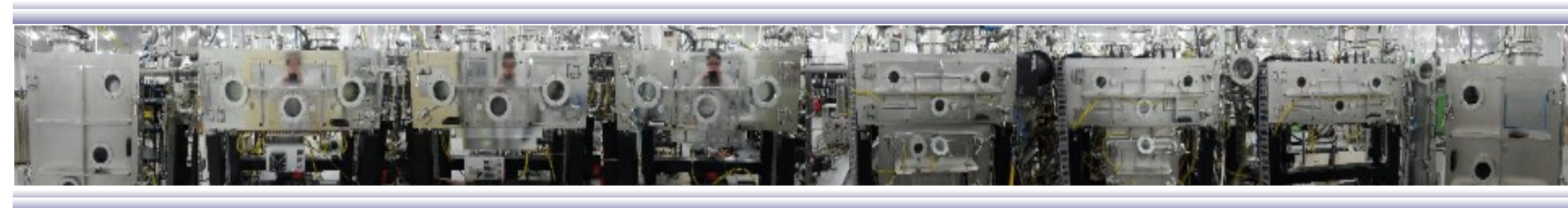


Recent progress on SuNAM's coated conductor development; performance, price & utilizing ways



Seung Hyun Moon, Jae-Hoon Lee & Hunju Lee
SuNAM Co., Ltd.

2016. 09. 13.

CCA 2016, Aspen, Colorado, US.

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	$J_c > 10^4$	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 copper

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.

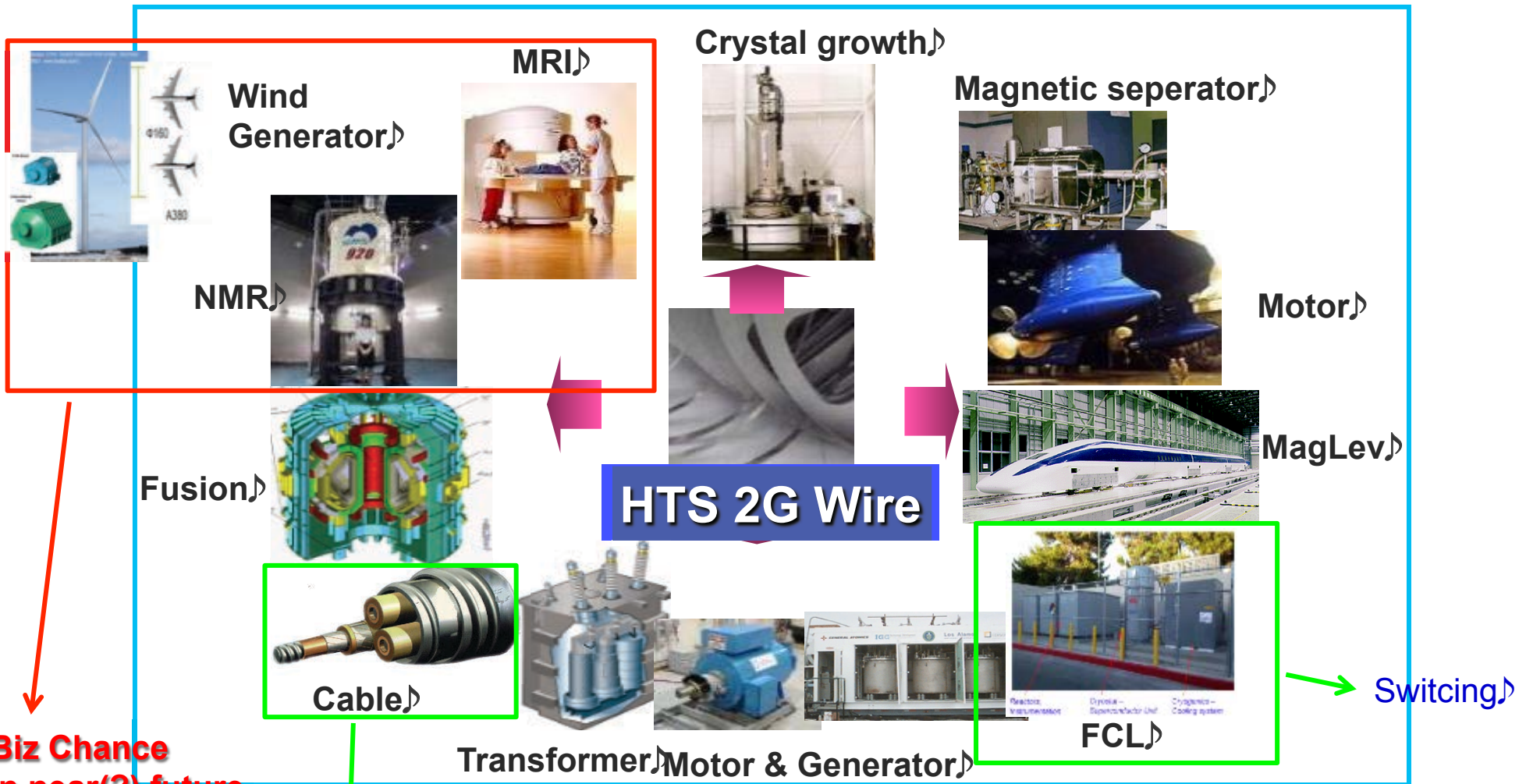
Technology Attributes	Near-Term Goals (present – 2007)	Mid-Term Goals (2008 – 2011)	Long-Term Goals (2012 – 2016)
Critical current	250 A/cm, 77 K, sf 125 A/cm, 65 K, 2 T	500 A/cm, 77 K, sf 250 A/cm, 65 K, 2 T	1000 A/cm, 77 K, sf 500 A/cm, 65 K, 2 T
Cost/Performance Ratio	\$400/kA-m, 77 K, sf \$800/kA-m, 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.



Applications of Superconductivity♪

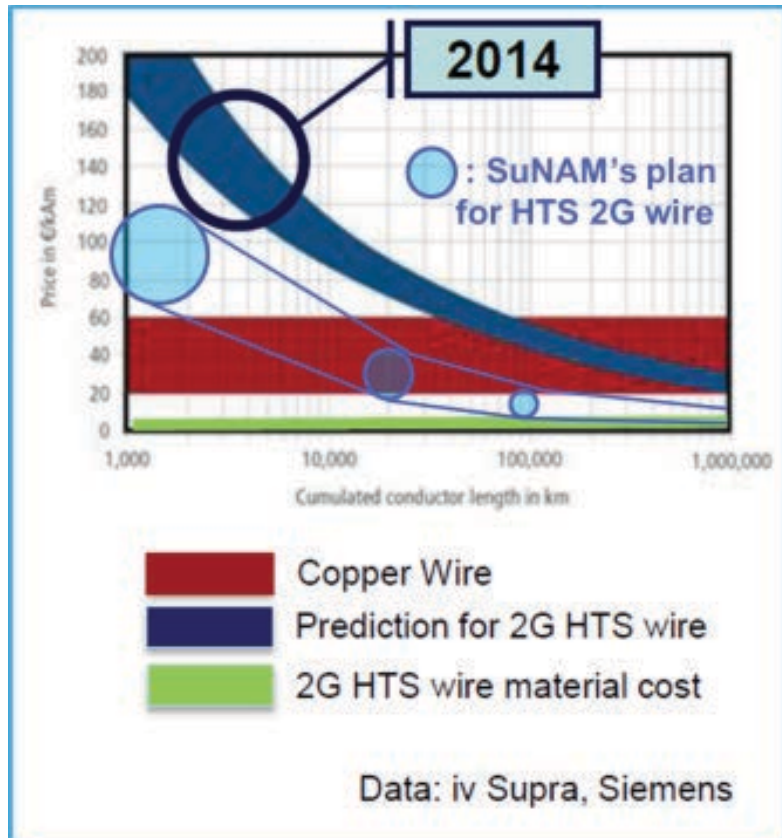


Biz Chance in near(?) future

Current carry♪

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

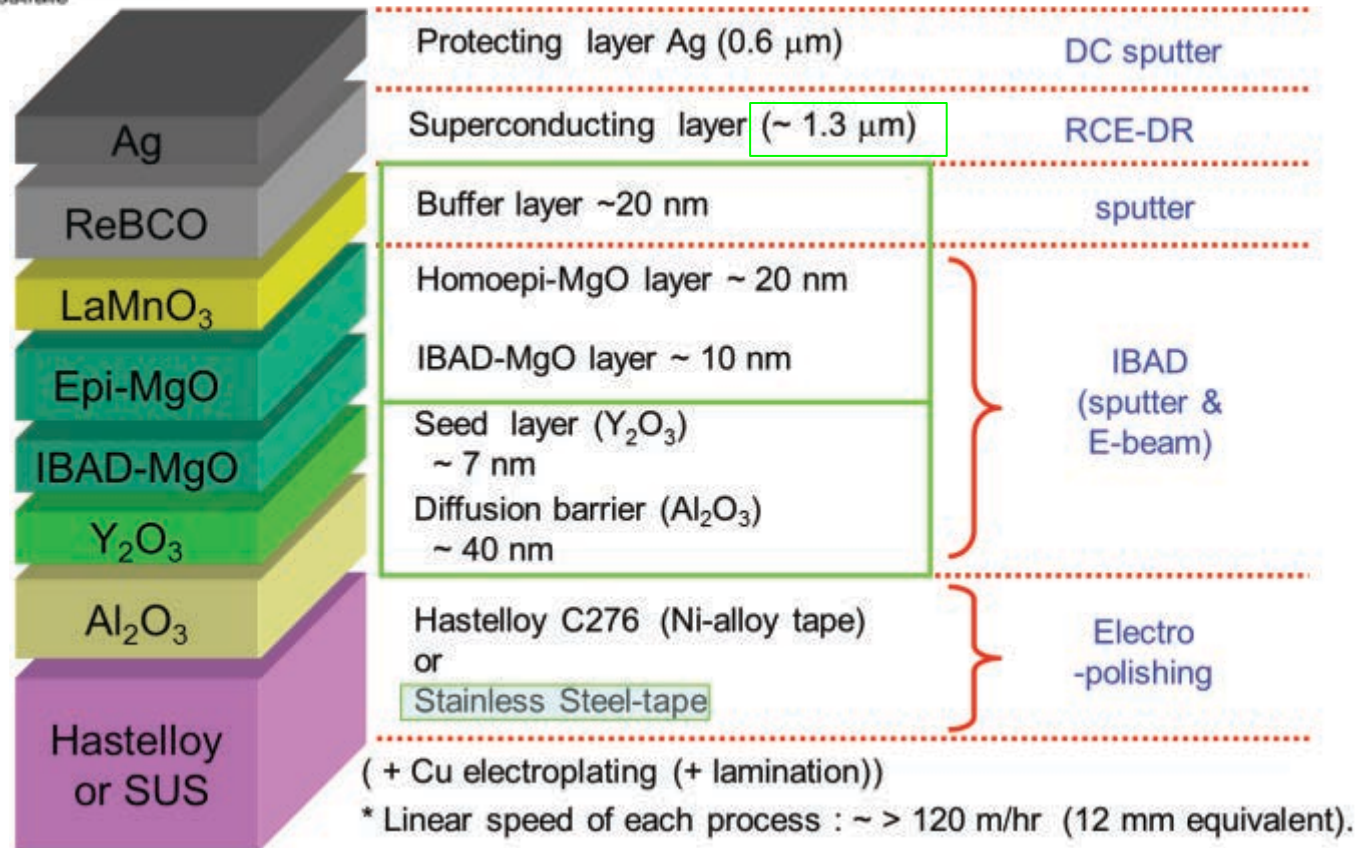
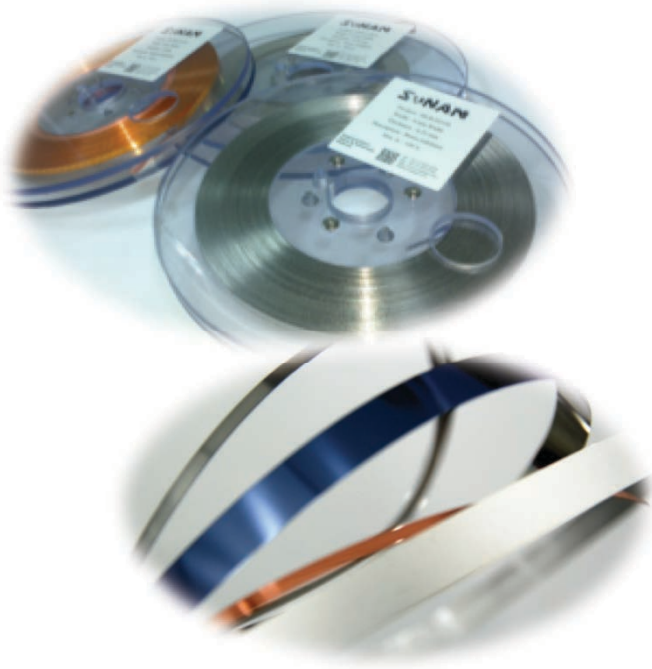
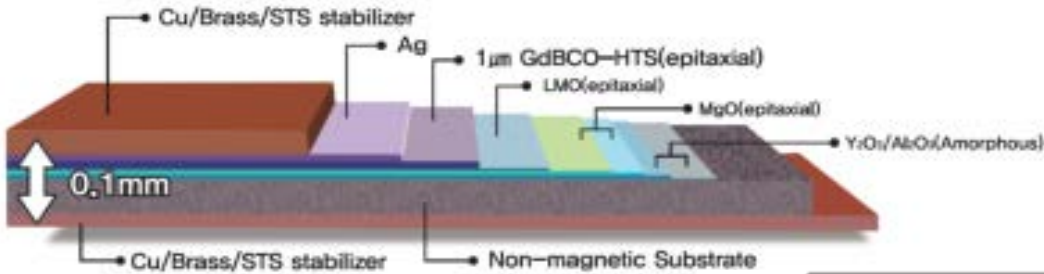
How can we realize practical HTS 2G wire?



- 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

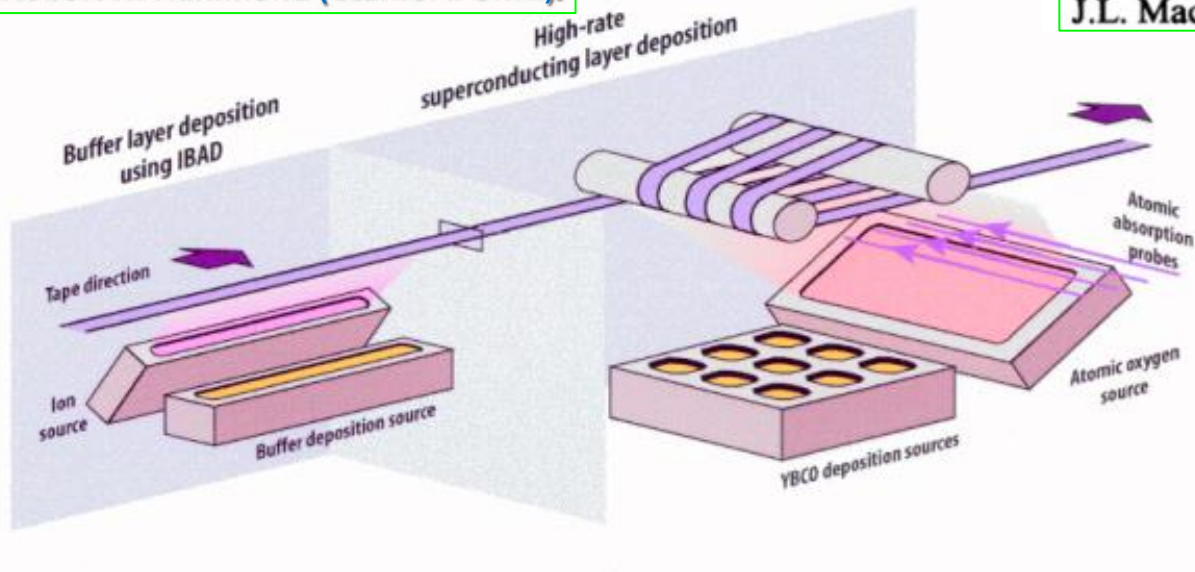
Structure



- Typical $I_c \sim > 700\text{A}/12\text{mmW}$ at 77K Self-field ($J_c \sim > 5 \text{ MA}/\text{cm}^2$)

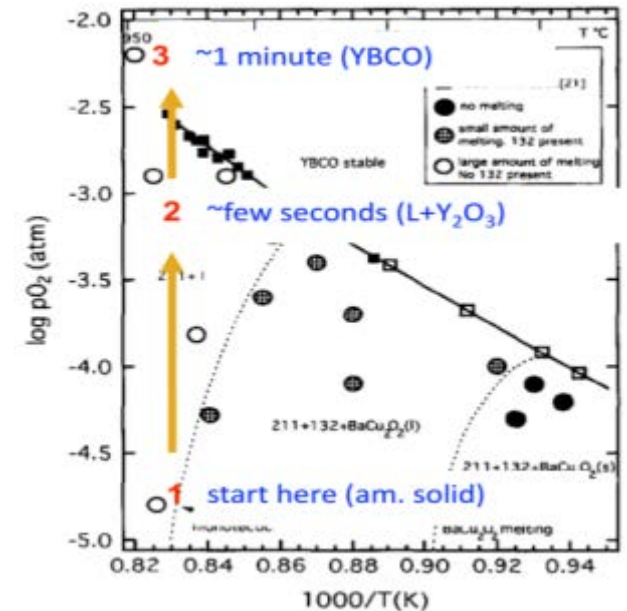
Scale up Issues: IBAD & *in-Situ* High Rate E-Beam

Robert H. Hammond (Stanford Univ.)



J.L. MacManus-Driscoll^{a,*}, J.C. Bravman^a, R.B. Beyers^b

Physica C 241 (1995) 401-413



- 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

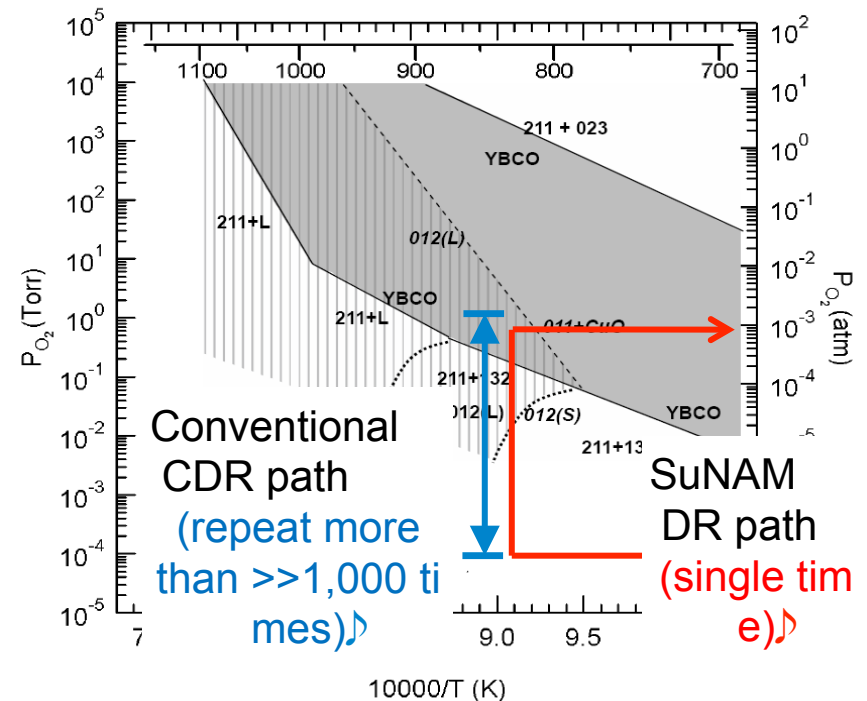
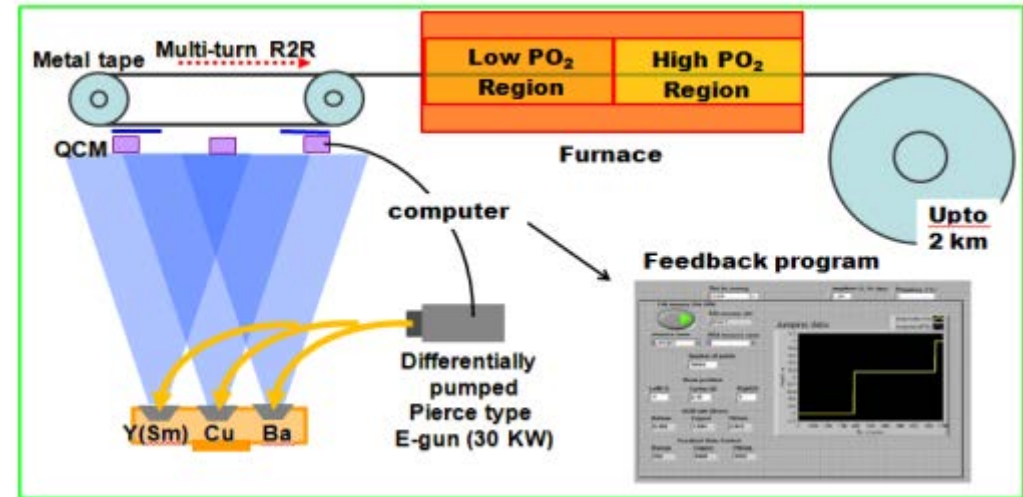
$$C/P \Rightarrow \$ \text{ per year} / R(L \times W) J_c$$

Study ISS' 95:

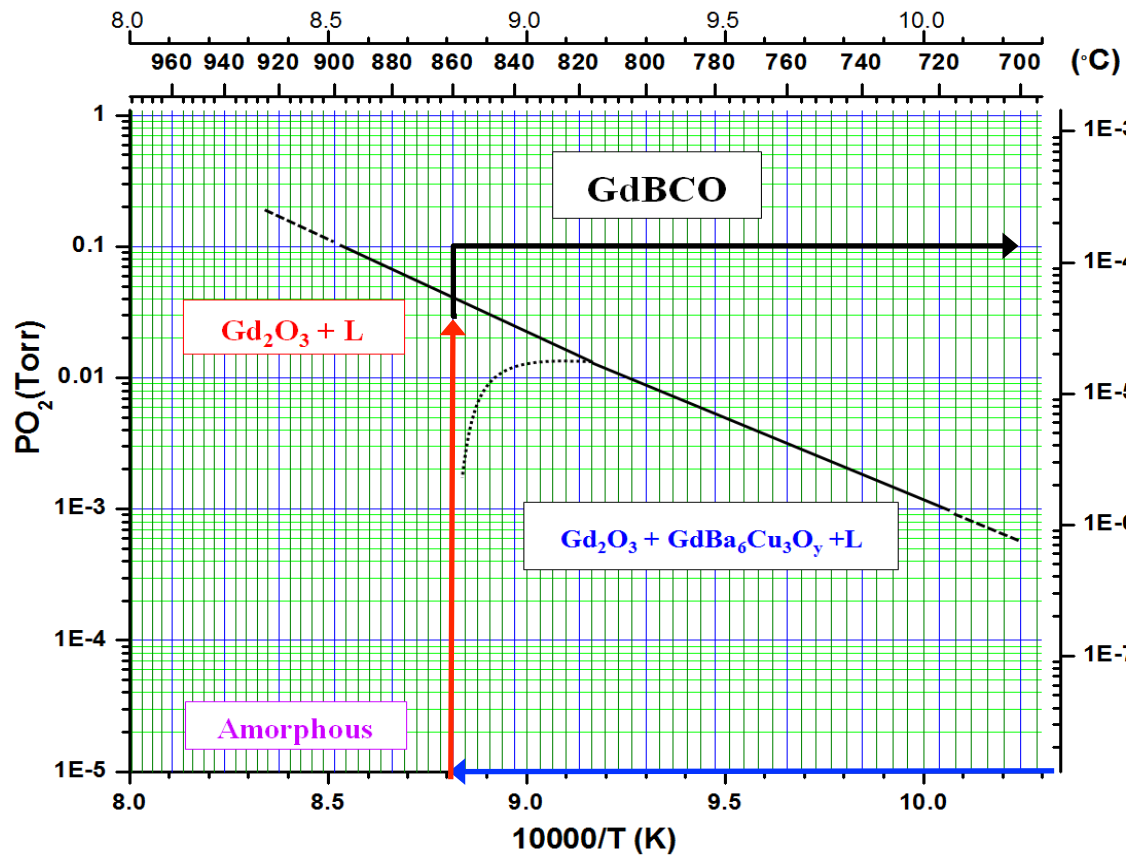
$$\left\{ \begin{array}{l} R = 100 \text{ \AA} / \text{sec} \\ L = 30 \text{ cm} \\ W = 1 \text{ meter} \\ J_c = 10^6 \text{ A} / \text{cm}^2 \end{array} \right\} \rightarrow C/P = \$10 / \text{kA-m} @ 6000 \text{ km/year}$$

SuNAM RCE-DR process

- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R 2R)
- High rate co-evaporation at low temperature & pressure to the target thickness ($> 1 \mu\text{m}$) at once in deposition zone ($6 \sim 10\text{nm/s}$)
- **Fast ($\ll 30 \text{ sec.}$) conversion** from a **morphous 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**

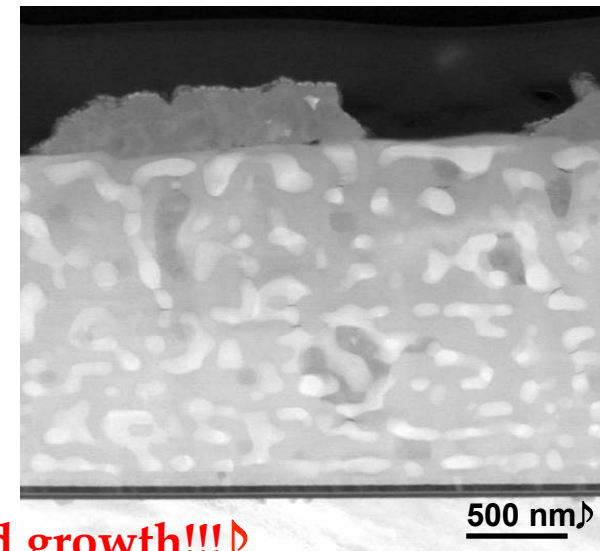
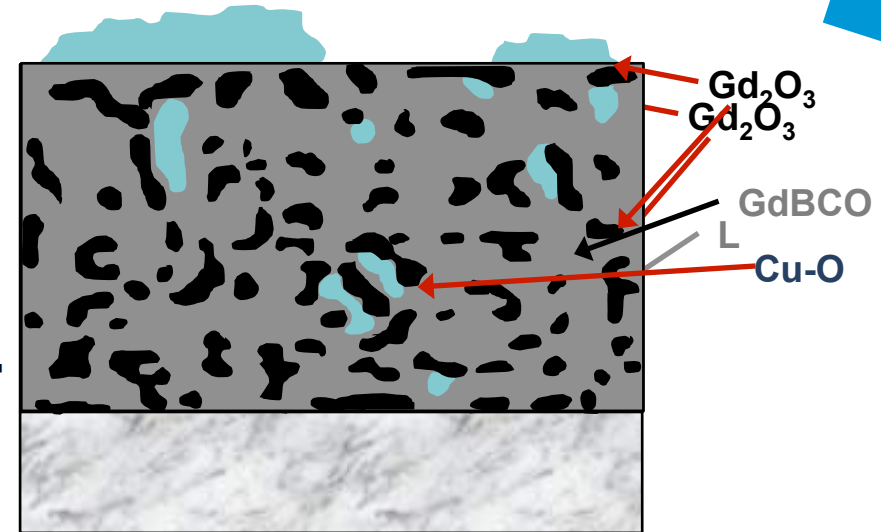


Growth mechanism of the GdBCO film by RCE-DR

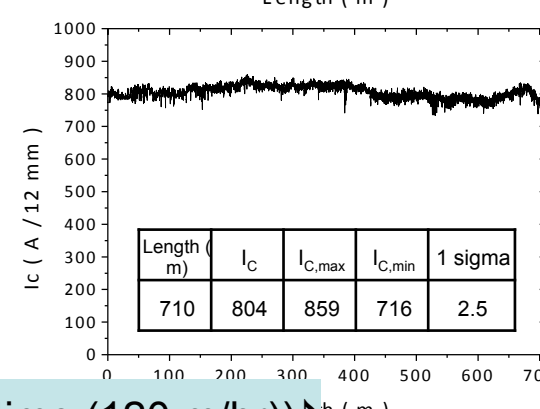
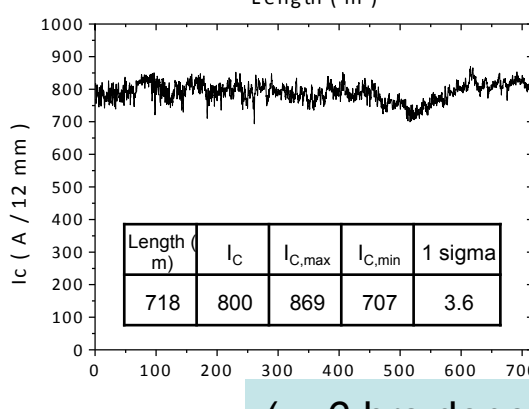
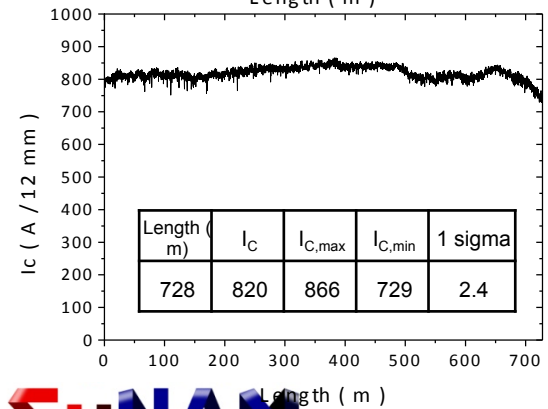
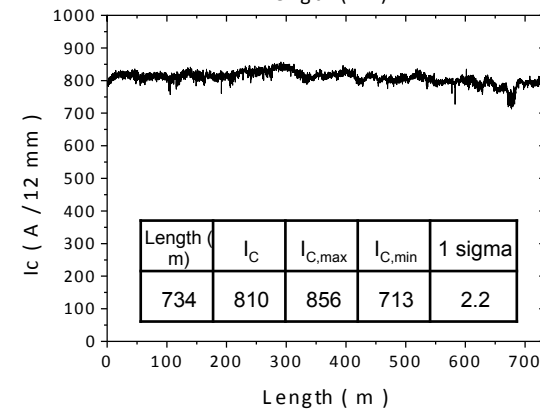
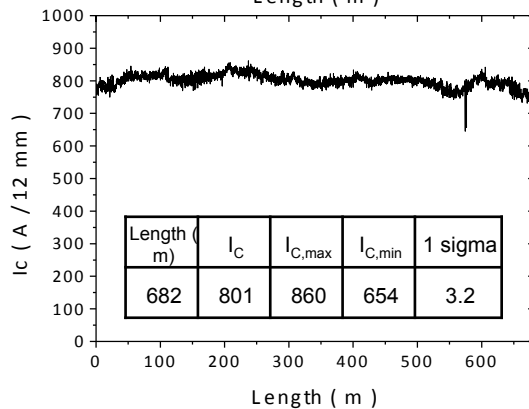
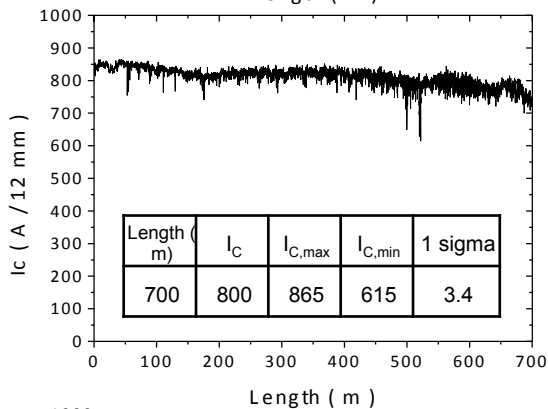
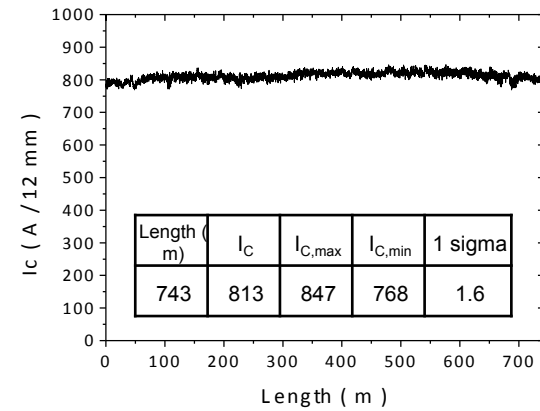
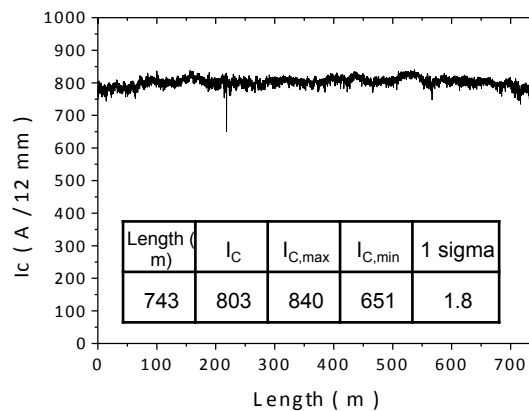
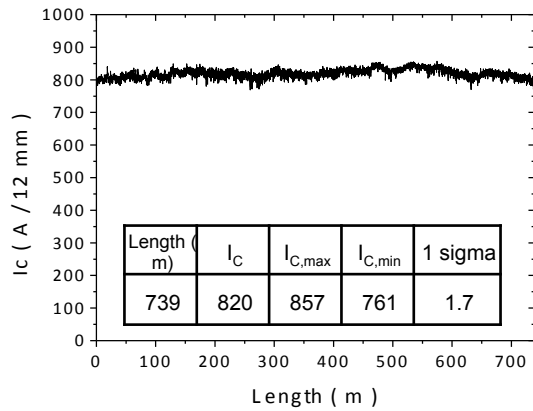


- Very low PO_2 zone ($\sim 10^{-5}$ Torr): **Amorphous Film**
- Lower PO_2 zone (~ 30 mTorr): **Gd₂O₃ + Liquid (< 5 sec)**
- Higher PO_2 zone (~ 100 mTorr): **GdBCO Film (< 20 sec)**

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

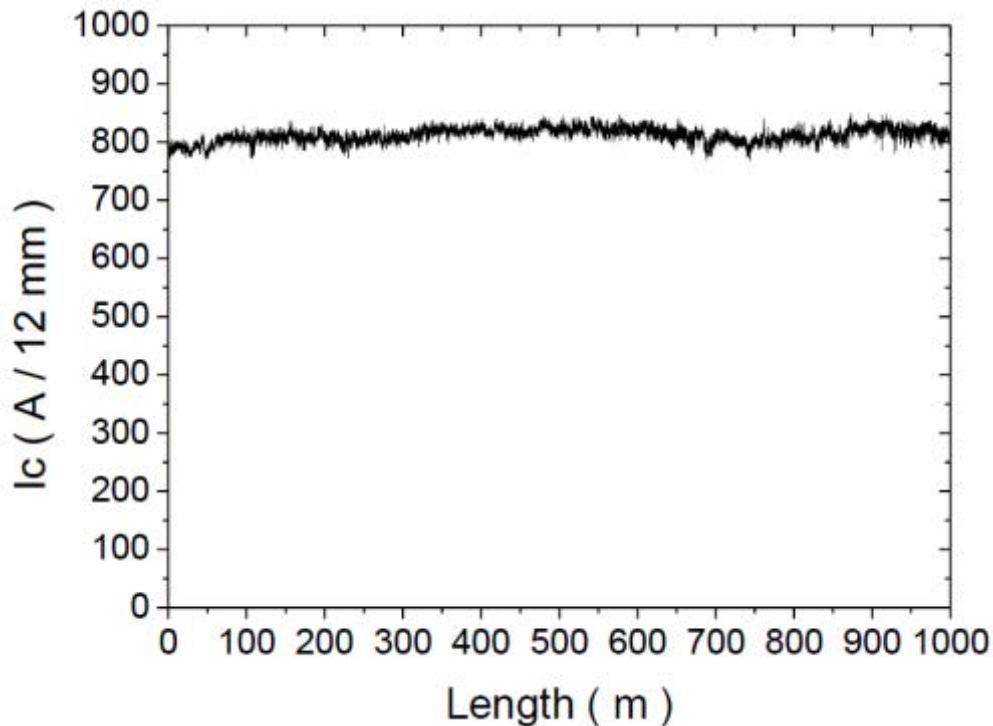


Daily Production 2G wire performances

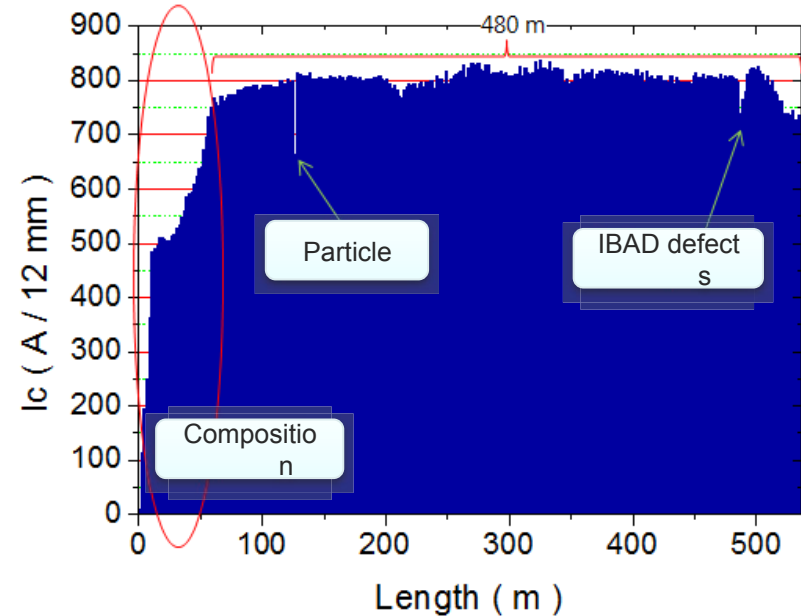


(~ 6 hrs deposition time (120 m/hr))

RCE-DR Results on Stainless Steel Substrate



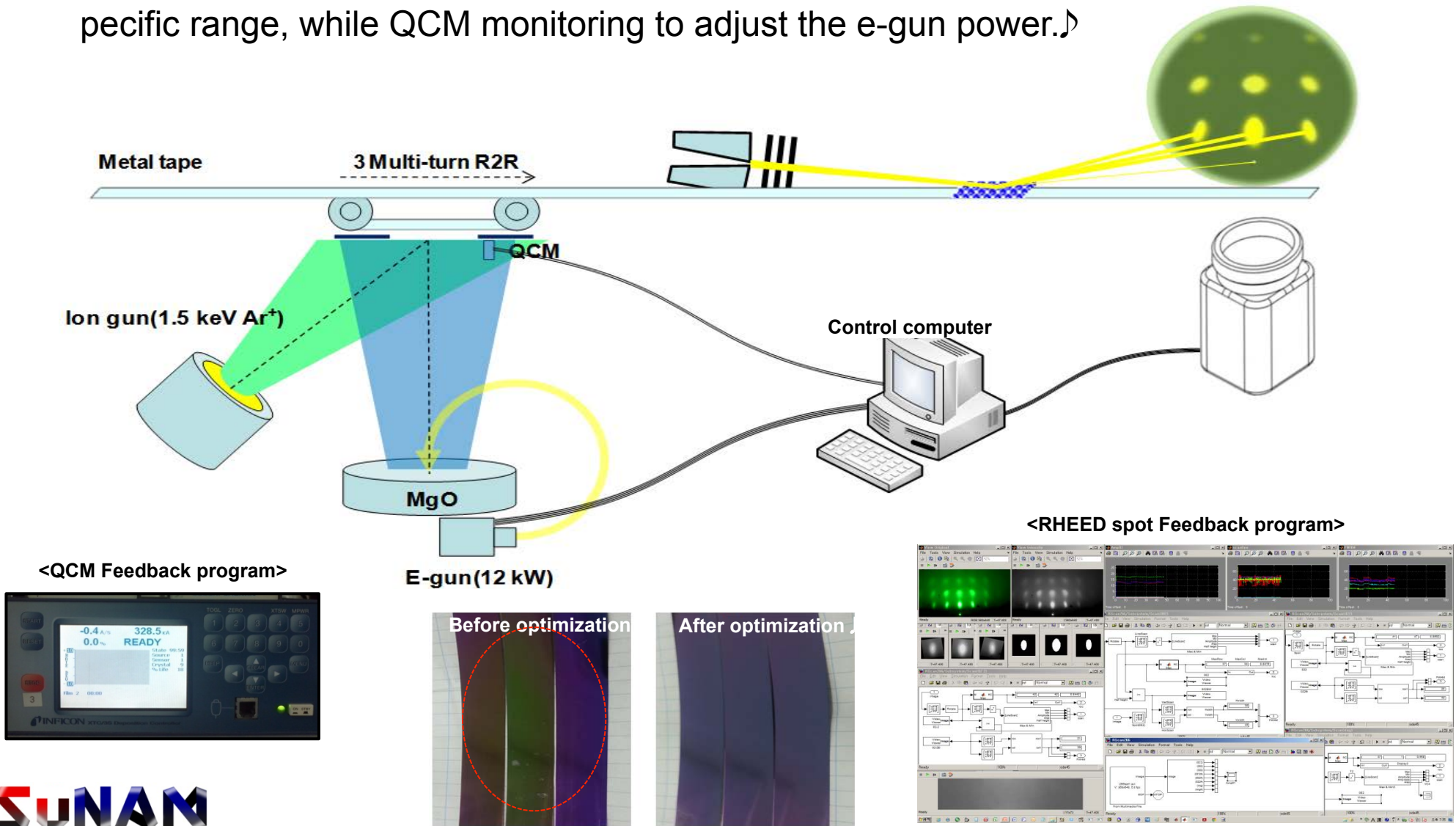
- Min I_c (A/cm-width) x L (m) > 0.6 Million A-m
- Production speed of **120 m/hr (12 mm width)**
(1 km for ~ 8 hrs)



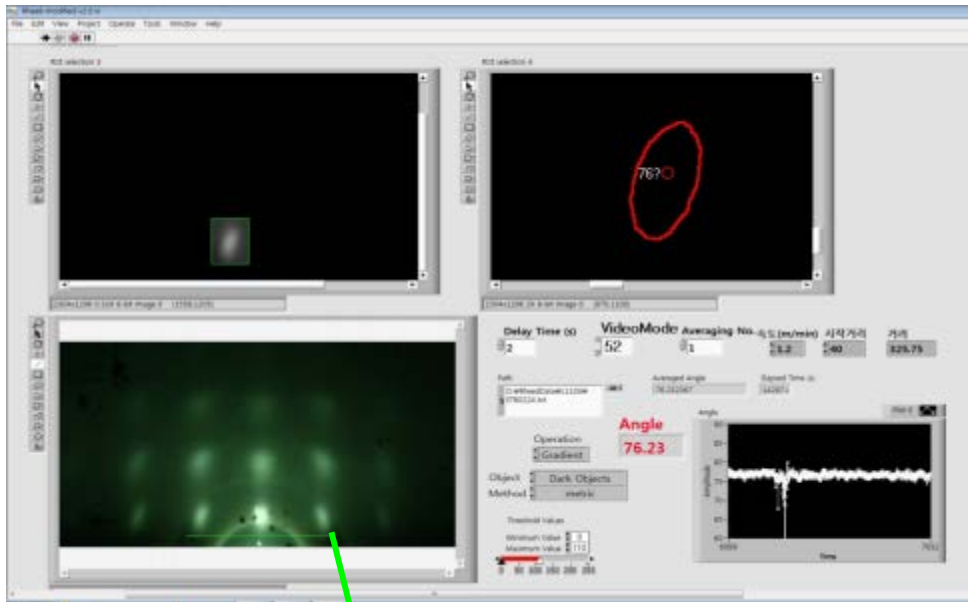
Width (mm)	Length (m)	AVG. I_c (A)	1σ (A)	Min. I_c (A)	Max. I_c (A)	COV(%)	$I_c \times L$ (Am)
12	480	799	23	664	838	2.8	318,765
10		666	19	553	699		265,638
12	534	768	110	8	838	14.3	4,474
10		640	91	7	699		3,728

Quality Control : RHEED Vision System

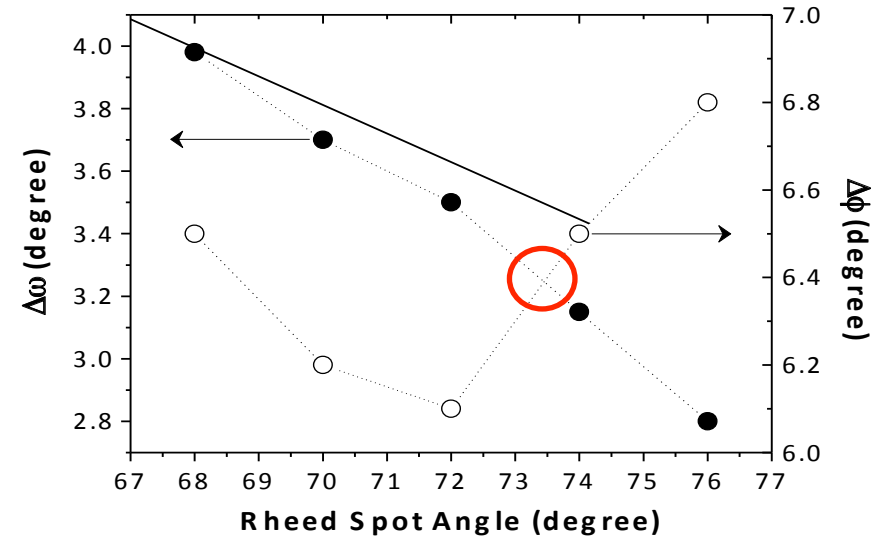
- An appropriate feedback algorithm can keep the shape of the RHEED spot in the specific range, while QCM monitoring to adjust the e-gun power.♪



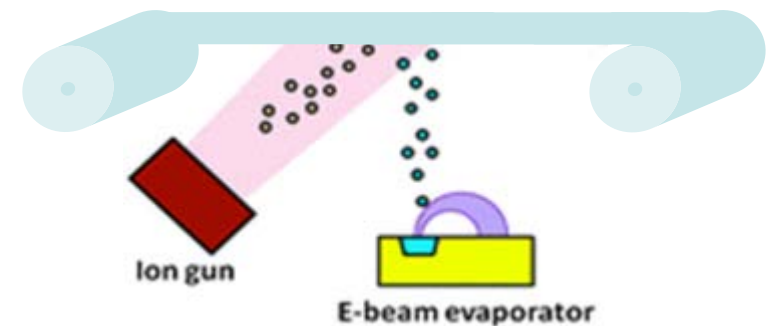
Feedback route based on RHEED spot analysis



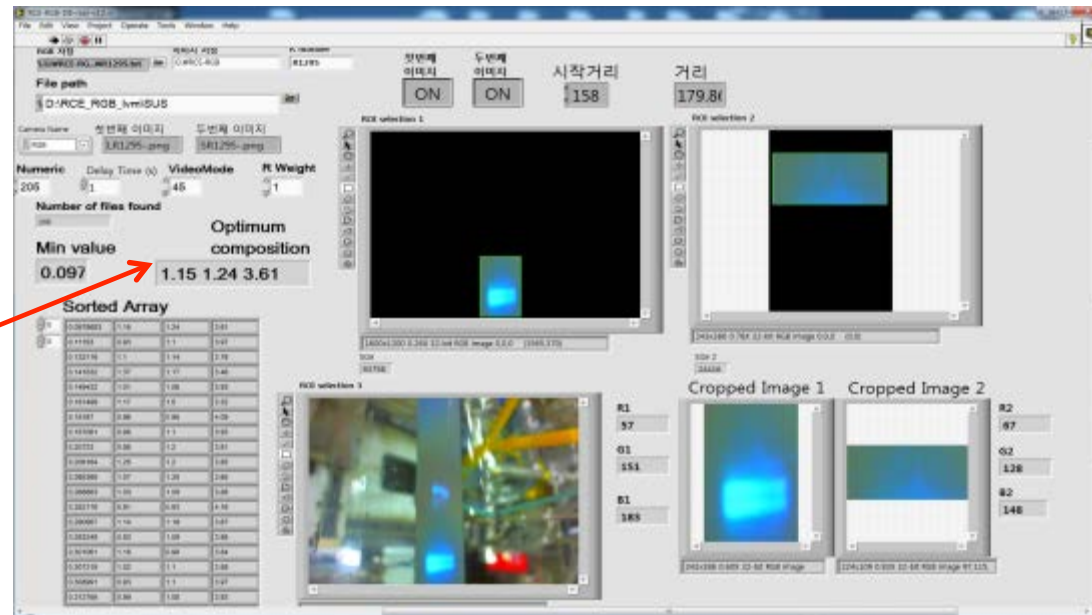
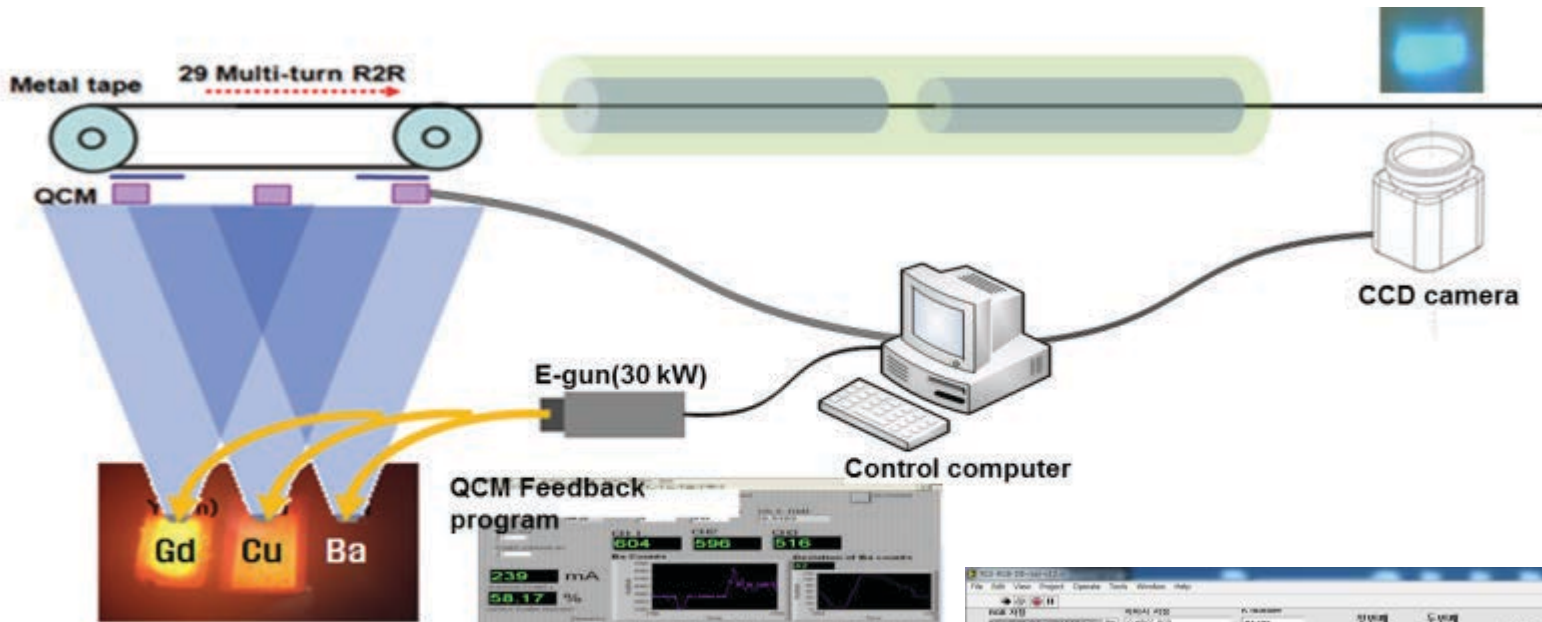
(110) spot



- Because of different evolution of $\Delta\phi$ & $\Delta\omega R$, optimization is very important for high quality 2G wire.
- Intensity & tilt angle of MgO (110) spot is one of the most important parameter. ♪



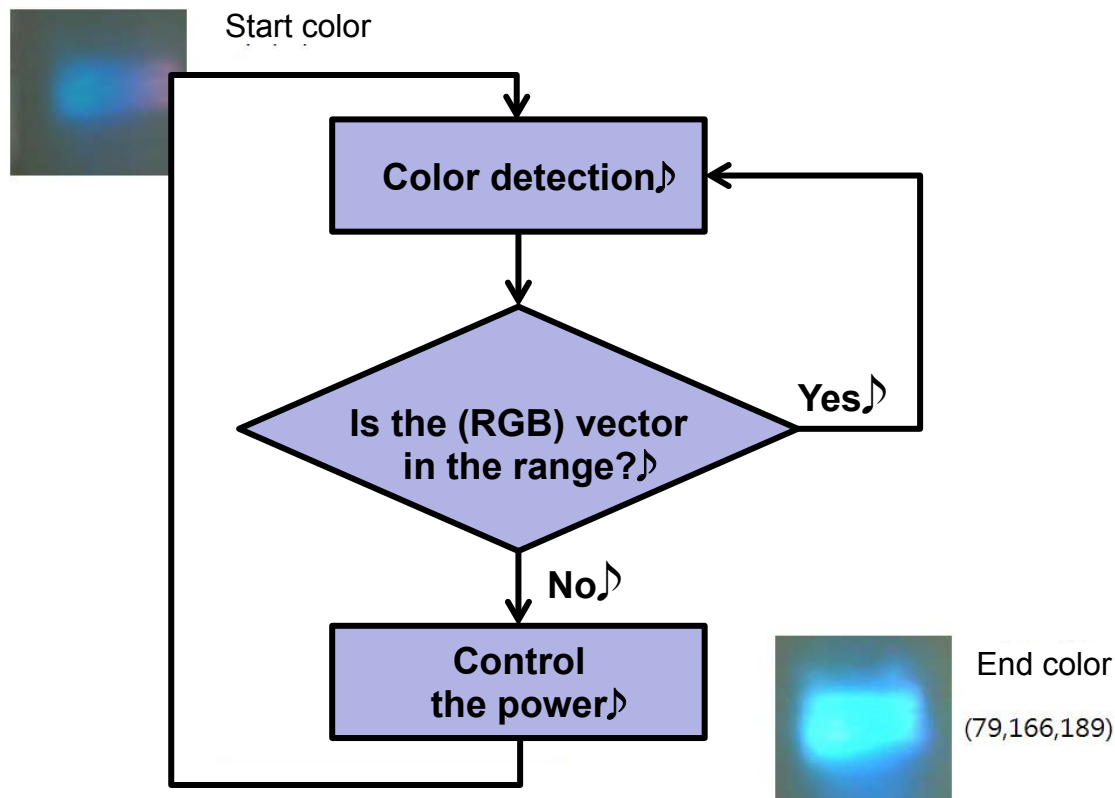
Quality Control : RCE Vision Inspection System



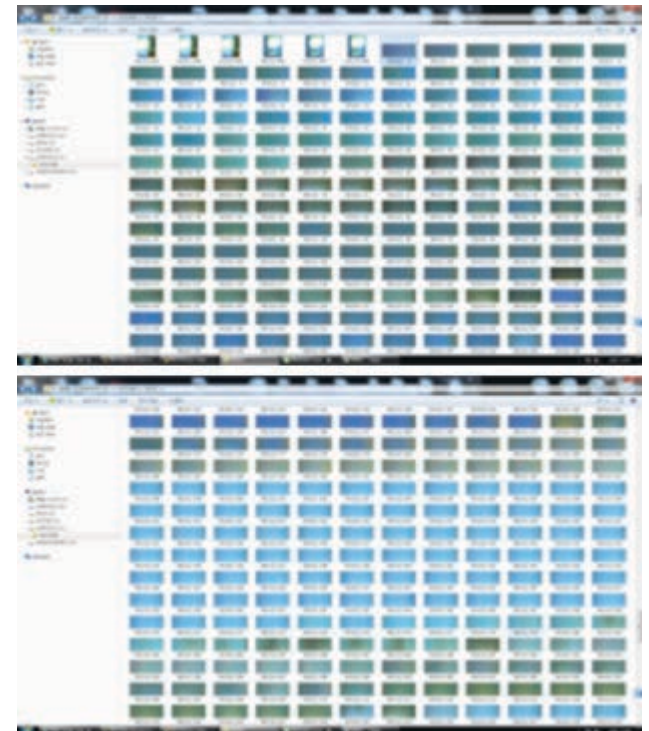
Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)

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.



(Composition DB)




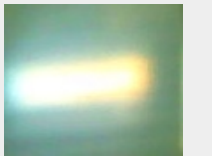



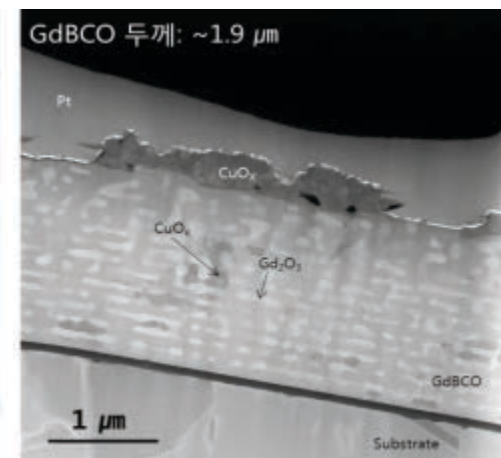
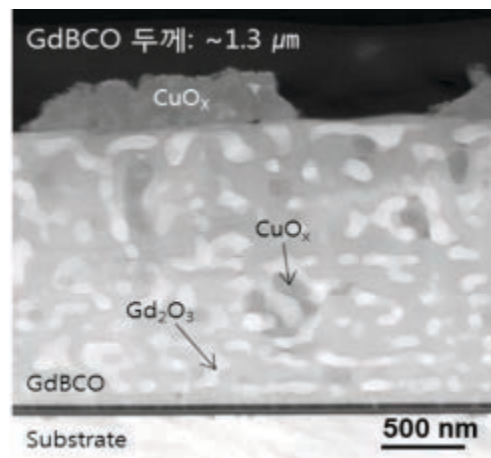
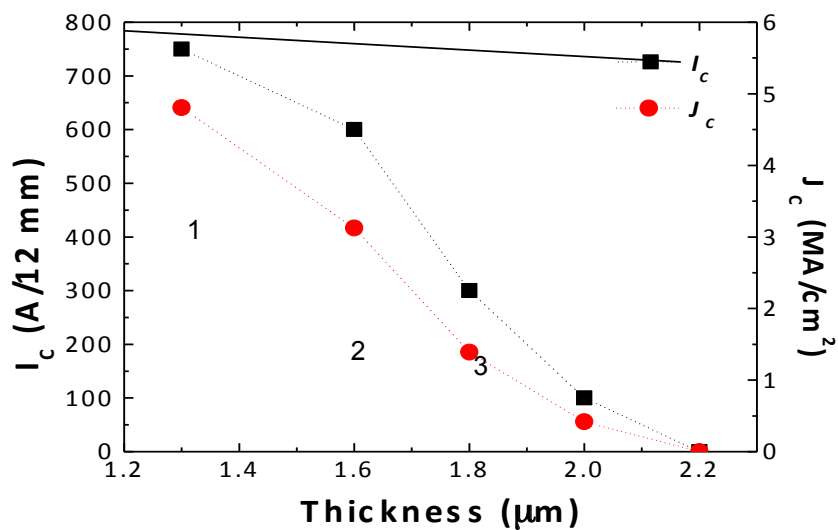
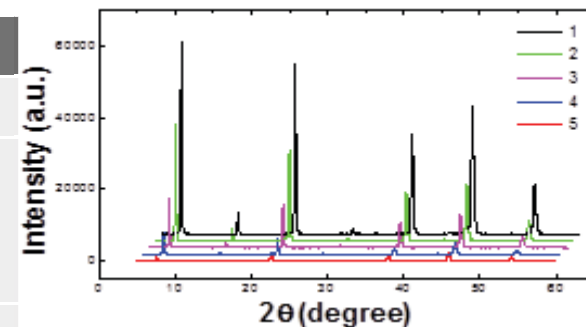


Higher J_e : Thicker S.C. layer

Normal RCE-DR process : before optimization

❖ Thickness dependence of I_c and surface color for GdBCO

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



As increasing the thickness, J_c and I_c are decreased.
 All the samples were prepared by same process speed.♪

● TEM analysis

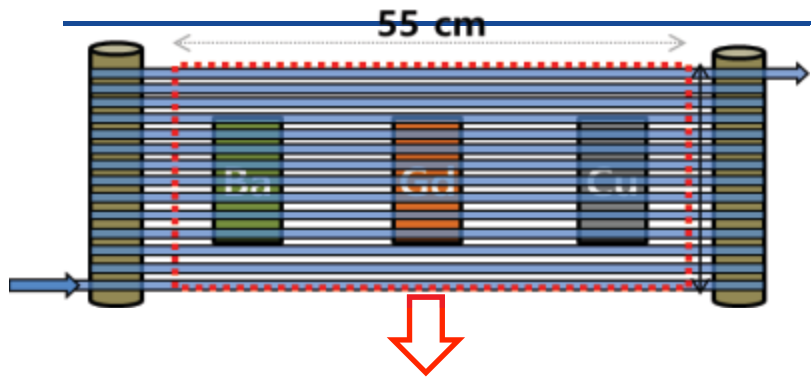
→ 1.3 μm -thickness:

Gd_2O_3 are randomly distributed

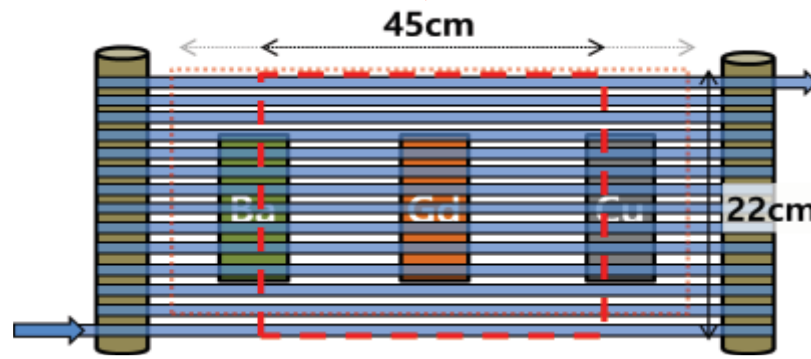
→ 1.9 μm -thickness:

Gd_2O_3 are distributed the boundary of the layers

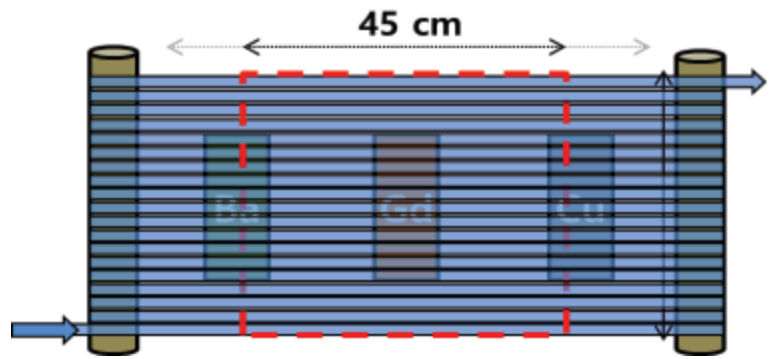
Optimization of deposition region for making thick GdBCO films



- 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 \rightarrow 19 turns)

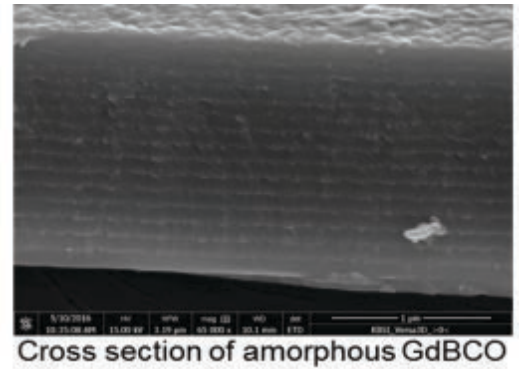


14 \rightarrow 19



	Normal	Optimization	
As increasing the thickness, J_c is decreased \Downarrow		Same total thickness Layer thickness is different	As increasing the thickness, J_c is not decreased \Downarrow

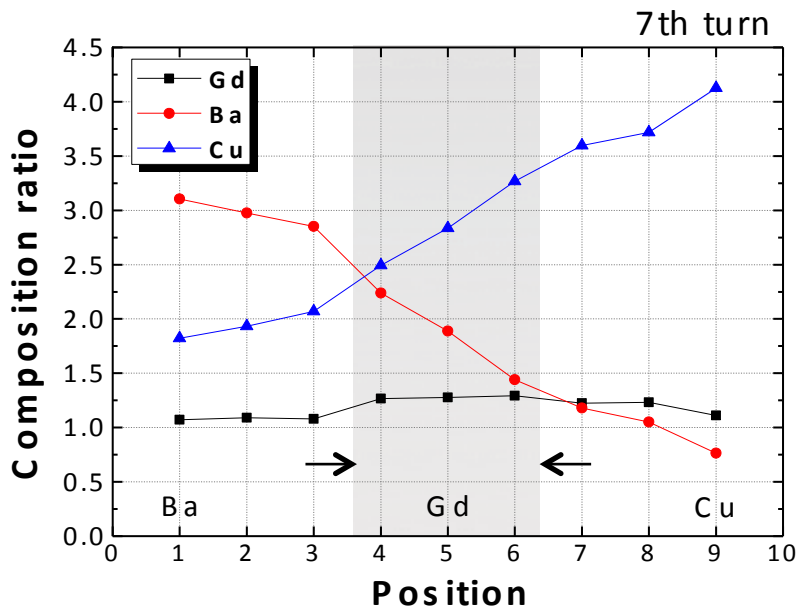
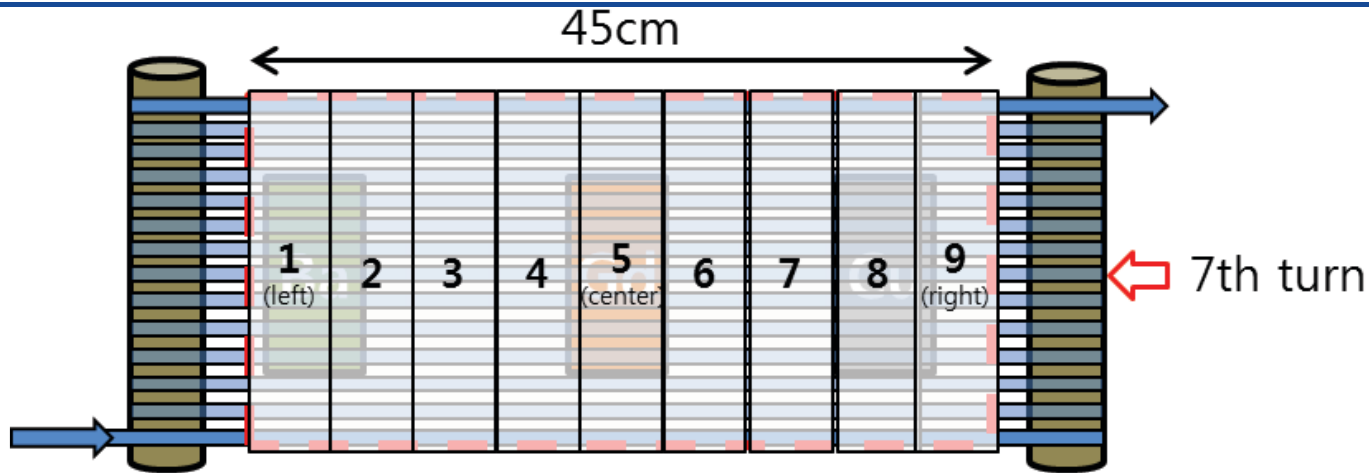
All the samples were prepared by same process speed. \Downarrow



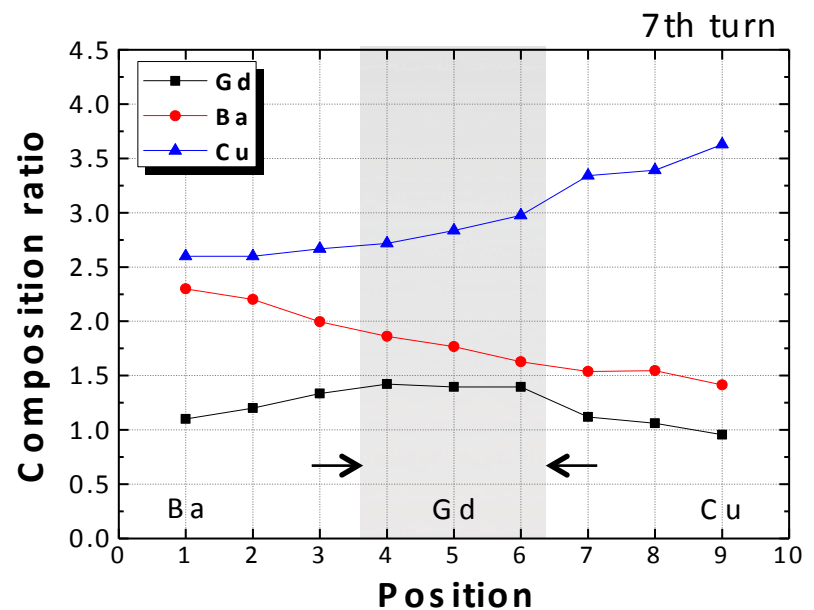
Cross section of amorphous GdBCO

1.6 μm -thick \Downarrow

Optimization of Deposition region

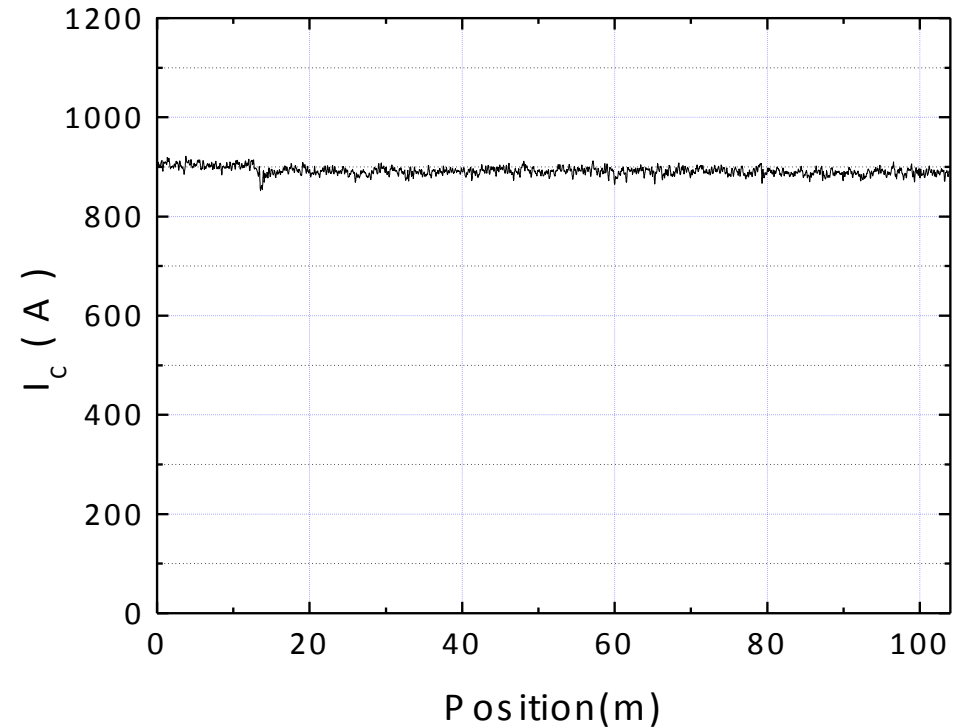
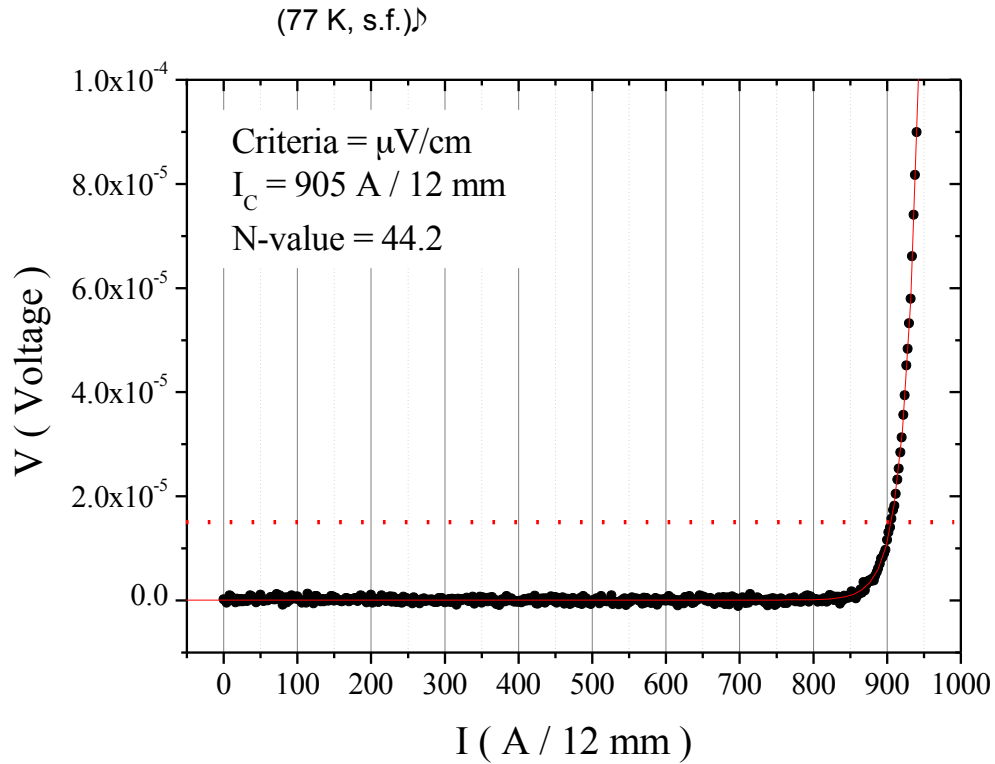


Distance between source and substrate : ~♪

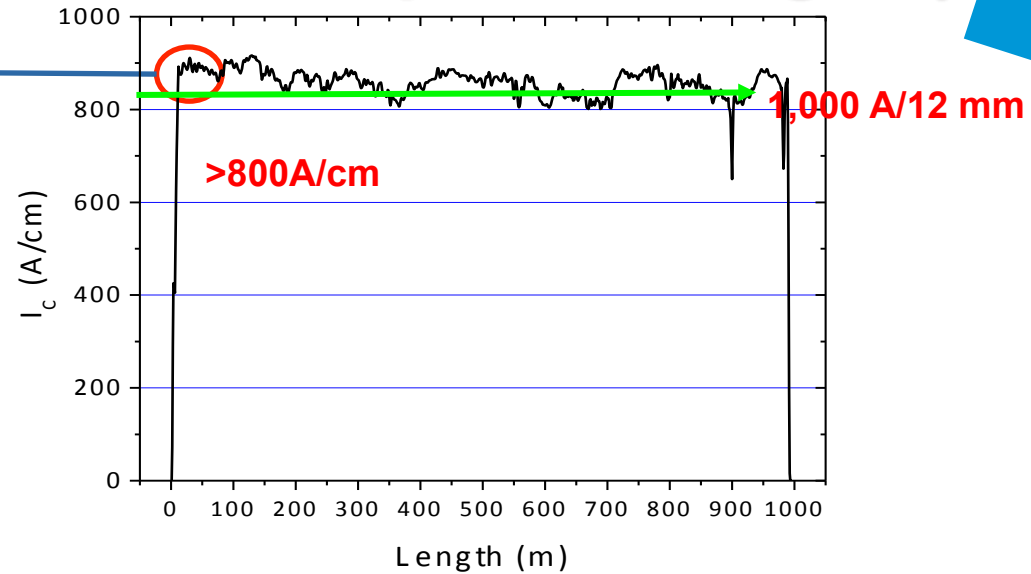
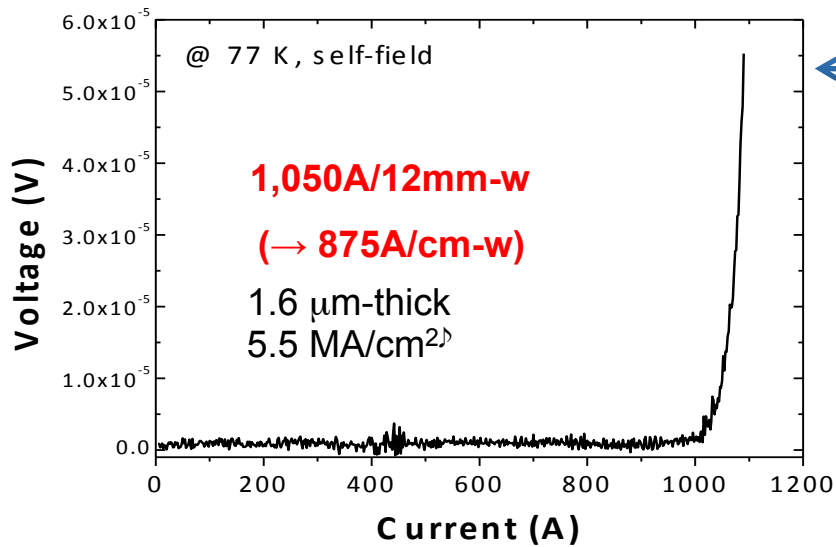


Distance between source and substrate : ~♪

Optimization of RCE-DR process for thick superconducting layer

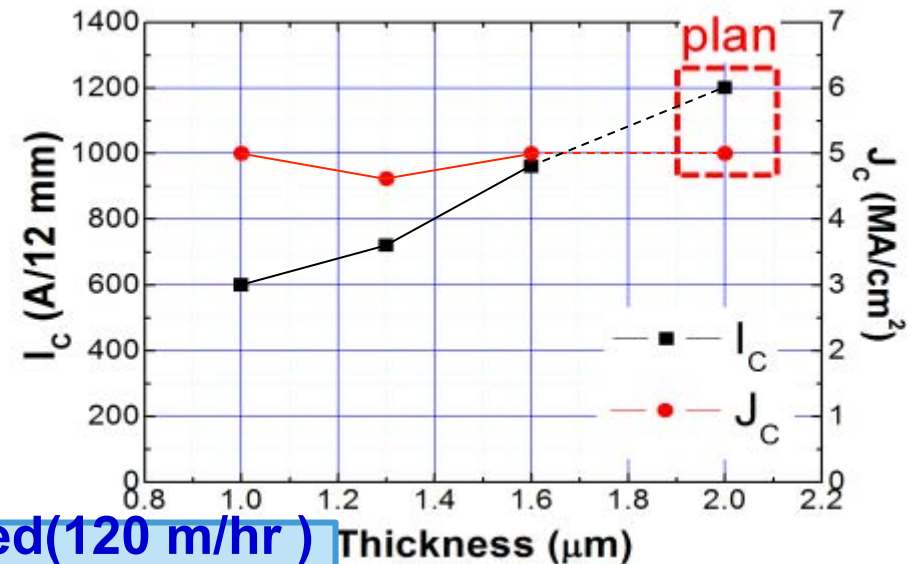


RCE-DR results (with optimization deposition region)



2016 Plan for making 400 A / 4 mm CC

	Speed (m/min)	Turns	Thickness (μm)	I_c (A/cm)	J_c (MA/cm^2)
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



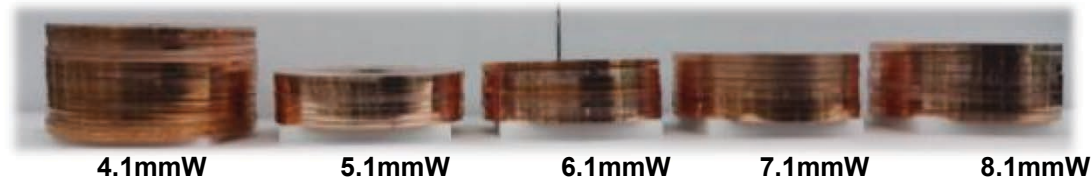


MCI(Metal Clad Insulation) 2G wire f or high field magnet

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

No-insulation, multi-width, and compact !

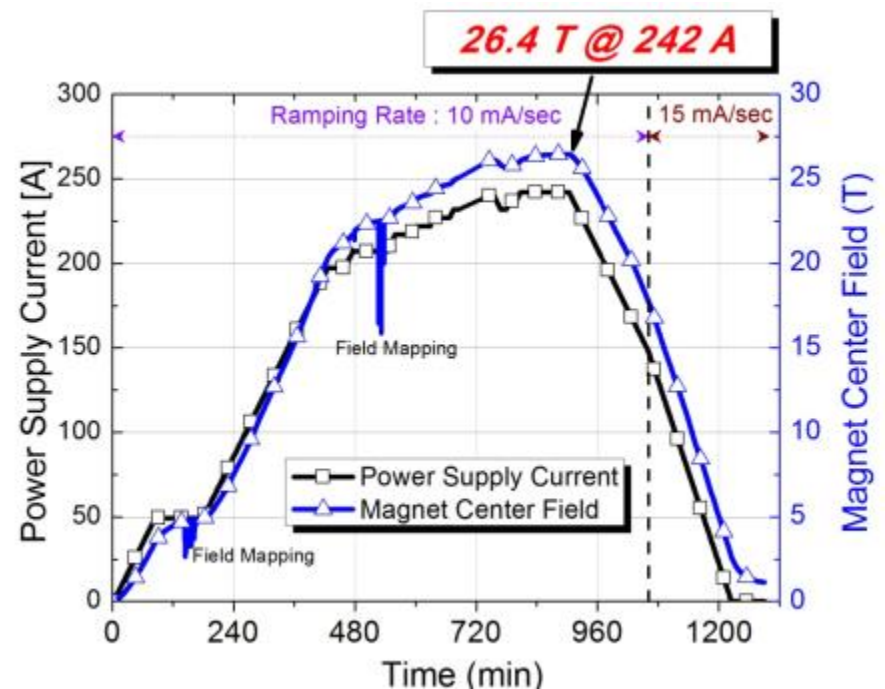
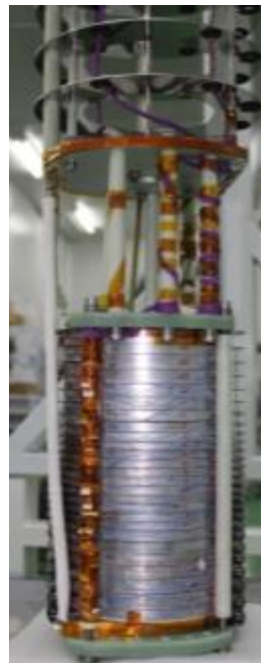
- ✓ Multi-width Double Pancake Coils



- ✓ Stacked Double Pancake Coils

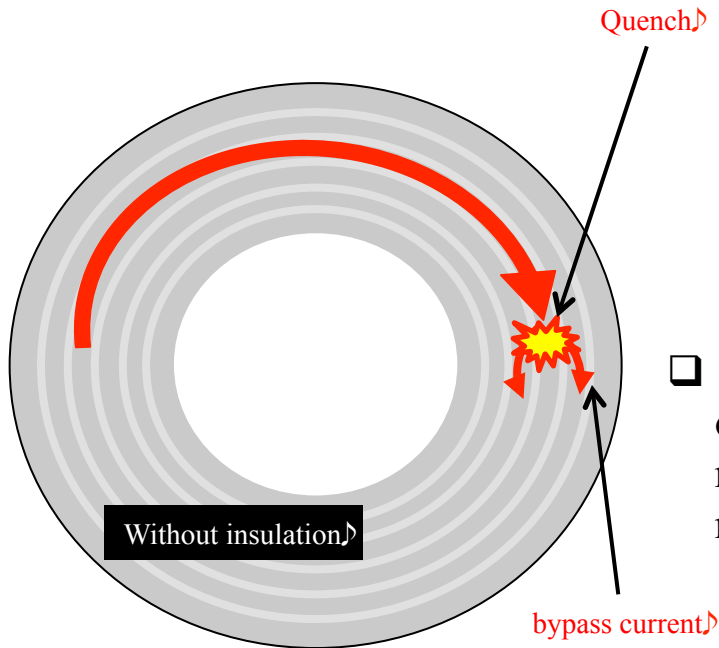


- ✓ Fully assembled

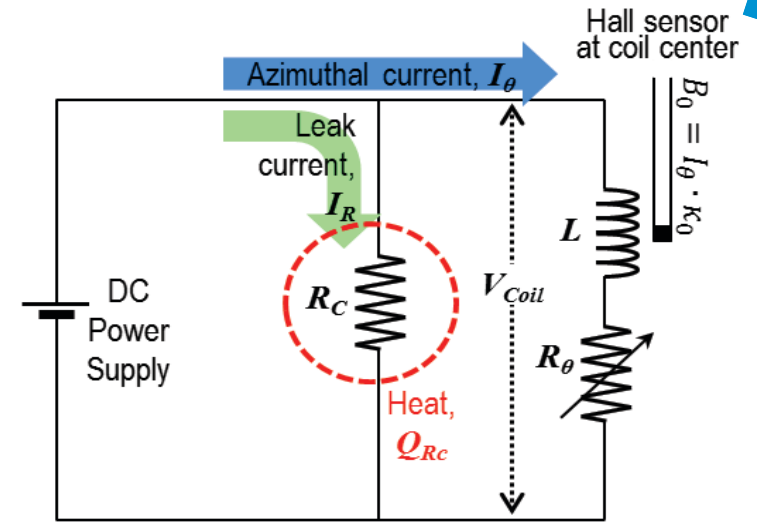


Immersed in liquid Helium

NI-MW winding technic – No insulation♪



☐ **“Automatic bypass”**
of the exceeding current and better protection to quench



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

where, $I_R = I_{PS} - I_{\theta} = I_{PS} - B_{10} / k_{10}$ ♪

No-insulation winding technic :

Pros :

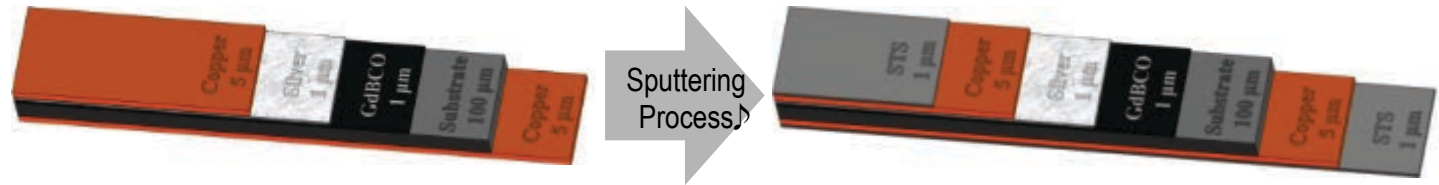
- ✓ Compactness : without thick stabilizer
- ✓ Strong mechanical strength : without soft insulation material
- ✓ Self protection : automatic bypass
- ✓ Rapid quench propagation

Cons :

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

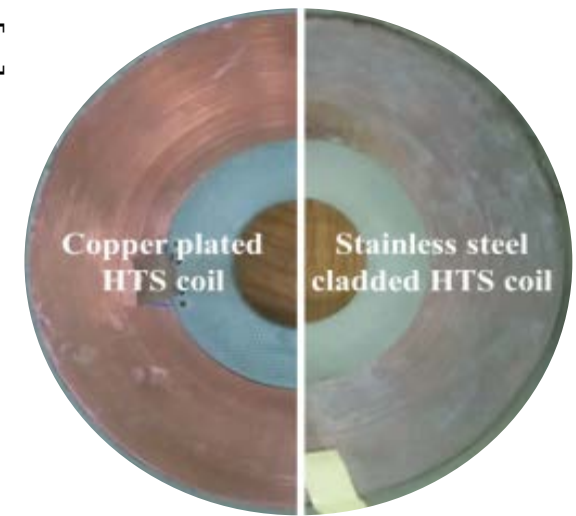
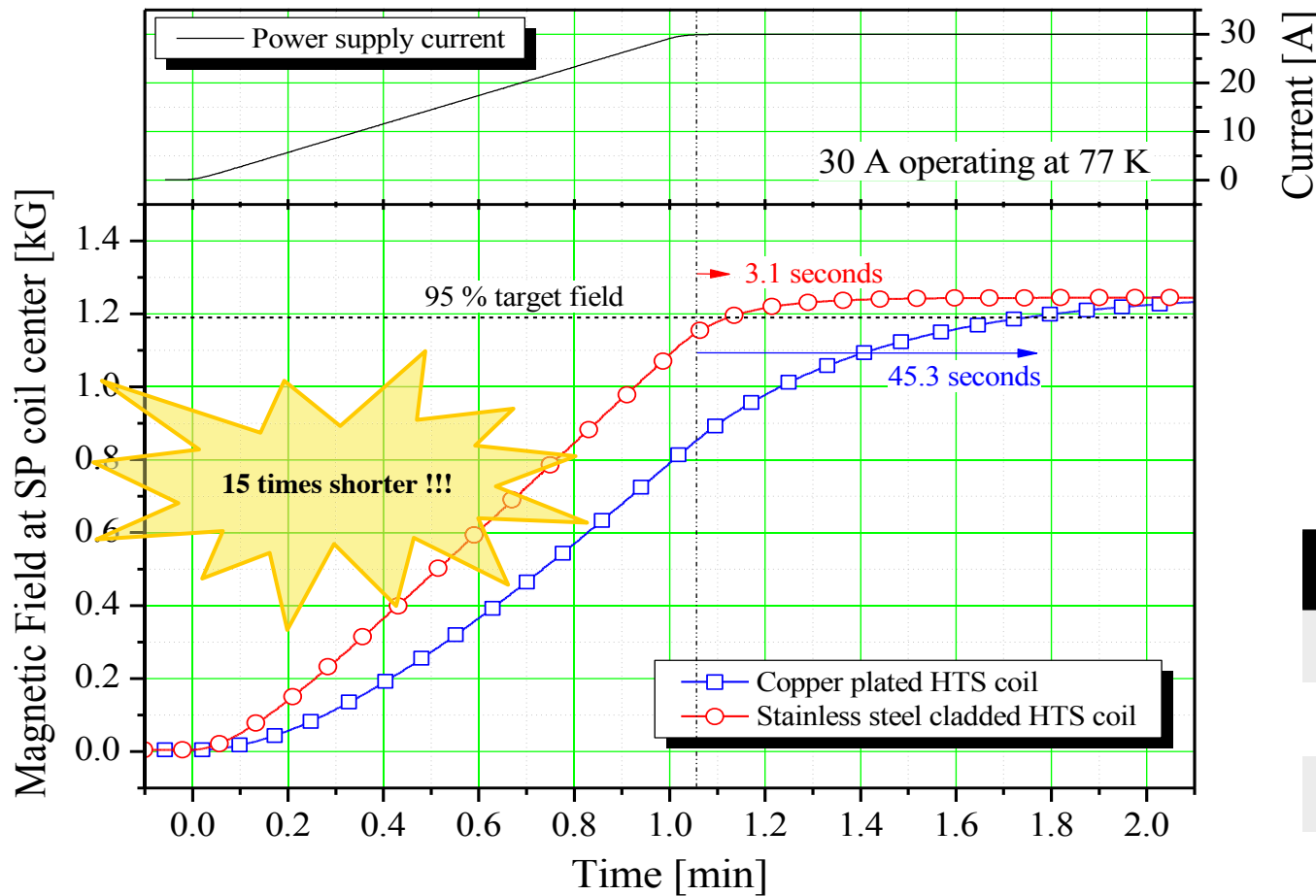
♪

Metal Clad HTS 2G wire & coil



< Copper plating CC tape >

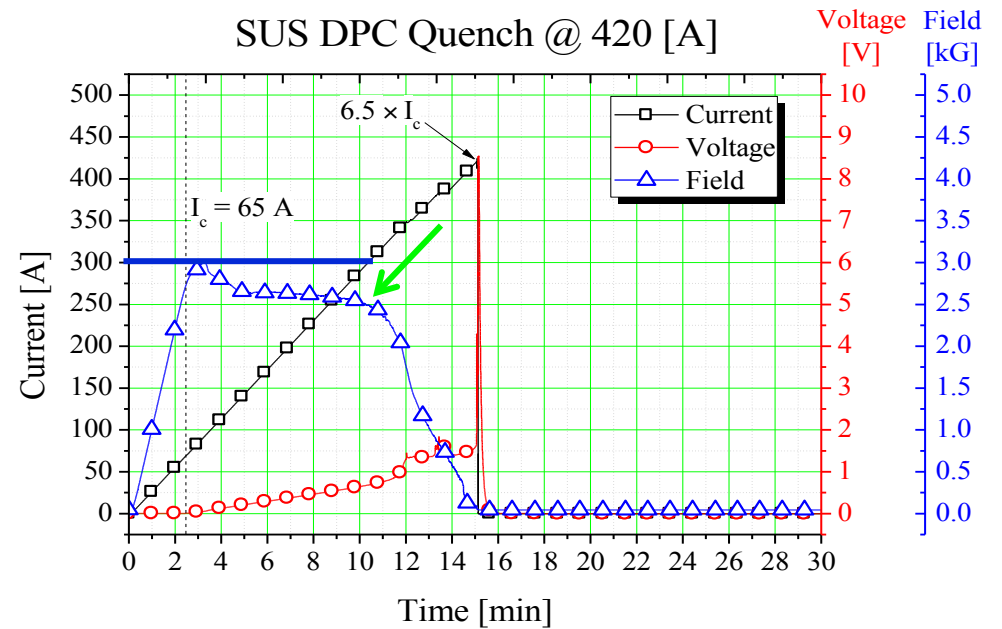
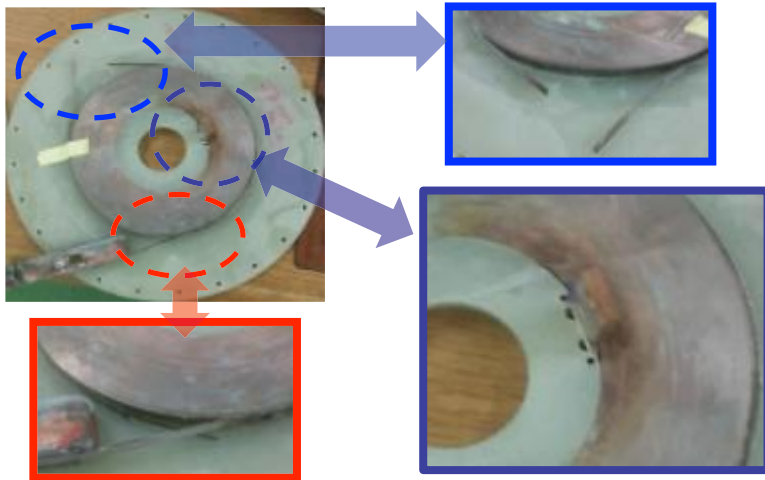
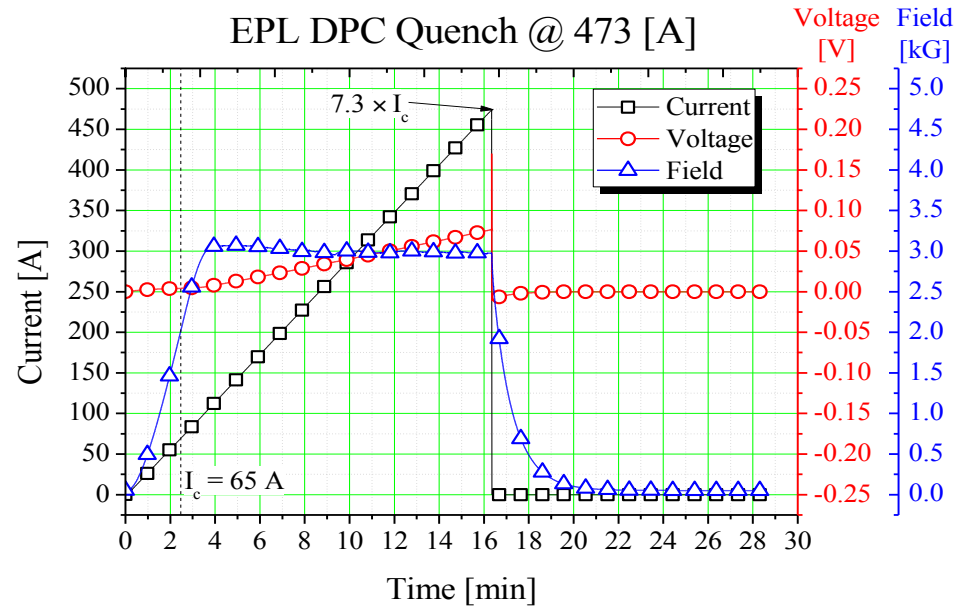
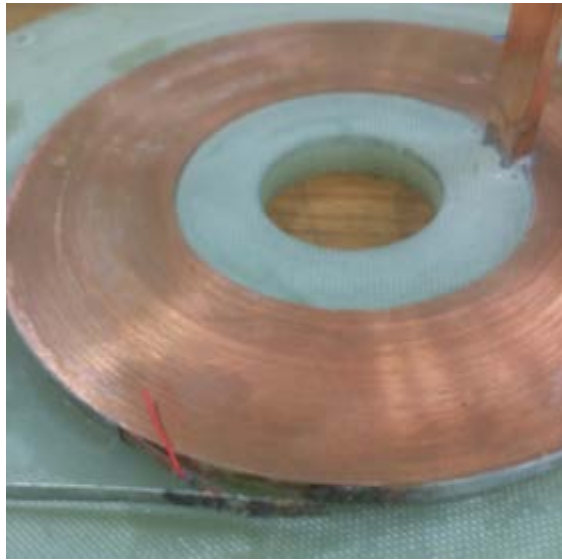
< Stainless steel cladding CC tape >



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

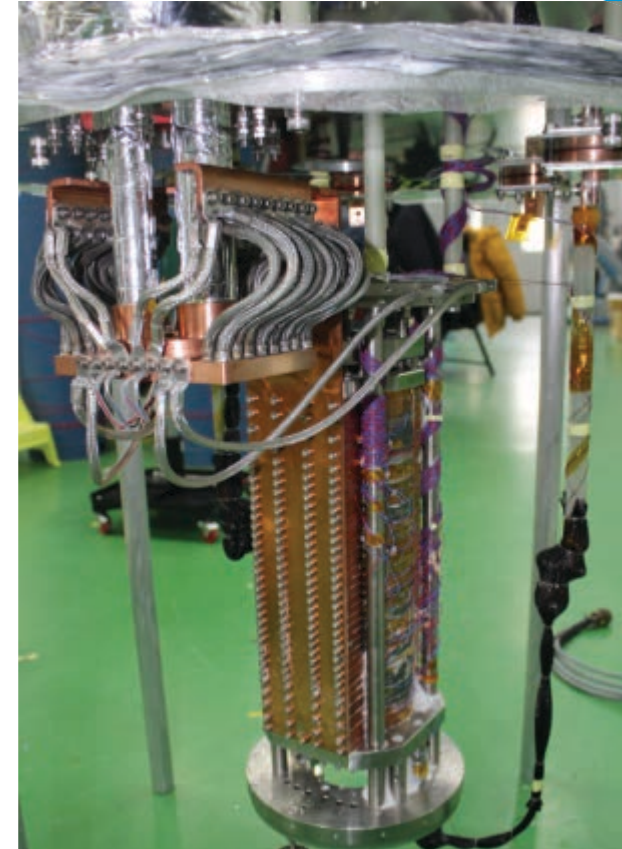
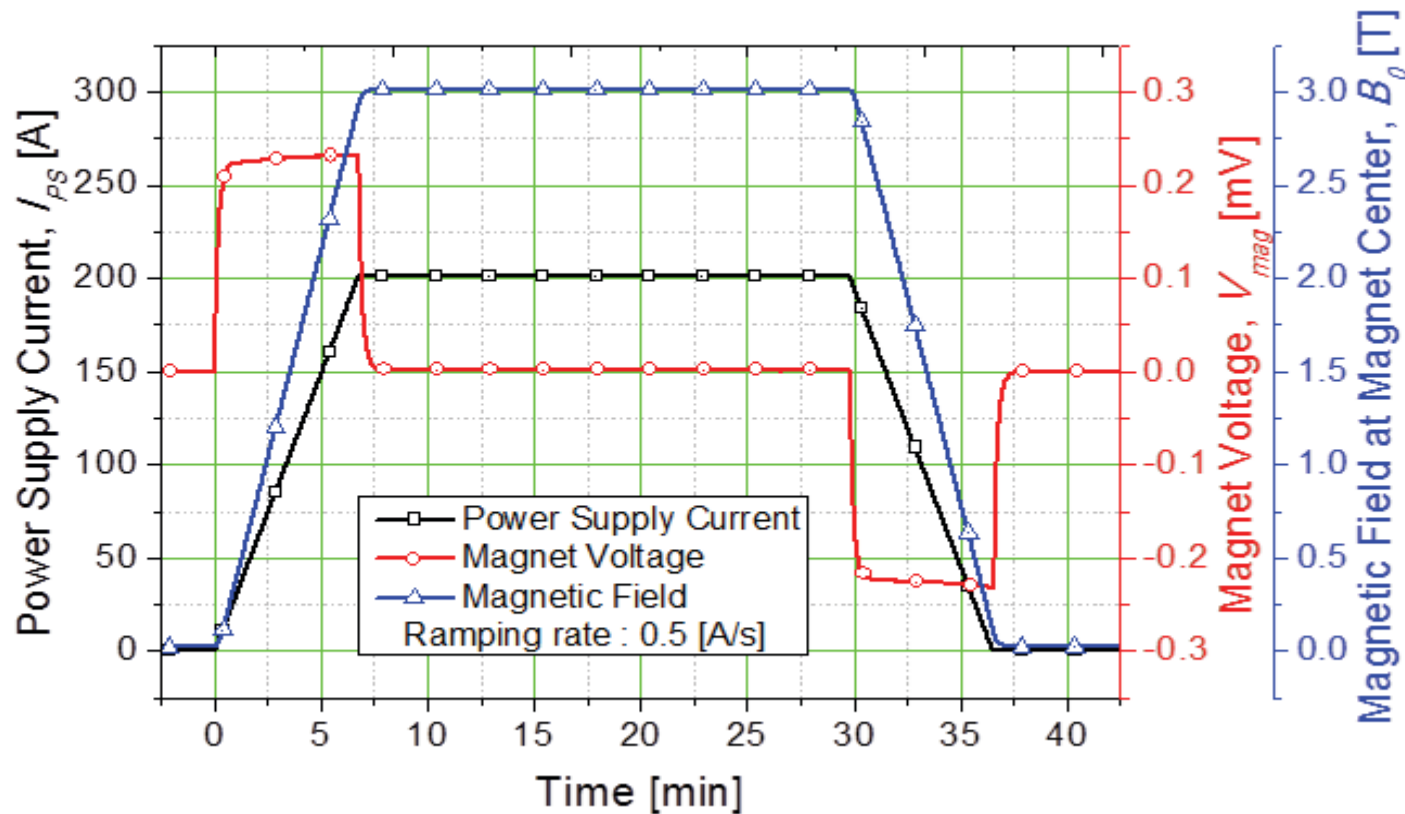


Burn out test @ 77 K (SPC with Copper stabilizer vs. MCI)



Magnet Operation Results

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



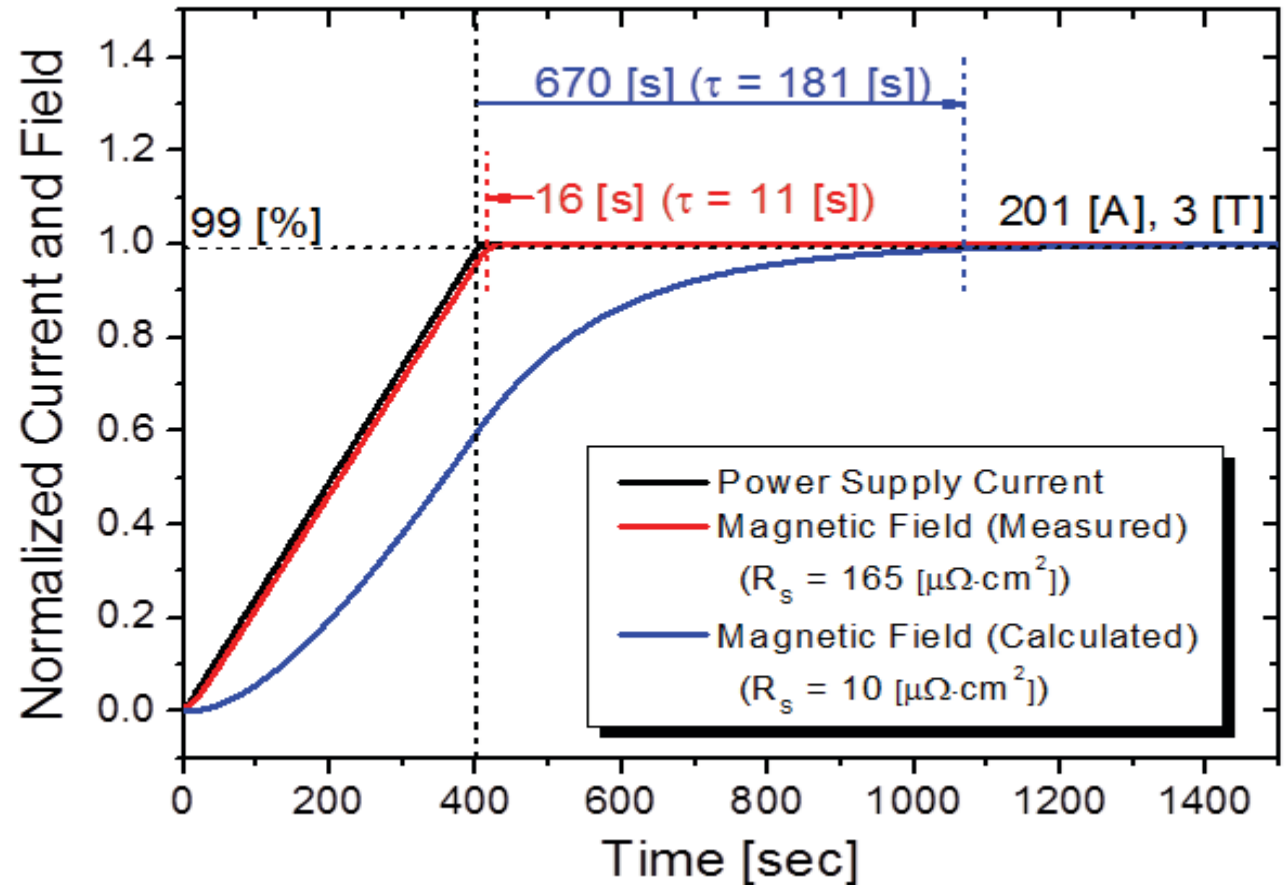
➤ Time constant, τ , is calculated to 11 seconds.

➤ Contact resistance between turns, $R_{S,STS} = 165 [\mu\Omega\cdot\text{cm}^2]$

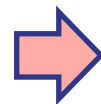
Reduction of Charging Delay

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

If magnet was wound with copper plated tape,



STS cladded tape

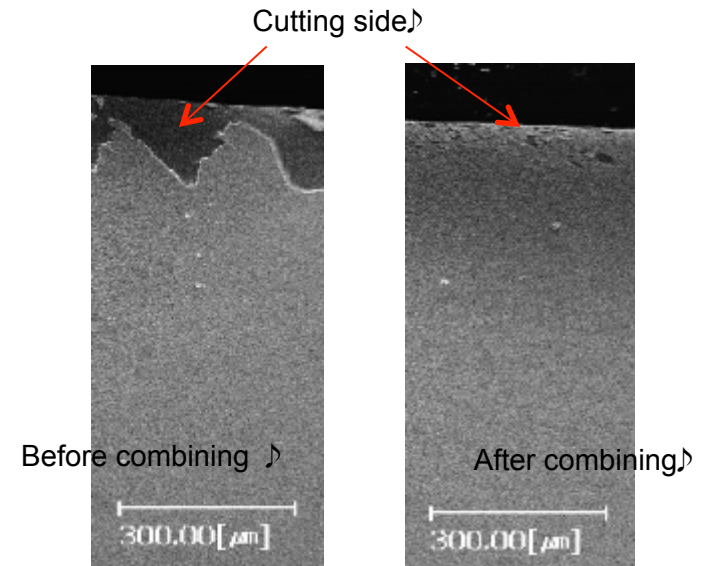
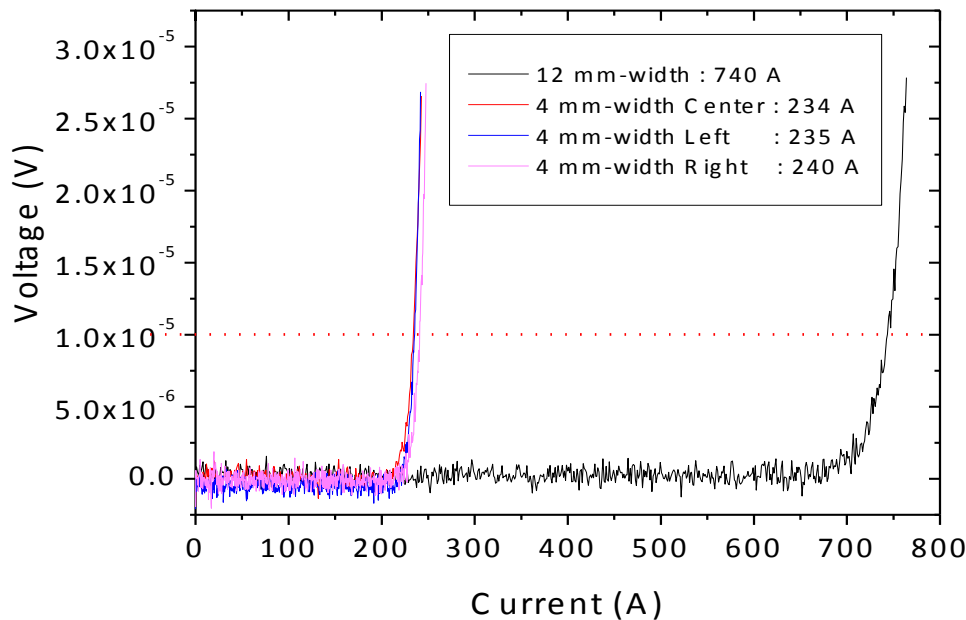
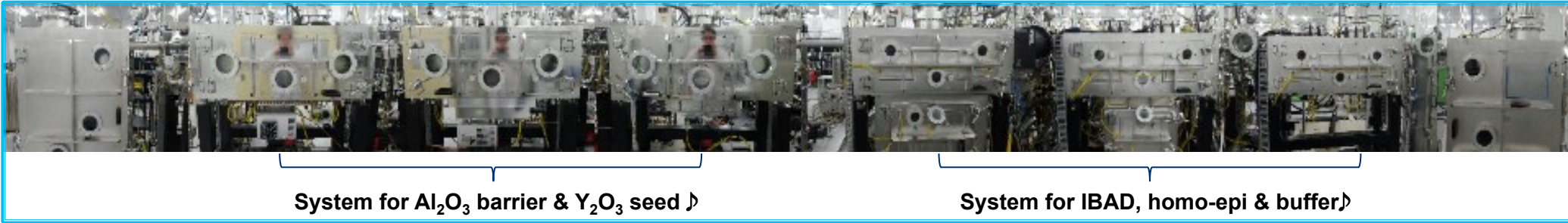


Charging time is **41 times shorter**♪



Higher Je : metal substrate removal process

Combining Barrier, Seed, IBAD, Buffer Systems in One

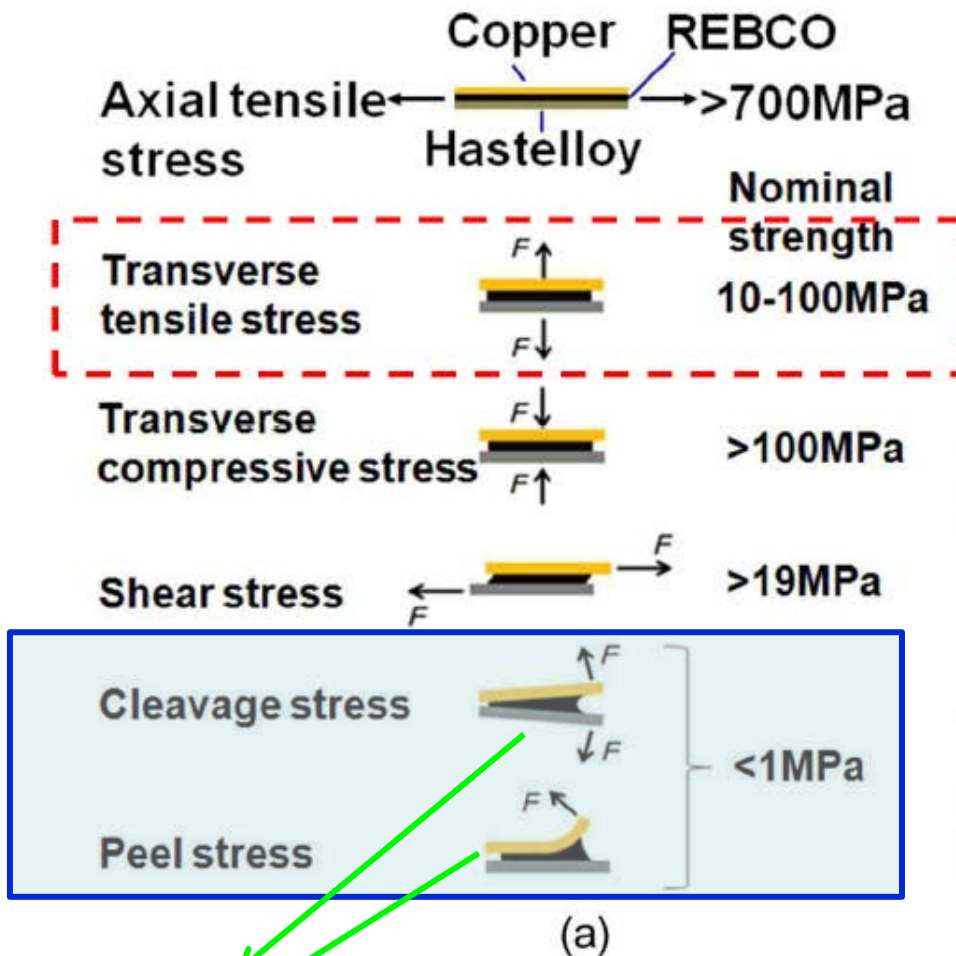


For standard process,
 Stainless steel ~ 100 μm thick
 Hastelloy ~ 60 μm thick

Stress limits for HTS tapes under various loading conditions

REBCO conductor

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?

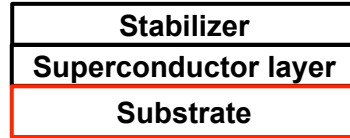
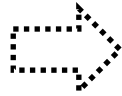
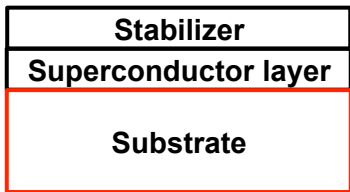
• Significantly weaker in out-of-plane loading conditions

- major concern especially in superconducting coils and magnet application designs

Utilize this properties !!

High Je wire by removal of thick metal substrate

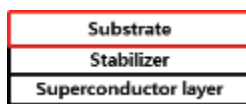
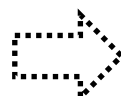
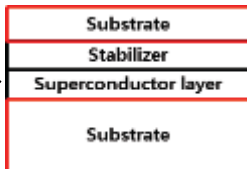
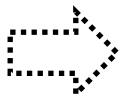
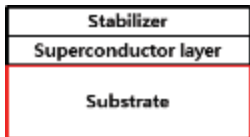
For Je, substrate thickness must be thin



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

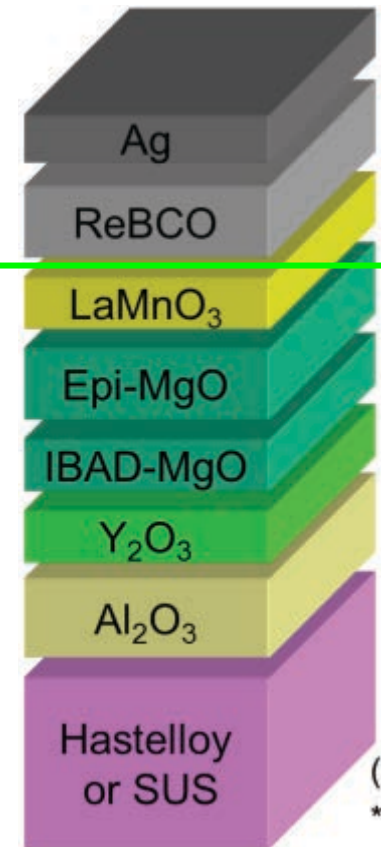


Improvement of Je



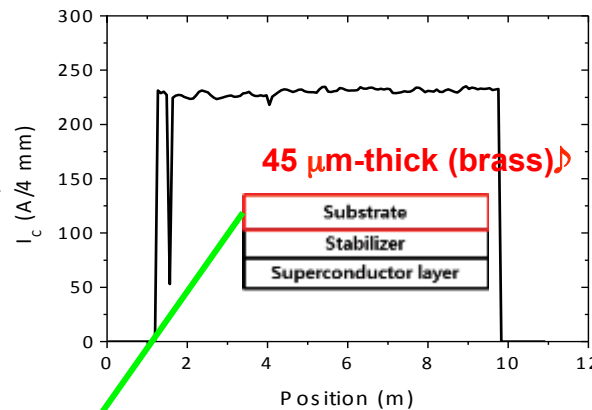
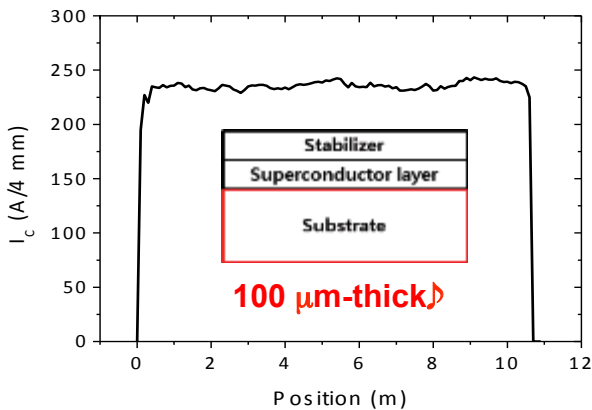
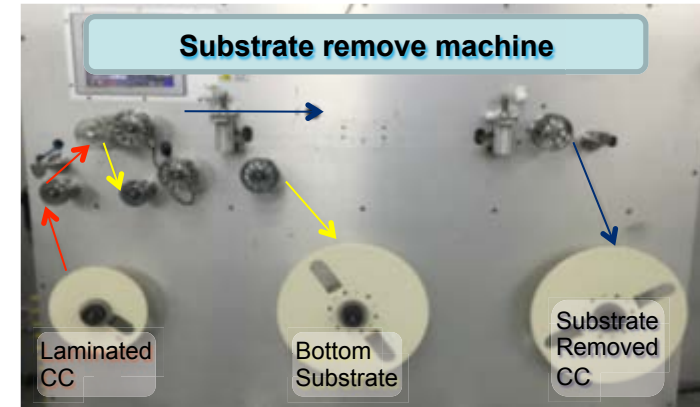
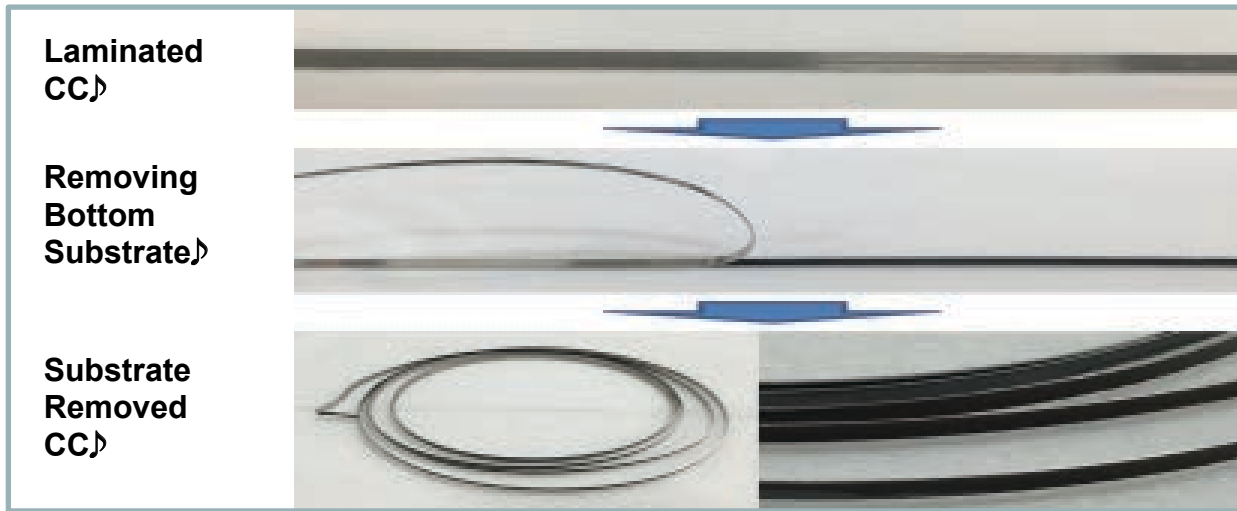
Soldering thin substrate on top of CC

Remove bottom substrate



Intentionally making a weak interface by some treatment

Demonstration of High Je wire by removal of thick metal substrate



May possible...

	Laminated Substrate
	Stabilizer
	Superconductor layer
2 μm	Superconductor layer
5 μm	Stabilizer
20 μm	Laminated Substrate

- Easily reduce the thickness $\sim < 20 \mu\text{m}$
- Choice of any materials(SUS, Copper...)

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 ($1.3 \mu\text{m} \rightarrow 1.6 \mu\text{m}$) S.C. layer, we achieved $>1,000 \text{ A}/12 \text{ mm}$ in production.
- We demonstrated 3 T magnet using MCI coated conductor.
- Initial test of substrate removal & suggesting a new way of high J_e wire structure.

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 ”

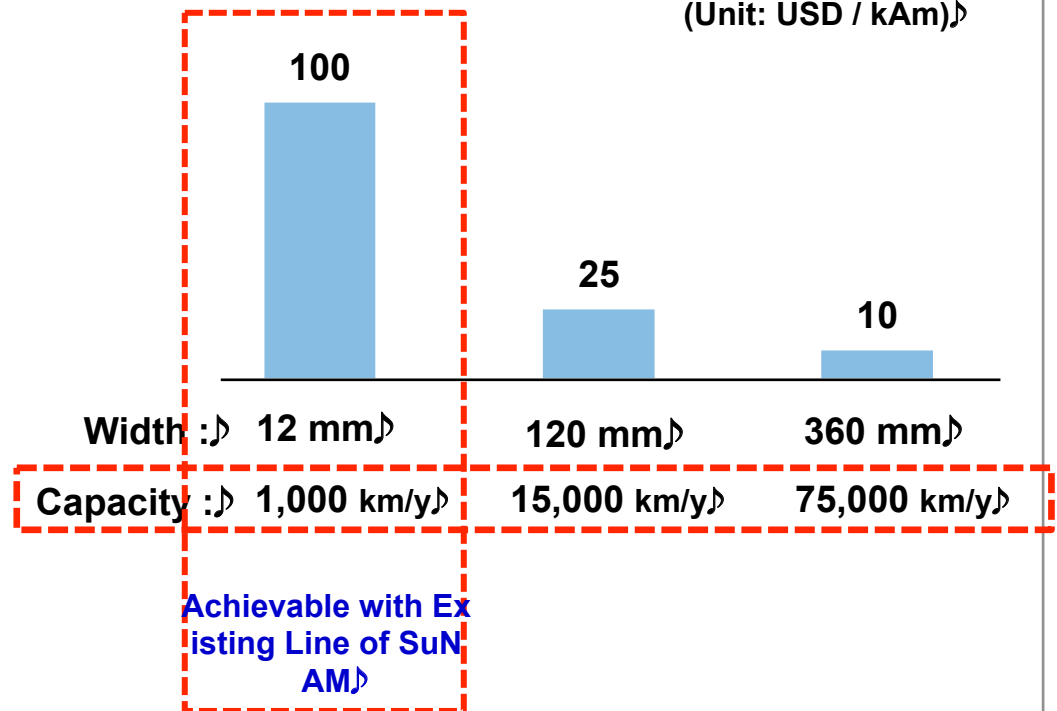
“Price Reduction will ignite an exponential growth of demand for HTS 2G wire”

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

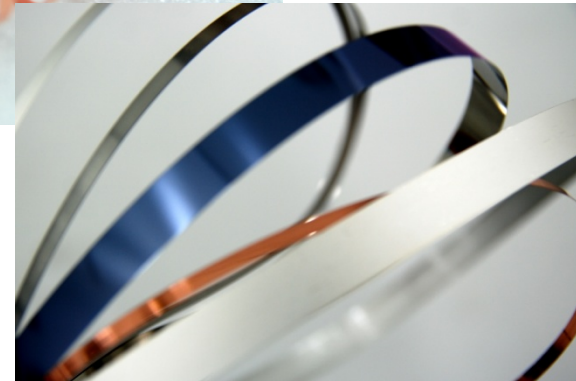
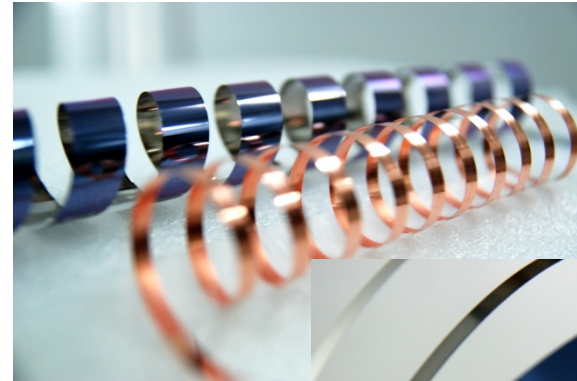
Price Reduction in RCE DR proces

s♪

(Unit: USD / kAm)♪



Thanks for Attention !



www.i-sunam.com

Acknowledgement

- SuNAM : J. H. Lee, H. K. Kim, B. J. Mean, Y. S. Kim, S. W. Yoon, K. K. Cheon, and H. J. Lee.
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***Thanks for
Attention !***