CCA2016
Coated Conductors for Applications 2016
September 11-14, 2016, Aspen, Colorado, USA

Recent progress on SuNAM's coated conductor development; performance, price & utilizing ways

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2016. 09. 13.

CCA 2016, Aspen, Colorado, US.

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Superconductor, Nano & Advanced Materials

Contents

- SuNAM's coated conductor; architecture, characteristic.
  - Quality control tools for uniformity and yield
- Higher Je : Thicker S.C. layer → 1.6 μm, >1,000 A/12 mm.
- MCI(Metal Clad Insulation) 2G wire for high field magnet.
  - Solution for charging time delay problem in NI(No-Insulation) coil.
- Higher Je : metal substrate removal process.
- Summary

SuNAM's Coated Conductor

High Temperature Superconductivity Market Readiness Review

Office of Electricity Delivery and Energy Reliability

Investigation of the status of HTS technology, the requirements of key applications and barriers to future success

Peer Review Presentation
July 25, 2006

Navigant Consulting, Inc.

HTS Technology Platforms » Wire Requirements

Wire performance and price requirements vary by application, and will drive the timing of market entry.

Industry Consensus Wire Performance Requirements for Various Utility Device Applications

Application	J_c (Acm^{-2})	Field (T)	Temp. (K)	I_c (A)	Wire Length (m)*	Strain (%)	Bend Radius (m)	Cost ($/kA- m)*
Power Cable (transmission)	>10^5	0.15	67-77	200 A, 77 K, sf	>500	0.4	2 (cable)	10-50
Synchronous Condenser	10^5‡	2-3‡	30-77‡	100-500‡	>1,000‡	0.2‡	0.1‡	30-70‡
Fault Current Limiter	10^4-10^5	0.1-3	70-77	300‡	>1,000	0.2	0.1	30-70‡
Large Industrial Motor (1,000 hp)	10^5	4-5	30-77	100-500	>1,000	0.2-0.3	0.1	10-25‡
Utility Generator	J_e >10^4	2-3	50-65	125 at T_{op} , 3 T	>1,000	0.4-0.5	0.1	5-10
Transformer	J_c >10^6 J_e >12,500	0.15	70-77	>100 @ 0.15 T	>1,000	0.3	0.05	10-25‡

Original Data R. Blaugher, et. al., Updated by Gouge, Ashworth – January, 2006,
*Wire mfg, some equipment mfg indicate shorter length is adequate for early applications
‡ Based on NCI assessment
*Cost target for a commercial market to develop. Target cost of wire is likely to be higher today due to rising price of copp

NAVIGANT CONSULTING

HTS Peer Presentation Document – July 25, 2006

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Once a marginal level of performance is achieved by HTS wire, demonstration devices can be built, but the cost-performance ratio must be reduced for market entry and commercialization.

Technology Attributes	Near-Term Goals (present – 2007)	Mid-Term Goals (2008 – 2011)	Long-Term Goals (2012 – 2016)
Critical current	250 A/cm, 77 K, sf 125 A/cm, 65 K, 2 T	500 A/cm, 77 K, sf 250 A/cm, 65 K, 2 T	1000 A/cm, 77 K, sf 500 A/cm, 65 K, 2 T
Cost/Performance Ratio	$400/kA-m, 77 K, sf $800/kA-m, 65 K, 2 T	$50/kA-m, 77 K, sf $100/kA-m, 65 K, 2 T	$10/kA-m, 77 K, sf $20/kA-m, 65 K, 2 T
Wire Length	100 m	1000 m	>1000 m
AC Losses	1 – 2 W/m	0.5 – 1.0 W/m	< 0.50 W/m

Source: NCI Analysis, Southwire, DOE.

The Utility/Energy market may be largest long-term opportunity, but will require HTS sales from other segments to drive improvements in the cost-performance ratio before 2020.

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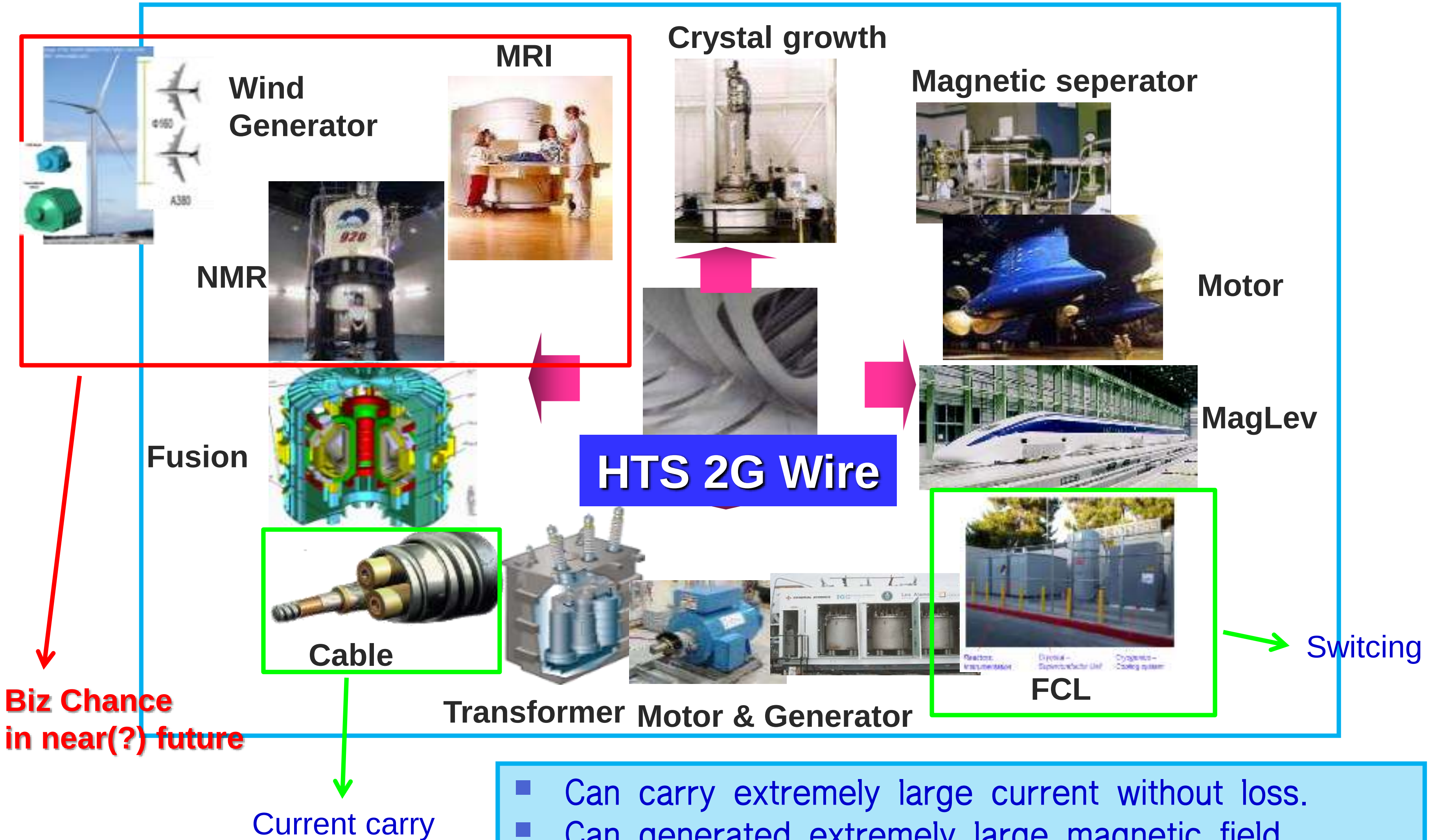
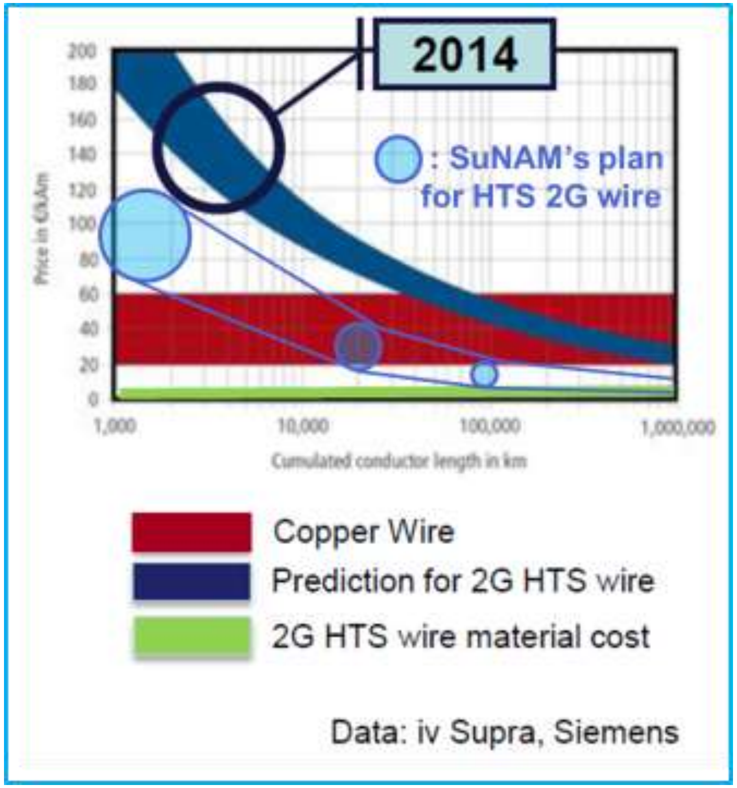
Applications of Superconductivity



- Can carry extremely large current without loss.
- Can generated extremely large magnetic field.
- High energy efficiency with compact volume & mass.

How can we realize practical HTS 2G wire?



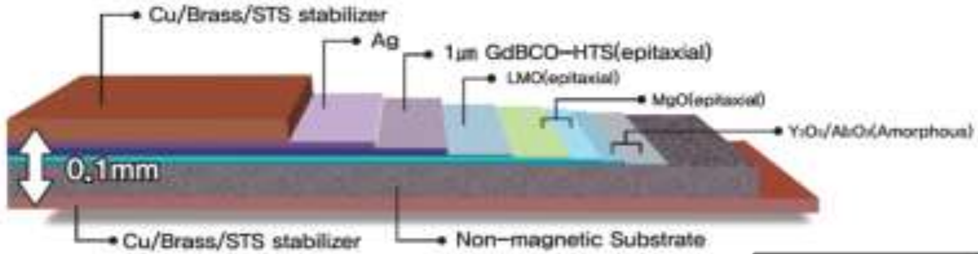
- **Throughput : growth rate & large deposition area**
- **Yield : process margin & (in-line) Quality Control**
- **Robustness : shelf life, stability (mechanical, thermal cycling, thermal expansion…)**
- **Customer friendly : joints, easy to use…**
- **In-line production, automation…**

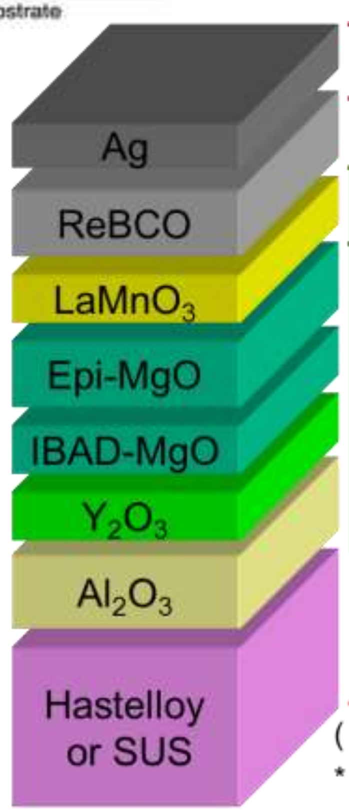
- **For reasonable size market creation,**
  → Target price ($/kA-m) : 50, 25, or less?
  → Availability : ~ 1,000 km/yr or /month or ??

➢ RCE DR : ~ 100 nm/sec or faster (SuNAM) → The highest throughput process

- **RCE-DR process : easy to scale-up to wide strip.**

Structure





Protecting layer Ag (0.6 μm)	DC sputter
Superconducting layer (~ 1.3 μm)	RCE-DR
Buffer layer ~20 nm	sputter
Homoepi-MgO layer ~ 20 nm IBAD-MgO layer ~ 10 nm Seed layer (Y_2O_3) ~ 7 nm Diffusion barrier (Al_2O_3) ~ 40 nm	IBAD (sputter & E-beam)
Hastelloy C276 (Ni-alloy tape) or Stainless Steel-tape	Electro -polishing

(+ Cu electroplating (+ lamination))

* Linear speed of each process : ~ > 120 m/hr (12 mm equivalent).

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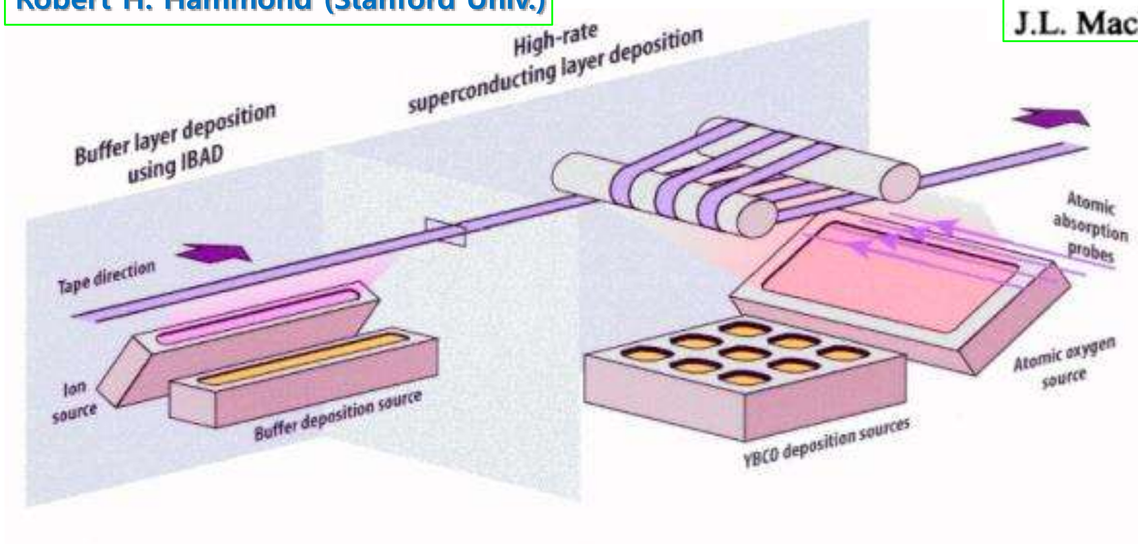
- Typical I_c ~ > 700A/12mmW at 77K Self-field (J_c ~ >5 MA/cm^2)

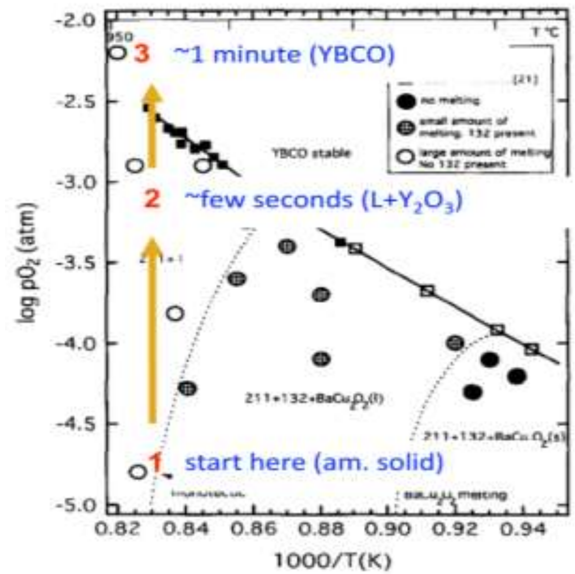
Scale up Issues: IBAD & *in-Situ* High Rate E-Beam

Robert H. Hammond (Stanford Univ.)



Physica C 241 (1995) 401–413

J.L. MacManus-Driscoll [a,*], J.C. Bravman [a], R.B. Beyers [b]



- New Ideas, Directions?
  - High rate, large area, high I_C and low cost of materials processes will eventually be required – not immediately but in 10 years.
  - High rate may require growth in liquid flux.

Cost Example

$C/P \Rightarrow \$ \text{ per year}/R(L\times W)J_c$

Study ISS' 95:

$$\begin{Bmatrix} R = 100\,\mathring{A}/\sec \\ L = 30cm \\ W = 1meter \\ J_c = 10^6\,A/cm^2 \end{Bmatrix} \rightarrow$$

C/P = $10 /kA-m
@ 6000 km/year

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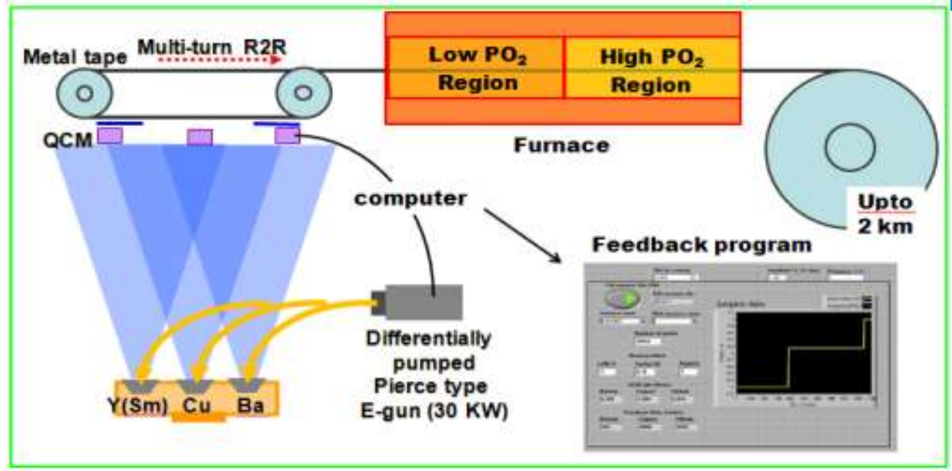
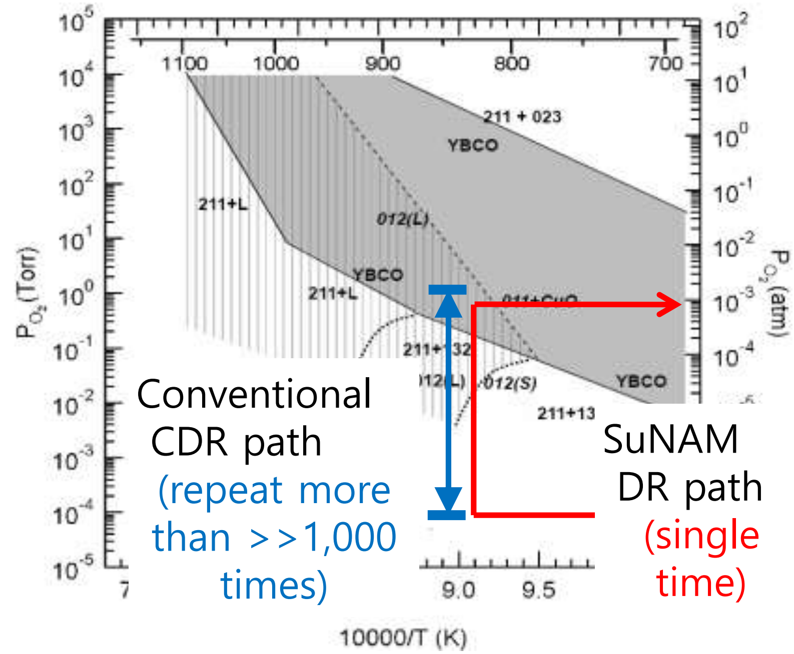
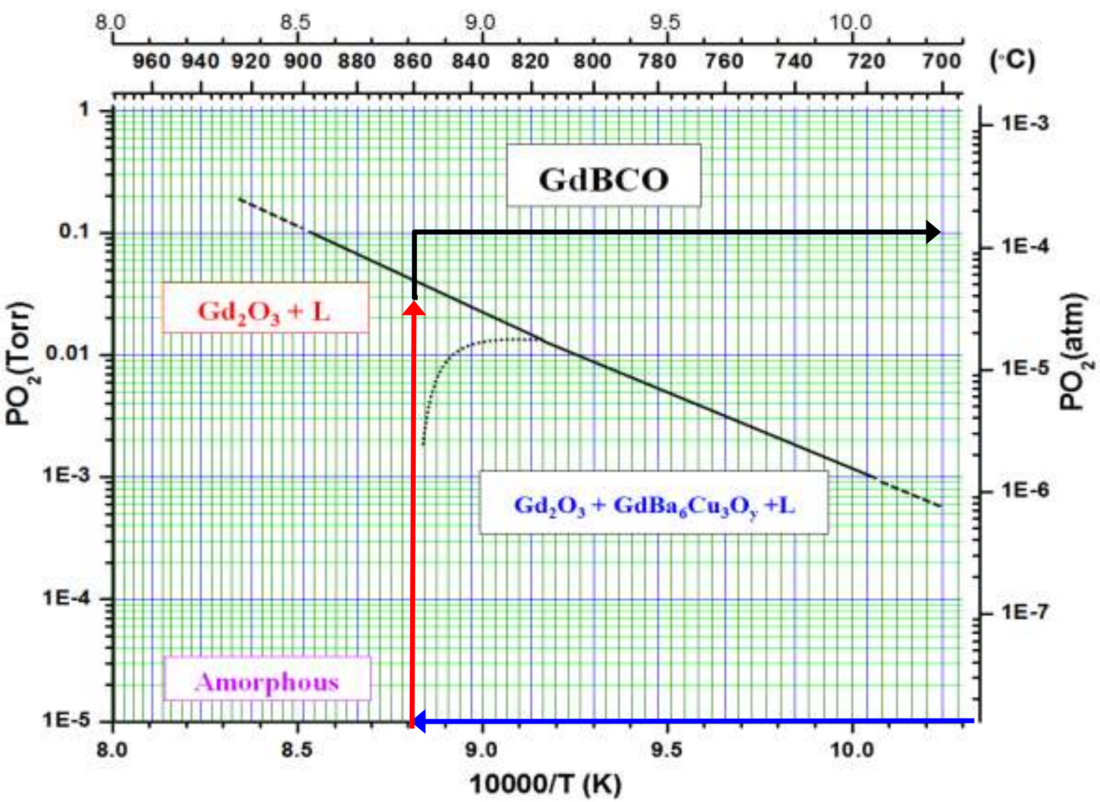
SuNAM RCE-DR process

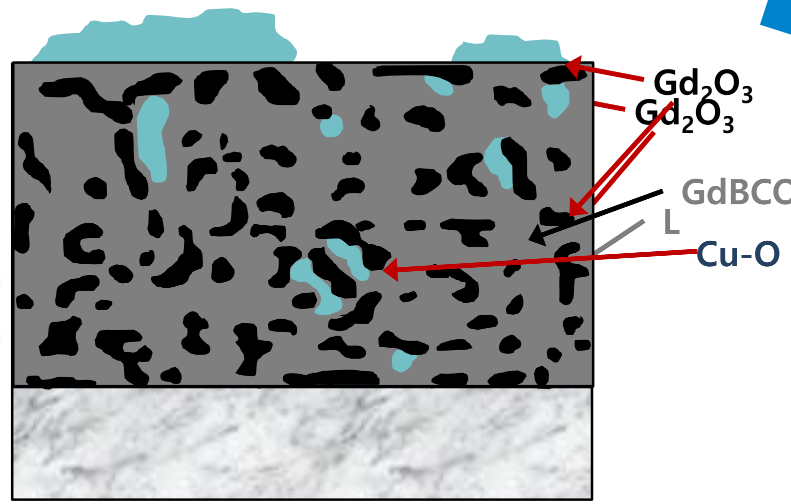
- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R)
- High rate co-evaporation at low temperature & pressure to the target thickness(> 1 μm) at once in deposition zone (6 ~ 10nm/s)
- Fast (<< 30 sec.) conversion from amorphous glassy phase to superconducting phase at high temperature and oxygen pressure in reaction zone
- Simple, higher deposition rate & area, low system cost
- Easy to scale up :single path

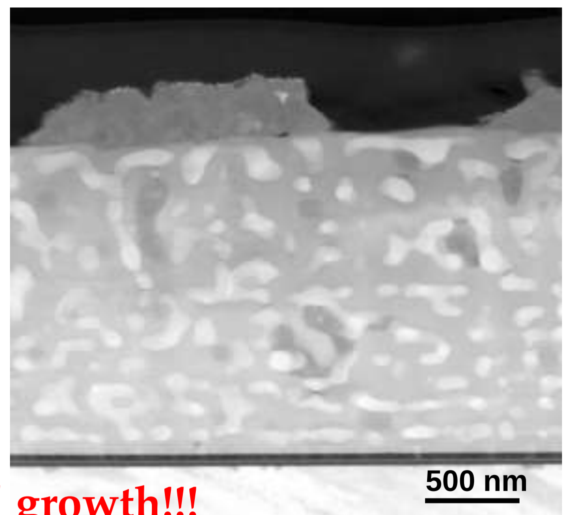




Growth mechanism of the GdBCO film by RCE-DR



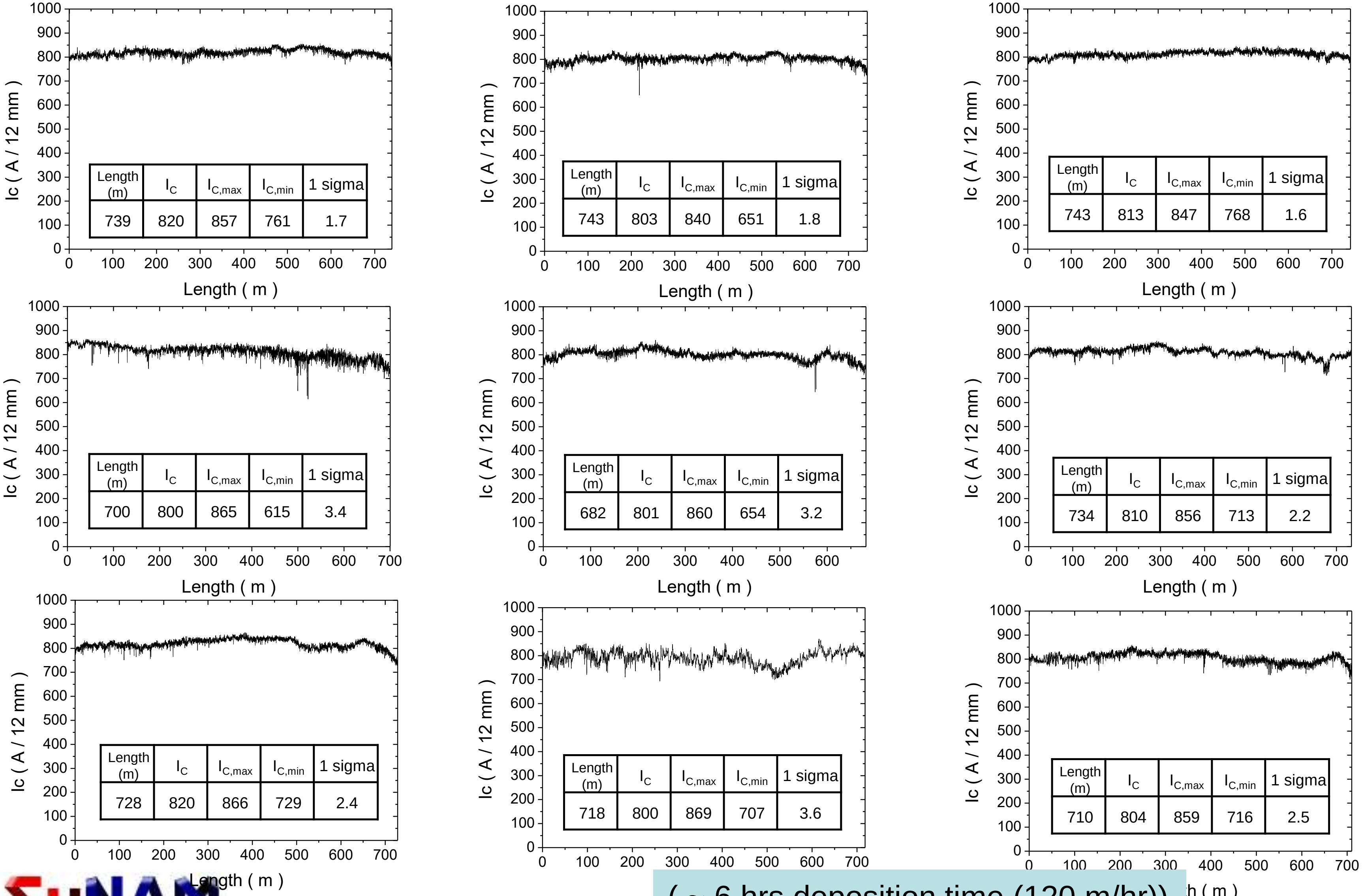




- Very low PO_2 zone (~ 10^{-5} Torr): **Amorphous Film**
- Lower PO_2 zone (~30 mTorr): **Gd_2O_3 + Liquid (< 5 sec)**
- Higher PO_2 zone (~100 mTorr): **GdBCO Film (< 20 sec)**

GdBCO growth mechanism: a seeded melt-textured growth!!!

Daily Production 2G wire performances



Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
739	820	857	761	1.7

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
743	803	840	651	1.8

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
743	813	847	768	1.6

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
700	800	865	615	3.4

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
682	801	860	654	3.2

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
734	810	856	713	2.2

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
728	820	866	729	2.4

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
718	800	869	707	3.6

Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
710	804	859	716	2.5

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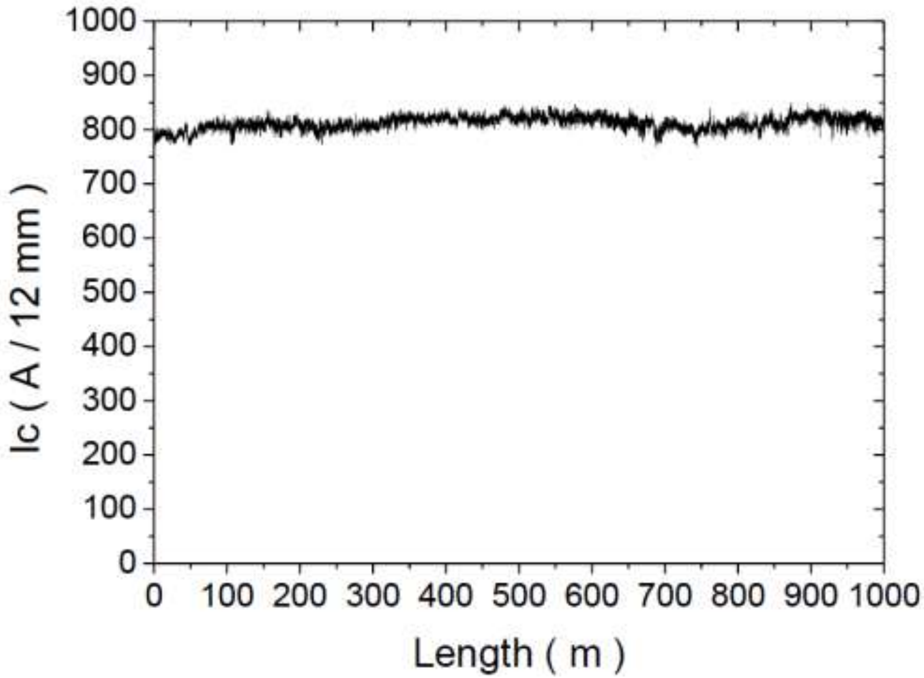
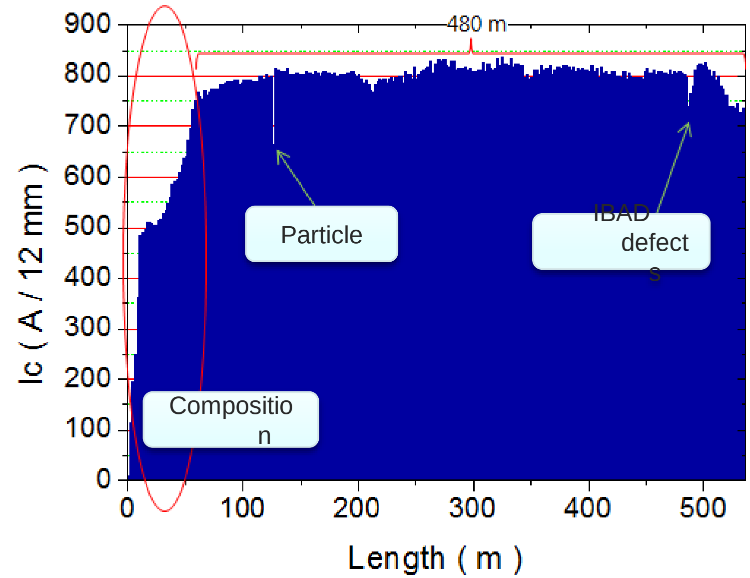
(~ 6 hrs deposition time (120 m/hr))

RCE-DR Results on Stainless Steel Substrate



- Min Ic (A/cm-width) x L (m) > 0.6 Million A-m
- Production speed of **120 m/hr (12 mm width)**

  (1 km for ~ 8 hrs)



Width (mm)	Length (m)	AVG.Ic (A)	1σ(A)	Min.Ic (A)	Max.Ic (A)	COV(%)	Ic x L (Am)
12	480	799	23	664	838	2.8	318,765
10		666	19	553	699		**265,638**

Width (mm)	Length (m)	AVG.Ic (A)	1σ(A)	Min.Ic (A)	Max.Ic (A)	COV(%)	Ic x L (Am)
12	534	768	110	8	838	14.3	4,474
10		640	91	7	699		3,728

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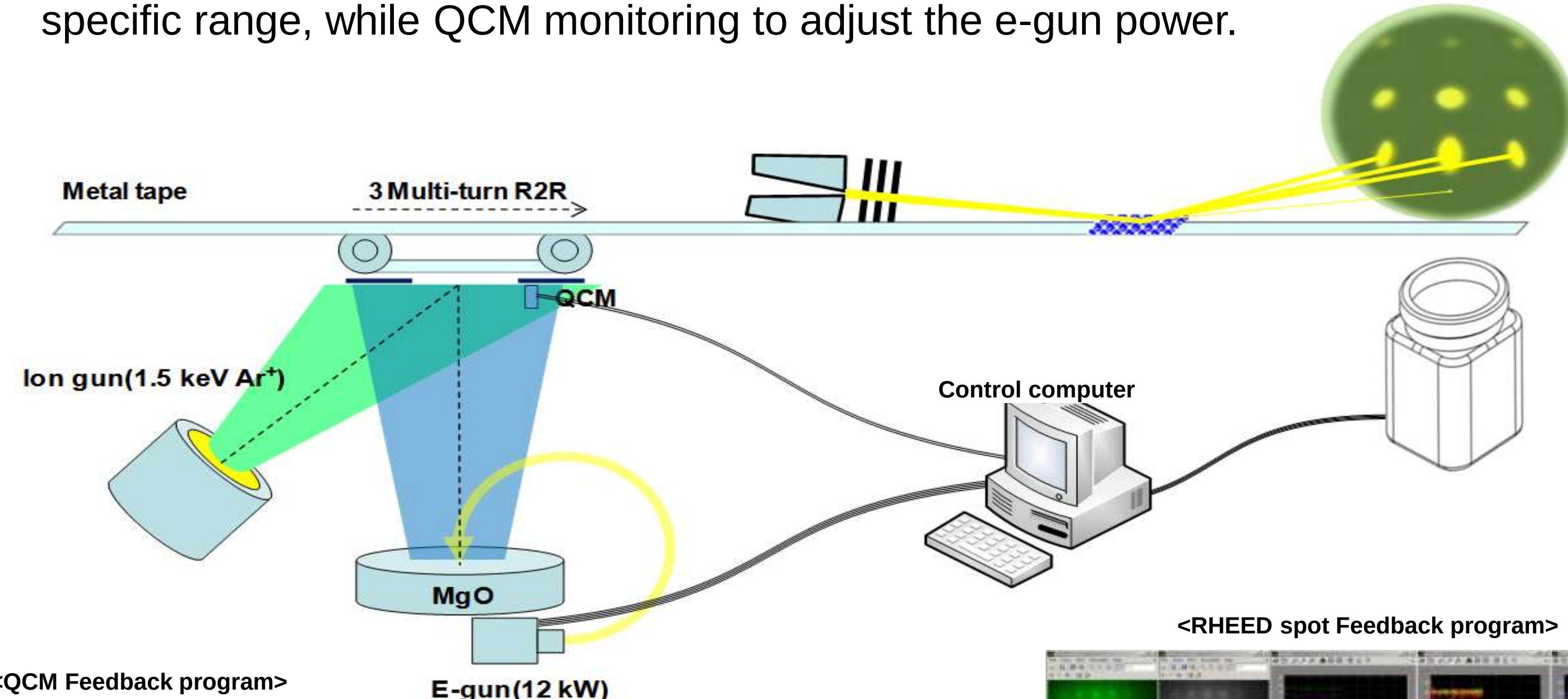
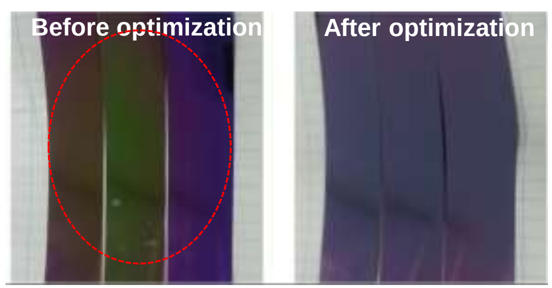
Quality Control : RHEED Vision System

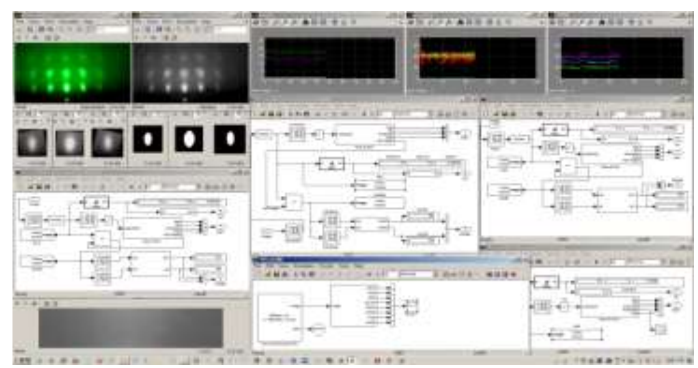
- An appropriate feedback algorithm can keep the shape of the RHEED spot in the specific range, while QCM monitoring to adjust the e-gun power.



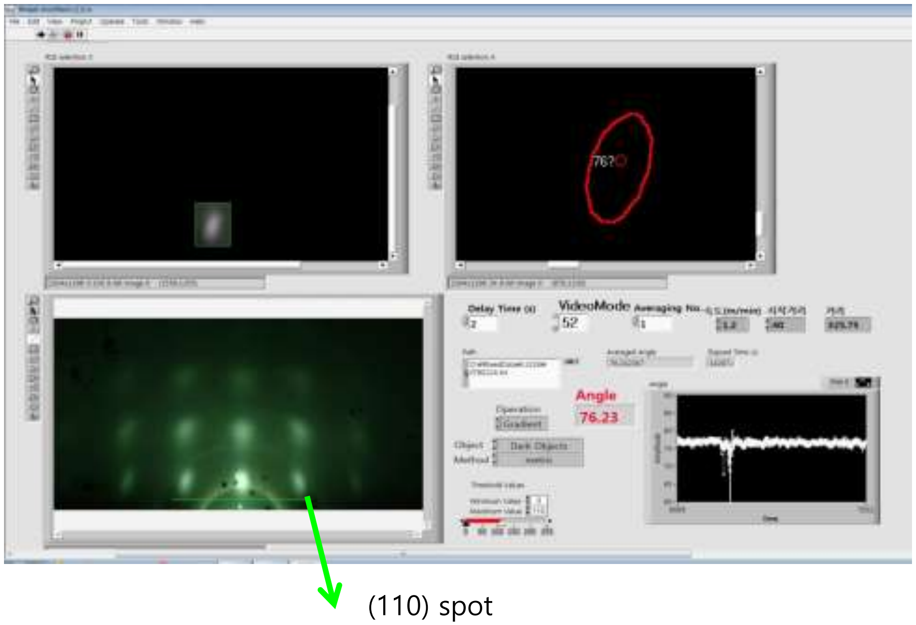
<QCM Feedback program>

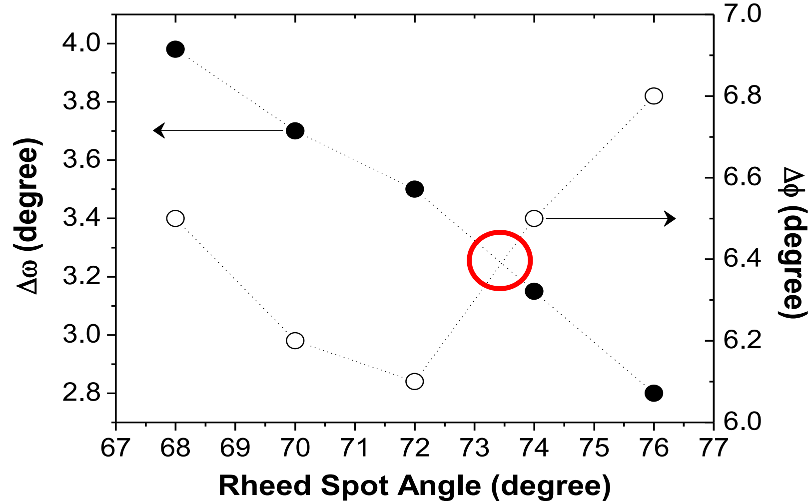


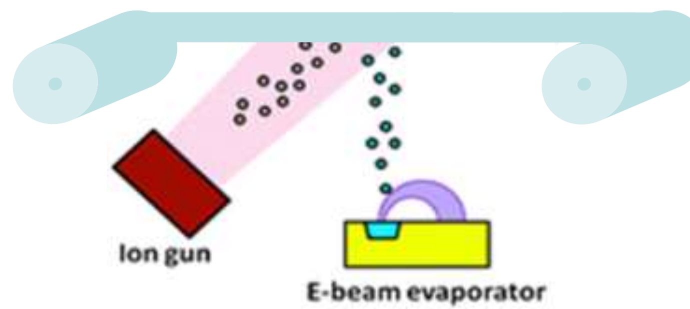
<RHEED spot Feedback program>



Feedback route based on RHEED spot analysis







- Because of different evolution of Δϕ & ΔωR, optimization is very important for high quality 2G wire.
- Intensity & tilt angle of MgO (110) spot is one of the most important parameter.

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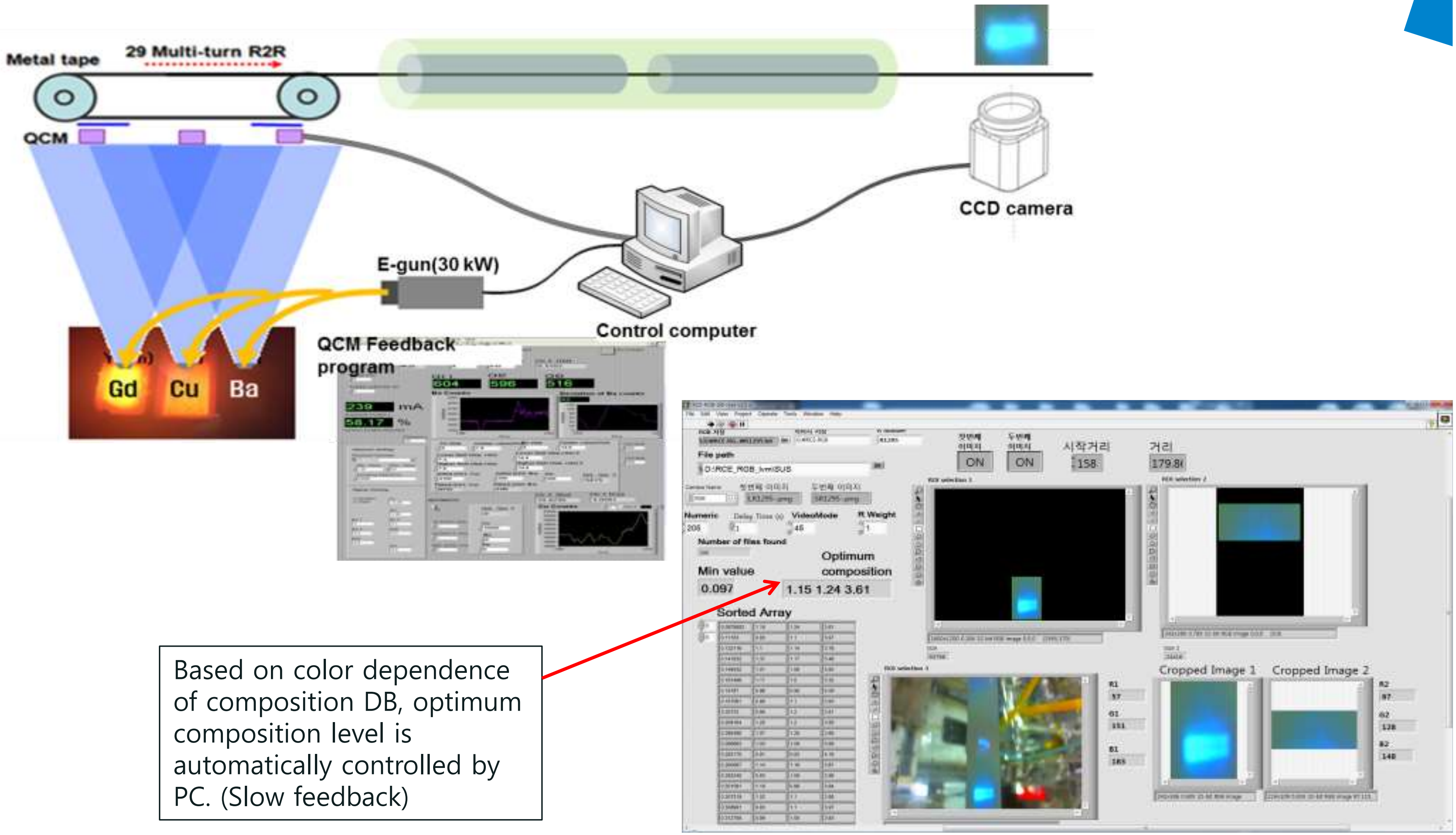
Quality Control : RCE Vision Inspection System



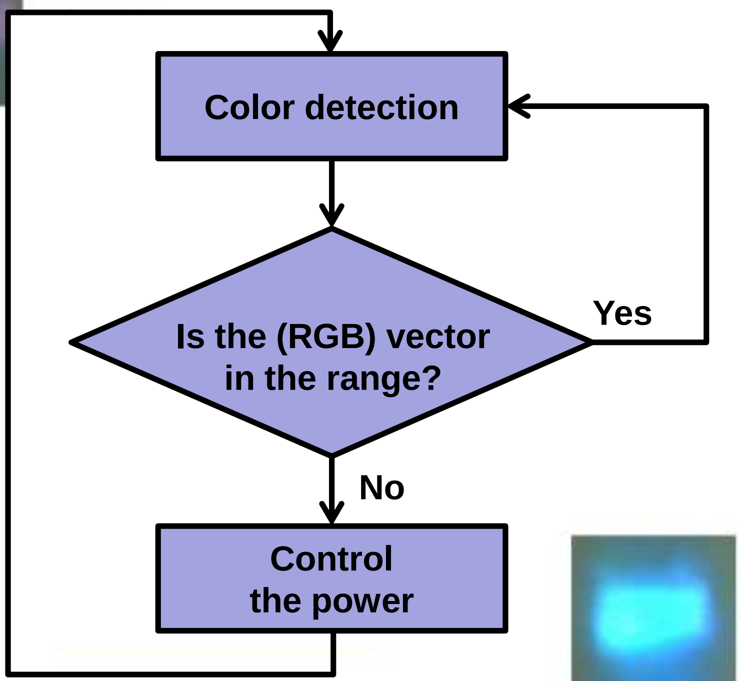
Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)

Quality Control : RCE Vision Inspection System

- RCE Vision System will be introduced for increasing the uniformity of composition in RCE-DR process. The control computer takes (RGB) values in three-dimensional vector space which is transformed from the color of the tape surface.

[Start]  [End]

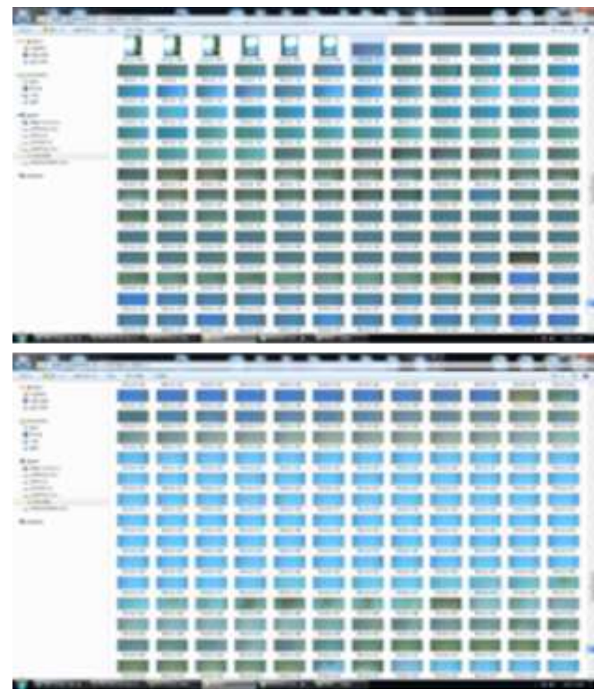
Start color



End color

(79,166,189)

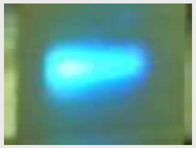
(Composition DB)

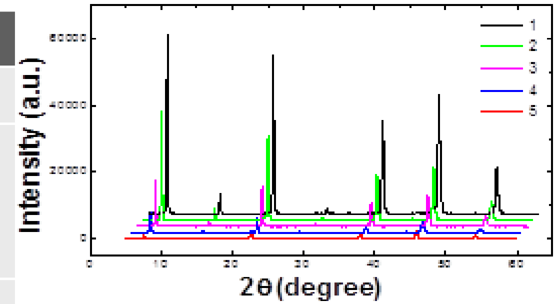


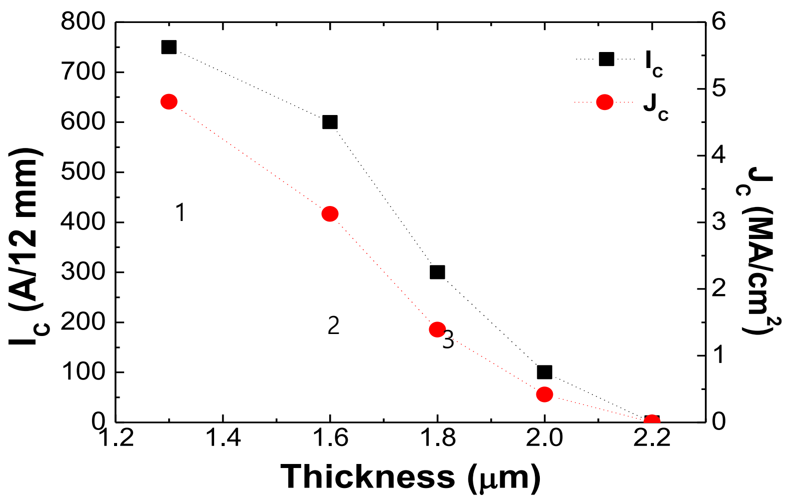
Higher Je : Thicker S.C. layer

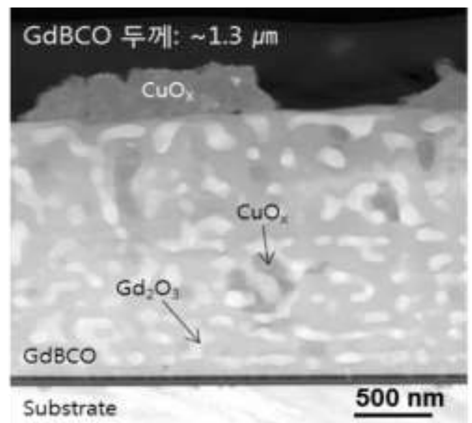
Normal RCE-DR process : before optimization

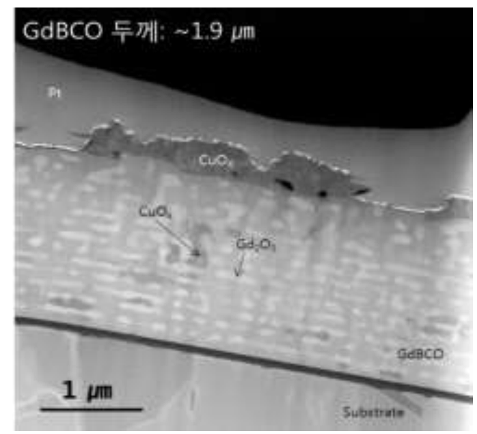
❖ Thickness dependence of Ic and surface color for GdBCO

	1	2	3	4	5
Thickness	1.3㎛	1.6㎛	1.8㎛	2.0㎛	2.2㎛
Surface color for GdBCO					
Ic	750A/12mm	600A/12mm	300A/12mm	100A/12mm	0A/12mm









As increasing the thickness, Jc and Ic are decreased.
All the samples were prepared by same process speed.

- TEM analysis

→ 1.3 ㎛-thickness:
Gd_2O_3 are randomly distributed
→ 1.9 ㎛-thickness:
Gd_2O_3 are distributed the boundary of the layers

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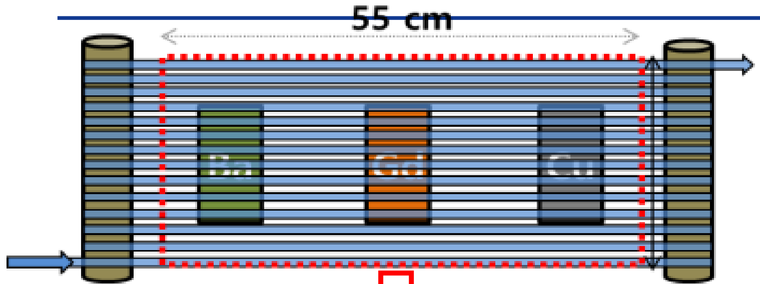
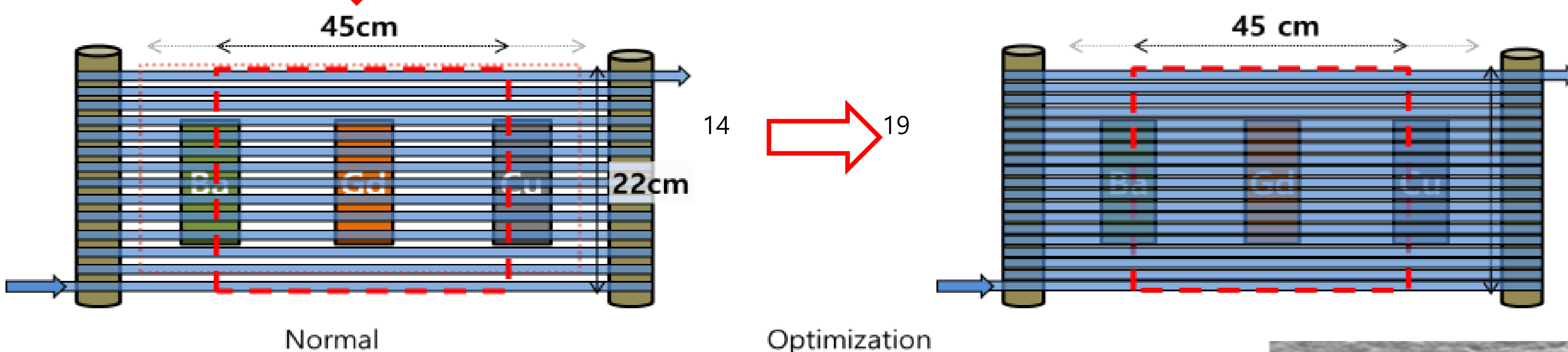
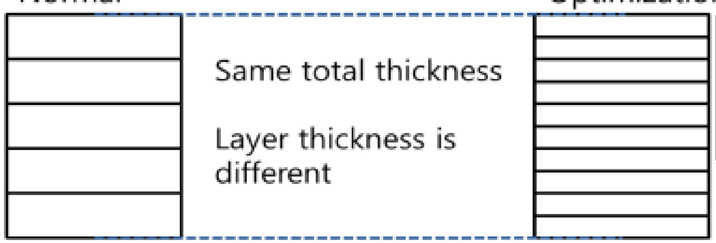
Optimization of deposition region for making thick GdBCO films



For uniformity,

1. Decrease deposition region from 55 cm to 45 cm.
2. Increase distance between source and substrate.
3. **Increasing turns of deposition region (14 turns → 19 turns)**

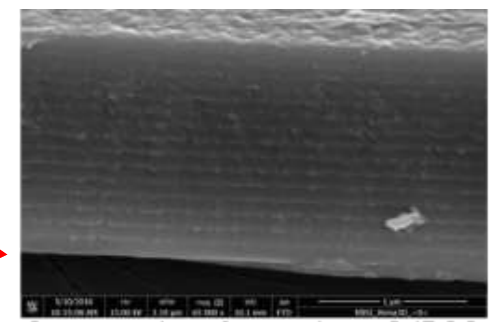




As increasing the thickness, Jc is decreased

As increasing the thickness, Jc is not decreased

All the samples were prepared by same process speed.



Cross section of amorphous GdBCO

1.6 μm-thick

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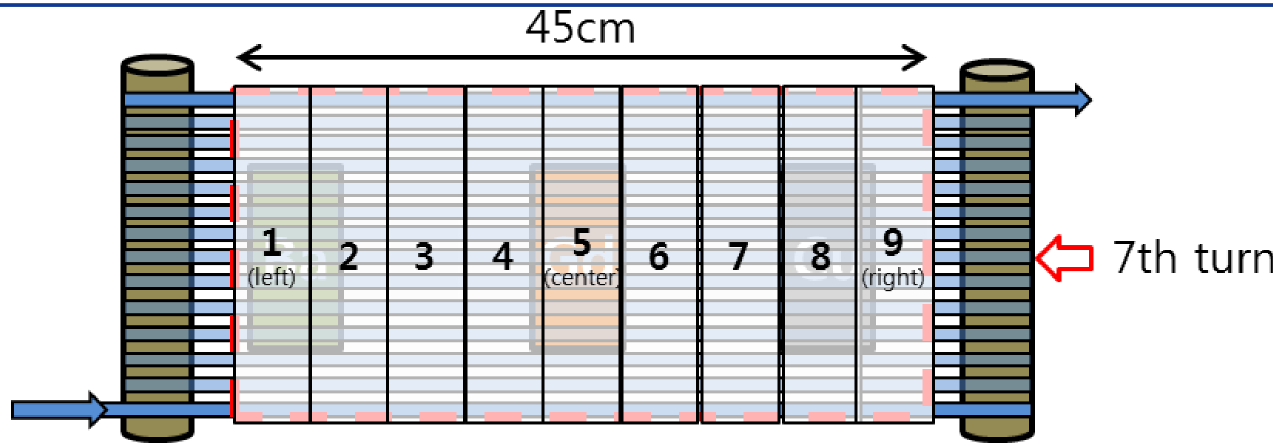
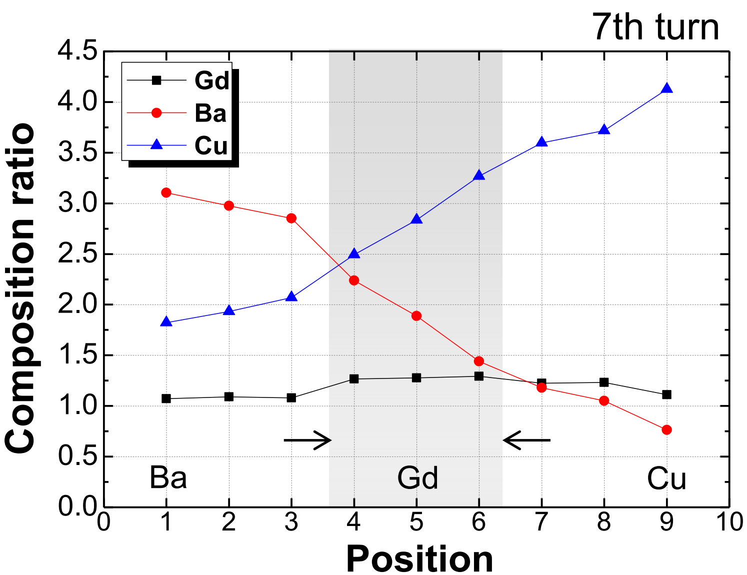
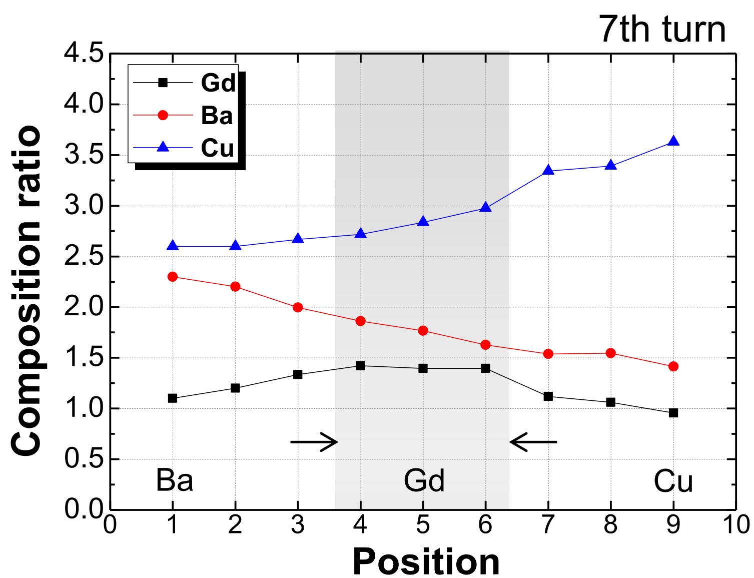
Optimization of Deposition region



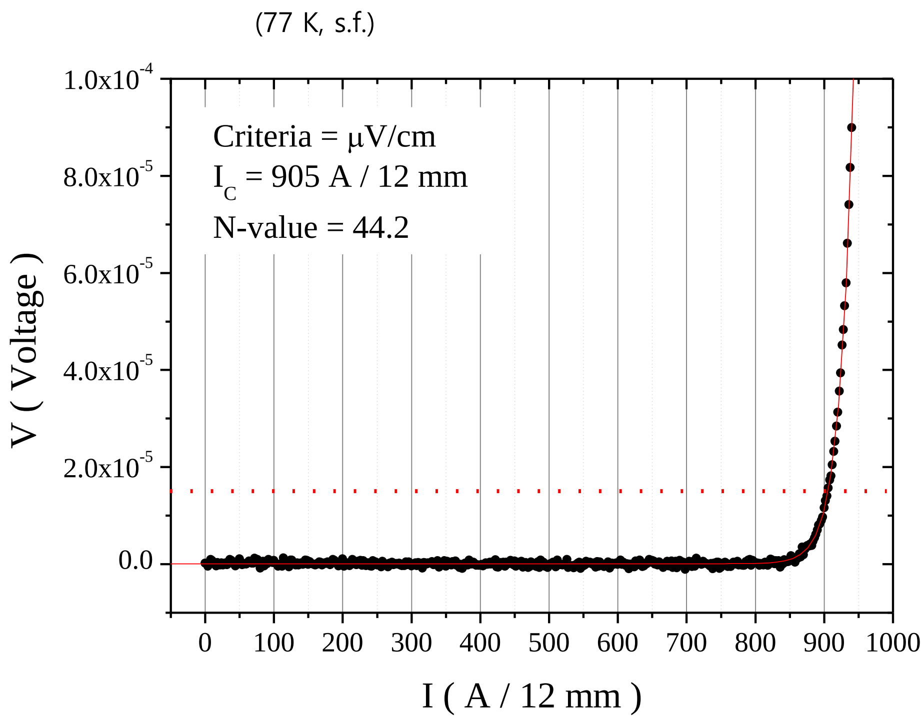


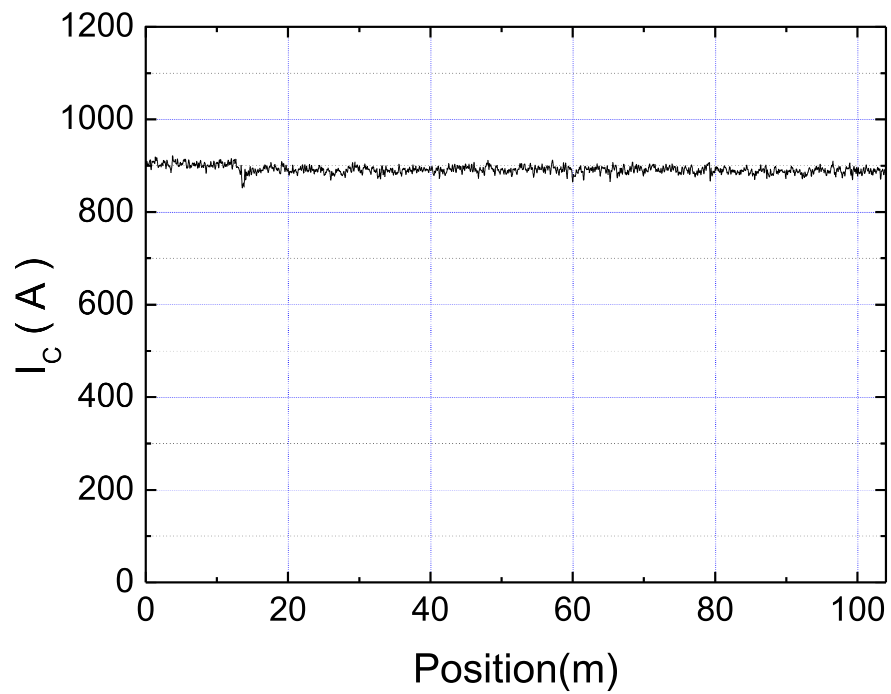
Distance between source and substrate : ~



Distance between source and substrate : ~

Optimization of RCE-DR process for thick superconducting layer





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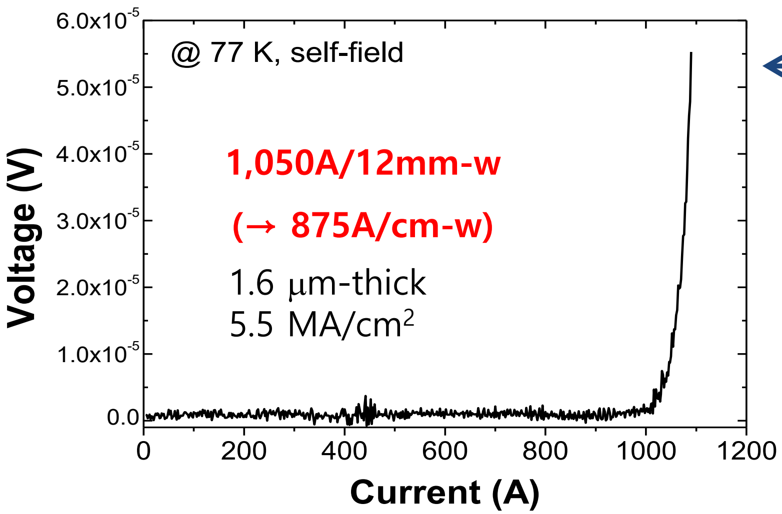
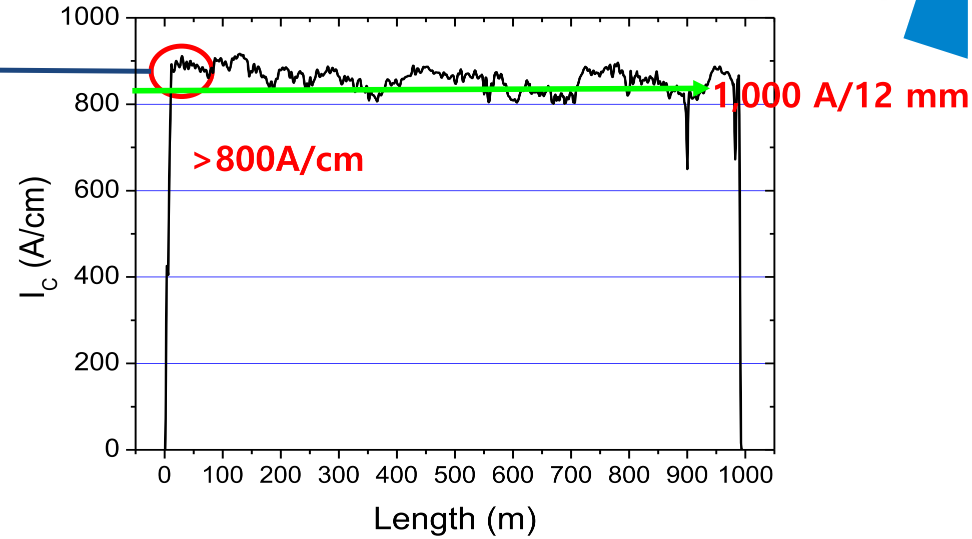
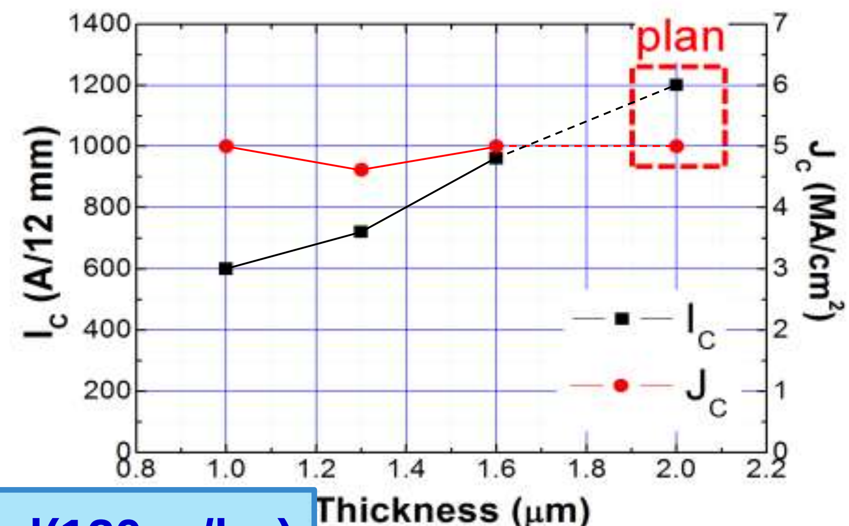
RCE-DR results (with optimization deposition region)





2016 Plan for making 400 A / 4 mm CC

	Speed (m/min)	Turns	Thickness (μm)	I_C (A/cm)	J_C (MA/cm²)
results	2	14	1	500	5
	2	14	1.3	600	4.6
	2	14	1.9	400	2.1
	2	16	1.6	800	5
plan	2	> 20	2 ~ 2.5	> 1,000	> 5



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- **The same process speed(120 m/hr).**

MCI(Metal Clad Insulation) 2G wire for high field magnet

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26.4 T all 2G wire one-body(non-nested) magnet

No-insulation, multi-width, and compact !

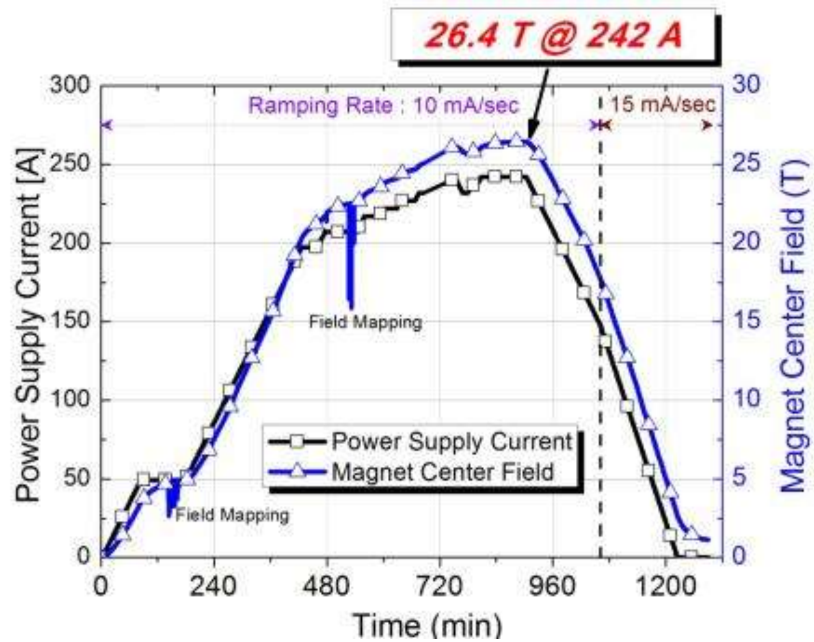
- ✓ Multi-width Double Pancake Coils

4.1mmW 5.1mmW 6.1mmW 7.1mmW 8.1mmW

- ✓ Stacked Double Pancake Coils

O.D. 172mm
I.D. 35mm

- ✓ Fully assembled



Immersed in liquid Helium

(Designed by S. Hahn (MIT→ NHMFL/FSU))

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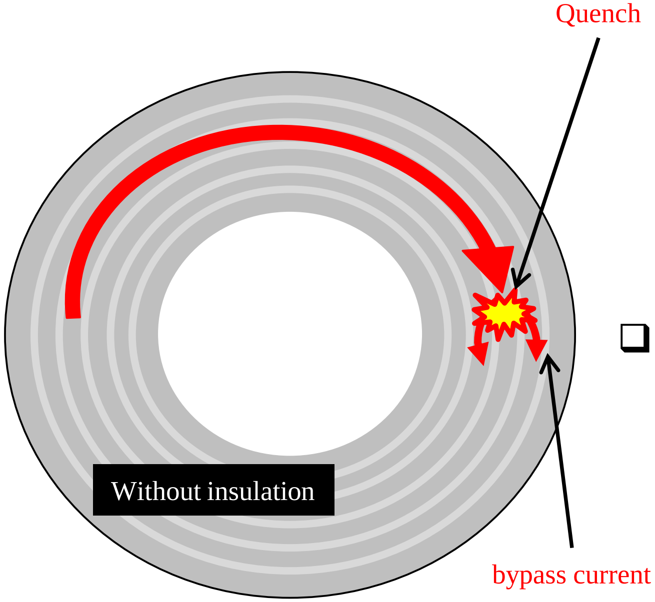
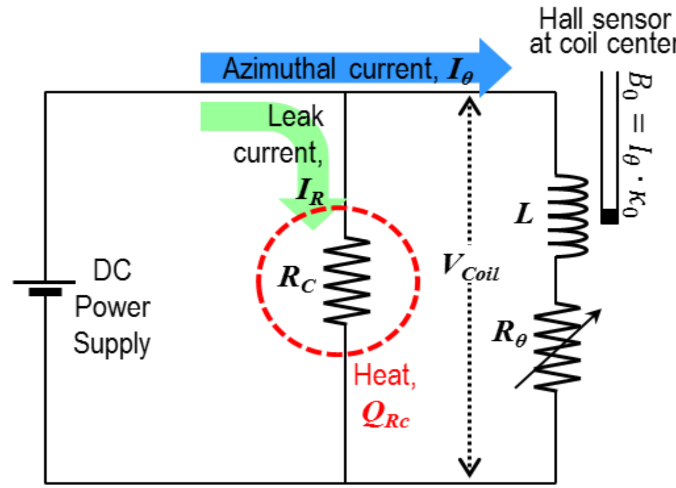
NATIONAL HIGH MAGNETIC FIELD LABORATORY

NI-MW winding technic – No insulation



- **"Automatic bypass"** of the exceeding current and better protection to quench



Q_{R_C} [W] $= {I_R}^2 \cdot R_C$

where, $I_R = I_{PS} - I_\theta = I_{PS} - \frac{B_0}{k_0}$

No-insulation winding technic :

Pros :

- ✓ **Compactness : without thick stabilizer**
- ✓ **Strong mechanical strength : without soft insulation material**
- ✓ **Self protection : automatic bypass**
- ✓ **Rapid quench propagation**

Cons :
Charging time delay.
(excess heat generation/ Impractically slow for charging)

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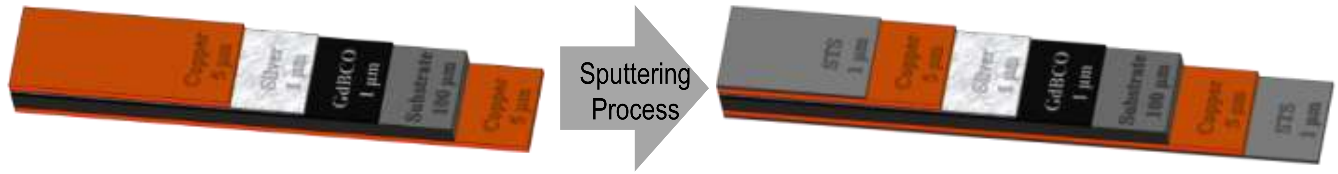
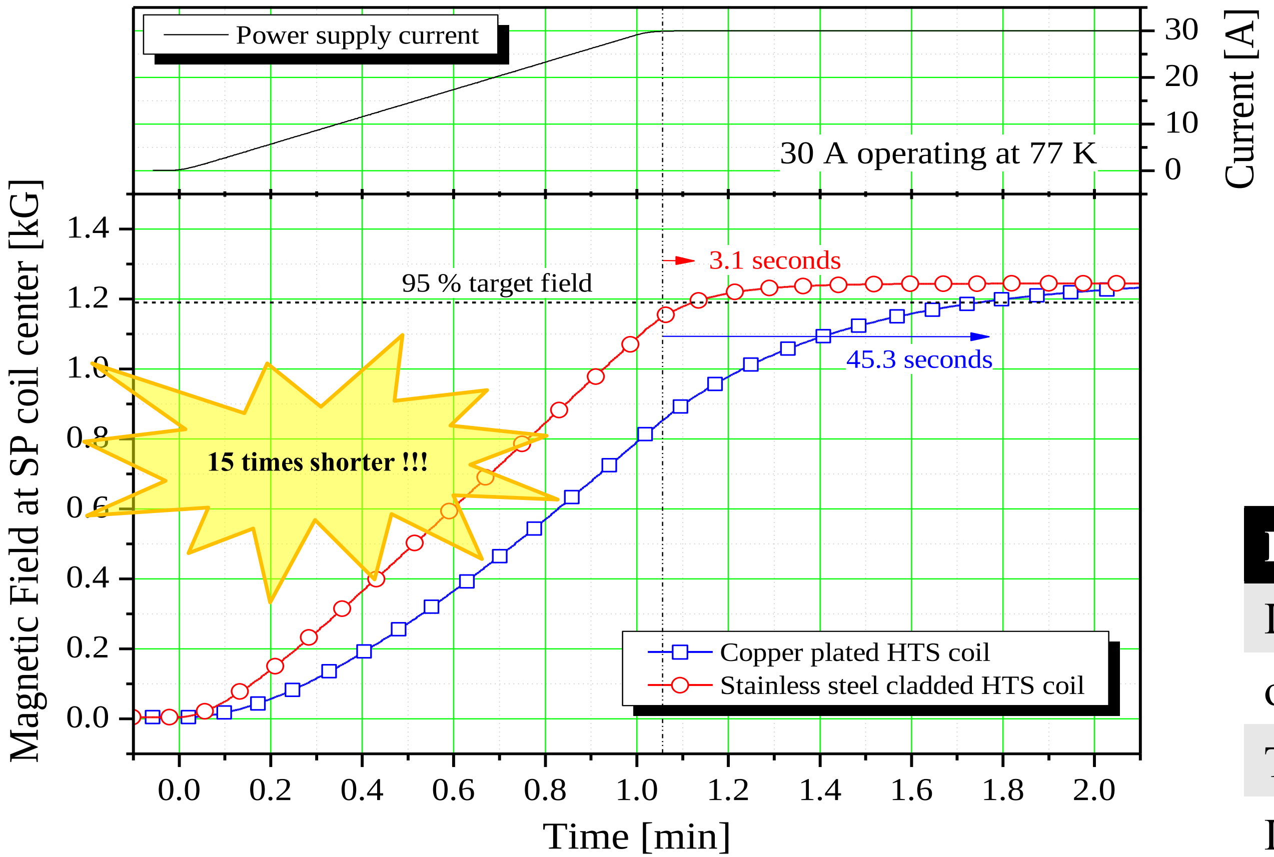
(by S. Hahn)

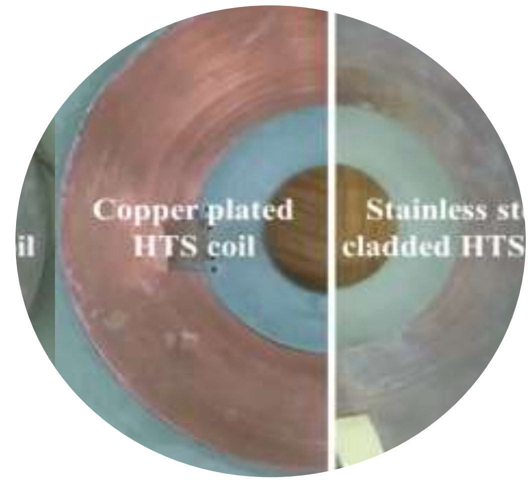
NATIONAL HIGH MAGNETIC FIELD LABORATORY (by S. Y. Hahn)

Metal Clad HTS 2G wire & coil



< Copper plating CC tape > < Stainless steel cladding CC tape >





Parameters	Values
Inner diameter	58 mm
outer diameter	115 mm
Turns	275
Inductance	7.8 mH

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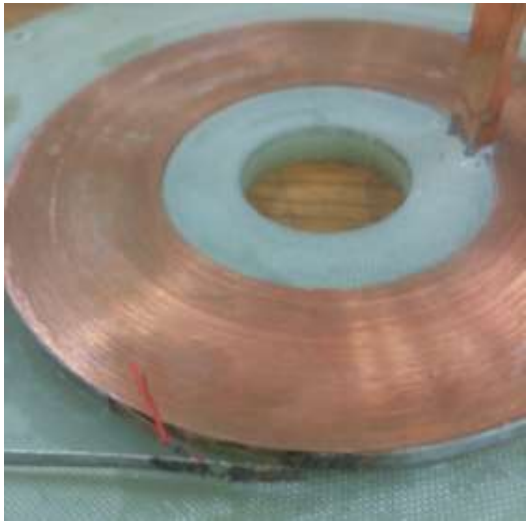
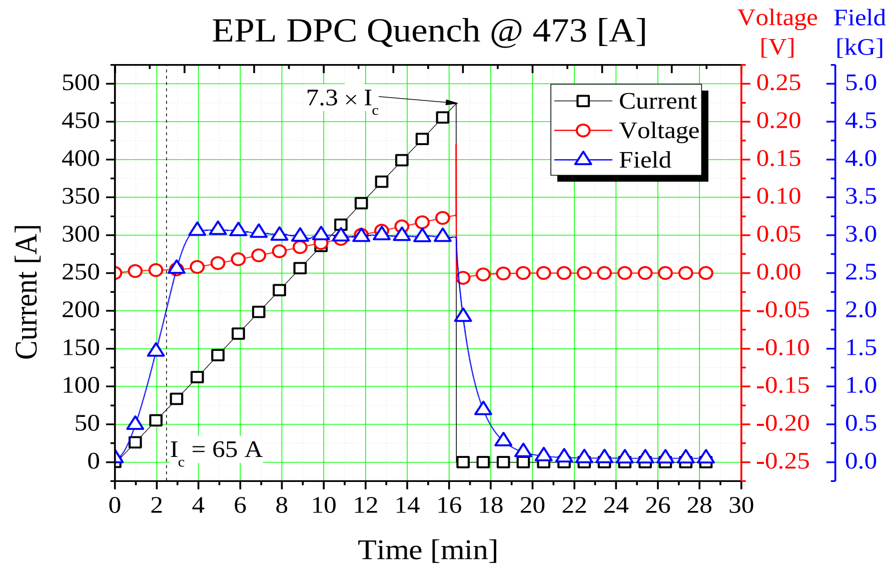
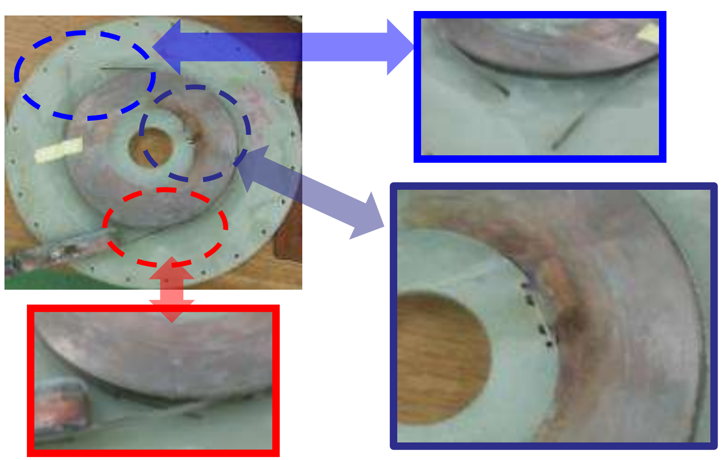
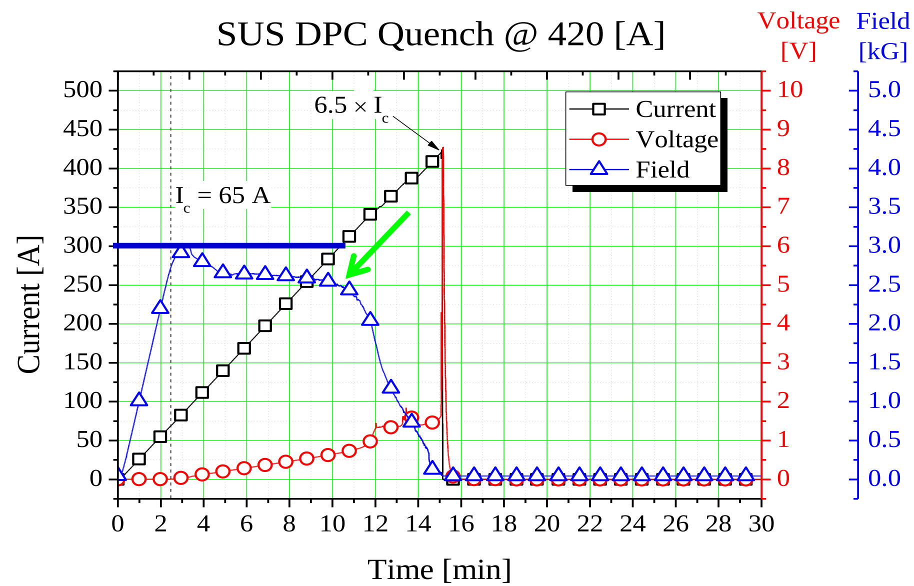
. Kim et al, "Effect of Resistive Metal-Cladding of HTS Tape on the Characteristic of No-Insulation Coil," *IEEE Trans. Appl. Supercond., 2016*

Burn out test @ 77 K (SPC with Copper stabilizer vs. MCI)









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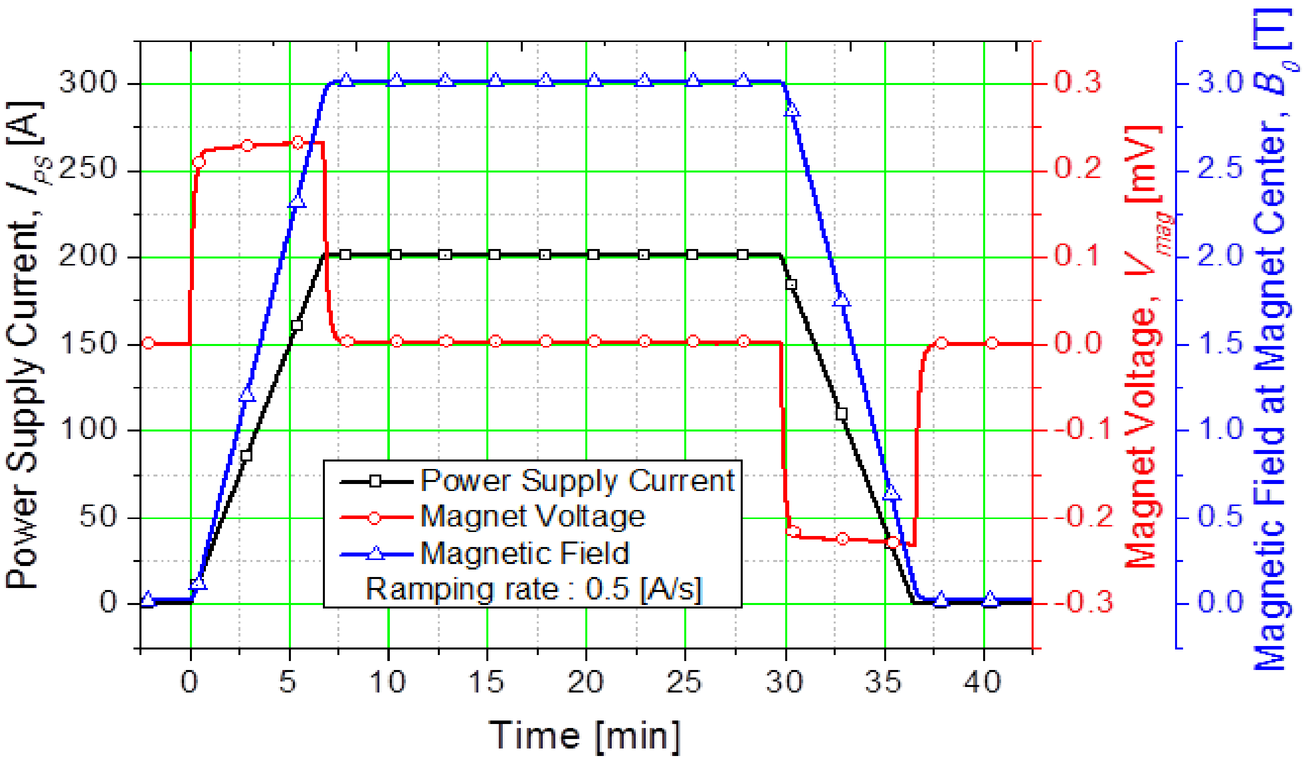
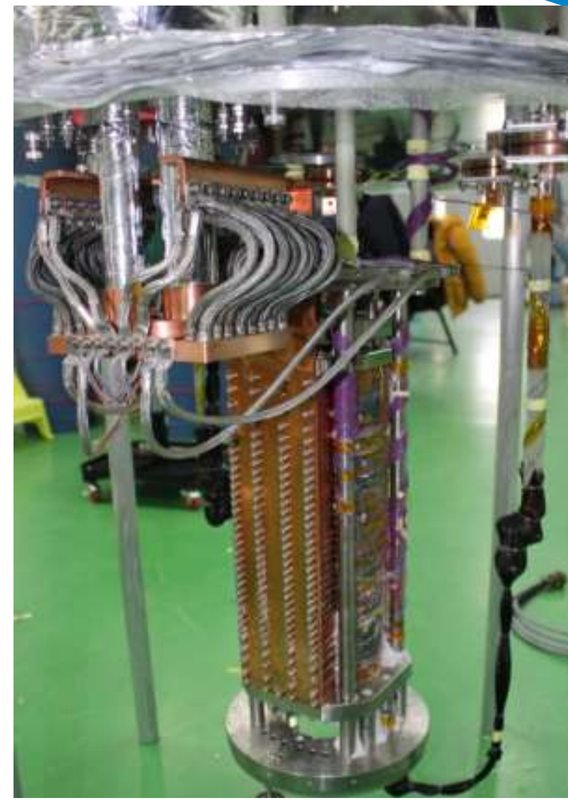
Magnet Operation Results

(By J. Kim et. al., CP-14, yesterday)





- Time constant, τ, is calculated to 11 seconds.
- Contact resistance between turns, $R_{S,STS}$ = 165 [$\mu\Omega\cdot cm^2$]

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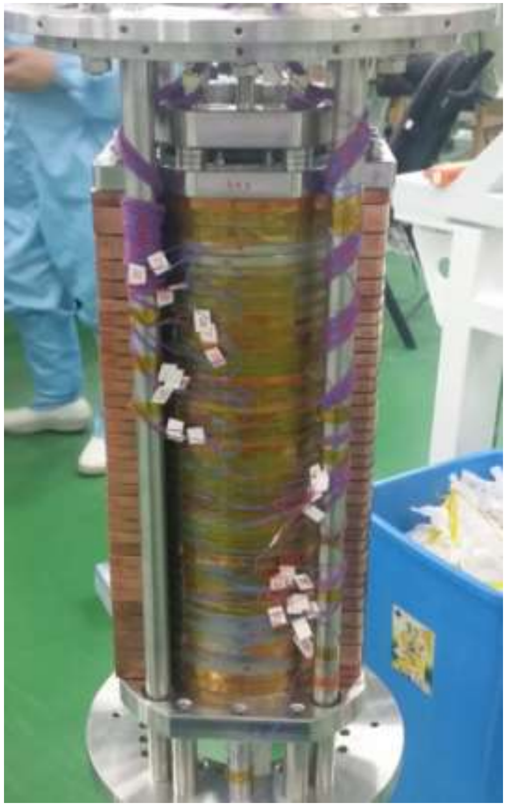
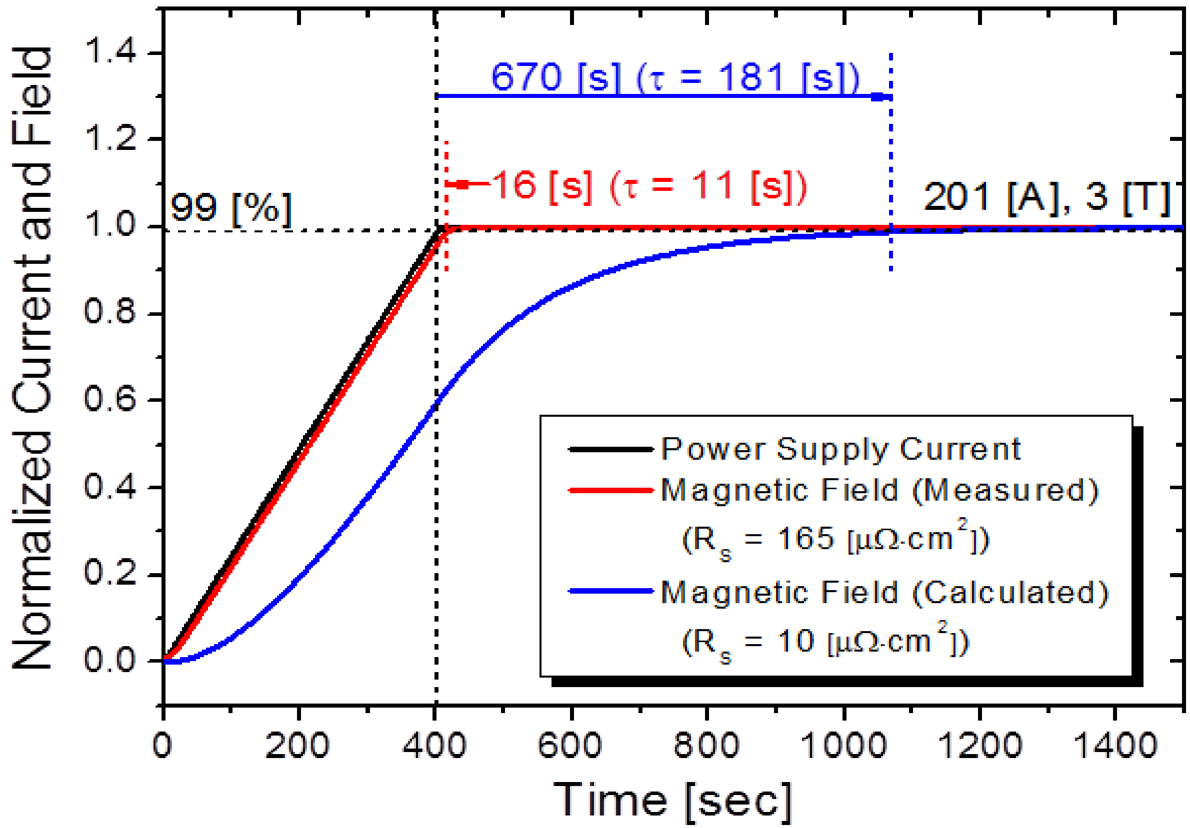
Reduction of Charging Delay

(By J. Kim et. al., CP-14, yesterday)

If magnet was wound with copper plated tape,





STS cladded tape ⇨ **Charging time is 41 times shorter**

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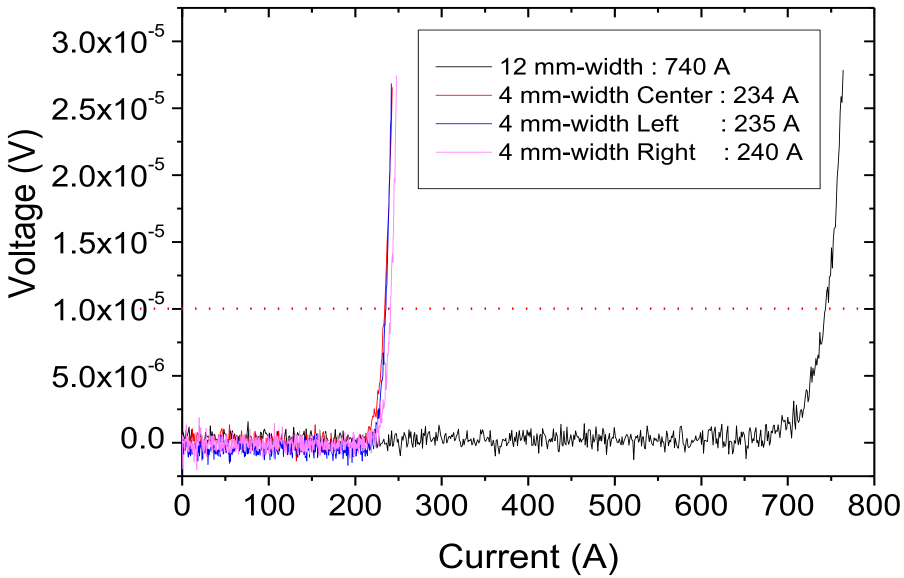
Higher Je : metal substrate removal process

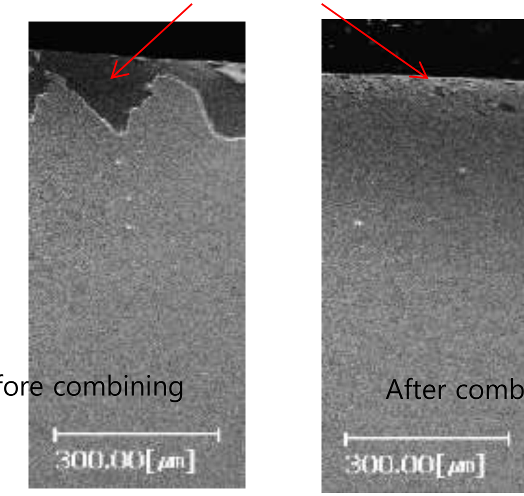
Combining Barrier, Seed, IBAD, Buffer Systems in One

System for Al_2O_3 barrier & Y_2O_3 seed

System for IBAD, homo-epi & buffer



Cutting side



Before combining

After combining

After bending

For standard process,
Stainless steel ~ 100 μm thick
Hastelloy ~ 60 μm thick

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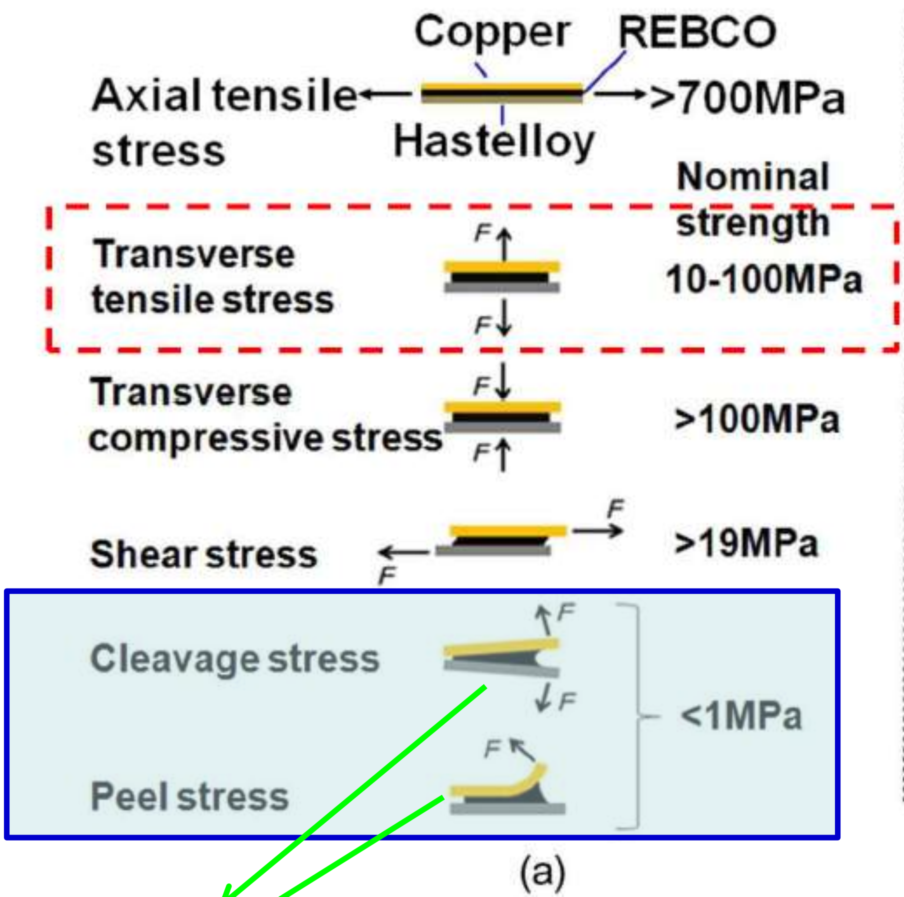
Stress limits for HTS tapes under various loading conditions

REBCO conductor



Utilize this properties !!

Bi2223 conductor

- **In-plane characteristics of REBCO CC tapes were significantly improved.**
  - higher strength substrate materials
  - addition of Cu stabilizer and brass laminate
- **Safe due to enough margin in In-plane loading**

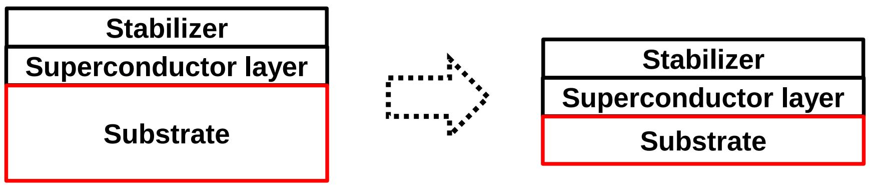
Not to worry?

- **Significantly weaker in out-of-plane loading conditions**
  - major concern especially in superconducting coils and magnet application designs

H. Maeda and Y. Yanagisawa, IEEE Trans Appl. Supercond., vol. 24, 4602412 (2014)

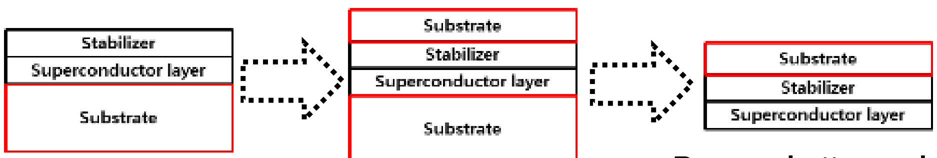
High Je wire by removal of thick metal substrate

For Je, substrate thickness must be thin



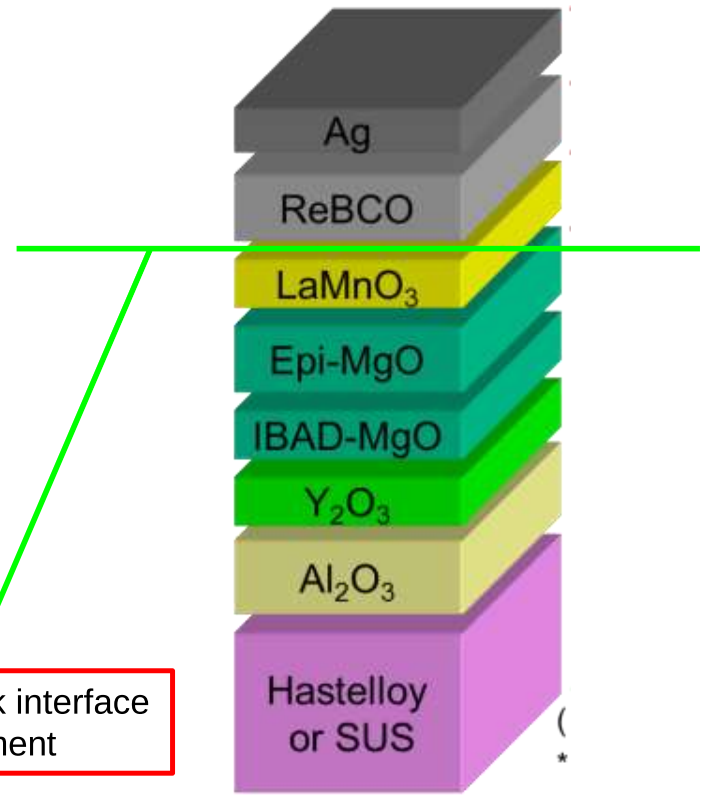
For thin substrate, easy to damage during the reel to reel process

Improvement of Je



Soldering thin substrate on top of CC

Remove bottom substrate



Intentionally making a weak interface by some treatment

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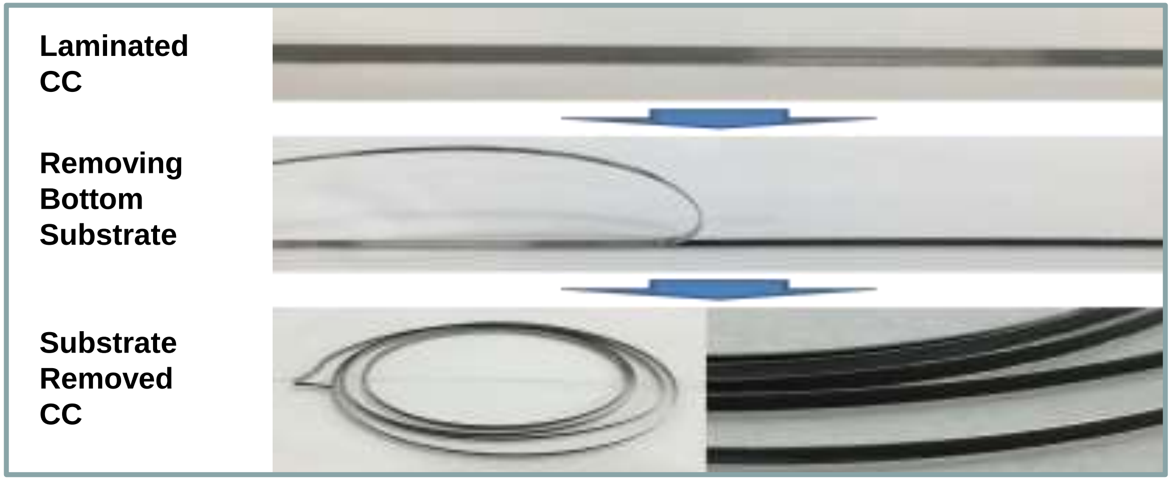
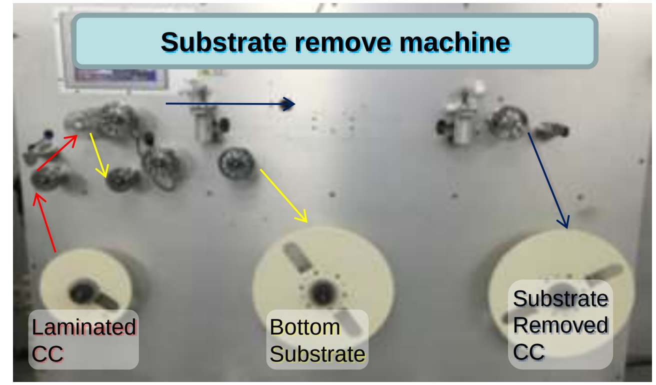
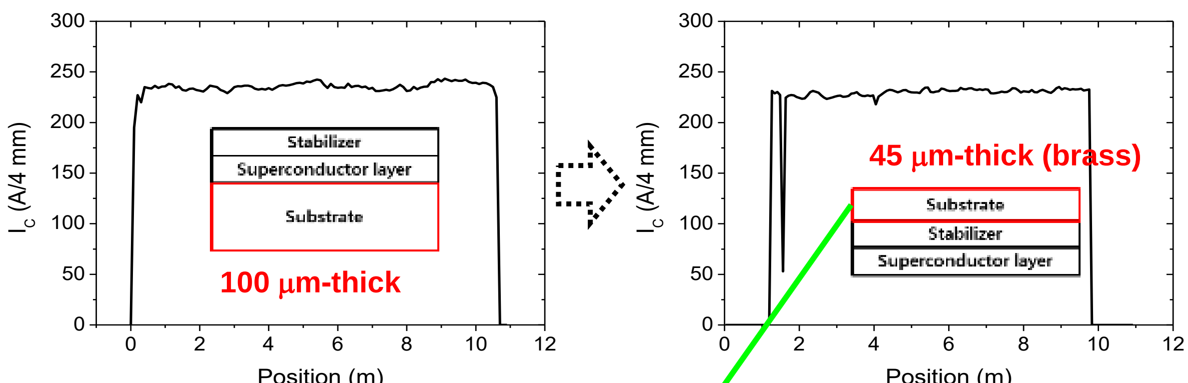
Demonstration of High Je wire by removal of thick metal substrate

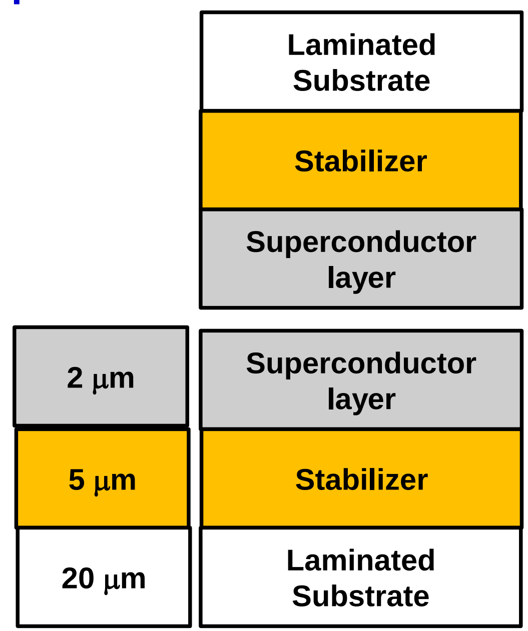






- Easily reduce the thickness ~ < 20 μm
- Choice of any materials(SUS, Copper…)

May possible…



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Summary

- SuNAM has been producing high I_C coated conductors consistently.
- Introduction of in-line Q.C. measures enhanced wire uniformity & production yield.
- With thicker(1.3 μm → 1.6 μm) S.C. layer, we achieved >1,000 A/12 mm in production.
- We demonstrated 3 T magnet using MCI coated conductor.
- Initial test of substrate removal & suggesting a new way of high Je wire structure.

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Direction of Technology Development in the Future

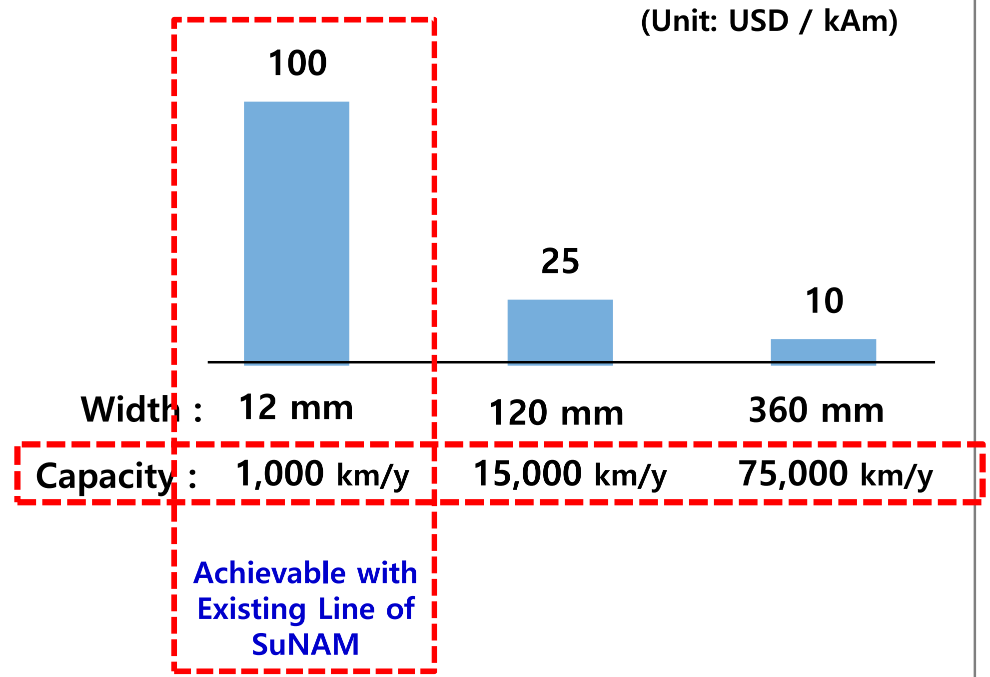
"Increasing Demand for HTS 2G wire has surpassed the supply"

"For market entrance $ 50 / kAm is the threshold "

"Price Reduction will ignite an exponential growth of demand for HTS 2G wire"

"High throughput, low material cost, High yield is 3 Critical Success Factor"

Price Reduction in RCE DR process



Thanks for Attention !

SUNAM www.i-sunam.com

Acknowledgement

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- MIT : Y. Iwasa

Thanks for Attention !