GdBCO Coated Conductor and Magnet Development in SuNAM

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SuNAM Co., Ltd.

2018. 2. 18.

SuNAM

Superconductor, Nano & Advanced Materials

Contents

- SuNAM's coated conductor; architecture, characteristic, process, quality control

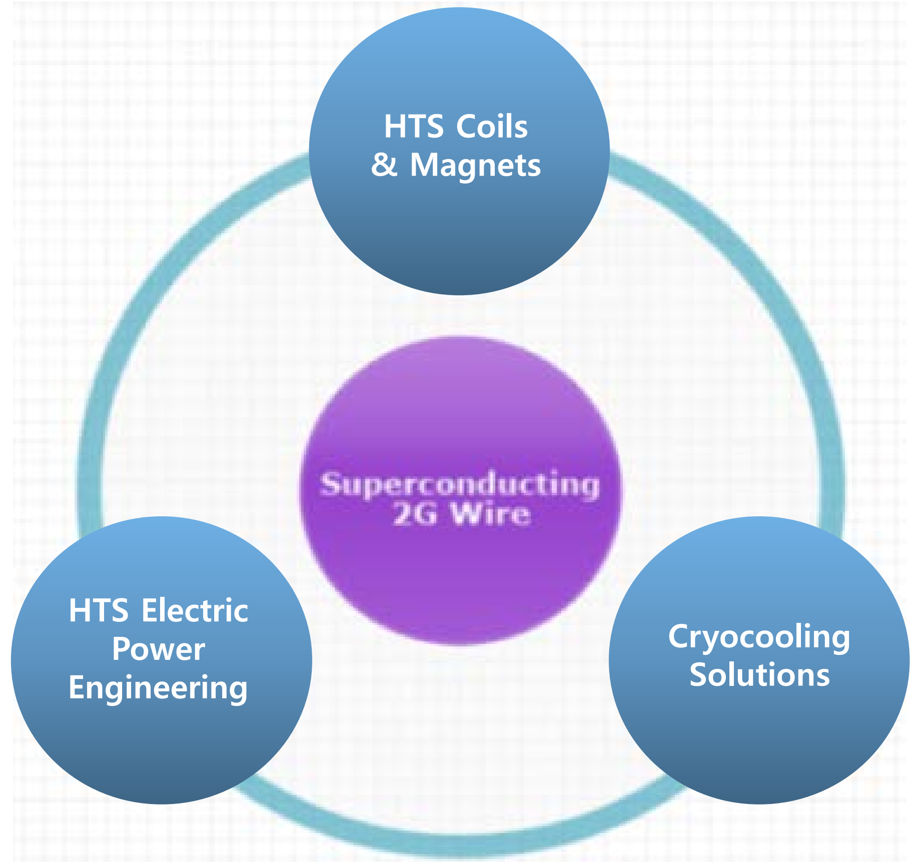
- Magnet
  - Low field conduction cooled magnet
  - Coil for linear synchronous motor
  - 26 T LHe-cooled magnet
  - Conduction-cooled NMR magnet
  - 18 T magnet for Axion detection

Company Overview

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

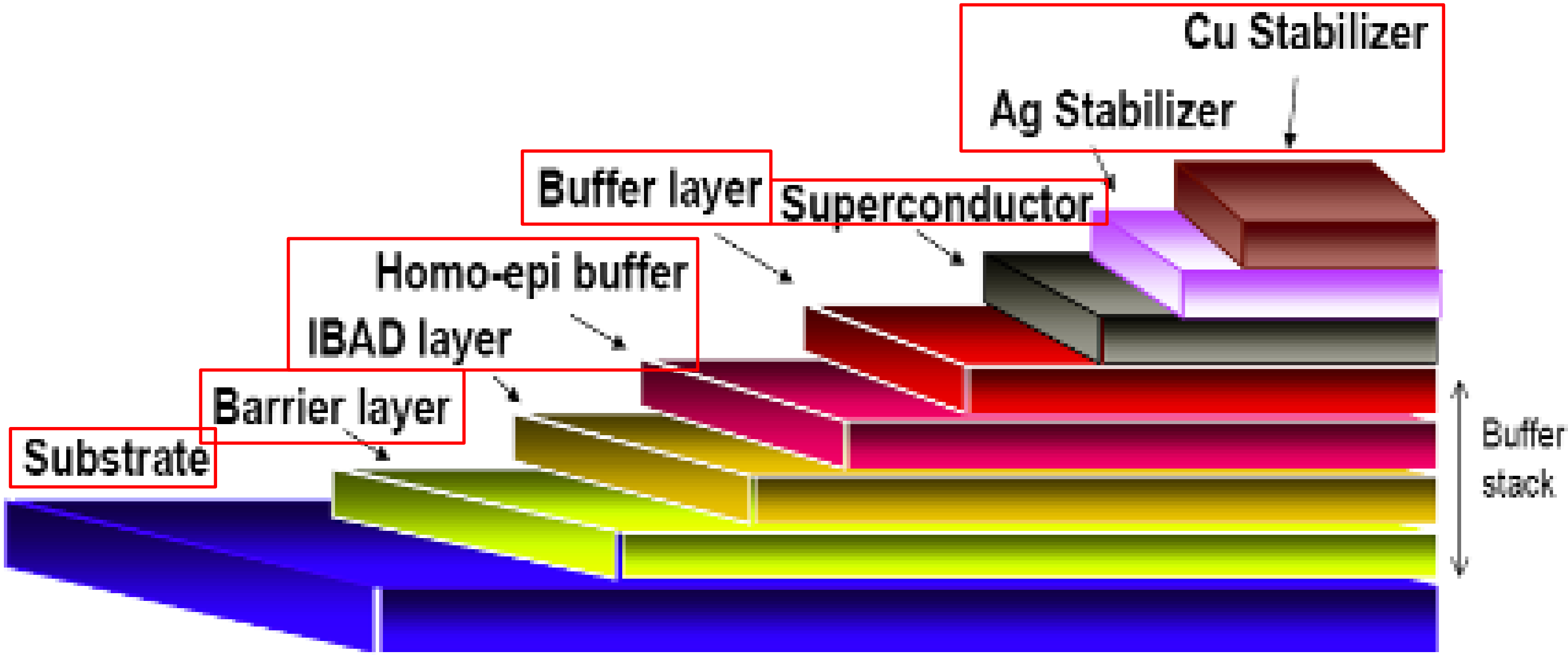
Establishment	2004. 11. 17., for commercialization of HTS wire
CEO	Seung-Hyun Moon
Registered Capital	~$6M
No. of Employees	~ 35 (7 Ph.Ds)
H.Q.	Gyeonggi-do, Korea
Current Production Capacity	~ 60 km / month (4 mm > 150 A)
Core Technology	2G HTS manufacturing technology based on RCE-DR process & No-Insulation HTS Magnet

Business Area



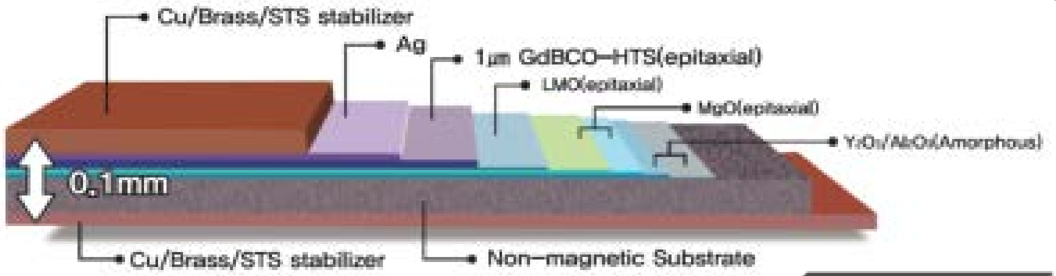
Coated Conductor (2nd G. Wire)

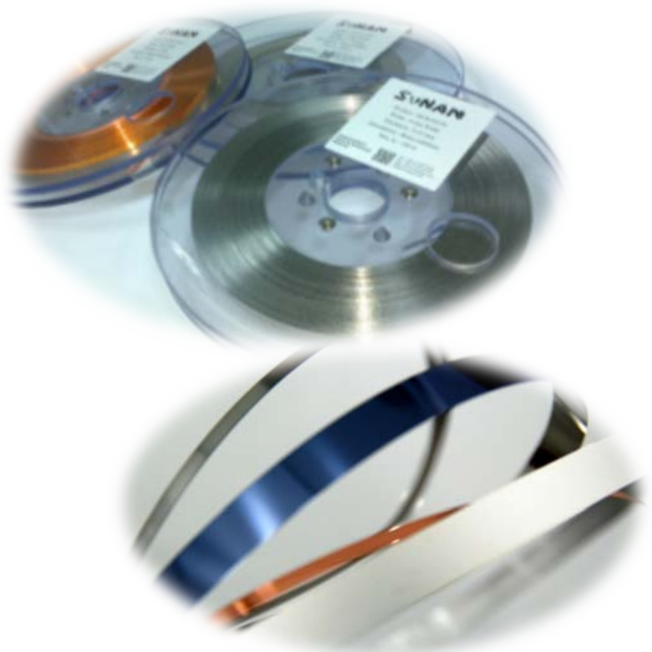
- Superconductor, the main ingredient
- Metal substrate, which gives mechanical strength & flexibility
- Needs good crystallinity for higher current conduction
- Lattice constant mismatch should be small
- Metal diffusion at high processing temperature should be avoided
- Current should by by-passed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

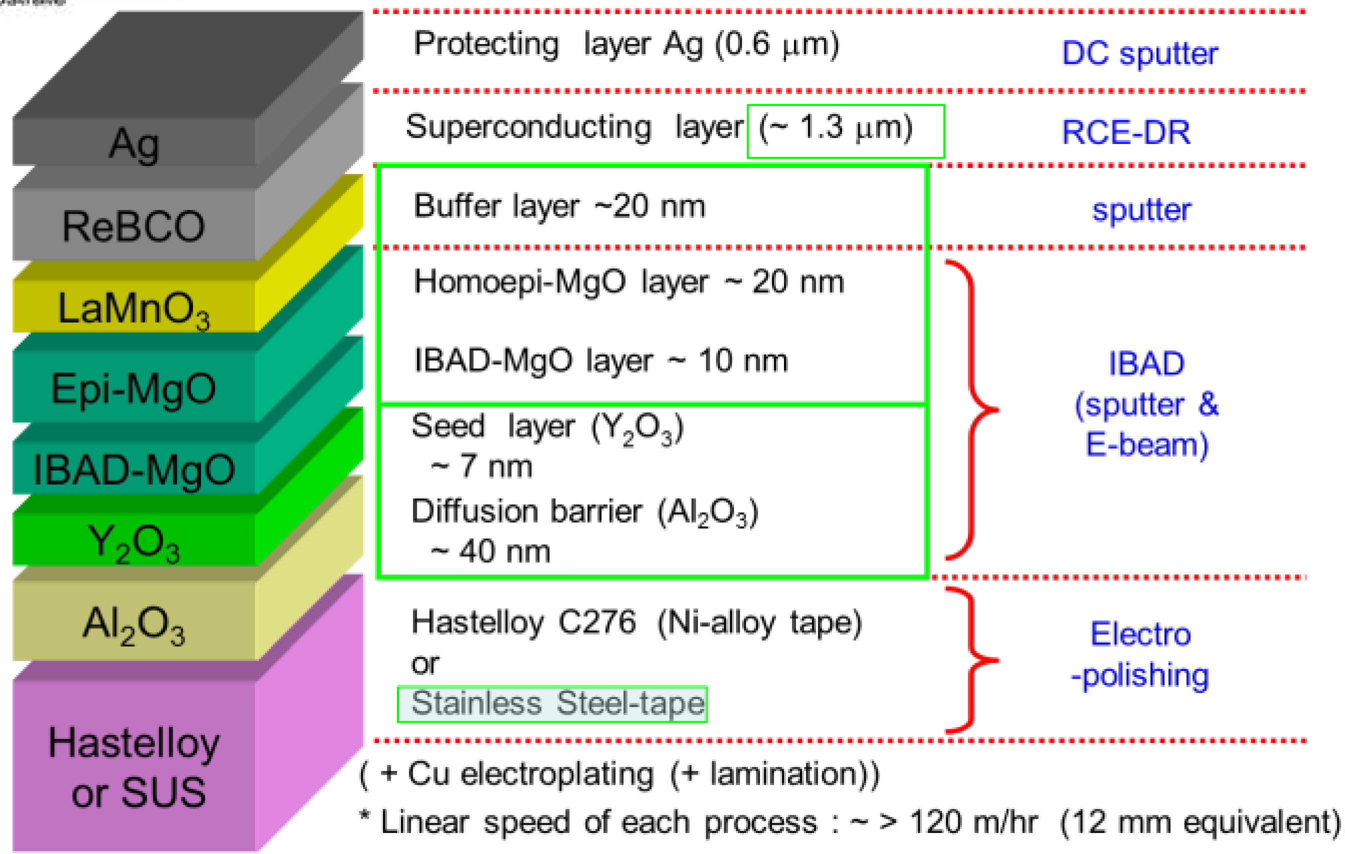


Not to scale

Structure







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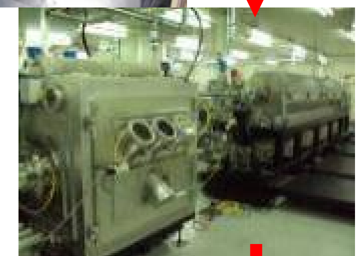
- Typical I_c ~ > 750A/12mmW at 77K Self-field (J_c ~ >5 MA/cm^2)

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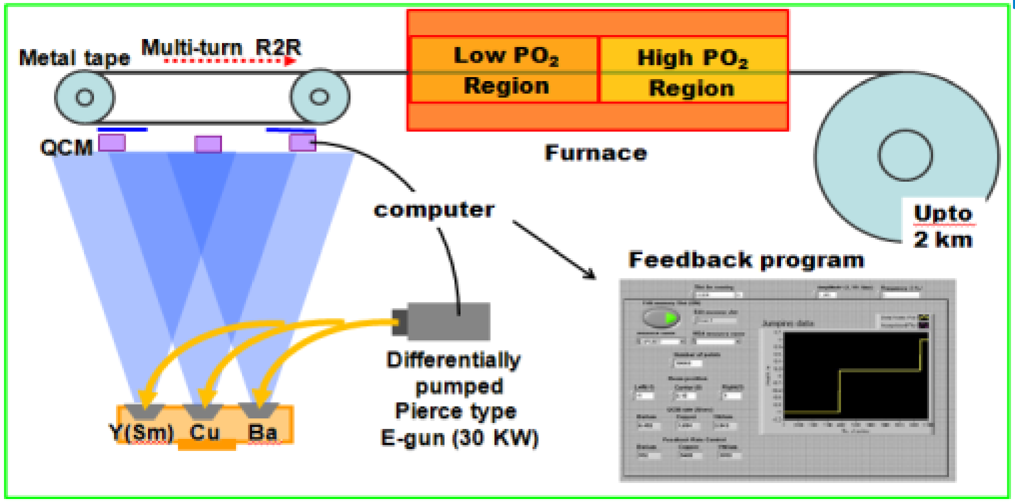
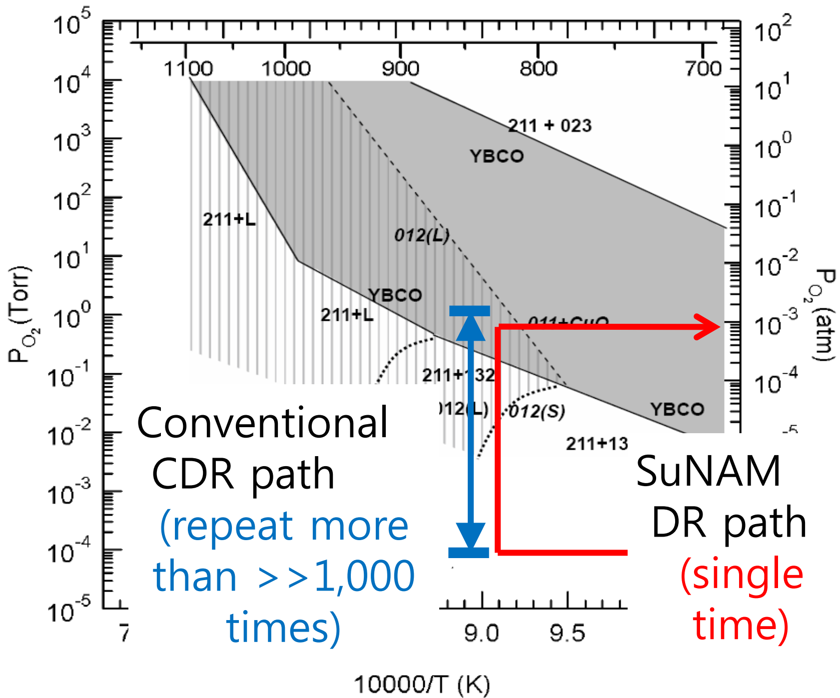
- Production capacity ~ 60 km/month(4 mm width) considering the yield(~ 70 %)

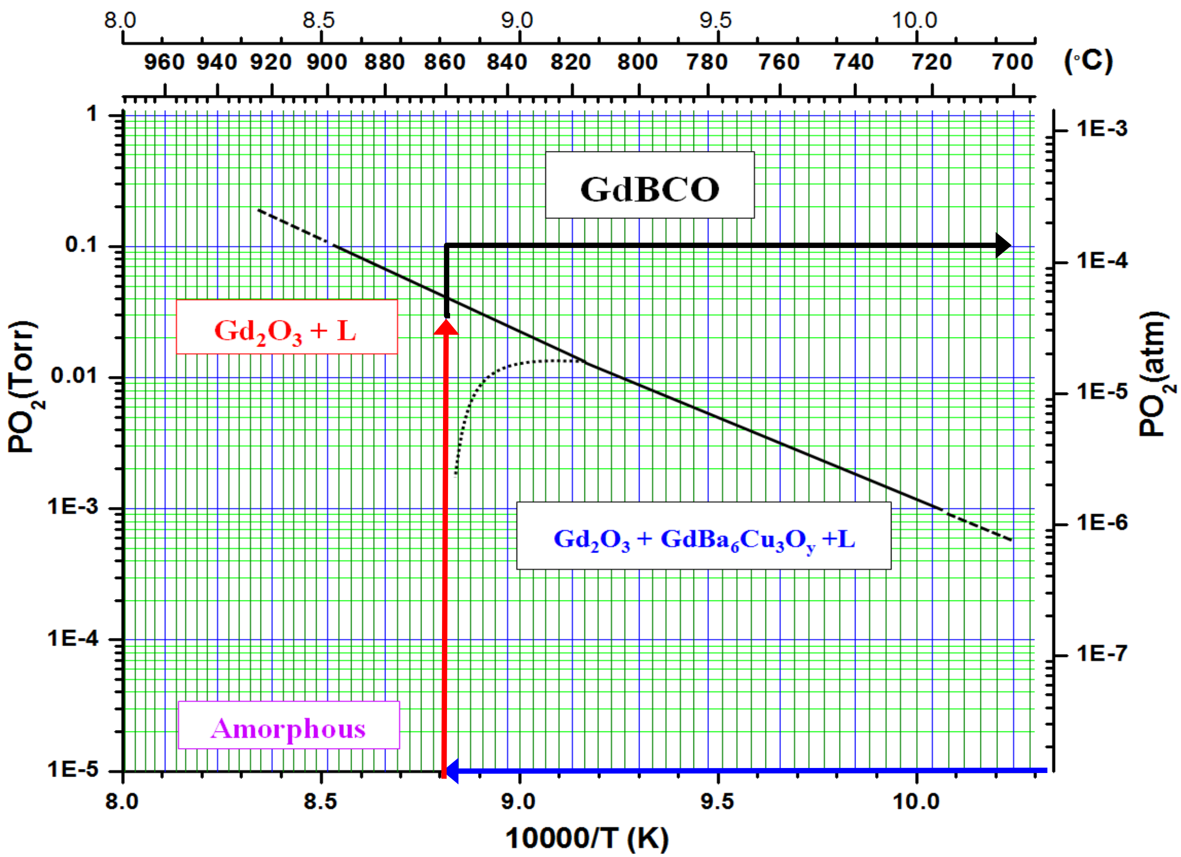
SuNAM RCE-DR process; SC layer

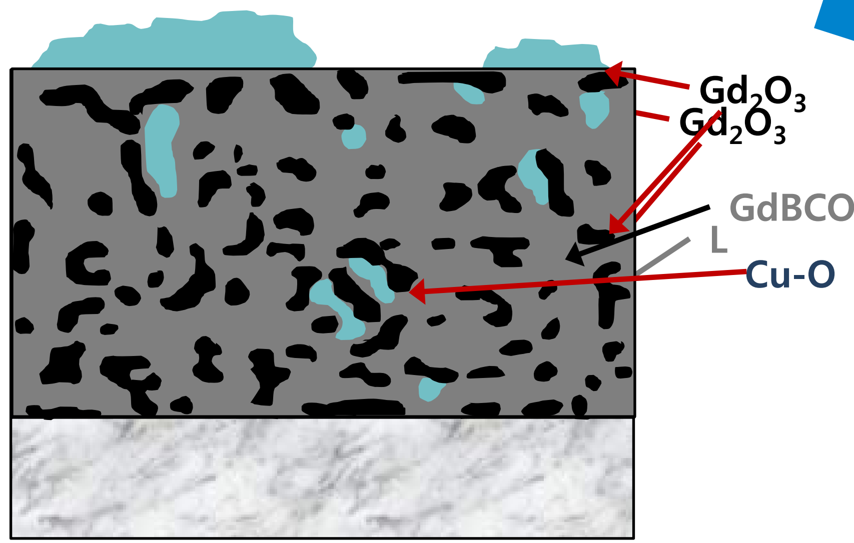
- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R) : Patented
- High rate co-evaporation at low temperature & pressure to the target thickness(> 1 μm) at once in deposition zone (6 ~ 10nm/s)
- Fast (<< 30 sec.) conversion from amorphous glassy phase to superconducting phase at high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

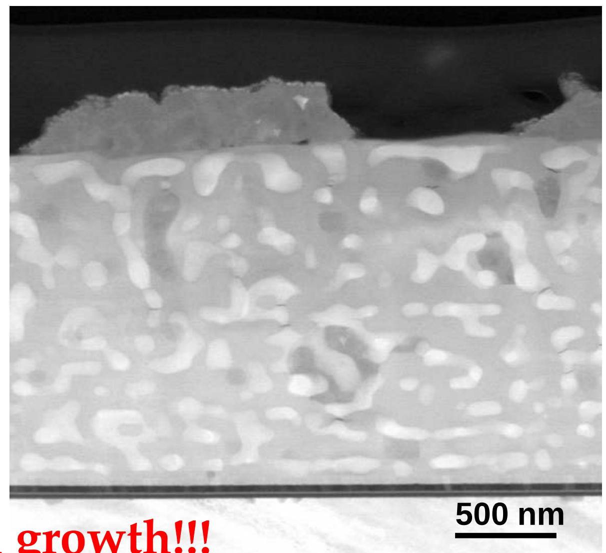




Growth mechanism of the GdBCO film by RCE-DR







- 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!!!

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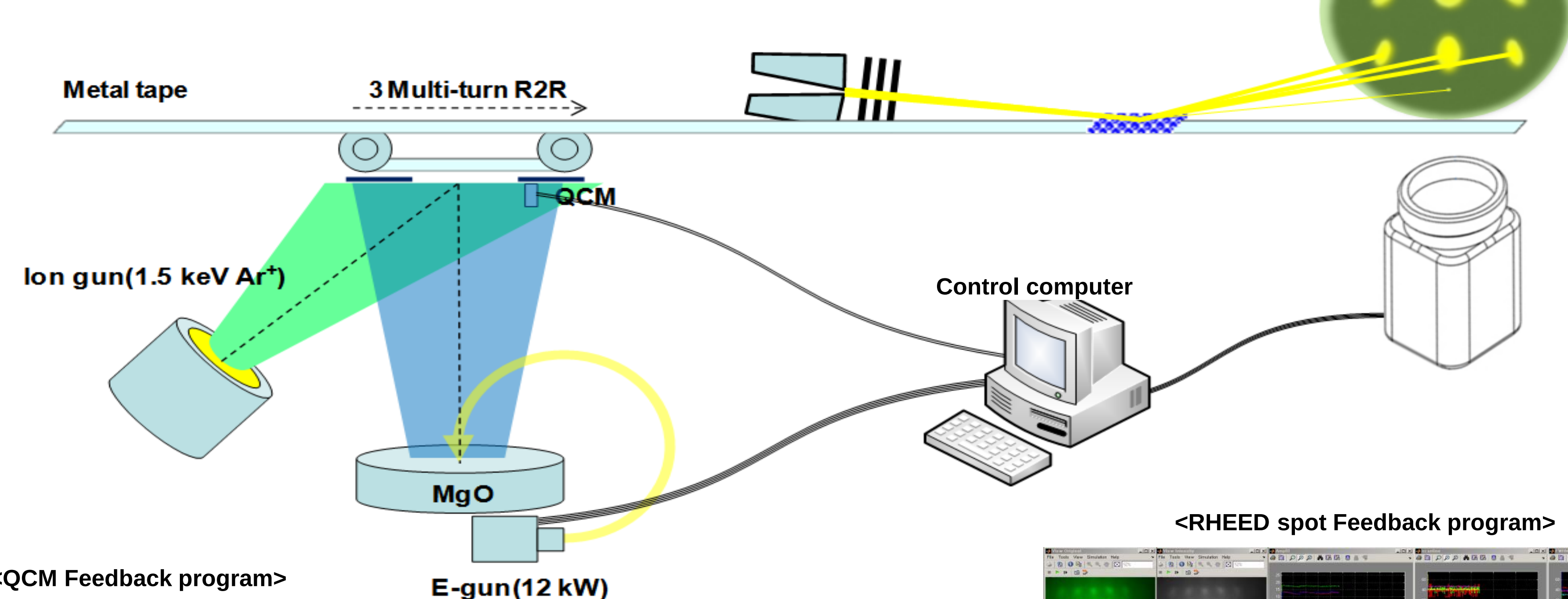
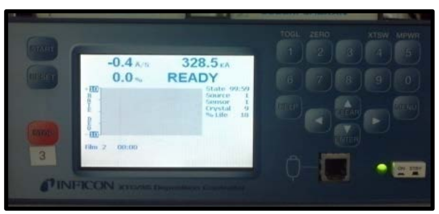
Seoul National University
Department of Material Science & Engineering

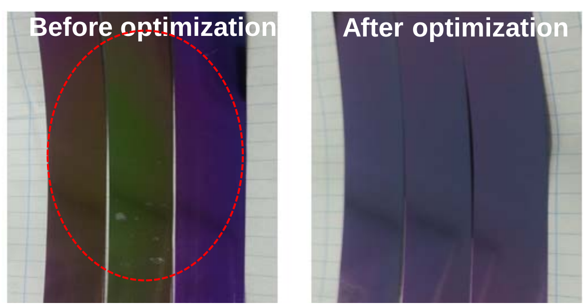
Quality Control : RHEED Vision System on MgO layer for better crystallinity

- 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.

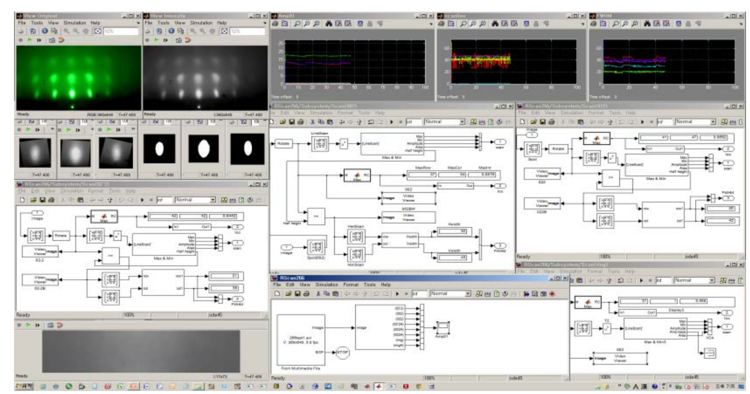


<QCM Feedback program>

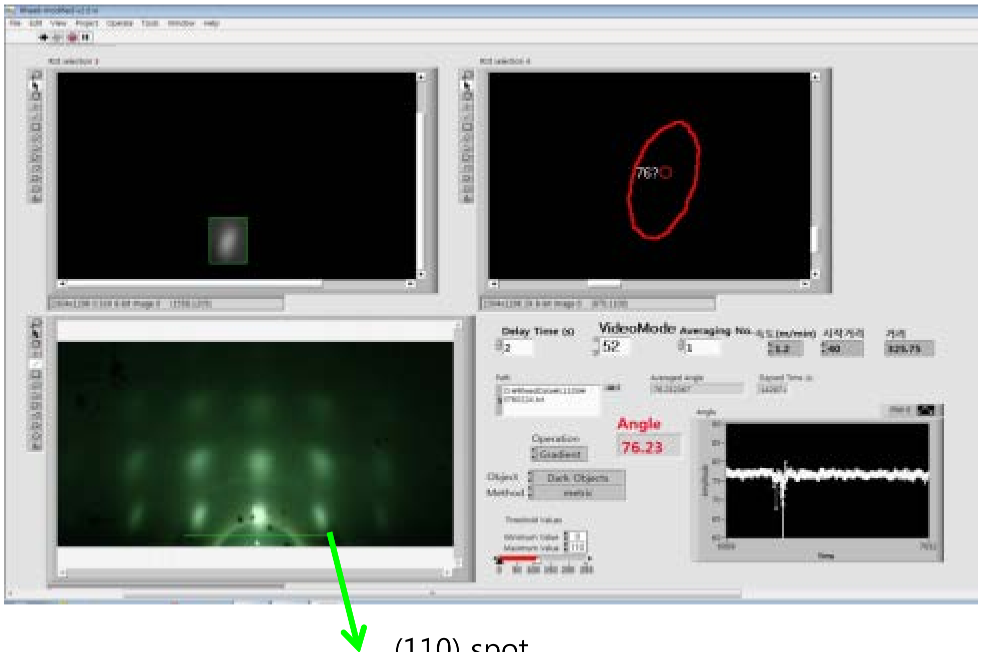




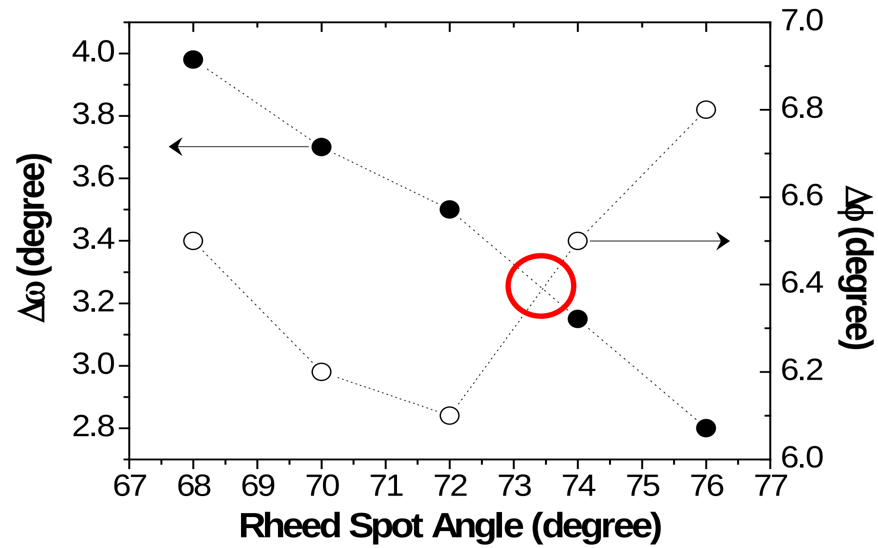
<RHEED spot Feedback program>



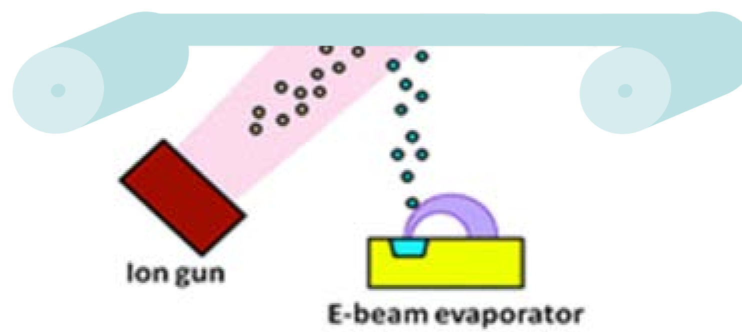
Feedback route based on RHEED spot analysis



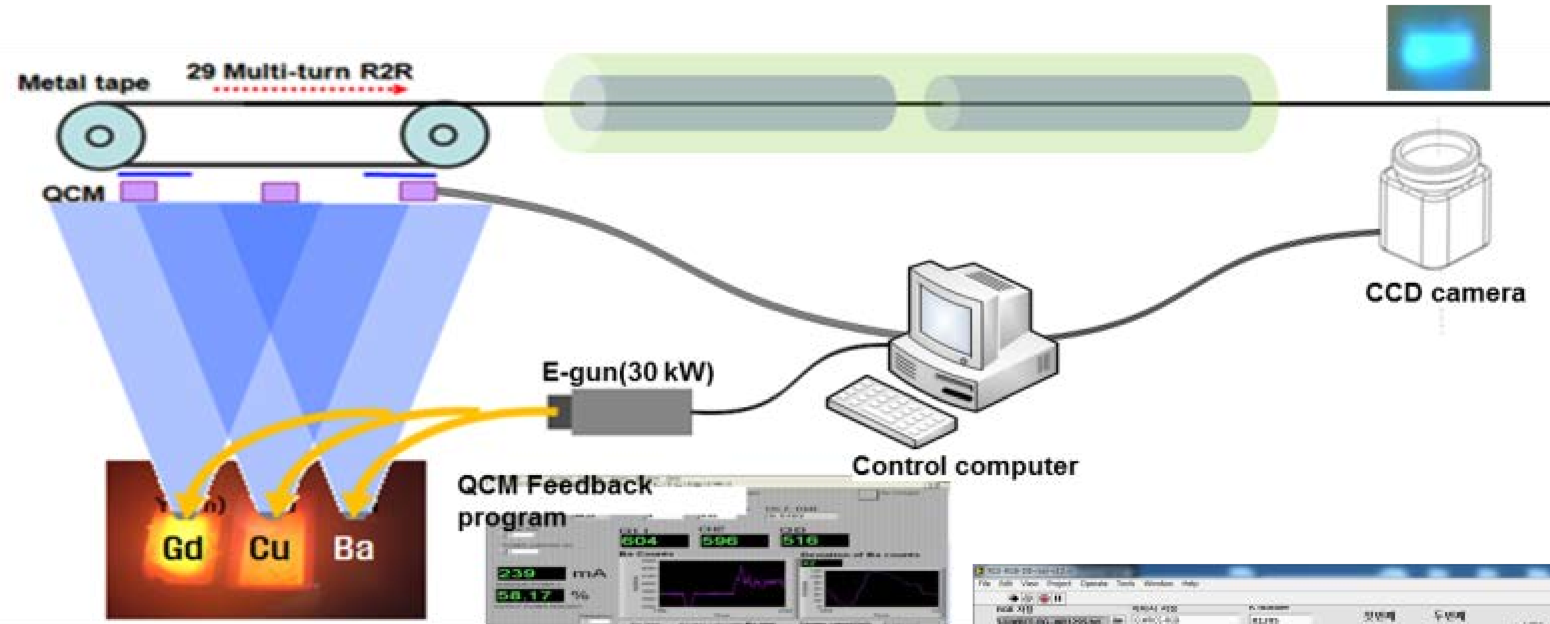
(110) spot

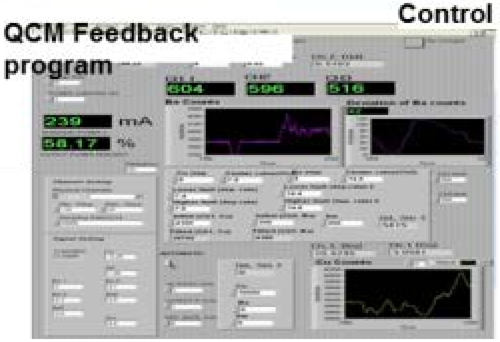


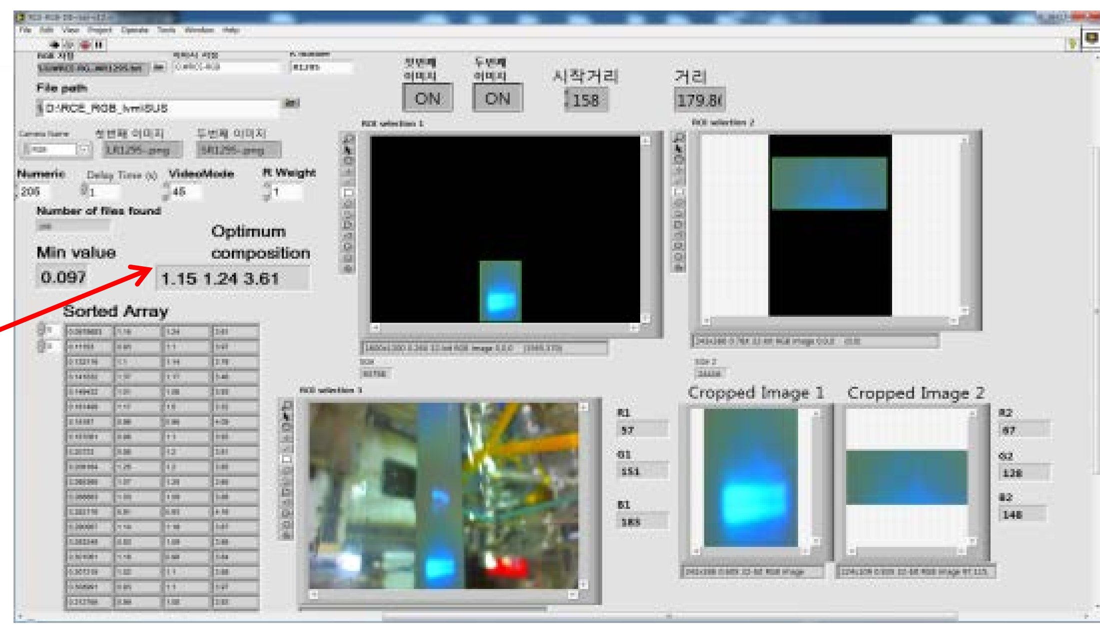
- Because of different evolution of Δϕ & Δω, optimization is very important for high quality 2G wire.
- Intensity & tilt angle of MgO (110) spot is one of the most important parameter.



Quality Control : RCE Vision Inspection System on SC layer for precise composition control (higher I_C)



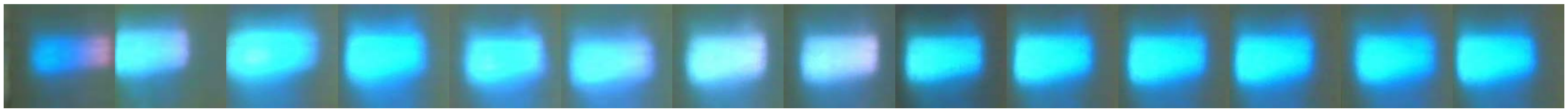


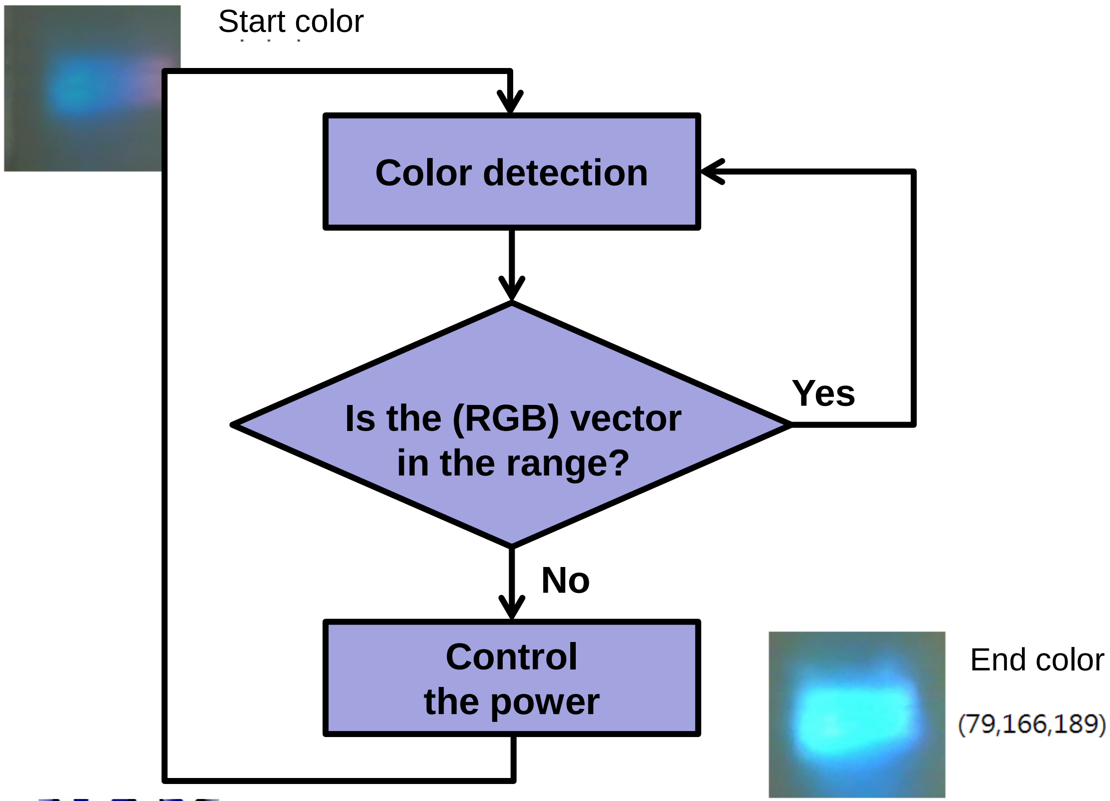


Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)

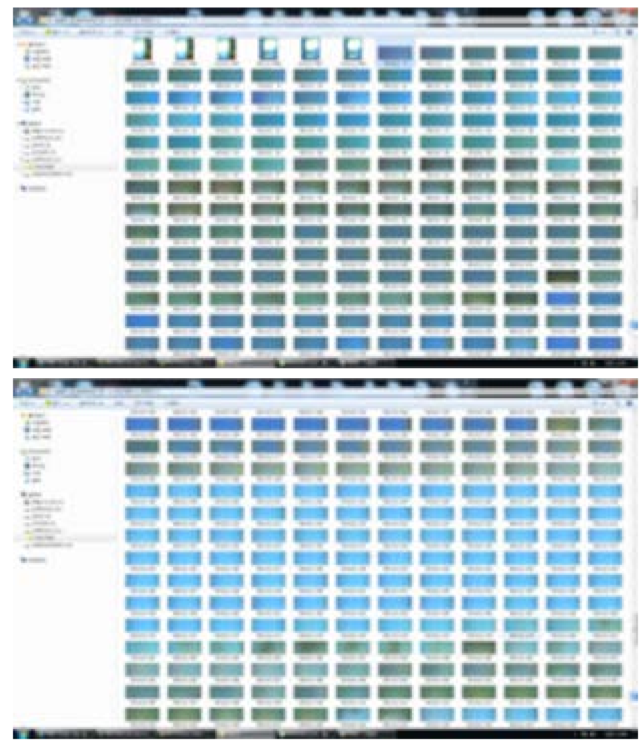
Quality Control : RCE Vision Inspection System

- 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.

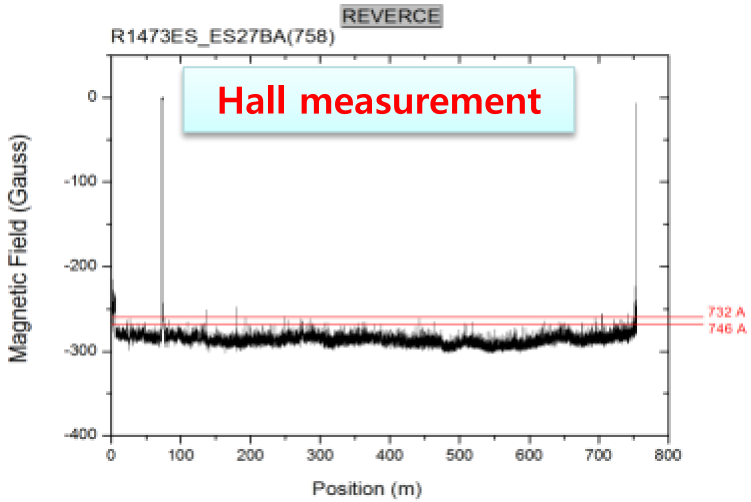
[Start]  [End]

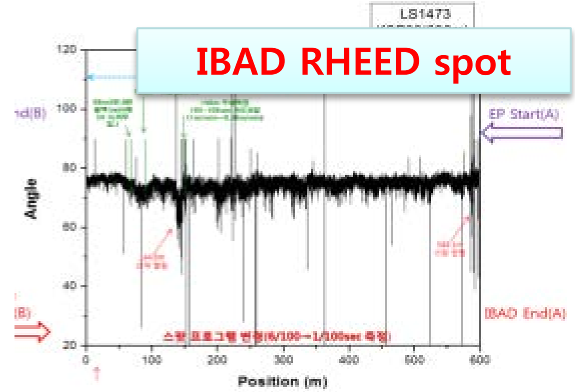


(Composition DB)

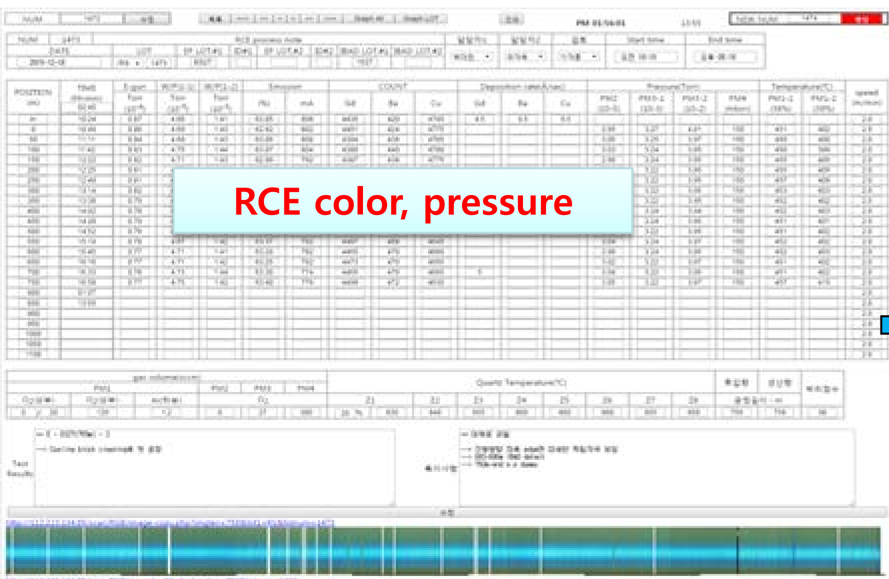


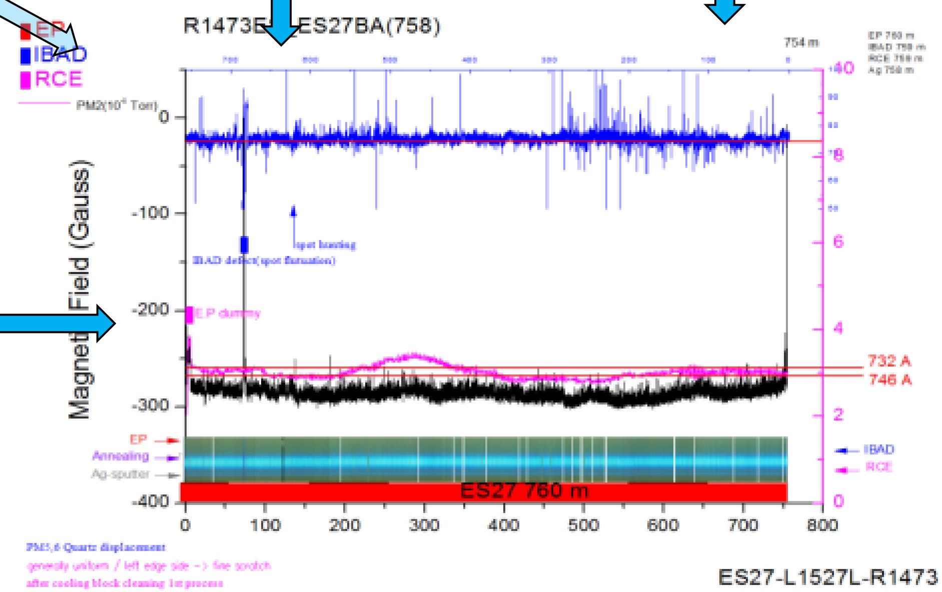
(In-line) QC examples : Root Cause Analysis





EP report





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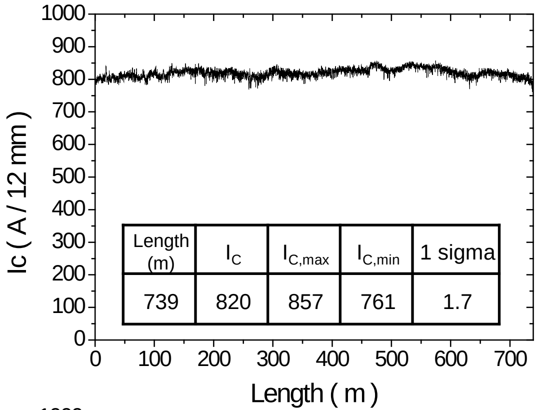
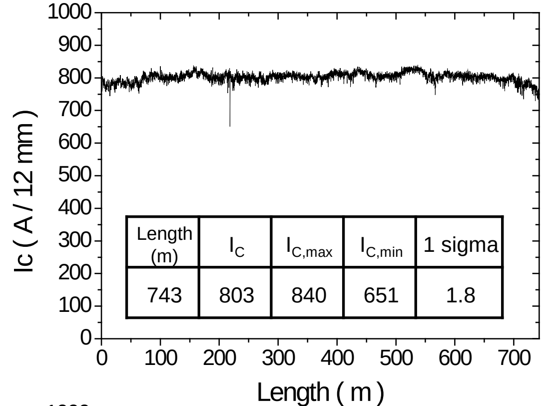
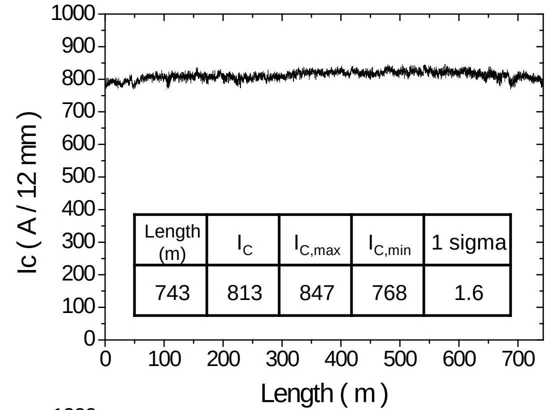
HTS 2G wire performances (daily production)



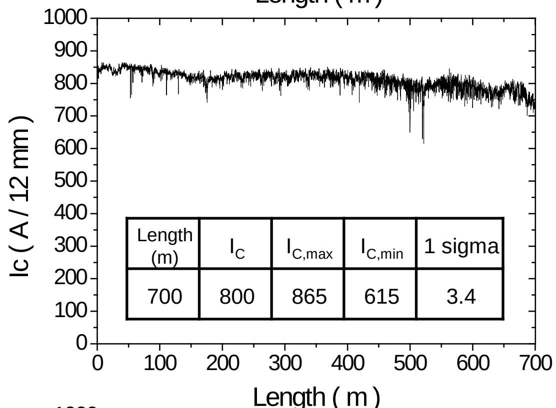
Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
739	820	857	761	1.7



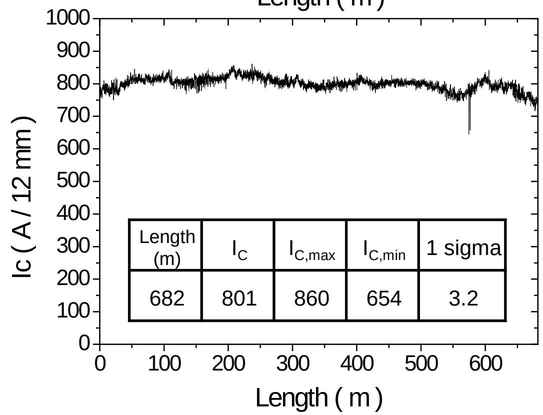
Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
743	803	840	651	1.8



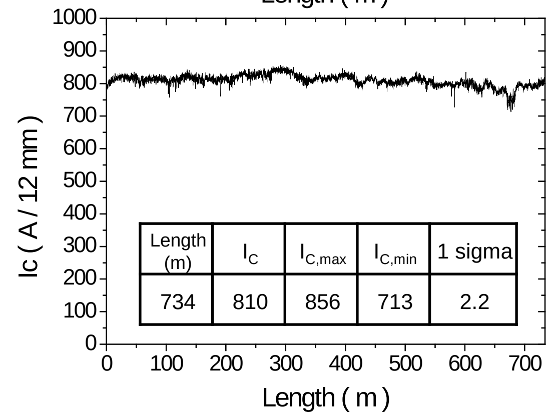
Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
743	813	847	768	1.6



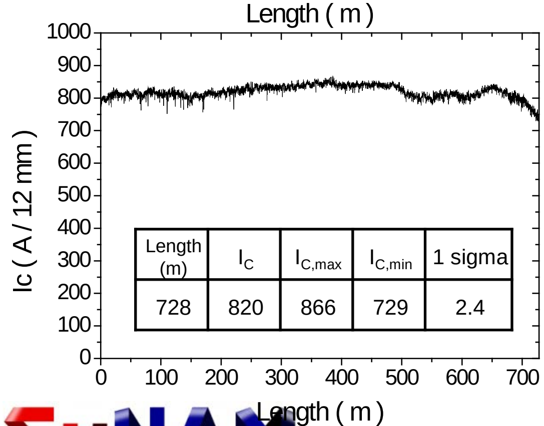
Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
700	800	865	615	3.4



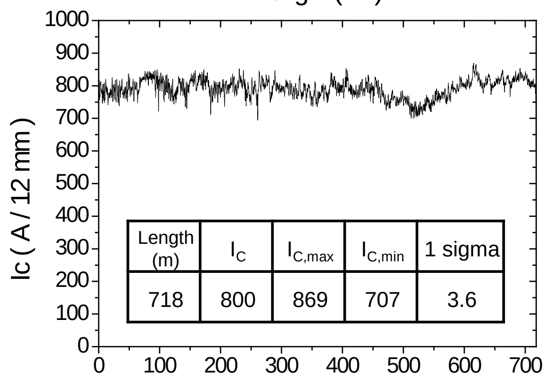
Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
682	801	860	654	3.2



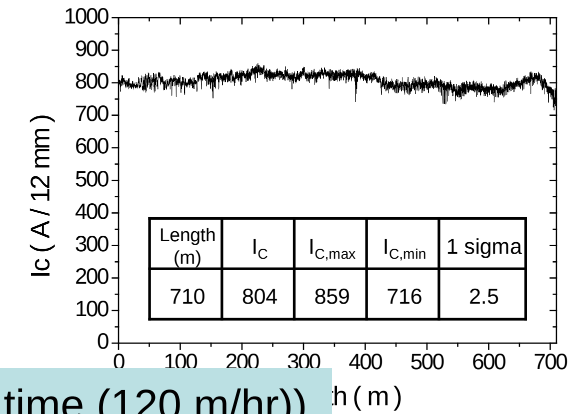
Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
734	810	856	713	2.2



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

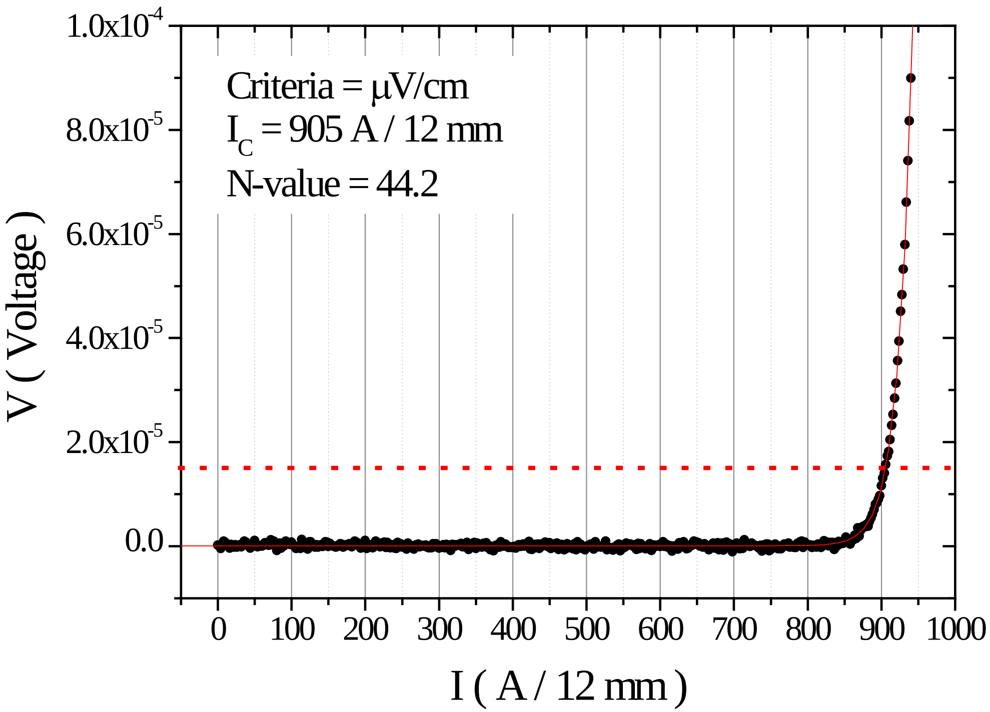


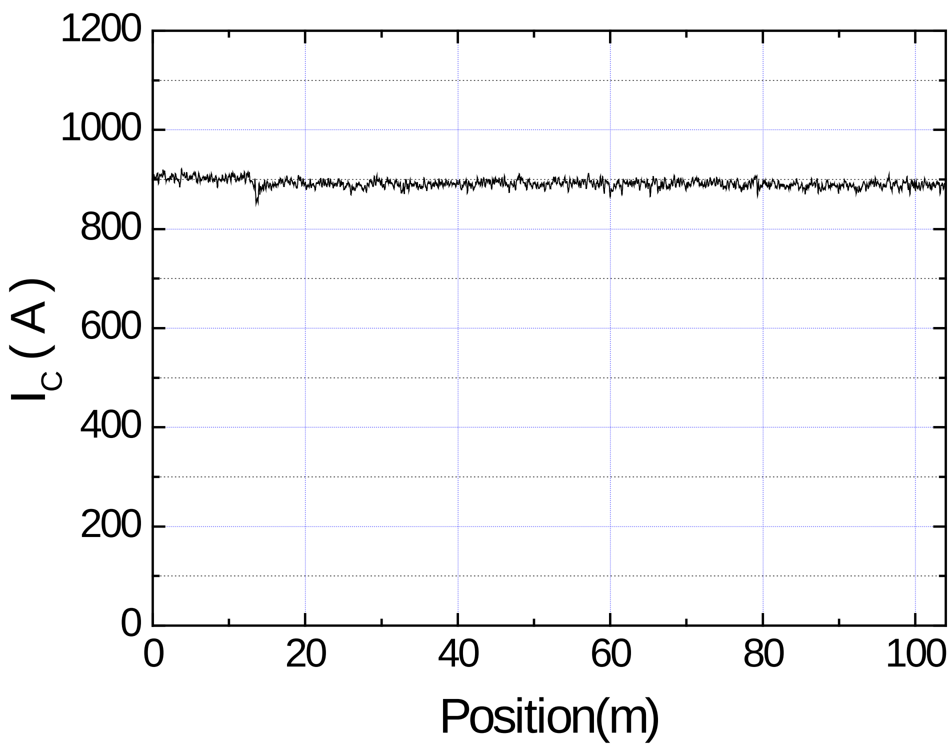
Length (m)	I_C	$I_{C,max}$	$I_{C,min}$	1 sigma
710	804	859	716	2.5

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

Optimizated 2G wire performance with 1.6 μm thickness

(77 K, s.f.)

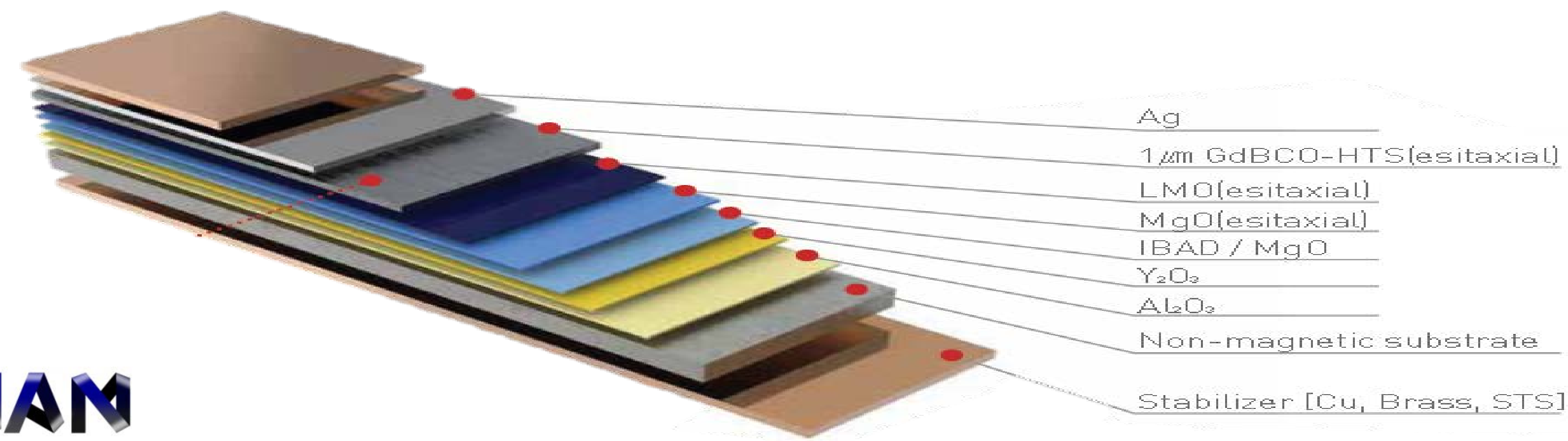




SuNAM's 2G HTS Wire

[Specification Table]

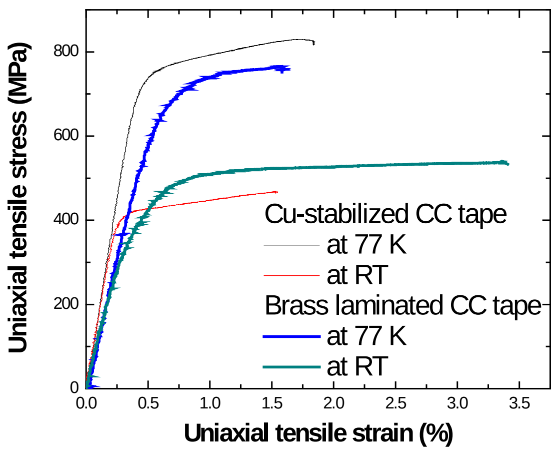
Model	AN	CN	LB/LS/LC	K
Description	Silver(+Cu…) Dry coating	Copper Wet Coating	Brass/STS/Copper Lamination	Polyimide tape(+) Insulation
	Special offer STS metal cladding / Tin coating / Single side lamination			
Substrate	Hastelloy C-276 or Non-magnetic Stainless Steel STS310S			
Width [mm]	Commercial : 4 mm, 12 mm. Special Order : 2 ~ 10 mm multi width is available			
Thickness [mm]	HAS : 0.06~0.07 STS : 0.11~0.12	HAS : 0.09~0.11 STS : 0.14~0.16	Customized	+ 0.1
Final Process	Sputtering	Electro Plating	Lamination	Wrapping
Piece Length	Above 100 m , 200 m , 300 m + without Splice			
Min. Ic @ 77 K S.F.	> 150 / 200 / 250 A + @ 4 mm > 500 / 600 / 700 / 800 A + @ 12 mm			



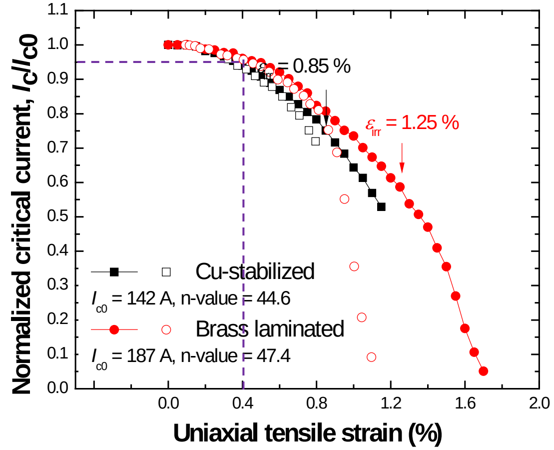
Electro-Mechanical performance of Single Side Brass-Laminated tape

- The CC tapes with brass lamination has the higher irreversibility of 1.25% strain.
- Higher irreversible stress limit of 734 MPa was shown for the CC tapes with brass lamination, as compared to the Cu stabilized CC tapes.

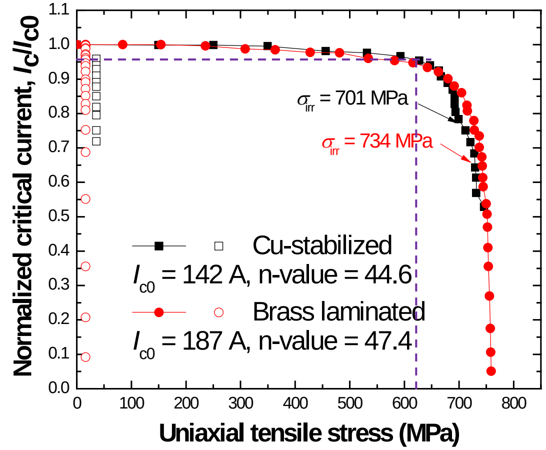
Stress-Strain Curves of Brass-Laminated CC tape



Ic/Ic_0-strain Curves of Brass-Laminated CC tape

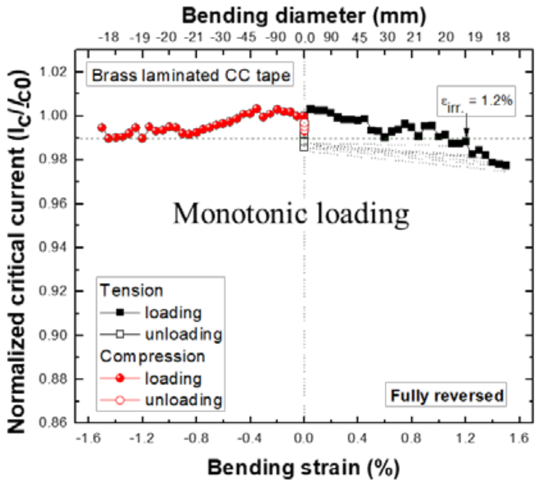


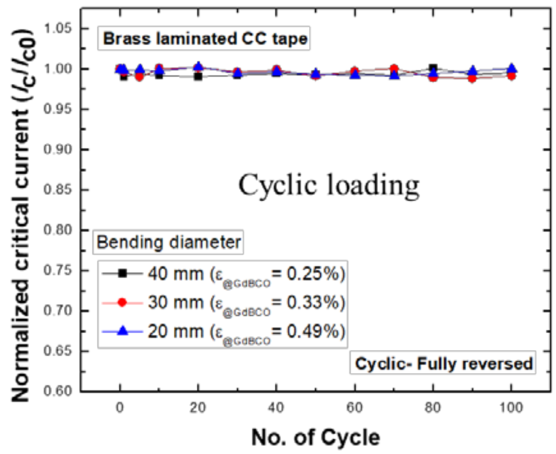
Ic/Ic_0-strain Curves of Brass-Laminated CC tape



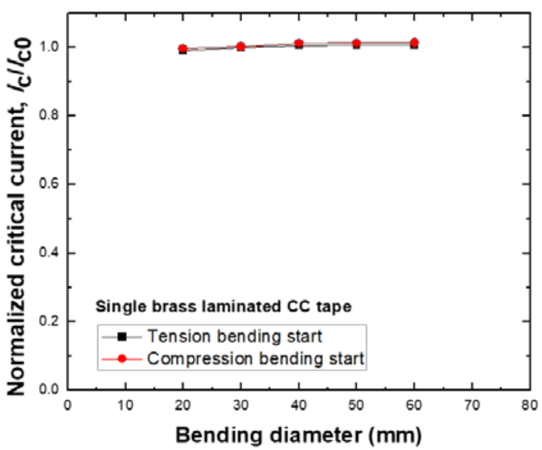
CC Tape	At RT		At 77 K				σ_{max} (MPa)
	E (GPa)	σ_y (MPa)	E (GPa)	σ_y (MPa)	$\varepsilon_{irr.}$ (%)	$\sigma_{irr.}$ (MPa)	
Cu-stabilized	**160**	340	**163**	589	0.85	701	701
Brass-Laminated	**120**	**450**	**125**	**704**	**1.25**	**734**	**668**

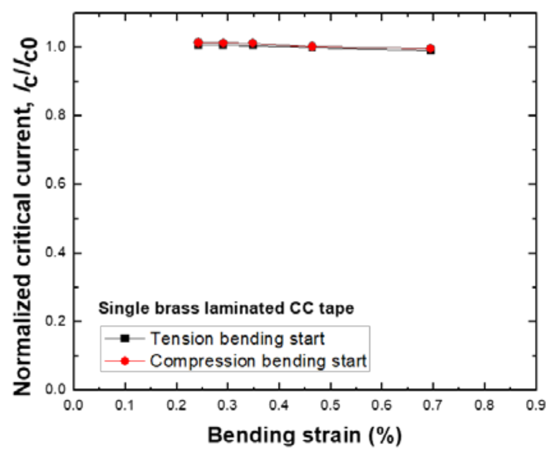
Electro-Mechanical performance of Single Side Brass-Laminated tape _ Bending





- $\varepsilon_{irr.}$ **of 1.2 %** was observed in the case of monotonic loading during tension loading.
- No I_c degradation behavior was found on the cyclic tension loading up to **20 mm diameter**.





- Laminated CC tapes showed no I_c degradation up to 20 mm ($\varepsilon_{@GdBCO}$= 0.25%) bending diameter.

Published paper
Evaluation of the electromechanical properties in GdBCO coated conductor tapes under low cyclic loading and bending
Hyung-Seop Shin, Alking Gorospe, Zhierwinjay Bautista and Marlon James Dedicatoria
Supercond. Sci. Technol. 29 (2016) 014001 (12pp)

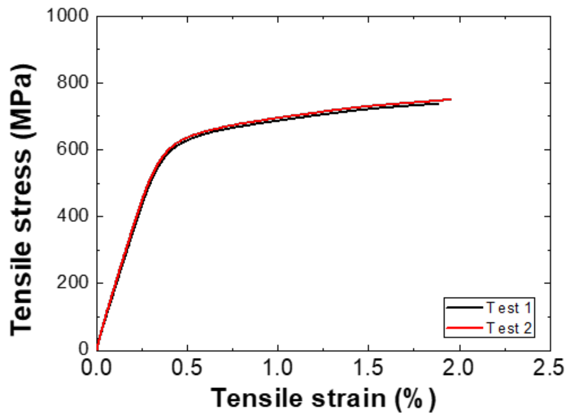
Electro-Mechanical performance of Sn/Cu stabilized tape

- Sn/Cu stabilized GdBCO CC tape exhibited

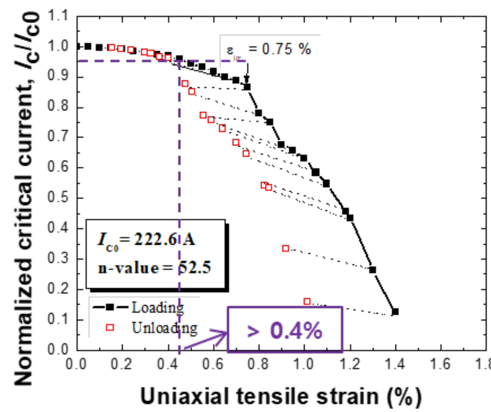
  an irreversible strain limit, $\boldsymbol{\varepsilon_{irr}}$ **=0.75%**

  an irreversible stress limit, $\boldsymbol{\sigma_{irr}}$ **= 641 MPa**, respectively.

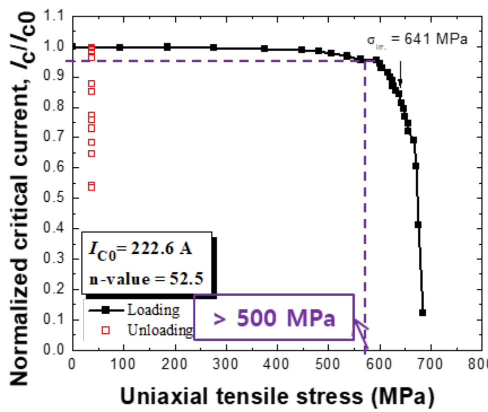
Stress-Strain Curves of Sn/Cu Stabilized CC tape



Ic/Ic0-strain Curves of Sn/Cu Stabilized CC tape



Ic/Ic0-strain Curves of Sn/Cu Stabilized CC tape



Sample		Dimension, Width/Thickness [mm]	Yield strength (MPa)	Ultimate Tensile strength (MPa)
Sn/Cu stabilized CC tape	Test 1	4.05/0.138	644	829
	Test 2	4.05/0.137	650	936

Continuous bending & other mechanical tests

[Continuous Ic measurement system with Bending-Double bending rollers]

[Sample based Stranding-Thermal cycle test]

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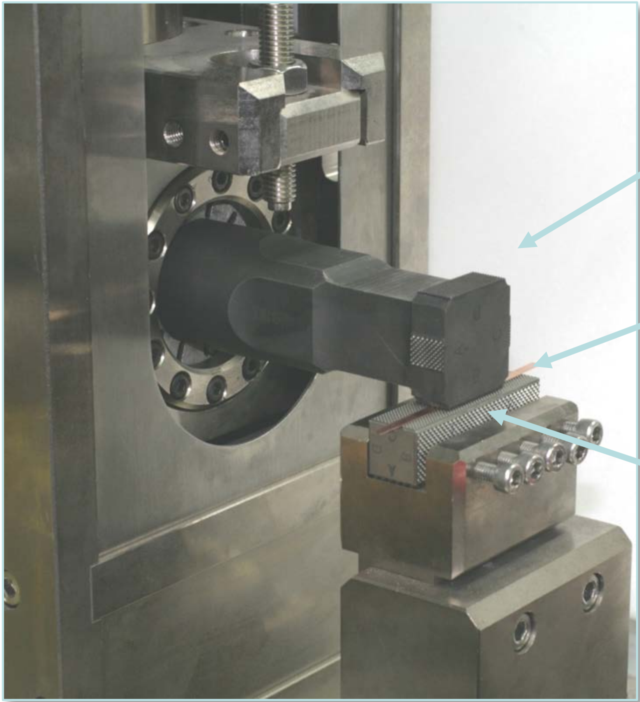
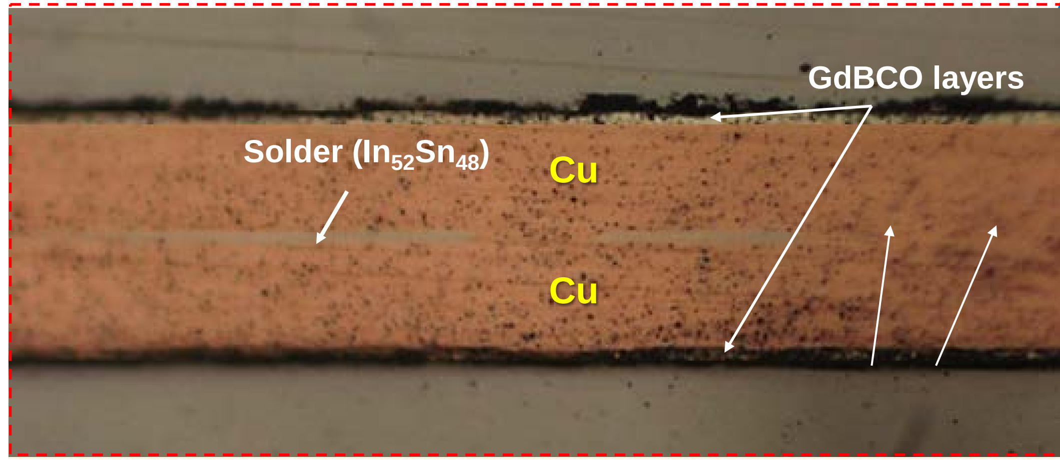
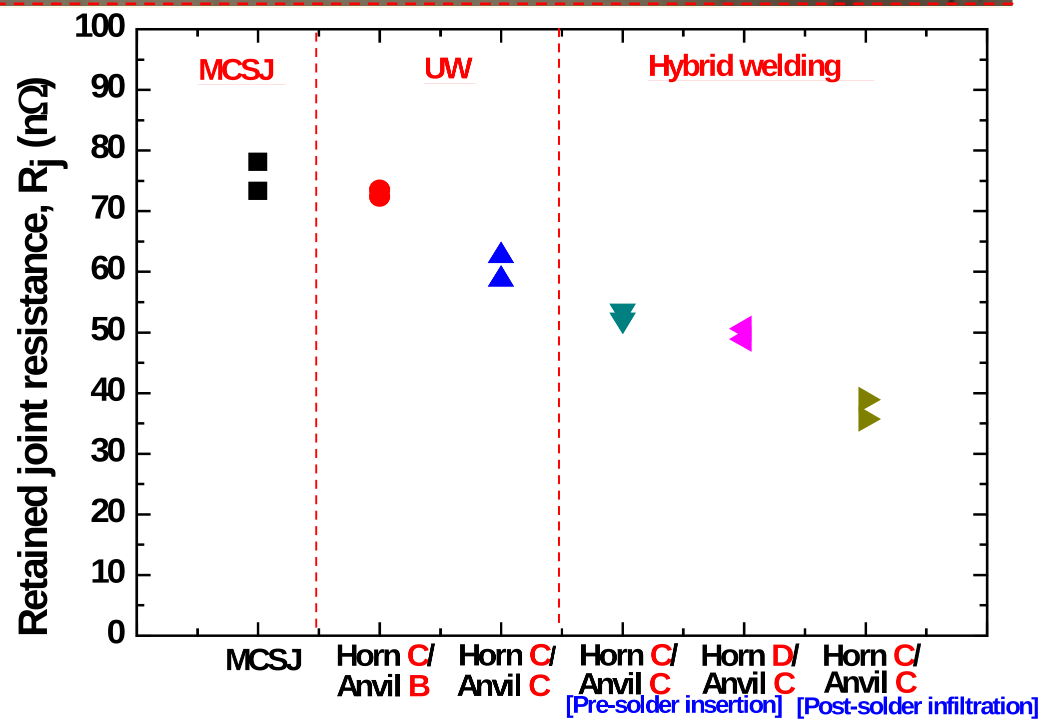
Simple, Fast & Reliable Hybrid Ultrasonic Welding joint method

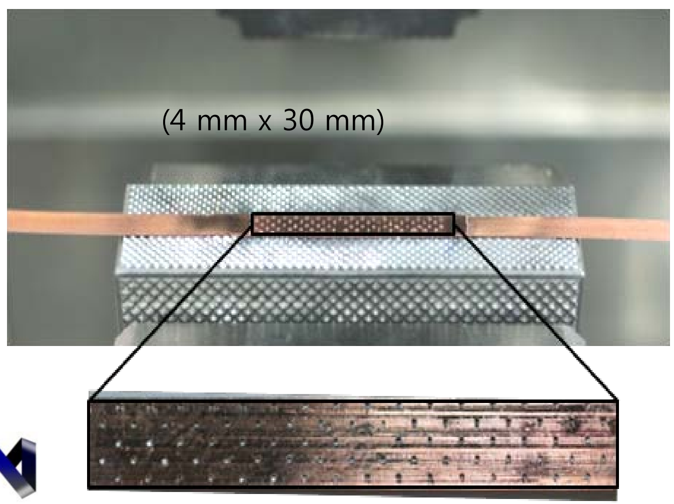


Ultrasonic welder machine





(Patented)



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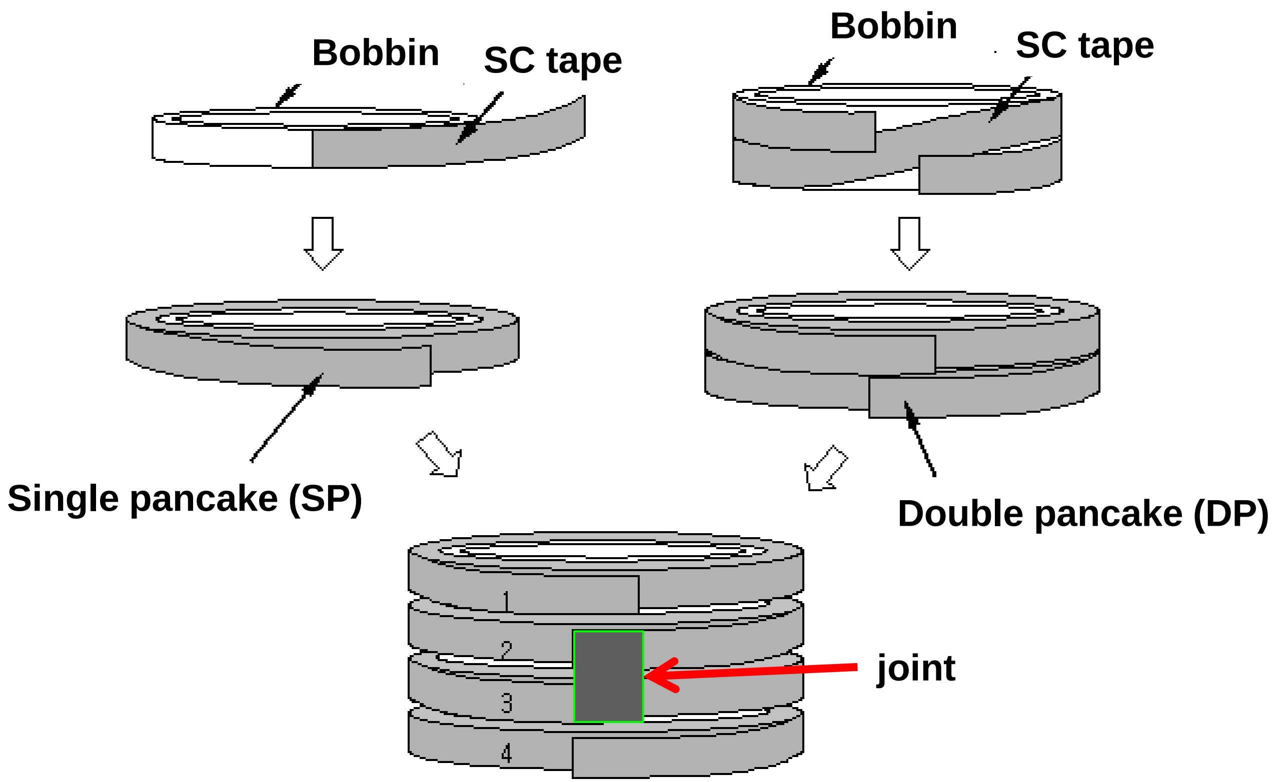
ANDONG NATIONAL UNIVERSITY

Magnet & Coil

(Double) Pancake Coil

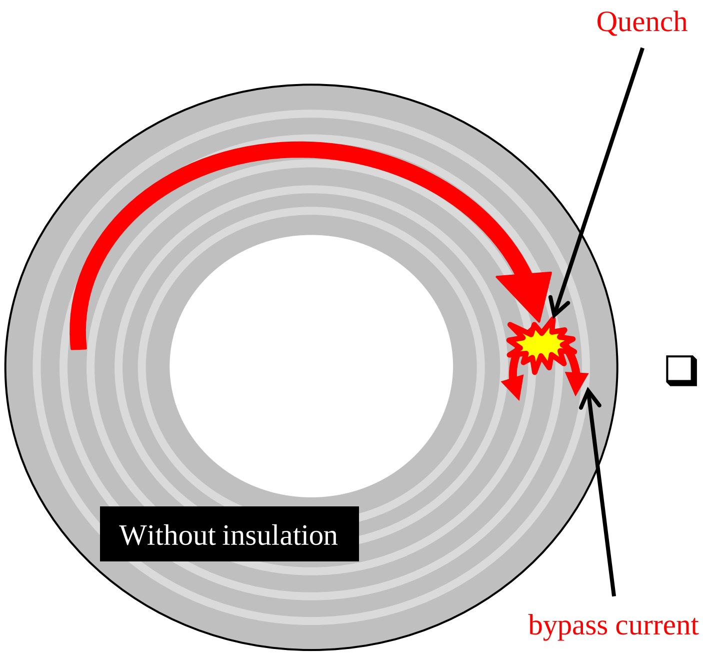
- Pancake winding is adopted due to tape-form of HTS wire



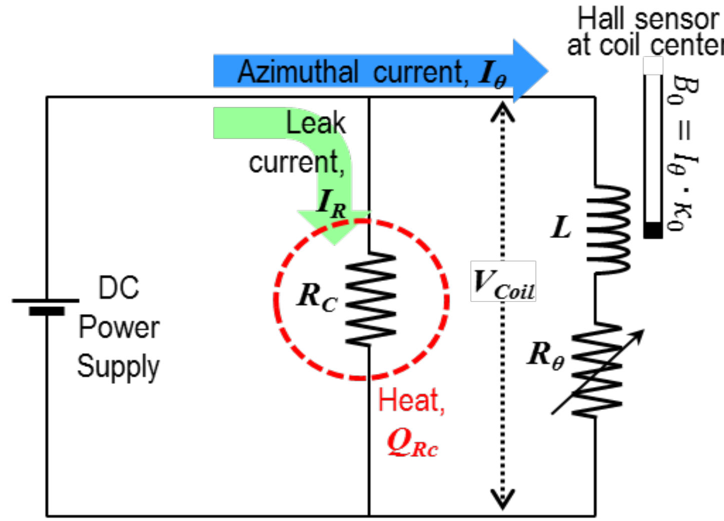
Coil with 4 Single Pancakes or 2 Double Pancakes;
For SP case, SP 1-2 & 3-4 are joined inside, 2-3 outside.

- 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} [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)

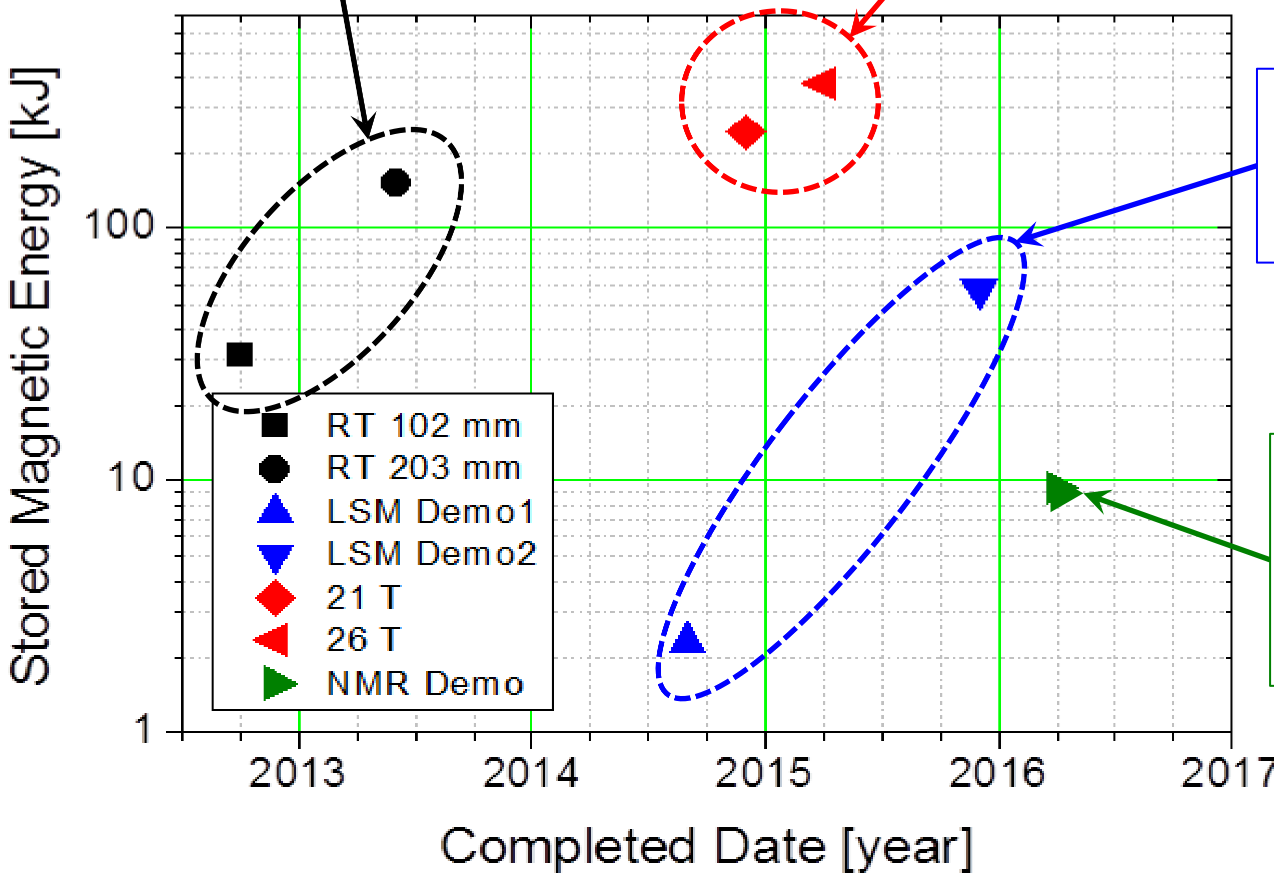
(by S. Hahn)

(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

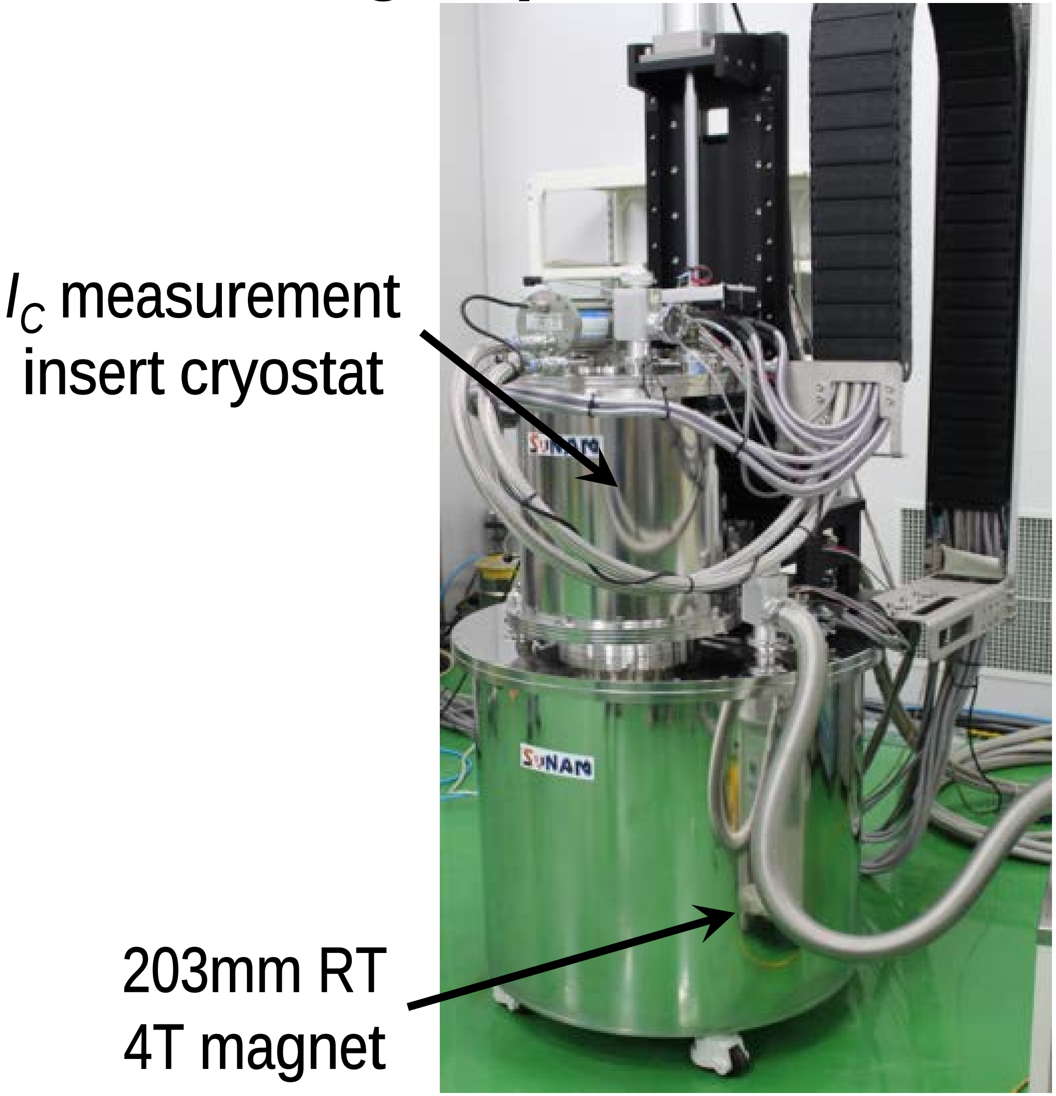


➢ Racetrack magnet
- For motor application
- Cryogen-free

➢ **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(B-T-θ) measurement system >

HTS magnet for 10kW generator

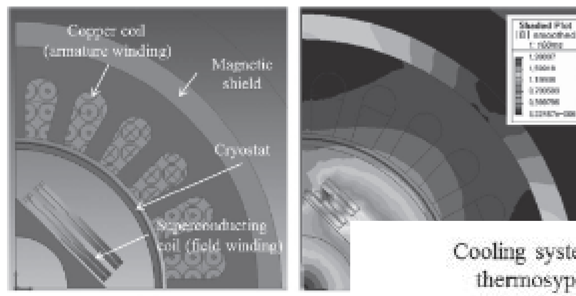
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 25, NO. 3, JUNE 2015 5202004

Performance Analysis of a 10-kW Superconducting Synchronous Generator

A-Rong Kim, Kwang-Min Kim, Heecheol Park, Gyeong-Hun Kim, Tae-Joon Park, Minwon Park, Seokho Kim, Sangjin Lee, Hongsoo Ha, Sangwon Yoon, and Hunju Lee

Abstract—POSCO and the Research Institute of Industrial Science and Technology developed a 10-kW superconducting synchronous generator using high-temperature superconducting wire. The generator consists of four-pole racetrack-type superconducting coils using GdBCO wire for rotor and 24 slots copper windings for stator. The rated power of the generator was 10 kW at 600 r/min, and the operating temperature was 30 K by thermosyphon cooling method using liquid neon. The output power was measured when the generator was connected to a vector motor, and the detailed results were discussed in this paper.

Index Terms—GdBCO, liquid neon, rotating machine, superconducting generator.

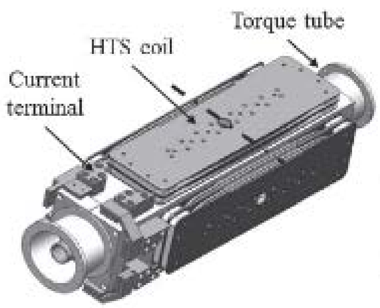


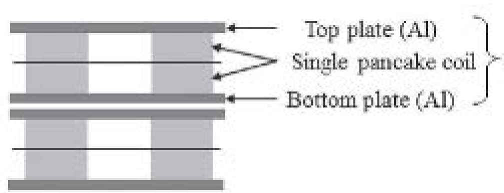
(a)

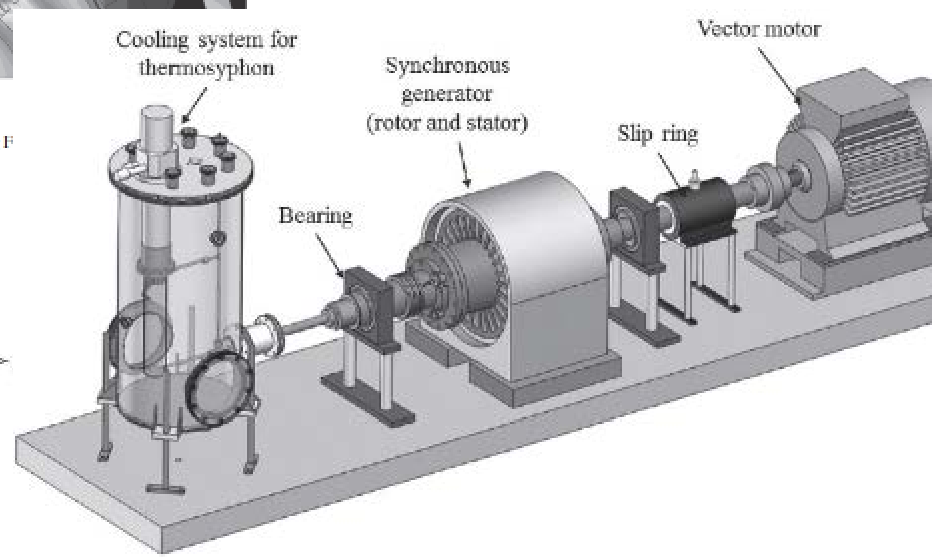
Fig. 1. Design results of the generator using F
area. (b) Magnetic field distribution.

I. Introduction

BECAUSE of increasing the electricity demands, larger power systems are expected with high efficiency. To in-







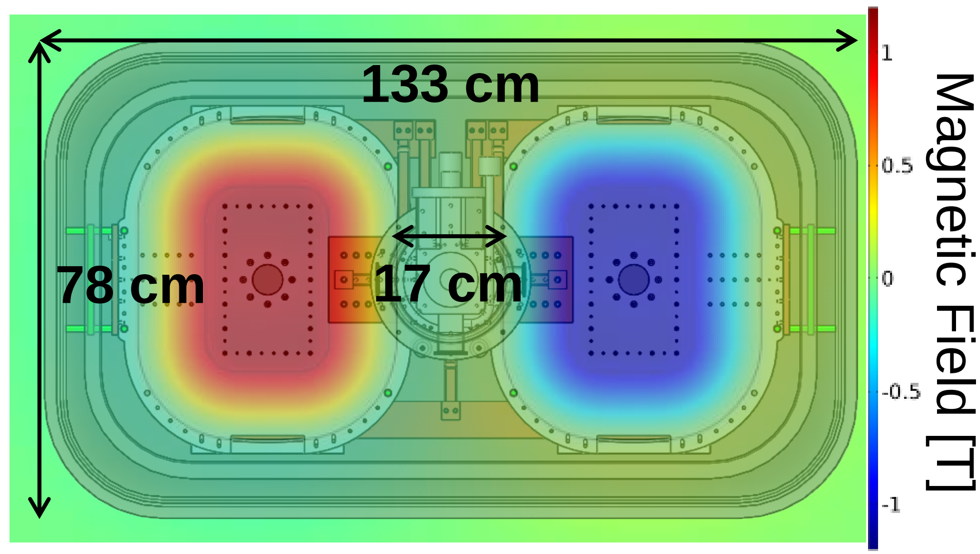
SUNAM RIST KERI

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

HTS magnet for LSM

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TEC.2016.2577058, IEEE Transactions on Energy Conversion

Development of a Small-scale Superconducting LSM using Gd-Ba-Cu-O High-Temperature Superconducting Wire

Chan-Bae Park, *Member*, *IEEE*, Chang-Young Lee, *Member*, *IEEE*, Sangwon Yoon and Seokho Kim

***Abstract*—In this research, a 600 km/h-class high-speed train with wheel-rail support and a linear synchronous motor (LSM) propulsion system is being considered. Prior to the development of superconducting LSM for propulsion of 600 km/h-class high-speed trains, pre-performance validation through a small-scale prototype is required. Therefore, a small-scale 7 kW-class superconducting air-core-type LSM prototype was designed, one that includes a superconducting magnet with 2 poles. High-temperature superconducting (HTS) wire of the Gd-Ba-Cu-O series was used for the magnet. Next, the various characteristics of the designed model were estimated through a numerical approach, with the finite element method (FEM). Finally, a small-scale superconducting LSM prototype was produced and installed in a bogie on a 10-m track. A performance test of the superconducting magnet and a no-load induced voltage and thrust measurement test of the small-scale superconducting LSM were completed. The effectiveness of the proposed superconducting LSM design techniques and design model was verified.**

***Index Terms*— Linear synchronous motor, LSM, High-temperature superconducting, HTS, High-speed train**

propulsion system that is based on rotary-type traction motors, it is quite difficult to operate trains with an ultra-high speed of 500 km/h or beyond. In order to overcome the speed limitations of the trains due to the adhesive drive propulsion system, a magnetic levitation vehicle (Maglev) that uses a linear motor propulsion system has been invented [3]. At present, the fastest train in the world is Japan's superconducting Maglev, at a high speed of 581 km/h. Japan is almost finished experimenting on the test track and it will be ready for commercial operation [1]. However, the Maglev's commercial operations are being delayed due to numerous issues, including technical and economic problems. The hybrid-type train system is emerging as an alternative to the conventional high-speed train and the Maglev system [4]. The hybrid-type train system incorporates the strengths of the wheel-rail supported adhesive drive propulsion system and the Maglev system. Although the hybrid-type train system is based on a wheel-rail guided system, a linear motor is used for propulsion instead of a rotary motor. The non-adhesive drive propulsion system by a linear motor is able to overcome the speed limitation of the conventional high-speed train [5]. Figure 1 shows a conceptual diagram of an

TABLE I
DESIGN RESULTS OF THE SMALL-SCALE SUPERCONDUCTING LSM MODEL

Contents	Value
Output power	7 kW
Max. thrust	118 N
Max. operating frequency	2.8 Hz
Length of test track	10.08 m
Pole-pairs in test track	12
Turns/Pole (Armature coil)	20 Turns
Max. current/Phase for whole track	44 A_{rms}
Resistance/Phase for whole track	0.431 Ω
Air-gap / Pole pitch	65 mm / 420 mm
Pole numbers (SC magnet)	2
Required MMF (SC magnet)	72 kA-Turns
Operating current (SC magnet)	120 A

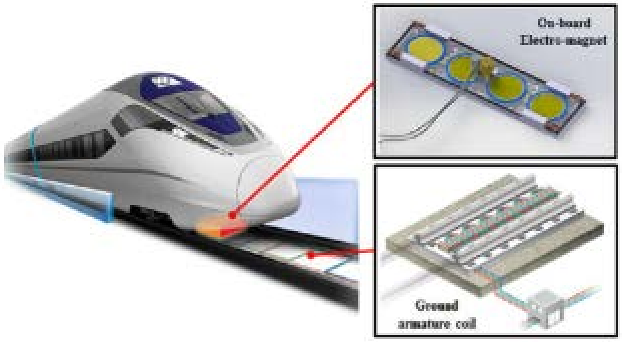


Fig. 1. Conceptual diagram of the ultra-high speed 600 km/h trains [4]

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

No-insulation, multi-width, and compact !

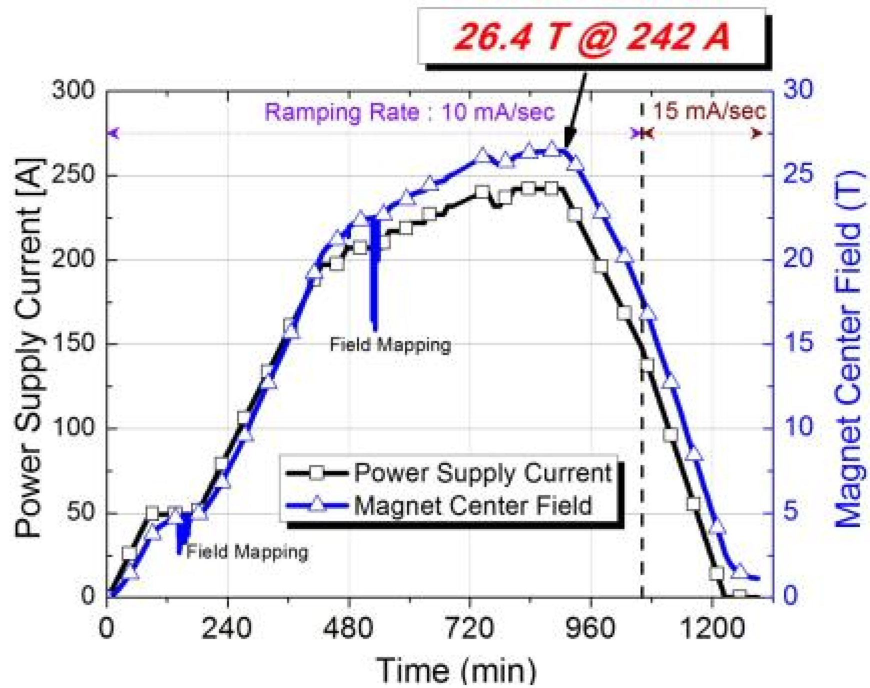
✓ Multi-width Double Pancake Coils

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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Key Parameters of 26 T Magnet

Ref.) S. Yoon *et al*, "26T 35mm all-$GdBa_2Cu_3O_{7-x}$ multi-width no-insulation…," *Supercond. Sci. Technol.*

Parameter		M1	M2	M3	M4	M5
Tape Width	[mm]	4.1	5.1	6.1	7.1	8.1
I.D.; O.D.	[mm]	35.0; 171.8				
Height	[mm]	327				
No. of DP		10×1	2×2	2×2	2×2	2×2
Turn per DP (Avg.)		946				
Operating Current, I_{OP}	[A]	242				
Operating Temp., T_{OP}	[K]	4.2 (in liquid helium)				
Magnetic Field	[T]	26.4				
Inductance	[H]	12.3				
J_e @ I_{OP}	[A/mm²]	404	327	293	247	221
$B_{perp.}$ @ I_{OP}	[T]	1.54	1.59	1.82	2.08	3.68

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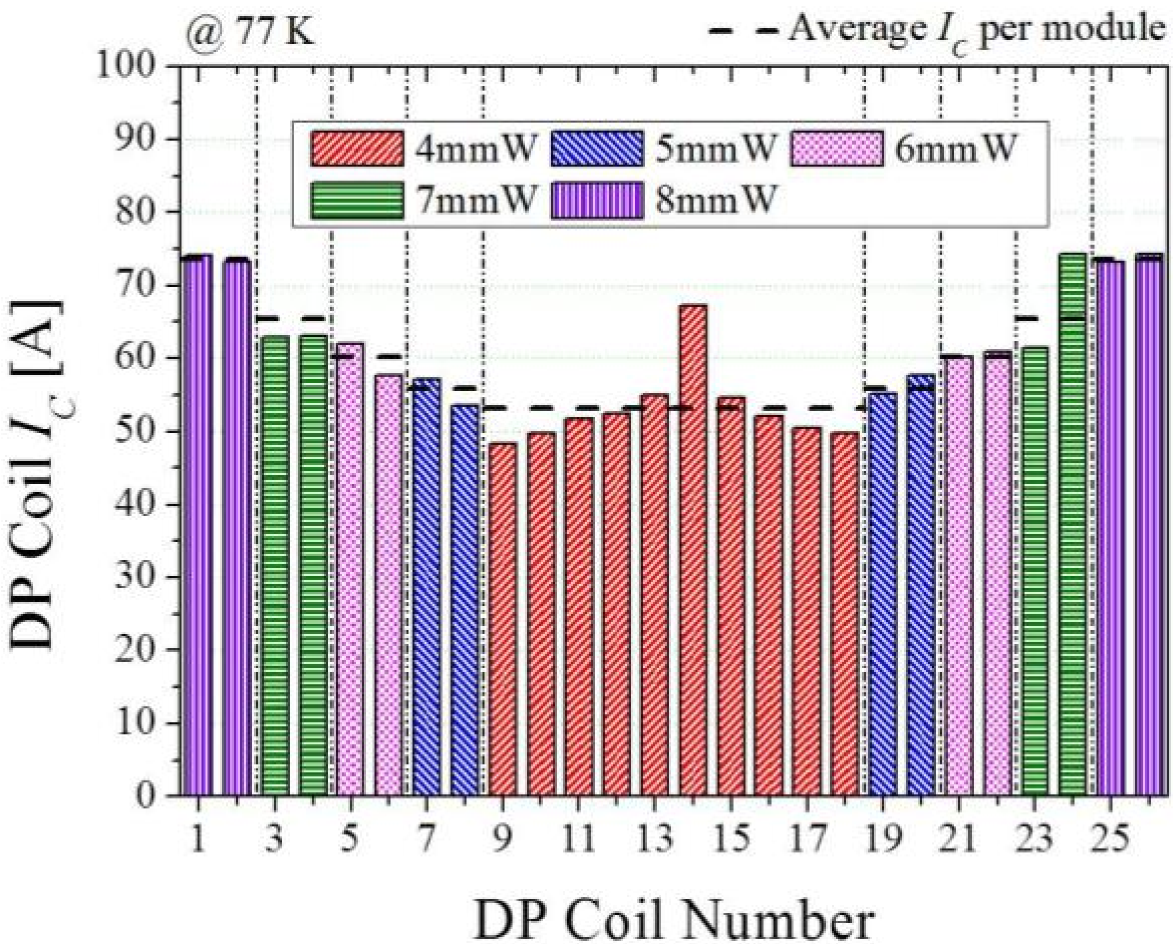
Coils are arranged by 77 K I_C

✓ Critical current (I_c) of each DP coil with a 0.1-μV/cm criterion was measured in a bath of liquid nitrogen at 77 K



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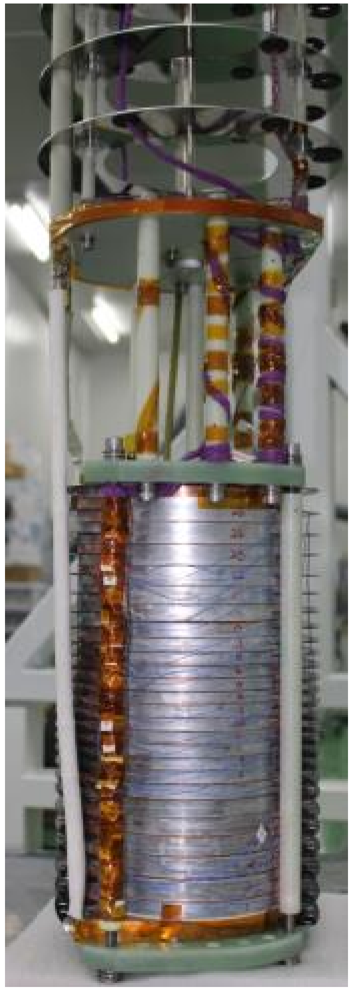
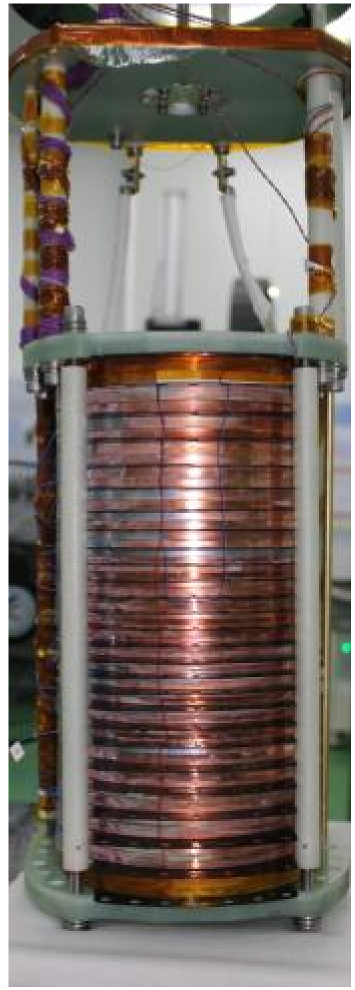
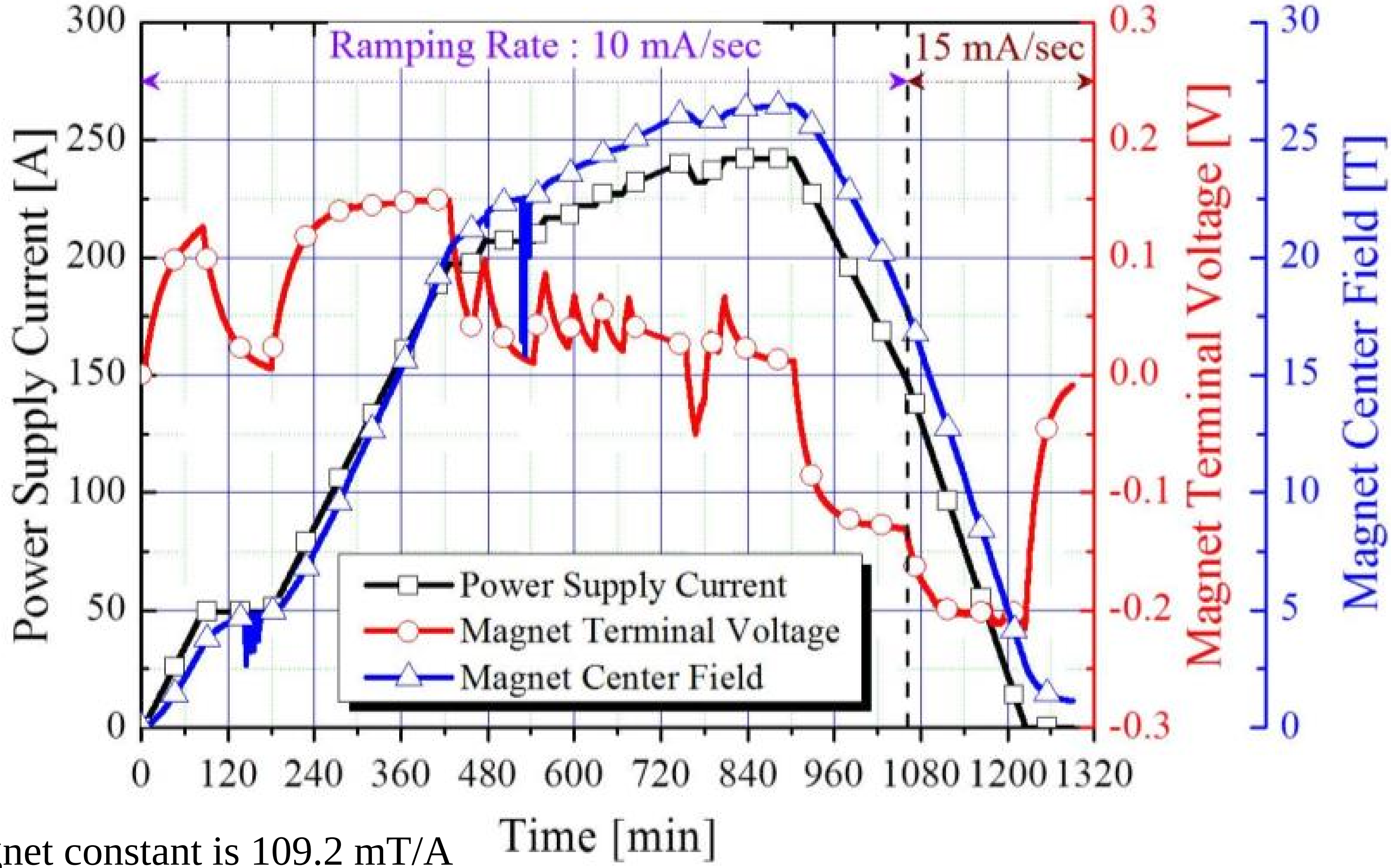
Magnet Assemble

✓ completed magnet after the final assembly in accordance with the stacking order


Magnet operation in LHe

- ✓ The magnet center field reached 26.4 T at 242 A (404 A/mm^2 for 4.1-mm DPC)



- ✓ Magnet constant is 109.2 mT/A

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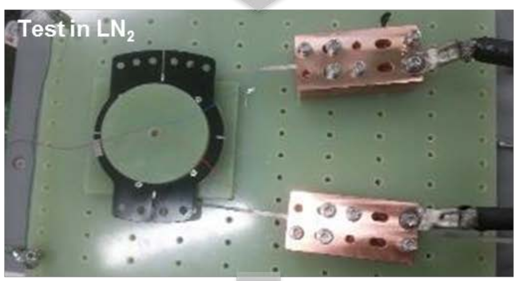
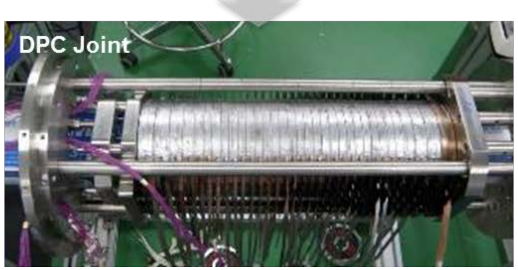
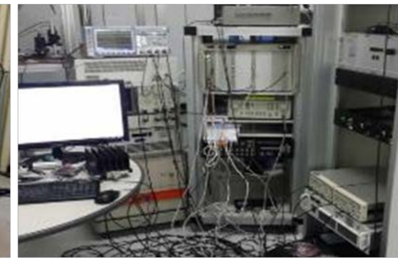
Cryogen free all HTS NMR





Final Assemble

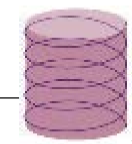
[3T DEMO]



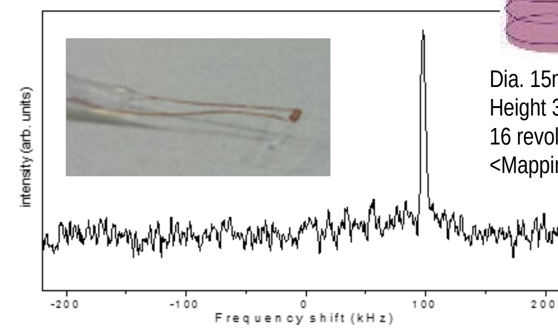
[NMR spectrometer]

NMR detect

[0.3 mm NMR sensor]



Dia. 15mm
Height 30mm
16 revolutions
<Mapping path>



[128MHz (3T) 1H NMR spectrum of water]

NATIONAL HIGH MAGNETIC FIELD LABORATORY

KBSI KOREA BASIC SCIENCE INSTITUTE

KIMM KOREA INSTITUTE OF MACHINERY & MATERIALS

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18 T magnet for Axion detection @IBS, Korea

Axion to photon conversion power :

$$P = g_{\alpha\gamma\gamma}^{2} \frac{\rho_a}{m_a} V B_0^2 C min(Q_L, Q_a)$$

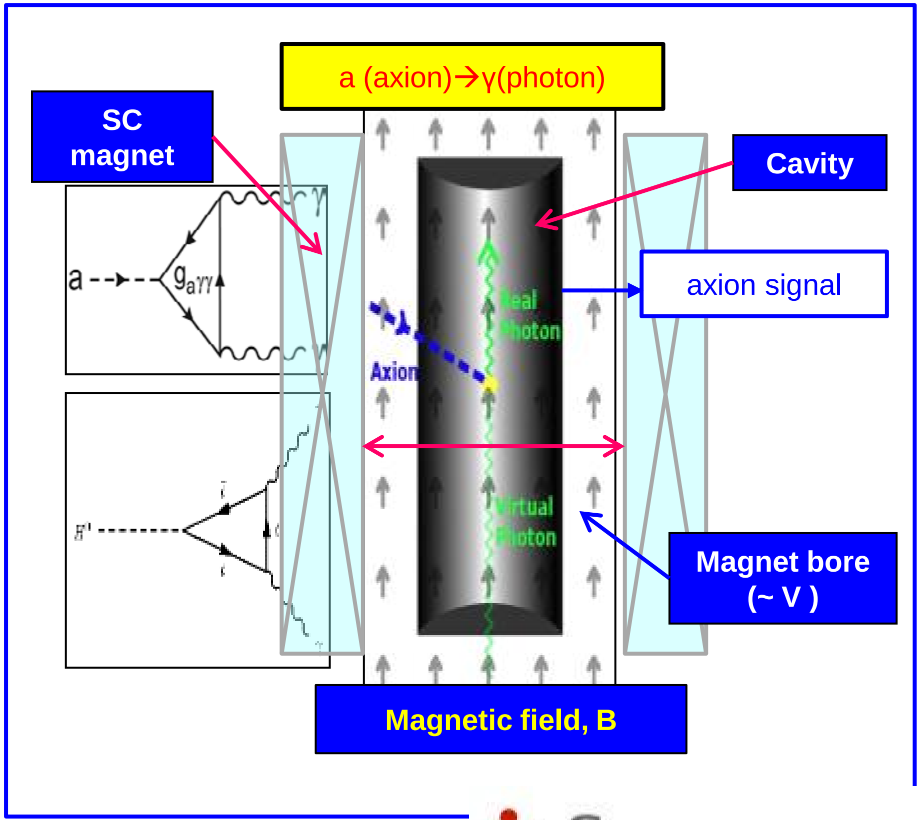
→ cavity

axion-photon - photon coupling

Magnetic field & cavity volume

- Axion-photon conversion : proportional to **$B^2 \cdot V$**

⇒ Strongly Depends on the Magnet



axion signal power is exceedingly weak, $<10^{-21}$ Watt (zepto-watt)

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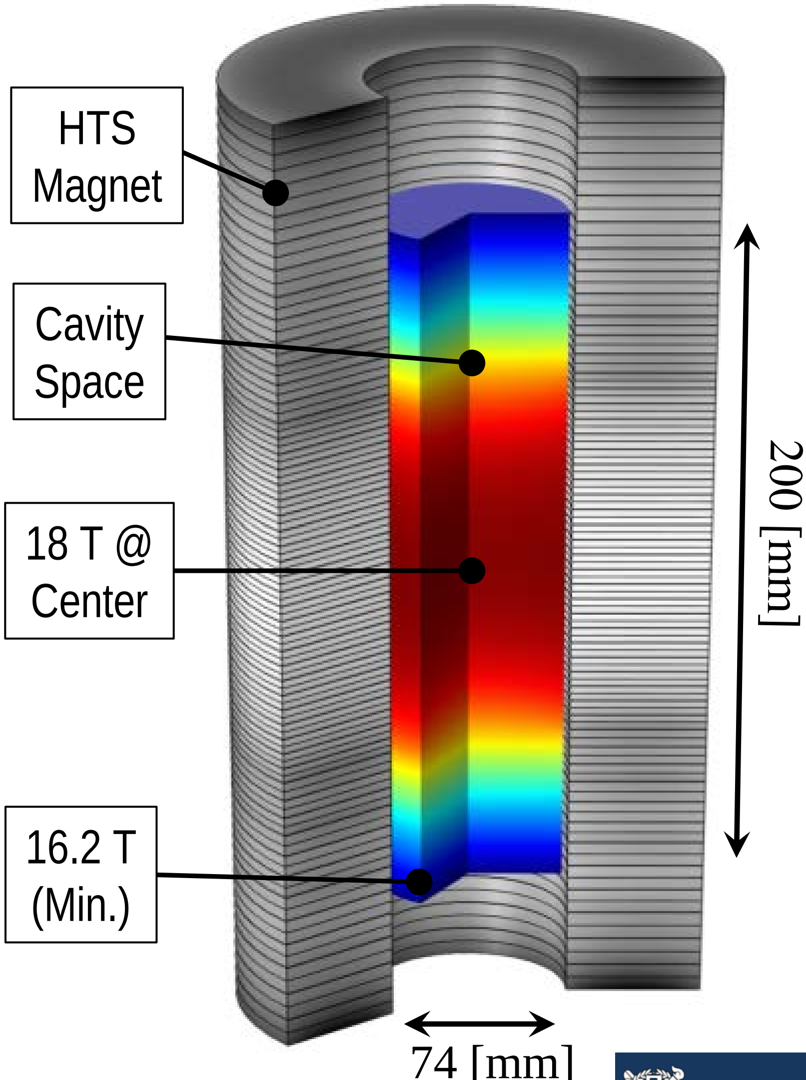
18 T magnet -design



◆ **Key design parameters**

- 18 T at magnet center
- In 66 mmΦ, 200 mmL cylinder,
  90 % Uniformity in Cavity Space
  ➔ |B| ≥ 16.2 [T]
- Operating in liquid helium (4.2 K)

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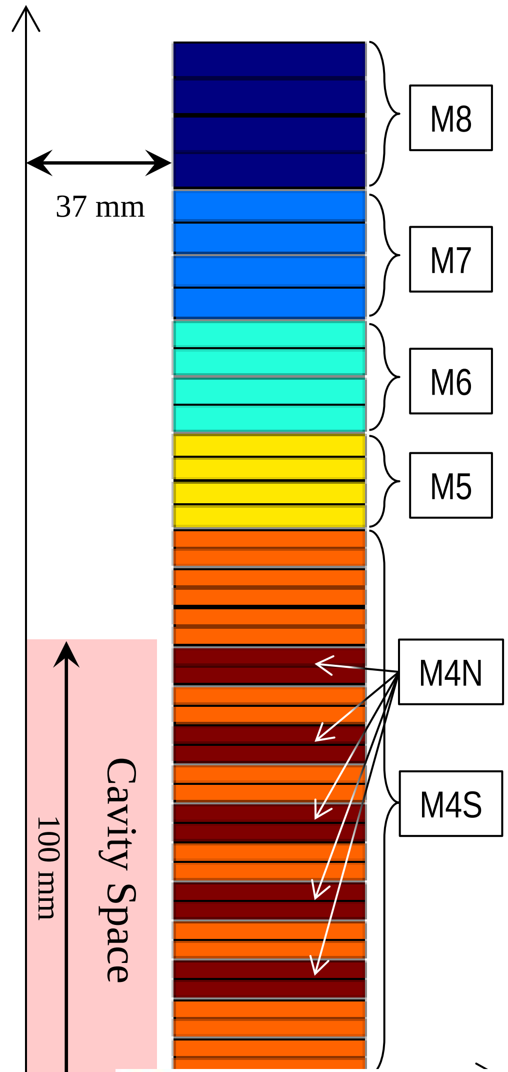
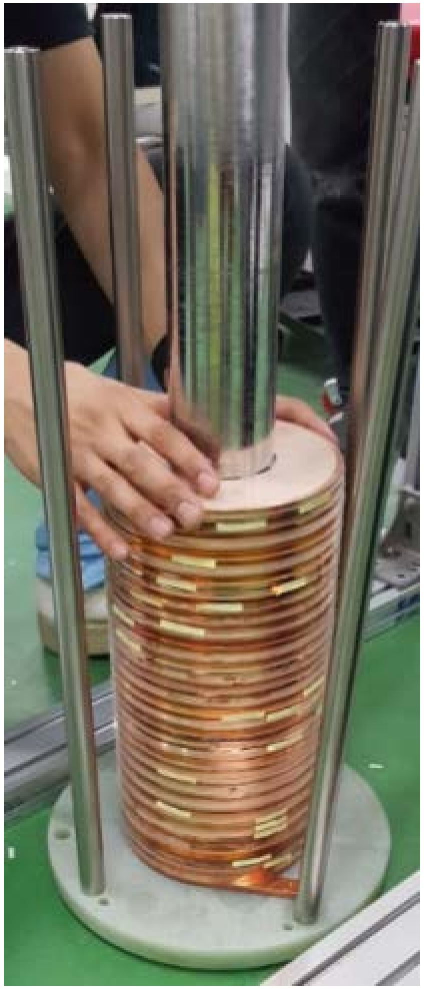
18 T magnet - design

Coil Configuration	Unit	M4N	M4S	M5	M6	M7	M8
Tape Dimension	[mm]	4.1	4.1	5.1	6.1	7.1	8.1
Tape Thickness	**[mm]**	**0.12**	**0.14**	**0.12**	**0.12**	**0.12**	**0.14**
Cold Bore; Magnet Height	[mm]	70; 476					
Winding I.D.; O.D.	[mm]	74.0; 162					
Number of DPC		10	18	4	4	4	4
Turn per SPC		365	322	364	363	366	317
Operating Current, I_{op}	[A]	202.6					
Magnetic Field at Center	[T]	18.0					
Min. |B| in Cavity Space (z < ± 100 mm)	[T]	16.7 (92.5 %)					
Inductance	[H]	20.2					
Stored Energy	[kJ]	375					
Magnetic Hoop Stress	[MPa]	276					
Eng. Current Density	[A/mm^2]	408	358	328	274	236	181
Peak Magnetic Hoop Stress	[MPa]	280 @ M4N(DP20)					

< Upper Half Magnet >



18 T magnet - assemble

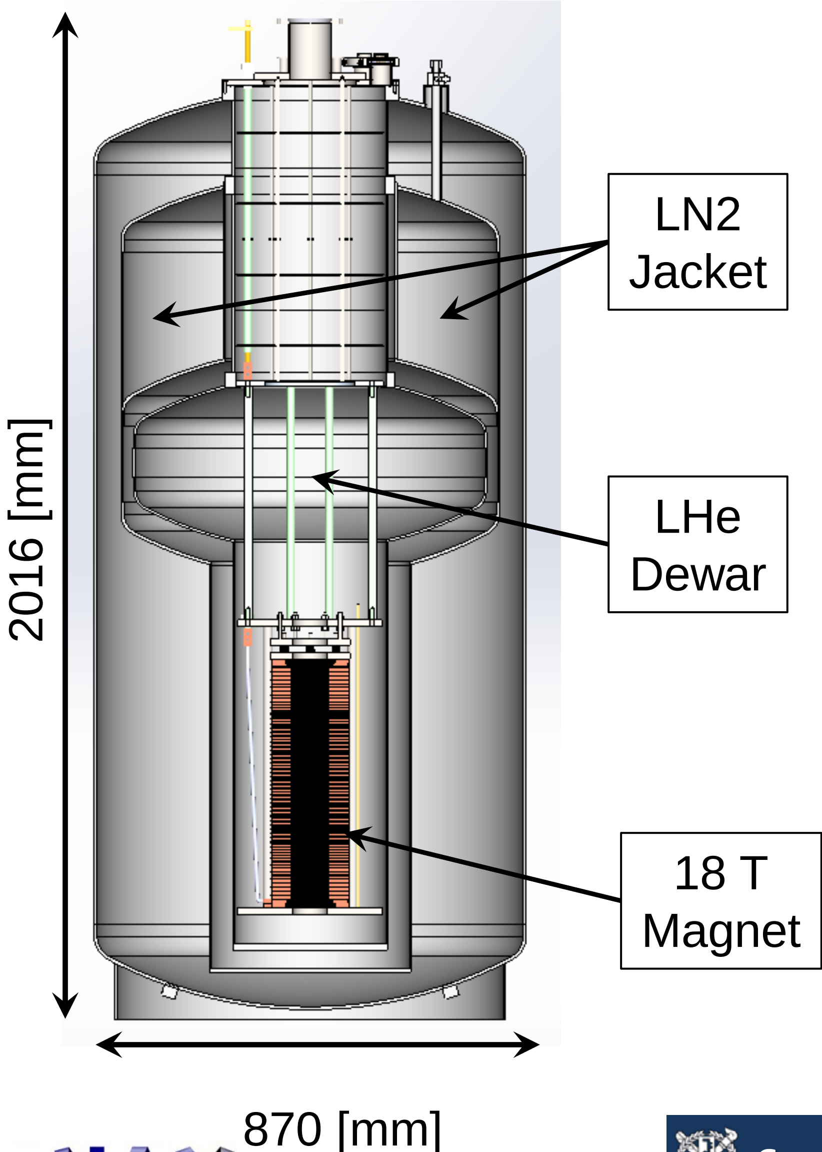


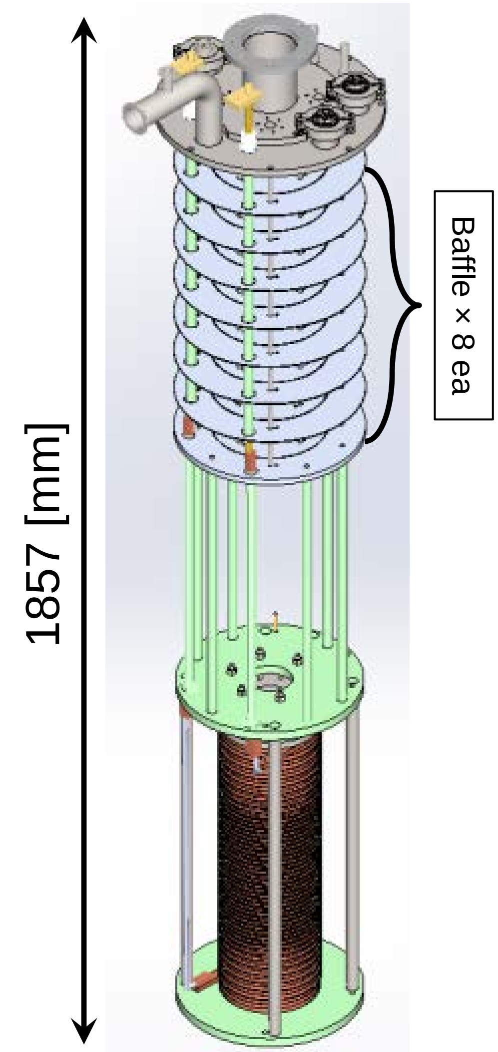
< DP Stack >

< Splice Joints >

< Overbanding >

18 T magnet - cryostat





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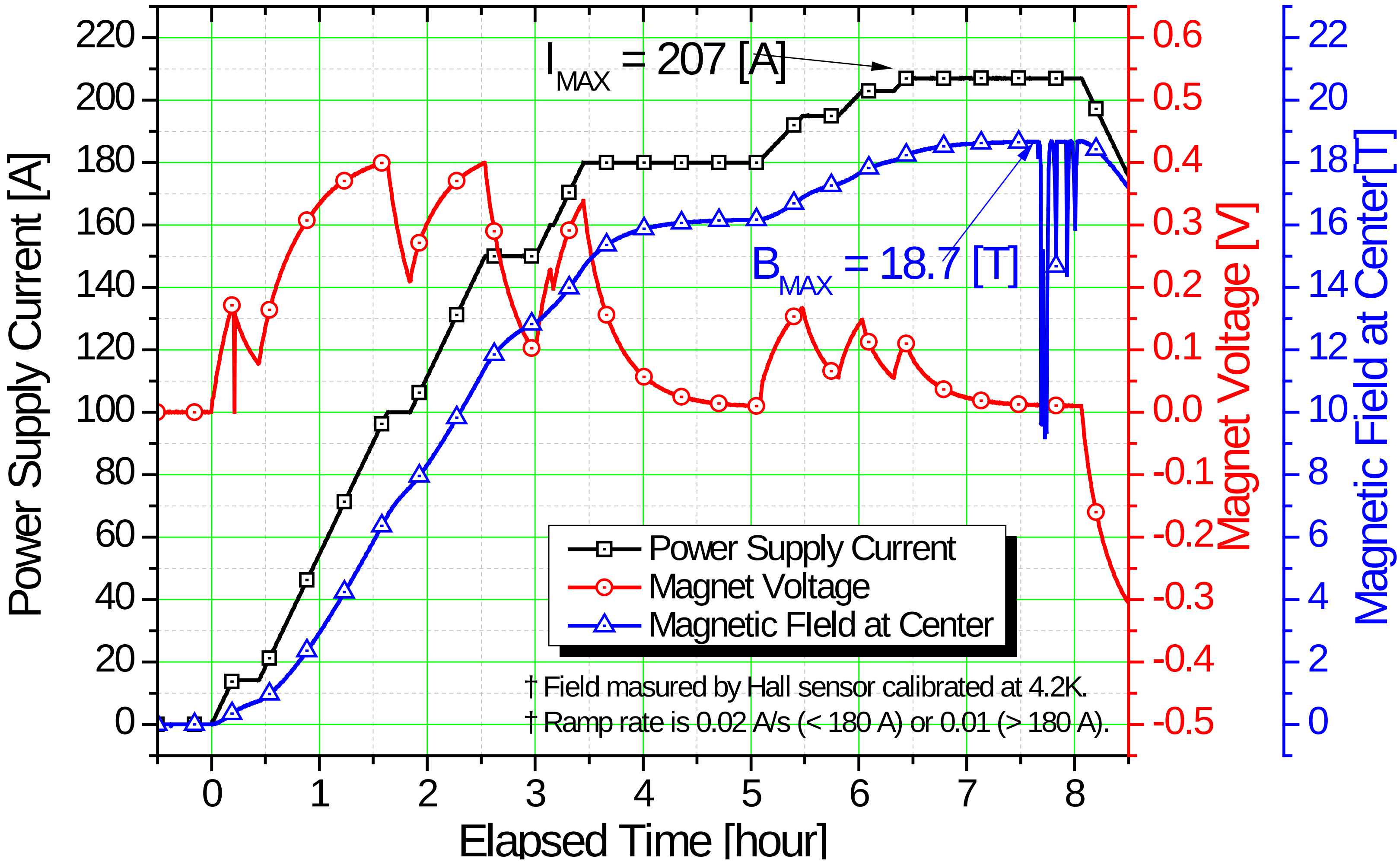
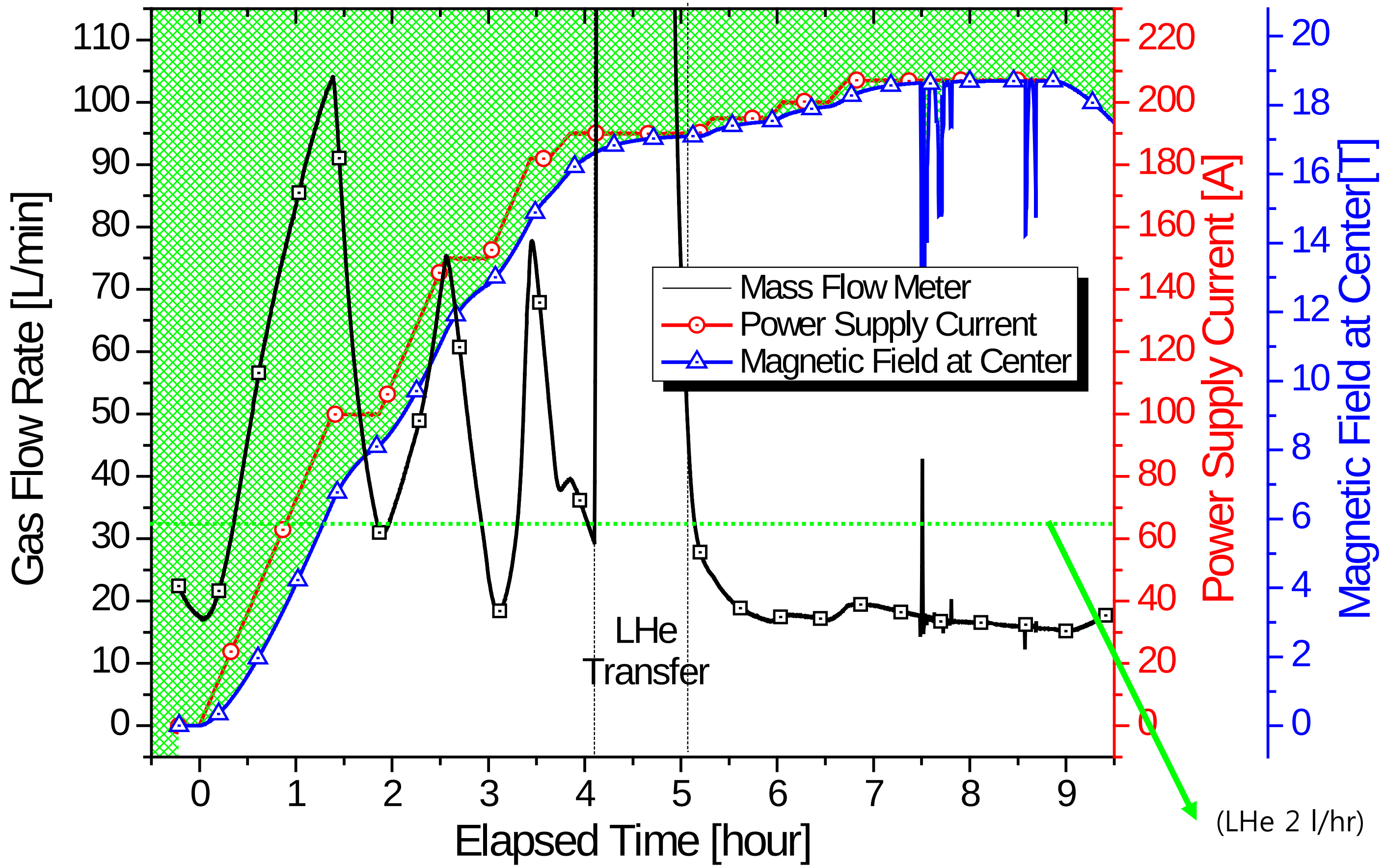
18 T magnet - operation



- Field measured by hall sensor calibrated at 4.2 K
- Ramp rate : 0.02 A/s (under 180 A), 0.01 A/s (Over 180 A)

LHe Consumption @ 18 T



- ➢ Temperature of Outlet Gas : 15 ~ 25 ℃
- ➢ Correlation Between Radial Current & Heat

18 T magnet – delivery & comparison to 26 T

- ✓ Delivered to Center for Axion and Precision Physics Research, IBS(Institute for Basic Science) in Korea; Aug. 2017.
- ✓ 18.7 T at 4.2 K, 70 mm clear bore.
- ✓ Compared to 26 T magnet
  twice larger I.D.(2.1X),
  slightly smaller O.D.(0.9X),
  ~1.5 times taller,
  roughly the same stored energy
  about 20% more tape used
- ✓ LHe boil rate < 2 liters/hr

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 mm → 1.6 mm) S.C. layer, we achieved >1,000 A/12 mm in production.
- We have made different kinds of NI magnet for various applications.

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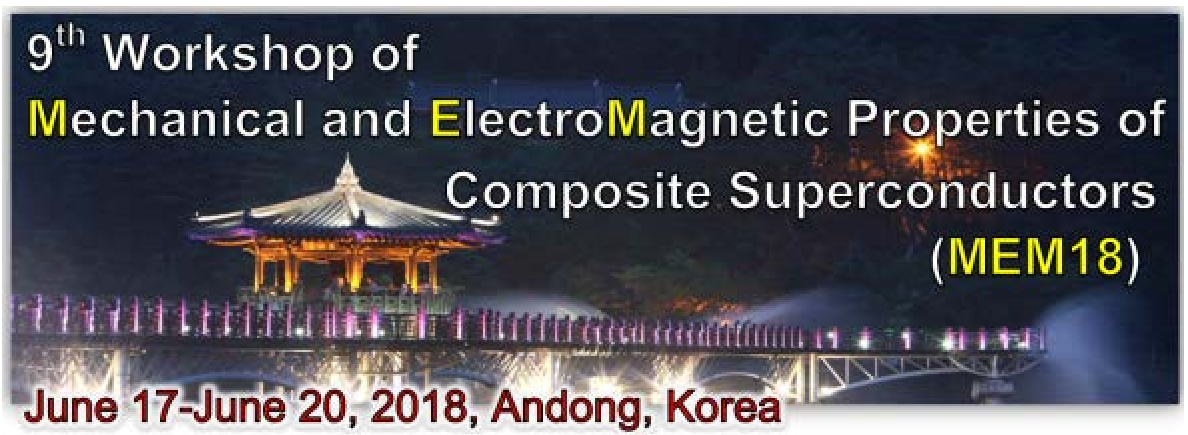
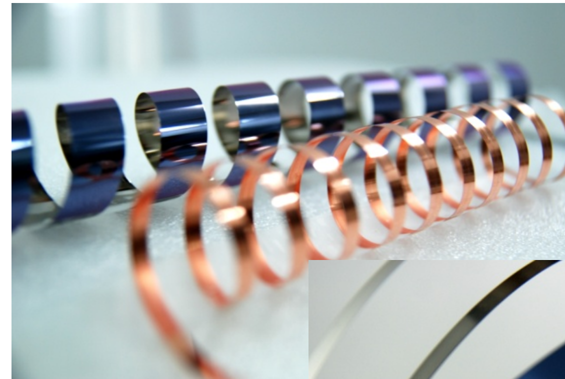
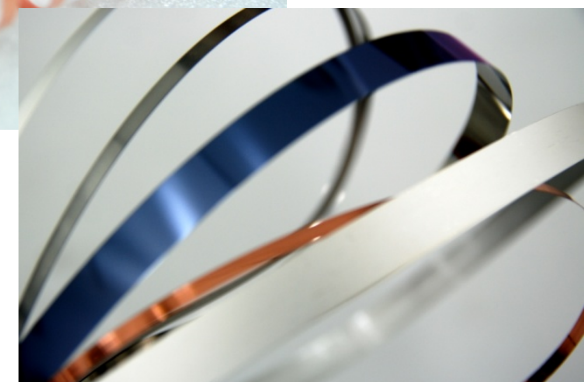
Thanks for Attention !







http://mem18.org/

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9th Workshop of Mechanical and Electromagnetic Properties of Composite Superconductors

June 17 – 20, 2018, Andong, Korea

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