Stable Mass-Production by Hot-Wall PLD Approach for Uniform REBCO Wires and Magnet Applications

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N. Nakamura, S. Hanyu and M. Daibo

Fujikura Ltd.

Fujikura

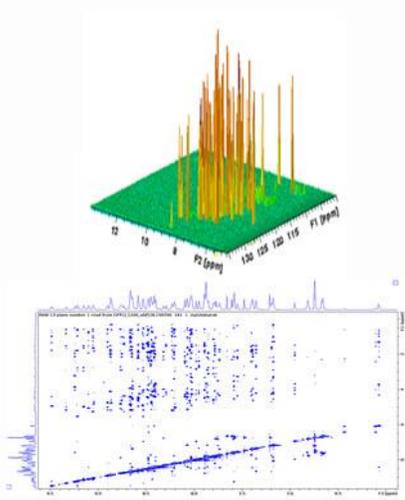# Contents

☐ **REBCO wire mass production started:**
- ☐ Market started from high-field application : NMR, Fusion
- ☐ **Why IBAD/PLD process?** High in-field Jc / Strong in-field mechanical strength
- ☐ Trade-off of laser cost and PLD advantage

☐ **Advantages of PLD process for mass-production**
- ☐ **Reproducibility:** controllable near best phase point
- ☐ **High in-field Ic :** small and dispersed pinning centers by vapor deposition
- ☐ **High growth rate:** high transfer yield, high supersaturation and adequate adatom energy
- ☐ **Uniformity:** temperature stability improved by Hot-wall architecture

☐ **Uniform REBCO wire lineup by Fujikura for magnet applications**
- ☐ **Demand of magnet technology: Uniformity and Mechanical reliability**
- ☐ New area: NI technology, assembled conductors, quench protection,,,,

☐ **Summary**

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Business demand of REBCO urged scale-up investment

BRUKER 1.0/1.2GHz NMR (2019~)

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

First Commercial Practical device using REBCO wire

1.2 GHz NMR 28.2 T magnet with 54 mm bore
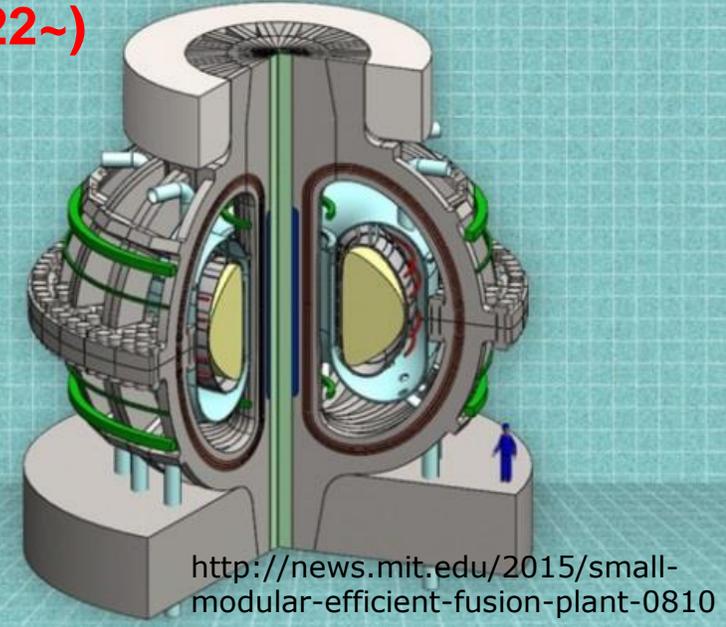
1.0 GHz NMR with compact 23.5 T magnet

<u>**longitudinal Ic uniformity strongly required**</u>

Compact fusion reactor (2022~)

Compact design marketable by using private funding

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

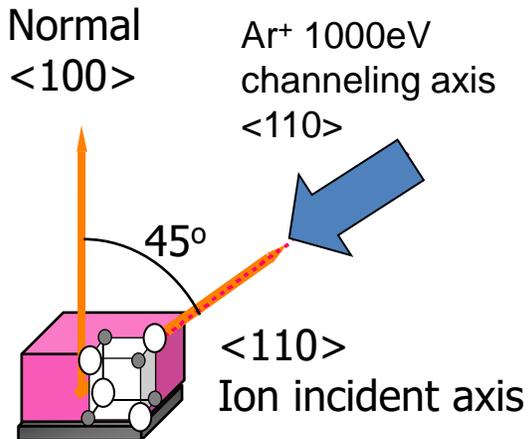**Neutron radiation damage inevitable come from thinner shield**

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

REBCO wire demand up to 10000s km/reactor

<u>**On going reactor program:**</u> **SPARC (CFS), ST80 (Tokamak energy(TE))**
<u>**Planned reactor program:**</u> **ARC (CFS), ST-E1 (TE), STEP (UKAEA), and many others**

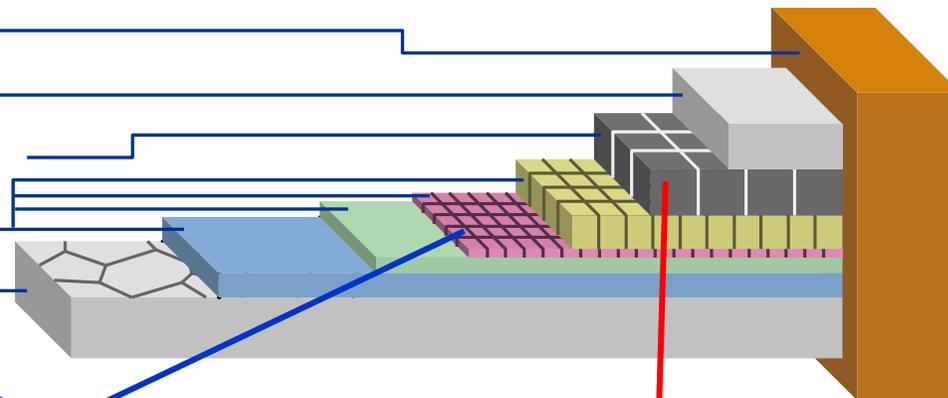<u>**Big demand come from large scale/large current magnets with NI technology / assembled conductors**</u>
High quality wires with desired delivery&cost

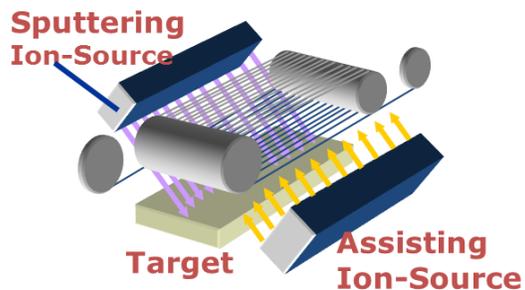**Fujikura**

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

Normal
<100>

Ar+ 1000eV channeling axis <110>

45°

<110>
Ion incident axis

Sputtering Ion-Source

Target

Assisting Ion-Source

Reel-to-Reel IBAD system

＜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）**

Ni-Alloy tape   Cu plating

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

Tensile Stress [MPa] vs Tensile Strain [%]

Pulsed Laser Deposition（PLD）

vacuum chamber   optics

heater block

substrate   window

ablation plume

REBCO Target

Ultraviolet Pulse

λ＝248~308nm
pulse width: 20-30nsec
pulse energy: ~1J

Excimer Laser

**Pulse duration~10nsec
Peak Power at Target surface >GW/cm^2**

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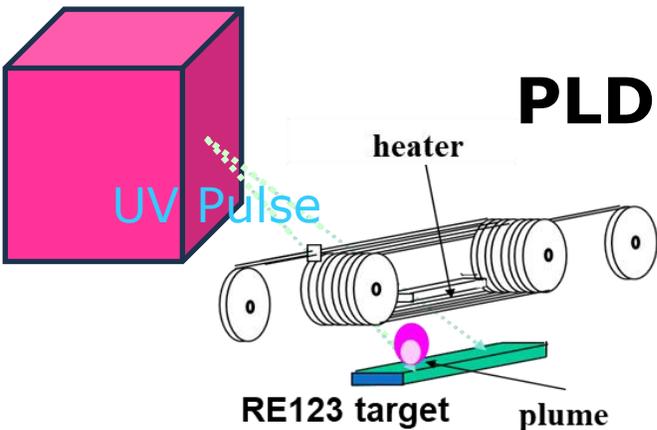
General cost evaluation of REBCO film production process

☐ **PLD system has costly Excimer Laser, but the equipment cost shrinks by High Throughput, Operation Lifetime, and High Production Yield.**

$$\text{Cost}_{REBCO} \sim \left(\text{Cost}_{op.} + \left(\frac{\text{Cost}_{equipment}}{\text{Throughput} \times T_{op.}} \right) \right) \times \frac{1}{\text{Production Yield}}$$
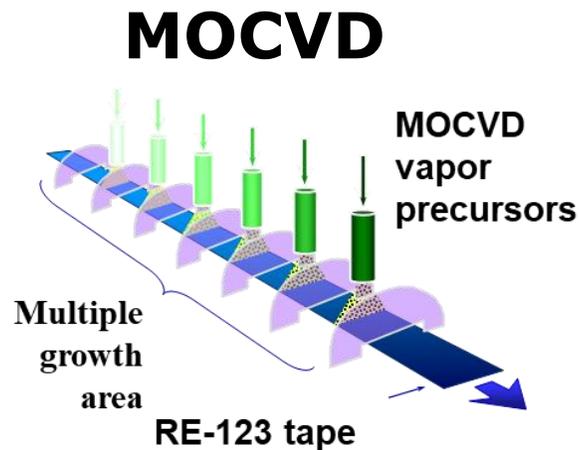
◆ Growth rate
◆ Laser power
◆ Laser lifetime

◆ Reproducibility
◆ In-field Jc/Ic
◆ Uniformity

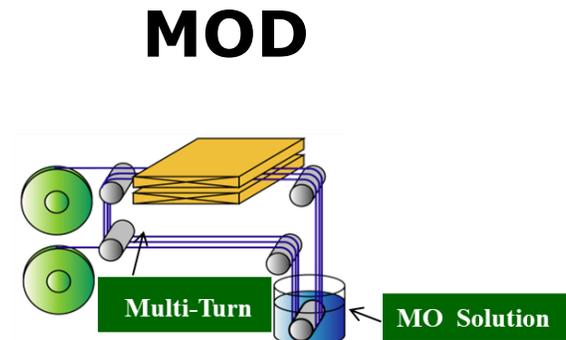**Industrial Excimer Laser**

UV Pulse

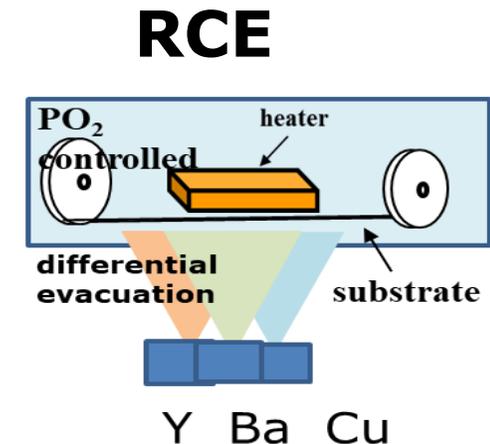**PLD**

heater

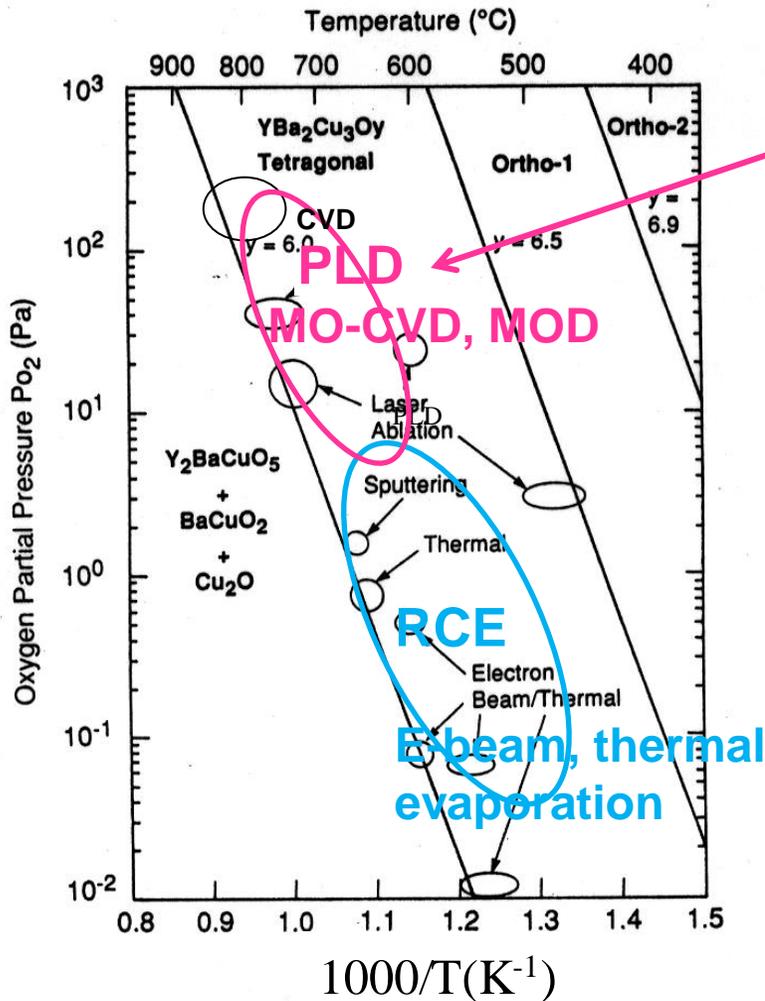RE123 target   plume

MOCVD

MOCVD vapor precursors

Multiple growth area

RE-123 tape

MOD

Multi-Turn   MO Solution

RCE

PO$_2$ controlled   heater

differential evacuation   substrate

Y Ba Cu

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Temperature (°C)

900 800 700 600 500 400

10^3 YBa$_2$Cu$_3$Oy Tetragonal | Ortho-1 | Ortho-2

CVD y = 6.0

PLD
MO-CVD, MOD

10^2 y = 6.5 | y = 6.9

Oxygen Partial Pressure Po$_2$ (Pa)

10^1 Laser Ablation PLD

Y$_2$BaCuO$_5$ + BaCuO$_2$ + Cu$_2$O

Sputtering

10^0 Thermal

RCE

10^{-1} Electron Beam/Thermal

E-beam, thermal evaporation

10^{-2}

0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5
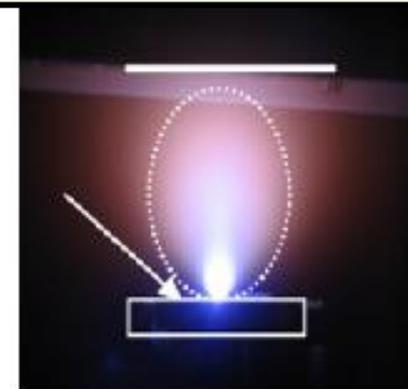
$1000/\mathrm{T(K^{-1})}$

R. H. Hammond and R. Bormann; Physica C, 162 (1989)703

◆ **Rapid, energetic and fine evaporation** by **UV pulse laser**
◆ **Large window of oxygen pressure**
   ◆ **Favorable P_{O2} >10Pa with growth temp. 700-800 °C**
   ◆ **Ablation Plume can reach far longer than mean free path (λ = 7mm @10Pa) which cannot be expected in conventional evaporation process**

Dense & high energy gas forms **Blast Wave** advancing in Oxygen atmosphere over 10 Pa

UV pulse Fluence >GW/cm^2

Elemental composition ~ REBCO target Transfer yield ~ 50 %

High temp. 1000s °C

Ablation Plume
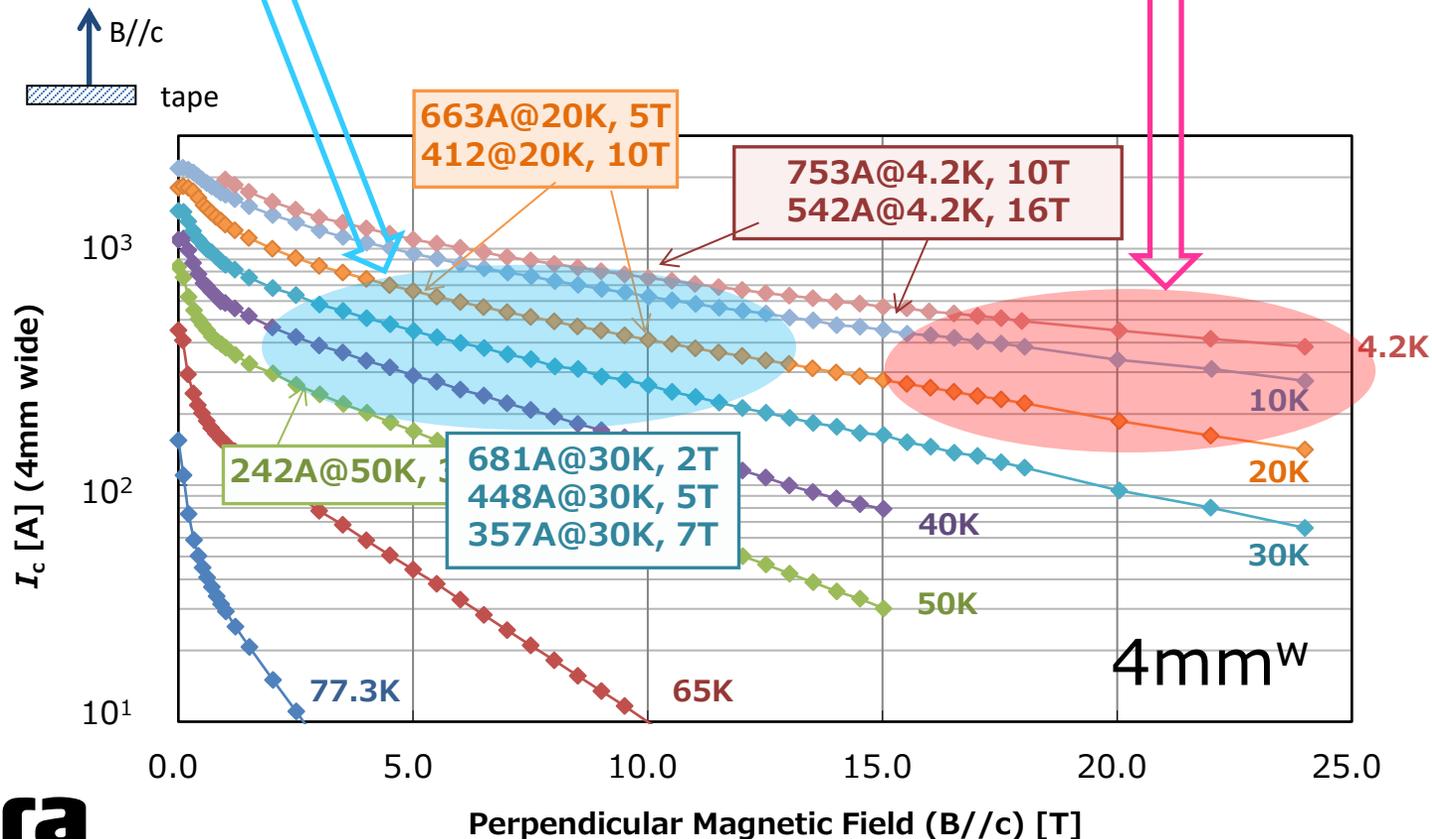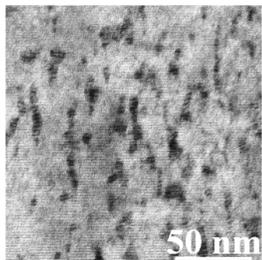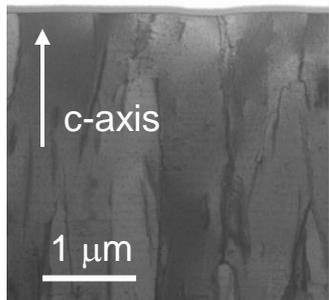
R. Delmdahl et ai. Appl. Phys. A 93(3):611-615 (2008)

A.V. Bulgakov, N.M. Bulgakova, "Dynamics of laser-induced plume expansion into an ambient gas during film deposition", J. Phys. D: Appl. Phys. 28 (1995) 1710–1718.

◆ **PLD is the only in-situ vapor deposition process controllable near best phase position with simple physical parameters**
◆ **No need of differential pumping or chemical decomposition**

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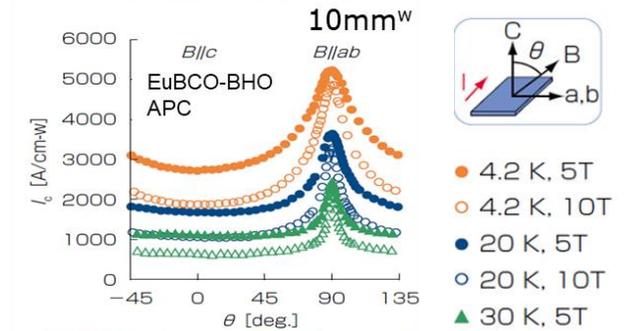# Why high in-field Jc: vapor phase deposition with supersaturated gas

◆ **PLD: Vapor growth process with**
  ◆ **Favorable condition of cation composition & oxygen-temperature diagram**
  ◆ **Dense & supersaturated gas with favorable particle energy for adatom mobility**

Good c-axis aligned matrix growth with dense and small defects of secondary phase, nanorod, nanoparticles, point defects, oxygen vacancy…
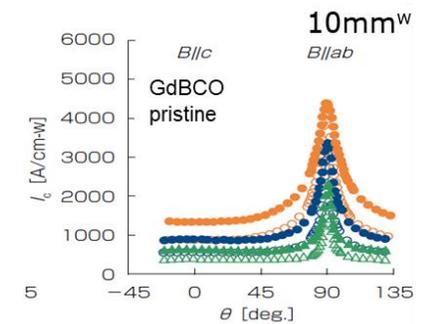

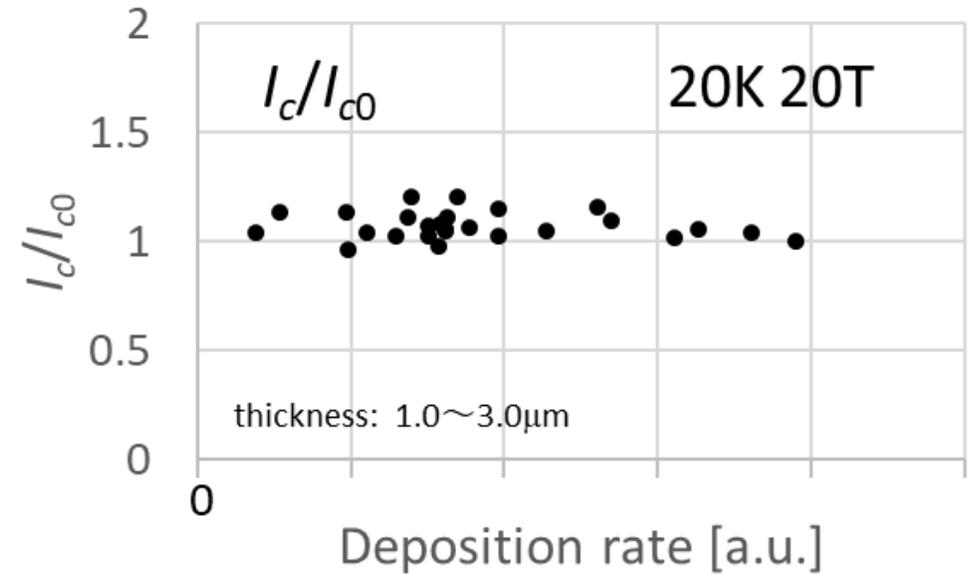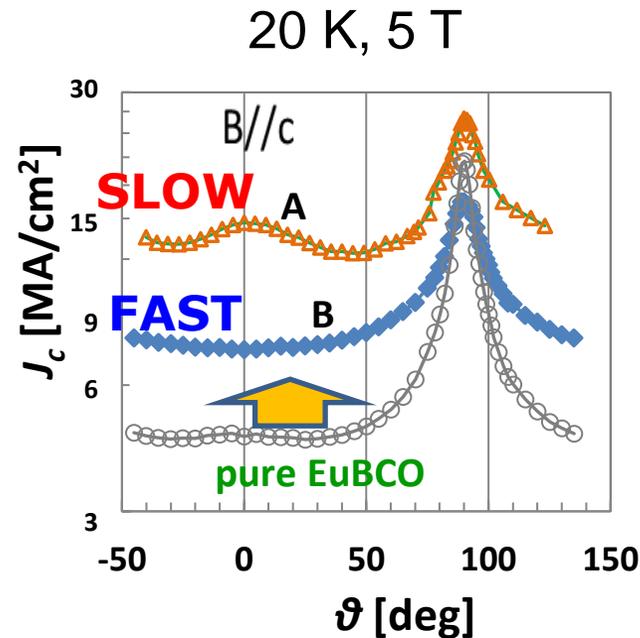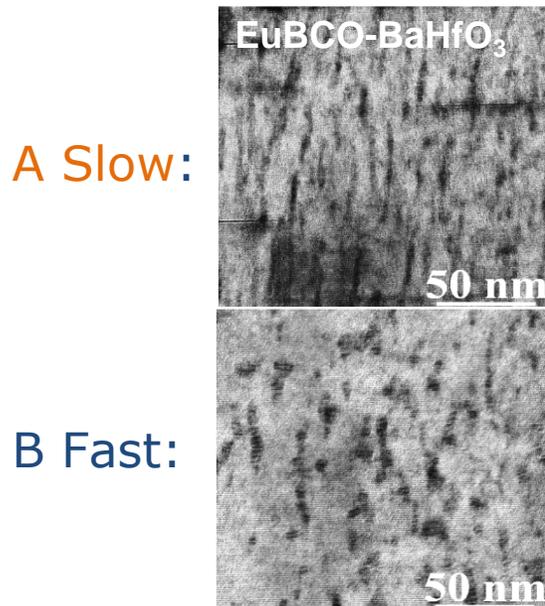Ic-B-θ in lower field ~ 10T

FESC (APC type)

FYSC (non-APC type)

Why fast? Growth rate dependence for I_c properties

◆ **High-rate growth by high-rate evaporation with high transfer yield ~50%**

◆ **High-rate limit not observed for Ic in high field**
  ◆ **High adatom mobility compensate defective growth by dense & supersaturated gas**

◆ **Ic in lower field affected by growth rate**
  ◆ **Nanorod shape depends on growth speed**

I_c/I_{c0} 20K 20T

thickness: 1.0～3.0μm

Deposition rate [a.u.]

A Slow:
EuBCO-BaHfO$_3$
50 nm

B Fast:
50 nm

20 K, 5 T

B//c
SLOW   A
FAST   B
pure EuBCO

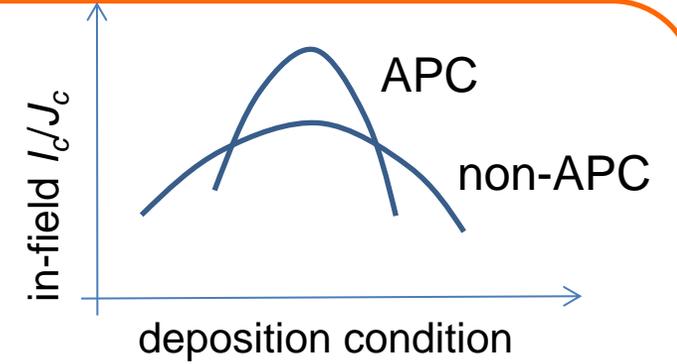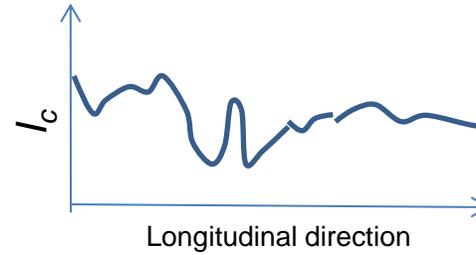J_c [MA/cm^2]
ϑ [deg]

◆ **High growth rate obtained just by high power laser**

◆ **which allows high throughput even with not too large deposition area**

◆ **Controllability maintains with simple deposition parameters**

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Why uniform? Development of substrate heating stability

Long-length & Longitudinal I_c uniformity

Depends strongly on temperature stability during continuous deposition at growth area

I_c

Longitudinal direction

in-field I_c/J_c

APC

non-APC

deposition condition

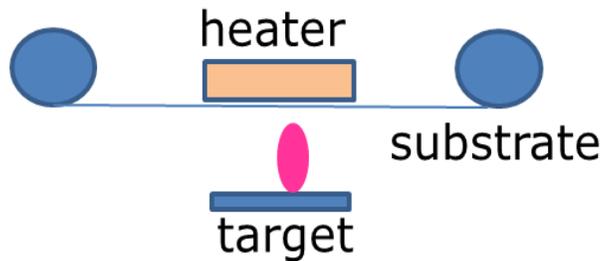**Hot-wall PLD** system has furnace-like stable substrate heating

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

Heater block system

Single-lane PLD
Used 1990s-1999

Short piece ~ 10s m long

heater

substrate

target

Multi-lane / beam scanned

Used 2000-2008

~100s m long
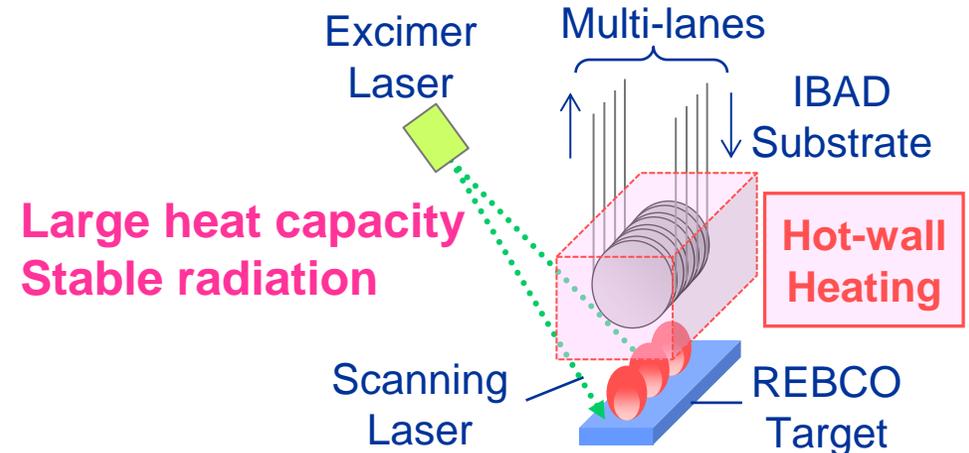
heater

RE123 target   plume

Hot-wall PLD system

Initial set up 2003-2008
reformed   2016-2018

>1 km long

Excimer
Laser

Multi-lanes

IBAD
Substrate

**Large heat capacity
Stable radiation**

Hot-wall
Heating

Scanning
Laser

REBCO
Target

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

BaHfO$_3$-EuBa$_2$Cu$_3$O$_y$

g=006

CeO$_2$

500 nm

40 K, 5 T

- 2.6um
- 3.3um
- 4.2um

30 K, 7 T

- 2.6um
- 3.3um
- 4.2um

20 K, 7 T

- 2.6um
- 3.3um
- 4.2um

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

20 K
B // c

- 2.6um 20K
- 3.3um 20K
- 4.2um 20K

$I_c \propto B^{-\alpha}$

J_e=595 A/mm^2 (I_c=357A. 4mm wide) @30K,7T
obtained with 2.5μm thick
at high throughput

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

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

77K, Self-field
Avg. Ic 136A, σ =1.3A, Min. n-value : 20.7

* Ic criterion：1 μ V/cm
* Range of n-values：$10^{-6} \sim 10^{-7}$ V/cm

≧ 500m

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

77K(LN$_2$), Self-field

1,400m !!

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

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

General evaluation of PLD-REBCO process

☐ **Excimer laser cost** has effectively been compensated by **good throughput and excellent production yield of PLD** with wide process window.

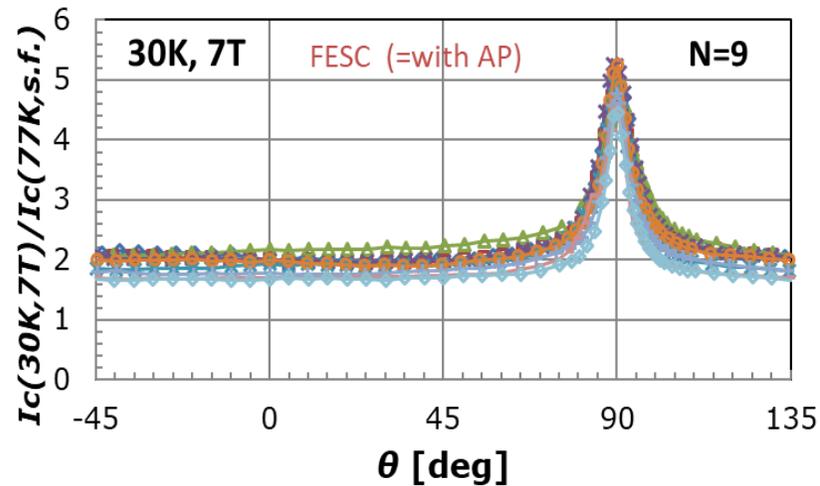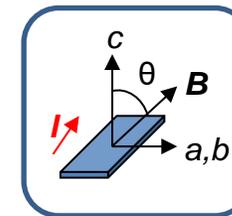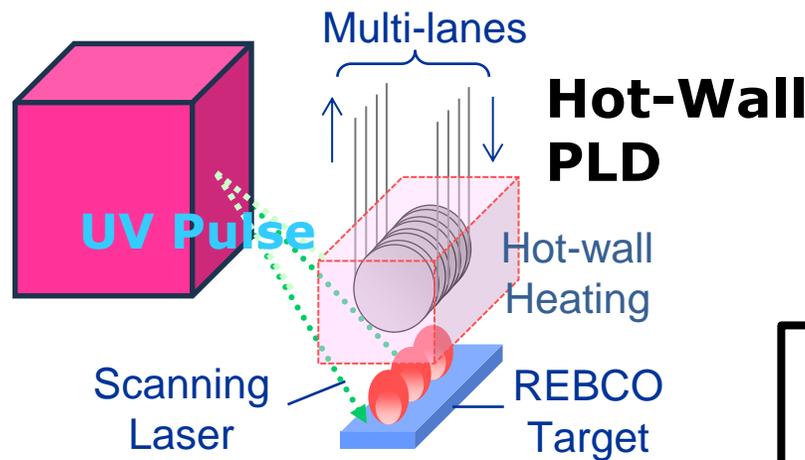$$Cost_{REBCO} \sim \left(Cost_{op.} + \left(\frac{Cost_{equipment}}{Throughput \times T_{op.}} \right) \right) \times \frac{1}{Production\ Yield}$$

Industrial Excimer Laser

UV Pulse

Multi-lanes

Hot-Wall PLD

Hot-wall Heating

Scanning Laser

REBCO Target

◆ **High growth rate**
  ◆ **High materials yield**
  ◆ **High supersaturated gas**
  ◆ **High adatom mobility**

◆ **Laser power/lifetime**
  ◆ Still improving by **strong demand of FPD industry**

◆ **Reproducibility**
  ◆ **Large oxygen window** without differential pumping or chemical decomposition
  ◆ **Cation Stoichiometric stability** with **fine evaporation by UV**

◆ **Jc/Ic in high field**
  ◆ **Point defects & secondary phase APC introduced** just by simple vapor process

◆ **Uniformity**
  ◆ **Growth temperature control** succeeded by **Hot Wall**

> **PLD should still contribute for tough final goal of C.C. with low cost, & high quality by a reliable & accountable mass production approach**

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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.	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.

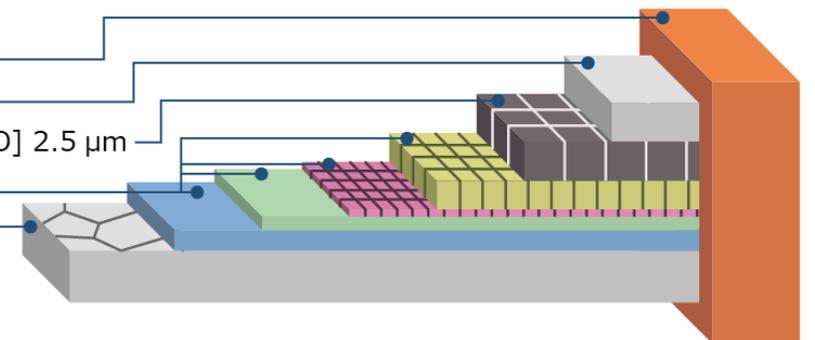*5 If requested, an option **customizing copper plating thickness is also available**. (e.g., 5μm, 10μm or 40μm)

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

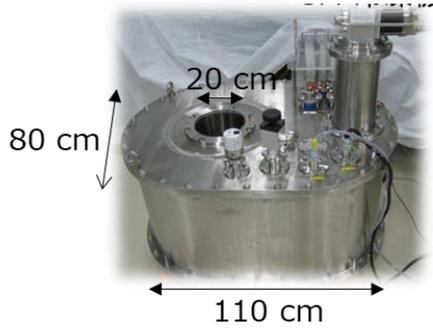Ni-Alloy tape   Cu plating

<Schematic of RE-based HTS tape>

Stabilizer [Cu plating] 20μm
Protection layer [Ag] 2μm
Superconducting Layer [GdBCO] 2 μm / [EuBCO+BHO] 2.5 μm
Buffer layer [MgO, etc.] 0.7μm
Substrate [Hastelloy®] 75 / 50 μm

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Demand from magnet application for IBAD/PLD REBCO wires
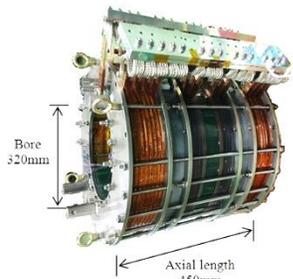
■ **5 T cryocooled magnet by Fujikura Ltd. (2012)**

20 cm

80 cm

110 cm

>400kJ with 20 cm RT bore

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

Brain
Lung
Tongue Heart
Gastrointestinal Tract

Bore 320mm

Axial length 450mm

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

■ **TELOS Project (2016-2019)**

Airbus, KIT, Siemens
Presented at EUCAS 2019

■ **World 1st 1.2GHz NMR by BRUKER (2019)**

◆ **Drastic improvement toward high-field inner magnet for NMR in 2010s**

  ◆ **Ic uniformity and Mechanical reliability of IBAD/PLD REBCO wires**

  ◆ **Coiling technology of insulated wires avoiding delamination**

◆ **NEW era started for large scale magnet as fusion etc. requires**

  ◆ **NI technology / assembled conductors used for large current operation**

  ◆ **Quench protection for both NI and insulated magnet**

■ **Compact Tokamak by CFS (2022-)**

Ic uniformity anyway important

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

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10T small test coil to check I_c uniformity & quench protection

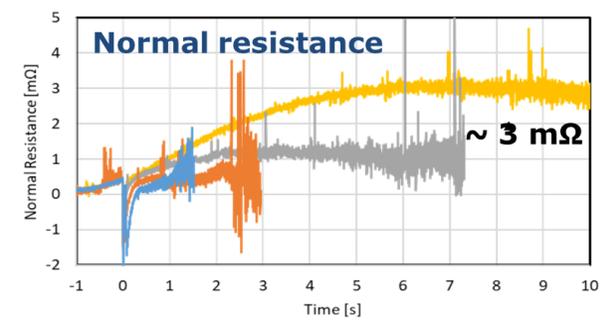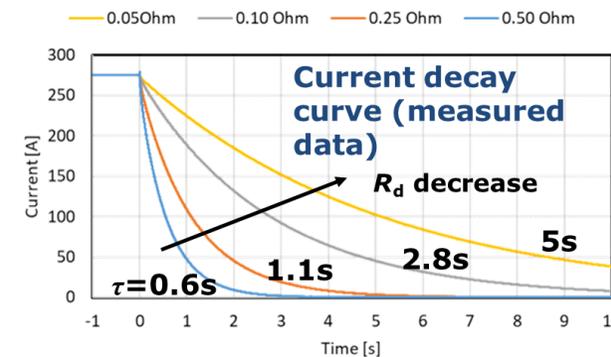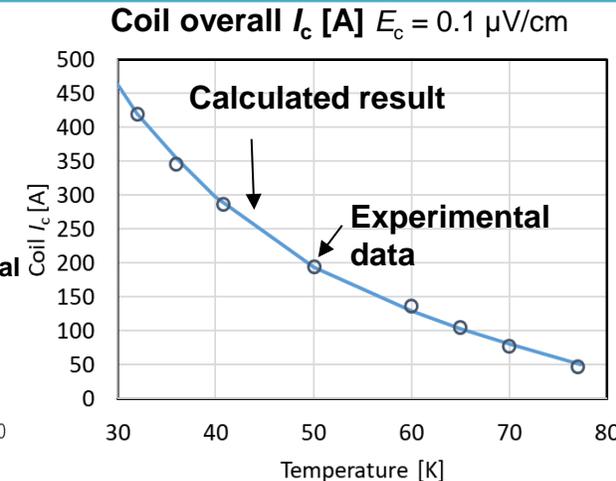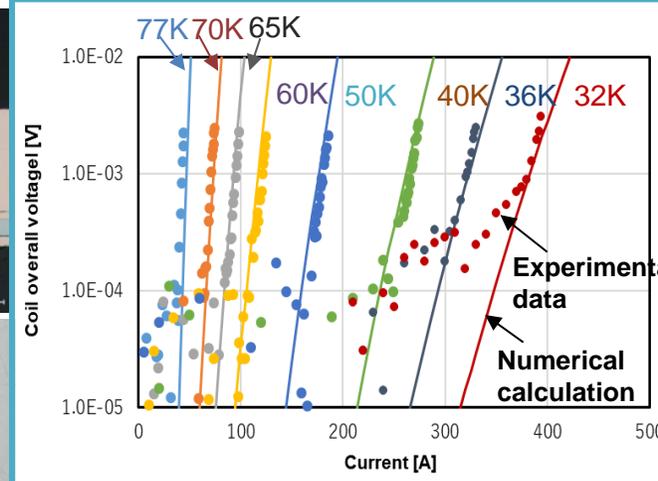| Parameters	REBCO tape
Substrate thick.	50 µm
Copper thick.	20 µm×2 (plates)＋**300** µm
Type of HTS tape	FESC-SCH04
Insulation	Fluorine coating polyimide tape/Polyimide tape
Width/Thickness	4.1 mm / 0.47 mm

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%

Cross section

Copper tape

2G HTS tape

200 µm

ID50mm

OD~146mm

×16

Φ 150mm

Coil overall I_c [A] E_c = 0.1 µV/cm

77K 70K 65K

60K 50K 40K 36K 32K

Experimental data

Numerical calculation

Calculated result

Experimental data

Current decay curve (measured data)

0.05 Ohm   0.10 Ohm   0.25 Ohm   0.50 Ohm

R_d decrease

τ=0.6s   1.1s   2.8s   5s

Normal resistance

~ 3 mΩ

- **Good agreement** between experimental and calculated results for coil Ic
- **No degradation** observed after quench test.

Summary

- ## IBAD/PLD: most reliable process to answer current business demand
  - **strong mechanical strength, in-field high-Jc** and **production reliability**.

- ## The advantage of Hot-wall PLD process covers laser cost well under mass production so far
  - **Reproducibility**: controllable near best phase point with simple parameters
  - **High in-field Ic** : small and dispersed pinning centers by vapor deposition
  - **High growth rate**: high transfer yield and adequate adatom energy
  - **Uniformity**: temperature stability improved by Hot-wall architecture

- ## Uniformity is still essential for magnet applications
  - **Demand** of magnet technology: **Uniformity** and **Mechanical reliability**
  - **New area**: **NI technology, assembled conductors, quench protection…..**
    ,,,,also require **uniformity**

> **PLD should contribute for tough final goal of C.C. with low cost & high quality as a reliable approach**
>
> **Scale-up investment is on-going at Fujikura**
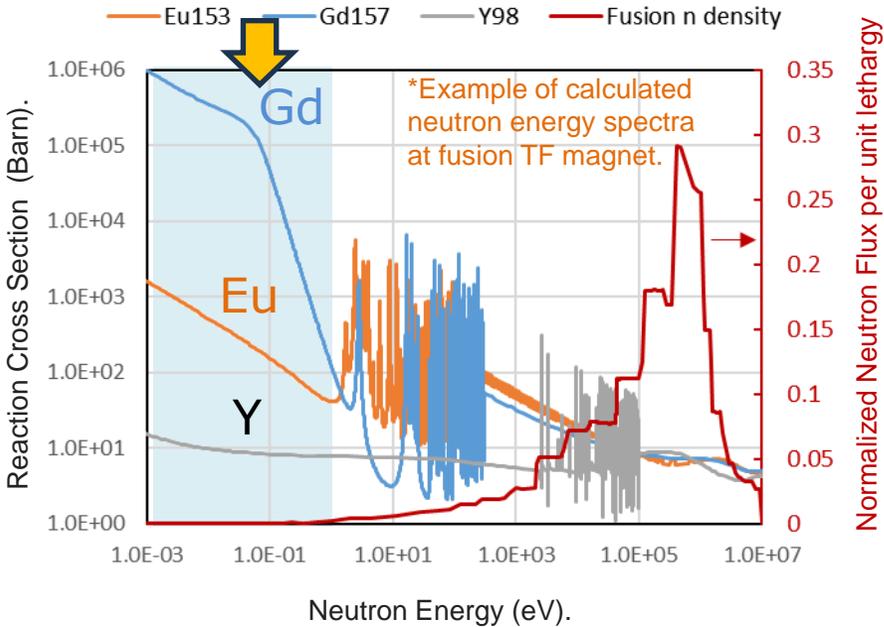
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END

Thank you for attention

RE elemental dependence of neutron radiation damage

Large cross section of neutron capture for Gd/Eu **isotopes ~ 1 eV anticipated to damage lattice structures** by gamma decay with large recoil energy

K. Shibata, et al., "JENDL-4.0: A New Library for Nuclear Science and Engineering," *J. Nucl. Sci. Technol.* **48**(1), 1-30 (2011).

* Weber, H.: *Int. J. Mod. Phys. E* 20.06 (2011): 1325-1378.

Fission reactor environment often used for irradiation tests has big peak in neutron spectra below 1 eV come from cooling water

where fusion ones estimated by calculation have quite low flux there

□ **RE=Gd, Eu:** irradiation strength should be <u>carefully</u> evaluated for fusion environment

JAEA report 2010-007

JAEA Oarai JRR3

fission reactor neutron spectra

M.R.Gilbert and J.Ch.Sublet: Nuclear Fusion 2011 **51** 043005

fusion reactor neutron spectra

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

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

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

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

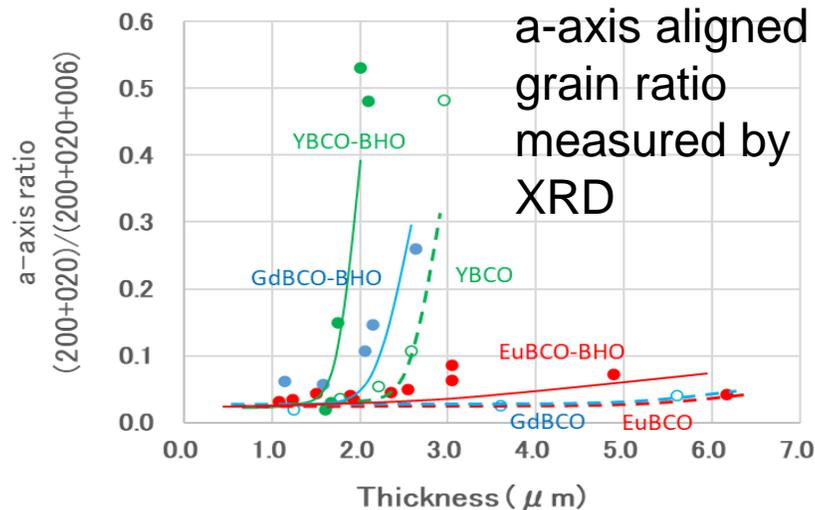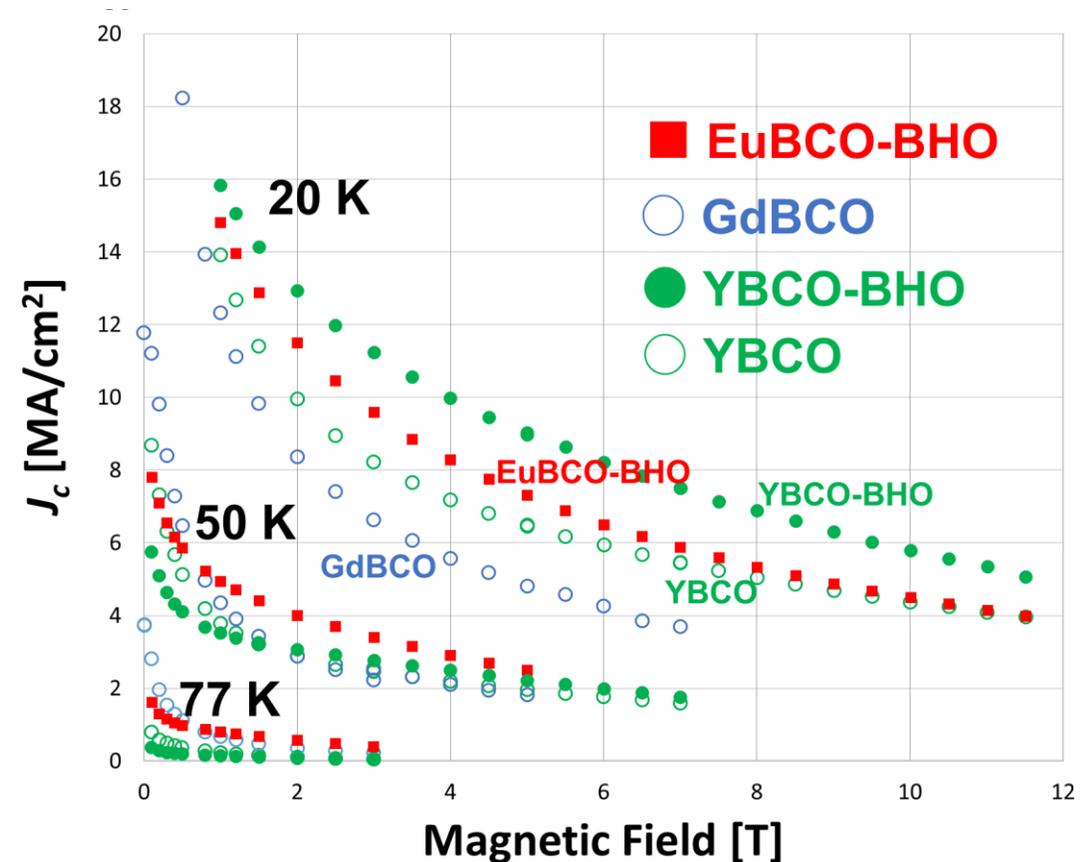$$f_2(\omega_2(B), \theta) = \frac{1}{\sqrt{\omega_2^2 \sin^2\theta + \cos^2\theta}} \quad \leftarrow B//ab$$

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

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

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

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

30 K T = 30 K B = 0.1 - 5 T

40 K T = 40 K B = 0.1 - 5 T

50 K T = 50 K B = 0.1 - 5 T

Angle [deg.]

I_c/I_{c0}

magnetic field inside coil A/B

46turn   1turn

A
B

$(I_{op} = 100 A)$

$B_{max} = 0.66$ T

B=0.56 T, θ~35°

A

B

■ **4-layer single pancake coils**

$V_c = 0.34$ mV
($E_c = 0.01$ μV/cm)

77.3K
65K
50K
40K
35K
30K

LN₂ 4mm→

n=12

←noise level

Voltage [mV]

Transporting current [A]

No degradation observed after quench test

S. Muto et al. presented in MT-28, 2PoM03-2

10T small test coil to check I_c uniformity & quench protection

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%

Cross section

Copper tape

2G HTS tape

200 μm

ID50mm

OD~146mm

×16

Φ 150mm

Coil overall I_c [A] E_c = 0.1 μV/cm

77K 70K 65K

60K 50K 40K 36K 32K

Experimental data

Numerical calculation

Calculated result

Experimental data

Screening Current induced Field

T= 20 K

Experiment

Simulation

2nd run

1st run

60 min. HOLD

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

Fujikura

Tensile Properties Evaluation of Divided 4 mm-wide

- Tensile properties of 3 parts of 4 mm-wide tapes divided from 12 mm-wide tape in LN_2

Samples (FYSC-SCH04)		Reversible I_c	
		Strain [%]	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

4mm — 1 : one edge side

4mm — 2 : center — 12mm

4mm — 3 : the other edge side

* Reversible I_c is defined at $I_c/I_{c0} > 0.99$. (I_{c0} : Initial)

- **Each divided 4 mm-wide HTS tapes by laser slitting have shown equivalent tensile properties.**
- **Laser slitting has been introduced to the production process at Fujikura for over 10 years.**

REBCO Thickness Dependence

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

Load cell (10 kN)
Data logging system   Power supply
Current lead
Voltage tap
CC sample
Strain gauge
LN_2
Chuck electrode
Insulation plate

FYSC (GdBCO)

FESC

Ic/Ic_0 versus tensile strain

FESC   FYSC (GdBCO)

(4 mm-wide tapes with 20 μm Cu plating)

Ic/Ic_0

- Ic_1/Ic_0 - 4mmw/75μmt
- Ic_2/Ic_0 - 4mmw/75μmt
- Ic_1/Ic_0 - 4mmw/50μmt
- Ic_2/Ic_0 - 4mmw/50μmt

Tensile Strain [%]

Irreversible Strain [%]

Hastelloy 50μm 75μm   REBCO
GdBCO pure
BHO-EuBCO

FESC-SCH04

FYSC-SCH04

$y = 0.5838x^{-0.231}$

T = 77.3 K

REBCO thickness [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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Evaluation method for delamination strength of REBCO tapes

Stud-pull Test	Anvil Test	Impregnated Coil Test

Stud-pull Test

Backing Plate
Coated Conductors
Epoxy Adhesive
Supporting Column
Stud Pin (ϕ = 2.7 mm)
3-Jaw Gripper

Load rate : 60 N/s   Load

Pin
Backing plate

Test area：**Small** (5.7 mm^2*)
*in case of φ2.7 mm Pin
Delamination strength：**High**
　　　　　(～ several 10 MPa)

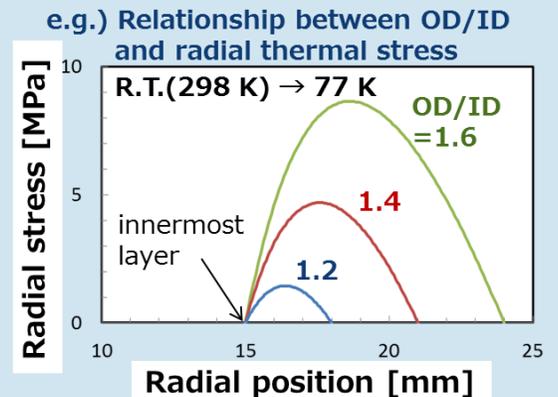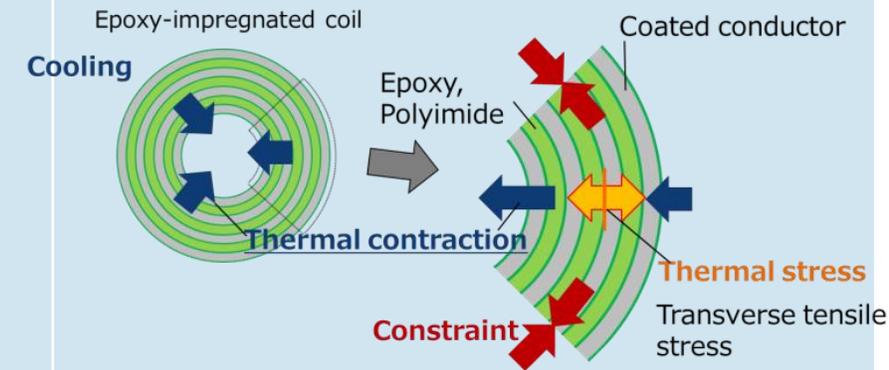T. Oyama, *et al.,* Journal of The Surface Finishing Society of Japan, **58** (2007) P. 292

Anvil Test

Upper anvil
Conductor
Lower anvil
Solder

Pull

Test area：**Medium** (32 mm^2*)
*in case of 4×8 mm Anvil
Delamination strength：**Medium**

H. Shin, *et.al.*, SuST, **27** (2014) 025001

Impregnated Coil Test

Epoxy-impregnated coil
Cooling
Coated conductor
Epoxy, Polyimide
Thermal contraction
Thermal stress
Constraint
Transverse tensile stress

e.g.) Relationship between OD/ID and radial thermal stress

R.T.(298 K) → 77 K
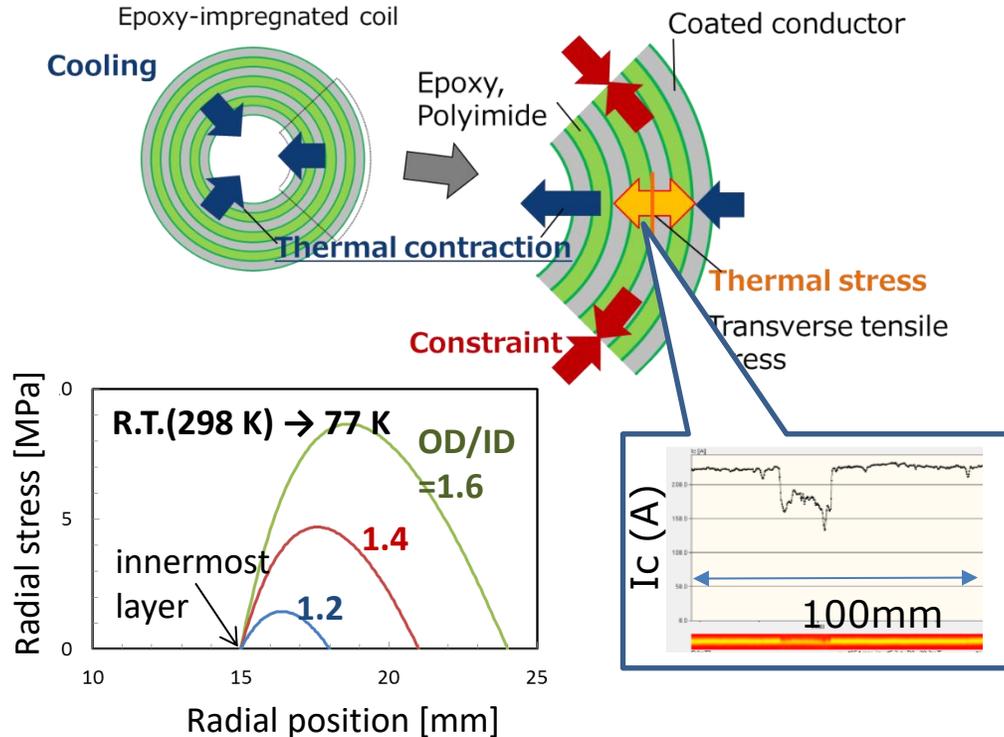OD/ID =1.6
1.4
1.2
innermost layer
Radial stress [MPa]
Radial position [mm]

OD/ID: The ratio of outer diameter to inner diameter

Test area：**Large** (16000 mm^2*)
*in case of 4 mm wide×4 m tape
Delamination strength：**Low**
　　　　　(several MPa)
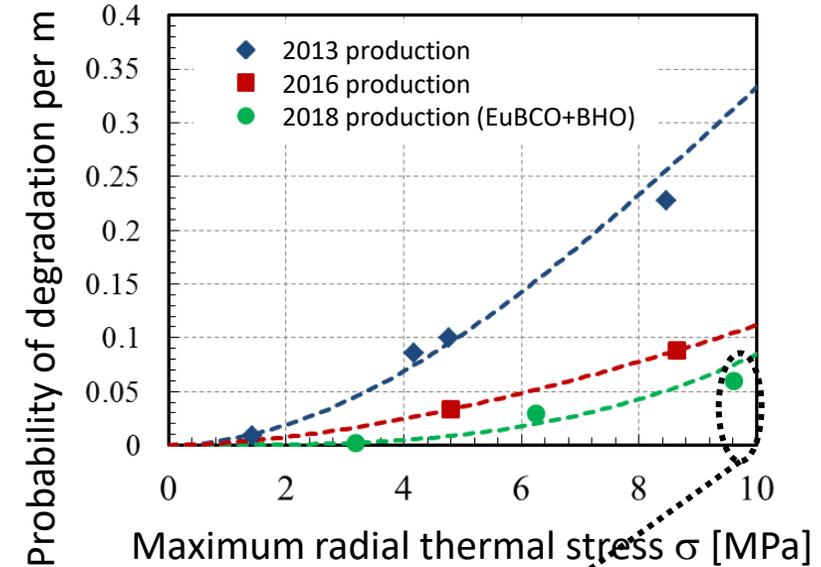
H. Miyazaki *et al*., IEEE TAS, **25** (2015) 6602305

Delamination strength evaluated by epoxy impregnated coils

<Delamination stress test by thermal stress inside impregnated coil>

Epoxy-impregnated coil

Cooling

Thermal contraction

Constraint

Coated conductor

Epoxy, Polyimide

Thermal stress

Transverse tensile stress

R.T.(298 K) → 77 K

Radial stress [MPa]

OD/ID =1.6

1.4

innermost layer

1.2

Radial position [mm]

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

Ic (A)

100mm

Probability of degradation per m

- ◆ 2013 production
- ■ 2016 production
- ● 2018 production (EuBCO+BHO)

Maximum radial thermal stress σ [MPa]

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

I_c [A]

cooling rate: 20 K/min

No degradation up to 100 cycles

number of heat cycles

- coil #1
- coil #2
- coil #3
- coil #4
- coil #5

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

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