HTS Development and Industrialization at SuNAM

Seung Hyun Moon
SuNAM Co., Ltd.

2014. 05. 21.

@ 1st Workshop on Accelerator Magnets in HTS

Contents

Industry of HTS Tapes: performance, length, yield, width. Is it possible to think of round wire? What is now, in 2 years and in 5 years?

- **Brief introduction to SuNAM**

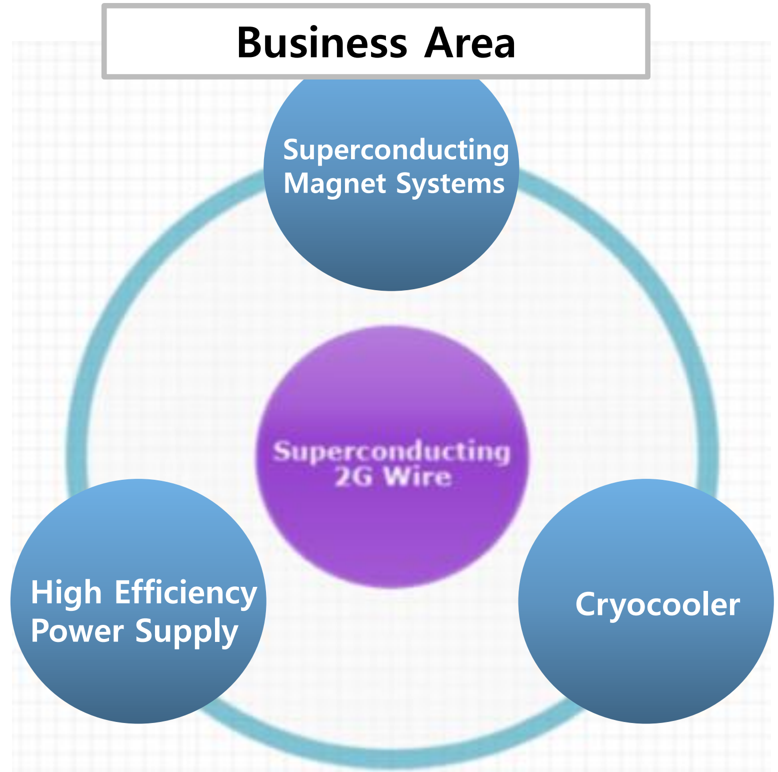
- **SuNAM's strategy to practical 2G wire (performance, price & availability)**
  - **Strategy : performance, throughput & yield.**
  - **RCE-DR :The highest throughput unique SuNAM's process.**

- **SuNAM's now & the future direction**
  - **Now : product performances & customer oriented R&D results.**
  - **Future : wide strip full in-line process & ready for use 2G wires.**

Company Overview

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

Establishment	2004. 11. 17.
CEO	SeungHyun Moon / SoonChul Hwang
Registered Capital	$3M
No. of Employees	~ 59 (10 Ph.Ds)
H.Q.	Gyeonggi-do, Korea
Current Production Capacity	~ 60 km / month (4 mm/ > 150 A)
Core Technology	2G HTS manufacturing technology based on RCE-DR process



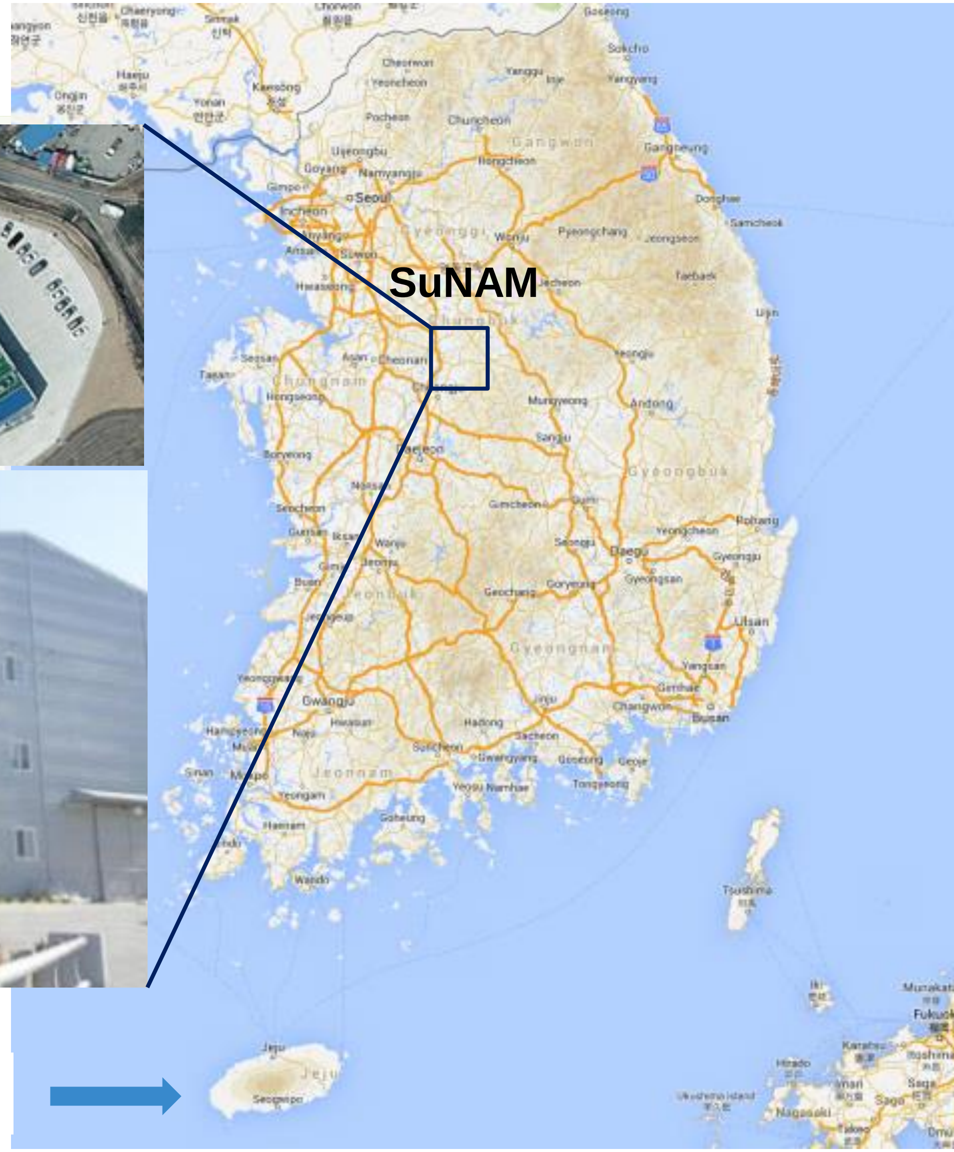
SuNAM is a technology-intensive venture company established to achieve a noble mission, a commercialization of superconductor and cutting-edge/nano materials.

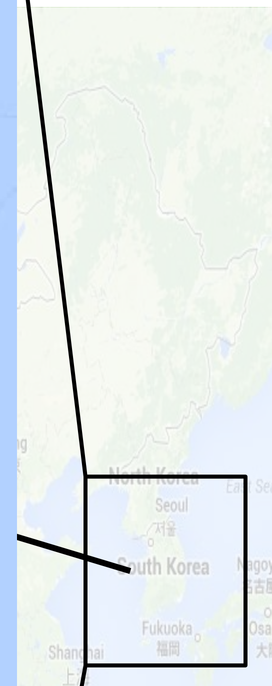
SuNAM, a specialized green energy material company, pursues the second generation HTS wires and its applications along with associated equipment system under the motto,

"Development of highly efficient and environmentally friendly energy-use technology"

SuNAM's Location

60 km south from Seoul





CCA 2014 in Jeju

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

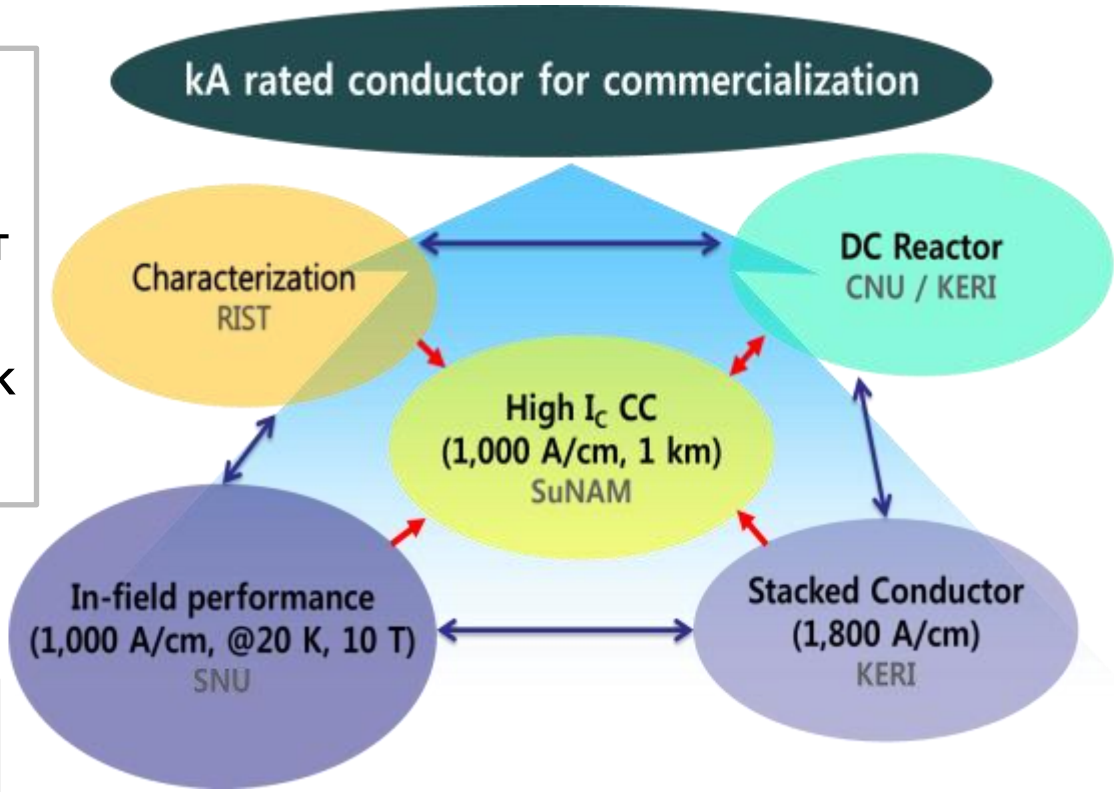




New Gov't Sponsored Coated Conductor Project

Target

- Critical current; I_C > 1,000 A/cm @77 K, s.f. (length > 1 km, uniformity > 96%)
- In-field performance; I_C > 1,000 A/cm @20 K, 10 T
- Stacked conductor; I_C > 1,800 A/cm @77 K, s.f.
- I_C measurement tech.; 0-10 T, > 1,800 A/cm, 20~77 K
- DC reactor demo; 400 mH, 1,500 A



Budget

~US$13M; $9M from Gov't, $4M from SuNAM
(June 2013 ~ May 2017, 4 years)

Sponsored by Ministry of Trade, Industry & Energy(MOTIE), through Inst. of Energy Tech. Evaluation and Planning(KETEP)

SuNAM

SuNAM's Strategy to Practical 2G Wire (Performance, Price & Availability)

SuNAM

Motivation

…there is a technology gap from 2G wire to practical applications…

2G Manufacturer

SuNAM, AMSC, Bruker, d-nano, Fujikura, Sumitomo, Superpower, STI, Theva, …

Industry

AMSC, Bruker, GE, Innopower, LS Cable, Nexans, nkt cables, Oswald, Siemens, Sumitomo, Southwire, …

Industry needs

- **Scalable currents and various geometries**
- **Reproducible quality and quantity within an acceptable time**
- **Mechanical and electrical stability**
- **Low degradation, long lifetime**
- **Reliable and specific electrical insulation**
- **Simple, low ohmic contacts and joints**
- **Low losses**
- **Competitive cost**
- **….**

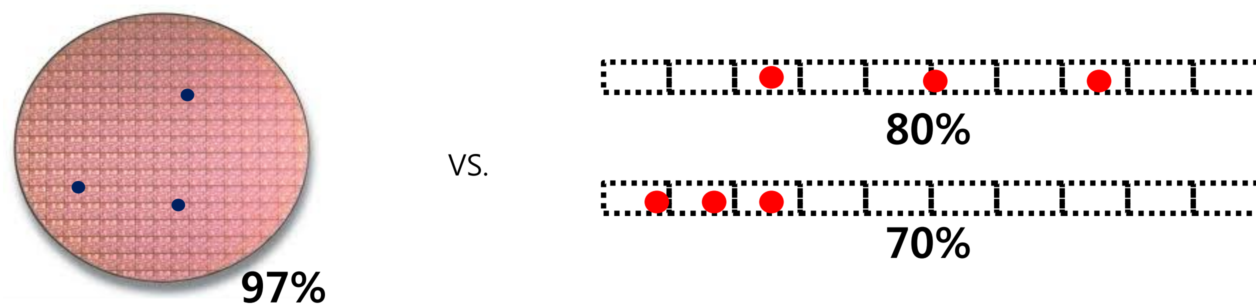
- presented by KIT

…there is a need for ready to use 2G conductor concepts…

How can we realize practical HTS 2G wire? (I)

- Performance : architecture, processes(materials including HTS & packaging)
  - High critical current(Ic) & critical current density(Jc, Je) at the specific application conditions(temperature(T) & B-field(B, q)).
  - Good mechanical properties(Ys) & low ac loss.
  - Stabilities : mechanical, electrical, low degradation, long life-time in shelf.
  - Ready to use : insulation, joint, ohmic contact, piece length & geometries.

- Yield : Important for availability & cost!!
  - Numbers of process?? → $0.9^5 = 0.59$, $0.9^{10} = 0.35$, $0.95^{10} = 0.60$…
  - Process margin is more important in our experiences.
  - Yield definition?



How can we realize practical HTS 2G wire? (II)

- Throughput : Important for availability & cost!!

Throughput is the key

Equipment cost share = capital investment / throughput

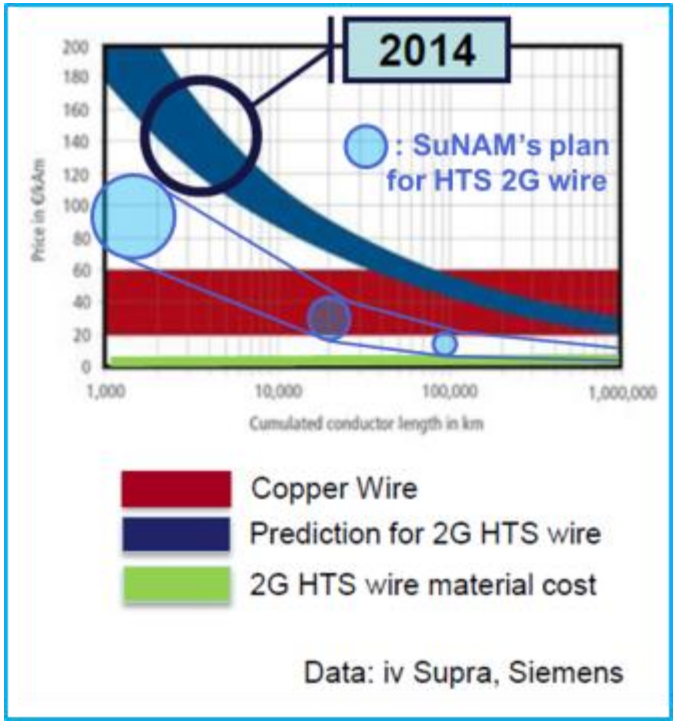
↑ Key to lowering cost

Throughput ≡ volume production rate

P = A × R = L × W × R ≡ v × W × D

- A: processing area (↑ Wide web process !!)
- R: thickness growth rate ⇓ ~~physically limited (material property)~~ → RCE-DR (melt growth)
- L: tape length
- W: tape width
- v: tape speed
- D: film thickness

THEVA creating the future



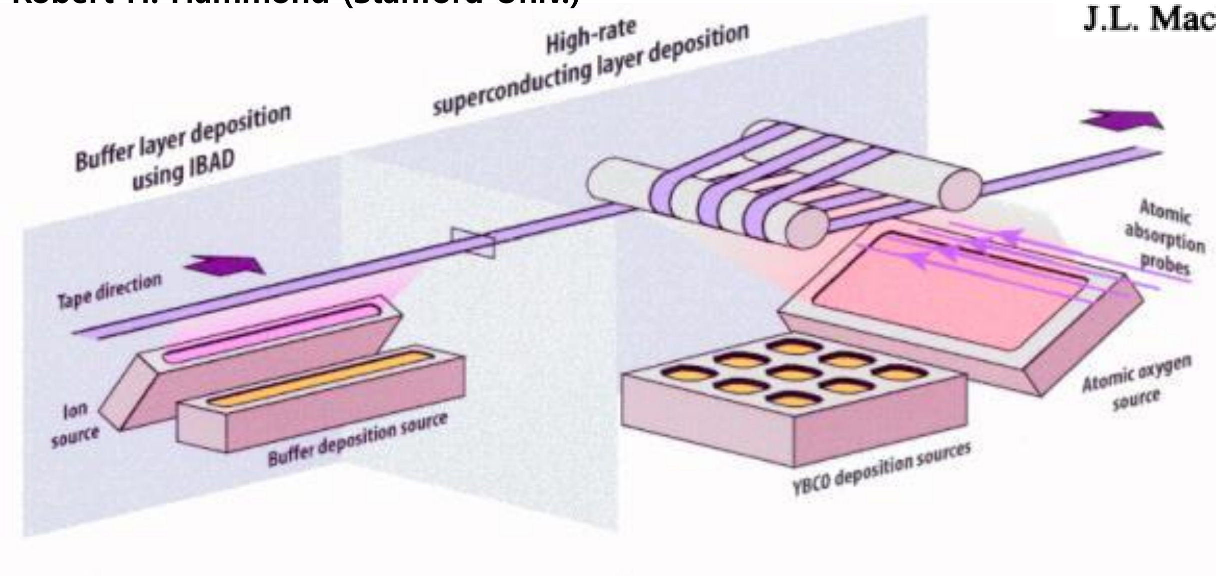
- ➢ RCE DR : ~ 100 nm/sec or faster (SuNAM)
- ➢ PLD, MOCVD ~ 10 nm/sec, MOD ~ 1 nm/sec

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

SuNAM

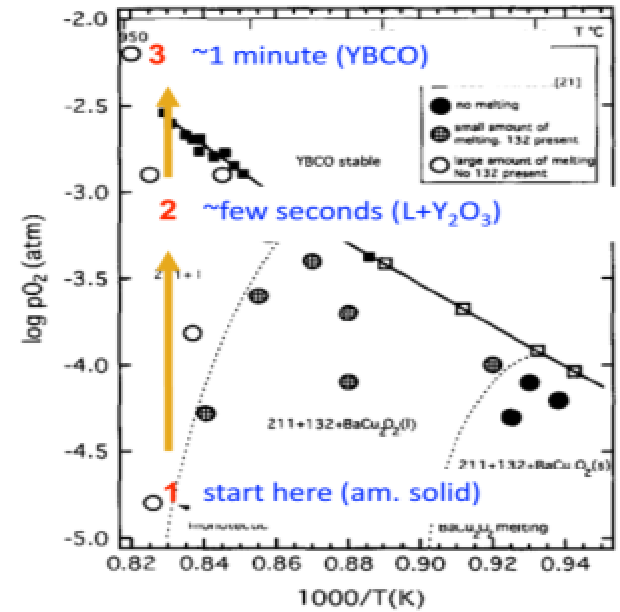
Scale up Issues: IBAD & *in-Situ* High Rate E-Beam

Robert H. Hammond (Stanford Univ.)



Physica C 241 (1995) 401–413

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



- **New Ideas, Directions?**
  - **High rate, large area, high I_C and low cost of paterials processes will eventually be required – not immediately but in 10 years.**
  - **High rate may require growth in liquid flux.**

Cost Example

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

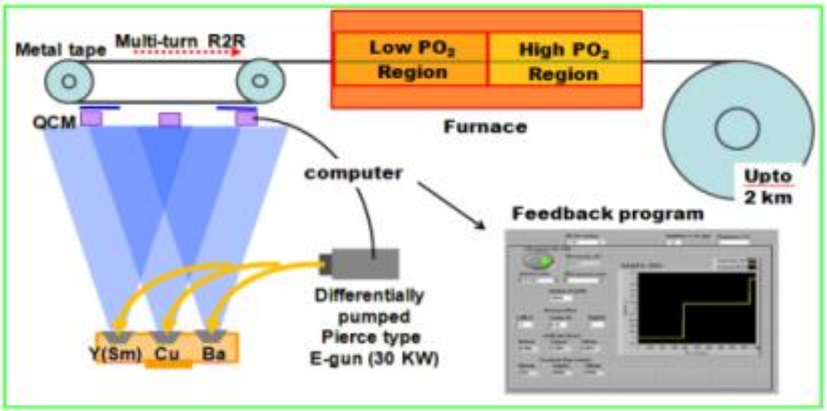
Study ISS' 95:

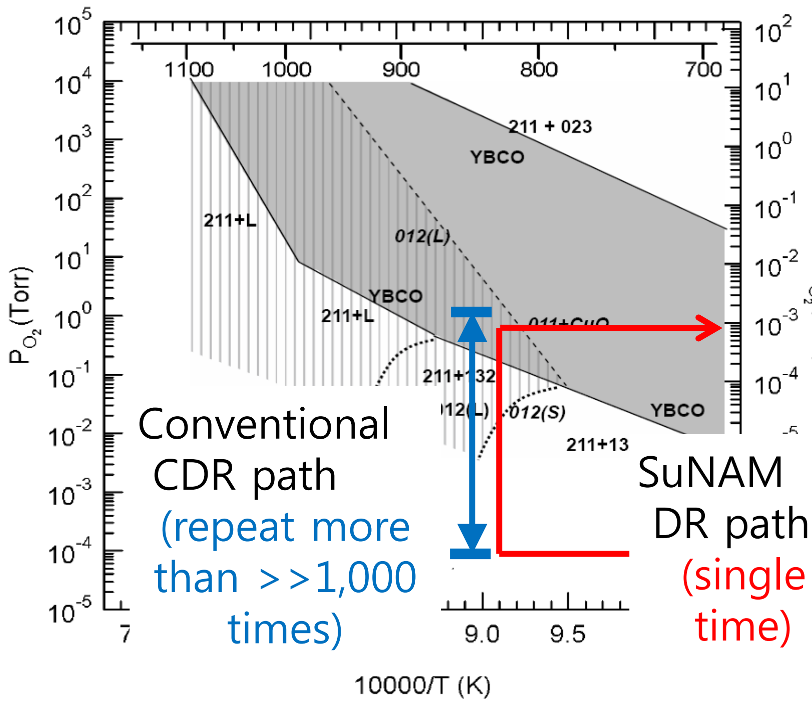
$$\begin{Bmatrix} R = 100\,\mathring{A}/\sec \\ L = 30cm \\ W = 1meter \\ J_c = 10^6\,A/cm^2 \end{Bmatrix} \rightarrow$$

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

SuNAM

RCE-DR process by SuNAM

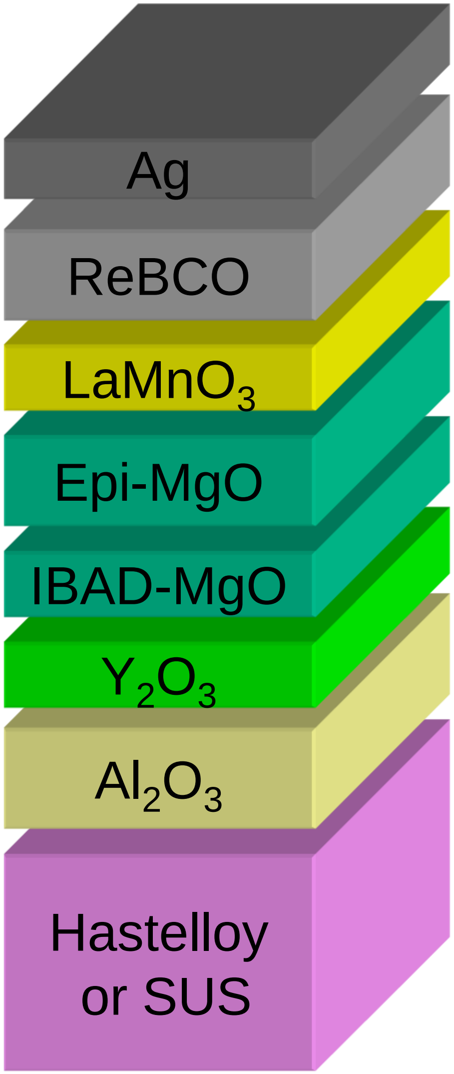




- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R) : Patent pending(PCT)
- High rate co-evaporation at low temperature & pressure to the target thickness(> 1 μm) at once in deposition zone (6 ~ 10nm/s)
- Fast (<< 30 sec.) conversion from amorphous glassy phase to superconducting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

SuNAM's Now

SuNAM's 2G Wire Architecture – 12 mm width



Protecting layer (0.6 μm)	DC sputter
Superconducting layer (1.3 ~ 1.5 μm)	RCE-DR
Buffer layer ~20 nm	sputter
Homoepi-MgO layer ~ 20 nm IBAD-MgO layer ~ 10 nm Seed layer (Y_2O_3) ~ 7 nm Diffusion barrier (Al_2O_3) ~ 40 nm	IBAD (sputter & E-beam)
Hastelloy C276 (Ni-alloy tape) or Stainless Steel-tape	Electro -polishing

or SDP (Solution Deposition Planarization) [alternative to the IBAD seed/diffusion barrier layers and electro-polishing]

(+ Cu electroplating (+ lamination))

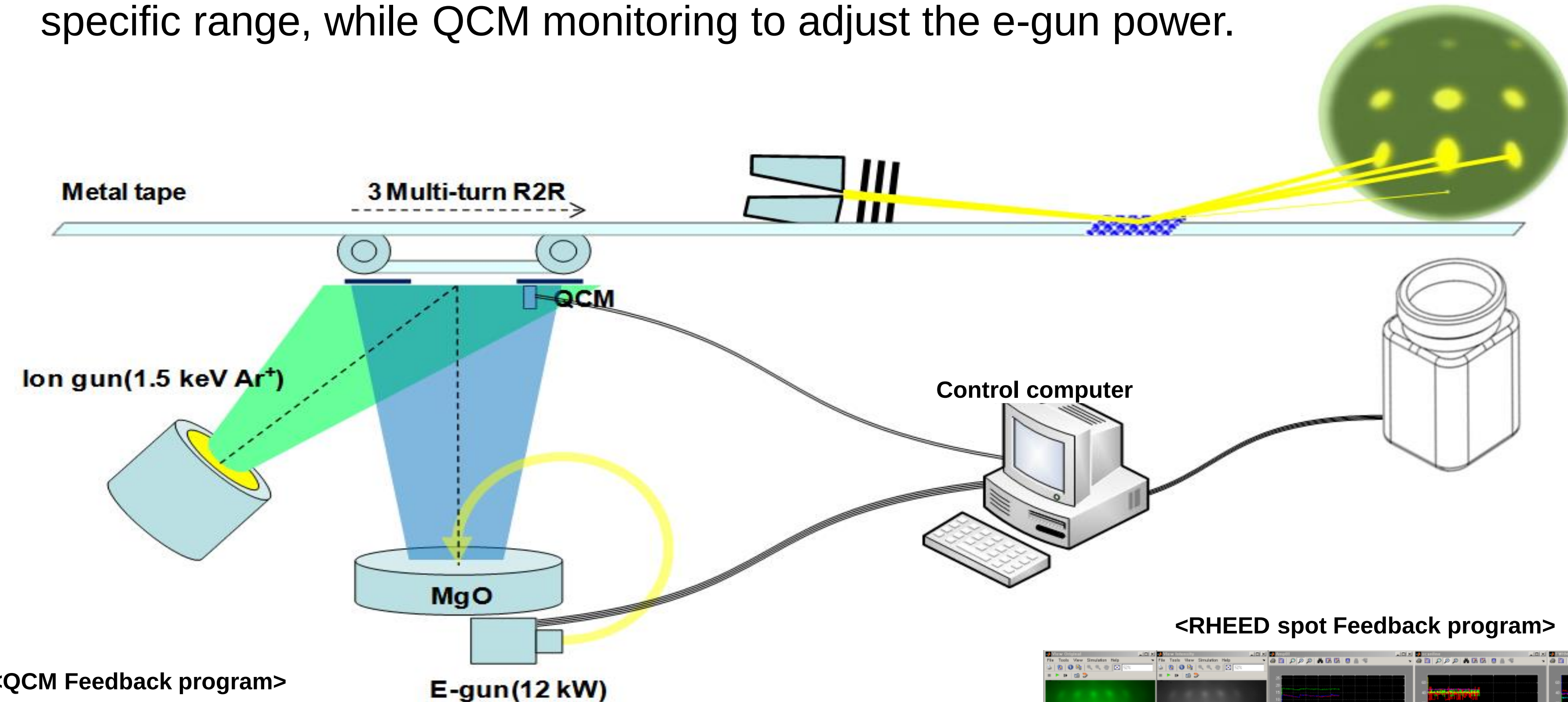
* Linear speed of each process : 120 m/hr or more.

- Typical I_c ~ > 700 A/12 mm at 77 K self-field (J_c > 4 MA/cm^2)

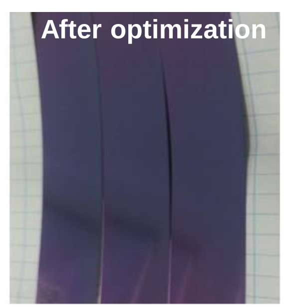
SuNAM

Quality Control : RHEED Vision System

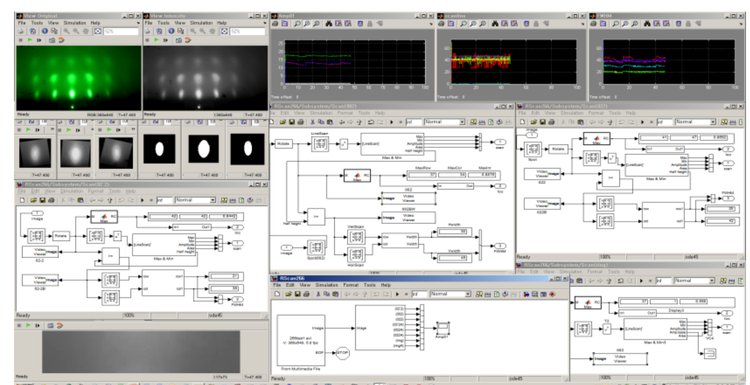
- An appropriate feedback algorithm can keep the shape of the RHEED spot in the specific range, while QCM monitoring to adjust the e-gun power.



<QCM Feedback program>



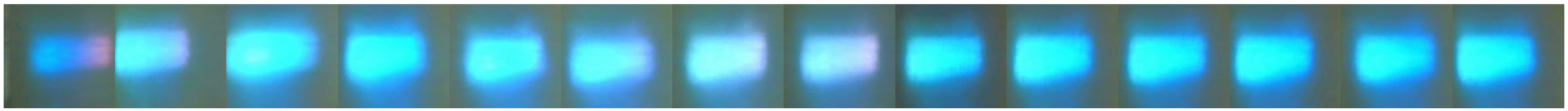
<RHEED spot Feedback program>



Quality Control : RCE Vision System

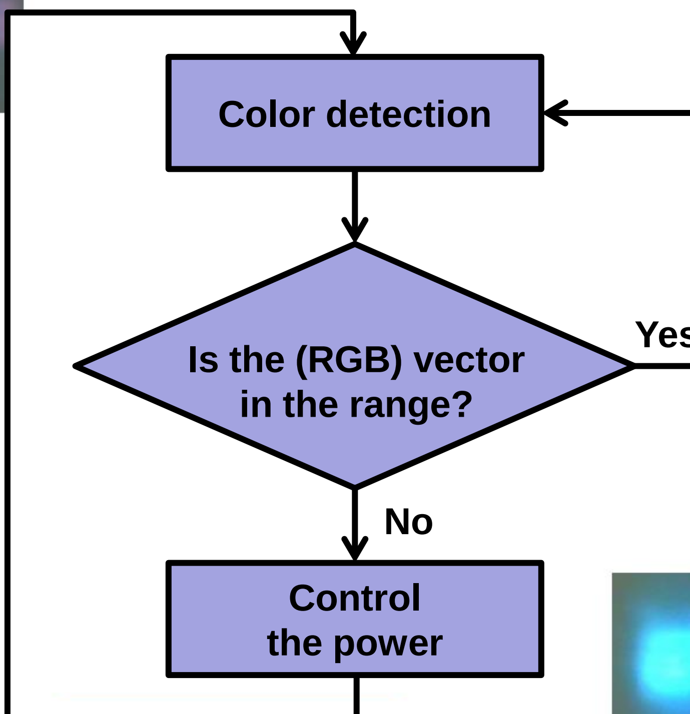
- RCE Vision System will be introduced for increasing the uniformity of composition in RCE-DR process. The control computer takes (RGB) values in three-dimensional vector space which is transformed from the color of the tape surface.

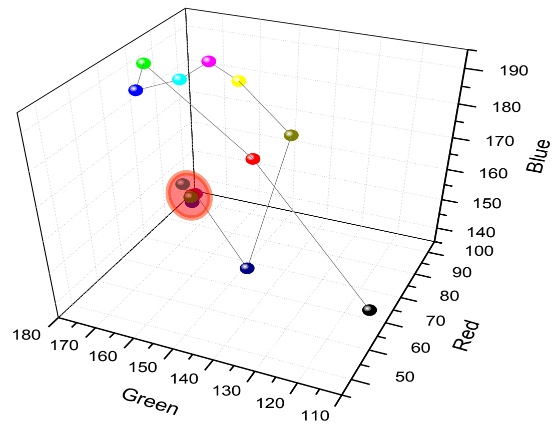
[Start]



[End]

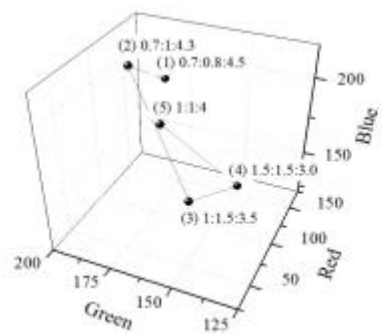
Start color

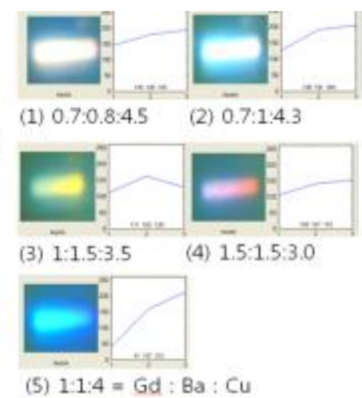




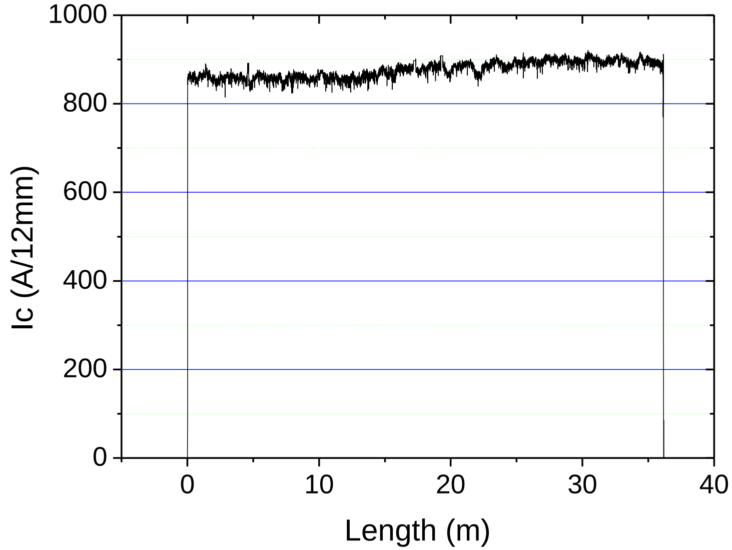
End color

(79,166,189)



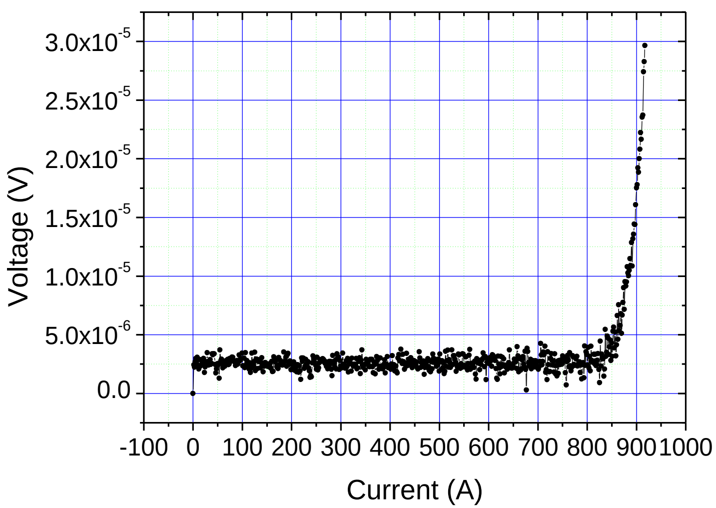


Optimization Properties of GdBCO CC on STS substrate

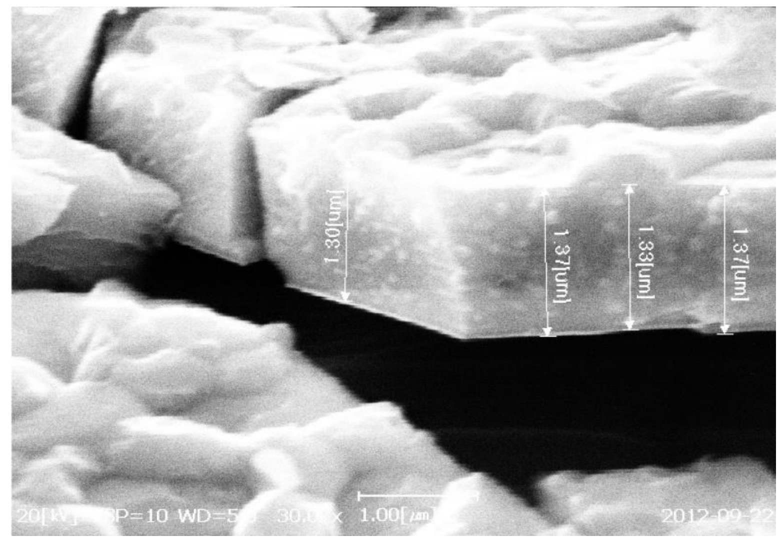


Average Ic = 742 A/cm

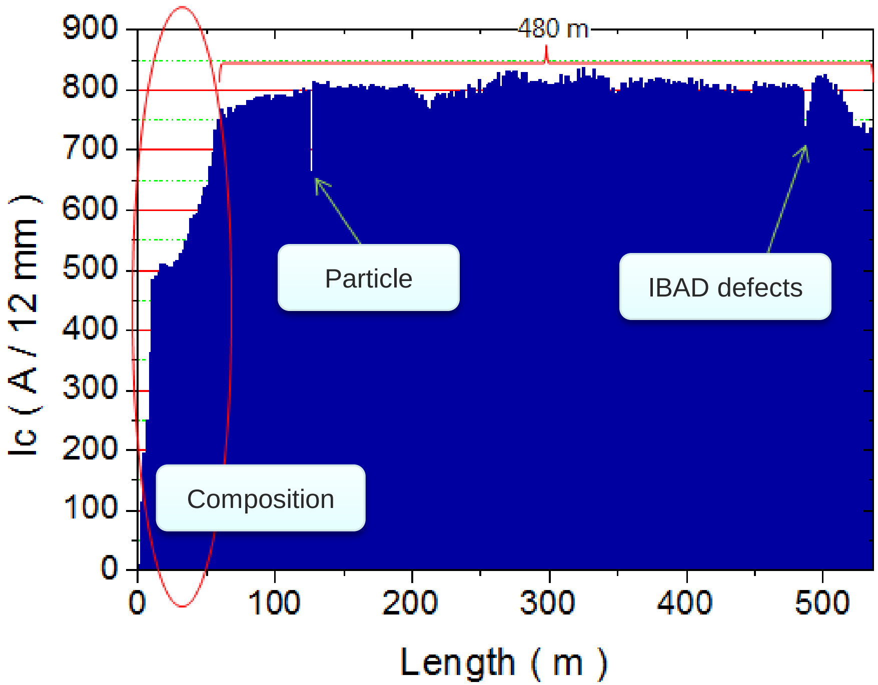
Jc ~ 5.3 MA/cm^2



Thickness : ~ 1.32 um

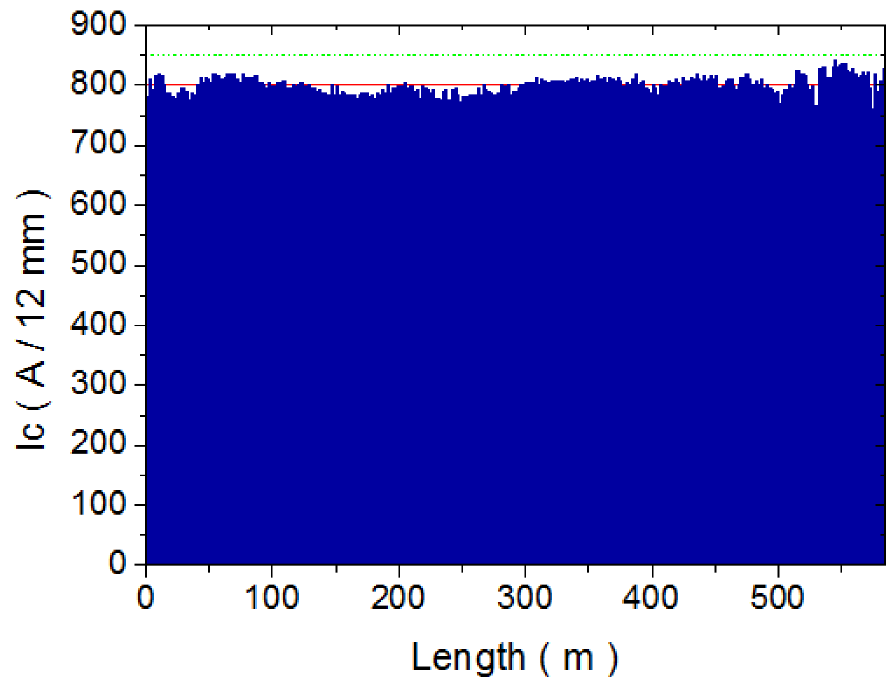


RCE-DR Results on Stainless Steel Substrate



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



Width (mm)	Length (m)	AVG.Ic (A)	1σ(A)	Min.Ic (A)	Max.Ic (A)	COV(%)	Ic x L (Am)
12	582	800	14	759	843	1.7	441,963
10		667	11	633	702		**368,303**

$$COV_{|min-max|} = \frac{|I_{C,max} - I_{C,min}|}{\bar{\chi}} \times 100(\%)$$

$$COV(\text{coefficient of variation}) = \frac{\sigma}{\bar{\chi}} \times 100(\%)$$

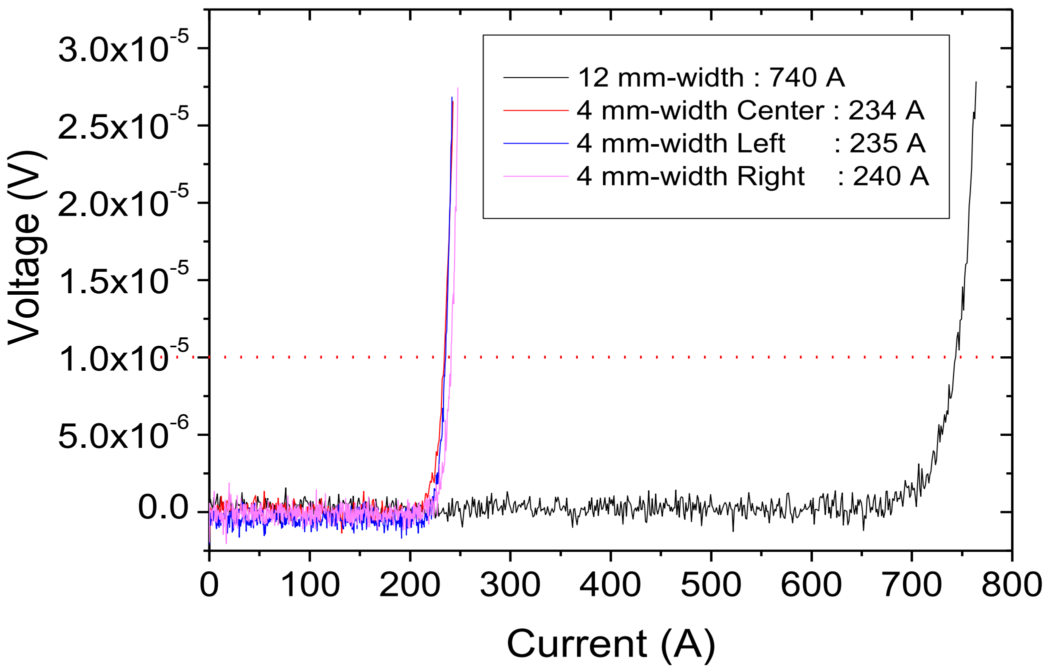
σ : Standard Deviation, $\bar{\chi}$: Mean I_C

SuNAM

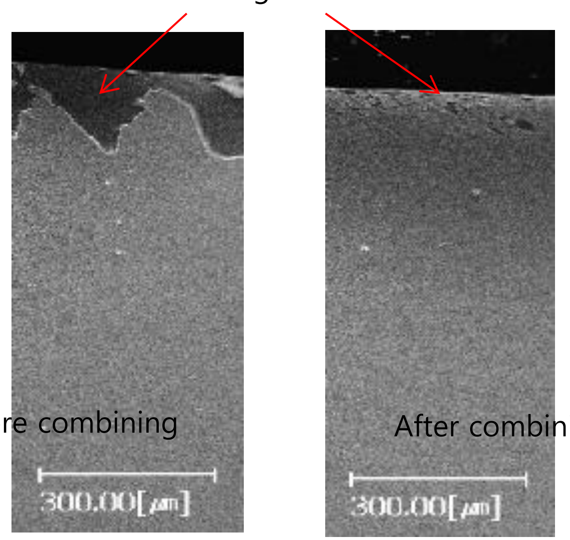
Combining Barrier, Seed, IBAD, Buffer Systems in One

System for Al_2O_3 barrier & Y_2O_3 seed

System for IBAD, homo-epi & buffer



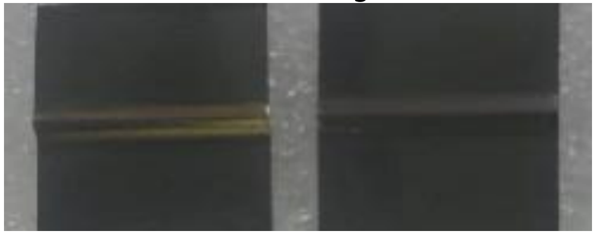
Cutting side



Before combining

After combining

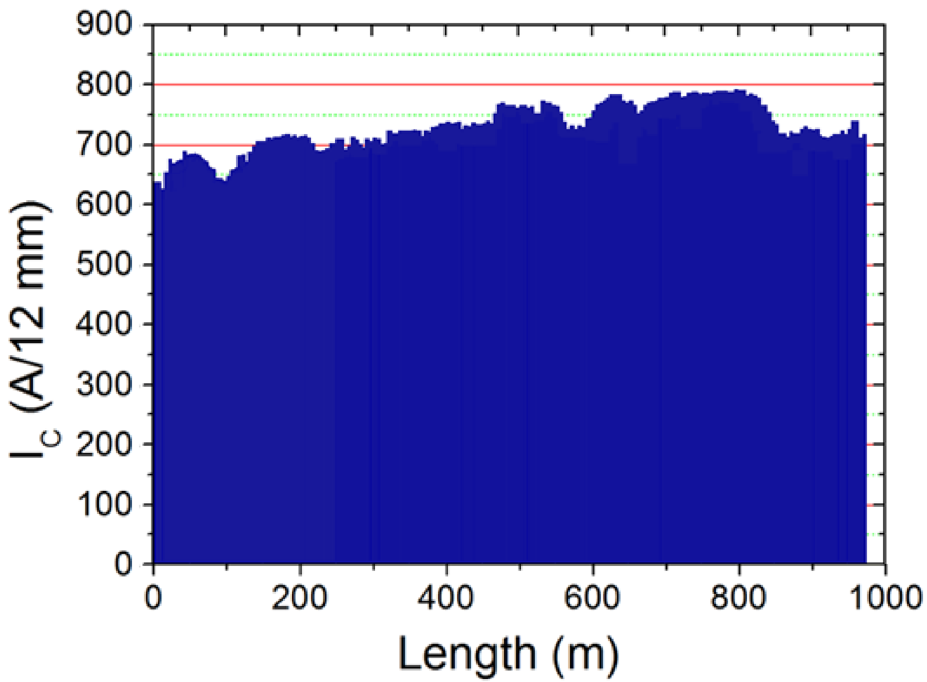
After bending



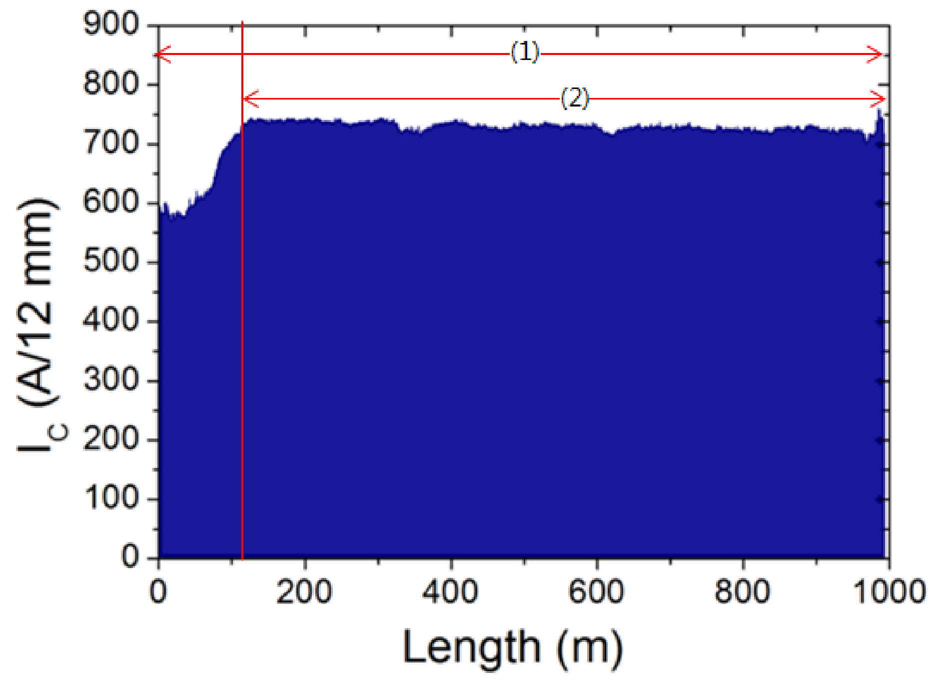
We can achieve higher yield > 70 %

SuNAM

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	975	730	39	626	792	5.3	610,350
10		608	33	522	660		**508,625**

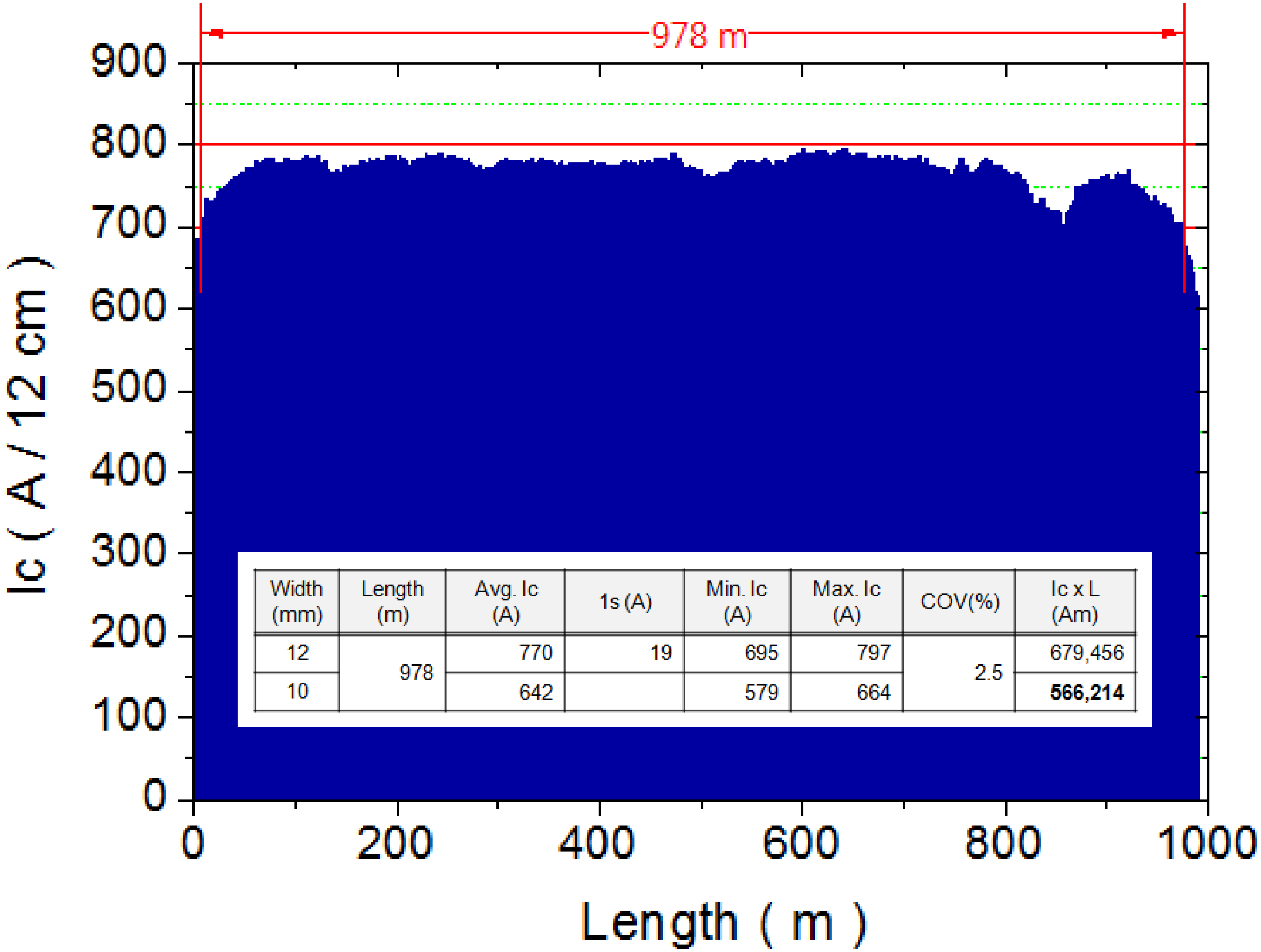


Width (mm)	Length (m)	AVG.Ic (A)	1σ(A)	Min.Ic (A)	Max.Ic (A)	COV(%)	Ic x L (Am)
12	980	710	36	571	760	5.1	559,776
10		592	30	476	633		**466,480**

Width (mm)	Length (m)	AVG.Ic (A)	1σ(A)	Min.Ic (A)	Max.Ic (A)	COV(%)	Ic x L (Am)
12	860	732	18	720	760	2.5	618,770
10		610	15	600	633		**515,642**

SuNAM

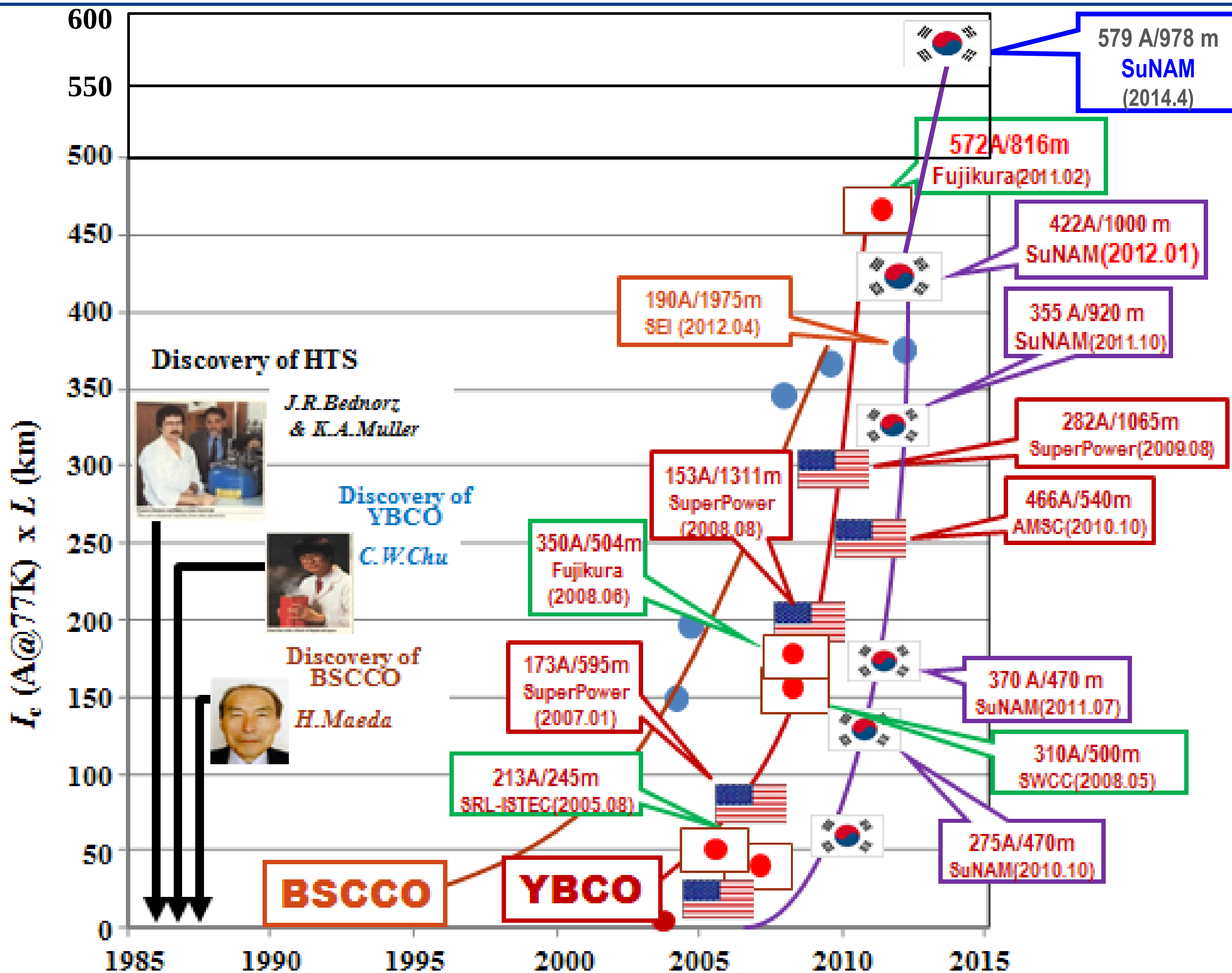
RCE-DR Results on Stainless Steel Substrate



Width (mm)	Length (m)	Avg. Ic (A)	1s (A)	Min. Ic (A)	Max. Ic (A)	COV(%)	Ic x L (Am)
12	978	770	19	695	797	2.5	679,456
10		642		579	664		**566,214**

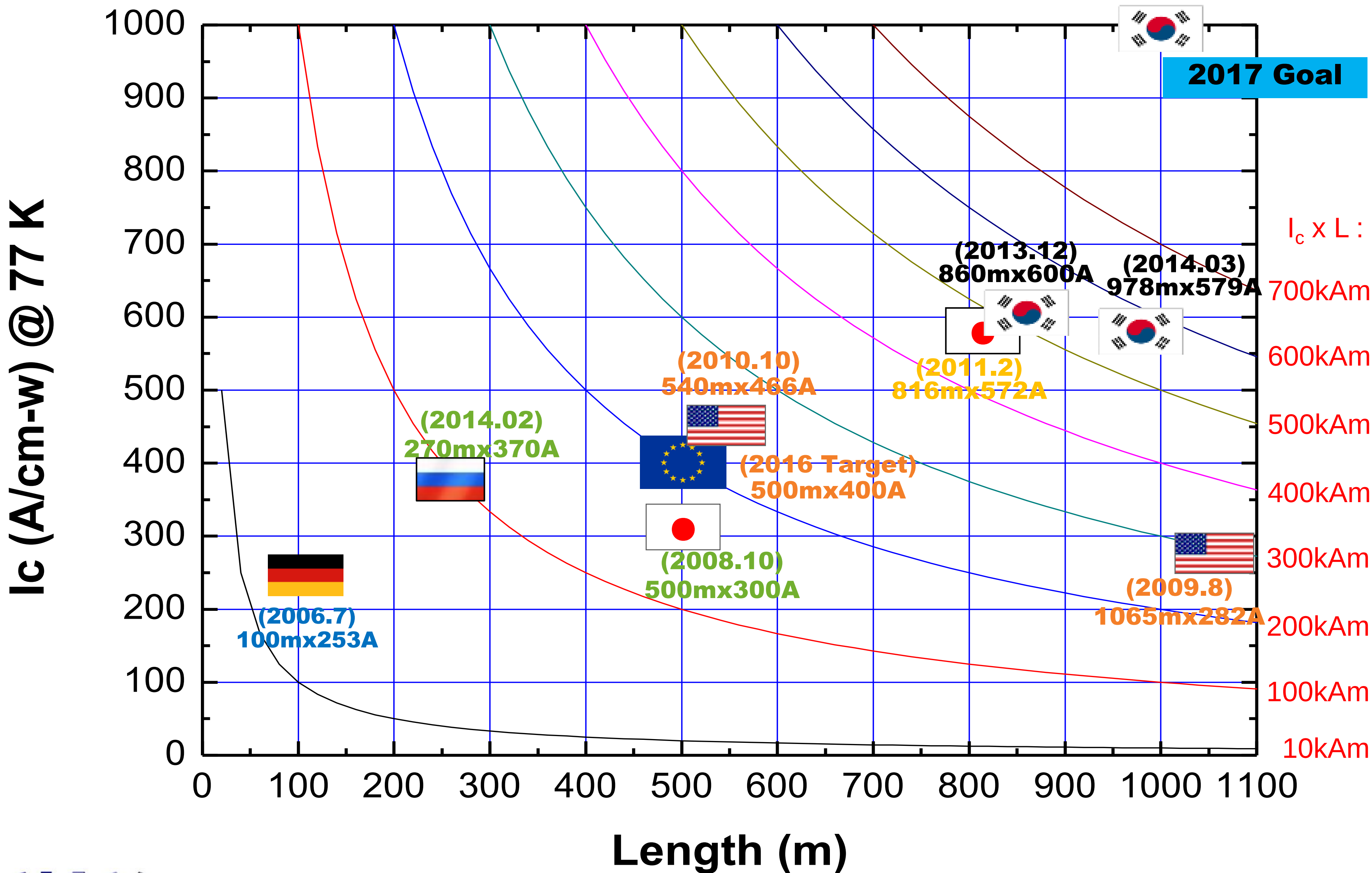
SuNAM

Development of HTS 2G Wire



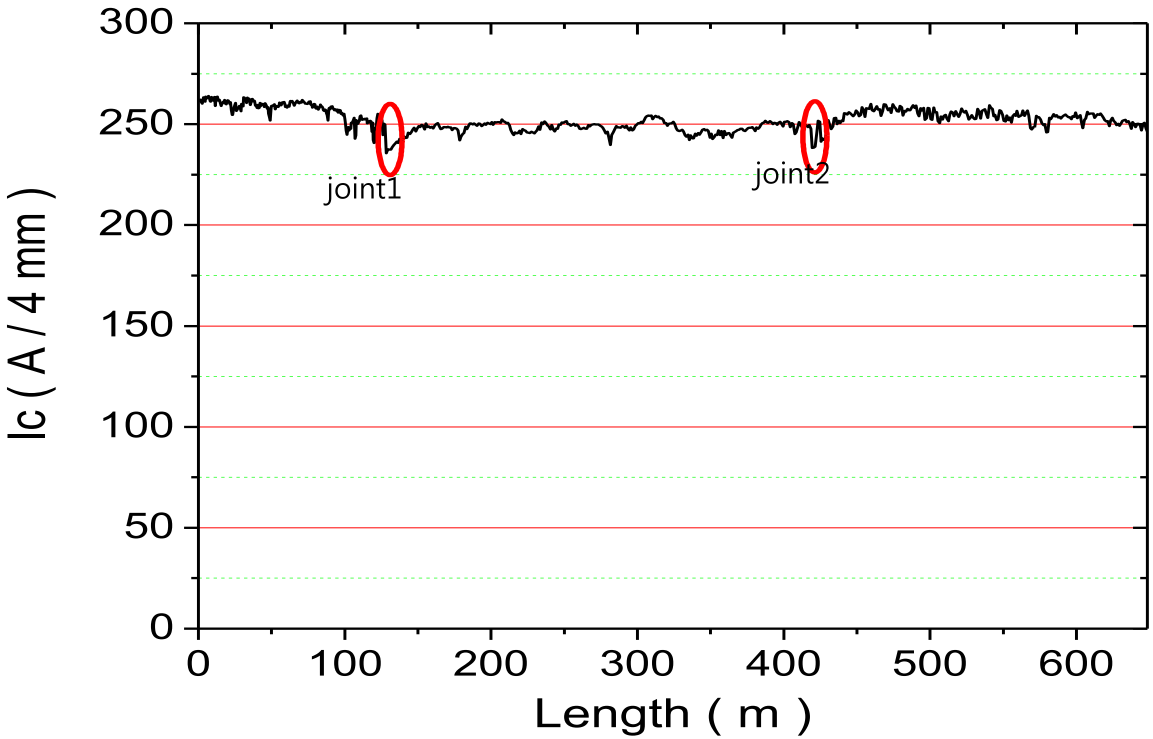
(by Dr. Izumi, ISTEC, Japan & EUCAS2013)

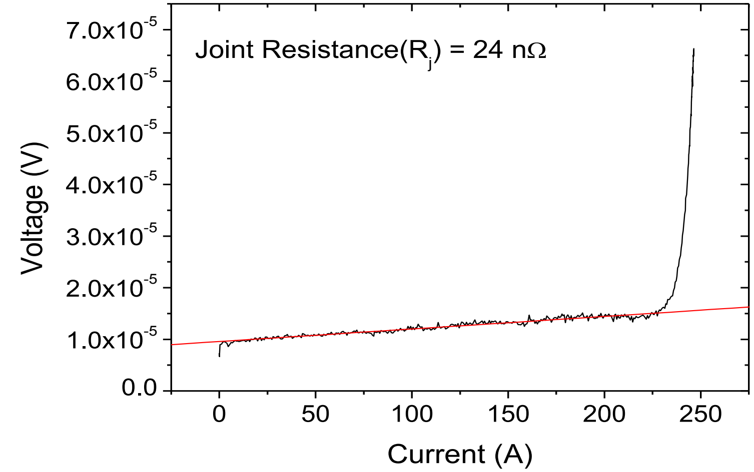
Development of HTS 2G Wire

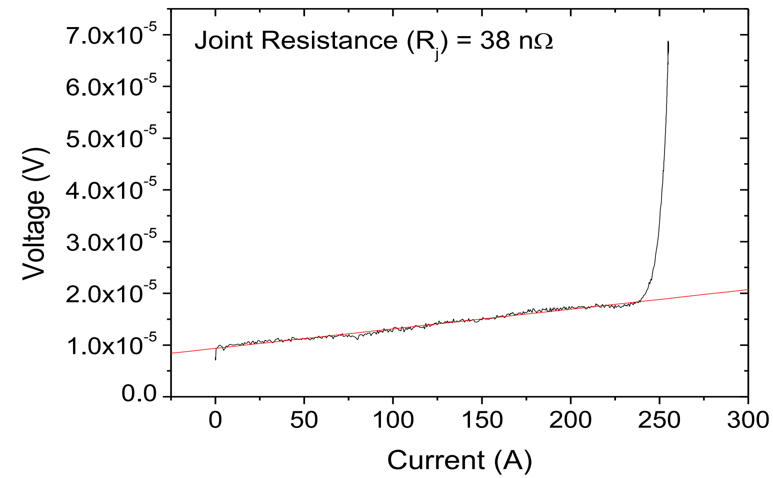


SUNAM

I_C/4mm and Joint Resistance for Brass Laminated CC



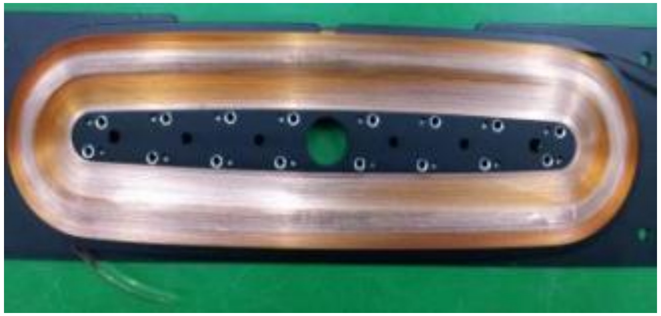


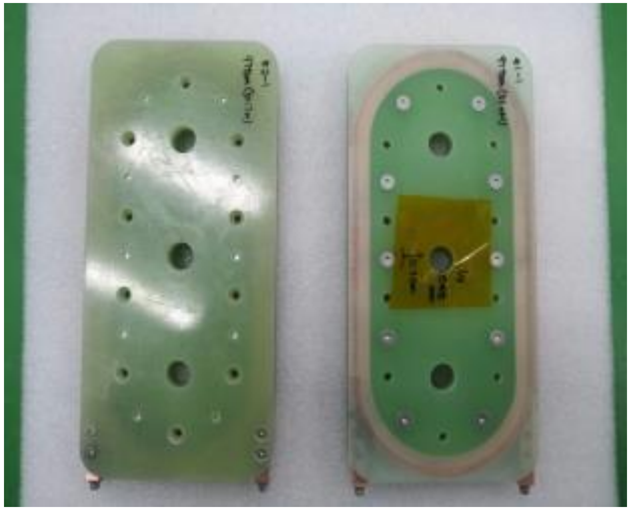


Width (mm)	Length (m)	AVG.Ic (A)	1σ(A)	Min.Ic (A)	Max.Ic (A)	COV(%)	Ic x L (Am)
4	649	253	6	236	264	2.2	153,164
10		633	14	590	660		382,910

- Joint overlap length : typically 100~150 mm

Coil Example





Paraffin molding

→ **Coil winding service up to 1.4 m diameter is available now**

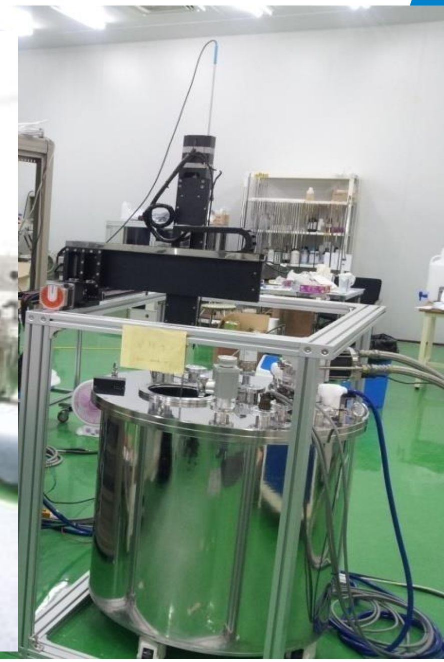
→ **No-insulation, polyimide(tape & solution) insulations**

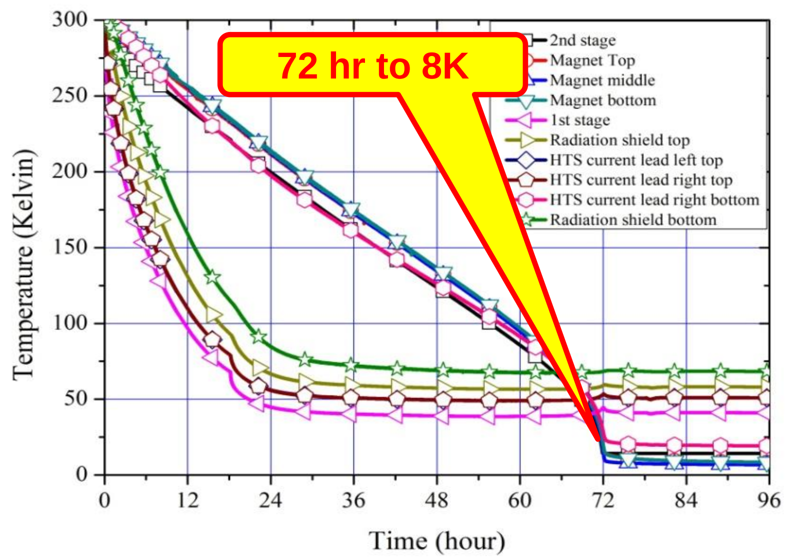
→ **Various kinds of epoxy, paraffin molding(or wet winding)**

SuNAM

4T, 203 mm Diameter RT Bore Cryogen Free Magnet

Superconducting magnet parameter			
Conductor	Width; Thickness	[mm]	4.1(12.1); 0.21(0.1)
	Ic @ 20 K, B⊥=1.5 T	[A]	> 180A
Coil	# of DP coils, (4mmW; 12mmW)		**28; 2**
	turn per pancake		133
	Winding i.d.; o.d.;	[mm]	245(274); 300.9
	Overall height	[mm]	452
	Conductor per DP (4mmW; 12mmW)	[m]	**232; 255**
	Total Conductor (4mmW; 12mW)	[m]	**6,496; 510**
Operation	B_c	[T]	4.0
	I_{op}	[A]	205
	T_{op}	[K]	8
Cryostat	Clear bore	[mm]	**203**
	Cold bore	[mm]	245



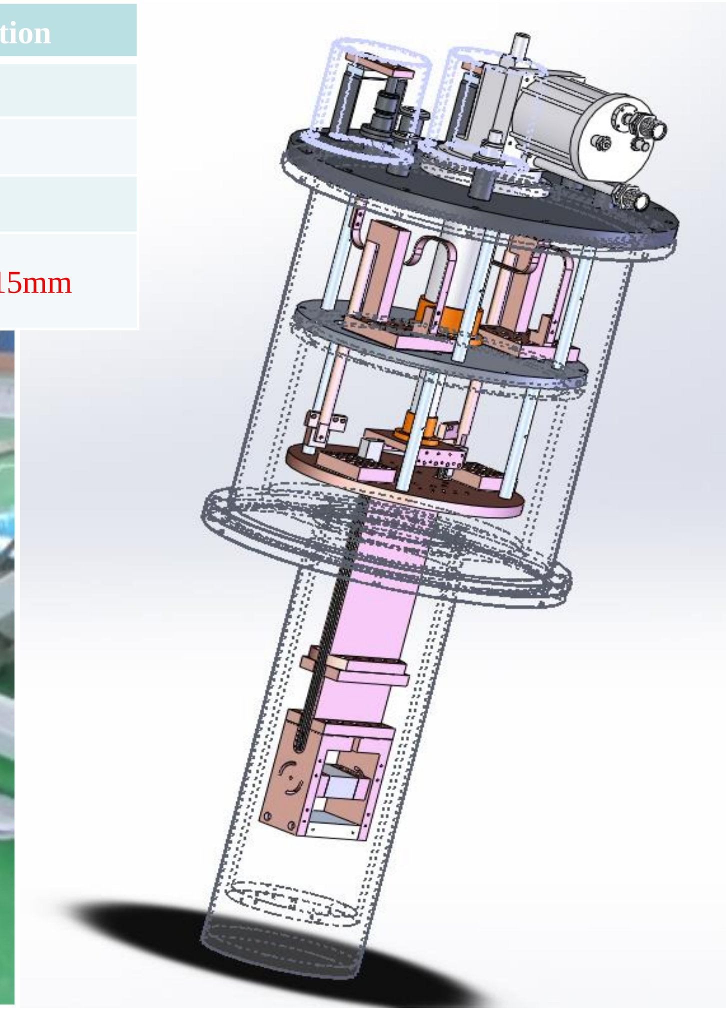


SUNAM

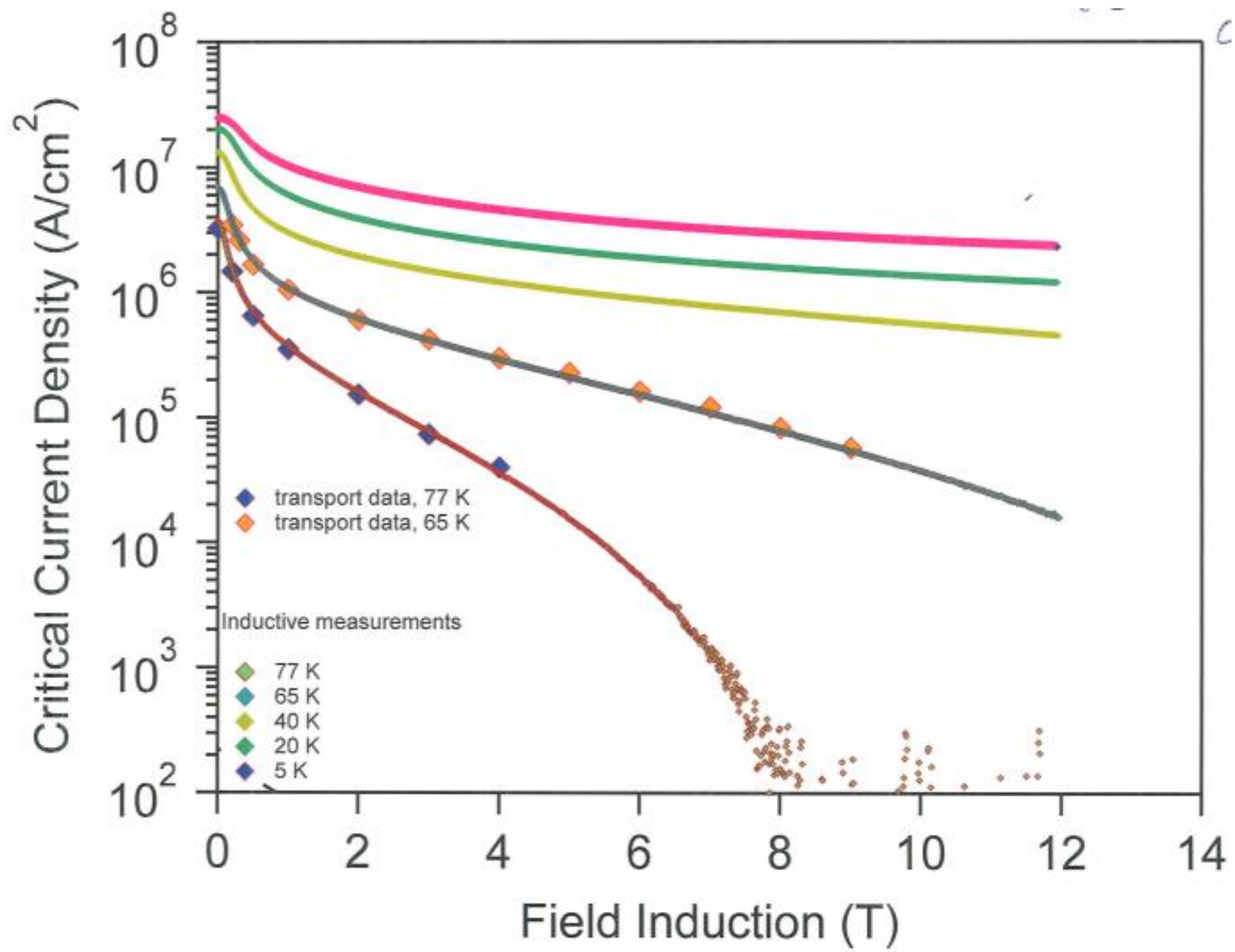
MIT MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Development of Ic (B, T, ϴ) Measurement System

Parameters	Specification
Maximum current	1000A
Temperature	12K ~ 70K
Angle	0~135°
Sample length, width	30 ~ 90mm, <15mm



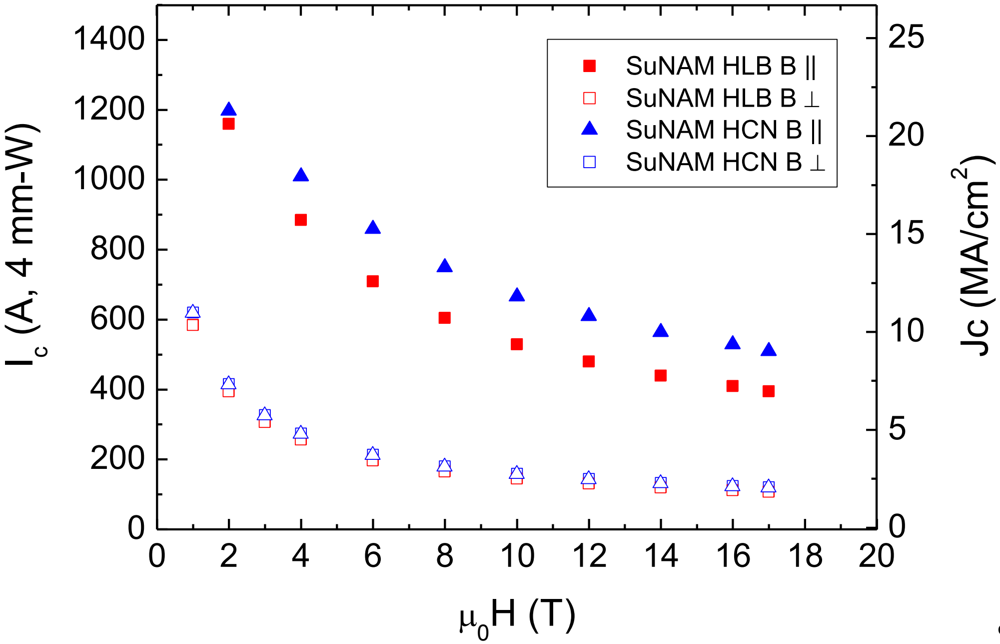
RCE-DR : in B-field Properties

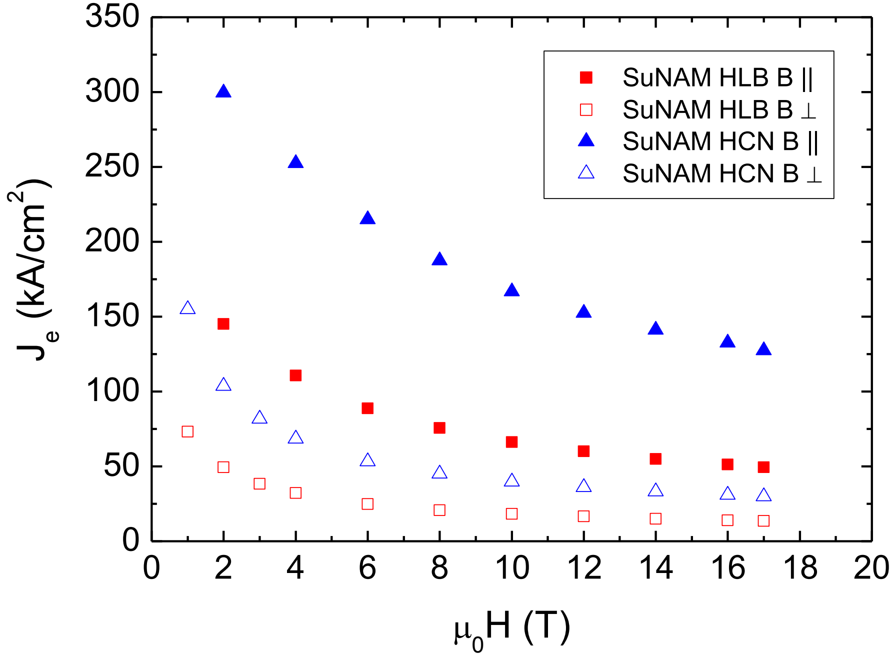


(measured by ENEA, 2013)

SUNAM

In-field Performance

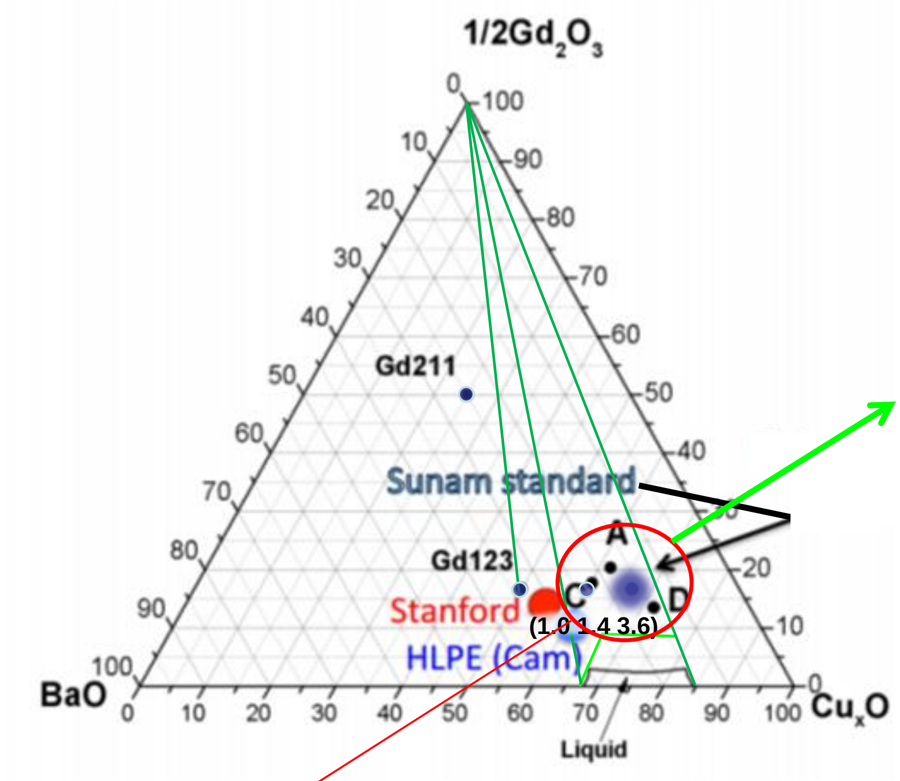


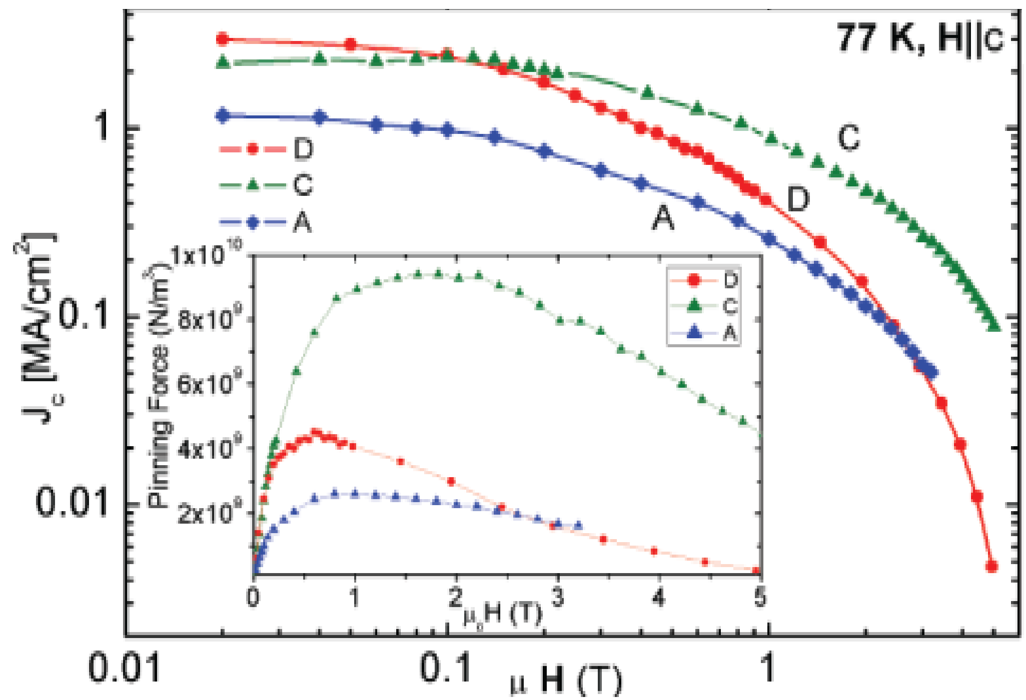


SuNAM

Measured at LNCMI (by Miyoshi)

Increase the pinning by composition control





Compositions studied here give a more Cu rich liquid which influences growth dynamics and pinning

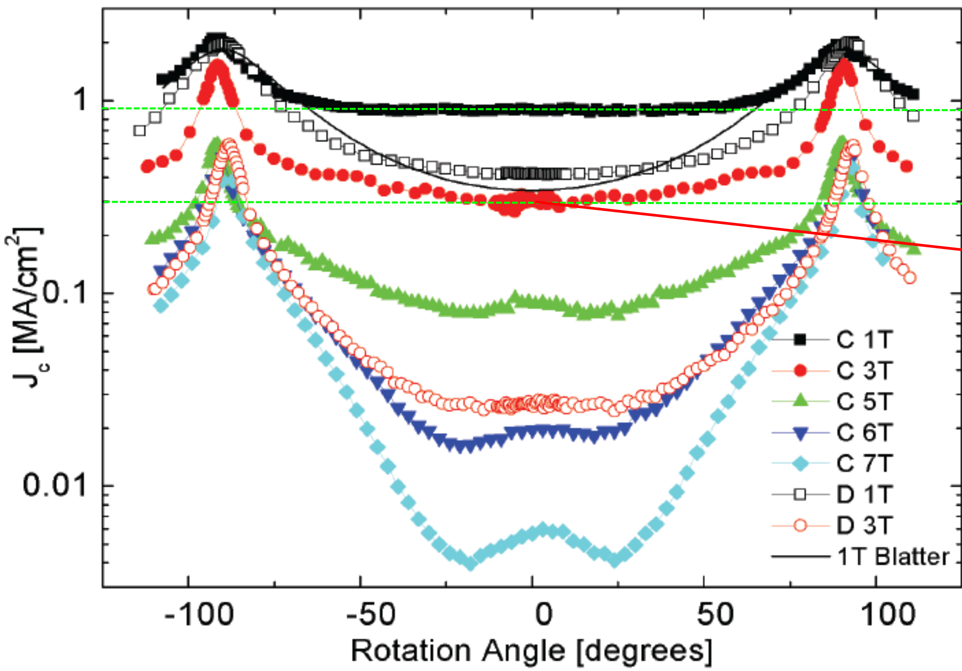
There will be excess Gd_2O_3 in all the samples but the specific composition, pO2, T is key to performance. It is clear what is best place to get very fine nanoparticles. Particles in C could be made smaller

SUNAM

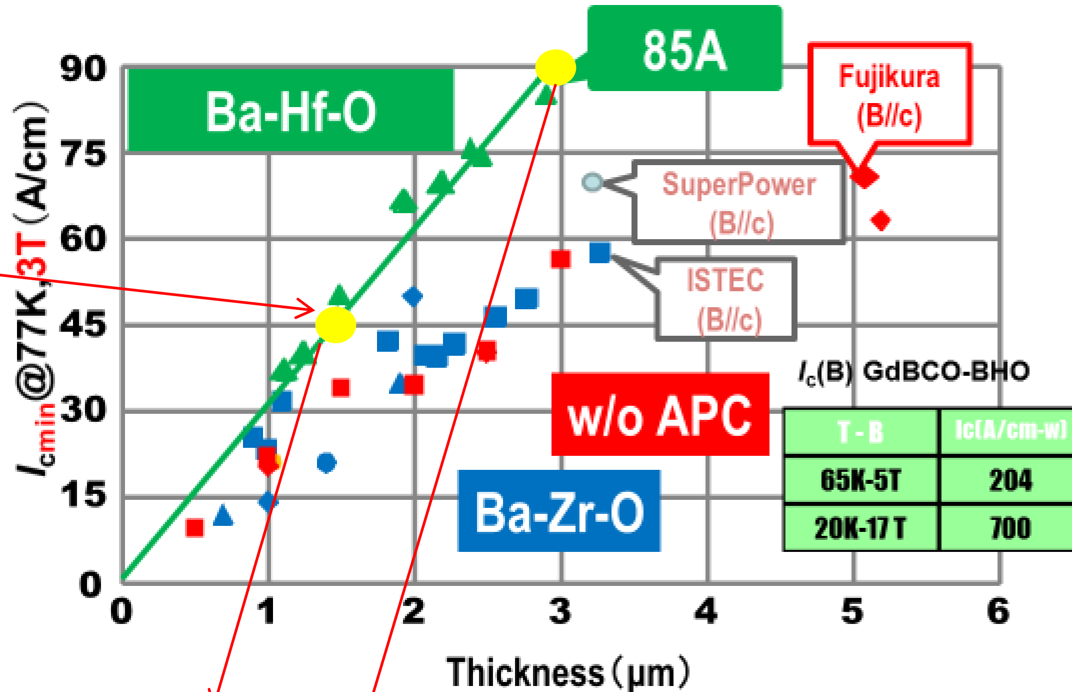
UNIVERSITY OF CAMBRIDGE

In-field Performance (77 K)

RCE-DR GdBCO w/o APC (C,D composition)



PLD-GdBCO with APC on IBAD-MgO Template



SuNAM's present : 1.4 um

SuNAM's future direction for magnet : ~ 3 um

(By Dr. Izumi, ISS2012(Japan))

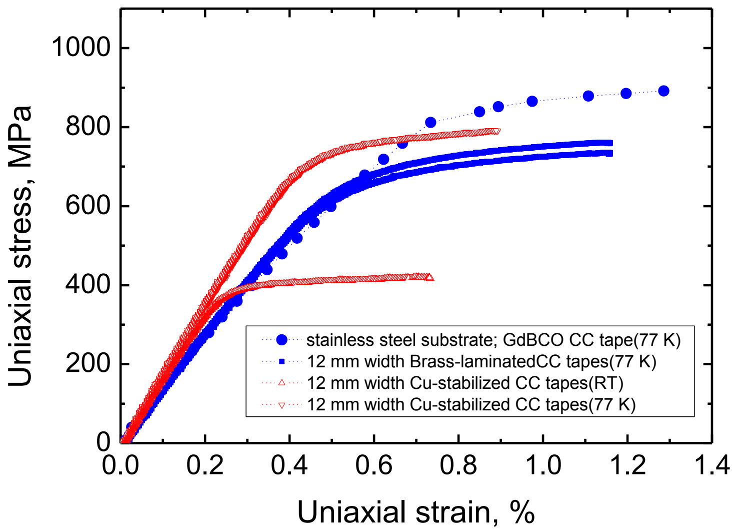
ISTEC

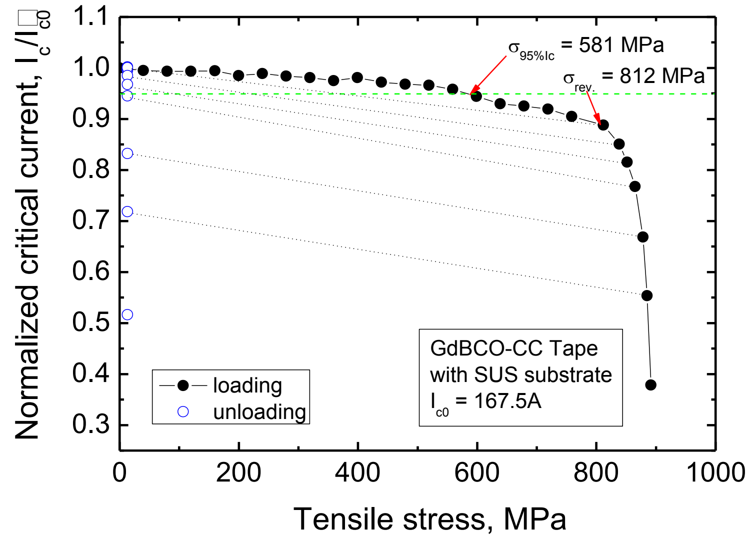
Only with composition control in RCE-DR process, we can achieve strong pinnings without APCs.

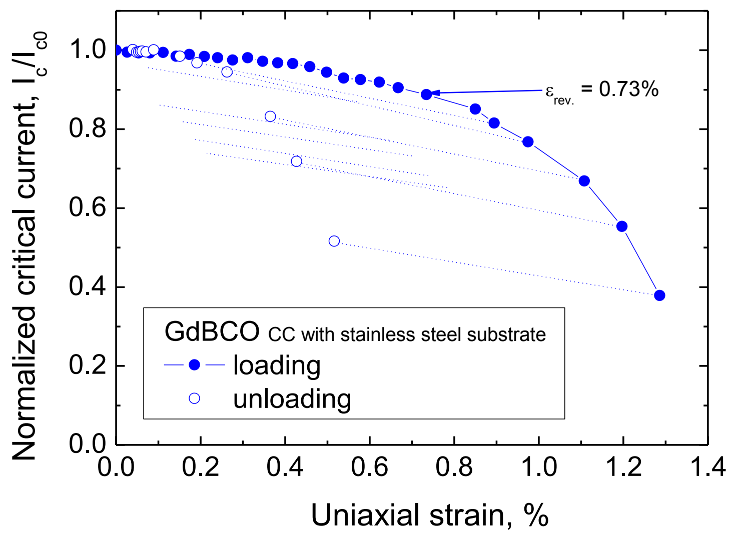
SuNAM

UNIVERSITY OF CAMBRIDGE

Tensile stress







- **5 % reduction of Ic @ 581 MPa**
- **Reversible strain limit : 812 MPa**
- **Reversible strain limit :**
  - **~ 0.73 % for GdBCO/SUS**

- **Mechanical Properties of CC on SUS good enough**

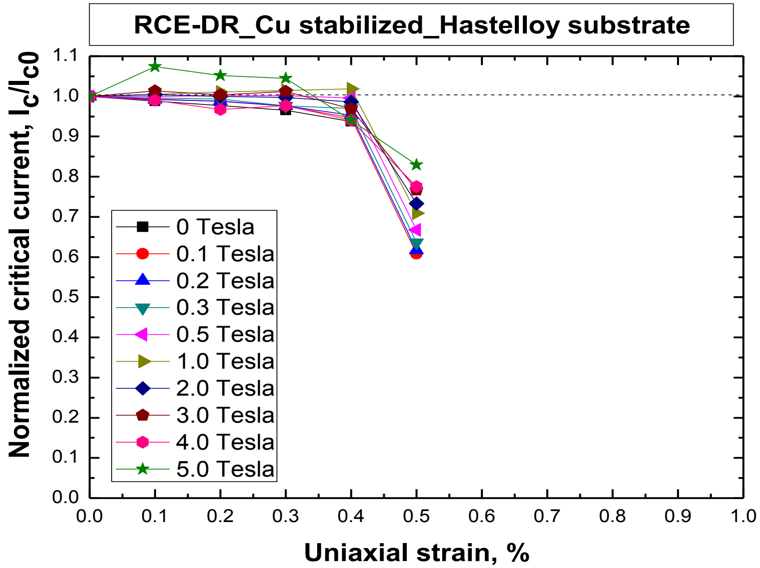
SUNAM

국립안동대학교 ANDONG NATIONAL UNIVERSITY

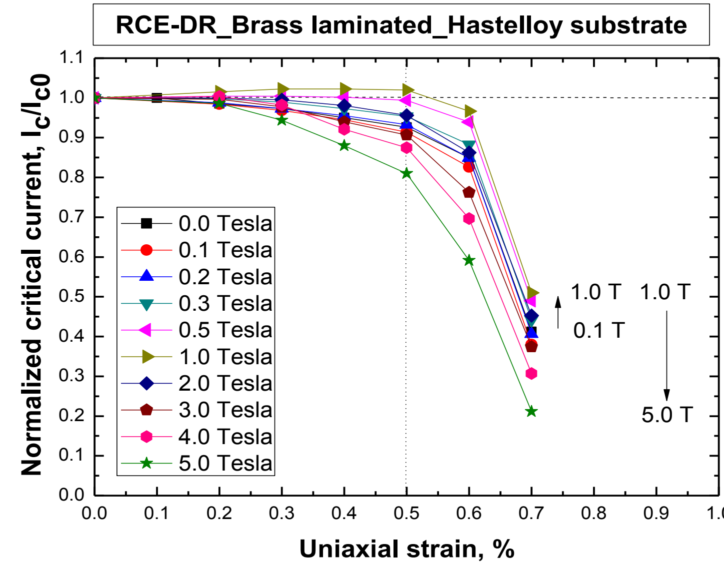
I_c(e,B) Characteristics in Various 2G Wires – Strains

B//c

Hastelloy

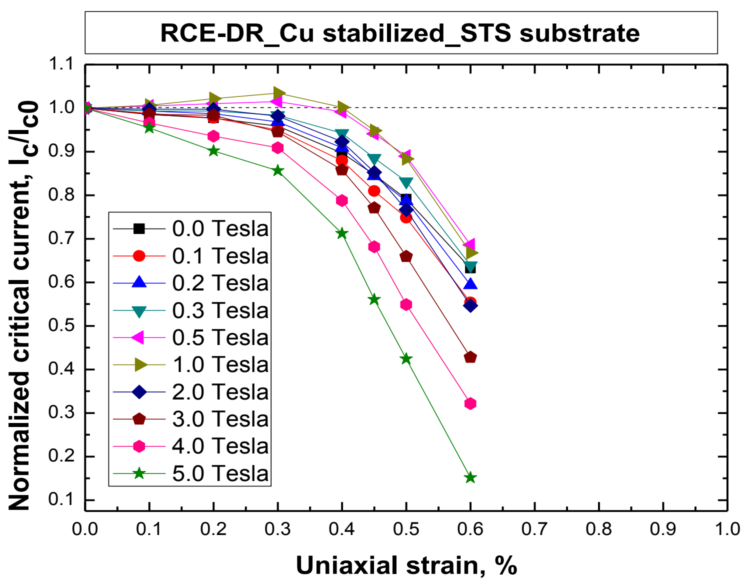


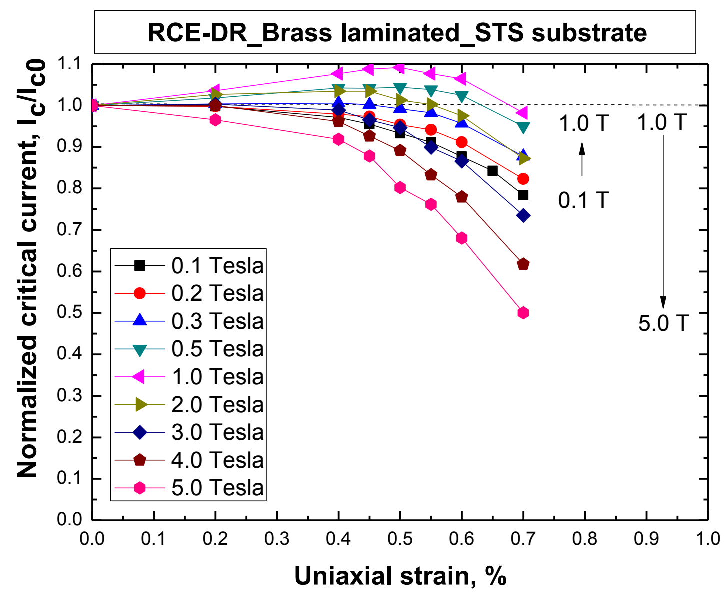
(a) Cu-stabilized CC



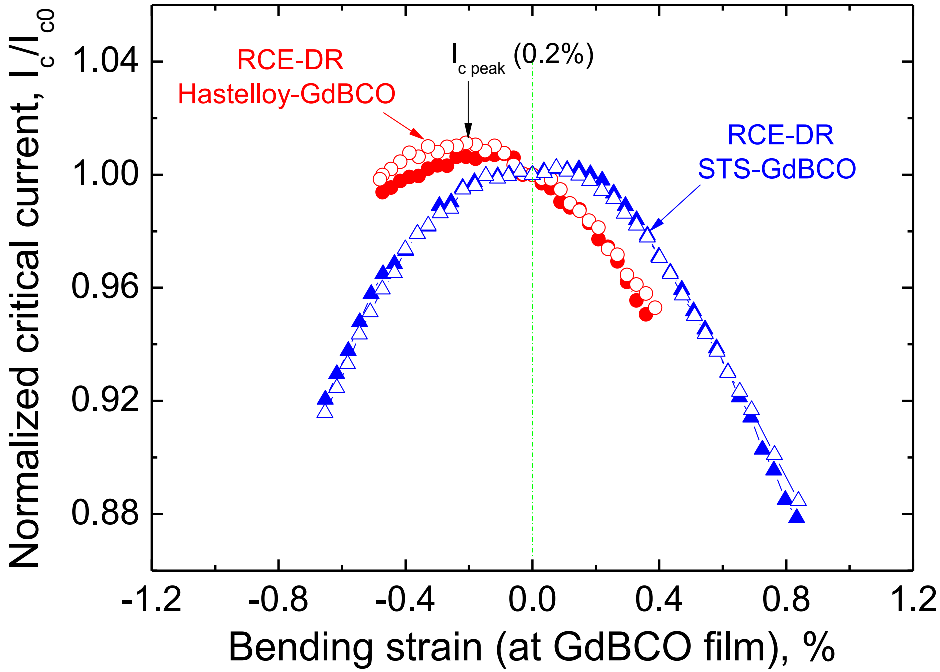
(b) Brass-laminated CC

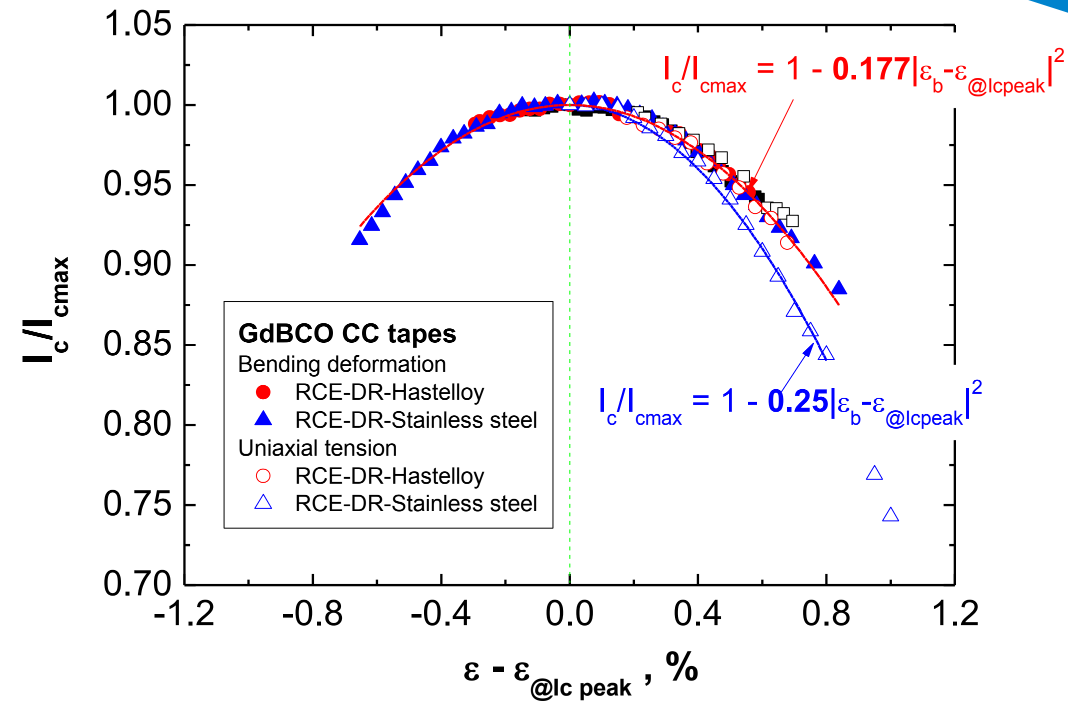
STS

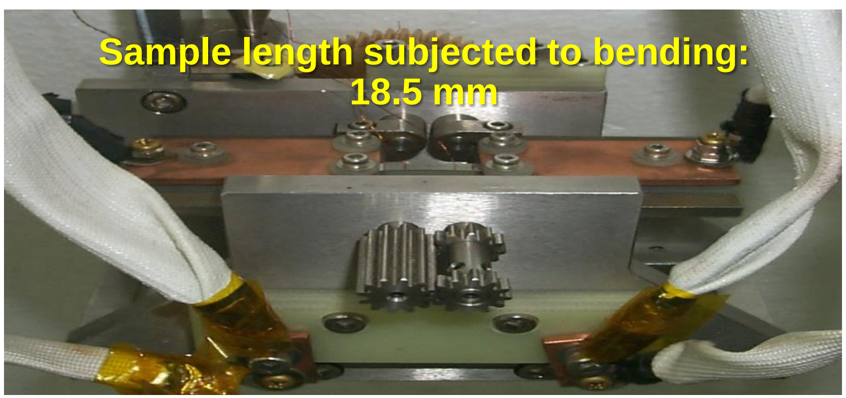


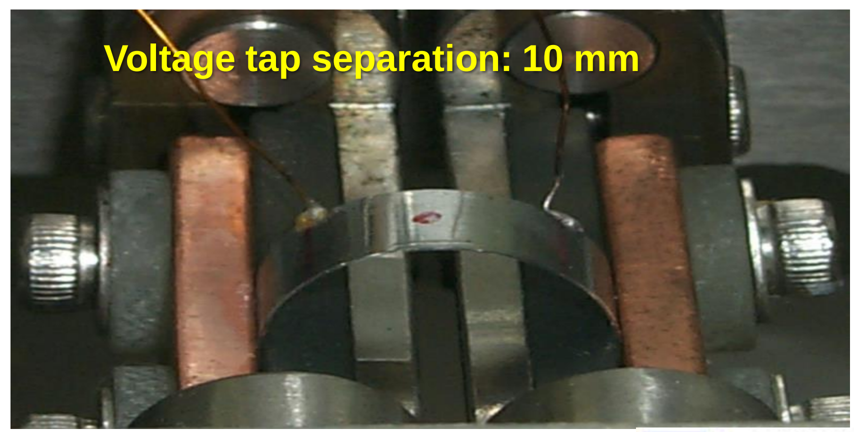


Bending Characteristics





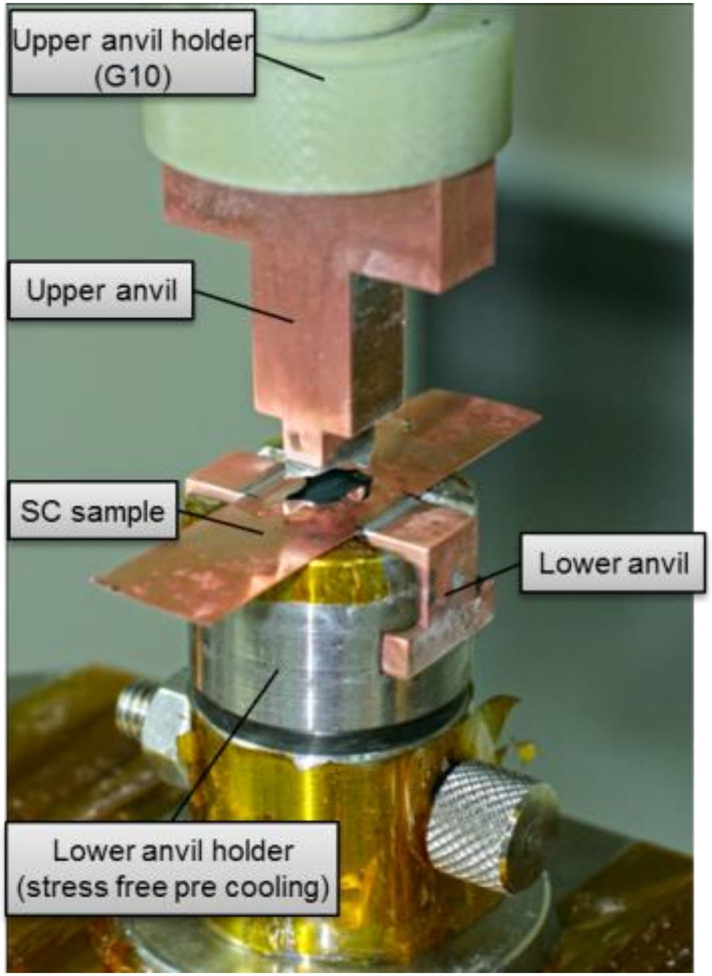


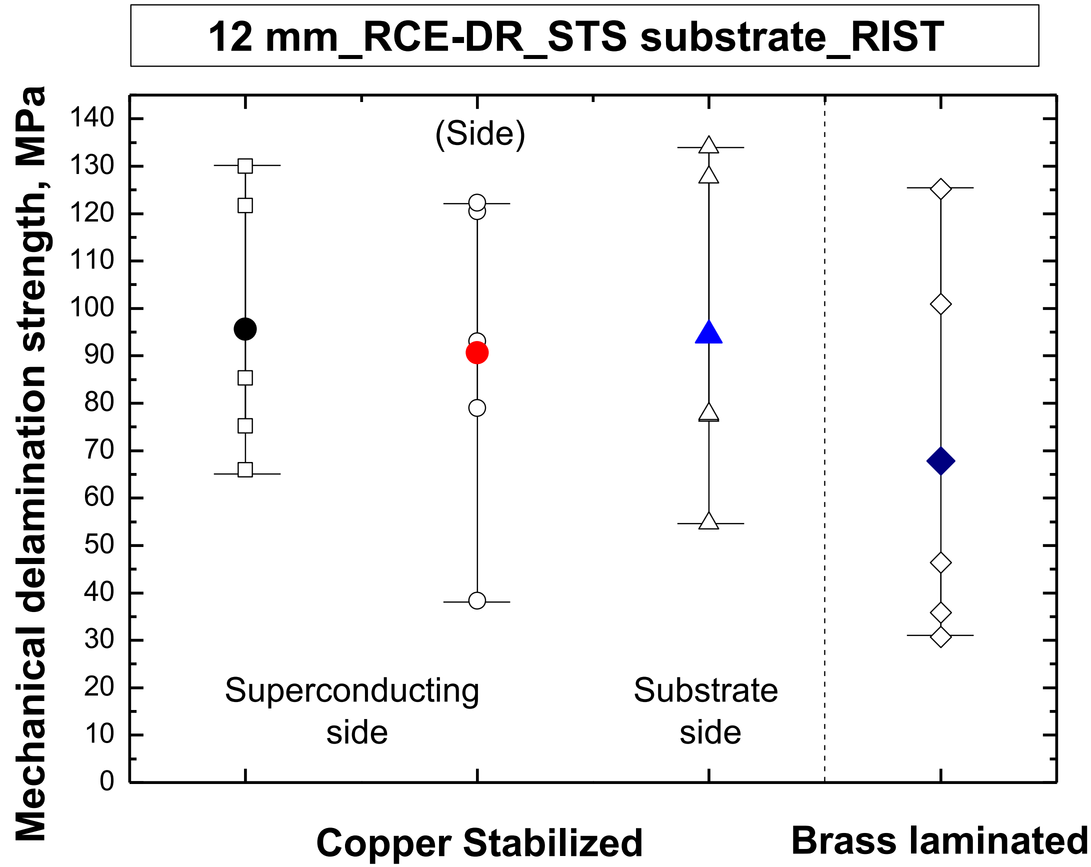


SuNAM

국립안동대학교
ANDONG NATIONAL UNIVERSITY

De-lamination Strength Test Results





Superconductor side

center

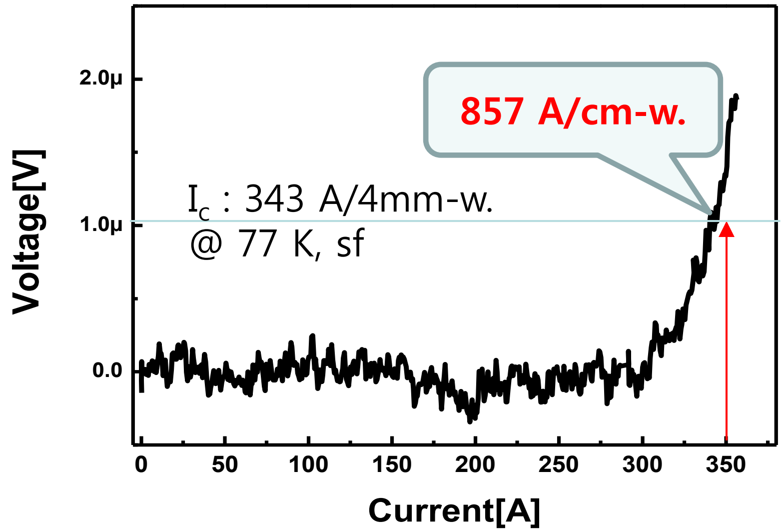
side

Substrate side

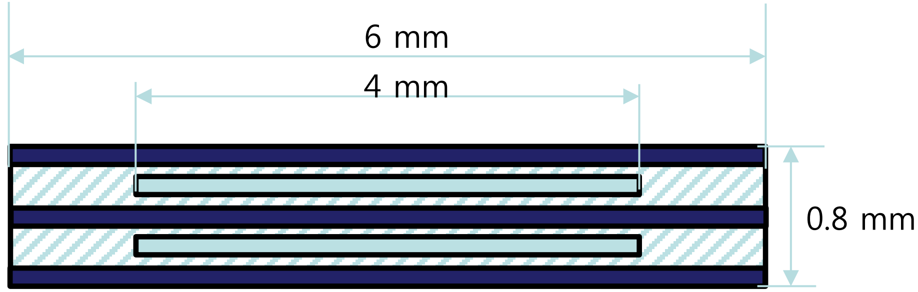
center

Stacking Wire

I_C for stacking wire

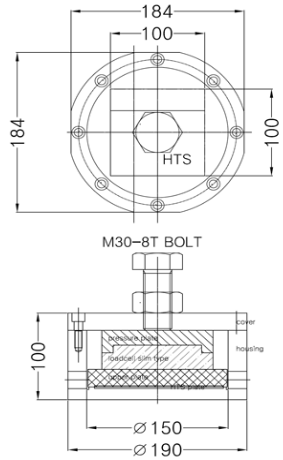


Cross section of 5-ply stacking wire



- CC tape width : 2 ~ 4 mm
- Cu buffer layer width : 10 mm
- Stacking method : soldering

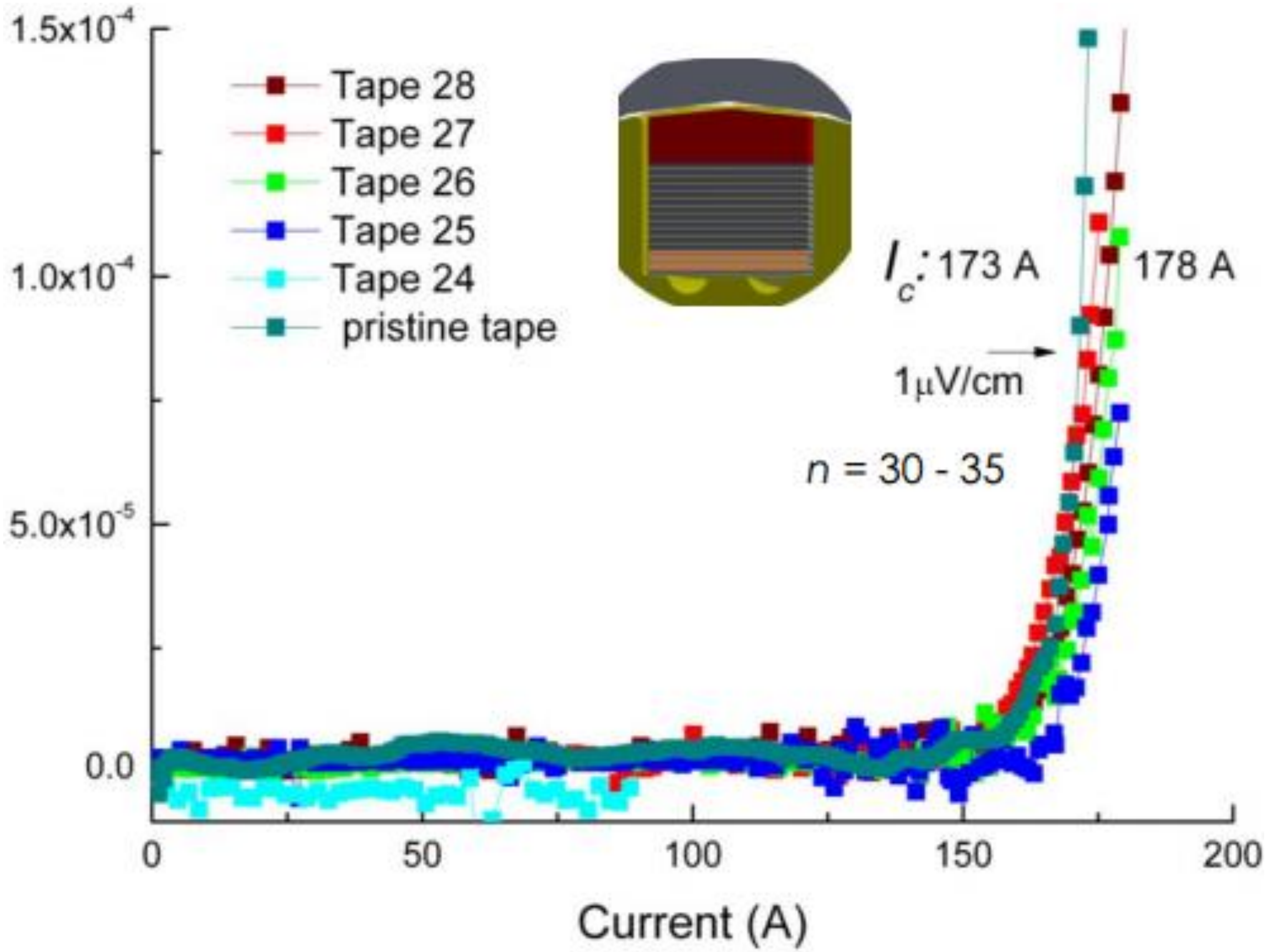
Scaler for soldering



- Stacking wire made of 2G HTS CC

SuNAM KERI

Stacking Wire



SuNAM's Future Direction

Direction of Technology Development in the Future

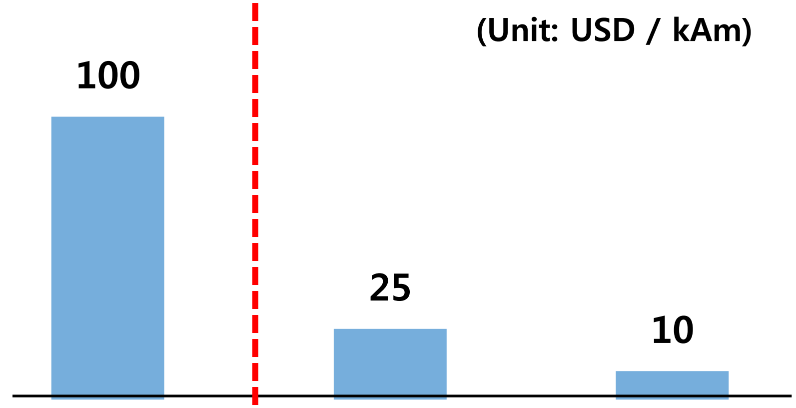
“Increasing Demand for HTS 2G wire has surpassed the supply”

“For market entrance $ 50 / kAm is the threshold ”

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

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

Price Reduction



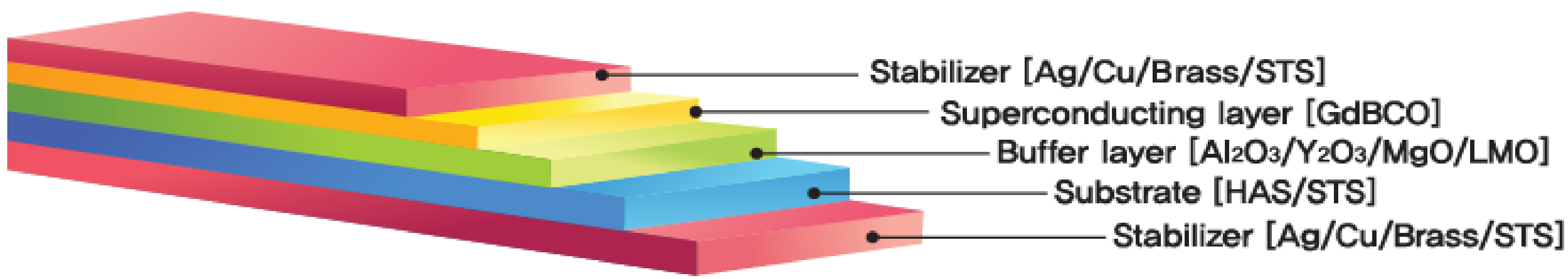
Width :	12 mm	120 mm	360 mm
Capacity :	1,000 km/y	15,000 km/y	75,000 km/y
Max Revenue :	$ 20 Mil.	$ 75 Mil.	$ 150 Mil.
CAPEX* :	$ 7 Mil.	$ 20 Mil.	$ 30 Mil.
	Achievable with Existing Line of SuNAM		

* Capital Expense : Required Investment in Production Line

SuNAM's 2G HTS Wire

[Specification Table]

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



SuNAM's Future

	Value
Ic(77K, 0T) (A/cm-w)	> 500
Ic(20K, 10T) (A/cm-w)	> 300
Uniformity (1σ, %)	< 6
Stacked wire Ic (A/cm-w)	> 800
Width (mm)	= < 12
Max. piece length (km)	~ 1
Price($/kA-m)	~ 150

Present, 2014

	Value
Ic(77K, 0T) (A/cm-w)	> 700
Ic(20K, 10T) (A/cm-w)	> 600
Uniformity (1σ, %)	< 5
Stacked wire Ic (A/cm-w)	> 1,200
Width (mm)	= < 12
Max. piece length (m)	~ 1.2
Price($/kA-m)	~ 100

2 years later

	Value
Ic(77K, 0T) (A/cm-w)	> 1,000
Ic(20K, 10T) (A/cm-w)	> 1,000
Uniformity (1σ, %)	< 4
Stacked wire Ic (A/cm-w)	> 1,800
Width (mm)	= < 120
Max. piece length (km)	> 2
Price($/kA-m)	< 50

5 years later

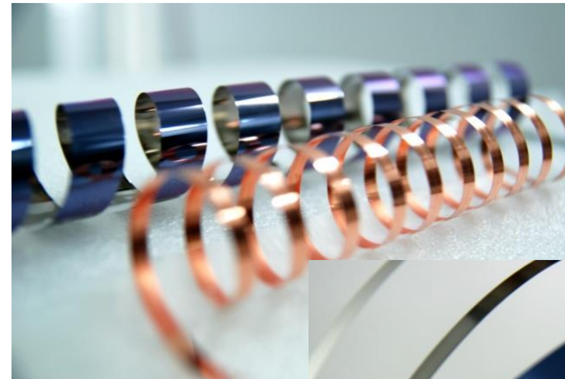
Acknowledgement

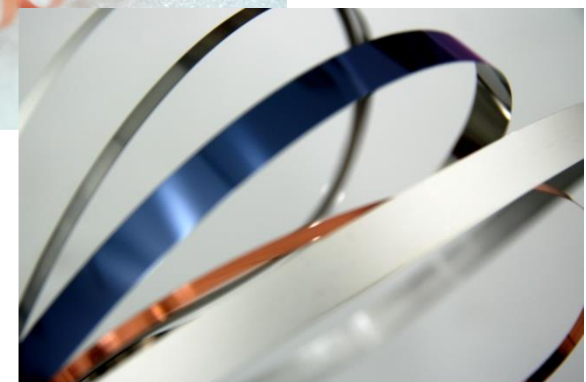
- SuNAM : J. H. Lee, H. K. Kim, B. J. Mean, Y. S. Kim, S. W. Yoon, K. K. Cheon, and H. J. Lee.
- Seoul Nat'l Univ. : J. W. Lee, S. M. Choi, S. I. Yoo.
- KERI : H. S. Ha, S. S. Oh.
- Korea Polytech. Univ. : G. W. Hong, H. G. Lee.
- Andong Nat'l Univ. : H. S. Shin.
- RIST : J. S. Lim

- Stanford Univ. : R. H. Hammond.
- iBeam Materials : V. Matias
- Univ. of Cambridge : J. M. Driscoll
- MIT : S.Y. Hahn, Y. Iwasa

SuNAM

Thanks for Attention !





See you at

CCA 2014

(Nov. 30 ~ Dec. 3)

JEJU ISLAND, KOREA