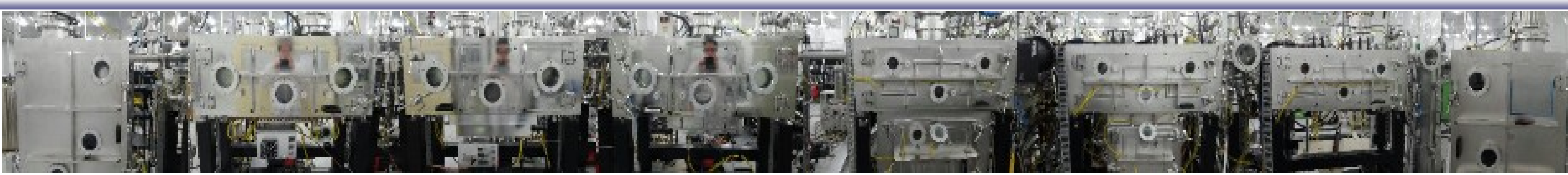
Recent Highlights from SuNAM;
HTS Conductor & Magnet



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SuNAM Co., Ltd.

2017. 1. 19.

"Accelerator Physics" Meeting, Hong Kong

SuNAM

Superconductor, Nano & Advanced Materials

Contents

- SuNAM's coated conductor; architecture, characteristic.
  - Quality control tools for uniformity and yield
- Higher I_C : Thicker S.C. layer → 1.6 μm, >1,000 A/12 mm.
- Higher J_e : metal substrate removal process.
- SuNAM's HTS magnet activity
- Summary

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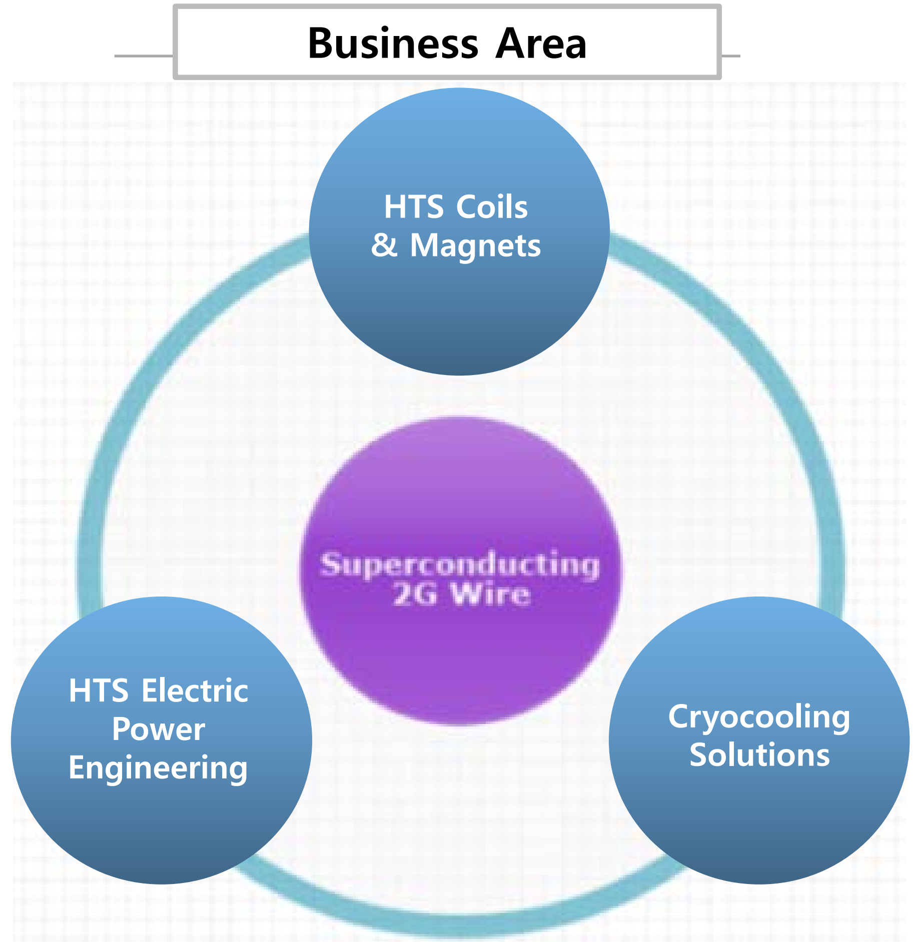
Company Overview

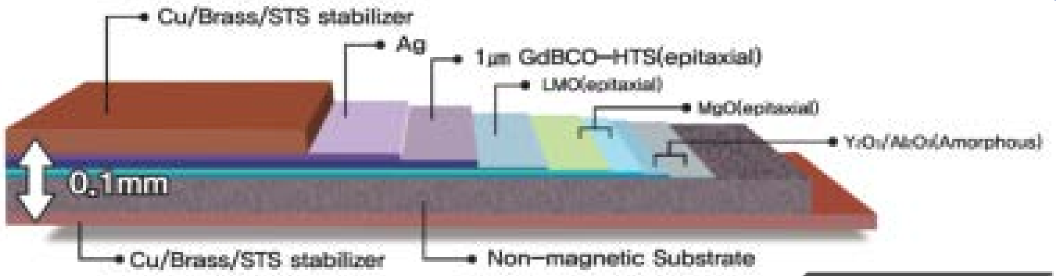
SuNAM : Superconductor, Nano & Advanced Materials (서남, 瑞藍)

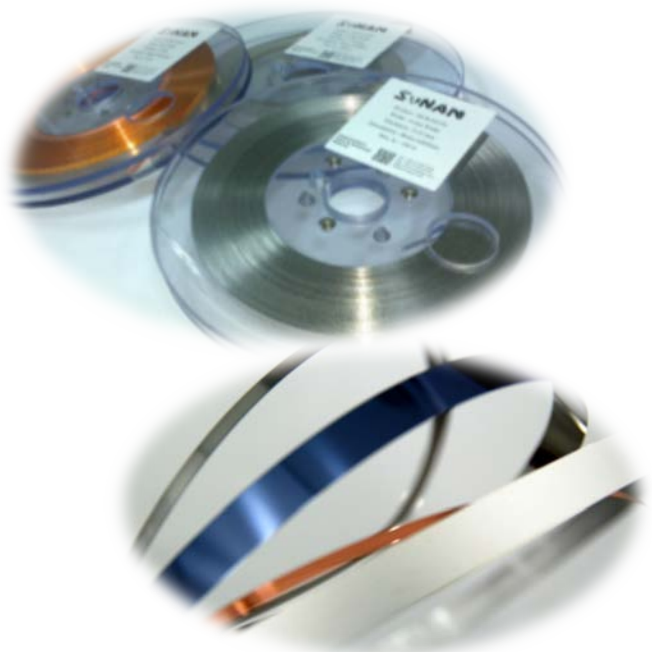
Establishment	2004. 11. 17., for commercialization of HTS wire
CEO	Seung-Hyun Moon
Registered Capital	~$6M
No. of Employees	~ 33 (7 Ph.Ds)
H.Q.	Gyeonggi-do, Korea
Current Production Capacity	~ 60 km / month (4 mm > 150 A)
Core Technology	2G HTS manufacturing technology based on RCE-DR process

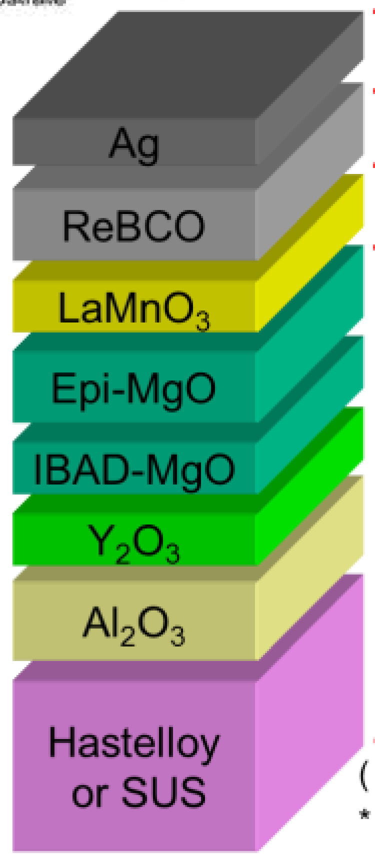


SuNAM’s Coated Conductor

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

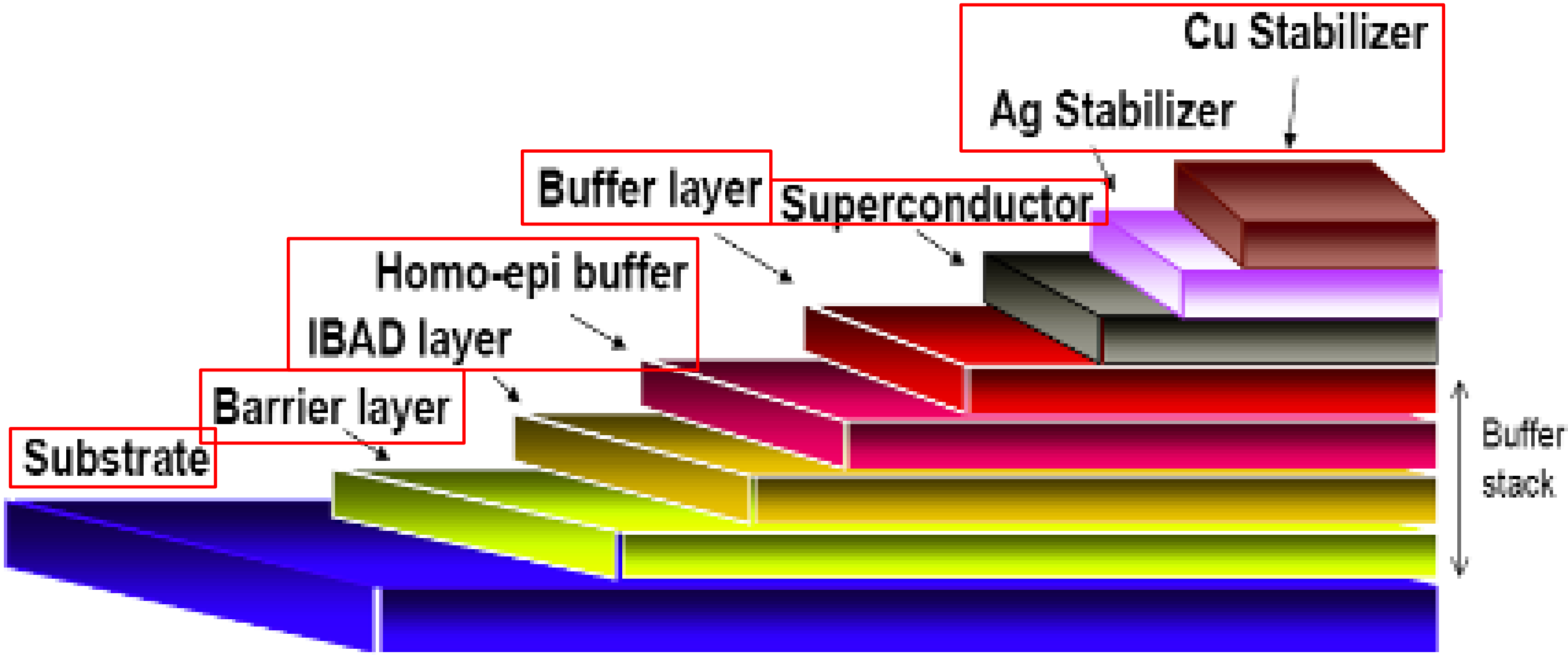
(+ Cu electroplating (+ lamination))

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

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

Coated Conductor (2nd G. Wire)

- Superconductor, the main ingredient
- Metal substrate, which gives mechanical strength & flexibility
- Needs good crystallinity for higher current conduction
- Lattice constant mismatch should be small
- Metal diffusion at high processing temperature should be avoided
- Current should by by-passed at quench (breakdown of superconductivity)



Not to scale

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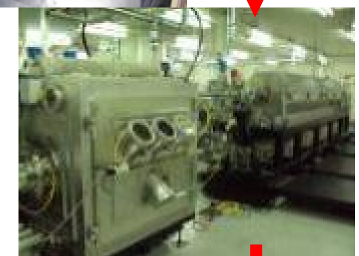
Production facilities

- Site area : 5,500 m^2,
  Building area : 1,750 m^2,
  Gross floor area : 3,050 m^2.

- Class < 10,000 clean room area : 1,000 m^2 .



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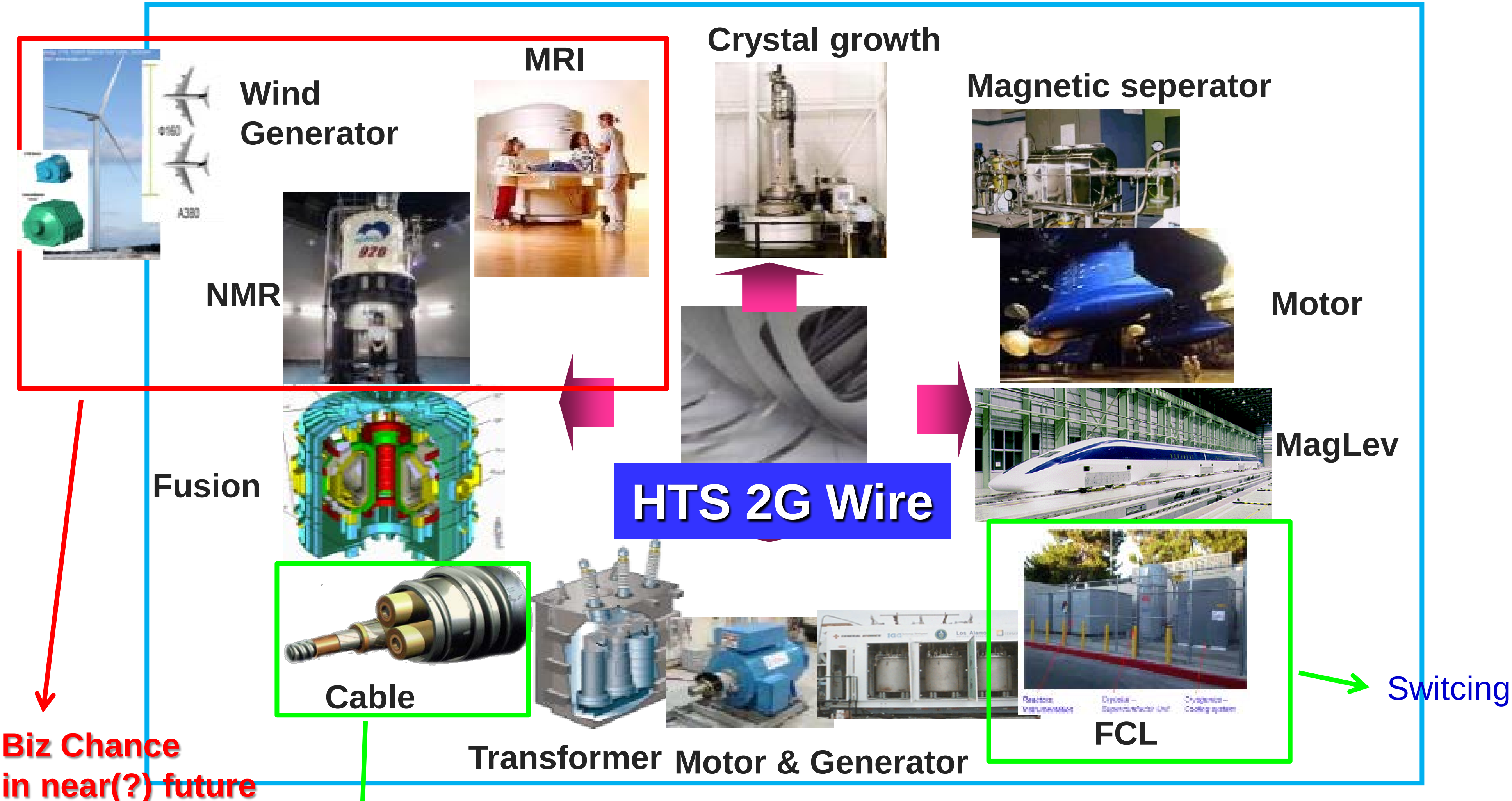
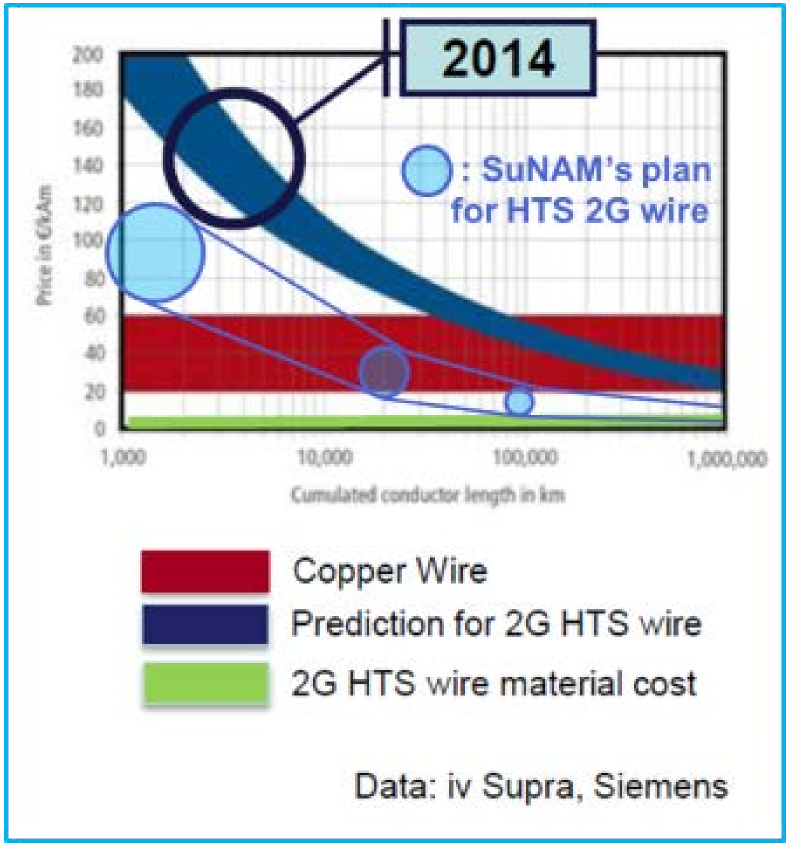
- Production capacity ~ 60 km/month(4 mm width) considering the yield(~ 70 %)

Applications of HTS wire



- 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

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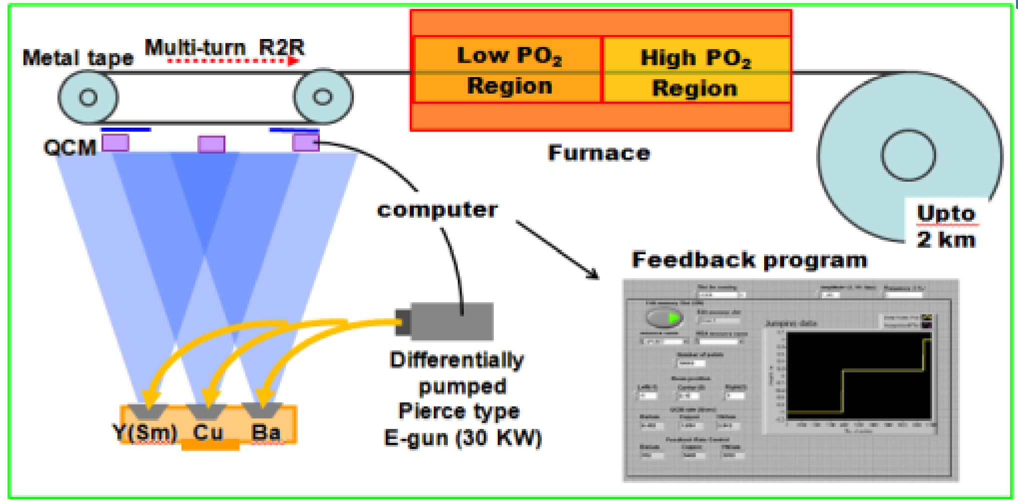
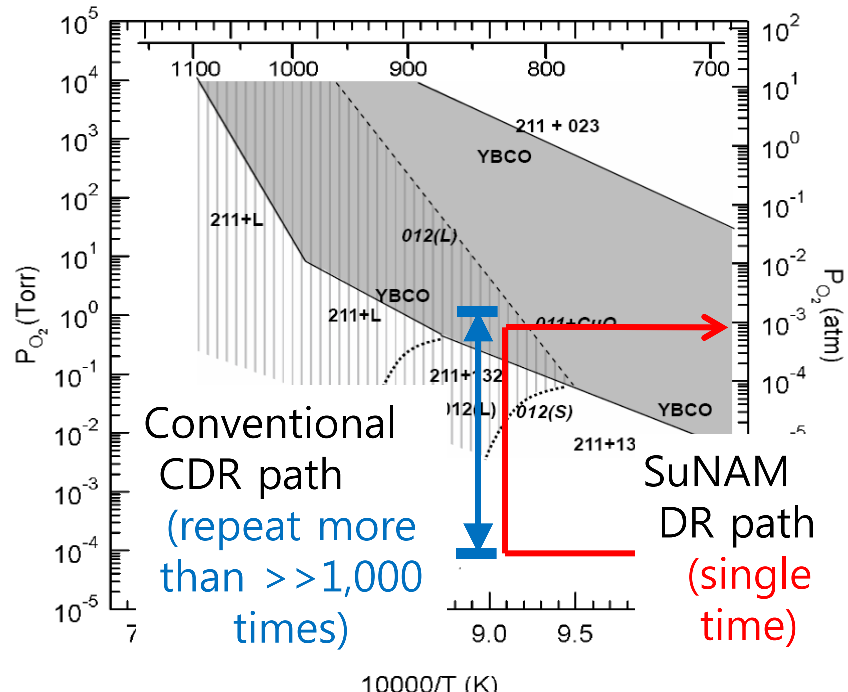
- RCE-DR process : easy to scale-up to wide strip.

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





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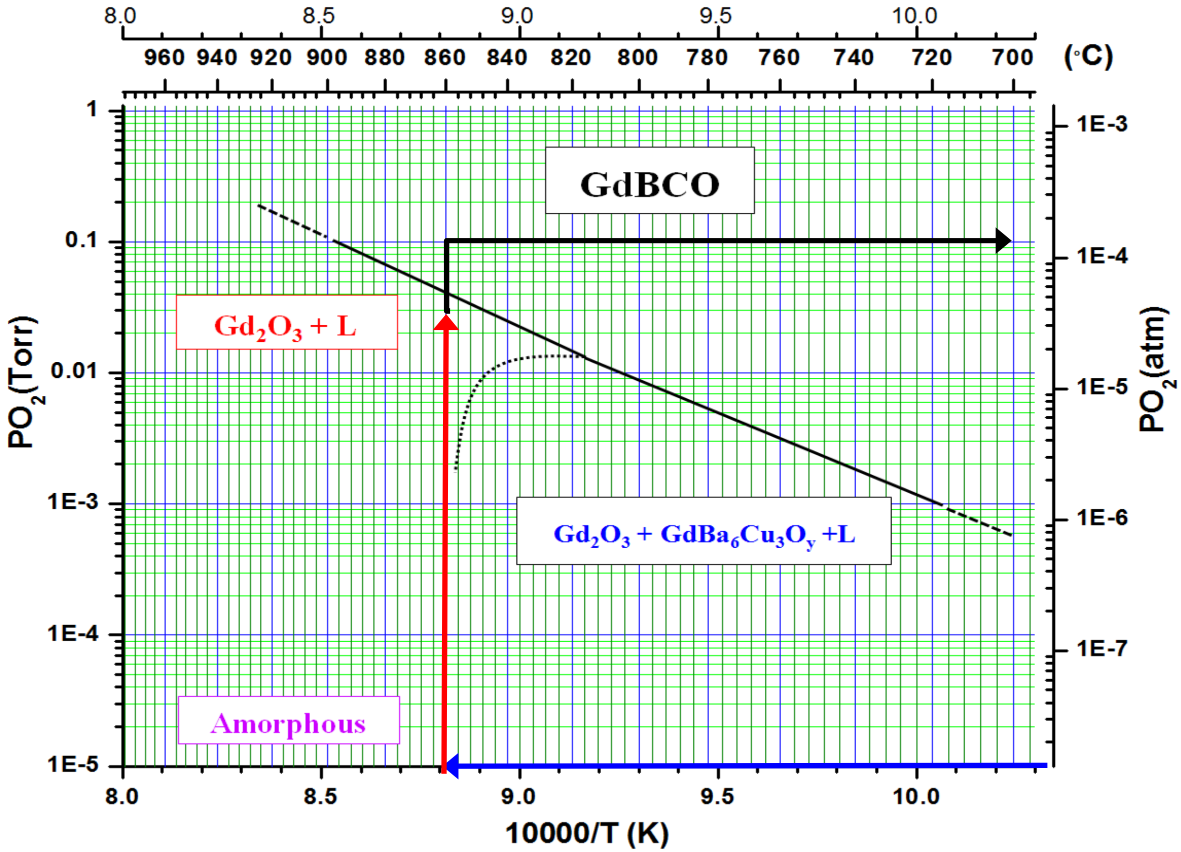
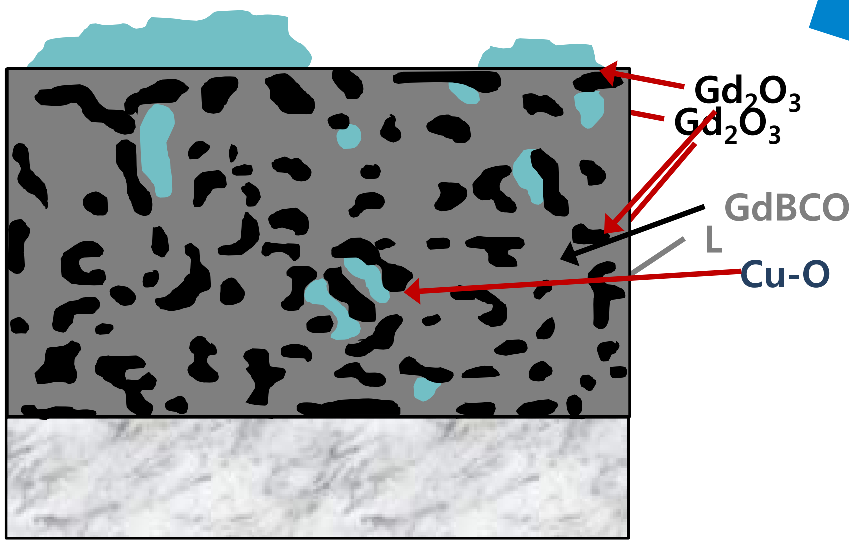
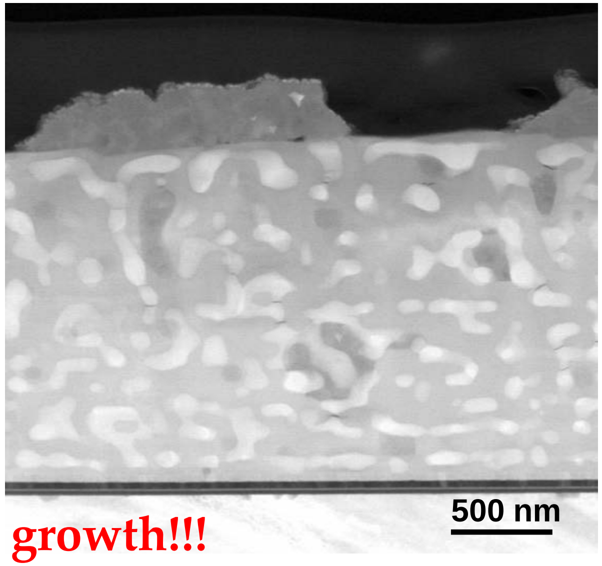
Growth mechanism of the GdBCO film by RCE-DR



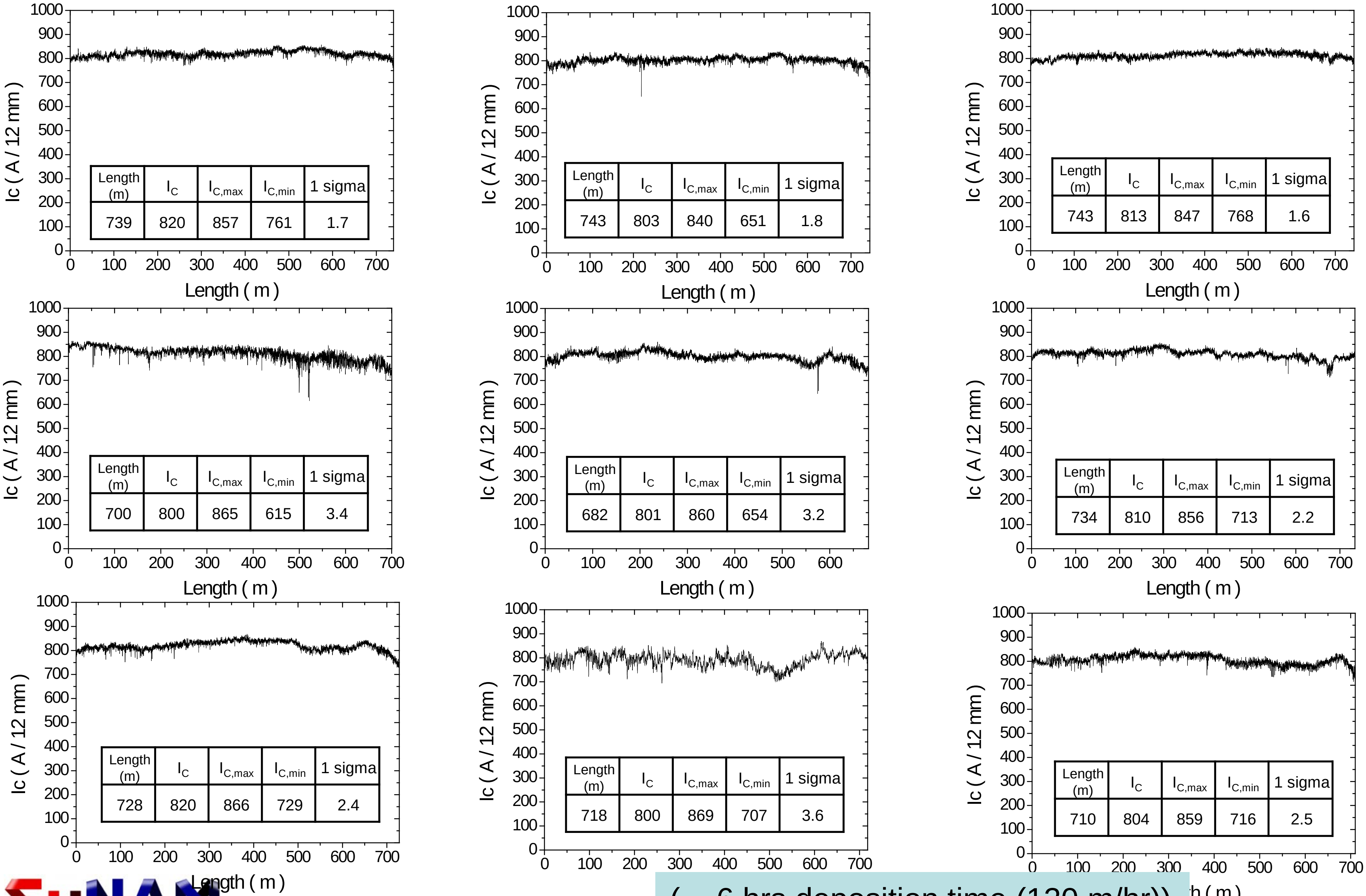




- Very low *PO*$_2$ zone (~ 10^{-5} Torr): **Amorphous Film**
- Lower *PO*$_2$ zone (~30 mTorr): **Gd_2O_3 + Liquid (< 5 sec)**
- Higher *PO*$_2$ zone (~100 mTorr): **GdBCO Film (< 20 sec)**

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

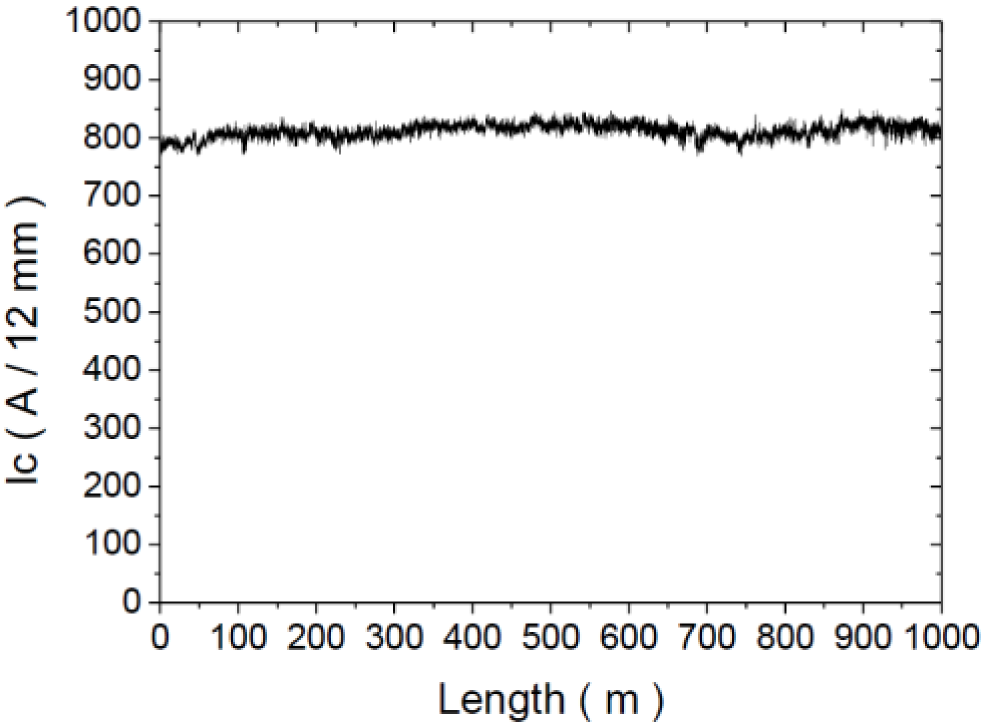
Daily Production 2G wire performances

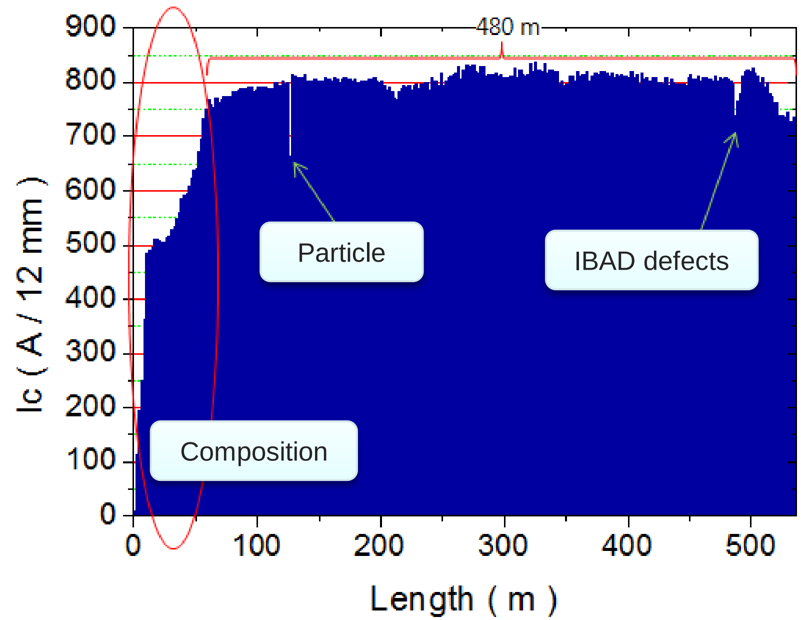


Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
739	820	857	761	1.7
743	803	840	651	1.8
743	813	847	768	1.6
700	800	865	615	3.4
682	801	860	654	3.2
734	810	856	713	2.2
728	820	866	729	2.4
718	800	869	707	3.6
710	804	859	716	2.5

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

RCE-DR Results on Stainless Steel Substrate





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

- 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)

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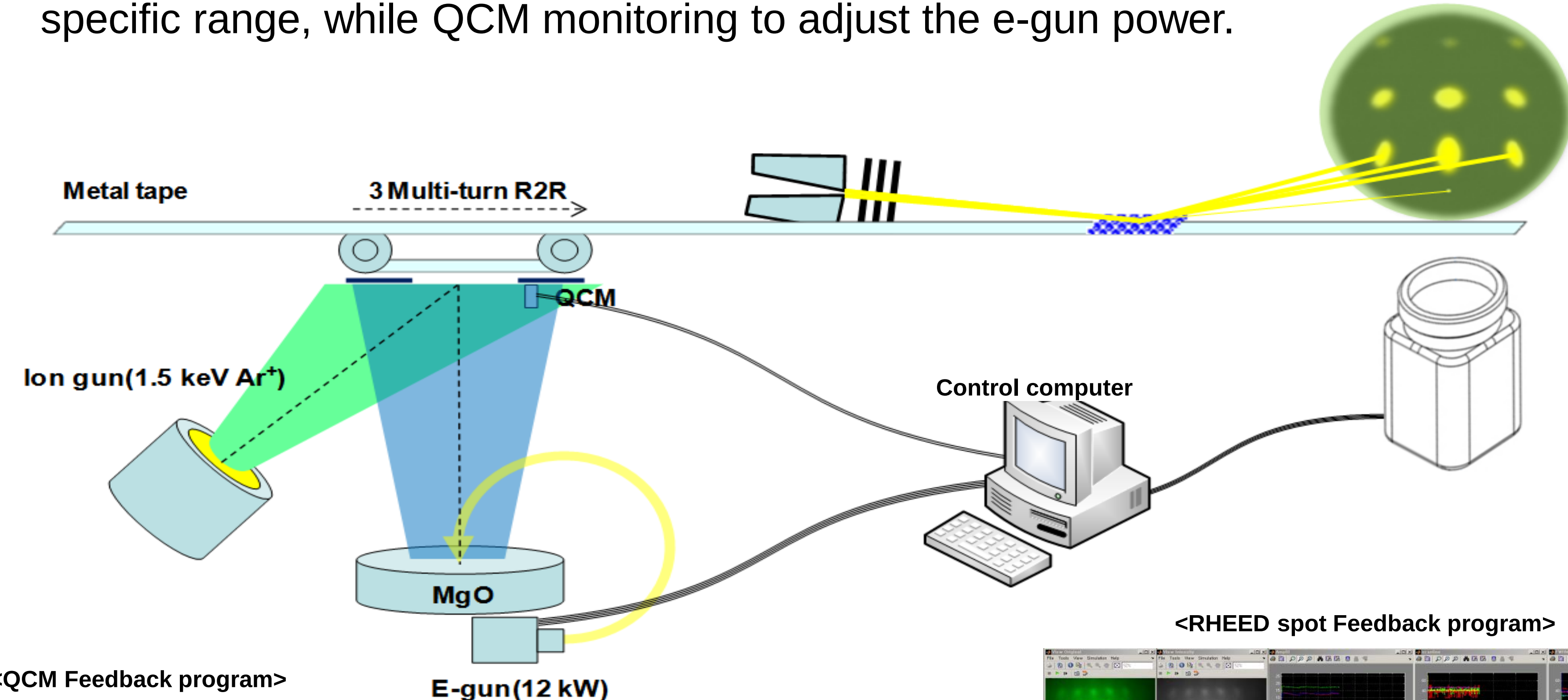
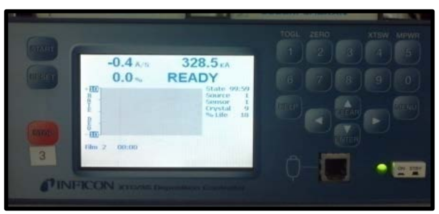
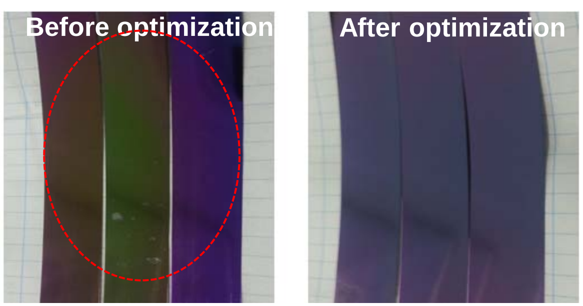
Quality Control : RHEED Vision System

- 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.

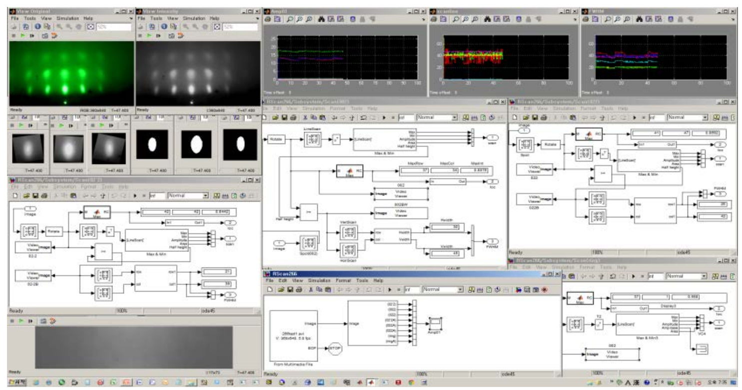


<QCM Feedback program>

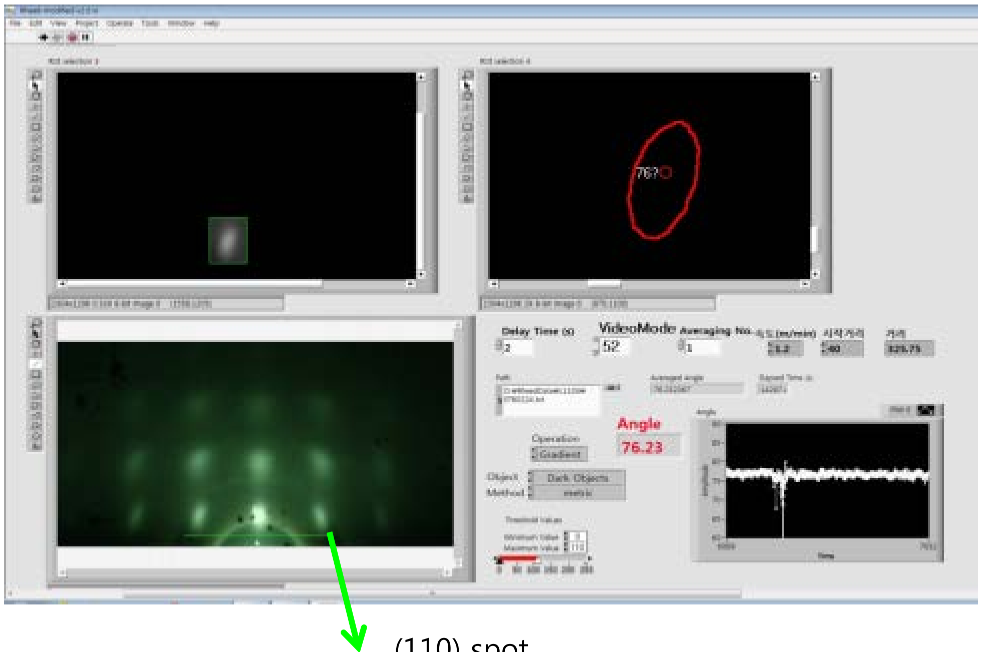




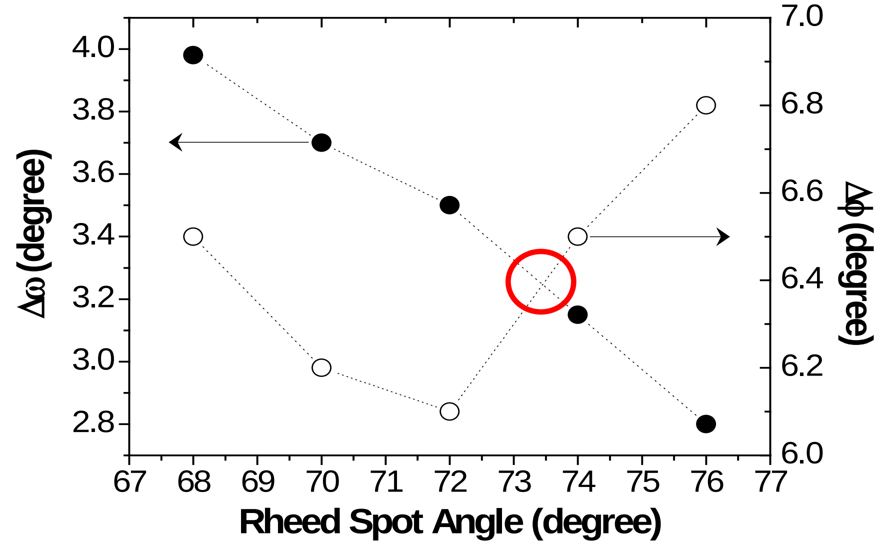
<RHEED spot Feedback program>



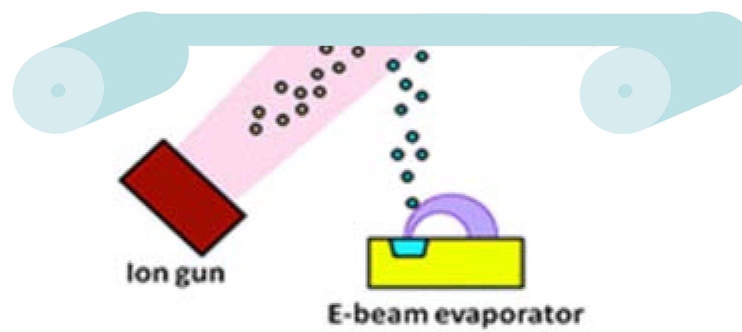
Feedback route based on RHEED spot analysis



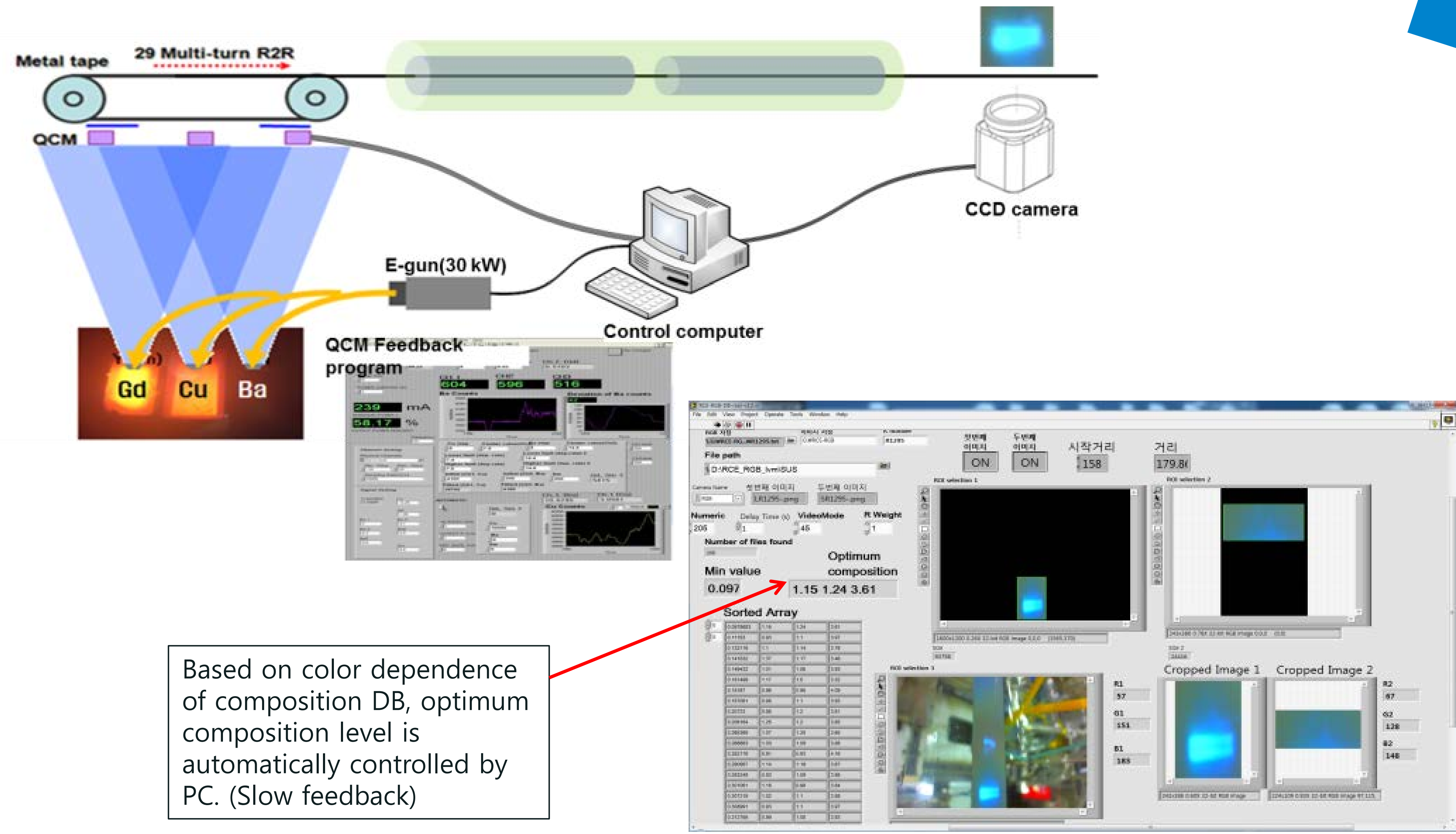
(110) spot



- 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.



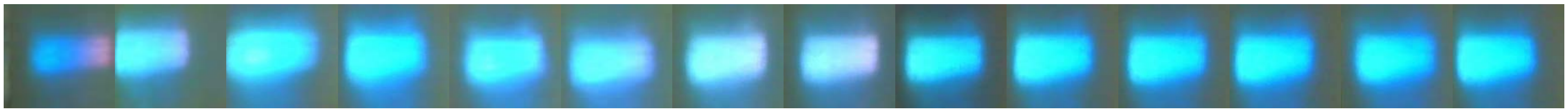
Quality Control : RCE Vision Inspection System

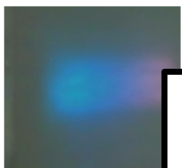


Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)

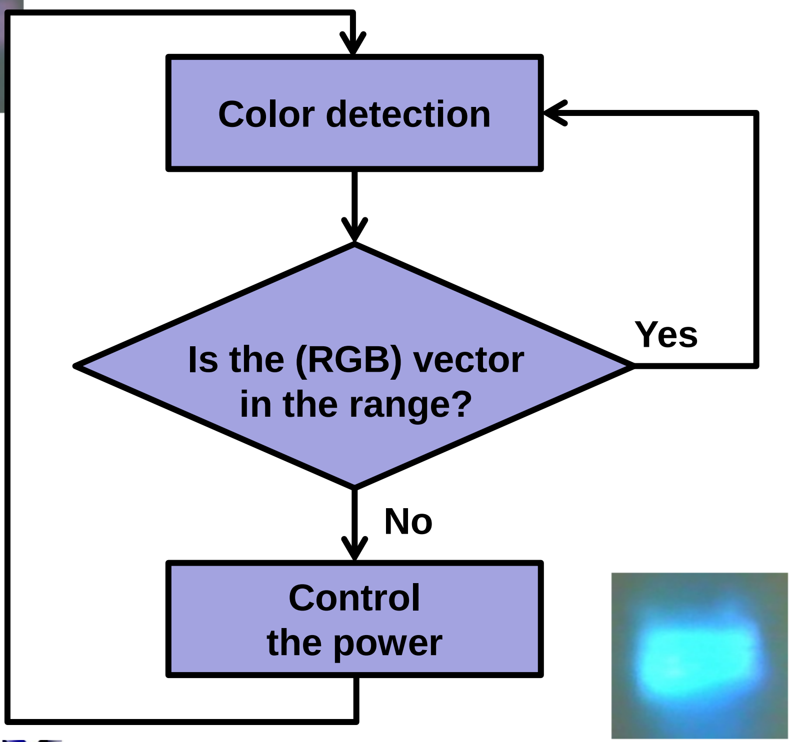
Quality Control : RCE Vision Inspection System

- 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]



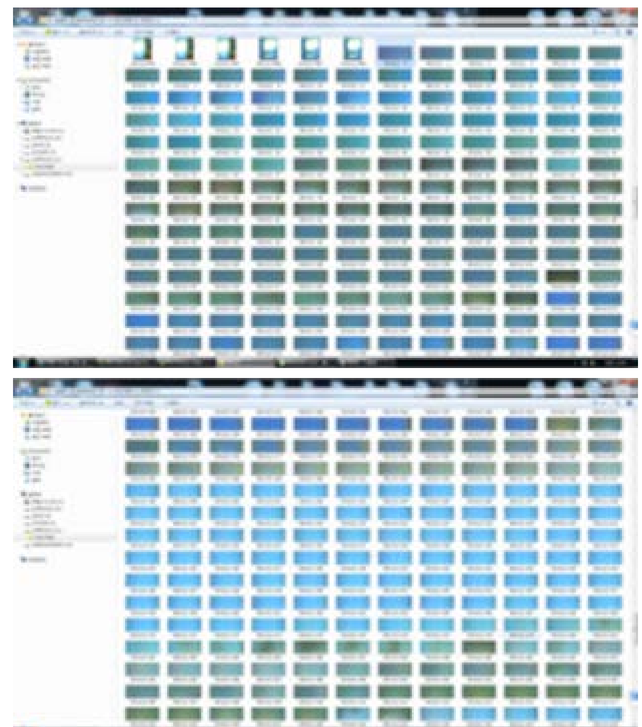
Start color



End color

(79,166,189)

(Composition DB)

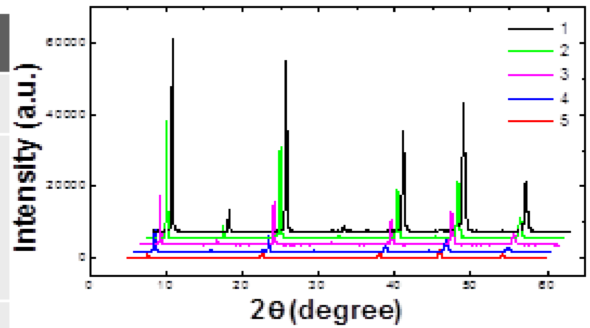


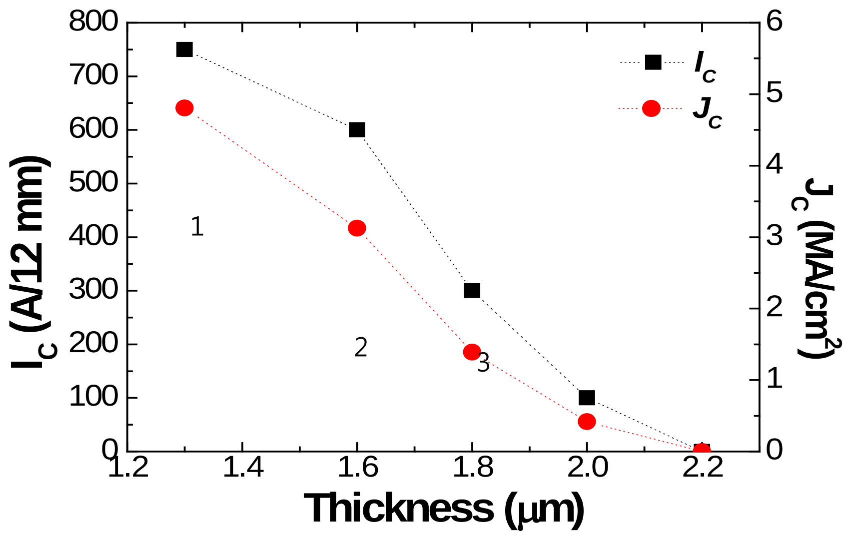
Higher I_C : Thicker S.C. layer

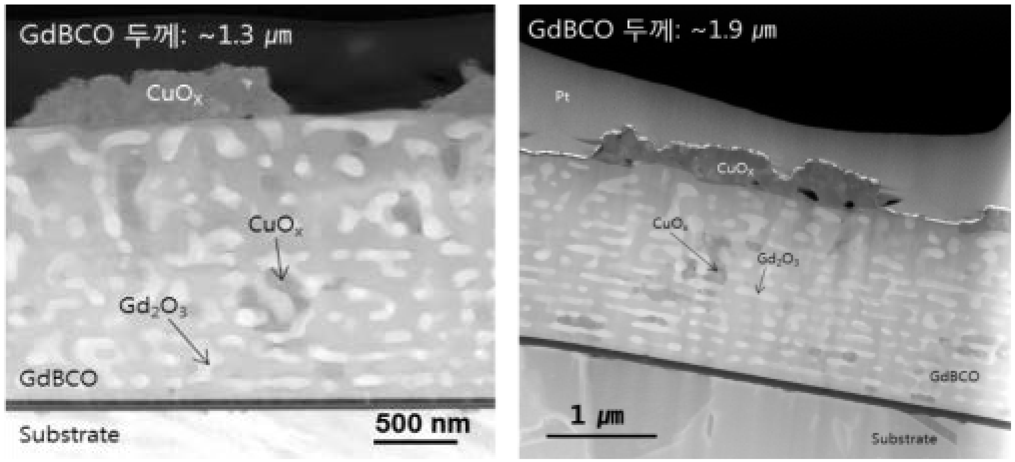
Normal RCE-DR process : before optimization

❖ **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



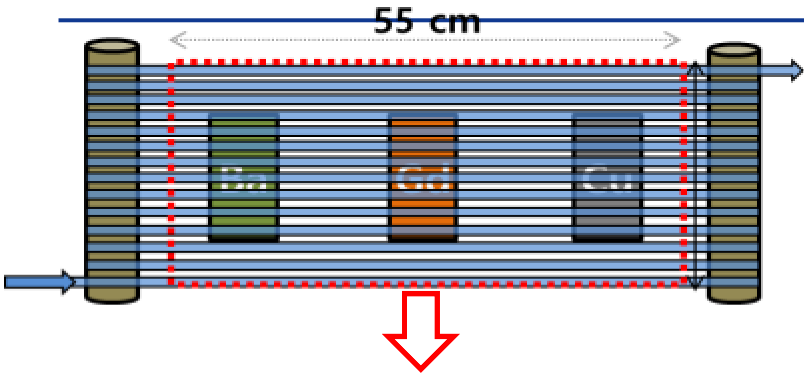




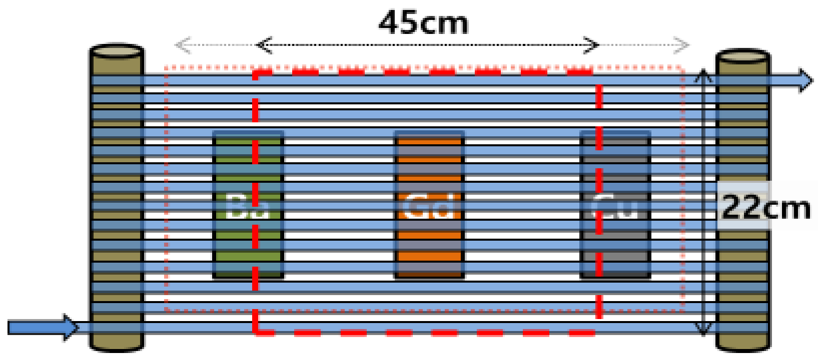
As increasing the thickness, Jc and Ic are decreased.
All the samples were prepared by same process speed.

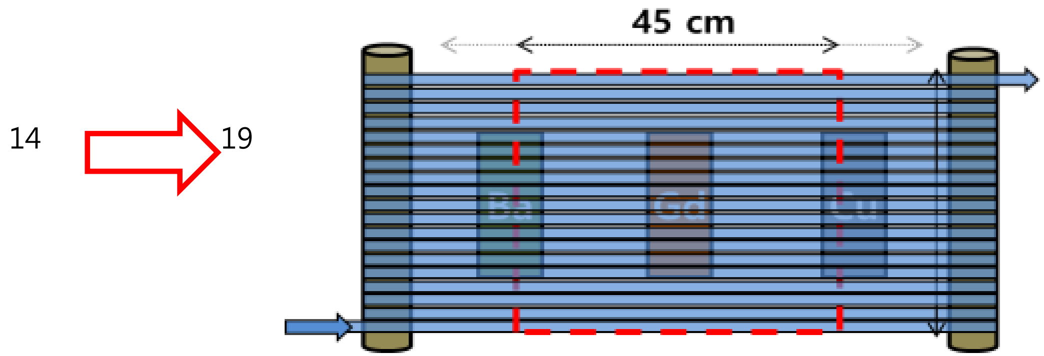
●TEM analysis
→ 1.3 ㎛-thickness:
Gd_2O_3 are randomly distributed
→ 1.9 ㎛-thickness:
Gd_2O_3 are distributed the boundary of the layers

Optimization of deposition region for making thick GdBCO films

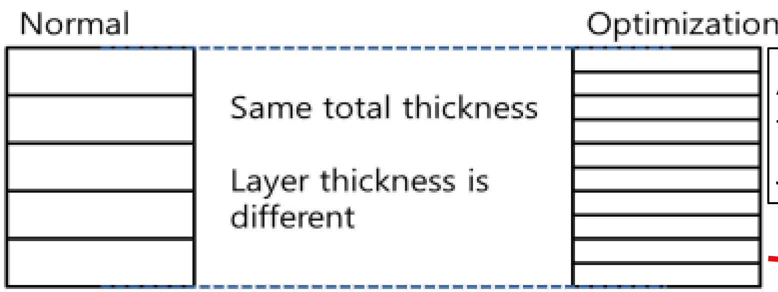


For uniformity,
1. Decrease deposition region from 55 cm to 45 cm.
2. Increase distance between source and substrate.
3. **Increasing turns of deposition region (14 turns → 19 turns)**



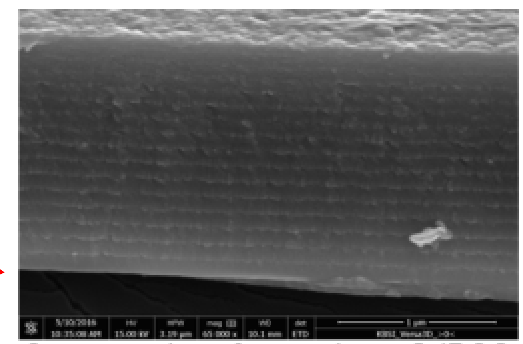


As increasing the thickness, Jc is decreased



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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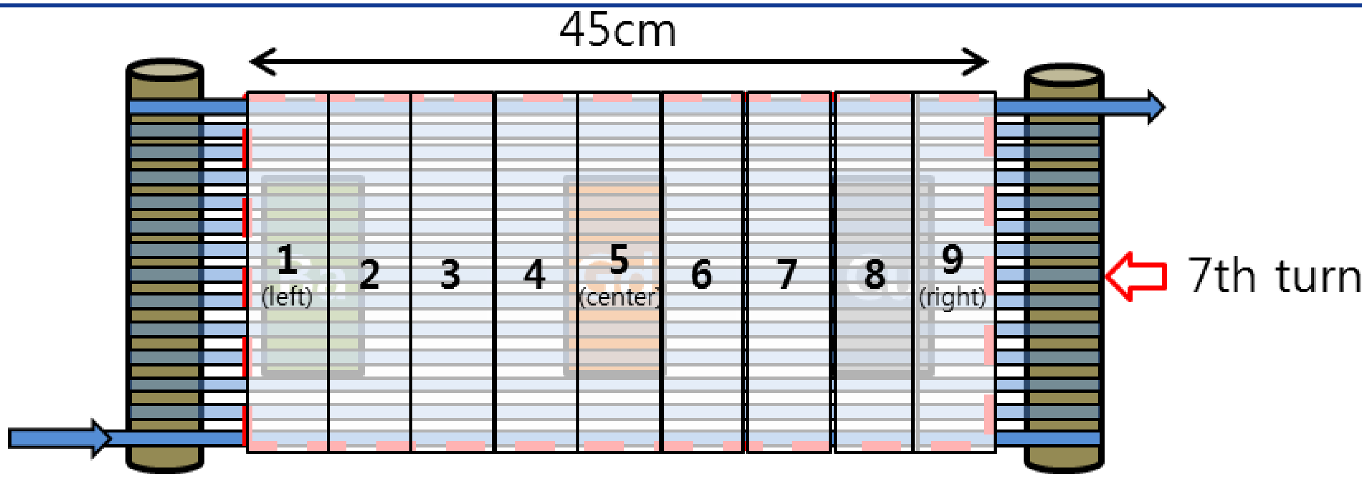
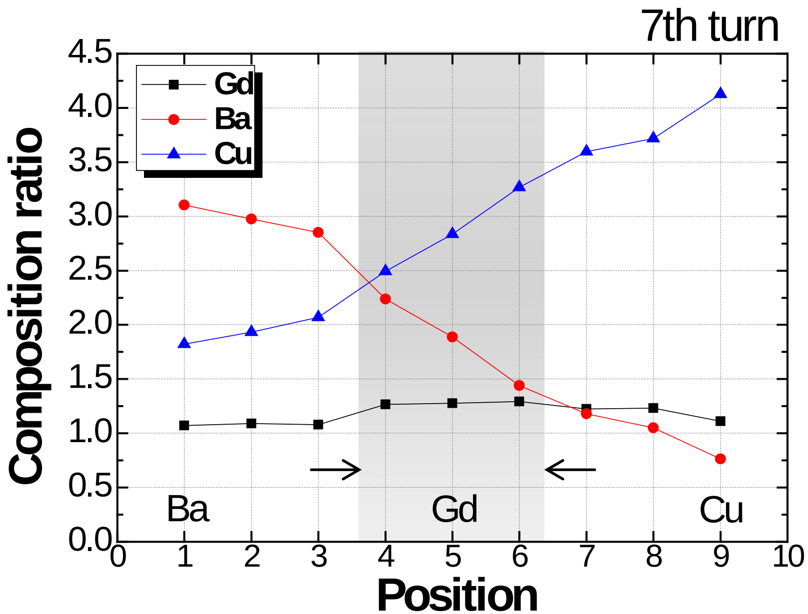
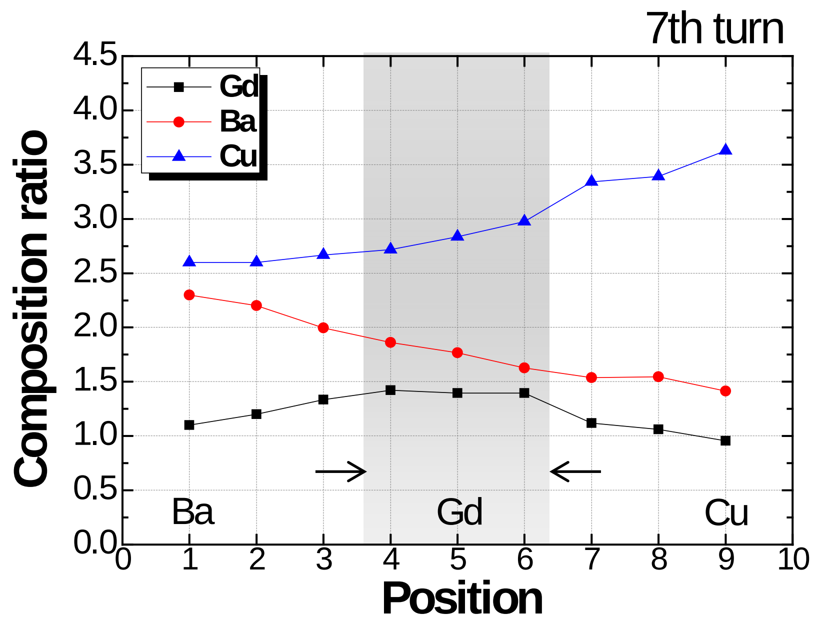
Optimization of Deposition region



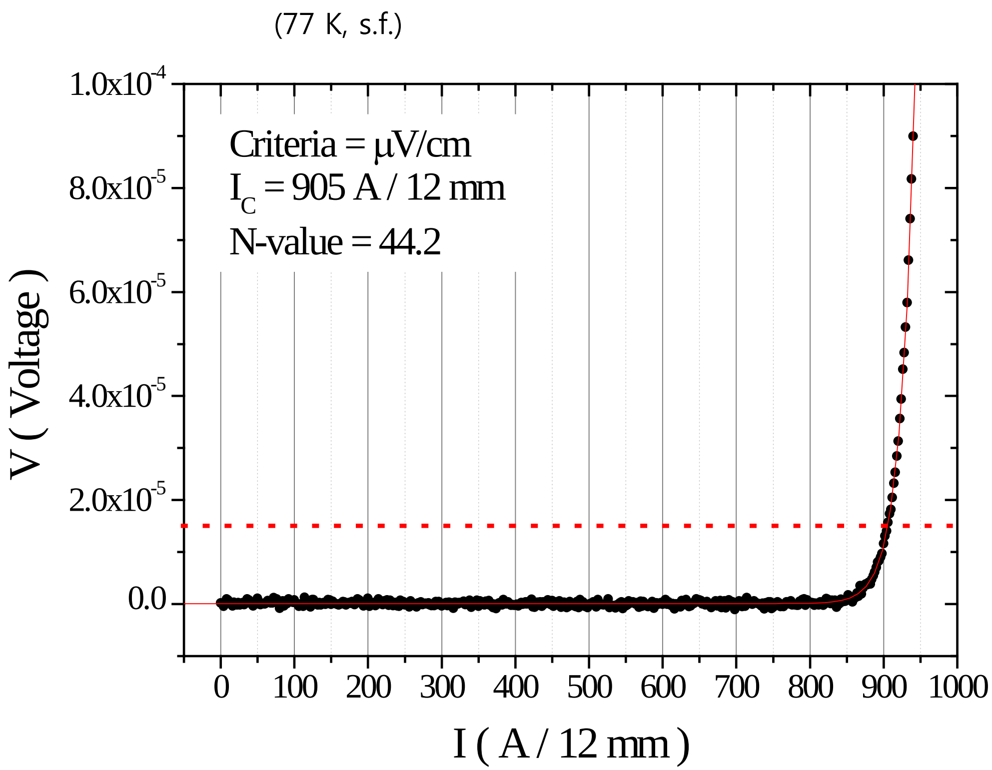


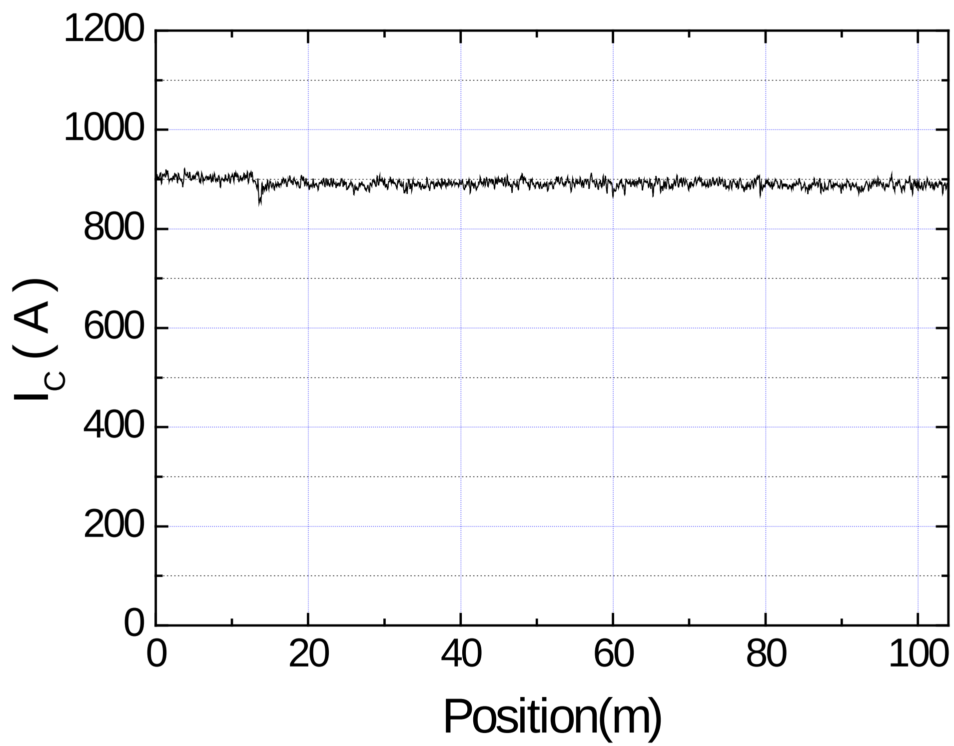
Distance between source and substrate : ~



Distance between source and substrate : ~

Optimization of RCE-DR process for thick superconducting layer





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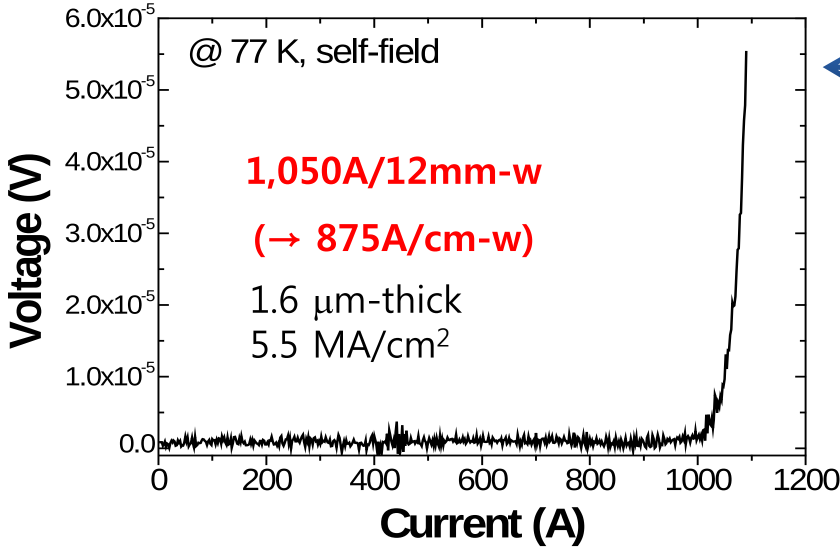
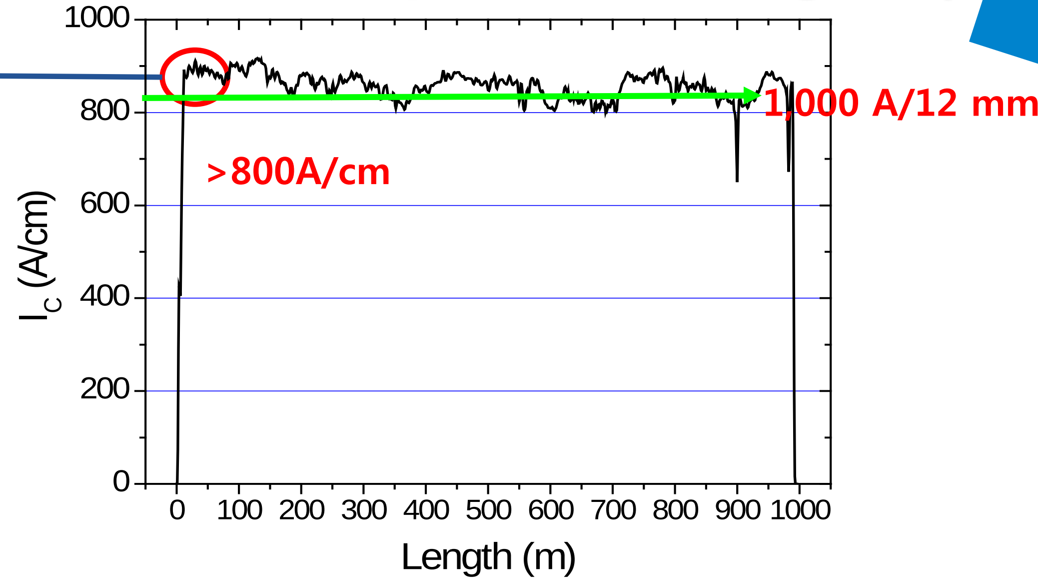
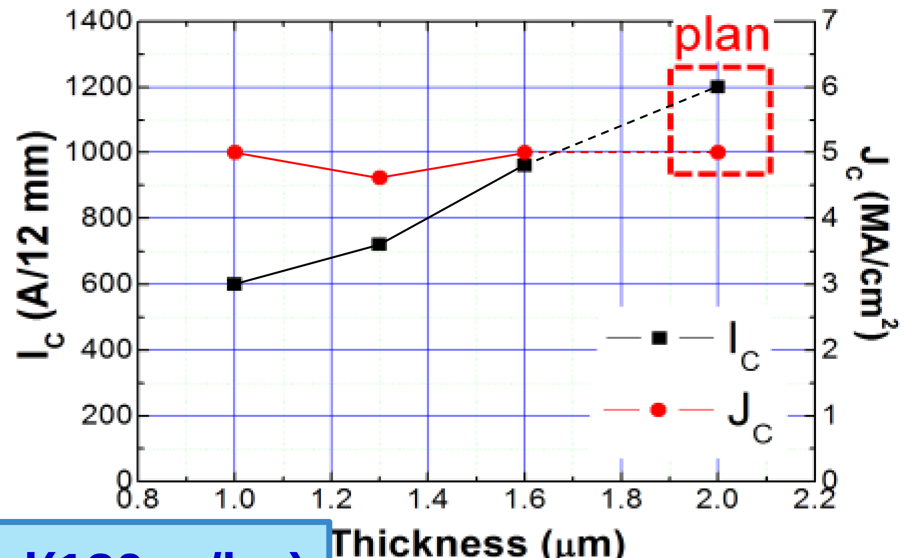
RCE-DR results (with optimization deposition region)





2016 Plan for making 400 A / 4 mm CC

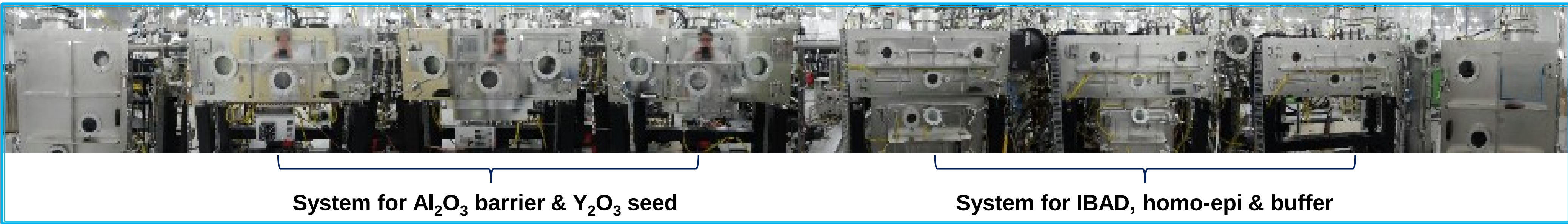
	Speed (m/min)	Turns	Thickness (μm)	I_C (A/cm)	J_C (MA/cm²)
results	2	14	1	500	5
	2	14	1.3	600	4.6
	2	14	1.9	400	2.1
	2	16	1.6	800	5
plan	2	> 20	2 ~ 2.5	> 1,000	> 5

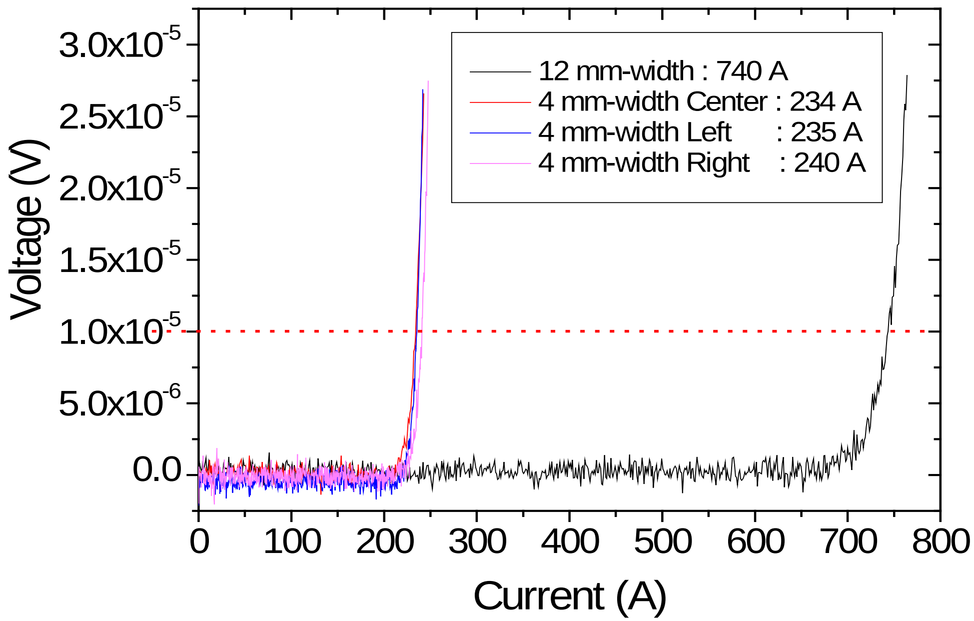


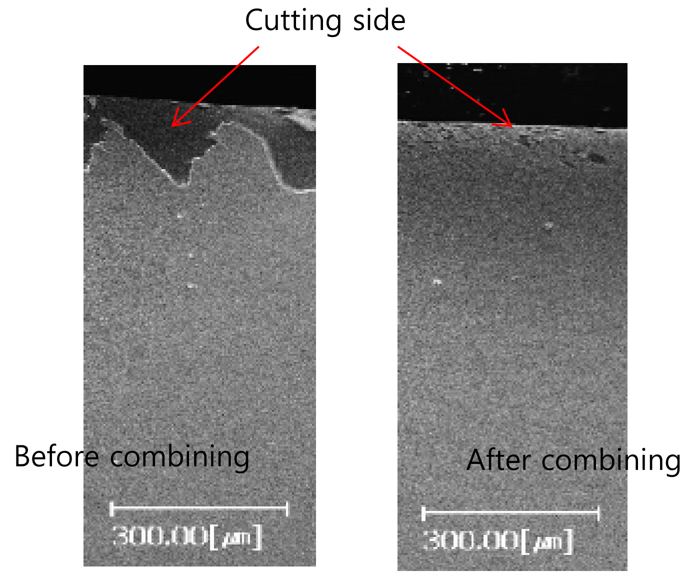
■ The same process speed(120 m/hr).

Higher Je : metal substrate removal process

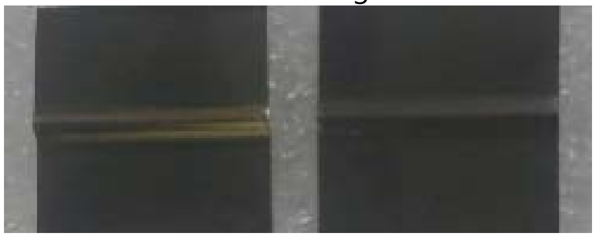
Combining Barrier, Seed, IBAD, Buffer Systems in One







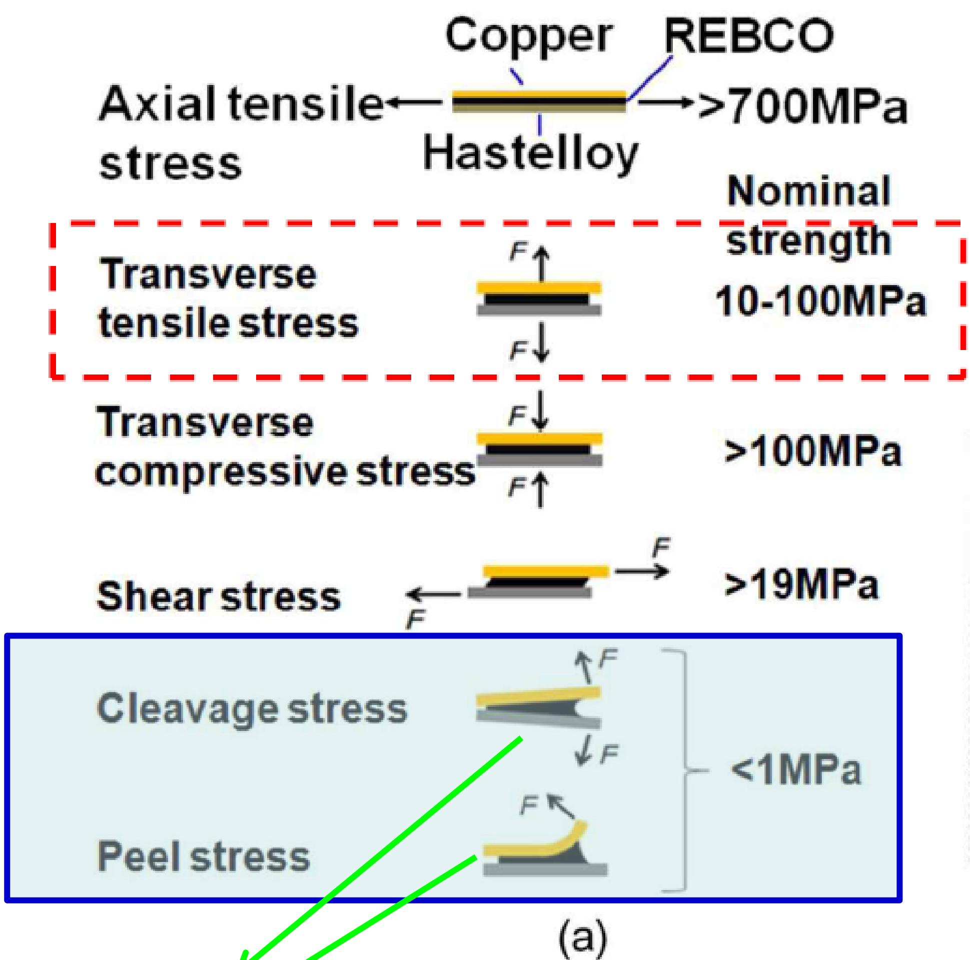
After bending



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

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**

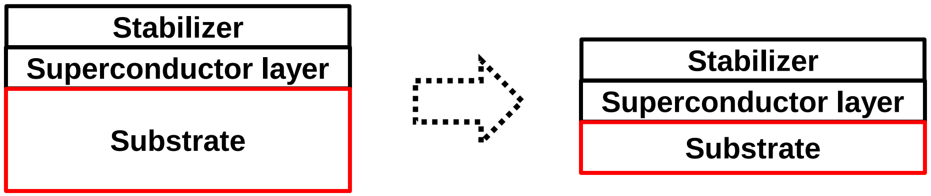
Not to worry?

- **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)

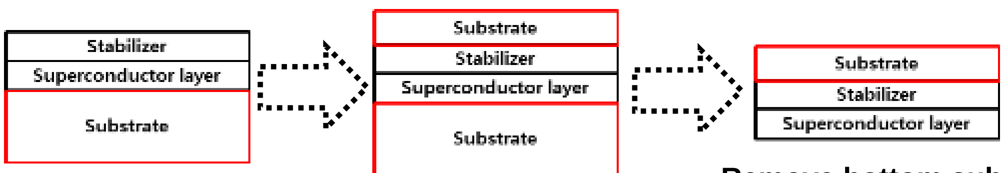
High Je wire by removal of thick metal substrate

For Je, substrate thickness must be thin



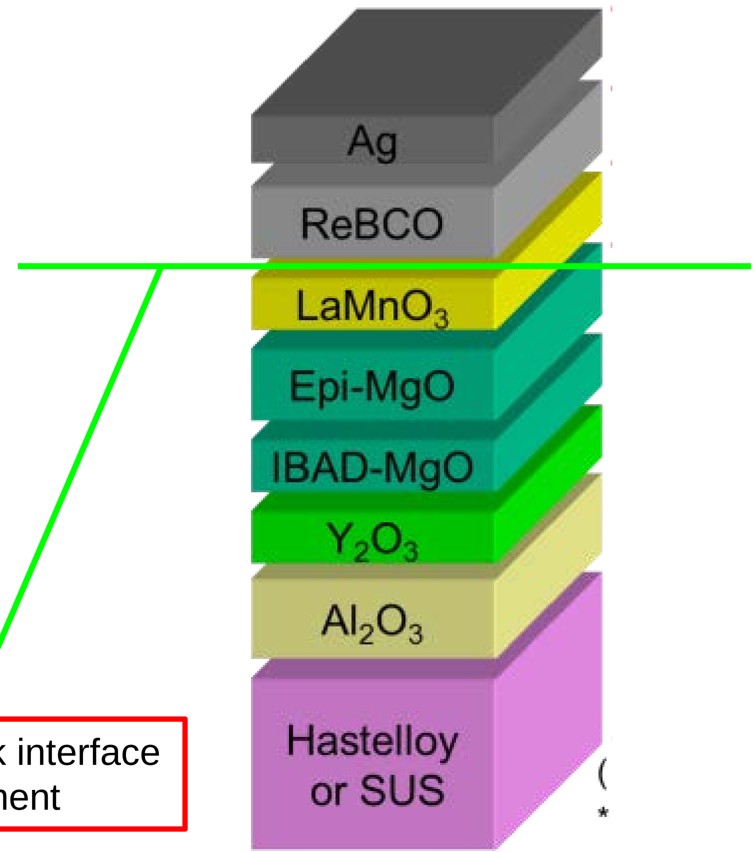
For thin substrate, easy to damage during the reel to reel process

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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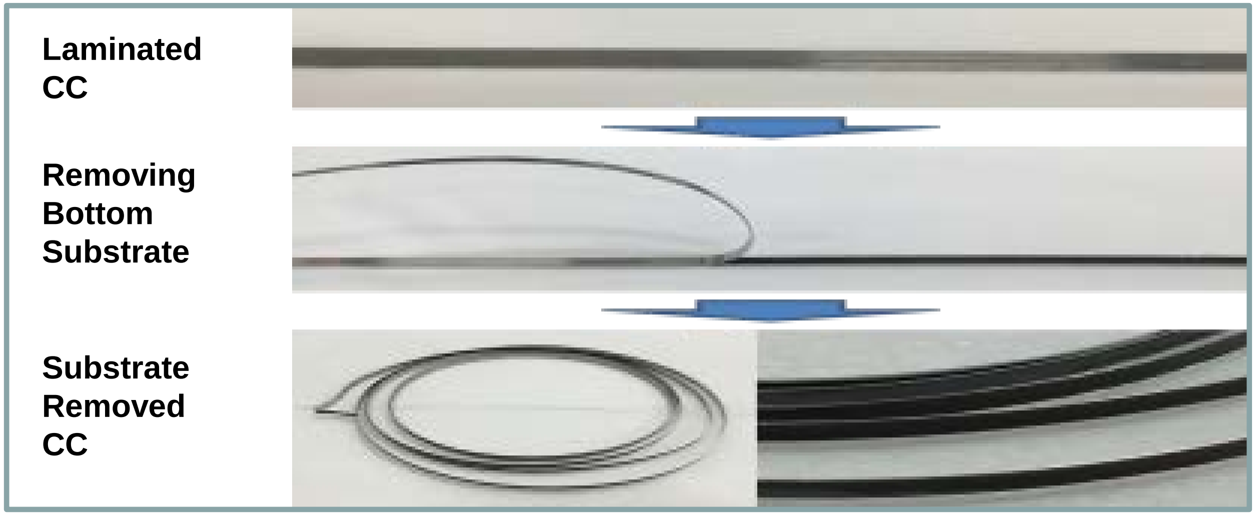
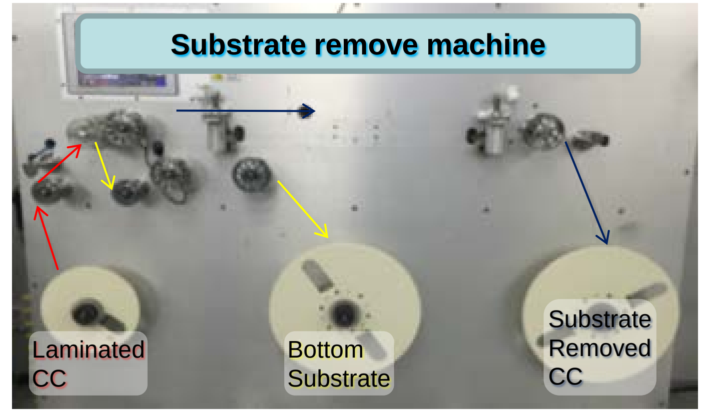
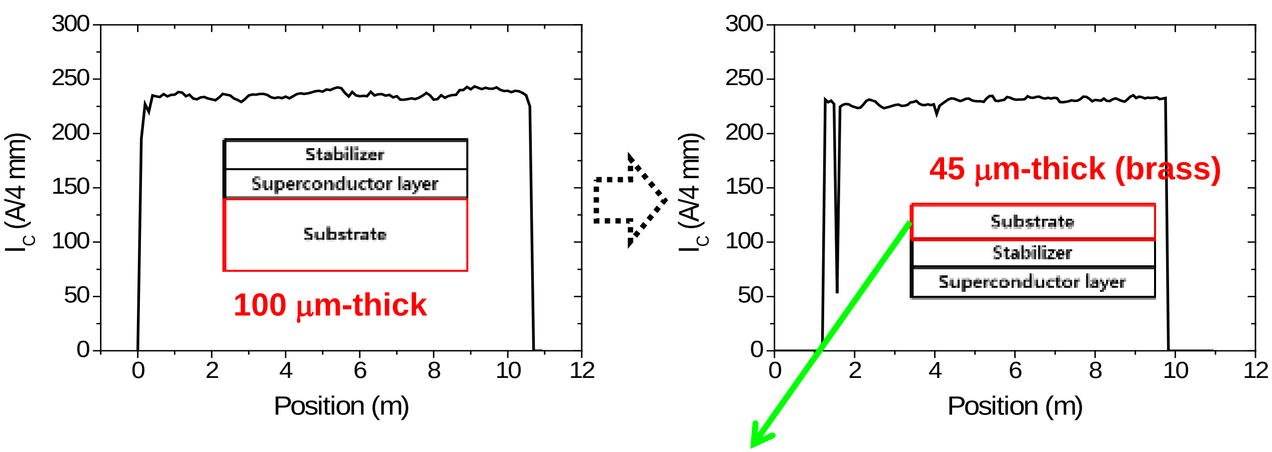
Demonstration of High Je wire by removal of thick metal substrate

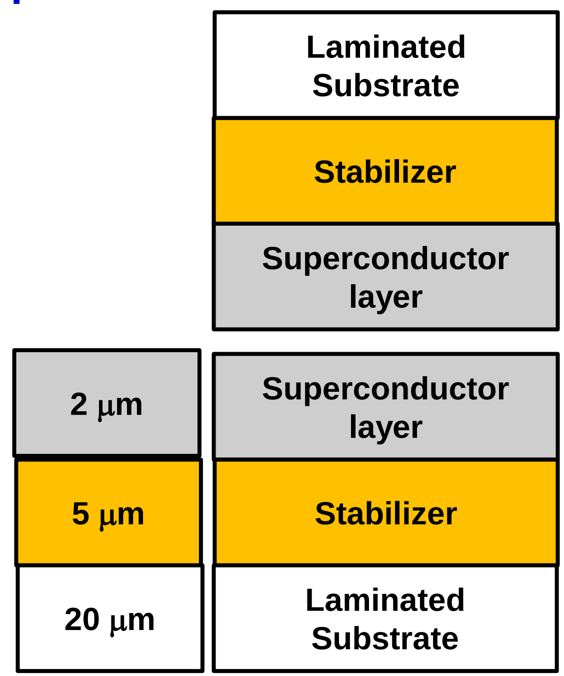






- Easily reduce the thickness ~ < 20 μm
- Choice of any materials(SUS, Copper…)

May possible…



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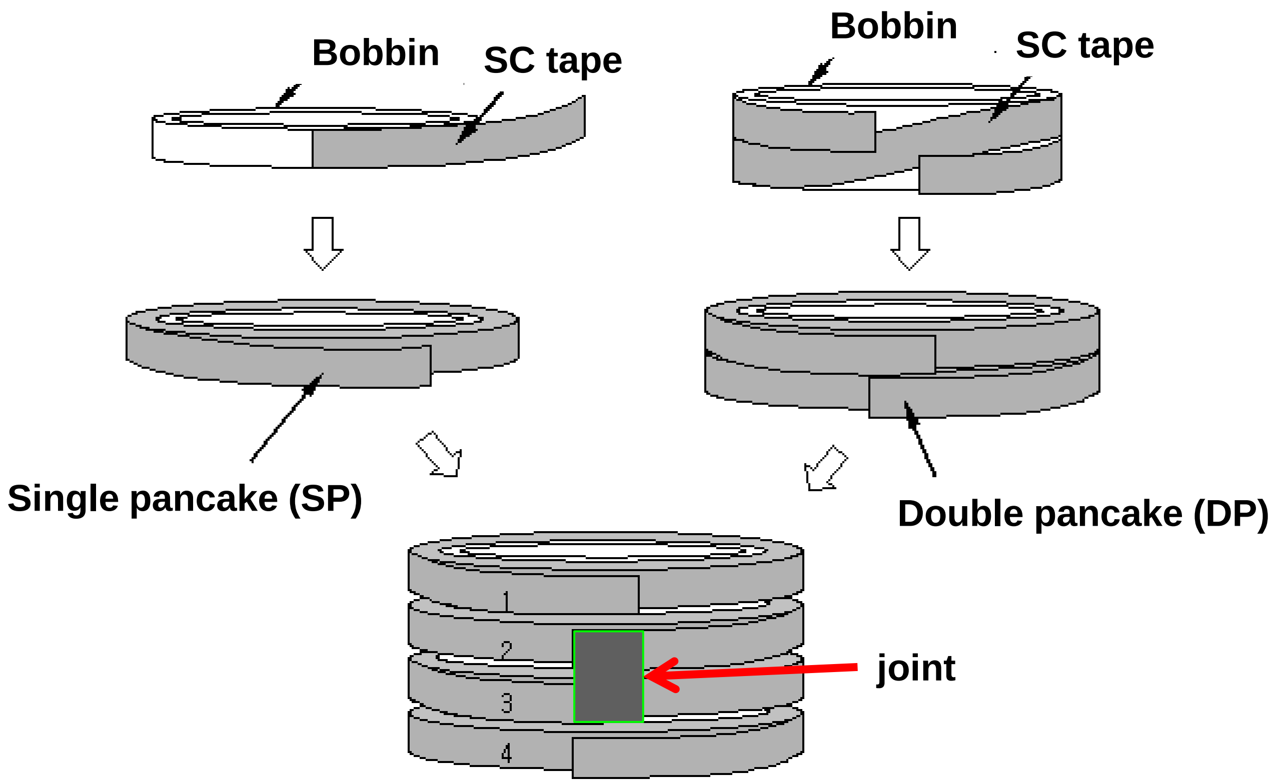
Magnet & Coil

(Double) Pancake Coil

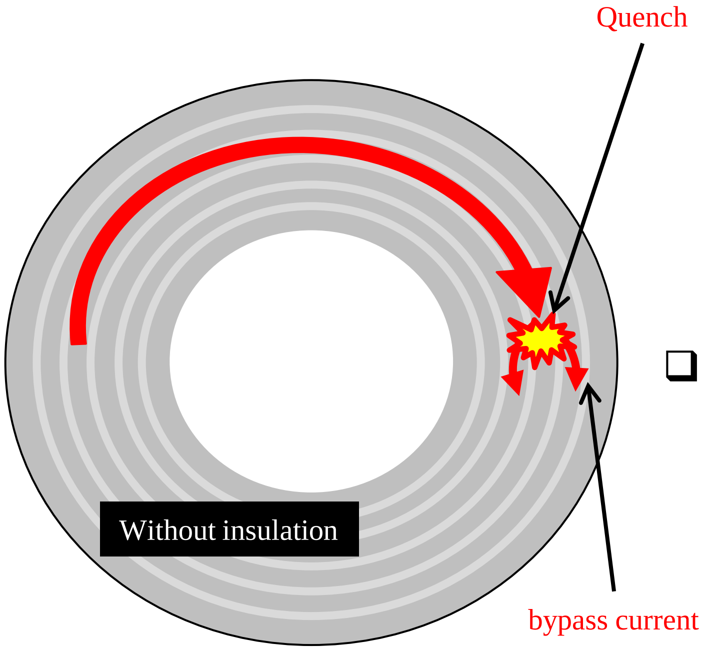
- Pancake winding is adopted due to tape-form of HTS wire



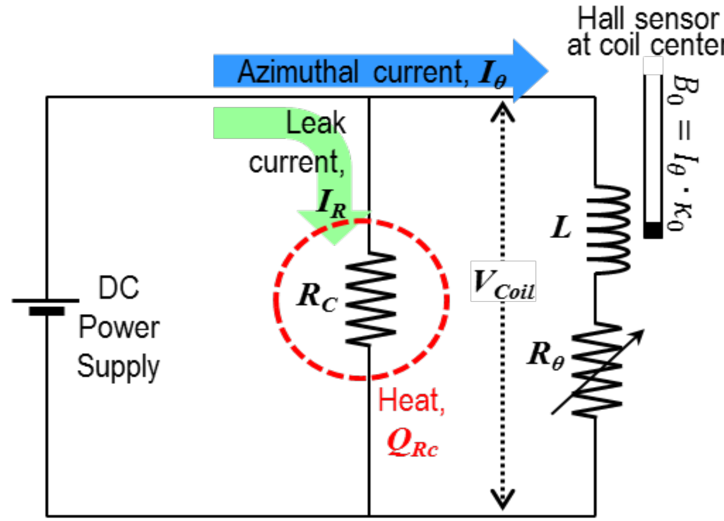
Coil with 4 Single Pancakes or 2 Double Pancakes;
For SP case, SP 1-2 & 3-4 are joined inside, 2-3 outside.

- Layer winding is also exercised for better uniformity

NI-winding technic – No insulation



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



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

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)

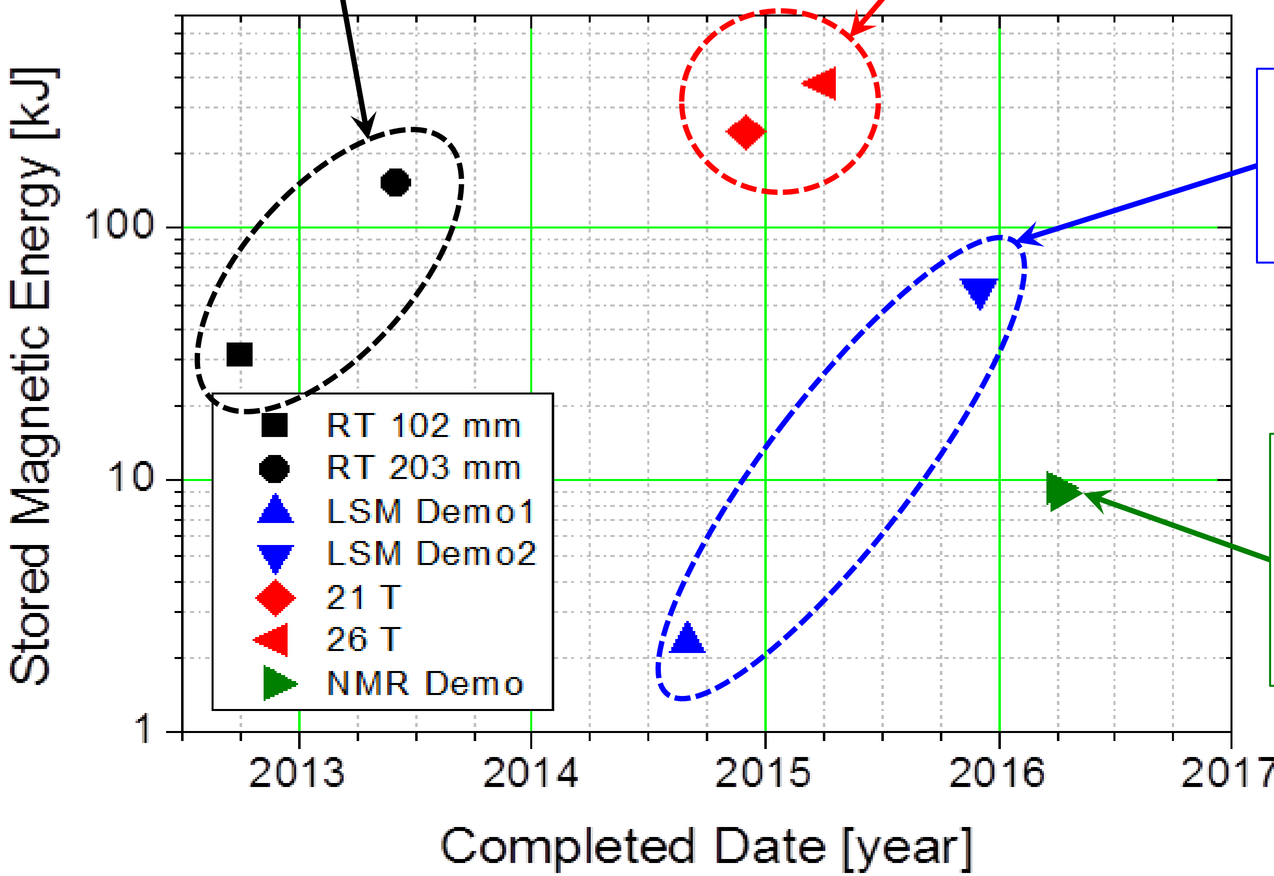
(by S. Hahn)

(by S. Y. Hahn)

Progress in NI Magnet at SuNAM

➢ Wide RT bore magnet
- Over 4 [T] at center
- For I_C measurement
- Cryogen-free

➢ High field magnet
- Over 20 [T] at center
- Liquid helium cooling



➢ Racetrack magnet
- For motor application
- Cryogen-free

➢ **Homogeneity magnet**
- For NMR appication
- Over 3 [T] at center
- Cryogen-free

Long-Term Operation (203mm Magnet)

- Cooling time (operation)
  : 3 years

- Total field charging time
  : > 200 times, **> 700 hours**

- I_C-B-T-θ measuring times
  : > 4,000 points

- Quenches
  : more than 6 times

I_C measurement insert cryostat

203mm RT 4T magnet

< I_C(B-T-θ) measurement system >

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

No-insulation, multi-width, and compact !

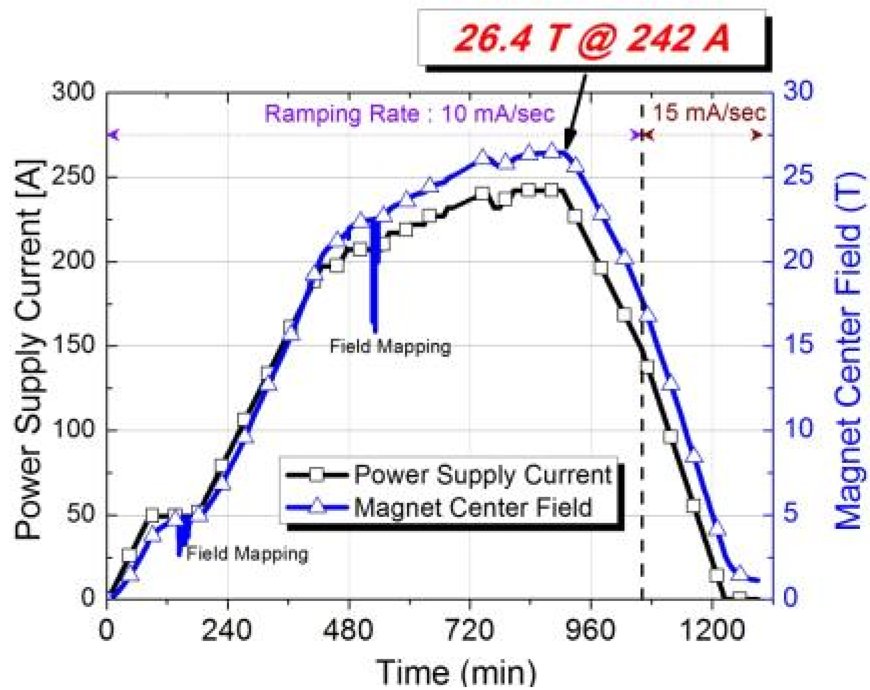
- ✓ Multi-width Double Pancake Coils

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)

SuNAM NATIONAL HIGH MAGNETIC FIELD LABORATORY

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.
- Initial test of substrate removal & suggesting a new way of high Je wire structure.
- We condtructed HTS magnets including 26.4 T magnet.

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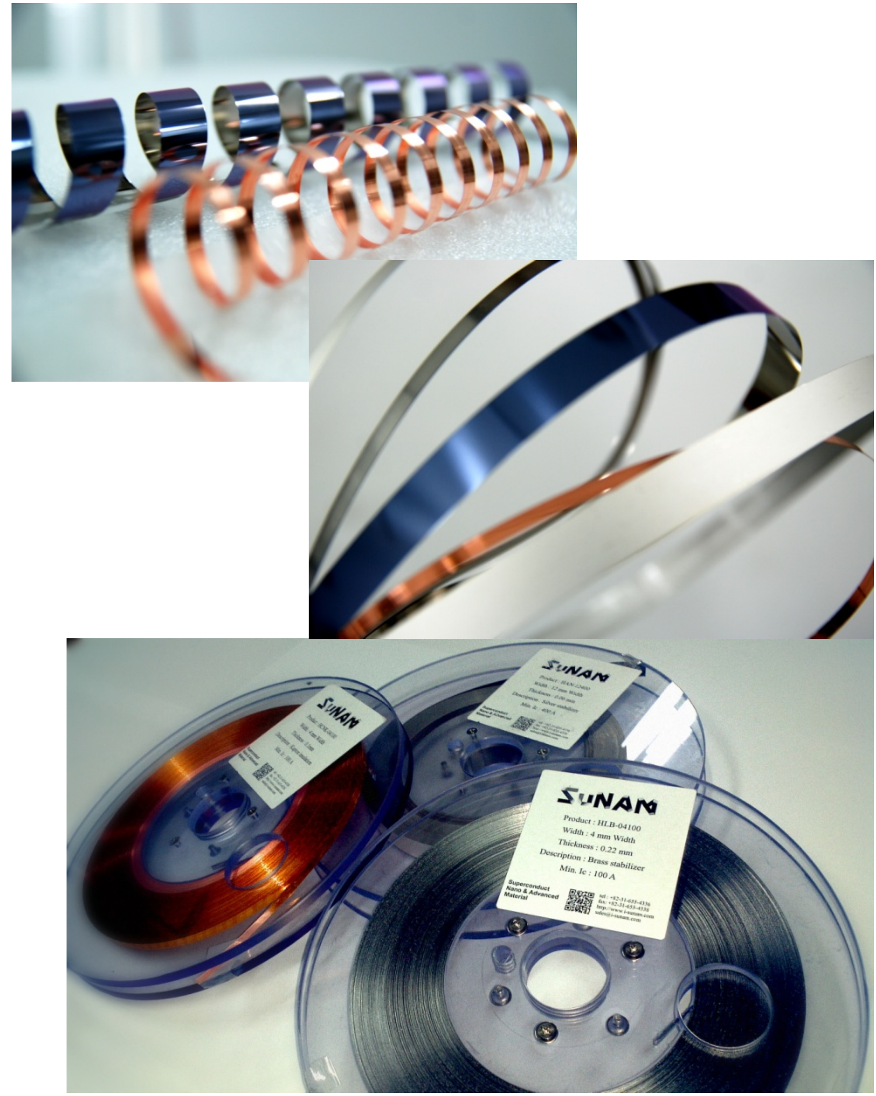
Thanks for Attention !



Direction of Technology Development in the Future

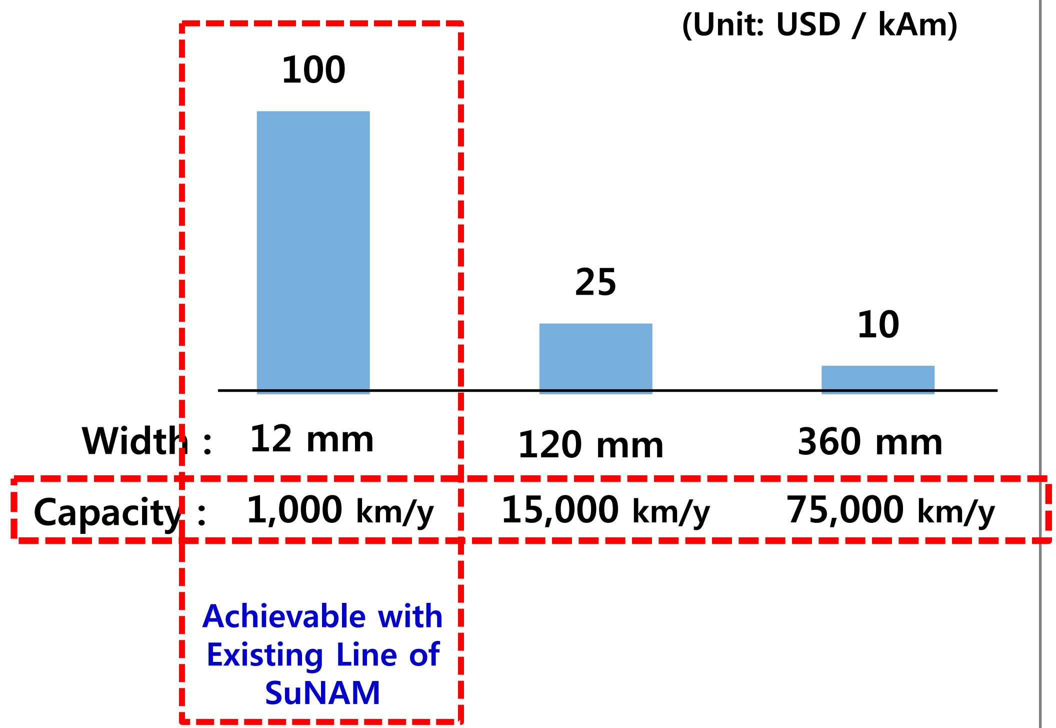
"Increasing Demand for HTS 2G wire has surpassed the supply"

"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



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