# 'High Tc superconductors in real world : Industrialization way of HTS 2G wires.'


**Seung Hyun Moon**

**SuNAM Co., Ltd.**

***2018. 10. 17.***

SEOUL NATIONAL UNIVERSITY

PHYSICS

Departement of PHYSICS & ASTRONOMY

SUNAM

*Superconductor, Nano & Advanced Materials*

# Contents

- Introduction
  - Complex oxide high temperature superconductor(HTS) & wire
- Applications & markets using HTS 2G Wire (Coated Conductor).
- SuNAM's high rate e-beam process with oxide epitaxy (RCE-DR).
- Some application examples of coil/magnet
- Summary.

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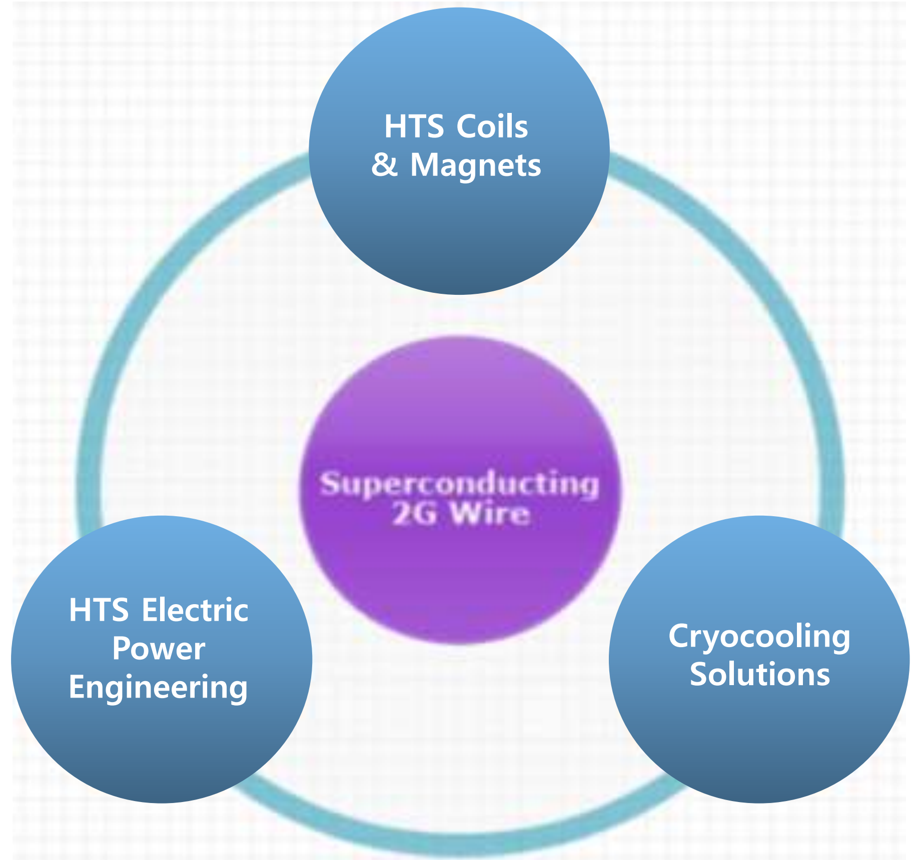
# Company Overview

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

| | |
|---|---|
| **Establishment** | 2004. 11. 17., for commercialization of HTS wire |
| **CEO** | Seung-Hyun Moon |
| **Registered Capital** | ~$7M |
| **No. of Employees** | ~ 45 (10 Ph.Ds) |
| **H.Q.** | Ansung, Korea |
| **Current Production Capacity** | ~ 60 km / month (4 mm > 150 A) |
| **Core Technology** | 2G HTS manufacturing technology based on RCE-DR process. NI-base ultra high field magnet technology |

**Business Area**




SUNAM Vision & Core Value

Vision

전기 에너지의 새로운 패러다임 디자이너.
(The New Paradigm Designer of Electric Energy.)

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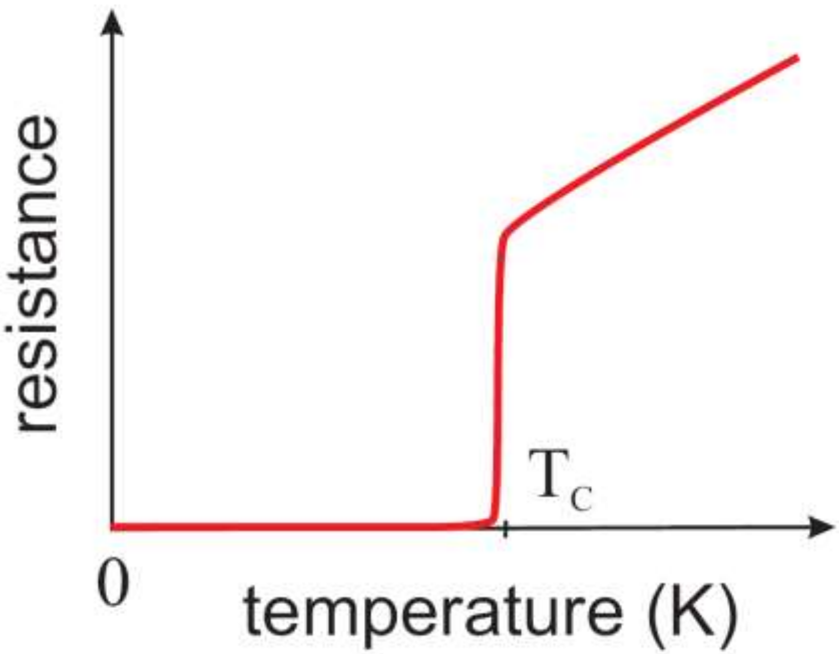
# Introduction on HTS

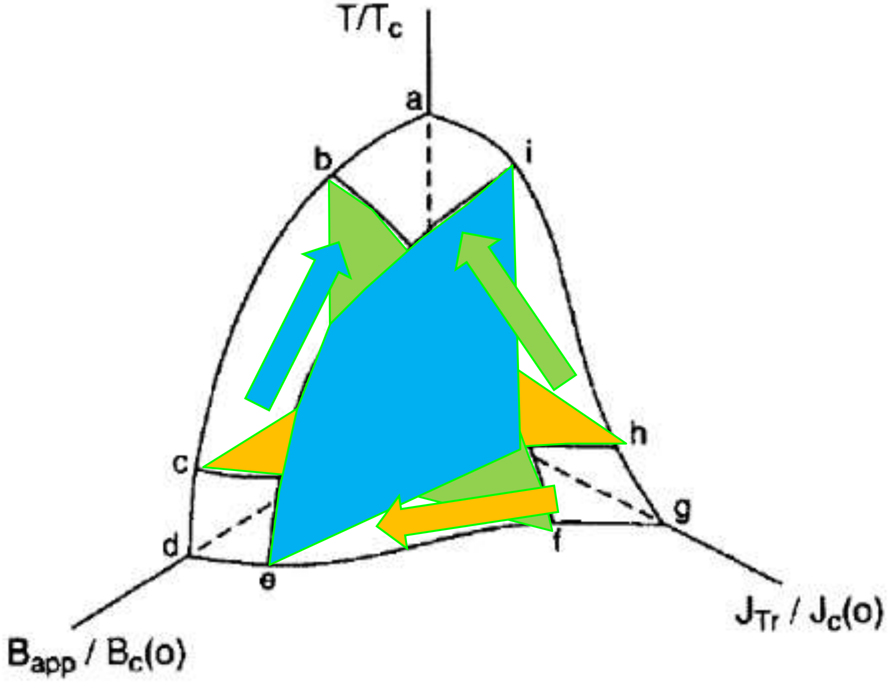
# 초전도체, Superconductor, 超電導體, 超傳導體

- 전기저항이 영(zero)이 되어, 손실 없이 전류를 흘릴 수 있는 물질 (DC)
- 전류밀도는 구리의 10,000배 이상 → 전력기기의 소형화, 경량화




- 응용
  - 초전도 케이블, 변압기 등 전력기기
  - 초전도 모터 / 발전기
  - MRI / NMR 등의 초전도 전자석
  - 에너지 저장장치(SMES)
  - 한류기

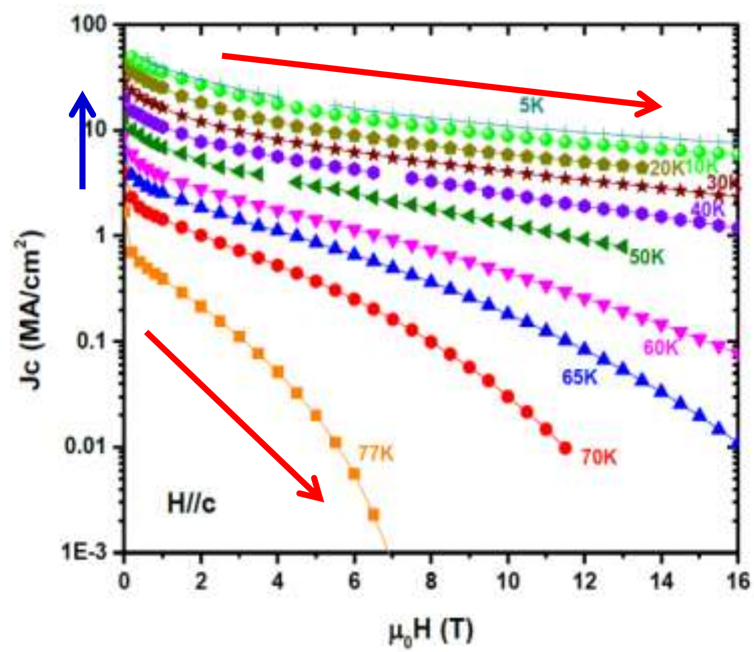
# 초전도 상태




일정한 외부자기장 하에서
온도가 올라가면 임계전류 감소

일정한 통전전류 하에서
온도가 올라가면 임계자장 감소

일정한 온도 하에서
외부자장이 증가하면 임계전류 감소

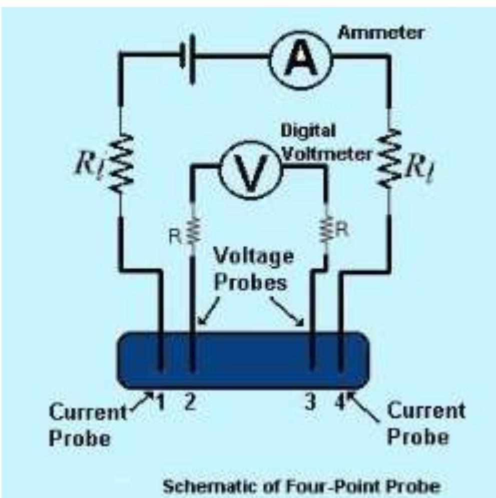



- 임계온도 이하; $T_C$
- 임계자장 이하; $H_C$
- 임계전류 이하; $J_C$

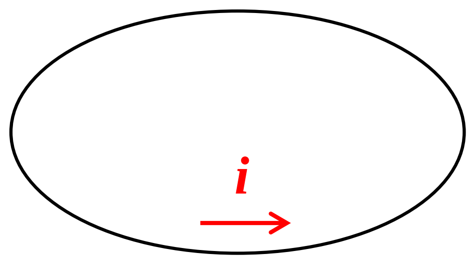
# 초전도체, Superconductor, 超電導體, 超傳導體

- 저항이 얼마나 작은가?
- 일반적인 4-단자법으로는 측정 분해능 이하
- 원형 도체에서 저항에 의해 전류가 감소하는 것을 측정

$$\rho < 10^{-23}\ \Omega m$$



Schematic of Four-Point Probe



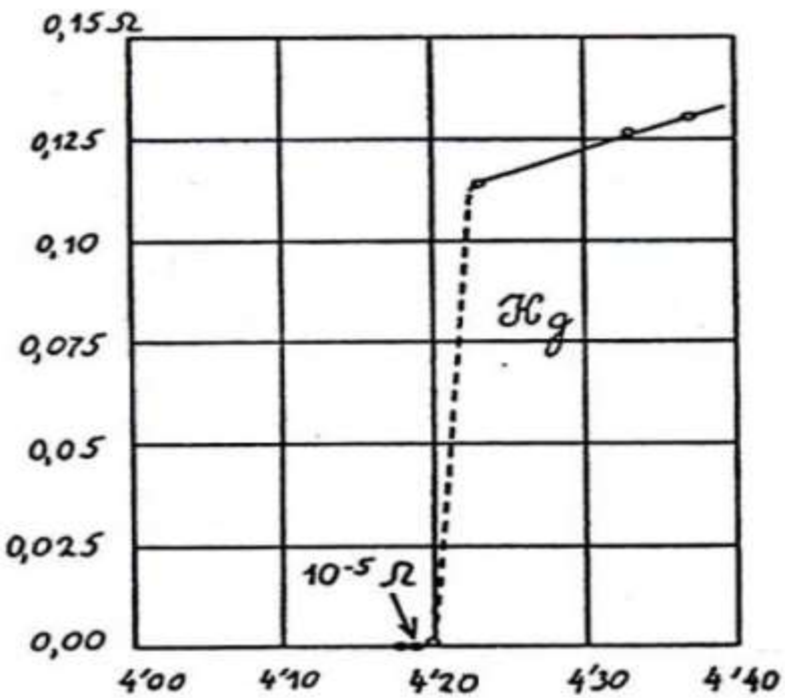

$$i(t) = i_0 \cdot e^{-\frac{R}{L}\cdot t}$$

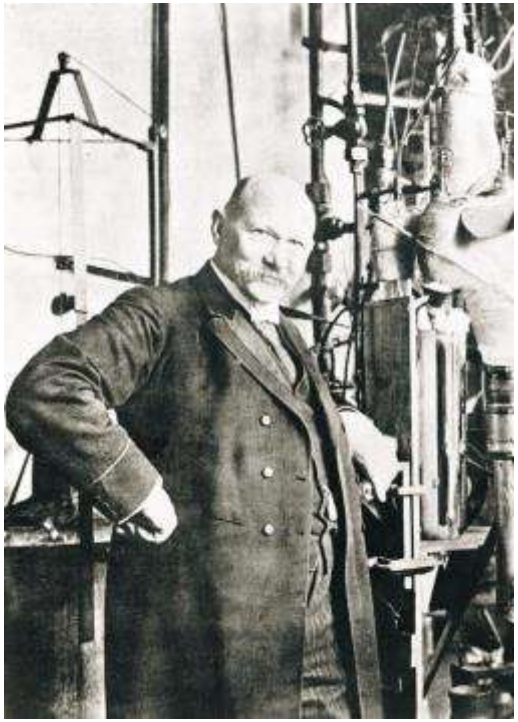
**S. C. Collins, 2년 반 동안 유지 ~$10^{-23}\ \Omega m$**

†No perceptible decay was noticed from March 16, 1954, when the test was initiated, until September 11, 1956, at which time the test was discontinued. In order that no change of flux be detectable the resistance must be less than $10^{-21}$ ohms, assuming a measurement accuracy of 1%.

# 초전도체의 발견

- 낮은 온도에서 금속의 저항은?
- 끓는 점이 낮은 물질의 액화가 필요; 헬륨 1908
- 순도가 매우 높은 시료 제작이 가능한 수은 ⇒ 초전도 현상 (1911)



Door meten tot weten (‘Through measurement to knowledge’)

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# 초전도 원소

Superconducting elements known in 1920

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |

8. Superconducting elements shown in the periodic table, as known in 1920, 1930, and 1950. A modern version is shown in Figure 33

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H Hydrogen | | | | | | | | | | | | | | | | | 2 He Helium |
| 3 Li Lithium 0.4m K | 4 Be Beryllium 0.026 K | | | | | | | | | | | 5 B Boron 11.2 K | 6 C Carbon 15 K | 7 N Nitrogen | 8 O Oxygen 0.6 K | 9 F Fluorine | 10 Ne Neon |
| 11 Na Sodium | 12 Mg Magnesium | | | | | | | | | | | 13 Al Aluminium 1.18 K | 14 Si Silicon 8.5 K | 15 P Phosphorous 18 K | 16 S Sulphur 17 K | 17 Cl Chlorine | 18 Ar Argon |
| 19 K Potassium | 20 Ca Calcium 15 K | 21 Sc Scandium 0.34 K | 22 Ti Titanium 0.5 K | 23 V Vanadium 5.4 K | 24 Cr Chromium 3 K | 25 Mn Manganese | 26 Fe Iron 2 K | 27 Co Cobalt | 28 Ni Nickel | 29 Cu Copper | 30 Zn Zinc 0.85 K | 31 Ga Gallium 1.08 K | 32 Ge Germanium 5.4 K | 33 As Arsenic 2.7 K | 34 Se Selenium 7 K | 35 Br Bromine 1.4 K | 36 Kr Krypton |
| 37 Rb Rubidium | 38 Sr Strontium 4 K | 39 Y Yttrium 2.8 K | 40 Zr Zirconium 0.6 K | 41 Nb Niobium 9.25 K | 42 Mo Molybdenum 0.92 K | 43 Tc Technetium 0.5 K | 44 Ru Ruthenium | 45 Rh Rhodium 35 μK | 46 Pd Palladium 3.2 K | 47 Ag Silver | 48 Cd Cadmium 0.52 K | 49 In Indium 3.4 K | 50 Sn Tin 3.7 K | 51 Sb Antimony 3.6 K | 52 Te Tellurium 7.4 K | 53 I Iodine 1.2 K | 54 Xe Xenon |
| 55 Cs Cesium 1.66 K | 56 Ba Barium 5 K | * | 72 Hf Hafnium 0.38 K | 73 Ta Tantalum 4.4 K | 74 W Tungsten 0.01 K | 75 Re Rhenium 1.7 K | 76 Os Osmium 0.7 K | 77 Ir Iridium 0.1 K | 78 Pt Platinum | 79 Au Gold | 80 Hg Mercury 4.15 K | 81 Tl Thallium 2.4 K | 82 Pb Lead 2.7 K | 83 Bi Bismuth 8.7 K | 84 Po Polonium | 85 At Astatine | 86 Rn Radon |
| 87 Fr Francium | 88 Ra Radium | † | 104 Rf Rutherfordium | 105 Db Dubnium | 106 Sg Seaborgium | 107 Bh Bohrium | 108 Hs Hassium | 109 Mt Meitnerium | | | | | | | | | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | 57 La Lanthanum 6 K | 58 Ce Cerium 1.75 K | 59 Pr Praseodymium | 60 Nd Neodymium | 61 Pm Promethium | 62 Sm Samarium | 63 Eu Europium | 64 Gd Gadolinium | 65 Tb Terbium | 66 Dy Dysprosium | 67 Ho Holmium | 68 Er Erbium | 69 Tm Thulium | 70 Yb Ytterbium | 71 Lu Lutetium 0.1 K |
| † | 89 Ac Actinium | 90 Th Thorium 1.4 K | 91 Pa Protactinium 1.4 K | 92 U Uranium 1.3 K | 93 Np Neptunium | 94 Pu Plutonium | 95 Am Americium 1 K | 96 Cm Curium | 97 Bk Berkelium | 98 Cf Californium | 99 Es Einsteinium | 100 Fm Fermium | 101 Md Mendelevium | 102 No Nobelium | 103 Lr Lawrencium |

33. The periodic table. Elements that superconduct at ambient pressure are shown as black squares. Those that can be made to superconduct in special circumstances (e.g. under pressure or in thin-film form) are shown as grey squares. The temperature listed is the critical temperature, below which superconductivity occurs

# 여러 가지 초전도체

- 단원소 금속 (25종 이상)

Hg(4.2), Pb(7.2), Sn(3.7), V(5.4), Nb(9.3), Ta(4.5), In(3.4), Al(1.2), …

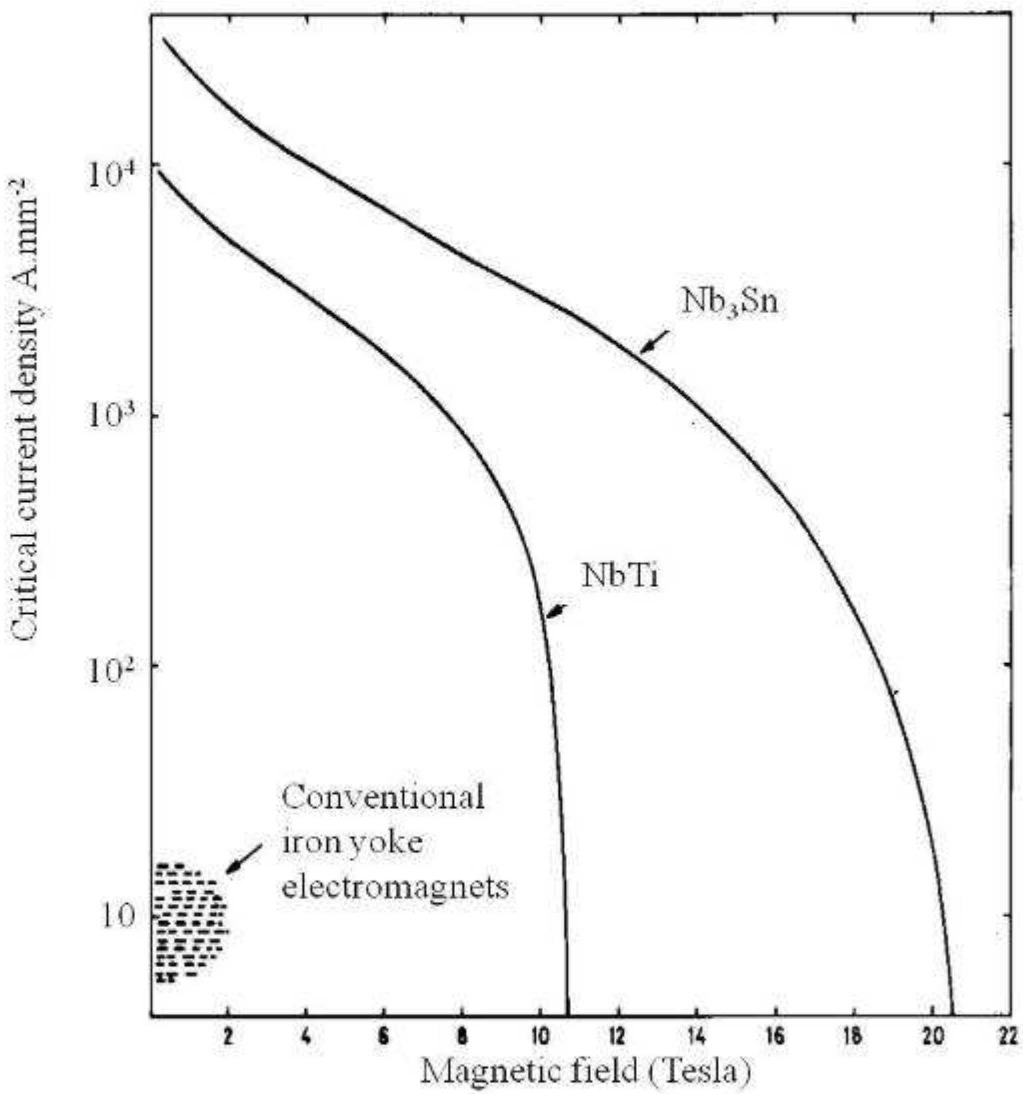
- 합금 / 금속간 화합물 (수천종)

NbTi(9.2), $Nb_3Sn$(18.3), $Nb_3Ge$(**23.2**)

- Heavy Fermions (30여종) ; Unconventional(non s-wave)

$CeCu_2Si_2$(0.7 K, 1978, F. Steglich), $CeCoIn_5$(**2.3 K**), $UPt_3$(0.48), $URu_2Si_2$(1.3)

# Two workhorses of S.C. business




- **NbTi** is the standard ‘work horse’ of the superconducting magnet business
- It is a ductile alloy
- Niobium tin (**$Nb_3Sn$)** has a much higher performance in terms of critical current field and temperature than NbTi
- But it is brittle intermetallic compound with poor mechanical properties

# 고온 초전도체

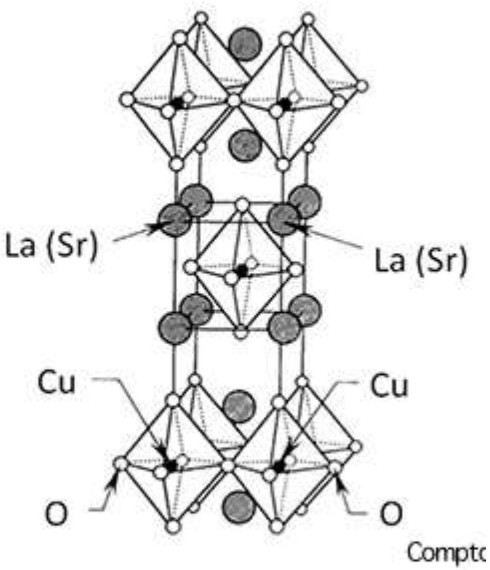
- 고온(산화물) 초전도체

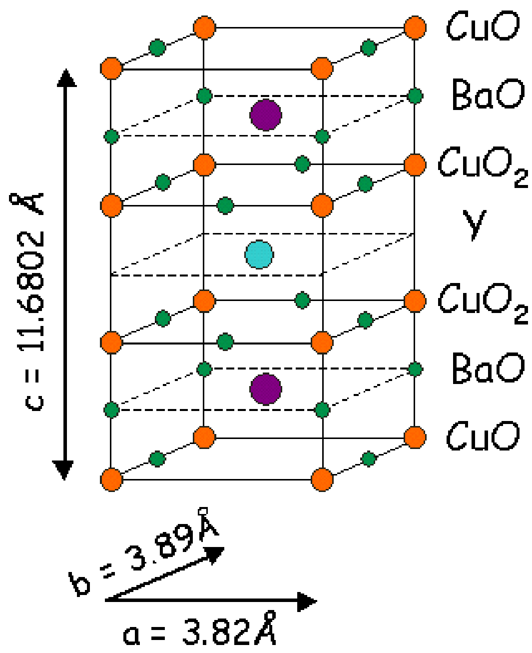
• $La_{2-x}Ba_xCuO4$ (~35K), J.G. Bednortz and K.A. Muller, 1986

• 합금이나 금속간 화합물이 아닌 산화물(세라믹)

• 초전도를 나타내는 CuO 평면과 전하 공급 역할을 하는 층; 이방성

• CuO평면의 수에 따라 임계온도 증가




# 고온 초전도체의 장 단점

- 높은 임계온도로 냉각에 유리
- 냉매를 이용한 냉각; 증발열 LHe 21 J/g, LN2 199 J/g
- 냉매의 가격
- 질소는 대기의 ~80%, 헬륨은 우주에서 두 번째로 많은 원소 (24% mass),
- 그러나 지구에서는… (5 ppmv in air, cf. $CO_2$~390 ppmv)
- 냉동기를 이용한 냉각도 유리

$$\eta_{Carnot} = \frac{T_C}{T_H - T_C}$$ 1.4%(4.2 K), 34.5%(77 K)

## Air Products Announces North America Price Increase for Liquid and Bulk Helium Gases

**December 15, 2011**
Effective January 1, 2012, or as contracts permit, Air Products (NYSE: APD) will be implementing a price increase for liquid and bulk helium gases in North America. Specific adjustments are being communicated directly to customers.

**Press Contact**
Art George
(610) 481-1340

- 그러나 세라믹이라 기계적 성질 취약, Grain Boundary 특성에 크게 좌우됨

**Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure**

M. K. Wu, J. R. Ashburn, and C. J. Torng
*Department of Physics, University of Alabama, Huntsville, Alabama 35899*

and

P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu[(a)]
*Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004*
(Received 6 February 1987; Revised manuscript received 18 February 1987)

A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field $H_{c2}(0)$ between 80 and 180 T was obtained.

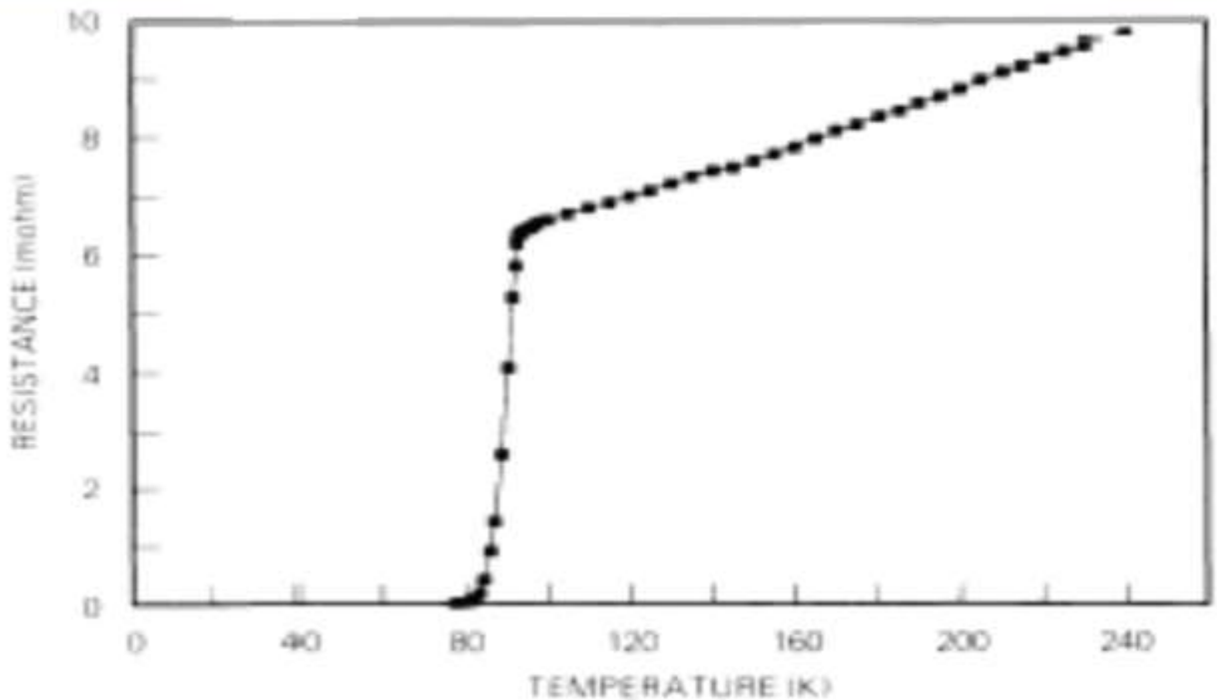
PACS numbers: 74.70.Ya

# Discovery of Tc > 77K SC

**$LN_2$**

- **1/100 price of LHe**
- **20 times higher cooling power than Lhe**

- **Possibilities of large scale applications like cable, fault current limiter, motor, generator, MagLev, etc.**

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# The APS March Meeting of 1987
# The "Woodstock of Physics" in New York City, March 18-19

The significance of this meeting was to announce the development of new, high-temperature superconducting materials. The chief topic at this meeting was a session devoted to the discovery of cuprate superconductors. Papers were given, starting at 7:30pm and lasting until 3:15am.

**Prof. Paul C.W. Chu claimed a transition temperature of 93 K in a yttrium-barium-copper oxide (YBCO) compound.**

On the night of the session, 1800 scientists poured into a room meant for 1100. Outside the room 2000 more watched on television monitors.


Michael Schluter, Malcolm Beasley (Stanford), Morrel Cohen (Chicago), Philip Anderson (Princeton) Paul Grant (IBM)

A press conference was held on March 19 (next day) to announce the developments.
Karl Alexander Muller, Paul Chu, Shoji Tanaka,

Scientists met the press the day after the sessions. Explaining the new findings to reporters



Courtesy of the Niels Bohr Library & Archives at the American Institute of Physics

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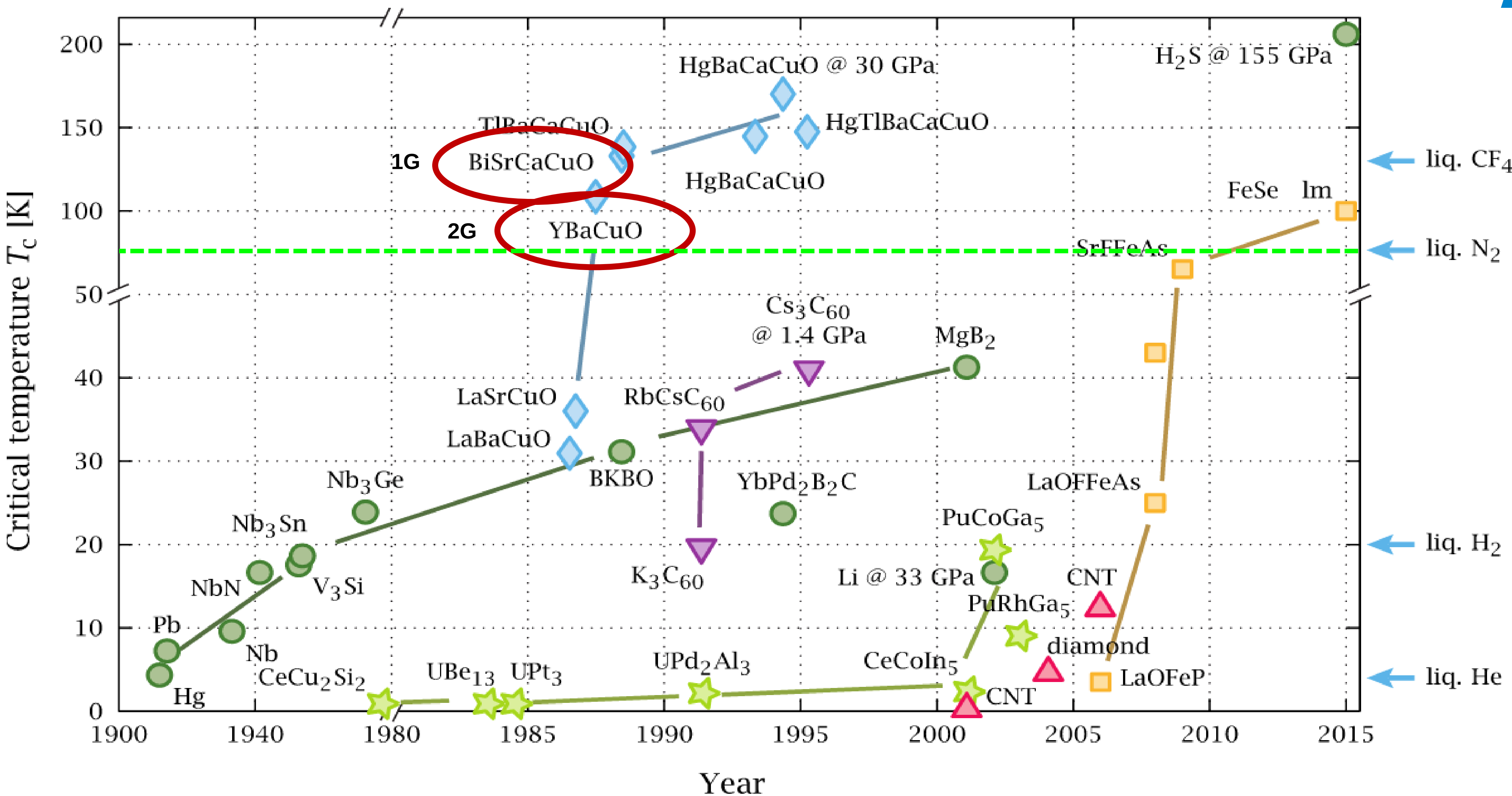
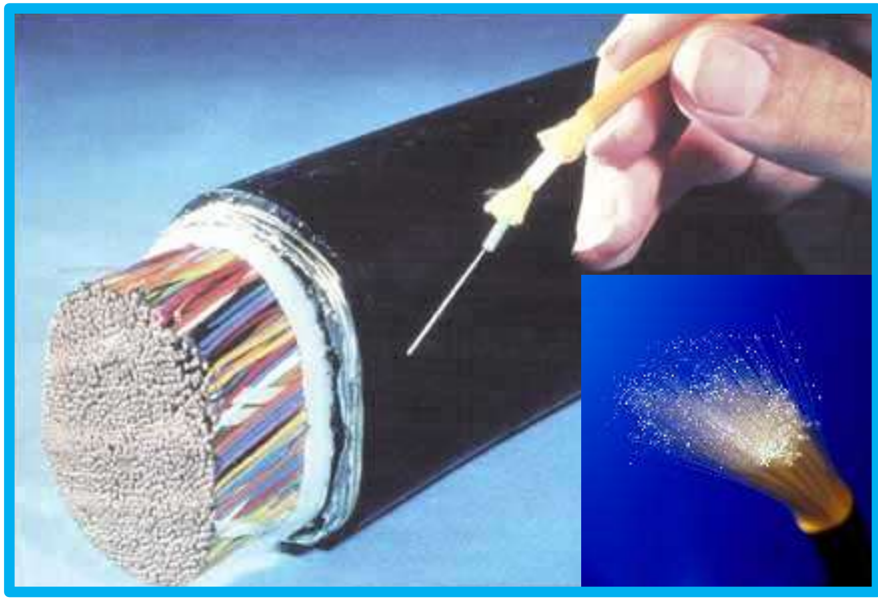
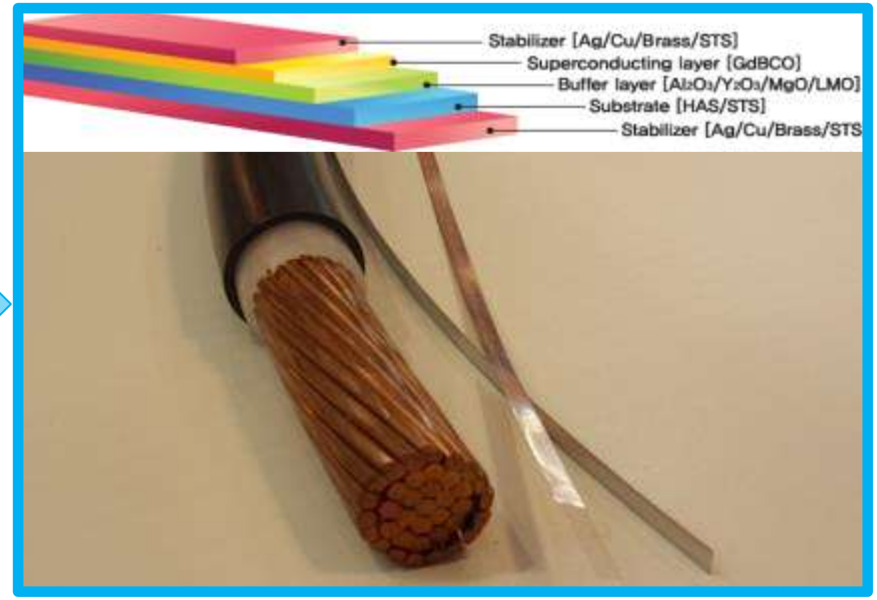
# Timeline of Superconductivity from 1900 to 2015




https://en.wikipedia.org/wiki/Superconductivity

# Paradigm change in Electrical Power Industry






**In communication(or IT) industry,**

Cu wire vs. Optical fiber

**In electrical power industry,**

Cu wire vs. HTS 2G wire

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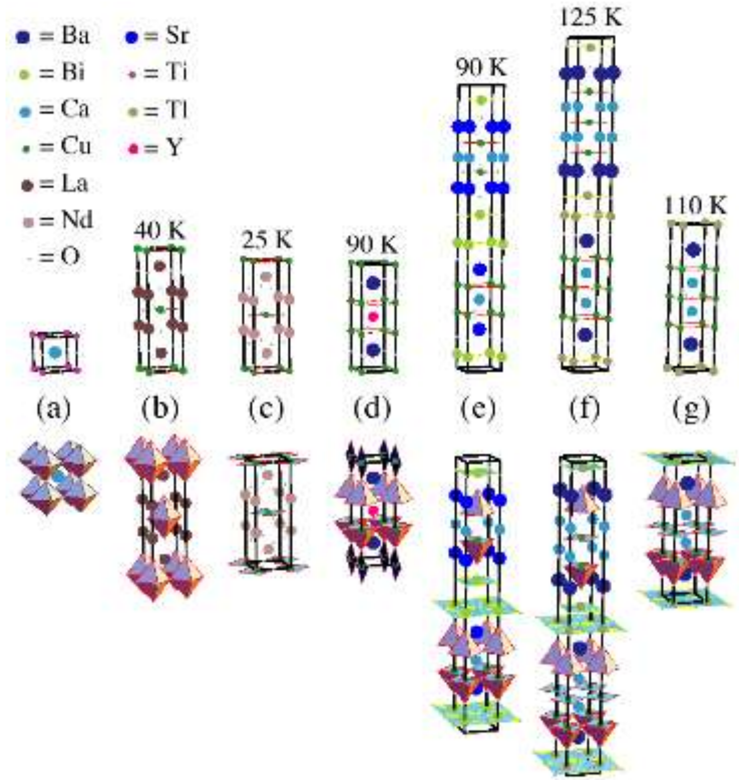
# Oxide High Temperature Superconductors

- (La,Sr)2CuO4 (40 K), 1987
- YBa2Cu3O7-δ (92 K), REBa2Cu3O7-δ (90-96 K), 1987, $T_C$ > 77 K!
- Bi-Sr-Ca-Cu-O system (Bi-2212 (85 K), Bi-2223 (110 K)), 1988
- Tl-Ca-Ba-Cu-O system (Ti-2223: 125 K), 1988
- Hg-Ca-Ba-Cu-O system (Hg-2223, 135 K), 1994

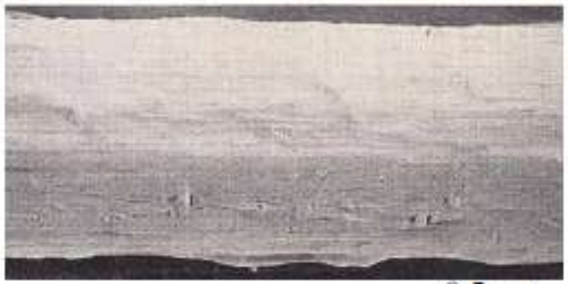



(a) $CaTiO_3$ , (b) $(La,Sr)_2CuO_4$ ,
(c) $(Nd,Ce)_2CuO_4$ ,
(d) $YBa_2Cu_3O_{7-\delta}$ ,
(e) $Bi_2Sr_2CaCu_2O_8$ ,
(f) $Tl_2Ba_2Ca_2Cu_3O_{10}$ , and
(g) $TlBa_2Ca_2Cu_3O_9$ .

# The First HTS Wires (1987) -Before Discovery of BSCCO -

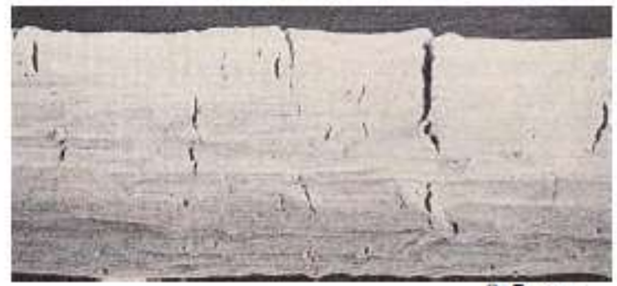
*Tetragonal to orthorhombic phase transition: decrease of c-axis lattice parameter ⇒ crack generation*

***Before heat treatment***

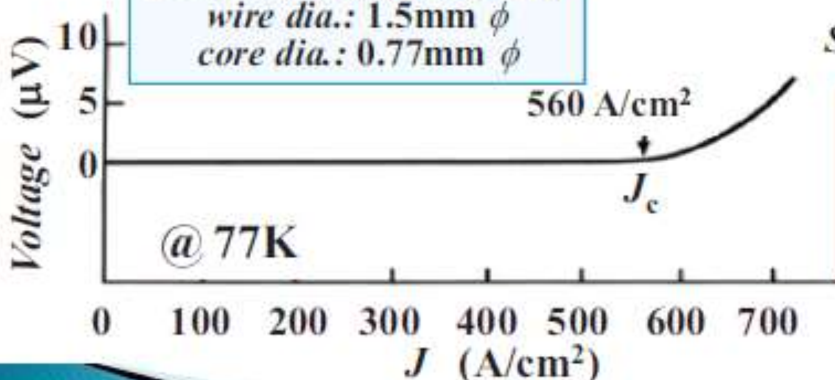


0.5mm

***After heat treatment***



0.5mm




*Powder in Tube (PIT)*: $Y_2O_3$ $BaO$ $CuO$

*Sintering*: @900-1000 ºC, $O_2$ *Annealing*: @400 ºC

*YBCO* : 4.1x10 $^3$A/cm$^2$ (@77K,s.f.)

*BSCCO*: 3.5 x 10 $^4$A/cm$^2$ (@77K,s.f.)

*TBCCO*: 1.0 x 10 $^4$A/cm$^2$ (@77K,s.f.)



Fujikura
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# Science : 26 May (1989)p. 914-916

## Superconductivity: Is the Party Over ?

*Recent findings about high-temperature superconductors have revealed a possibility insurmountable obstacles to many of the hoped-for applications*

➢ *no super-efficient power transmission, for example, and no low cost levitated trains. Further, the problems with the lattice seem to have put the Holy Grail of useful room-temperature superconductivity forever out of reach, barring the discovery of an entirely new type of superconductor.*

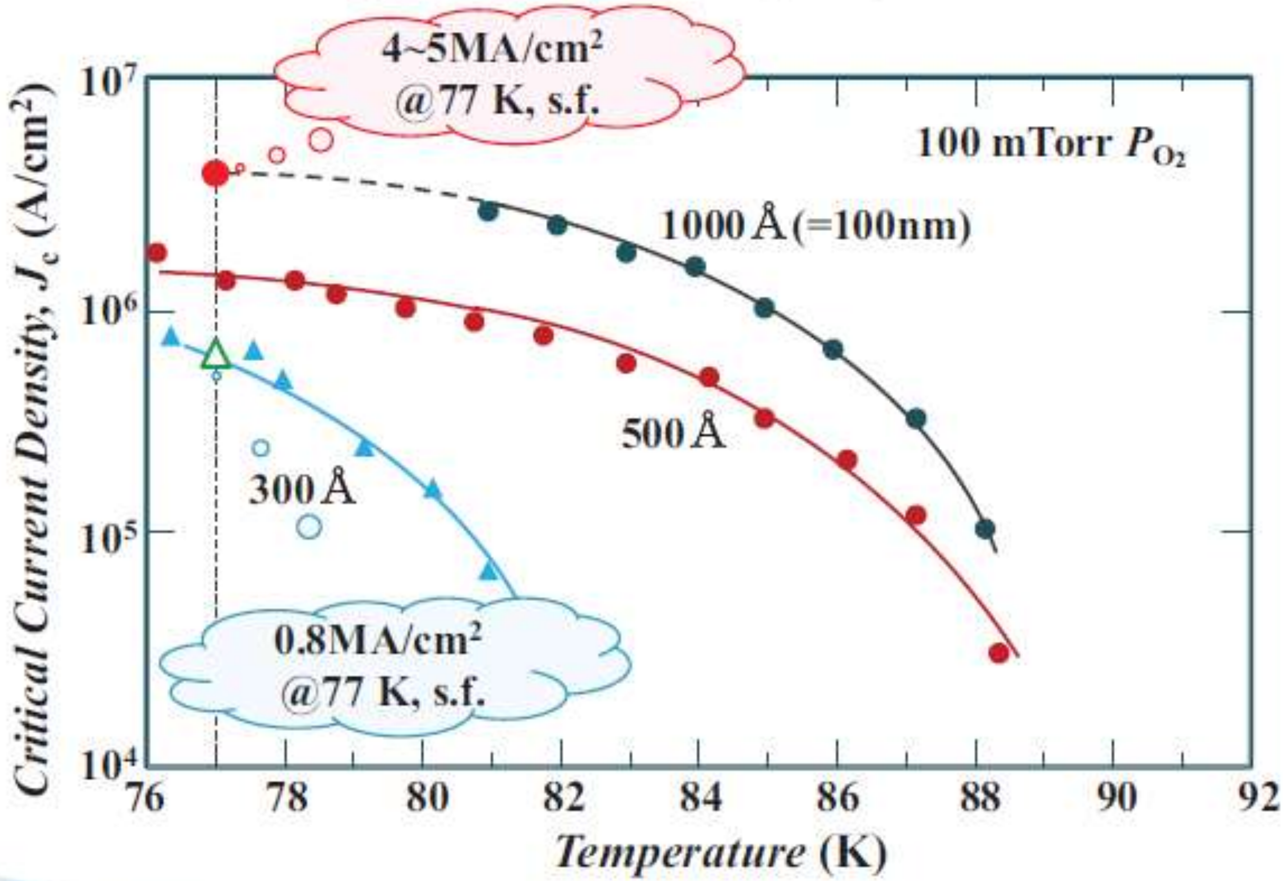
The New York Times *June 06, 1989*

## Superconductors showing a flaw that dims hope

*Recent discoveries have dimmed hopes that a new class of superconductors will ever find wide use, despite predictions two years ago that they could bring vast economic benefits. New findings by AT&T Bell Laboratories, I.B.M.'s Thomas J. Watson Research Center and other research groups say that the substances, which conduct electricity with no loss to resistance, may be inherently incapable of carrying enough current to be very useful. And all of them cease to be superconductive when they are exposed to the large magnetic fields required for or created in most large-scale applications, including energy-storage systems, power-line transformers and medical imaging equipment. Wary of Short-Term Projects*

# $J_c$ vs Temperature for Different YBCO Film Thicknesses Deposited on (100)$SrTiO_3$ by PLD (1989)

*World First Success of HTS Thin Film Deposition by PLD on Oxide Single Crystal by T. Venkatesan et al.* (1989)






*T. Venkatesan, X.D.Wu et al.: Appl. Phys. Lett., Vol. 54, No.6, 6 February (1989), P.581~583*

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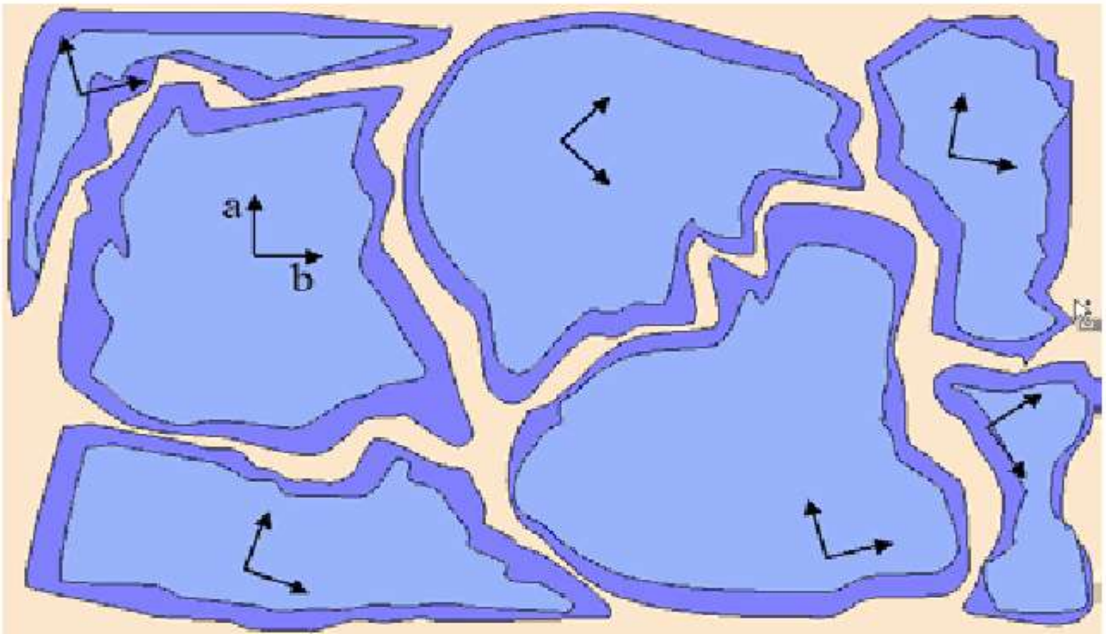
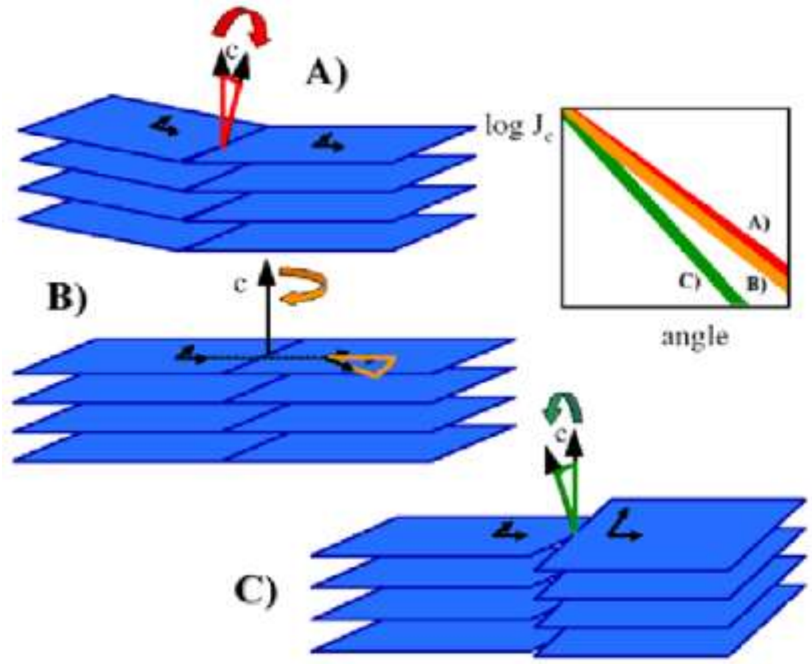
# Why texture matters? (Schematics of the HTS microstructure)




- Differently oriented single crystal grains are separated by regions filled with secondary phases. In addition, oxygen depletion may occur at grain boundaries.

- Different Basic GB geometries and $J_c$ reduction $J_c \sim e^{-\alpha/\alpha_0}$ ($\alpha$ : misalignment angle )

  $\alpha_0 \sim 5^o$, for A) and B),

  $\alpha_0 \sim 3^o$, for C).

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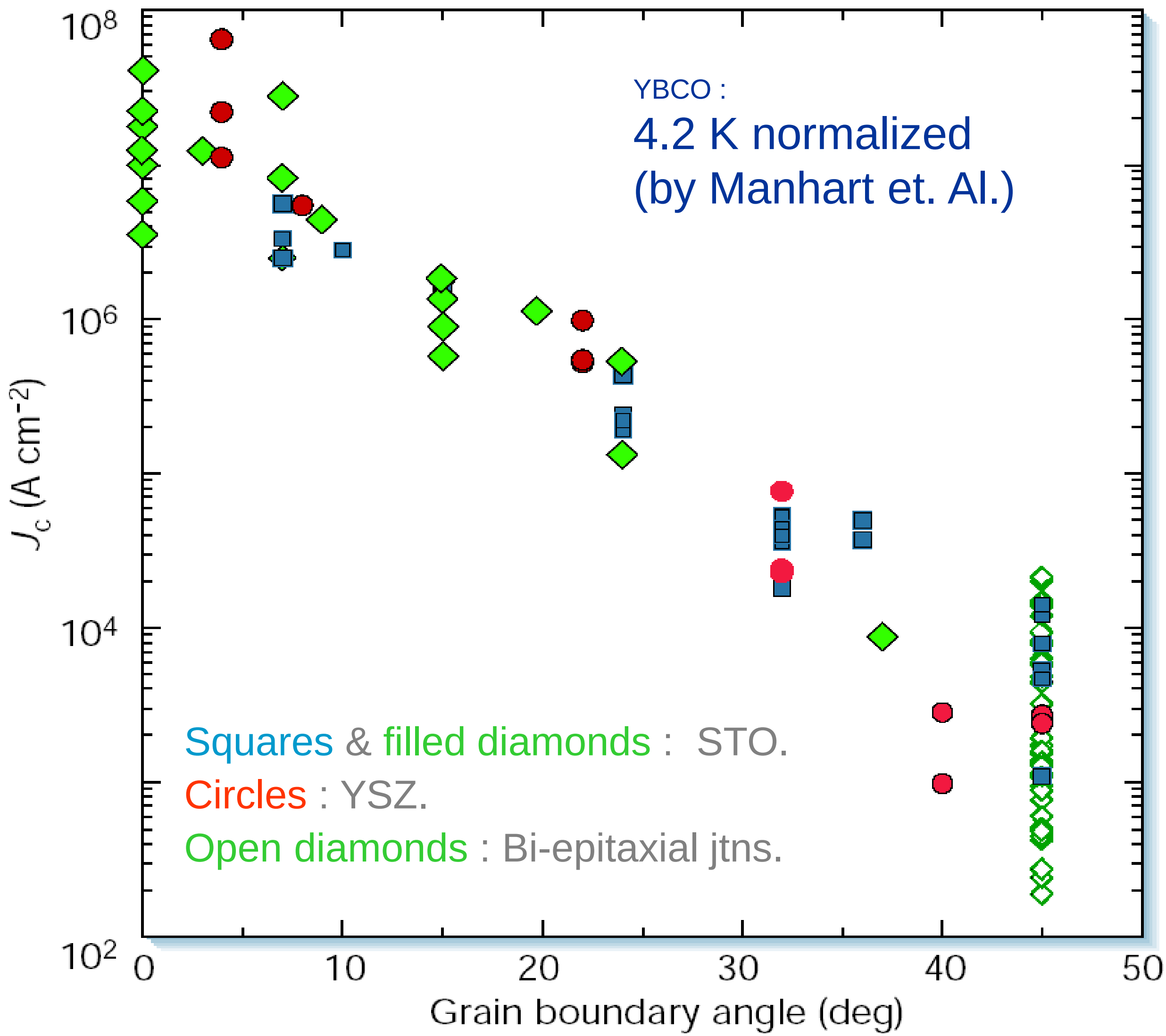
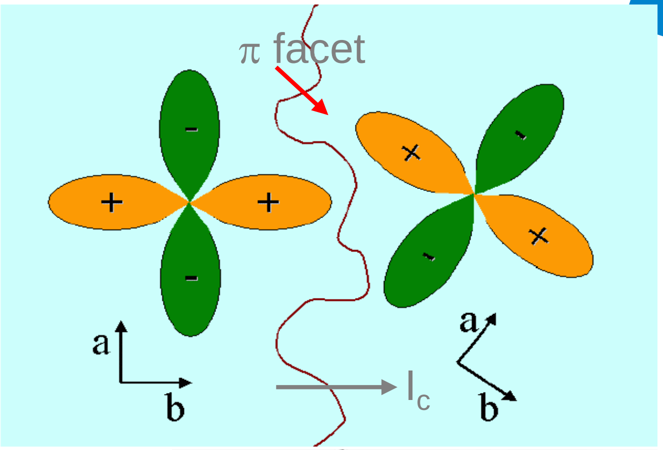
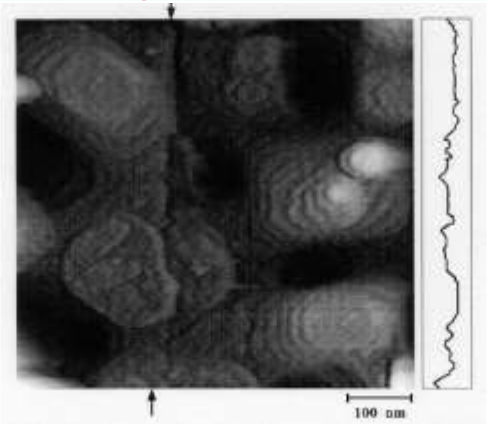
# $J_c$ vs (001) tilt GB angle (YBCO)




- Misorientation of the d-wave order parameter : partial cancellation of the supercurrents.

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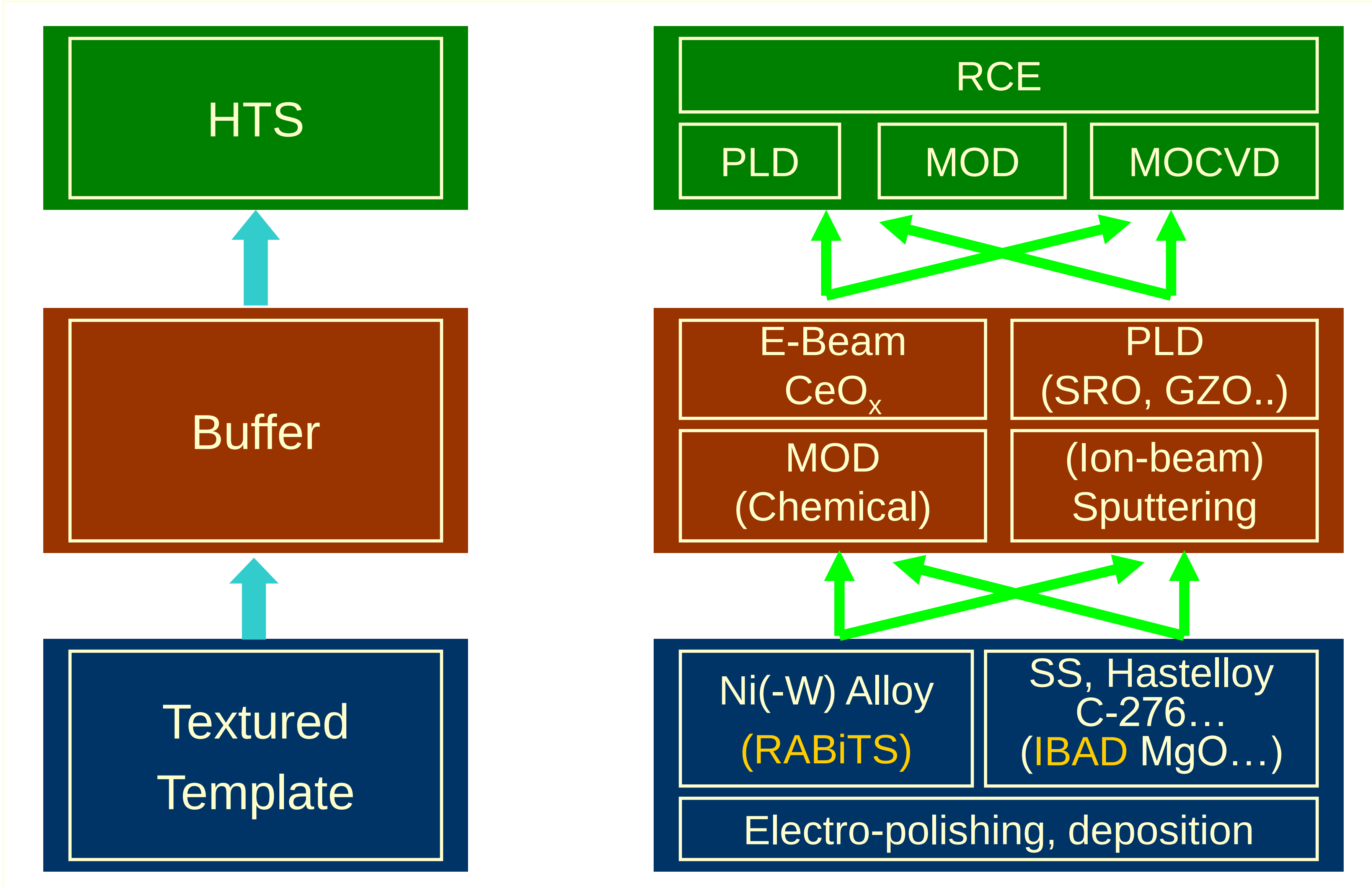
# Various routes reach at HTS 2G wire

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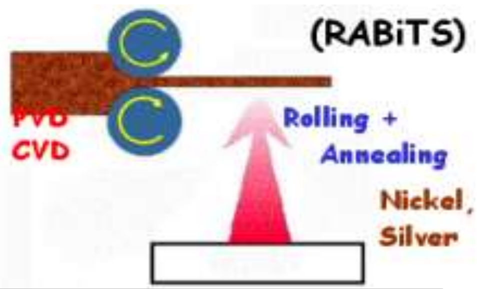
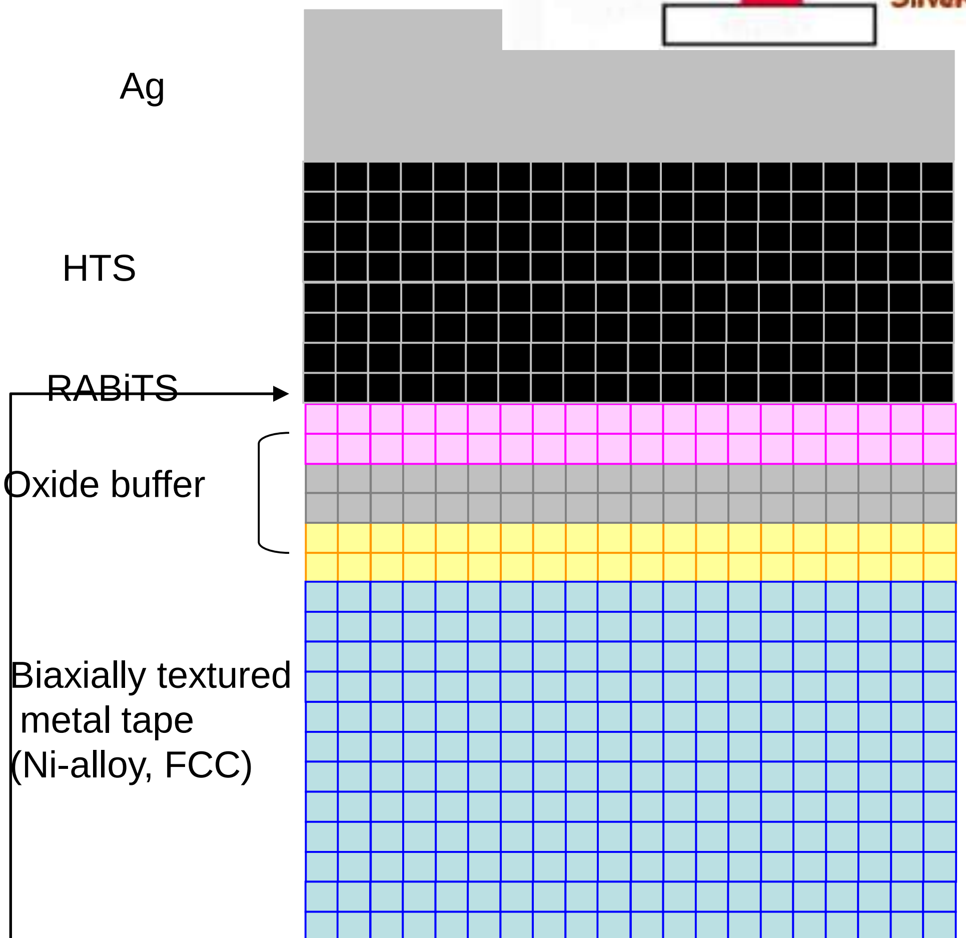
# HTS 2G Wire : RABiTS™ vs. IBAD

## RABiTS™

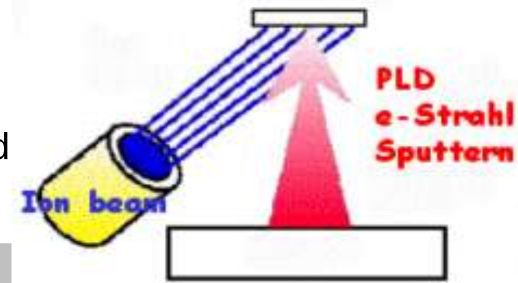
(Rolling Assisted Biaxially Textured Substrate)

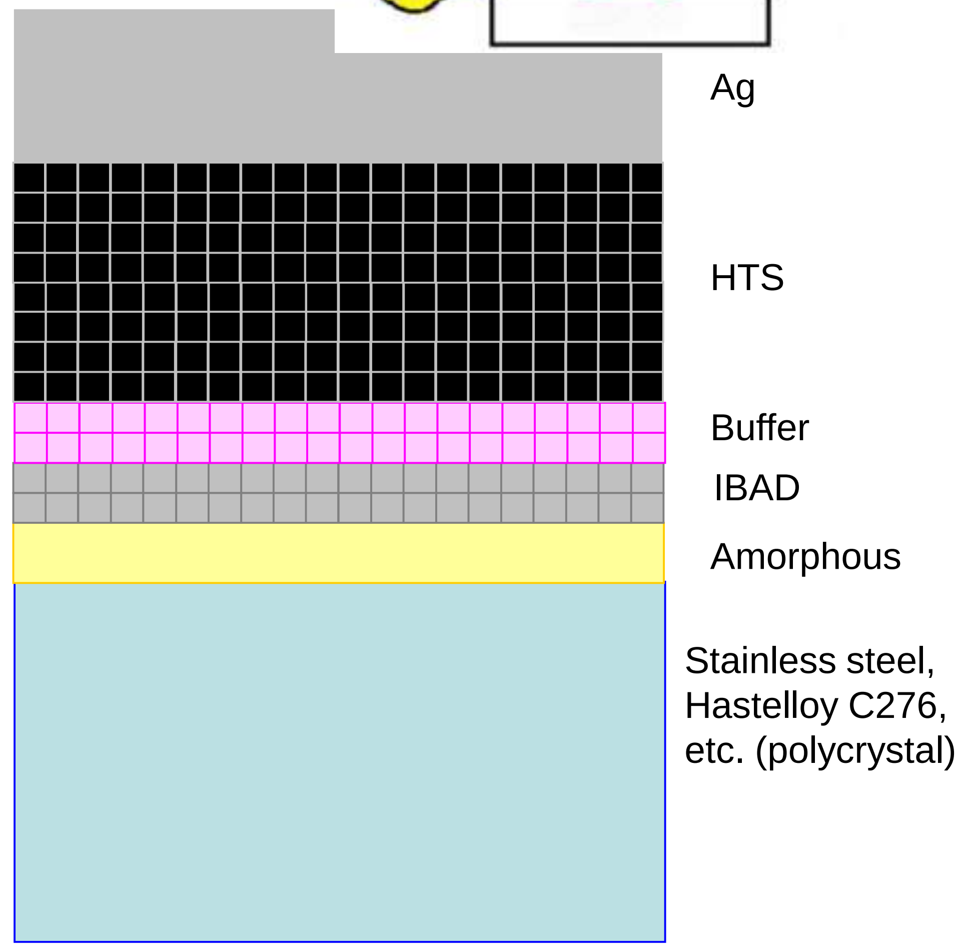



## IBAD

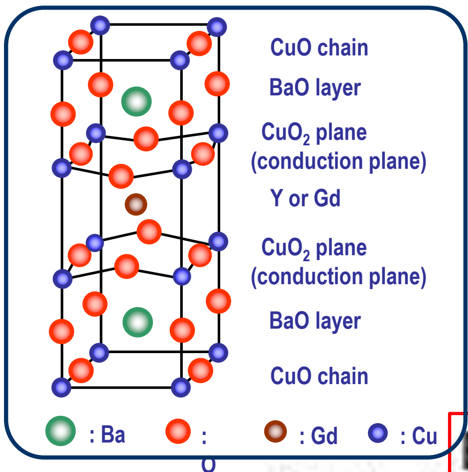
(Ion Beam Assisted Deposition)

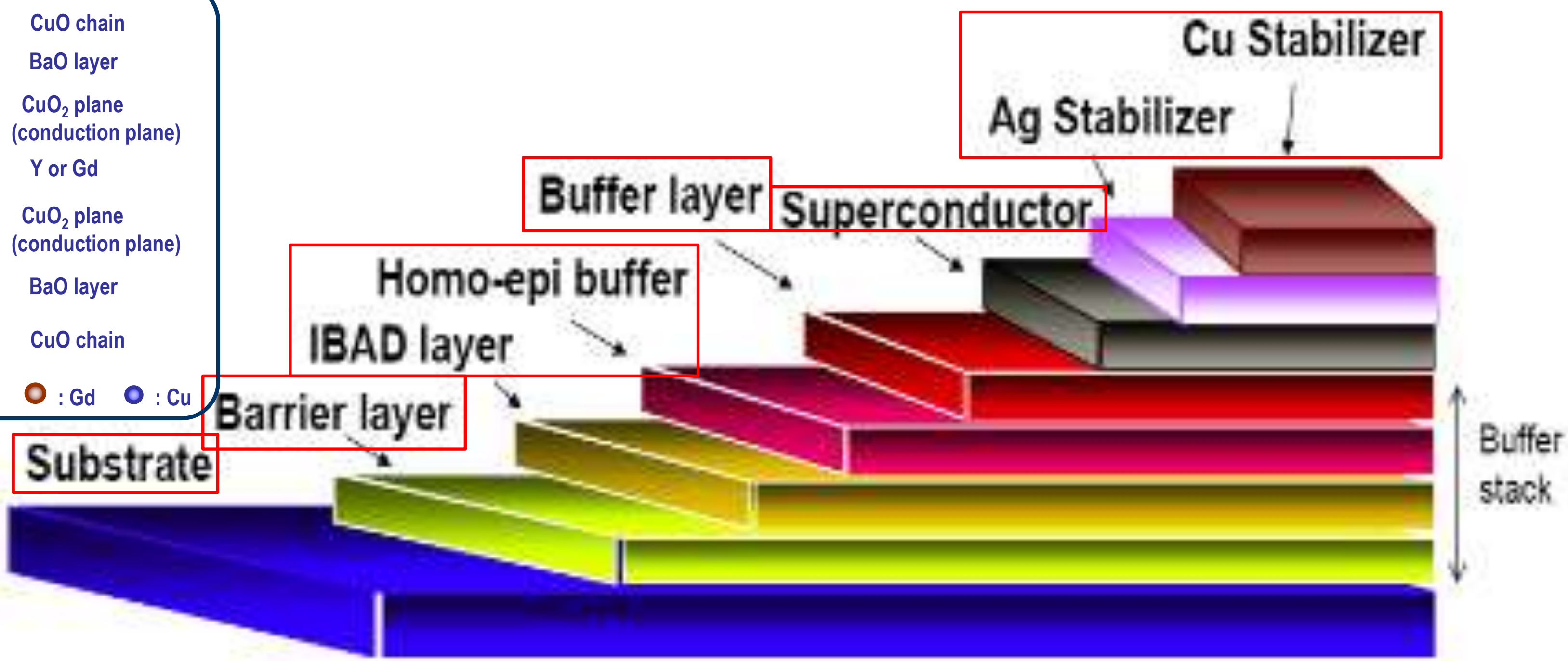


# Coated Conductor ($2^{nd}$ G. Wire)

- 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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# 25 Years of Coated Conductors

- Yasuhiro Iijima at Fujikura, 1991
- Typically takes 20 years to bring new materials to marketplace

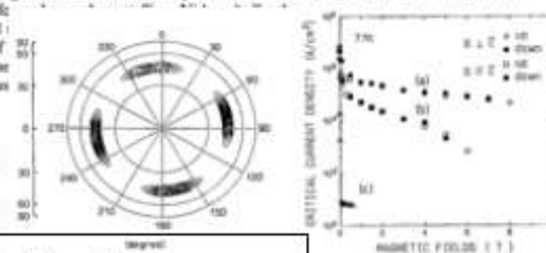
**In-plane aligned $YBa_2Cu_3O_{7-x}$ thin films deposited on polycrystalline metallic substrates**

Y. Iijima, N. Tanabe, O. Kohno, and Y. Ikeno
*Materials Research Laboratory, Fujikura Ltd., 1-5-1, Kiba, Koto-ku, Tokyo 135, Japan*

(Received 11 September 1991; accepted for publication 25 November 1991)

C-axis oriented $YBa_2Cu_3O_{7-x}$ thin films are conventionally obtained on polycrystalline substrates, but a- and b-axes are randomly distributed. Due to the weak links at the high-

Y. Iijima et al Physica C 185-189, 1959 (1991)



First CC

ORNL RABiTS

IBAD-MgO Stanford

LANL first 1 meter CC

AMSC first commercial CC

SuperPower 10km to Sumitomo

Cable, FCL, Magnet Projects

6 Companies producing CC

1991 — 1996 — 2001 — 2006 — 2011 — 2016



Vladimir Matias
iBeam Materials, Inc.
Santa Fe, NM

Robert H. Hammond
Stanford University
Stanford, CA

# Applications & markets using HTS 2G Wire (Coated Conductor).

# Applications of Superconductivity


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

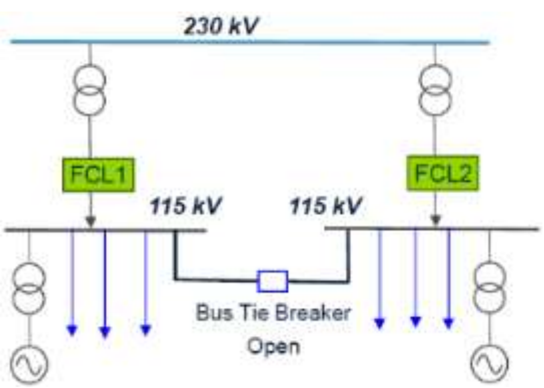
SUNAM

# 1st Commercial Transmission class SFCL x2 by AMAT …

Ref. JOINT TNC CIGRE & IEEE PES SEMINAR ON Understanding Superconducting Fault Current Limiters : Design and Application at PEA BKK, Sep. 29, 2015

Albert Nelson, "Fault Current Limiters - Unlocking Capacity in Fault Constrained Electrical Networks", Webinar broadcast via on24.com, July 11, 2017


| FCL Rating | |
|---|---|
| System Voltage, $V_s$ | 115 kV |
| Maximum Load Current, $I_L$ | 550 A |
| Prospective Fault Current, $I_p$ | 5 kA |
| Limited Fault Current, $I_{lim}$ | 2.5 kA |
| Current Reduction | 50 % |
| Shunt Reactor Impedance | 15 Ω |
| Voltage Drop Across FC | 37.5 kV |
| BIL | 550 kV |
| AC withstand Voltage | 230 kV |
| RIV at 73 kV | < 1200 μV |




115 KV SFCL - 2 identical units

.

APPLIED MATERIALS®


*** 40 ~ 90 km of CC are needed for 1 unit.**

SuNAM

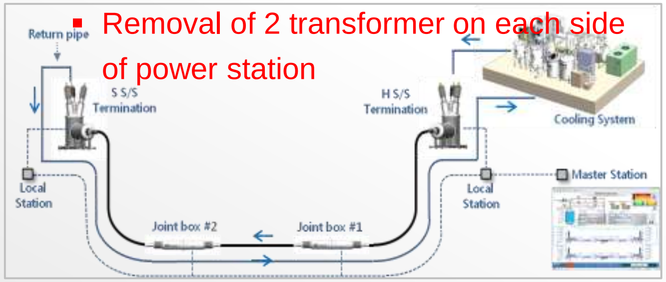
*Confidential*

# World 1st fully commercialized HTS power cable installation

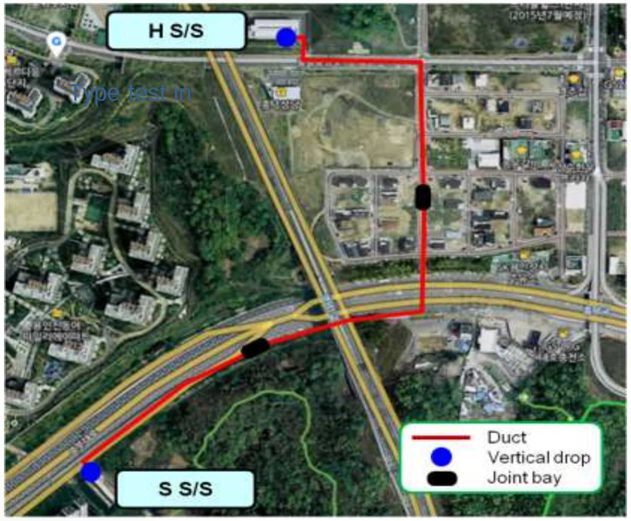
## R&D in advance ▶ Pilot demonstration ▶ **Commercialization**

### *First commercialization*

- Shingal project: 100% funded by KEPCO
  - Project period: Sep., ~ 2019
  - System configuration: AC23kV 50MVA, 1km-cct + 7.5kW @69K Turbo Brayton Cooling system
  - Project cost: USD10M
  - Type test in progress
    - Low voltage connection (154 kV → 23 kV)
    - Removal of 2 transformer on each side of power station




System configuration




Installation Site

(Director General
Dr. Y. J. Won)

KEPCO

- ~ 150 km of CC are needed for 1 km, 23 kV/50 MVA cable.
- ~ 600 km of CC are needed for 1 km, 154 kV/1 GVA cable.

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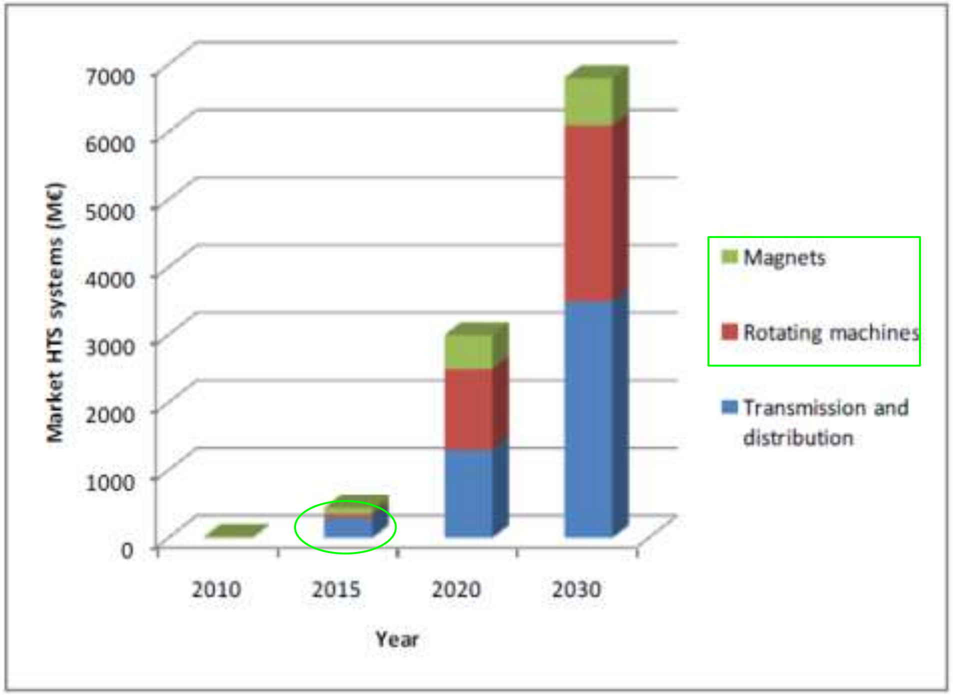
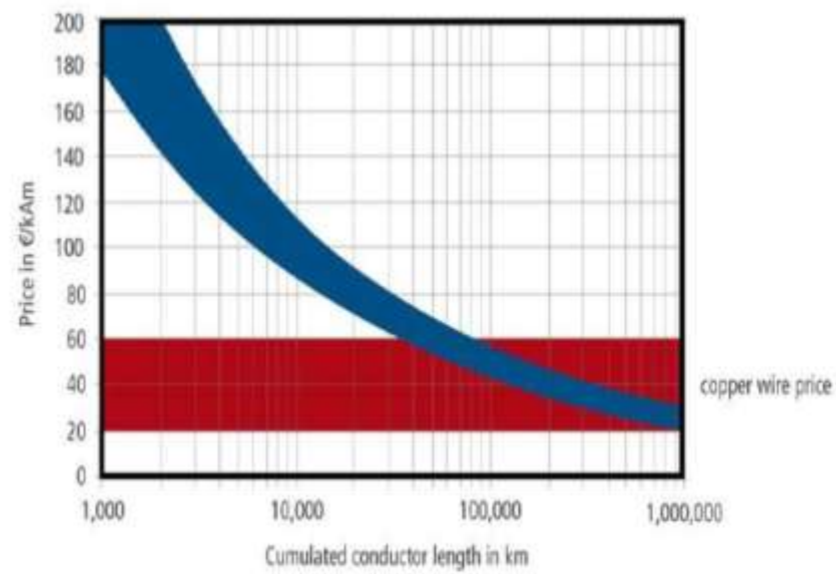
# CC's: expected market growth and cost decrease




Estimated world market evolution of SC systems

Throughput and performance are key to reduce cost/kAm: capital investment depreciation and total current




Estimated cost decrease of CC's with cumulated production: operating condition is the real metric

~ 6.5 bn € by 2030 (1.3 bn € in wires)

~ 1.500.000 km/year by 2030 (x 1000 present production)

# Merits of RCE(Reactive Co-Evaporation)

- Throughput : Important for availability & cost!!

## Throughput is the key

**Equipment cost share = capital investment / throughput**

**Key to lowering cost**

**Throughput ≡ volume production rate**

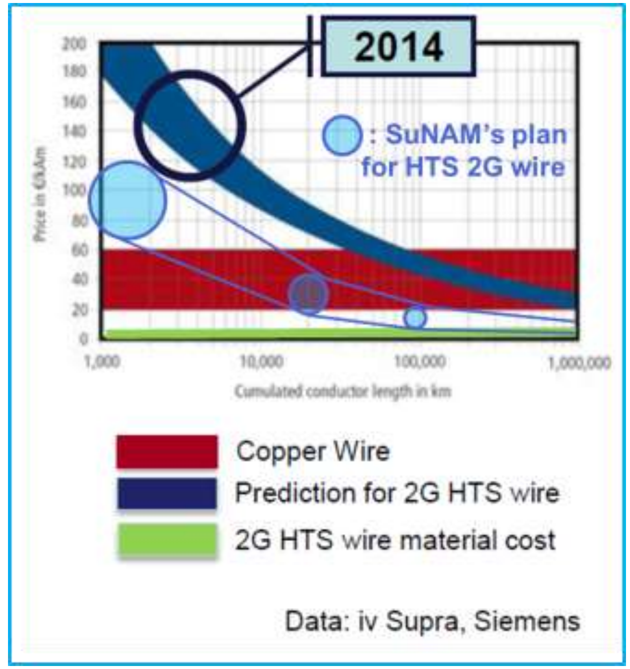
**P = A × R = L × W × R ≡ v × W × D**

- A: processing area
- R: thickness growth rate ⇓ physically limited (material property)
- L: tape length
- W: tape width
- v: tape speed
- D: film thickness

THEVA creating the future


**Wide web process !**

Depend on Process (liquid flux)




- RCE-DR : ~ 100 nm/sec or faster (SuNAM)
- RCE-DR : easy to scale-uo to wide strip.

- **3 Companies(SuNAM, Theva, STI) use RCE process !!**

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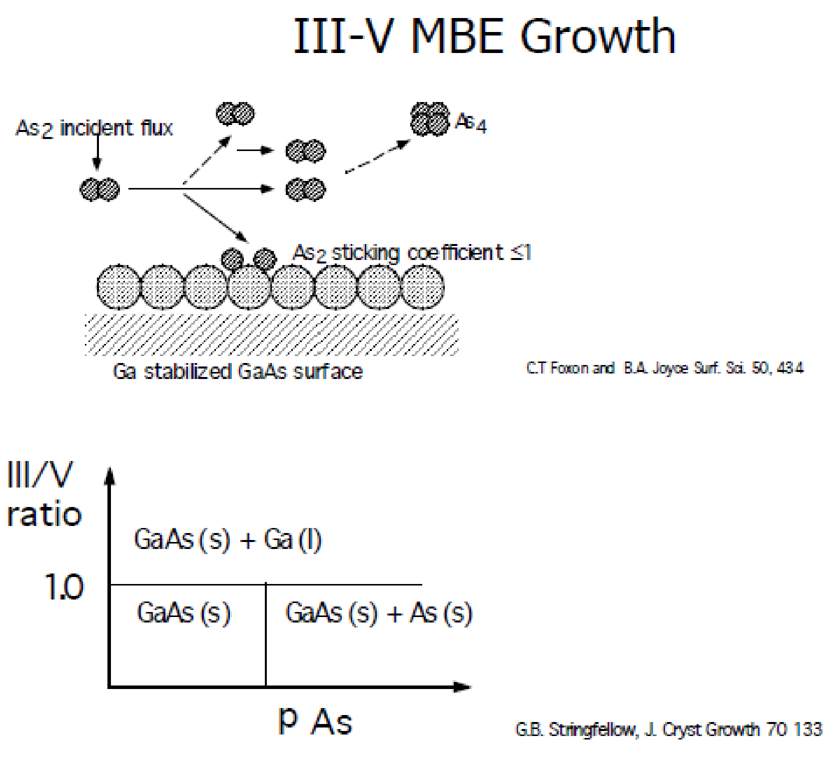
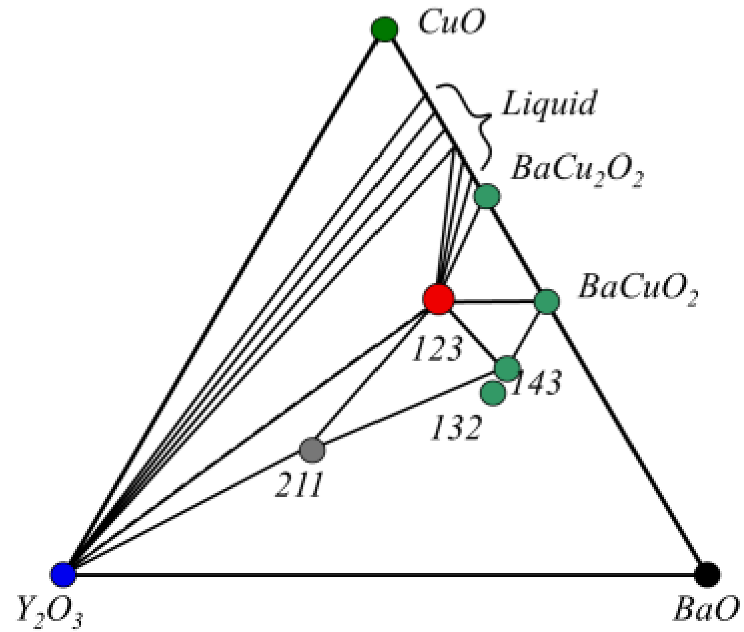
# SuNAM's high rate e-beam process with oxide epitaxy (RCE-DR).

# Difficulties of complex oxide epitaxy




**Importance of**
1. Rate control of each compositions with high rates.
2. Spatial uniformity (beam profiles : $\cos^n(\theta)$).

## Pseudo Phase Diagram of YBaCuO




- $Y + 2Ba + 3Cu + 6O = YBa_2Cu_3O_y + \ldots$
- Requirements : $\Delta G^0 < 0$.
- All the phases have low vapor pressures

→Will always get a mixture of phases.

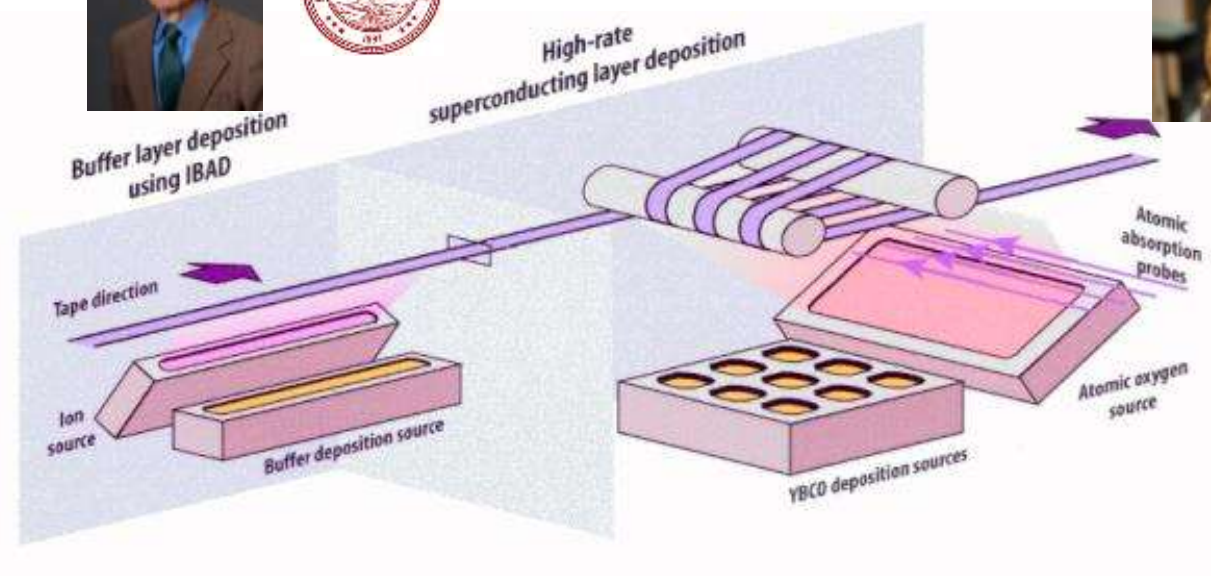
(Amount of second phases will ***depend on composition***)

(Bob Hammond, Vlad Matias)

SUNAM

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

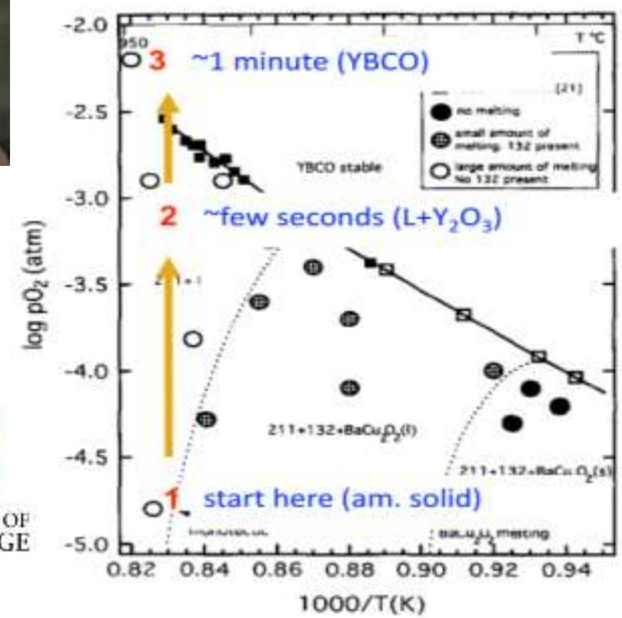
Robert H. Hammond (Stanford Univ.)




Physica C 241 (1995) 401–413

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

UNIVERSITY OF CAMBRIDGE




- **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 ⇒ \$ per year/R(L×W)$J_c$

Study ISS' 95:

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

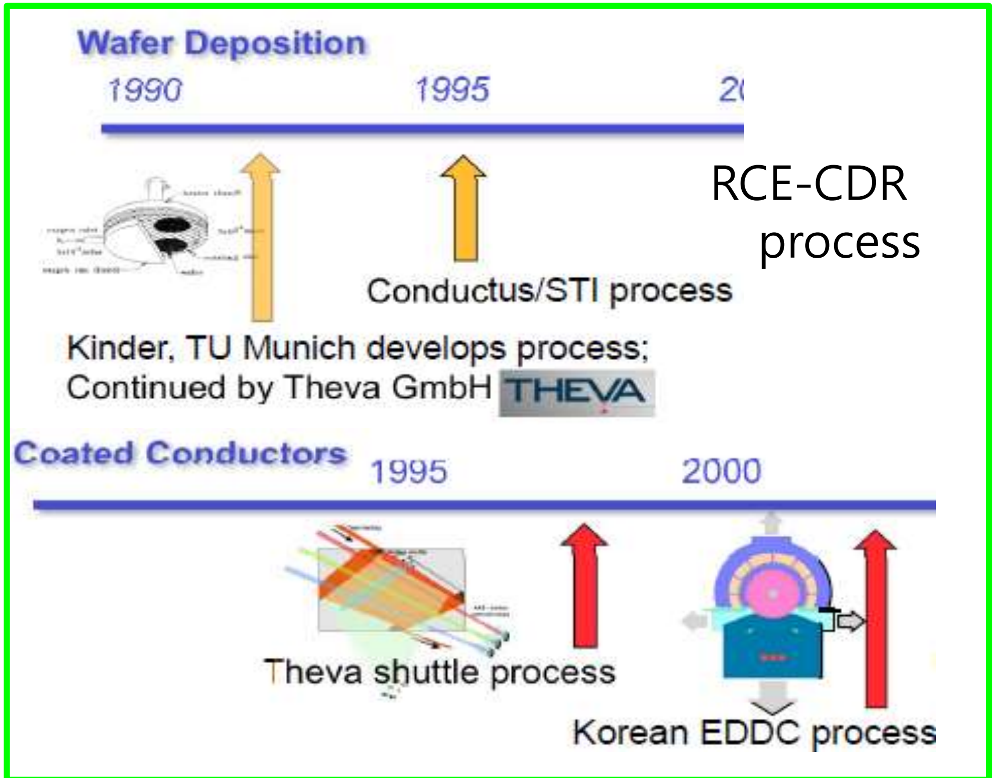
**C/P = \$10 /kA-m @ 6000 km/year**

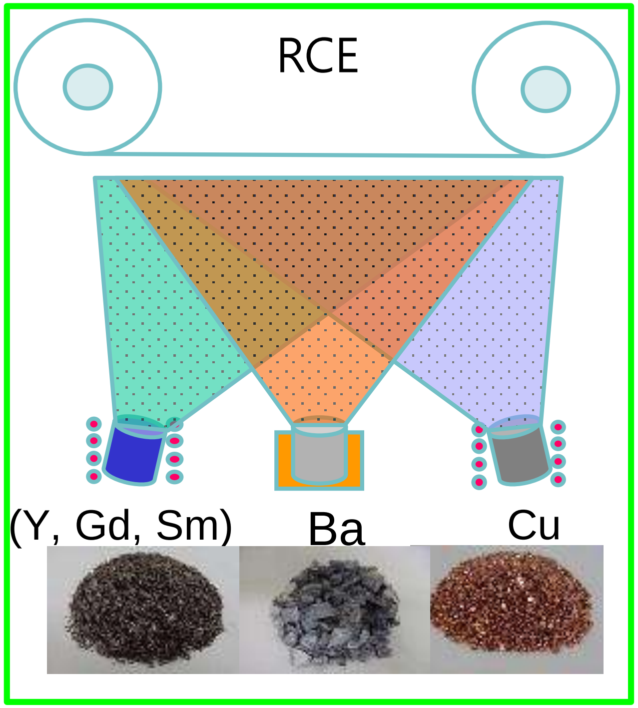
SuNAM

# RCE process

- Reactive Co-Evaporation (RCE) :
  - Using inherently least expensive sources
  - High deposition rate can be used & adjustable composition
  - Especially easy to scalable to large deposition area
  - Very promising methods for HTS wafer production : Theva, STI

Conventional e-beam web coater can produce > 1 M km/year of 4 mm width tape.

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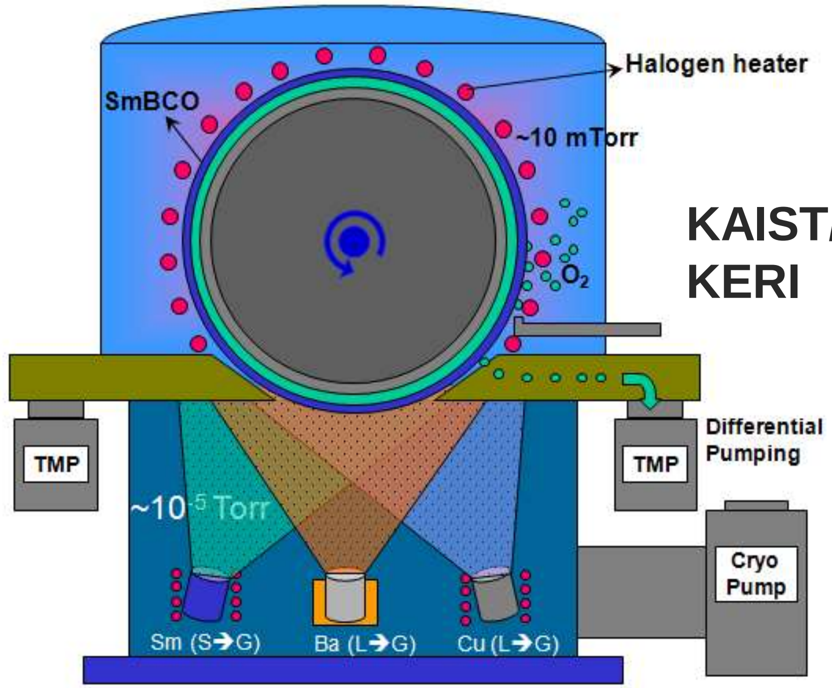
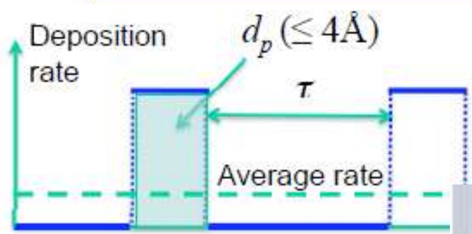
SuNAM develops RCE-DR process.

# Conventional RCE-CDR process

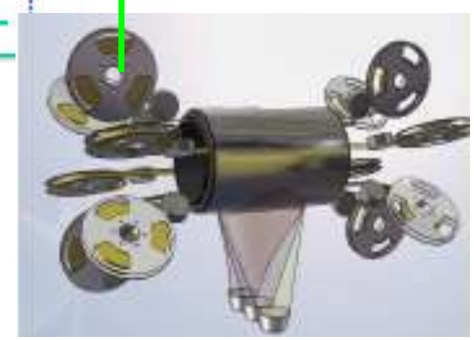
- RCE-CDR : Reactive Co-Evaporation by Cyclic Deposition & Reaction (EDDC(KAIST/ KERI, batch) & LANL/STI, R2R(planned))
- CDR : Co-evaporation at low $O_2$ pressure followed by reaction in high $PO_2$ in cyclic manner.
- Pulsed deposition : low average growth rate.
- High speed(> 100 rpm), high temperature(> 800 °C) mechanically rotated drum is required : complexity, cost, difficult to scale up




KAIST/ KERI




Massive(> 100's of kg on scale-up)

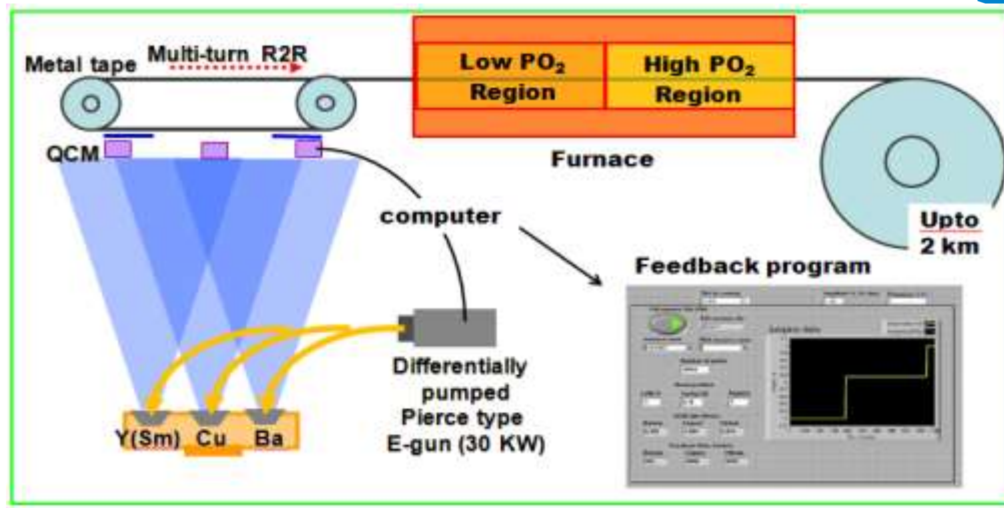


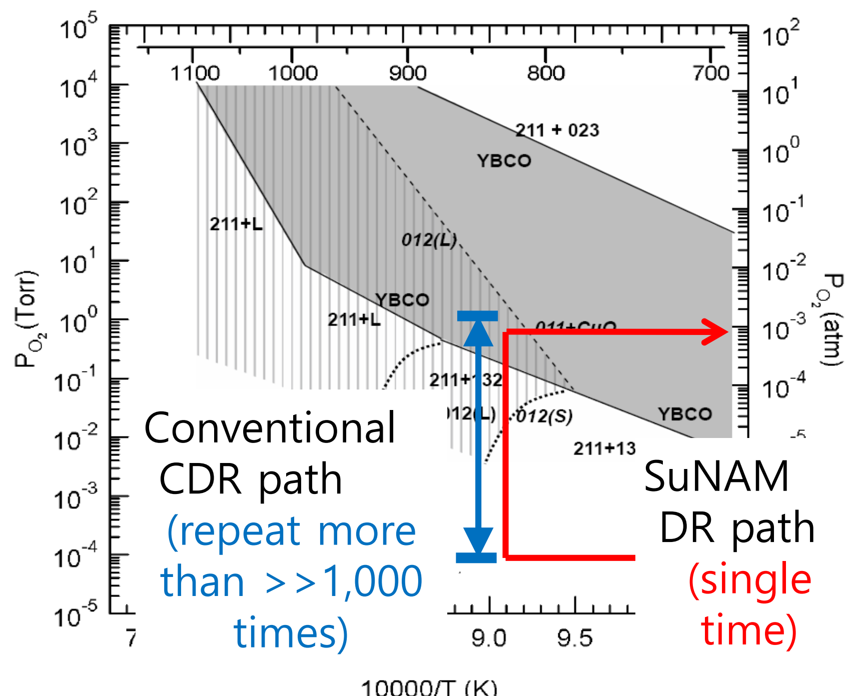
LANL/ STI

SuNAM KERI KAIST

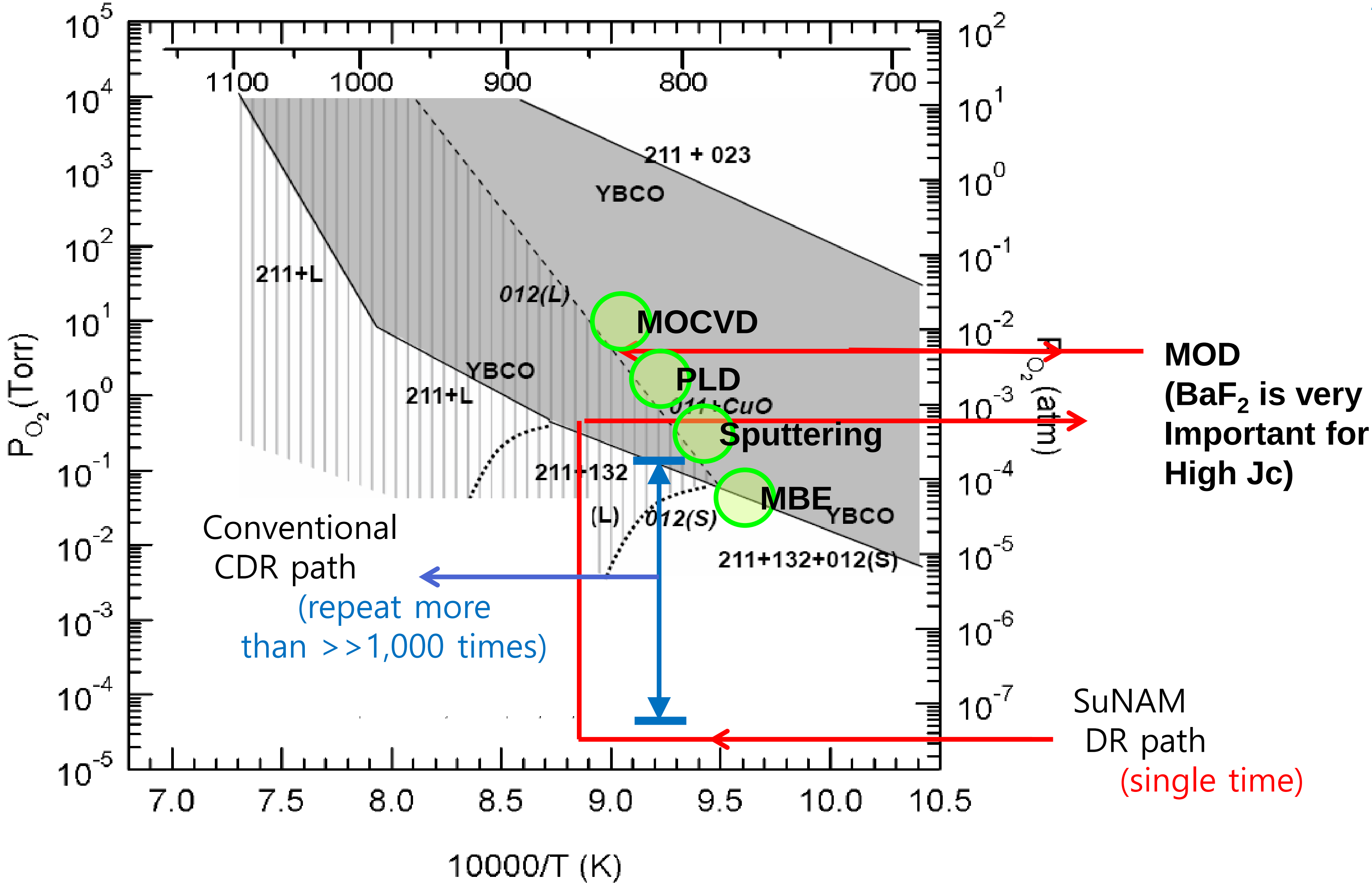
# New SuNAM RCE-DR process

- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R) : Patent pending(PCT)
- High rate co-evaporation at low temperature & pressure to the target thickness(> 1 $\mu$m) 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

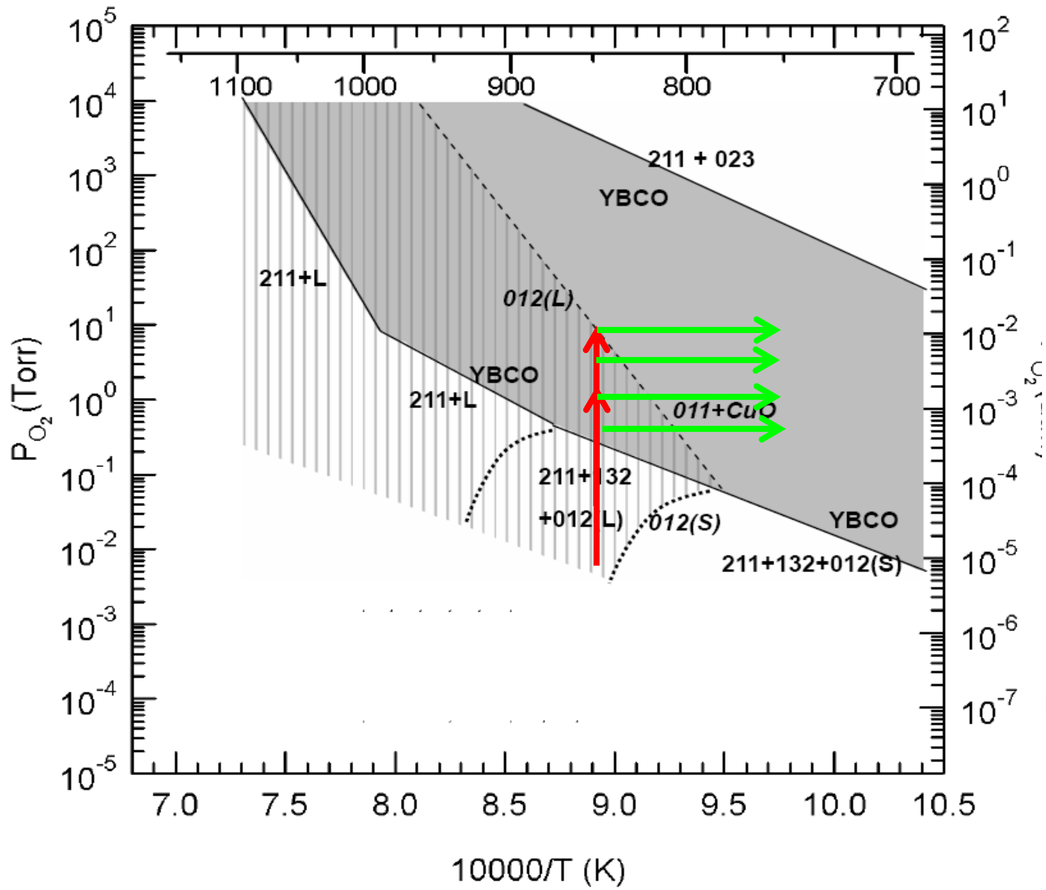


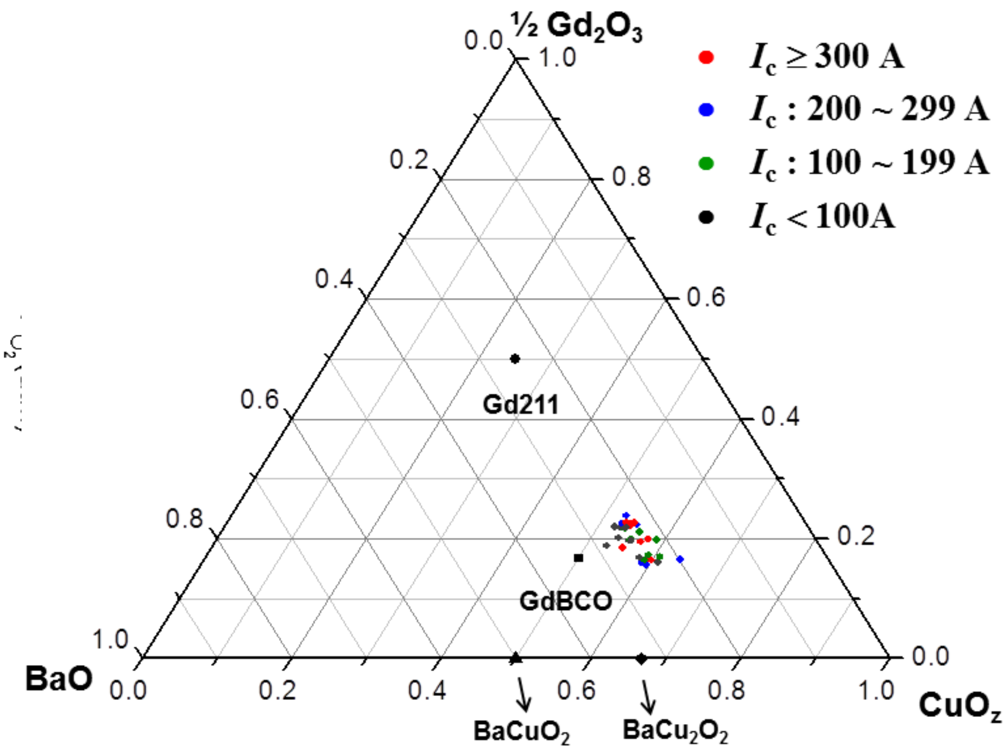



# Comparison of various deposition methods



# RCE – DR Process : Phase Diagram




- **Understanding of phase diagram at low $PO_2$**
- **Liquid phase is very important**

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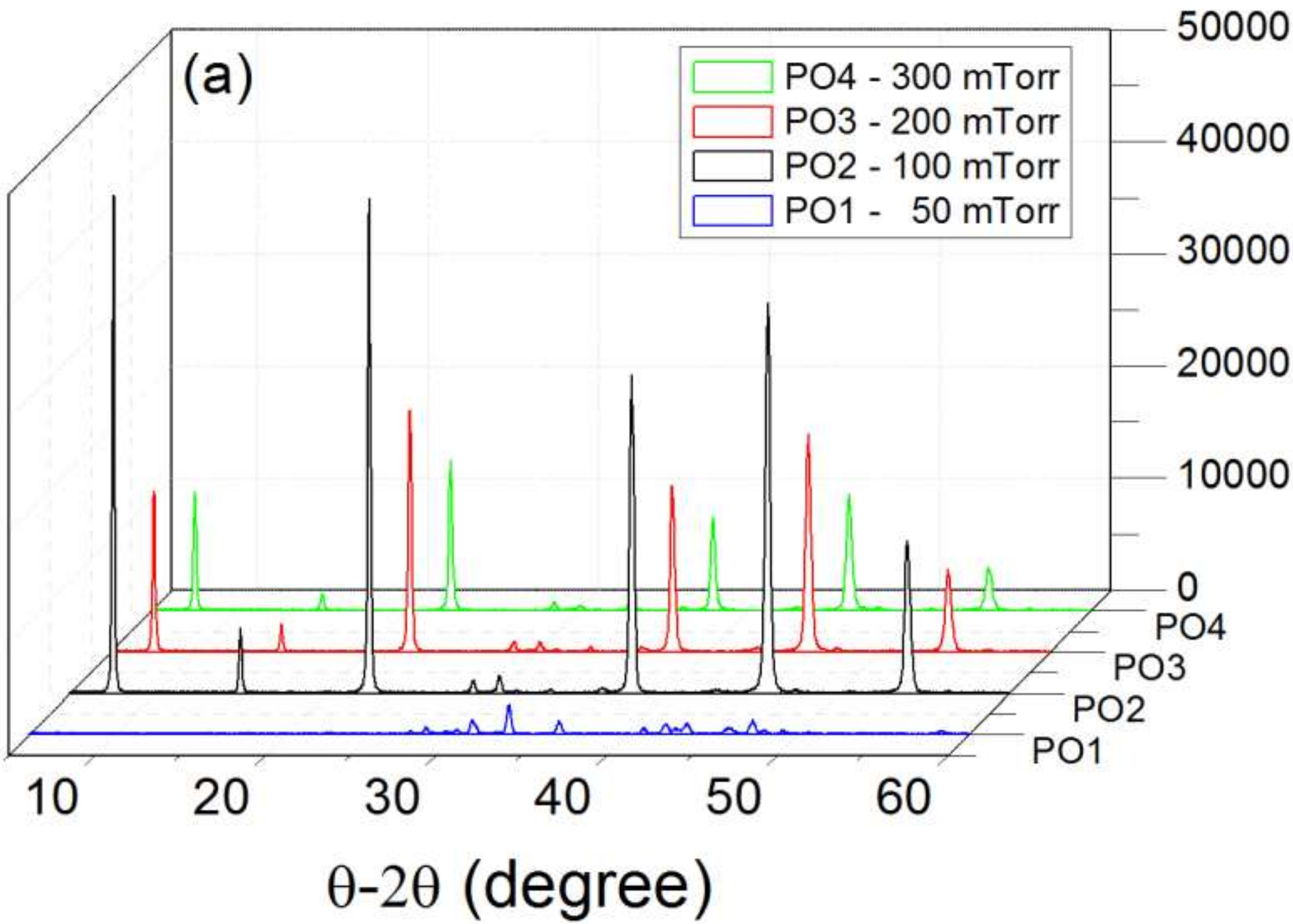
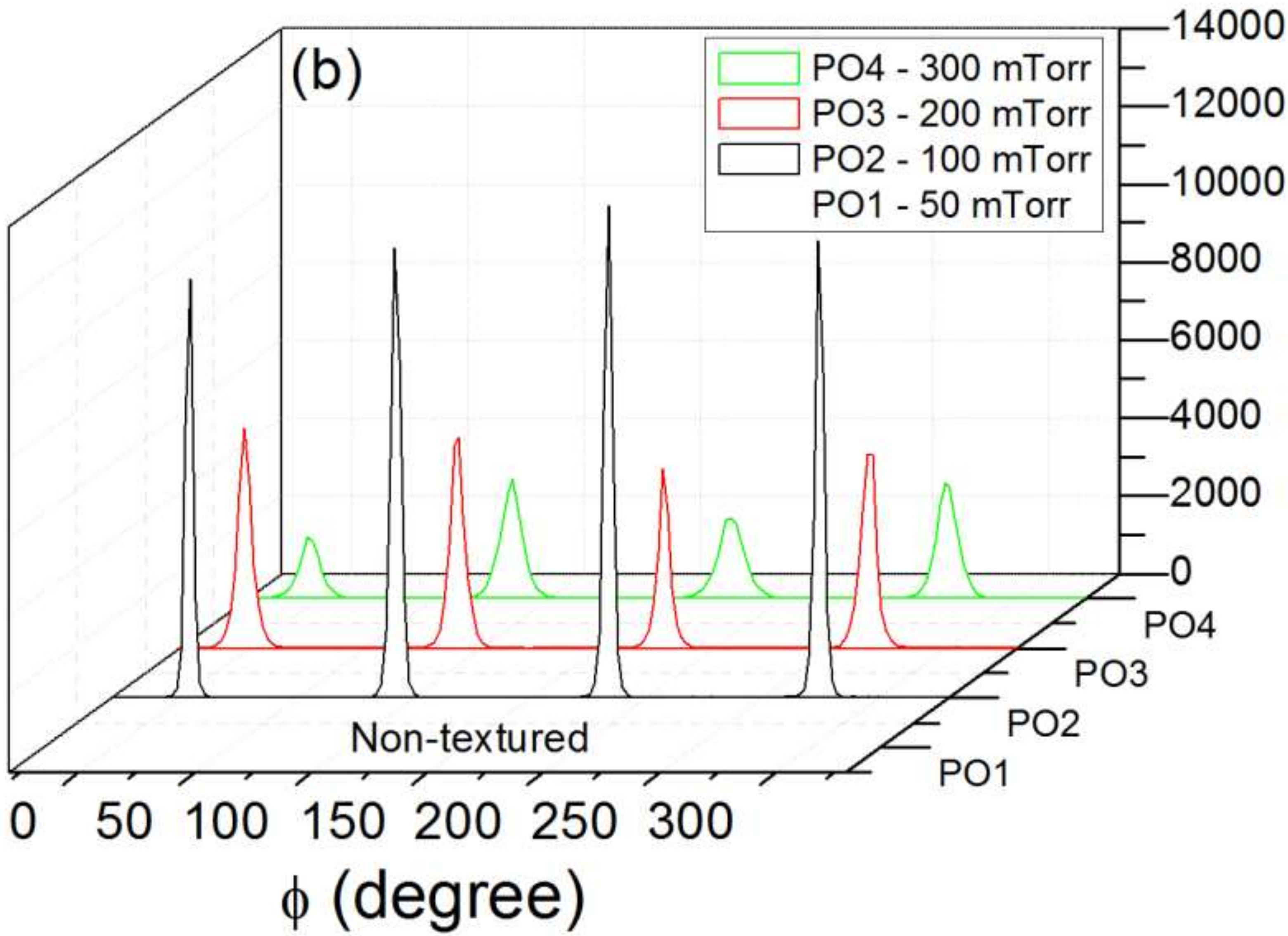
# RCE – DR Results : XRD θ-2θ



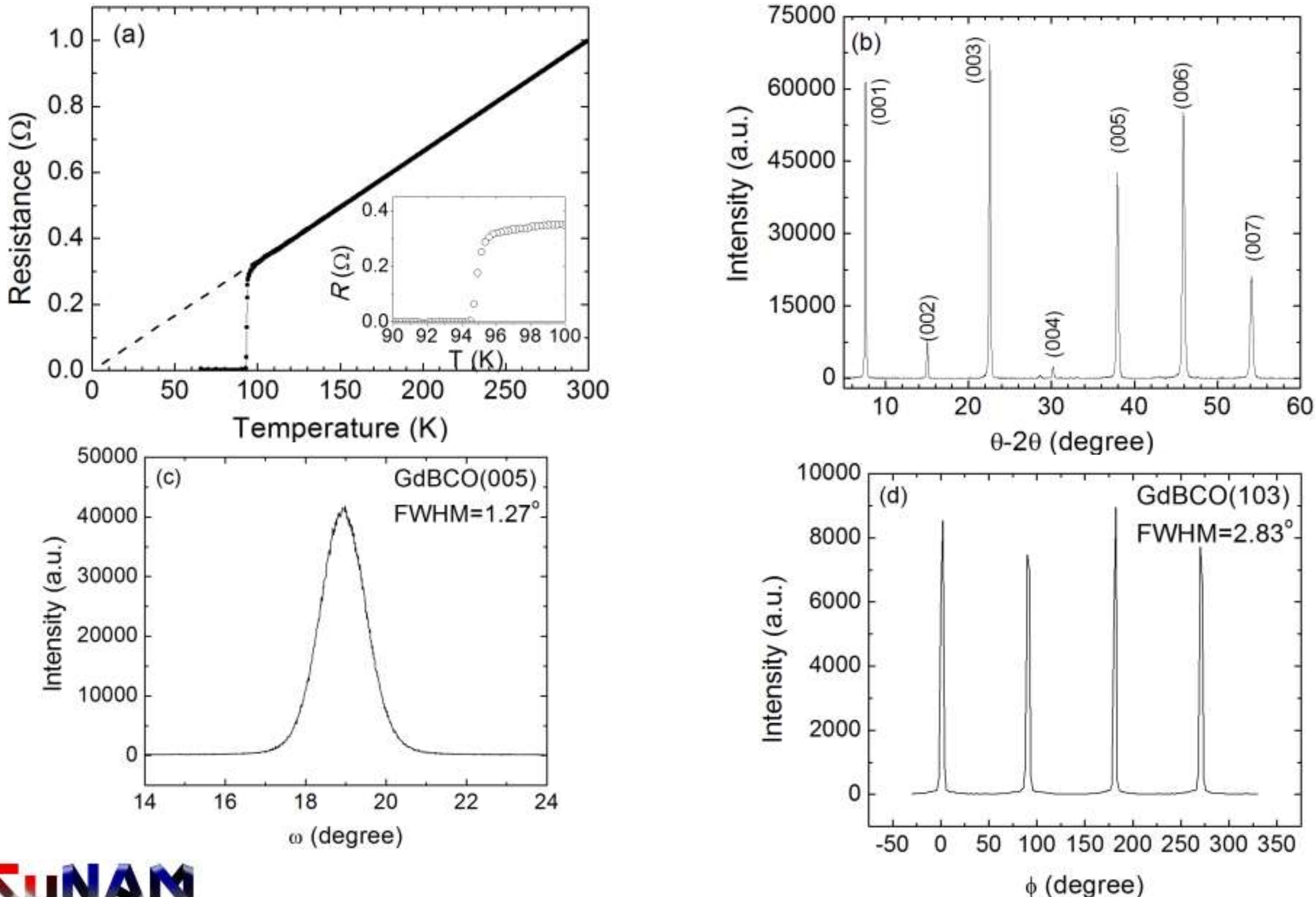

- The same batch, $PO_2$ increases.

# RCE – DR Results : XRD $\phi$-scan (103)




- The same batch, $PO_2$ increases.

# R-T & XRD for optimized tape by RCE – DR

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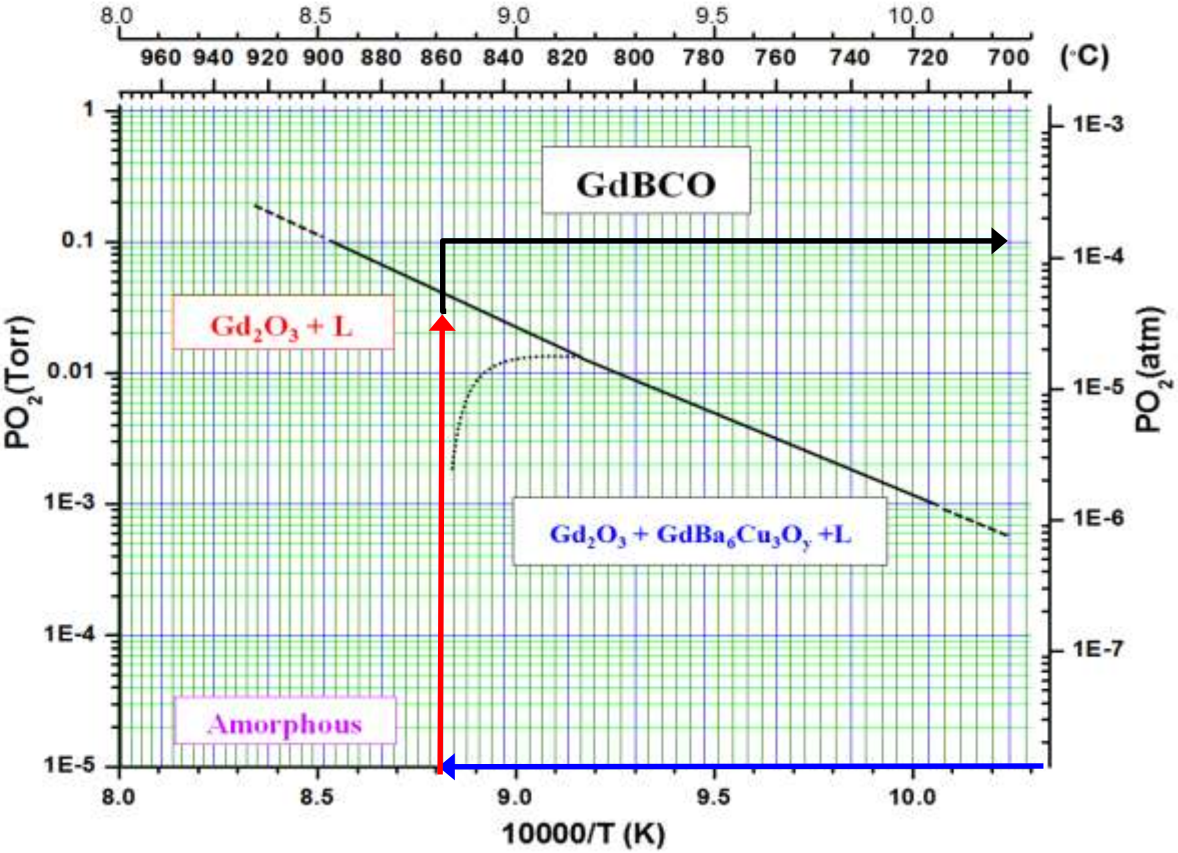
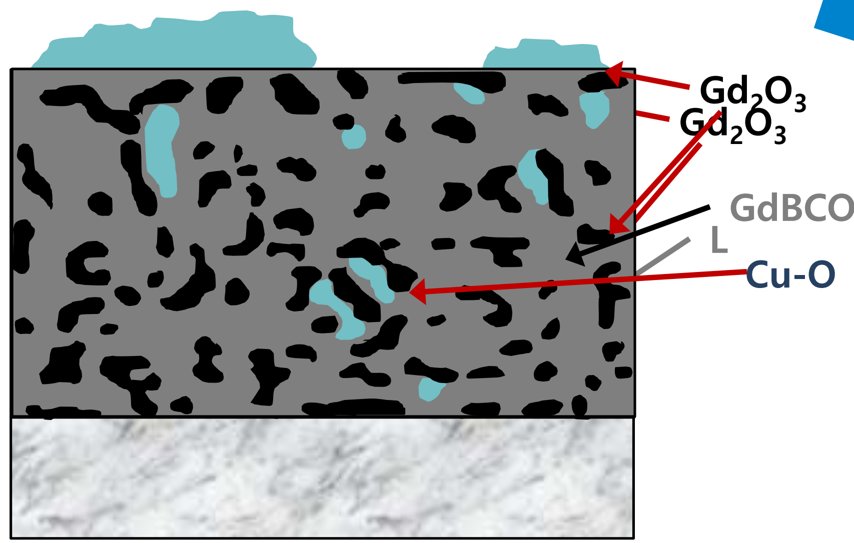
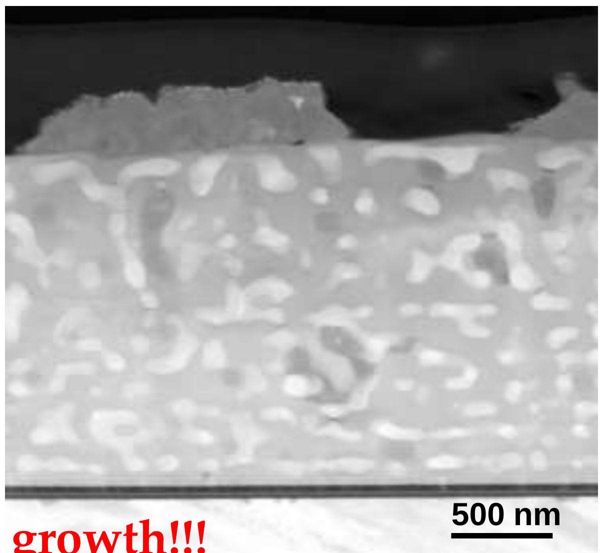
# Growth mechanism of the GdBCO film by RCE-DR




- 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!!!**

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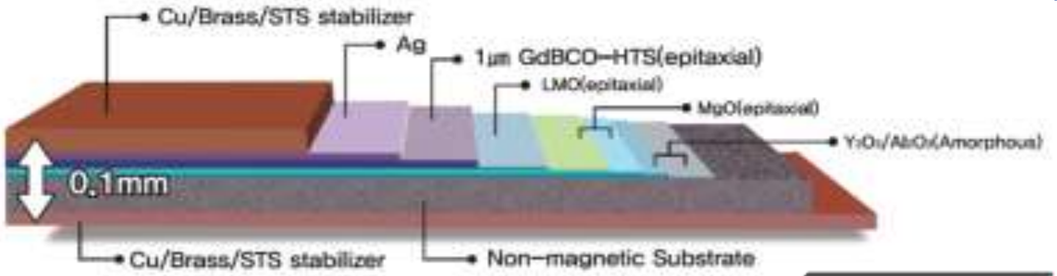
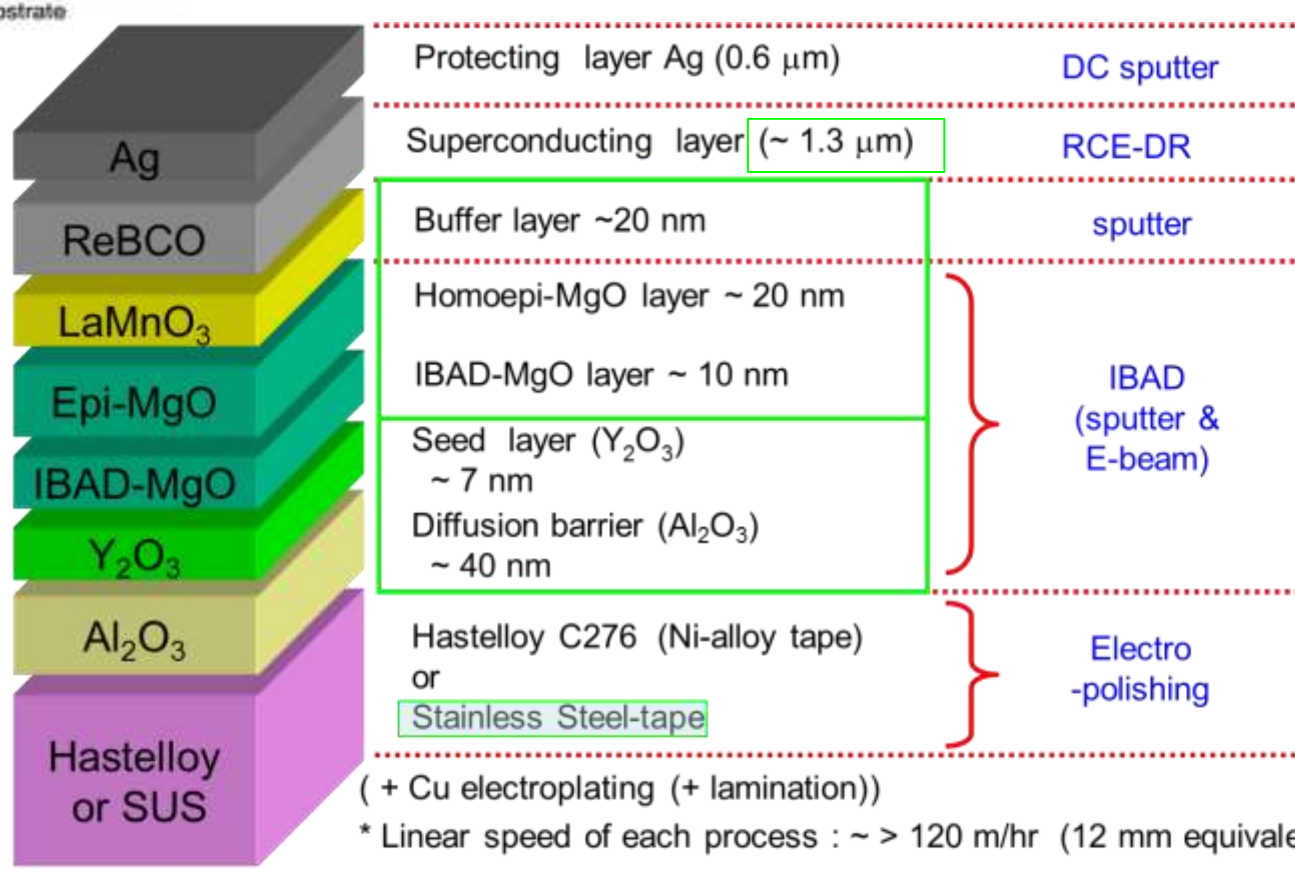
- Production capacity ~ 60 km/month(4 mm width) considering the yield(~ 70 %)

# Structure



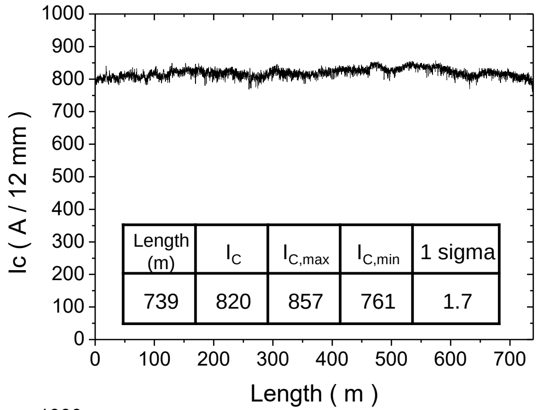




( + Cu electroplating (+ lamination))

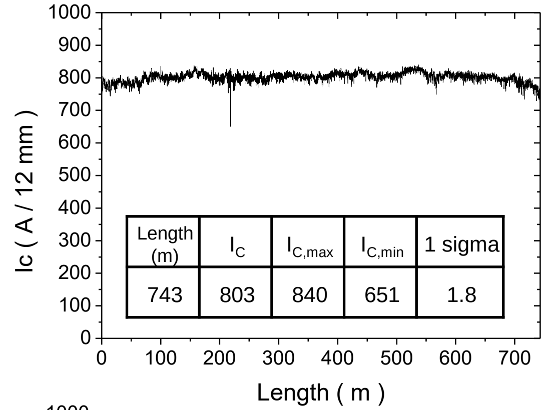
* Linear speed of each process : ~ > 120 m/hr (12 mm equivalent).

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

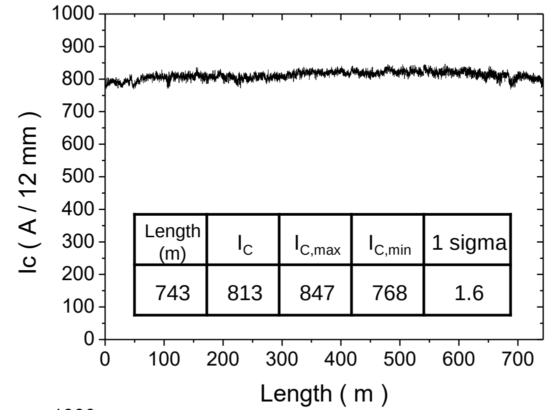
# HTS 2G wire performances (daily production )



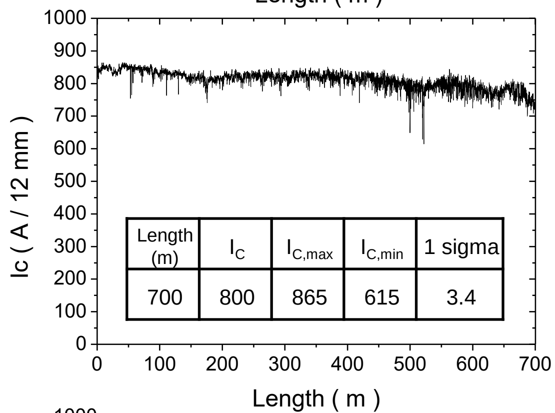

| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 739 | 820 | 857 | 761 | 1.7 |



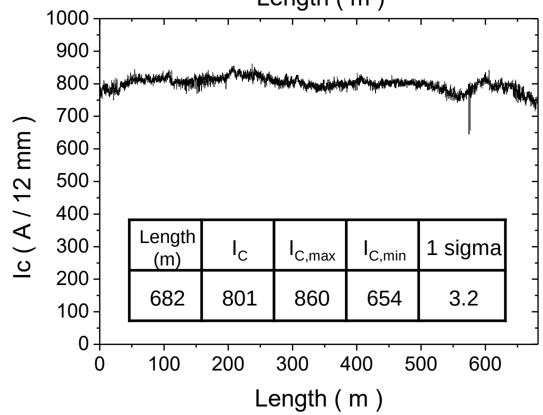

| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 743 | 803 | 840 | 651 | 1.8 |



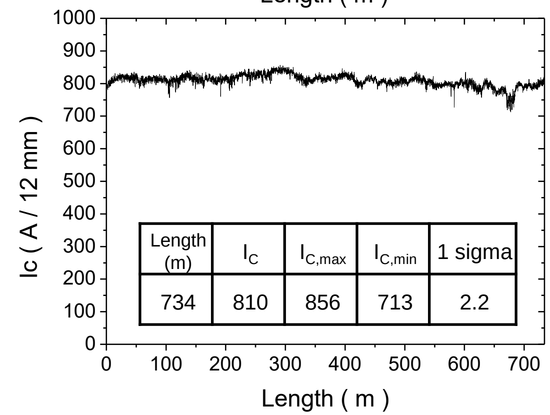

| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 743 | 813 | 847 | 768 | 1.6 |



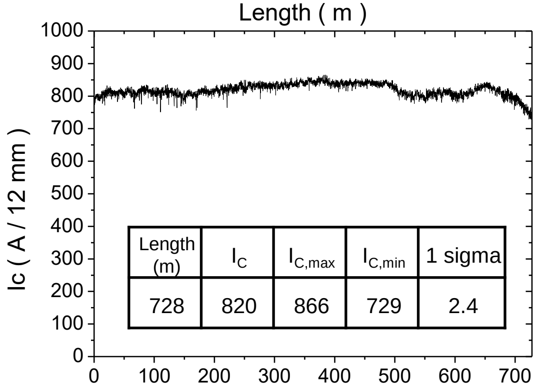

| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 700 | 800 | 865 | 615 | 3.4 |



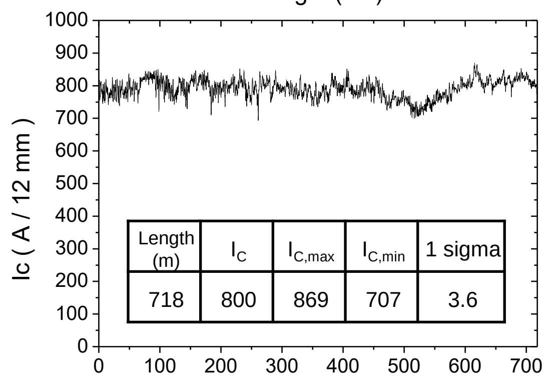

| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 682 | 801 | 860 | 654 | 3.2 |



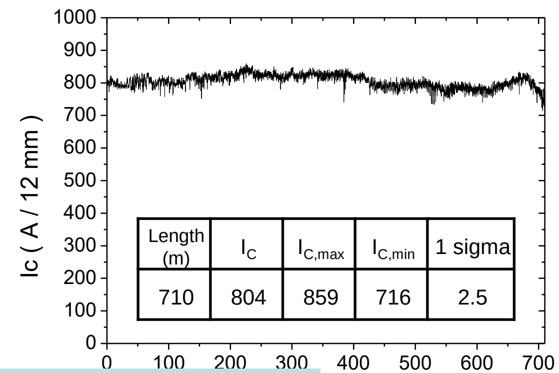

| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 734 | 810 | 856 | 713 | 2.2 |




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



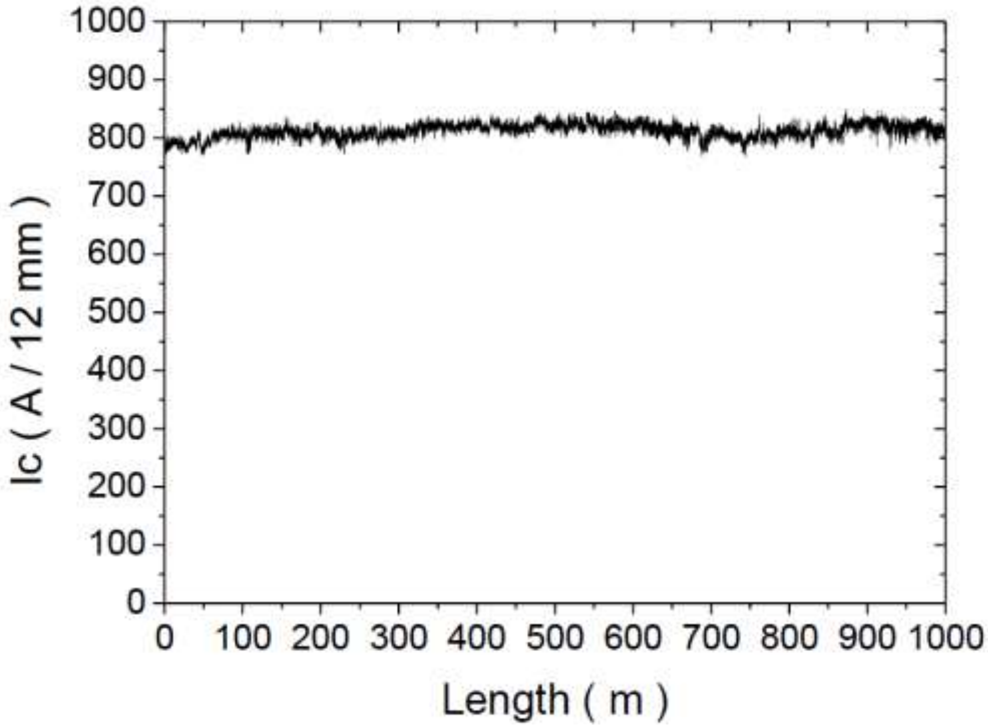

| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 718 | 800 | 869 | 707 | 3.6 |

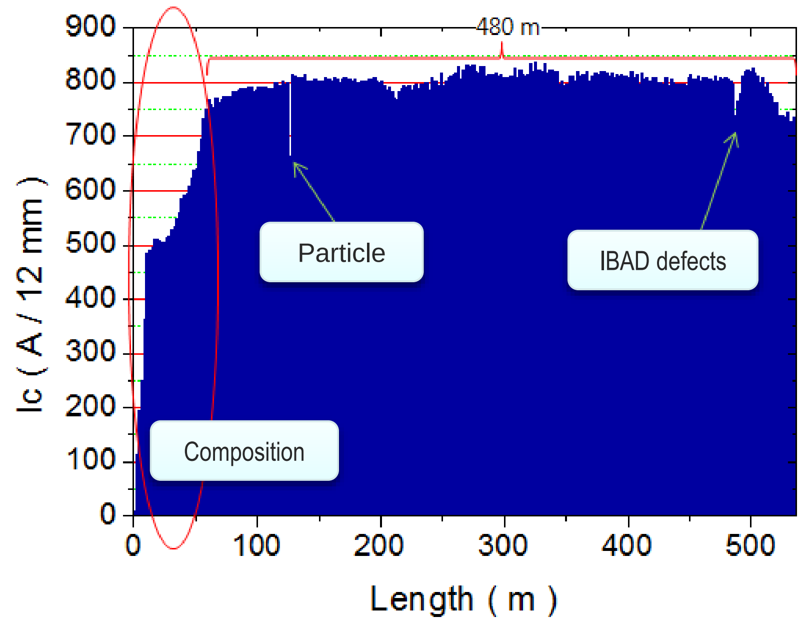



| Length (m) | $I_C$ | $I_{C,max}$ | $I_{C,min}$ | 1 sigma |
|---|---|---|---|---|
| 710 | 804 | 859 | 716 | 2.5 |

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

# 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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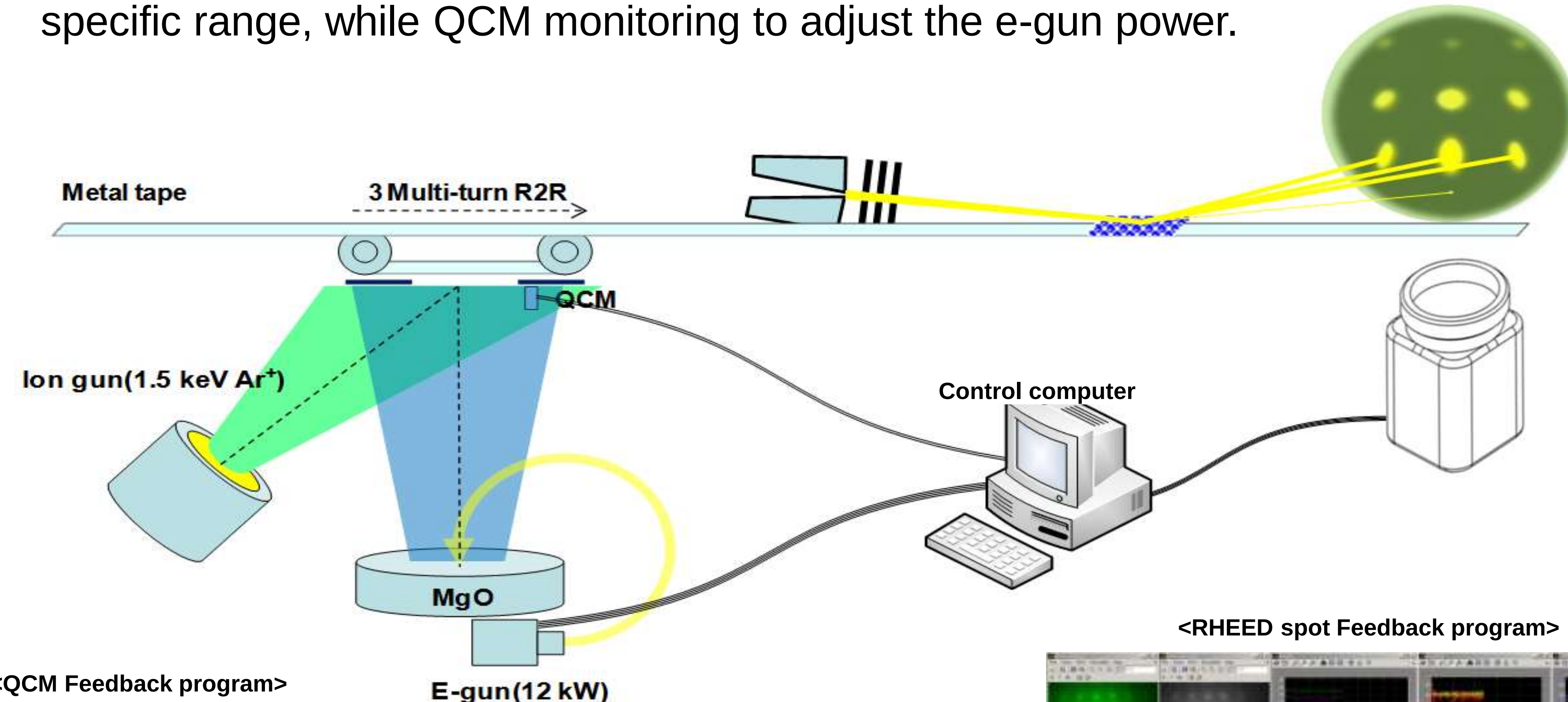
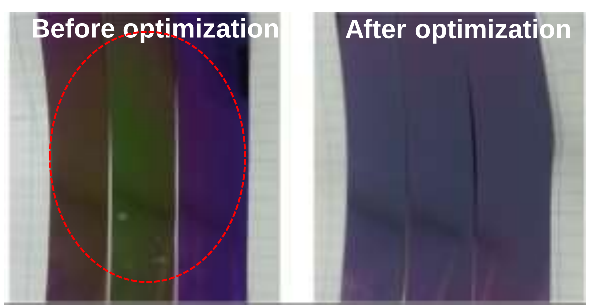
# Quality Control : RHEED Vision System

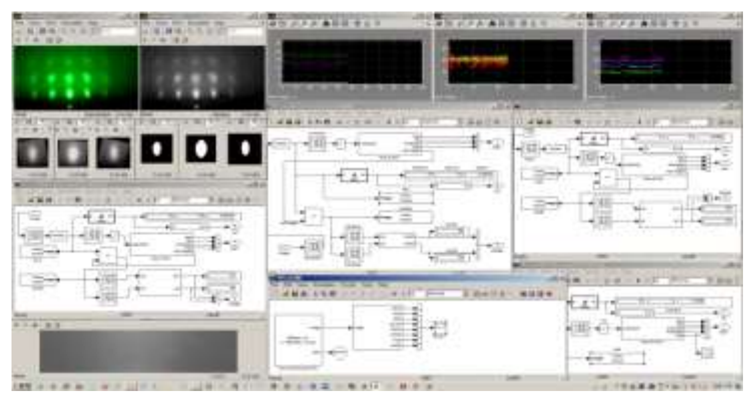
- An appropriate feedback algorithm can keep the shape of the RHEED spot in the specific range, while QCM monitoring to adjust the e-gun power.




<QCM Feedback program>




<RHEED spot Feedback program>



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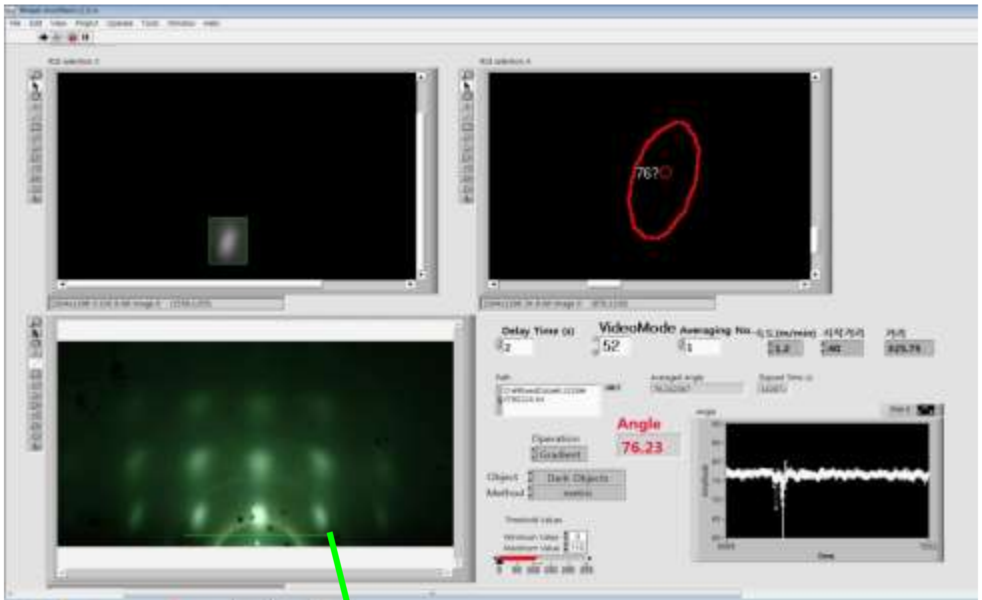
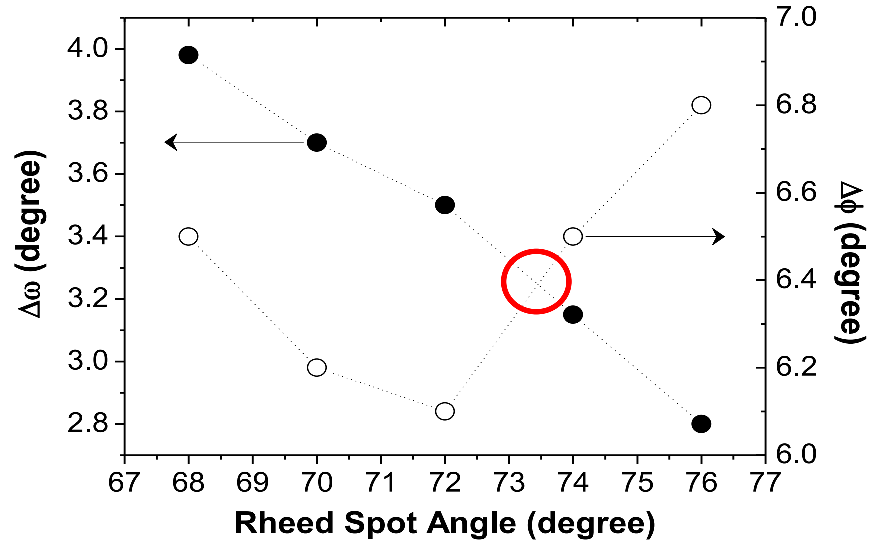
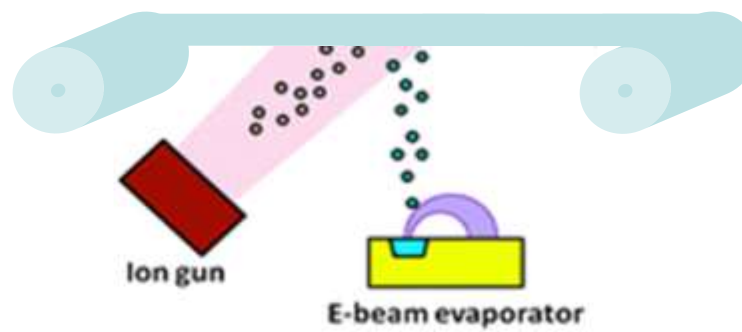
# Feedback route based on RHEED spot analysis




(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.

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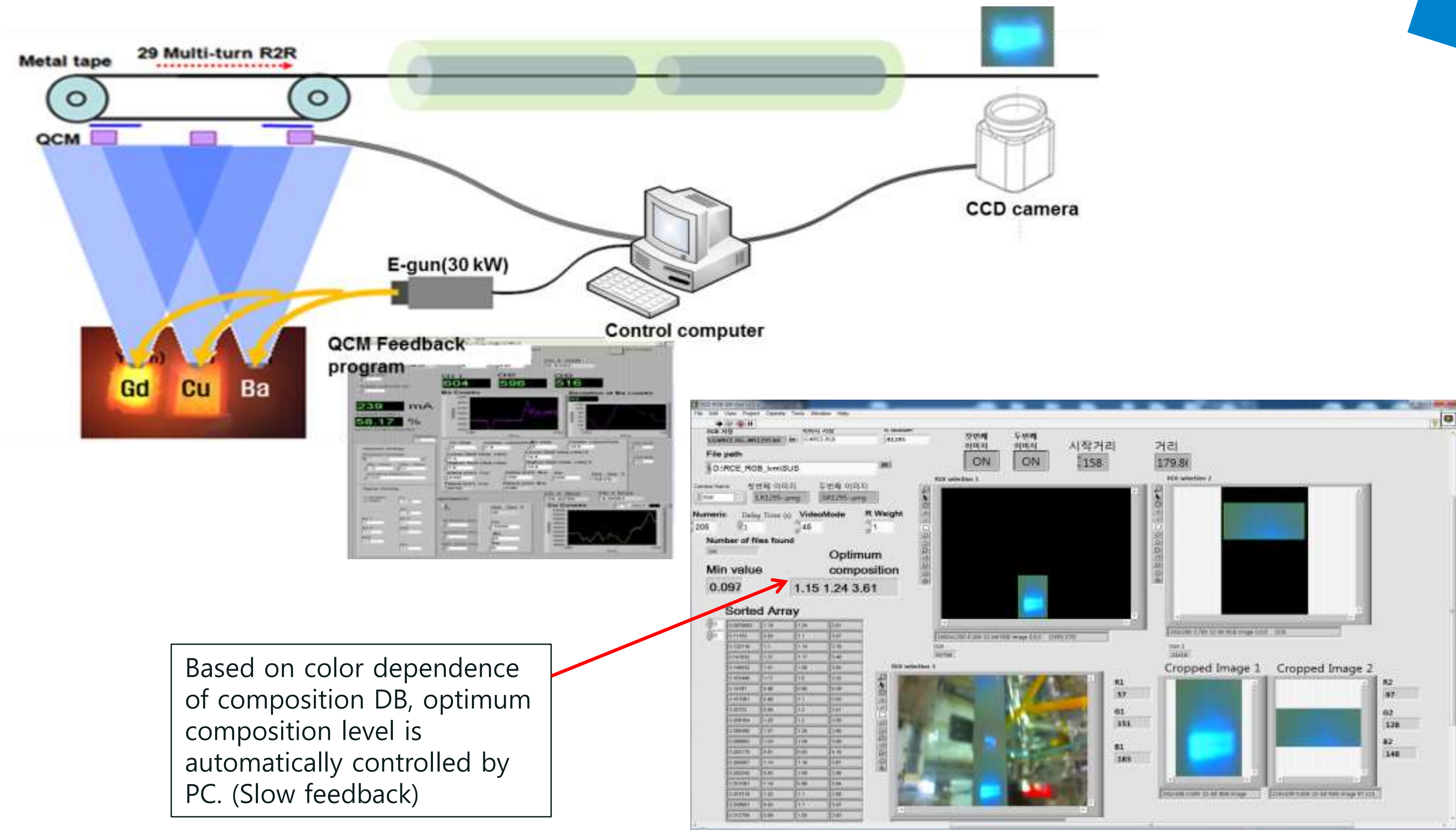
# Quality Control : RCE Vision Inspection System




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

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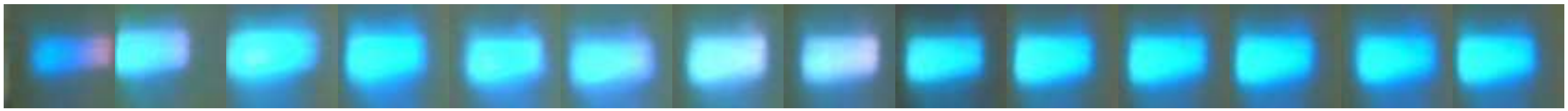
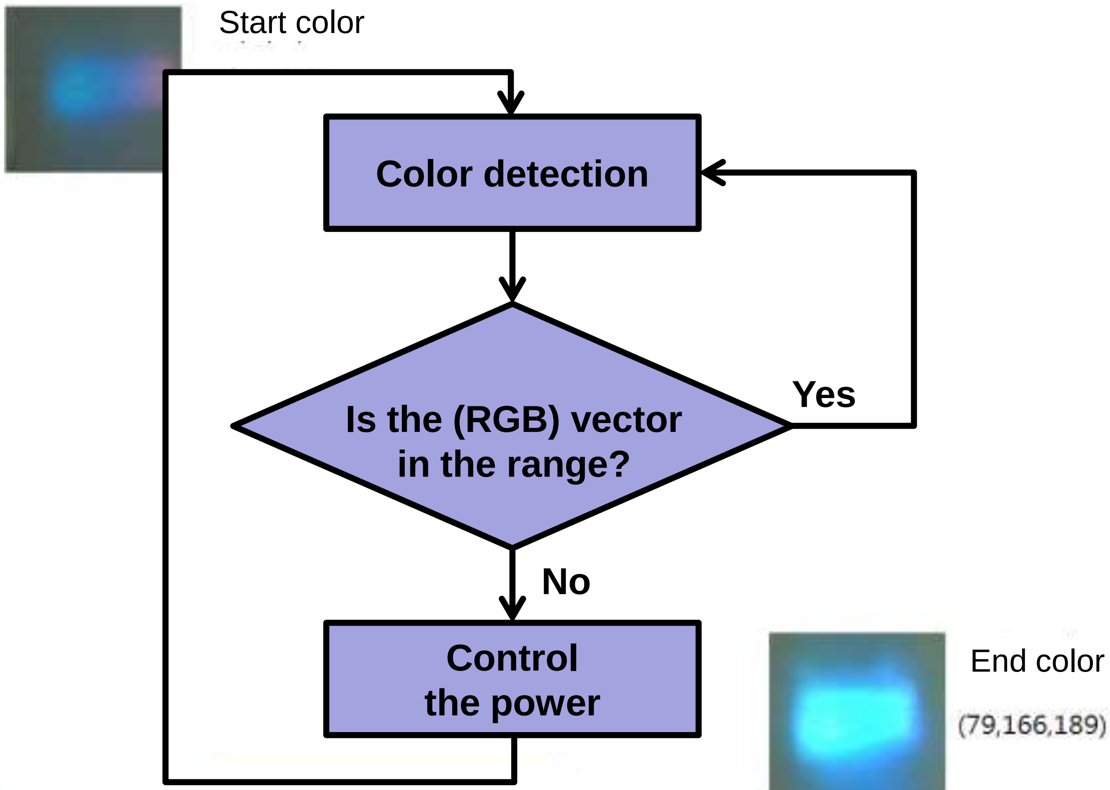
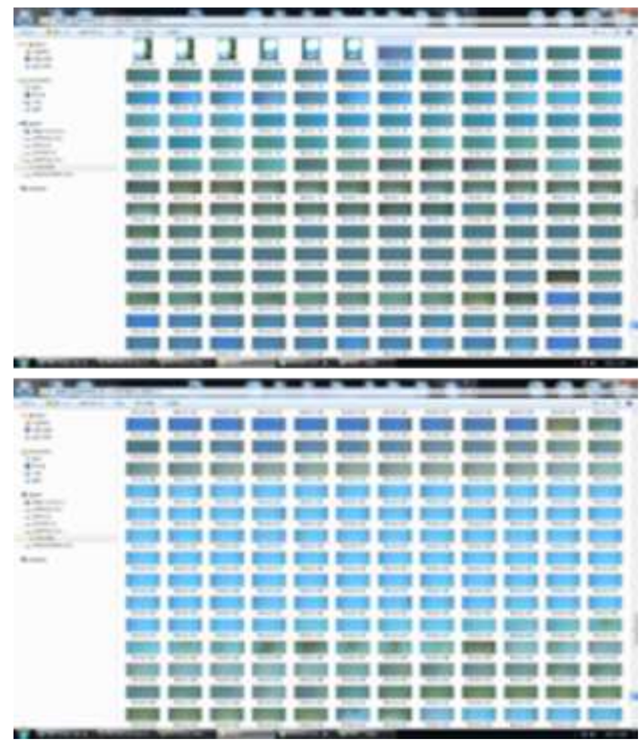
# Quality Control : RCE Vision Inspection System

- 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]



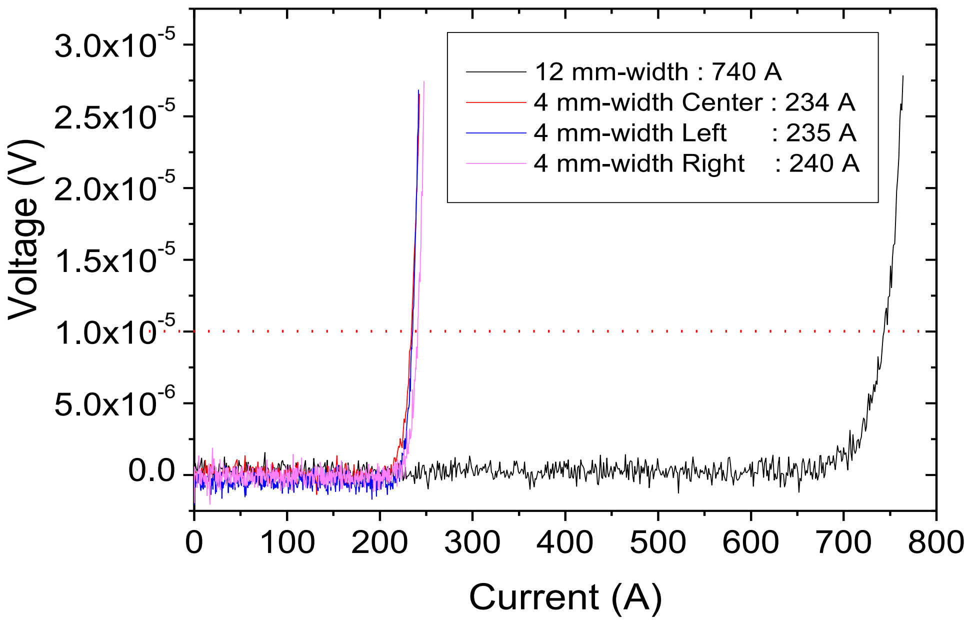

(Composition DB)

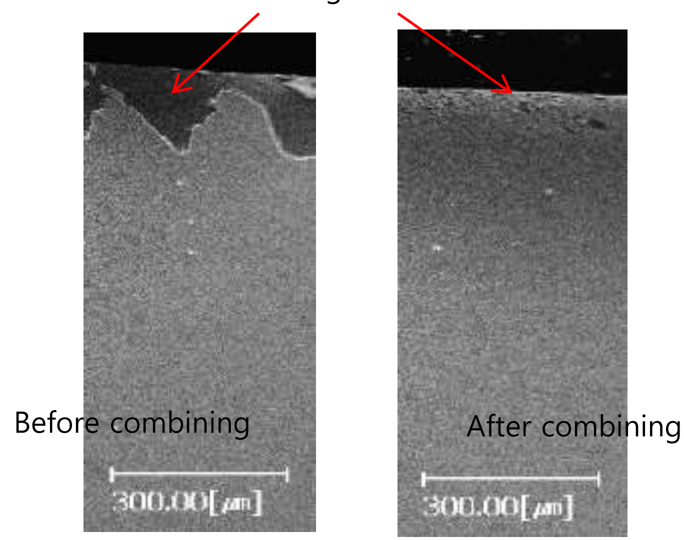


# Combining Barrier, Seed, IBAD, Buffer Systems in One

System for $Al_2O_3$ barrier & $Y_2O_3$ seed

System for IBAD, homo-epi & buffer




After bending

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

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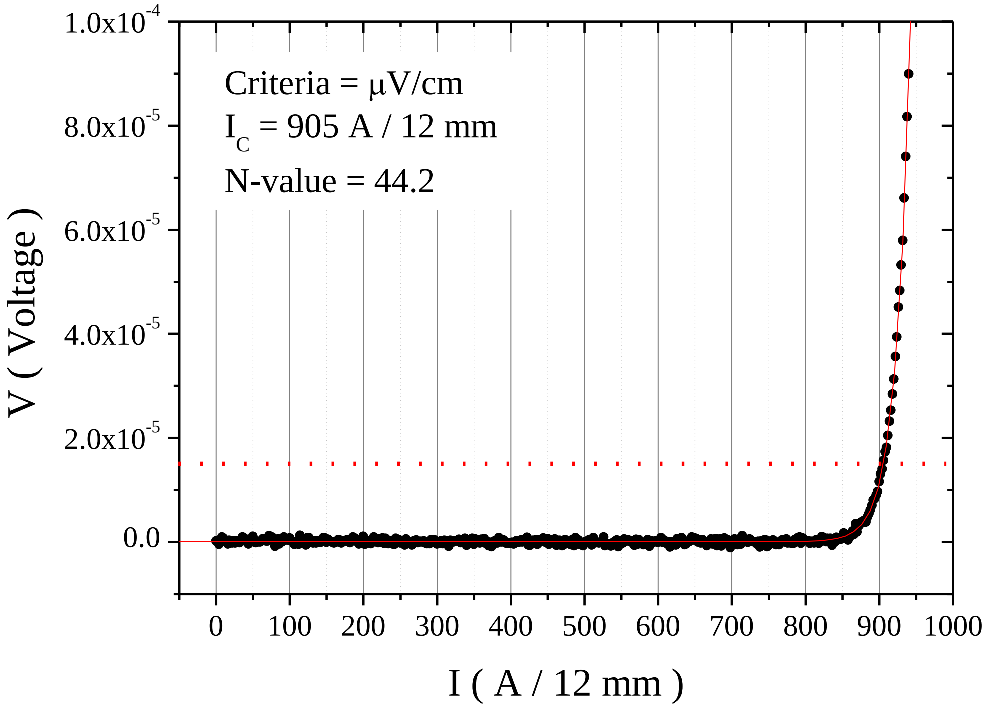
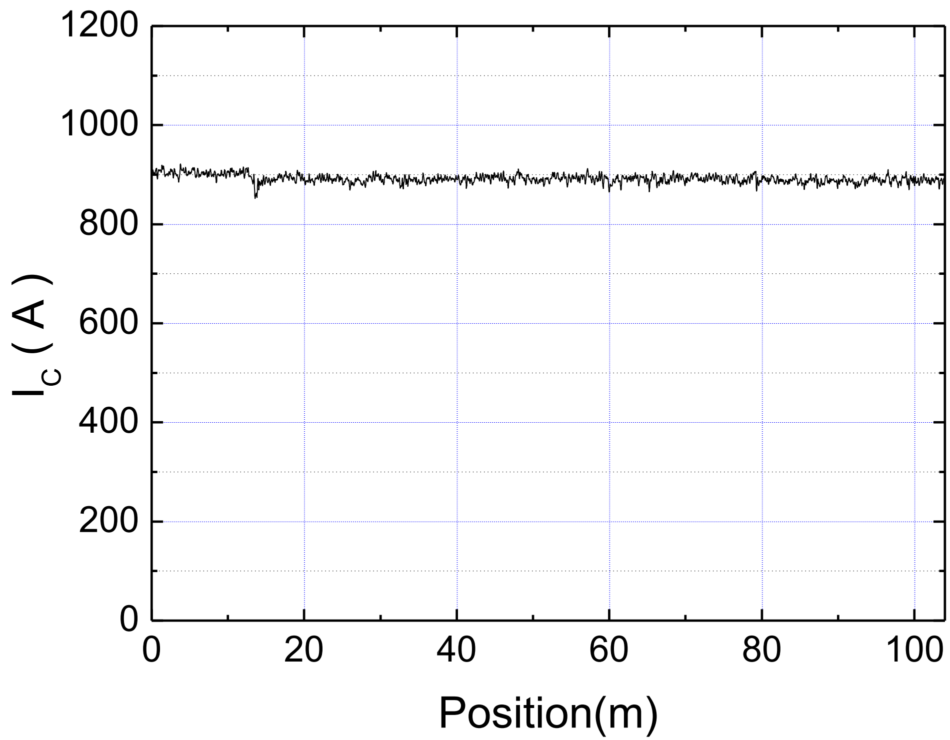
# Optimizated 2G wire performance with 1.6 μm thickness

(77 K, s.f.)

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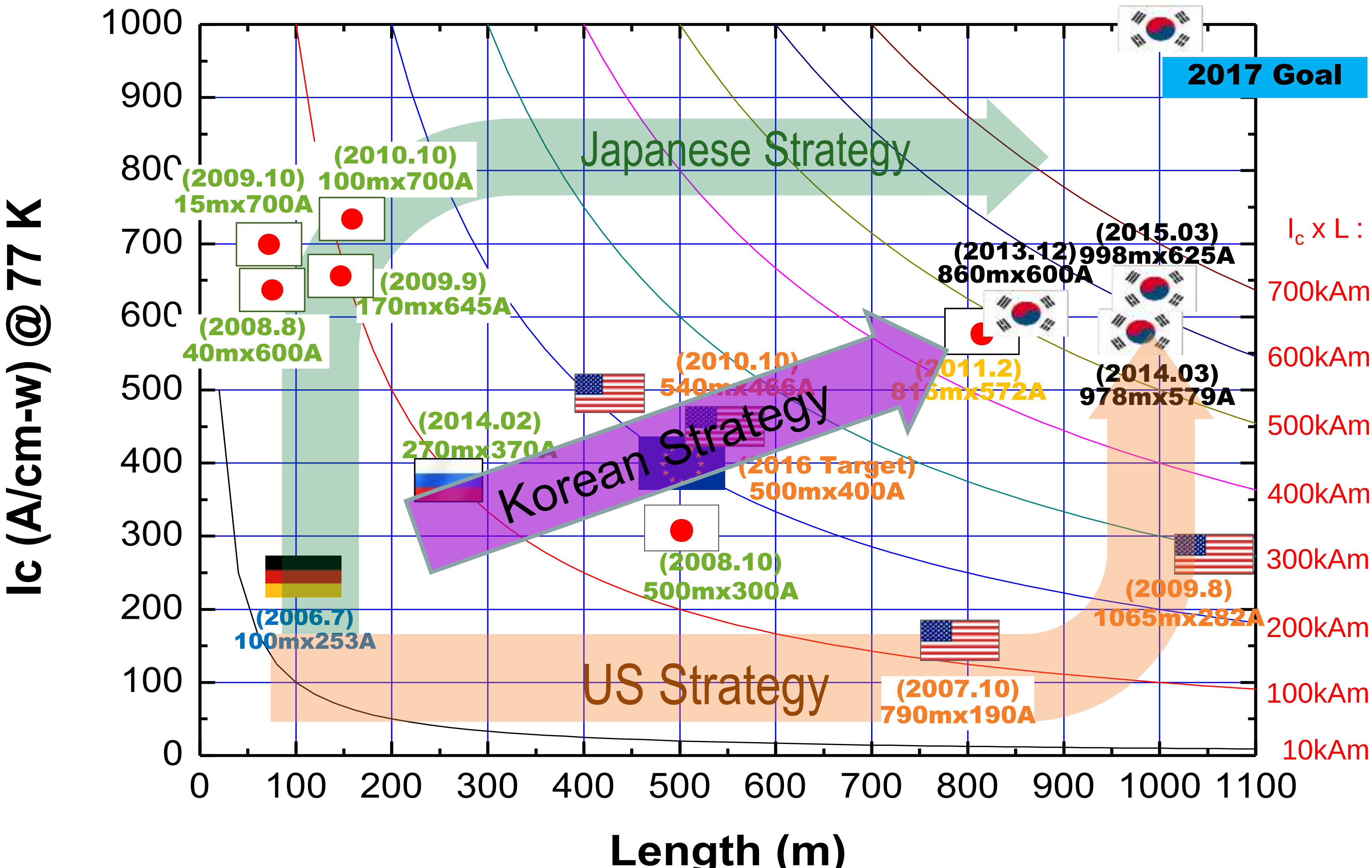
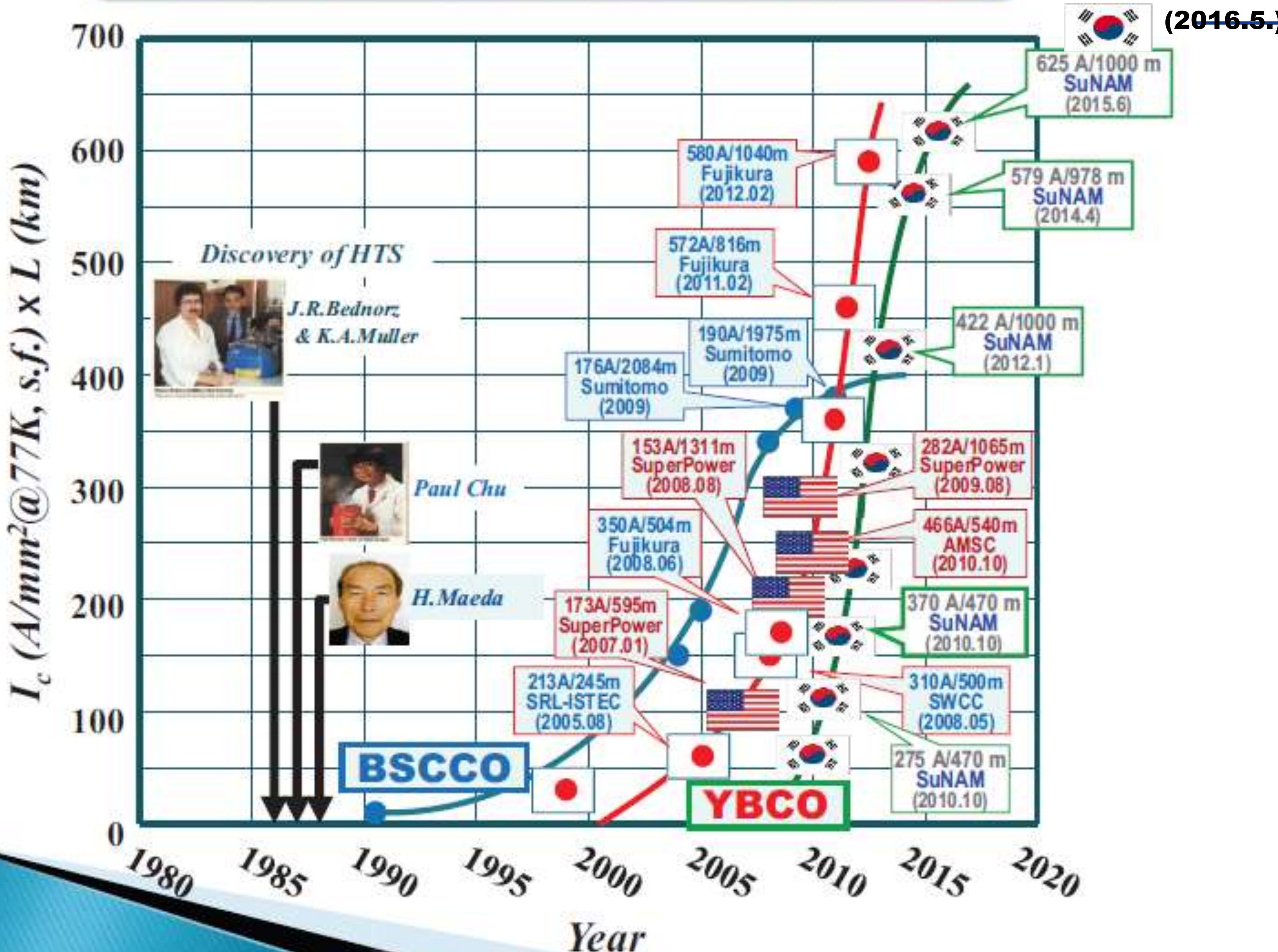
# 임계전류 향상




SuNAM

# Progress of HTS Conductors (as of 2015.6.8)




Courtesy: Yuh Shiohara

# Some application examples of coil/magnet

# 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.

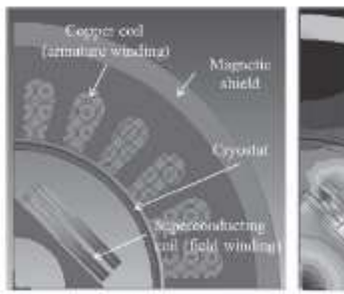
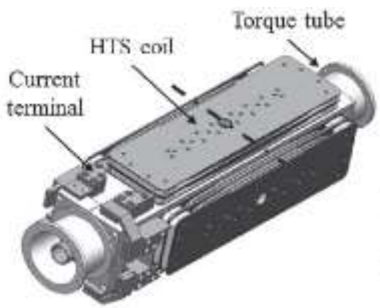
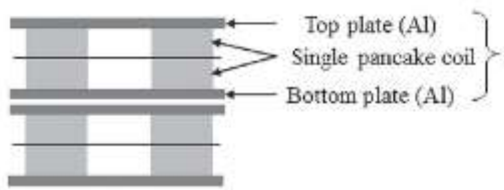


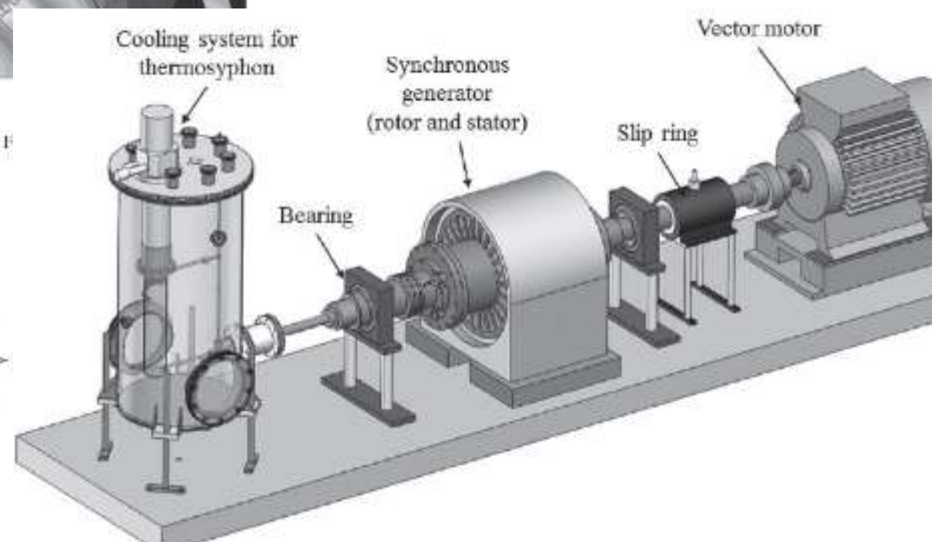

Fig. 1. Design results of the generator using F
area. (b) Magnetic field distribution.

### I. Introduction

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




SuNAM RIST KERI

# 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 |

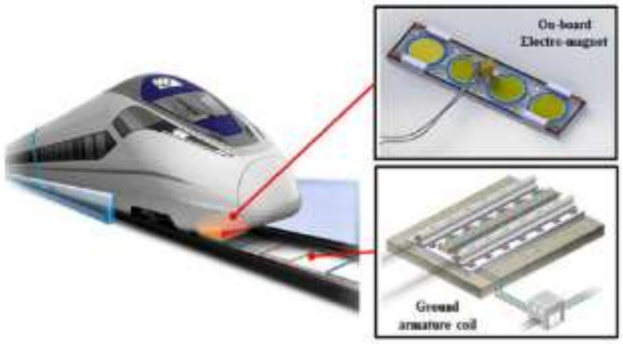


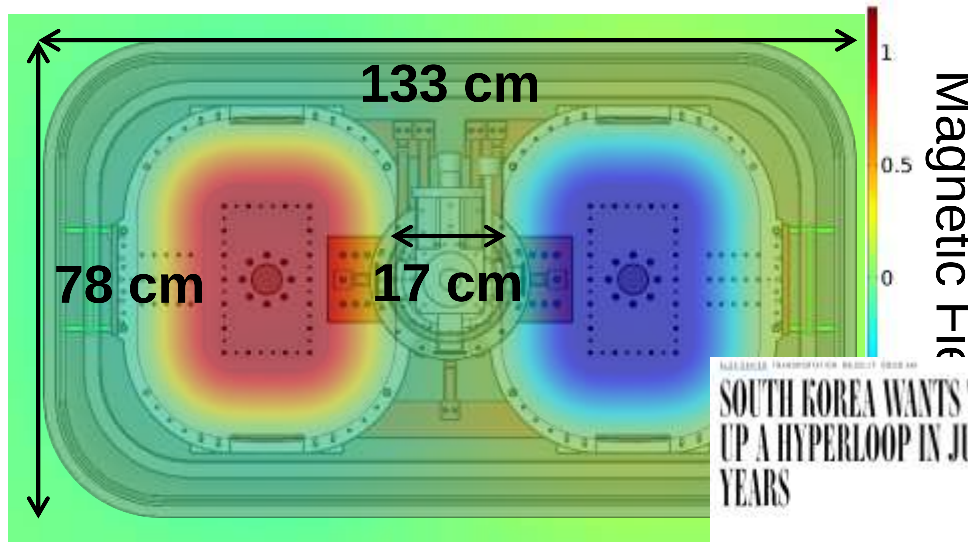

Fig. 1. Conceptual diagram of the ultra-high speed 600 km/h trains [4]

# 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


SOUTH KOREA WANTS TO FIRE UP A HYPERLOOP IN JUST 4 YEARS


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

SUNAM KRRI

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

**IOP** Publishing — Superconductor Science and Technology

Supercond. Sci. Technol. **29** (2016) 04LT04 (6pp) — doi:10.1088/0953-2048/29/4/04LT04

Letter

## 26 T 35 mm all-$GdBa_2Cu_3O_{7-x}$ multi-width no-insulation superconducting magnet

Sangwon Yoon[1], Jaemin Kim[1], Hunju Lee[1], Seungyong Hahn[2,3,4] and Seung-Hyun Moon[1]

[1] SuNAM Co., Ltd. 103 Seongeun-ri, Wongok-myeon, Anseong-si, Gyeonggi-do, 456-812, Korea
[2] Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, 170 Albany Street, Cambridge, MA 02139, US

E-mail: shahn@asc.magnet.fsu.edu

Received 28 July 2015, revised 22 December 2015
Accepted for publication 24 December 2015
Published 10 March 2016

CrossMark

**Abstract**

A 26 T 35 mm winding diameter all-$GdBa_2Cu_3O_{7-x}$ (GdBCO) magnet was designed by the MIT Francis Bitter Magnet Laboratory, and constructed and tested by the SuNAM Co., Ltd. With the multi-width (MW) no-insulation (NI) high temperature superconductor (HTS) winding technique incorporated, the magnet is highly compact; its overall diameter and height are 172 and 327 mm, respectively. It consists of a stack of 26 NI double pancake coils wound with MW GdBCO tapes in five different widths ranged 4.1–8.1 mm. In a bath of liquid nitrogen at 77 K, the magnet had a charging time constant of 16 min due to the intrinsic NI characteristics. In liquid helium at 4.2 K, the magnet generated a 26.4 T field at the center, a record high in magnetic fields from all-HTS magnets. The results demonstrate a strong potential of MW-NI GdBCO magnets for direct current high-field applications.

**IOP** Publishing

Viewpoint

## Viewpoint: Are no-insulation magnets a paradigm shift for high-field DC superconducting magnets?

Justin Schwartz
*Materials Science and Engineering Department, North Carolina State University, 911 Partners Way, Raleigh, NC 27695-7907, USA*

This is a viewpoint on the letter by Sangwon Yoon *et al* (2016 *Supercond. Sci. Technol.* 29 04LT04).

Superconducting magnets generating magnetic fields above 25 T have been an aspirational target of the magnet community since the Seitz-Richardson report was released in 1988 [1]. At the time of the report, there were no superconducting materials capable of transporting high supercurrent density at magnetic fields

In short, these results indicate that the no-insulation approach to (RE)$Ba_2Cu_3O_x$ magnet construction will remain an important option for high field superconducting magnets for many years to come. The game is on!

SuNAM — MIT MASSACHUSETTS INSTITUTE OF TECHNOLOGY — NATIONAL HIGH MAGNETIC FIELD LABORATORY

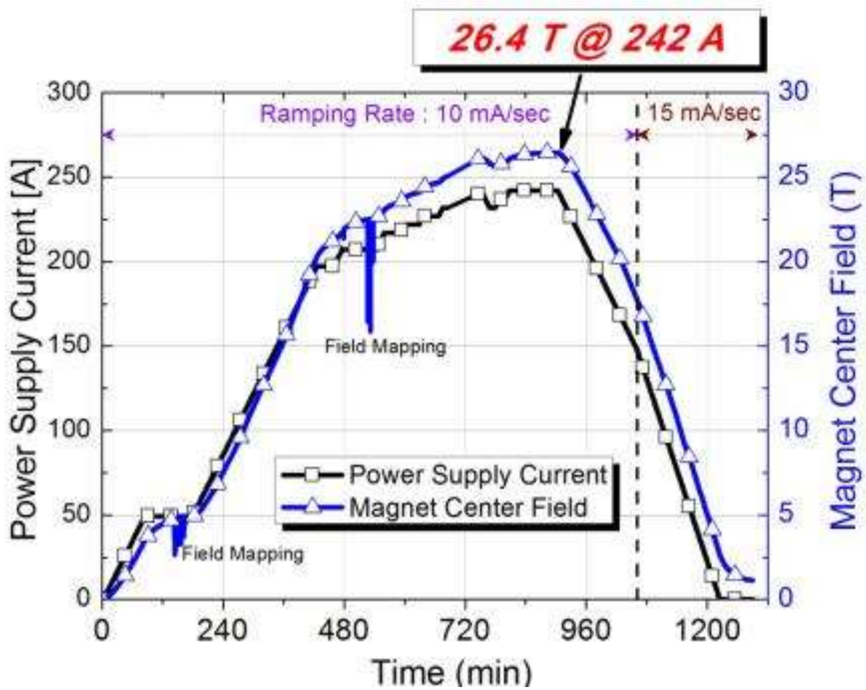
# 26.4 T all 2G wire one-body(non-nested) magnet

## No-insulation, multi-width, and compact !

✓ Multi-width Double Pancake Coils


✓ Stacked Double Pancake Coils


✓ Fully assembled




Immersed in liquid Helium

(Designed by S. Hahn (MIT→ NHMFL/FSU)

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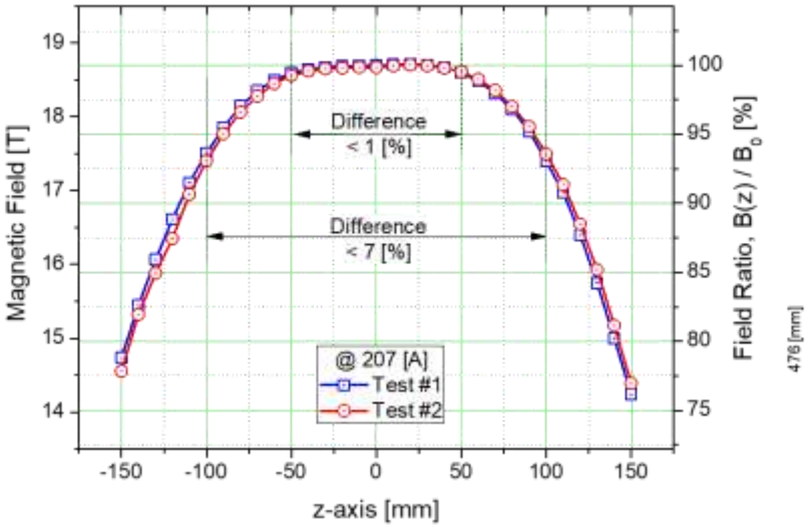
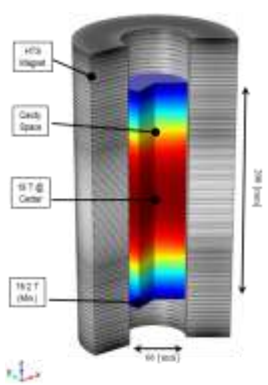
NATIONAL HIGH MAGNETIC FIELD LABORATORY

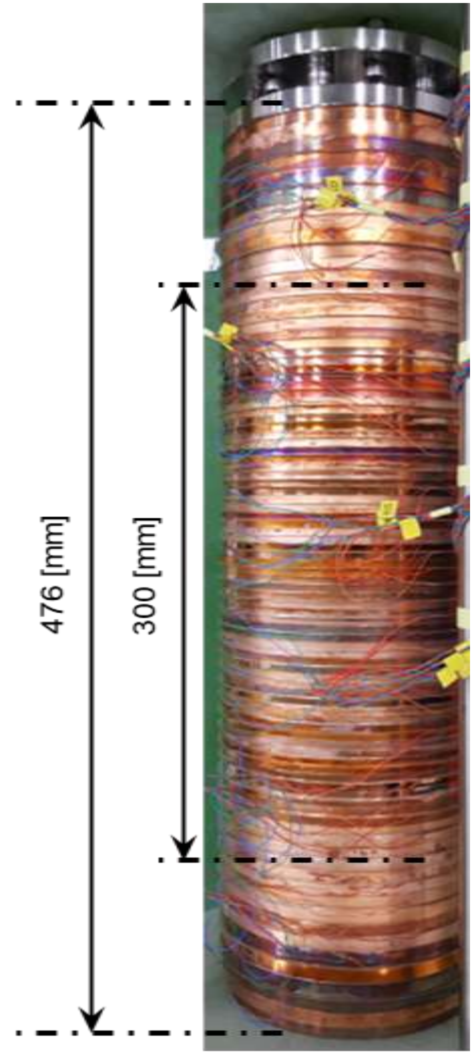
# World 1st All HTS Commercial Magnet for Axion Detection




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

: Delivered to Institute for Basic Science

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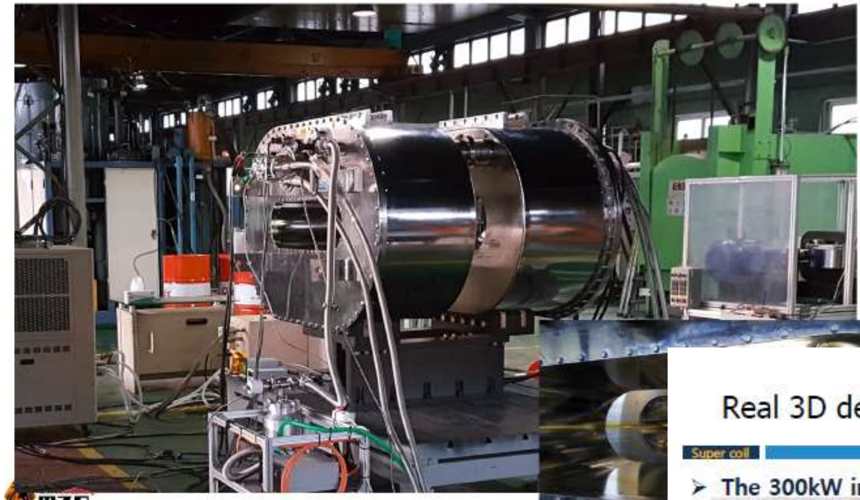
*Confidential*

# Commercial proto-type DC Induction Heater (All HTS Coil)

➢ Operation test of Superconducting magnet : Success!!

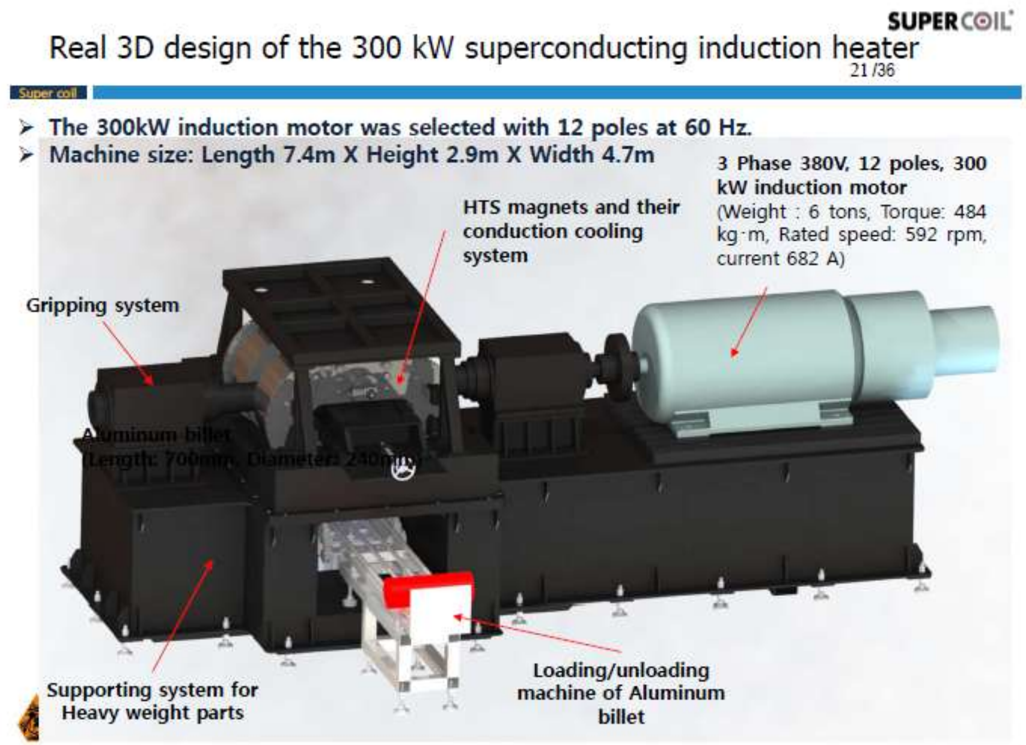


SUPERCOIL

- ➢ We fabricated the large-sized two HTS magnets for induction furnace in the world.
- ➢ The HTS magnet size: length 1.25m X height 0.62 m

(12 mm SuNAM wires, SS tape cowinding)

• 300kW의 초전도인덕션히터 철빌렛, 680 도 가열 테스트 성공!

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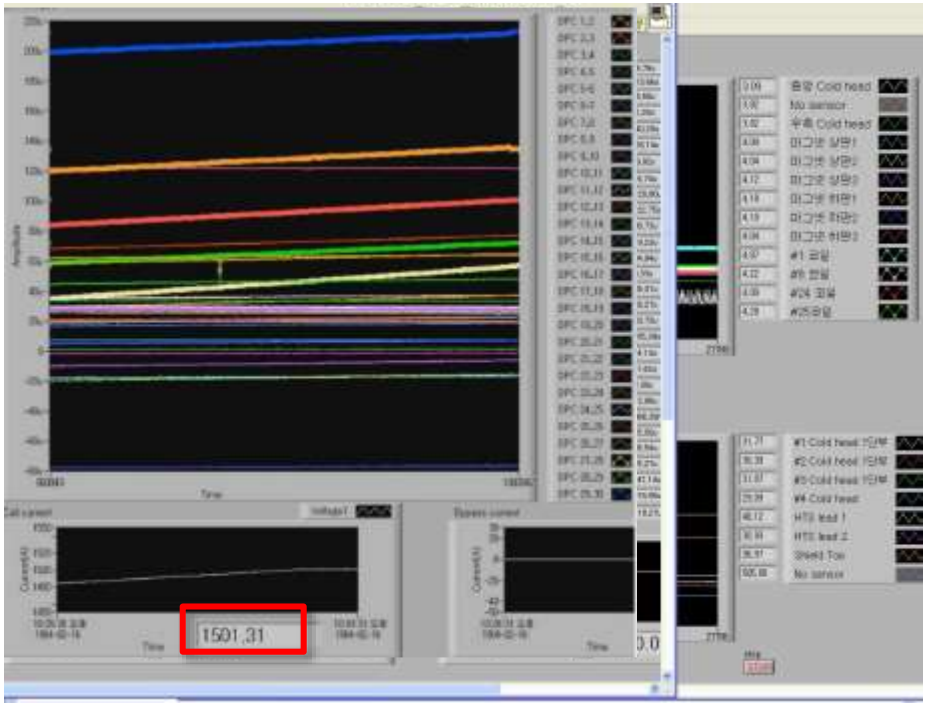
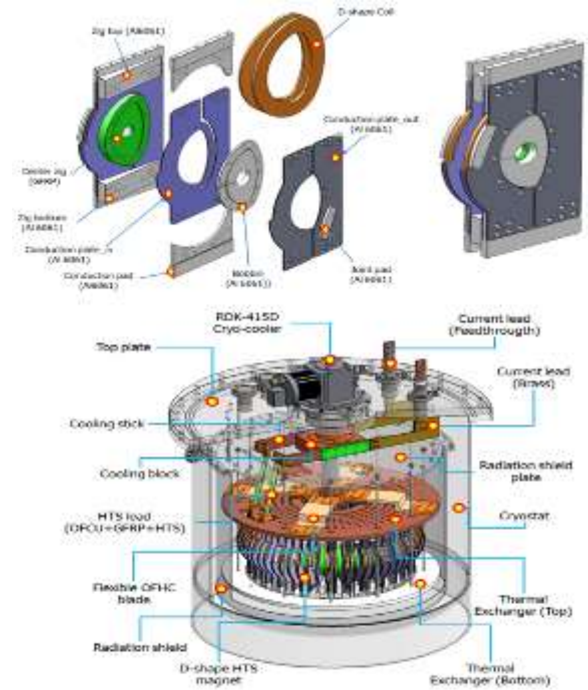
*Confidential*

# 400 mH HTS DC Reactor : Applying 1500 A & Cryogen Free



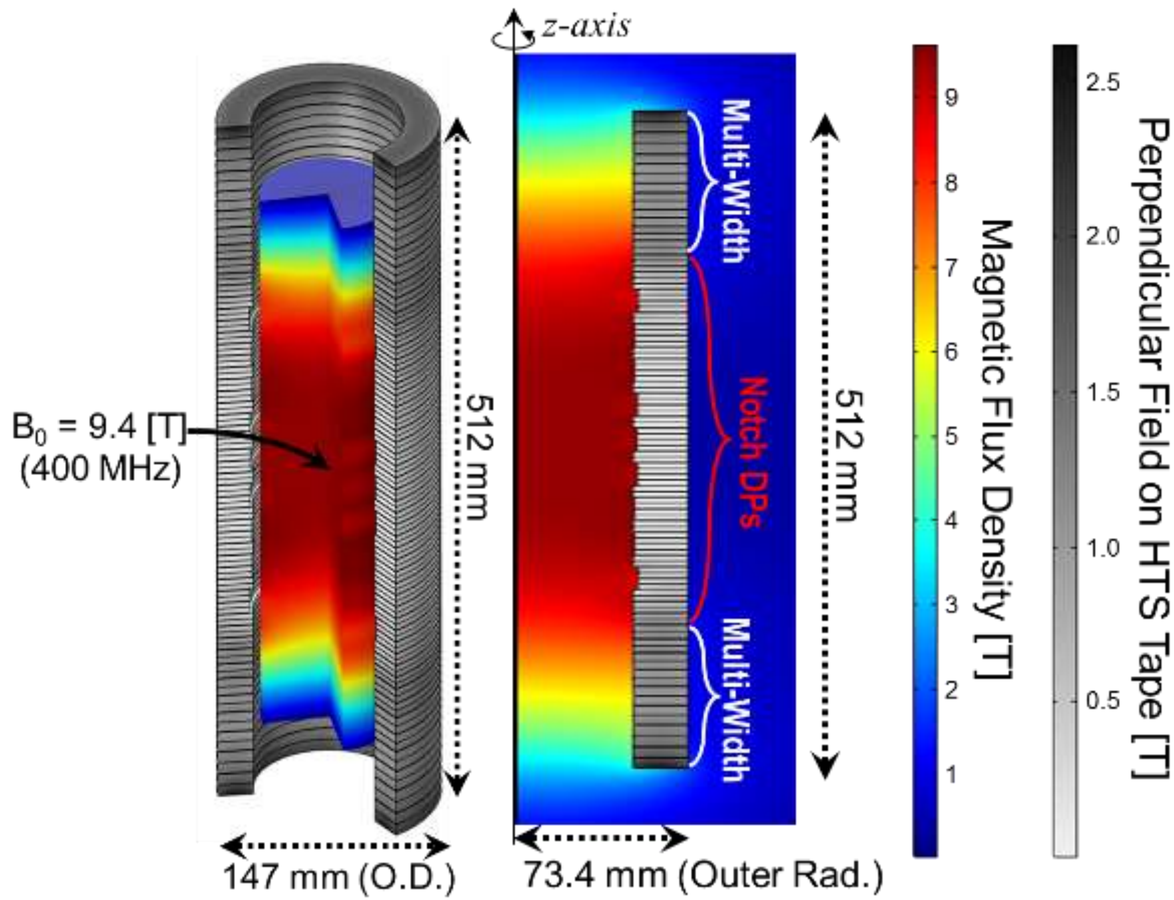

1,500 A Charging Charcteristics



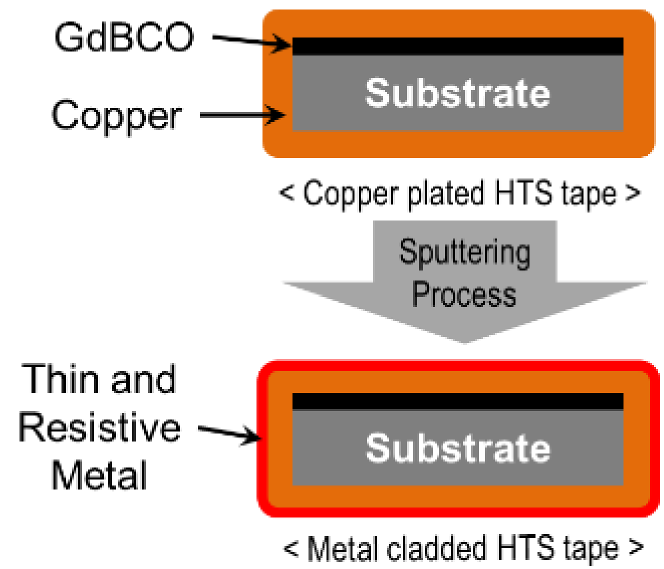

Assemble Process of conduction cooled 30 toroidal coils for 400 mH reactor

SuNAM KERI

# 400 MHz conduction cooled NMR : Magnet Design




< Field profile of NMR magnet design >




- No-Insulation with Metal cladding HTS tape enclosed as STS with 1 mm thick
- Multi-width winding for high $I_{op}$
- Inside notch design for homogenous field

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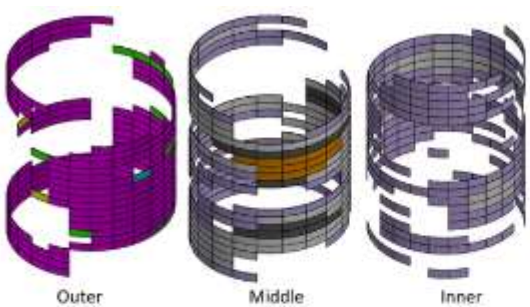
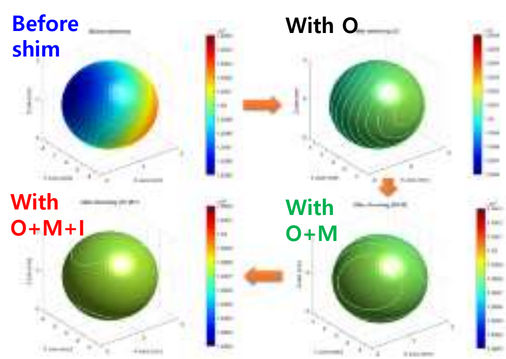
KSI KIMM SUNAM

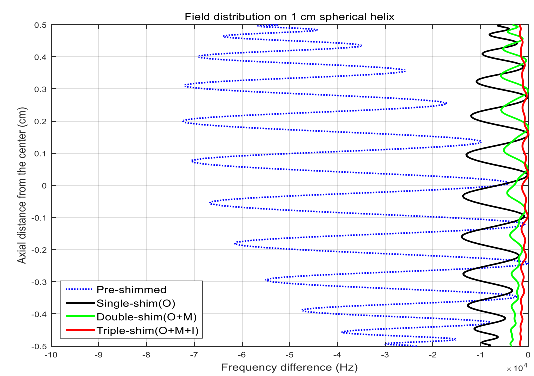
# 400 MHz conduction cooled NMR : Magnet Assemble

## 400 MHz NMR Magnet Assemble


## Ferro-Shimming Technique

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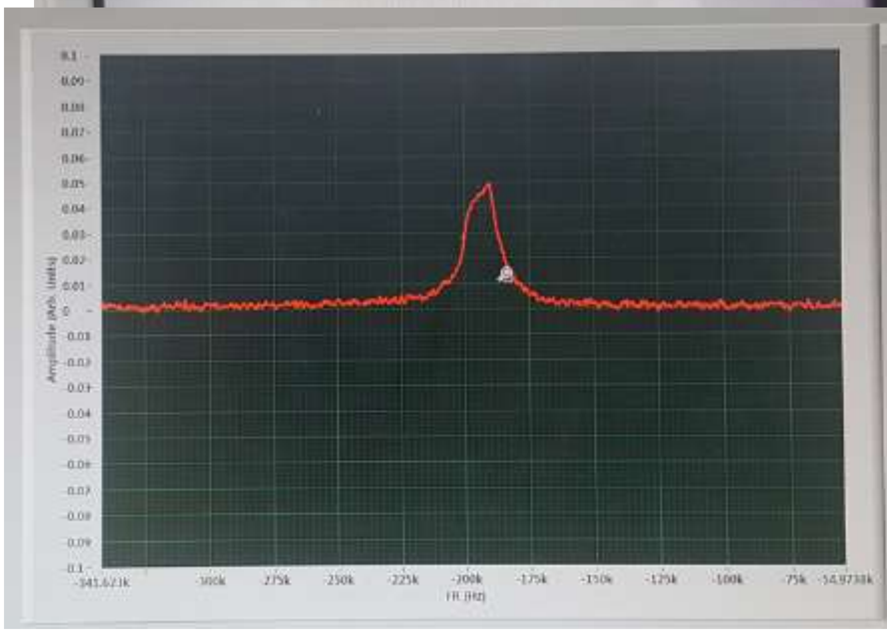
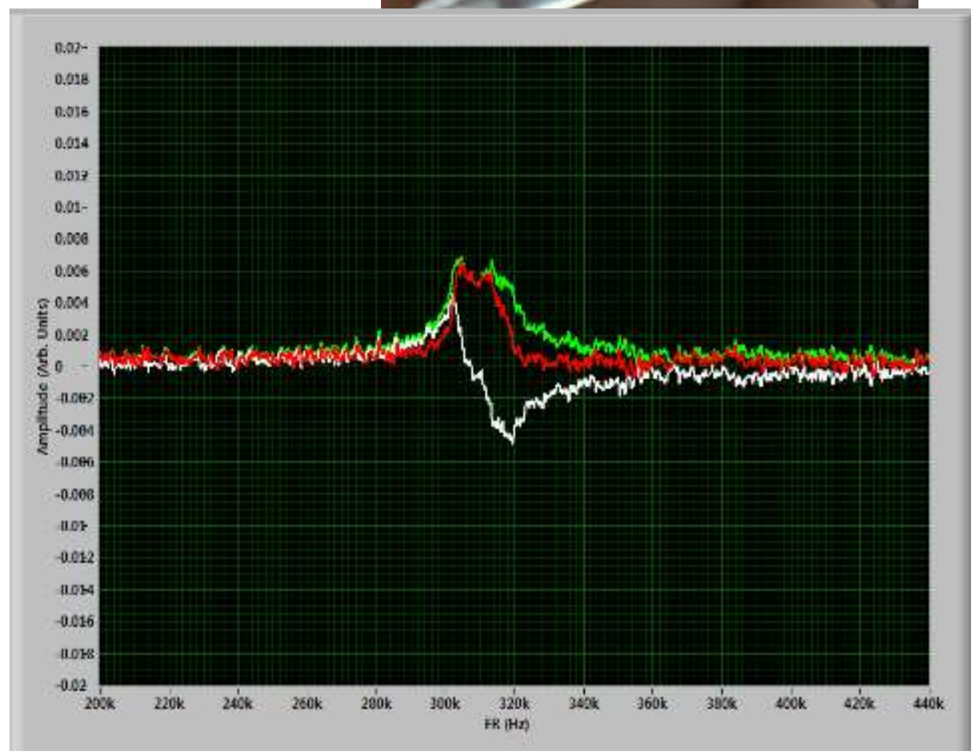
# 400 MHz conduction cooled NMR : $^{1}$H NMR Signal






- **Future works**
  - ✓ Faster charging rate
  - ✓ Investigation of field profile
  - ✓ Shimming

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# Summary

- SuNAM has been producing high $I_C$ coated conductors consistently.
- Introduction of in-line Q.C. measures enhanced wire uniformity & production yield.
- With thicker(1.3 μm → 1.6 μm) S.C. layer, we achieved >1,000 A/12 mm in production.
- We have made different kinds of NI(including MCI) magnet for various applications.

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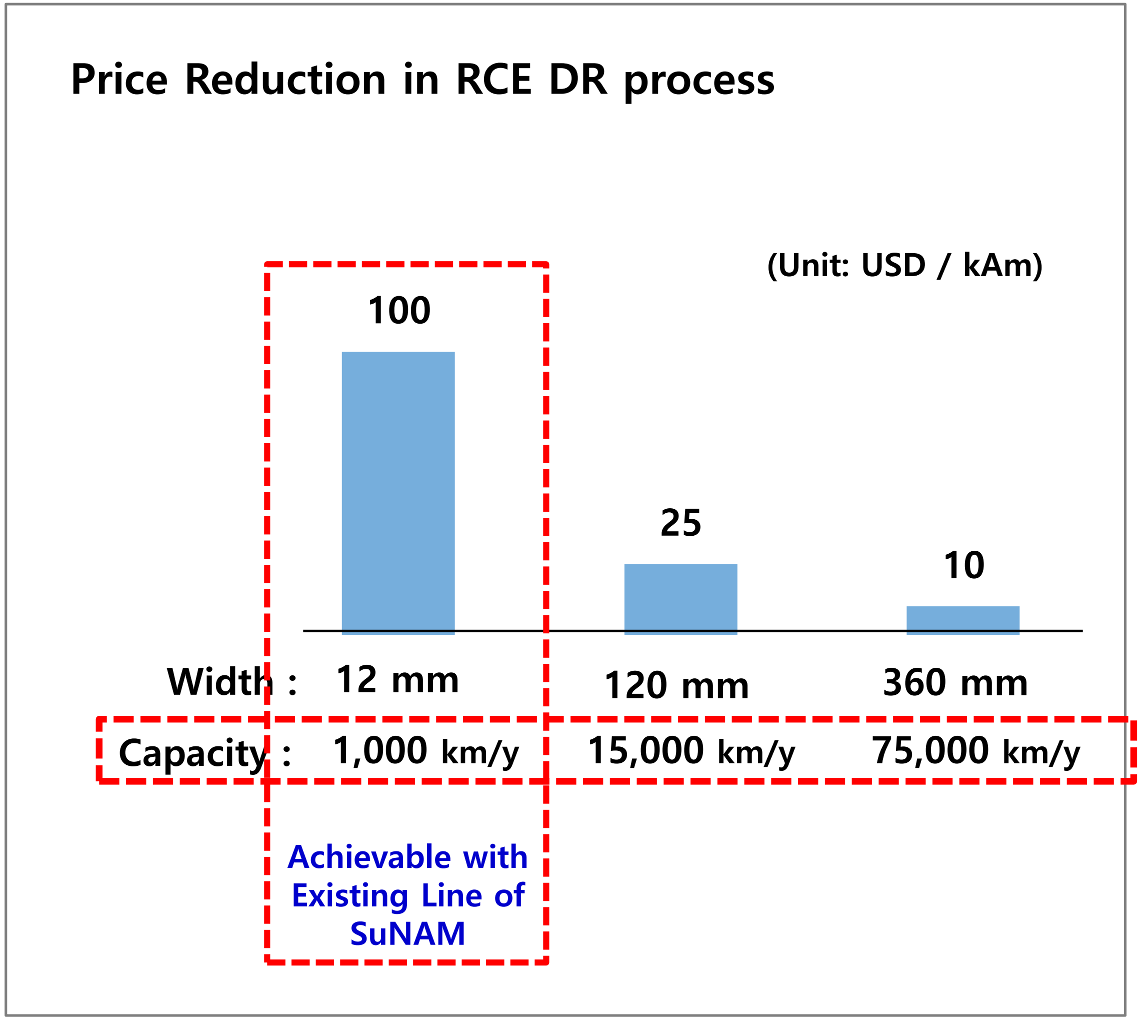
# Direction of Technology Development in the Future
## - HTS 2G wire

"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"

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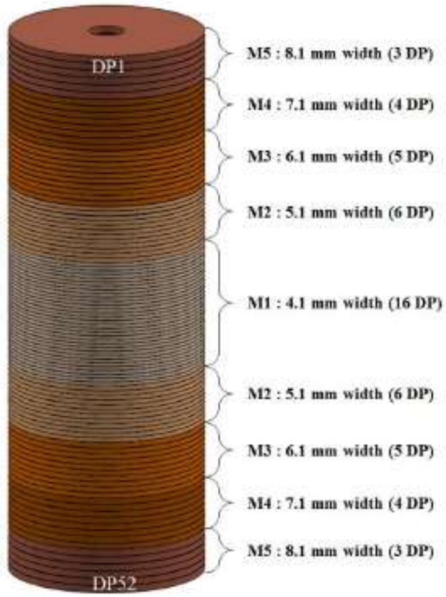
# Direction of Technology Development in the Future - HTS Magnet

- For NMR magnet, near term(2017), 400 MHz cryogen free system with shimming.
  → will go to > 1.3 GHz proto-type.
- For R&D magnet, next goal is 35 T, 35 mm user magnet (2019 KBSI-MagLab-SuNAM).

*35 T 35 mm All-REBCO User Magnet (2019, KBSI-MagLab-SuNAM)*

- High Field DC User Magnet at KBSI after Successful Completion in 2019
  - "*Standalone* (single stack of DP coils)": 40 mm ID; *222 mm OD*
  - Estimated $\tau_c$: 19.4 min with "NI"; 2 min with "metallic cladding".




*35 T Magnet in the Existing Multi-Purpose Cryostat at KBSI*

Ref: S. Hahn, et al., "Design of a 35 T 35 mm Multi-Width No-Insulation All-REBCO Magnet," 1LOr2A-05.

SuNAM | NATIONAL HIGH MAGNETIC FIELD LABORATORY | KBSI KOREA BASIC SCIENCE INSTITUTE

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- KERI : H. S. Ha, S. S. Oh.
- Korea Polytech. Univ. : G. W. Hong, H. G. Lee.
- Andong Nat'l Univ. : H. S. Shin.
- Changwon Nat'l Univ. : M. W. Park, S. H. Kim.
- KBSI : S. G. Lee.

- Stanford Univ. : R. H. Hammond.
- iBeam Materials : V. Matias
- Univ. of Cambridge : J. M. Driscoll
- FSU/NHMFL : (S.Y. Han), D. Labalastier
- MIT : Y. Iwasa


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Thanks for Attention !
감사합니다 !