

Status of HTS wire and magnet activities in SuNAM



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SuNAM Co., Ltd.

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- **Company overview & Product portfolio**

- **HTS 2G Wire**

- Process; equipment, parameters
- Critical current behavior
- Quality control
- Electro-mechanical properties
- Substrate removal/replace for higher J_e

- **Magnets**

- Large bore
- High-field
- Linear synchronous motor
- NMR

- **Summary.**

Company Overview

SuNAM : **Su**perconductor, **N**ano & **A**dvanced **M**aterials (서남, 瑞藍)

Establishment	2004. 11. 17., for commercialization of 2G HTS wire*
CEO	Seung-Hyun Moon
Registered Capital	~\$7 M
No. of Employees	~45 (~8 Ph.Ds)
H.Q.	Anseong, Korea
Current Production Capacity	~ 50 km / month (4 mm > 150 A)
Core Technology	2G HTS manufacturing technology based on RCE- DR process. NI**- base high field magnet technology



* 2G HTS wire : 2nd Generation High Temperature Superconducting Wire

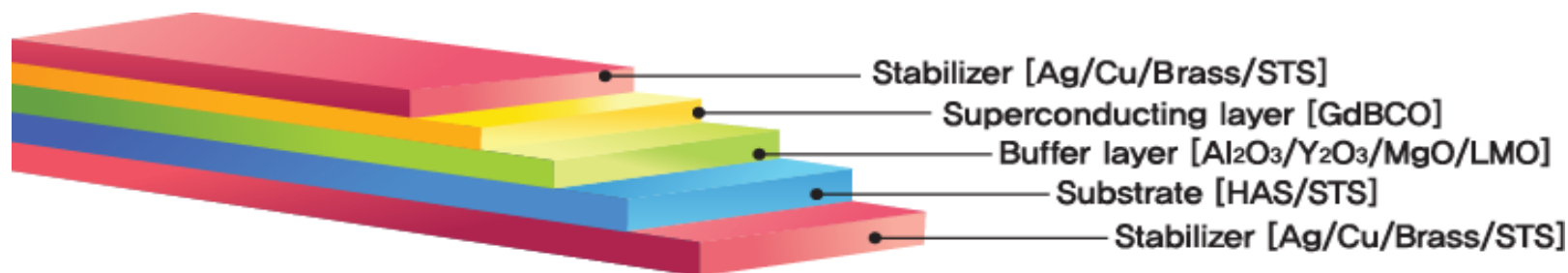
** NI : No Insulation



Product Portfolio

[Specification Table]

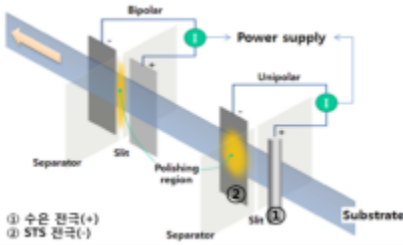
Model	AN	CN	LB/LS	K
Description	Silver(+Cu...) Dry coating	Copper Wet Coating	Brass/ Stainless steel Lamination	Polyimide tape(+) Insulation
Substrate	Hastelloy or Non-magnetic Stainless Steel			
Width [mm]	Commercial : 4 mm, 12 mm. Special Order : 2 ~ 10 mm multi width is available			
Thickness [mm]	HAS : 0.06~0.07 SS* : 0.11~0.12	HAS : 0.09~0.11 SS* : 0.14~0.16	HAS : 0.18~0.22 SS* : 0.23~0.27	+ 0.1
Final Process	Silver Sputter	Copper Plating	Brass or SS* Lamination	Wrapping
Piece Length	Above 100 m , 200 m , 300 m + without Splice			
Min. Ic @ 77 k S.F.	(100) / 150 / 200 A + @ 4 mm (300 / 400) / 500 / 600 / 700 A + @ 12 mm			



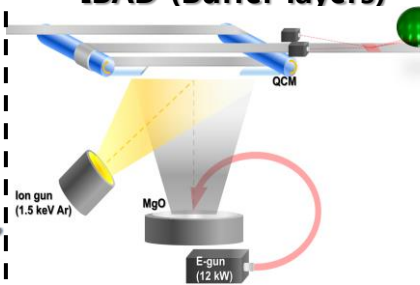
HTS 2G Wire Process of SuNAM



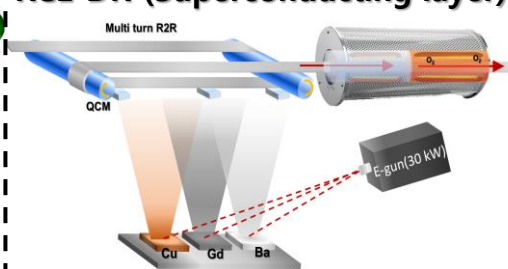
Electro polishing



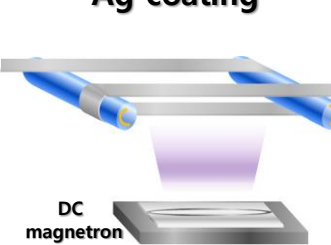
IBAD (Buffer layers)



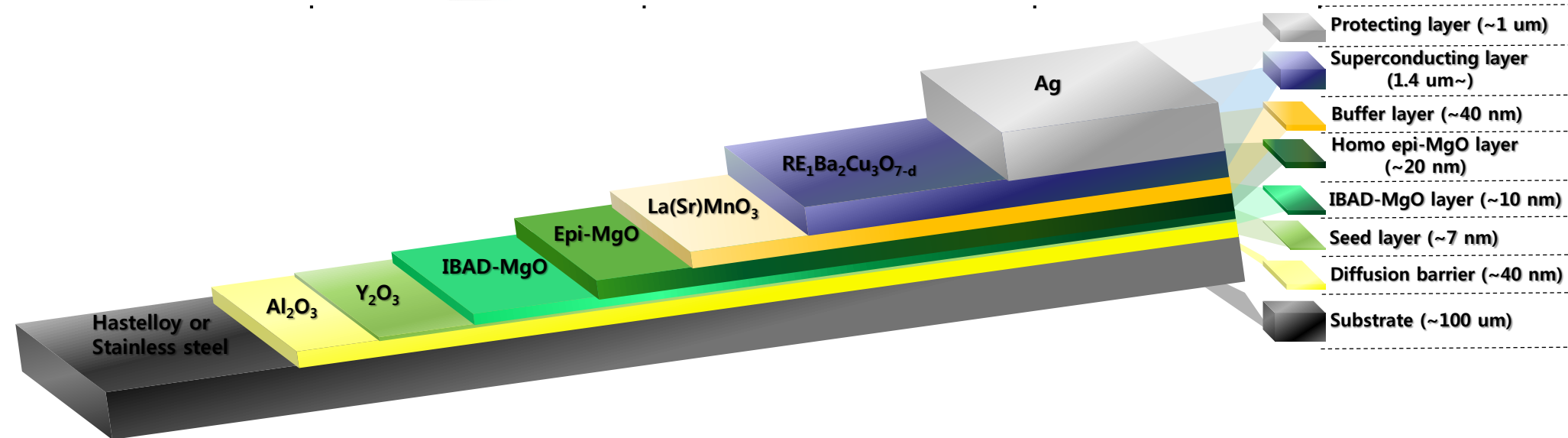
RCE-DR (Superconducting layer)



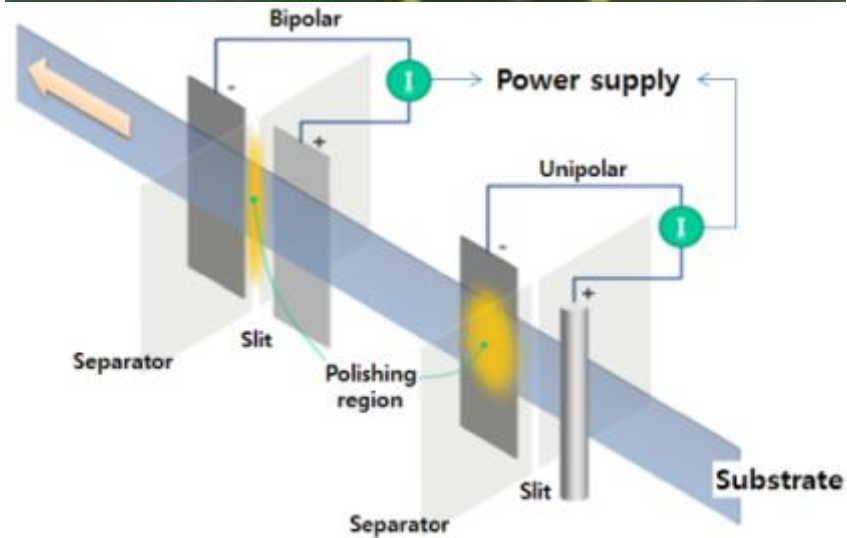
Ag coating



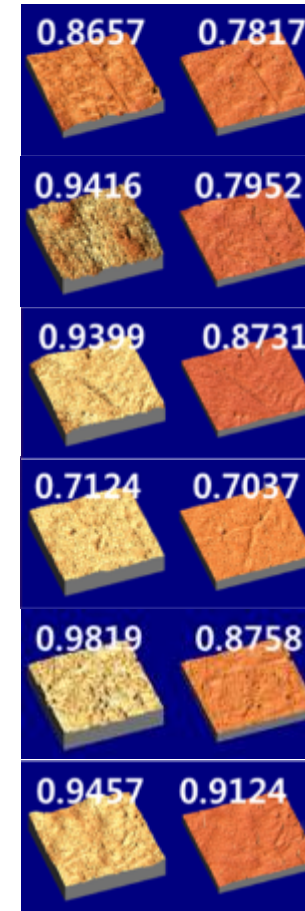
CCs



Electro-polishing of metal substrate



AFM image of E.P. STS



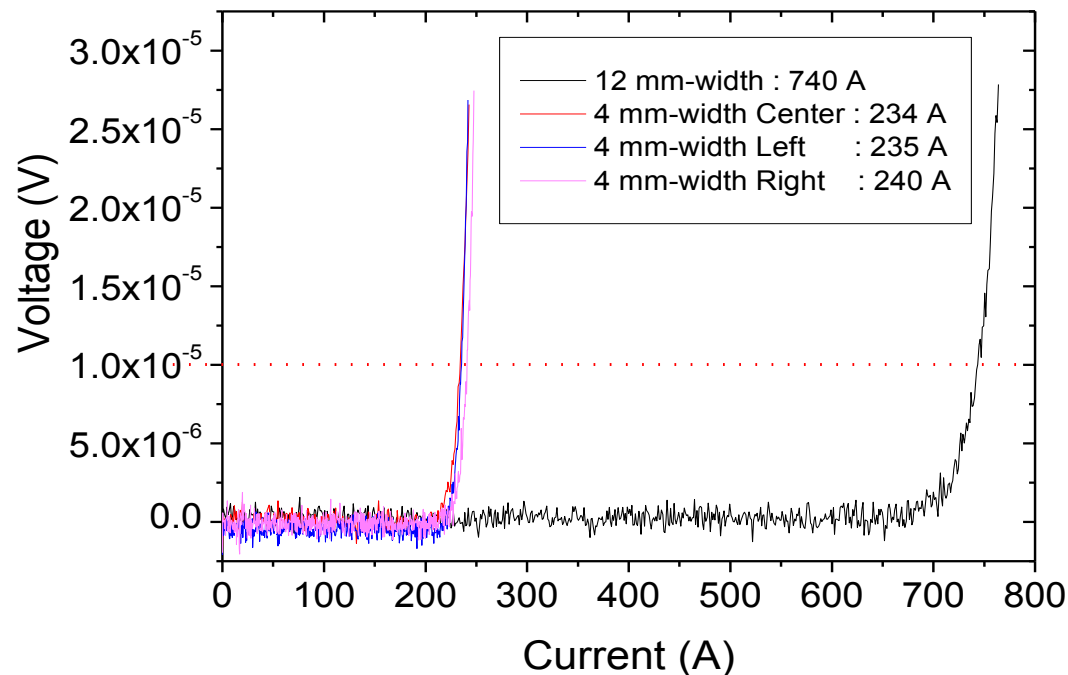
Average rms roughness : 0.87 nm

Combining Barrier, Seed, IBAD, Buffer Systems in One

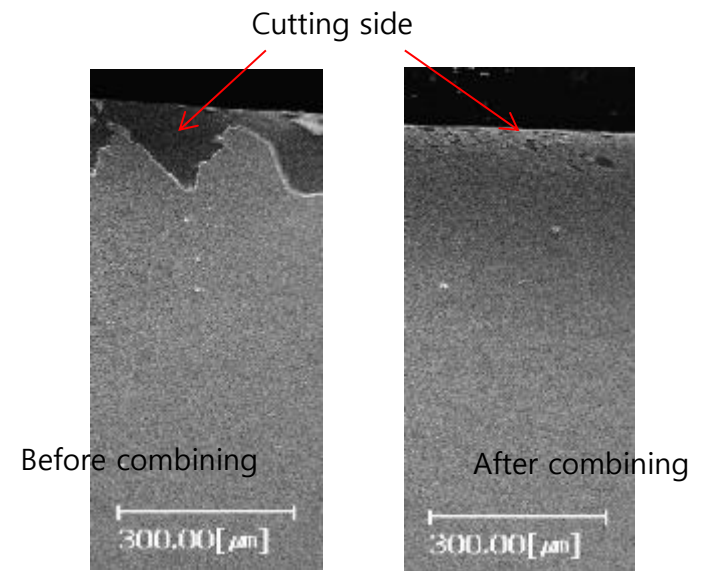


System for Al_2O_3 barrier & Y_2O_3 seed

System for IBAD, homo-epi & buffer

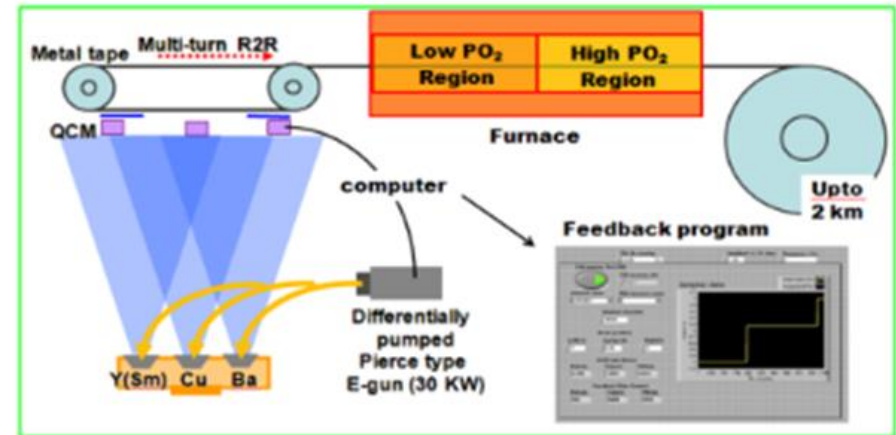
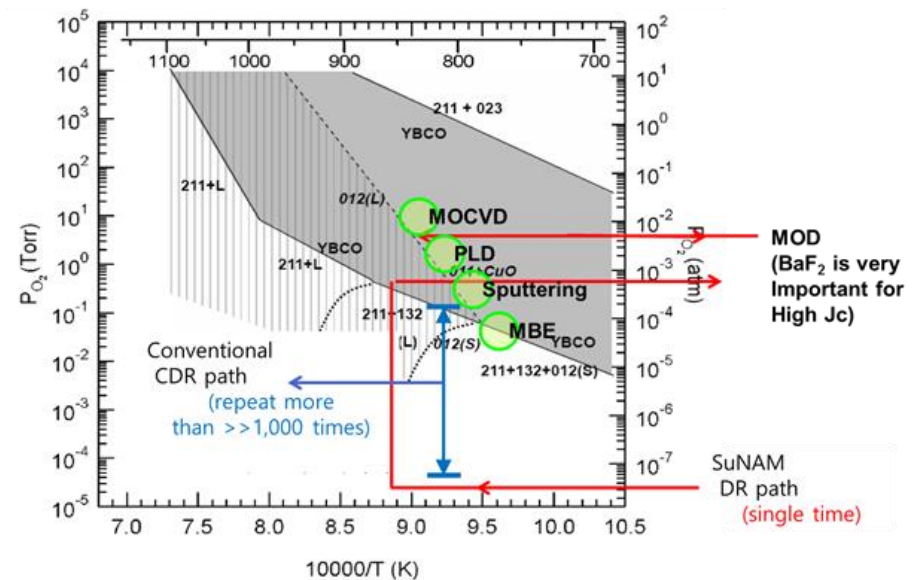


- We used to have 3 + 3 buffer processing chambers
→ combined into 6 in-line chambers

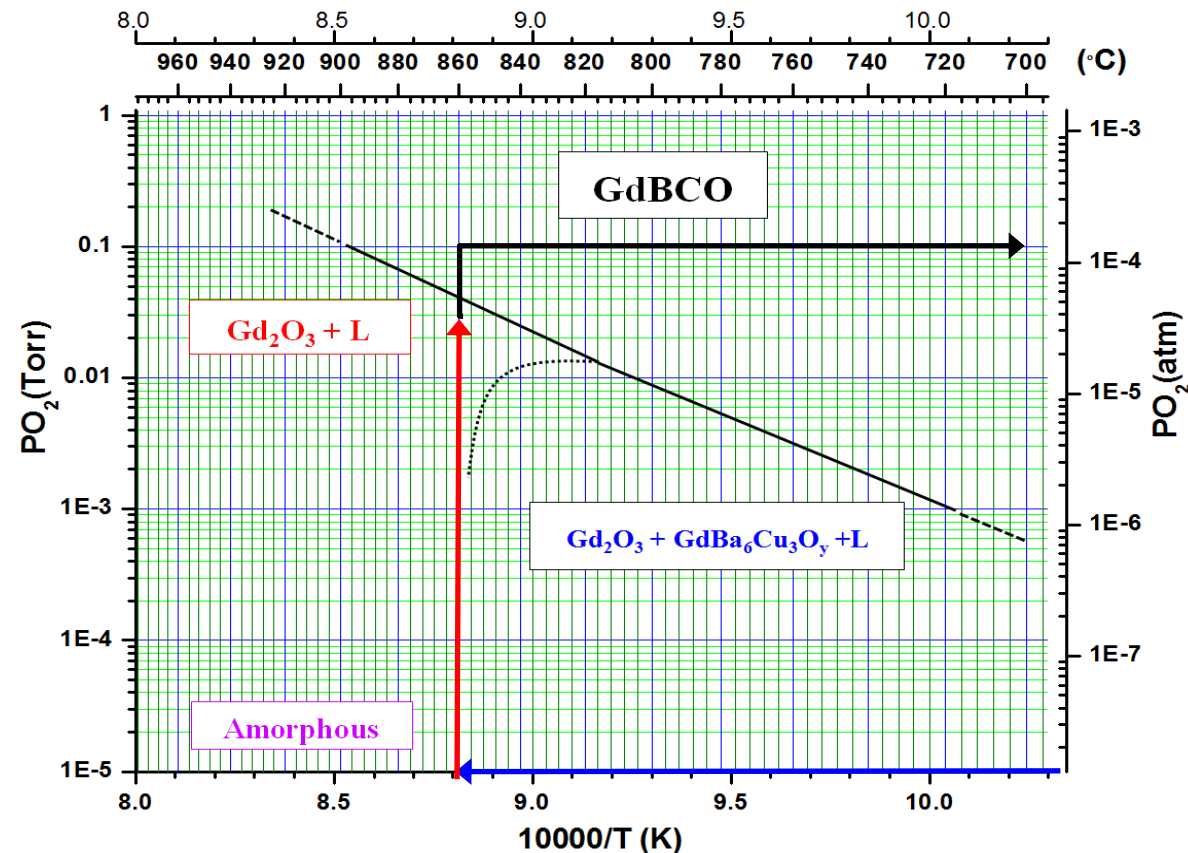
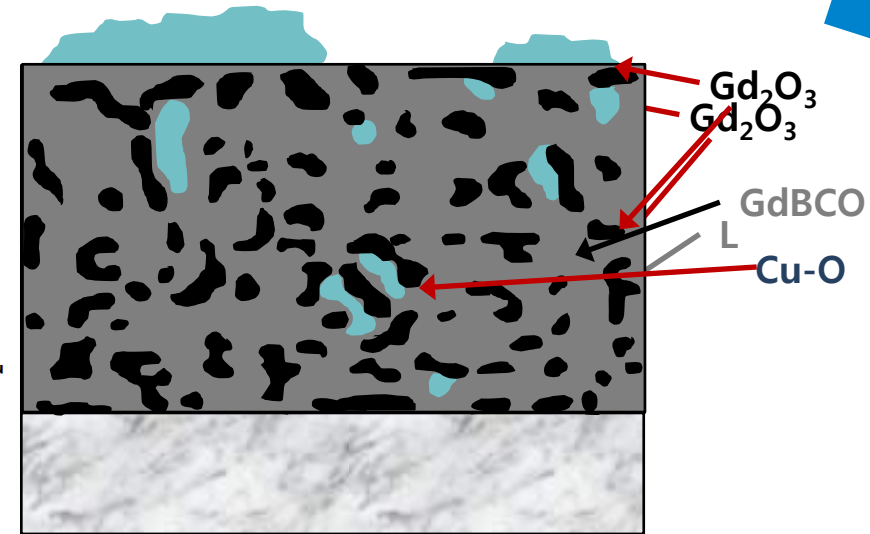
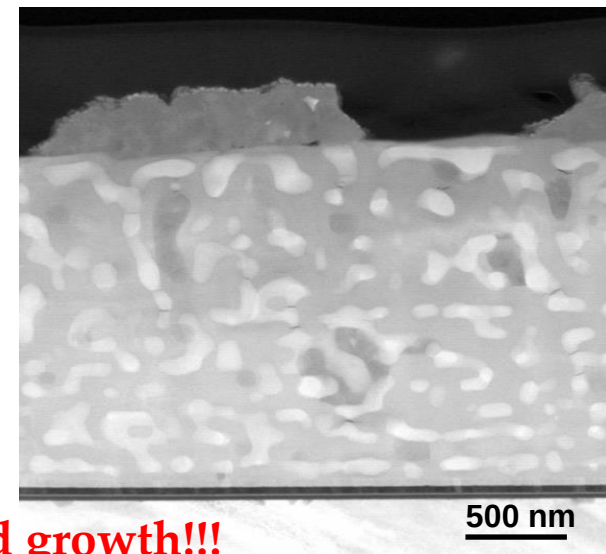


SuNAM's RCE-DR process

- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R) : Patented(PCT)
- 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



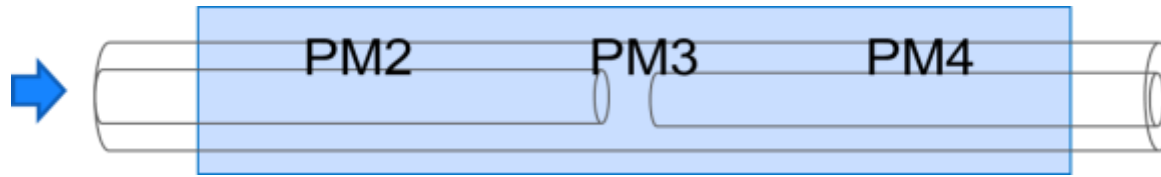
Growth mechanism of the GdBCO film by RCE-DR



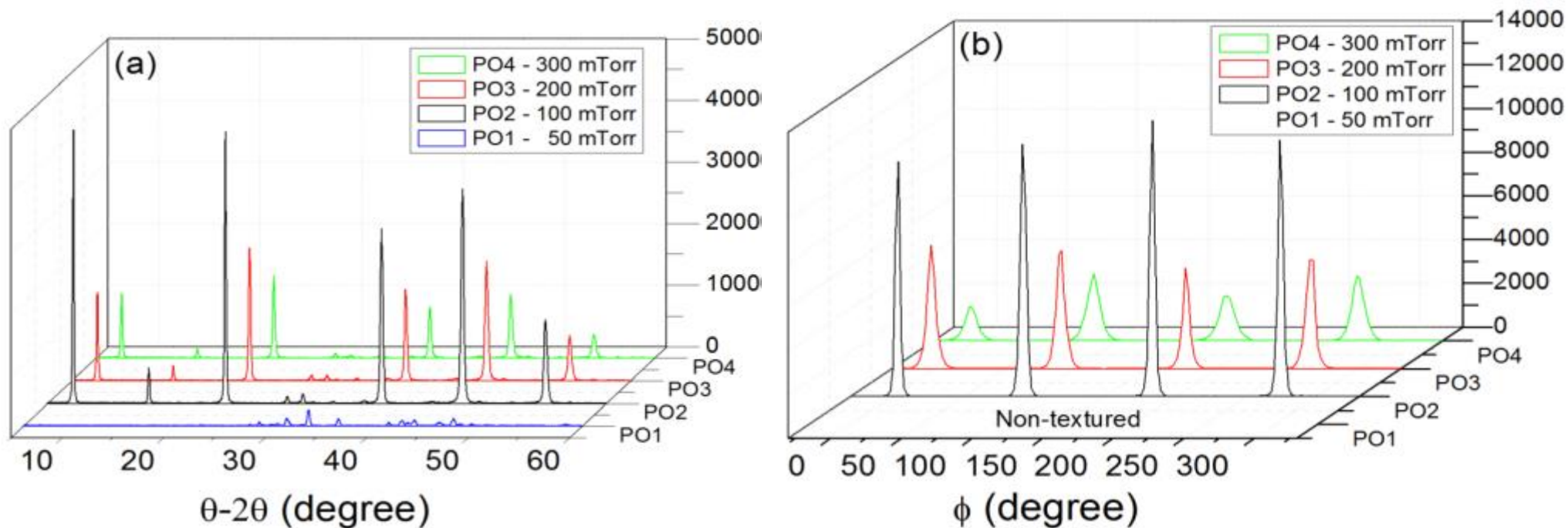
- Very low PO_2 zone ($\sim 10^{-5}$ Torr): **Amorphous Film**
- Lower PO_2 zone (~ 30 mTorr): **$Gd_2O_3 + Liquid$ (< 5 sec)**
- Higher PO_2 zone (~ 100 mTorr): **GdBCO Film (< 20 sec)**

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

Main parameter : Oxygen pressure

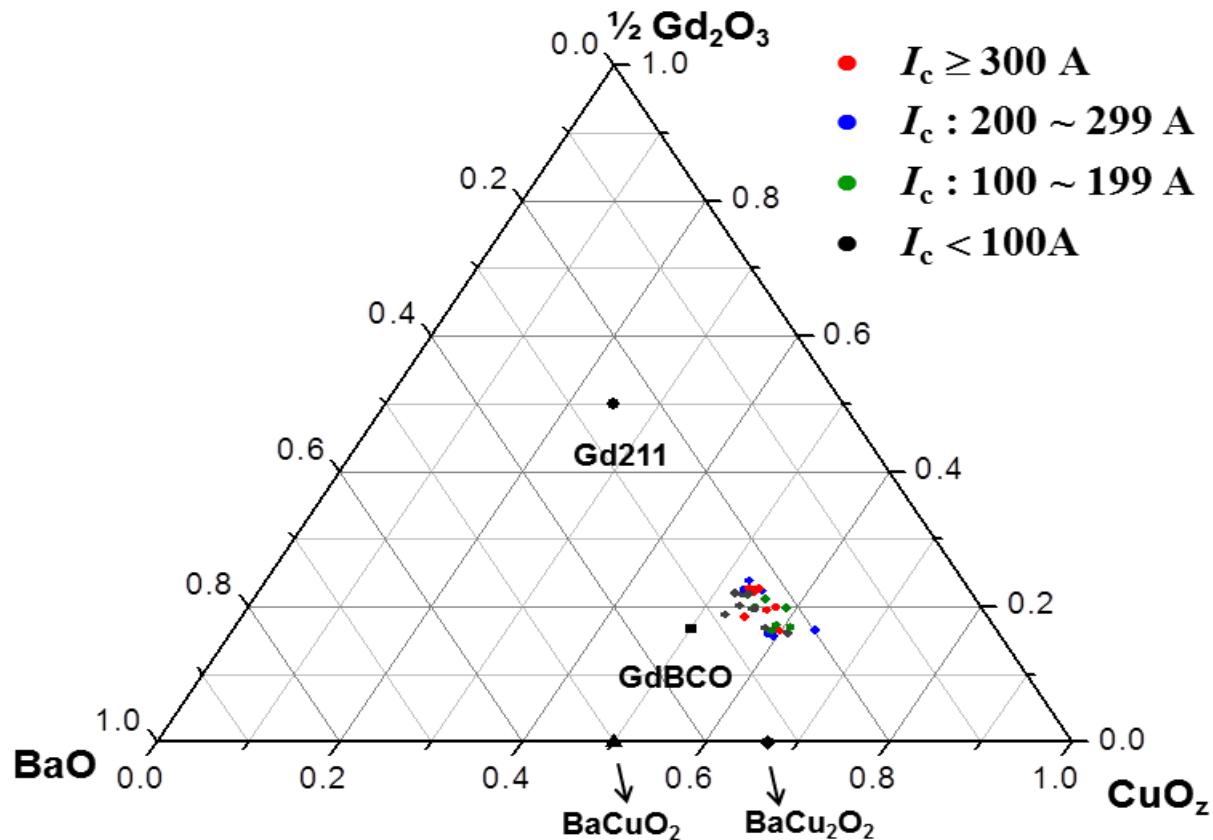


PM4 oxygen pressure dependence of crystallinity at 860 °C



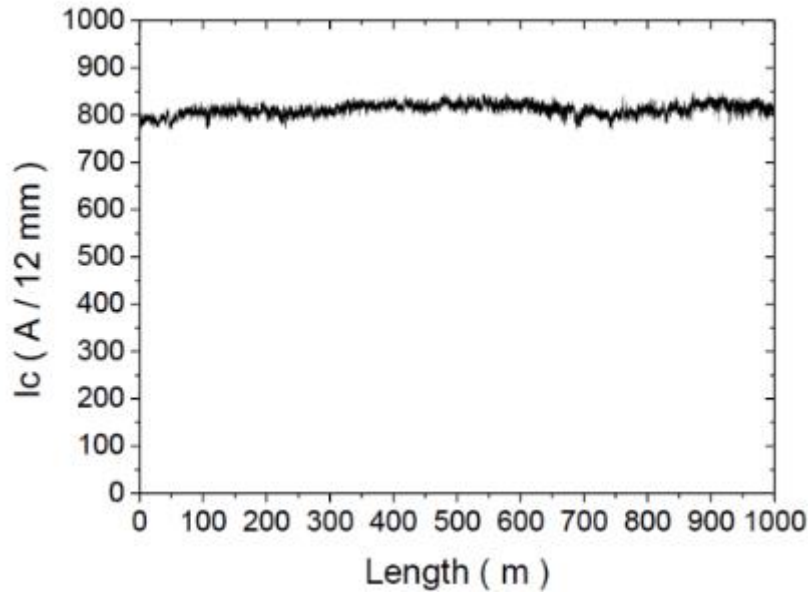
- The same batch, PO_2 increases.
- Optimum PO_2 is 100 ~ 200 mTorr.

Main parameter : Composition

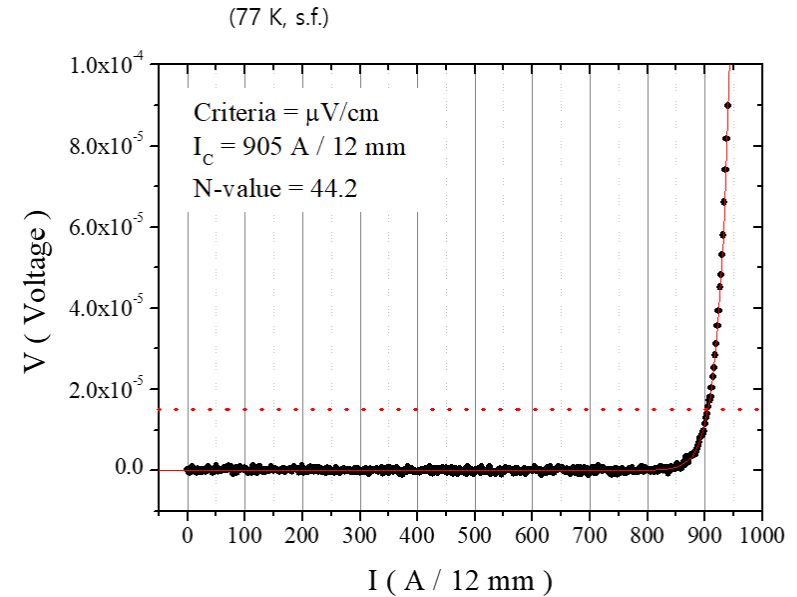
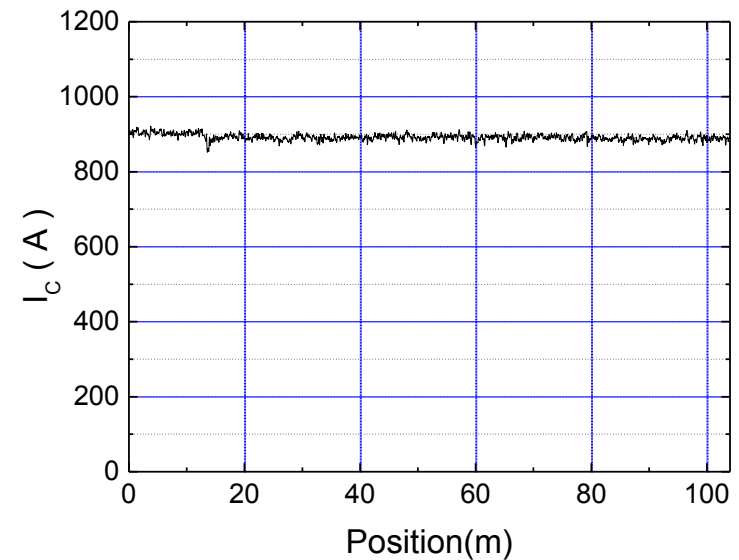


- The variation of the critical current according to the composition is very large.

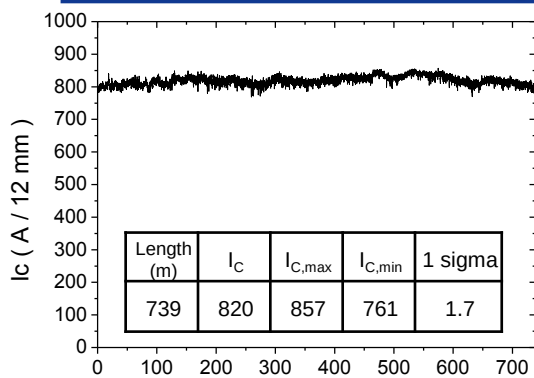
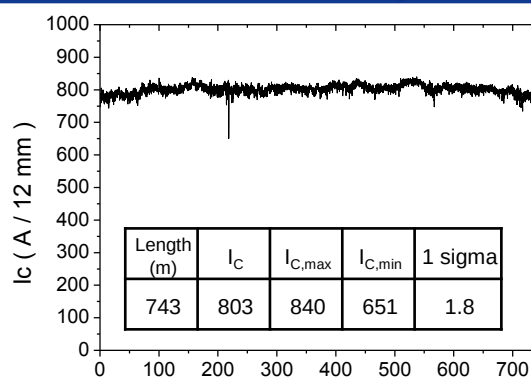
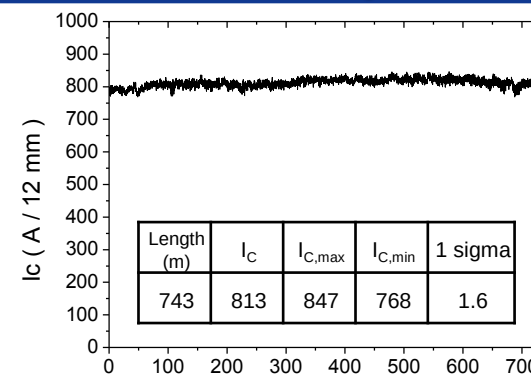
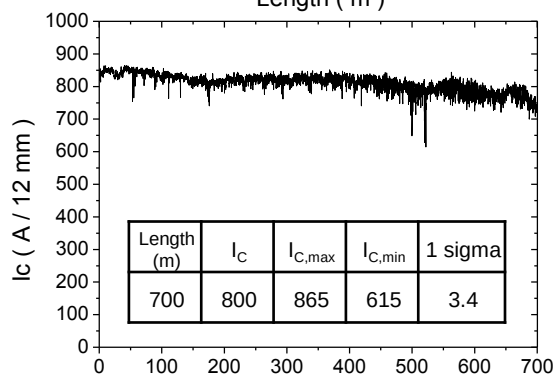
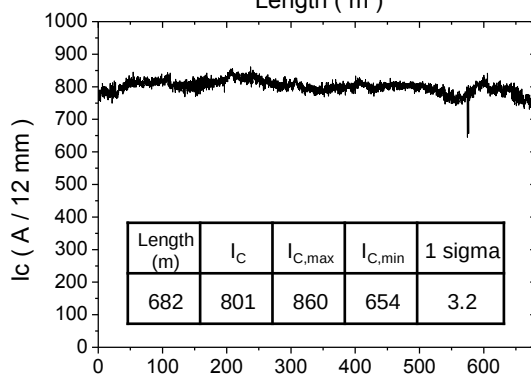
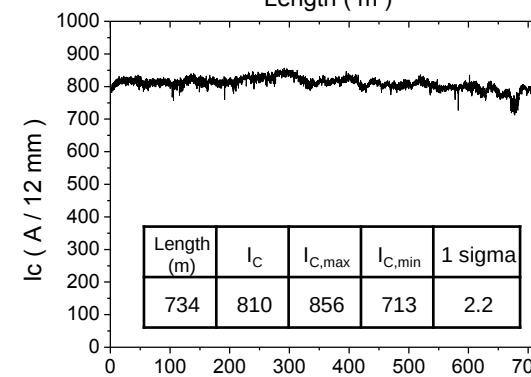
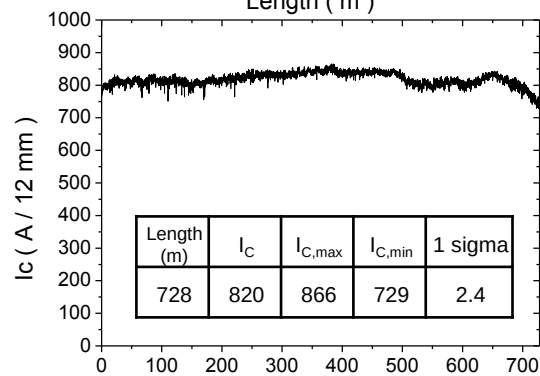
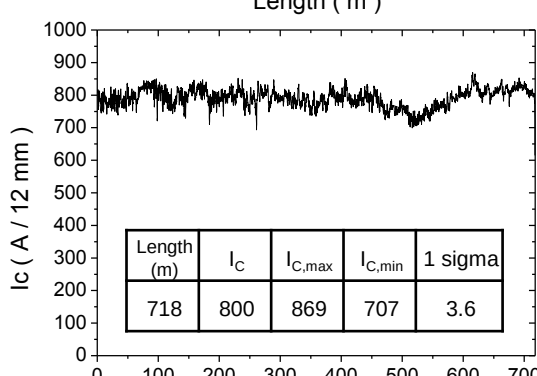
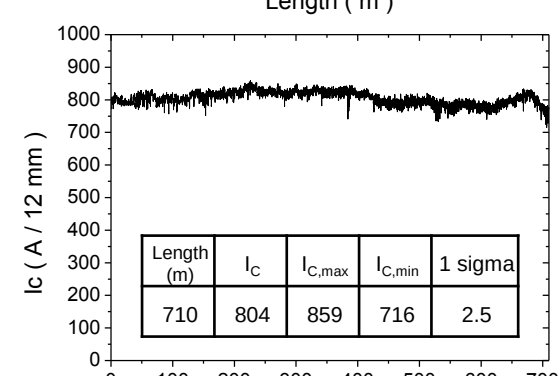
HTS 2G Wire Production Example



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

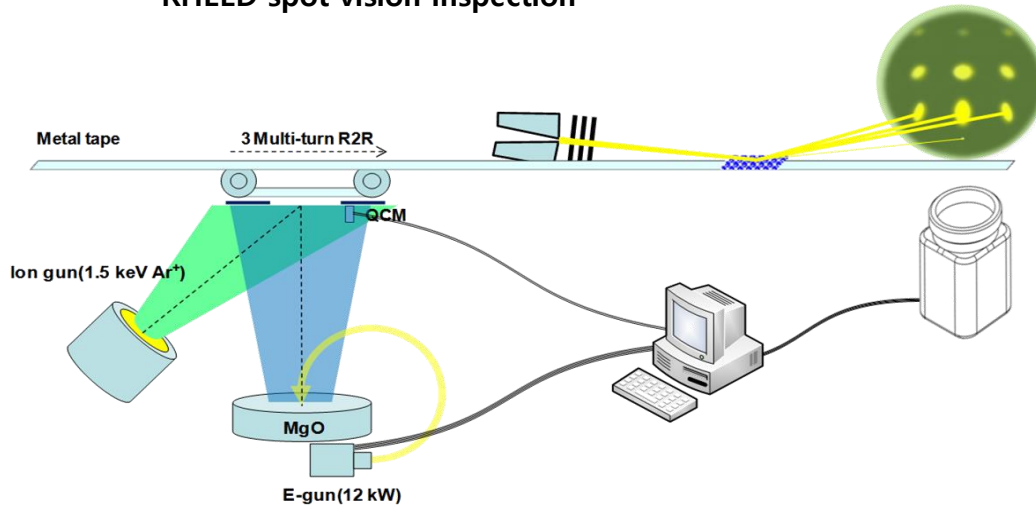
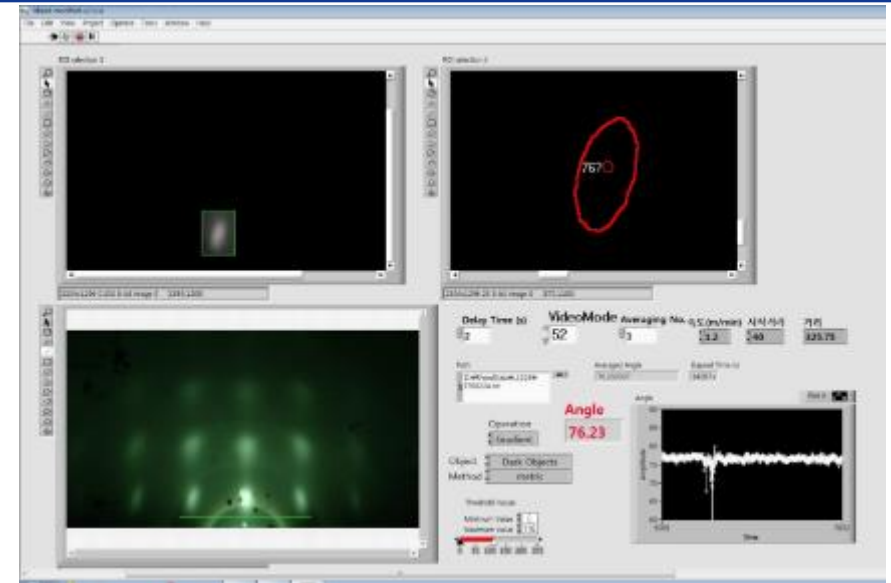


HTS 2G wire performances (daily production)

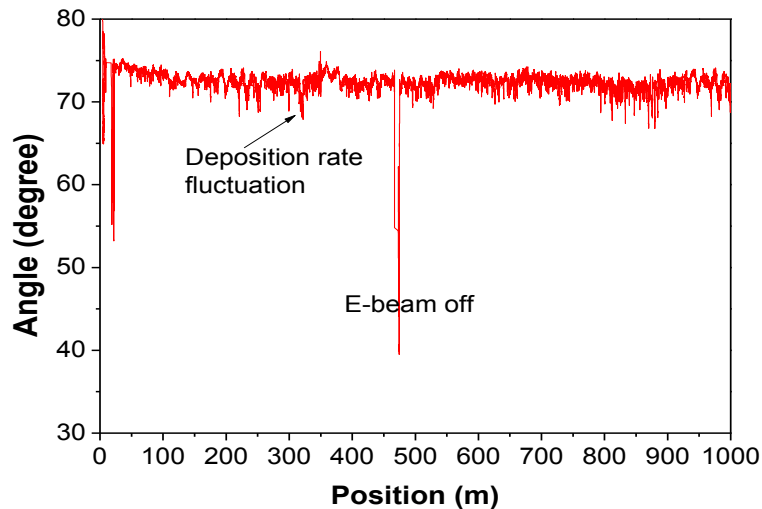
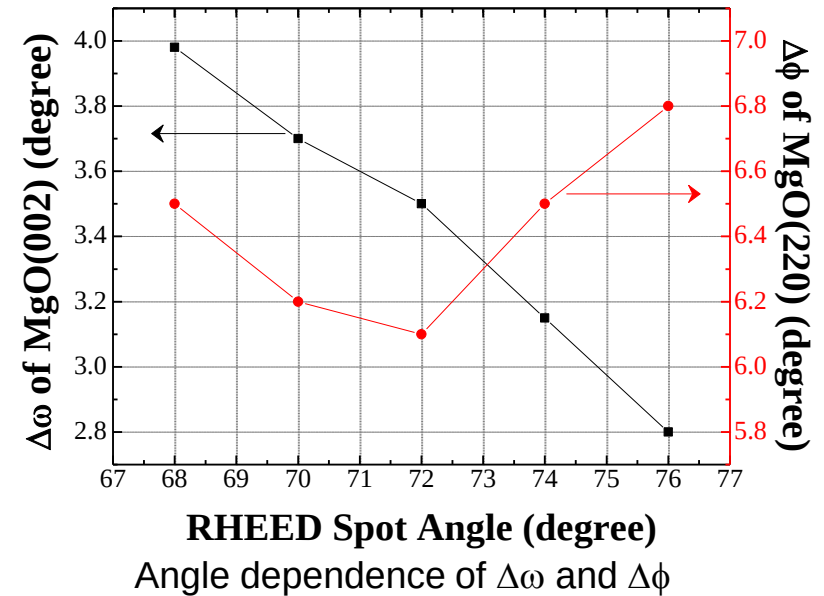


Various roll to roll quality control system : Buffer layers

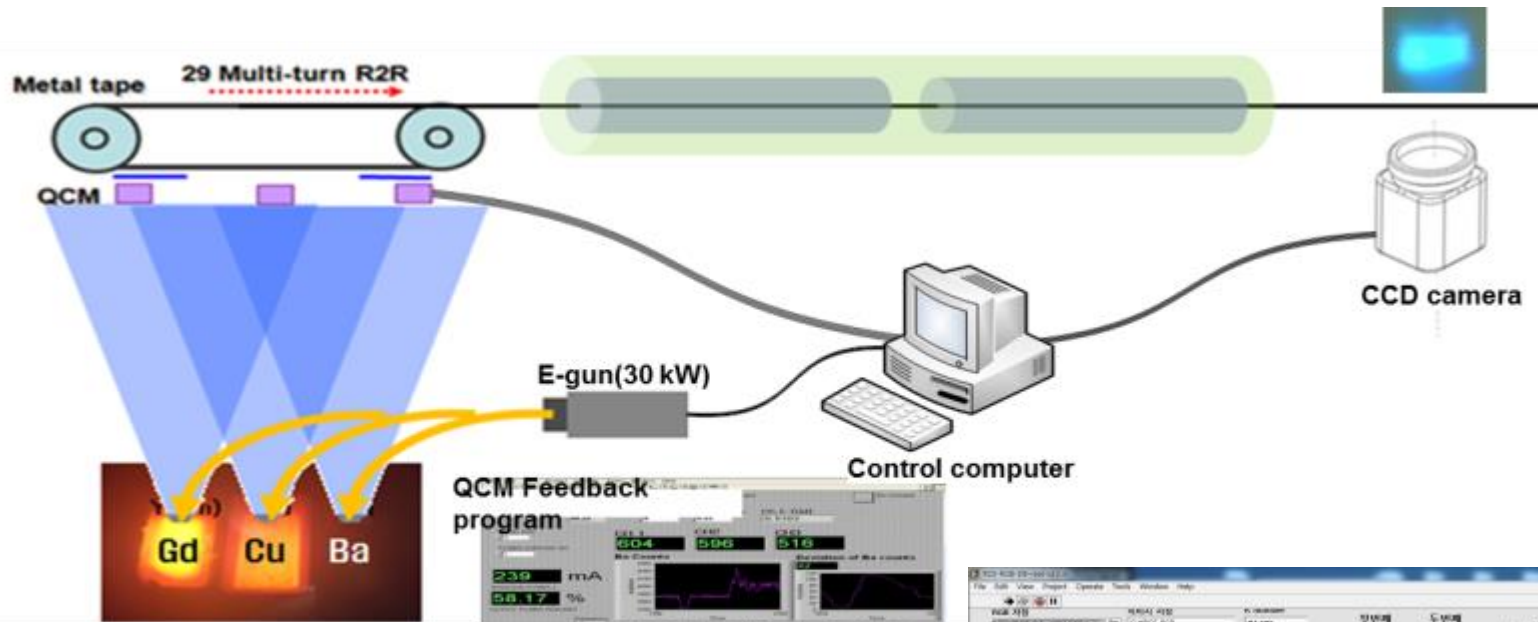
▪ RHEED spot vision inspection



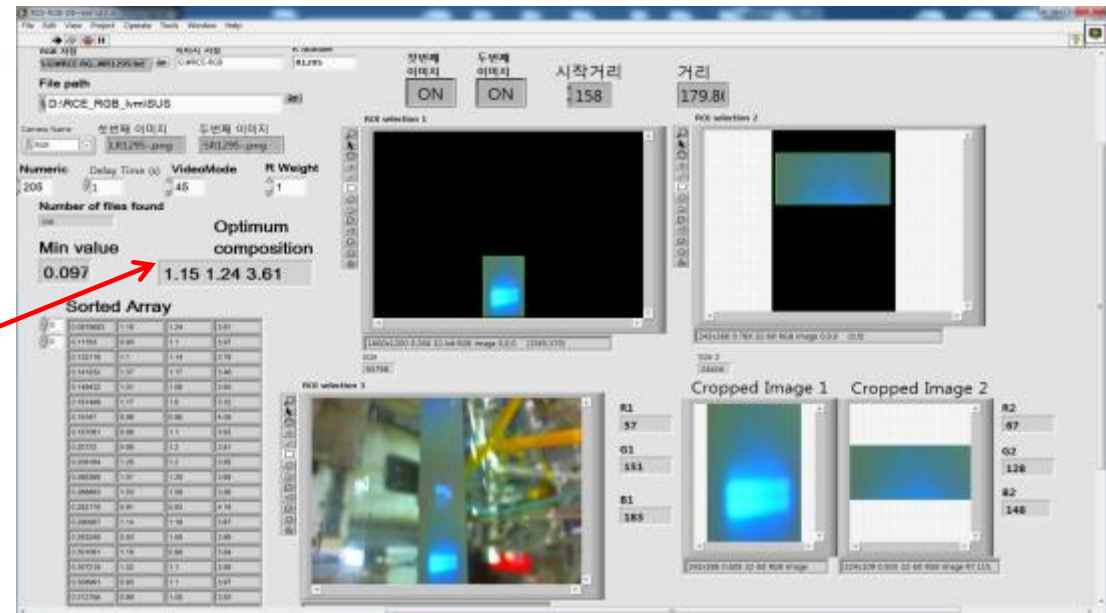
Real time RHEED spot inspection program



Quality Control : RCE Vision Inspection System

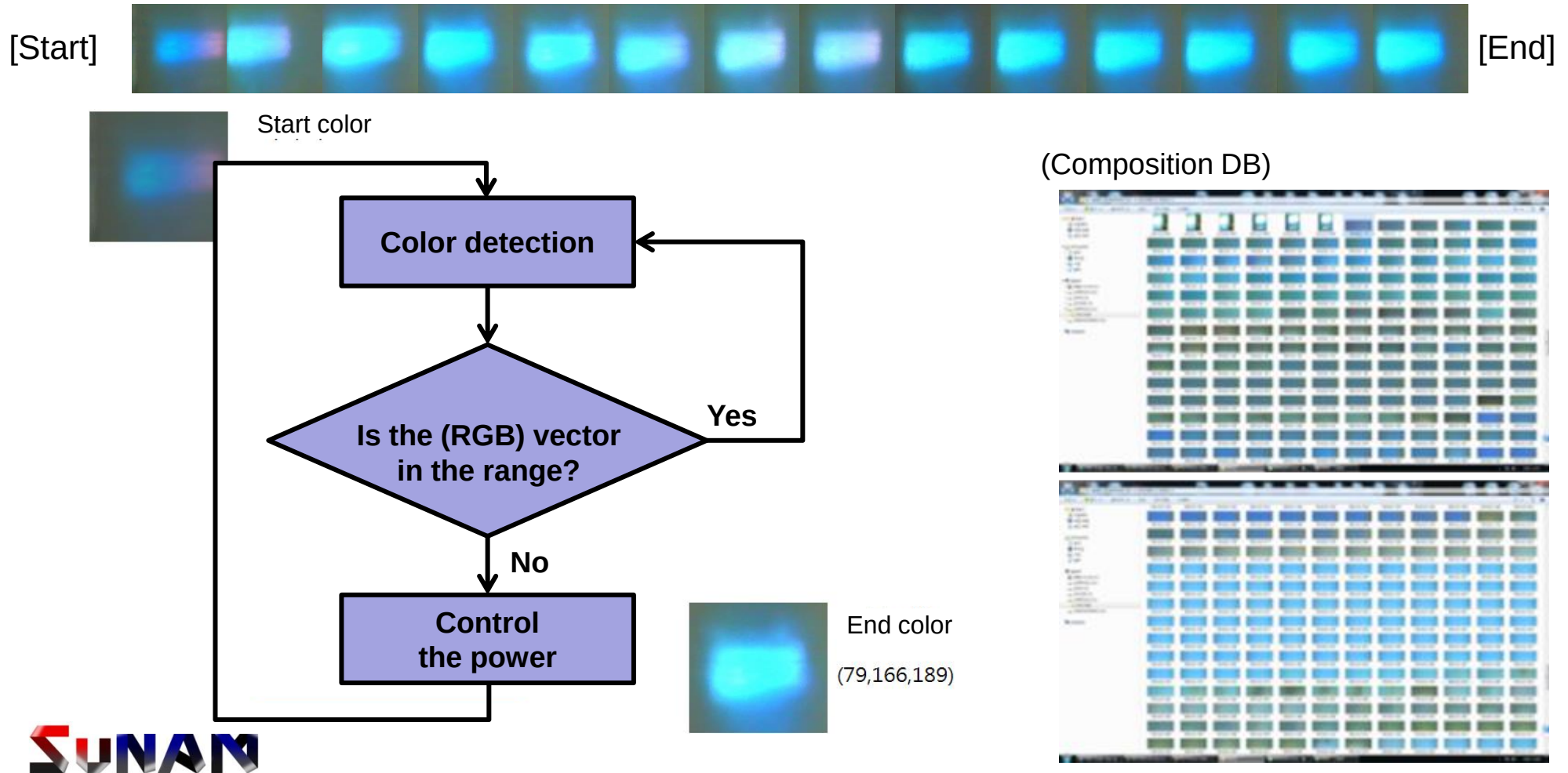


Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)

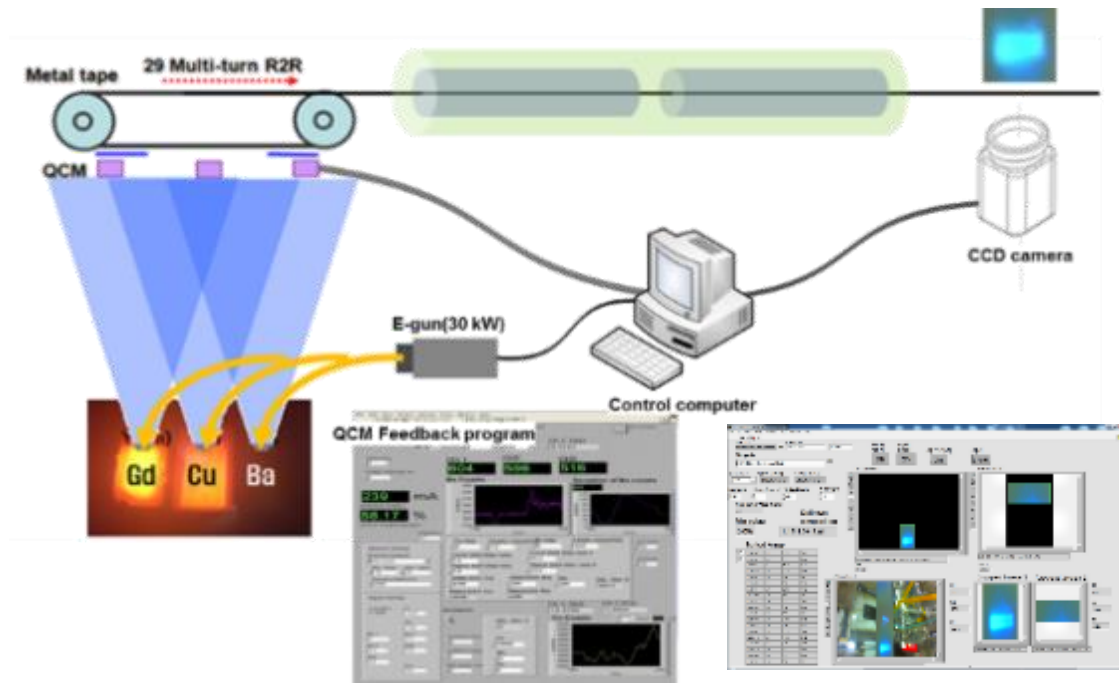
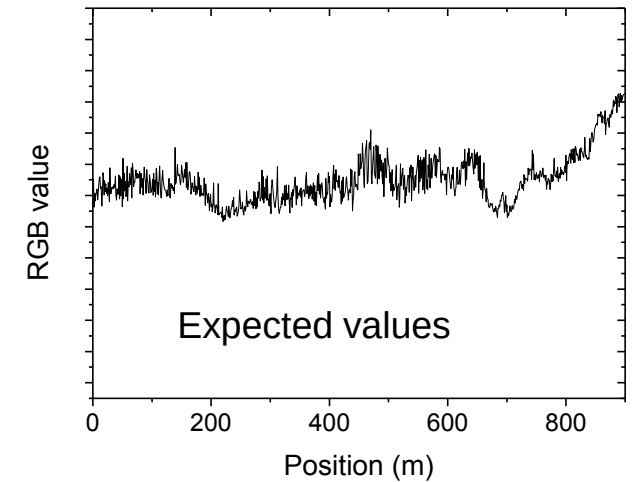


Quality Control : RCE Vision Inspection System

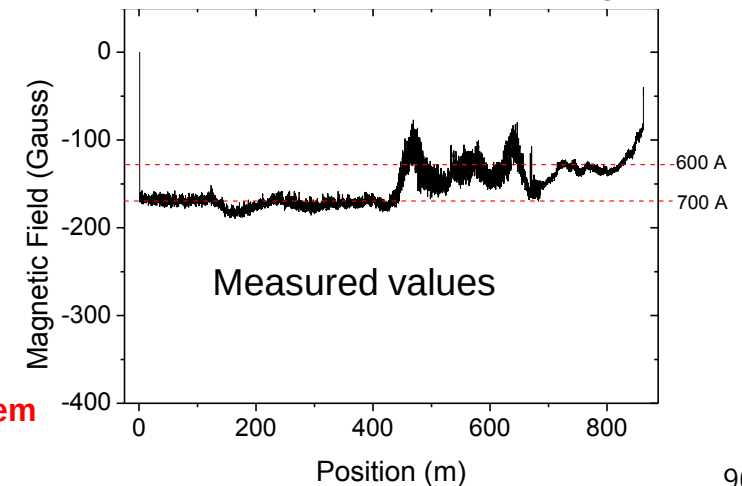
- RCE Vision System will be introduced for increasing the uniformity of composition in RCE-DR process. The control computer takes (RGB) values in three-dimensional vector space which is transformed from the color of the tape surface.



Various roll to roll quality control system : Superconducting layer



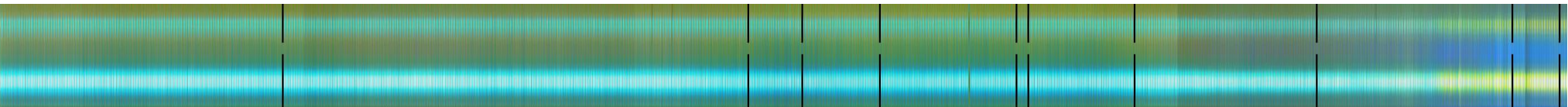
From RGB colors, can expect superconducting properties



RGB color system is the most powerful quality control program in RCE-DR system

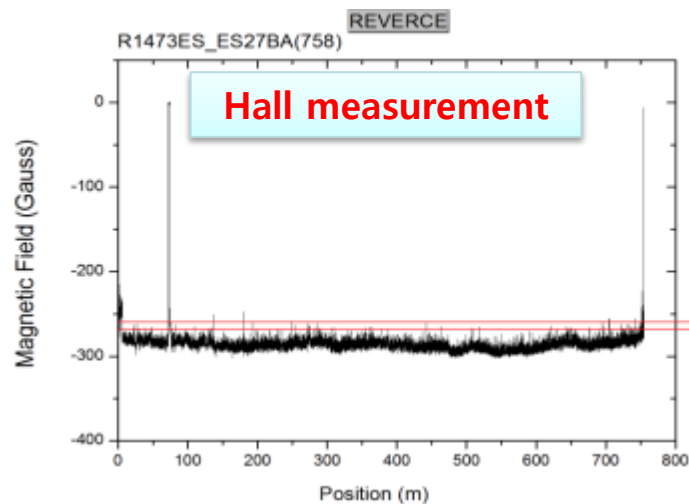
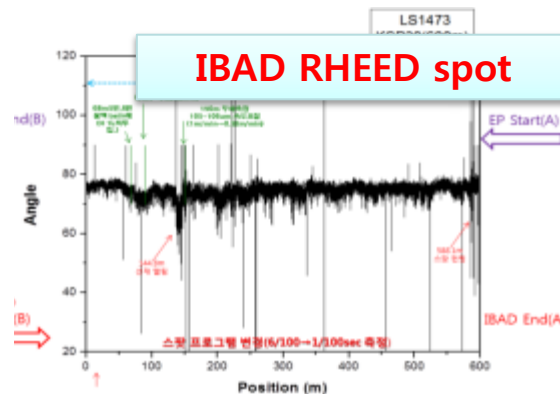
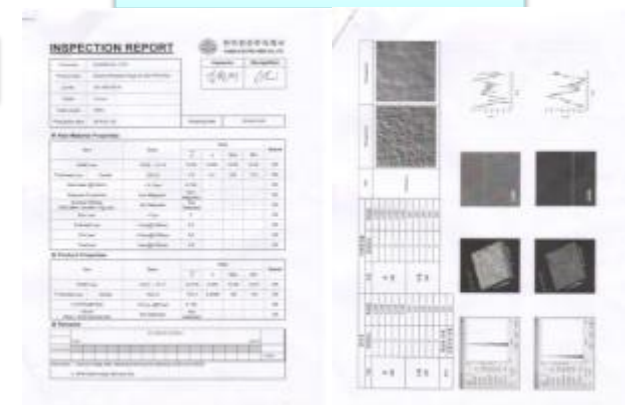
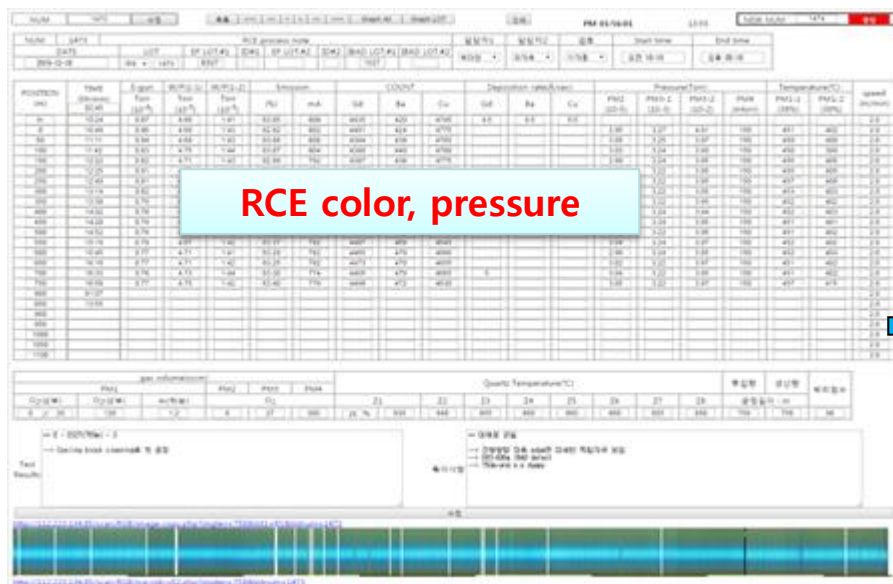
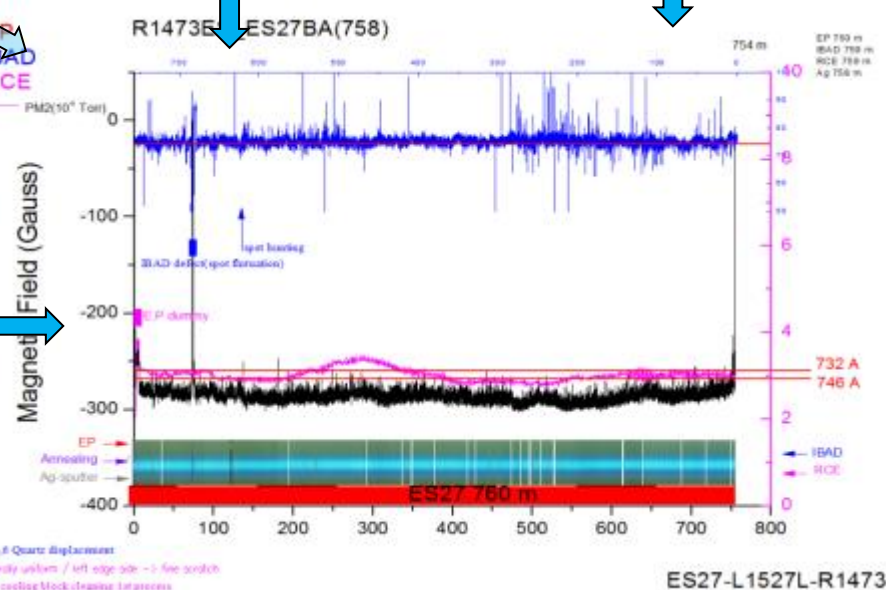
0 m CC color

900 m



Integration of process notes & wire performance

EP report



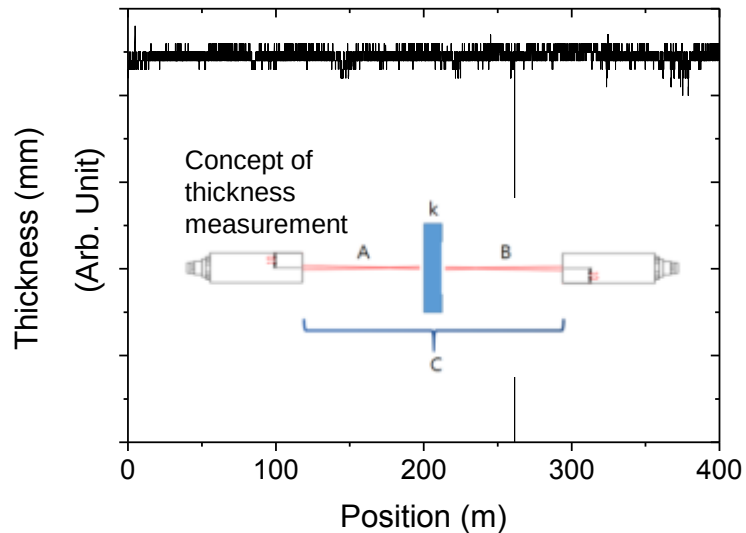
Quality control system : dimension & I_c



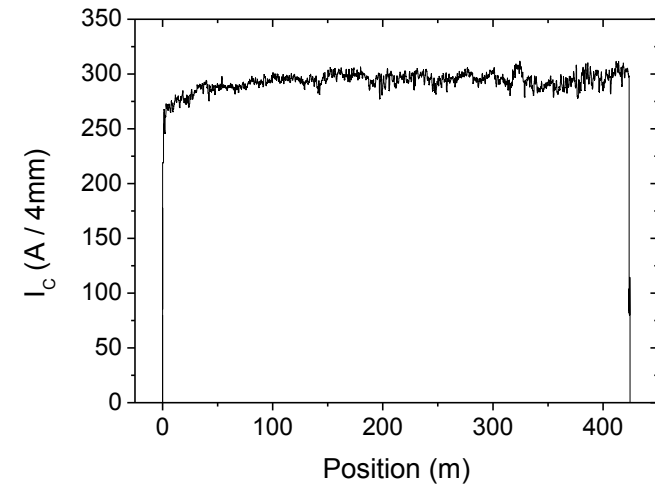
Continuous dimension measurement system :
measurement speed ~ 10 m / min



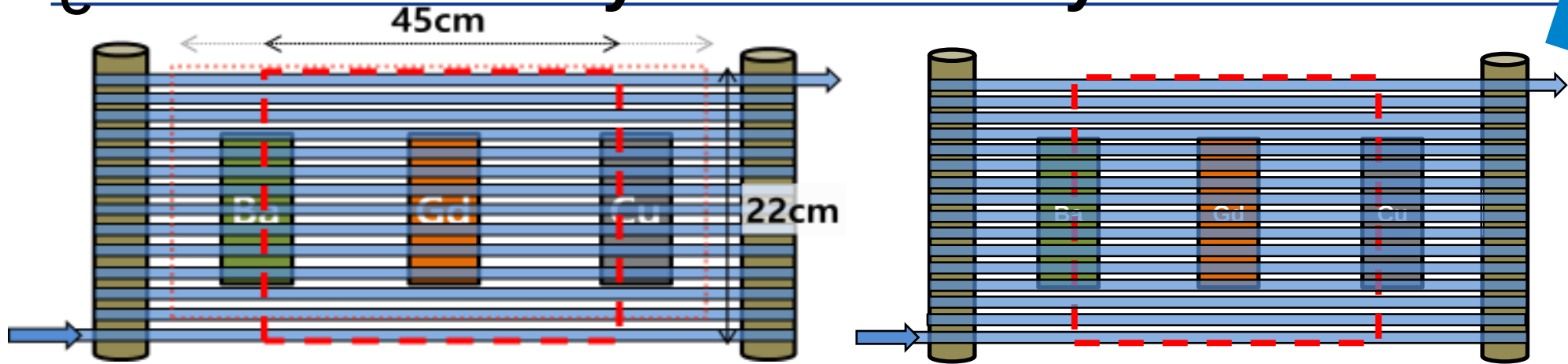
Transport I_c measurement system with Bending-double bending rollers : Measurement speed ~ 500 m / hr



Thickness of laminated CC



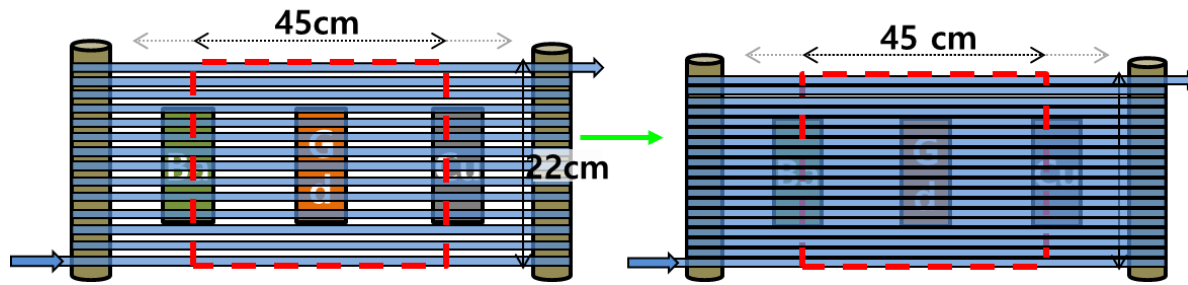
I_C enhancement by thicker SC layer



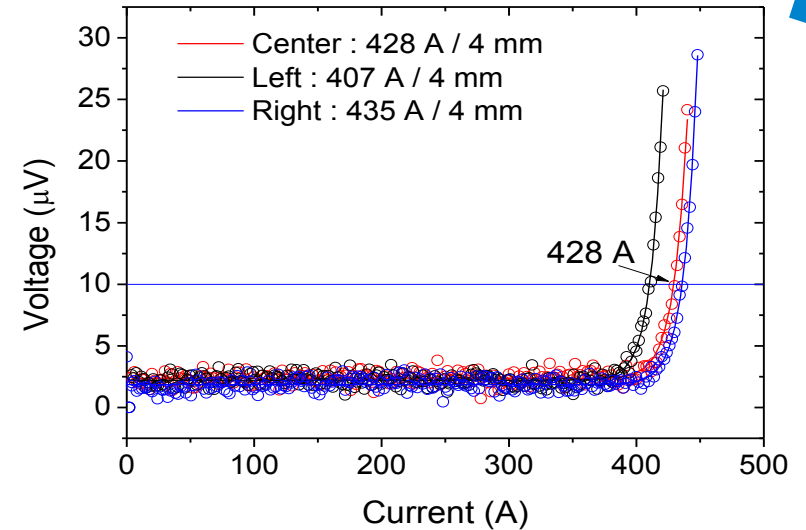
- ✓ It is needed to increase layer thickness without compromising high J_C
- ✓ We 'squeezed' more turns into the same deposition area, and/or increased evaporation rates of metal sources, and/or decrease the moving speed of tapes
- ✓ Achieved ~ 700 A/cm in $1.6 \mu\text{m}$ film & ~ 900 A/cm in $2.2 \mu\text{m}$ film



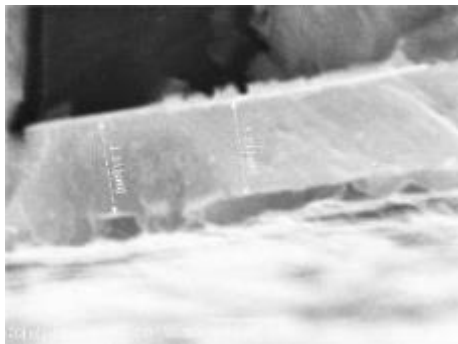
Thicker GdBCO layer for higher I_c



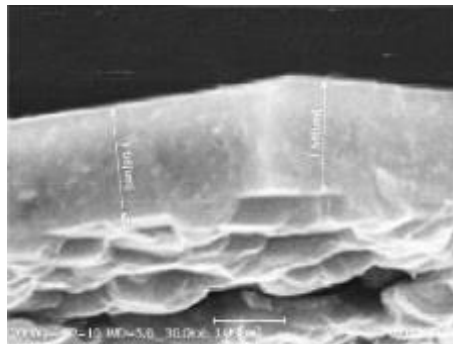
Increasing superconducting layer thickness with deposition layers, deposition rate, and moving speed.



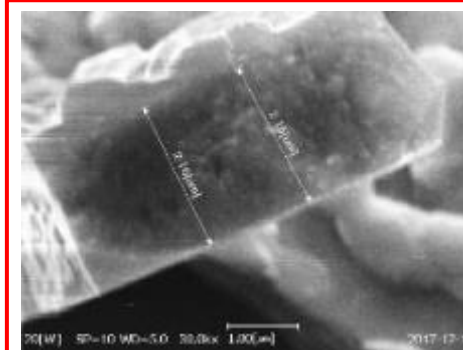
423 A/4 mm → 1,058 A/cm-w



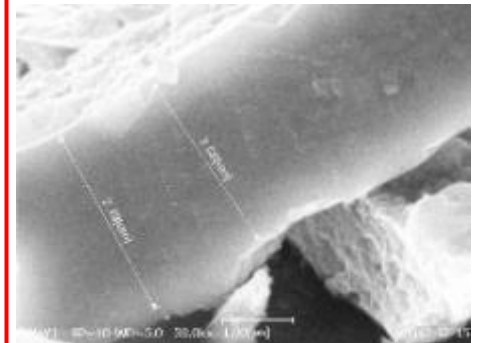
1.3 μm ,
600 ~ 800 A/12 mm



1.6 μm ,
700A/12 mm ~ 900 A/12 mm



2.2 μm ,
900 A/12 mm ~ 1200 A/12 mm



2.7 μm , 600 A/12 mm

Critical current retention after tensile stress

Conditions:

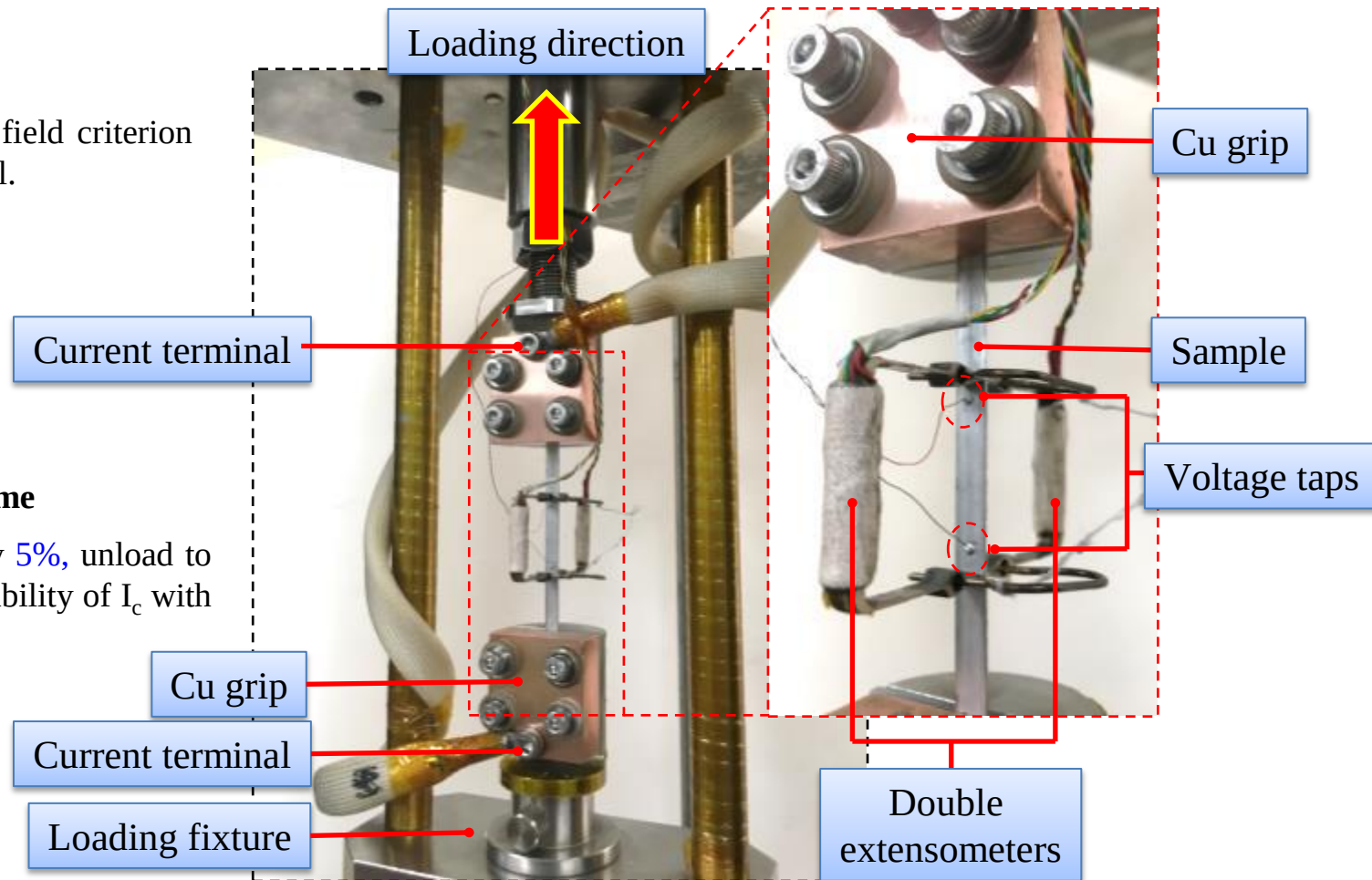
❑ I_c was measured at an electric field criterion of $1 \mu\text{V}/\text{cm}$ in 0.05% strain interval.

❑ Ram rate: 1 mm/min

Measurement of Irreversible stress/strain limits

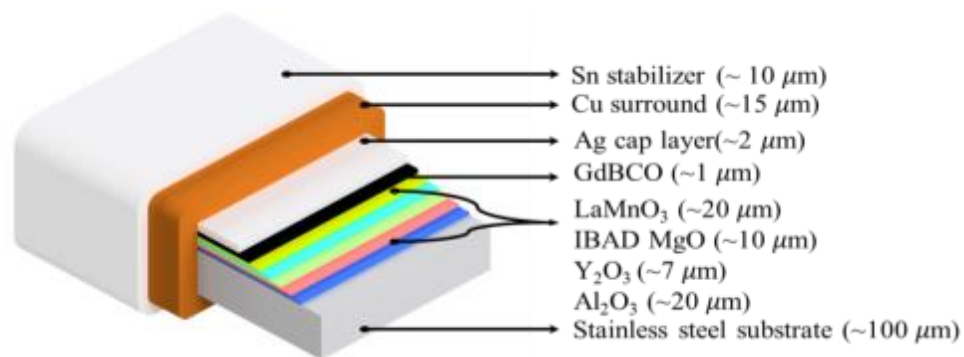
❑ Loading and unloading scheme

- when the initial I_c decreases by 5%, unload to 20 N, and measure the recoverability of I_c with a criterion of 99% I_c retention

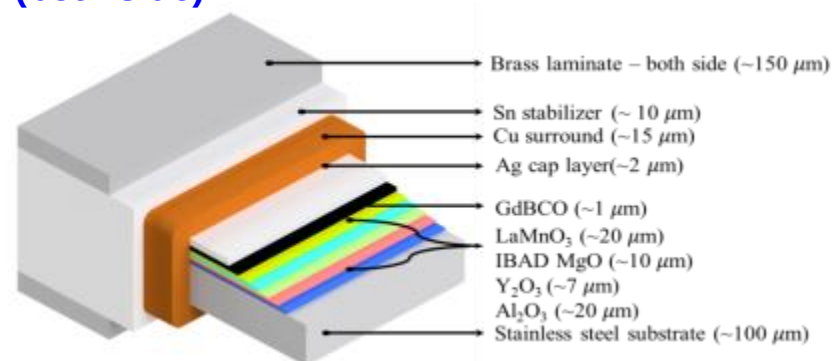


Critical current retention after tensile stress

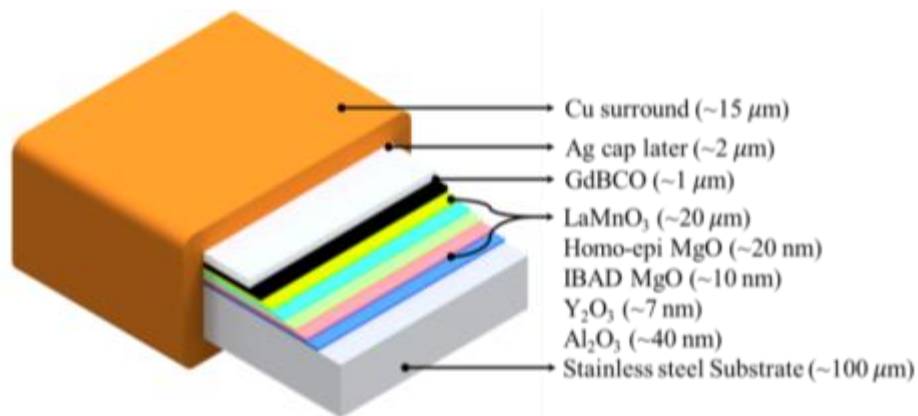
➤ Sn-Cu double layer stabilized CC tape



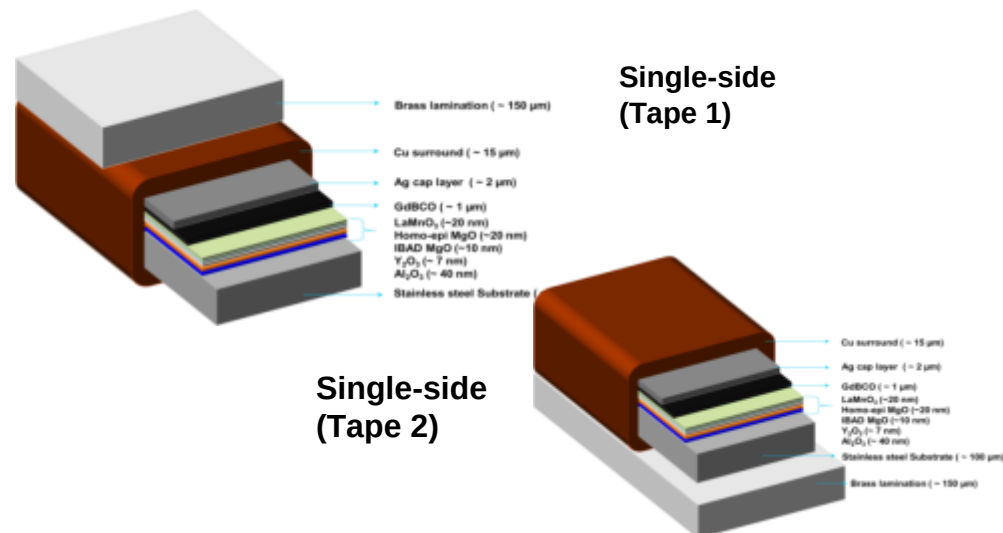
➤ Brass laminated Sn-Cu double layer CC tape (both side)



➤ Cu layer stabilized CC tape

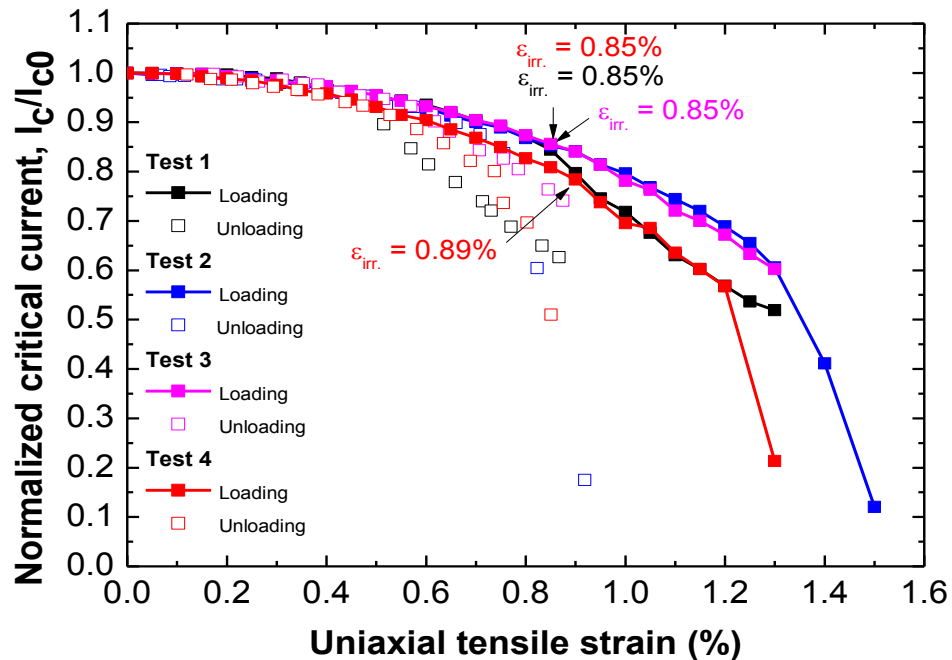
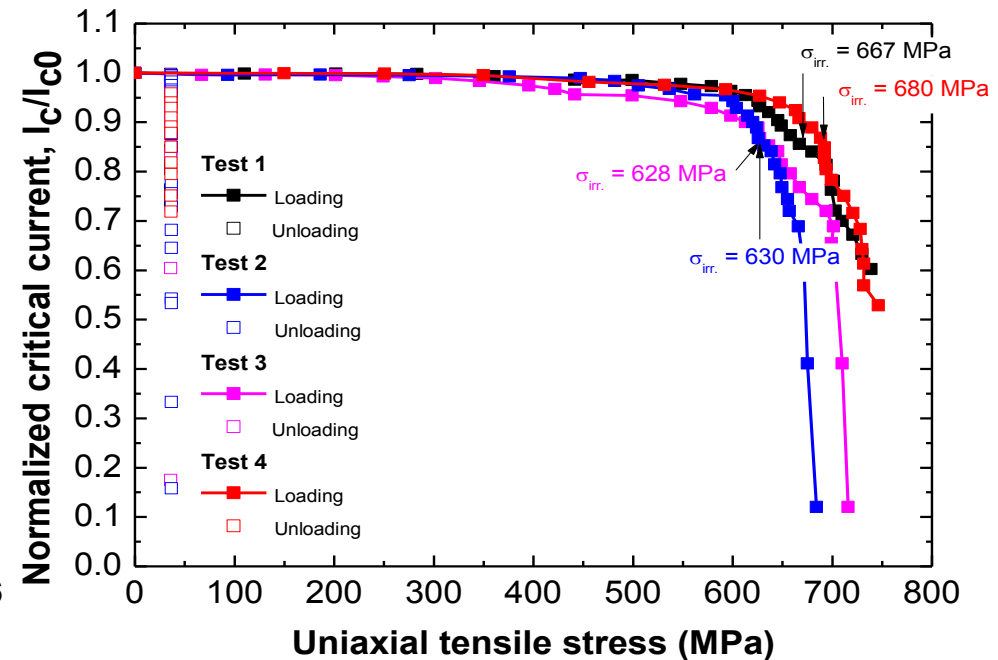


➤ Brass laminated Cu layer stabilized CC tape (Single side)



Critical current retention after tensile stress

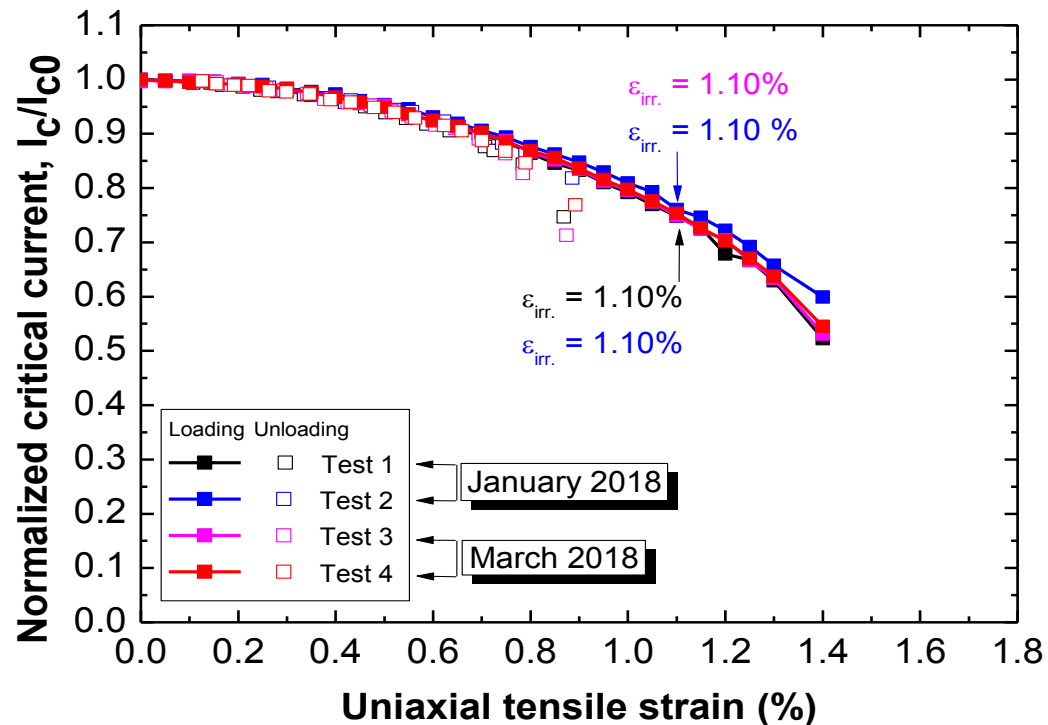
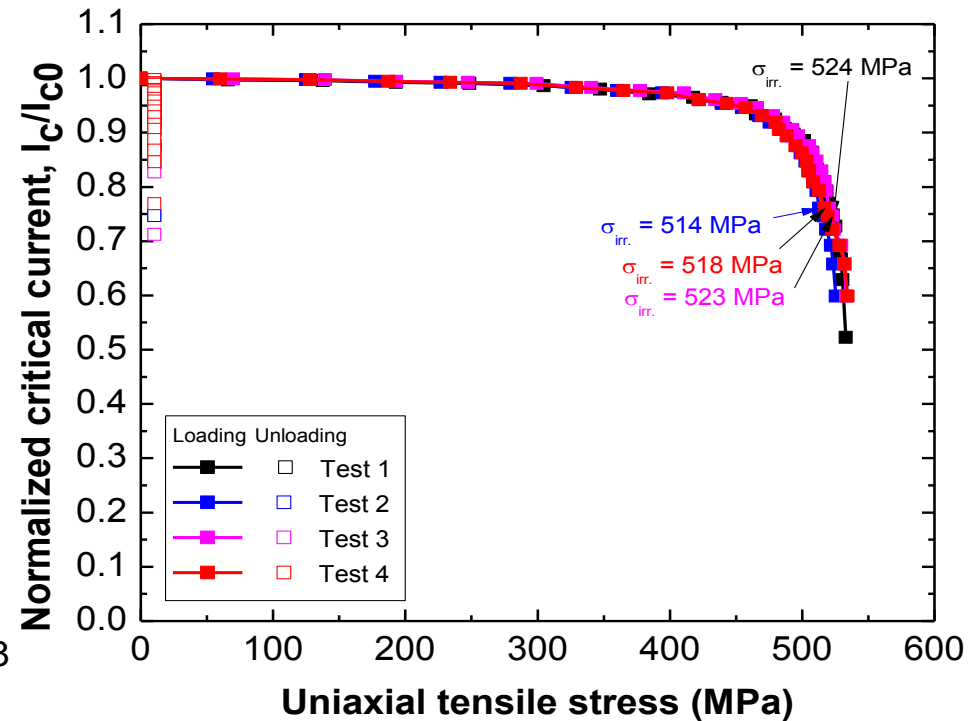
❖ Electromechanical Properties at 77K; Sn-Cu



Critical current retention after tensile stress

❖ Electromechanical Properties at 77K; brass laminated Sn-Cu

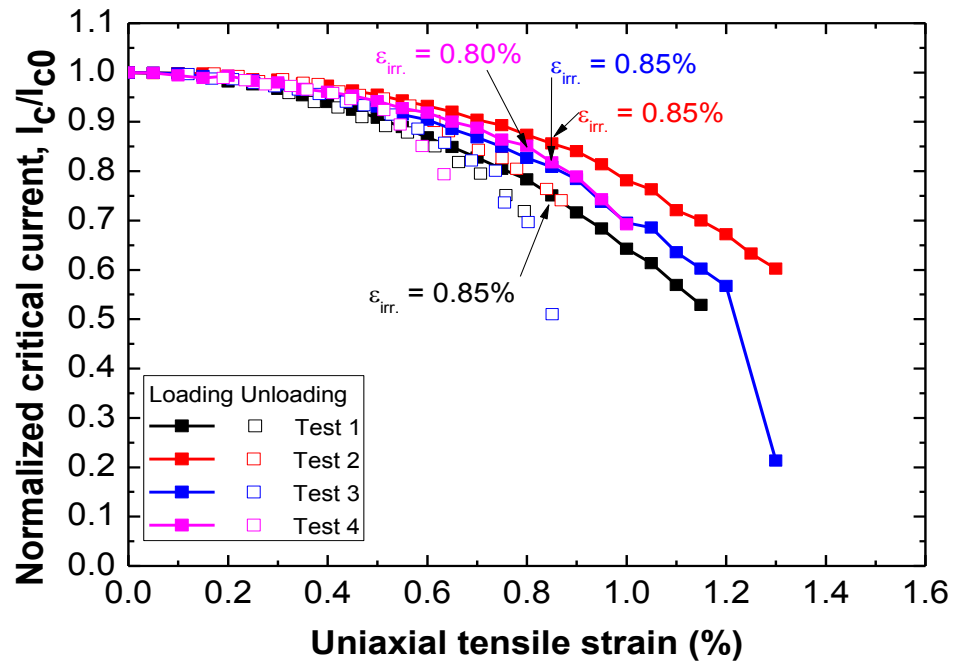
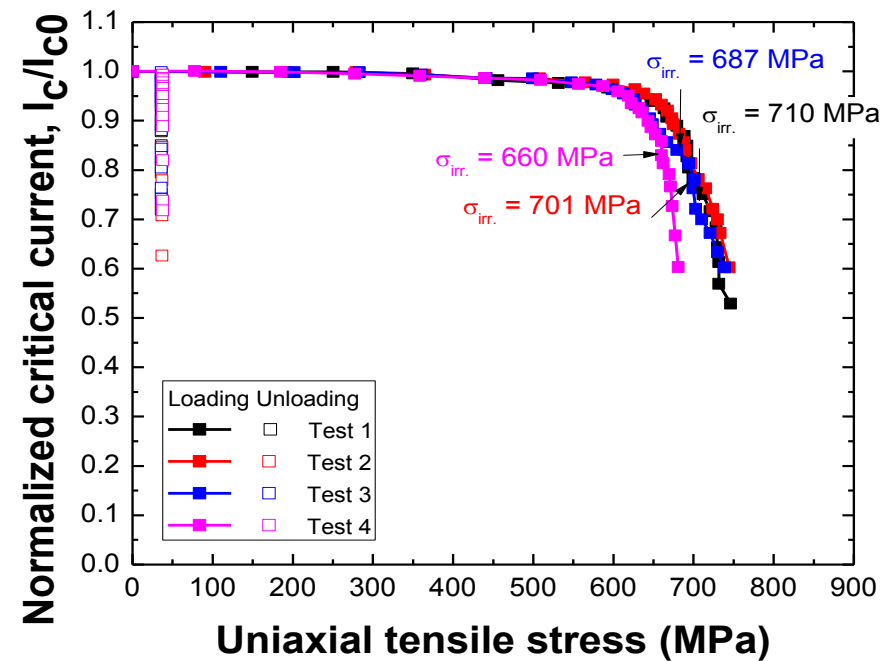
Both-side



❖ All of the tests exhibited the same behavior when it comes to irreversible strain limit even if they were tested with 1 month difference.

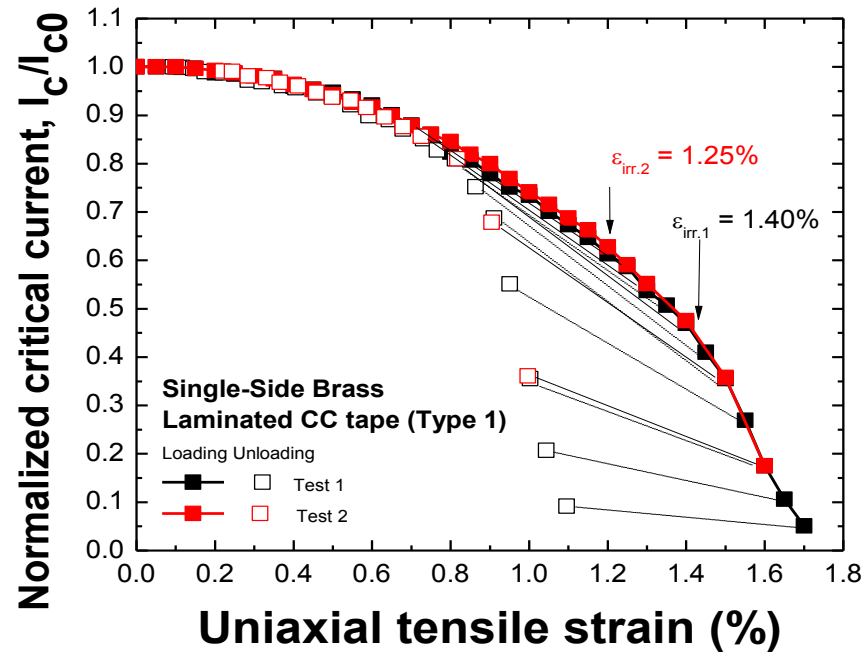
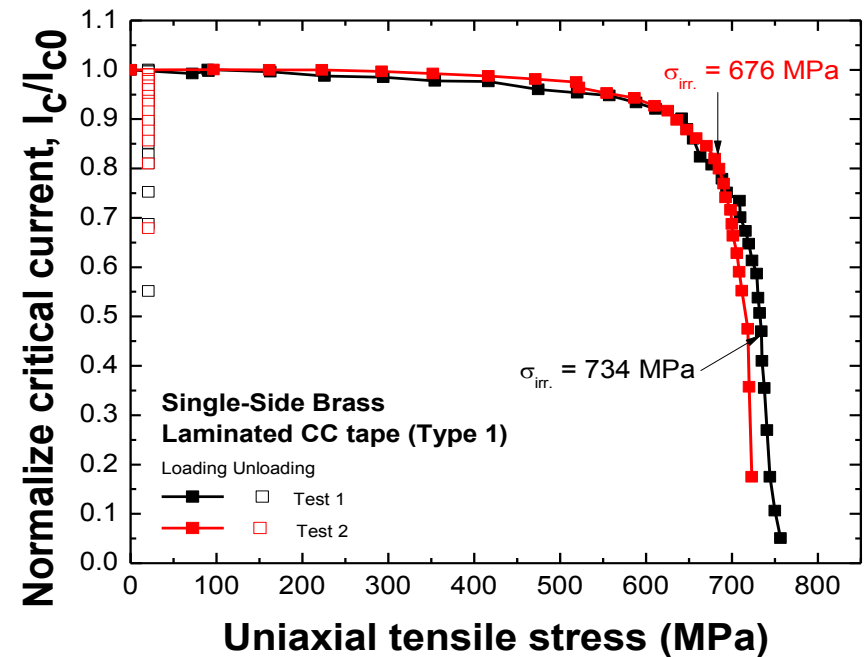
Critical current retention after tensile stress

❖ Electromechanical Properties at 77K; Cu



Critical current retention after tensile stress

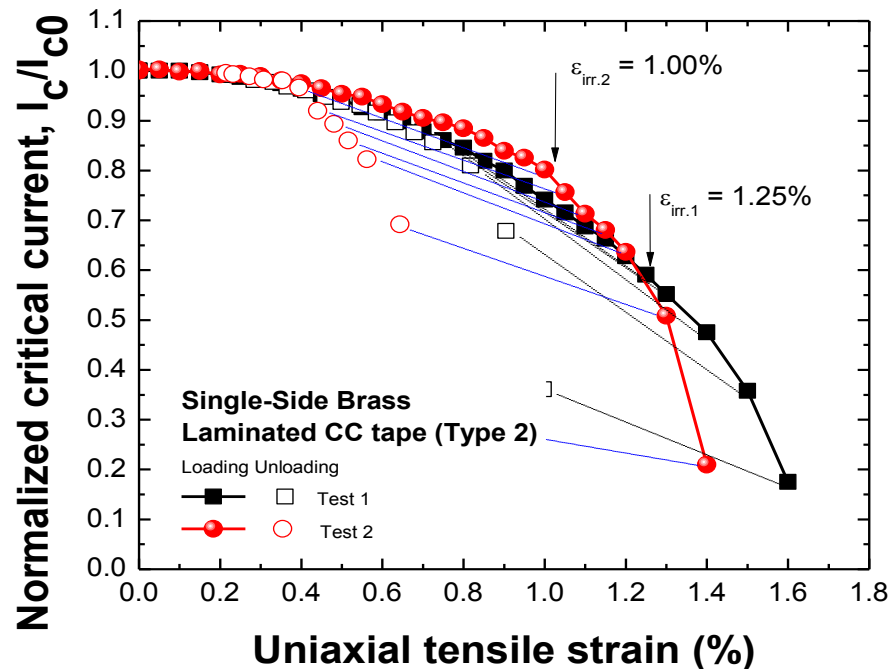
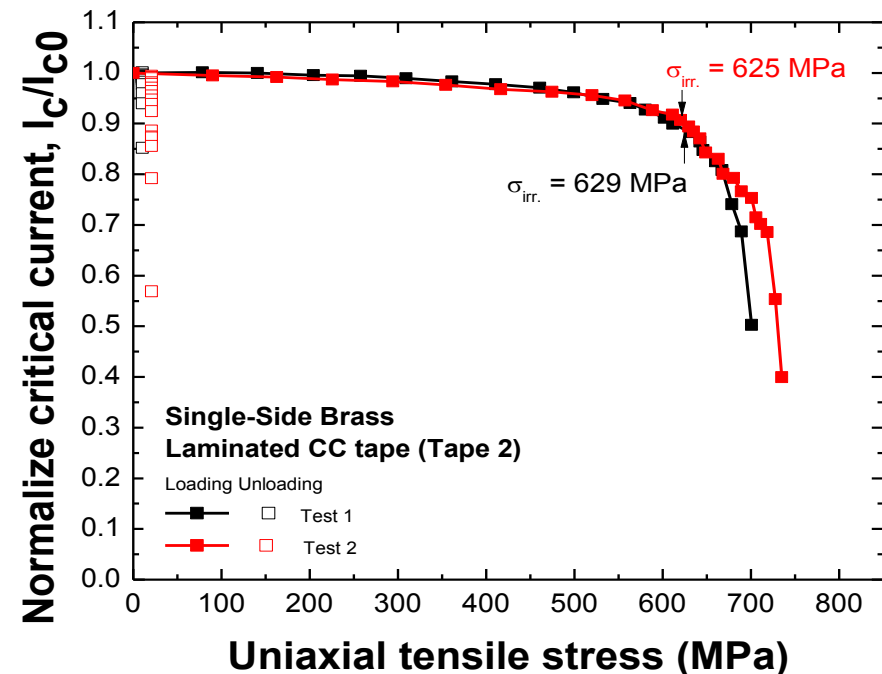
- ❖ Electromechanical Properties at 77K; brass laminated Cu, SC side



Critical current retention after tensile stress

❖ Electromechanical Properties at 77K; brass laminated Cu, substrate side

→ Substrate side(Brass Lamination)



Summary of electromechanical properties

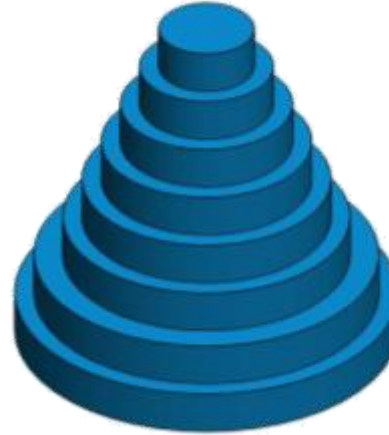
Sample designation		Irreversible strain limit, $\epsilon_{irr.} (\%)$	Irreversible stress limit, $\sigma_{irr.}$ (MPa)
1) Sn-Cu double layer stabilized CC tapes	Test 1	0.85	667
	Test 2	0.85	630
	Test 3	0.85	628
	Test 4	0.89	680
	Mean	0.86	651
2) Brass laminated (both side) Sn-Cu stabilized CC tapes	Test 1	1.10	524
	Test 2	1.10	514
	Test 3	1.10	523
	Test 4	1.10	518
	Mean	1.10	520
3) Cu-stabilized CC tapes	Test 1	0.85	710
	Test 2	0.85	701
	Test 3	0.85	687
	Test 4	0.80	660
	Mean	0.84	690
4) Brass laminated (one side) Cu stabilized CC tapes	Test 1 (Type 1)	1.40	734
	Test 2 (Type 1)	1.25	676
	Test 3 (Type 2)	1.00	629
	Test 4 (Type 2)	1.25	625
	Mean	1.23	667

Double bending exp.



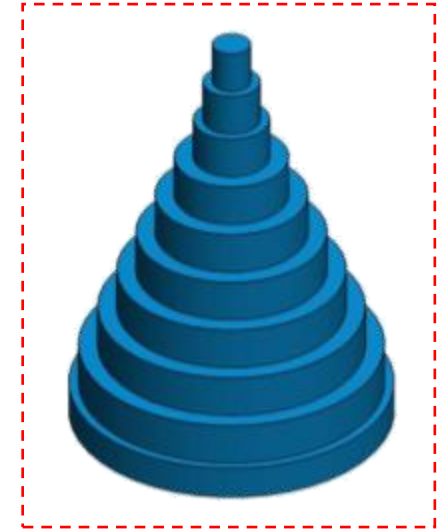
Double bending test photograph

Bending radius :
25, 35, 45, 55, 65, 75, 90,
100 mm



Mandrel (3D model)

Bending radius :
10, 15, 20, 30, 40, 50, 60,
70, 80 mm



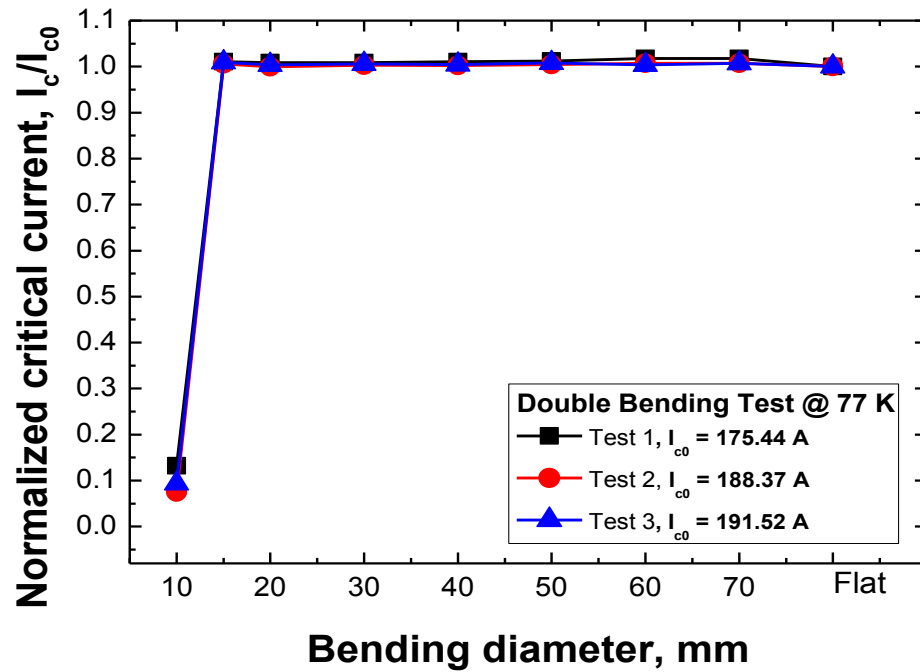
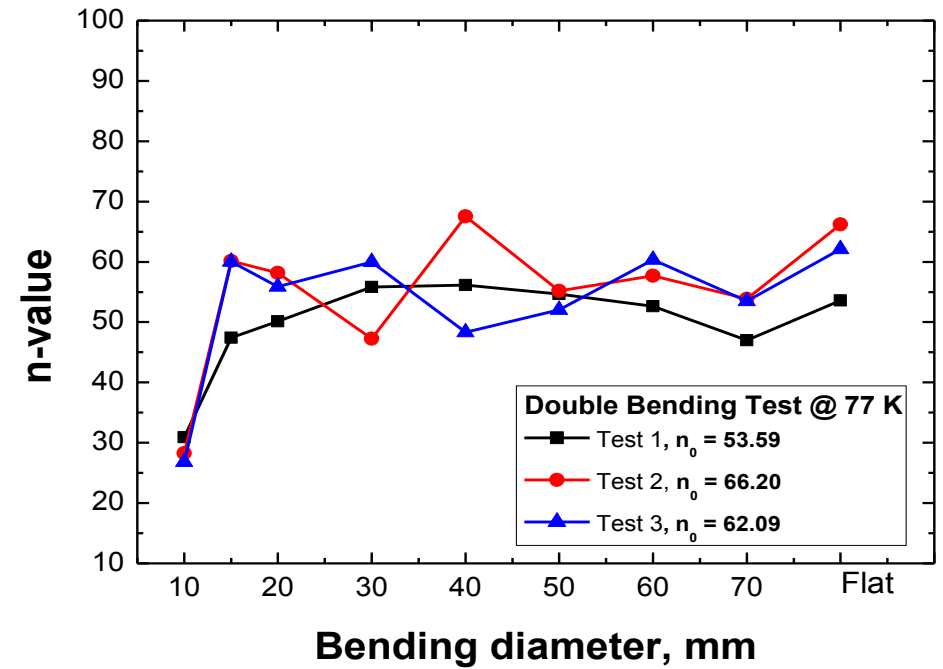
Double bending test: **Manufacturing actual coil windings**

Experimental method

- After the CC tapes are measured its dimensions, I_c is then measured at flat state.
- After measuring the I_c at flat state, double bending was done at room temperature from 80 mm diameter down to 10 mm diameter of the mandrel.
- After bending, I_c was measured at 77 K with respect to the bending diameter.

Double bending exp.

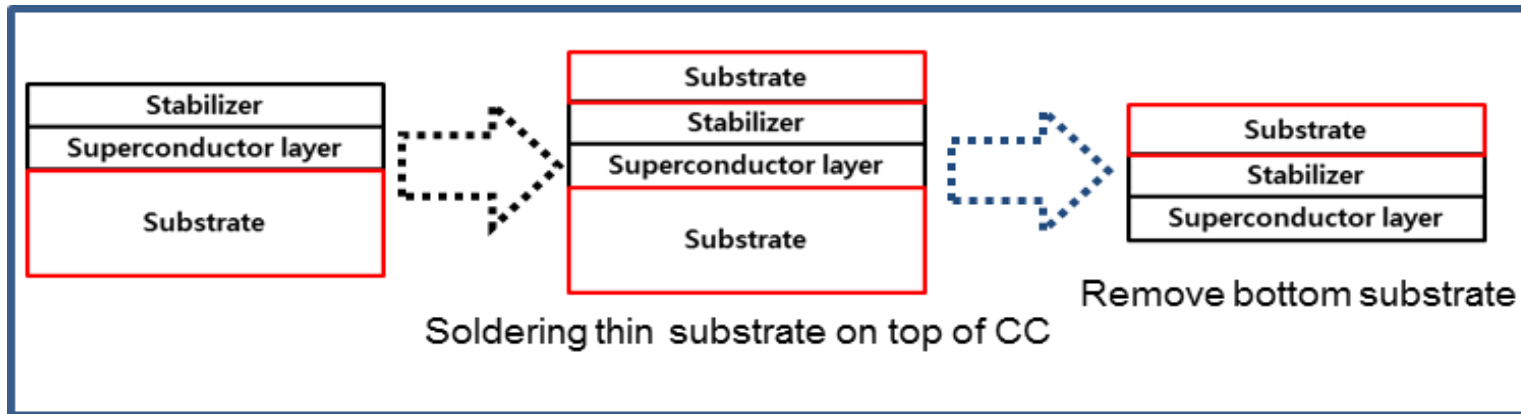
❖ Double bending test at 77K; Cu



Summary of double bending exp.

Sample		Dimensions Width/Thickness [mm]	Critical Current, I_{c0} (A)	Critical Bending Diameter (mm)	n-value
1) Sn-Cu double layer Cu stabilized CC tapes	Test 1	4.04/0.137	265	15	56
	Test 2	4.05/0.138	264	15	65
	Test 3	4.05/0.136	264	20	56.
	Mean		264	16.7	59
2) Brass laminated (both side) Sn-Cu double layer stabilized CC tapes	Test 1	4.45/0.430	230	15	61
	Test 2	4.45/0.435	242	15	81
	Test 3	4.45/0.434	243	15	62
	Mean		238	15	68
3) Cu-stabilized CC tapes	Test 1	4.08/0.137	175	15	54
	Test 2	4.08/0.138	188	15	66
	Test 3	4.08/0.136	192	15	62
	Mean		185	15	61
4-1) Brass laminated (one side) Cu-stabilized CC tapes (Type 1)	Test 1	4.05/0.280	174	15	46
	Test 2	4.04/0.282	184	15	48
	Test 3	4.05/0.281	184	15	49
	Mean		181	15	48
4-2) Brass laminated (one side) Cu-stabilized CC tapes (Type 2)	Test 1	4.04/0.282	186	50	49
	Test 2	4.05/0.280	186	50	48
	Mean		186	50	48

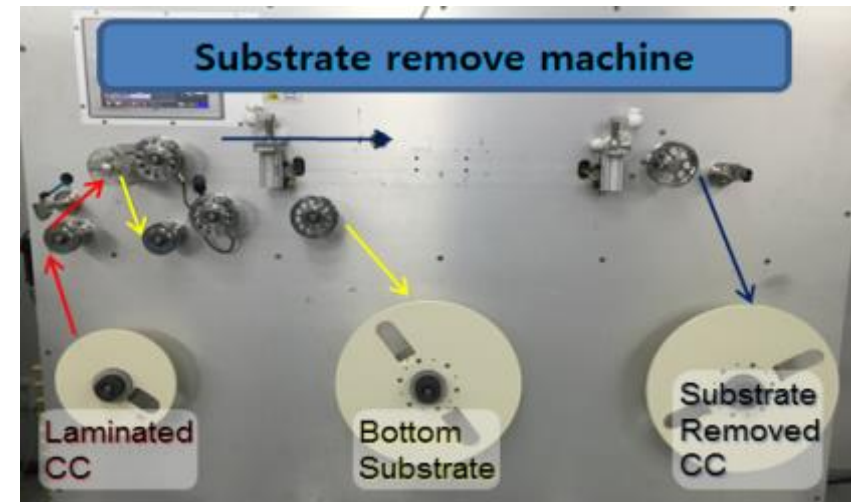
Effort to enhance J_e by removing substrate



Laminated
CC

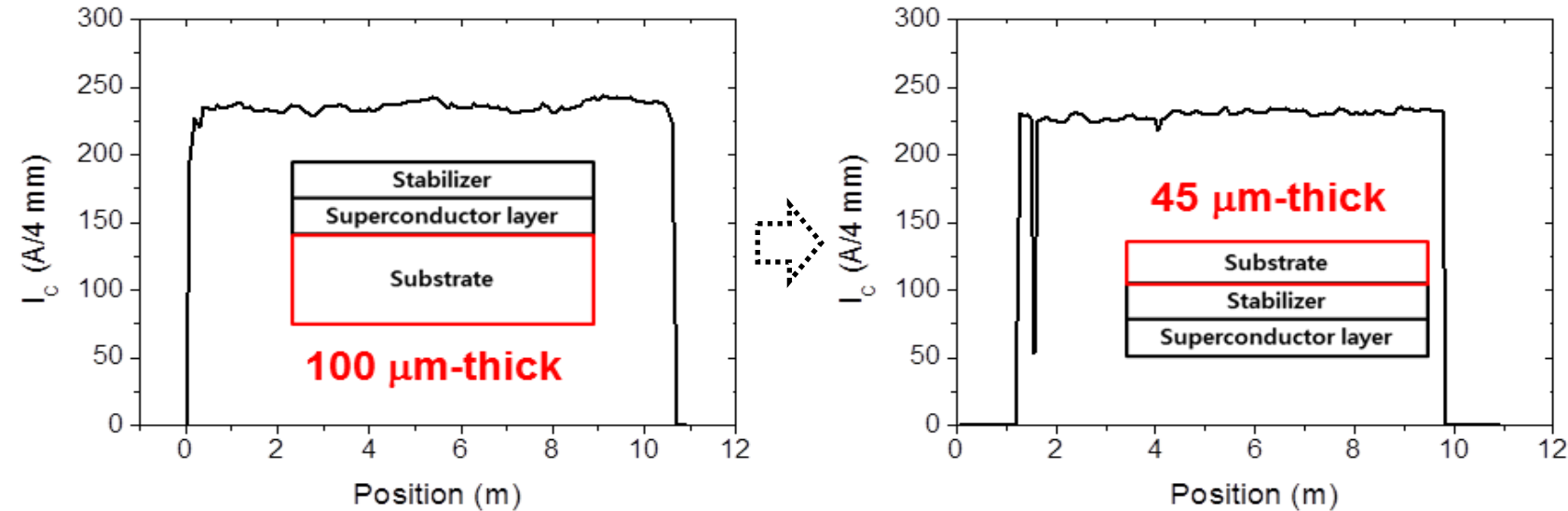
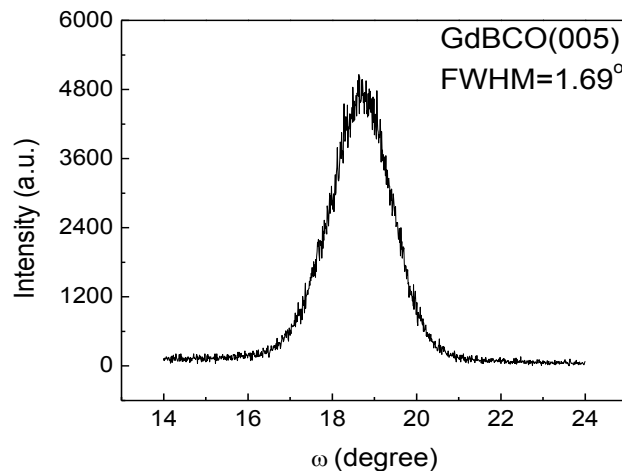
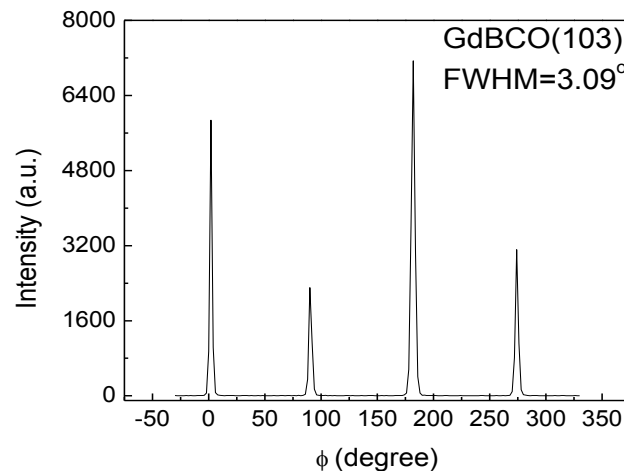
Removing
Bottom
Substrate

Substrate
Removed
CC



- ✓ Thinner substrate $\rightarrow$ higher J_e , but cause problem in our multi-turn depo. system
- ✓ Remove substrate $\rightarrow$ thin laminated metal acts as a substrate

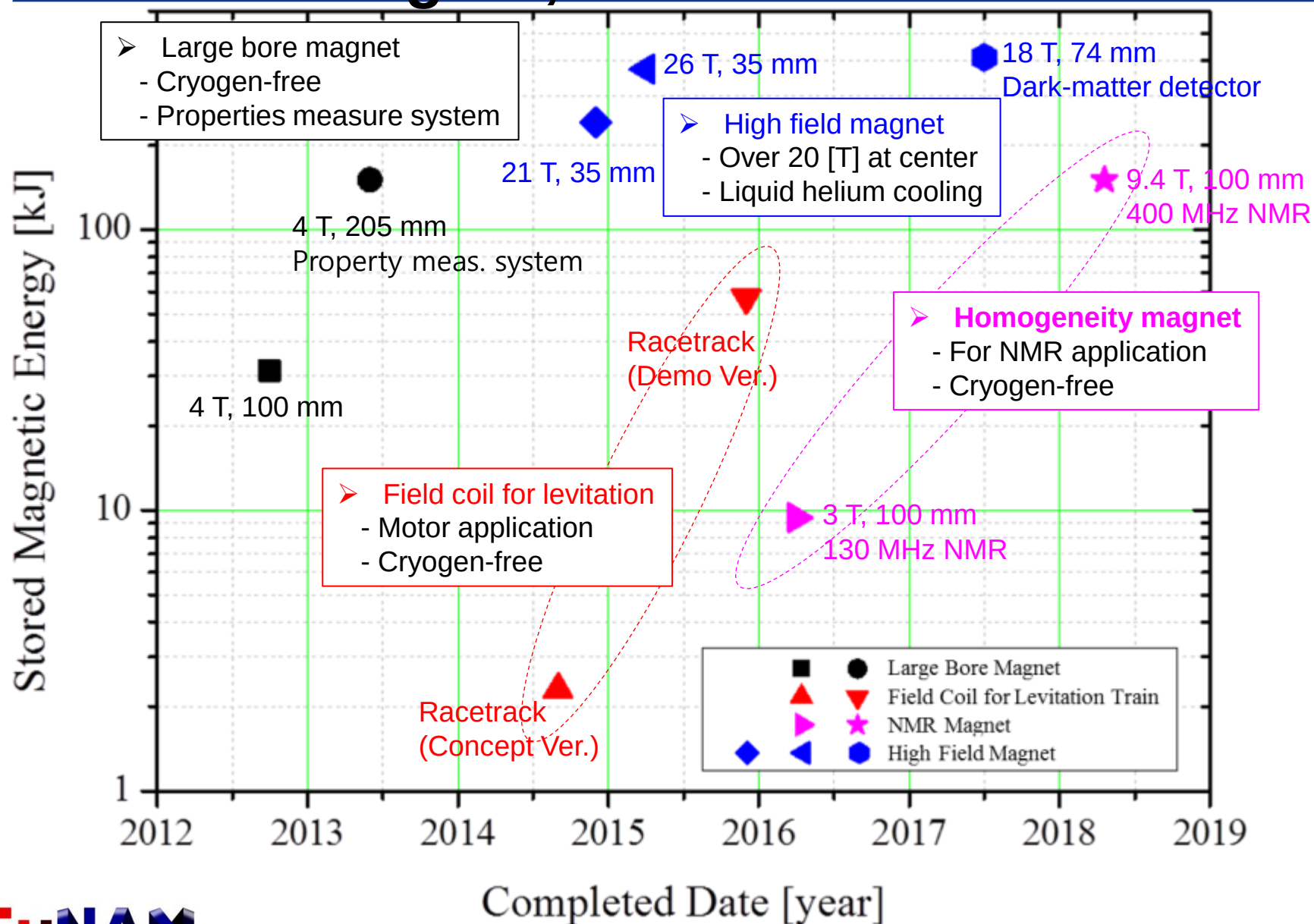
Effort to enhance J_c by removing substrate



- ✓ I_c only slightly degraded
- ✓ Very good crystallinity
- ✓ Mechanical strength to be verified with STS lamination

SuNAM's activity in magnets

SuNAM's magnet; overview



Long-Term Operation (203mm Magnet)

- Cooling time (operation)
: 4.5 years
- Total field charging time
: > 250 times, **> 800 hours**
- I_C -B-T- θ measuring times
: > 4,500 points
- Quenches
: more than 6 times

I_C measurement
insert cryostat

203mm RT
4T magnet



< I_C (B-T- θ) measurement system >

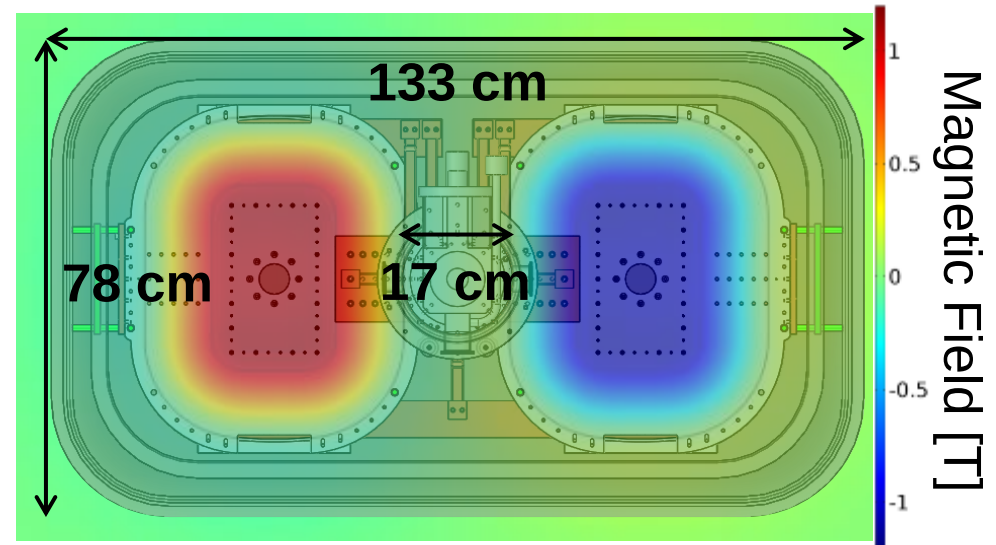
Racetrack Coil for Motor Application

Ref.) C.-B Park *et al*, "Development of a Small-Scale Superconducting LSM...", *IEEE Trans. Energy Conversion*

- 2 Poles and 3 double pancake coils per pole
- Peak field on the rail : > 1 Tesla (65 mm apart from magnet bottom)



< Linear synchronous motor >
(small coil)



Field profile at AC copper coil on track

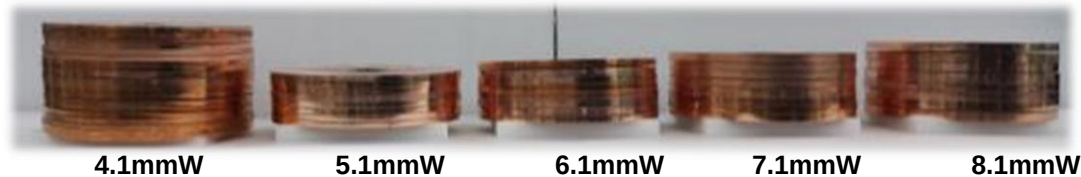
- ✓ Smooth but powerful movement
- ✓ No voltage fluctuation or field decay

26.4 T all HTS 2G one-body(non-nested) Magnet

(World highest magnetic field (all HTS))

No-insulation, multi-width, and compact !

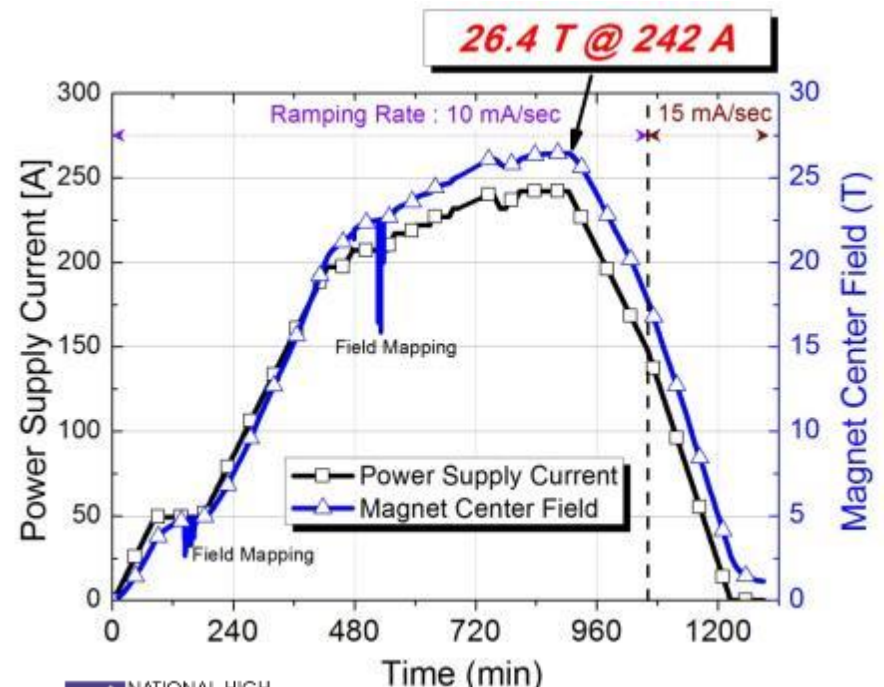
✓ Multi-width Double Pancake Coils



✓ Stacked Double Pancake Coils



✓ Fully assembled

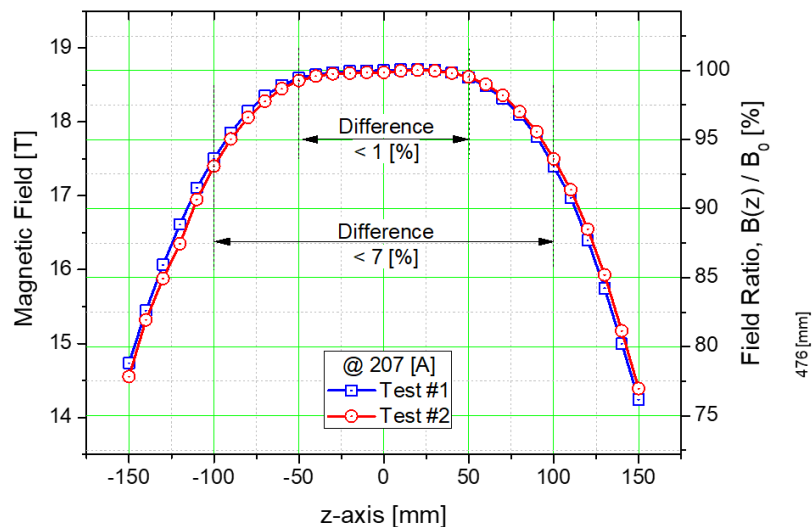


NATIONAL HIGH
MAGNETIC
FIELD LABORATORY

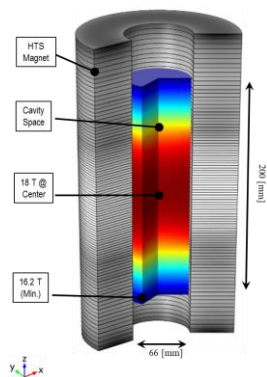
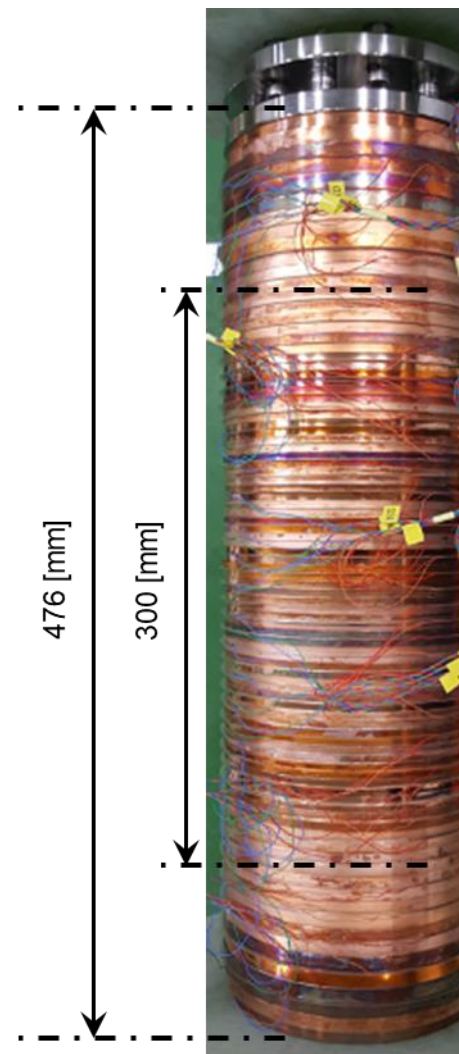
Immersed in liquid Helium

World 1st All HTS Commercial Magnet for Axion Detection

: Delivered to **ibs** Institute for Basic Science



- Field Homogeneity (on z-axis)
10 cm : 99 %, **20 cm : 93 %**



18 T HTS magnet for Axion detection - spec

Coil Configuration	Unit	M4	M5	M6	M7	M8
Coil Configuration						
Tape Width (Thickness 0.12 mm)	[mm]	4.1	5.1	6.1	7.1	8.1
Cold Bore; Magnet Height	[mm]	70; 476				
Winding I.D.; O.D.	[mm]	74.0; 155.6				
Number of DPC		28	4	4	4	4
Total DPC; Turn per SPC		44; 340				
Total Length	[km]	6.87	0.98	0.98	0.98	0.98

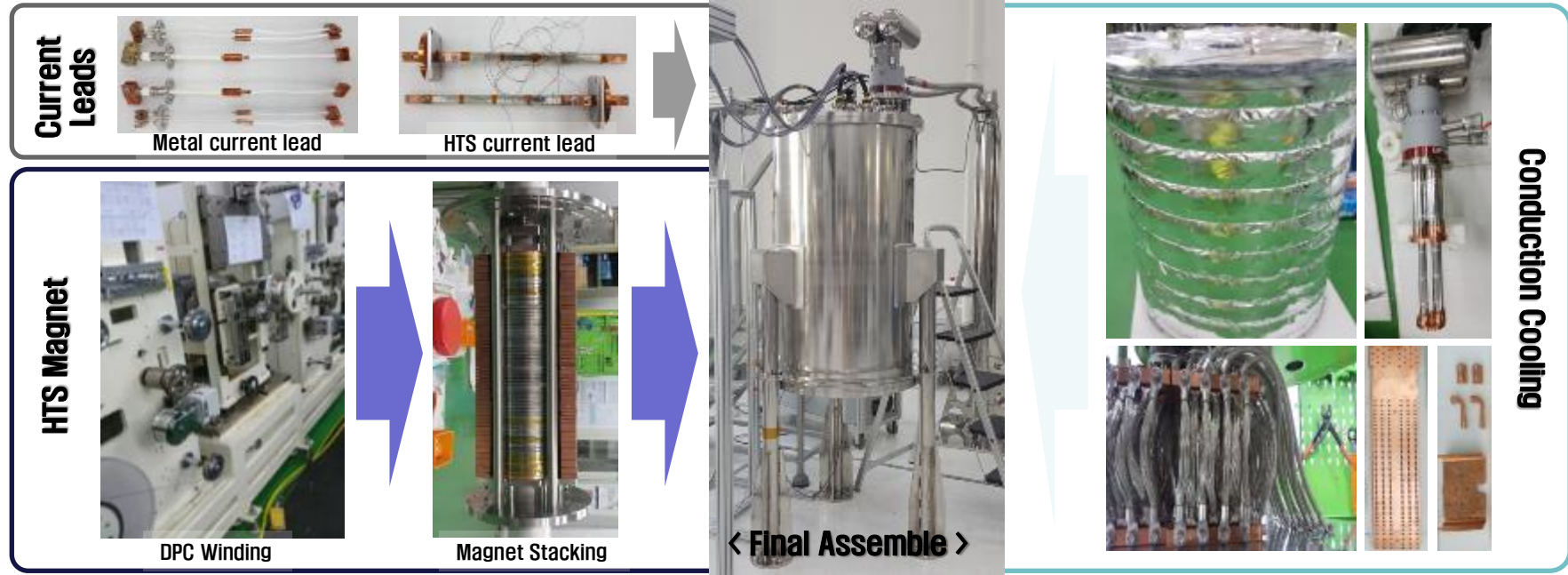
Operating Parameters	Unit	Value
Operating Current, I_{OP}	[A]	199.2
Magnetic Field at Center	[T]	18.0
Min. Magnetic Field in Cavity Space ($r < \pm 30$ mm, $z < \pm 100$ mm)	[T]	16.7 (92.5 %)
Inductance	[H]	18.9
Stored Energy	[kJ]	375
Magnetic Hoop Stress	[MPa]	276



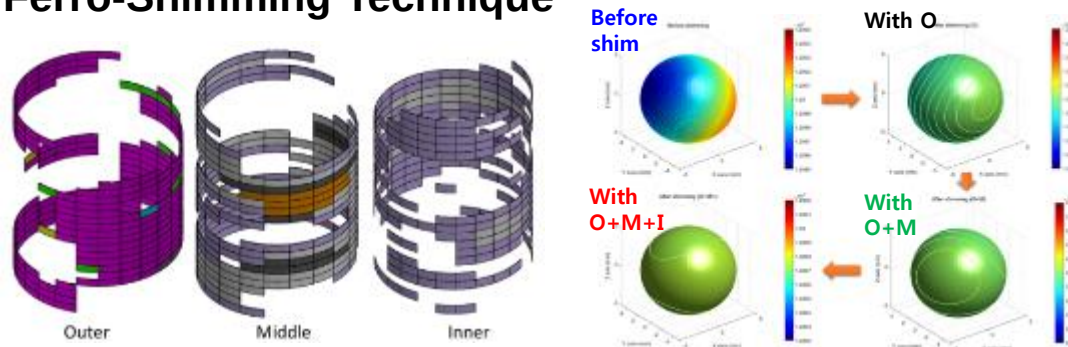
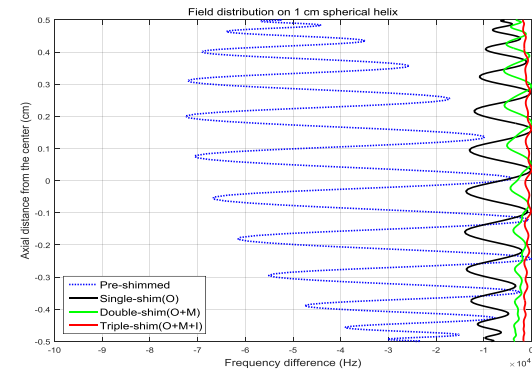
< Detector Magnet >

400 MHz conduction cooled NMR : Magnet Assemble

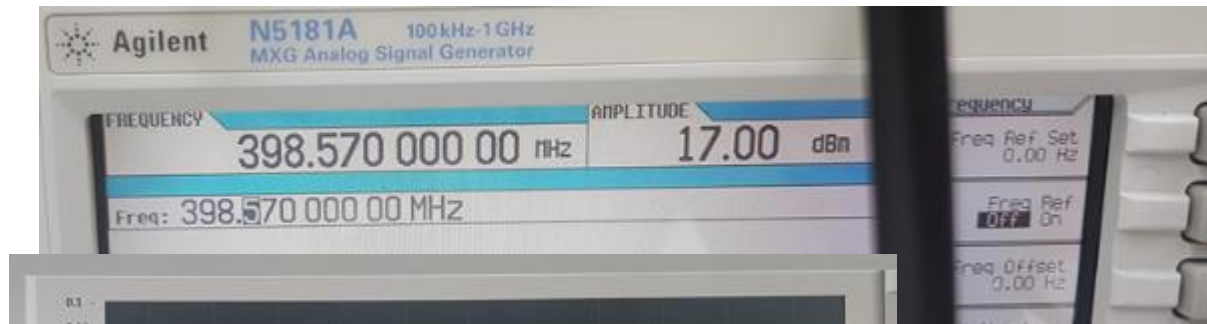
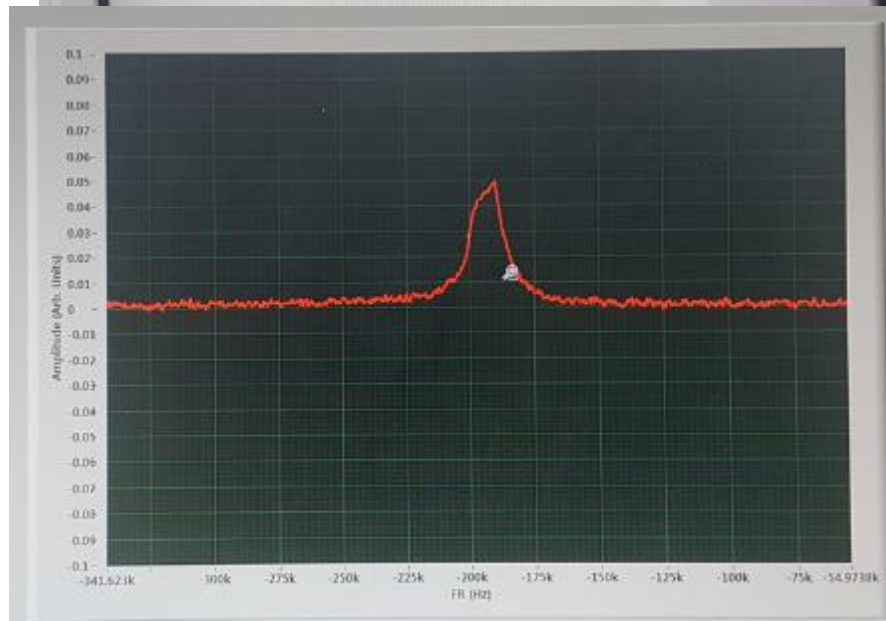
► 400 MHz NMR Magnet Assemble



► Ferro-Shimming Technique



400 MHz conduction cooled NMR : ^1H NMR Signal

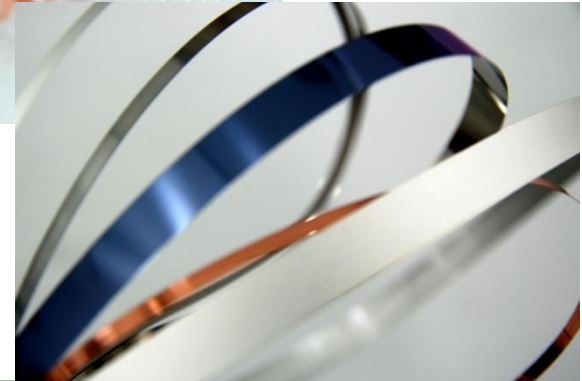


● Future works

- ✓ Faster charging rate
- ✓ Investigation of field profile
- ✓ Shimming

Summary

- SuNAM has been producing high- I_c tapes consistently with low-cost, high-throughput process.
- Various Q.C. measures enabled production of uniform tapes with high yield.
- We have clear roadmap for capacity increase to answer the customer needs.
- We've manufactured many magnets with varying size, shape, field-strength, and cooling method with our tapes.



www.i-sunam.com