High-Rate and Homogenous Production of BMO-Doped REBCO Coated Conductor by IBAD and Hot-Wall PLD Process

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Fujikura Ltd.

Acknowledgement:
We appreciate Prof. T. Kiss at Kyushu Univ. and Prof. S. Awaji at Tohoku Univ. for collaboration to sample evaluation. A part of this work was also performed at the High Field Laboratory for Superconducting Materials, IMR, Tohoku University.
These works include results obtained from *"Promotion Technology Development for Realization of HTS Applications(2016-2020)"* being consigned or subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

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Contents

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- **High rate and Homogenous REBCO wires by IBAD/Hot-wall PLD**
  - Advantage of PLD processed REBCO films :
  - High in-field Jc properties with high throughput and good homogeneity
    - High rate, non-equilibrium, but controllable and stable growth with favorable pinning defects come from rapid and fine evaporation by high fluence UV pulse irradiation
    - Drastic advancement of high-powered UV pulsed laser by FPD industry
    - Hot-wall architecture: temperature stability improvement in large growth area
- **Current status of Fujikura REBCO C.C.**
  - >1km long uniformity improvement
    - Uniformity evaluation by 10 T test magnet
  - Mechanical strength evaluation
- **Summary**

Application R&D of REBCO Coated Conductor

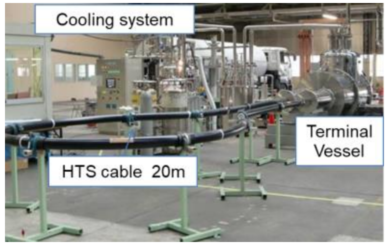
R&D of REBCO CC Application at Fujikura

- Commercialization of CC wire : 2009
- Low/Medium Field Applications:

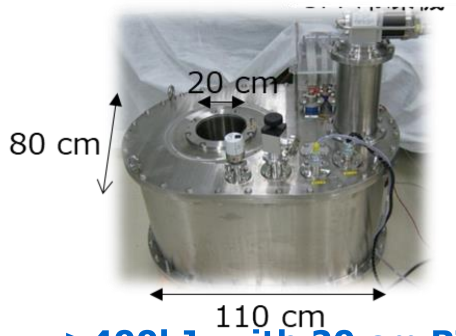
NEDO FCL Coil (2007)

T Yazawa et al 2008 J. Phys.: Conf. Ser. 97 012308

NEDO Power Cable (2013)

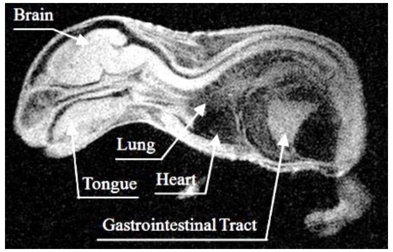


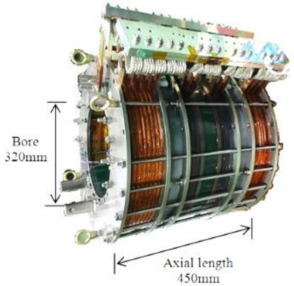
5 T cryocooled magnet by Fujikura Ltd. (2012)



>400kJ with 20 cm RT bore

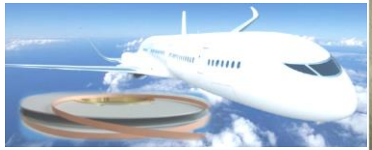
World 1st 3T MRI by Mitsubishi Electric (2015, 2016-2018)

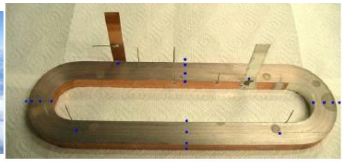




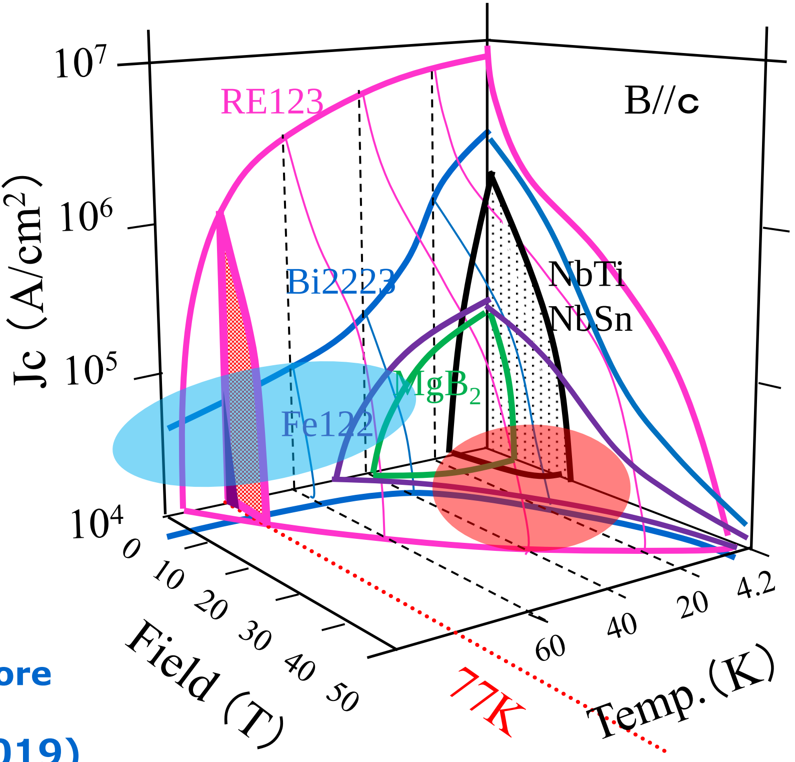
1/3 demo of drive mode 3 T class MRI (AMED/NEDO)

TELOS Project (2016-2019)





Airbus, KIT, Siemens Presented at EUCAS 2019



- High Field magnets (>20T):
  - Cryogen-free 25T magnet of at IMR, Tohoku Univ. (2015)
  - Bruker 1.2 GHz NMR magnet (2019-), Compact fusion activity (2022-)

Tough winding technique

High wire quality required

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024.
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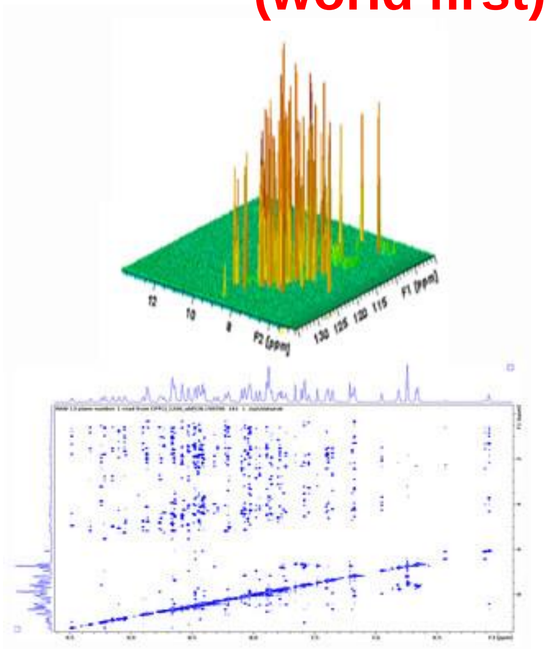
Business scale HF applications urged investment for C.C. production

BRUKER 1.0/1.2GHz NMR system (2019~) (world first)



Commercial Practical device

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

1.2 GHz NMR 28.2 T magnet with 54 mm bore

1.0 GHz NMR with compact 23.5 T magnet

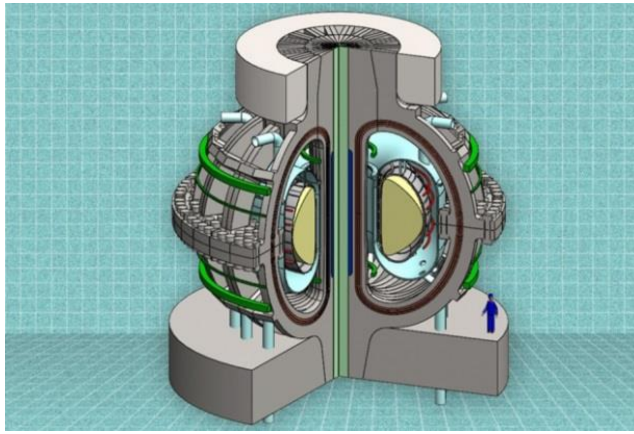
longitudinal uniformity of in field I_c strongly required

Compact fusion reactor R&D (2022~)

REBCO wire demand up to 10000s km/prototype reactor

Toroidal field ~9T (ITER/DEMO ~6T)

Small diameter, lower cost thinner shielding blanket than conservative design



http://news.mit.edu/2015/small-modular-efficient-fusion-plant-0810

Big R&D prototype

High Productivity of wire required with high in-field I_c at 20 K, 20 T, within affordable cost and I_c variations

lower neutron radiation damage favorable

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Invited presentation given at ISS 2023, Nov. 29, 2023, Wellington, New Zealand

Fujikura's 2G HTS wires processed by IBAD/PLD method

<Schematic of 2G HTS wire>

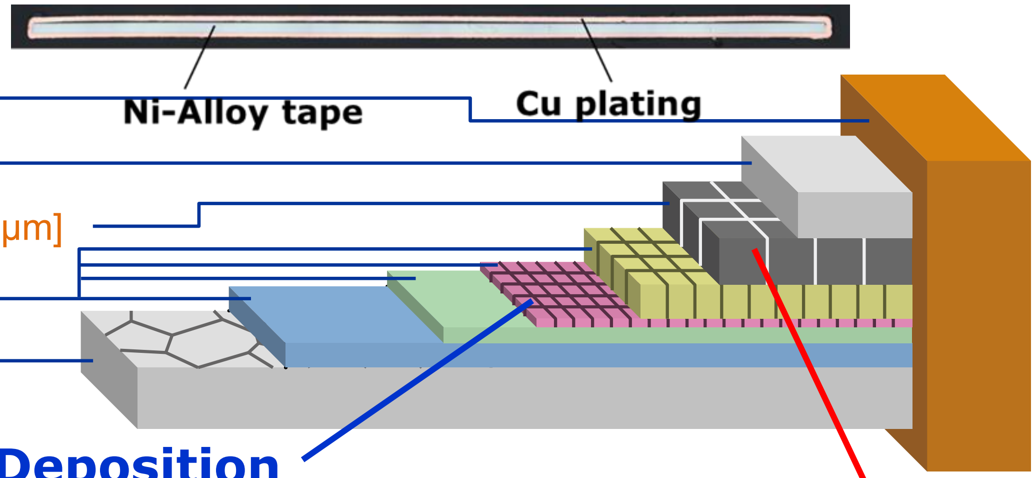
Stabilizer [electroplated copper] 20 μm

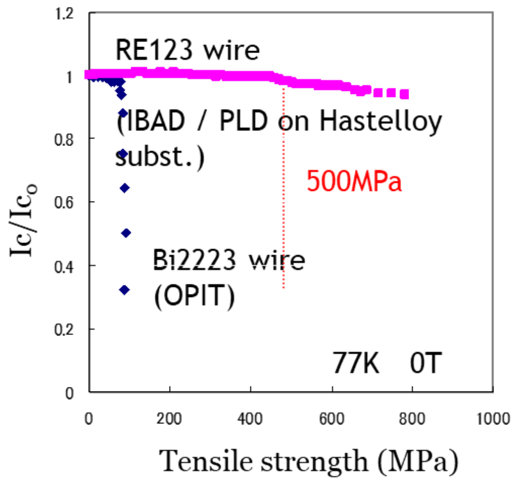
Protection layer [Ag] 2 μm~

HTS layer [GdBCO 2 μm] / [EuBCO+BHO 2.5 μm]

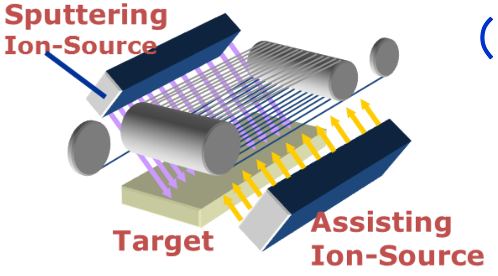
Buffer layer [MgO, etc.] ~0.7 μm

Substrate [Hastelloy®] 75 / 50 μm





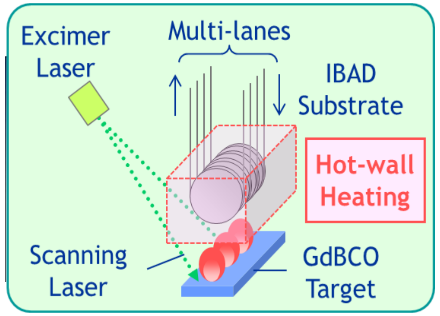
Ion-Beam-Assisted Deposition (IBAD)



Reel-to-Reel IBAD system

Off-normal directional ion beam process allows direct use of thin non-textured Ni-Cr alloy tapes with strong enough mechanical strength

Pulsed Laser Deposition (PLD)



Developed in NEDO/METI programs of:

"Super-GM" (1989-1999)

"Fundamental Technologies for Superconductivity Applications I/II" (1998-2007)

"Project to Promote Commercialization of High-Temperature Superconductivity Technology"(2016-2018)

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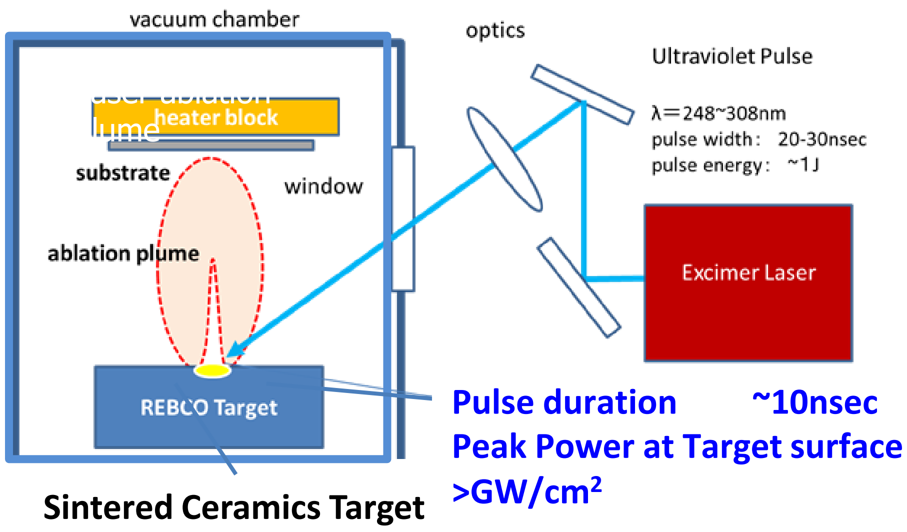
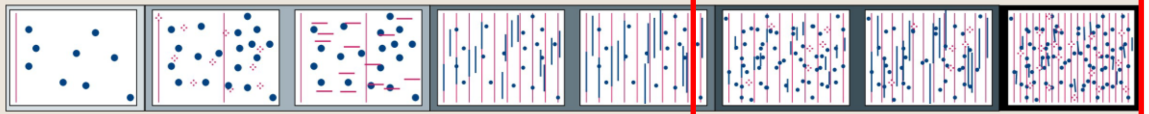
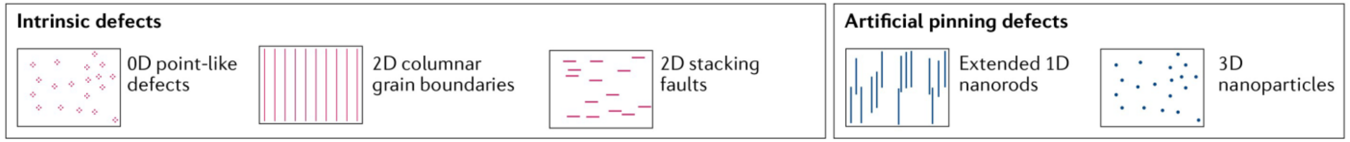
Pulsed Laser Deposition：fast & controllable, non-equilibrium process



J. L. MacManus-Driscoll & S. C. Wimbush:
"Processing and application of high-temperature superconducting coated conductors"
Nature Reviews Materials **vol. 6**, pages 587–604 (2021)

Most suited to		Region 1A	Region 1B	Region 1B, region 2				Region 3
	LPE	RCE-DR (e-beam)	CSD	RCE-CDR (thermal)	MOCVD	High-rate PLD + liquid	Standard-rate PLD	High-rate PLD
Degree of supersaturation	Very low	Low		Moderate			High	Very high
REBCO formation	In situ	Ex situ	Ex situ	In situ	In situ	In situ	In situ	In situ
Vacuum process	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Liquid-based	Yes	Yes	Yes	No	No	Yes	No	No
Commercialized	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Throughput	+++	+++	++	++	++	+++	++	+++
Typical maximum REBCO thickness	~3 µm	~2 µm	~1 µm	~3 µm	~3 µm	~5 µm	~5 µm	~5 µm
Potential for region 2 improvement	–	++/+++	+/++	+++	+++	+++	+	+
	Non-line-of-sight			Line-of-sight				





Fast and Controllable non-equilibrium process

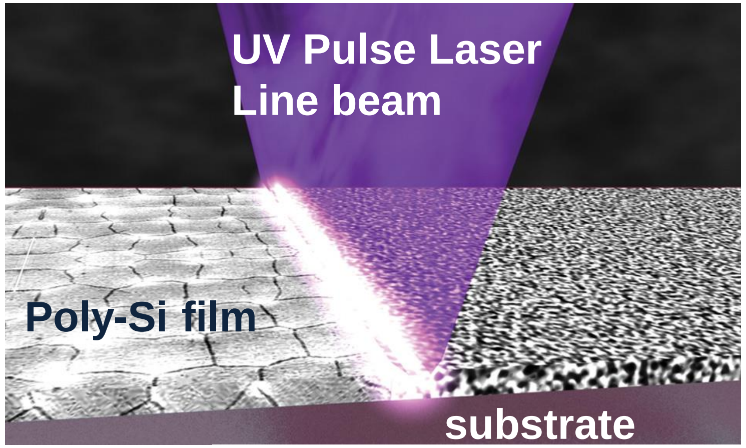
rapid and fine evaporation by UV pulse laser

- **Very high supersaturated growth with high adatom mobility**
  - **Very fast growth rate with good textured matrix**
  - **Dense small size secondary growth and defects suitable for flux pinning**
- **Stable controllability of simple depo. parameters as**
  - **Low fluctuation of elemental composition**
  - **Large window for oxygen pressure**

High supersaturation
➡dense, small defects

Stable deposition condition
for productive long length process

Development of High-Powered Excimer Laser for TFT annealing



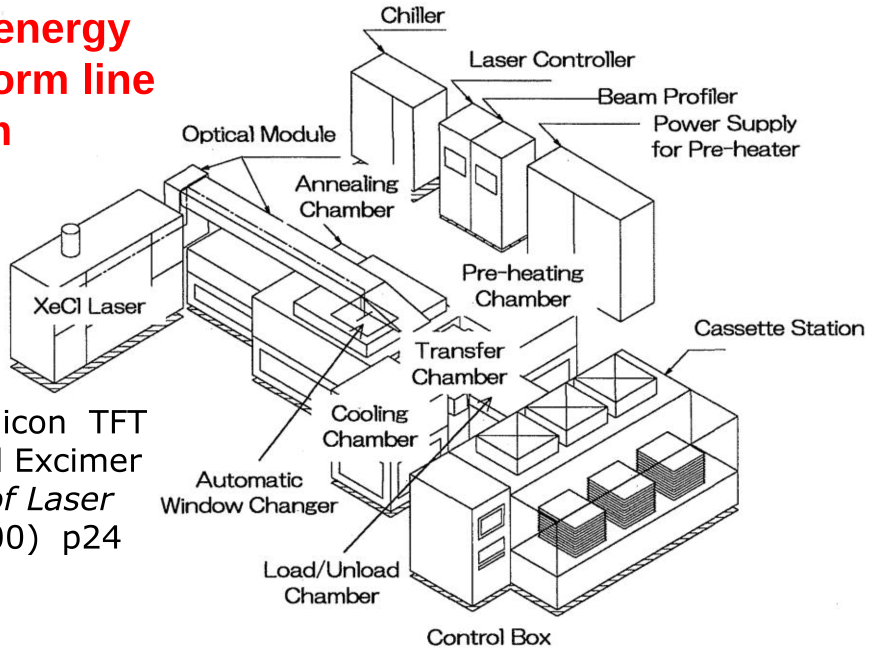
Amorphous Si film

https://www.coherent.com/ja/microelectronics-micromachining/displays

Industrial Excimer Laser with Large Pulse Energy（2000～）widely Introduced for poly-Si TFT annealing of FPD industry

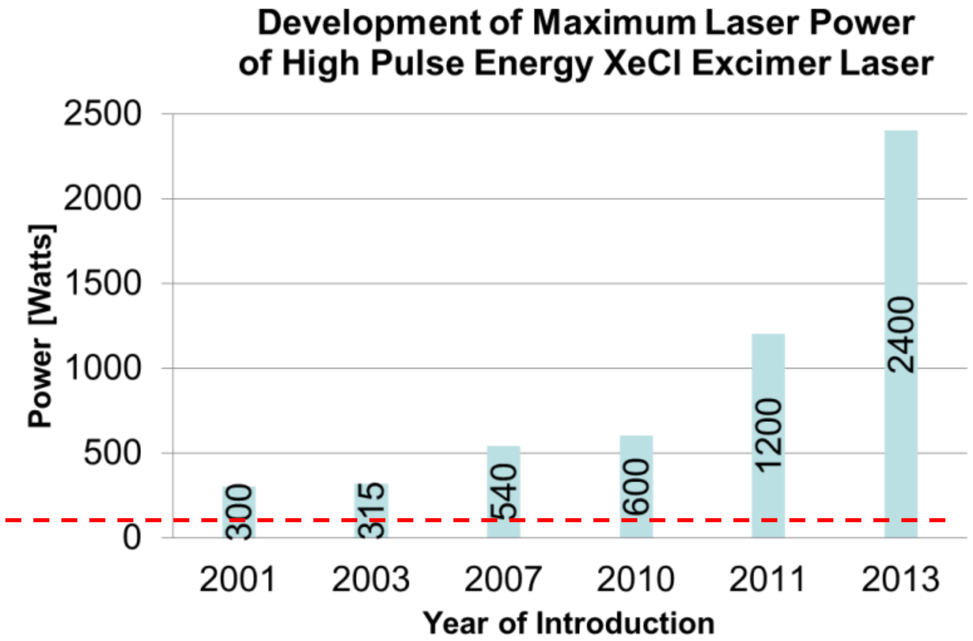
➡ **quite suitable to High rate PLD processing**

Large pulse energy required to form line shaped beam



Shida et al：”Poly－Silicon TFT Annealing with XeCl Excimer Laser,” *The Review of Laser engineering* **28**、(2000) p24 (in Japanese)

Laboratory use Excimer laser ：100-200w



courtesy of Coherent Inc.

Maintenance cost of discharge chamber come from corrosive halogen gases also decreased year by year

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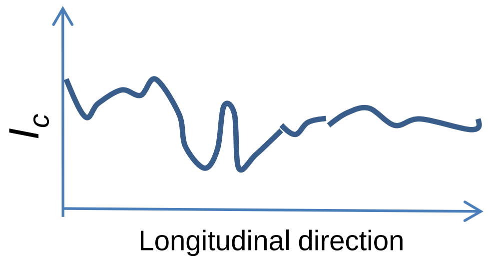
Development of large area substrate heating :Hot-wall PLD

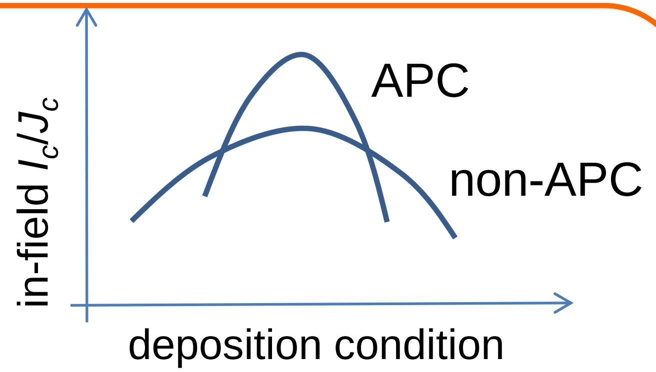
Key issues for REBCO wire :

"High in-field I_c & Reproducibility"

"Long-length & Longitudinal I_c uniformity"

Depends strongly on temperature stability during reel-to-reel continuous deposition





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

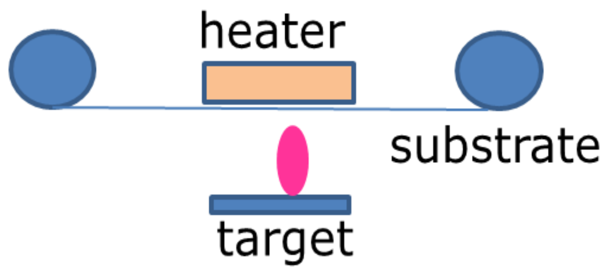
Window width **Y < Gd < Eu**
APC < non-APC

Heater block system

Single-lane PLD

Used 1990s-1999

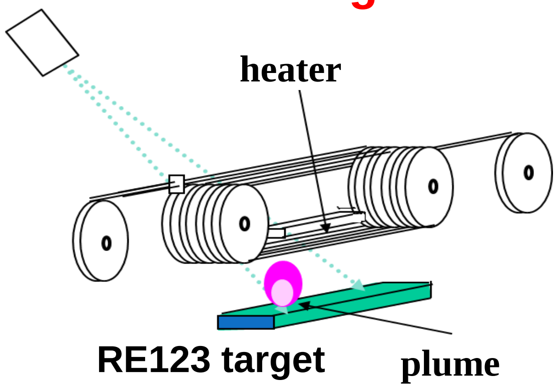
Short piece ~ 10s m long



Multi-lane / beam scanned

Used 2000-2008

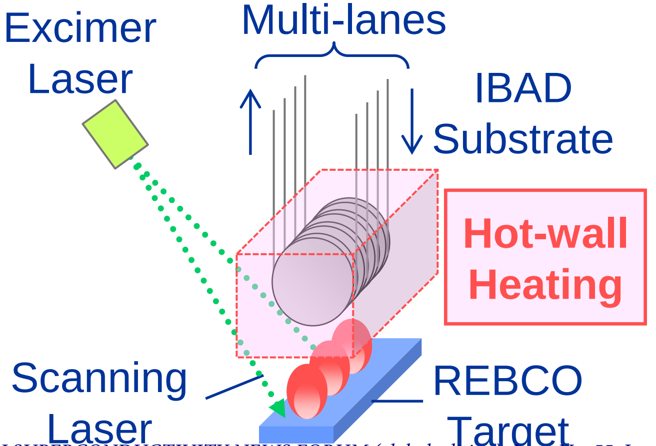
~100s m long



Hot-wall PLD system

Initial set up 2003-2008
reformed 2016-2018

>1 km long



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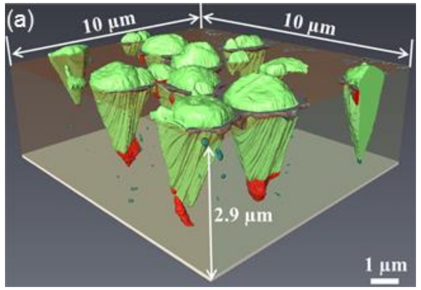
RE elemental dependent growth stability for BMO-REBCO

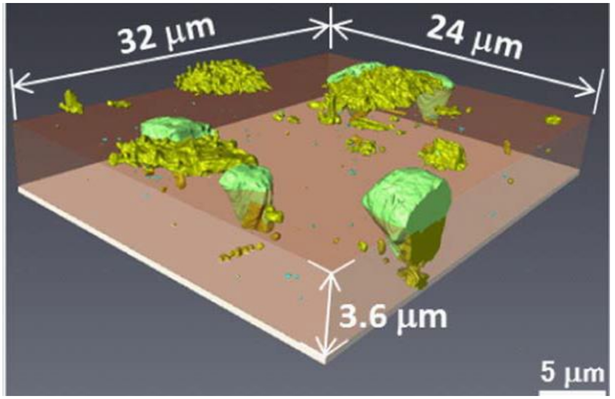
FIB-SEM 3D observation on misoriented grains (mainly a-axis aligned normal) for thick BMO-REBCO films

BaHfO-GdBaCuO



https://www.jfcc.or.jp/result/16r33.html

BaHfO-EuBaCuO

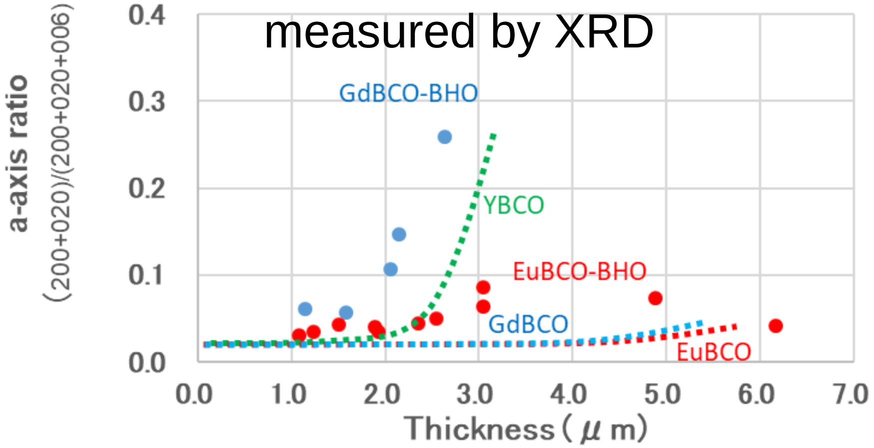


D. Yokoe et al., Supercond.Sci.Technol. **33** (2020) 024002
T. Yoshida et al., Physica C **504** (2014) 42

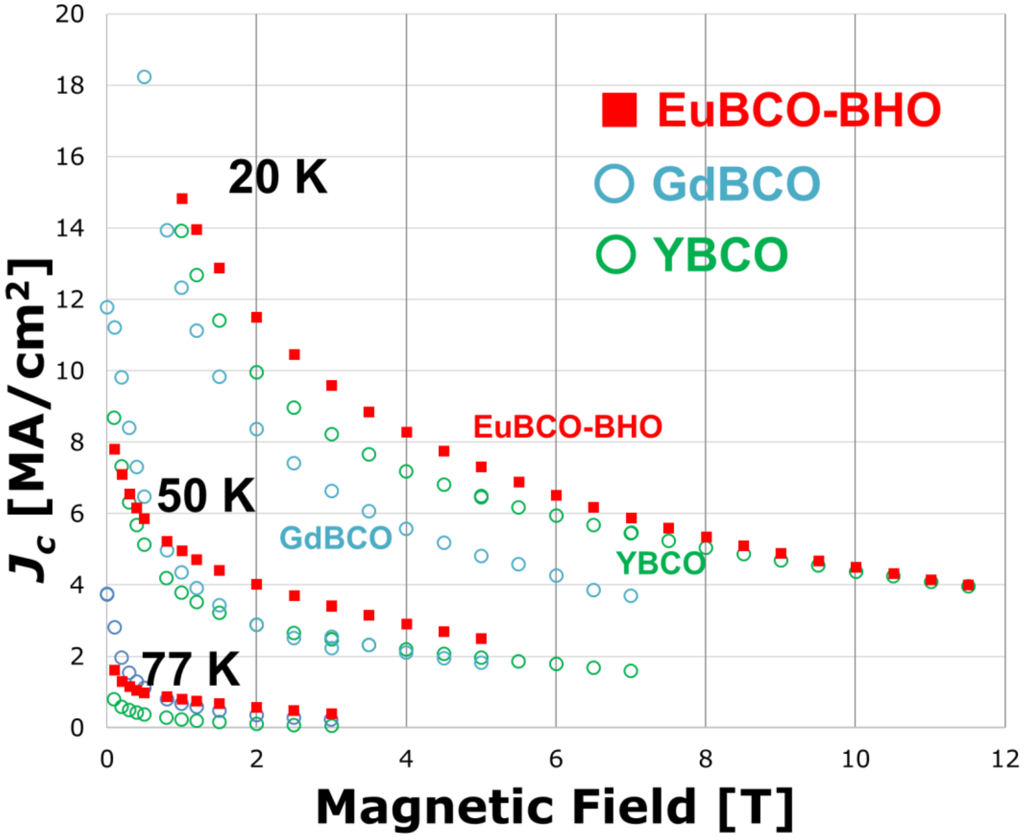
Oriented growth stability

EuBCO
>GdBCO
>YBCO

a-axis aligned grain ratio measured by XRD



Typical J_c-B characteristics for BHO-EuBCO and pristine GdBCO, YBCO films



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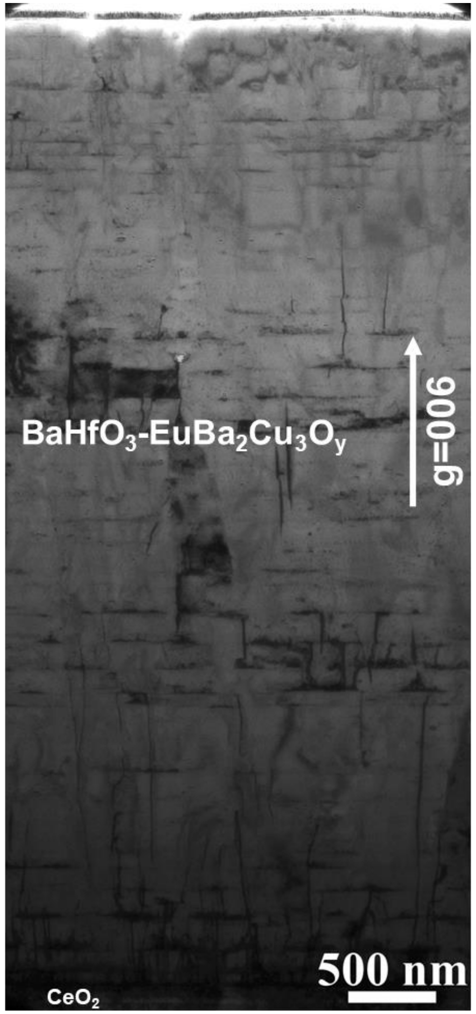
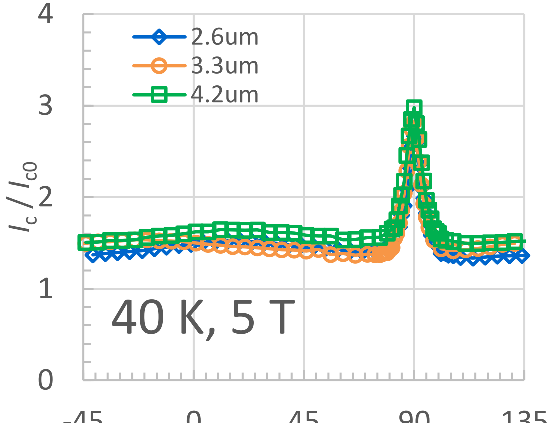
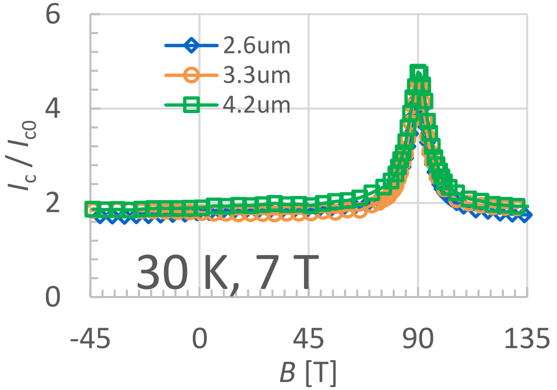
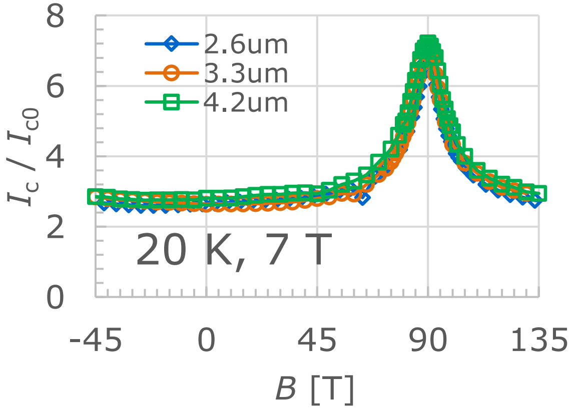
Thickness dependence for in-field I_c properties of BHO-EuBCO

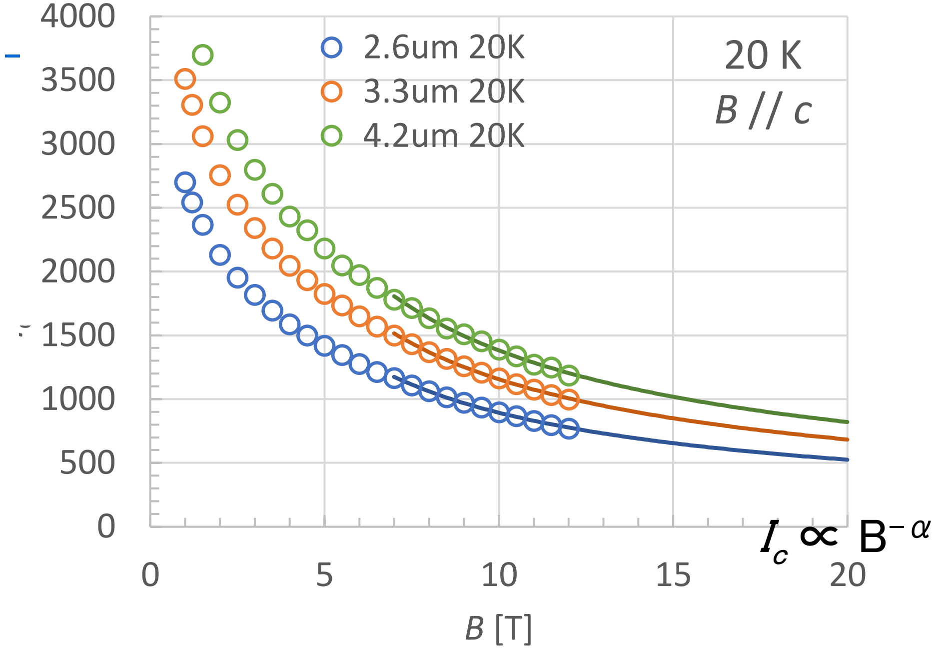








Almost the same *Ic-B-θ* shape up to 4.2 μm thick



J_e=595 A/mm² (I_c=357A. 4mm wide) @30K,7T
obtained with 2.5μm thick
at high throughput

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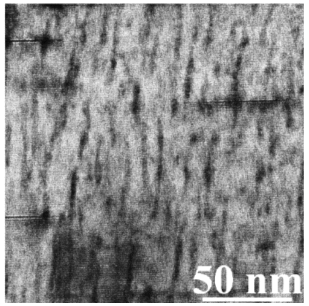
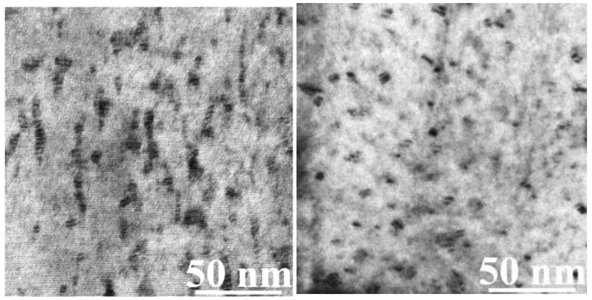
Growth rate dependence for I_c properties of BMO-EuBCO

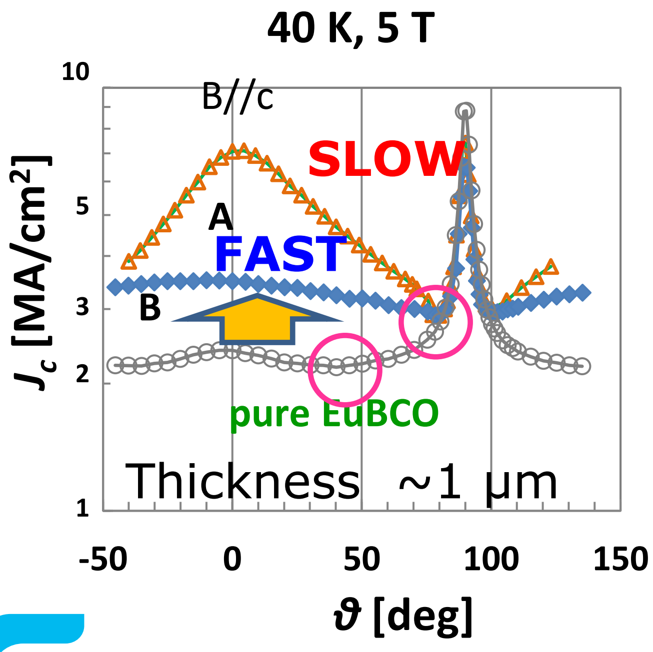
EuBCO-$HfBaO_3$

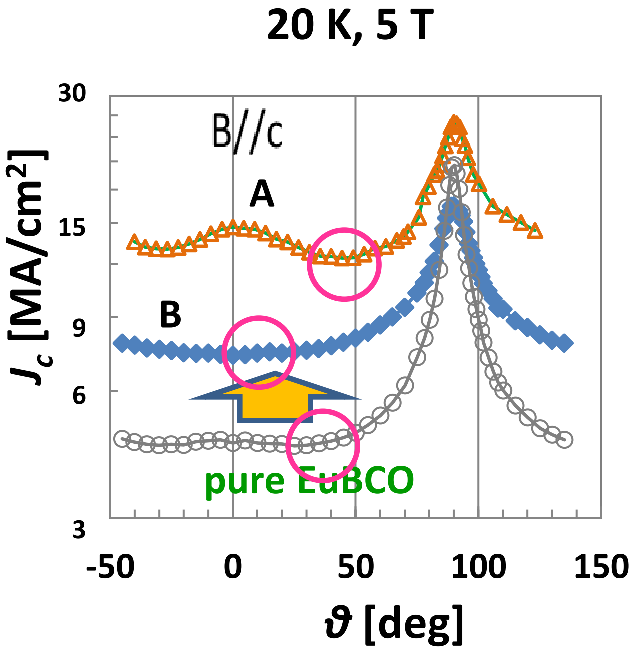
A Slow: B Fast:

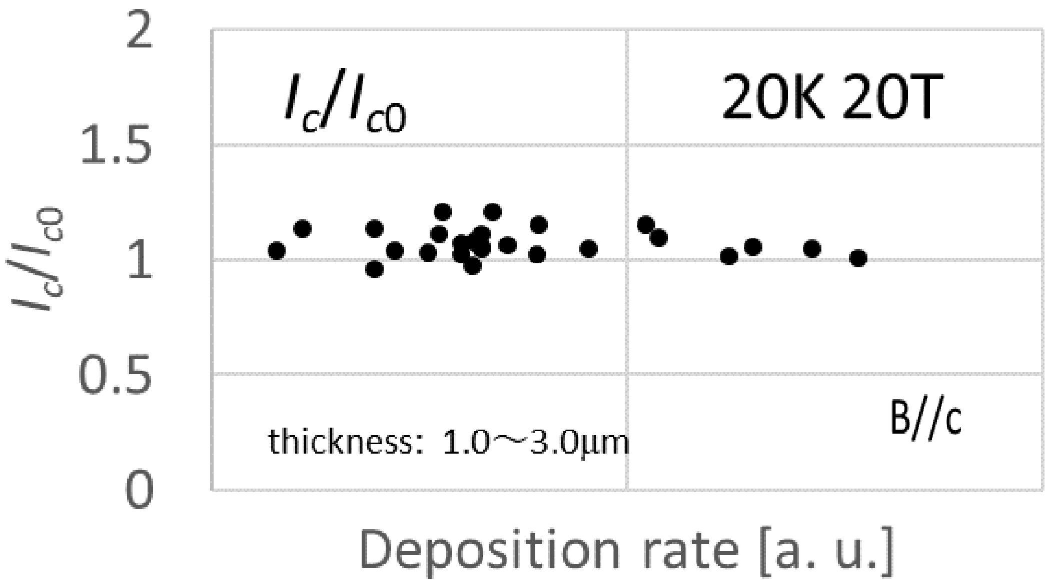




Scattered short nanorods observed in high-growth rate FAST samples







more isotropic property In wide temperature and field range

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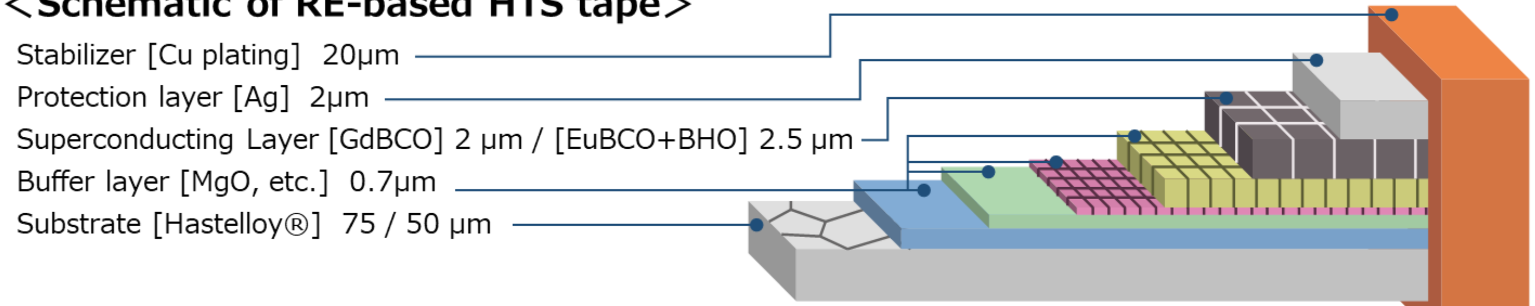
Typical Specifications of 2G HTS Tape at Fujikura

Products	Width [mm]	Thickness [mm]	Substrate [μm]	Stabilizer [μm] *5	APC Option	Critical Current [A] 77K, S.F.	Critical Current [A] 20K, 5T (Ref.) *4
FYSC-SCH04	4	0.13	75	20	Non-AP *2	≥ 165	368
FYSC-SCH12	12	0.13	75	20	Non-AP *2	≥ 550	1,104
FYSC-S12 *1	12	0.08	75	–	Non-AP *2	≥ 550	–
FESC-SCH02	2	0.11	50	20	AP *3	≥ 30	257
FESC-SCH03	3	0.11	50	20	AP *3	≥ 63	497
FESC-SCH04	4	0.11	50	20	AP *3	≥ 85	663
FESC-SCH04(05)	4	0.07	50	5	AP *3	≥ 85	663
FESC-SCH12	12	0.11	50	20	AP *3	≥ 250	1,990
FESC-S12 *1	12	0.06	50	–	AP *3	≥ 250	–

*1 Non-copper stabilizer specification is available in only 12mm-wide for current lead or low thermal conducting applications.
*2 Non-AP specification is mainly for conductors or other general use at relatively higher temperature.
*3 Artificial pinning specification is mainly for use in magnet applications at low temperature and high magnetic field.
*4 Ic@20K, 5T is a reference value and no guarantee of the actual performance.
*5 If requested, an option **customizing copper plating thickness is also available**. (e.g., 5μm, 10μm or 40μm)

- **FYSC(w/o APC) is mainly for power cables or other general use at relatively higher temperature.**
- **FESC(w/ APC) is recommendable for use in magnet applications at lower temperature and higher field.**

<Schematic of RE-based HTS tape>



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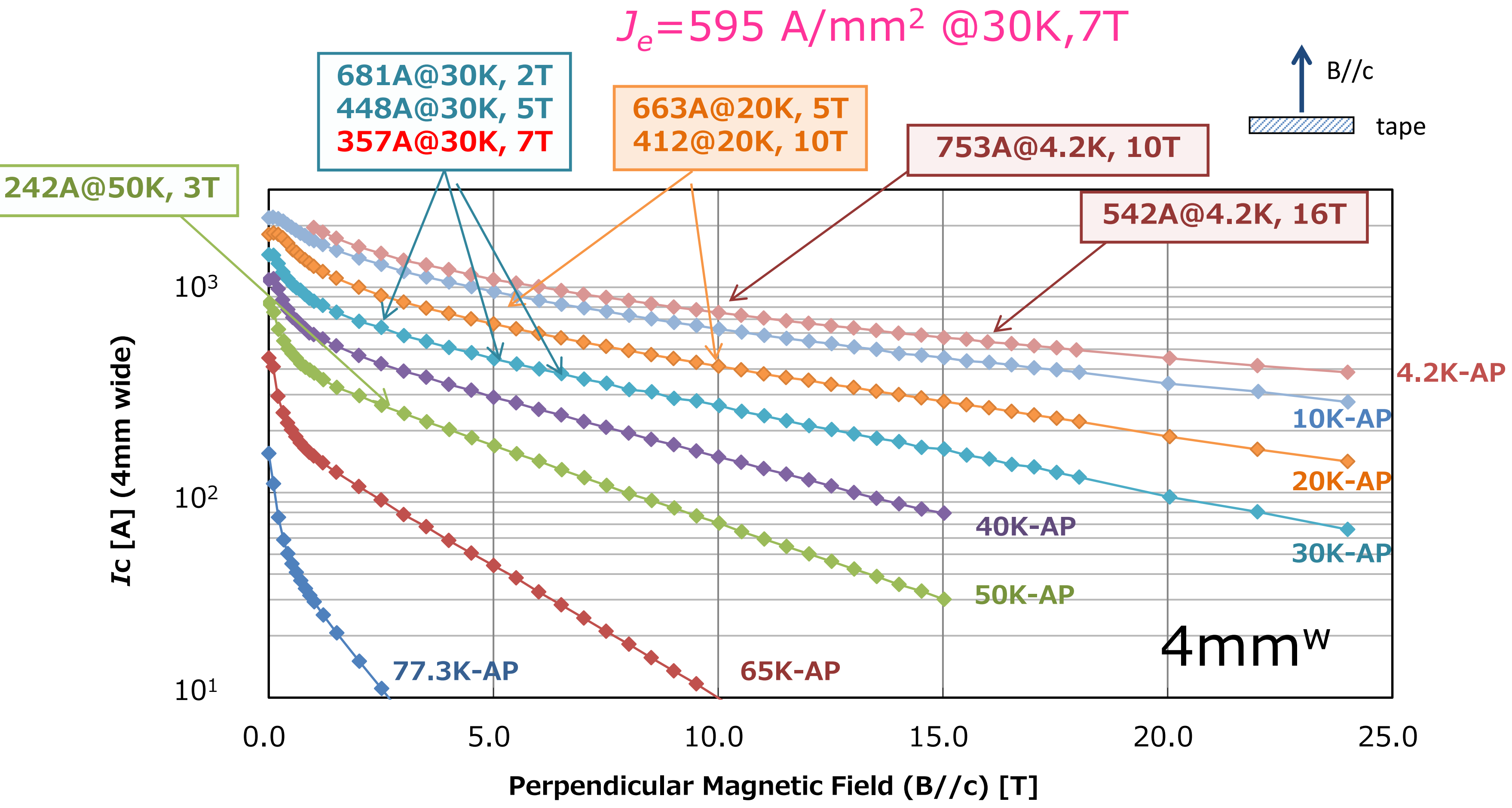
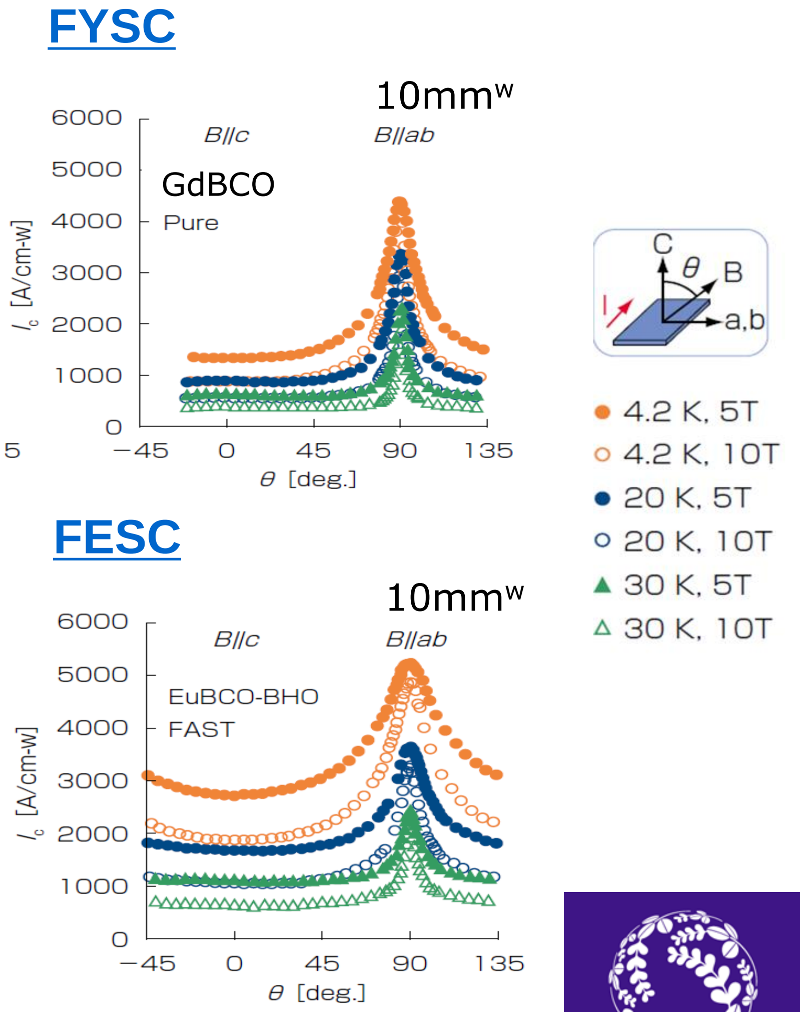
In-field *Ic* Performance – FESC type – (AP)





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

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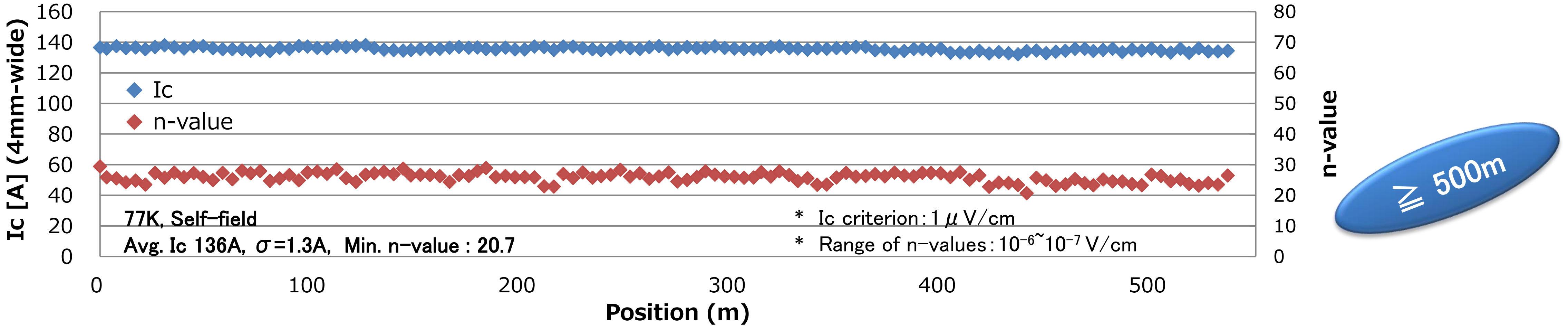
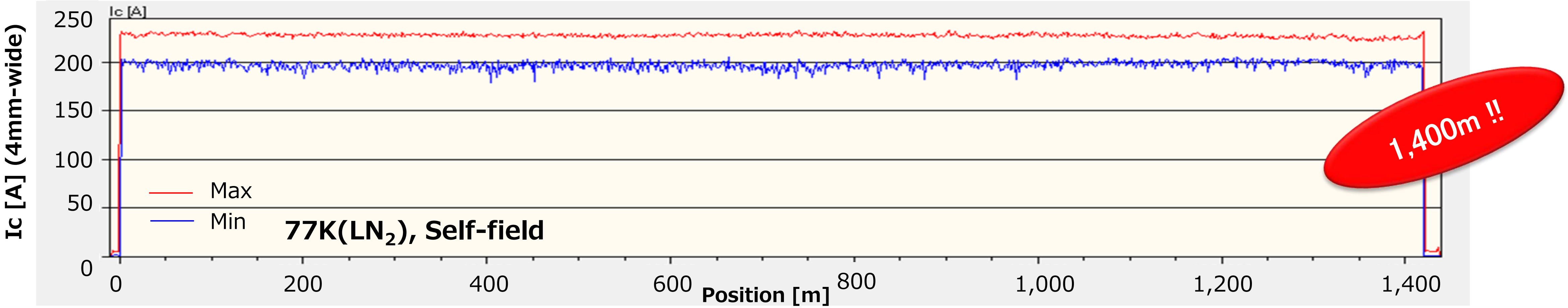
Example data of longitudinal I_c distribution of 4mm-wide tape

■ Measured by Current conduction measurement every 4.7 m (with APC / FESC-SCH04)



■ Magnetic measurement @Tapestar™ (4mm-wide with APC / FESC-SCH04)

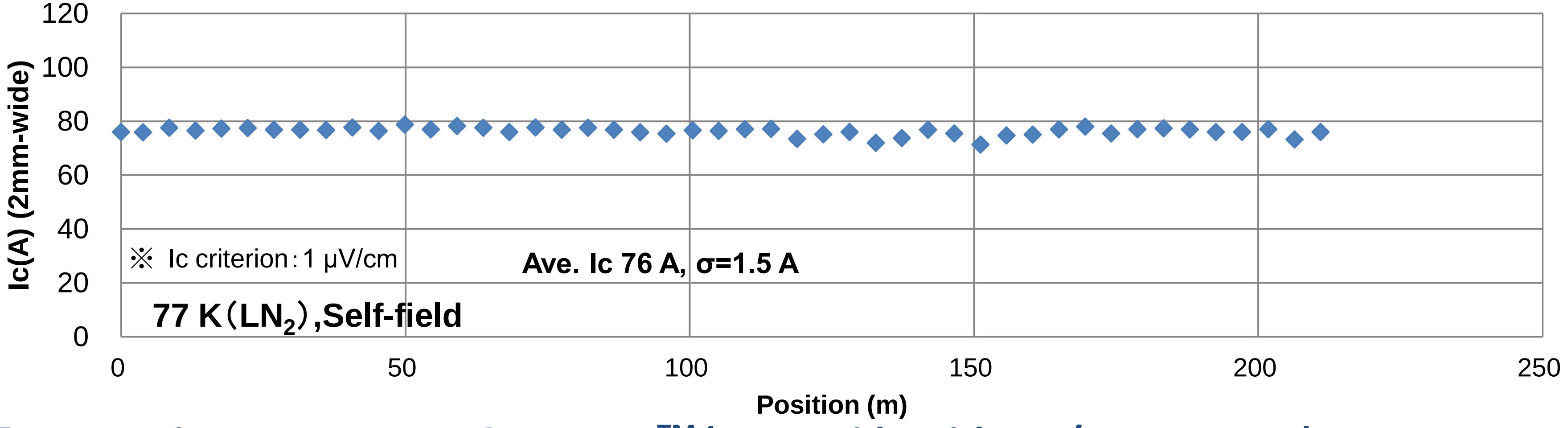


quite uniform I_c with artificial pinning tape and ~ 1,400 m are obtained

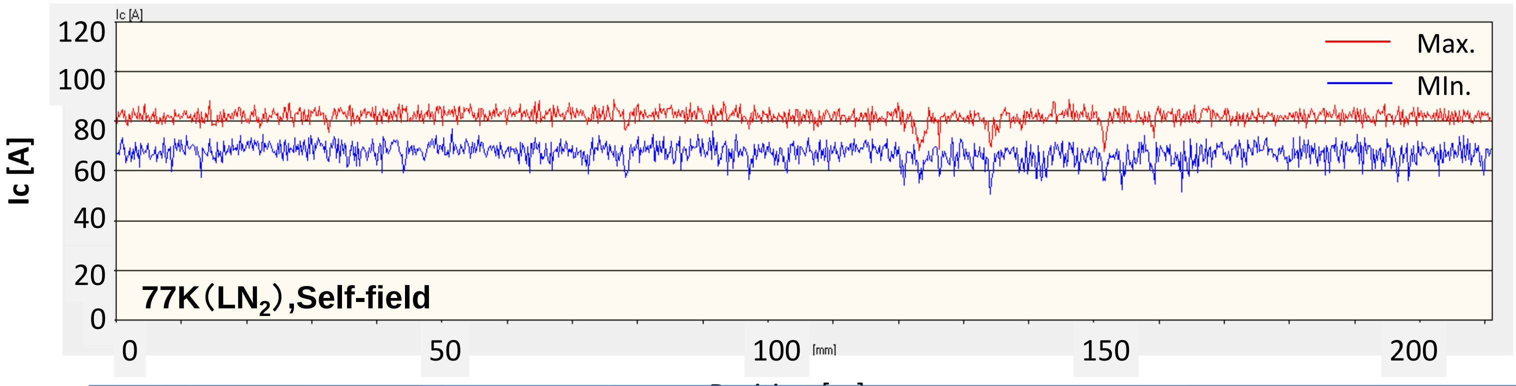
Example data of longitudinal I_c distribution of 2mm-wide tape

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

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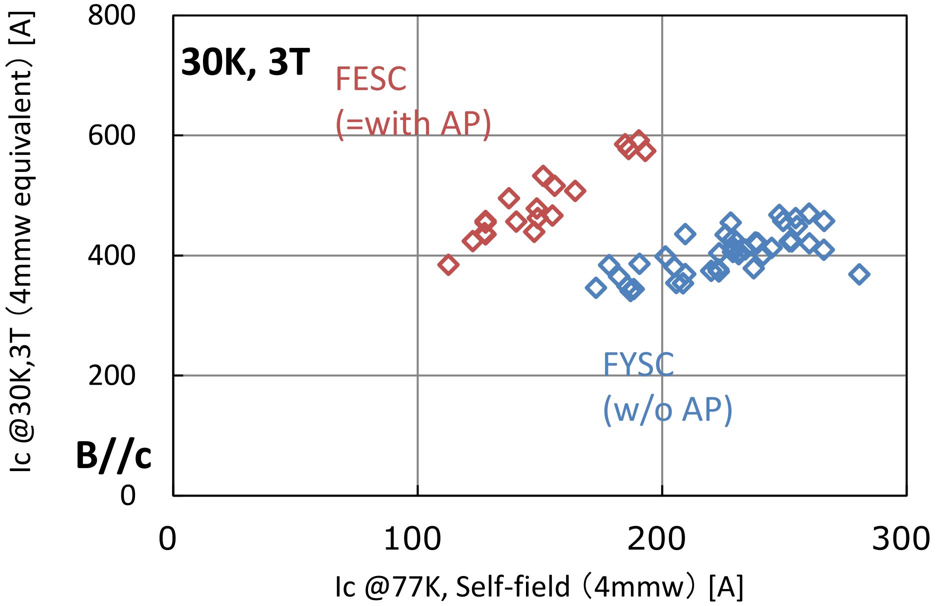
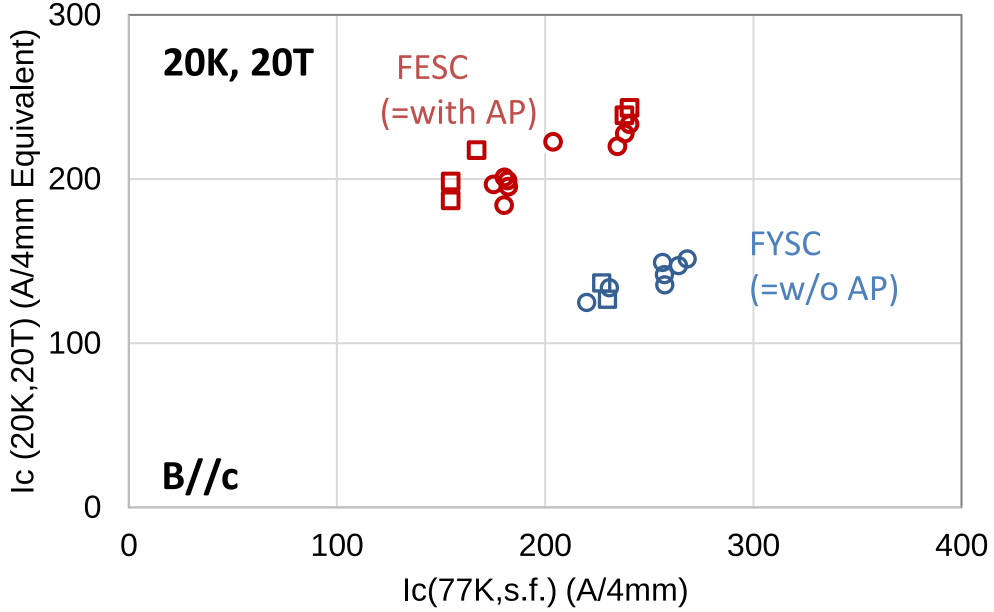
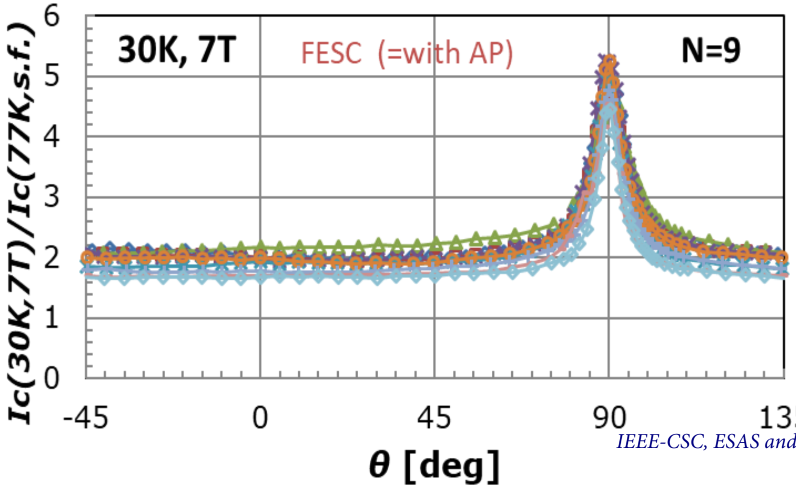
Lot-to-lot in-field I_c distribution of 4 mm^w wire

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

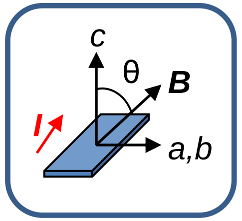




Good correlation to self field I_c and in-field I_c observed for both EuBCO+BHO and pristine GdBCO



◇○ measured at Fujikura, and exploited values with Ic
□ in-field Ic measured at Tohoku university



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A 10T small test coil at Fujikura Ltd.

Parameters	REBCO tape
Substrate thick.	50 μm
Copper thick.	20 μm×2 (plates)＋**300 μm**
Type of HTS tape	FESC-SCH04
Insulation	Fluorine coating polyimide tape/Polyimide tape
Width/Thickness	4.1 mm / 0.47 mm

Parameters	10 T test coil	
Inner diameter	50 mm	
Outer diameter	146 mm	
Coil height	166 mm	
Impregnation	Epoxy resin	
No. of pan cake	32 (2×16)	
Number of turns	2976 (93×32)	
Tape length	0.9 km	
I_{op}	300 A	500 A
B_0	5.8 T	9.7 T
Stored energy	13 kJ	35 kJ
Load factor at 20 K	44%	73%

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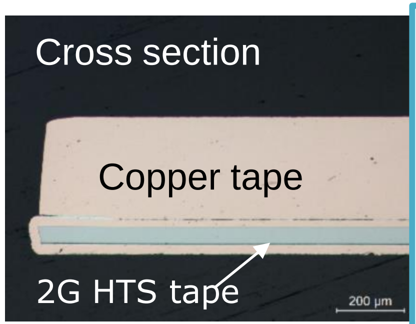
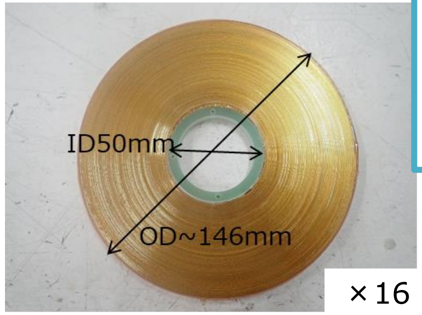
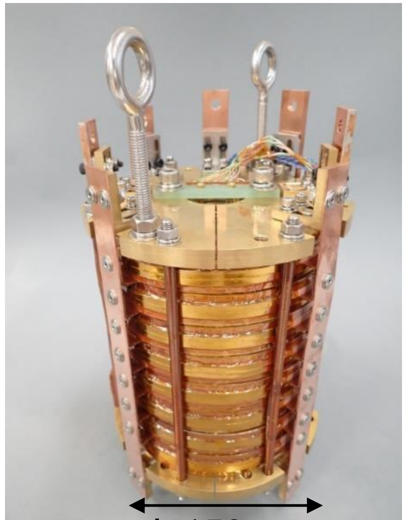
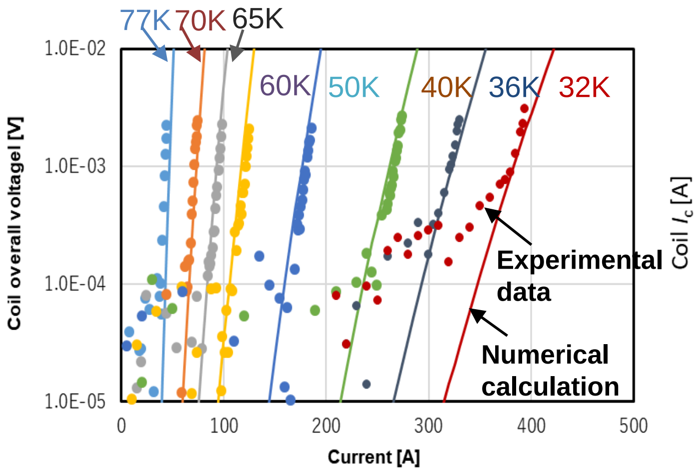
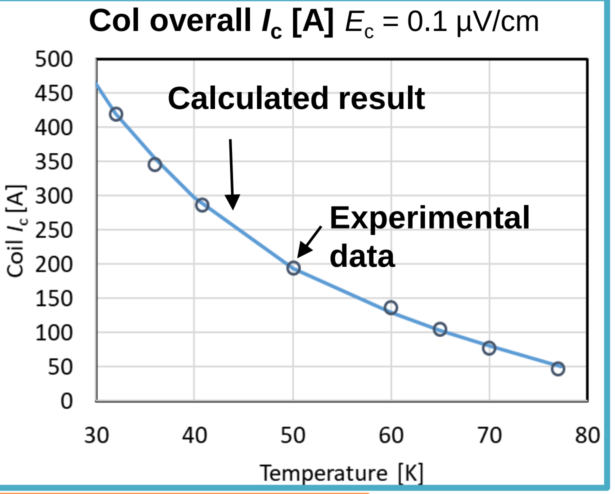


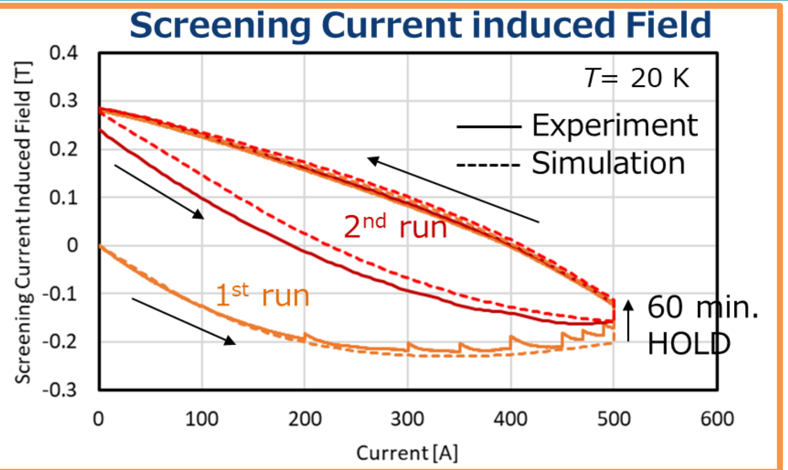


×16





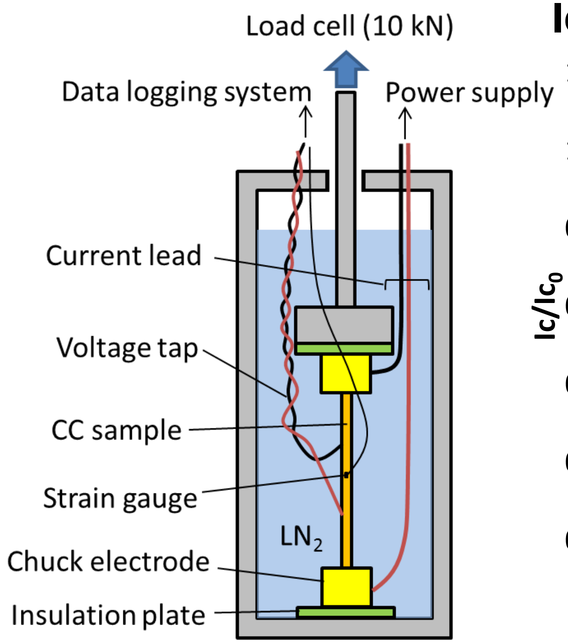


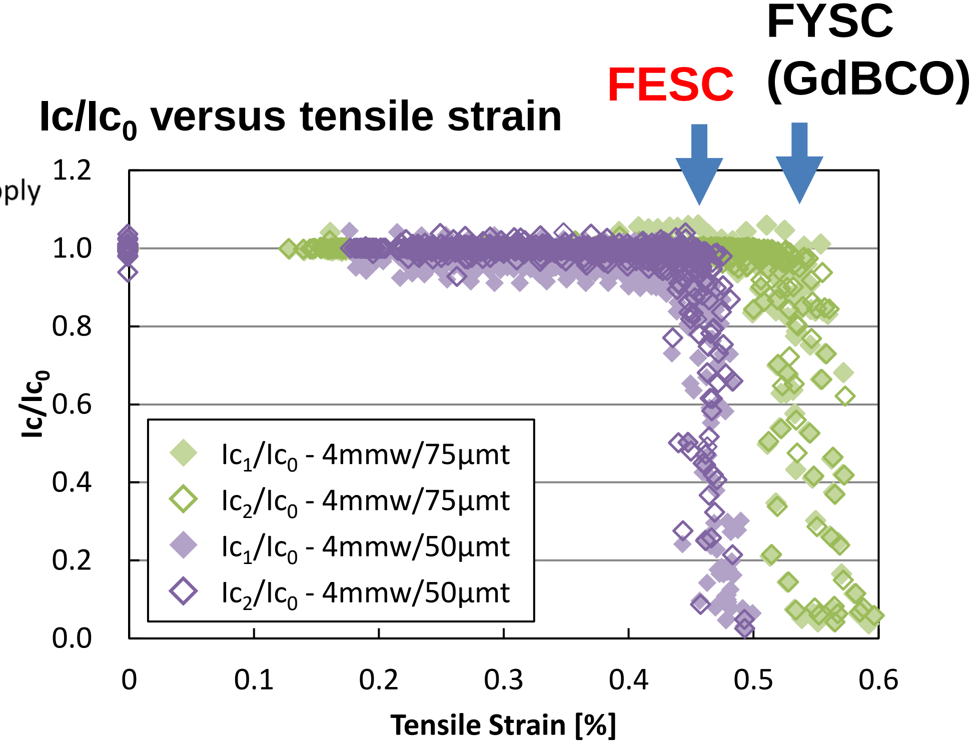


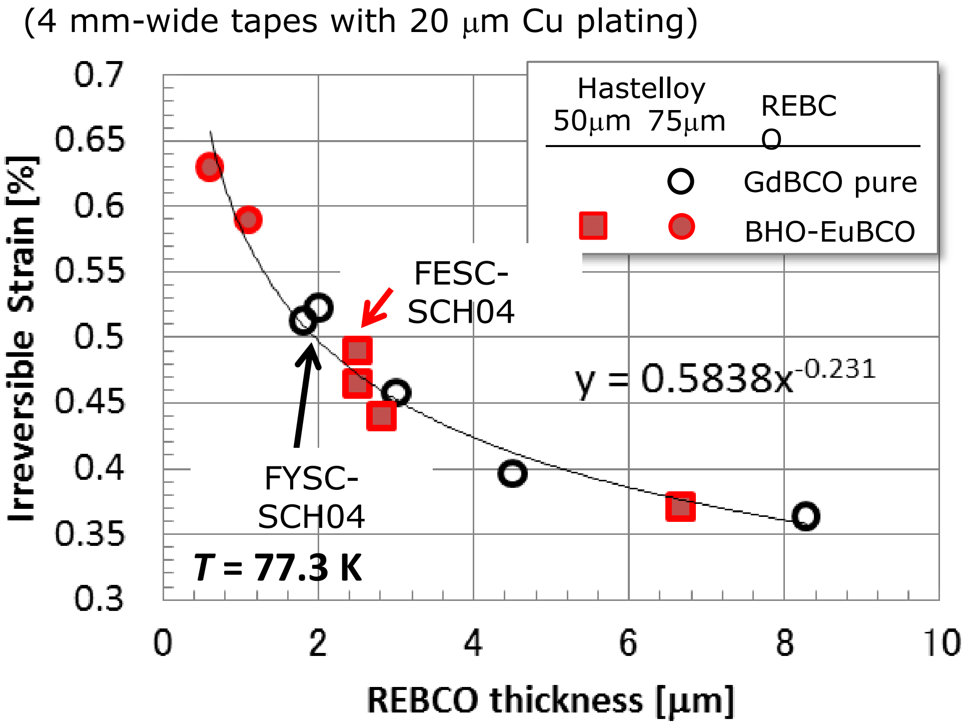
- **Good agreement** between experimental and calculated results for **coil Ic** and **screening current induced field**.

REBCO Thickness Dependence of Tensile Properties

The FESC (BMO-doped EuBCO) had,
- slightly smaller e_{irr} value due to the thicker REBCO layer: 2.5 μm.







- The REBCO thickness dependence of e_{irr} is due to the volume effect, which is general phenomena in ceramics.

$$\bar{\varepsilon} = \varepsilon_0 \Gamma\left(1+\frac{1}{m}\right)\left(\frac{V}{V_0}\right)^{-\frac{1}{m}} \propto V^{-\frac{1}{m}} \propto (\text{REBCO thickness})^{-\frac{1}{m}}$$

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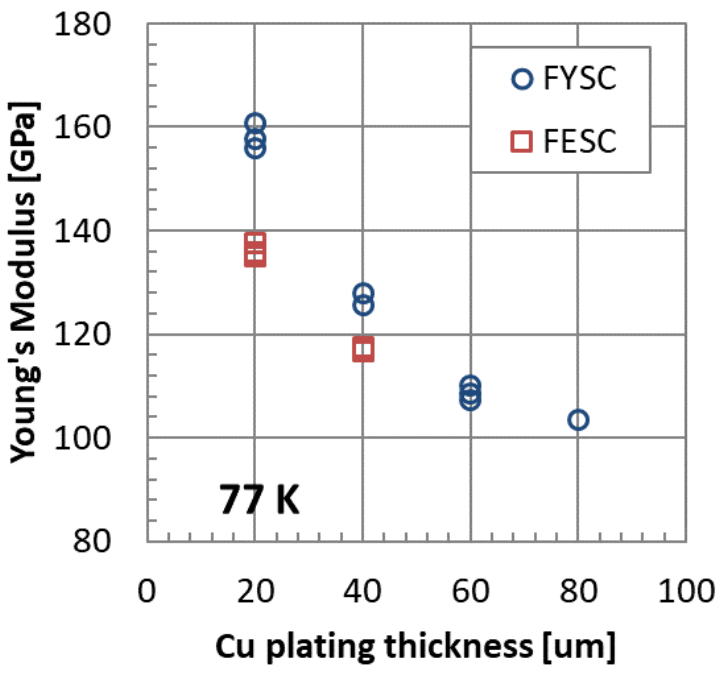
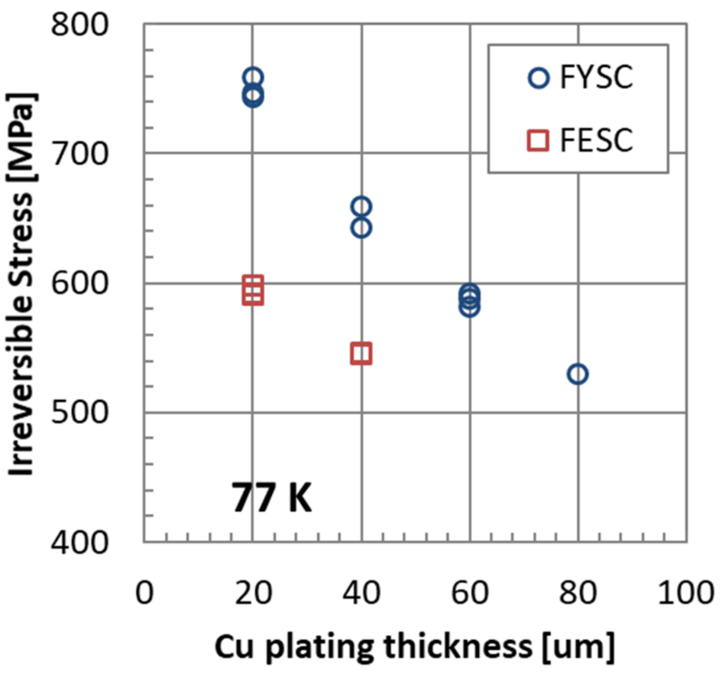
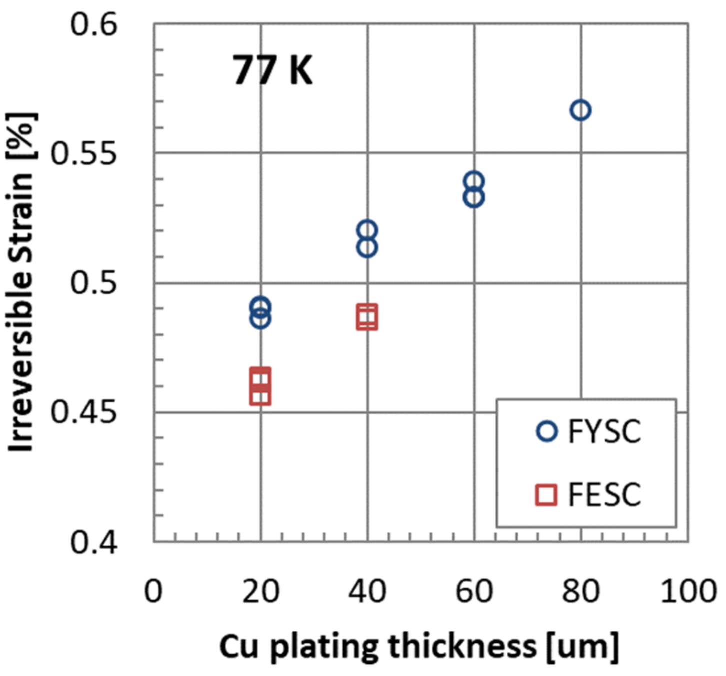
Copper Thickness Dependence of Tensile Properties

- The tensile properties of copper-plated HTS tapes with **various copper thicknesses** were investigated.







- **Young's modulus and Irreversible stress decreased with increasing copper thickness.**
  → Due to the increasing ratio of copper, which has lower stiffness than Hastelloy.
- **On the other hand, Irreversible strain increased with increasing copper thickness.**
  → Due to compressive strain caused by the difference in coefficient of thermal expansion (ΔCTE) between Hastelloy and copper.

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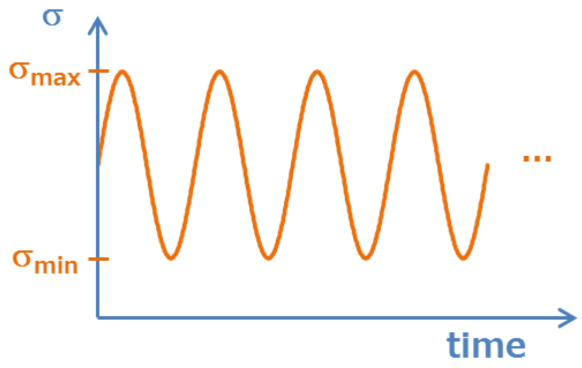
Cyclic Fatigue Tests

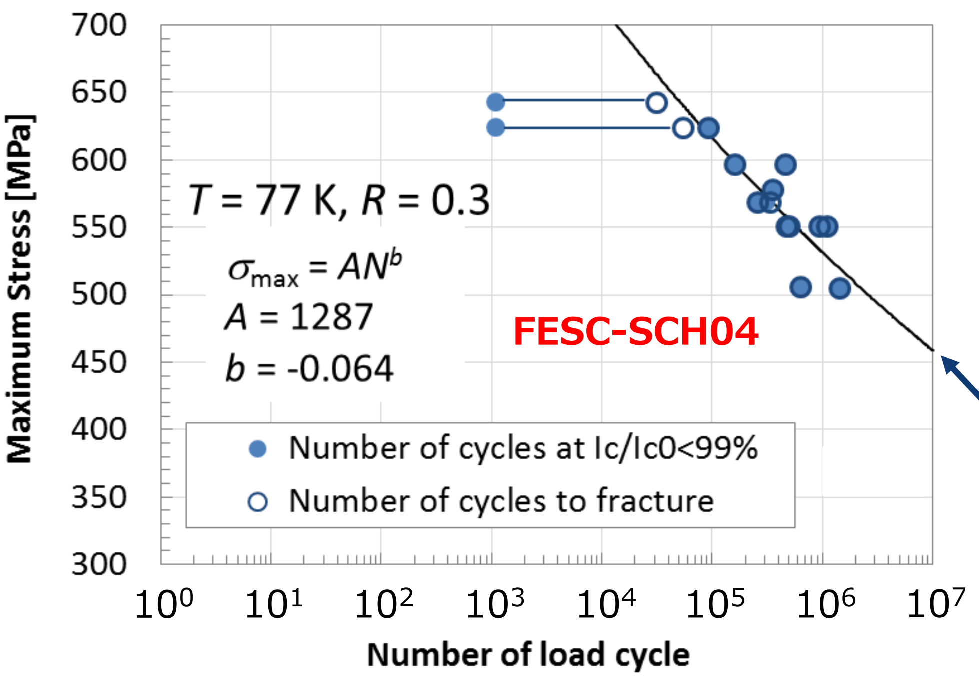
- In the high field magnet, HTS tapes are **repeatedly** subjected to tensile load by electromagnetic force.
  It is necessary to evaluate the **fatigue characteristics** of the HTS to ensure **long-term reliability**.
  → **Fast cycle repeated tensile tests** are performed in LN_2.

Experimental details

- Repetition frequency : 1 – 12 Hz (sine wave)
- Maximum stress : σ_{max} = 645 – 365 MPa
- Stress ratio : $R = \frac{\sigma_{\max}}{\sigma_{\min}} = 0.3$ (constant)



S-N curve (**S**tress - **N**umber of cycle to fracture)



High cycle fatigue with elastic deformation is described by **Baskin 's low** :

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} = CN^b$$

$$\sigma_{max} = AN^b$$,with $A = \frac{C}{1-R}$

b, C : material dependent constants

- **Tensile strength decreased due to fatigue of metal components of the HTS tape.**
- **The samples fractured before I_c degradation, below 600 MPa.**

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S. Fujita, et al.,IEEE Trans. Appl. Supercond. 30-4 (2020) 8400205

Summary

- **Business scale demands for high field applications urged investment**

- **High rate & homogenous REBCO wires by IBAD/Hot-wall PLD**
  - Advantage of Hot-wall PLD processed REBCO films :
    - High & homogenous in-field J_c properties coincide with high throughput
      - Growth stability of thick EuBCO-BHO allows minimal longitudinal in-field J_c perturbation
      - No dependence observed of in-field J_c lift factors on deposition rate at 20K 20T
    - Long length homogeneity
      - 1.4 km long uniform 4mm width sample obtained
      - Good consistency of 10-T magnet coil Ic with numerical simulation confirmed conductor uniformity
    - Good mechanical strength
      - Stable tensile strength accountable by thicknesses of wire components
      - Cyclic fatigue determined by strength of metal components

IBAD/PLD is a reliable choice for investment as large production with sufficient quality for HF application though additional cost of High-powered UV lasers

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END

Thank you for attention

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