculated and measured coil I_c at 77 K

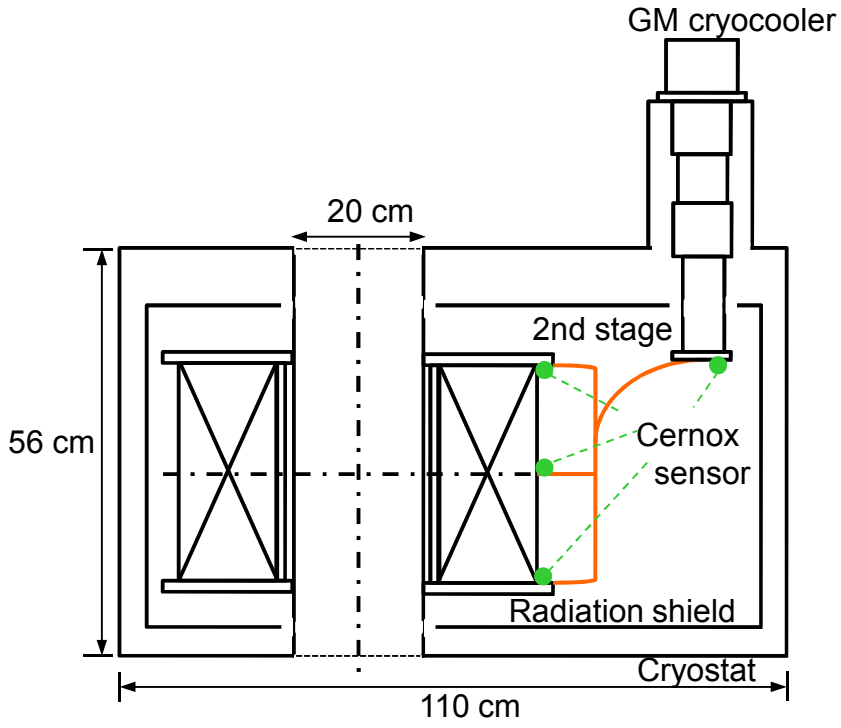


difference between calculated and measured coil I_c at 77 K : 2%
calculated coil I_c was in good agreement with measured I_c at 77 K

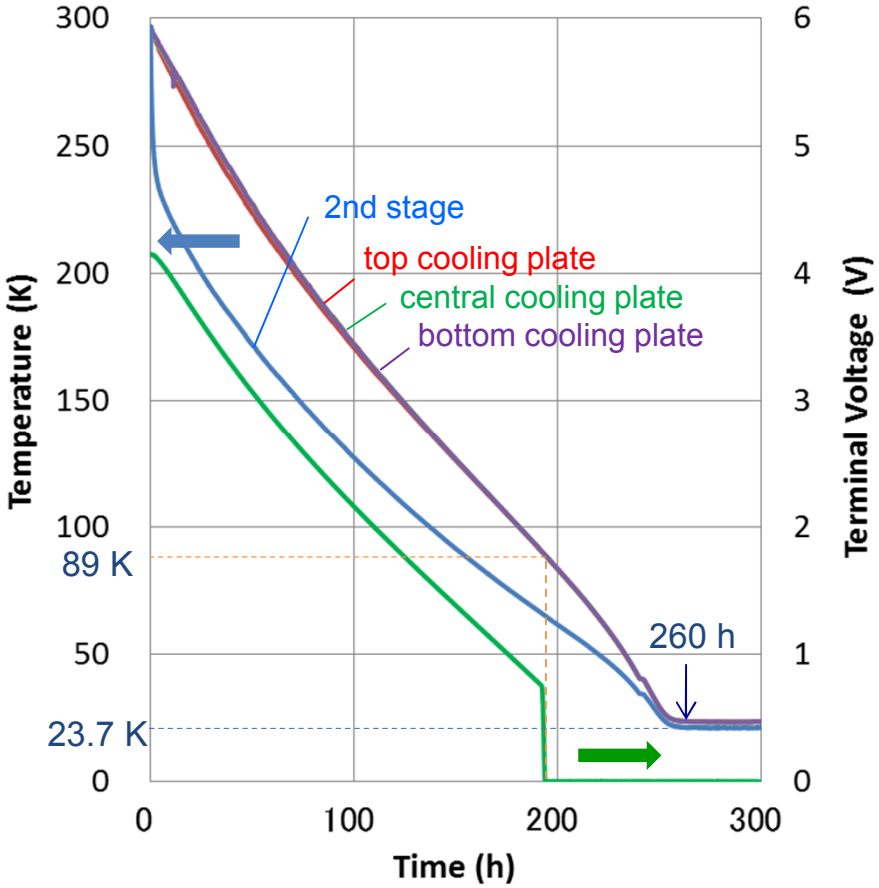
Schematic of 5 T 426 kJ REBCO magnet

5 T 426 kJ REBCO magnet was fabricated
after the evaluation of the 24-stacked coil in LN_2

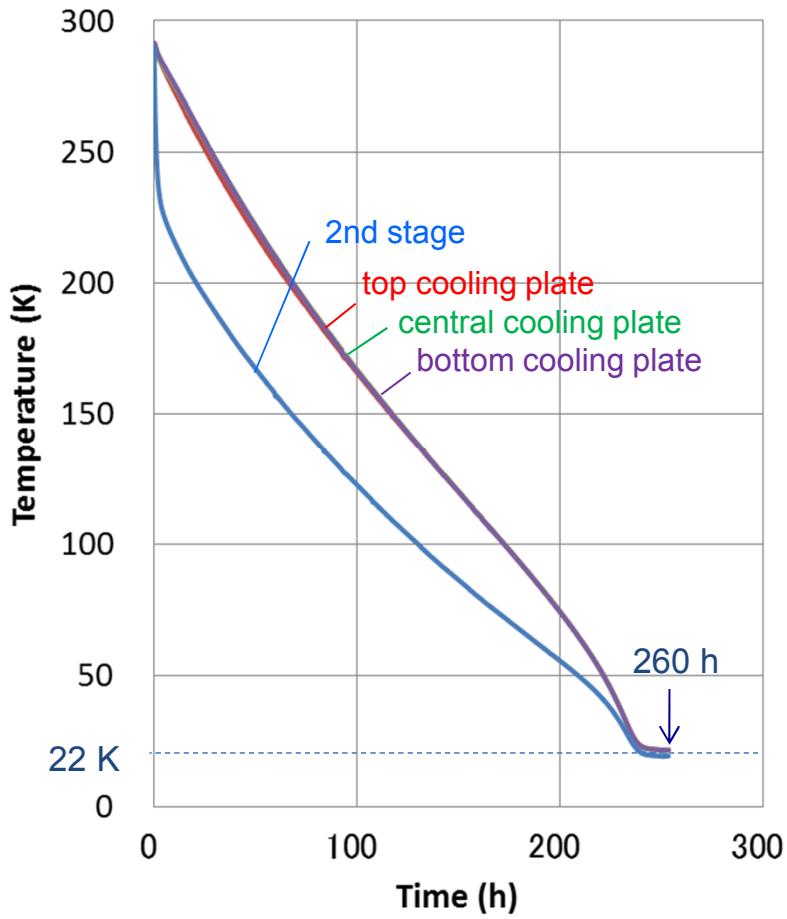




Cooling characteristics of 5 T 426 kJ REBCO magnet



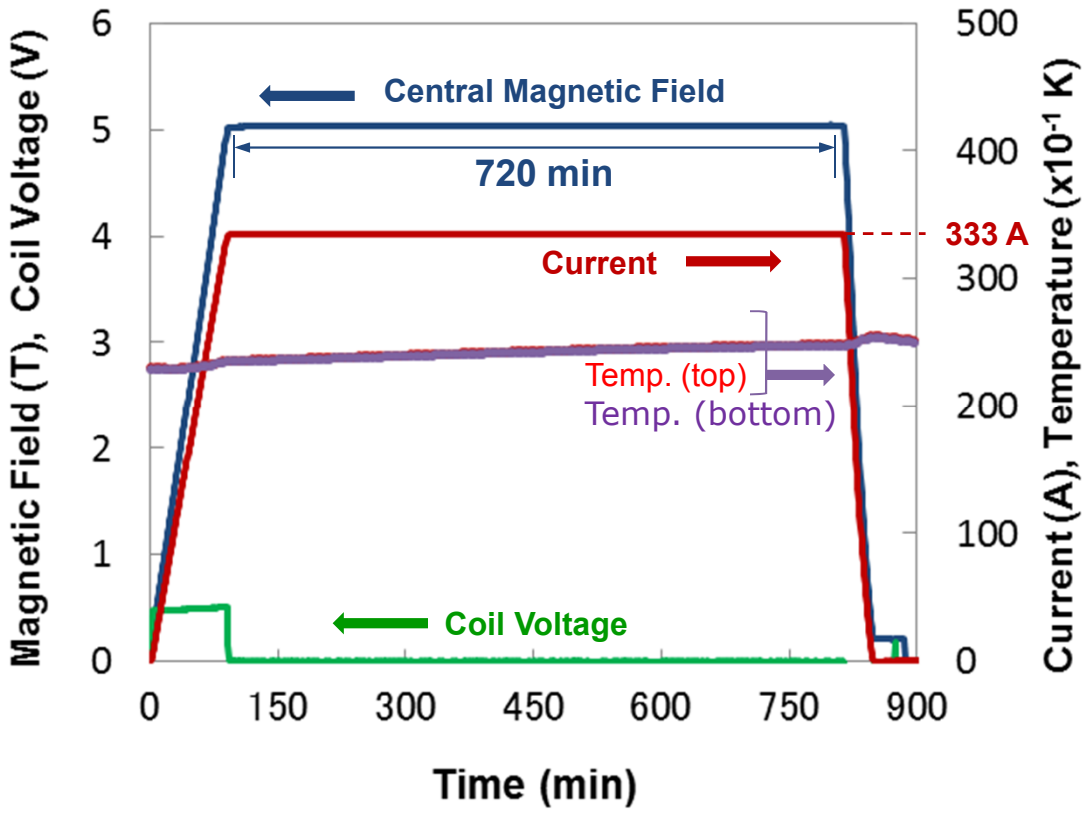
Initial cooling down



2nd cooling down

M. Daibo et al., IEEE Trans. Appl. Supercond. 23 (2013) 4602004.

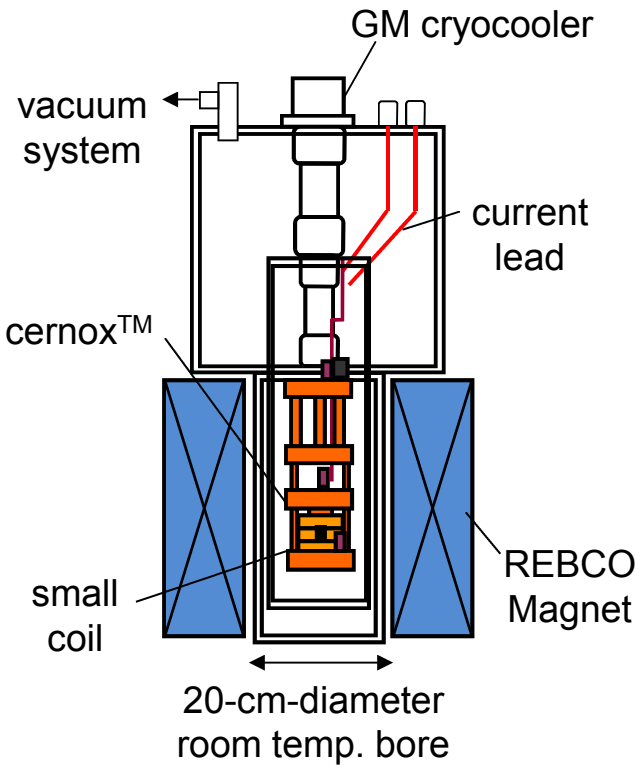
Example data of a 720-min. excitation test

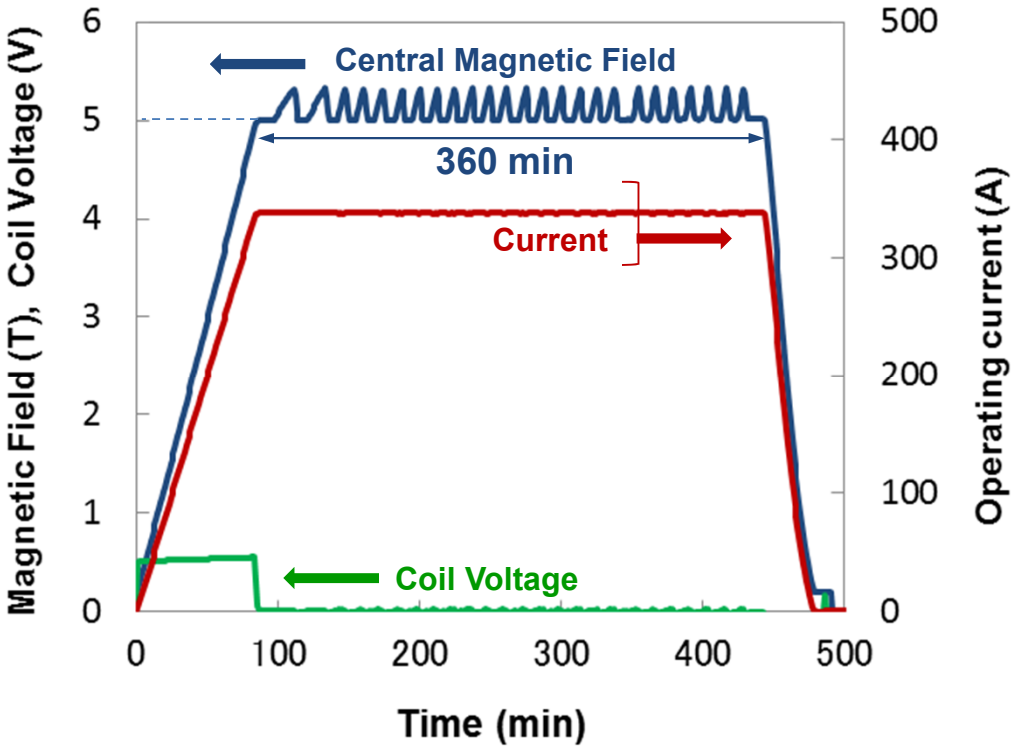


The 5 T REBCO magnet was excited up to 5.0 T for 720 min after 2nd cooling

M. Daibo et al., IEEE Trans. Appl. Supercond. 24 (2013) 4900304.

Background magnet for hoop stress test of small pancake coils





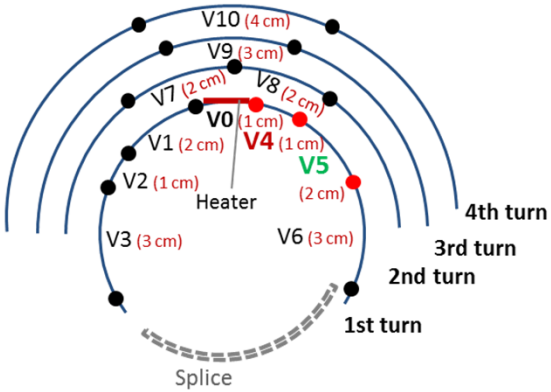
The magnet was excited up to 5 T 21 month after the fabrication
for example as a background magnet for repeated hoop stress test of small coils

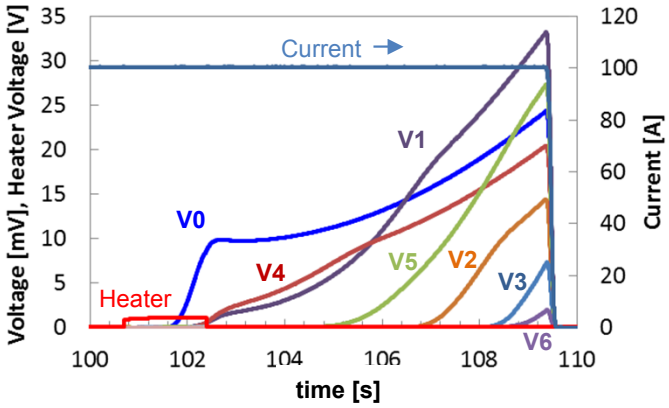
Outline

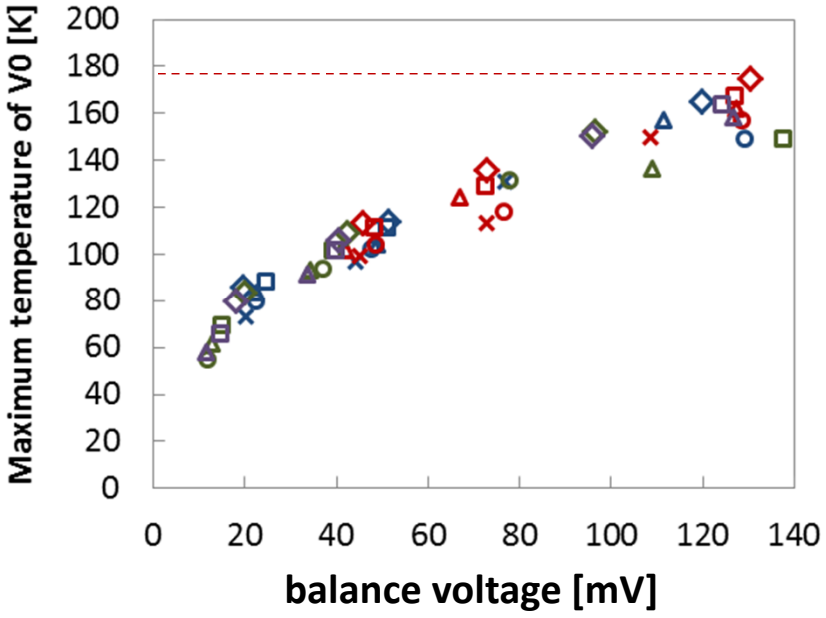
- Introduction
- Uniformity of REBCO coated conductors (c.c.) and In-field I_c properties
- Characteristics of REBCO coated conductors for 25 T Cryogen-free Superconducting Magnet
- Development of REBCO coils at Fujikura
  - Development of a 5 T 426 kJ REBCO magnet
  - Feasibility study for accelerator magnets
- Summary

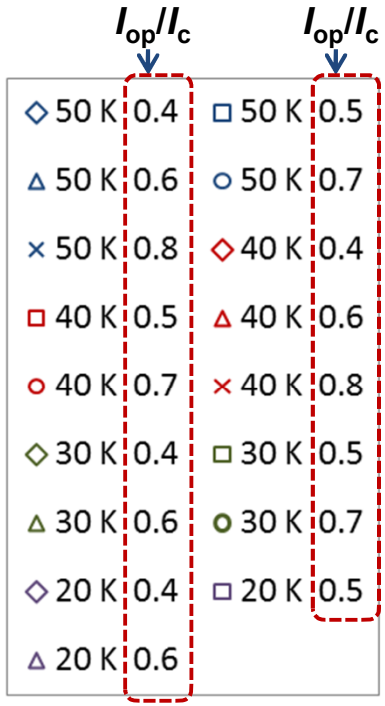
Study of quench behaviors of REBCO coil for accelerator magnet

collaborated with Prof. Tsuchiya and Prof. Ohuchi at KEK









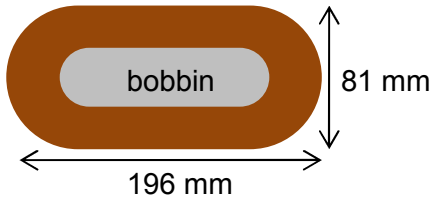
- **does not depend on the operating temperature**
- **increase with the balance voltage**

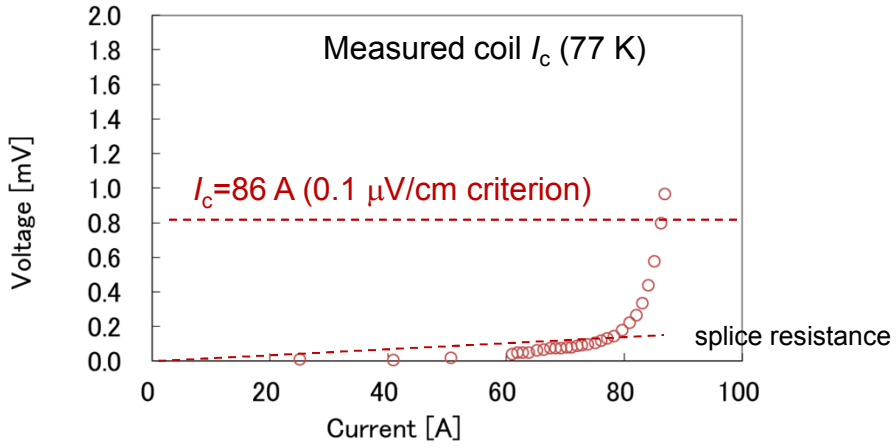
presented at 25th ICEC/ICMC2014, July, 2014

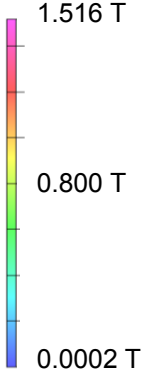
Small racetrack coil with VPI for accelerator magnets

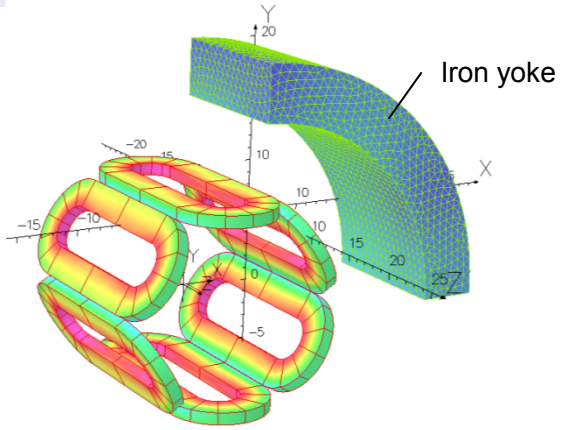
- Feasibility study of sextupole magnet collaborated with Prof. Tsuchiya and Ohuchi at KEK

Item	Specifications
I_c of REBCO tape	260 A (77 K, s.f., 1 μV/cm criterion)
n-value of REBCO tape	27 (77 K, s.f., 0.1～1 μV/cm criterion)
Coil size	81 mm × 196 mm, 10.7 mm (height)
Coil bobbin	116 mm, R=19 mm
Number of turns	94 turns × 2 layers (188 turns)
Tape length	40 m × 2 layers
Impregnation	VPI with epoxy resin
Coil I_c (77 K, 0.1μV/cm criterion)	calculated. 82 A measured. 86 A (4.9% difference)







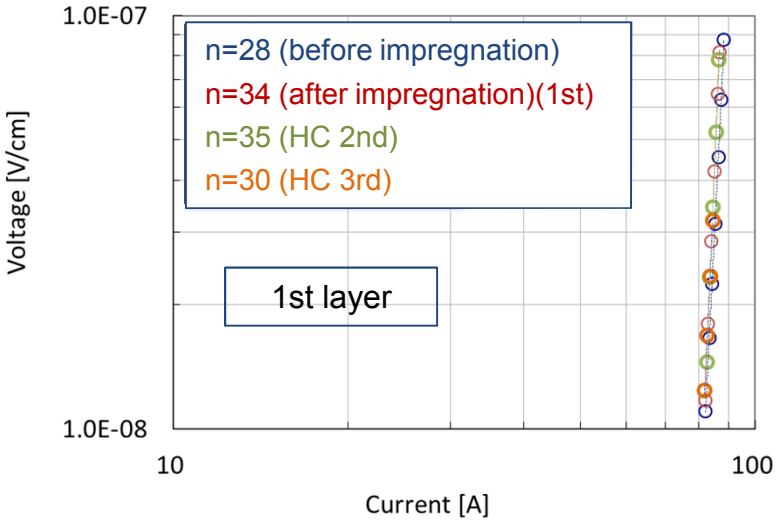


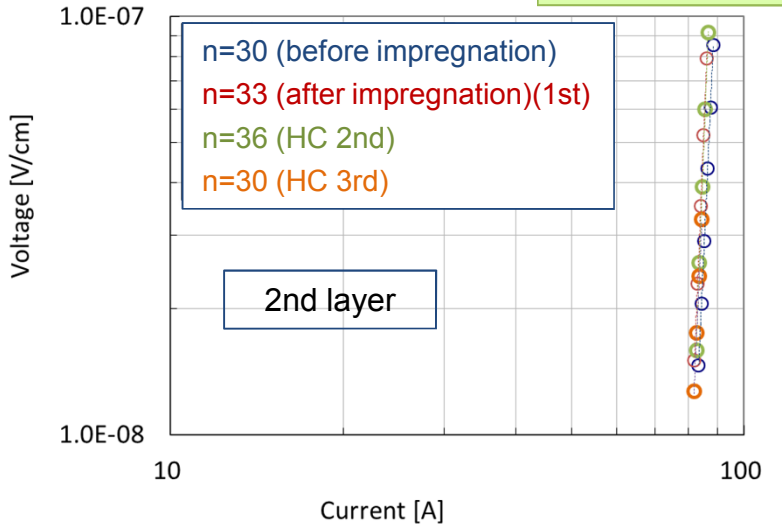
Sextupole magnet design by KEK

Heat cycle, conduction cooled test of a small racetrack coil

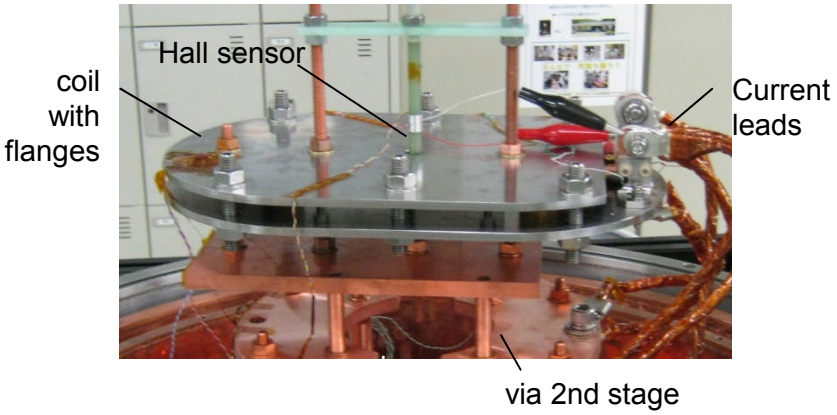
- *I-V* characteristics (77 K) of heat cycles

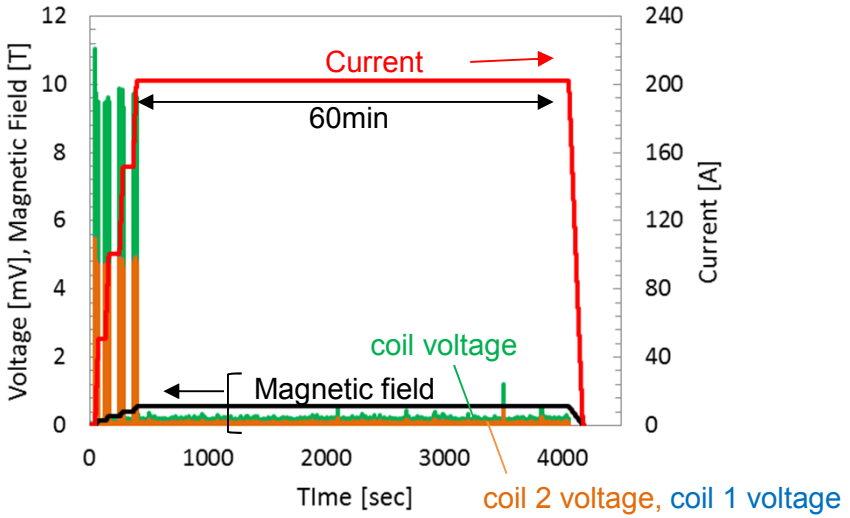
No degradation





- Evaluation under conduction cooled condition at 50 K (I_t=202 A, B_0=0.55 T) (load factor : 0.65)





Summary

- Uniformity, mechanical and I_c properties of REBCO c.c.
  - Focus on uniformity improvement for long-length coated conductors
  - Ic (20 K, 15 T) have stronger correlation with Ic (77.3 K, 0.6 T) rather than Ic (77.3 K, s.f.)
  - Tensile stress of the mass-produced c.c. was investigated at 77 K

- Development of Coils and Magnet
  - Fujikura successfully developed the 5 T REBCO magnet
  - The magnet has been used as background magnet at Fujikura over 21 month
  - Feasibility study for accelerator magnet has been investigated with Prof. Tsuchiya and Prof. Ohuchi at KEK

Thank you for your attention !!

Please visit Fujikura website!!

- Global Site
  http://www.fujikura.com/solutions/superconductingwire/
- Fujikura website
  http://www.fujikura.co.jp/eng/products/new/index.html


Fujikura