Homogenous REBCO Coated Conductor Production Developed by Using IBAD and Hot-wall PLD Process

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We appreciate Prof. T. Kiss at Kyushu Univ. and Prof. S. Awaji at Tohoku Univ. for collaboration to sample evaluation. A part of results was also performed at the High Field Laboratory for Superconducting Materials, IMR, Tohoku University.
They also 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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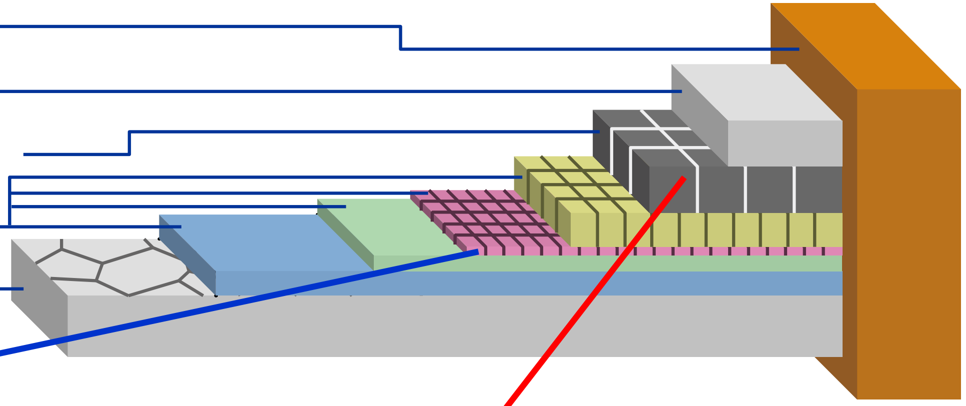
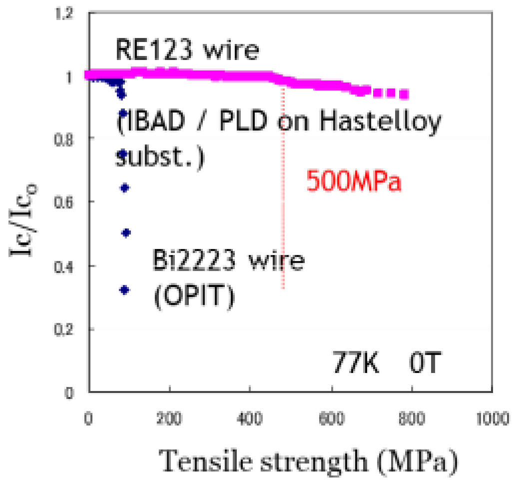
IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue 53, July 2023.
Presentation given at Coated Conductors for Applications Workshop, Houston, TX, USA, April 2023.

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

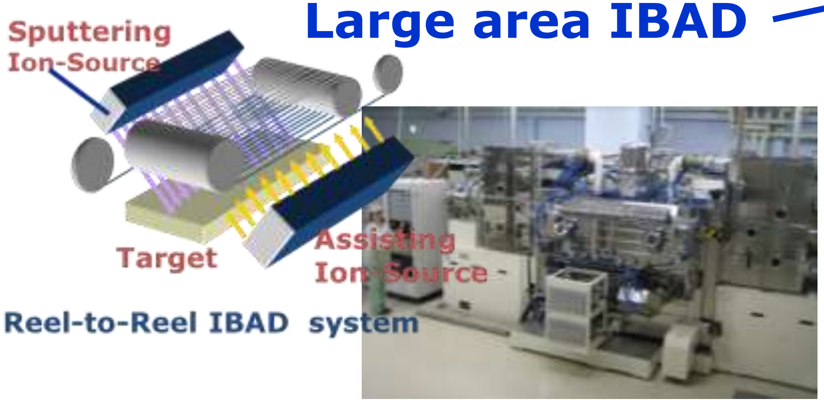
<Schematic of 2G HTS wire>

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

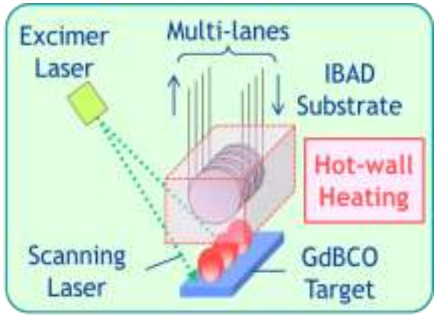




Large area IBAD



Hot-Wall PLD



Developed in NEDO/METI programs
"super-GM" (1989-1999)
"Fundamental Technologies for Superconductivity Applications I/II" (1998-2007)
"Project to Promote Commercialization of High-Temperature Superconductivity Technology"(2016-2000)

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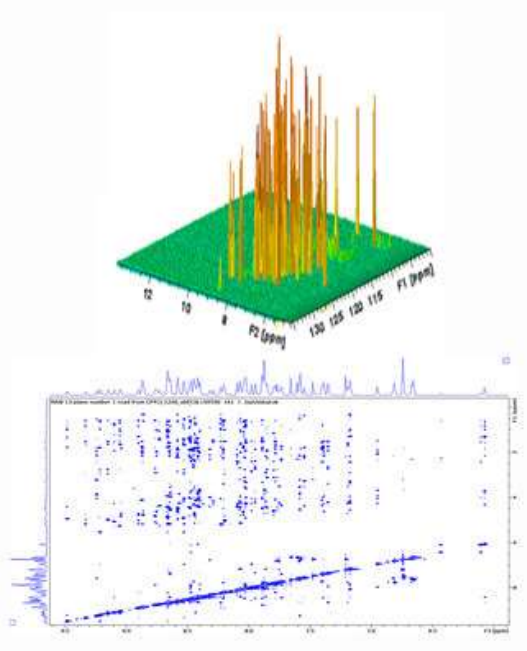
Drastic improvement of industrial excimer laser technology for semiconductor annealing process （2000～）Reduction of maintenance cost

High field applications of IBAD/PLD REBCO coated conductor

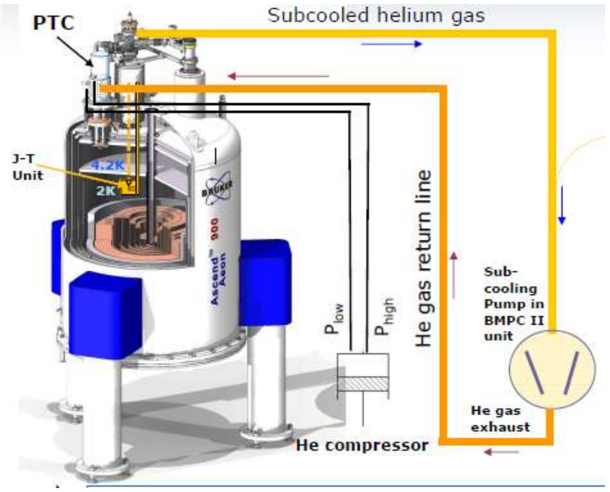
high field NMR system



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

Commercial Practical device



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

1.0 GHz NMR with compact 23.5 T magnet

longitudinal uniformity of in field I_c Strongly required

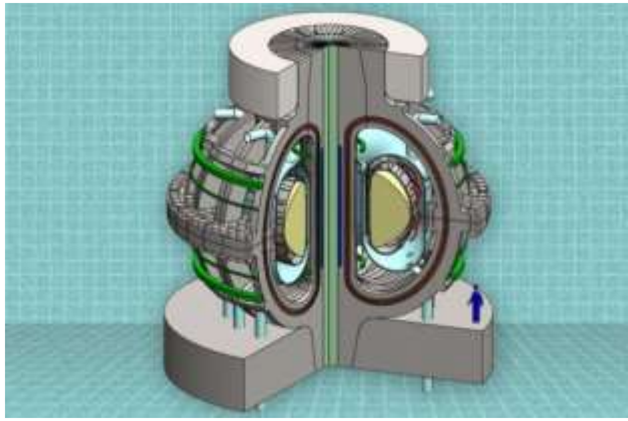
Compact fusion reactor

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

Big R&D prototype



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

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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Contents

- **Coated conductors by IBAD/Hot-wall PLD process**
  - Advantage of IBAD/Hot-wall PLD process:
    - Very high growth rate, with controllable pinning defects
    - Growth stability of thick EuBCO-BHO with high J_c in wide temp. field range
  - Line up of C.C. @Fujikura Ltd.
  - Gaps in Technology
  - Cost, volume projections, Supply Chain issues

- **Current status of Fujikura C.C. uniformity**
  - 1km long uniformity improvement for varied width
  - Mechanical reliability improvement

- **Desired advancements in conductor research**
  - Internally pursued improvements with customer collaborations
  - Potential areas of collaboration with research institutes, etc.

- **Summary**

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Growth structure & J_c-B-θ properties of BMO-EuBCO by PLD

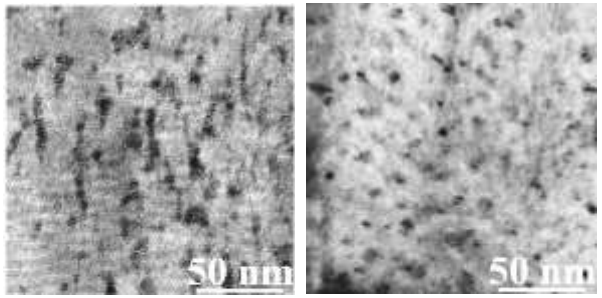
PLD: Fast and Controllable non-equllibrium process

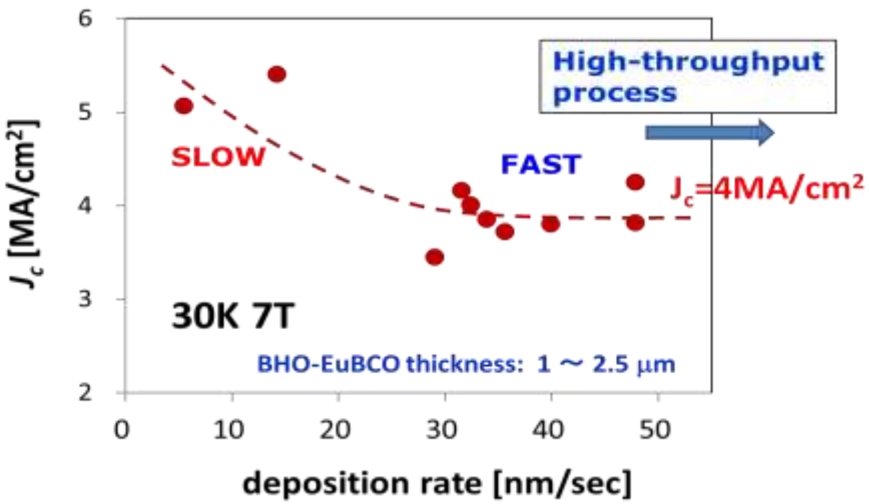
rapid and fine evaporation by UV pulse laser

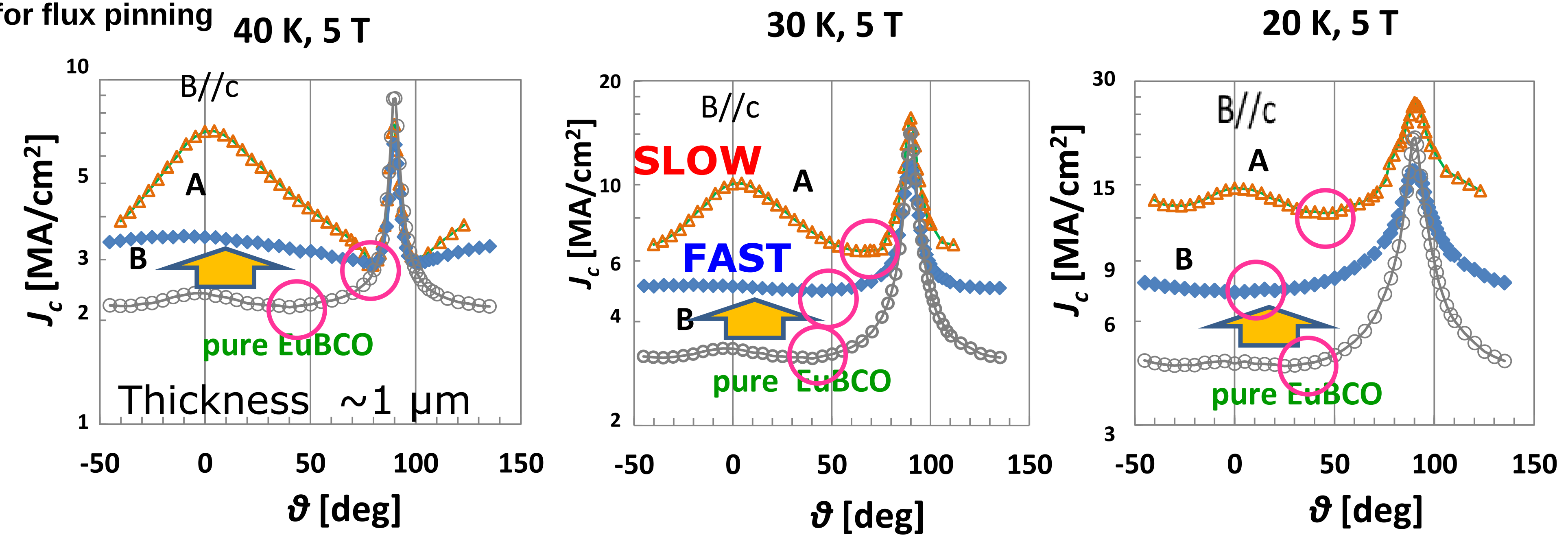
- Very high supersaturated growth with high adatom mobility & low compositional fluctuation
  - Very fast growth rate with good textured matrix
  - Dense small size secondary growth and defects suitable for flux pinning

EuBCO-$HfBaO_3$

Scatterd short nanorods in high-growth rate FAST samples







more isotropic property
In wide temperature and field range

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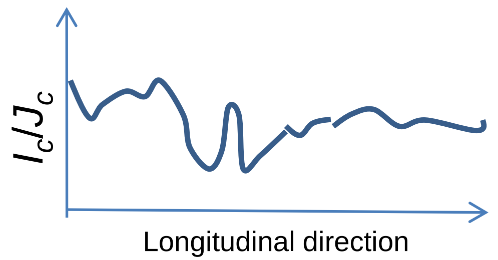
Reproducible uniformity pursued by Hot-wall PLD

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

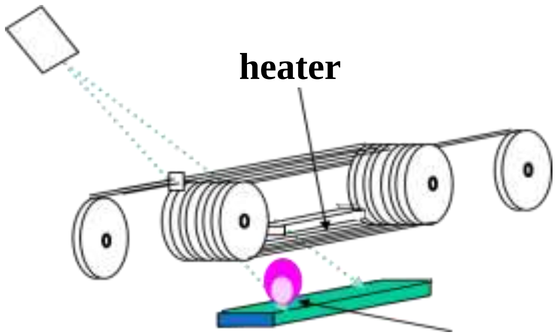


Additional deposition parameters: BMO nanorod structure

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

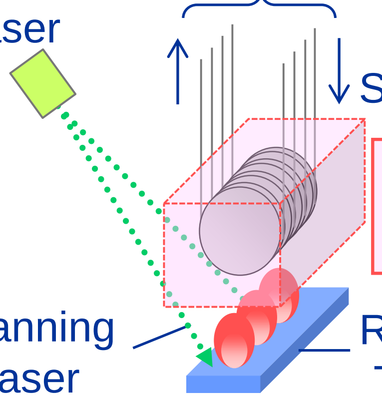
Heater block system

Used 1990s-2005



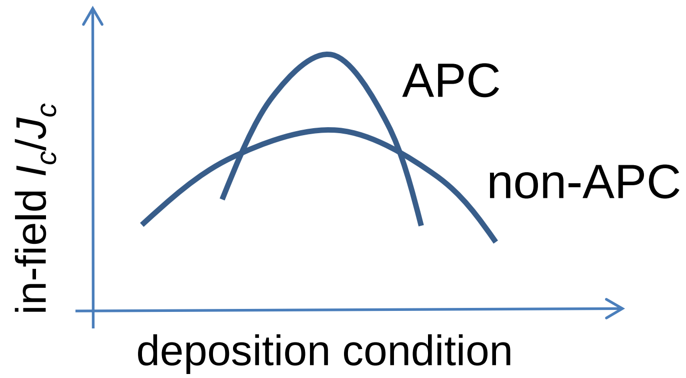
Hot-wall PLD system

Initial set up 2003-2008
reformed 2016-2018



Window width **Y < Gd < Eu**

APC < non-APC



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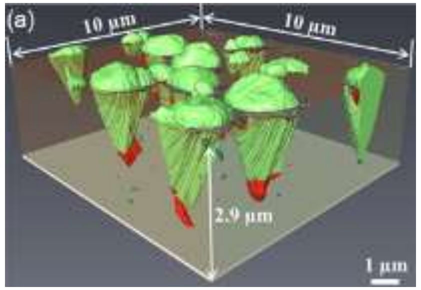
RE elemental dependent growth stability for BMO-REBCO

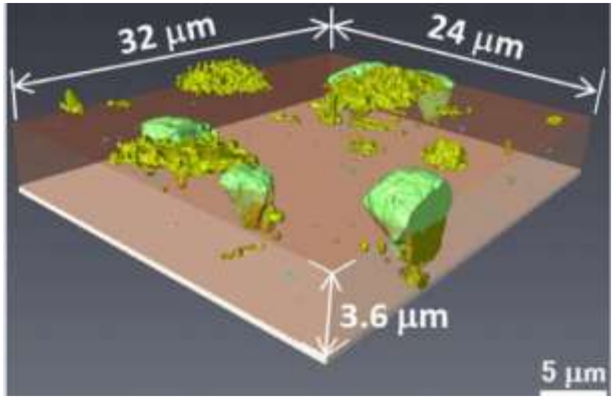
FIB-SEM 3D observation on misoriented grains (mainly a-axis aligned normal) for thick BMO-REBCO films

BaHfO-GdBaCuO



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

BaHfO-EuBaCuO

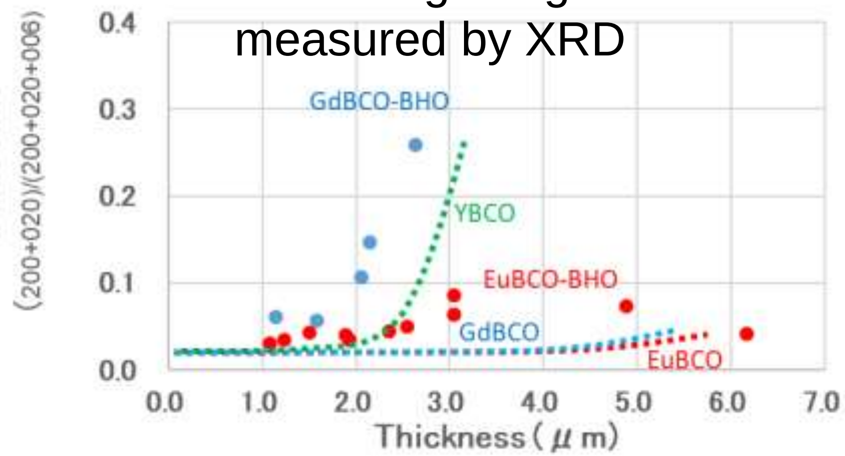


D. Yokoe et al., Supercond.Sci.Technol. **33** (2020) 024002
T. Yoshida et al., Physica C **504** (2014) 42

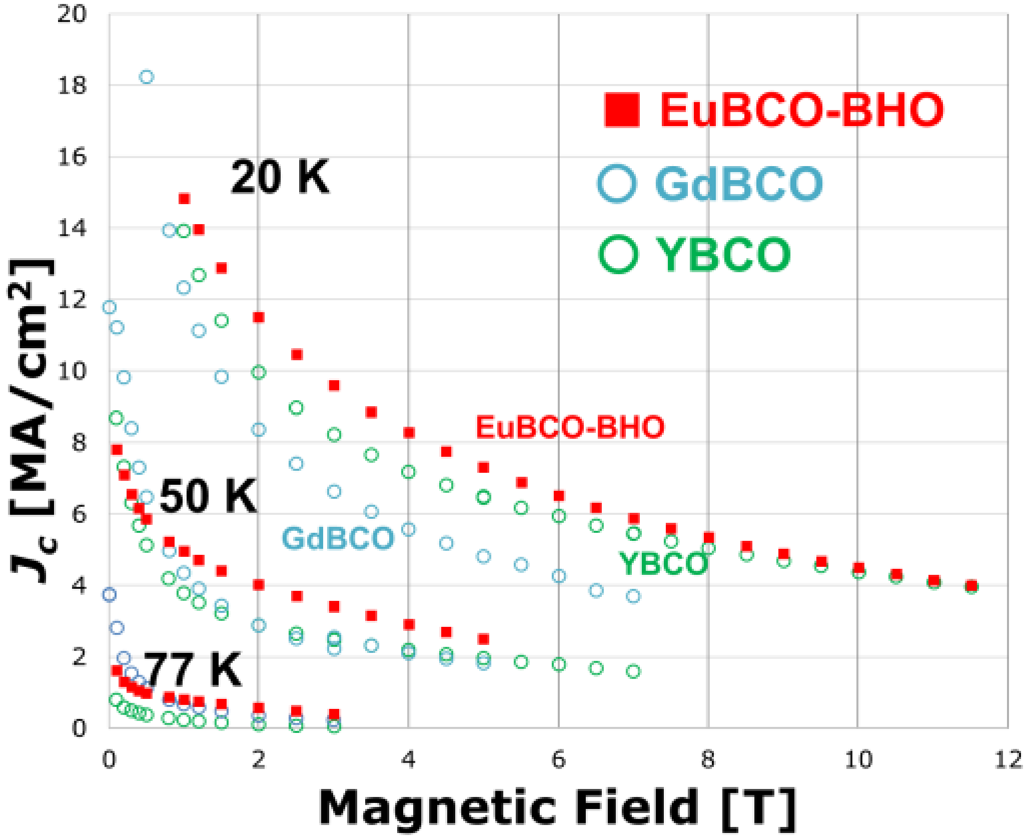
Oriented growth stability

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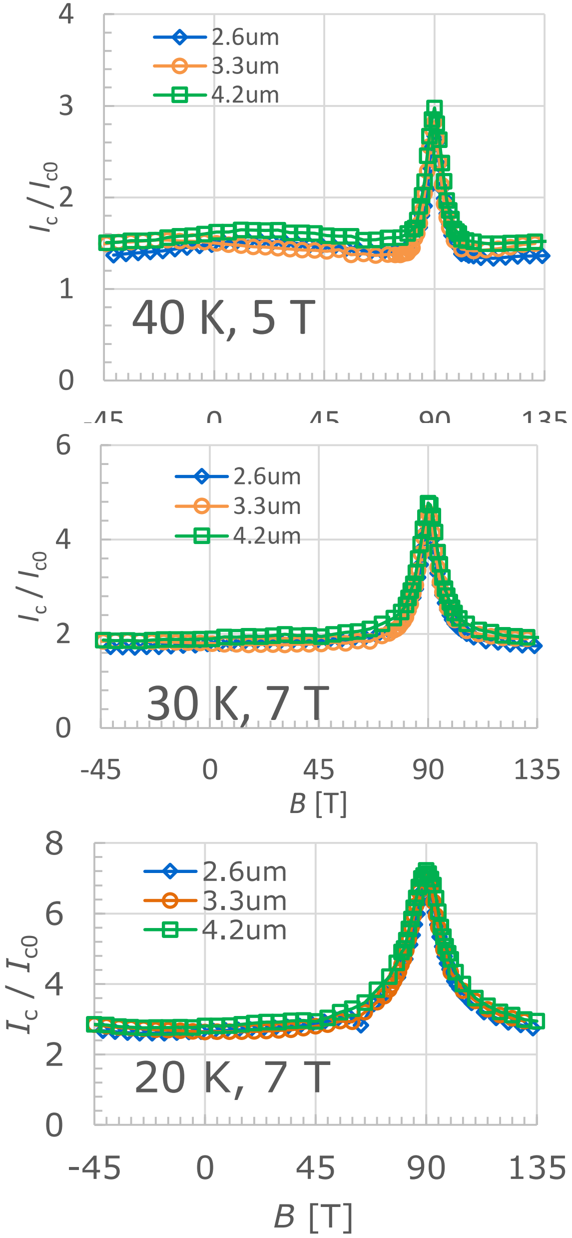
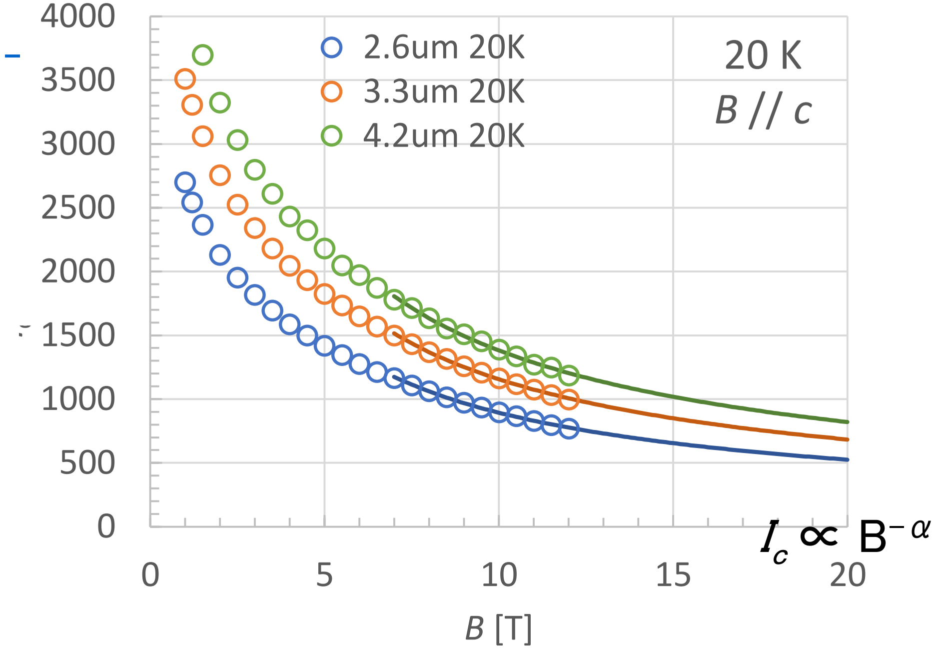
Thickness dependence for in-field I_c properties of BHO-EuBCO



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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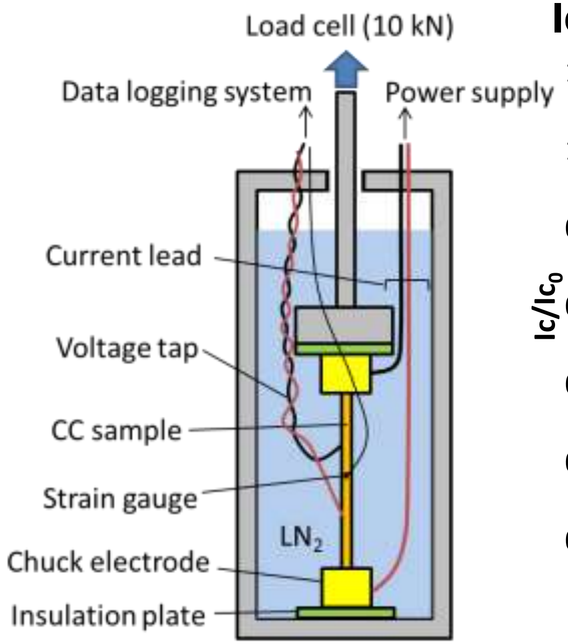
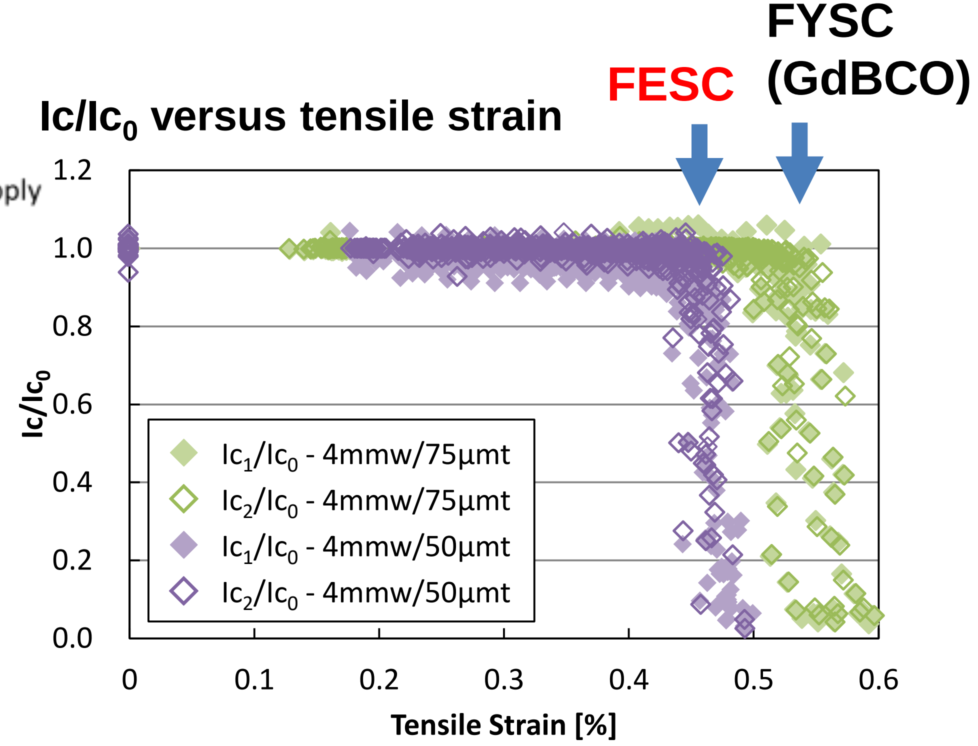
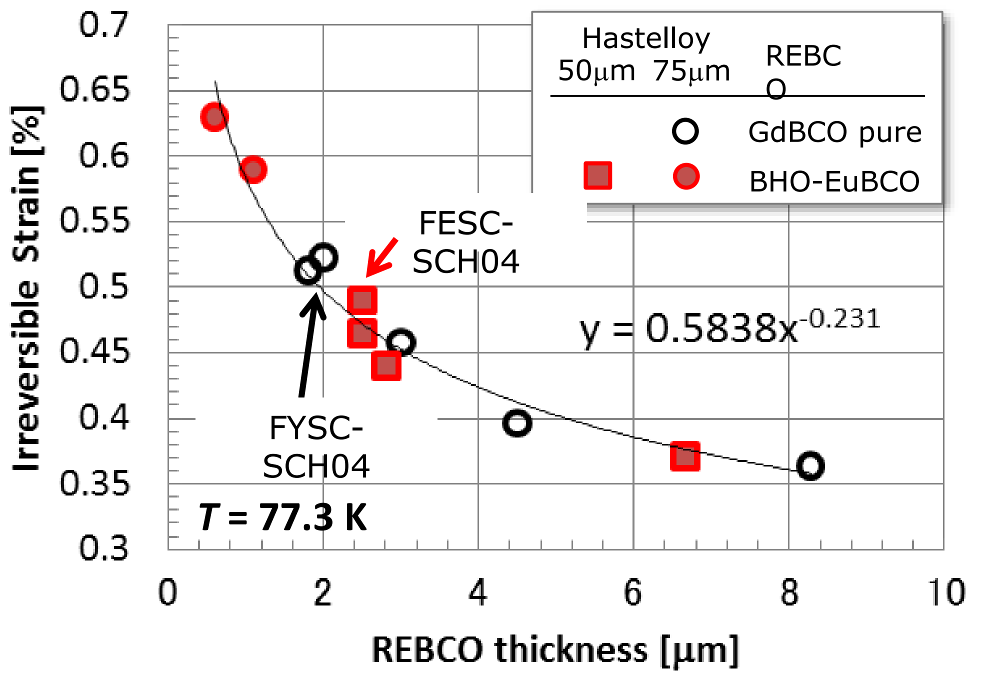
Thickness dependent tensile strength

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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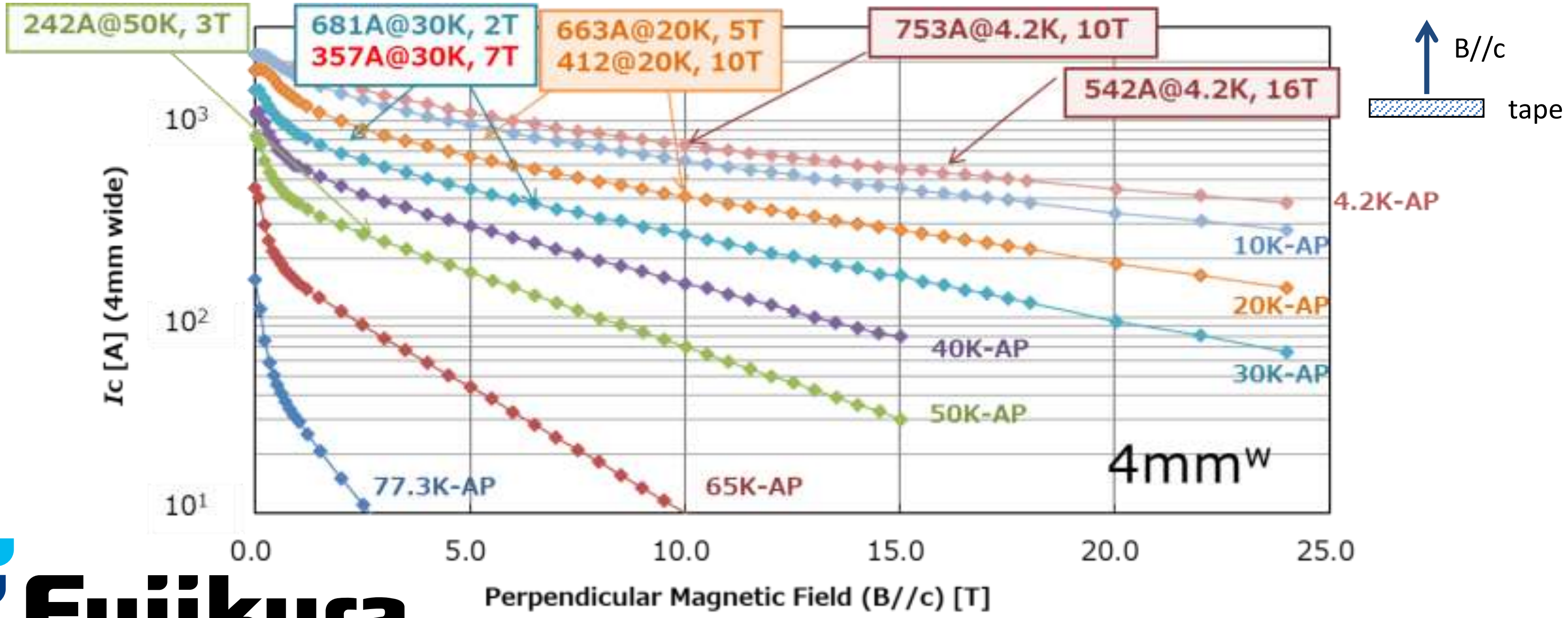
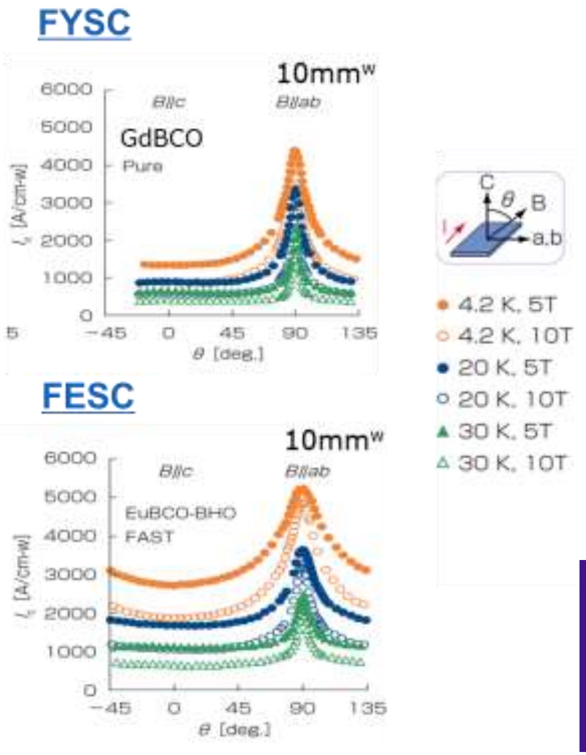
Typical specifications of 2G-HTS wire at Fujikura

Products	Width [mm]	Thickness [mm]	Substrate [μm]	Stabilizer Cu [μm]	Critical Current [A]	
					77K, S.F.	20K, 5T*3
FYSC-SCH04	4	0.13	75	20	≥ 165	368
FYSC-SCH04(40)	4	0.17	75	40	≥ 165	368
FYSC-SCH12	12	0.13	75	20	≥ 550	1,104
FESC-SCH02 *2	2	0.11	50	20	TBD	(257)
FESC-SCH03 *2	3	0.11	50	20	≥ 63	497
FESC-SCH04 *2	4	0.11	50	20	≥ 85	663
FESC-SCH12 *2	12	0.11	50	20	≥ 250	1,990





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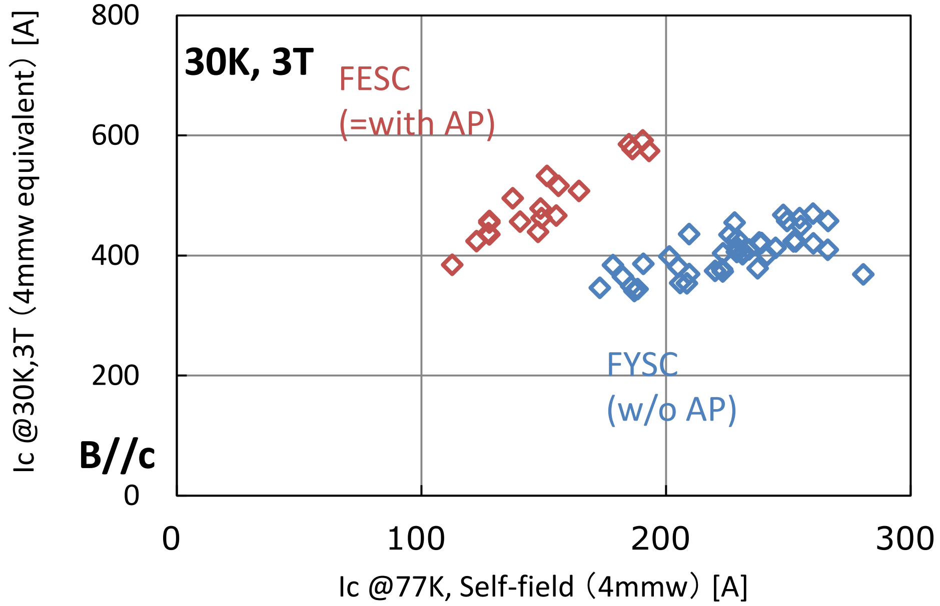
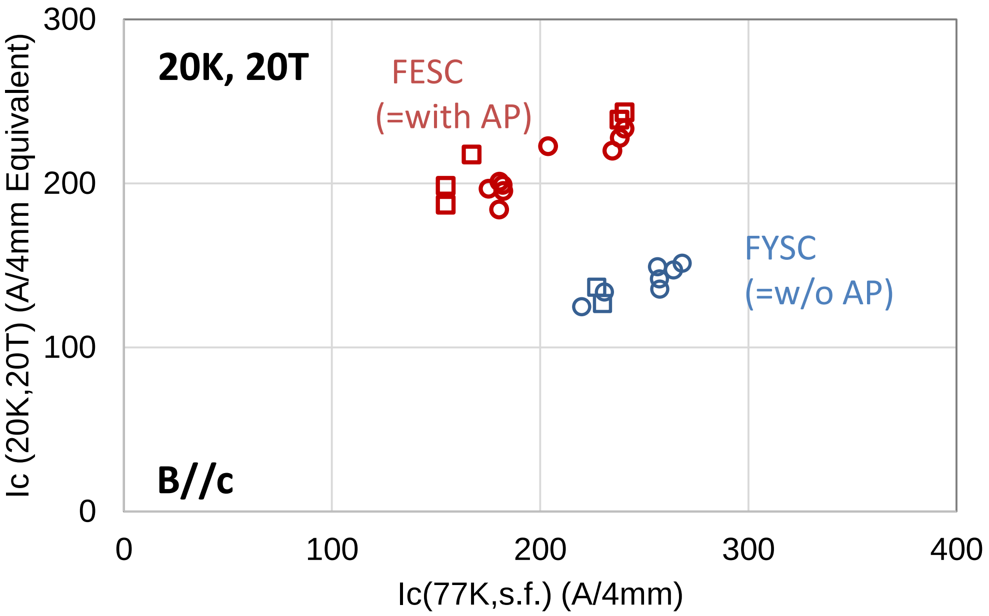
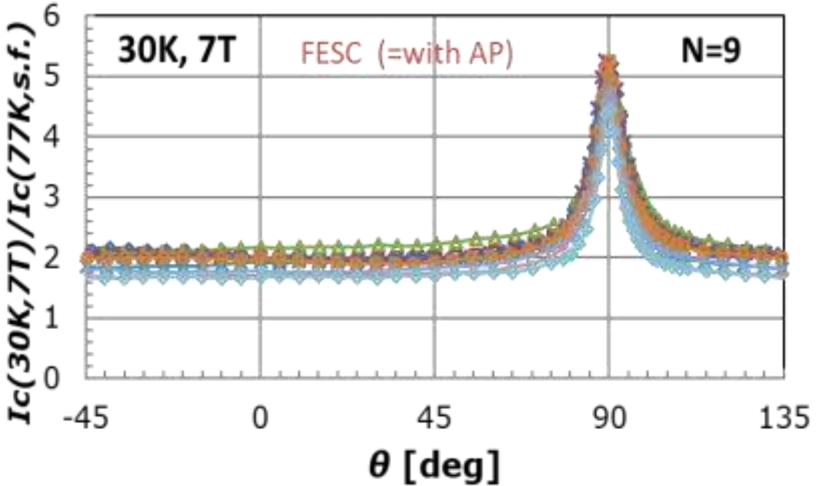
Self & in-field I_c distribution of 4 mm^w EuBCO-BHO wire

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

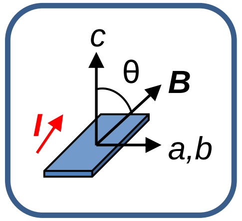




Good correlation to self field I_c and in-field I_c observed for both EuBCO+BHO and pristine GdBCO



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



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Gaps in technology

･Jc-B-T enhancement	strong enough	desired for higher throughput
･piece length（determined by homogeneity）	0.3 – 1 km	~5km ideally in future
･mechanical reliability	enough tensile/bend/ delamination strength	coiling results accumulation desired
･cross-sectional dimension	width 2~12mm	thinner thickness desired
･cost down （≒productivity）	still higher than Nb_3Sn	

moderate scale driven mode DC magnet

･superconducting joints	required for PCM applications as MRI, etc.
･coil protection for large scale	must be achieved for large scale, as fusion, etc.
･radiation damage	must be evaluated for compact fusion
･AC loss/screening current ･lower inductance cabling	desirable for AC/ very large scale applications

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Cost, volume projections, Supply Chain issues

- Cost, volume projections – 3 years, 5 years
  - Cost: approaching to high spec Nb_3Sn wires in future
    - Running cost for excimer laser drastically decreased in past 20 years
  - Volume: under investment for double capacity
- Supply Chain issues – raw materials, equipment
  - Optimistic
  - Raw materials:
    - rare earth elements :widely used in fluorescent substance, etc.
    - Ni-based alloys : widely used in chemical/nuclear plants, etc.
    - Inert gases： temporary shortage observed by war
  - Vacuum equipment: widely used in semiconductor or FPD industry including excimer laser sources

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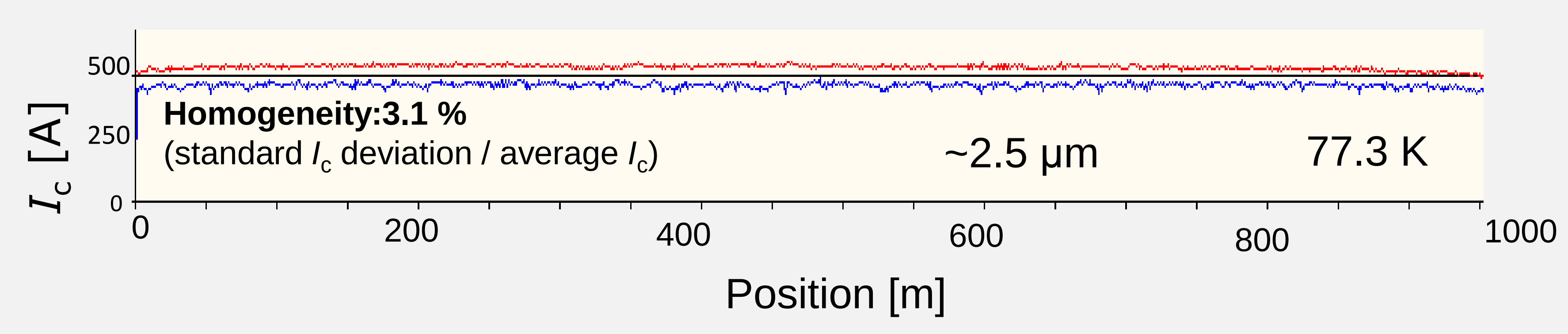
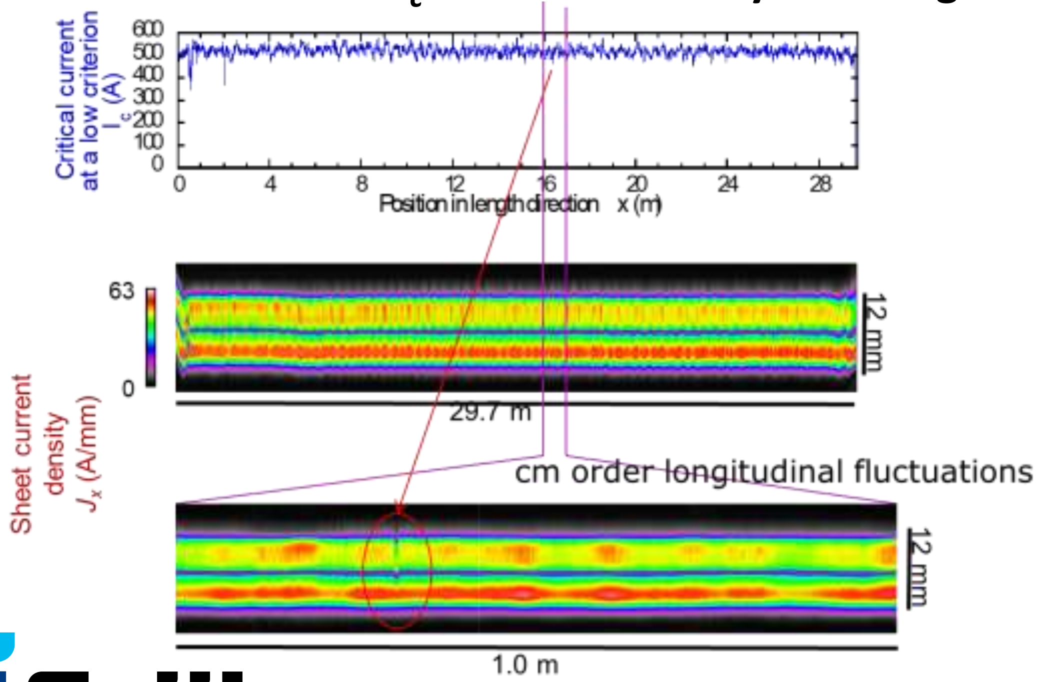
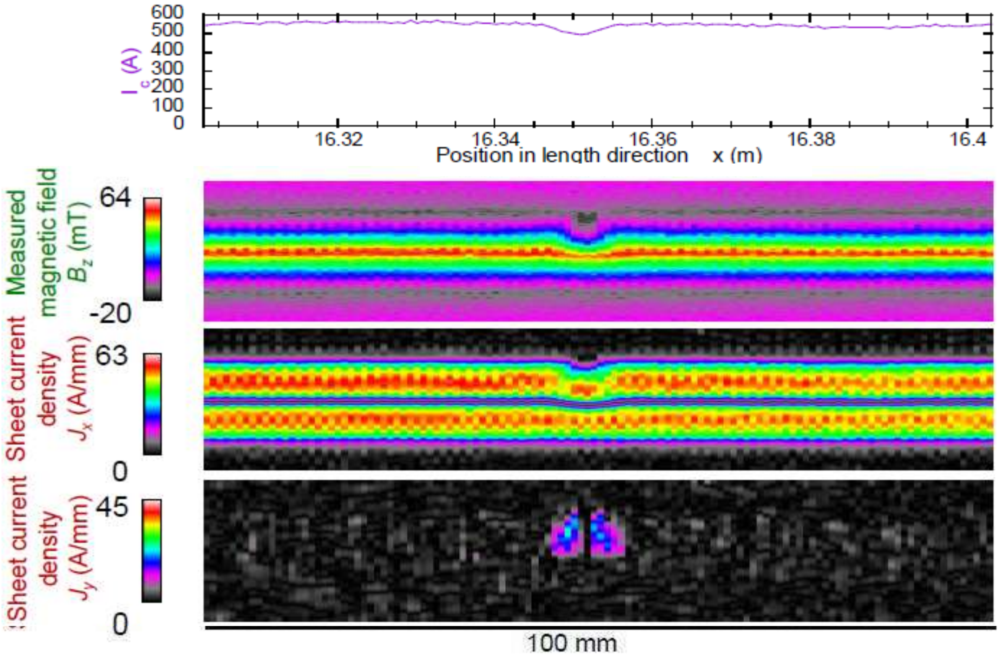
I_c uniformity of BHO-EuBCO wire of 12 mm^w^

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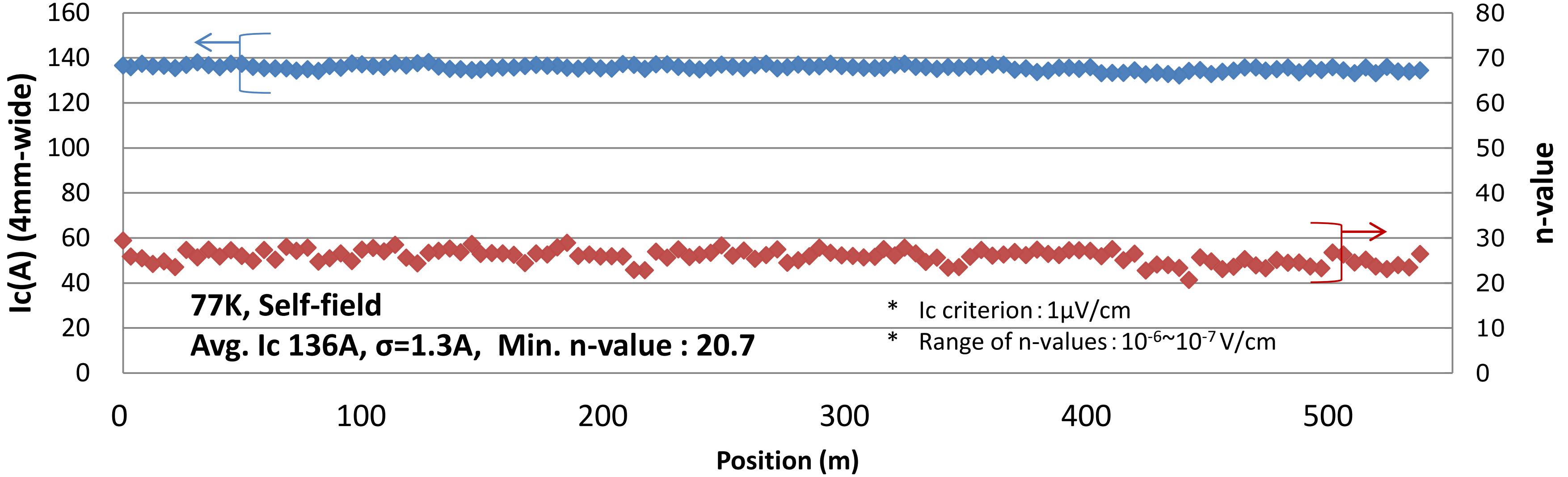
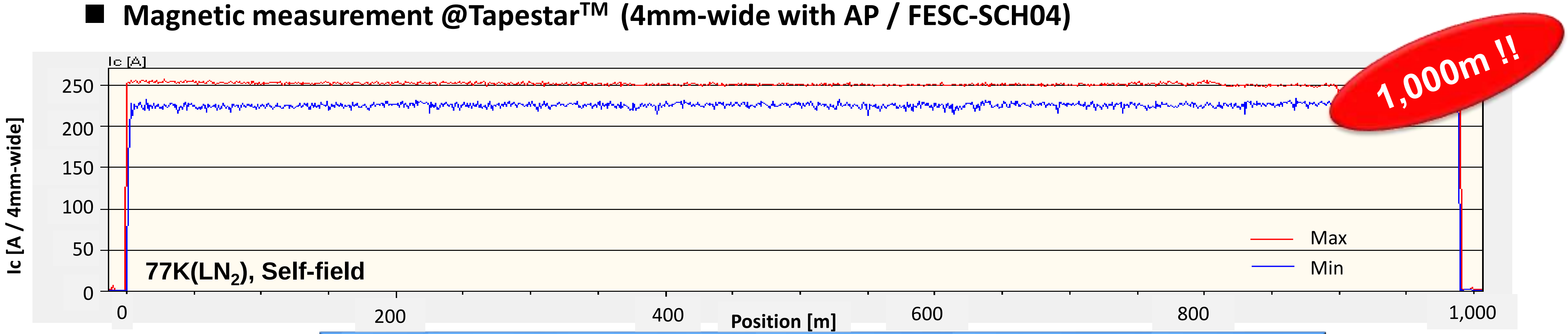
Example data of longitudinal I_c distribution of 4mm-wide tape

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



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



quite uniform I_c with artificial pinning tape and ~ 1,000 m are obtained

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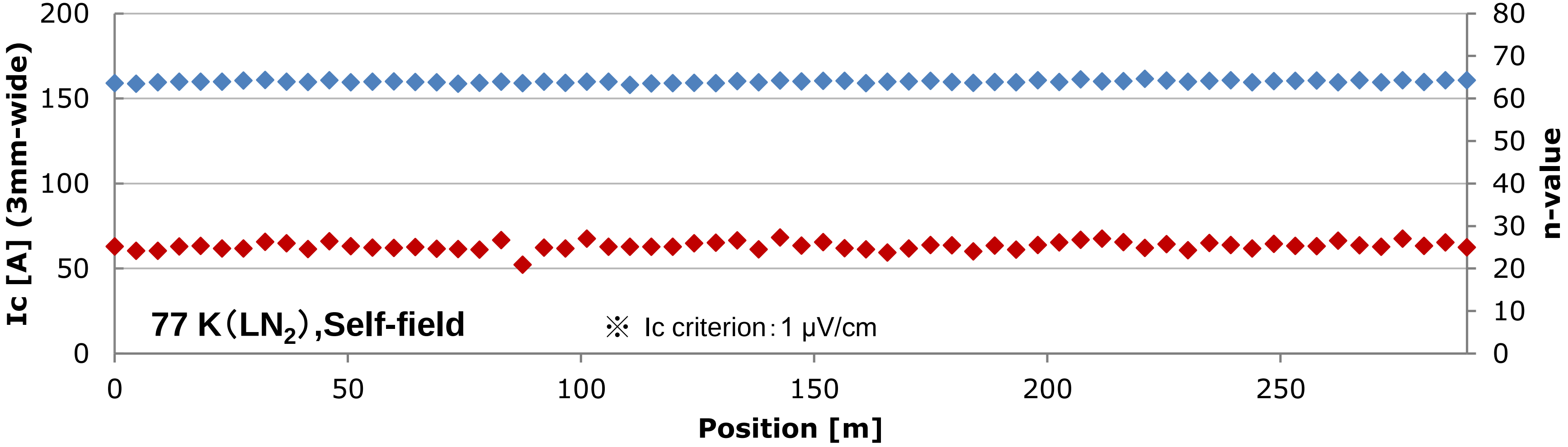
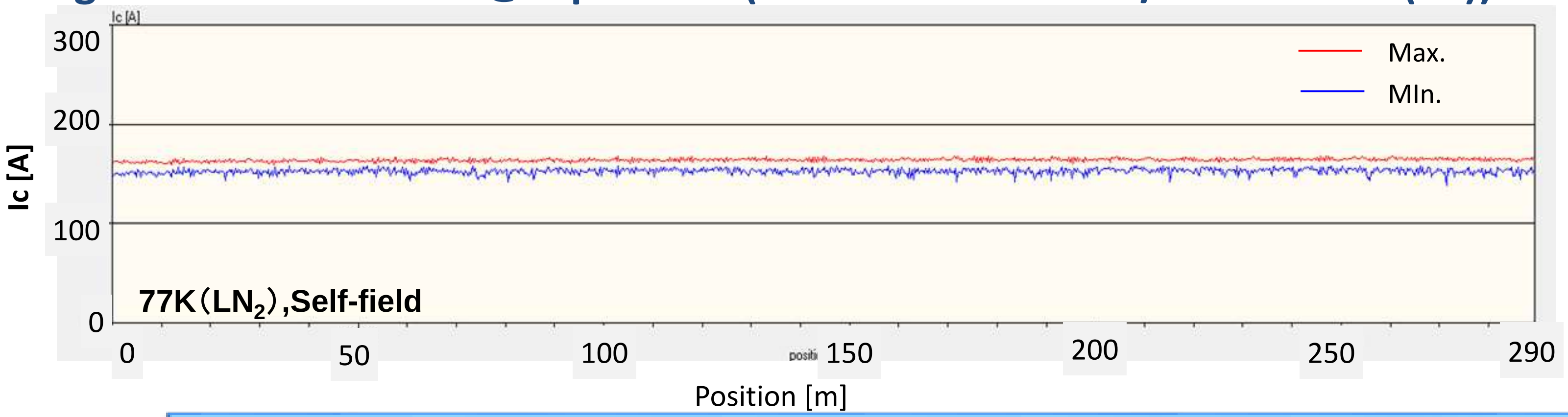
Example data of longitudinal I_c distribution of 3mm-wide tape

3 mm-wide tape: FESC-SCH03

- Measured by 4-terminal method current conduction measurement at every 4.7 m



- Magnetic measurement @Tapestar[TM] (3mm-wide with AP / FESC-SCH03(40))



Uniform I_c with artificial pinning and approx. 300m length tape are obtained

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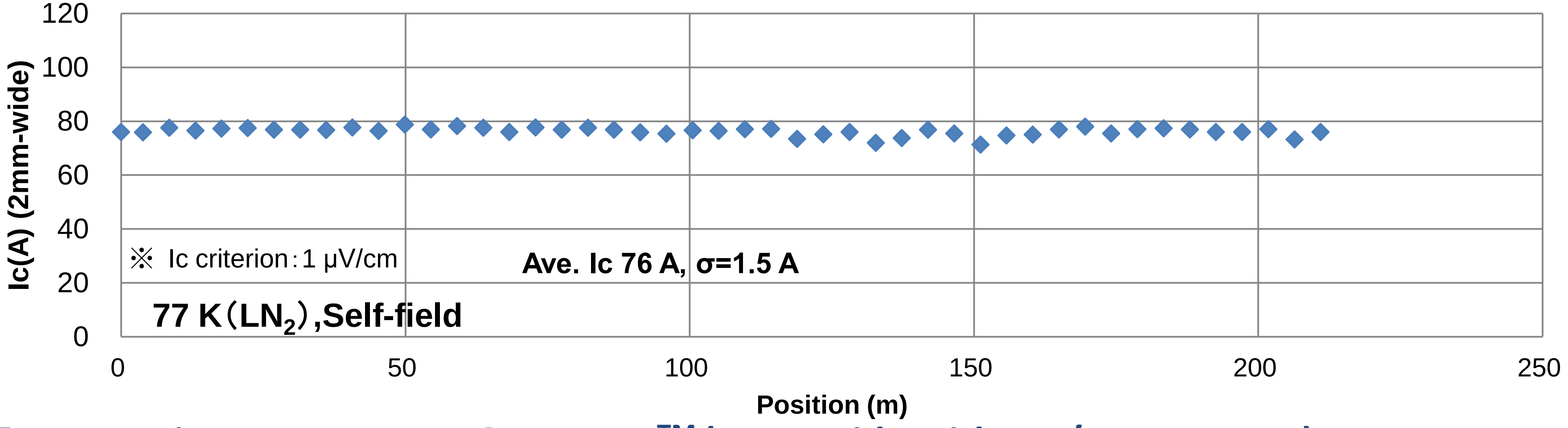
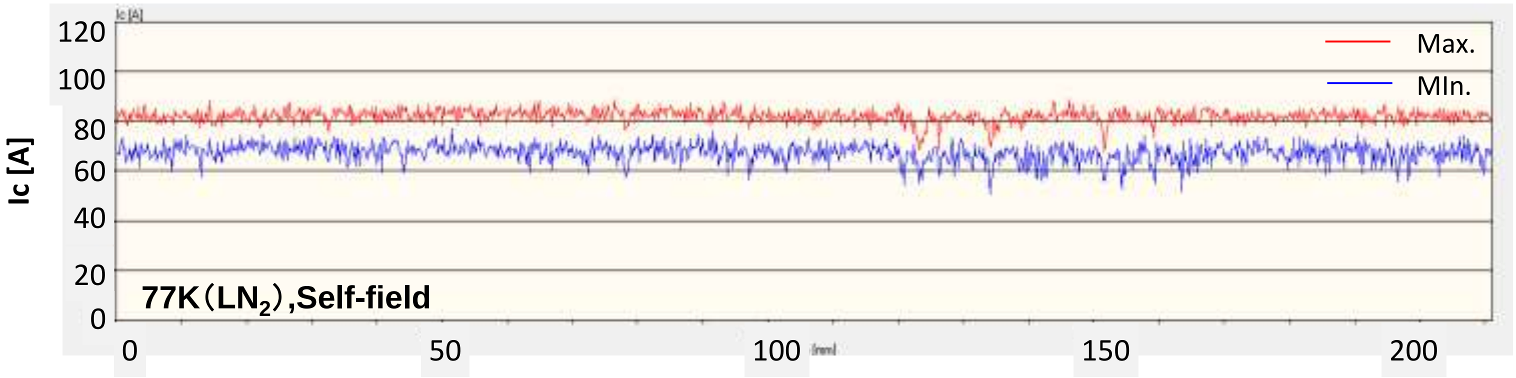
Example data of longitudinal I_c distribution of 2mm-wide tape

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)**



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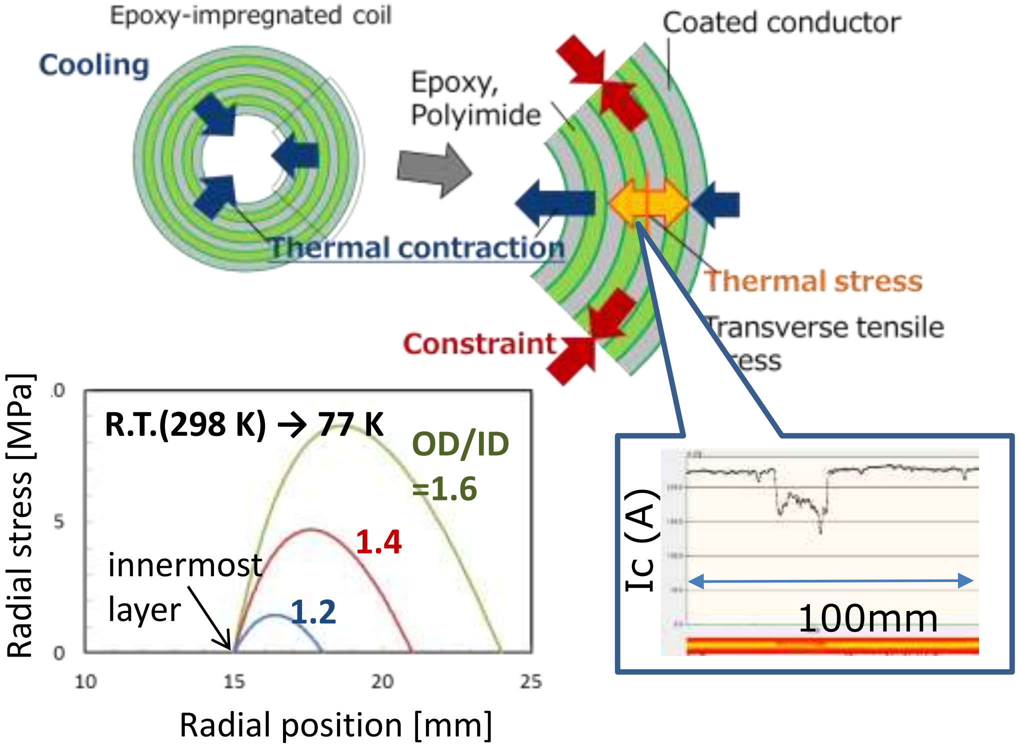
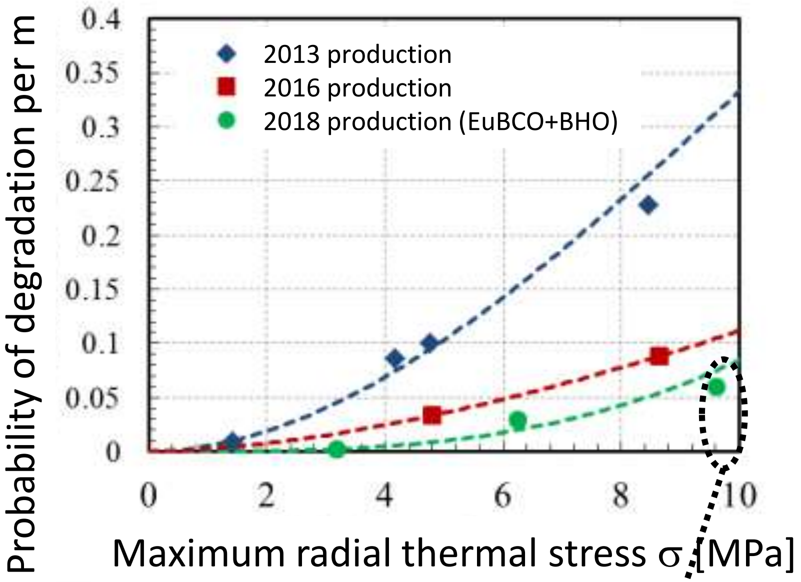
For 2mm long-tape, stable I_c with artificial pinning wire are obtained

Delamination strength distribution evaluated by impregnated coils

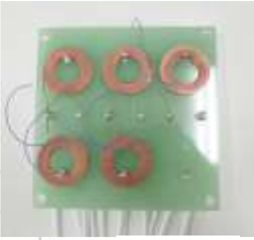
<Vertical stress test by thermal stress inside impregnated coil controlled by OD/ID ratio >

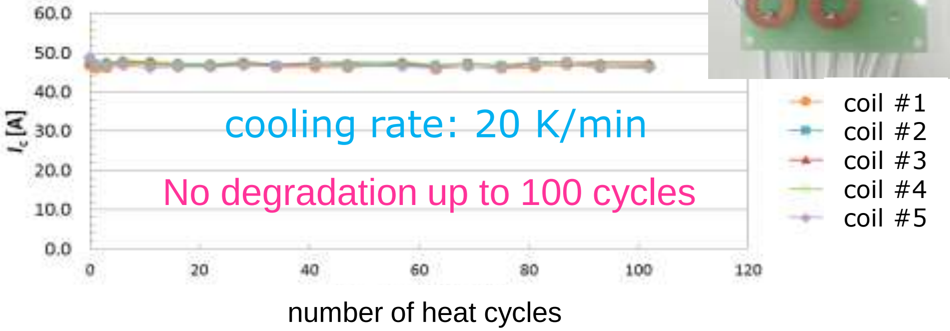


H. Miyazaki *et al*., IEEE TAS, **25** (2015) 6602305



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





Fully impregnated coil without release structure can severely evaluate the weakest point of mechanical reliability for C.C.

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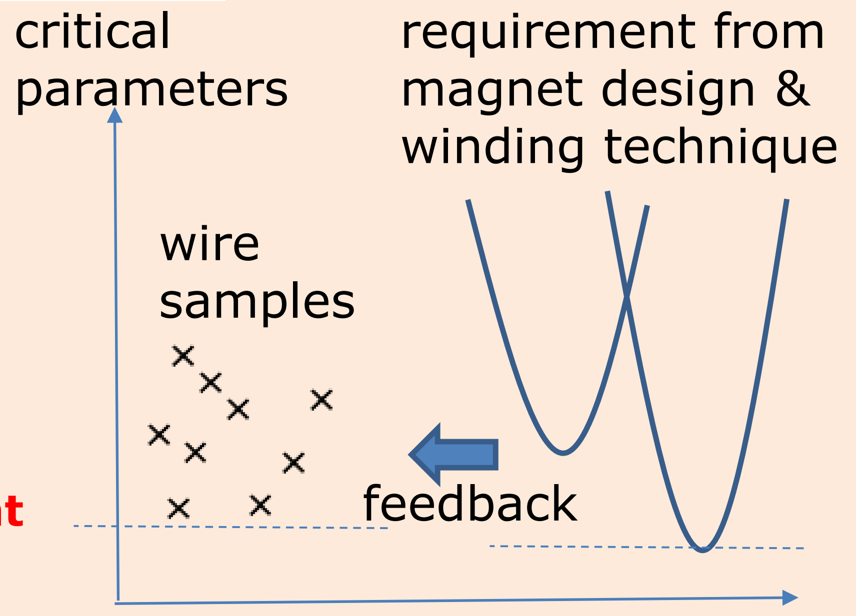
Desired advancements in conductor research – prioritize

Internally pursued with customer collaborations

- ･Jc-B-T enhancement — HTS thickness reduction
- **･piece length (determined by homogeneity)** — **higher production yield ~1km**
- **･mechanical reliability** — **coiling results accumulation**
- **･cross-sectional dimension** — **Substrate thickness reduction**
- **･cost down (≒productivity)** — **production sequence improvement +Jc-B, length enhancement**
- ･superconducting joints



- **･radiation damage** — **neutron/proton irradiation results useful for compact fusion**
- **･coil protection for large scale** — **protection tests by moderate scale coils**
- ･AC loss/screening current — striation, assembled cables
- ･lower inductance cabling

Potential areas of collaboration with research institutes, etc.

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Summary

☐ Coated conductors by IBAD/PLD process

- Suitable for mass production of recent demands from high field application
  - ☐ PLD process: non equilibrium, very high growth rate, with controllable pinning defects
- Current status of Fujikura REBCO C.C. by Hot-wall PLD
  - ☐ Growth stability of thick EuBCO-BHO better than GdBCO-BHO, pristine YBCO
  - ☐ Good uniformity obtained in 1km long for 4 mm wide, 300m long for 2mm wide
- Gaps in technology: mostly completed for moderate scale DC magnet but cost

☐ Cost, volume projections, Supply Chain

- ☐ Cost: approaching to high spec Nb_3Sn wires in future
- ☐ Volume: invested for double capacity, future projection depends on top management
- ☐ Supply chain: generally optimistic

☐ Desired advancements in conductor research

- ☐ 1st priority: cost reduction by long length homogeneity & processing modernization
- ☐ 2nd :Trade-off judgement of smaller cross section, and mechanical reliability
- ☐ Neutron radiation damage evaluation
- ☐ Coil protection, Assembled wire, for large current, AC, etc.

} Potential areas of collaboration with research institutes, etc.

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END

Thank you for attention

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