IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Plenary presentation PL3 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
Not submitted to IEEE Trans. Appl. Supercond.

EUCAS 2015

12th European Conference on Applied Superconductivity
6th - 10th September 2015 Lyon - France

REBCO coated conductors in Japan - status and future -

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2015. 9. 7

Outline

1. HISTORY

- *Discovery of YBCO*
- *Features of YBCO*
- *Architecture of Coated Conductors*
- *Japanese Contributions (IBAD, Self-epitaxy, PLD, MOD)*

2. PRESENT STATUS

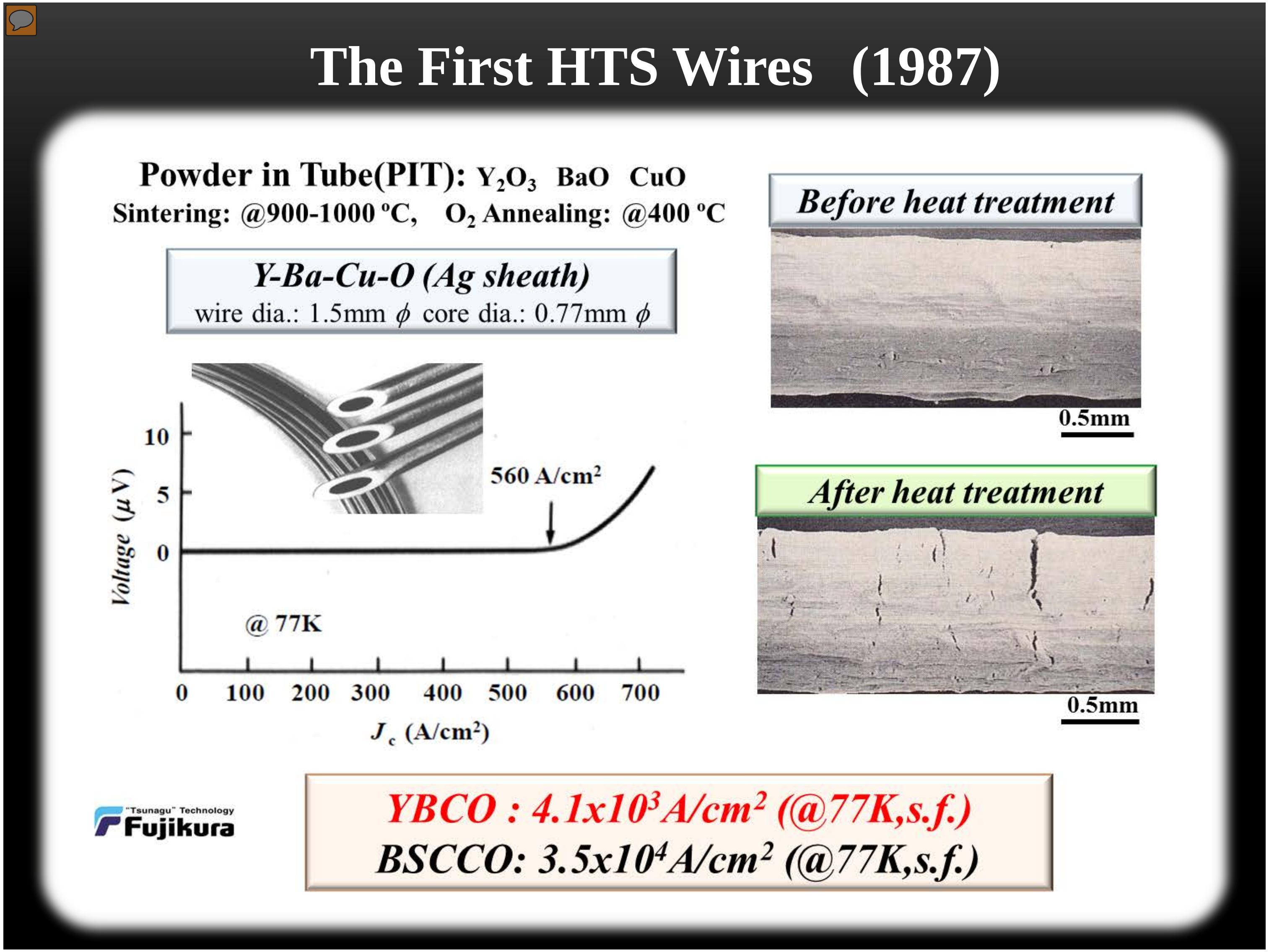
- *Higher In-field I_c by APC Control*
- *Lower AC Losses & Control of Magnetic Relaxation by Filamentation*

3. FUTURE PROSPECTS

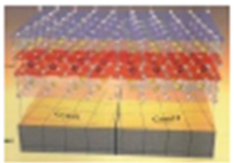
- *Lowering Cost*
- *Higher Performances*
- *New Concept of "ISOTROPIC C.C."*

1. HISTORY

- *Discovery of YBCO*
- *Features of YBCO*
- *Architecture of Coated Conductors*
- *Japanese Contributions (IBAD, Self-epitaxy, PLD, MOD)*


The First HTS Wires (1987)
Powder in Tube(PIT): Y2O3 BaO CuO
Sintering: @900-1000 ºC, O2 Annealing: @400 ºC
Y-Ba-Cu-O (Ag sheath)
wire dia.: 1.5mm ϕ core dia.: 0.77mm ϕ
10
5
0
Voltage (μV)
560 A/cm2
@ 77K
0 100 200 300 400 500 600 700
Jc (A/cm2)
Before heat treatment
0.5mm
After heat treatment
0.5mm
"Tsunagu" Technology
Fujikura
YBCO : 4.1x103 A/cm2 (@77K,s.f.)
BSCCO: 3.5x104 A/cm2 (@77K,s.f.)

Serious Effect of Misalignment Angle at Grain Boundaries on J_c



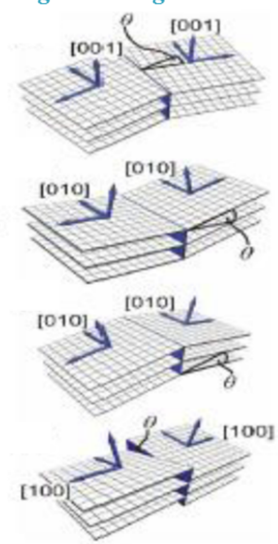
misalignment angle θ

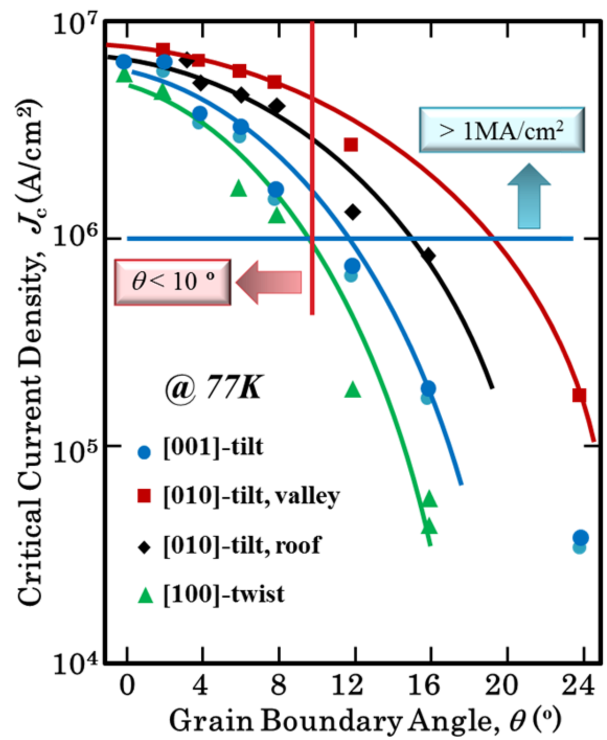
(a) **[001]-tilt**

(b) **[010]-tilt, valley**

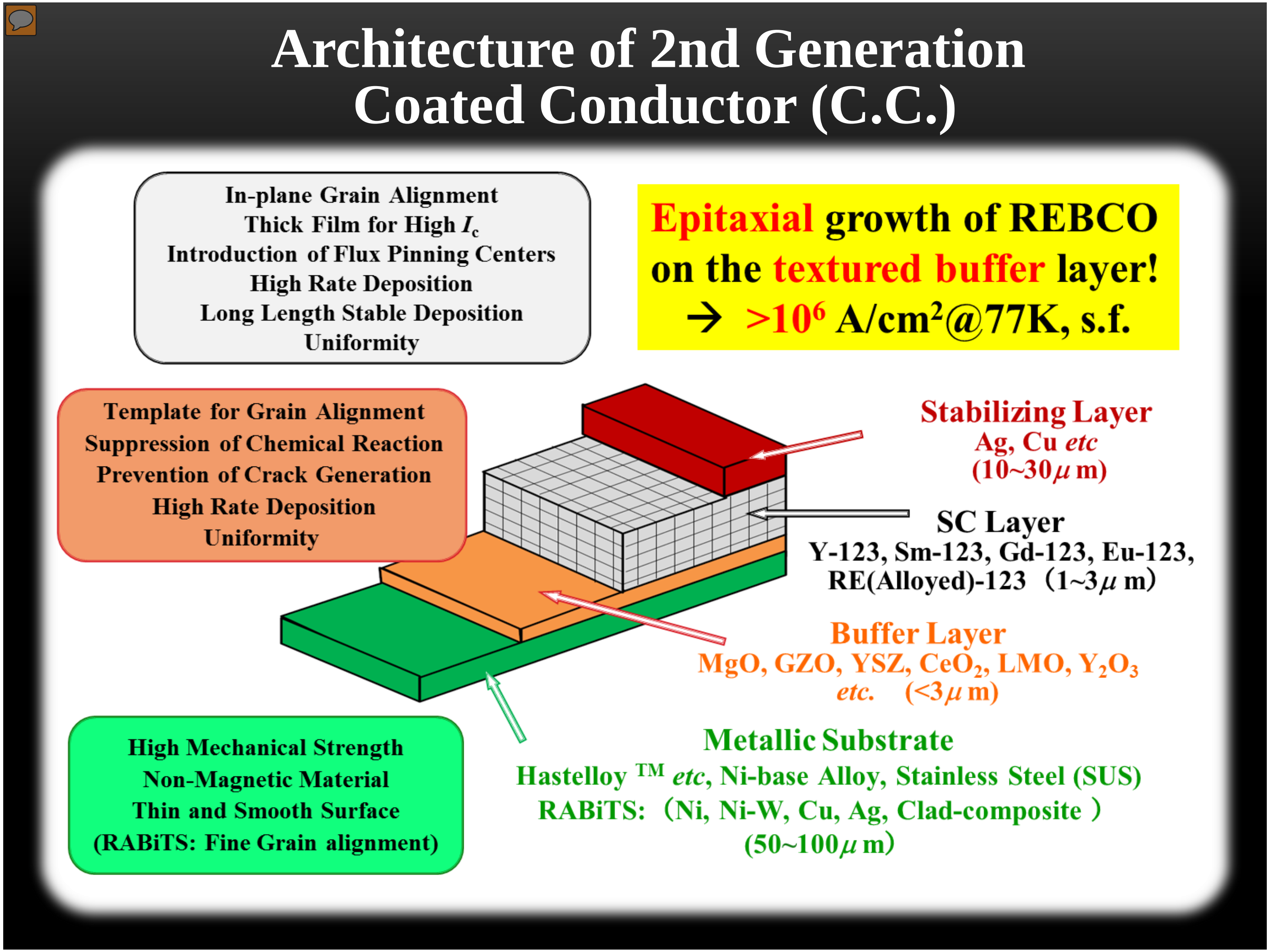
(c) **[010]-tilt, roof**

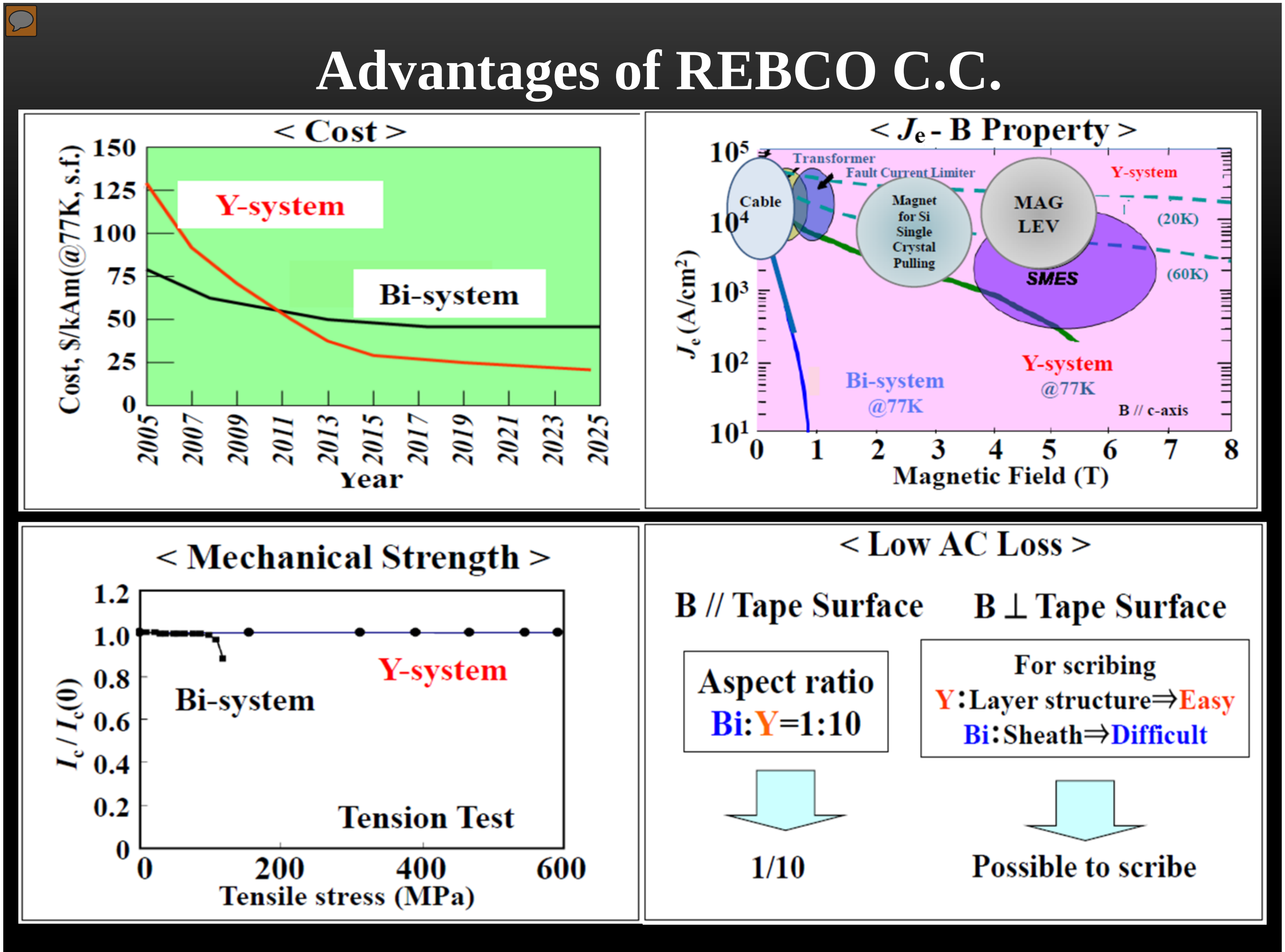
(d) **[100]-twist**

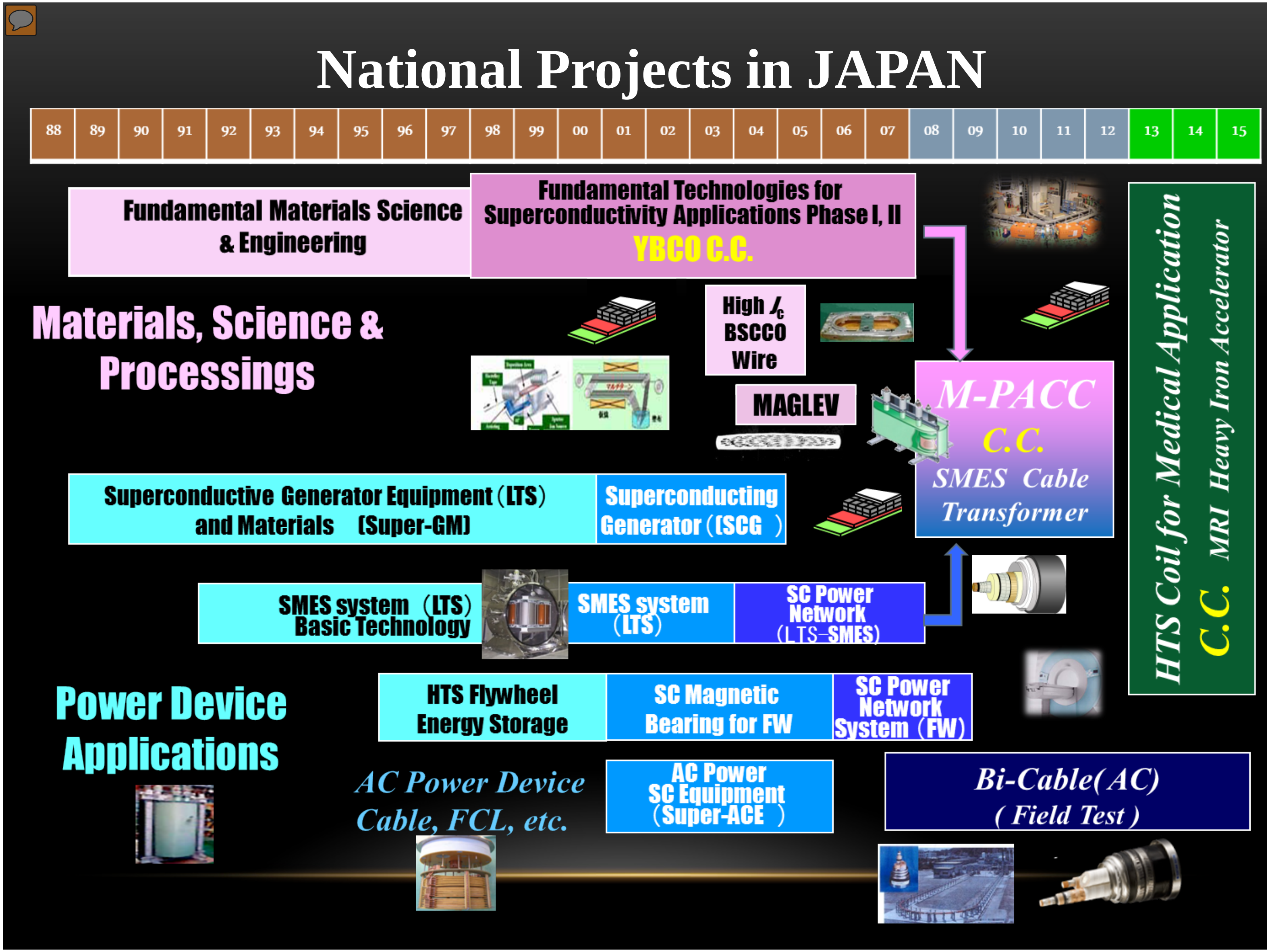


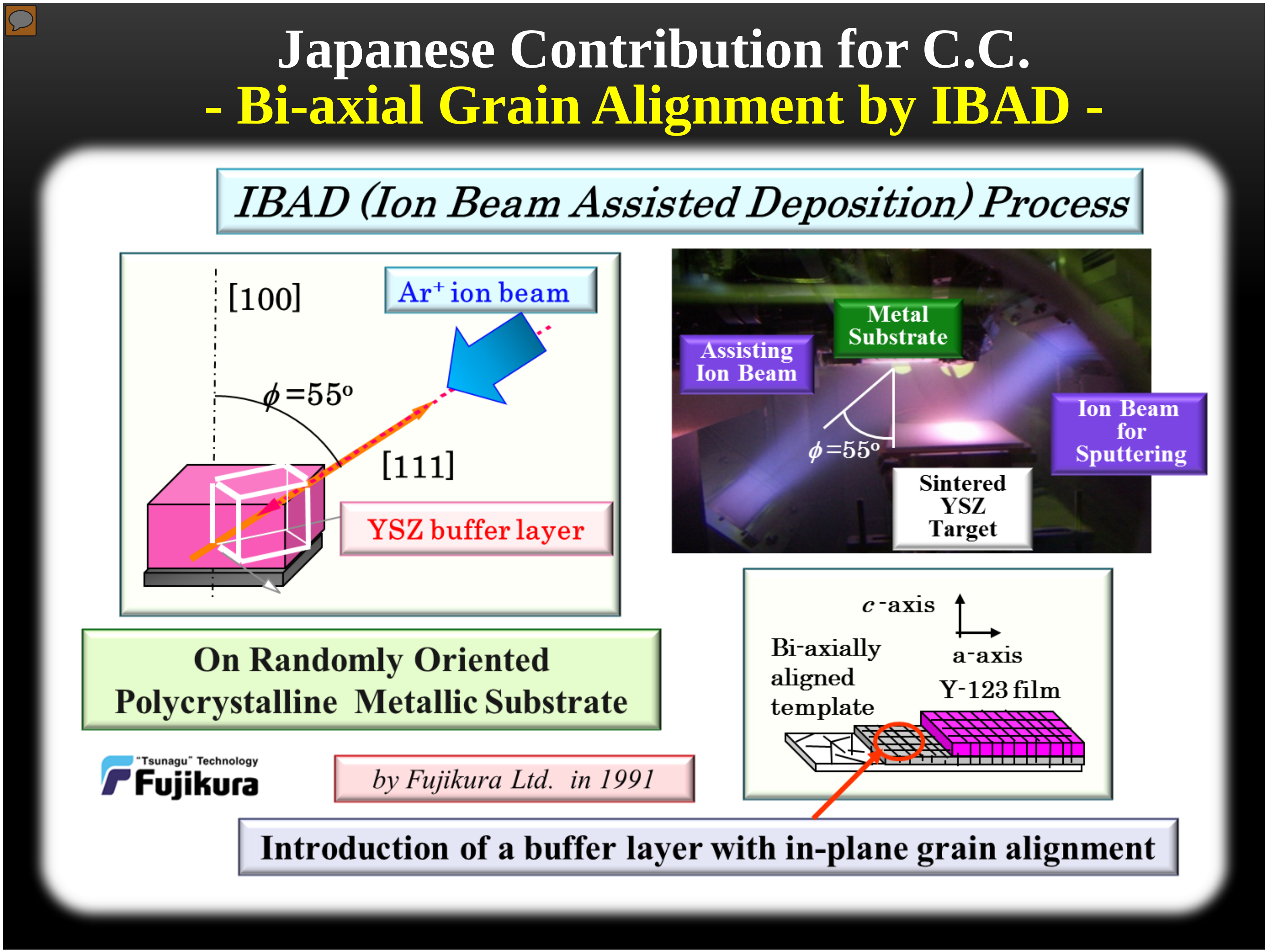


Ref: *R. Held, C. W. Schneider, J. Mannhart, L. F. Allard, K. L. More, and A. Goyal, Phys. Rev. B 79, 1, 014515 (2009)*


Architecture of 2nd Generation
Coated Conductor (C.C.)
In-plane Grain Alignment
Thick Film for High I_c
Introduction of Flux Pinning Centers
High Rate Deposition
Long Length Stable Deposition
Uniformity
Epitaxial growth of REBCO
on the textured buffer layer!
→ >10^6 A/cm^2@77K, s.f.
Template for Grain Alignment
Suppression of Chemical Reaction
Prevention of Crack Generation
High Rate Deposition
Uniformity
Stabilizing Layer
Ag, Cu *etc*
(10~30μm)
SC Layer
Y-123, Sm-123, Gd-123, Eu-123,
RE(Alloyed)-123 (1~3μm)
Buffer Layer
MgO, GZO, YSZ, CeO_2, LMO, Y_2O_3
etc. (<3μm)
High Mechanical Strength
Non-Magnetic Material
Thin and Smooth Surface
(RABiTS: Fine Grain alignment)
Metallic Substrate
Hastelloy ™ *etc*, Ni-base Alloy, Stainless Steel (SUS)
RABiTS: (Ni, Ni-W, Cu, Ag, Clad-composite)
(50~100μm)


Advantages of REBCO C.C.
< Cost >
Cost, $/kAm(@77K, s.f.)
150
125
100
75
50
25
0
Y-system
Bi-system
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
Year
< Je - B Property >
Je (A/cm²)
10⁵
10⁴
10³
10²
10¹
Transformer
Fault Current Limiter
Cable
Magnet for Si Single Crystal Pulling
MAG LEV
SMES
Y-system
(20K)
(60K)
Y-system @77K
Bi-system @77K
B // c-axis
0 1 2 3 4 5 6 7 8
Magnetic Field (T)
< Mechanical Strength >
Ic / Ic(0)
1.2
1.0
0.8
0.6
0.4
0.2
0
Y-system
Bi-system
Tension Test
0 200 400 600
Tensile stress (MPa)
< Low AC Loss >
B // Tape Surface
B ⊥ Tape Surface
Aspect ratio
Bi:Y=1:10
For scribing
Y:Layer structure⇒Easy
Bi:Sheath⇒Difficult
1/10
Possible to scribe


National Projects in JAPAN
88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15
Fundamental Materials Science & Engineering
Fundamental Technologies for Superconductivity Applications Phase I, II
YBCO C.C.
Materials, Science & Processings
High J_c BSCCO Wire
MAGLEV
M-PACC
C.C.
SMES Cable Transformer
HTS Coil for Medical Application
C.C. MRI Heavy Iron Accelerator
Superconductive Generator Equipment (LTS) and Materials (Super-GM)
Superconducting Generator (SCG)
SMES system (LTS) Basic Technology
SMES system (LTS)
SC Power Network (LTS-SMES)
Power Device Applications
HTS Flywheel Energy Storage
SC Magnetic Bearing for FW
SC Power Network System (FW)
AC Power Device Cable, FCL, etc.
AC Power SC Equipment (Super-ACE)
Bi-Cable(AC) (Field Test)

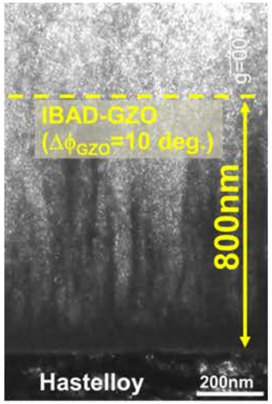

Japanese Contribution for C.C.
- Bi-axial Grain Alignment by IBAD -
IBAD (Ion Beam Assisted Deposition) Process
[100]
Ar+ ion beam
φ=55°
[111]
YSZ buffer layer
Metal Substrate
Assisting Ion Beam
Ion Beam for Sputtering
φ=55°
Sintered YSZ Target
On Randomly Oriented Polycrystalline Metallic Substrate
c-axis
a-axis
Bi-axially aligned template
Y-123 film
"Tsunagu" Technology Fujikura
by Fujikura Ltd. in 1991
Introduction of a buffer layer with in-plane grain alignment

Improvement of Rate in US for IBAD

Problem in IBAD of Early Stage (YSZ & GZO)

→ ***Long Time for Alignment***

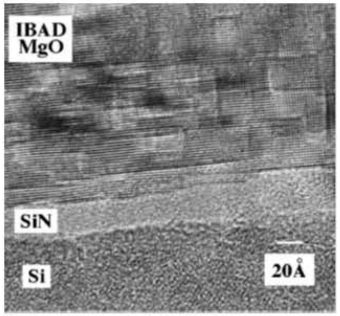
(e.g. 4hr for Δφ~10°)



Drastically Shortening Time for Alignment in U.S.

GZO → MgO

(e.g. ***2 min.*** *for Δφ~10°)*



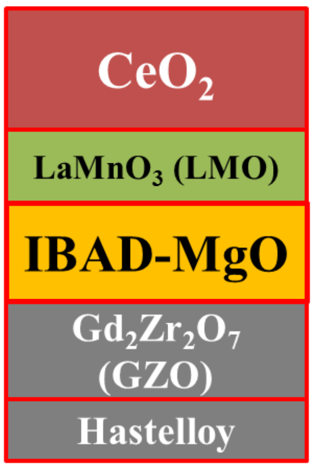
Ref: *C.P. Wang et al. APL vol.171(1997)2955*
P.N. Arendt et al. MRS Bulletin vol.29(2004)543

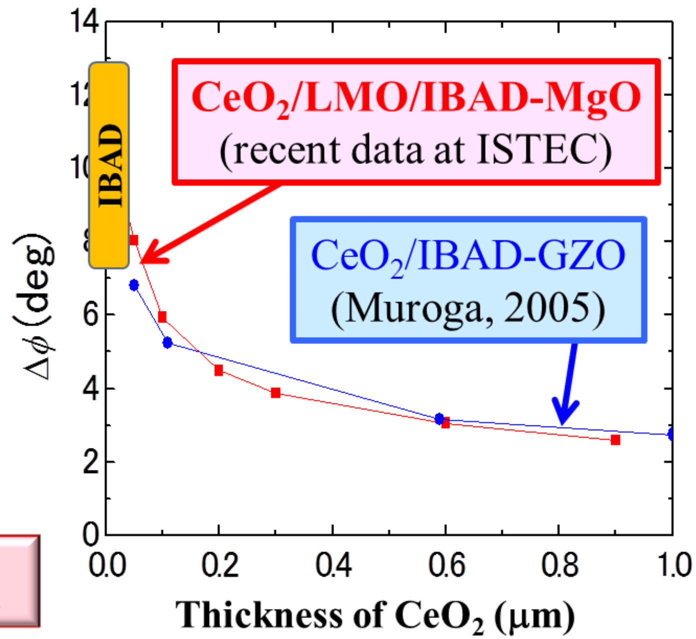
Japanese Contribution for C.C.
- Bi-axial Buffer by Self-epitaxy -

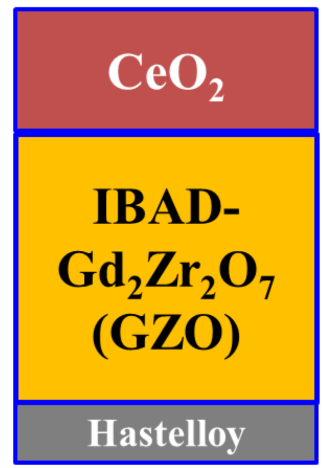
Definition: **in-plane misorientation angle ($\Delta\phi$) decreases with increasing film thickness**

(discovered by Muroga *et al*. in 2002)

$\Delta\phi$ vs. thickness of CeO_2



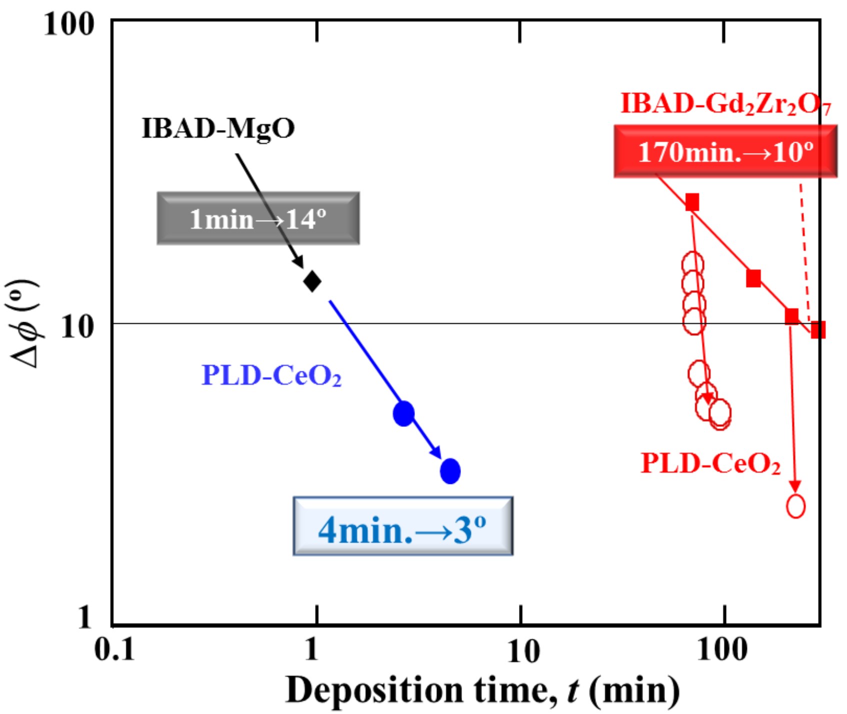




Ref: *Tekeumi Muroga, Ph.D. thesis (2005), p.50.*

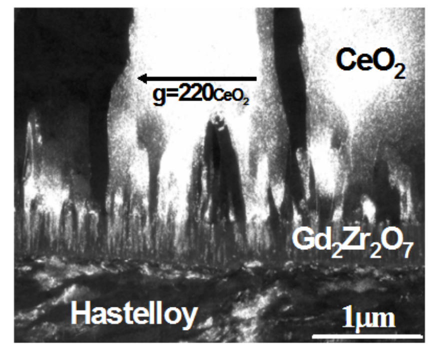
ISTEC

Japanese Contribution for C.C.
- Bi-axial Buffer by Self-epitaxy -

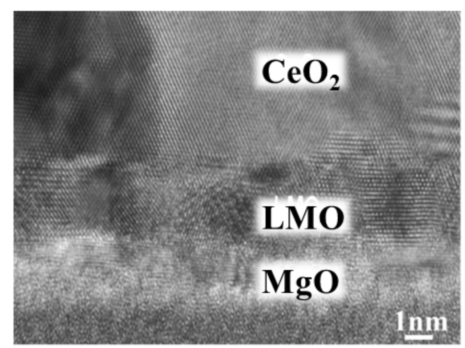


Drastic changes in the grain sizes at the interface

CeO_2/ IBAD-$Gd_2Zr_2O_7$



CeO_2/ (LMO) / IBAD-MgO



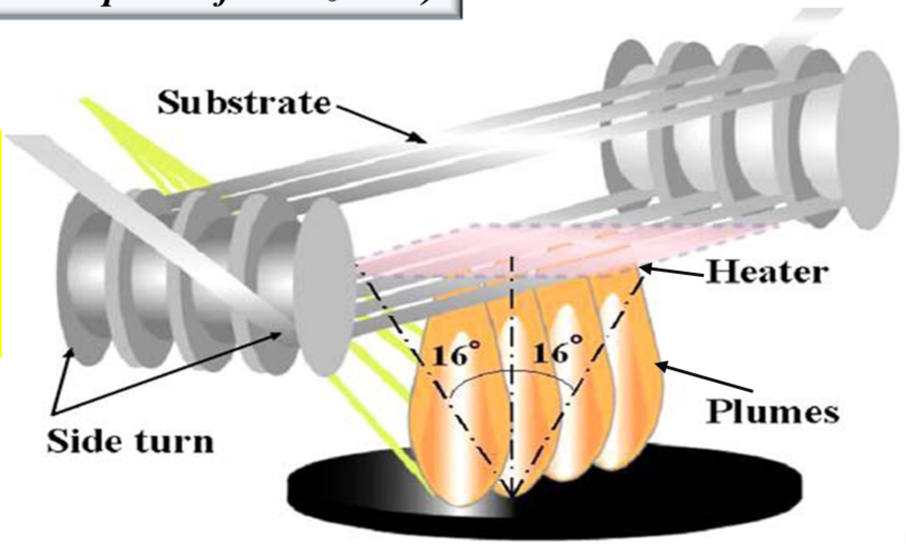
Japanese Contribution for C.C.
- MPMT-PLD Process for REBCO -

Multi-Plume & Multi-Turn PLD

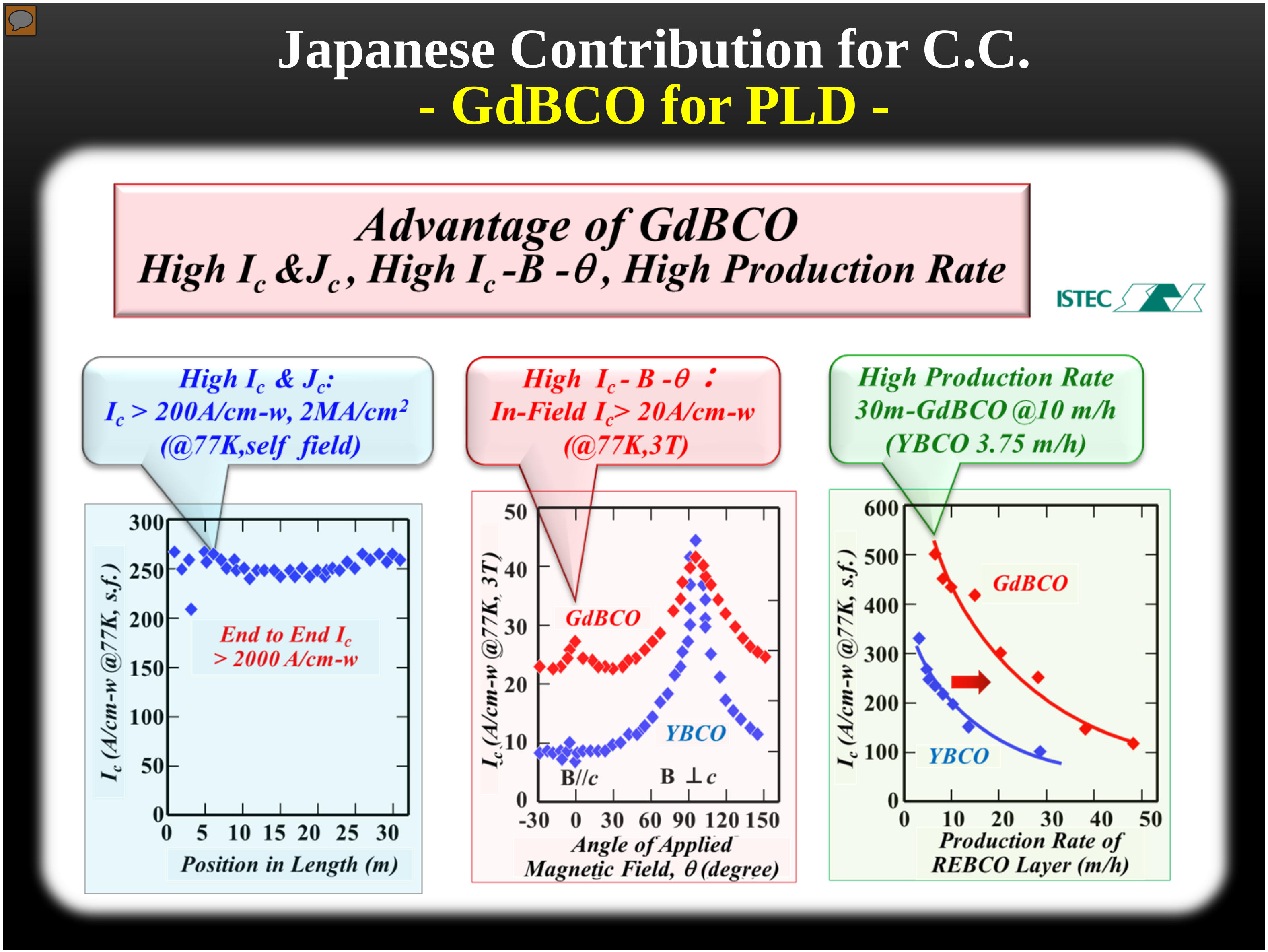
- *YBCO layer deposition temperature : 800 ~ 850 ºC*
- *Oxygen pressure: 200 m Torr*
- *Laser beam energy: 500 mJ*
- *Repetition rate of laser pulse: 160 Hz,*
  (divided to 4-plumes with laser pulse of 40 Hz each)

ISTEC

- **Production Rate**
- **High Material Yield**
- **Controlled Supersaturation**

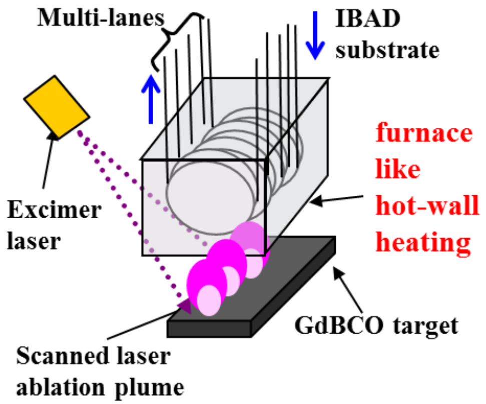


Ref: A.Ibi, Y, Shiohara, et al: Physica C ,445-448 (2006)525


Japanese Contribution for C.C.
- GdBCO for PLD -
Advantage of GdBCO
High I_c &J_c, High I_c-B -θ, High Production Rate
ISTEC
High I_c & J_c:
I_c > 200A/cm-w, 2MA/cm²
(@77K,self field)
High I_c- B -θ :
In-Field I_c> 20A/cm-w
(@77K,3T)
High Production Rate
30m-GdBCO @10 m/h
(YBCO 3.75 m/h)
End to End I_c
> 2000 A/cm-w
I_c (A/cm-w @77K, s.f.)
Position in Length (m)
GdBCO
YBCO
B//c
B ⊥c
I_c (A/cm-w @77K, 3T)
Angle of Applied Magnetic Field, θ (degree)
GdBCO
YBCO
I_c (A/cm-w @77K, s.f.)
Production Rate of REBCO Layer (m/h)

Long Length C.C. @Fujikura(ISTEC)

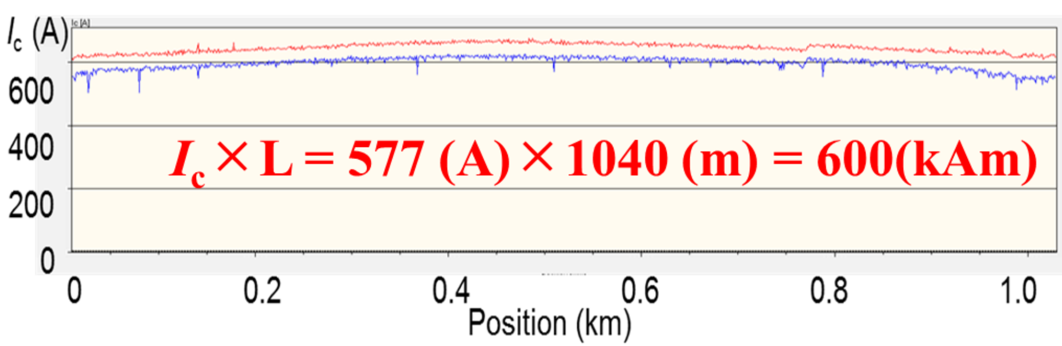
PLD(GdBCO)/IBAD Coated Conductors

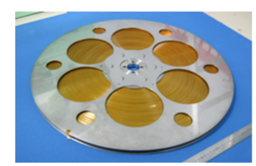


	Piece Length	$I_{c, max}$	$I_{c, min}$	$I_{c,ave}$	*Uniformity*
Wire A	621 m	700 A	649 A	677 A	7.5 %
Wire B	700 m	590 A	555 A	575 A	6.1 %
Wire C	587 m	562 A	533 A	550 A	5.2 %

I_c : A / cm-w@ 77 K, s.f.

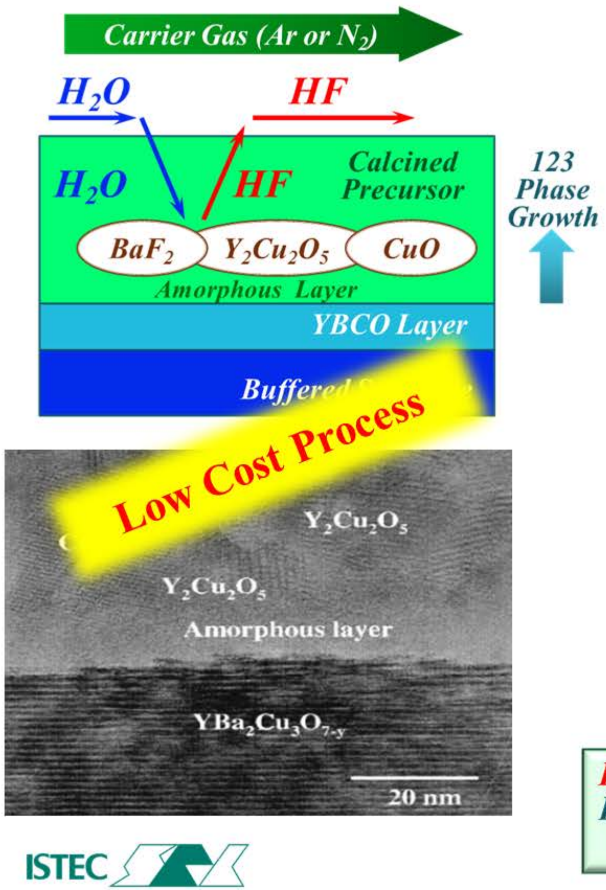
Uniformity : {I_c (max.) - I_c (min.)} / I_c (avg.) x 100



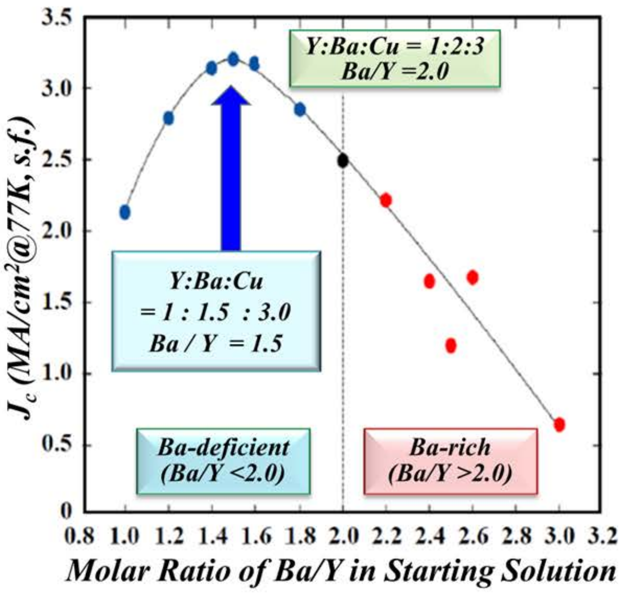


"Tsunagu" Technology Fujikura

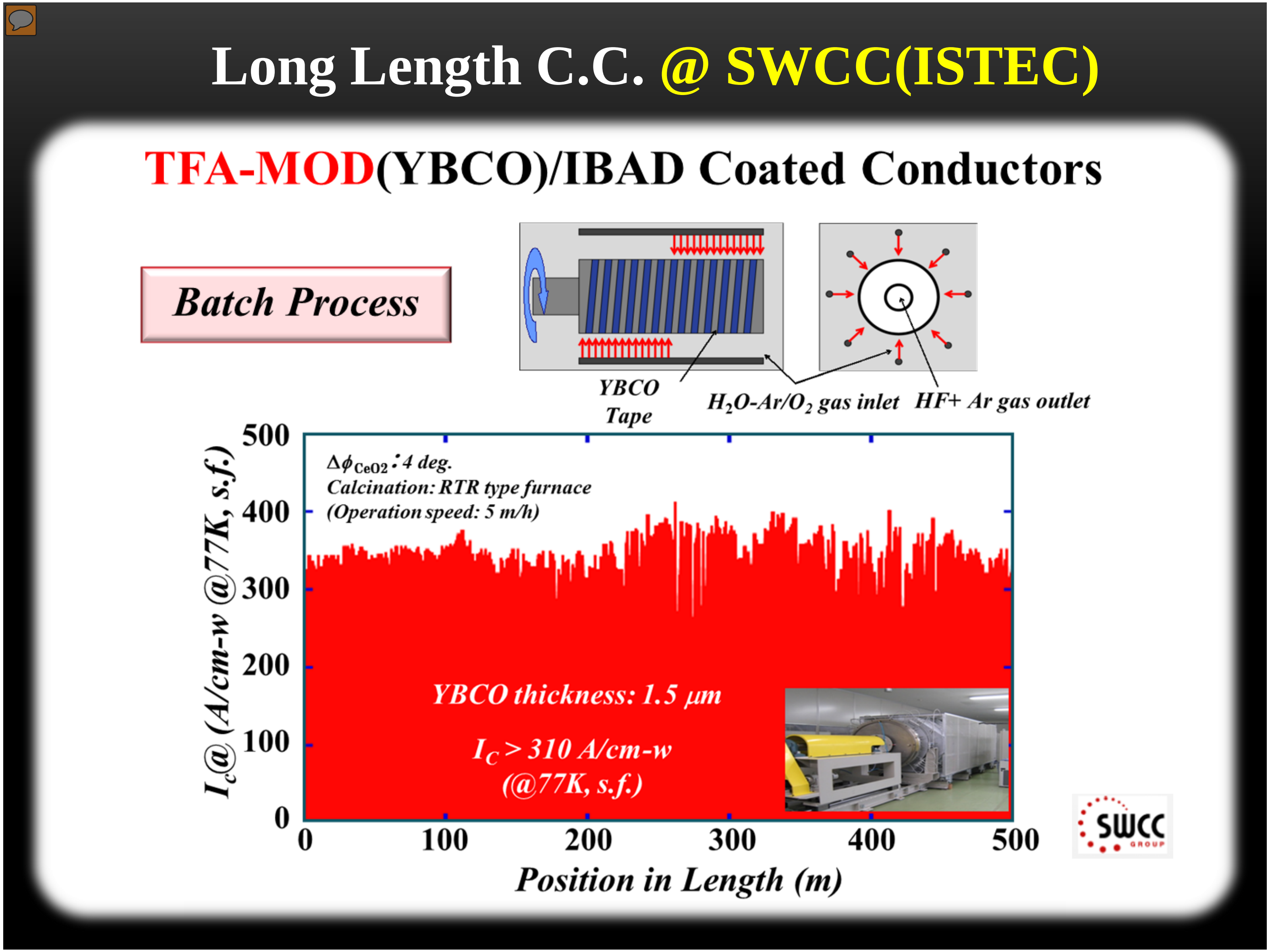
Japanese Contribution for C.C.
- Fundamental Analysis of TFA-MOD -



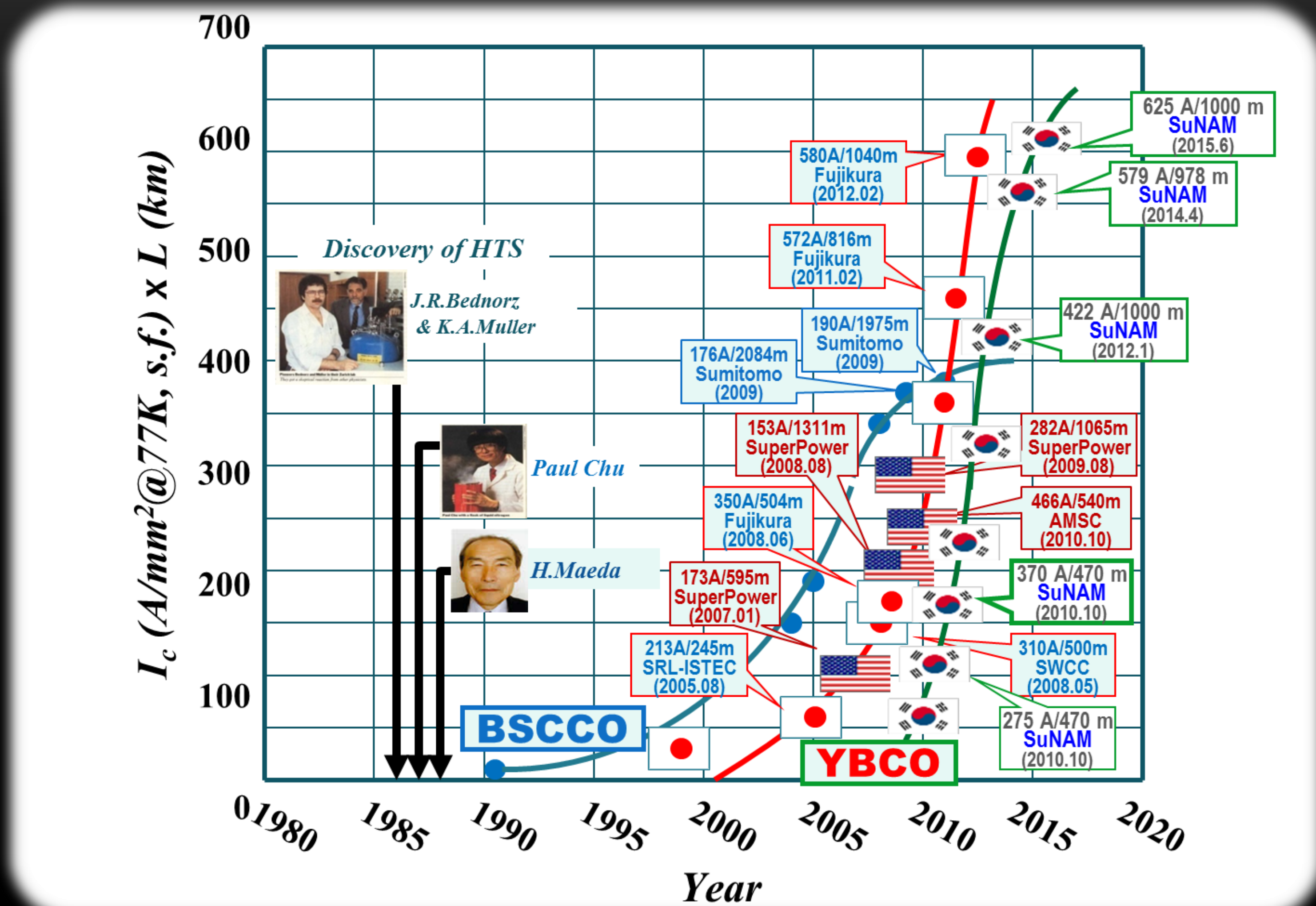
High I_c due to Ba-deficient Composition



Ba-rich: Huge pores
Ba-deficient: Smaller and less pores,
$CuO/Y_2Cu_2O_5$ particles in the 123 grains

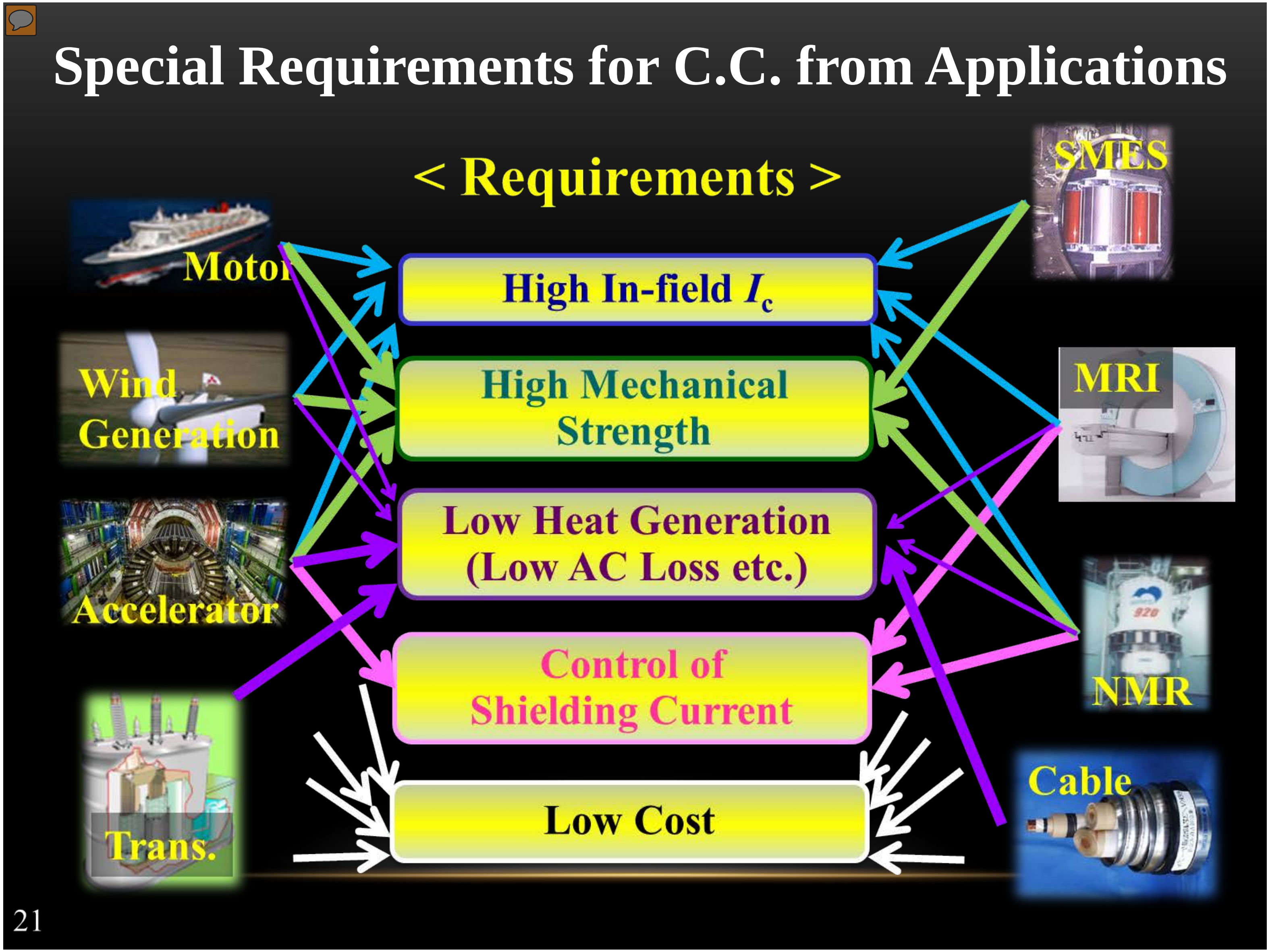

Long Length C.C. @ SWCC(ISTEC)
TFA-MOD(YBCO)/IBAD Coated Conductors
Batch Process
YBCO Tape
H_2O-Ar/O_2 gas inlet
HF+ Ar gas outlet
$\Delta\phi_{CeO2}$: 4 deg.
Calcination: RTR type furnace
(Operation speed: 5 m/h)
YBCO thickness: 1.5 μm
I_C > 310 A/cm-w
(@77K, s.f.)
I_c@ (A/cm-w @77K, s.f.)
Position in Length (m)
0
100
200
300
400
500
SWCC GROUP

Progress of Long C.C. (as of 2015.6.8)



2. PRESENT STATUS

- ***Higher In-field I_c by APC Control***
- ***Lower AC Losses & Control of Magnetic Relaxation by Filamentation***


Special Requirements for C.C. from Applications
< Requirements >
High In-field I_c
High Mechanical Strength
Low Heat Generation (Low AC Loss etc.)
Control of Shielding Current
Low Cost
Motor
Wind Generation
Accelerator
Trans.
SMES
MRI
NMR
Cable
21

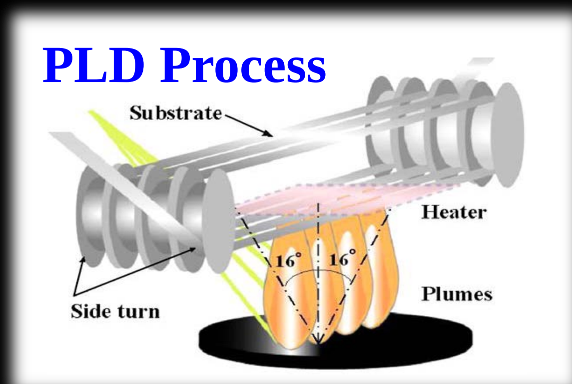
Improvement of In-field I_c in IBAD-PLD C.C.

PLD-REBCO

Epitaxial CeO_2

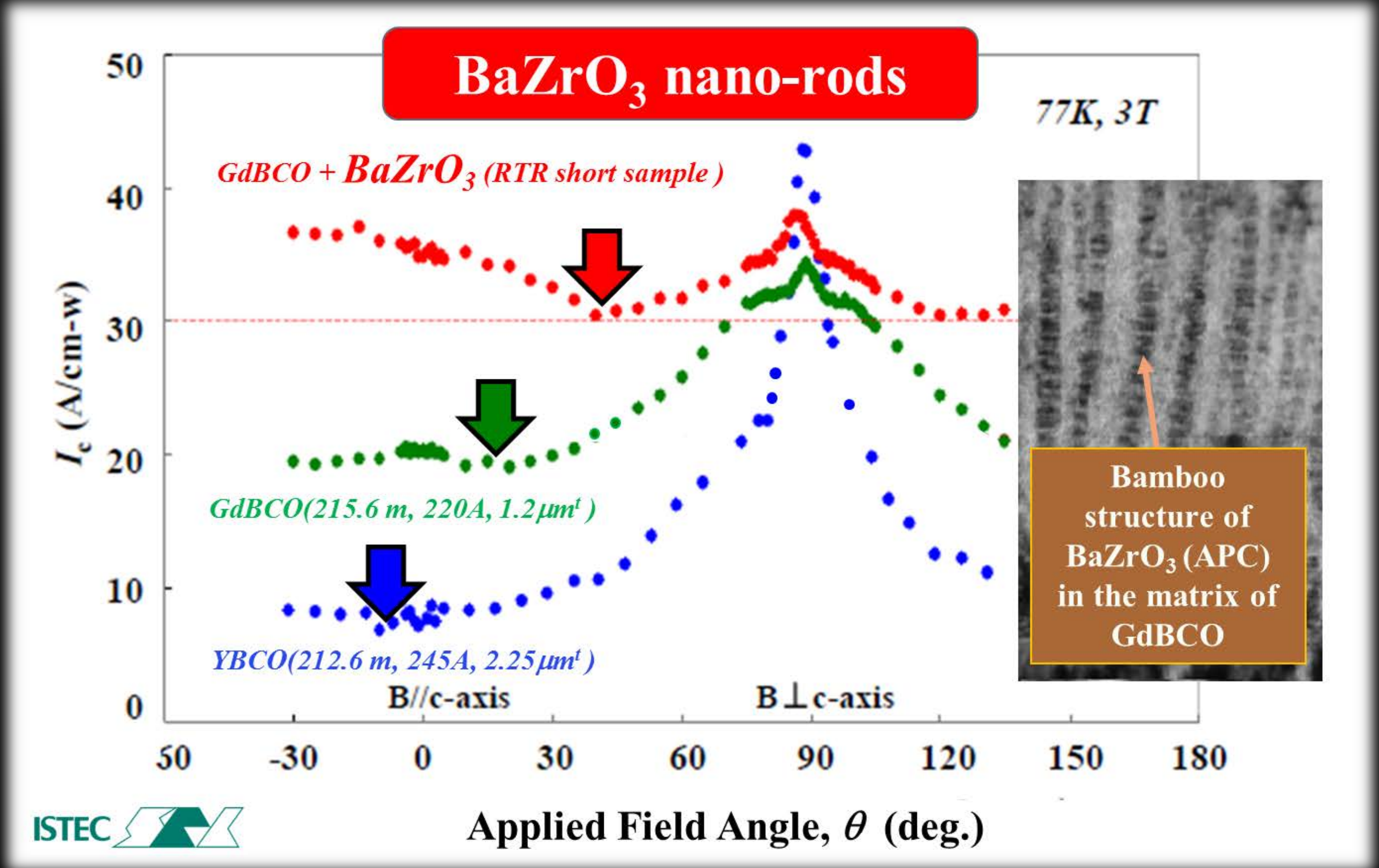
IBAD –MgO etc.

Untextured Metal Hastelloy™

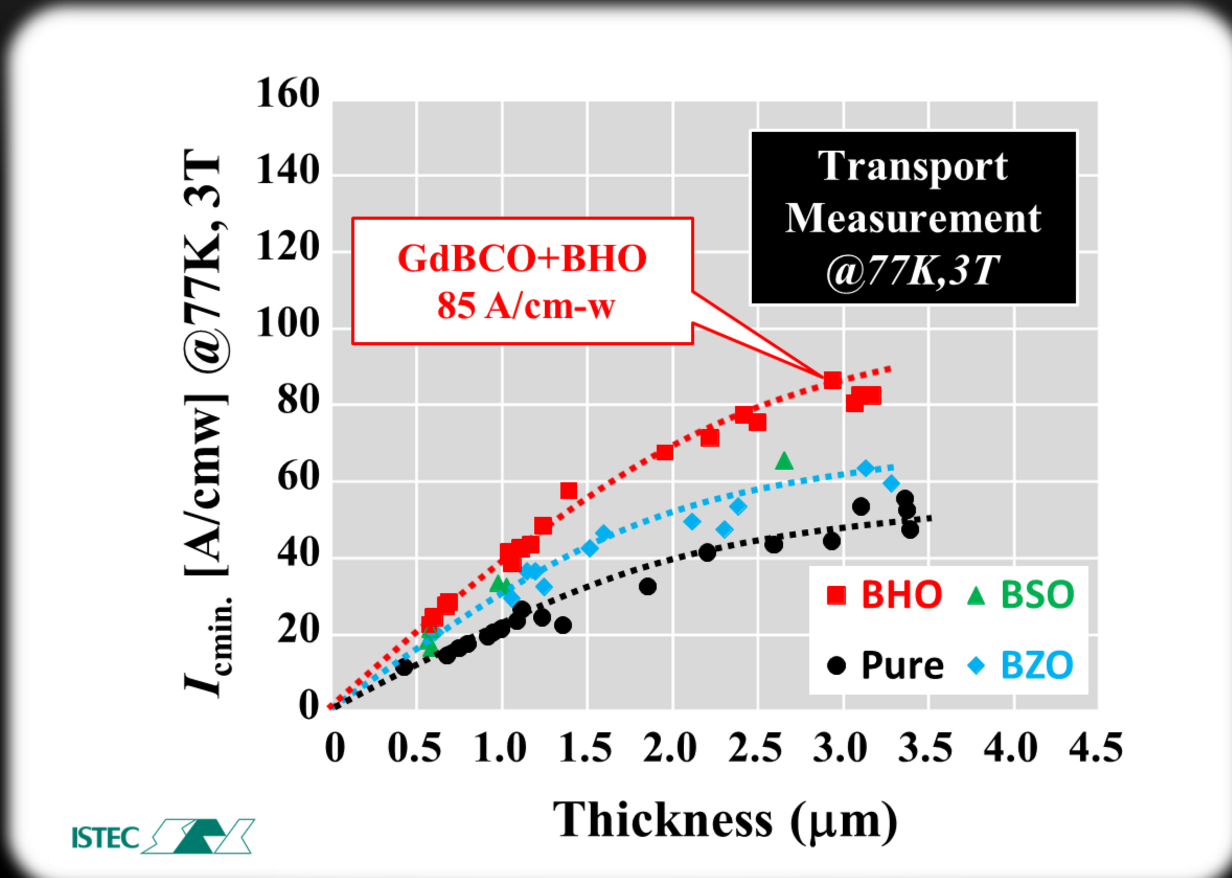


Early Stage of APC Introduction

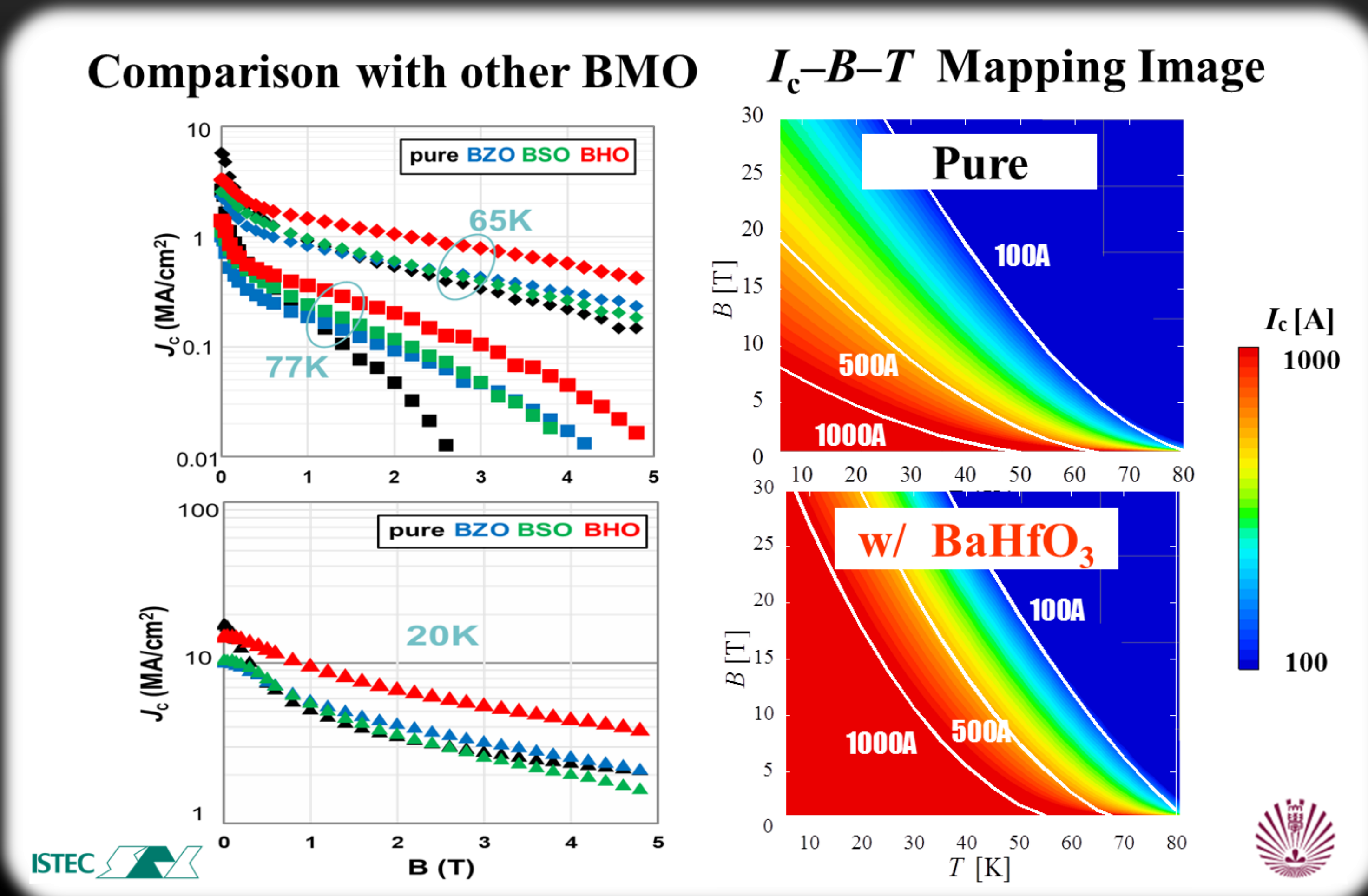
(APC : Artificial Pinning Center)



Effective APC Materials for IBAD-PLD C.C.



I_c-B-T in BHO doped IBAD-PLD GdBCO C.C.



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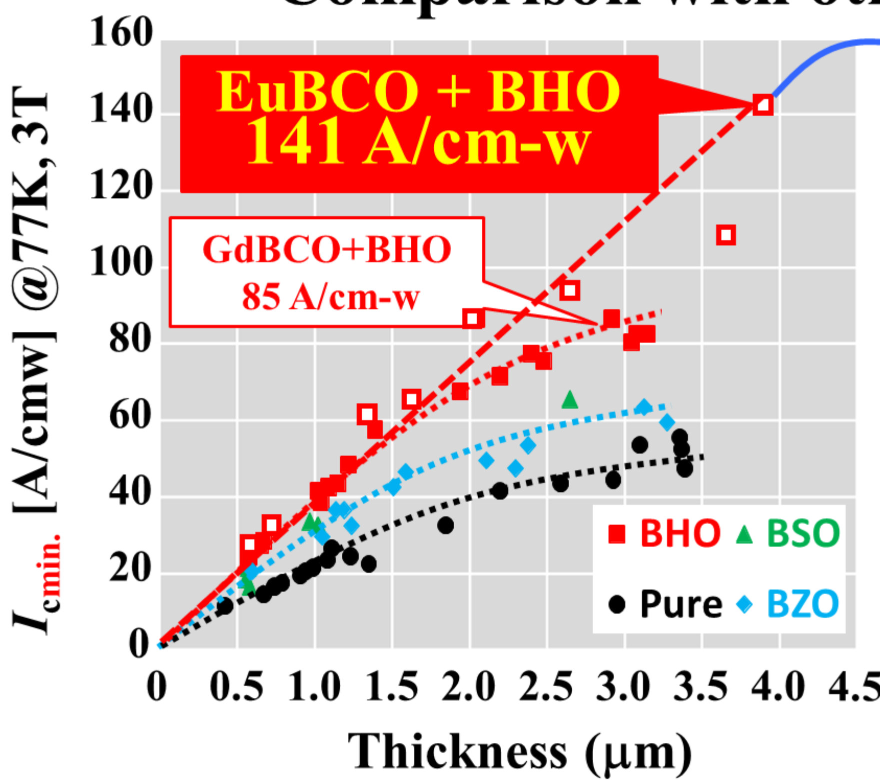
Features of EuBCO + BHO @ ISTEC

Comparison with other BMO



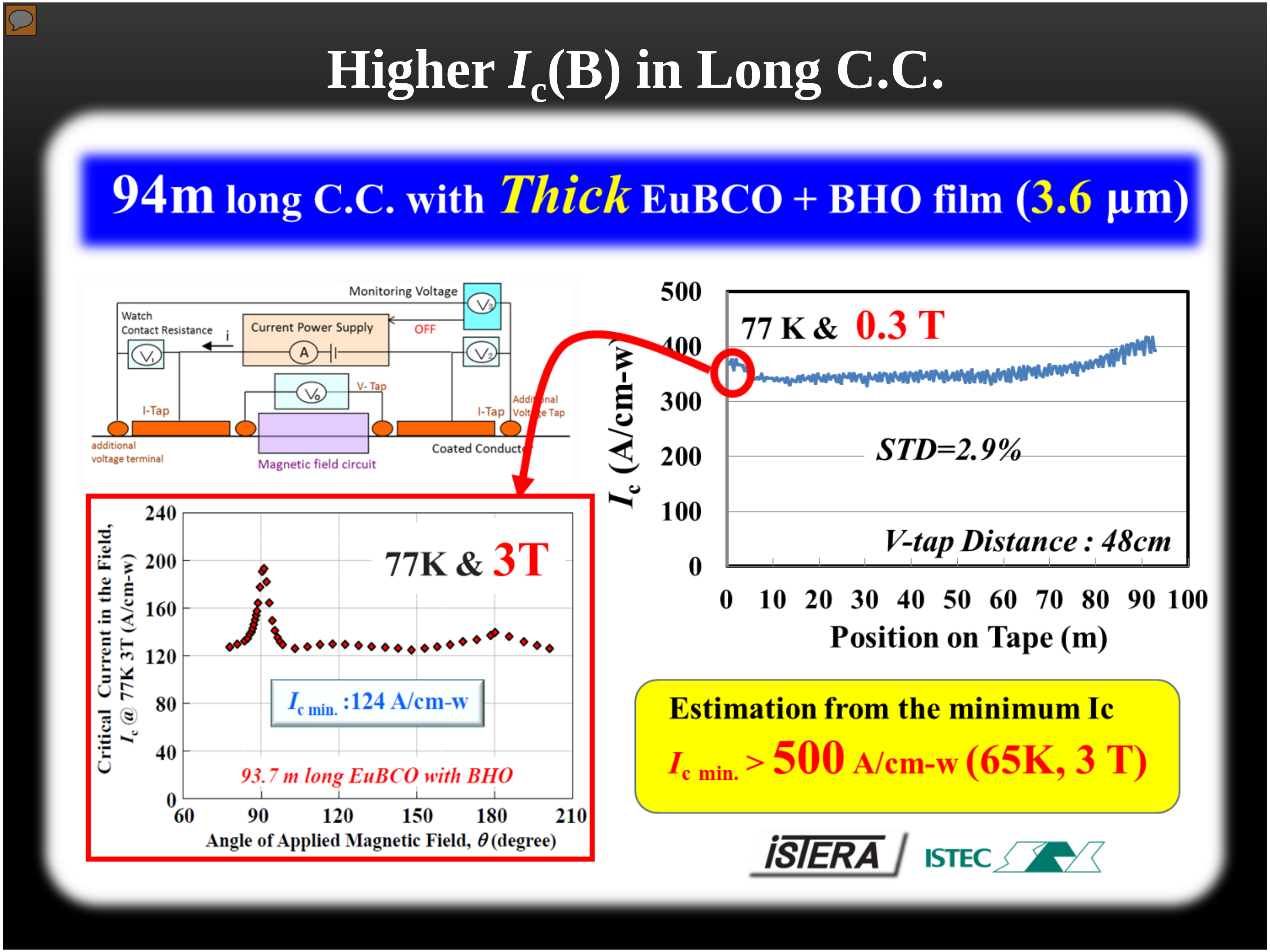
Estimated $I_{cmin.}$ Values of EuBCO + BHO

	3 T	10 T
65 K	616	
50 K	1400	500
30 K	2730	1180
20 K		1630

(A/cm-width)

I_c values were estimated using "Lift Factors(B//c)" of GdBCO + BHO

ISTERA ISTEC

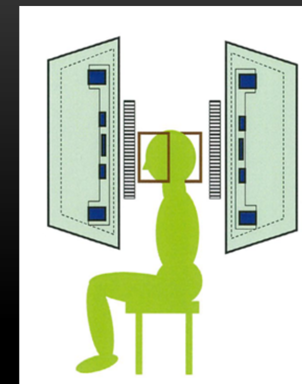

Higher I_c(B) in Long C.C.
94m long C.C. with Thick EuBCO + BHO film (3.6 µm)
Monitoring Voltage
Watch
Contact Resistance
Current Power Supply
OFF
V- Tap
I-Tap
I-Tap
Additional Voltage Tap
additional voltage terminal
Magnetic field circuit
Coated Conductor
77K & 3T
$I_{c\ min.}$:124 A/cm-w
93.7 m long EuBCO with BHO
Critical Current in the Field, I_c @ 77K 3T (A/cm-w)
Angle of Applied Magnetic Field, θ (degree)
77 K & 0.3 T
STD=2.9%
V-tap Distance : 48cm
I_c (A/cm-w)
Position on Tape (m)
Estimation from the minimum Ic
$I_{c\ min.}$ > 500 A/cm-w (65K, 3 T)
iSTERA
ISTEC

What can be expected in MRI ?

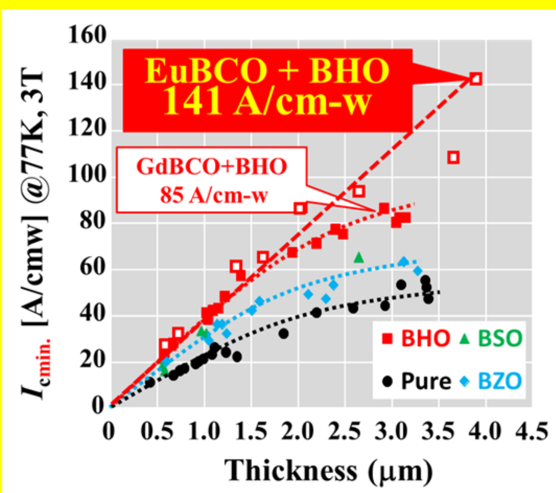
Conductor Specification for 3T-MRI
(from conceptual design of Prof. Fukuyama for BSCCO@20K,3T)

I_{op}=185A@**3.6T** Load=0.77 S=4.5x0.3mm²

$\Rightarrow I_c$ = 185/0.77x(10mm/4.5mm)= **534 A/cm-w**



Estimation of Operating Temperature



141 A/cmw@77K,3T

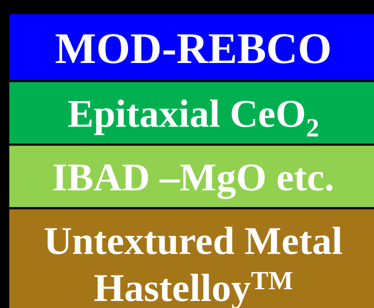
$\Rightarrow$ **527 A/cm-w**

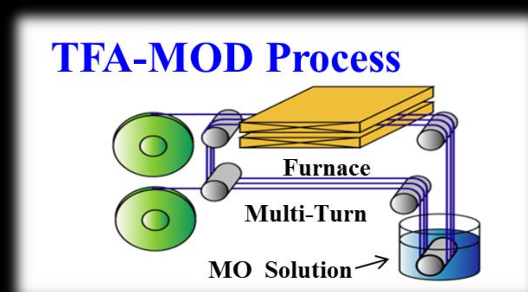
@65K,3.6T

Estimated using "Lift Factor(B//c)" of GdBCO + BHO

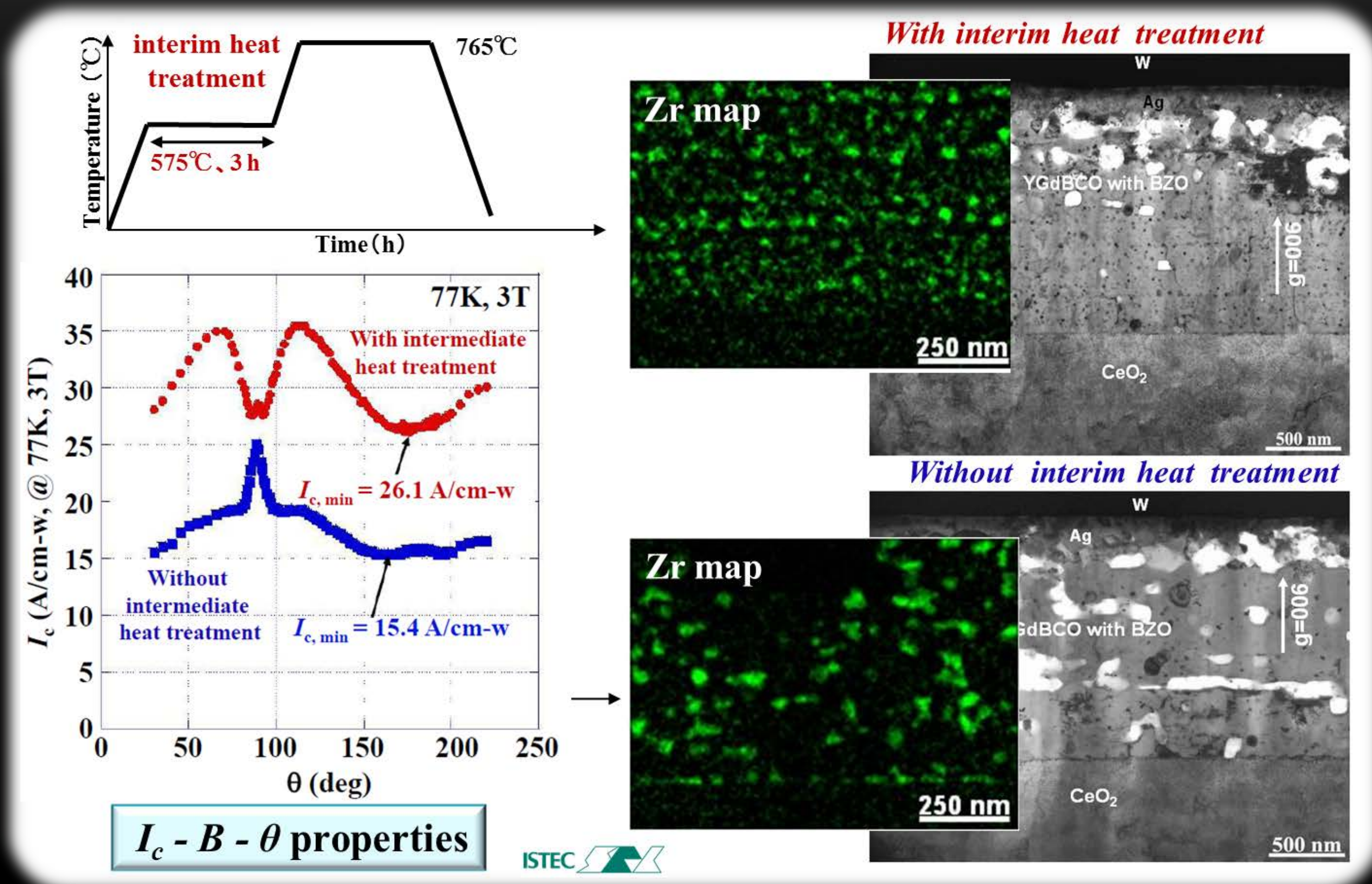
3T-MRI in Liq. N_2

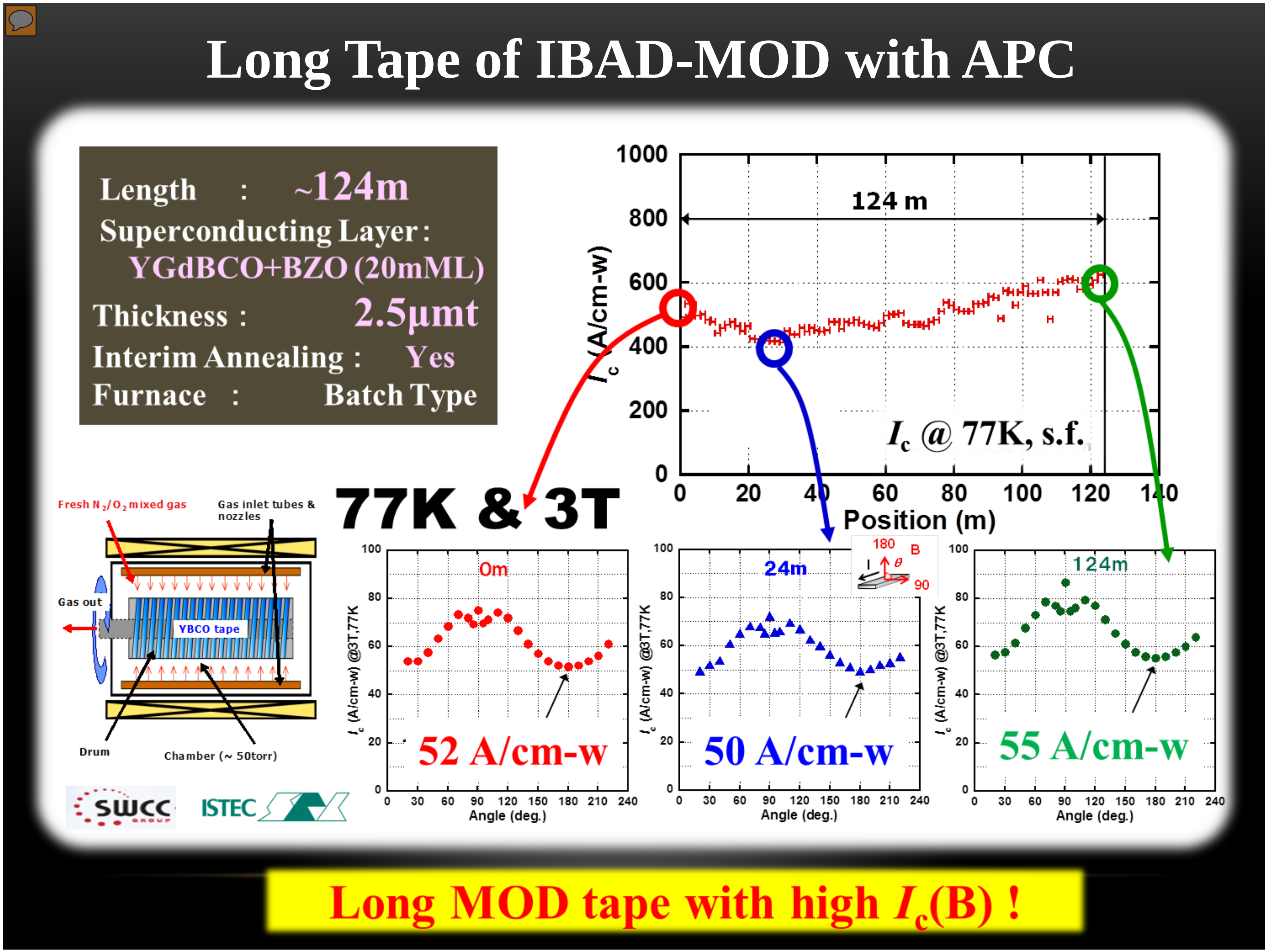
Improvement of In-field I_c in TFA-MOD C.C.



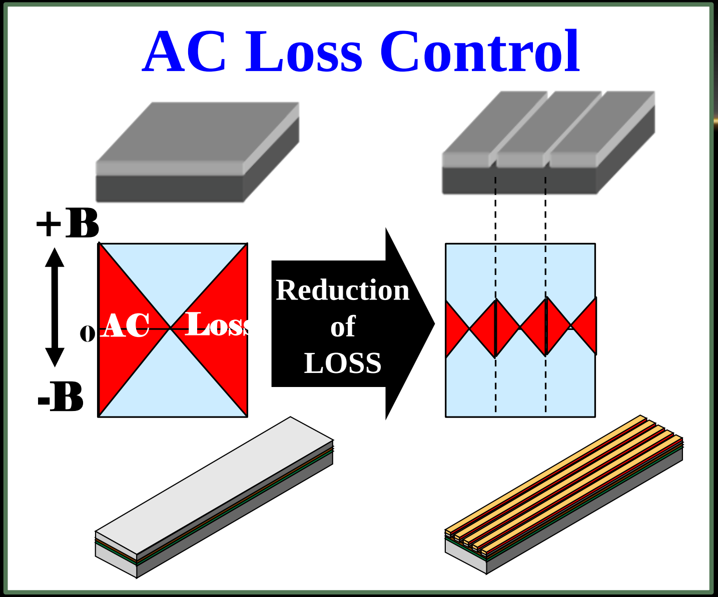


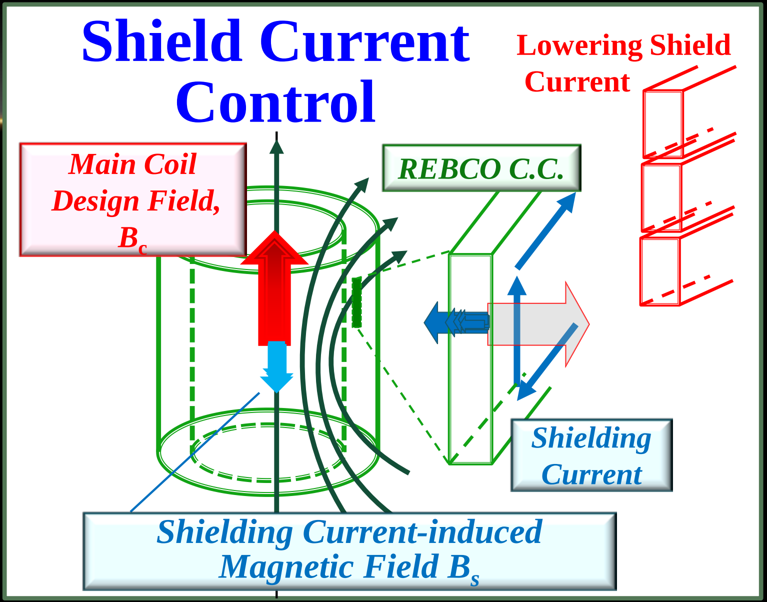
Interim Heat Treatment(IHT) in TFA-MOD for Finer BZO Particles

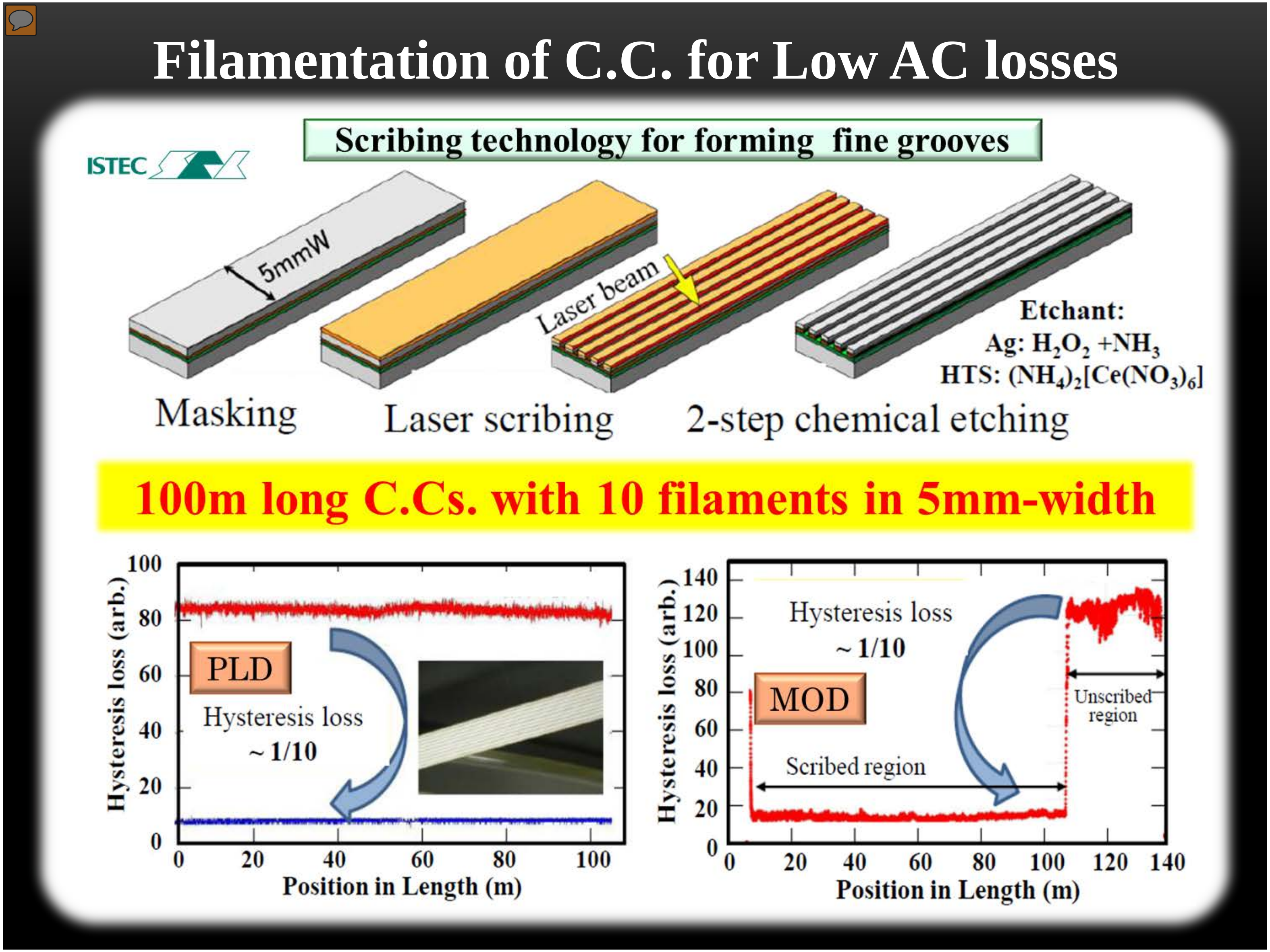



Long Tape of IBAD-MOD with APC
Length : ~124m
Superconducting Layer :
YGdBCO+BZO (20mML)
Thickness : 2.5μmt
Interim Annealing : Yes
Furnace : Batch Type
124 m
I_c (A/cm-w)
I_c @ 77K, s.f.
Position (m)
77K & 3T
Fresh N_2/O_2 mixed gas
Gas inlet tubes & nozzles
Gas out
YBCO tape
Drum
Chamber (~ 50torr)
SWCC GROUP
ISTEC
0m
52 A/cm-w
24m
50 A/cm-w
124m
55 A/cm-w
I_c (A/cm-w) @3T,77K
Angle (deg.)
180 B
I θ
90
Long MOD tape with high I_c(B) !

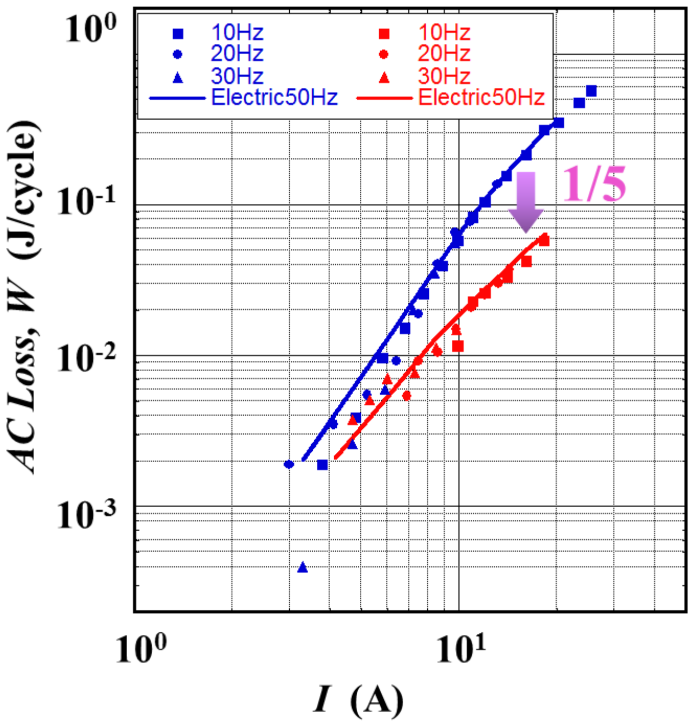
Lower AC Losses & Control of Magnetic Relaxation by Filamentation






Filamentation of C.C. for Low AC losses
Scribing technology for forming fine grooves
ISTEC
5mmW
Laser beam
Etchant:
Ag: H_2O_2 +NH_3
HTS: $(NH_4)_2[Ce(NO_3)_6]$
Masking
Laser scribing
2-step chemical etching
100m long C.Cs. with 10 filaments in 5mm-width
Hysteresis loss (arb.)
PLD
Hysteresis loss
~ 1/10
Position in Length (m)
MOD
Hysteresis loss
~ 1/10
Unscribed region
Scribed region
Position in Length (m)

Reduction of Hysteresis Loss in Solenoid Coil

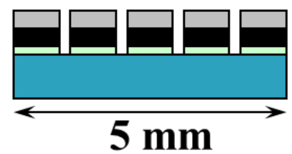


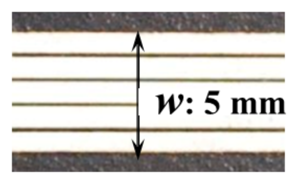
$$W = \frac{\alpha}{\gamma} B_m{}^{\gamma} \frac{w}{n}$$

$$J_c = \alpha B^{\gamma - 1}$$

B_m : Magnetic Flux Amplitude

$n = 5$



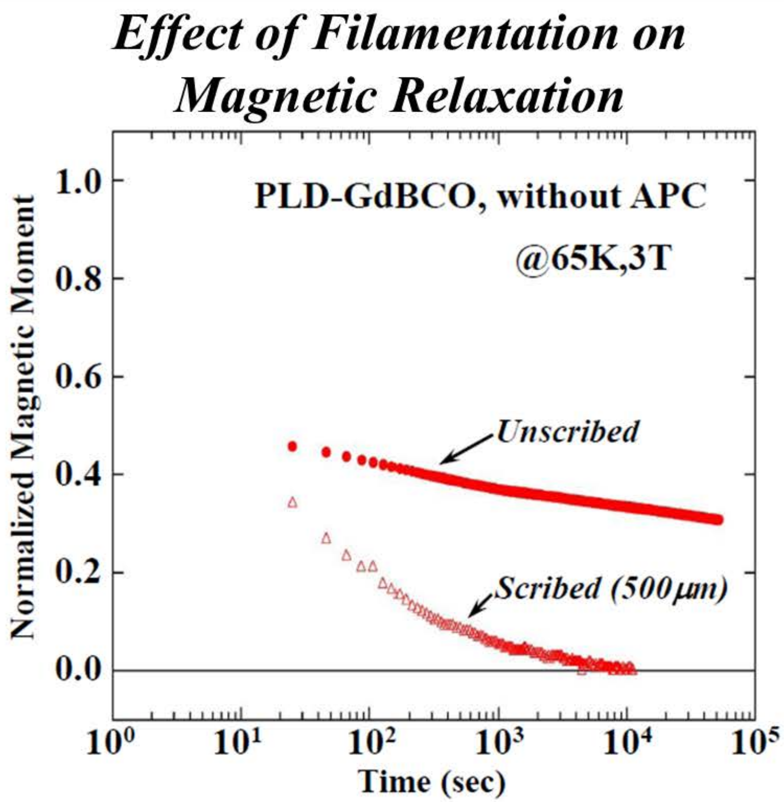


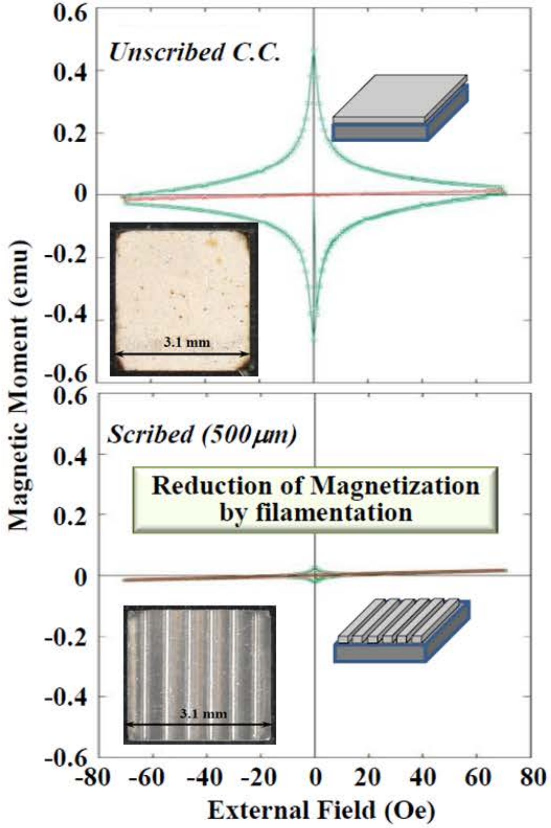
70 m long tape

AC-loss reduction even in “Coil Shape”

ISTEC KYUSHU Univ.

Control of Shielding Current for DC Coils @ ISTEC & Kyushu Univ.





3. FUTURE PROSPECTS

< Near Future >

- ***Lowering Cost***
- ***Higher Performances***

< Challenging Tasks >

- ***"ISOTROPIC C.C."***
- ***"Superconducting Joint" etc.***

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Plenary presentation PL3 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
Not submitted to IEEE Trans. Appl. Supercond.

Lowering Cost

Cost of C.C. (¥/Am)

Production Rate ⇗

$$\frac{\text{Process Cost (Equipment \& Materials)} + \text{Other Cost (Factory, Labor \& Indirect)}}{\text{Critical Current (A)} \times \text{Yield}}$$

J_c & Thickness ⇗

Elimination of Serious Defects

For Lower Cost→

- Reducing # of Buffer Layer
- Higher Ic @ operating T & B
- Higher Yield (Yield)
- Joint and/or Repair
- Volume of Order

et al.

Development of 3rd Generation Wires

"Present R&D for Applications"

▼

Confirmation for

" REALIZATION OF C.C. APPLICATIONS "

Enough for "Absolute Superiority" ? *NO!*

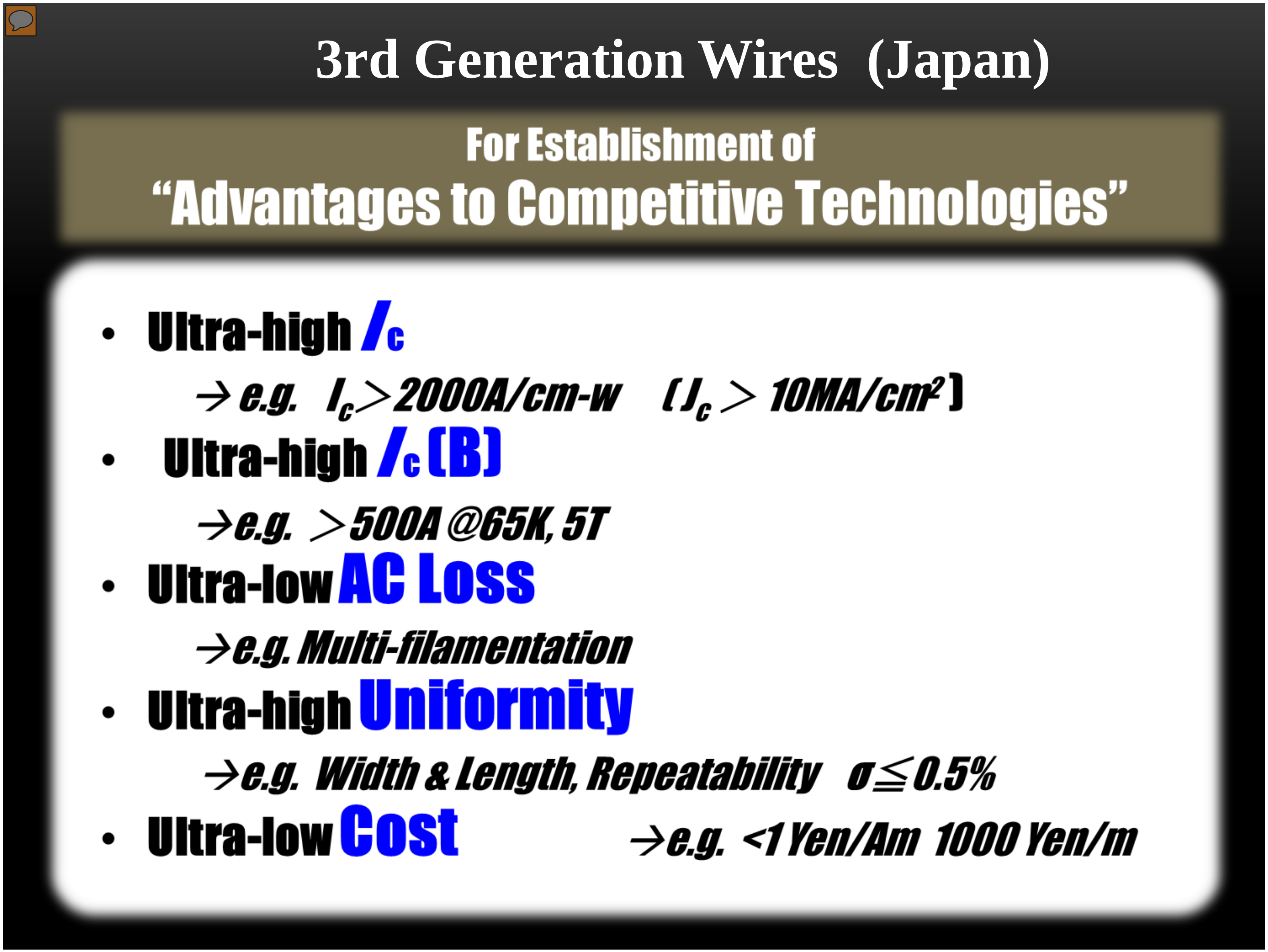
Establishment of

"Advantages to Competitive Technologies"

▼

" Third Generation Tapes"

Ultra-high Specifications beyond Present Forecast

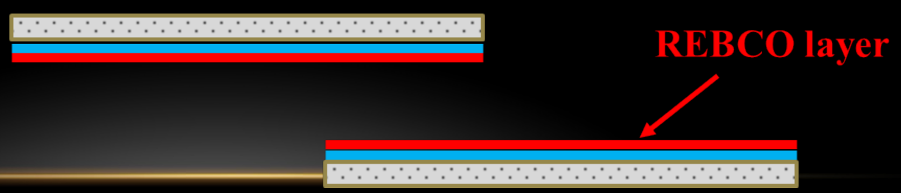

3rd Generation Wires (Japan)
For Establishment of
"Advantages to Competitive Technologies"
• Ultra-high I_c
→ e.g. I_c > 2000A/cm-w (J_c > 10MA/cm²)
• Ultra-high I_c(B)
→ e.g. > 500A @65K, 5T
• Ultra-low AC Loss
→ e.g. Multi-filamentation
• Ultra-high Uniformity
→ e.g. Width & Length, Repeatability σ ≦ 0.5%
• Ultra-low Cost
→ e.g. <1 Yen/Am 1000 Yen/m

What are the future tasks for C.C.?

1) “Round Wire” with
“Isotropic I_c-B-θ” for
“Complicate Shape of coil”.

→ “Mechanically & Electro - magnetically Isotropic C.C.”

2) Superconducting Joint by “Easy Process”.



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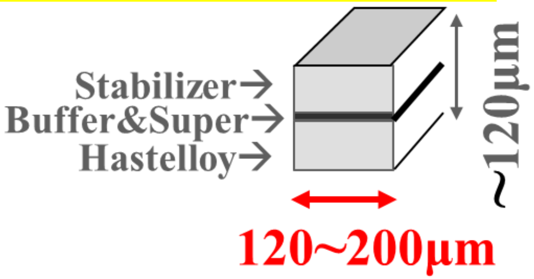
Isotropic Coated Conductors

(Mechanical & Electromagnetic Properties)

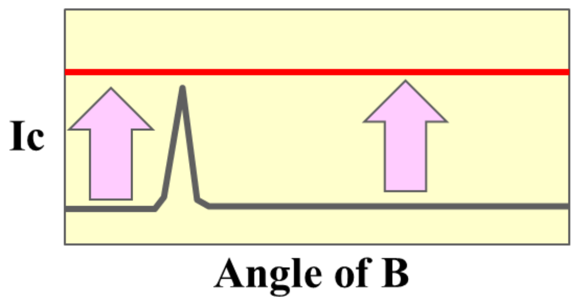
Control of Mechanical Properties

Low Aspect Ratio C.C.



- Higher I_c Uniformity
  +
- Precise Cutting & Scribing Techniques
  +
- Protection

Control of Electromagnetic Properties



- Precise Control of APC based on X'tal Growth
  ↓
- Isotropic Behavior at Temp. & B


Superconducting World !
He needs " Two Legs " to reach
" Superconducting World "!
MR. HTS
Application
Material (Tape)

End

Thank you for your attention!

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