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Recent progress of 2G HTS wires and coils at Fujikura

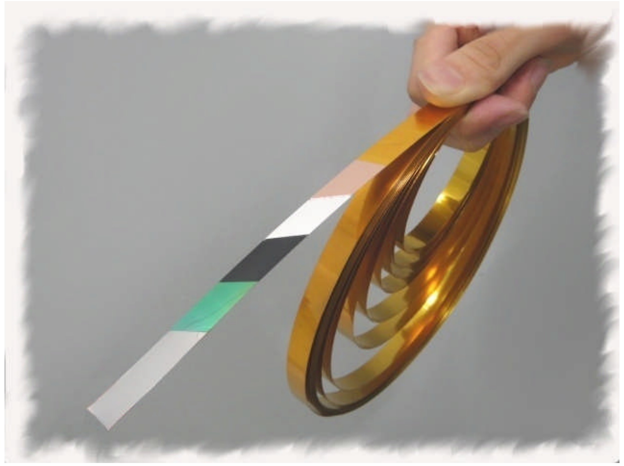
Masanori Daibo
(Fujikura Ltd.)

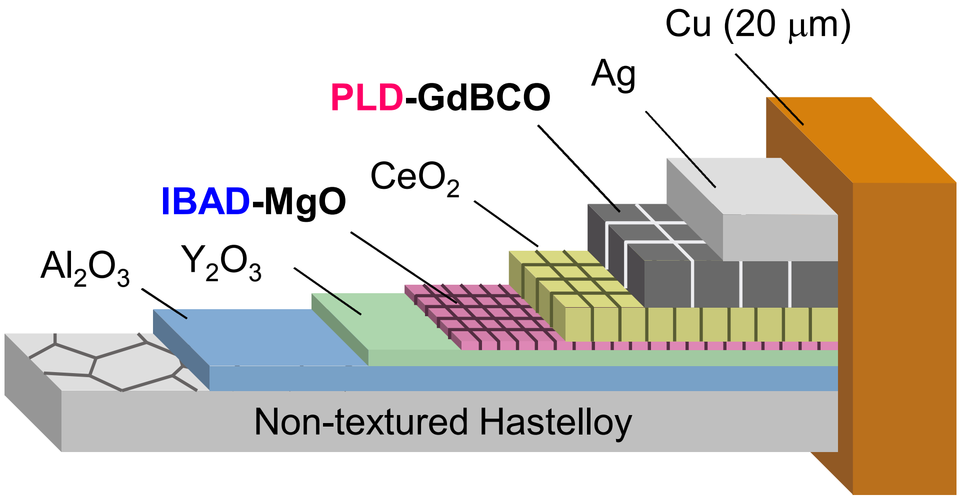
A part of this work has been commissioned by
the New Energy and Industrial Technology Development Organization (NEDO)

Outline

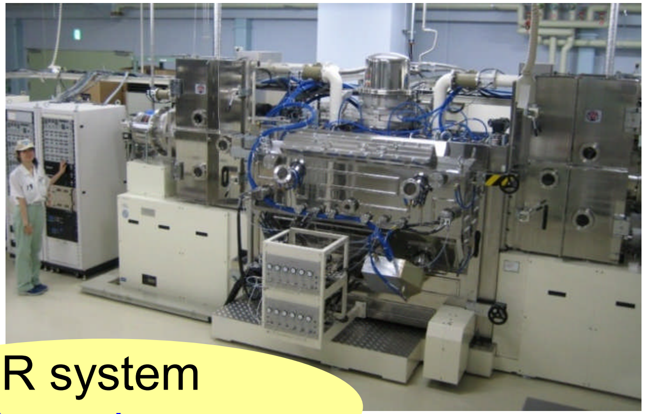
- Introduction
- Properties of Fujikura's conventional 2G HTS wires
- Recent progress of 2G HTS wires at Fujikura
- Evaluation of mechanical and fatigue properties of 2G HTS wires
- Feasibility Study of conduction-cooled sextupole HTS magnet
- Summary

Fujikura's 2G HTS wire (IBAD / PLD)





Ion Beam Assisted Deposition (IBAD)



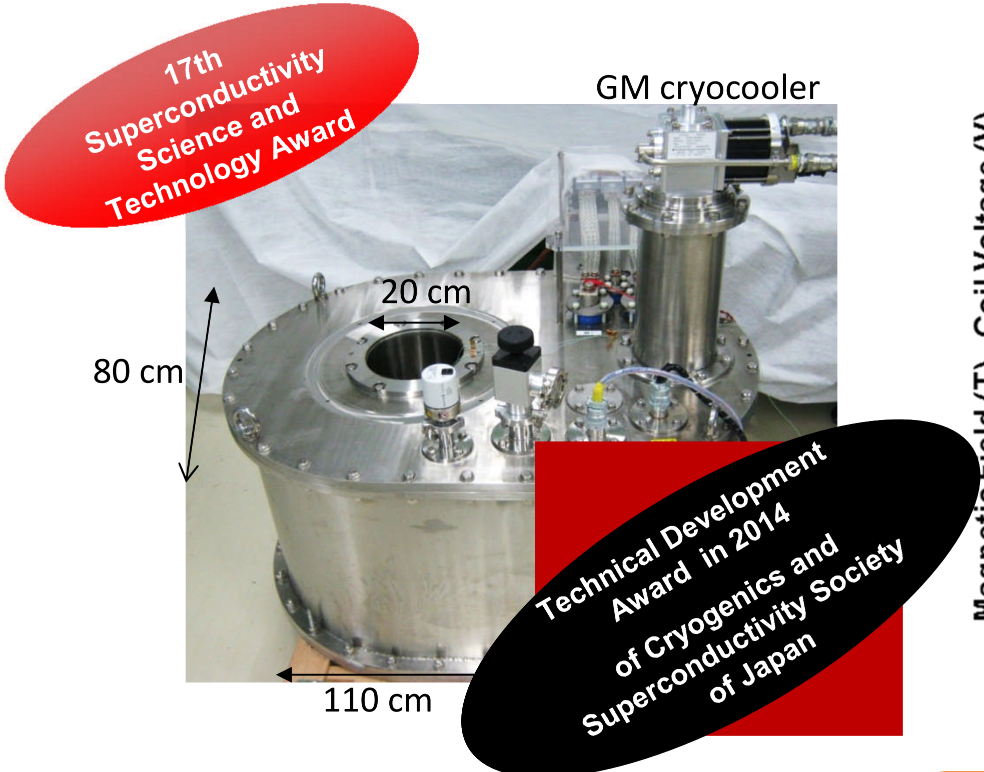
R-to-R system
with large ion source

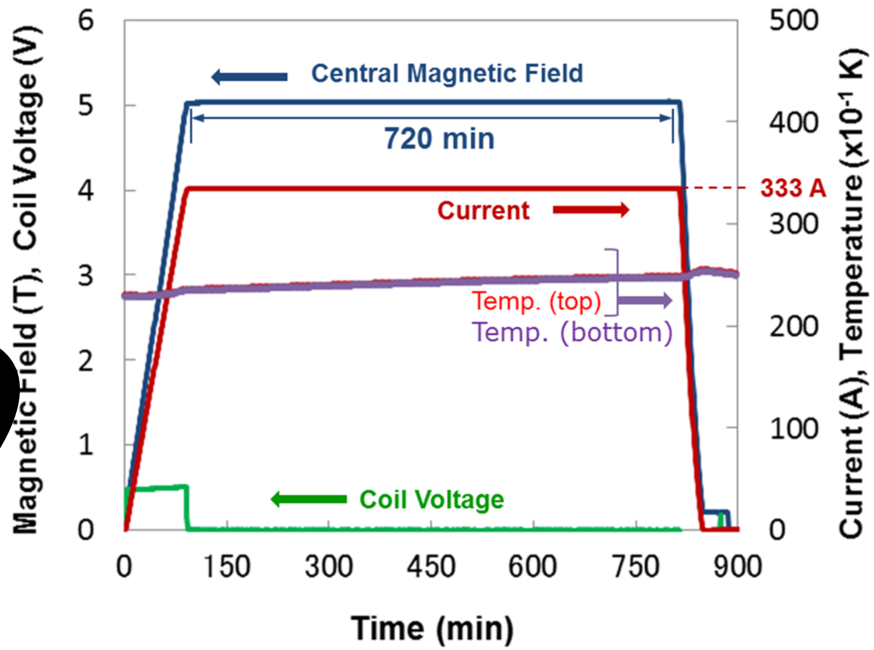
Pulsed Laser Deposition (PLD)

R-to-R system
with hot-wall heating

Development of 5 T 2G HTS magnet at Fujikura

- Fujikura's 10 mmw Y-based HTS wire
- 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





5 T 2G HTS cryocooled magnet developed successfully in 2012

The magnet excitation performance up to 5 T retained for 6 years after the fabrication

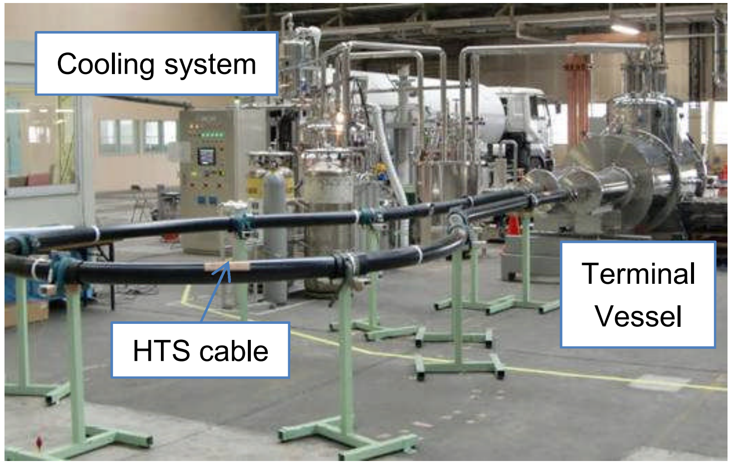
M. Daibo, et al.,IEEE Trans. Appl. Supercond. 23-3 (2013) 4602004

66kV/5kA Class Power Cable development(NEDO Program)

■ Development of HTS Power Cable with 500A class 2G HTS wires

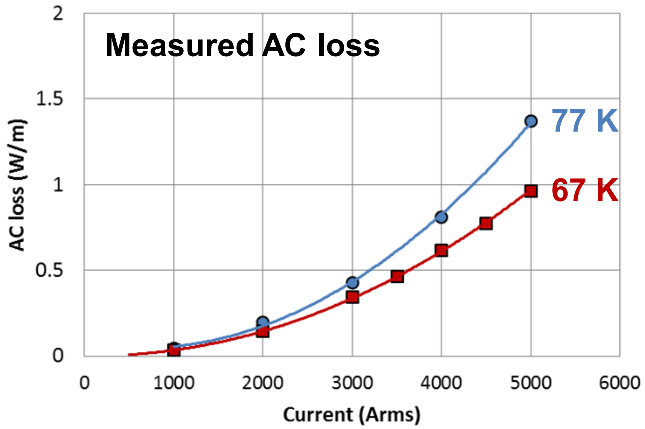
- Verification of AC Loss reduction with higher critical current HTS wires
- Single-core in one pipe cable system /66kV-5kA /10m class long
- Long term current loading test : 20 cycles (1 cycle = 8h ON / 16h OFF)
- Target AC loss : < 2 W/m @5kA

  Measured AC loss : 1.4W/m@77K, 1.0W/m@67K



< Design and Fabrication >

Items	Specifications
Former	Stranded copper wires (140 mm^2), 20 mmϕ
HTS conductor (Ic=14 kA)	4mm-wide wires, 4 layers Ic = 240 A/4 mm-w
Electric insulation	Craft papers (6mm-thick)
HTS shield (Ic=12.7 kA)	All 4mm-w tapes, 2 layers Ic = 240 A/4mm-w
Copper shield	Copper tapes (100mm^2), 44mm
Core protection	non-woven fabric, 45mmϕ
Cryostat / Outer sheath	Stainless steel double corrugated pipes with PE jacket, 114mmϕ



This work supported by NEDO

Fujikura has succeeded in developing 2G HTS power cable with 5 kA and extremely low AC loss 1.4 W/m in 2013.

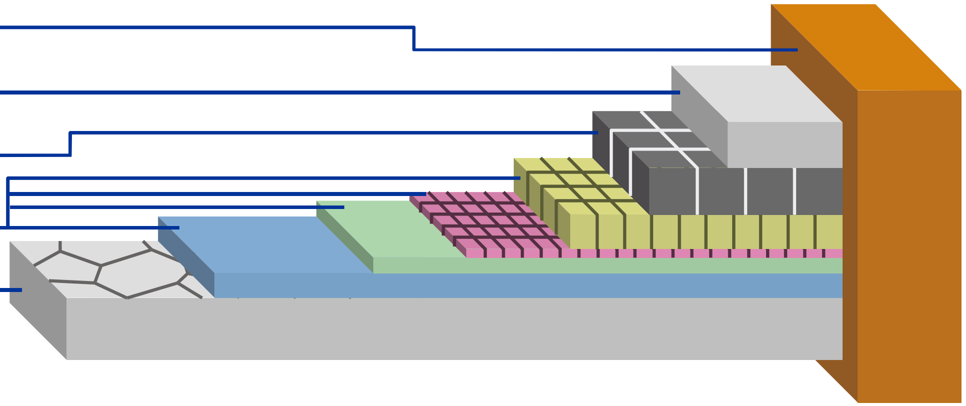
Fujikura's 2G HTS wires

■ Typical Specification

Item	Width [mm]*	Thickness [mm]*	Substrate [µm]	Stabilizer [µm]	Critical Current (I_c) [A] (@77K, S.F.)
FYSC-SCH04	4	0.13	75	20 x 2	≧165
FYSC-SCH12	12	0.13	75	20 x 2	≧550

* Dimensions do not include thickness of insulating tapes.

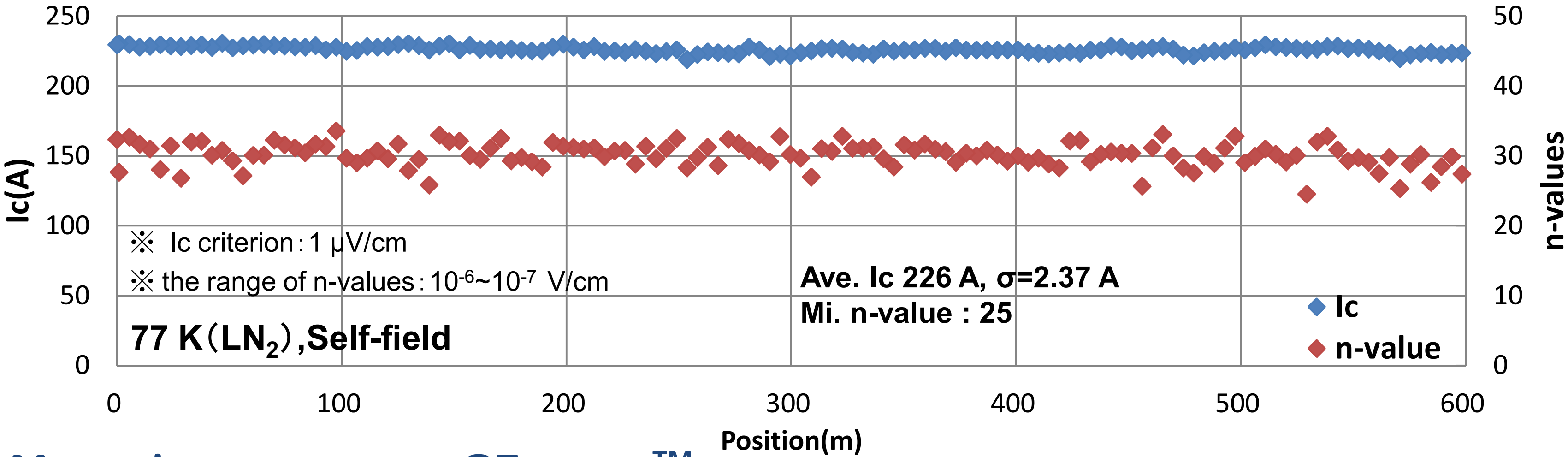
＜Schematic of 2G HTS wire (FYSC-SCH04)＞



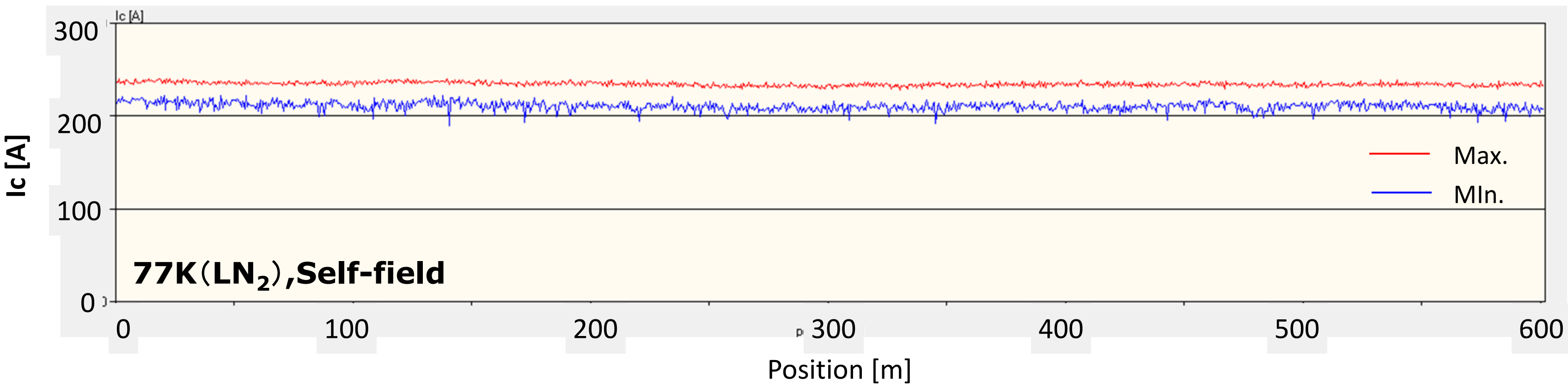
Example data of longitudinal I_c distribution

a production wire of 4 mm-wide : FYSC-SCH04

- **4-terminal method current conduction measurement at every 4.7 m**



- **Magnetic measurement @Tapestar™**

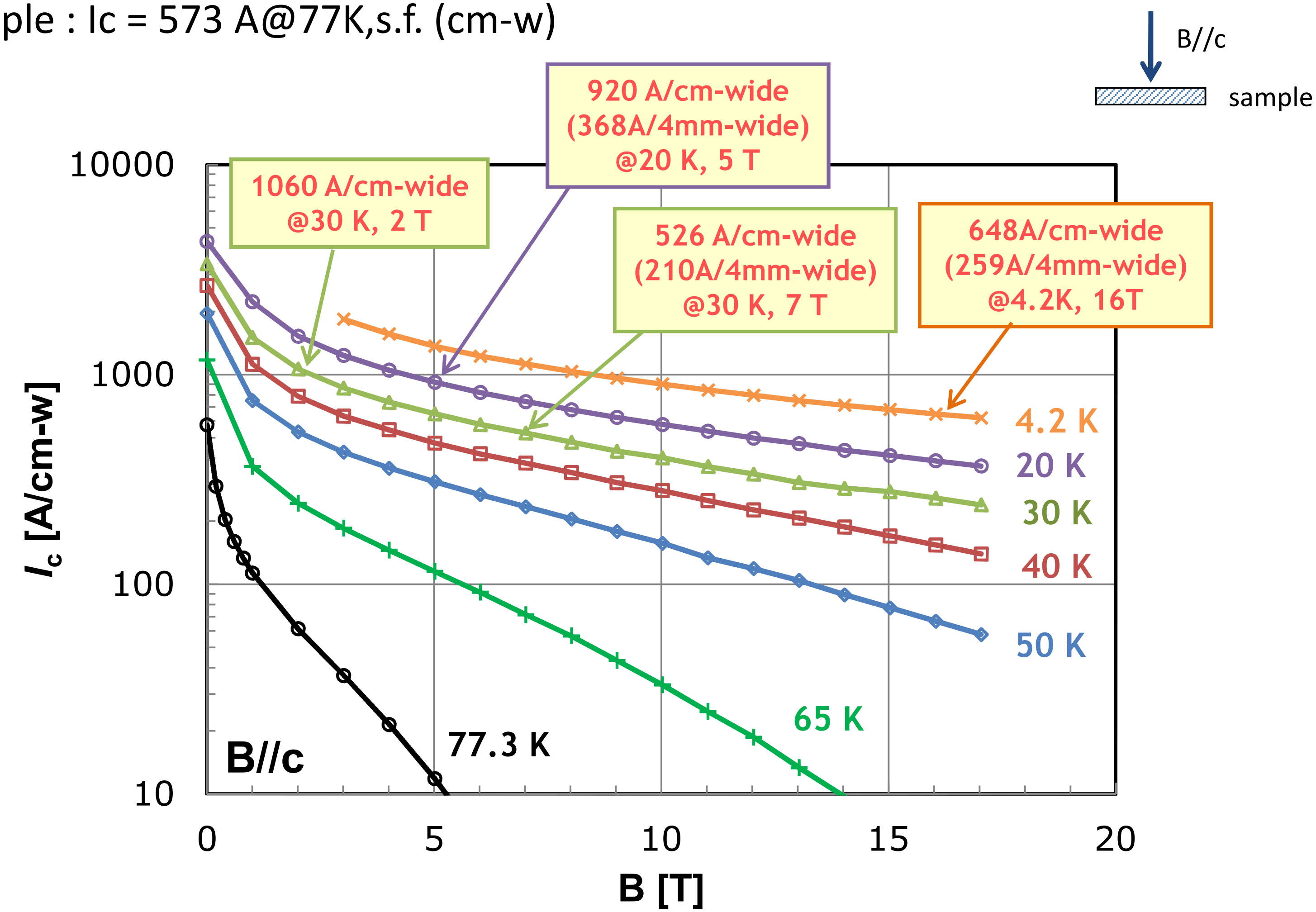


quite uniform I_c with 600m length are obtained

Fujikura

Typical In-field I_c of a production wire

- Example data of typical production wire (FYSC-SCH04)
- Sample : Ic = 573 A@77K,s.f. (cm-w)

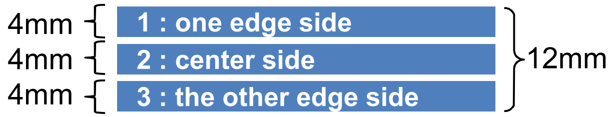


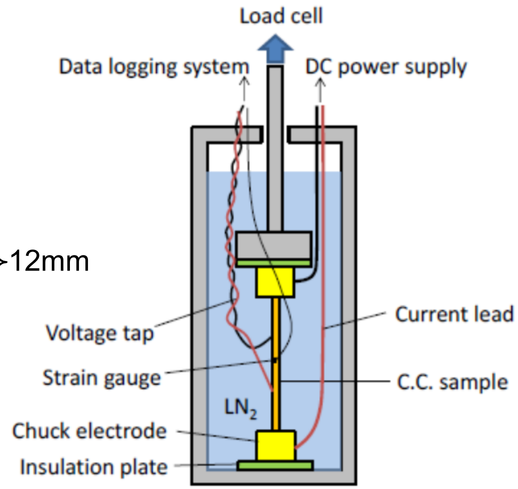
* This work includes some data measured at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

Evaluation of tensile properties of divided 4 mm-wide

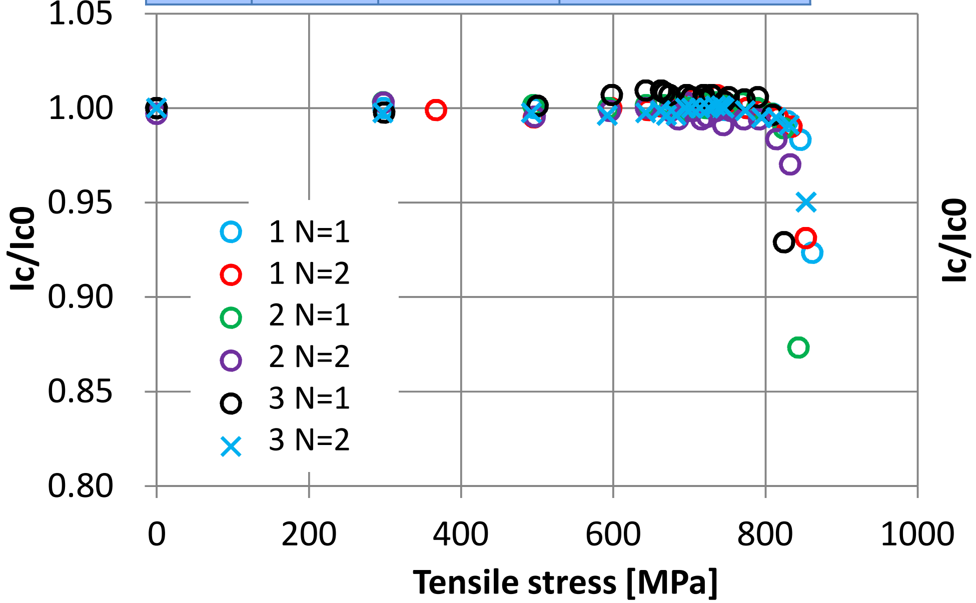
Tensile properties of 3 parts of 4 mm-wide wires divided from 12 mm-wide coated conductor in LN2

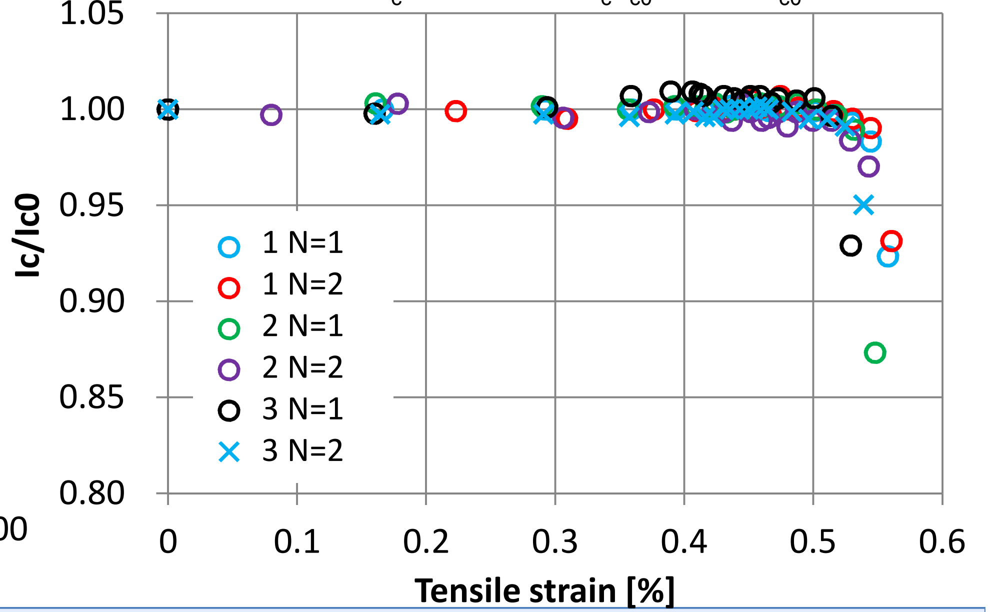
samples		reversible I_c Strain [%]	reversible I_c Stress[MPa]
1	N=1	0.523	820
	N=2	0.513	817
2	N=1	0.521	813
	N=2	0.497	768
3	N=1	0.514	810
	N=2	0.496	795





* Reversible I_c is defined at I_c/I_{c0} > 0.99 I_{c0} : Initial Ic





Each divided 4 mm-wide HTS wires have shown equivalent tensile properties in LN2

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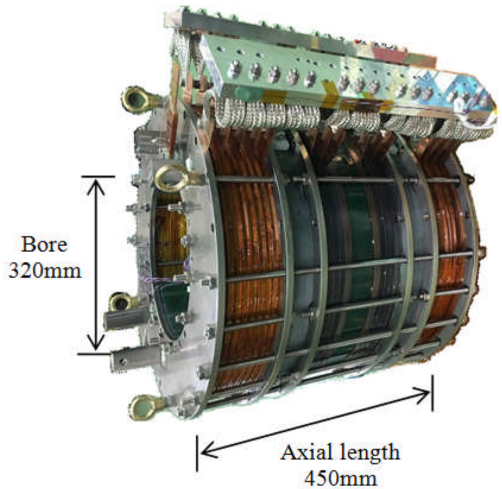
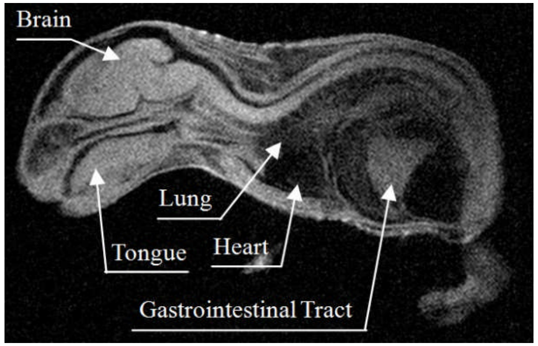
World's first 3 T HTS-MRI with 2G HTS in 2015

Mitsubishi Electric succeed in World's first 3T HTS-MRI

developed under a Ministry of Economy, Trade and Industry (METI) and Japan Agency for Medical Research and Development (AMED) project called "Fundamental Technology Development for High Temperature Superconducting Coils"



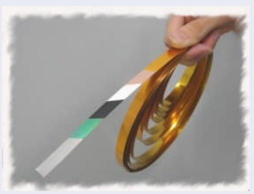


➡ Mitsubishi Electric, Kyoto University and Tohoku University plan to increase the size of the system to one half of a full-size MRI scanner by 2020 in NEDO program (FY2016-2020)

http://www.mitsubishielectric.com/news/2016/pdf/0524.pdf
http://www.nedo.go.jp/english/news/AA5en_100071.html

Abstract of 2G HTS development program by NEDO (FY2016~)

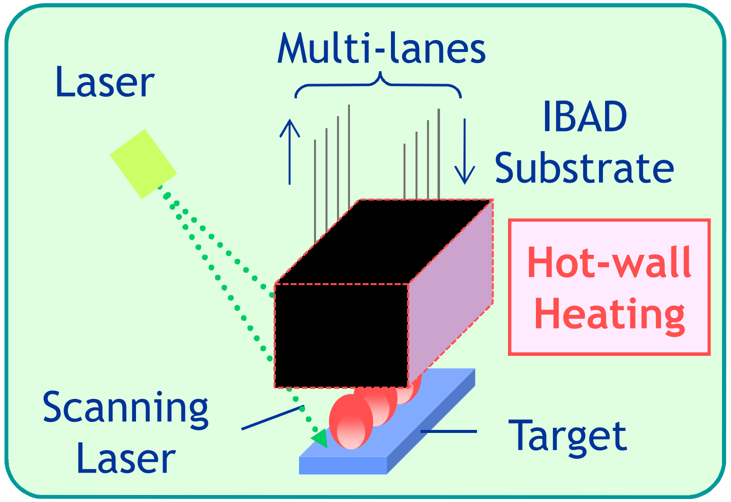
NEDO program of 2G HTS wires with the aim of promoting rapid commercialization

Cat.	Development Items		Institutions	Target	'16	'17	'18	'19	'20
HTS Power Cable systems	(1) Electric HTS Power Cable systems	AC	TEPCO Sumitomo Furukawa Maekawa	- Ensuring essential safety functions - Recovery methods - Refrigerators	Ensuring safety functions	Standards for design			
		DC	Isikari Association	- Standards for design/operations	Standards for design				
	(2) Railway HTS Power Cable systems	—	RTRI	- 2km refrigerator systems	Development of small scale refrigerator		Verifications of a 2km refrigerator system		
HTS Magnet Systems	(3) HTS highly stable magnet system for MRI	—	Mitsubishi Electric AIST	- Half-scale 3T MRI systems	Development of a half-scale 3T HTS-MRI system			Development of a half-scale 5T HTS-MRI system	
		joints	AIST etc.	- superconducting joints	Development of superconducting joints				
	(4) 2G HTS wires 	—	Fujikura	- In-field Ic and uniformity improvement - Evaluation of reliability of wires	In-field Ic improvement Uniformity Improvement				
		—	Fujikura	- High productivity	High productivity				

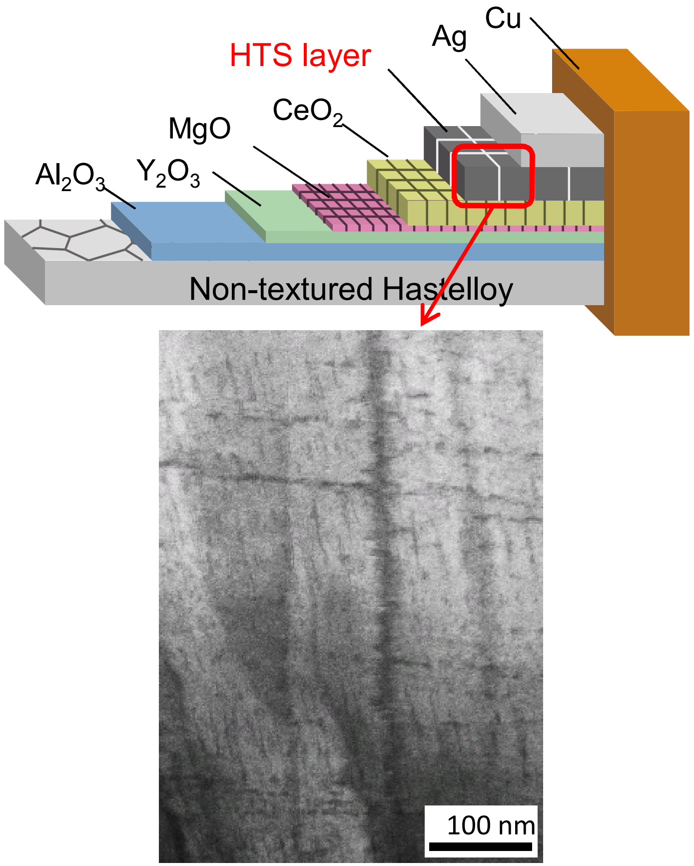
Fujikura supplied 80km 2G HTS wires to Mitsubishi Electric for the magnet in 2016-2017

Improvement of in-field I_c with artificial pinning

Improvement of in-field I_c of 2G HTS wire will be applied introducing artificial pinning techniques in HTS layer



BHO doping by hot-wall PLD system



< STEM image >

Typical dimensions of nano-rods

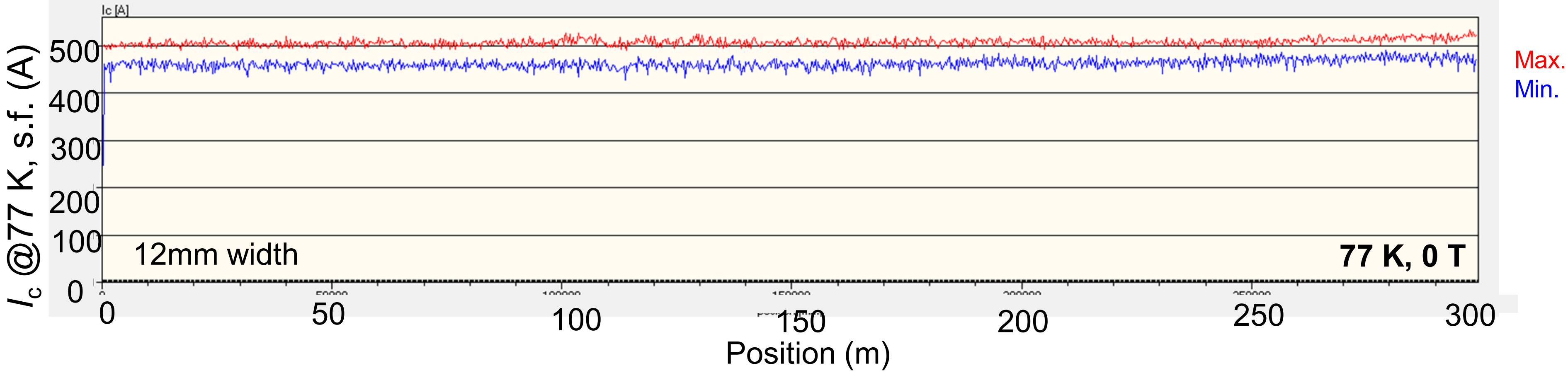
- **Length : ~100 nm**
- **Diameter : 3~5 nm**
- **Distance between rods : 10~30 nm**

Rod-shaped precipitates were observed

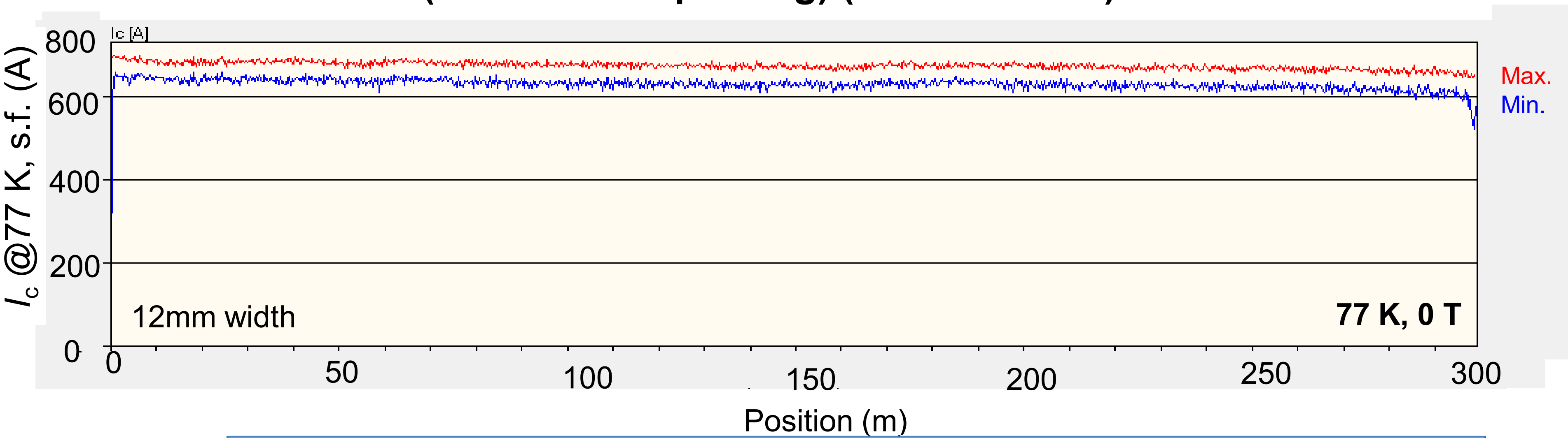
Comparison of uniformity of longitudinal I_c distribution

■ Artificial pinning wire (REBCO+BHO) (under development)

Tapestar® measurement



■ Production wire (w/o artificial pinning) (Conventional)

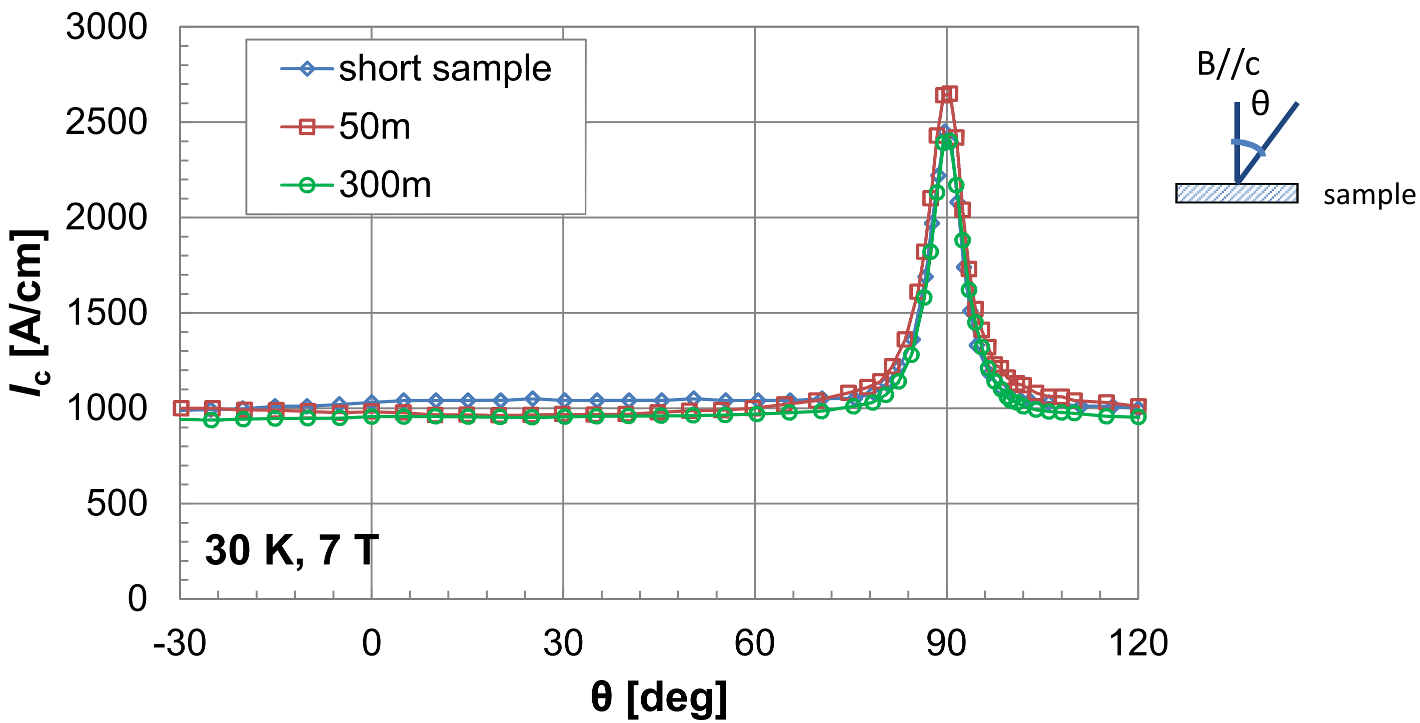


Uniform I_c with 300-m-long artificial pinning wire are obtained

Fujikura

Evaluation of reproducibility of I_c-B-θ properties

➢ Example data of trial samples with artificial pinning (REBCO+BHO)

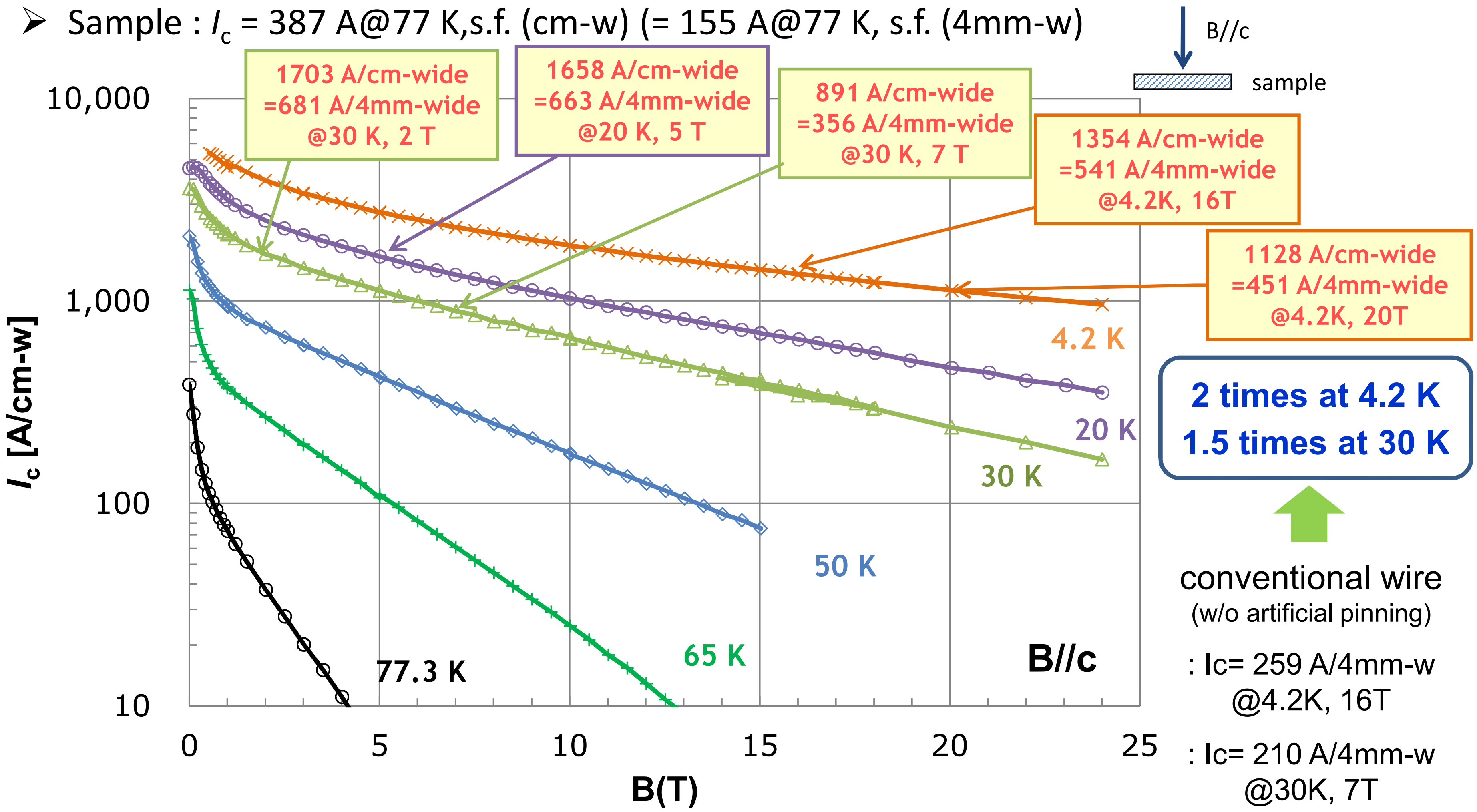


Good reproducibility of I_c-B-θ properties are obtained

Reproducibility have been evaluated with optimization of deposition conditions and thickness, etc.

Example data of in-field I_c with artificial pinning (B//c)

- Example data of **a sample from mass production** (EuBCO+BHO)
- Sample : I_c = 387 A@77 K,s.f. (cm-w) (= 155 A@77 K, s.f. (4mm-w)



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

Fujikura's 2G HTS wires

Typical Specification

Item	Width [mm]*	Thickness [mm]*	Substrate [μm]	Stabilizer [μm]	Critical Current (I_c) [A] (@77K, S.F.)
FYSC-SCH04	4	0.13	75	20	≧165
FYSC-SCH12	12	0.13	75	20	≧550
FESC-SCH04	4	0.11	50	20	≧85
FESC-SCH12	12	0.11	50	20	Under development

Release in March

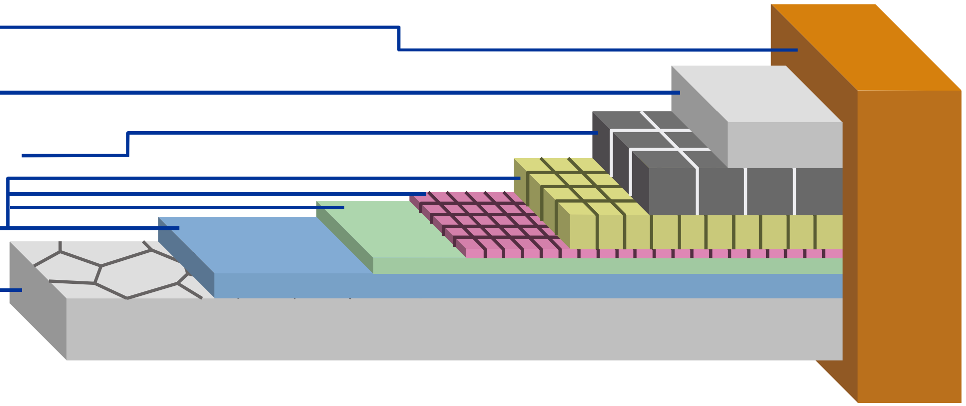
↑ E : Enhanced

* Dimensions do not include thickness of insulating tapes.

in field I_c : 1.5 times at 30 K
in field J_e : 2 times at 30 K

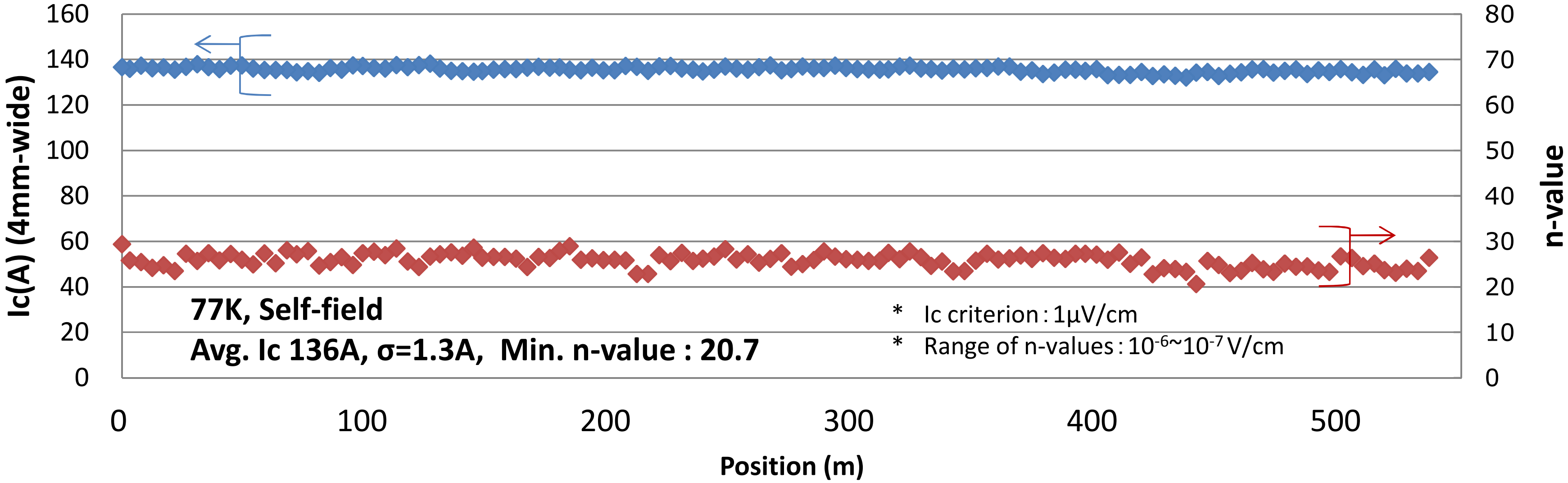
in field I_c : 2 times at 4.2 K
in field J_e : 2.4 times at 4.2 K

<Schematic of 2G HTS wire>

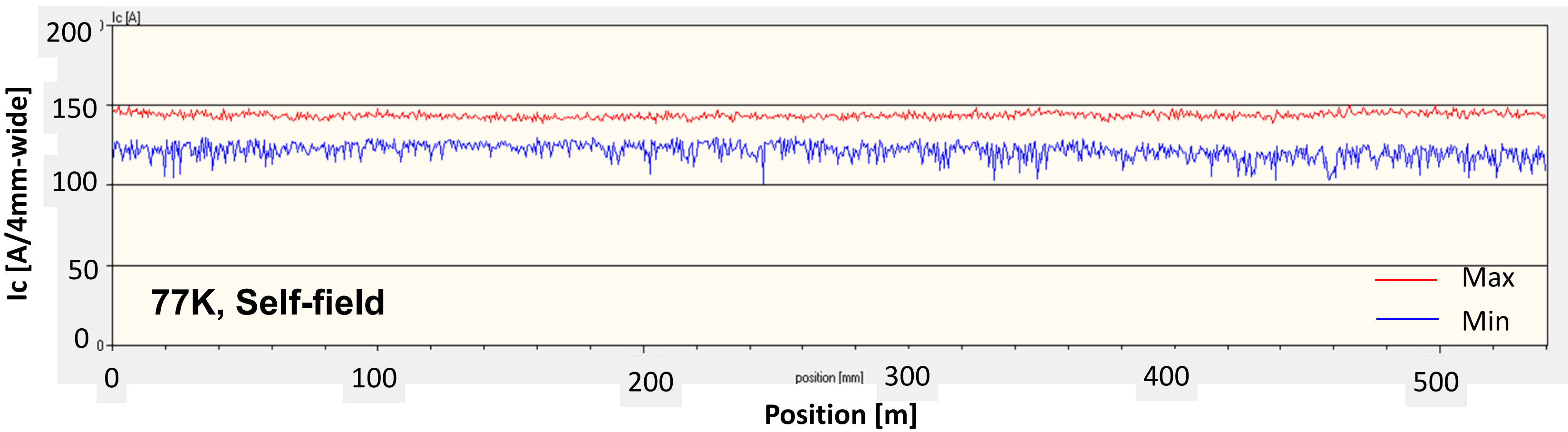


I_c Uniformity of 4mm-wide with Artificial Pinning(AP)

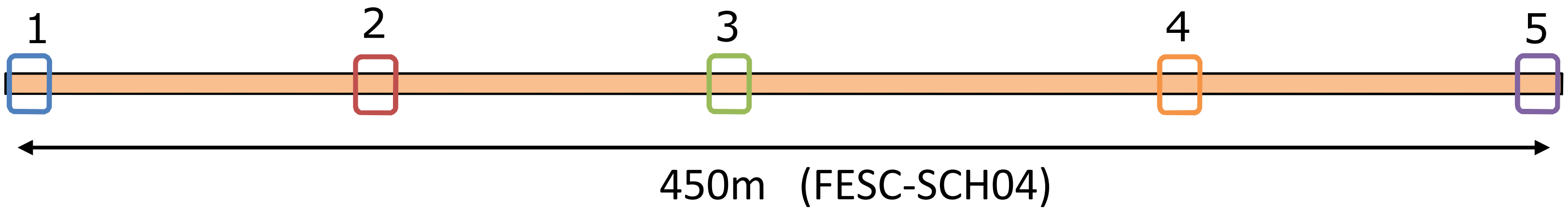
■ **Current conduction measurement (4mm-wide with AP / FESC-SCH04)**

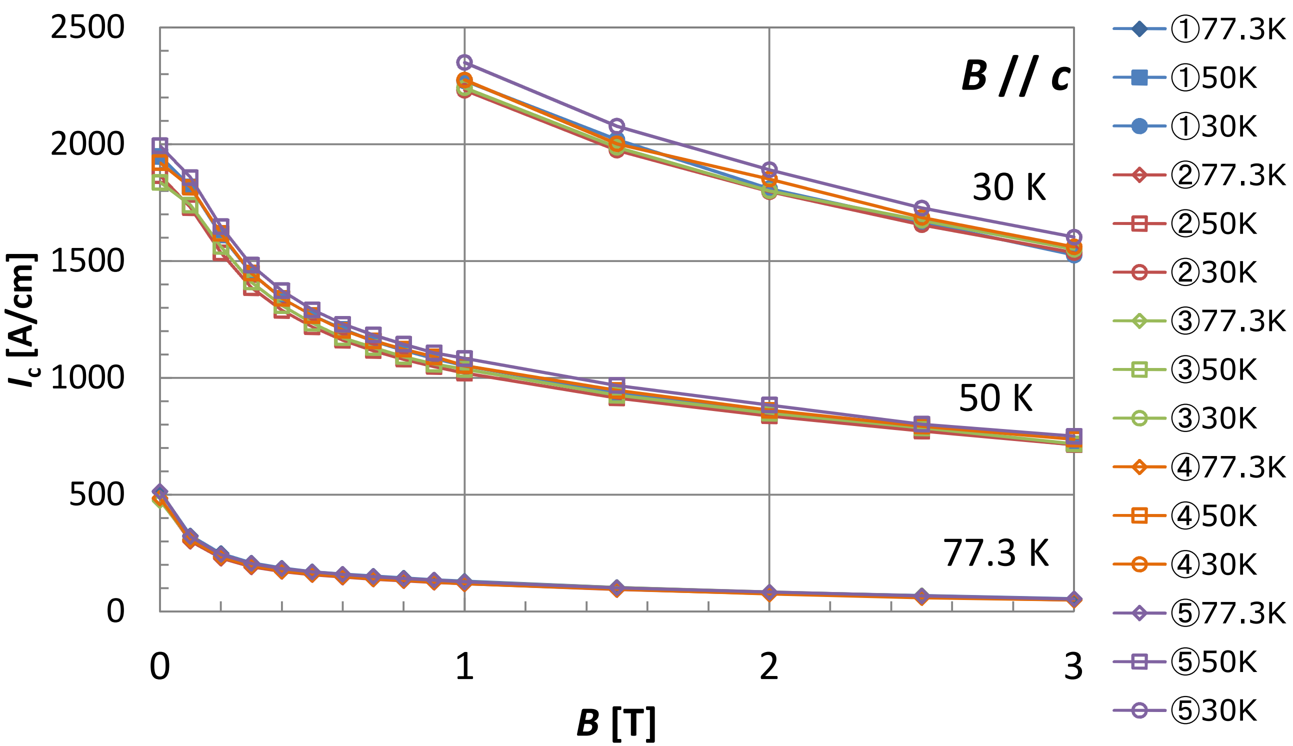


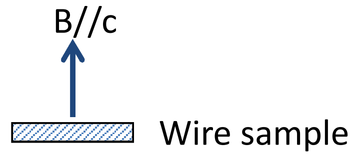
■ **Magnetic measurement @TapestarTM (4mm-wide with AP / FESC-SCH04)**



In-field I_c distribution in a 450m long sample (30, 50, 77 K, 3 T)



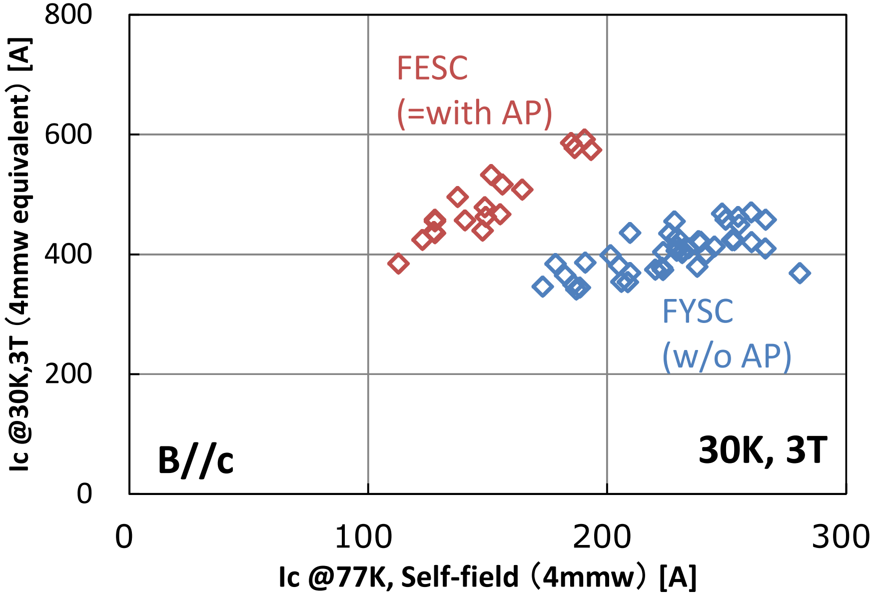


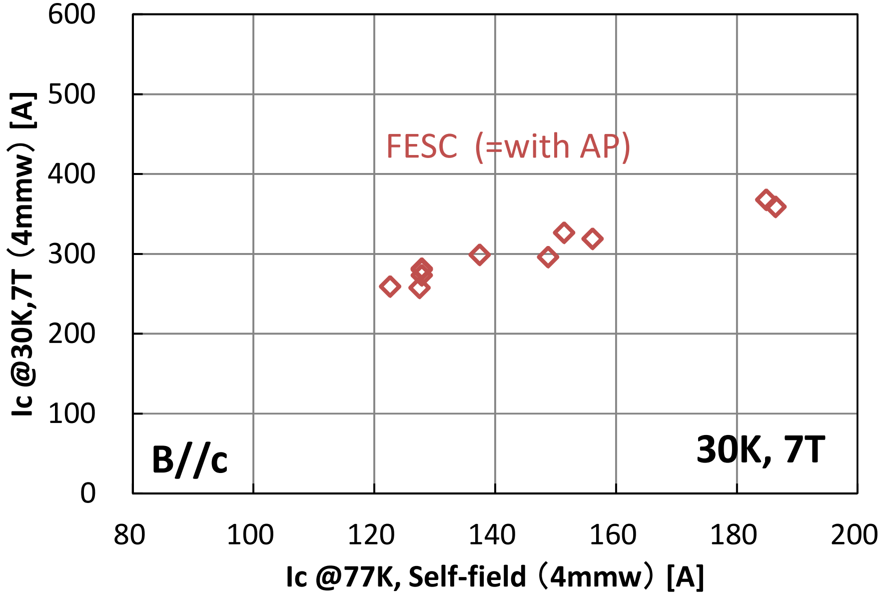


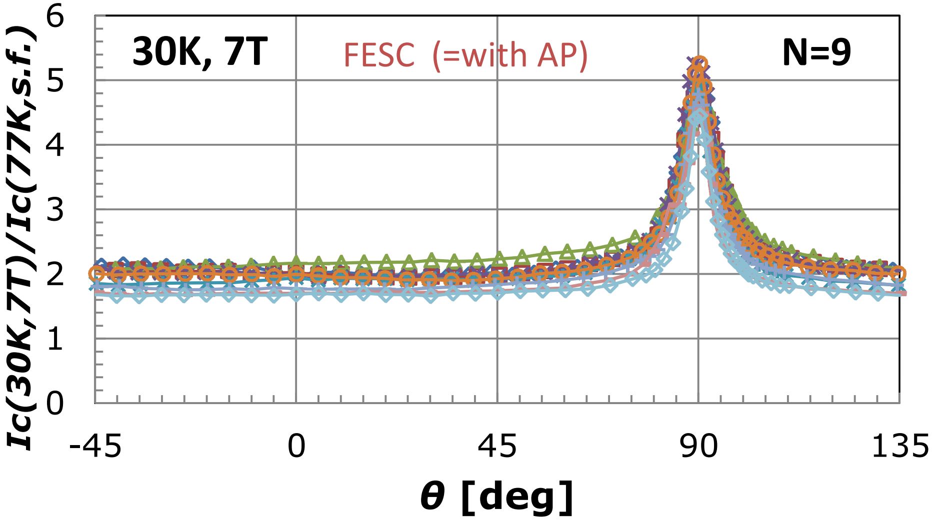
difference of Max. and Min. in-field Ic at 30K 1T ≦ 5%

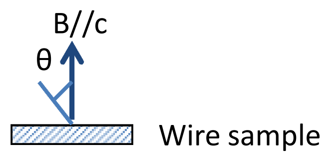
Evaluation of lot-to-lot variation of in-field Ic

Evaluation results between Ic at 77K, self-field and in-field Ic, compared with conventional(w/o AP) wires









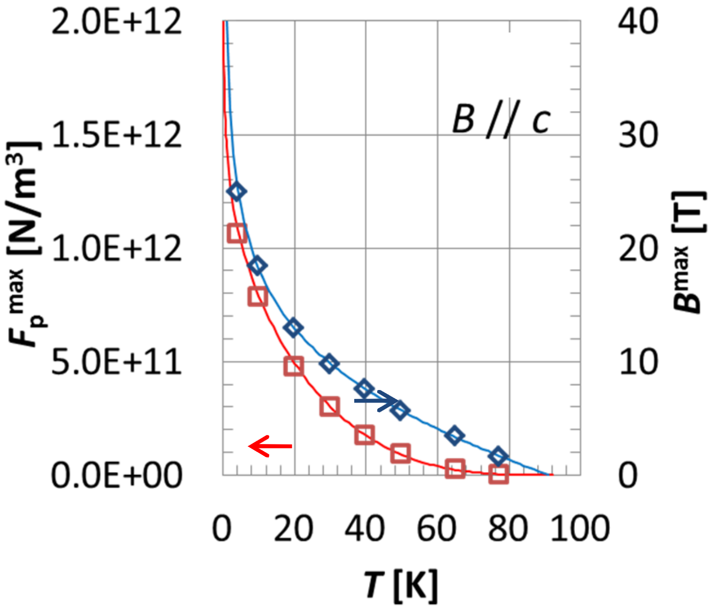
Good correlation

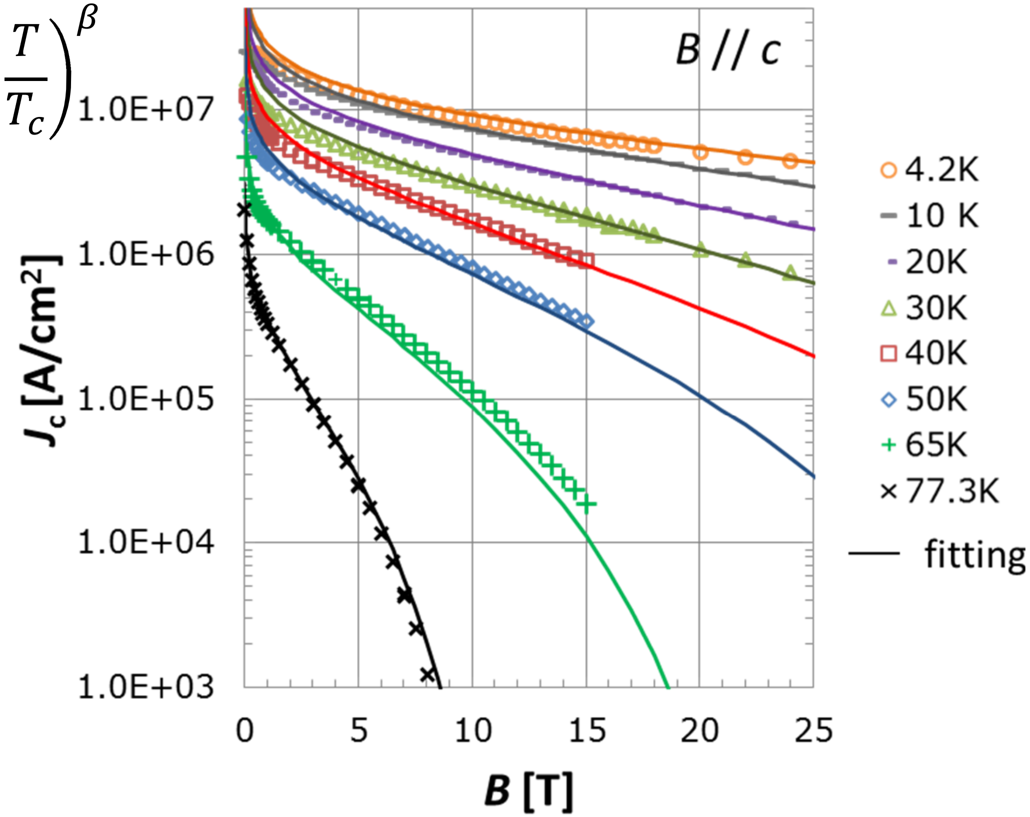
Current density(J_c) estimation of artificial pinning wires by F_p

Fitted B^{max} and F_p^{max} assuming the following.

$$F_p{}^{max}(T) \text{ or } B^{max}(T) = A\left(\frac{T}{T_c}\right)^{-\alpha}\left(1-\frac{T}{T_c}\right)^{\beta}$$

	A	a	b
F_p^{max}	8.3×10^{11}	0.13	2.9
B^{max}	10.5	0.3	1





In the sample of artificial pinning wires, $J_c(B,T)$ in $B//c$ are calculated from F_p.
It **fits well** especially **over 5 T**

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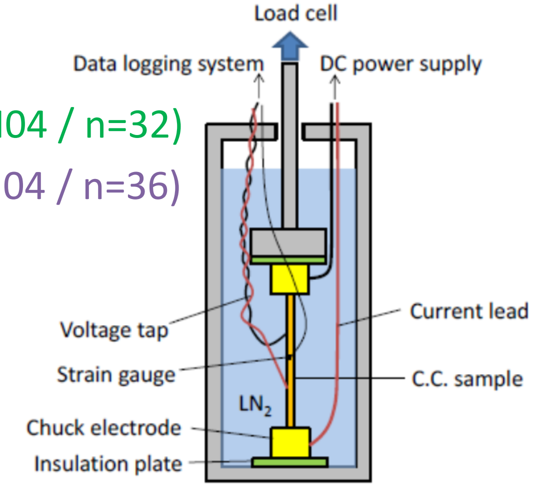
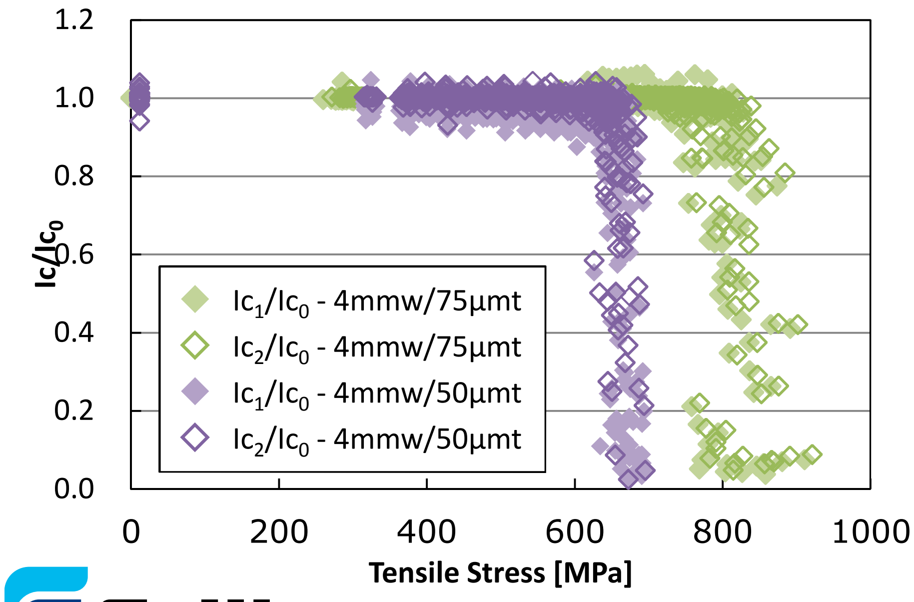
Tensile stress evaluation of 4mm-wide in LN_2

■ Tensile stress evaluation at LN_2 temperature (Reference)

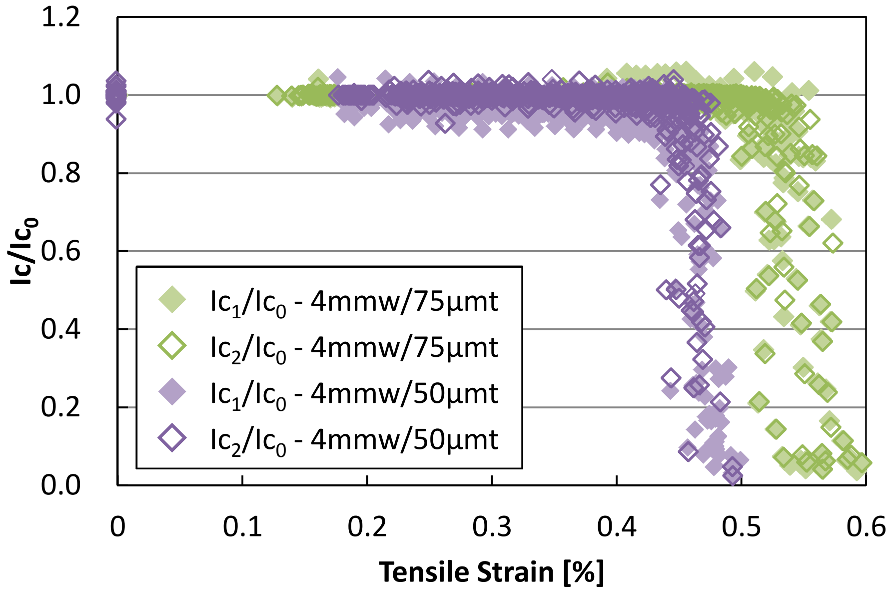
- Sample : 75µm-thick substrate + 20µm-thick electroplate copper (FYSC-SCH04 / n=32)
  50µm-thick substrate + 20µm-thick electroplate copper (FESC-SCH04 / n=36)
- Measurement method :
  1. Ic measurement without load at LN_2 (Ic_0)
  2. Ic measurement with applying tensile strain at LN_2 (Ic_1)
  3. Ic measurement without load (Ic_2) after applying tensile strain at LN_2



Ic/Ic_0 versus tensile stress

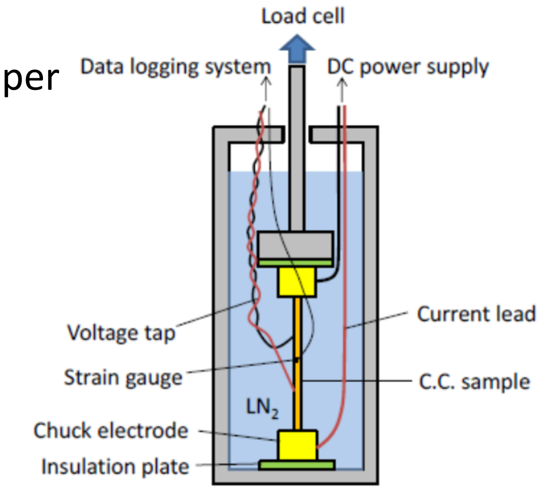


Ic/Ic_0 versus tensile strain



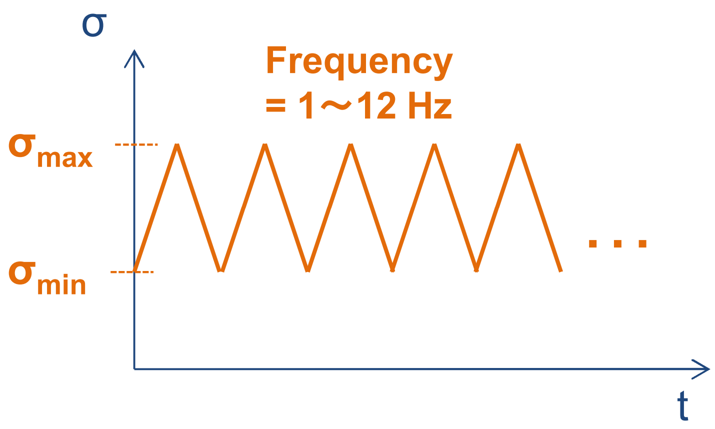
Repeated tensile stress evaluation of 4mm-wide in LN_2

- Sample : 4mm-wide, 50µm-thick substrate + 20µm-thick electroplate copper (FESC-SCH04)

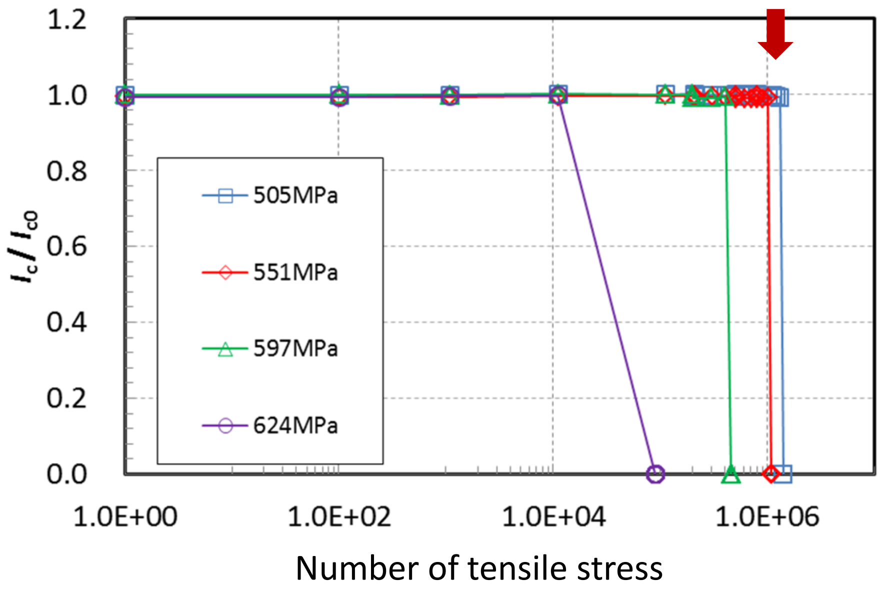


- Measurement method :
  1. Ic measurement without load at LN_2 (Ic_0)
  2. Ic measurement with applying repeated tensile stress in LN_2
  3. Ic measurement without load (Ic_2) after applying tensile stress in LN_2

$R = \sigma_{max} / \sigma_{min} = 0.3$



505 MPa in LN_2 is applied 10^6 times

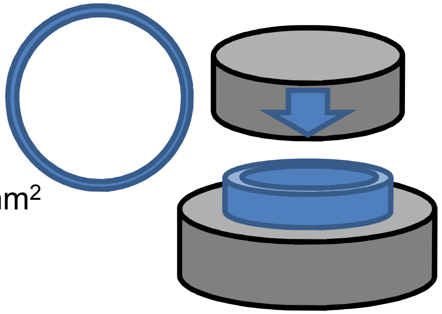


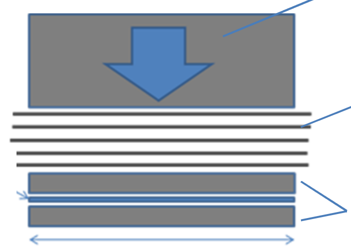
Example data of compressive test at room temperature

■ **Sample : FESC-SCH04 (4mm-wide, 50 μm-thick substrate + 20 μm-thick copper)**

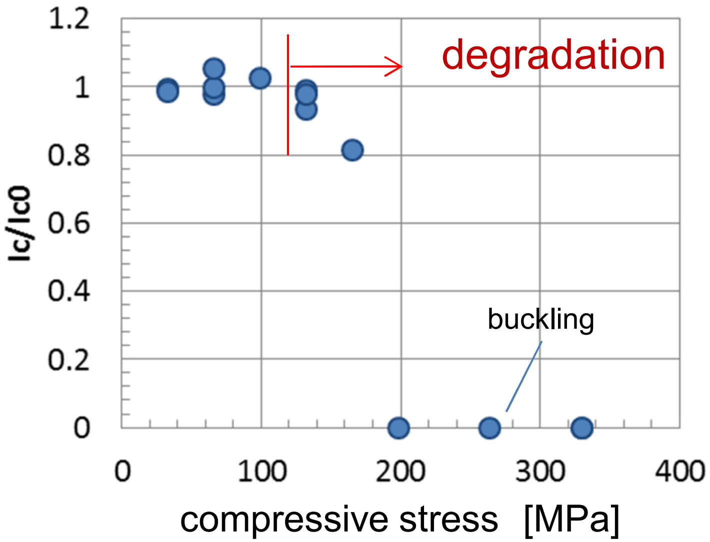
Sample

Coil configuration
ID 30mm、OD 33mm
Cross section : 148mm^2
Tape length 1.35m

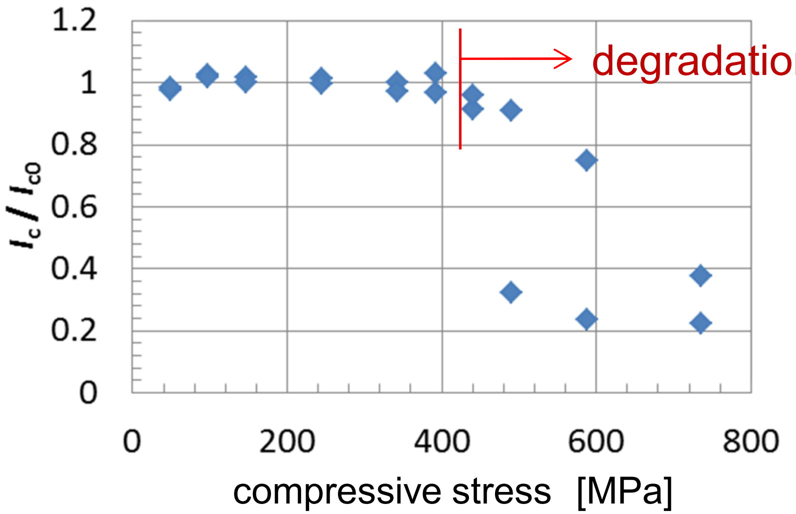




compressive stress in width direction



compressive stress in thickness direction

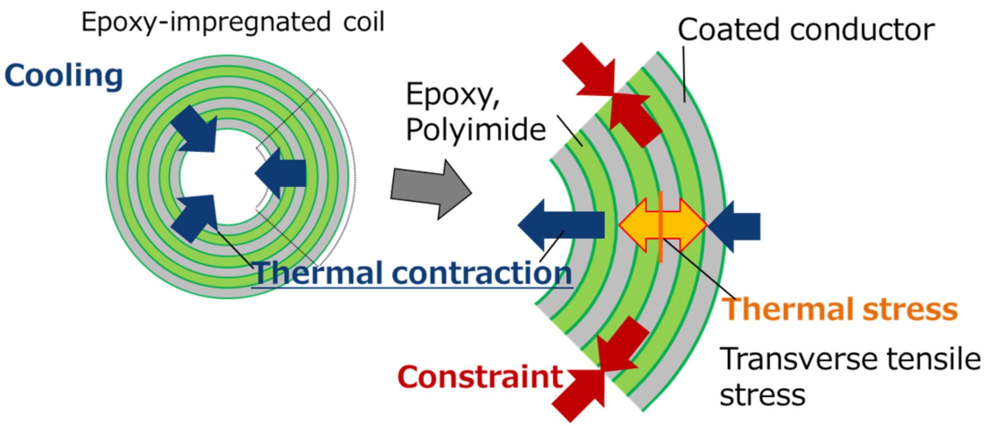


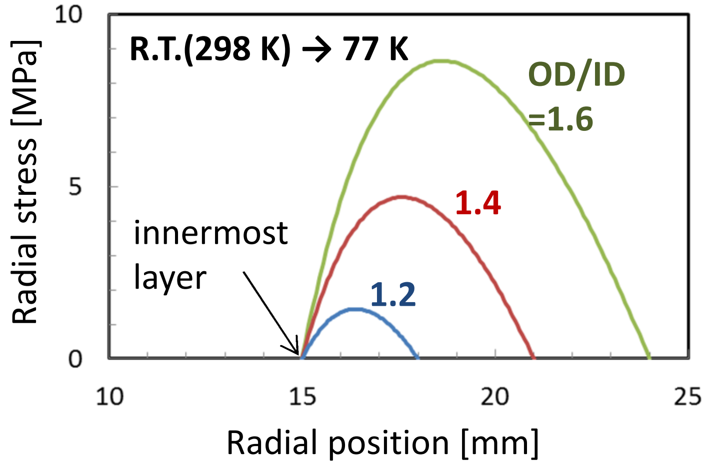
No degradation ~ 100 MPa

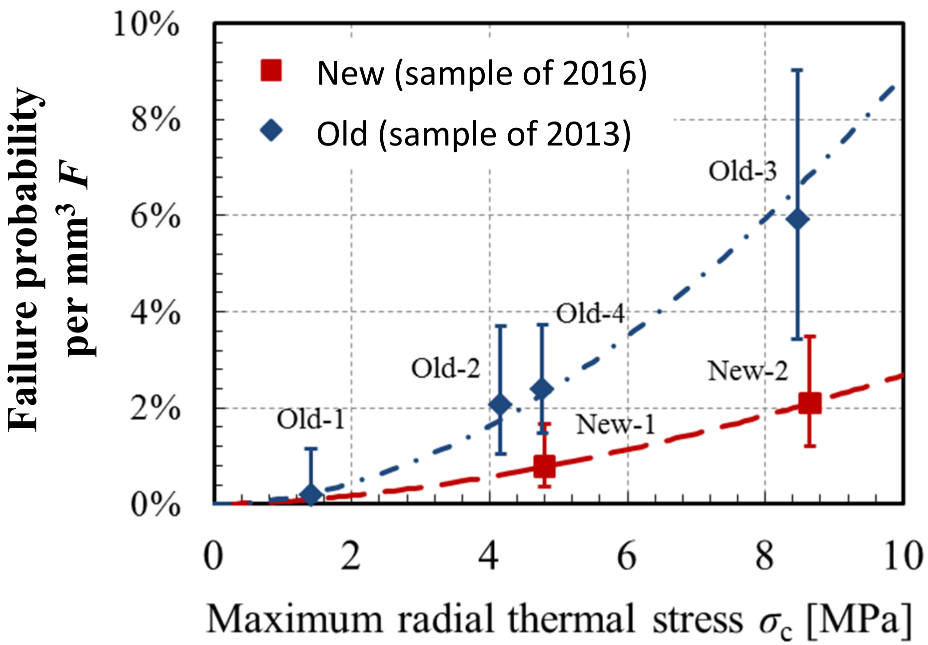
No degradation ~ 400 MPa

Evaluation of failure probability of delamination

<Delamination stress by thermal stress>







$$F(\sigma_c, V) = 1 - \exp\left[-V_{\mathrm{E}}(m,V)\left(\frac{\sigma_c}{\sigma_0}\right)^m\right]$$

$$V_{\mathrm{E}}(m,V) = \int_V \left(\frac{\sigma(\vec{x})}{\sigma_c}\right)^m \frac{dV}{V_0}$$

Average delamination stress of 2G HTS tapes have improved

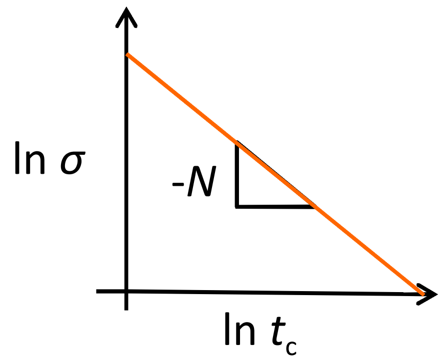
Fatigue Behavior of Ceramics

Fatigue of Ceramics

similar to stress corrosion cracking of metal

$$\sigma \propto {t_c}^{-N}$$

σ : Load stress
t_c : Failure time



Thermal activation phenomenon

→ **Lifetime estimation is possible by**

Fatigue factor *N* : characterizing the fatigue rate

Fatigue factor of common ceramics

- at Room Temp. → ***N* = 20-50**
- at Low Temp. e.g. in LN_2 → ***N* ~ 100** (Hard to fatigue)

→ Does 2G HTS wires behave similarly or not ?

Mechanical stress is applied to HTS wires **for long-term.**

→ In order to ensure **long-term reliability**,

it is necessary to understand the **fatigue behavior** of 2G HTS wires.

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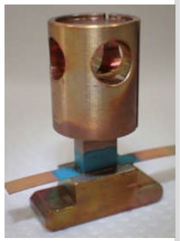
Evaluation of dynamic fatigue test

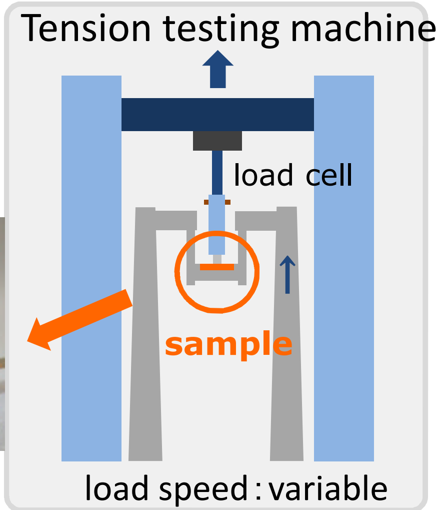
Dynamic fatigue test (Constant stress rate)

From the Weibull plot of fracture stress σ for various stressing rate a,
Data fitting was performed using the following equation on dynamic fatigue.
→ **Obtained the fatigue factor *N*.**

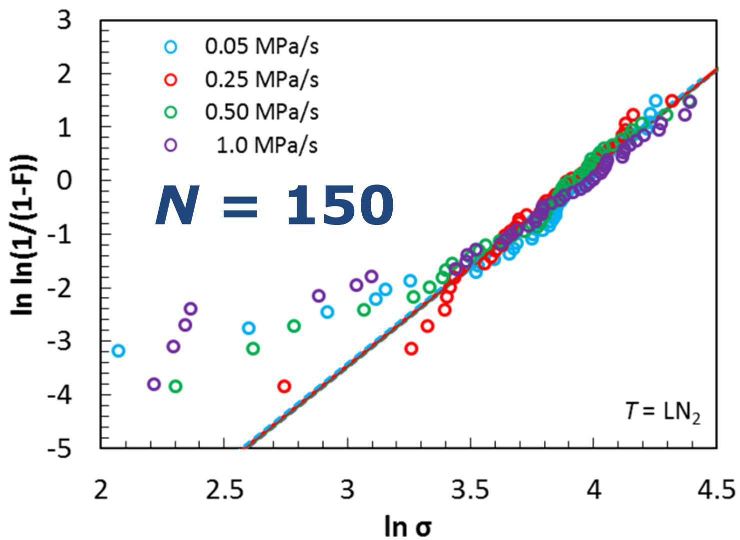
$$\ln(\ln(1-F)^{-1}) = \frac{m}{N-2}\{(N+1)\ln\sigma - \ln\alpha\} + C(N)$$

F : cumulative fracture probability
m : weibull parameter





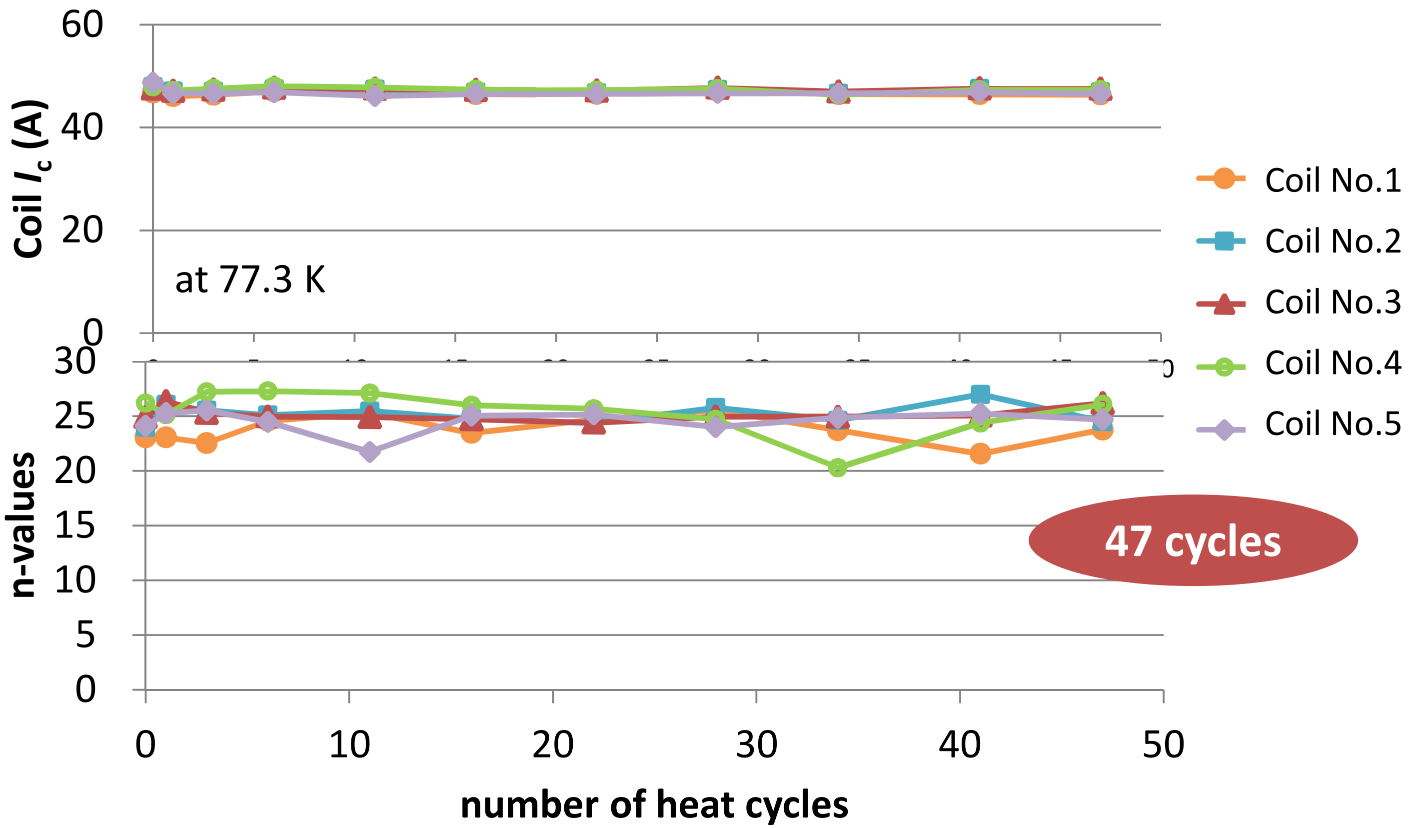
Fitting result of FYSC at 77.3 K



N > 100 in LN2 → Comply with the general theory of ceramics.
It suggests that the fatigue hardly occurs at low temperature.

Heat cycle test of small epoxy-impregnated coils

Sample : FESC-SCH04 (4mm-w, 50μm-thick substrate + 20μm-thick copper), Length :11m/coil
Inner diameter:30mm, Outer diameter:54mm, **OD/ID=1.8, Epoxy-impregnation**
Delamination stress : 9.6 MPa(calculated), RT ⇔ LN2



the impregnated coils showed good properties with initial were no degradation at 47 heat cycles

Outline

- Introduction
- Properties of Fujikura's conventional 2G HTS wires
- Recent progress of 2G HTS wires at Fujikura
- Evaluation of mechanical and fatigue properties of 2G HTS wires
- Feasibility Study of conduction-cooled sextupole HTS magnet
- Summary

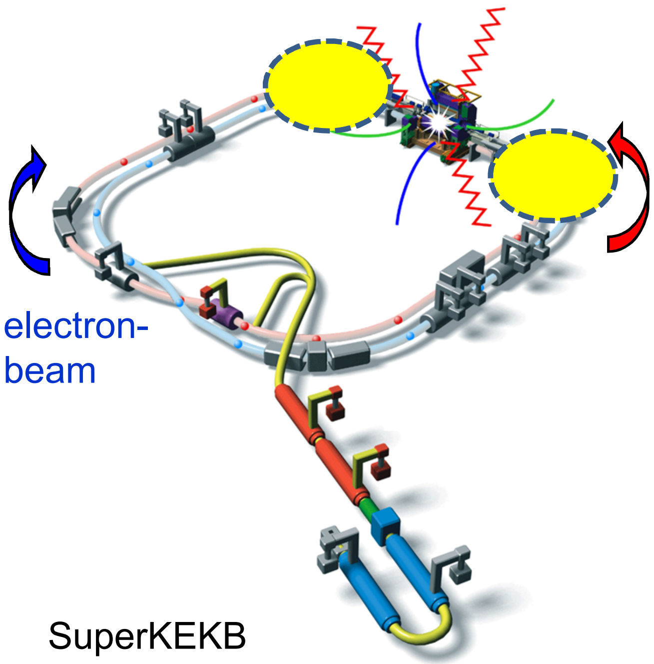
Feasibility Study of conduction-cooled sextupole HTS magnet

✓ **Development of quench detection and protection**
→ **Study of voltage detection**
→ **Optimization of copper stabilizer**

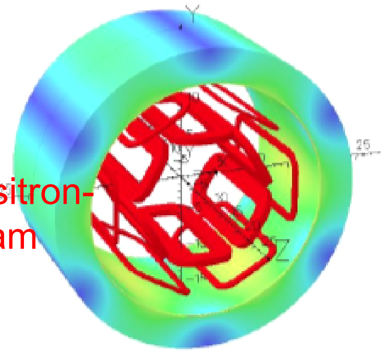
✓ Uniformity of magnetic field
→ Shield current
→ Windings

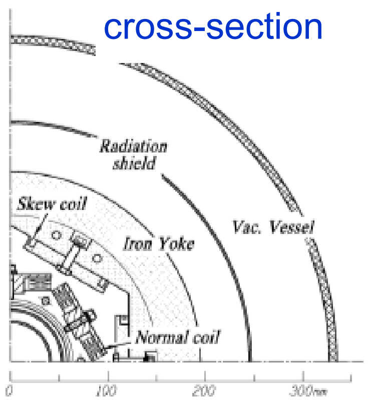
collaborate with KEK

K.Tsuchiya, et. al



SuperKEKB
KEK: High Energy Accelerator Research Organization





Parameter	Value
Bore radius	40 mm
Coil length	200 mm
Yoke radius(inner, outer), length	150.5, 195, 200 mm
Normal sextupole	
Coil width (inner, outer), height	38.6, 83.6 mm, 9.0 mm
Number of turns	112 x 2 turns
Operating current	257.6 A
Max B// on the conductor	2.27 T
Max B⊥ on the conductor	1.30 T
Stored energy	2.1 kJ
Skew sextupole	
Coil width (inner, outer), height	76.6, 94.0 mm, 4.5 mm
Number of turns	43 turns
Operating current	259.5 A
Max B// on the conductor	0.79 T
Max B⊥ on the conductor	0.56 T
Stored energy	0.13 kJ

Comparison of Experiment and simulation

Specifications of DP coil

Parameter	Value
Tape width	5 mm
Tape thickness	0.18 mm
Copper	40 um
Hastelloy	75 um
Inner/Outer diameter	50/69.7 mm
Height	11.7 mm
Turns	50 × 2
Coil I_c @77K, s.f. (10^{-7} V/cm)	101 A
Coil n @77K, s.f.	31

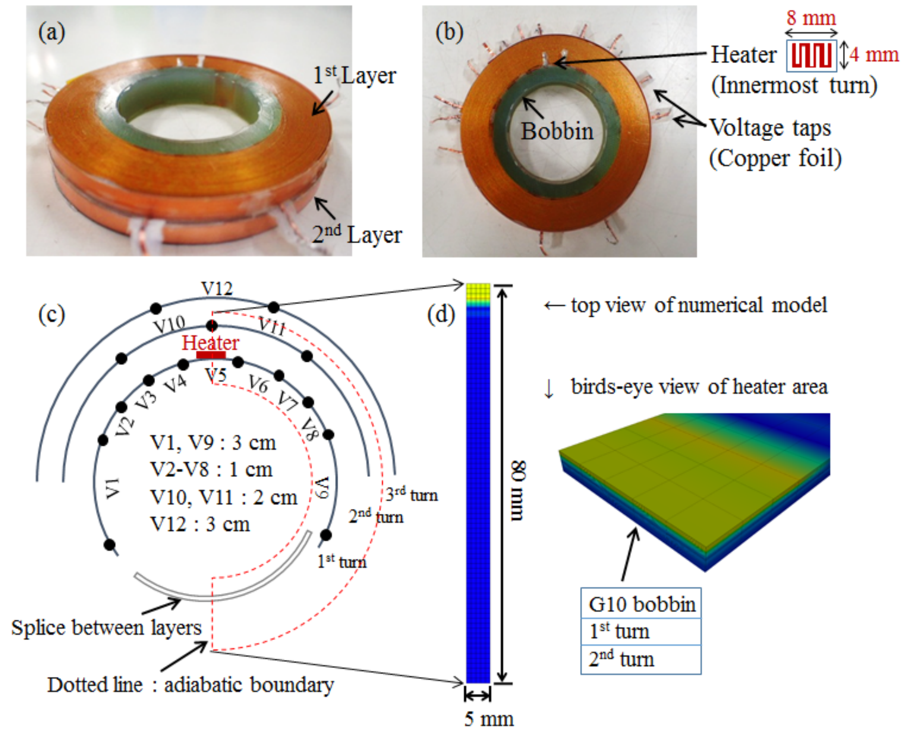
Simulation

$$\nabla \cdot \sigma(\nabla \phi) = 0 \qquad E_{sc} = E_c \left(\frac{J_{sc}}{J_c} \right)^n$$

Q_j ↓ FEM ↑ T

Thermal Simulation

$$C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_j + Q_{heater}$$

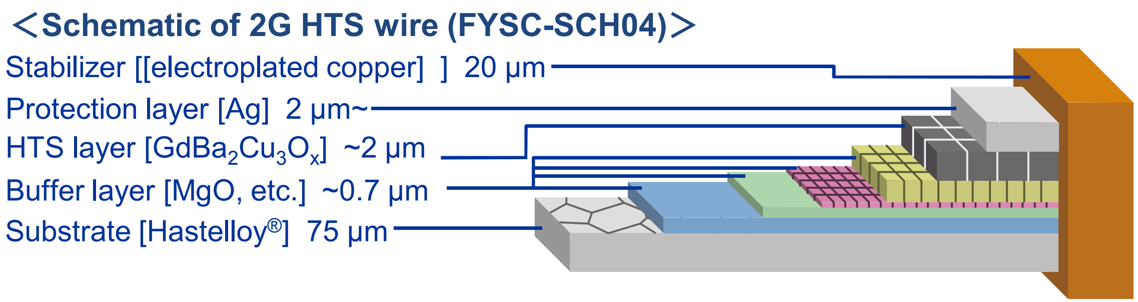


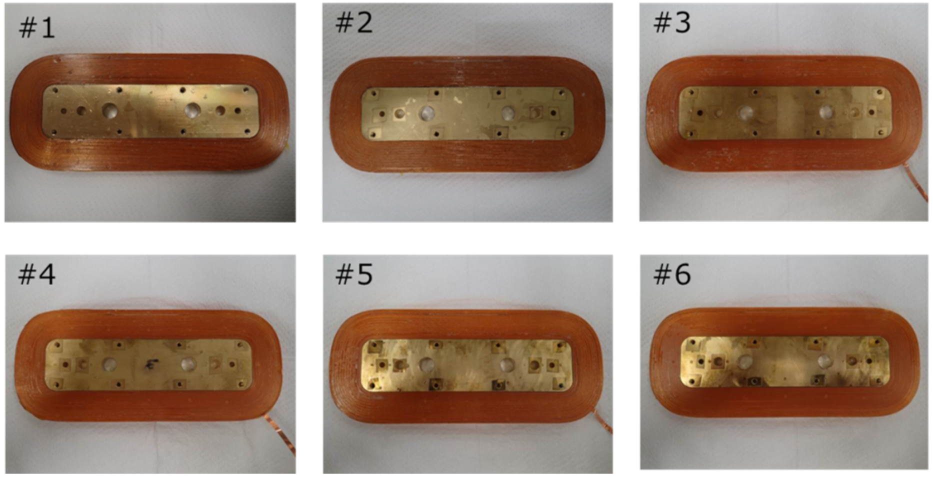
Hot Spot Temp.	Experiment		Simulation	
	40 mV	100 mV	40 mV	100 mV
10 ms	107 K	151 K	112 K	152 K
50 ms	118 K	164 K	121 K	165 K
100 ms	131 K	182 K	134 K	181 K

good agreement with simulation

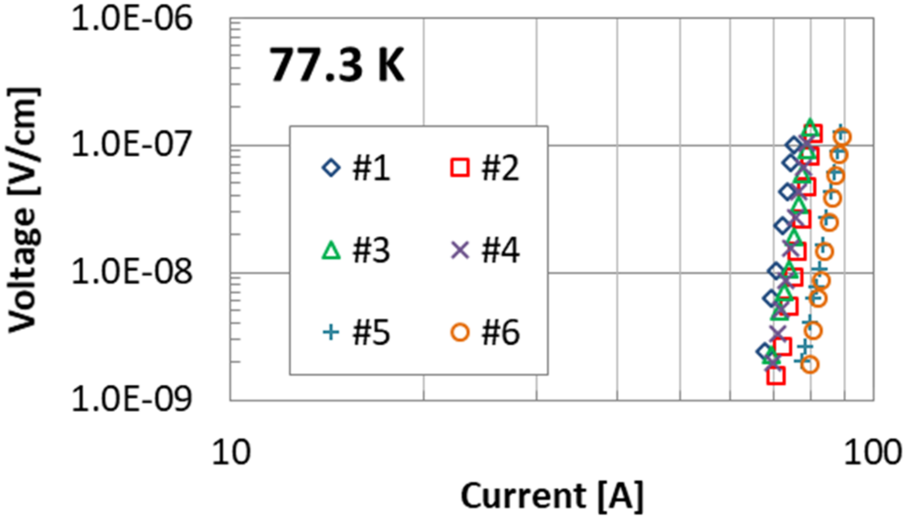
Fabrication and evaluation results of pancake coils

2G HTS wires : **FYSC-SCH04** with Fluorine coating polyimide tape insulation





6 DPCC with Vacuum Pressure Impregnation



I-V characteristics of 6 DPCC at 77 K

n-values > 25 at 77 K of all 6 DPCC → Good performance

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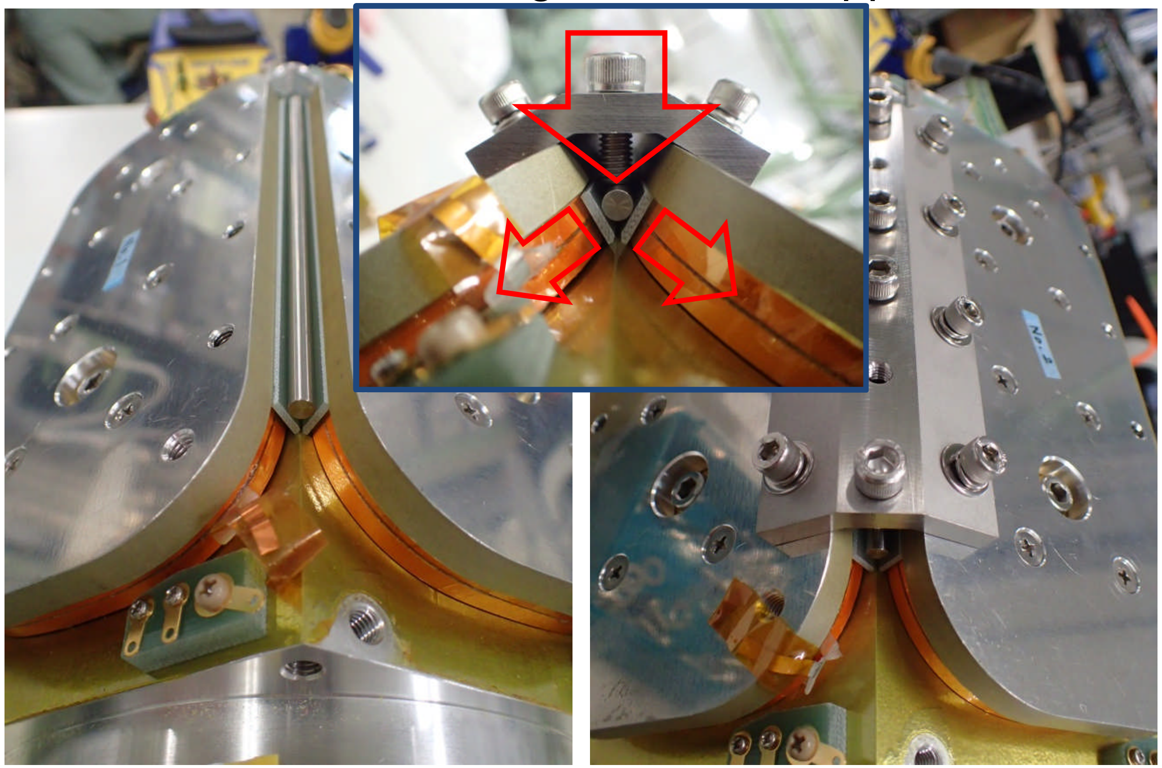
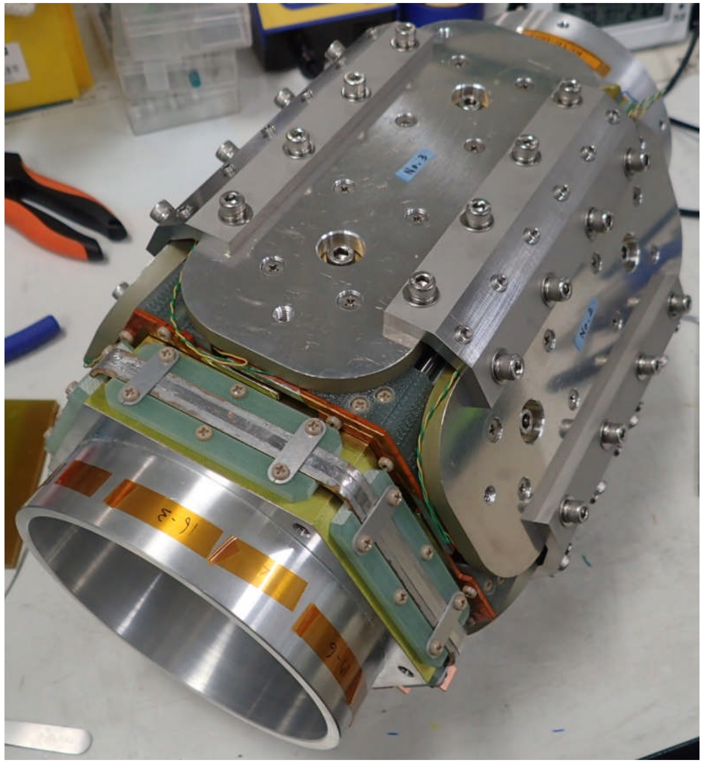
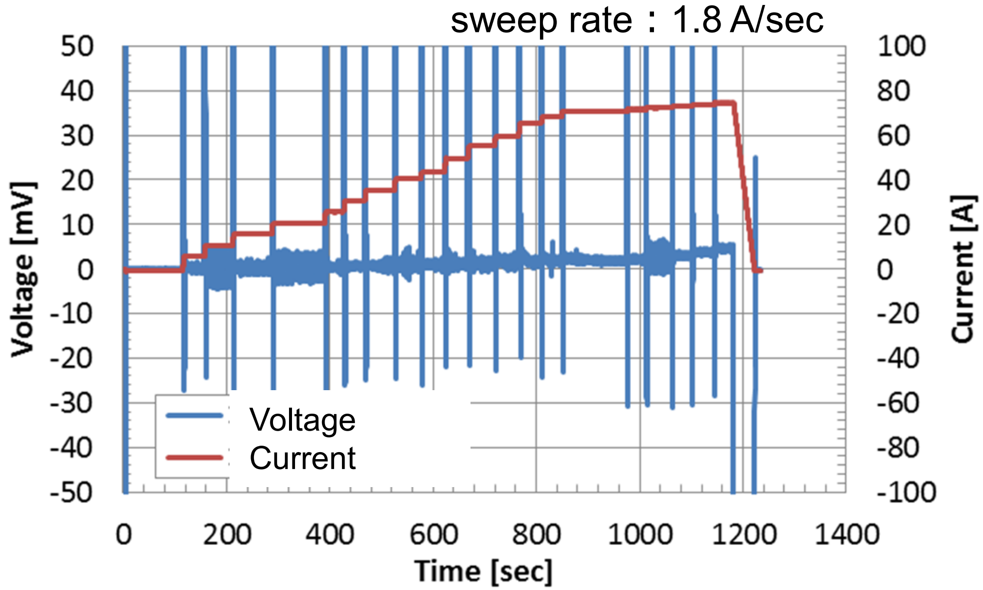
Assembled the sextupole HTS magnet

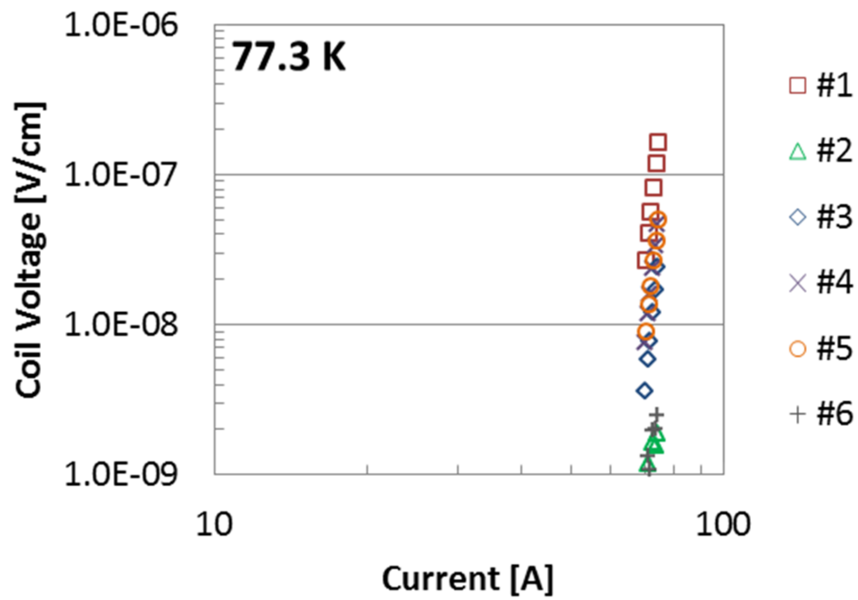
Electromagnetic force support





Measured results of the sextupole HTS magnet in LN_2





		#1	#2	#3	#4	#5	#6
each DPCC	I_c [A]	75.2	88.6	80.3	78.9	79.1	88.4
	n-value	36	37	34	31	29	30
sextupole magnet	I_c [A]	73.4	>75	77.9	76.3	76.2	>75
	n-value	33	-	31	30	30	-
	I_c ratio	0.98	-	0.97	0.97	0.96	-

I_c : 0.1 μV/cm criteria

Bmax (DPCC) : 0.356 T

Bmax (magnet) : 0.400 T

Calc. result
4% Ic reduction due to higher magnetic field

Summary

Introduction of conventional 2G HTS wires

- Stabilizers are applied 20 μm copper plate
- Uniform I_c with 600m length are obtained from mass-produced HTS wires without artificial pinning

Recent progress of 2G HTS wires and coils at Fujikura

- Fujikura has developed 2G HTS wires with artificial pinning (EuBCO+BHO) for Improvement in-field I_c by IBAD/PLD method
- Focus on uniformity and reproducibility for mass-production
- In order to investigate the fatigue behaviors of 2G HTS wires under delamination stress, we have evaluated the dynamic fatigue tests.
- Conduction-cooled sextupole HTS magnet for feasibility study have been fabricated and evaluated with KEK

Thank you for your attention !

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