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International Workshop / IRradiation Effects on HTS for Fusion (IREF 2025)
17 – 22 June 2025, Gallipoli, Italy

Reliable approach of mass production of REBCO coated conductor by using IBAD/hot-wall PLD for practical magnet applications

Y. Iijima, M. Ohsugi, K. Kakimoto, S. Muto, W. Hirata, S. Fujita, N. Nakamura, S. Hanyu and M. Daibo

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.

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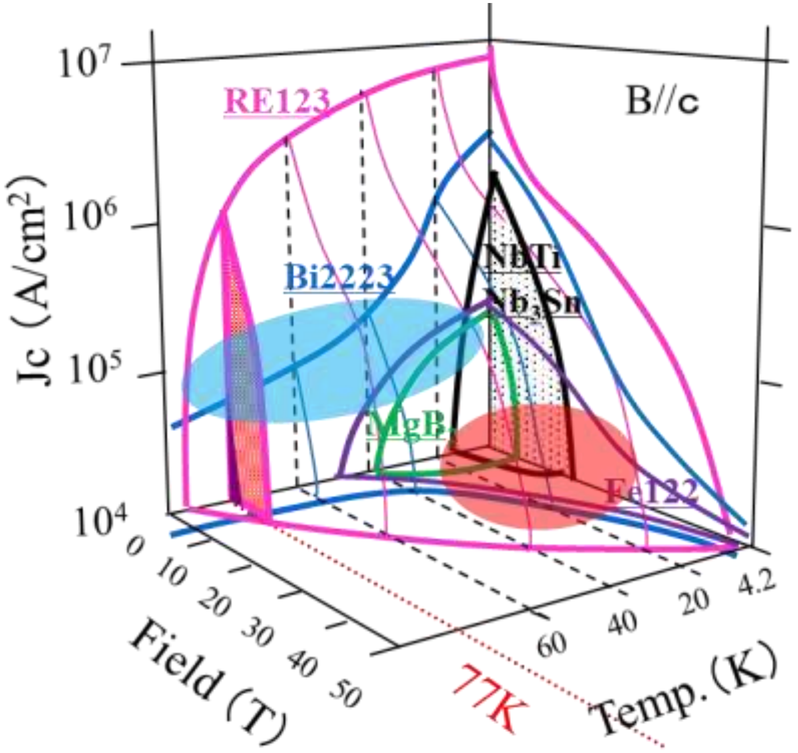
Contents

REBCO wire mass production started for magnet application

- Market started from high-field application : NMR, Fusion ➡ **ONLY HTS reach over 20 T applications**
- **Demand of magnet technology: Uniformity and Mechanical reliability**
- **Why peculiar vapor process of IBAD/PLD ?**

Advantages of IBAD/PLD process for mass-production

- **Wide process window come from:**
  - **IBAD substrates:**
    - **Sharp texture, flat surface, strong mechanical strength**
  - **PLD REBCO films:**
    - **Reproducibility:** controllable near best phase point
    - **High in-field Ic :** small and dispersed pinning centers
    - **High growth rate:** high transfer yield, high supersaturation
    - **Uniformity:** Hot-wall architecture
- **RE elemental dependance of process window**



REBCO wire lineup and neutron irradiation issues

- **RE elemental dependence of neutron collision cross section**
- **Thermal neutron flux at SC magnets in Fusion reactor**

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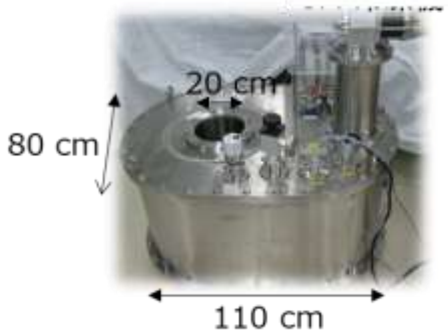
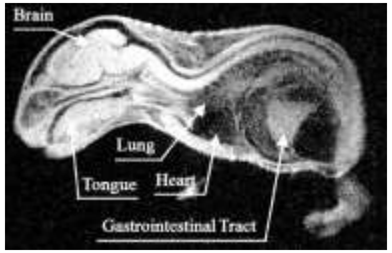
Demand from magnet application for IBAD/PLD REBCO wires

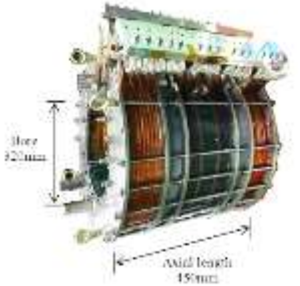
■ **5 T cryocooled magnet by Fujikura Ltd. (2012)**



>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)**

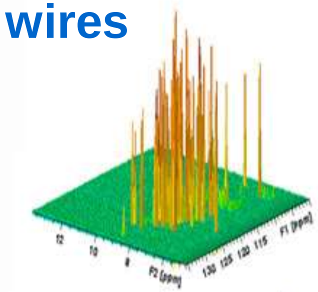
Airbus, KIT, Siemens

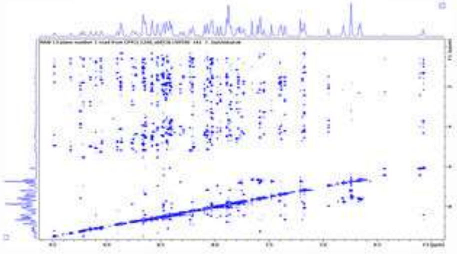
Presented at EUCAS 2019

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

1.2 GHz NMR 28.2 T magnet with 54 mm bore

- **Drastic improvement toward high-field DC magnet in 2010s**
  - **Ic uniformity and Mechanical reliability of IBAD/PLD REBCO wires**
    - **Contribute to accountability required for accurate field design**
  - **Coiling technology of insulated wires avoiding delamination**





1.0 GHz NMR with compact 23.5 T magnet

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 REBCO device: high-end NMR

the most severe application strongly requires hoop stress durability & longitudinal Ic uniformity

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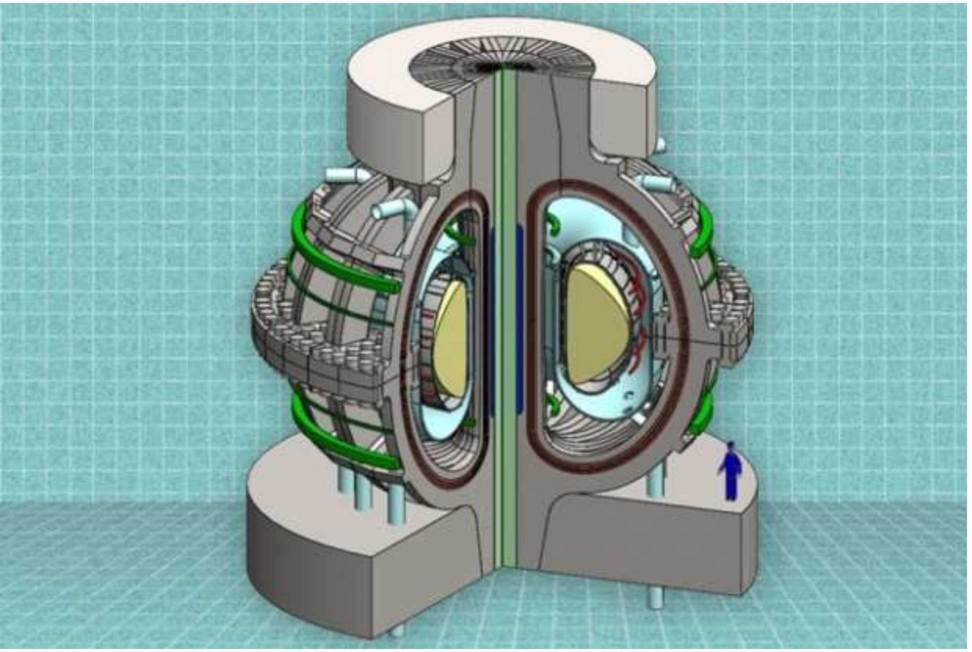
Business scale demand of REBCO wires for fusion



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

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

Big REBCO wire demand up to 10000s km/reactor

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

- NEW era started for large scale magnet as fusion etc. requires
  - Tons of high-quality wires with desired delivery & cost
  - NI technology / assembled conductors used for large current operation
  - Quench protection for both NI and insulated magnet

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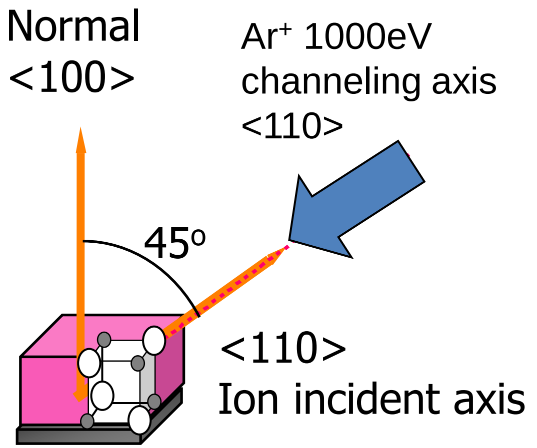
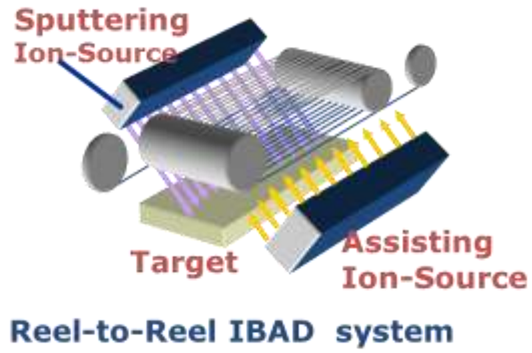
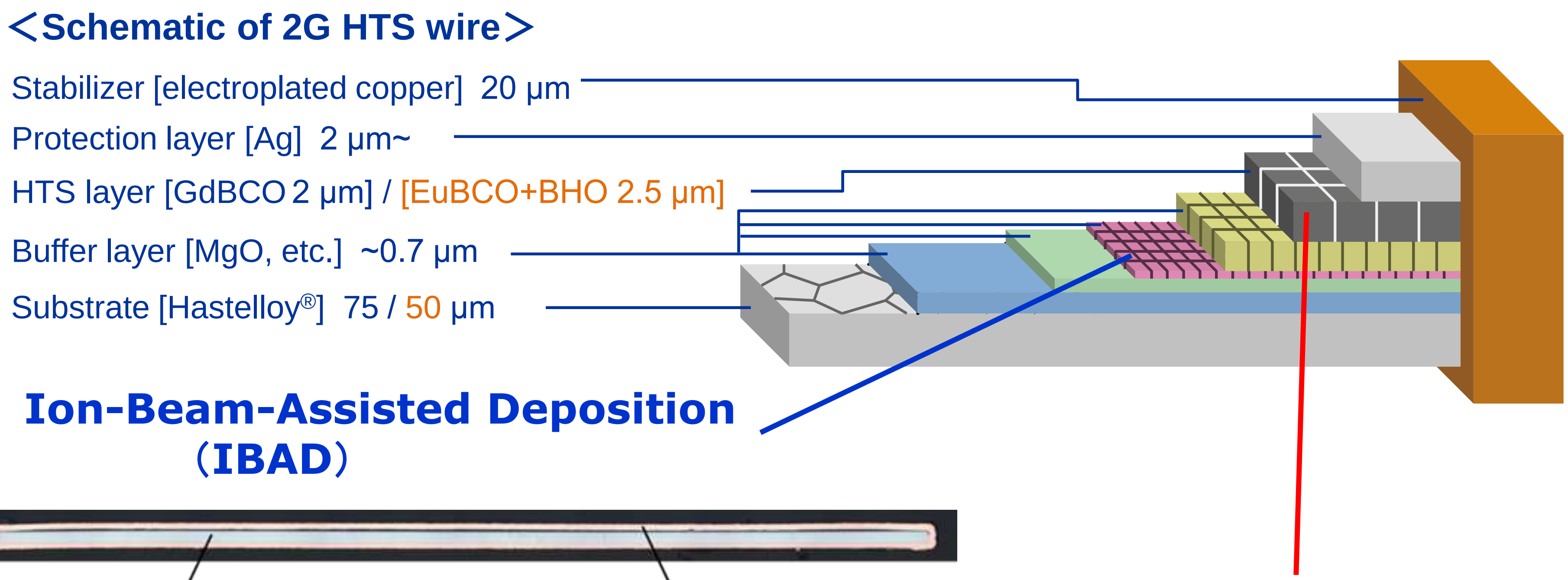
Ic uniformity anyway important

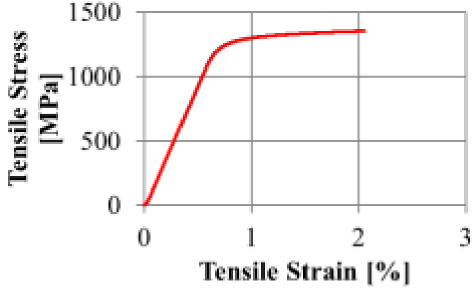
Fujikura's 2G HTS wires processed by IBAD/PLD method





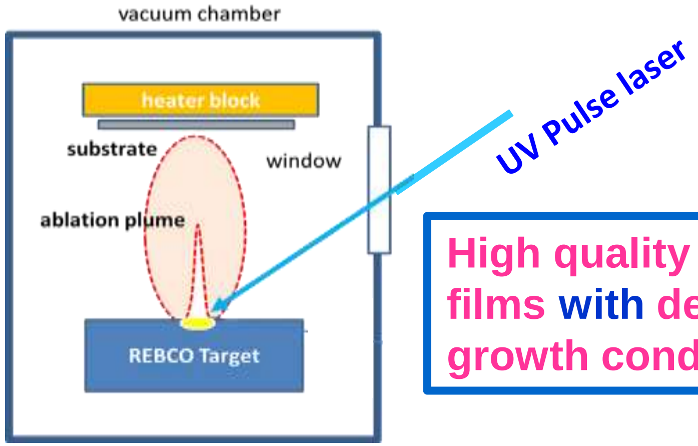
<Schematic of 2G HTS wire>





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)



High quality REBCO films with desired growth condition

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Manufacturer of REBCO C. C. 2024

World Capacity: >1000s km/y rapidly increasing

PLD 4 MOCVD 5 RCE 2 MOD 4

Mass Production Started mainly by PLD

IBAD textured substrates used by almost all manufacturers

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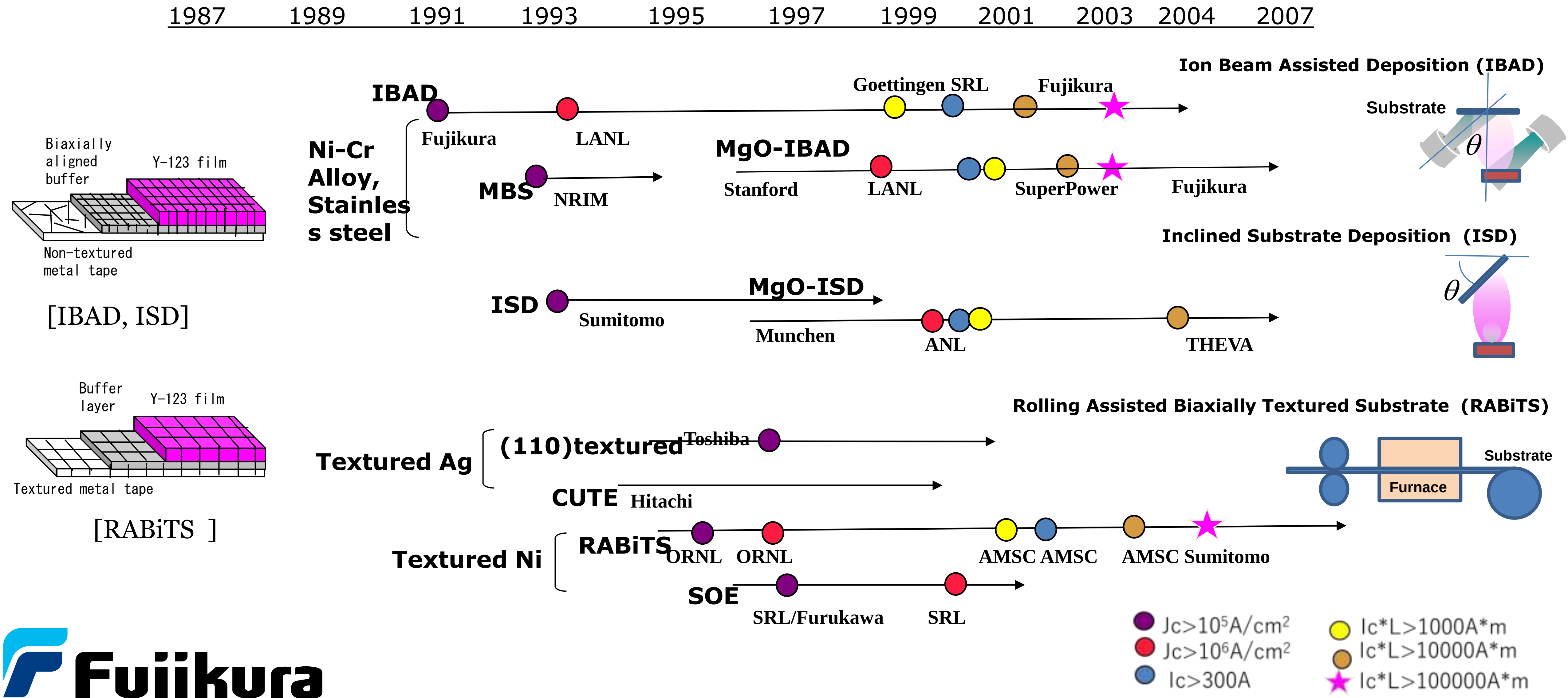
Development of biaxially textured substrate for C.C.

□ Many Process proposed ··· MgO-IBAD/ISD, RABiTS survived



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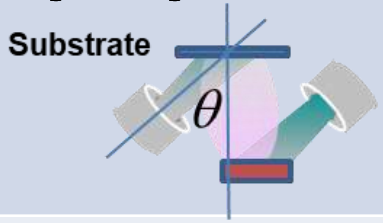
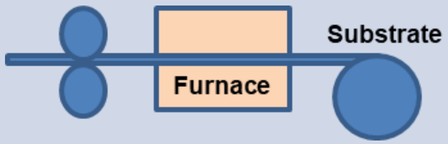
Advantage of IBAD process

Process	Substrate	In plane texture formation	Orientation sharpness	Surface flatness	Tensile strength
IBAD (Ion Beam Assisted Deposition)	Non-textured alloy (Ni-Cr, Fe-Cr etc.)	Ion beam modification during film growth 	◎ Improved by collimated ion channeling	◎	◎ Improved by High-Jc & film smoothness
ISD (Inclined Substrate Deposition)	Non-textured alloy (Ni-Cr, Fe-Cr etc.)	Anisotropic growth with inclined evaporation flux 	○	△ Deteriorated by shadowed grain growth	○
RABiTS (Rolling Assisted Biaxially Textured Substrates)	Textured metal (Ni, Ni-W)	Rolled, recrystallized texture of metals 	○	○ Deteriorated by grooving of metal grains	△ Deteriorated by lower Young modulus

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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**.

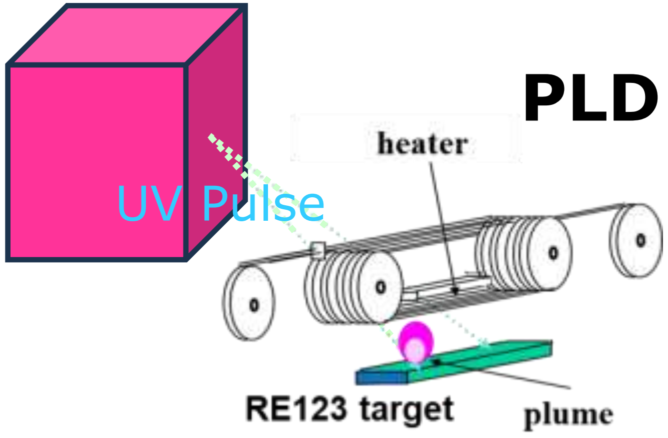
$$\text{Cost}_{\text{REBCO}} \sim \left(\text{Cost}_{\text{op.}} + \left(\frac{\text{Cost}_{\text{equipment}}}{\text{Throughput} \times T_{\text{op.}}} \right) \right) \times \frac{1}{\text{Production Yield}}$$

- Growth rate
- Laser power
- Laser lifetime

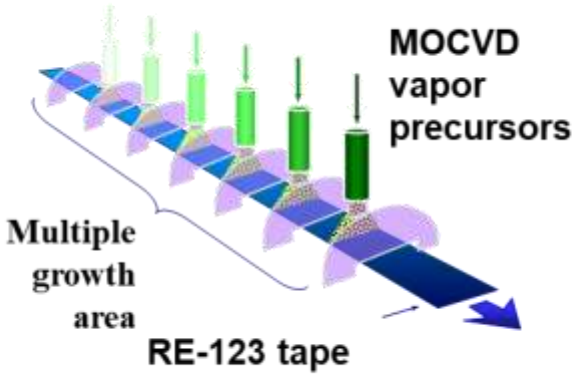
- Reproducibility
- In-field Jc/Ic
- Uniformity

Industrial Excimer Laser

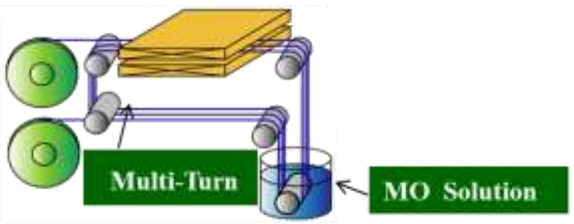
PLD



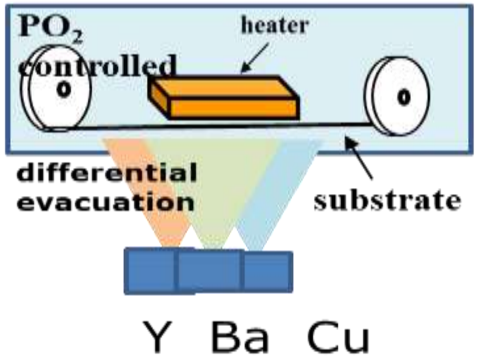
MOCVD



MOD



RCE



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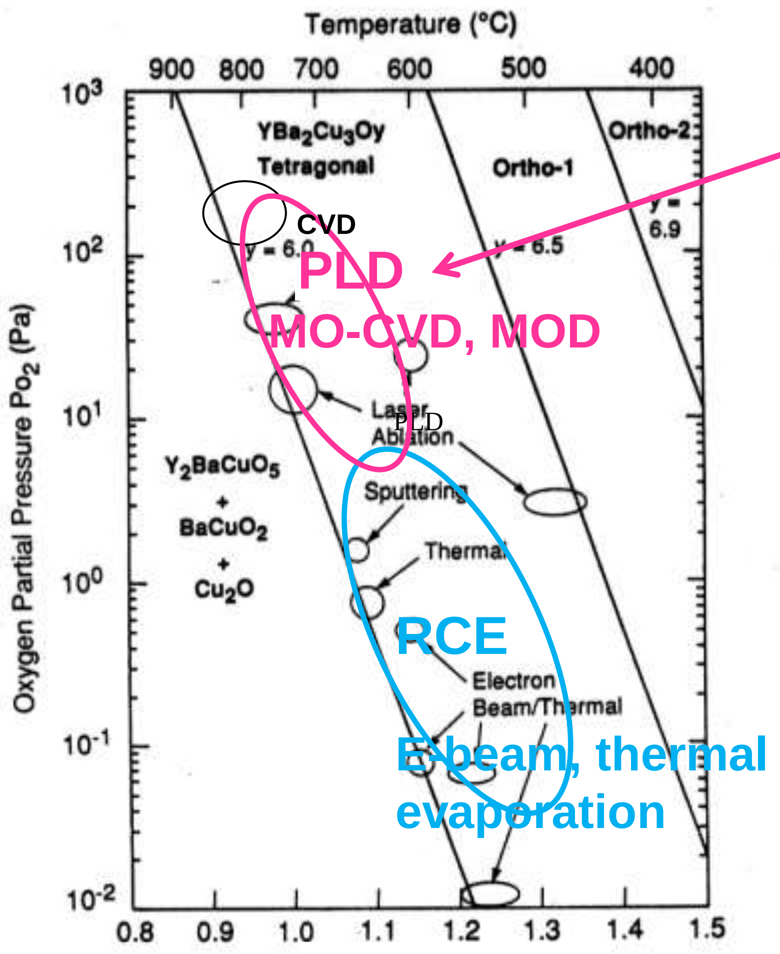
Why stable? : Controllable process at best phase position

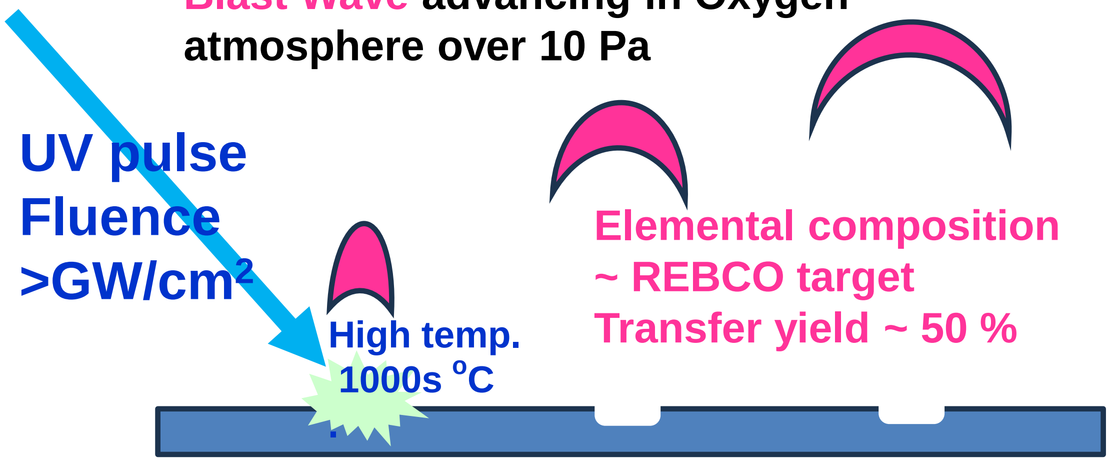


1000/T(K^{-1})

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

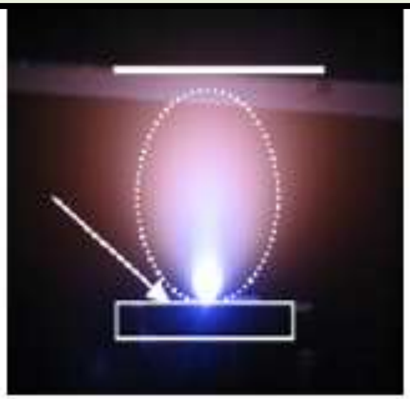
- **Rapid, energetic and fine evaporation by UV pulse laser**
- **Large window of oxygen pressure**
  - **Favorable P_{O2} >10Pa with growth temp. 700-800 °C**
  - **Ablation Plume can reach far longer than mean free path (λ = 7mm @10Pa) which cannot be expected in conventional evaporation process**

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



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.

Ablation Plume



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

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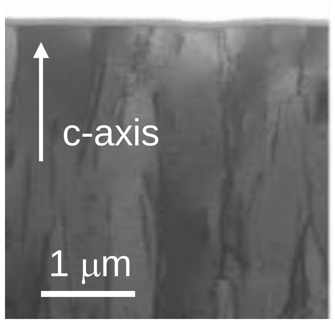
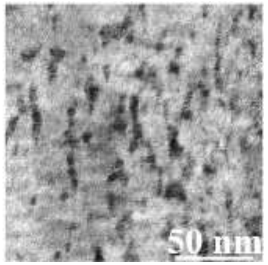
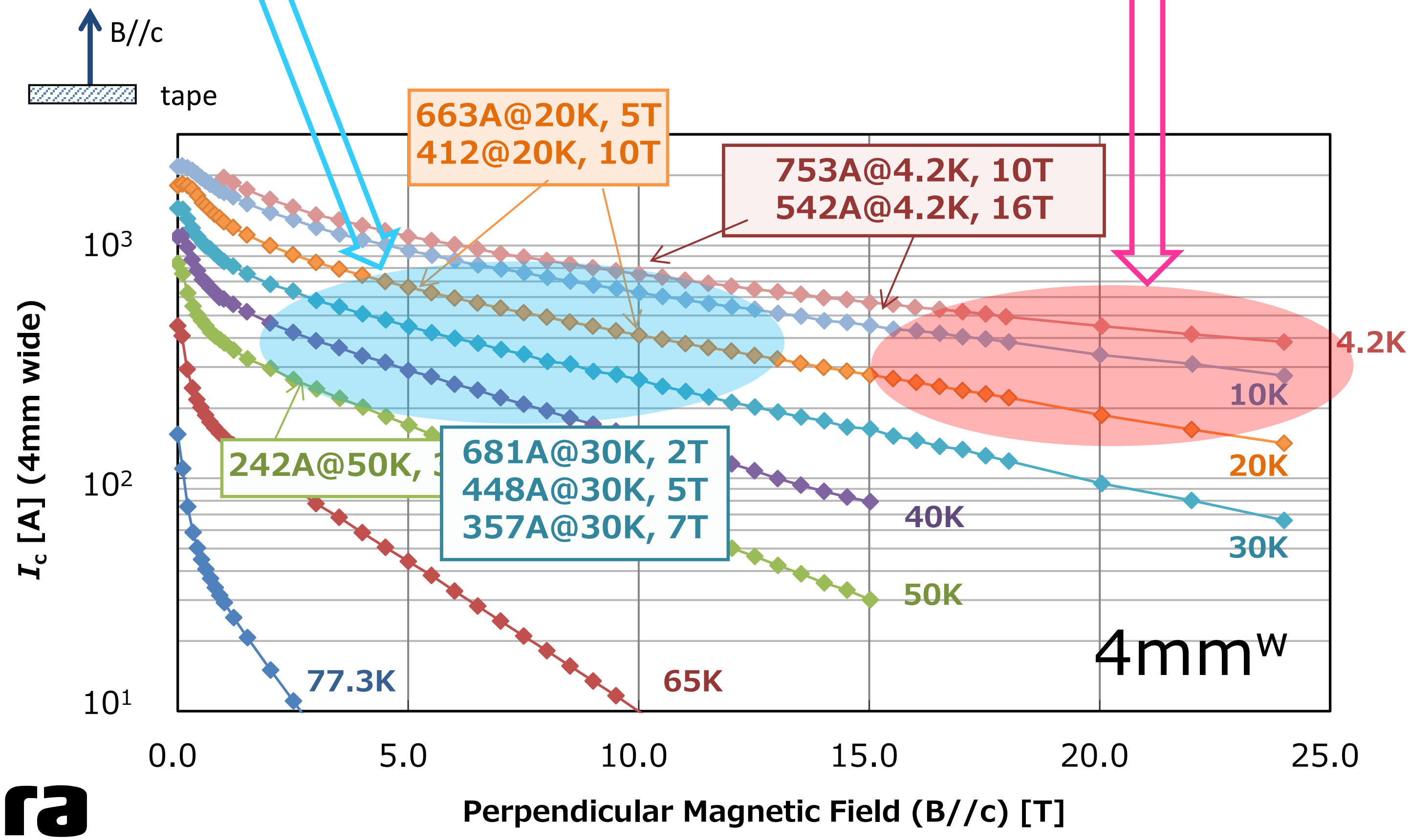
Why high in-field Jc: vapor phase deposition with supersaturated gas

- **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…

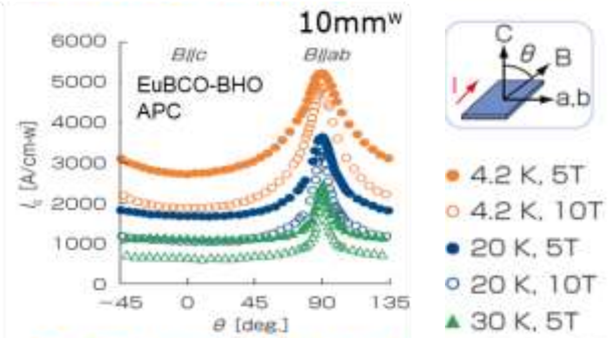




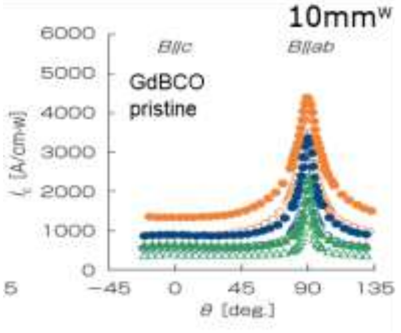


Ic-B-θ in lower field ~ 10T

FESC (APC type)



FYSC (non-APC type)



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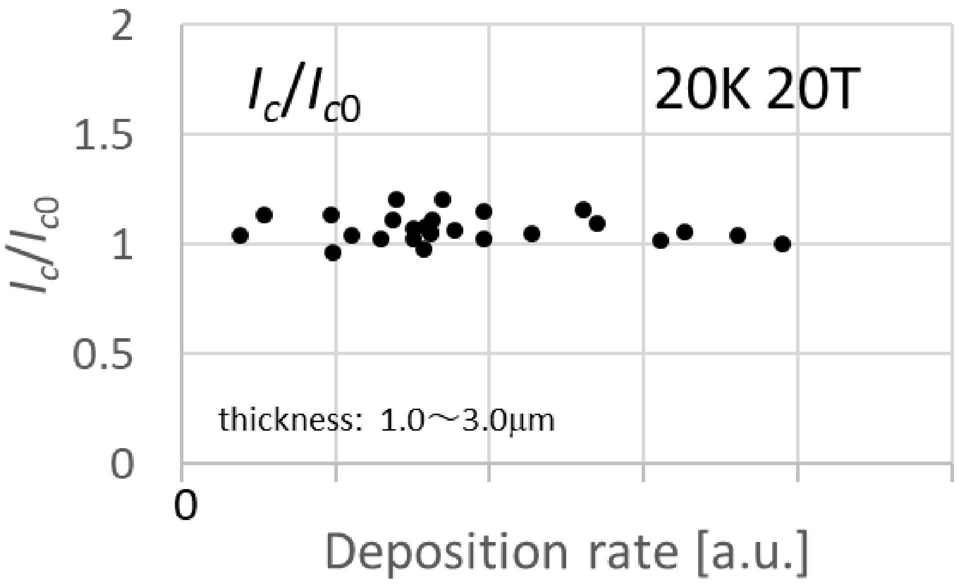
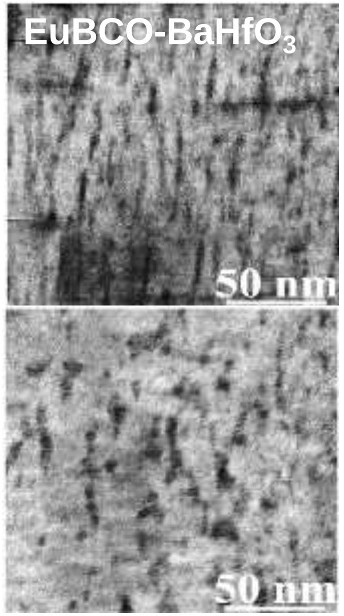
Why fast? Growth rate dependence for I_c properties

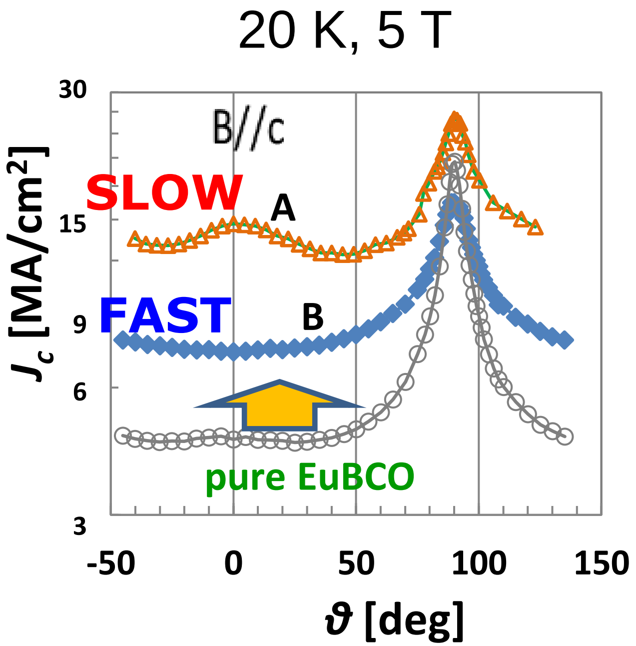
- High-rate growth by high-rate evaporation with high transfer yield ~50%
- High-rate limit not observed for Ic in high field
  - High adatom mobility compensate defective growth by dense & supersaturated gas
- Ic in lower field affected by growth rate
  - Nanorod shape depends on growth speed



A Slow:

B Fast:





- 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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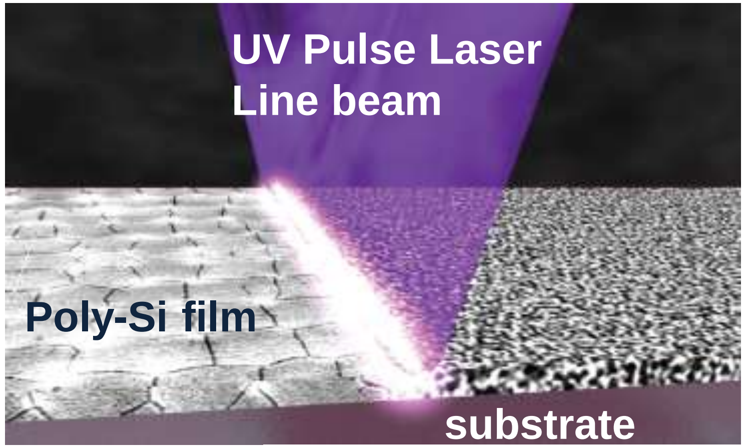
Development of high-powered excimer laser for FPD industry



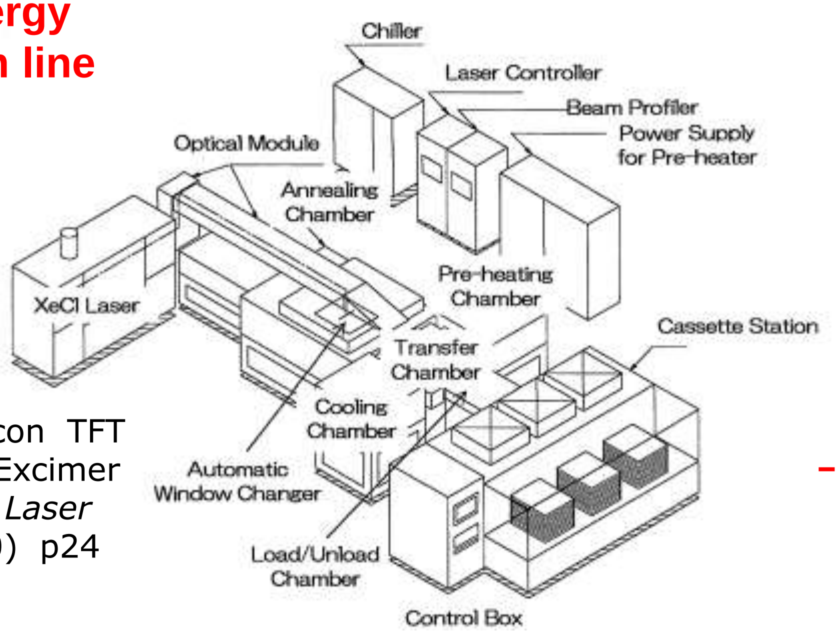
Amorphous Si film

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

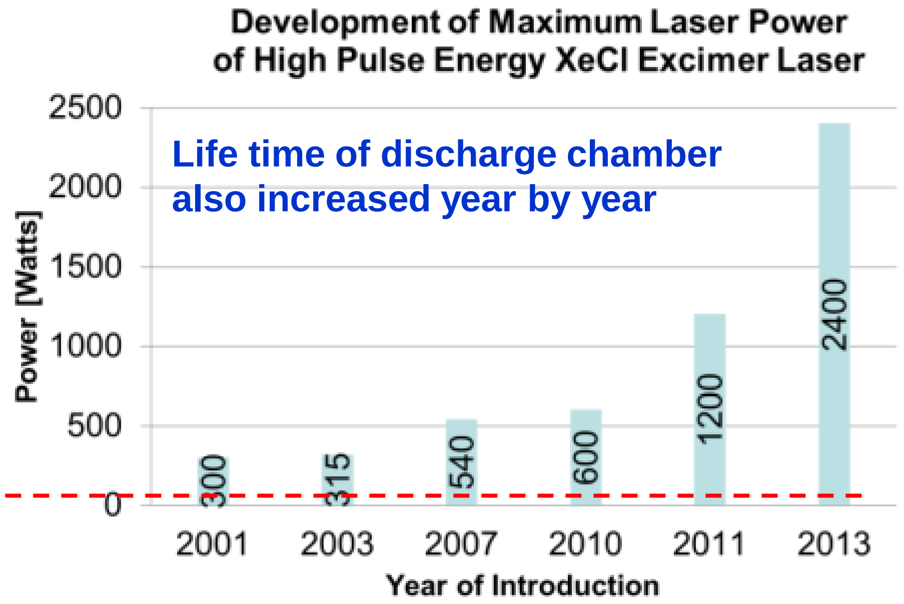
➡ **quite suitable to High rate PLD processing**

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.

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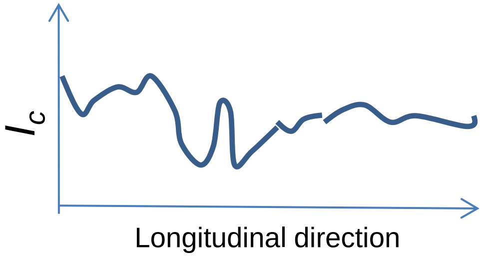
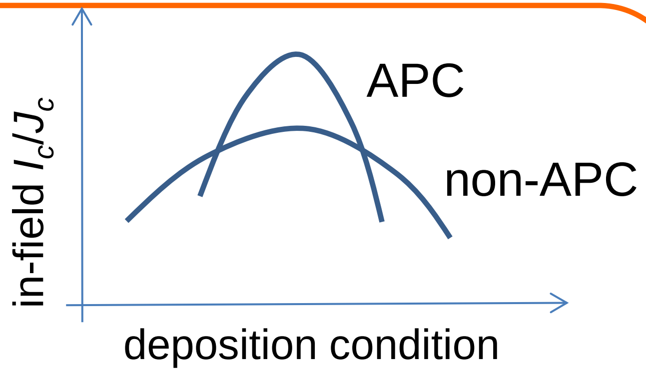
Why uniform? Development of substrate heating stability

Long-length & Longitudinal I_c uniformity

Depends strongly on temperature stability during continuous deposition at growth area





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

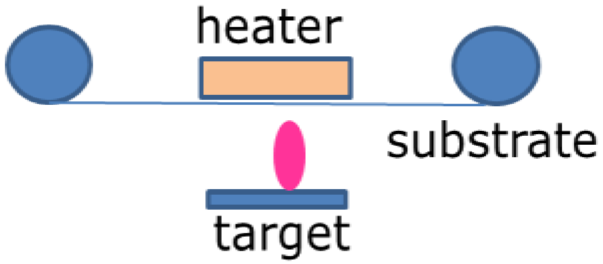
Window width Y < Gd < Eu
APC < non-APC

Heater block system

Single-lane PLD

Used 1990s-1999

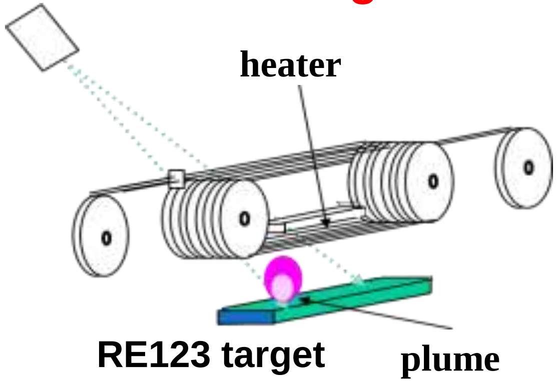
Short piece ~ 10s m long



Multi-lane / beam scanned

Used 2000-2008

~100s m long

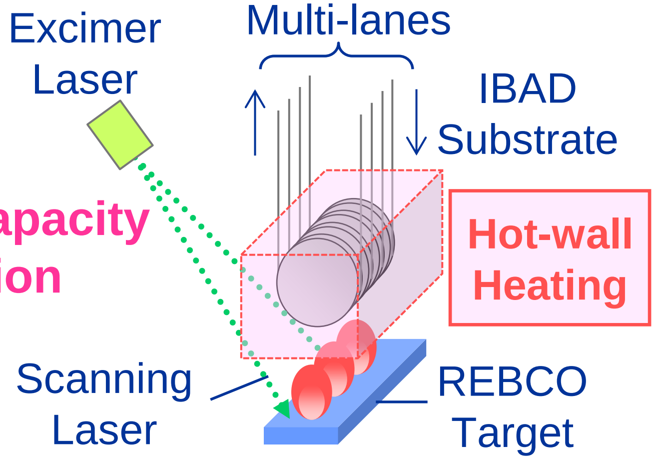


Hot-wall PLD system

Initial set up 2003-2008
reformed 2016-2018

>1 km long

Large heat capacity
Stable radiation



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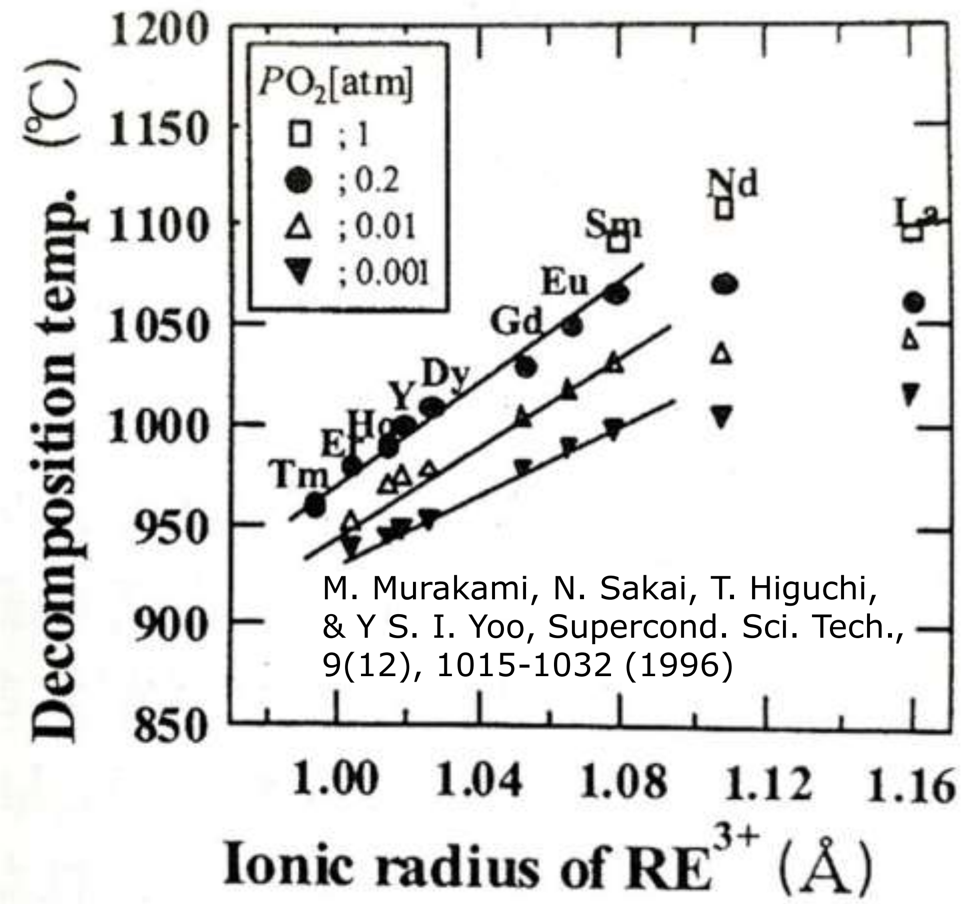
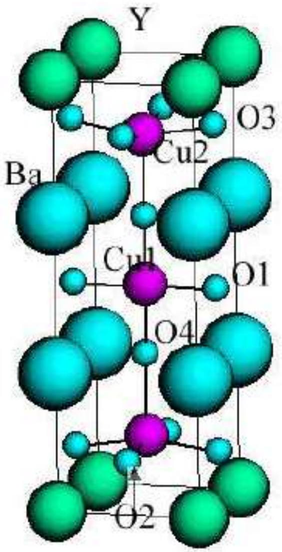
RE elemental dependent growth/lattice stability for REBCO



Dependence of oxygen partial pressure on ion radius and peritectic decomposition temperature (Tp) of various RE123

- **The bigger the RE^{3+} radius approaching to Ba^{2+} radius・・・**
  - **(1) The higher decomposition temperature with increased thermodynamic stability by the less internal strains etc.**
  - **(2) The less substitution energy between RE^{3+} /Ba^{2+} degrade superconductivity**
  - **Process window width determined by the trade-off of (1) and (2)**
  - **around Gd, Eu were favorable**



H. Su, D. O. Welch, and W. Wong-Ng, Phys. Rev. B 70, 054517 (2004)

Crystal	YBCO	GdBCO	EuBCO	SmBCO
$E_{Schottky}(eV)$	4.22	4.21	4.20	4.16
$T_{melting}(^oK)$	1250	1290	1300	1325

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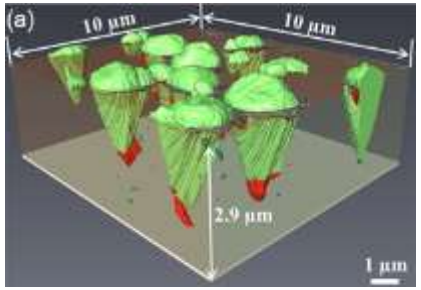
RE elemental dependent growth stability for BMO-REBCO

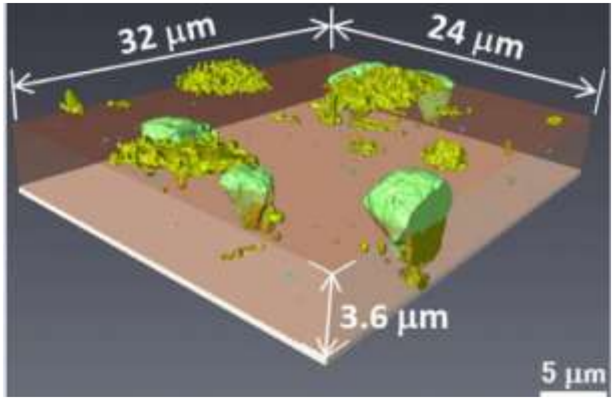
FIB-SEM 3D observation on misoriented grains (mainly a-axis aligned normal) for thick BMO-REBCO films

BaHfO-GdBaCuO



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

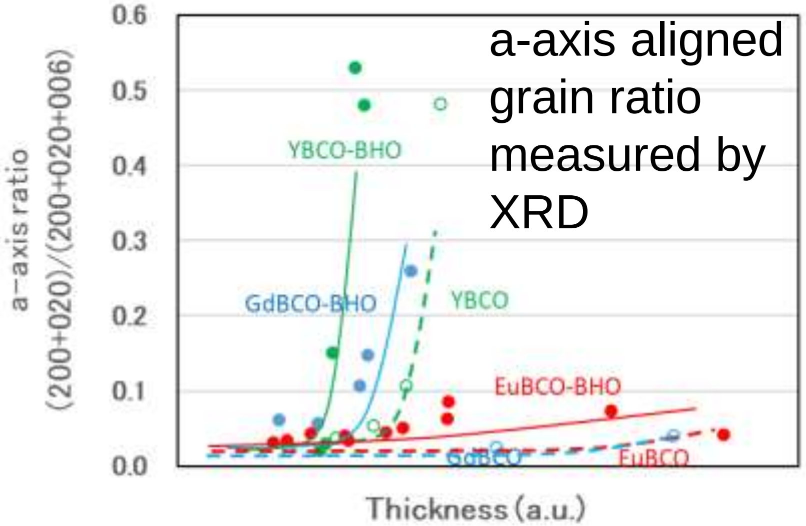
BaHfO-EuBaCuO



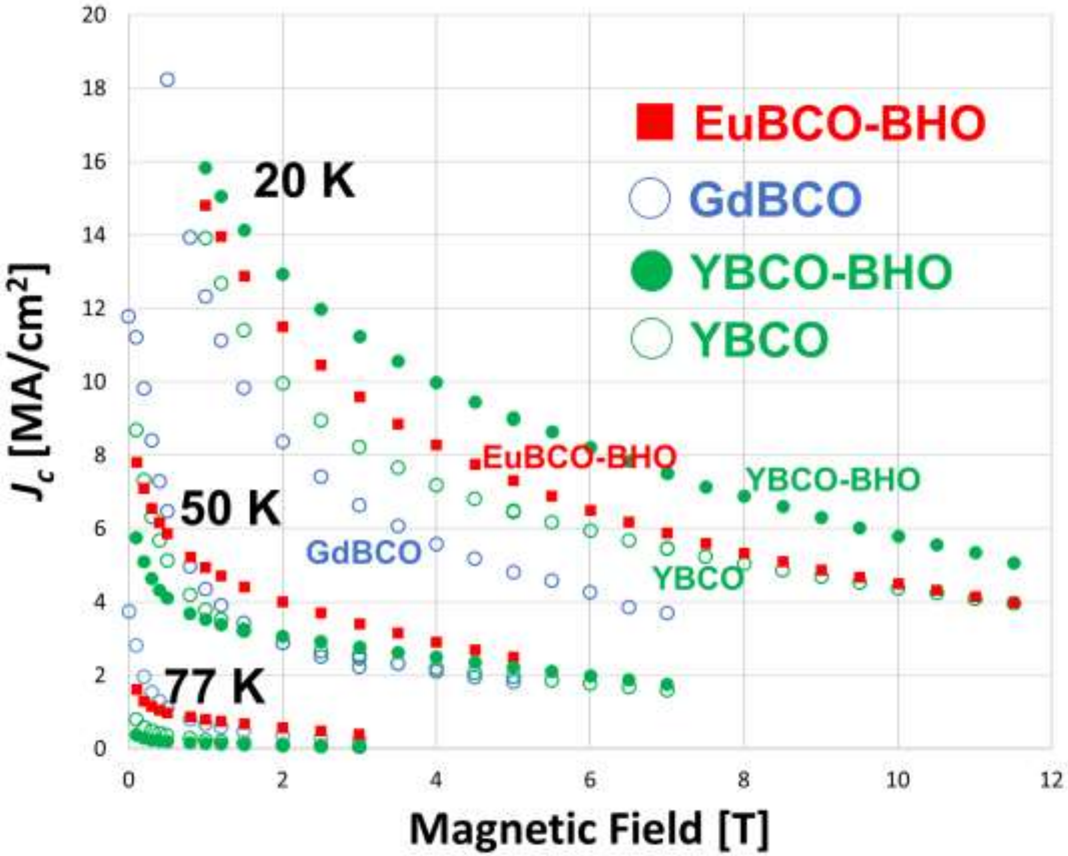
D. Yokoe et al., Supercond.Sci.Technol. **33** (2020) 024002
T. Yoshida et al., Physica C **504** (2014) 42

Oriented growth stability

EuBCO
>GdBCO
>YBCO



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



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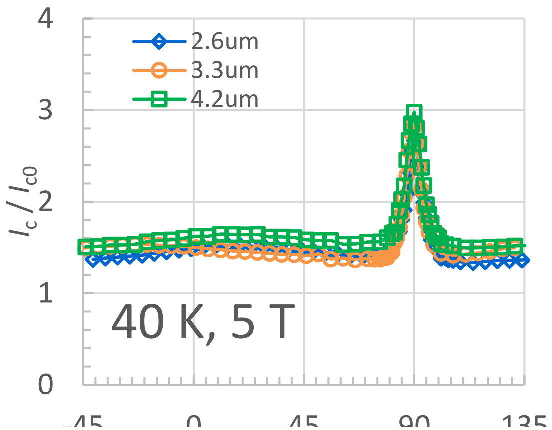
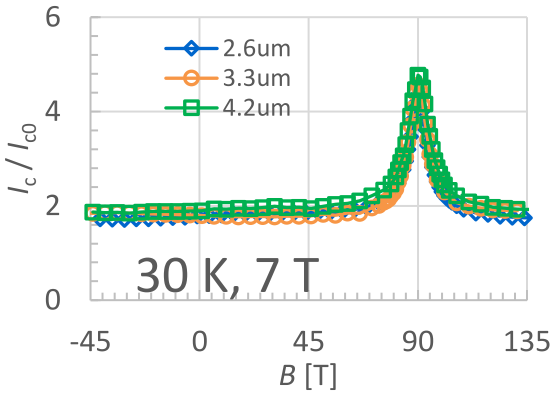
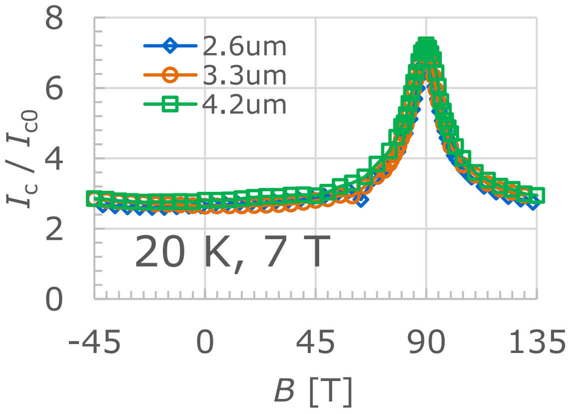
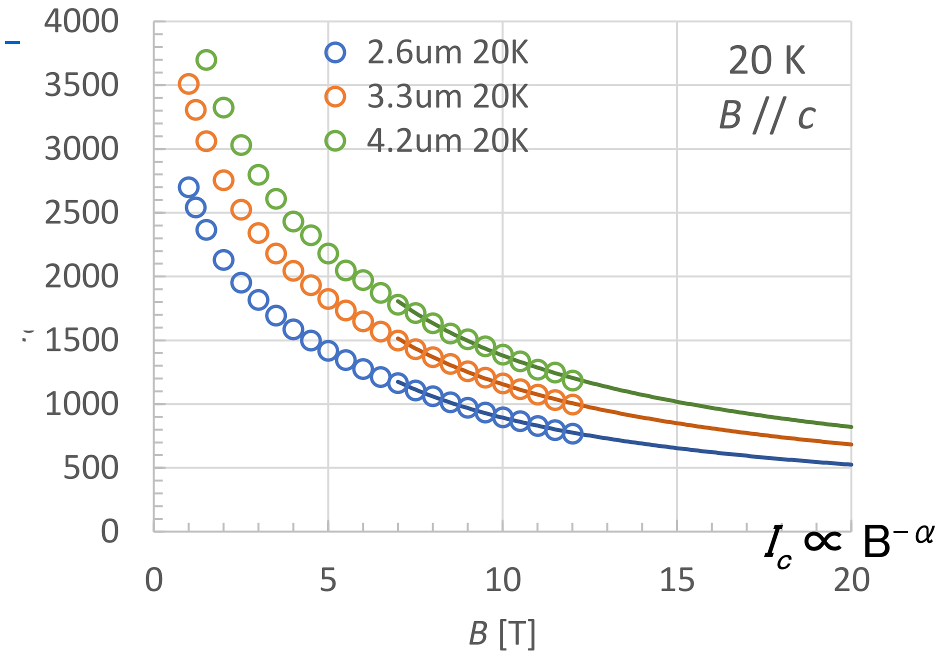
Thickness dependence for in-field I_c properties of BHO-EuBCO







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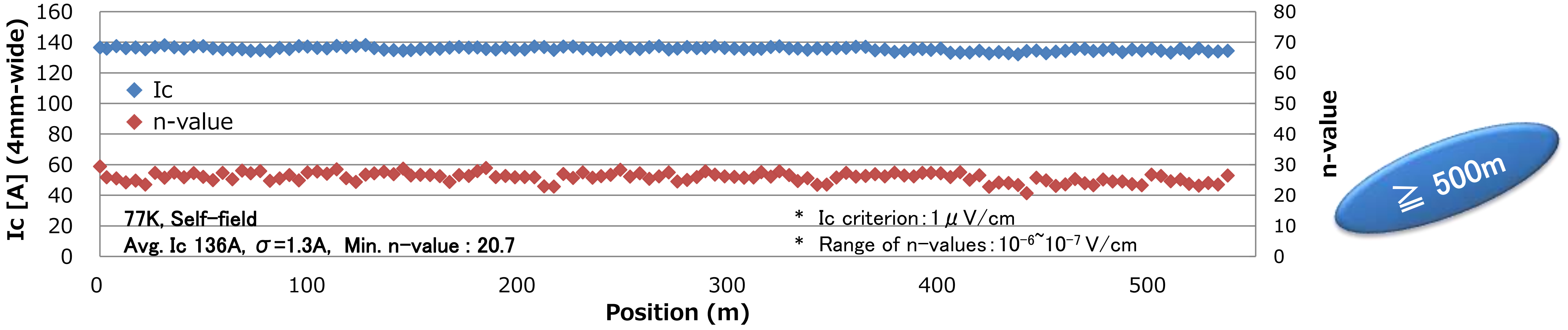
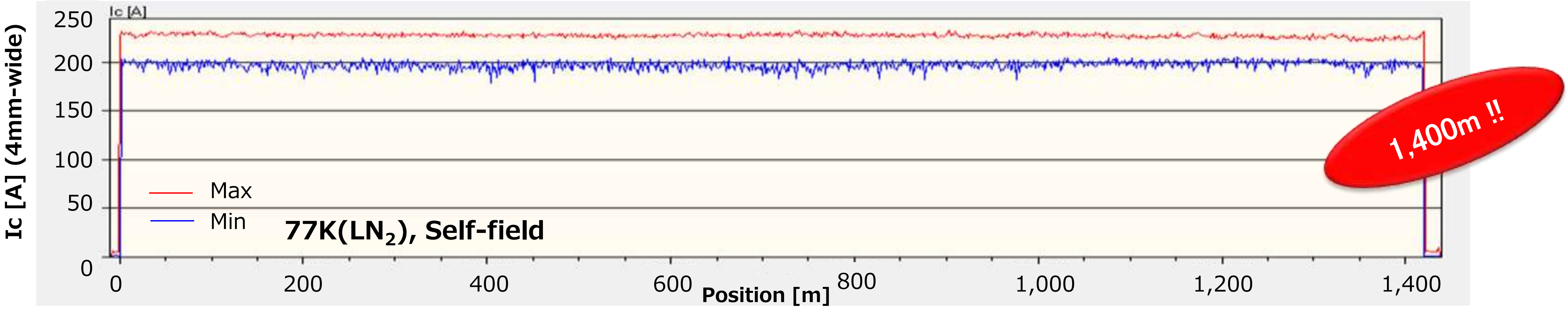
Example data of longitudinal I_c uniformity of 4mm-wide tape

- 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

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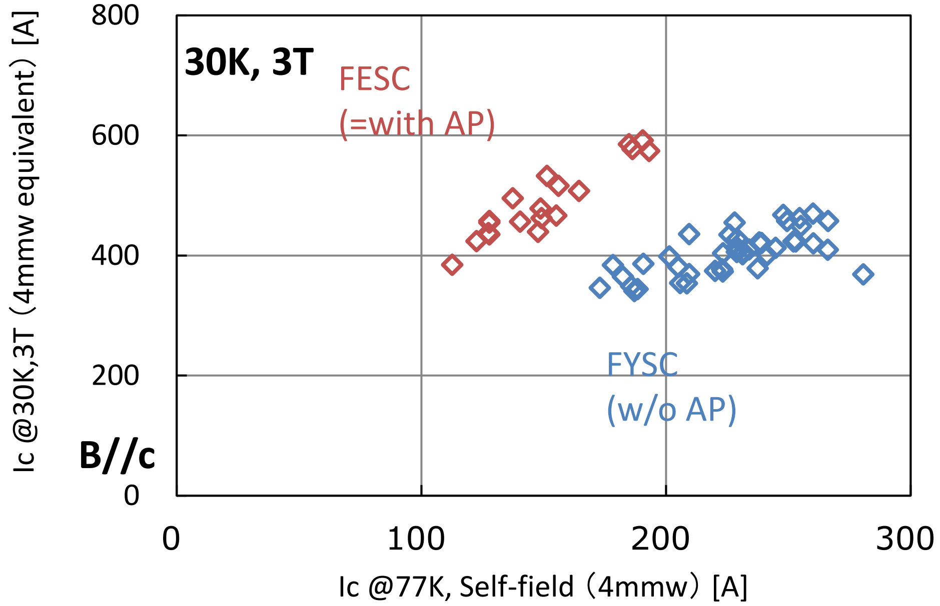
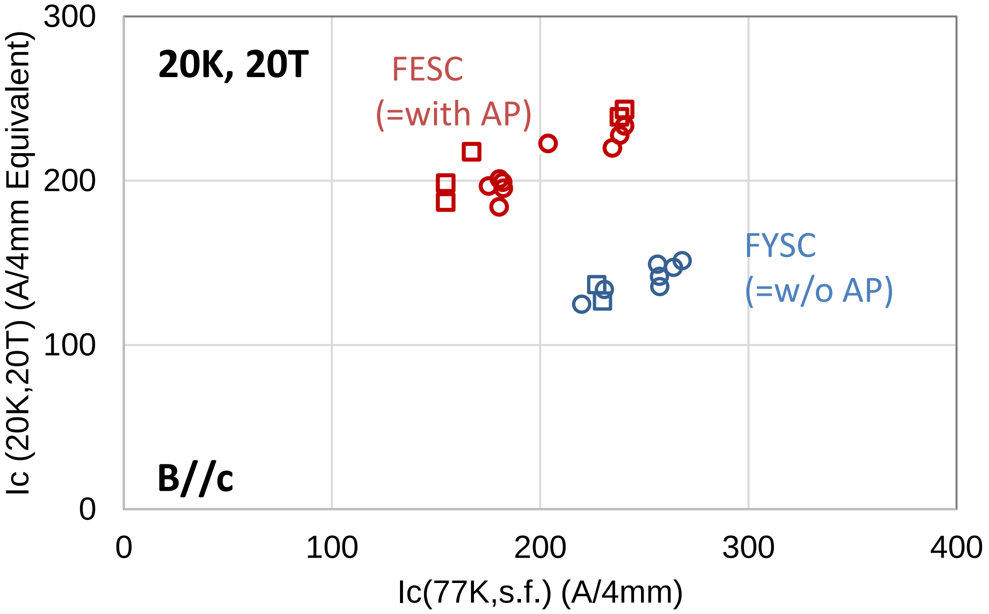
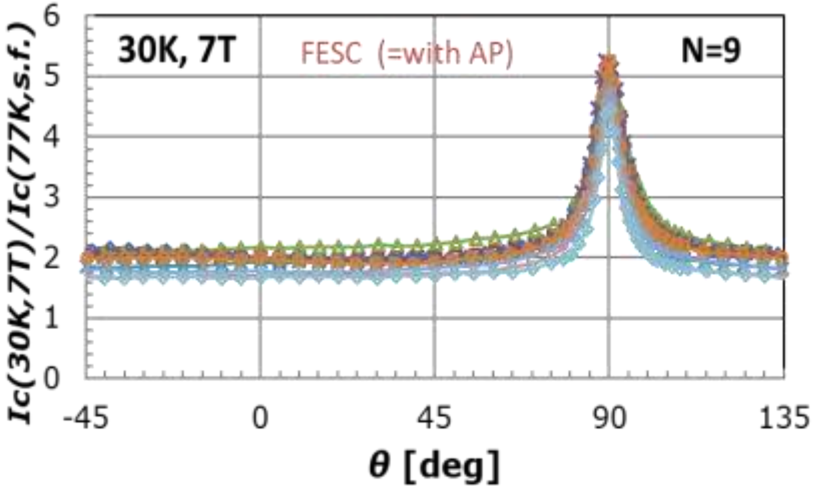
Lot-to-lot in-field I_c distribution of 4 mm^w wire

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

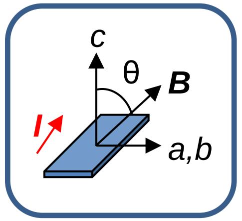




Good correlation to self field I_c and in-field I_c observed for both EuBCO+BHO and pristine GdBCO



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



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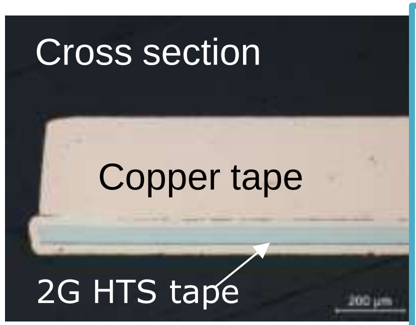
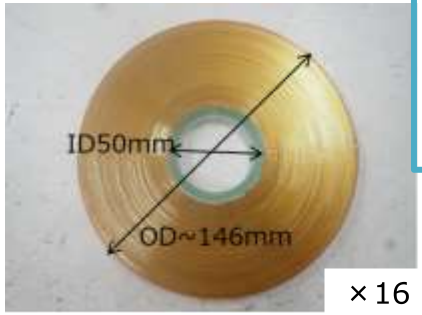
10T small test coil to check I_c uniformity & quench protection

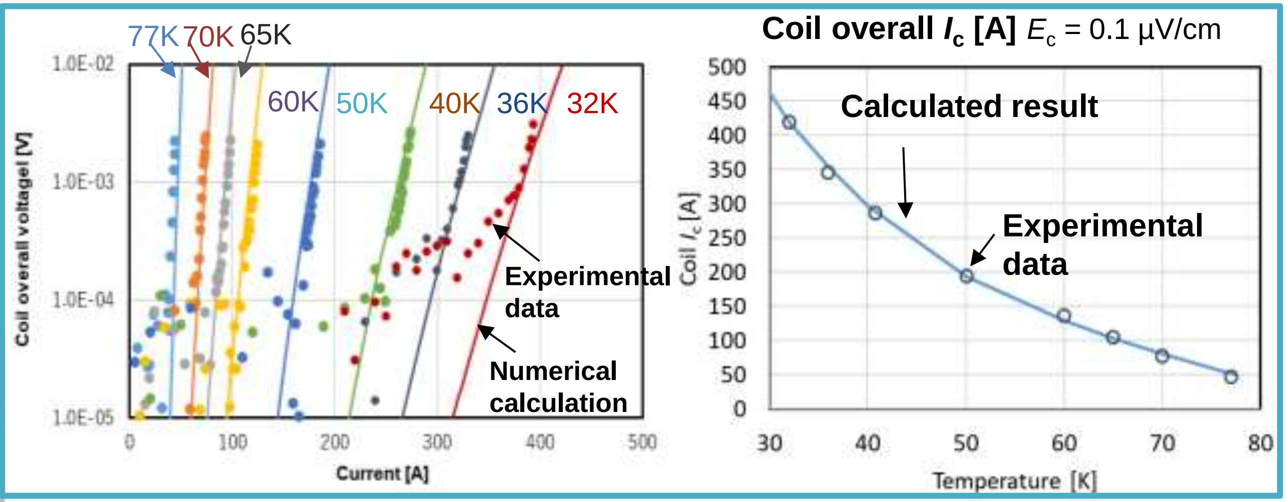
Parameters	REBCO tape
Substrate thick.	50 µm
Copper thick.	20 µm×2 (plates)+**300** µm
Type of HTS tape	FESC-SCH04
Insulation	Fluorine coating polyimide tape/Polyimide tape
Width/Thickness	4.1 mm / 0.47 mm

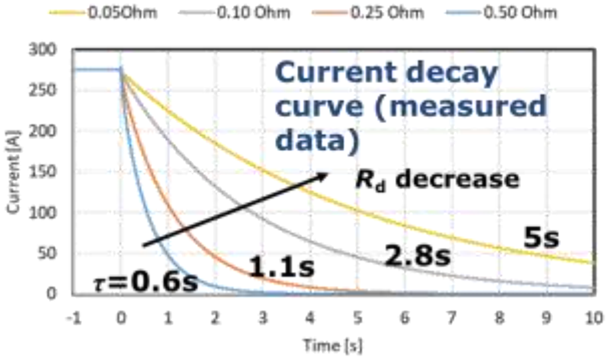
Parameters	10 T test coil	
Inner diameter	50 mm	
Outer diameter	146 mm	
Coil height	166 mm	
Impregnation	Epoxy resin	
No. of pan cake	32 (2×16)	
Number of turns	2976 (93×32)	
Tape length	0.9 km	
I_{op}	300 A	500 A
B_0	5.8 T	9.7 T
Stored energy	13 kJ	35 kJ
Load factor at 20 K	44%	73%

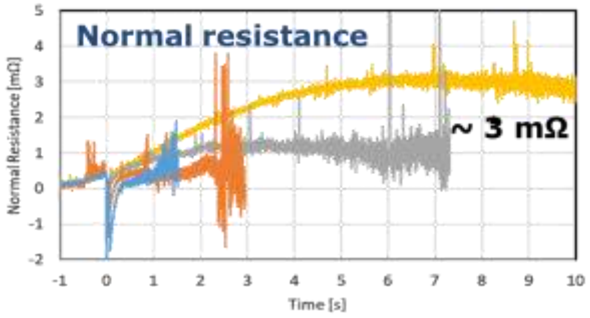




×16







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

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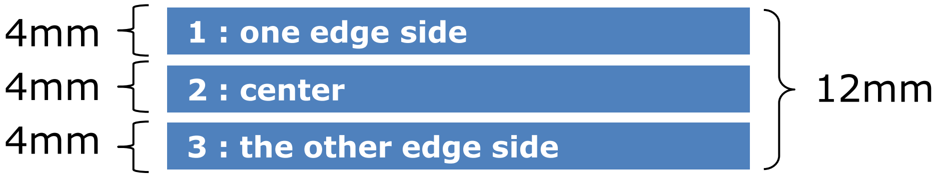
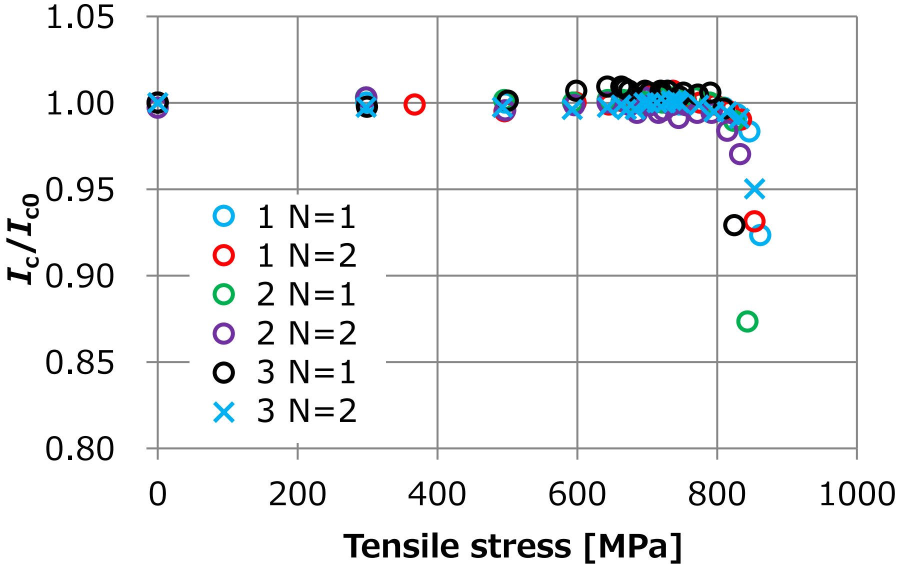
Tensile Properties Evaluation of Divided 4 mm-wide

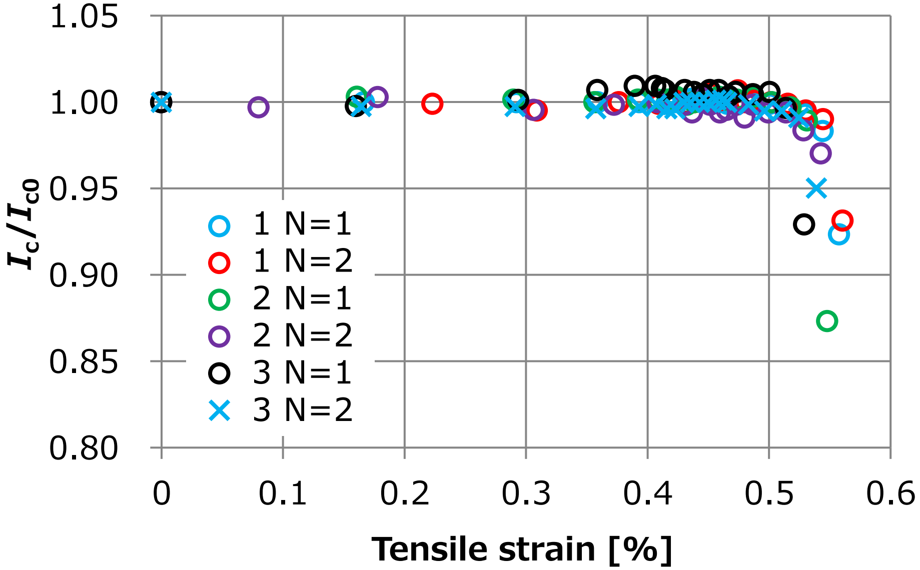
- Tensile properties of 3 parts of 4 mm-wide tapes divided from 12 mm-wide tape in LN_2

Samples (FYSC-SCH04)		Reversible I_c Strain [%]	Reversible I_c Stress[MPa]
1	N=1	0.523	820
	N=2	0.513	817
2	N=1	0.521	813
	N=2	0.497	768
3	N=1	0.514	810
	N=2	0.496	795



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





- **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.**

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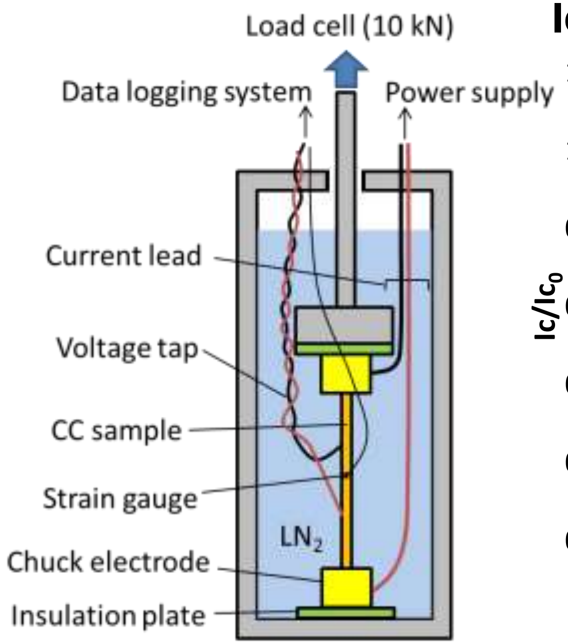
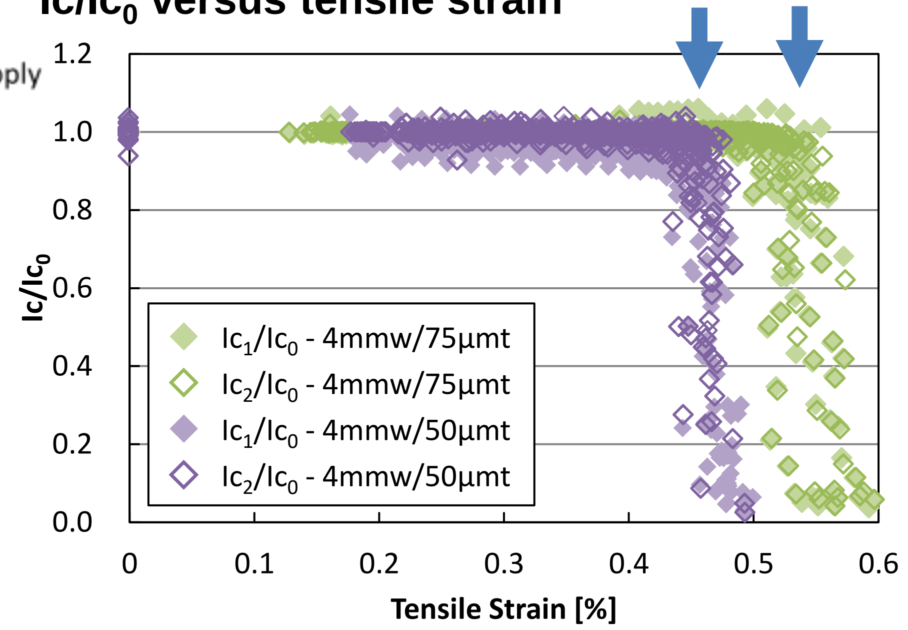
Tensile strength: REBCO thickness dependance

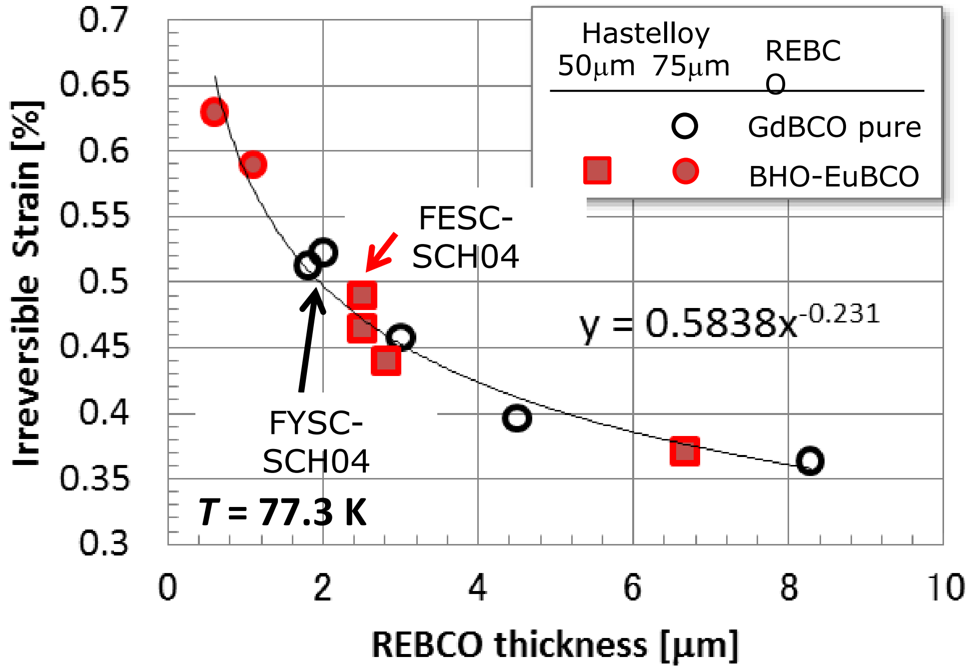
High quality, high Jc, thin REBCO film is favorable for stronger tensile strength



Ic/Ic_0 versus tensile strain



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



- 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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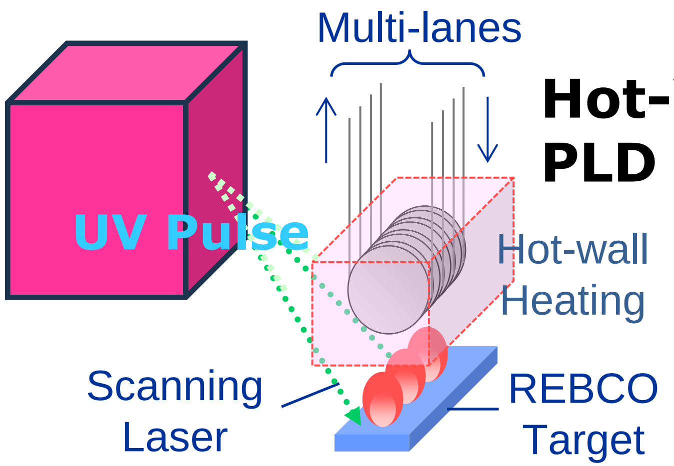
General evaluation of IBAD/PLD-REBCO process

- 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



- **High growth rate**
  - High materials yield
  - High supersaturated gas
  - High adatom mobility
- **Laser power/lifetime**
  - Still improving by **strong demand of FPD industry**

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

- **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**
- **Tensile strength**
  - High qurity Thinner film

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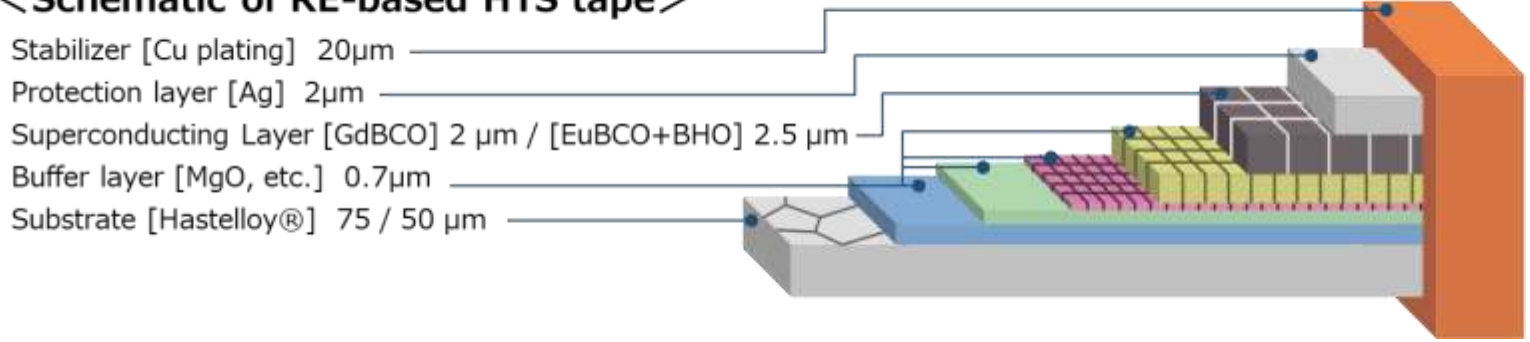
Typical Specifications of 2G HTS Tape at Fujikura

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.**

<Schematic of RE-based HTS tape>



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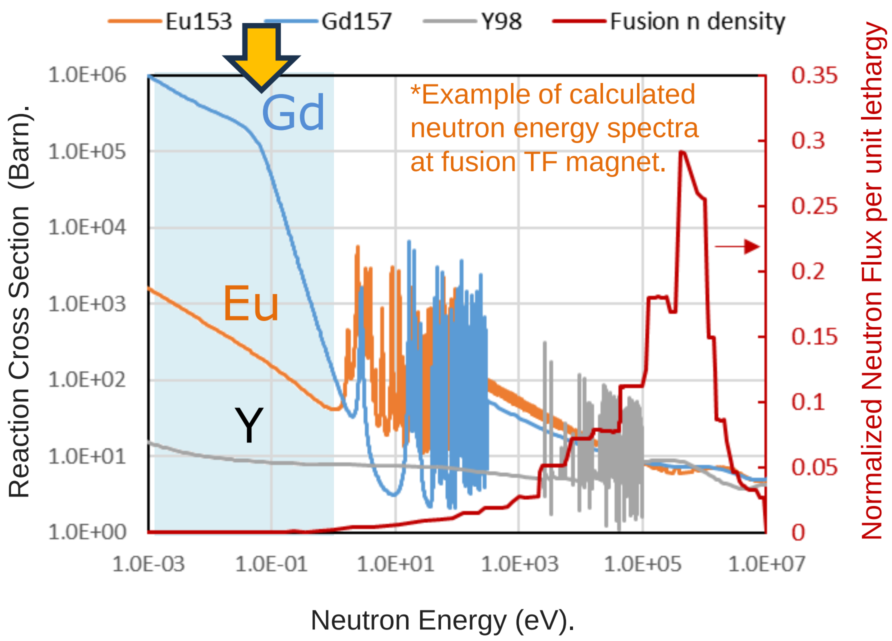
RE elemental dependence of neutron radiation damage

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).

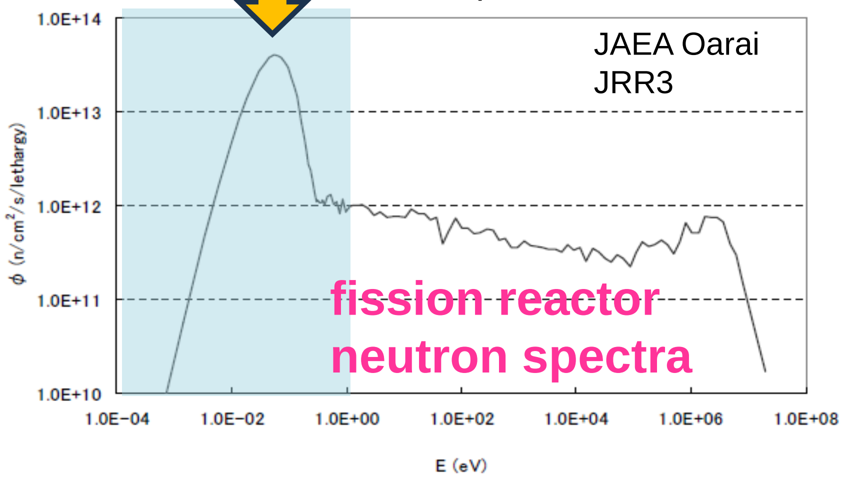
* Weber, H.: *Int. J. Mod. Phys. E* 20.06 (2011): 1325-1378.

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

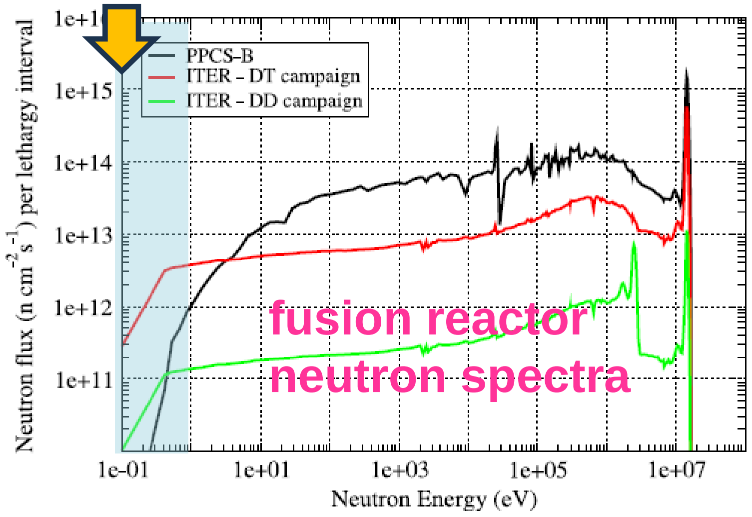
where fusion ones estimated by calculation have quite low flux there

- **RE=Gd, Eu:** irradiation spectra should be carefully evaluated for fusion environment

JAEA report 2010-007



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



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Summary

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

- **The advantage of Hot-wall PLD process covers laser cost well under mass production so far, with large process window**
  - **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**: improved by Hot-wall architecture
  - **RE dependent growth stability: Gd, Eu** desirable from the manufacturer standpoint

- **Neutron irradiation durability of REBCO wires line-up**
  - Depends on **Thermal neutron spectra** below 1eV for compact fusion magnet

PLD should contribute for tough final goal of C.C.
with low cost & high quality as a reliable approach

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END

Thank you for attention