IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation NM-6 given at CCA 2021, October 11 – 15, 2021, Virtual.

BMO-Doped REBCO Coated Conductor Development for Field Magnets by Using Hot-wall PLD Process

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AIST

Prof. T. Kiss
Kyushu Univ.

These works include results obtained from *" Project to Promote Commercialization of High-Temperature Superconductivity Technology (2016-2020)"* being consigned or subsidized by *the New Energy and Industrial Technology Development Organization (NEDO)*

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Contents

- **Over a decade passed from commercialization of REBCO wire, we learned much lessons…**
  - Productivity, for cost reduction
  - Longitudinal Uniformity, for magnet design ability
  - Mechanical reliability, for winding process stability
  - Middle & low temperature applications should be major market for the time being
- **NEDO program (2016-2020) assisted wire development in Fujikura**
  - Aiming for 3 T class compact MRI
- **BMO-doped REBCO lined up**
  - Higher in-field performance at temperature below 50 K
  - without spoiling
    - High throughput / high growth rate condition
    - Good-Uniformity, self & in-field J_c
  - 2 mm wide tapes (FESC-SCH02) also lined
  - Mechanical strength including delamination evaluated
- **Summary**

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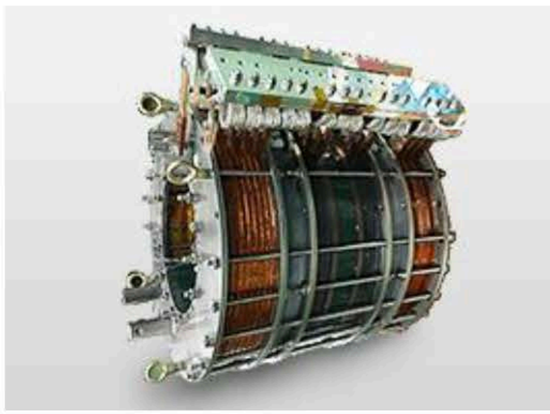
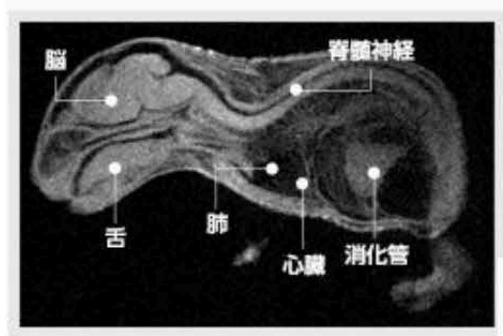
Major commercial shipment of Fujikura's REBCO coated conductor

19 km long 5 mm^w wire has shipped for Tohoku Univ. 25 T magnet (2013)
30 km long 4 mm^w wire has shipped for 3T class test MRI by Mitsubishi Electric (2015)
80 km long 4 mm^w wire has shipped for NEDO MRI program (2016-2018)

Operating temp. 4.2 K~30 K





マウス胎児の撮像画像(全長約25mm)

1/3 demo of drive mode 3-T class MRI

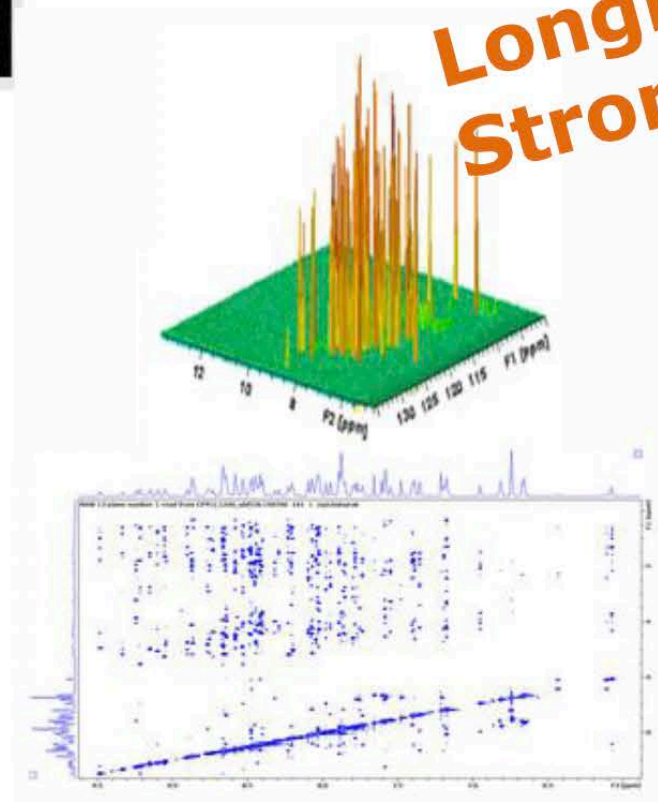
http://www.mitsubishielectric.co.jp/corporate/randd/spotlight/a32/index.html

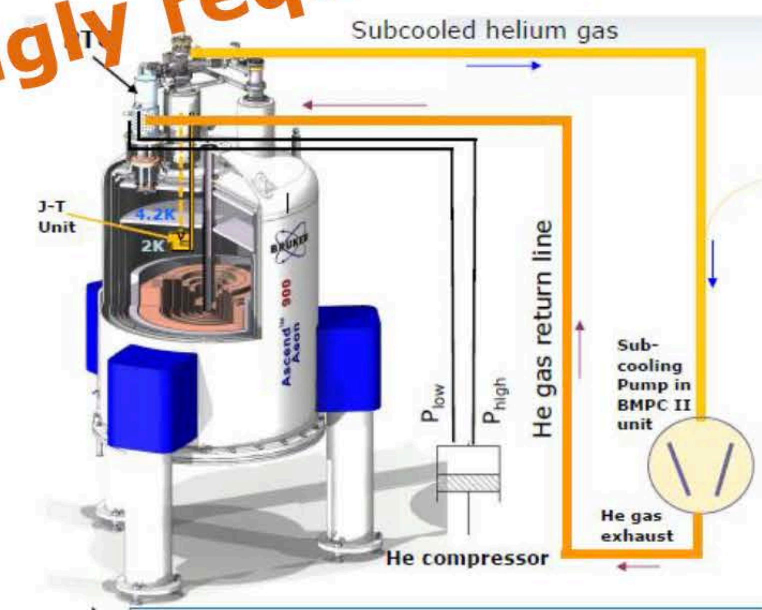
Longitudinal uniformity Strongly required

Bruker 1.2 GHz high field NMR system (2019)

World first 1.2 GHz NMR
28.2 T magnet
with 54 mm bore

REBCO wires shipped for the inner coil at the highest field part





Dr. Gerhard Roth:
"Ultra-High Field Magnets at Bruker"
UHF Workshop at NIH, Nov. 12-13, 2015

https://ir.bruker.com/press-releases/press-release-details/2019/Bruker-Announces-Worlds-First-12-GHz-High-Resolution-Protein-NMR-Data/default.aspx

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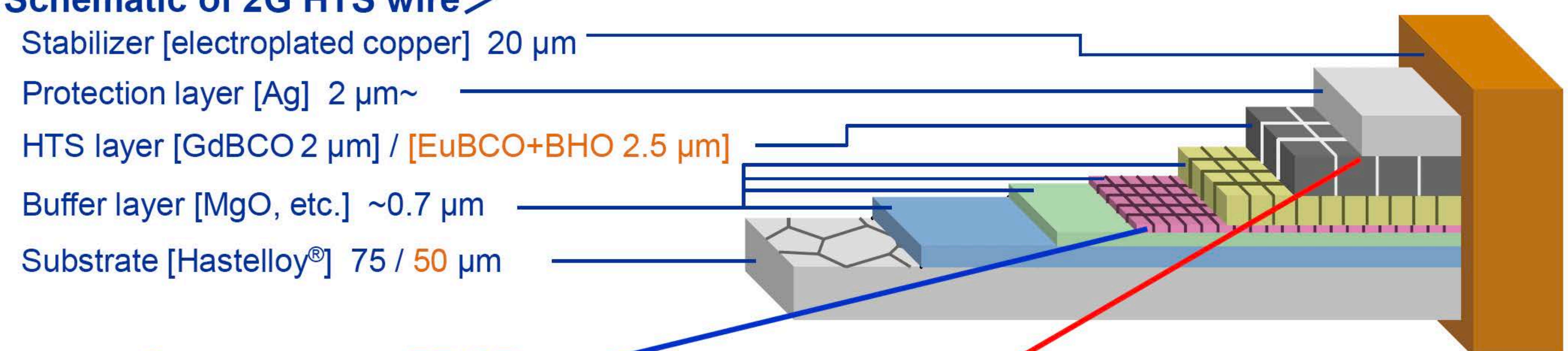
Typical specifications of Fujikura's 2G HTS wires

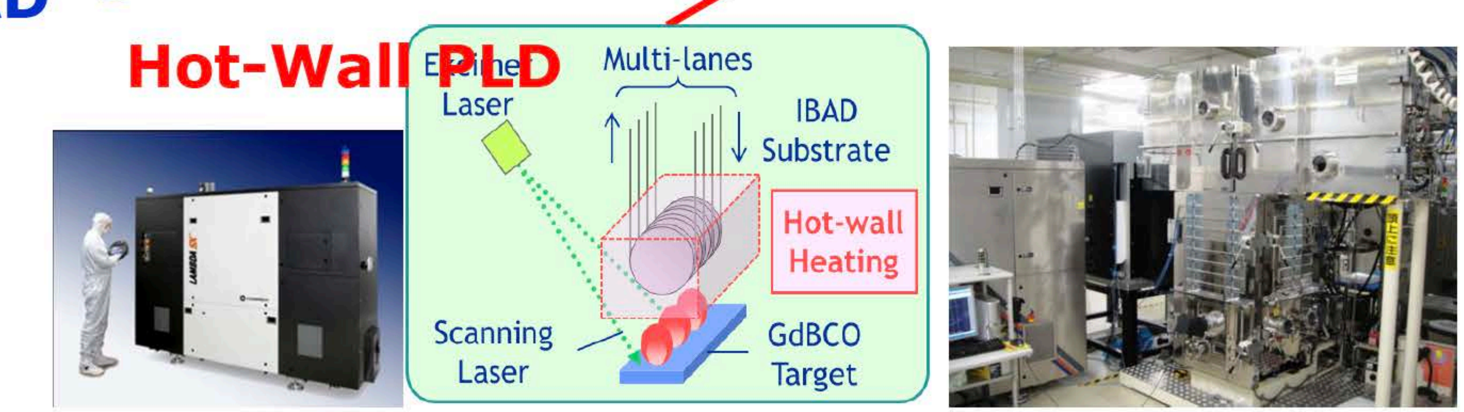
Item	Width [mm]*	Thickness [mm]*	Substrate [μm]	Stabilizer [μm]	Critical Current (I_c) [A] (@77K, s.f.)	Material of HTS layers
FYSC-SCH04	4	0.13	75	20	≧165	GdBCO
FYSC-SCH12	12	0.13	75	20	≧550	GdBCO
FESC-SCH04	4	0.11	50	20	≧85	EuBCO+BHO
FESC-SCH12	12	0.11	50	20	≧250	EuBCO+BHO

* Dimensions do not include thickness of insulating tapes.

in field I_c @ 5.0 T
~100 % up at 4.2 K
~35 % up at 30 K

<Schematic of 2G HTS wire>





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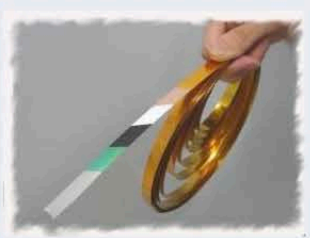
HTS development program by NEDO (FY2016~2020)

"Project to Promote Commercialization of High-Temperature Superconductivity Technology (2016-2020)"

Total budget ~50M$

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				

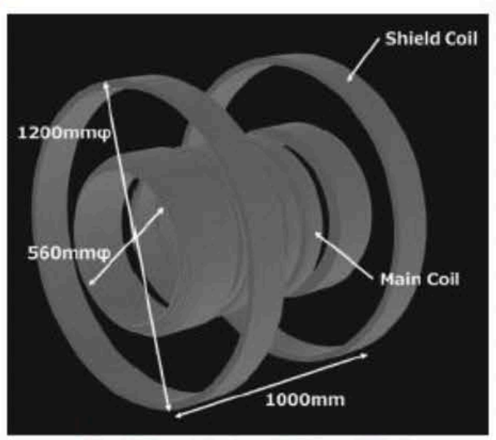


Fig. 1 Schematic view of half-size 3 T coil

Yokoyama et al. Abstract of CSSJ conf. vol.94 (2017) p76~

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

https://www.nedo.go.jp/events/report/ZZDA_100015.html

Conductor requirement for 3T class compact MRI magnet

3T class ½ size MRI
Total wire length: 80km
Field uniformity: 10ppm
Designed by Mitsubishi Electric

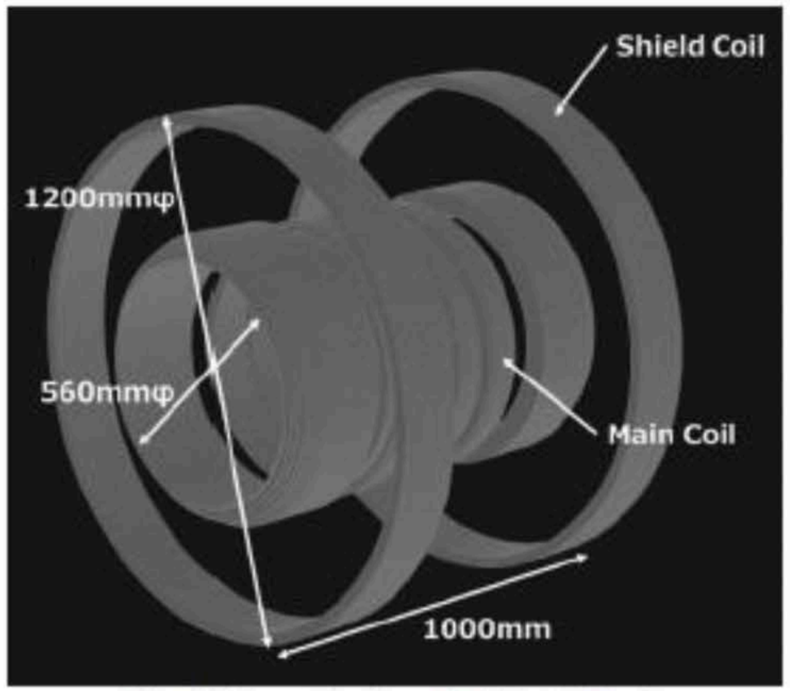


Fig. 1 Schematic view of half-size 3 T coil

Yokoyama et al. Abstract of CSSJ conf. vol.94 (2017) p76～

Required Specification for REBCO Wire by NEDO

Operation temperature: 30 K (for liq. He free)
Max. Experience Field: 7T
Max. Je: 400 A/mm^2
(for compact system as large as 1.5 T class)
Piece length with good homogeneity: 1 km
(to reduce joints for stable driven mode operation)

Elemental technology For Future PC mode

Joint resistance ~10^{-12} Ω by solder splicing
(for PC mode operation with inter-coil 100 joints)
to be presented in MT-27 / ISS2021

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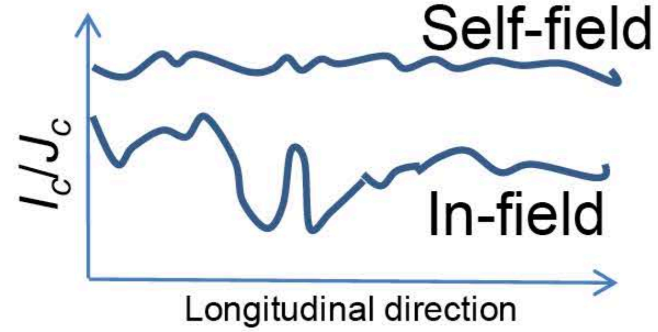
BMO doped REBCO by Hot-wall PLD

Key issues for BMO doped REBCO wire :
"High in-field I_c & Reproducibility"
"Long-length & Longitudinal I_c uniformity"

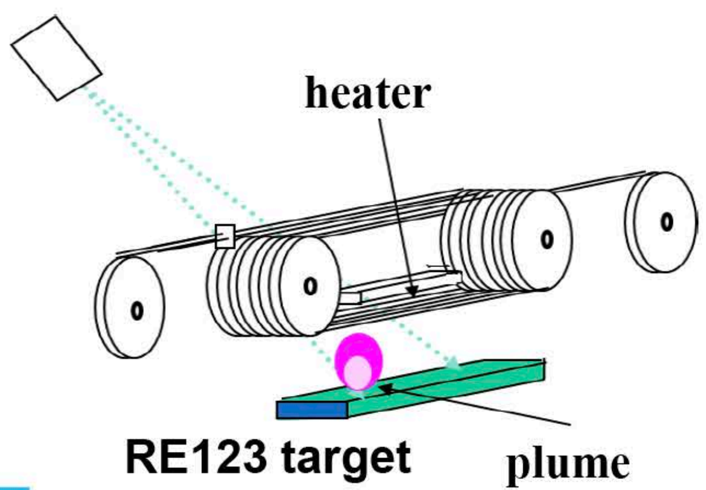


Additional deposition parameters: BMO nanorod structure

Hot-wall PLD system has furnace-like stable substrate heating

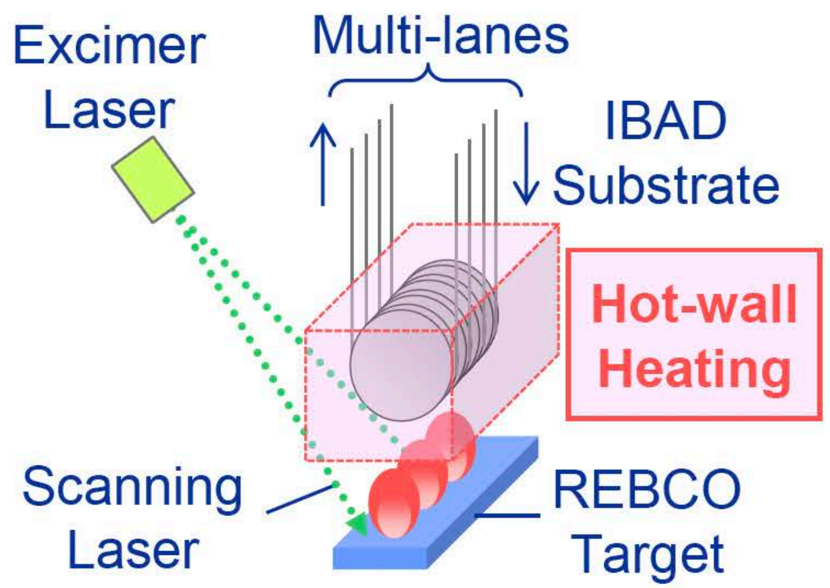
Heater block system

Used 1990s-2005

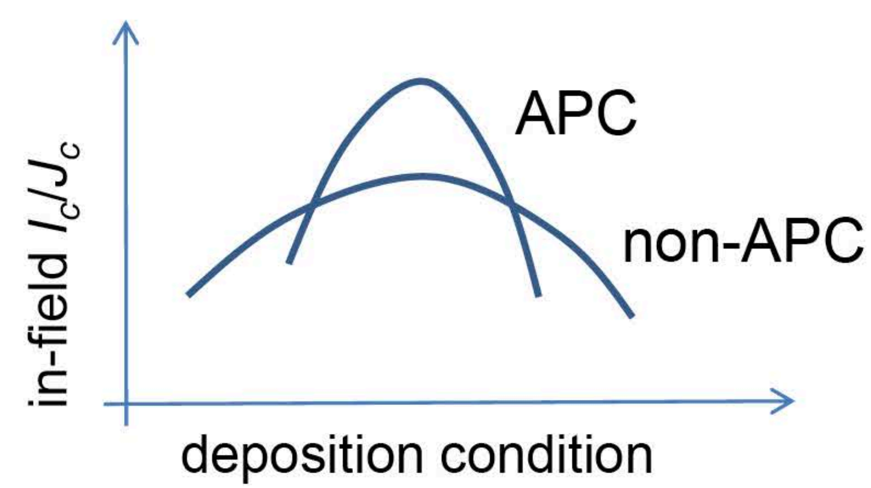


Hot-wall PLD system

Initial set up 2003-2008
reformed 2016-2018



Window width **Y < Gd < Eu**
APC < non-APC



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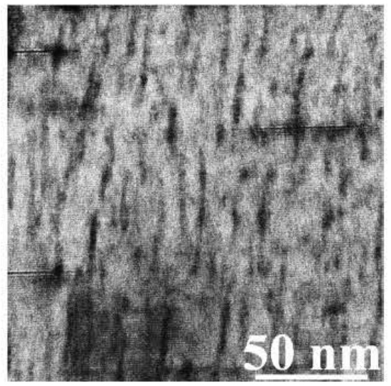
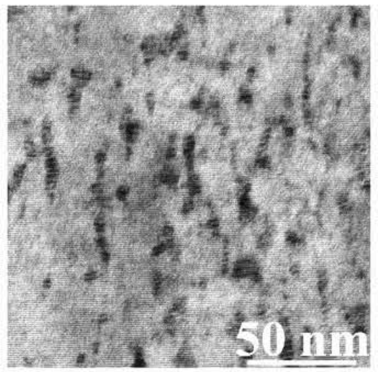
Growth rate dependence for J_c-B-θ properties of BMO-EuBCO

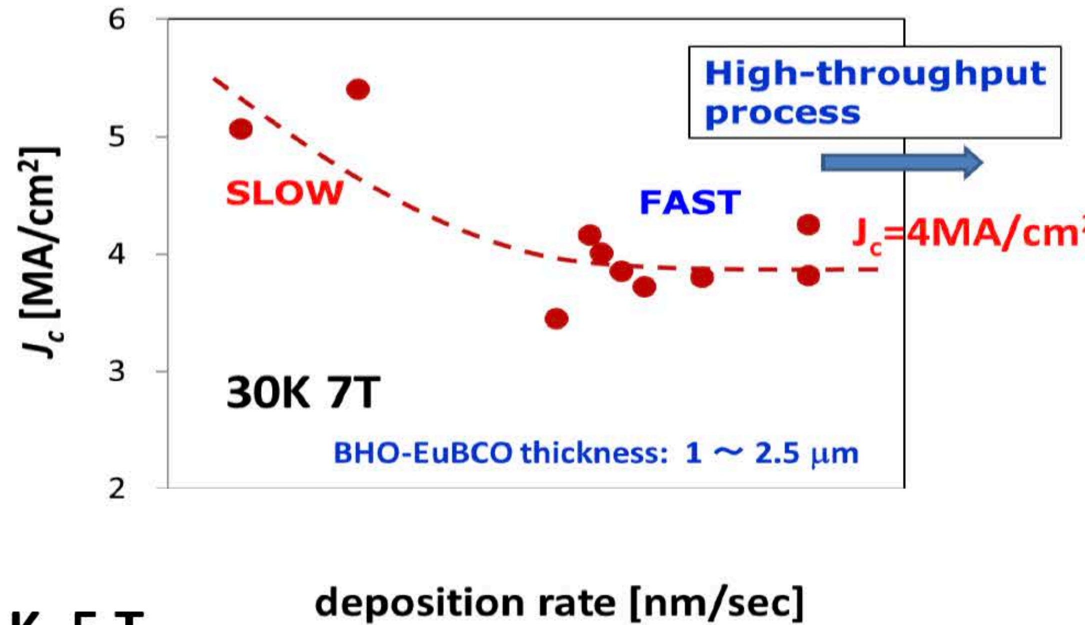
EuBCO-$HfBaO_3$

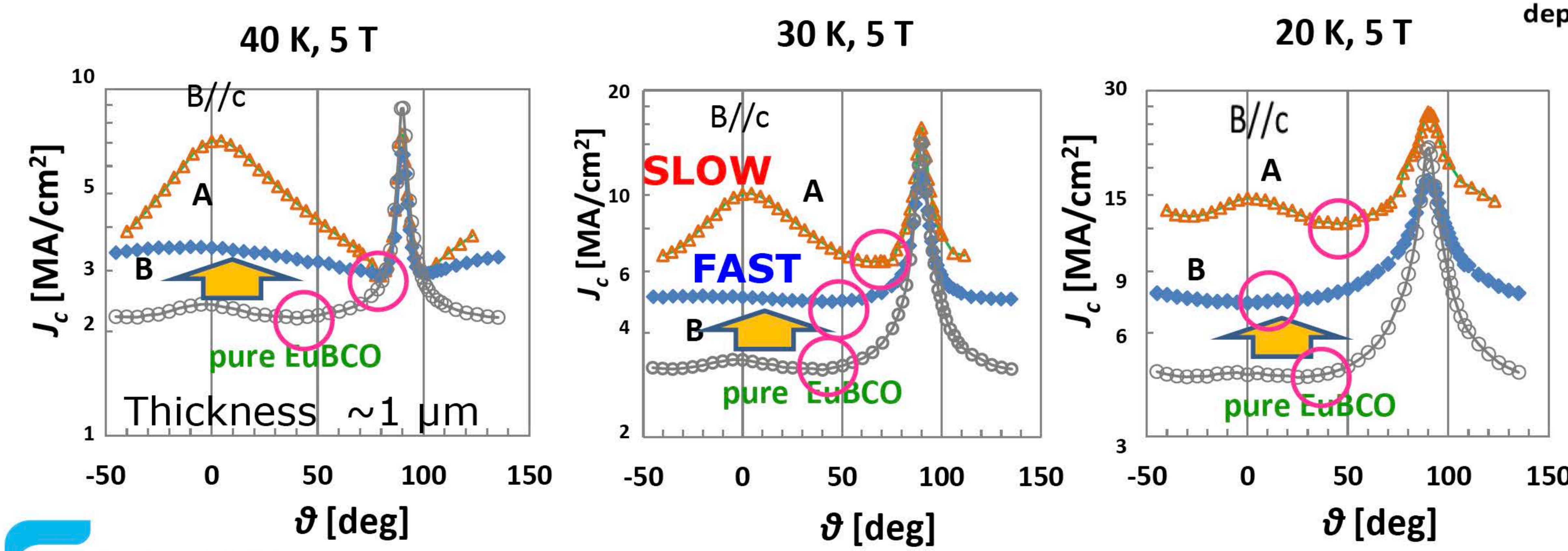
A Slow:5-7 nm/sec B Fast:20 nm/sec over





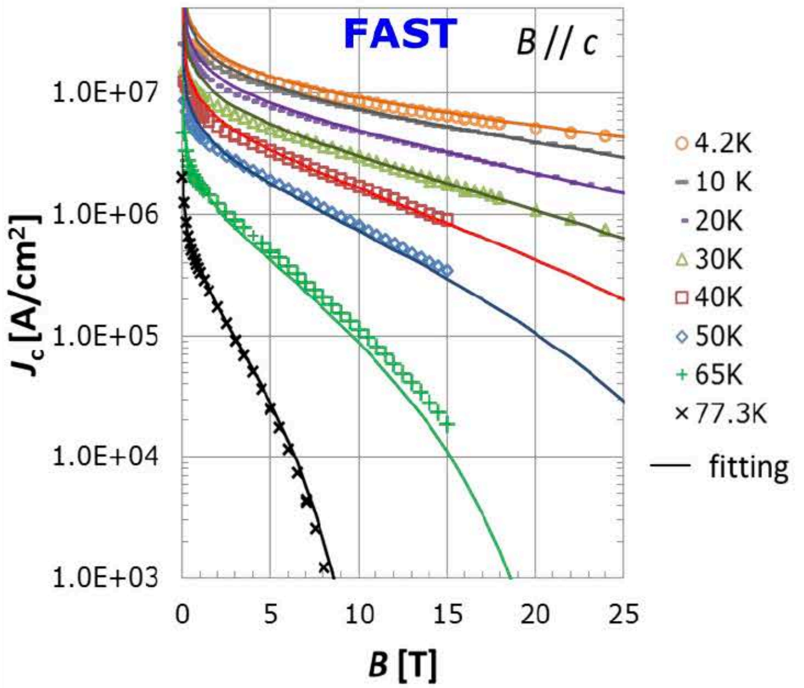
Scatterd short nanorods observed in high-growth rate FAST samples



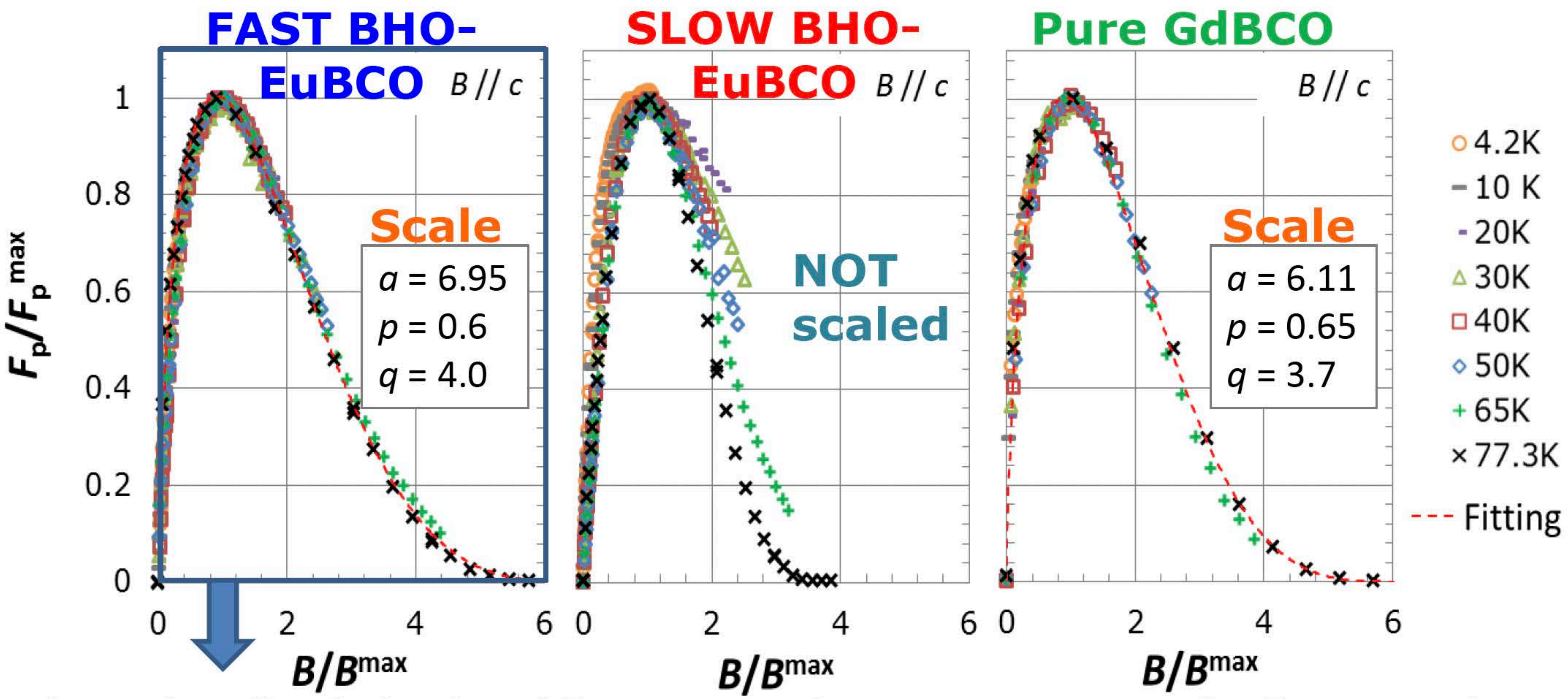


more isotropic property In wide temperature and field range

Scaling of flux pinning force density, F_p



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



A **good scaling behavior** of F_p curves can be seen **as same as the Pure sample**.

→ **Random pinning-like behavior of BHO.**

In case that F_p scales,

$$B_{irr} = aB^{max}$$

Scaling law for F_p

$$\frac{F_p}{F_p^{\,max}} = C\left(\frac{B}{B^{max}}\right)^{p}\left(a-\frac{B}{B^{max}}\right)^{q}$$

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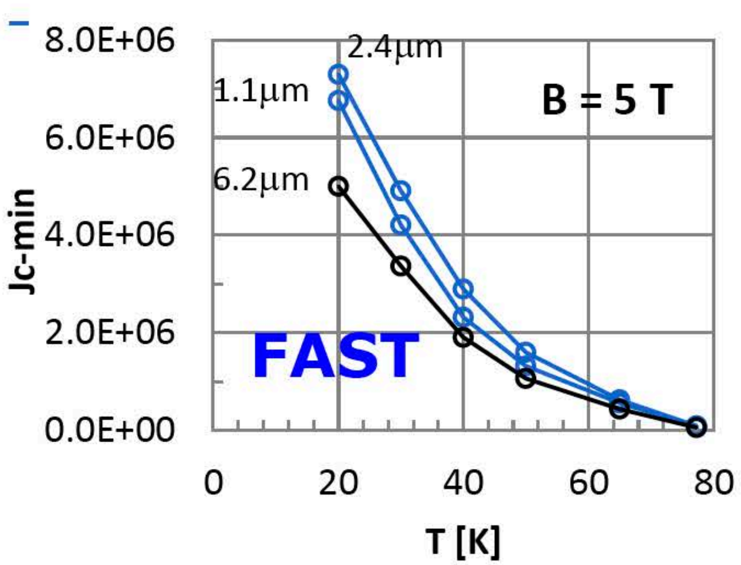
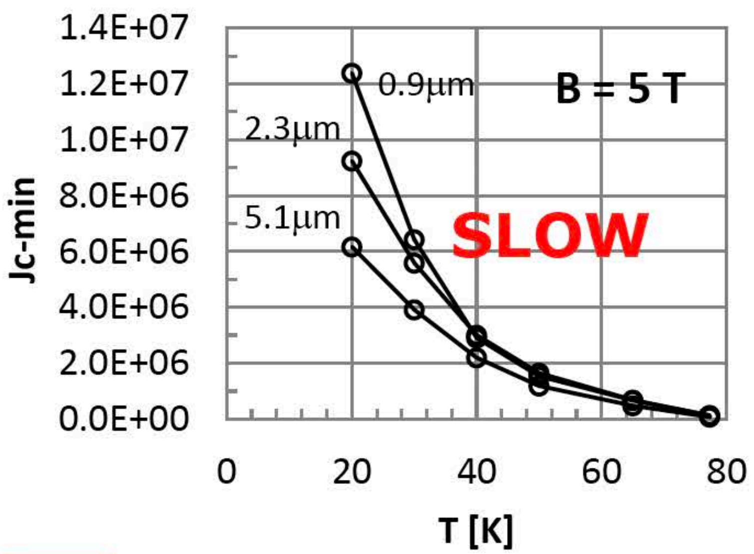
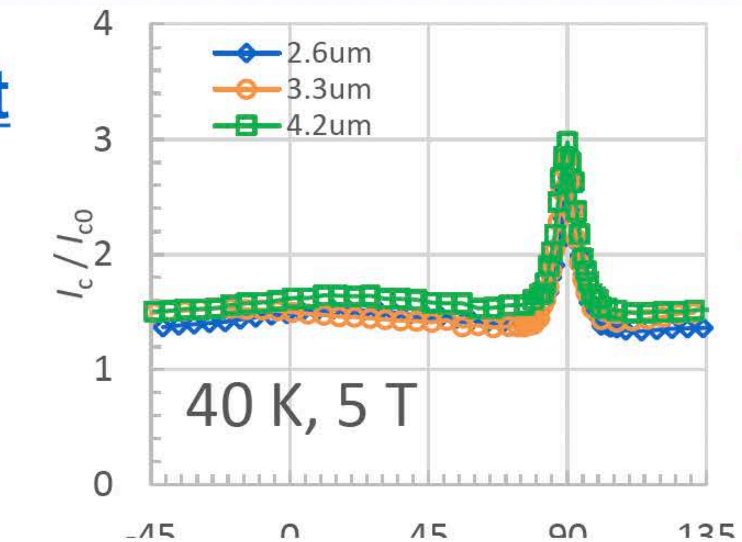
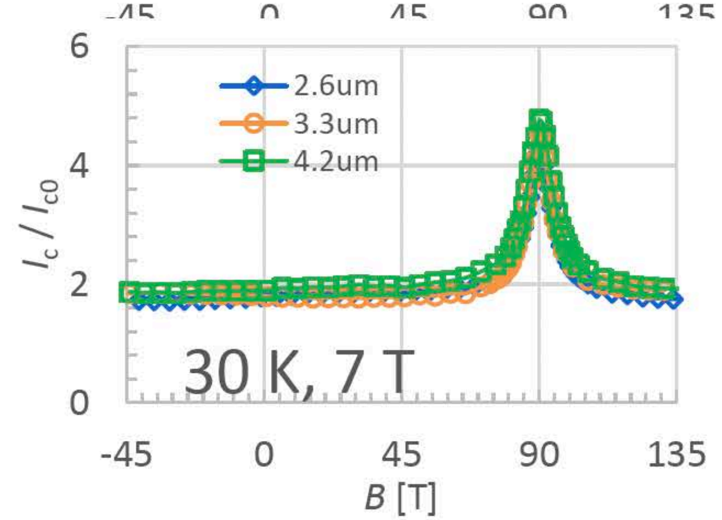
Thickness dependence for in-field I_c properties of FAST BHO-EuBCO

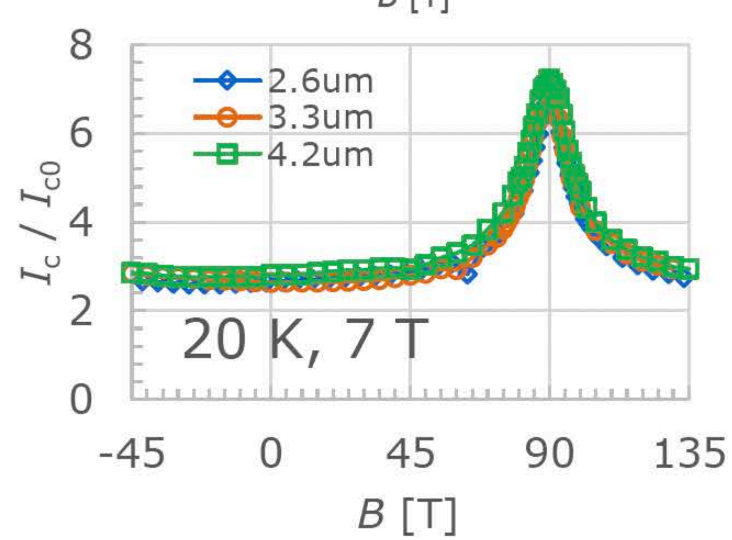
Less thickness dependent for FAST BHO-EuBCO



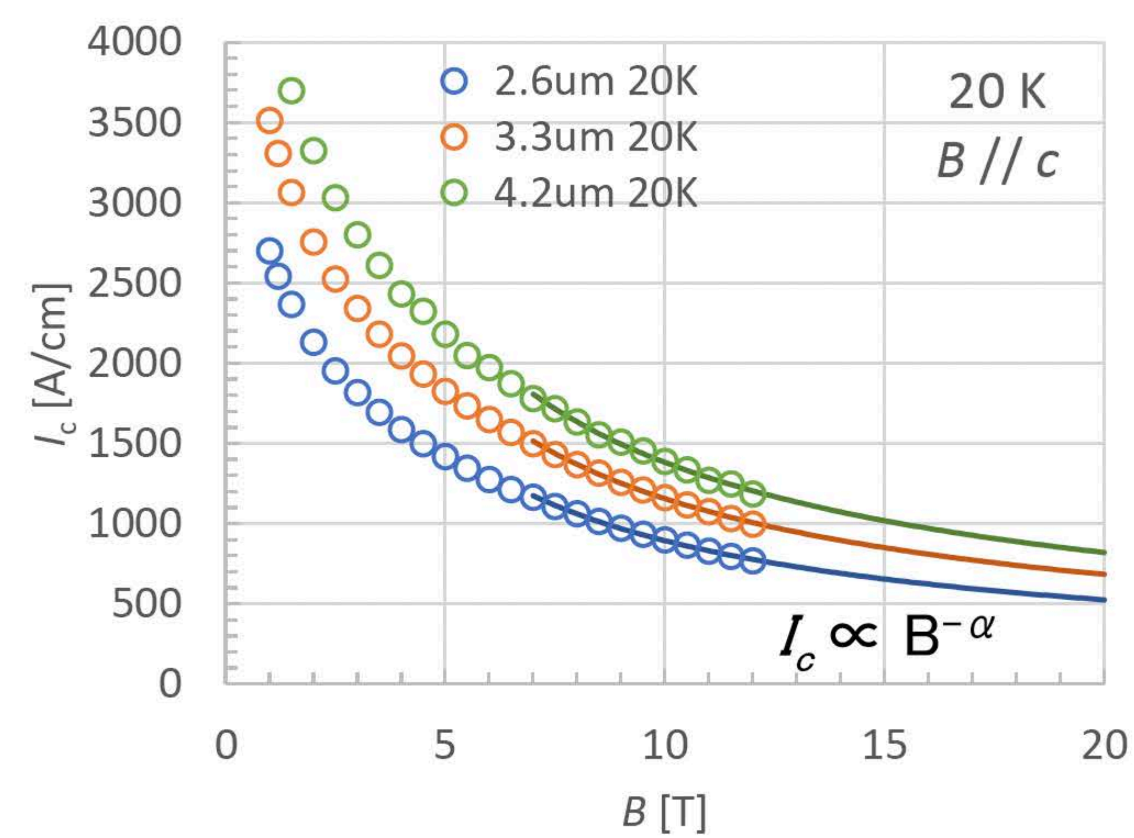


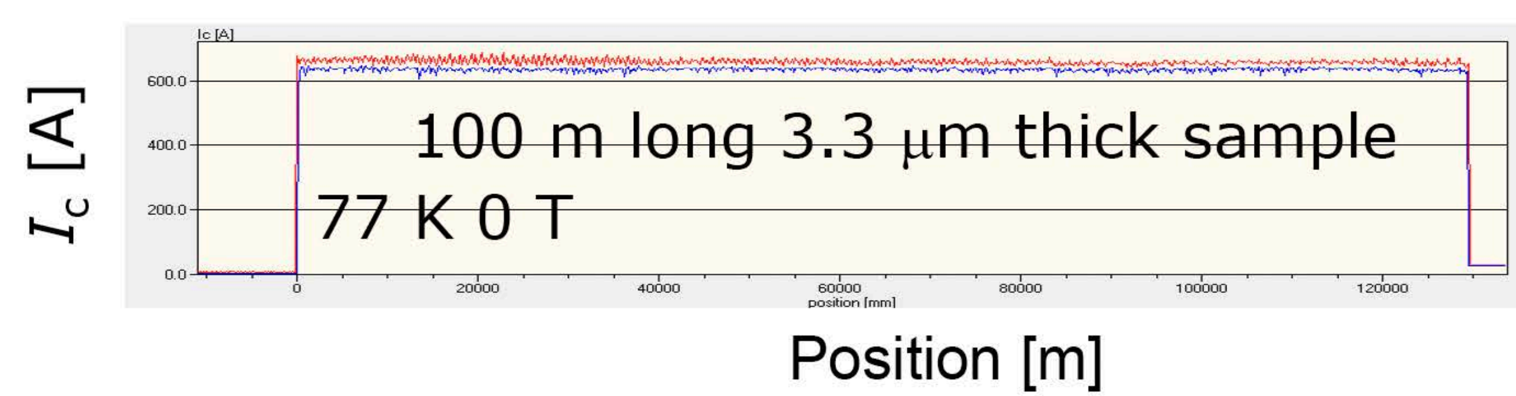






Almost the same *Ic-B-θ* shape up to 4.2 μm thick





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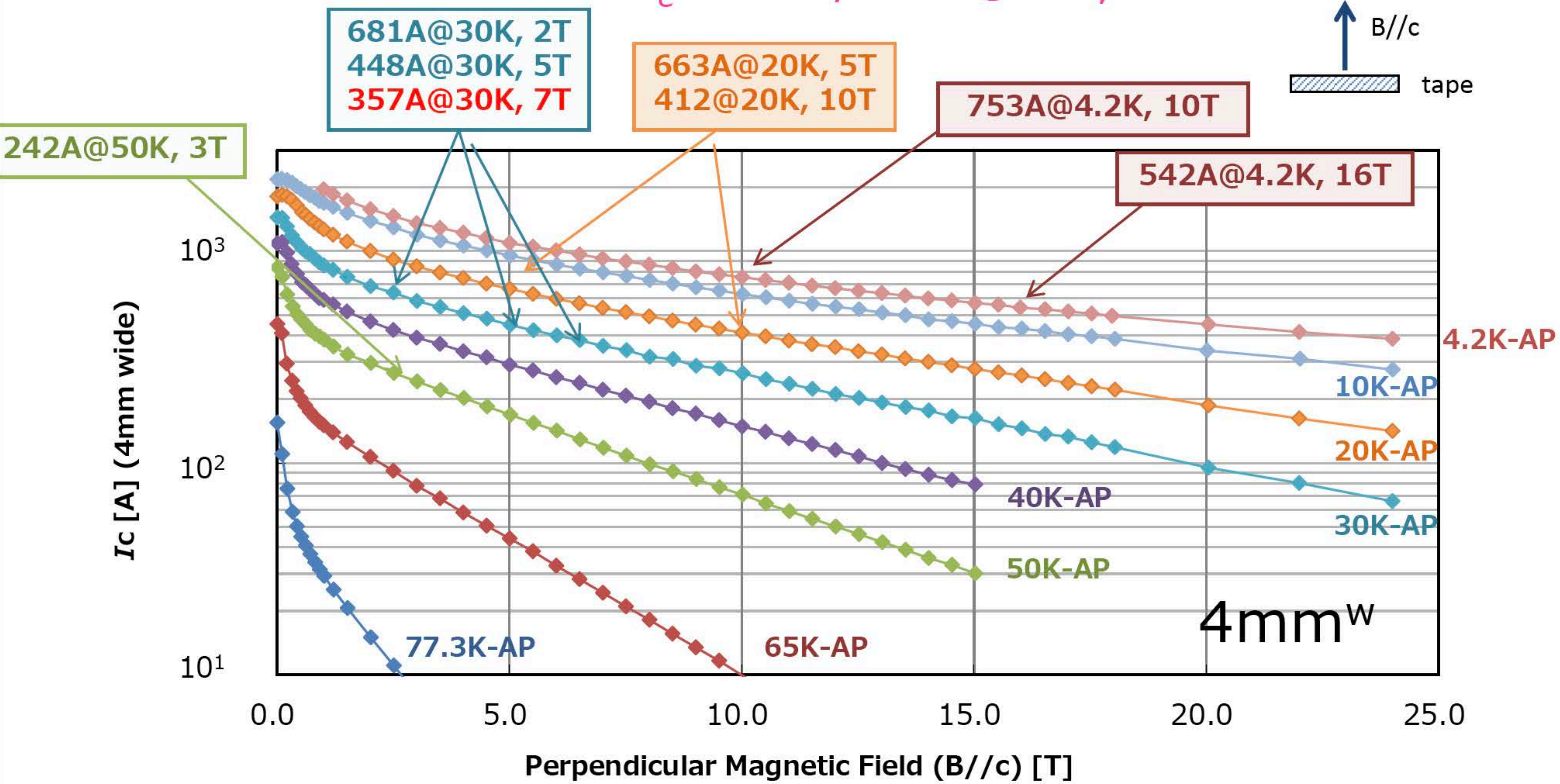
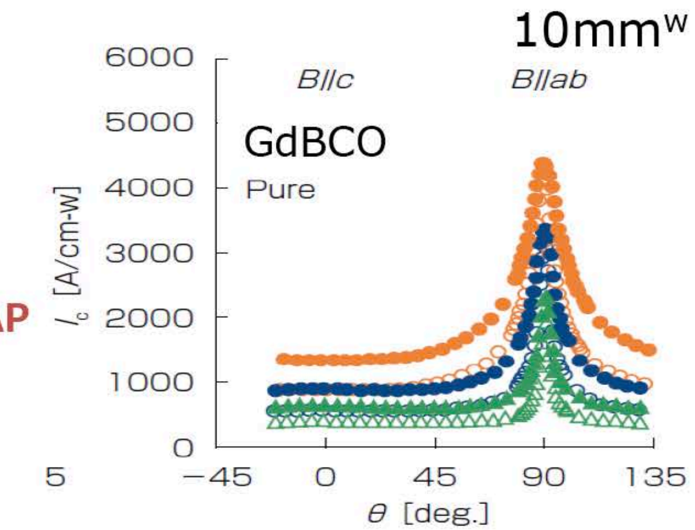
In-field *I*c Performance – FESC type – (AP)

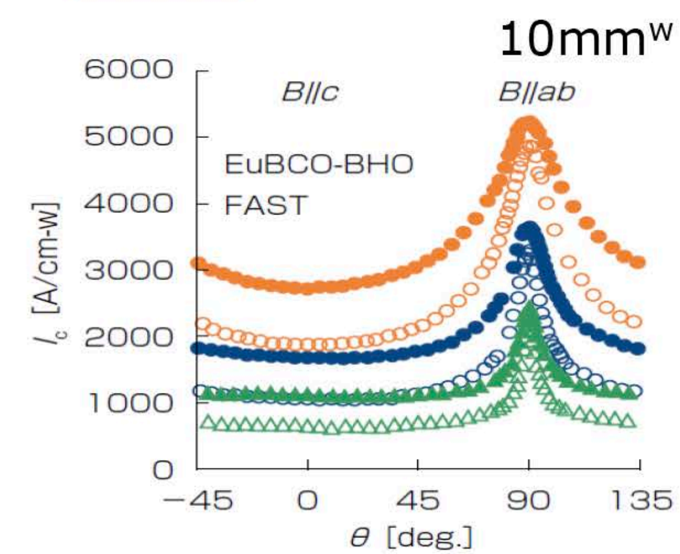
J_e=595 A/mm^2 @30K,7T



FYSC



FESC



AP specification is recommendable for use in magnet applications at lower temperature and higher magnetic field.

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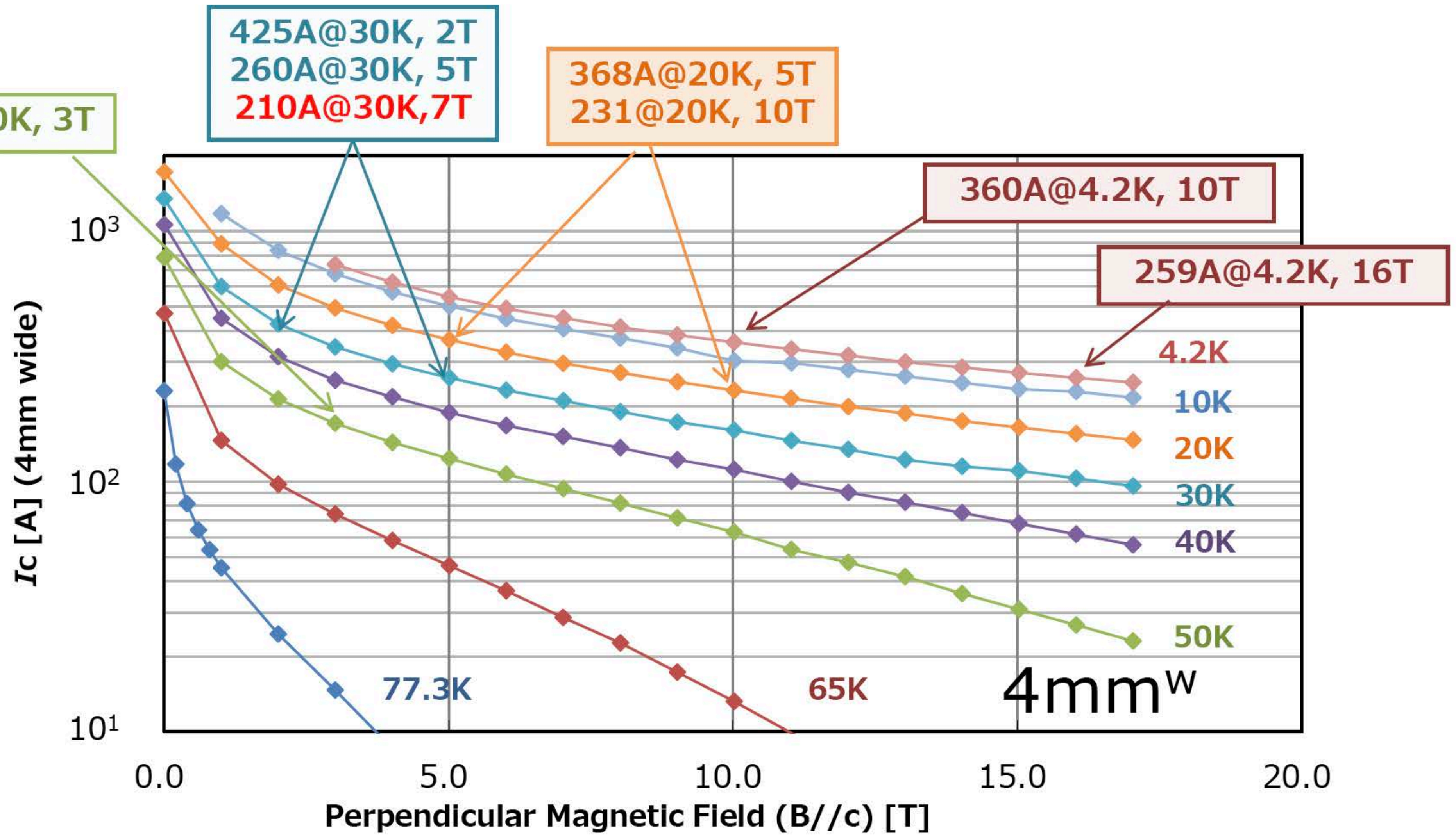
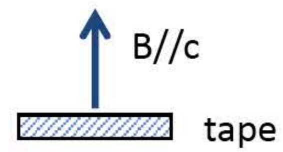
In-field *I*c Performance – FYSC type – (Non-AP)

J_e~300A/mm^2 @30K,7T





Non-AP specification is recommendable for cables or other general use at relatively higher temperature.

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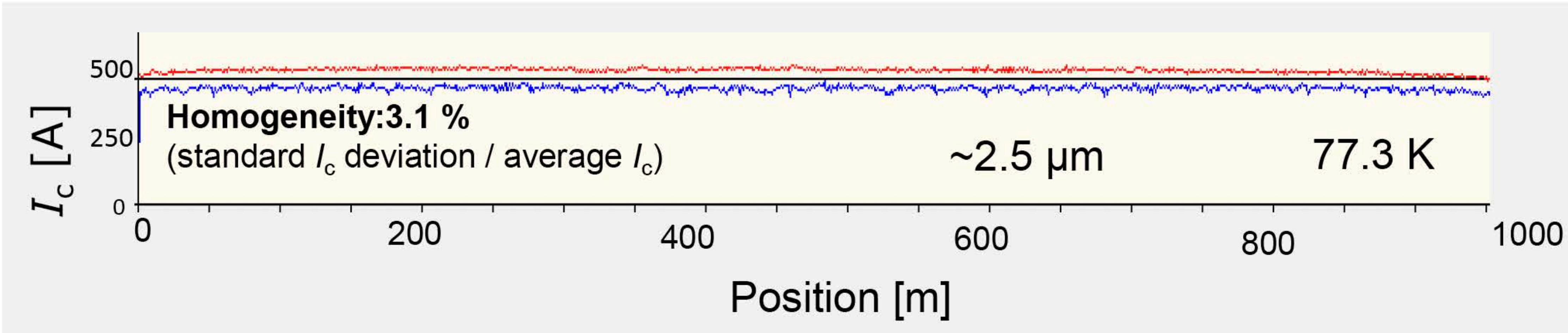
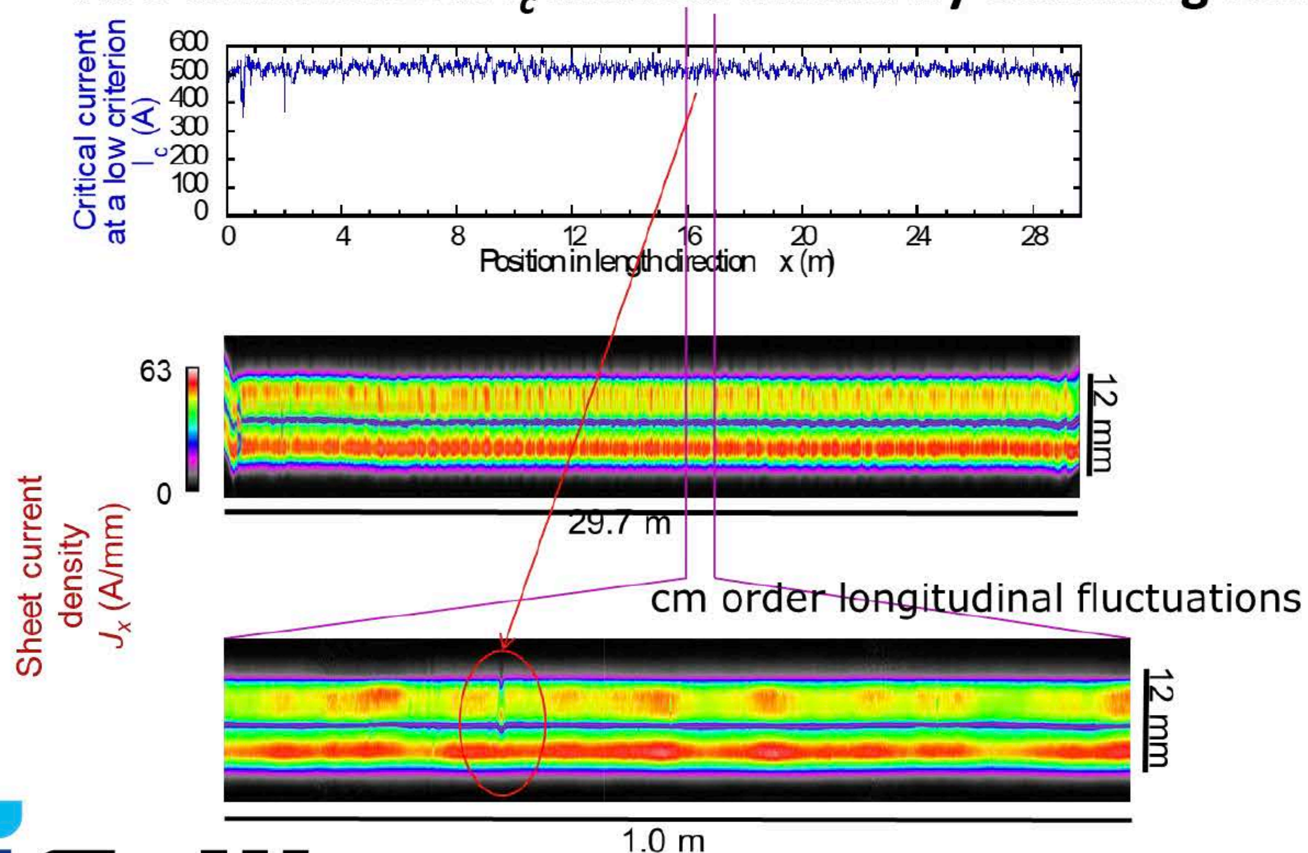
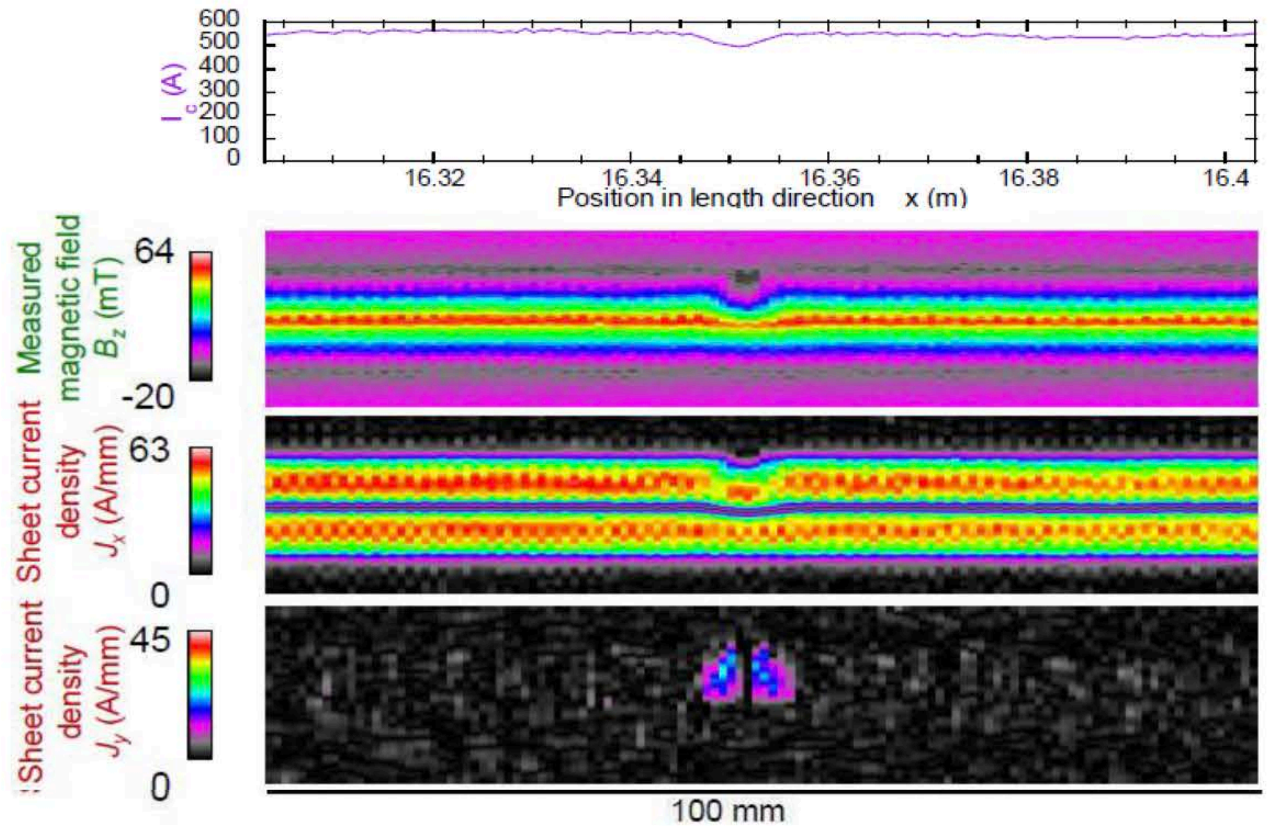
I_c uniformity of BHO-EuBCO wire of 12 mm^w

- Magnetization measurement of longitudinal I_c distribution for 1 km class wire



- Two dimensional I_c measurement by Scanning Hall Probe Microscope (SHPM)





mm size point defect affect E-to-E voltage for narrower wire

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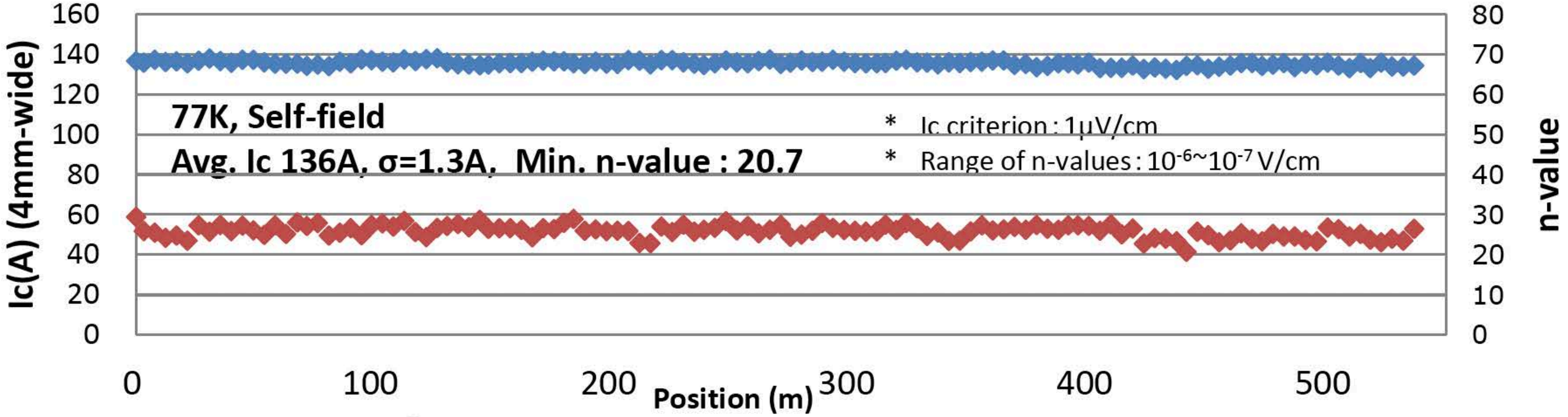
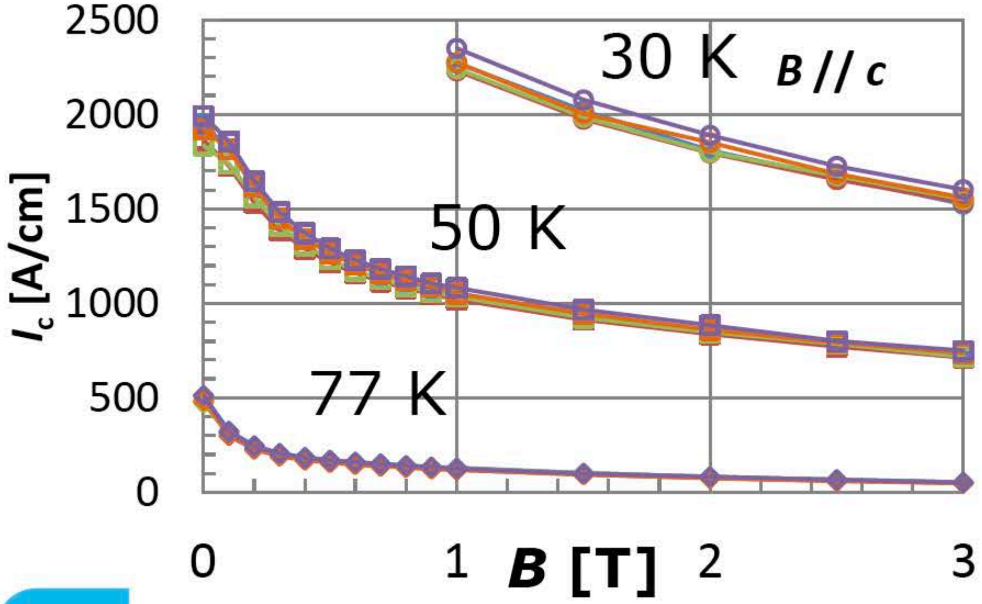
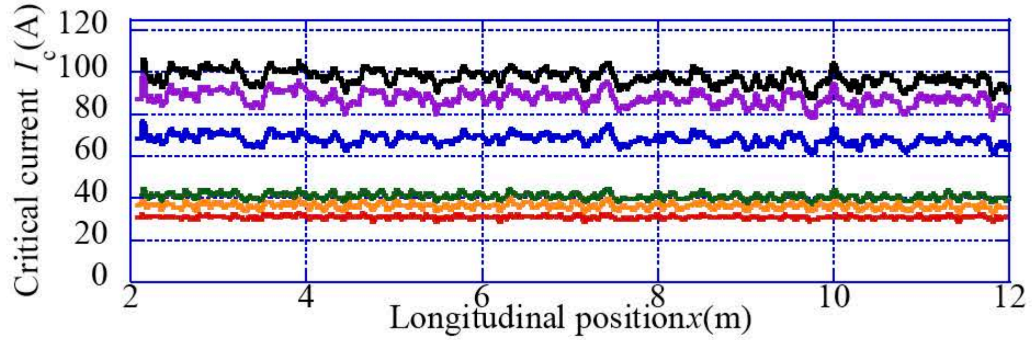
Self & in-field I_c uniformity of 4 mm^w BHO-EuBCO wire

■ current conduction measurement



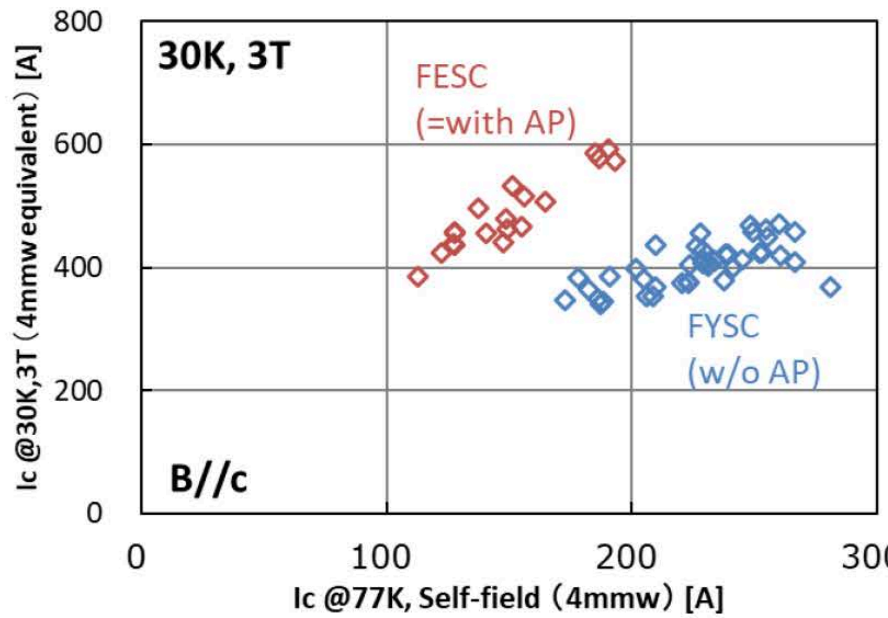


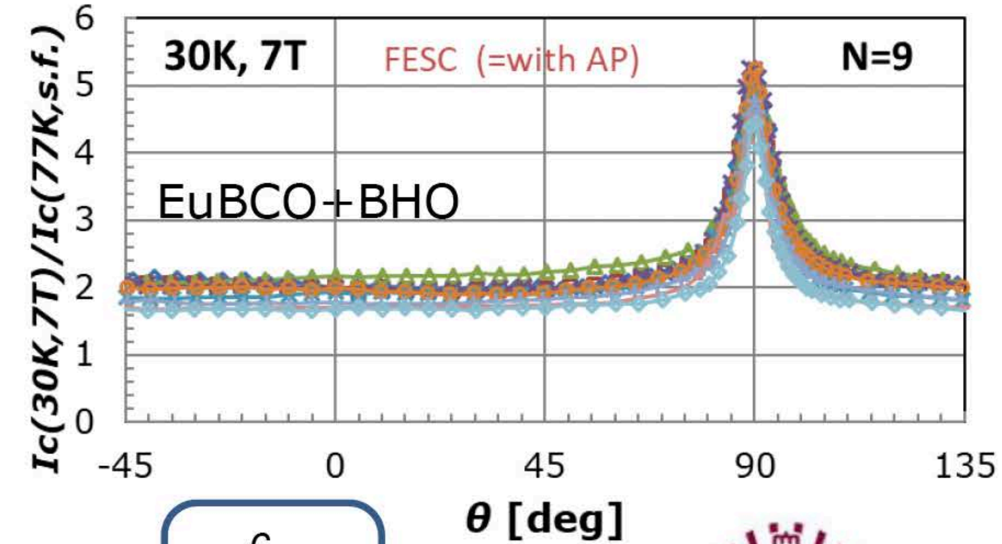
■ In-field magnetization measurement

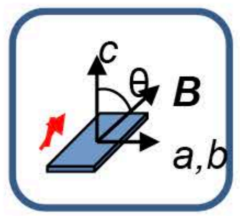


77 K B=0.025 T~2.0 T

■ rot-to-rot variation of in-field I_c / I_c (77 K, s.f.)







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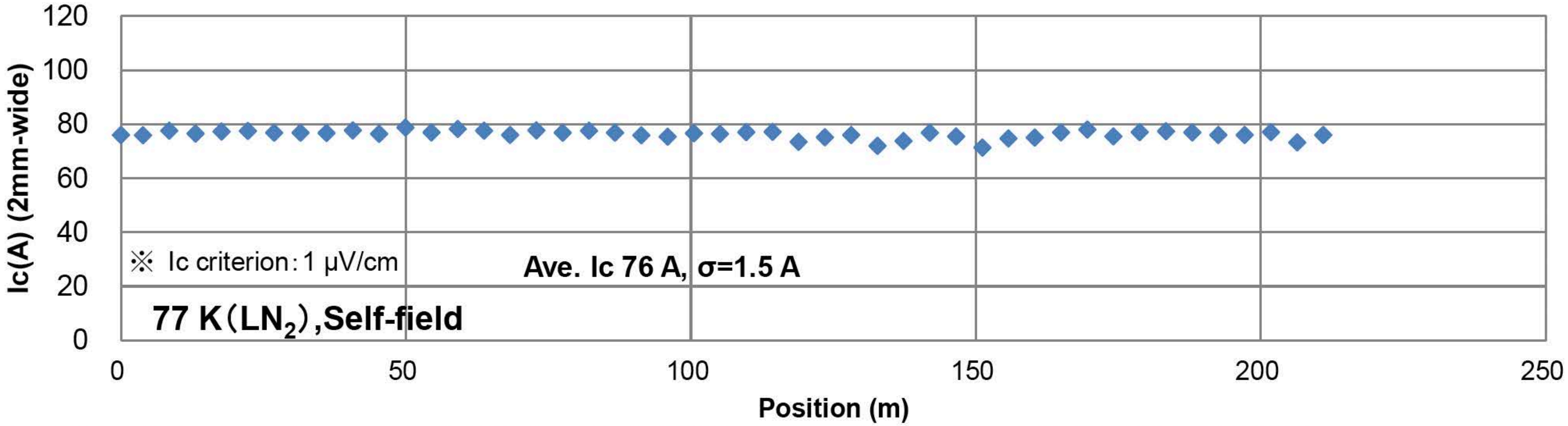
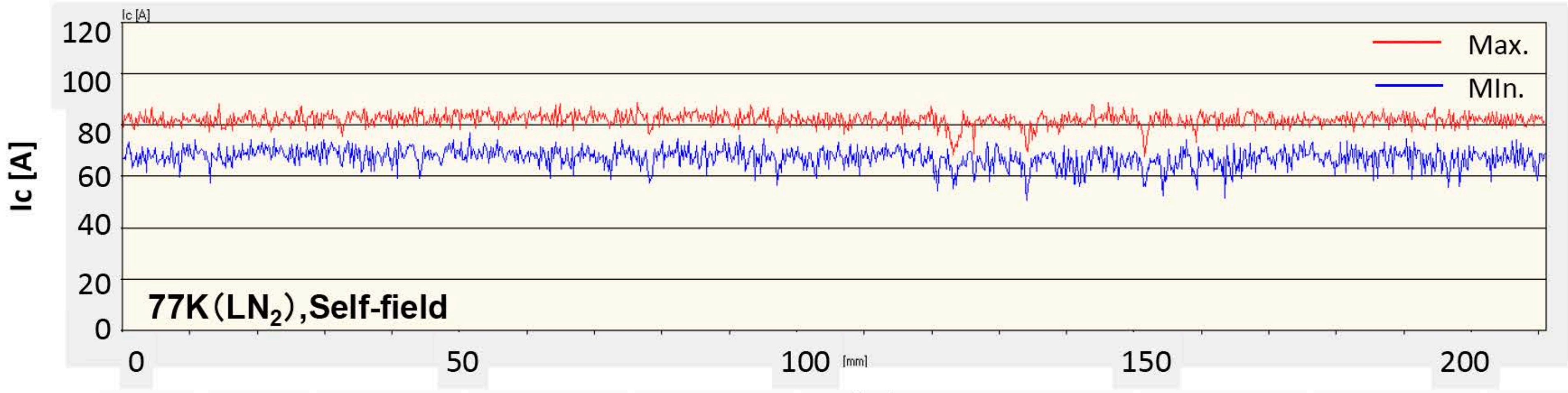
Example data of longitudinal I_c distribution of 2mm-wide tape

2 mm-wide tape: FESC-SCH02

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



- **Magnetic measurement @Tapestar™ (2mm-wide with AP / FESC-SCH02)**



For 2mm long-tape, stable I_c with artificial pinning wire are obtained

Comparison of transporting I_c and numerically estimated I_c for wounded coil of BMO-doped EuBCO wire

S.Muto et.al ., Abstracts of CSSJ Conference, vol. 98 (2019) p.124.

$I_c(\theta, B)$ fitting for 2 peak

$$I_c(\theta, B) = a_1 f_1(\omega_1(B), \theta) + a_2 f_2(\omega_2(B), \theta)$$

$$f_1(\omega_1(B), \theta) = \frac{1}{\omega_1^2 \cos^2\theta + \sin^2\theta} \quad \leftarrow \text{B//c}$$

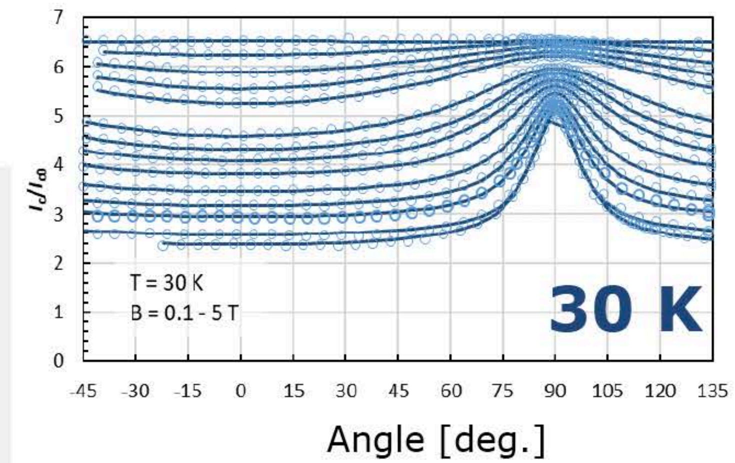
$$f_2(\omega_2(B), \theta) = \frac{1}{\sqrt{\omega_2^2 \sin^2\theta + \cos^2\theta}} \quad \leftarrow \text{B//ab}$$

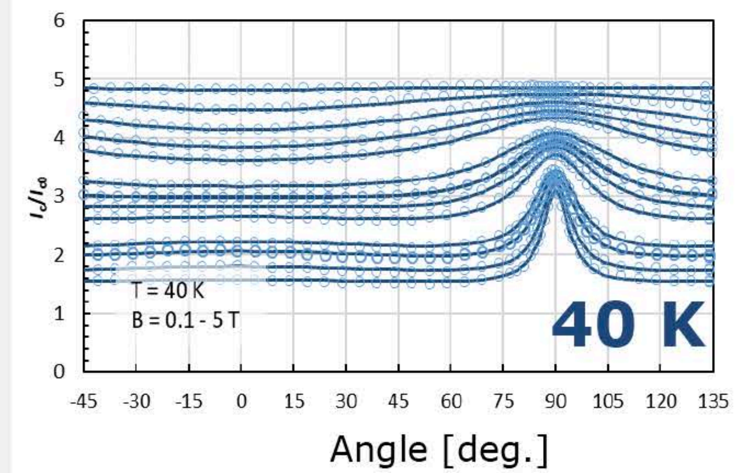
$$I_c(0°, B) = \frac{a_1}{\omega_1^2(B)} + a_2$$

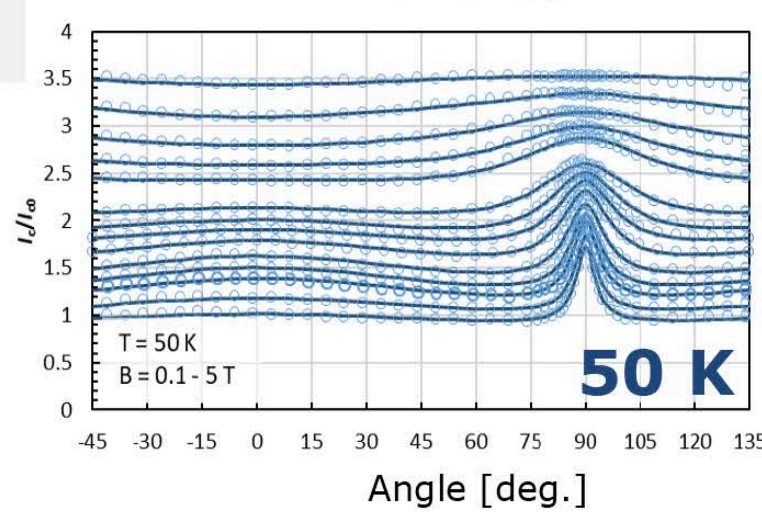
$$I_c(90°, B) = a_1 + \frac{a_2}{\omega_2(B)}$$

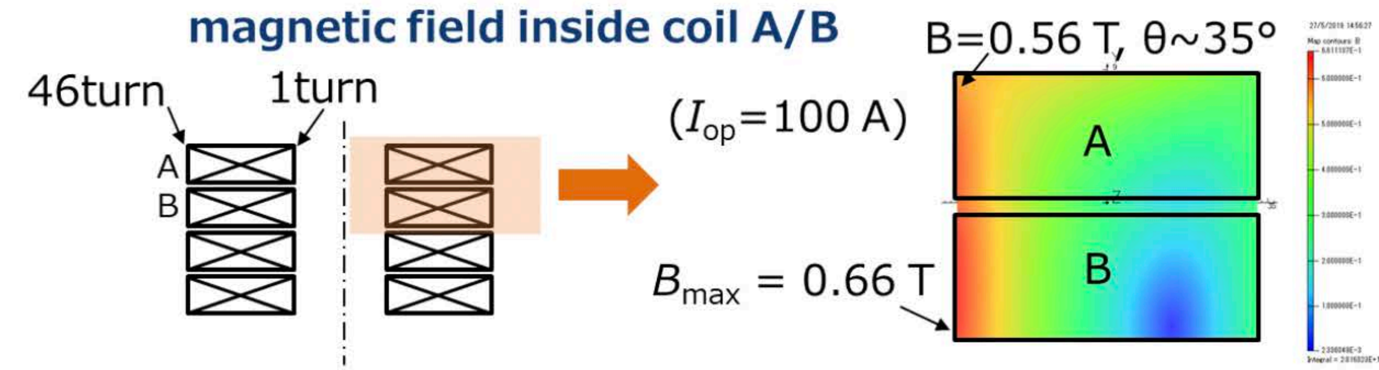
fitting parameter : $\omega_1(B), \omega_2(B)$

arranged from the equation derived by
D K.Hillton et. al., SuST **28** (2015) 074002

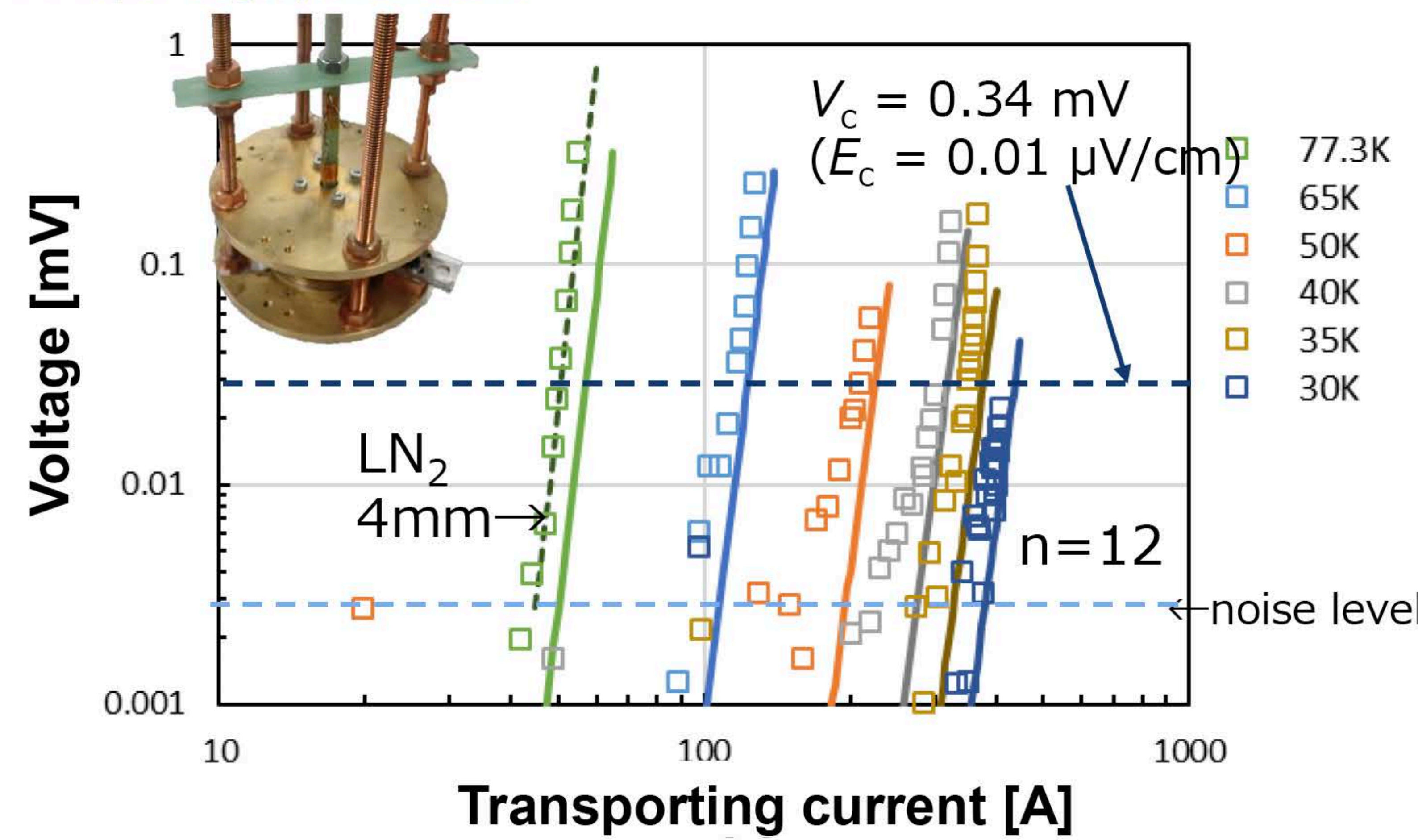








■ 4-layer single pancake coils



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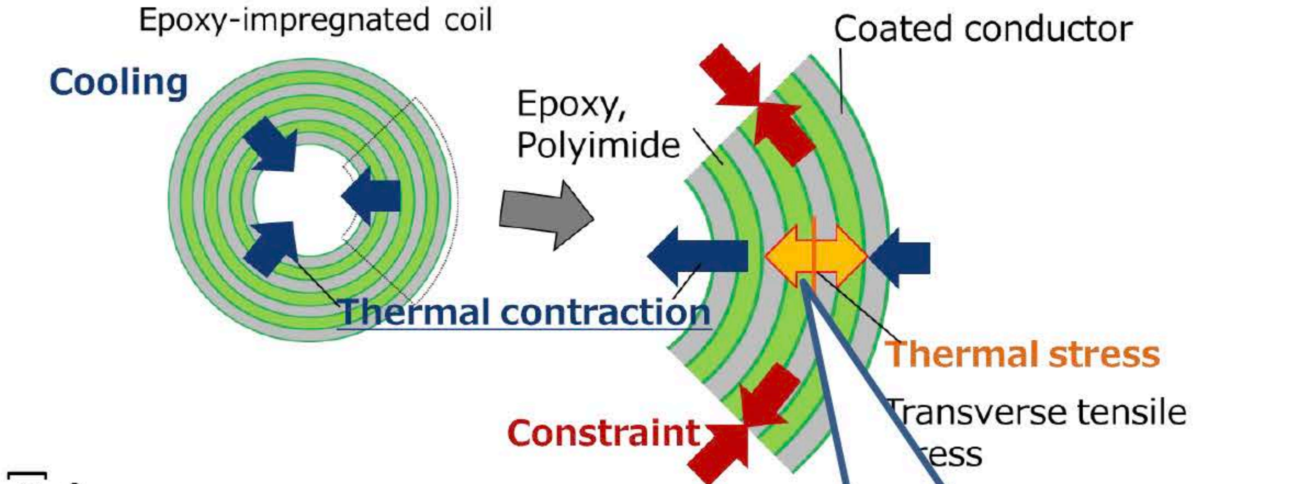
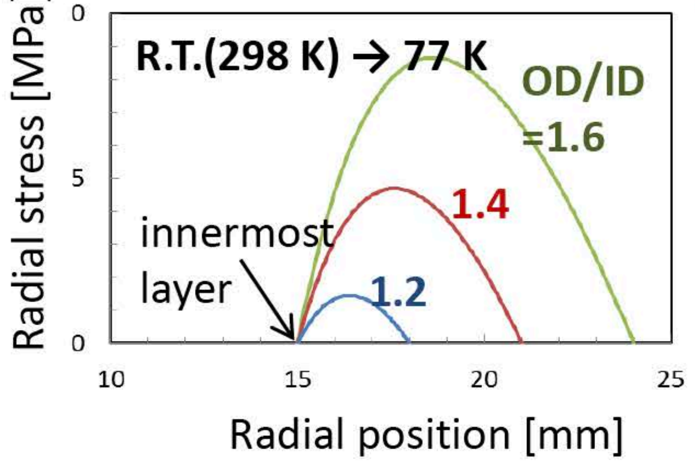
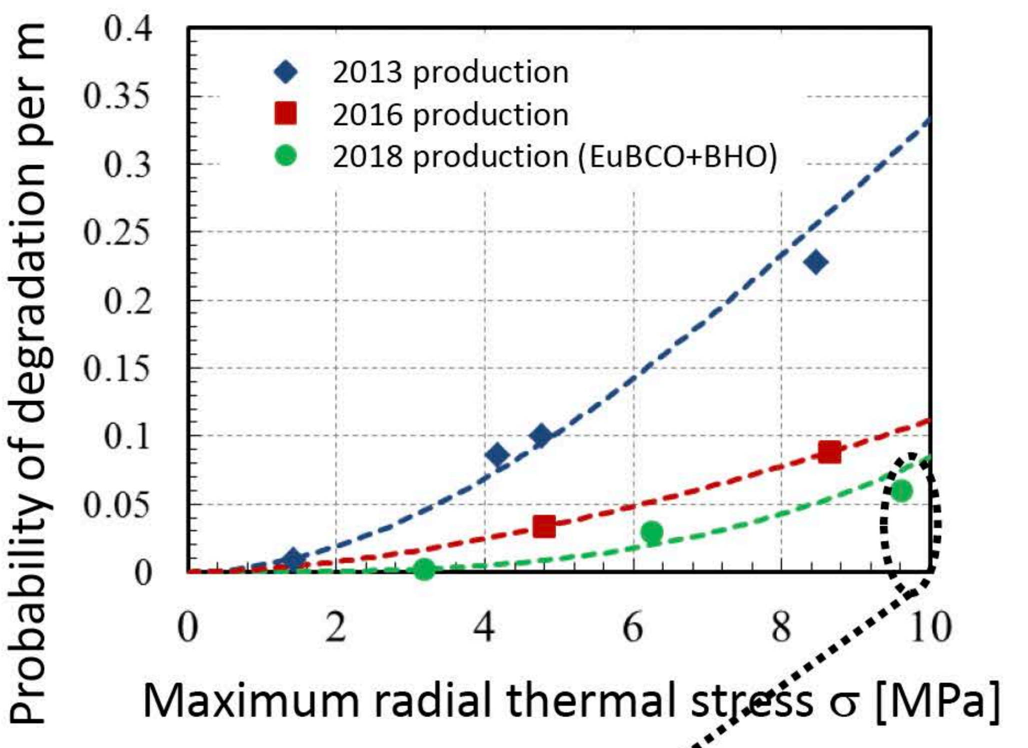
Improvement of delamination strength

<Delamination stress test by thermal stress inside impregnated coil>



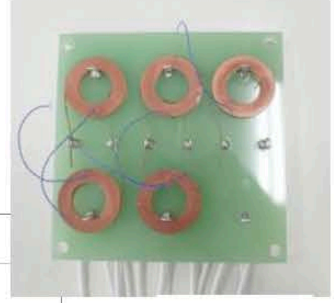


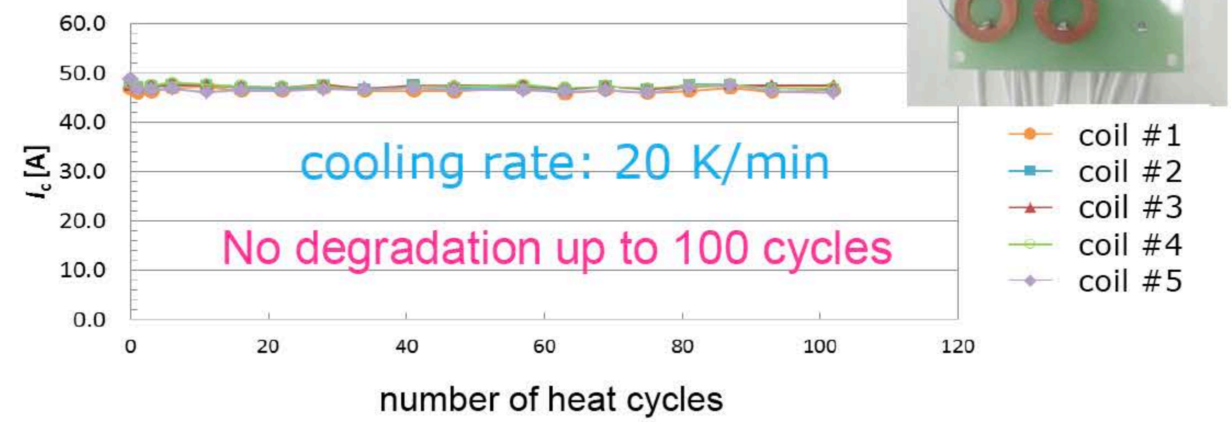
H. Miyazaki *et al.*, IEEE TAS, **25** (2015) 6602305



Average delamination stress of 2G HTS tapes have improved by Weibull analysis

<Heat cycle test (R.T. ~ 77K)>





Fujikura

Fujikura REBCO wire by IBAD and hot-wall PLD

- NEDO Program *" Project to Promote Commercialization of High-Temperature Superconductivity Technology (2016-2020)"* which aimed for 3-T class compact MRI system strongly assisted Fujikura REBCO wire development
- BMO-doped line-up launched with enhanced in-field Ic below 50 K
- High throughput BMO-doped EuBCO films of enhanced J_c had uniformly scattered nanorod structure with the improved temperature stability in hot-wall type PLD system
- Good I_c homogeneity & in-field I_c predictability obtained in 1 km long tapes
- Mechanical strength evaluated including improved delamination strength

New tape width joined in line-up

- 2mm width (FESC-FCH02)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation NM-6 was given at the virtual CCA 2021, October 11-15, 2021.

END

Thank you for attention

Fujikura