

# **Supraleiter für die Energietechnik**

Überblick Technologie und Stand der Technik

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THEVA Dünnschichttechnik GmbH

ZIEHL VII, Berlin, 05.03.2020

# Technisch genutzte Hochtemperatursupraleiter

## BiSCCO

Bi(Pb)-2223

2223:  $(\text{Bi,Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$  ( $x \approx 10$ )

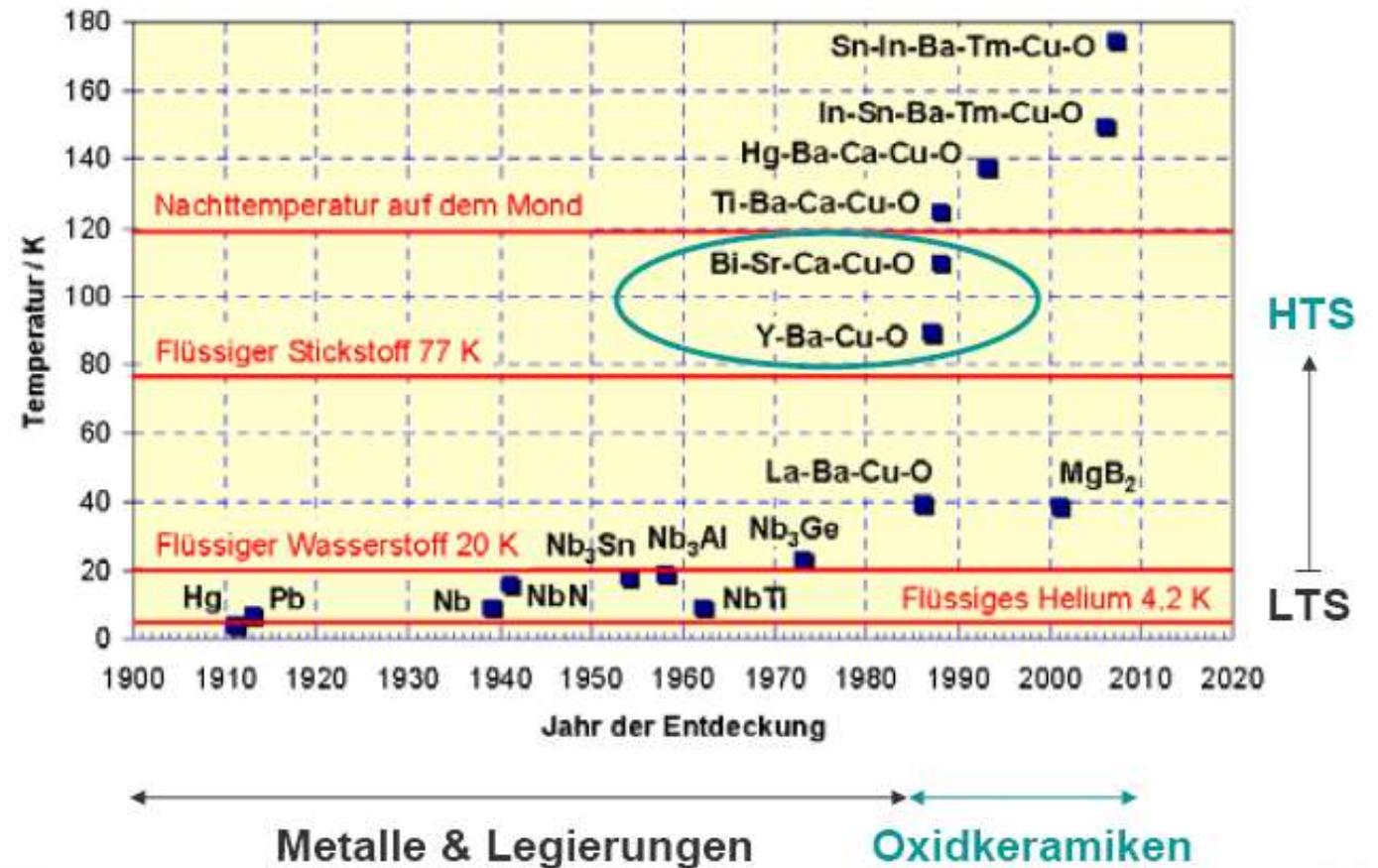
→ 1G Drähte

## REBCO

$\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$

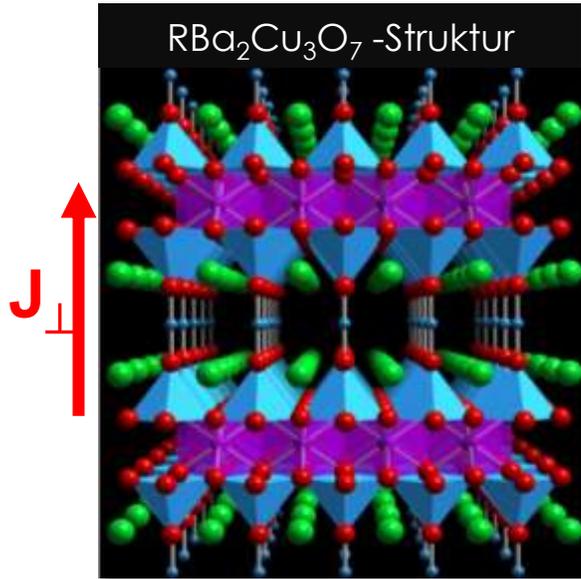
RE: Y, Gd, Eu, ...

→ 2G Drähte



# Stromtragfähigkeit der HTSL

2-dimensionale Struktur und Korngrenzen



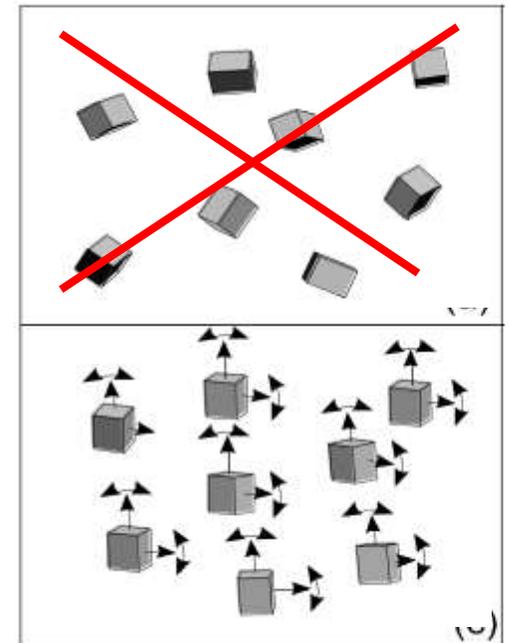
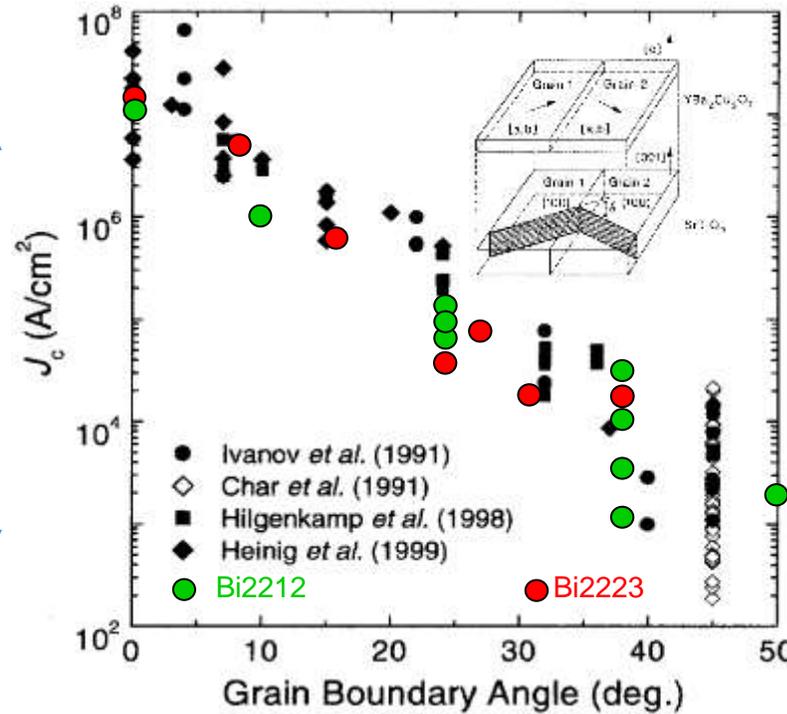
$J_{\parallel} \gg J_{\perp}$

$J_{\parallel}$ : Strom parallel zu CuO Ebene

$J_{\perp}$ : Strom senkrecht zu CuO Ebene

**Stark 2-D supraleitende + mechanische Eigenschaften**

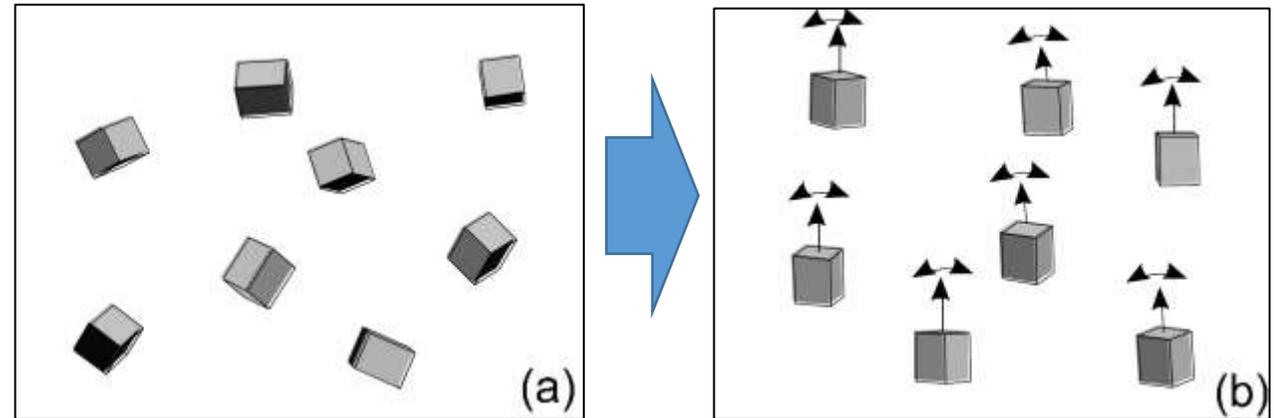
4 Größenordnungen!



**Nur als (quasi) Einkristall haben HTSL technisch nutzbare sehr hohe Stromtragfähigkeiten!**

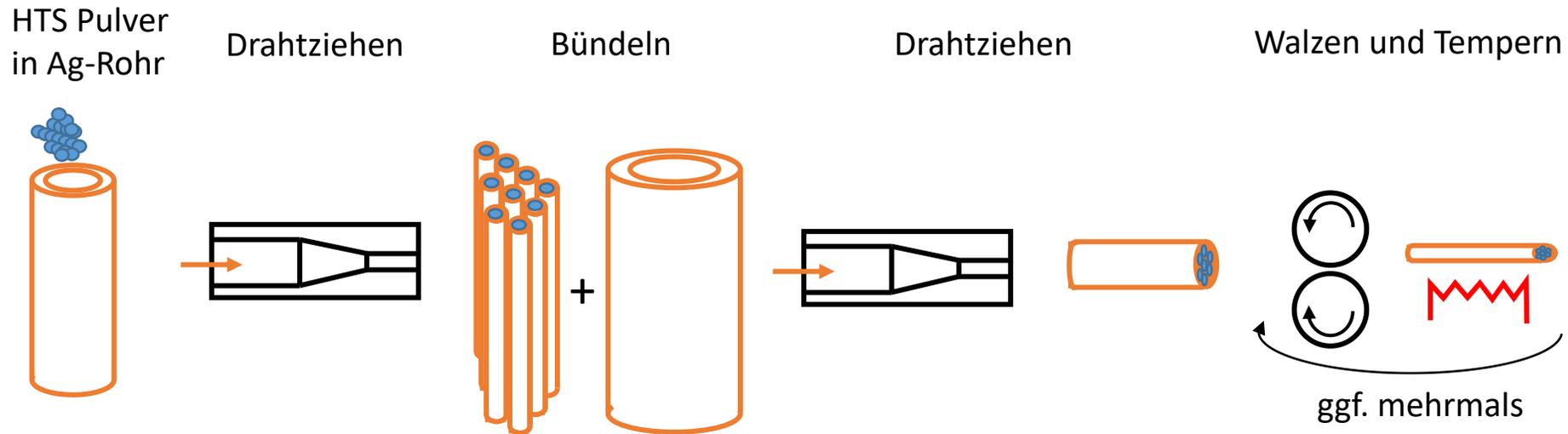
# Die Herausforderungen

- Komplexe Stochiometrie  
z.B.:  $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$
- Synthese bei ca.  $650^\circ\text{C}$  bis  $900^\circ\text{C}$
- Hohe Stromtragfähigkeit benötigt  
fast perfekte einkristalline  
Ausrichtung
- Brüchige "Keramik" muss zu einem  
flexiblem Leiter geformt werden



# Erste Generation HTS Drähte - 1G

## BiSCCO Powder in Tube (PIT) Technologie



Nach: Larbalestier, David et al. (1997) Ch. 5 "Sheathed or Powder-in-Tube Conductors" in WTEC Panel Report on Power Applications of Superconductivity in Japan and Germany [http://www.wtec.org/loyola/scpa/05\\_02.htm](http://www.wtec.org/loyola/scpa/05_02.htm)



**DI-BSCCO**

1G HTS Drähte sind seit vielen Jahre kommerziell mit hoher Qualität verfügbar

Aber: Silberanteil von ca. 70% führt zu hohen Materialkosten

# Zweite Generation HTS Drähte - 2G Wires

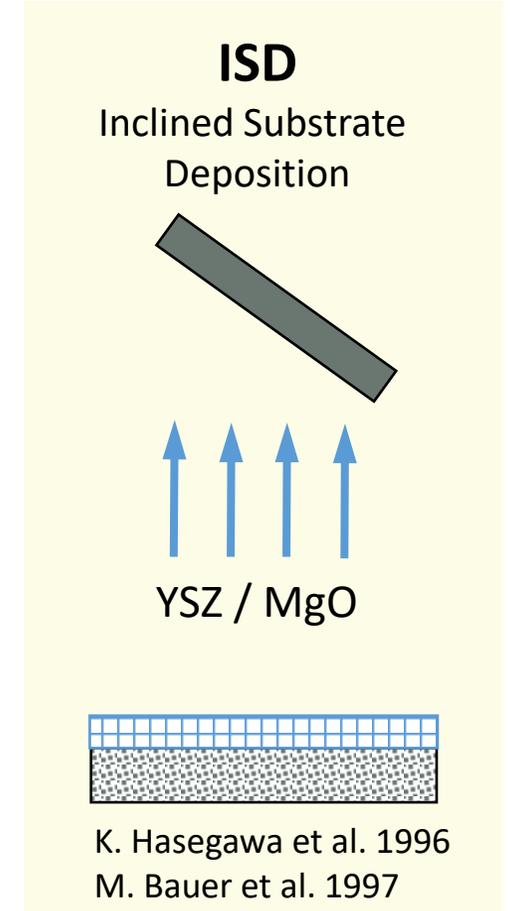
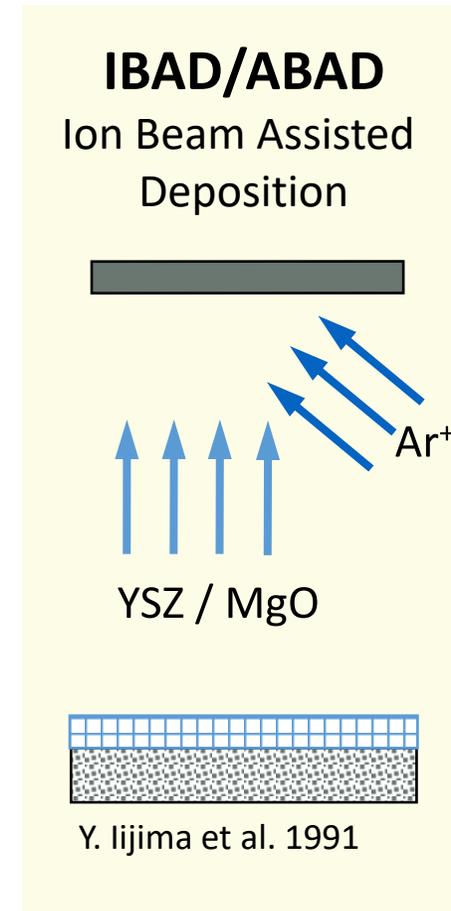
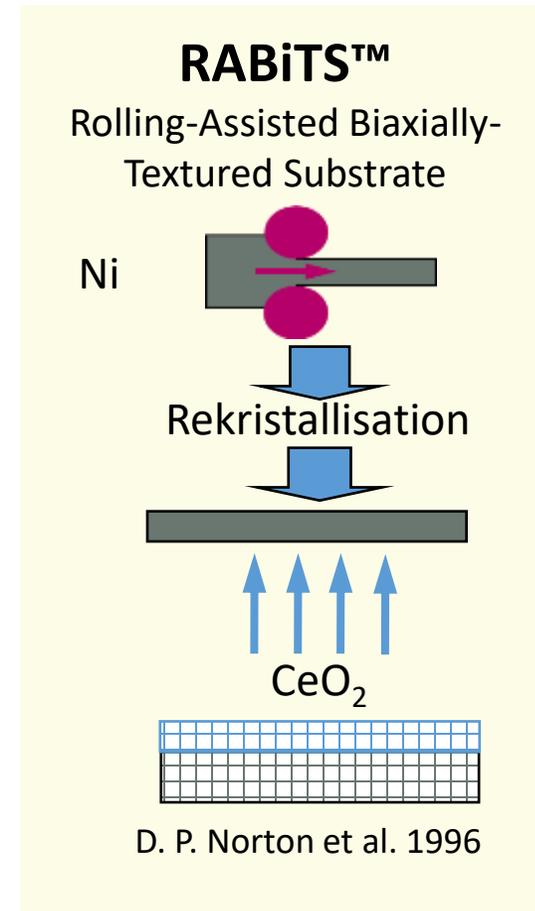
Herstellung einer geeigneten Unterlage

**Idee:**

Dünne Schicht des keramischen Supraleiters auf einem flexiblen metallischen Substrat

**1. Schritt:**

Herstellung eines langen Metallbandes mit quasi einkristalliner (biaxial texturierter) Oberfläche



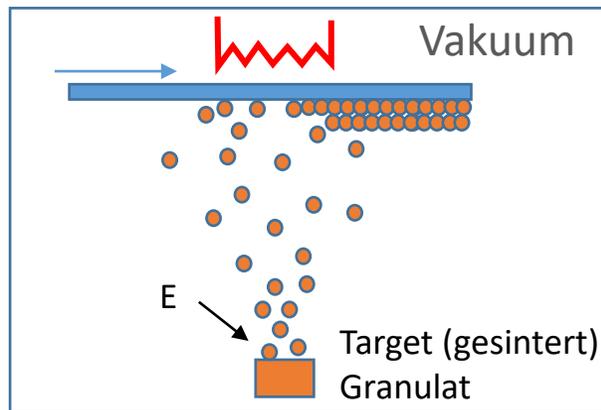
# Zweite Generation HTS Drähte - 2G

Abscheidung der HTS Schicht

Verschieden Methoden wurden entwickelt

## PVD

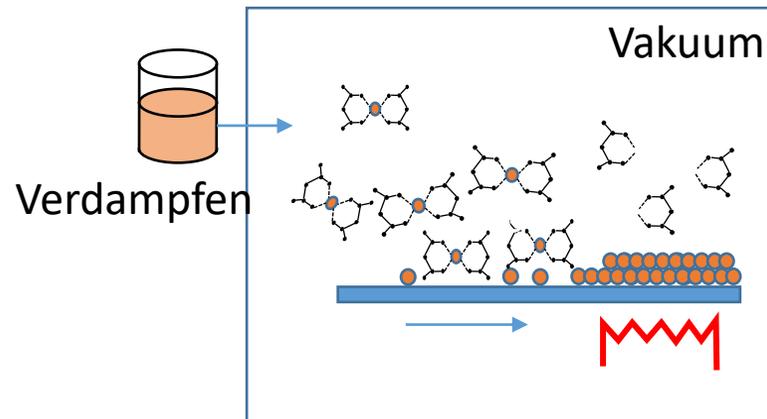
Physikalische Abscheidung



- Laserablation
- Elektronenstrahlverdampfen
- Ionen Sputtern)

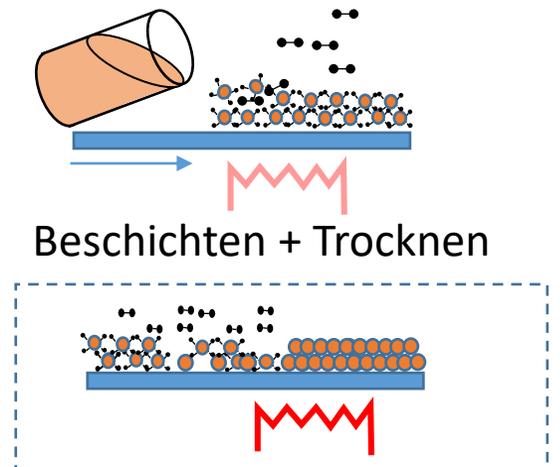
## MOCVD

Metallorganische chemische Gasphasenabscheidung



## CSD / MOD

Lösungsbeschichtung



Zersetzen + Kristallisieren

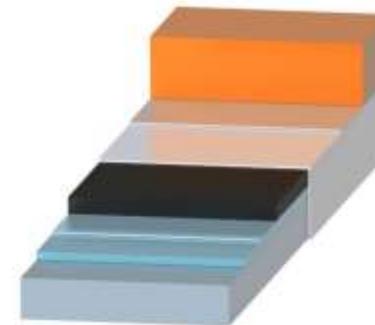
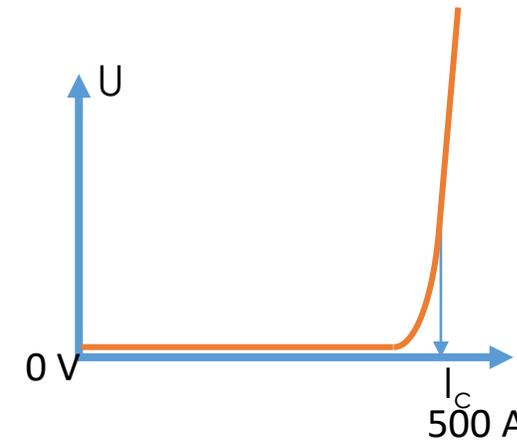
# Silber-Beschichtung und Kupfer-Stabilisierung

## Ag-Beschichtung

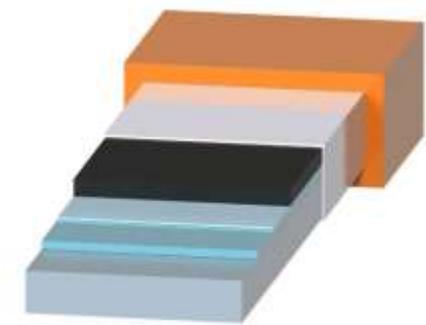
- Dünn: 1-3  $\mu\text{m}$
- Sauerstoffdurchlässig: Sauerstoffbeladung nach Ag-Beschichtung möglich
- Elektrische Kontaktierung
- Chemischer Schutz

## Stabilisierung mit Kupfer oder Legierungen

- Elektrische Stabilisierung für  $I > I_c$
- Art + Dicke abhängig von Anwendung
- Mechanischer Schutz



Laminieren



rundum Beschichten

- Galvanisch
- PVD

# HTS Drahthersteller weltweit



Die folgenden Folien wurden von den Firmen zur Verfügung gestellt. Für den Inhalt sind die Firmen verantwortlich. Sämtliche Rechte and den Folien liegen ausschließlich bei den einzelnen Firmen

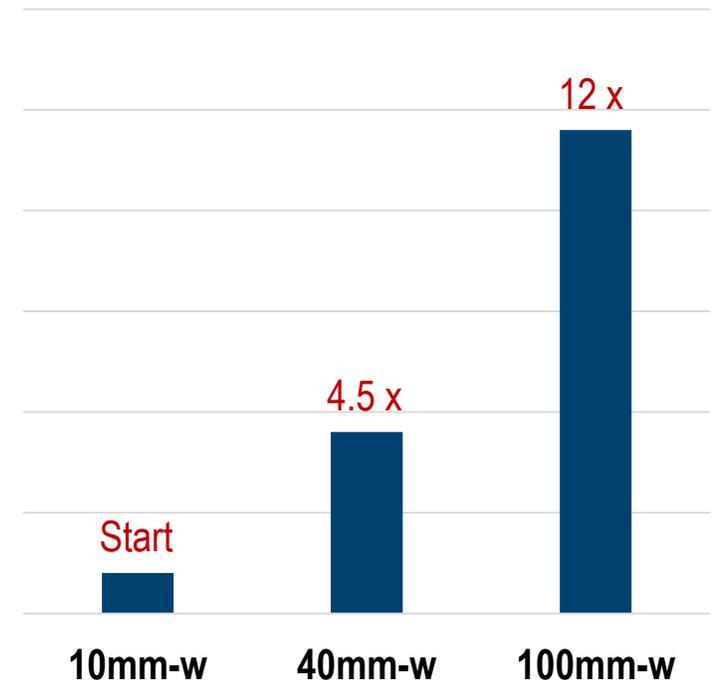
**d**eutsche  
**nano**schicht



# Industrial Scale 40mm wide HTS Wire Technology

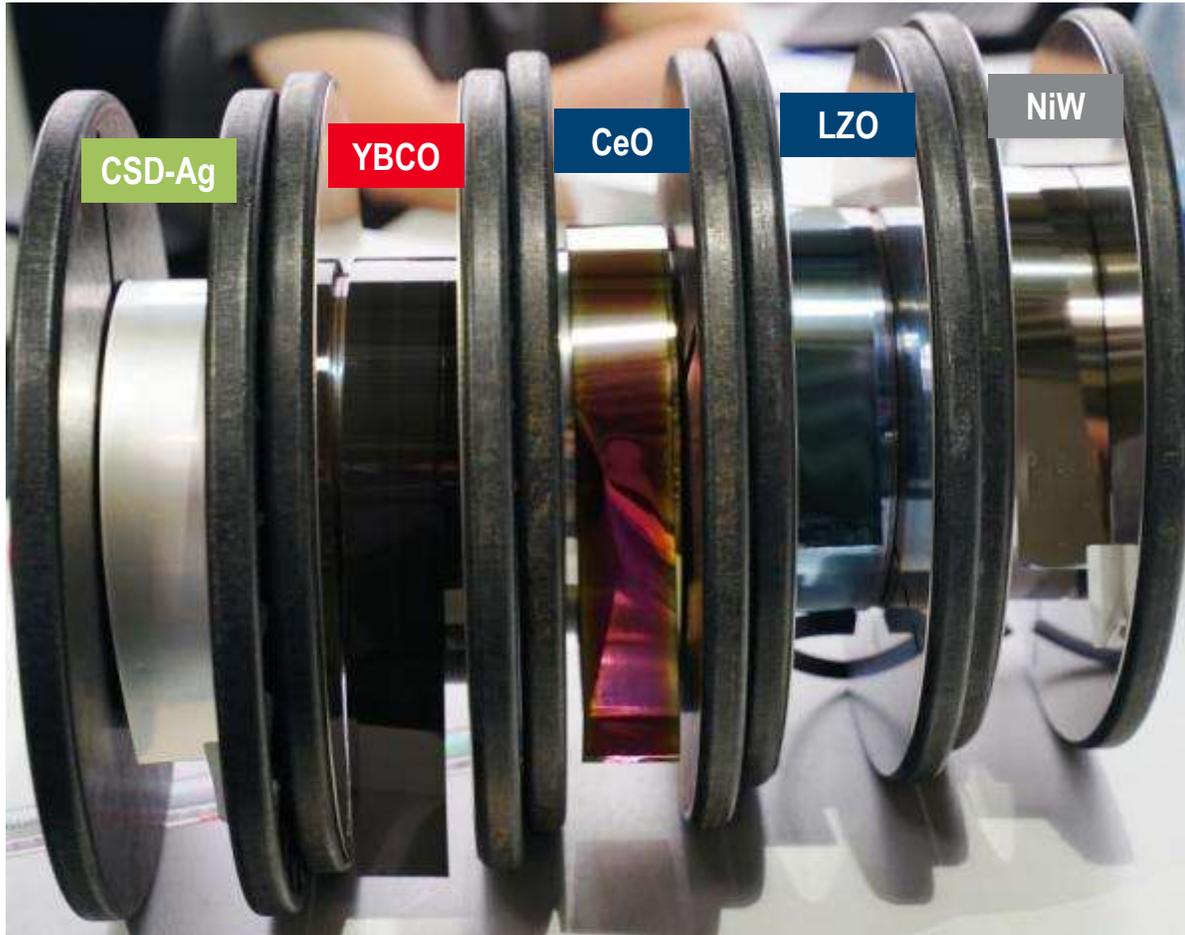
- ❑ Development of low-cost, large-scale HTS wire technology using wide-tape Chemical Solution Deposition (CSD) approach
- ❑ 2019 milestone realised – 40mm-w All-CSD technology successfully tested during Pilot Production Run
- ❑ Current production devices ready for further scale-up to 100mm tape width
- ❑ Project partner includes VDM Metals for industrial scale non-magnetic (Ni9W) substrate

Relative Production Capacity  
[km/year @ 4mm]



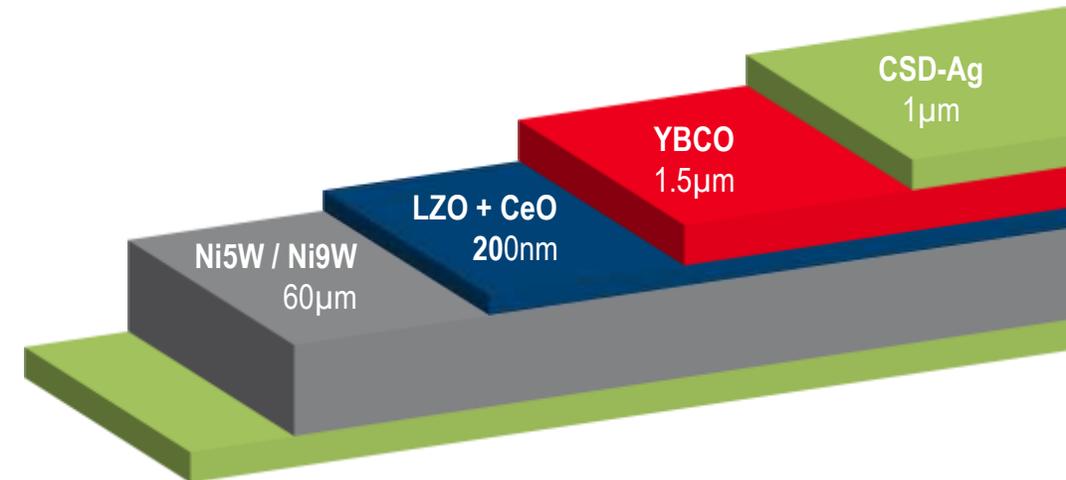
# 40mm All-CSD HTS Technology

deutsche  
nanoschicht



## D-Nano's 40mm wide CSD technology:

- simple functional layer architecture
- dramatic reduction of production costs and increase of manufacturing capacity
- suitable for demanding applications at high & low temperatures without artificial pinning centres (APC)





Februar 2020

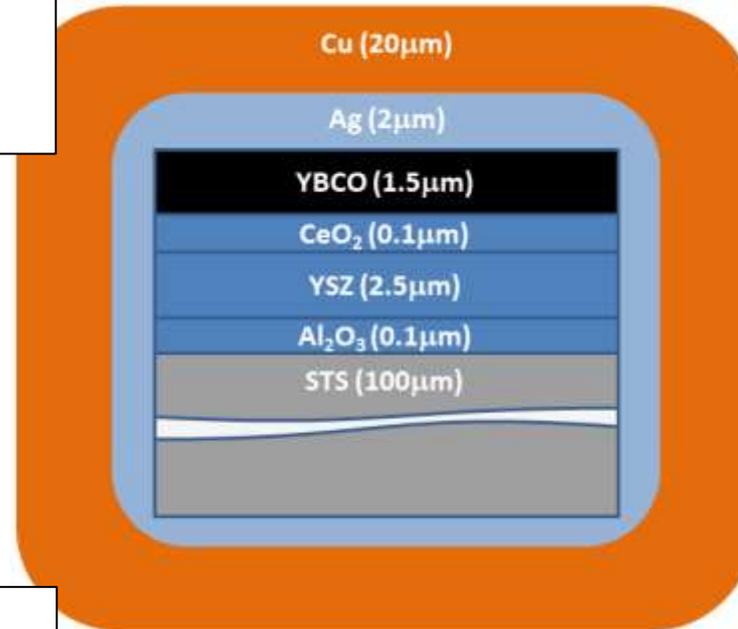


- BHTS ist Teil der Bruker Energy & Supercon Technologies Division BEST.
- BEST fertigt Niedrigtemperatur- und Hochtemperatursupraleiter (LTS & HTS) für Magnetfeldanwendungen in Medizin & Forschung.
- In der Betriebsstätte Alzenau werden Hochtemperatursupraleiter mittels Dünnschichtverfahren hergestellt.
- Zu den Kernkompetenzen von BHTS zählt das Abscheiden der ReBCO-supraleitenden Funktionsschicht mittels Laser-Ablationsverfahren (Pulsed Laser Deposition PLD).

Februar 2020

- Aufbau der HTS Leiter und Abfolge der Verarbeitungsschritte bei BHTS.

Schematischer Querschnitt eines BHTS Leiters



Querschliff 4mm HTS Leiter mit 40mic Kupferschicht



## PROCESSING CHAIN OF HTS PILOT-LINE PRODUCTION

SUBSTRATE PREPARATION (SUB)

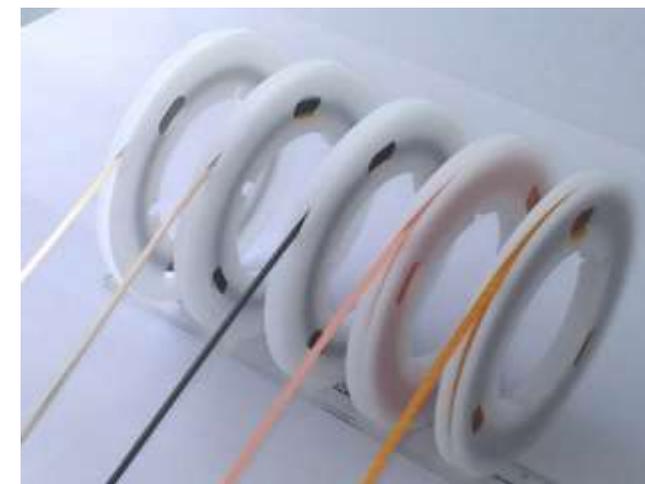
BUFFER LAYER COATING (ABAD)

HTS LAYER COATING (PLD)

METAL COATING (MET)

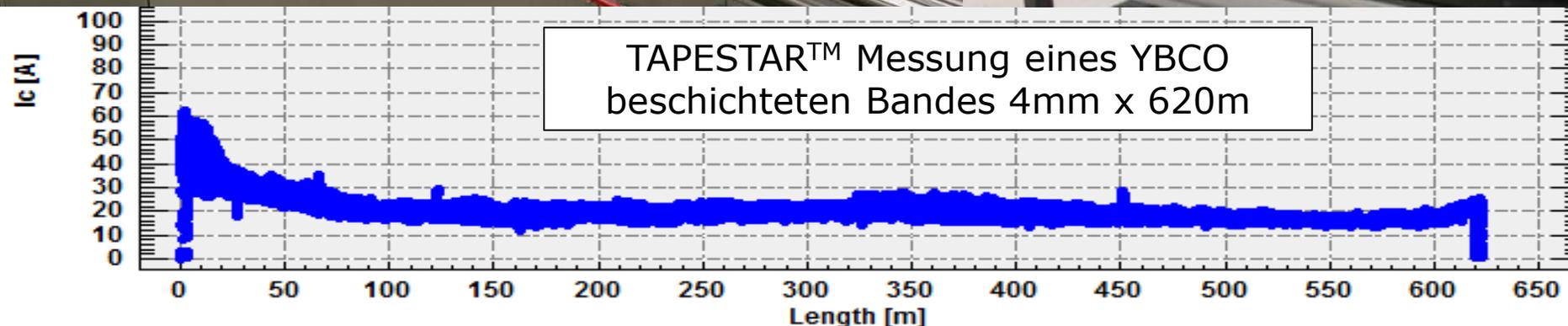
COPPER PLATING (PLA)

FINAL TAPE INSPECTION (INS)



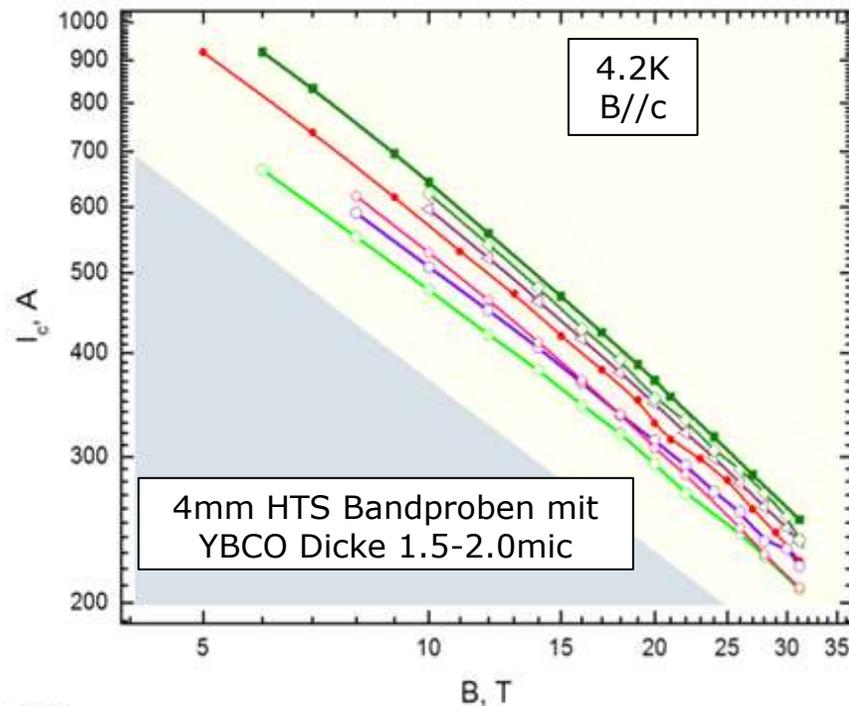
Februar 2020

- Bei BHTS werden HTS Bänder mit Breiten von 4mm, 12mm und 40mm sowie HTS Folien von 300mm x 1000mm hergestellt.

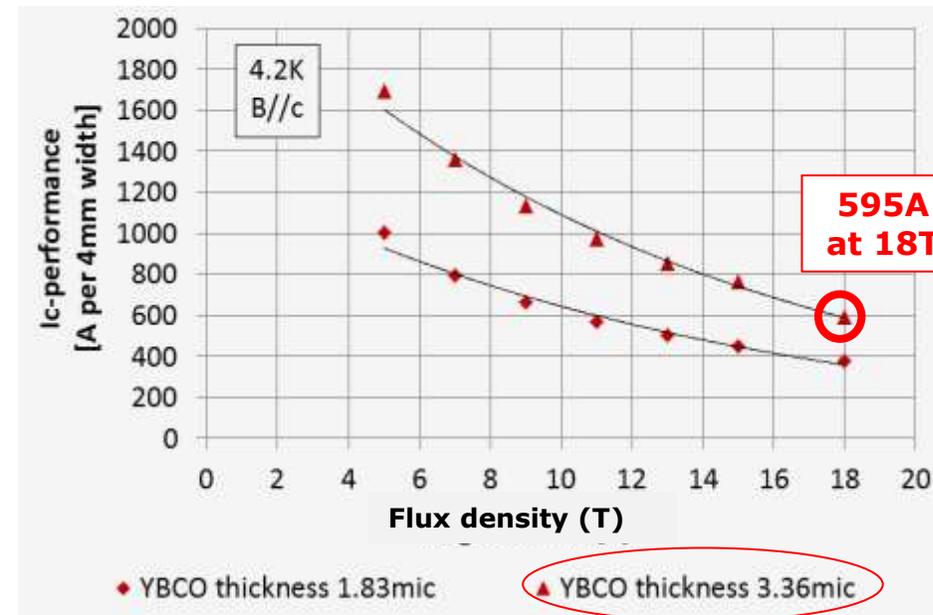


Februar 2020

- Charakteristisch für die BHTS Leiter sind moderate Ströme bei 77K und eine ausgezeichnete Stromtragfähigkeiten beim Einsatz in hohen Magnetfeldern und niedrigen Temperaturen.



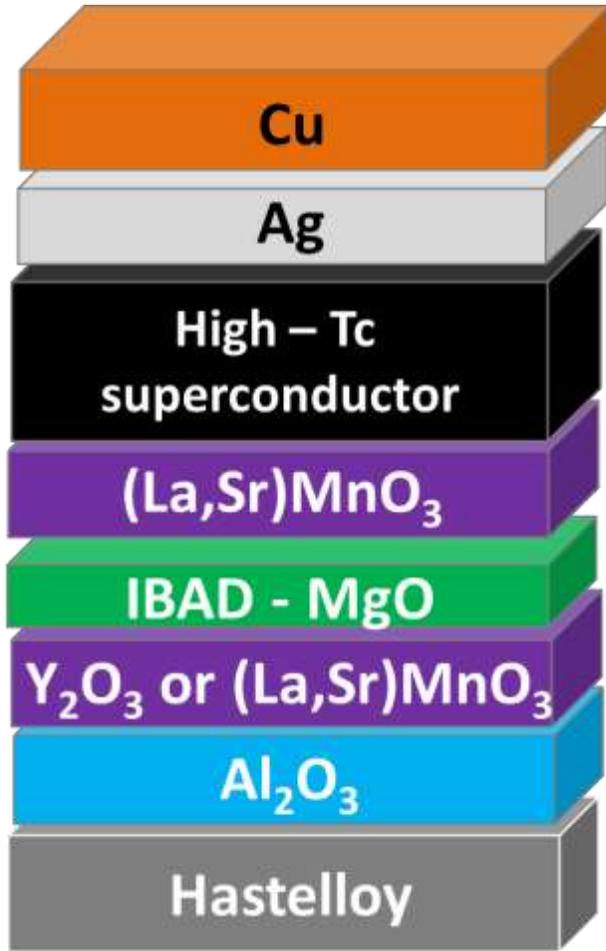
D. Abraimov, J. Jaroszynski, A. Francis, A. Juliao, Y. L. Viouchkov, and D. C. Larbalestier at NHMFL, FSU Tallahassee



A. Rutt measured at Bruker EAS, Hanau

The logo for S Innovations features a dark blue square on the left containing a white capital letter 'S'. To the right of the square, the word 'Innovations' is written in a black, sans-serif font.

**SUPEROX JAPAN**  
**SUPERCONDUCTIVITY FOR LIFE**



SuperOx Japan 2013

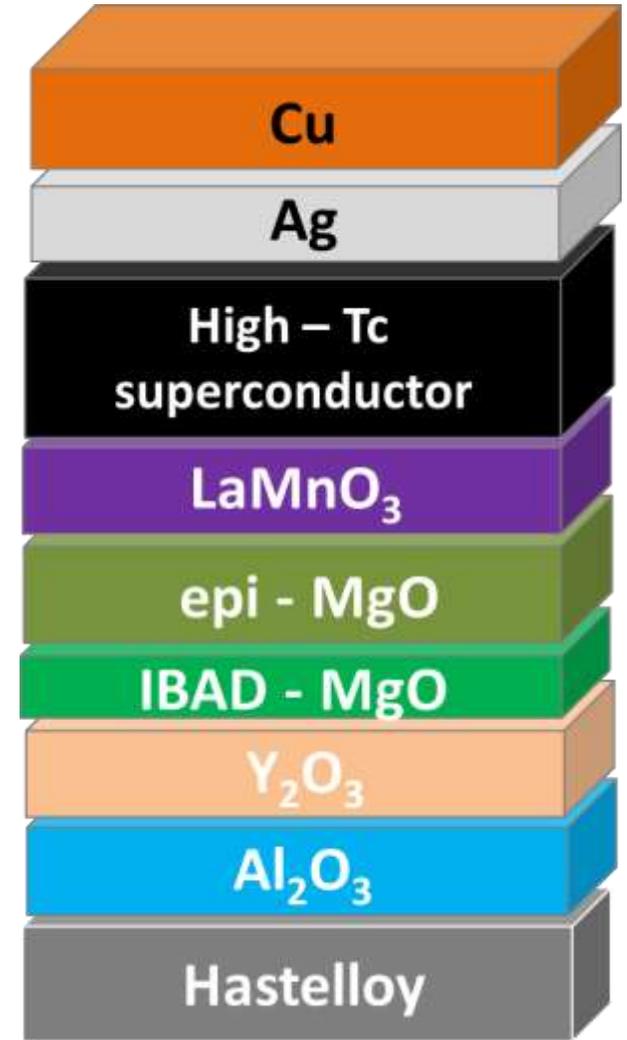
*Electroplating*

*DC Magnetron Sputtering*

*Pulsed Laser Deposition*

*Physical Vapor Deposition*

*Electropolishing*



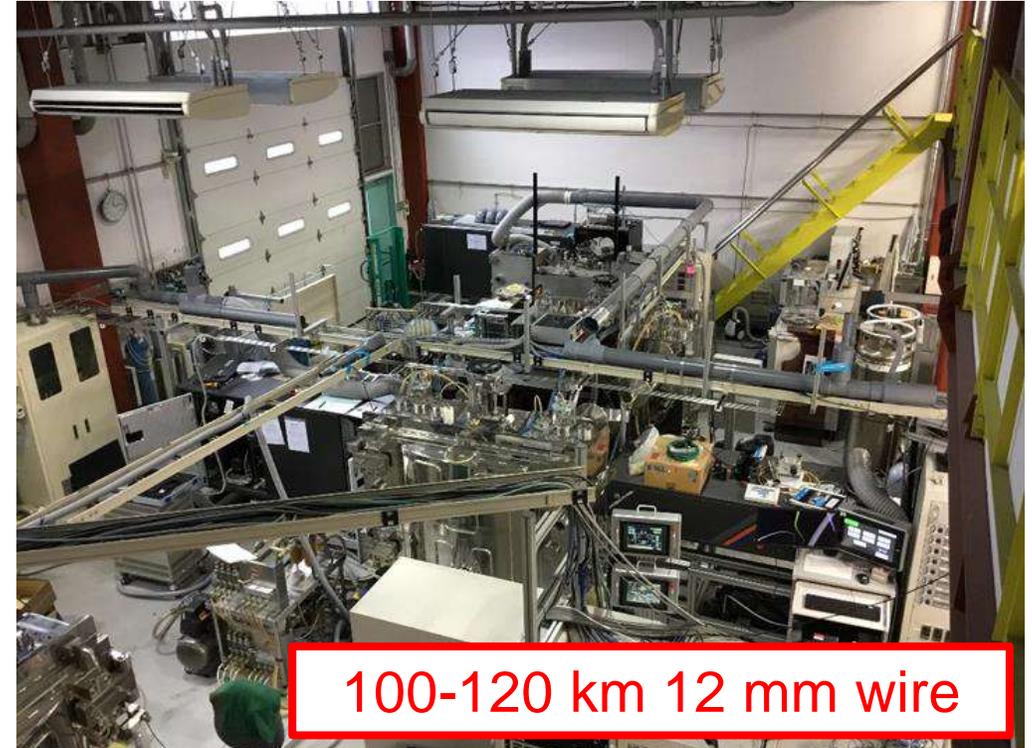
Current SuperOx Wire Architecture



60 km 12 mm wire

Operate at **full capacity**  
5-10x capacity increase scenarios in place

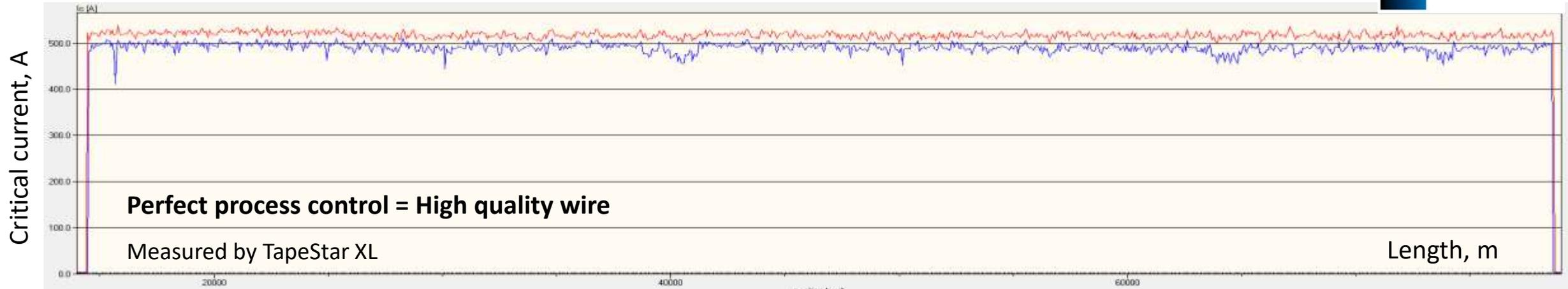
# Throughput: 2019 capacity increase at SuperOx Japan



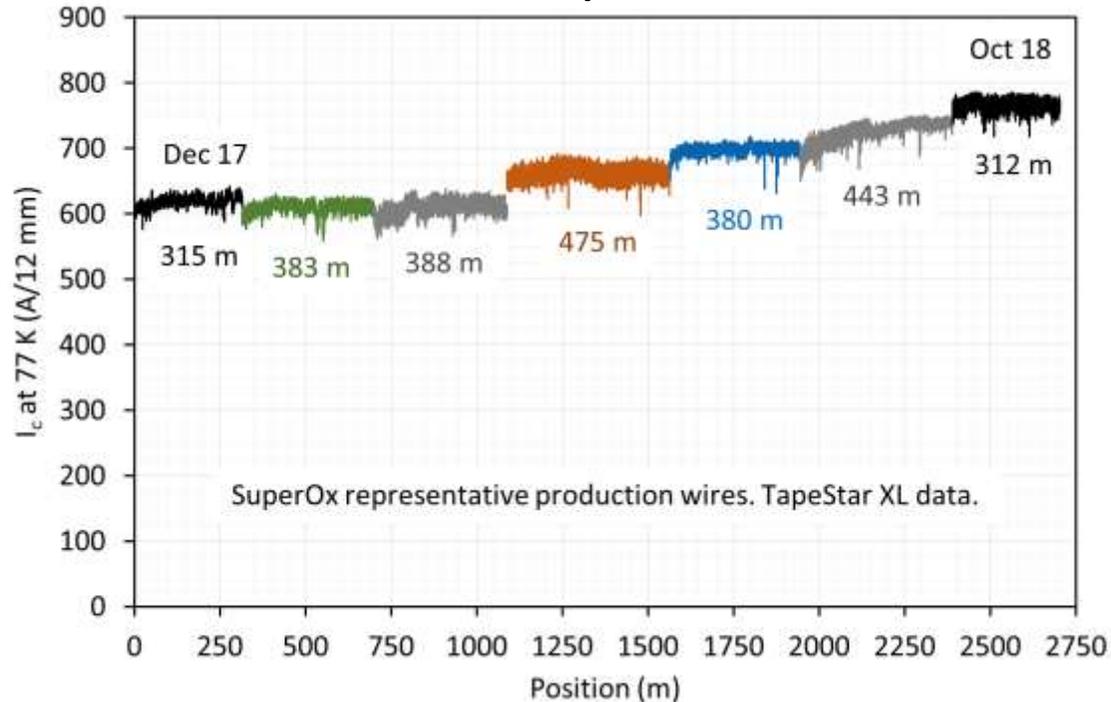
- New, more powerful laser successfully commissioned at SuperOx Japan in July 2019
- + 100% PLD throughput

Wire made at S-Innovations in Moscow and SuperOx Japan is of identical high quality

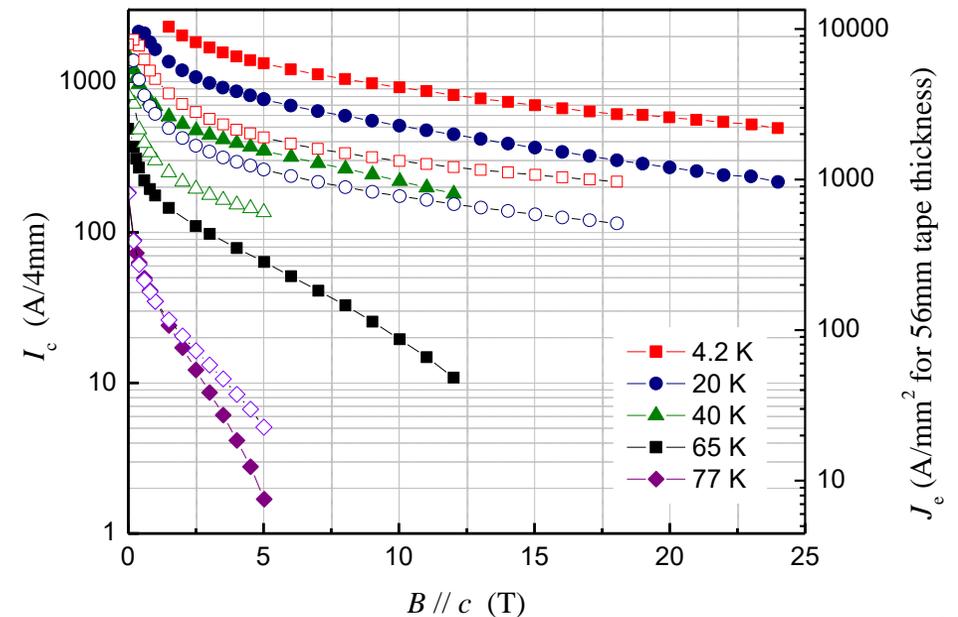
# Critical current and In-field performance of SuperOx Wires



## Continuous improvement of $I_c$



## HTS wires for LN2 and High-field applications



Open symbols – wires for LN2; Filled symbols – wires for High-Filed



1G HTS-Drähte

# Wire Specifications

	<b>Type H</b>	<b>Type HT-SS</b>	<b>Type HT-CA</b>	<b>Type HT-NX</b>	<b>Type G</b>
	High Current	High Current & Tough	High Current & Tough	High Current & Tough	Low Thermal Conductivity
Lamination thickness(μm)		Stainless Steel 20	Copper Alloy 50	Nickel Alloy 30	
Width (mm)	4.3	4.5	4.5	4.5	4.3
Thickness (mm)	0.23	0.30	0.36	0.32	0.23
Ic (A)	~200	~200	~200	~200	~200
Tensile Strength @77K(MPa)	130	270	250	400	90
Bending Dia. @RT (mm)	70	60	60	40	110
Now Developing		400Mpa 80μm lamination		500MPa 100μm lamination	

**Type H, G**



**Type HT-SS**



Stainless Steel

**Type HT-CA**



Copper alloy

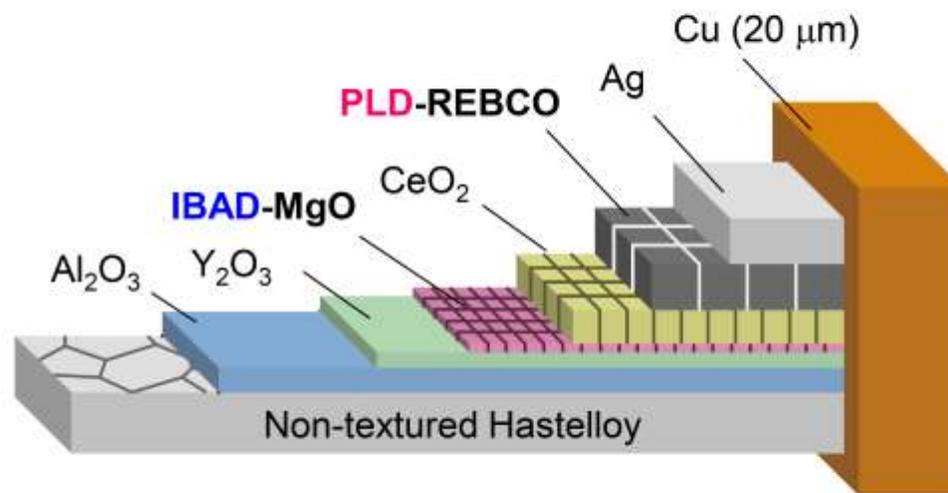
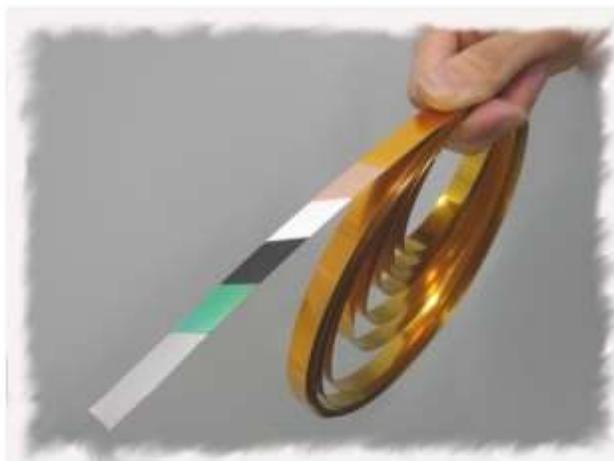
**Type HT-NX**



Nickel alloy



# Fujikura's 2G HTS wire (IBAD / PLD)



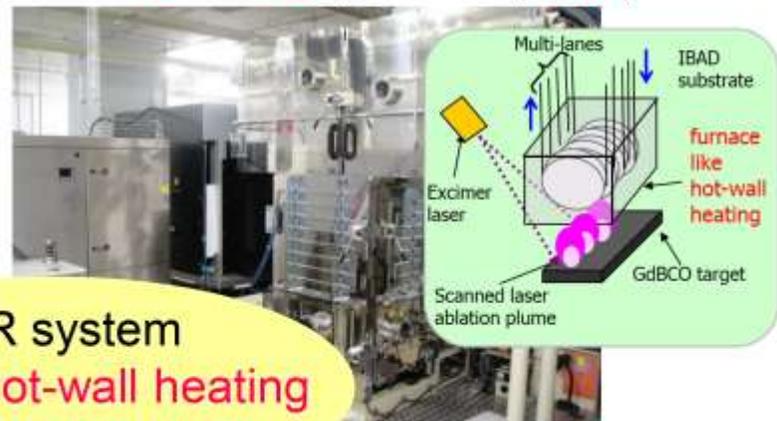
## Ion Beam Assisted Deposition (IBAD)



IBAD was developed by Fujikura Ltd. in 1991

R-to-R system with large ion source

## Pulsed Laser Deposition (PLD)



R-to-R system with hot-wall heating (Black-Body like)

# Typical specifications of Fujikura's 2G HTS wires

Item	Width [mm]*	Thickness [mm]*	Substrate [ $\mu\text{m}$ ]	Stabilizer [ $\mu\text{m}$ ]	Critical Current ( $I_c$ ) [A] (@77K, s.f.)	Material of HTS layers
FYSC-SCH04	4	0.13	75	20	$\geq 165$	GdBCO
FYSC-SCH12	12	0.13	75	20	$\geq 550$	GdBCO
FESC-SCH04	4	0.11	50	20	$\geq 85$	EuBCO+BHO
FESC-SCH12	12	0.11	50	20	$\geq 250$	EuBCO+BHO

\* Dimensions do not include thickness of insulating tapes.

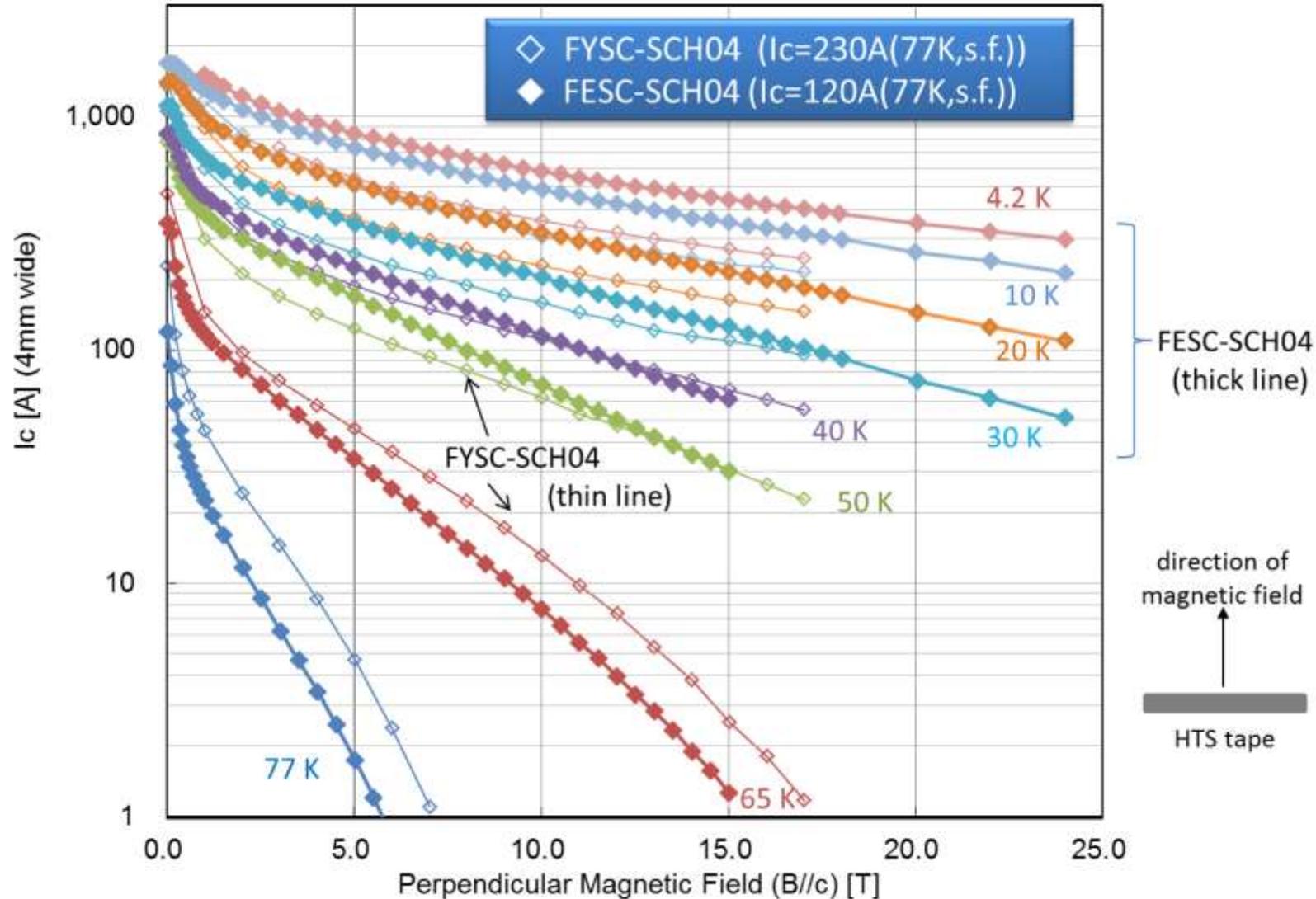
↑ E : Enhanced

FESC series  
APC(BaHfO<sub>3</sub>) doped

in field  $I_c$  : 1.35 times at 30 K  
in field  $J_e$  : 1.6 times at 30 K

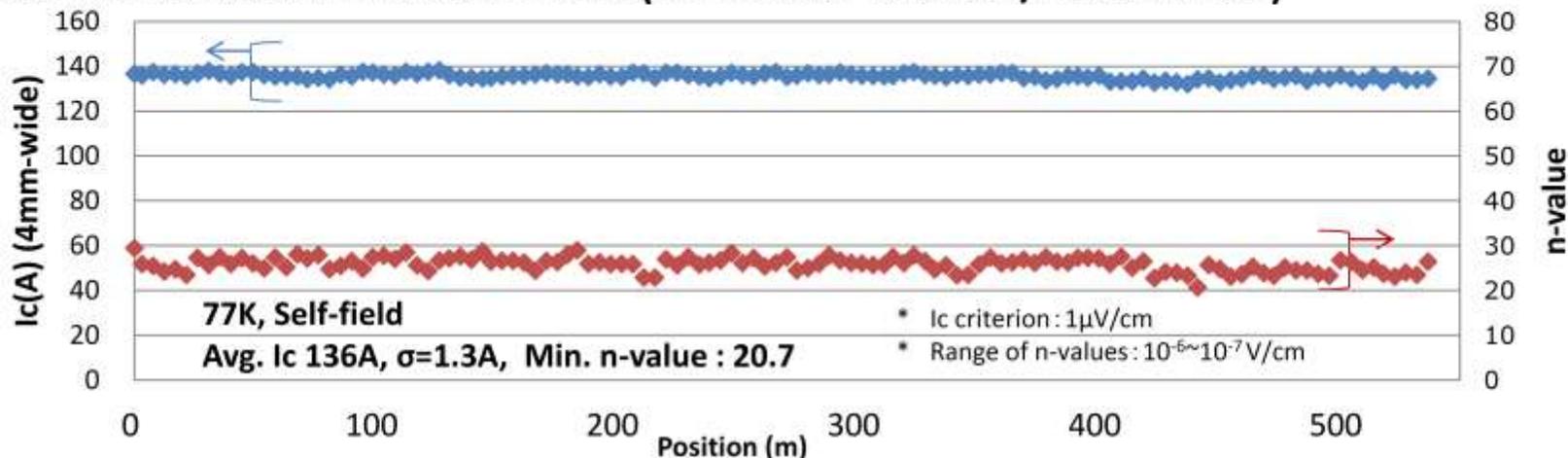
in field  $I_c$  : 1.6 times at 4.2 K  
in field  $J_e$  : 1.9 times at 4.2 K

# Typical $I_c$ -B-T properties

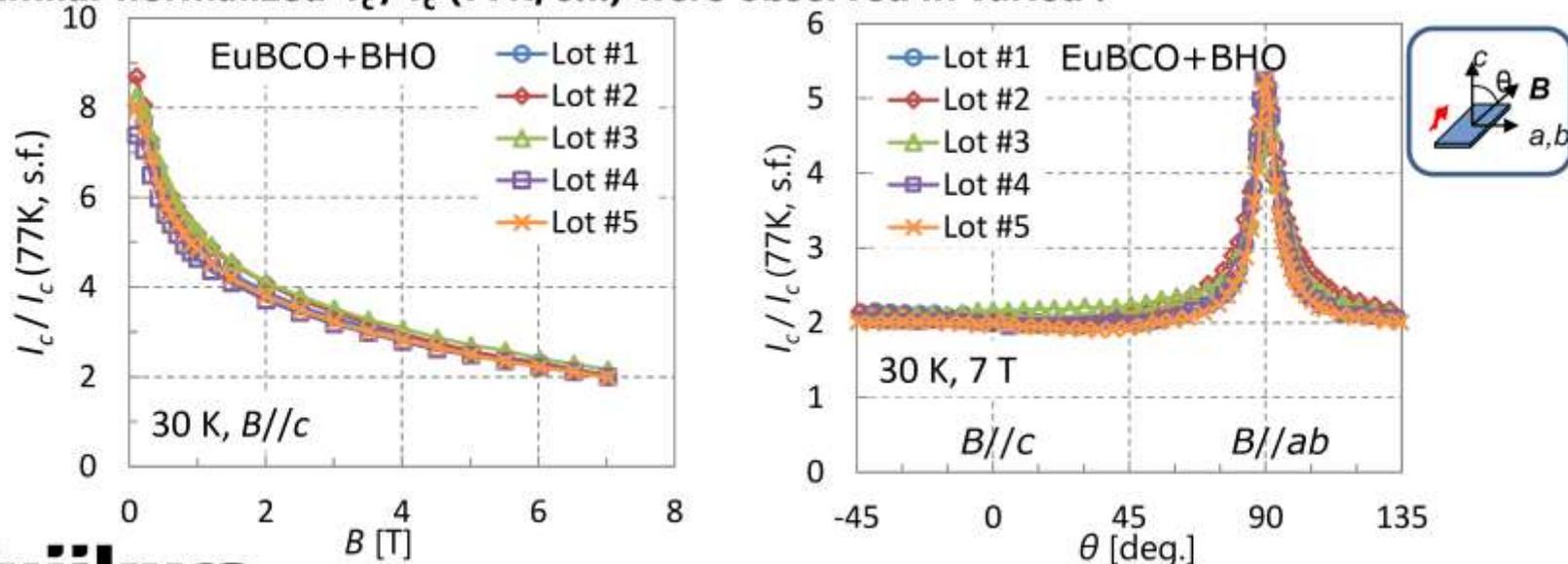


# $I_c$ uniformity of BHO-EuBCO wire 4mm<sup>w</sup>

## ■ Current conduction measurement (4mm-wide with AP / FESC-SCH04)

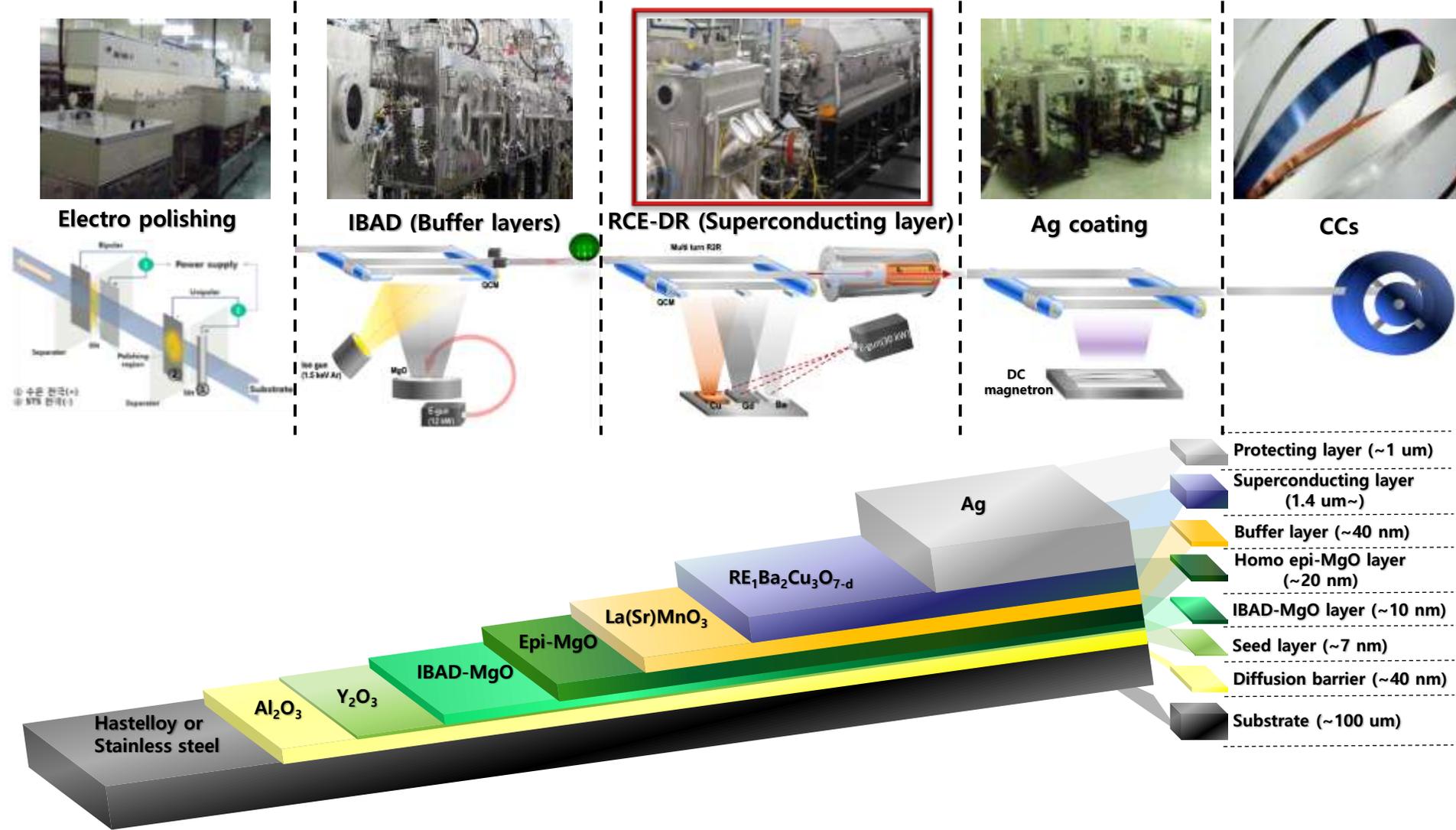


## ■ Similar normalized $I_c / I_c$ (77K, s.f.) were observed in varied .



SUNAM

# HTS 2G Wire Process of SuNAM



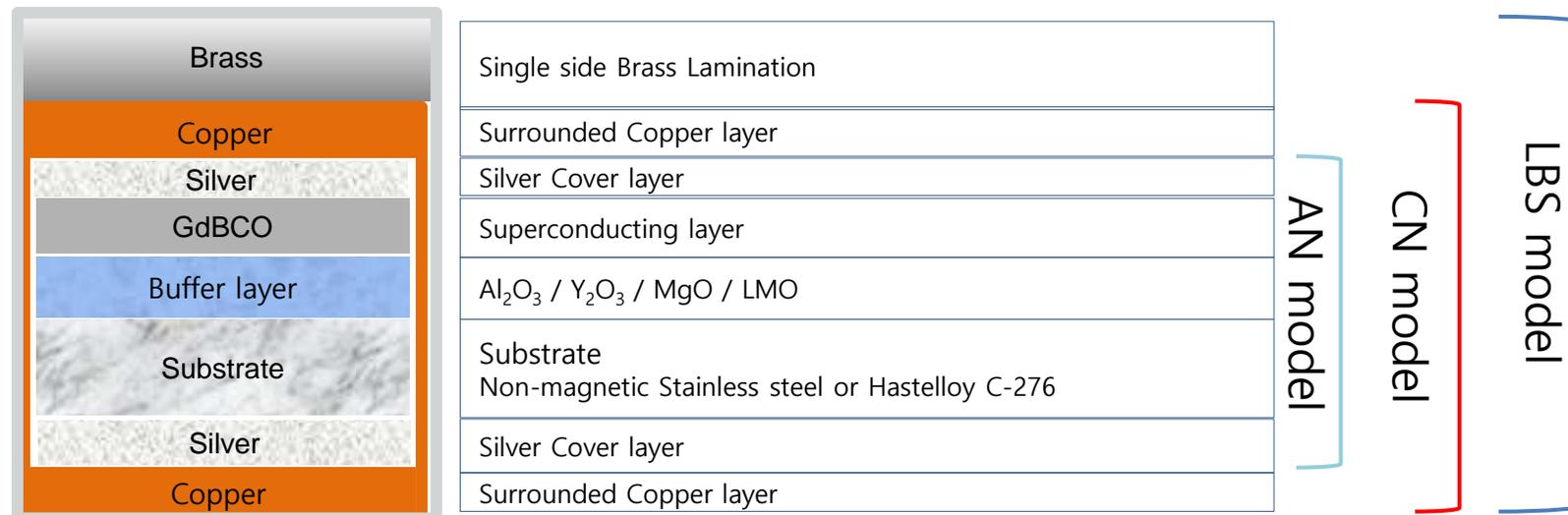
# Product Portfolio

The New Paradigm Designer of Electric Energy !

52 Seungnyang-gil, Wongok-myeon, Anseong-si, Gyeonggi-do, 17554, Korea  
 Tel: +82-31-655-4336 Fax: +82-31-655-4338 E-Mail: sales@i-sunam.com

[2G HTS wire portfolio]

Item	AN	CN	LBS
Cover layer	Silver	Copper	Brass
Substrate	Non-Magnetic Stainless steel (STS310S ~104 um) or Ni-alloy (Hastelloy C-276 ~ 62 um)		
Width [mm]	4 / 12 standard width 2/3/5/6/7/8/9/10 special order		
Thickness [mm] *depending on Substrate	HAS : 0.07 STS : 0.11	HAS : 0.10 STS : 0.14	HAS : N/A STS : 0.29
Final Process	Sputter	Electro-plating	Single side Lamination
Critical Current (@ 77K s.f.)	4 mm width : > 150 A, 200 A, 250 A 12 mm width : > 500 A, 600 A, 700 A, 800 A		

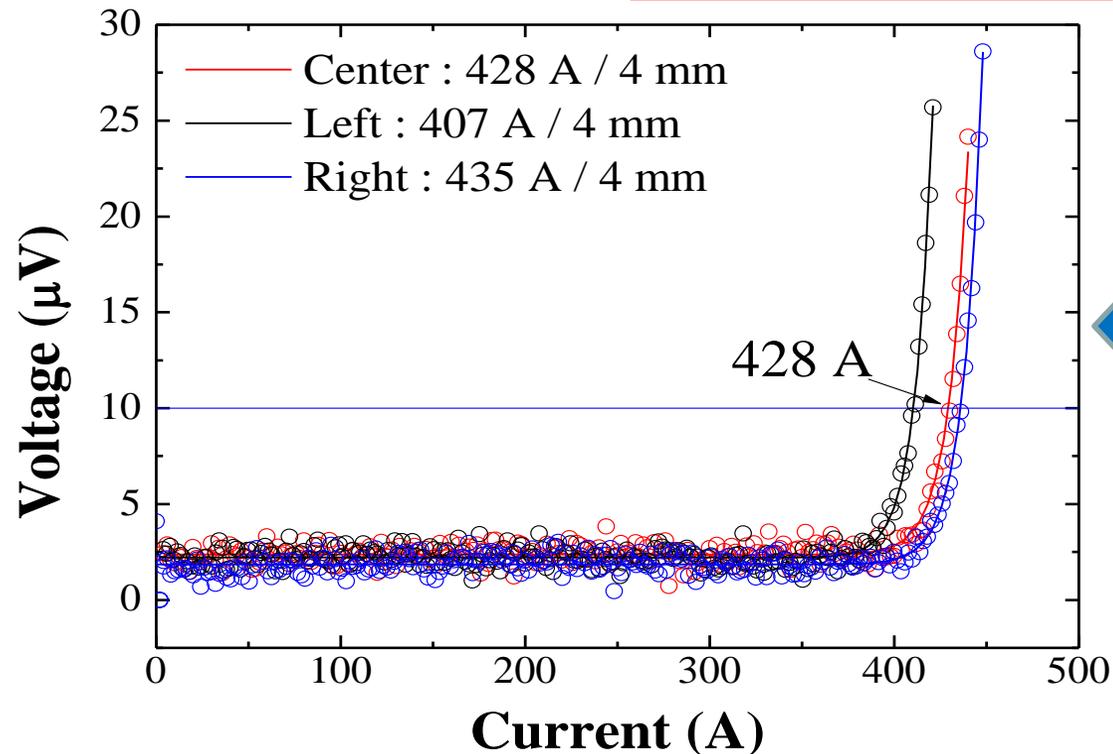


\* Not to scale

# Attainment of higher $I_c$ with thicker GdBCO

Thickness of GdBCO [ $\mu\text{m}$ ]	1.3	1.6	1.8	2.2
# of turns (RCE chamber)	16	18	18	18
$I_c$ [A/12mm-w]	600~800	700~900	800~1,000	1,000~1,200

Production thickness

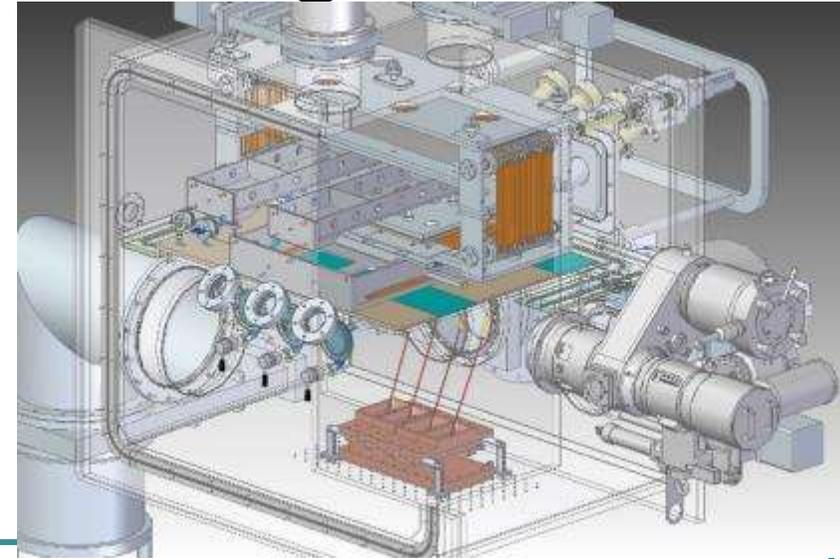
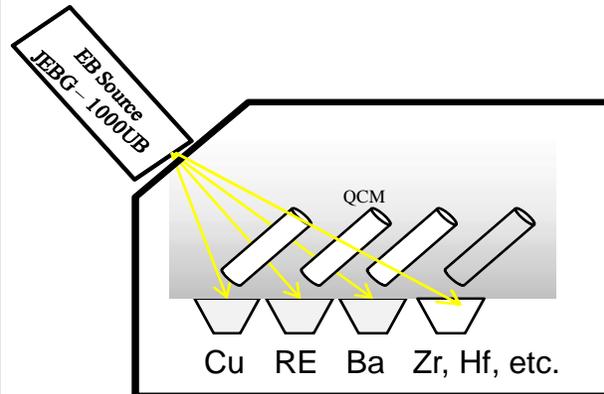


R&D run

Adapt the results on production with new machine  
 → 100 A/mm-width (400 A/ 4 mm) wire will be available on market from mid of 2020.

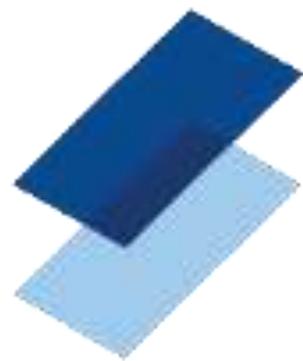
Critical current is steadily increasing.

# New RCE-DR system with 100kW e-gun



- Installation of 100kW class e-gun on RCE-DR by the end of 2019.
- As e-gun power increases,
  - various pinning materials can be deposited (Zr, Hf, Sn etc.)
  - Deposition rate can be increased (10 nm/sec → > 25 nm/sec)
  - Other rare earth materials can be deposited (Y, Y-Gd, Sm etc.)
- Development of 40 mm ~ 120 mm-width coated conductor manufacturing process

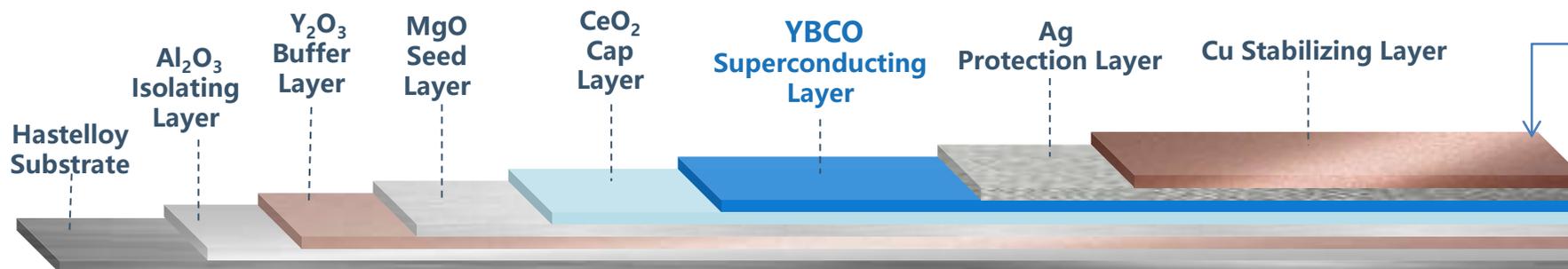
**Add 1,000 km/yr capa. to current 700 km/yr (4 mm)**



上海超导

SHANGHAI SUPERCONDUCTOR

# Production Line IBAD+PLD

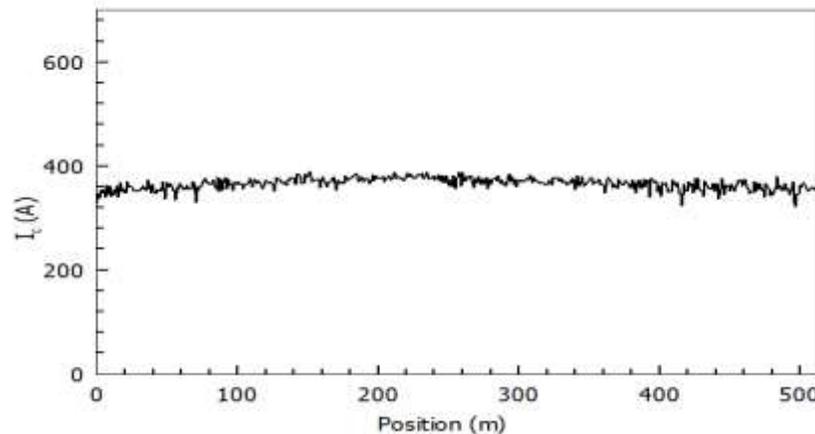
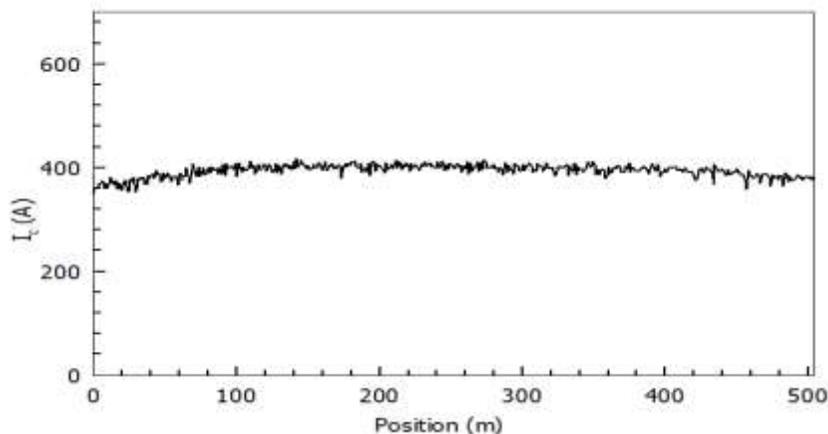
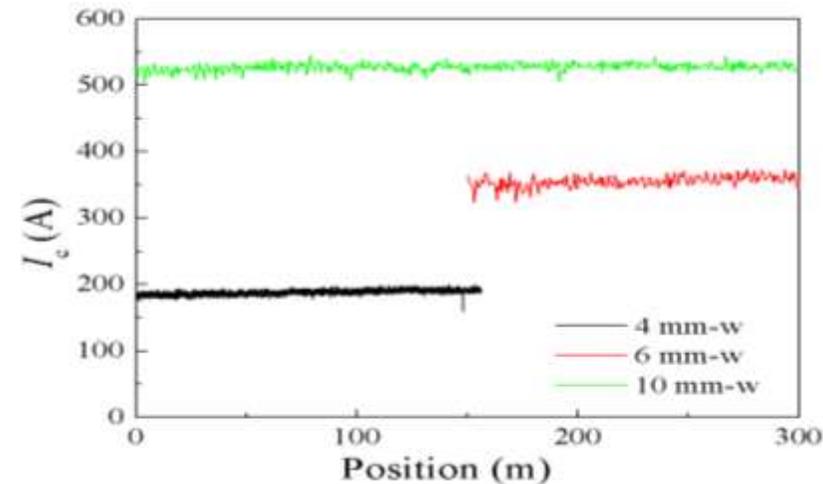
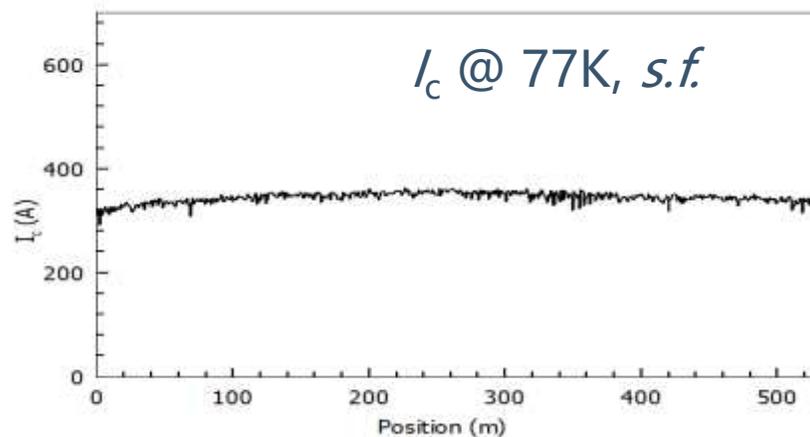
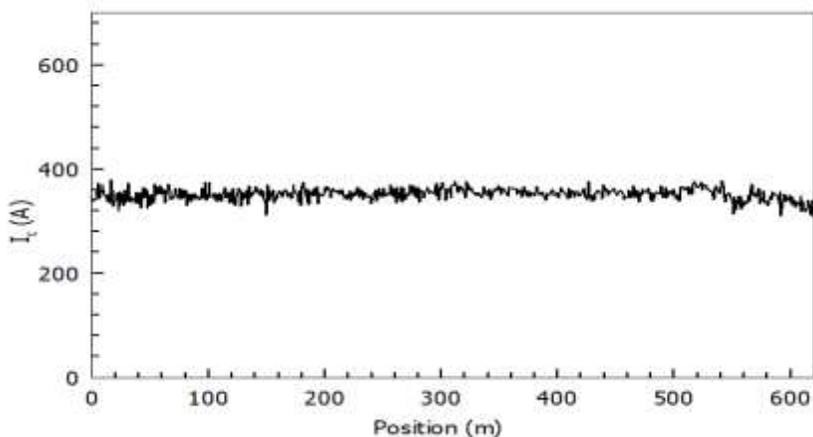


# REBCO Tape Mass-Production

$I_c$  increased much in these 2 years.

before 2018

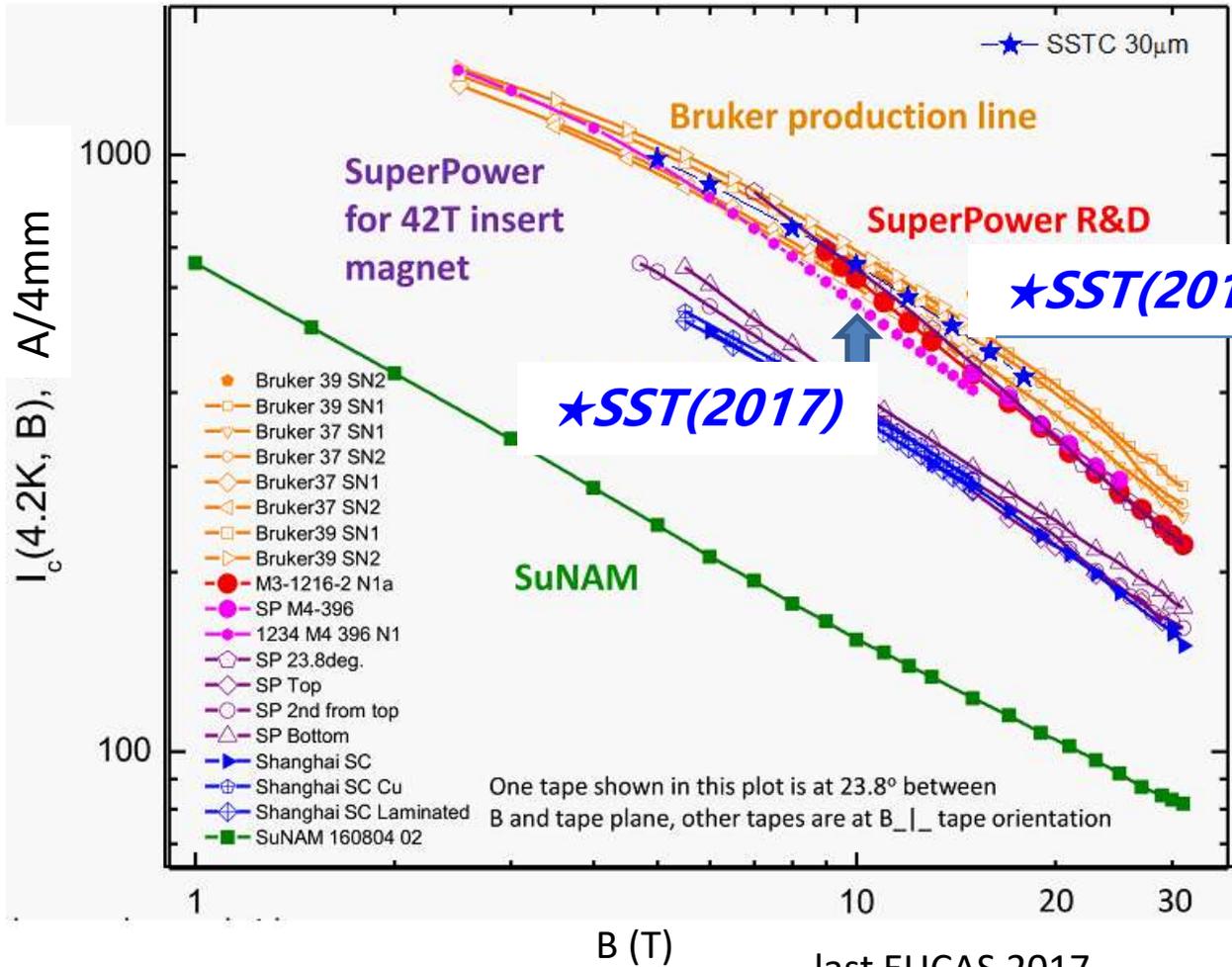
recently (2018) in  
optimized  
deposition process



- Stable long tape production of 300-500 m piece length
- Production rate is doubled while achieving high  $I_c$

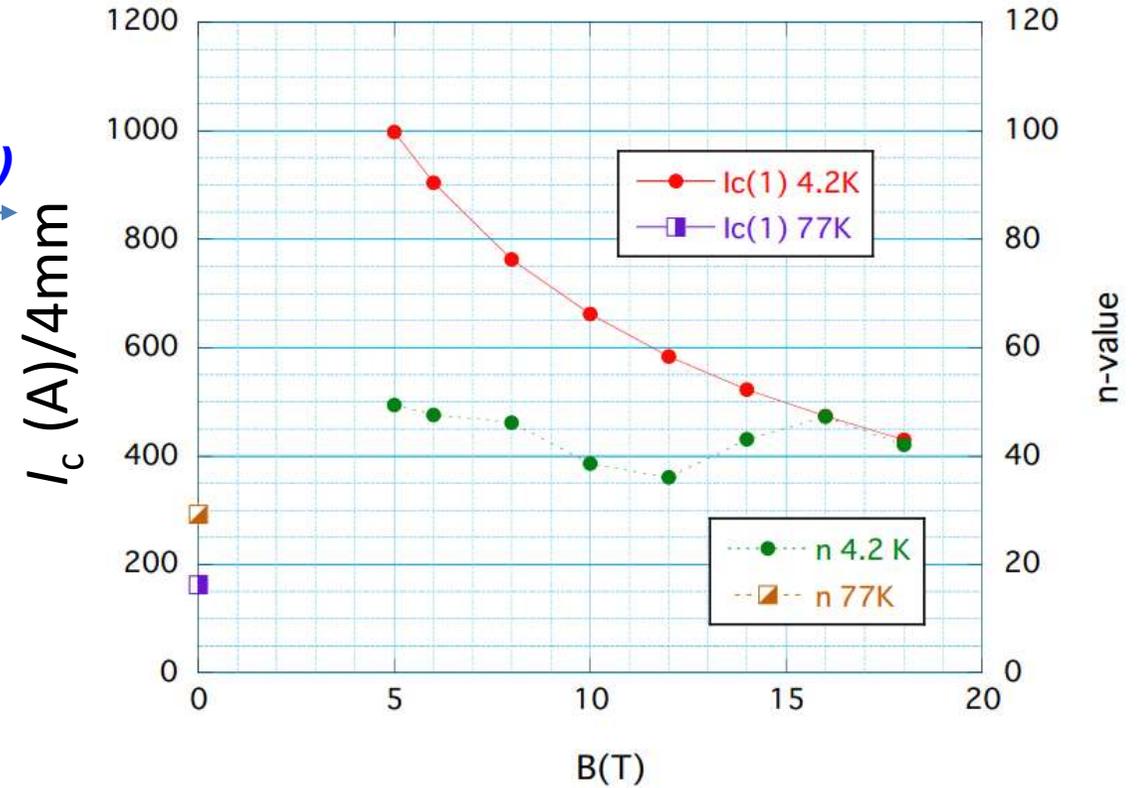
# Recent R&D Progress: $I_c$ at low temp. and high B

$I_c$  increased



last EUCAS 2017

- R&D sample (2018)
- Mass production (2019)



Measured by KEK



上海上创超导  
Shanghai Creative  
Superconductor  
Techonol. Co. Ltd.

# Main Groups and Techniques for 2G HTS Tapes in China



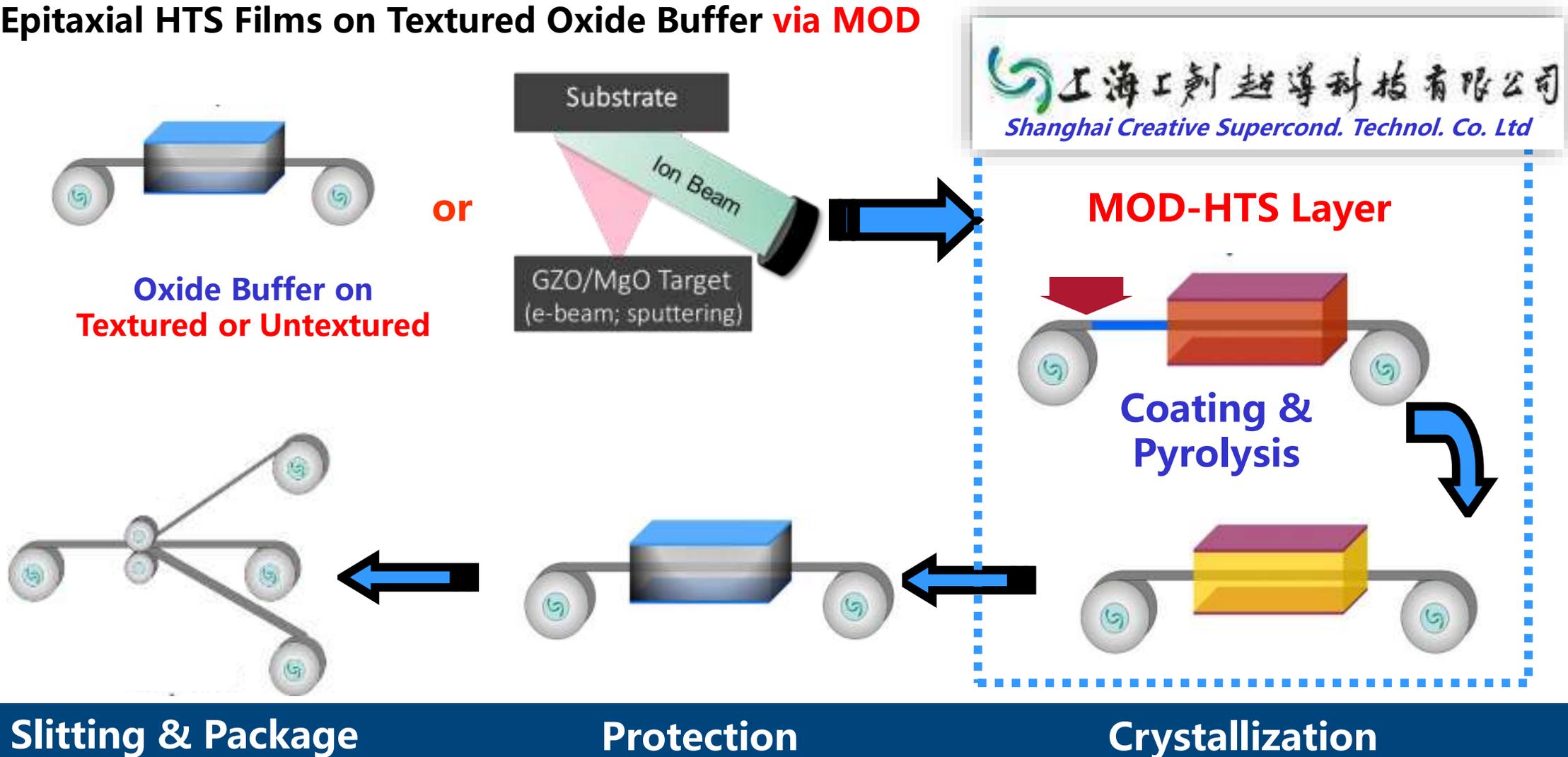
	Research Groups & Industry Partners	Buffer Layer		HTS Layer		
		textured NiW	untextured tape via IBAD	MOCVD	PLD	MOD
R&D	Tsinghua Uni.	√	√			√
	Beijing Tech. Uni.	√				√
	Northwest INM	√				√
	Southwest Jiaotong Uni.	√				√
	IEE CAS					√
	Uni. Electr. Sci.Tech	R2R	√	√		
	Beijing GRINM	R2R				R2R
R & D/ Industry	Suzhou Advanced Materials(SAMRI)		R2R	R2R		
	Shanghai Jiaotong Uni. /SSTC		R2R		R2R	
	Shanghai Uni. /SCSC		R2R		√	R2R

# HTS Coated Conductors

@Shanghai University & Spinning-off Company, SCSC



- ◆ Textured Oxide Buffers on Textured or Untextured Tape **via RABiTS or IBAD**
- ◆ Epitaxial HTS Films on Textured Oxide Buffer **via MOD**



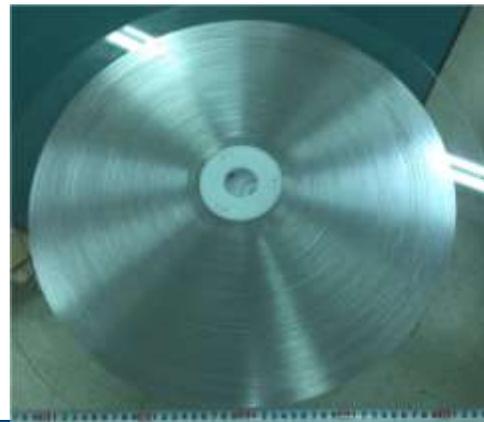
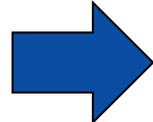
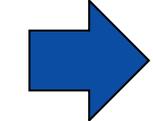
# Typical performances for 12mm/4mm-wide products



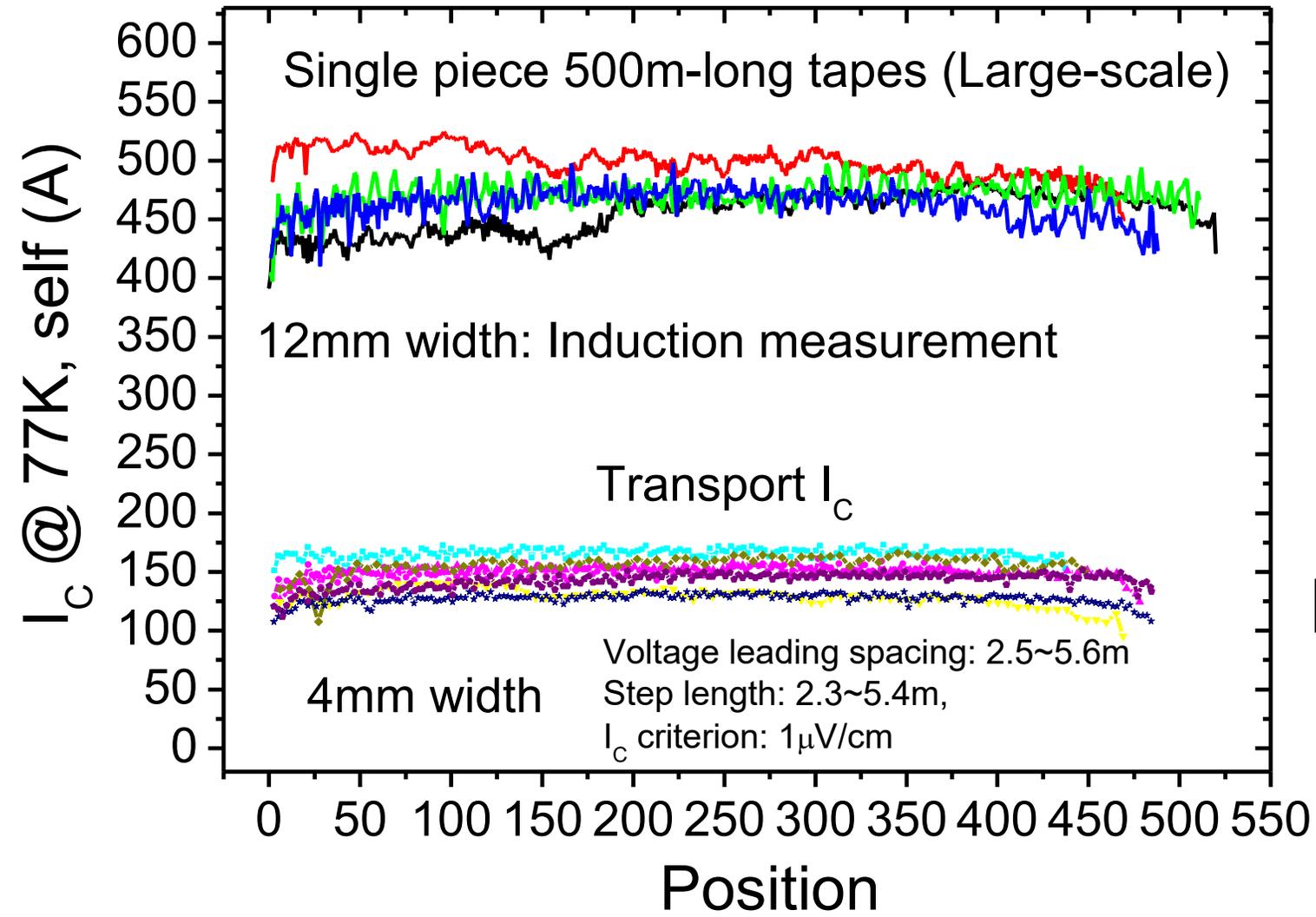
12mm-w  
pristine  
covered  
by Ag



12mm-w  
Electro-  
plated by  
Cu



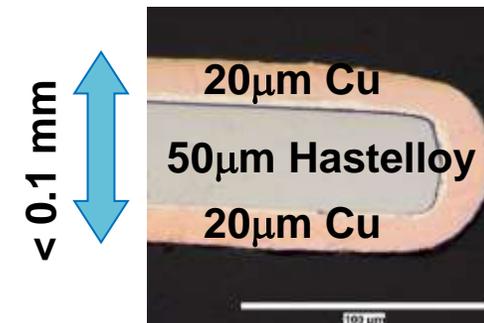
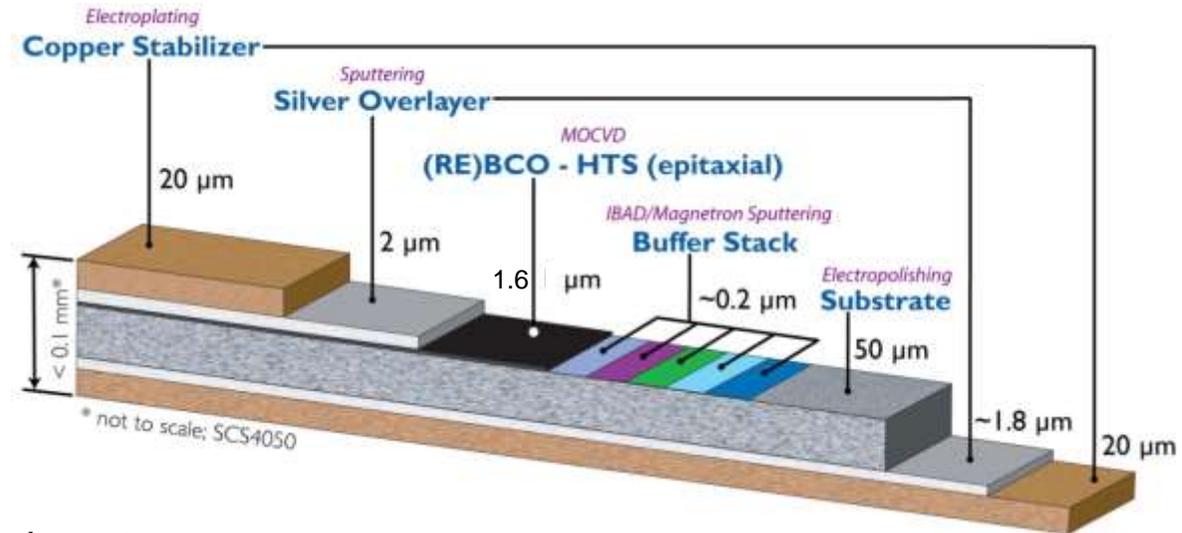
4mm-w  
Product  
laminated  
by Cu





# SuperPower's (RE)BCO superconductor with artificial pinning structure provides a solution for demanding magnet applications

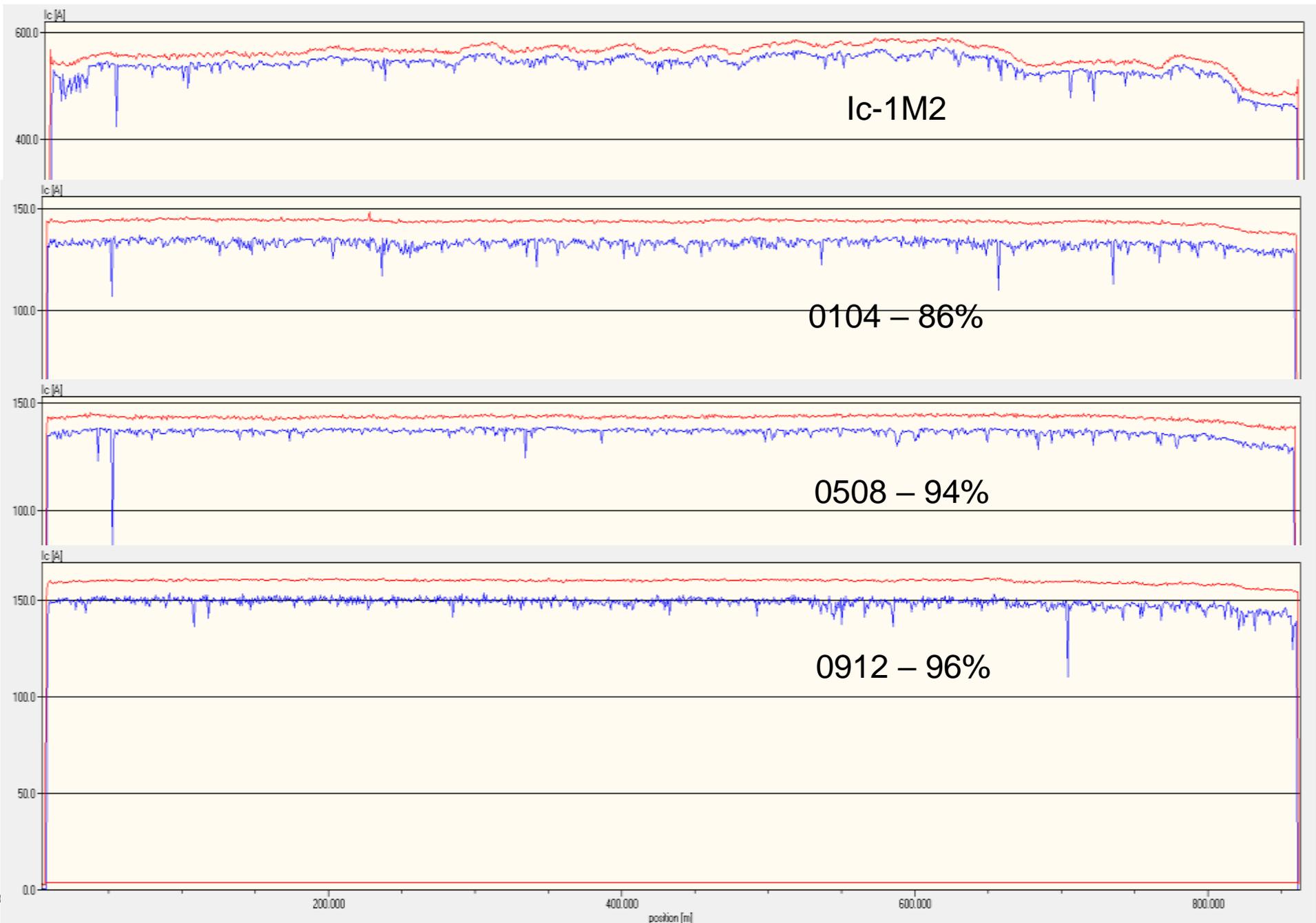
- Hastelloy® C276 substrate
  - 30, 50  $\mu\text{m}$  standard
  - high strength
  - high resistance
  - non-magnetic
- Buffer layers with IBAD-MgO
  - Diffusion barrier to metal substrate
  - Ideal lattice matching from substrate through REBCO
- MOCVD grown (RE)BCO layer with BZO nanorods
  - Flux pinning sites for high in-field  $I_c$
- Silver and copper stabilization



# **In order to meet skyrocketing demand, our efforts are focused on...**

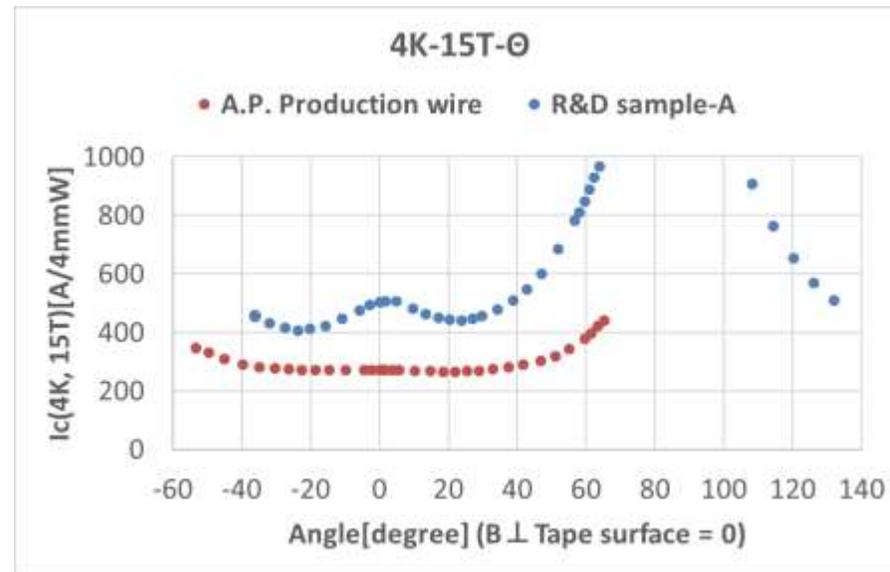
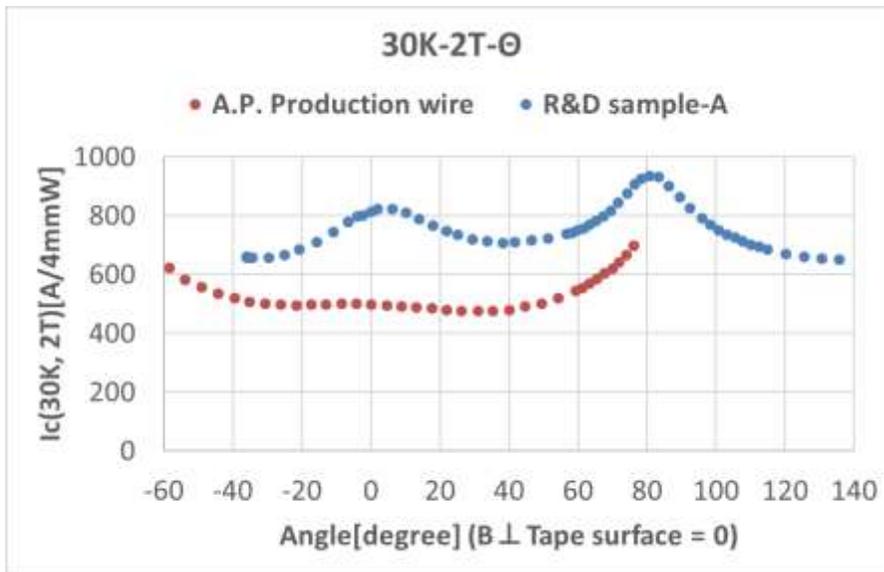
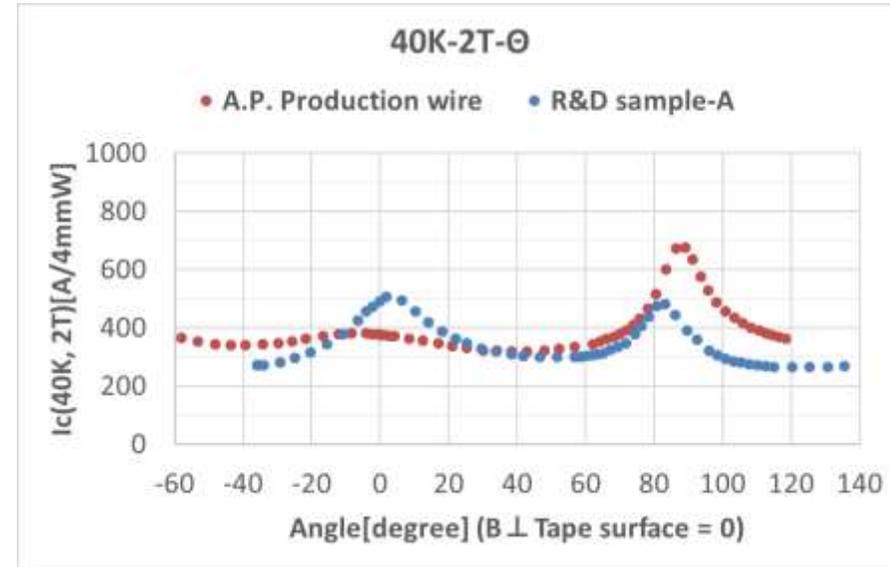
- 1. Stable wire production especially for In-field performance**
- 2. Longer piece length with homogeneous quality**
  - **up to 1000+ m charge lengths for MOCVD production runs are now being routinely run**
  - **up to 2000m charge lengths for MOCVD trials underway**
- 3. Achieve larger production MOCVD and lower cost by**
  - **stabilizing the whole process**
  - **bringing all processes in house**
  - **while adding new equipment**

# Recent Production M4-543-3 (7-865m)



# Recent R&D ; Optimization for Low-temp and High-field

	Ic_min[A/4mmW] Film thickness ≈1.6μm for both samples	
	A.P. wire	R&D sample A
77.3K-sf	193	107
50K-2T	198	107
40K-2T	317	264
30K-2T	492	652
30K-5T	239	320
20K-10T	193	278
10K-10T	288	536
4.2K-15T	266	406



All measurements in this slide were done at Tohoku Univ.

**THEVA**

## THEVA Pro-Line - Wire Production

Industrial production technology: Scalable, cost efficient

### Features of production

Operational since 2016

Capacity: 120 km/yr

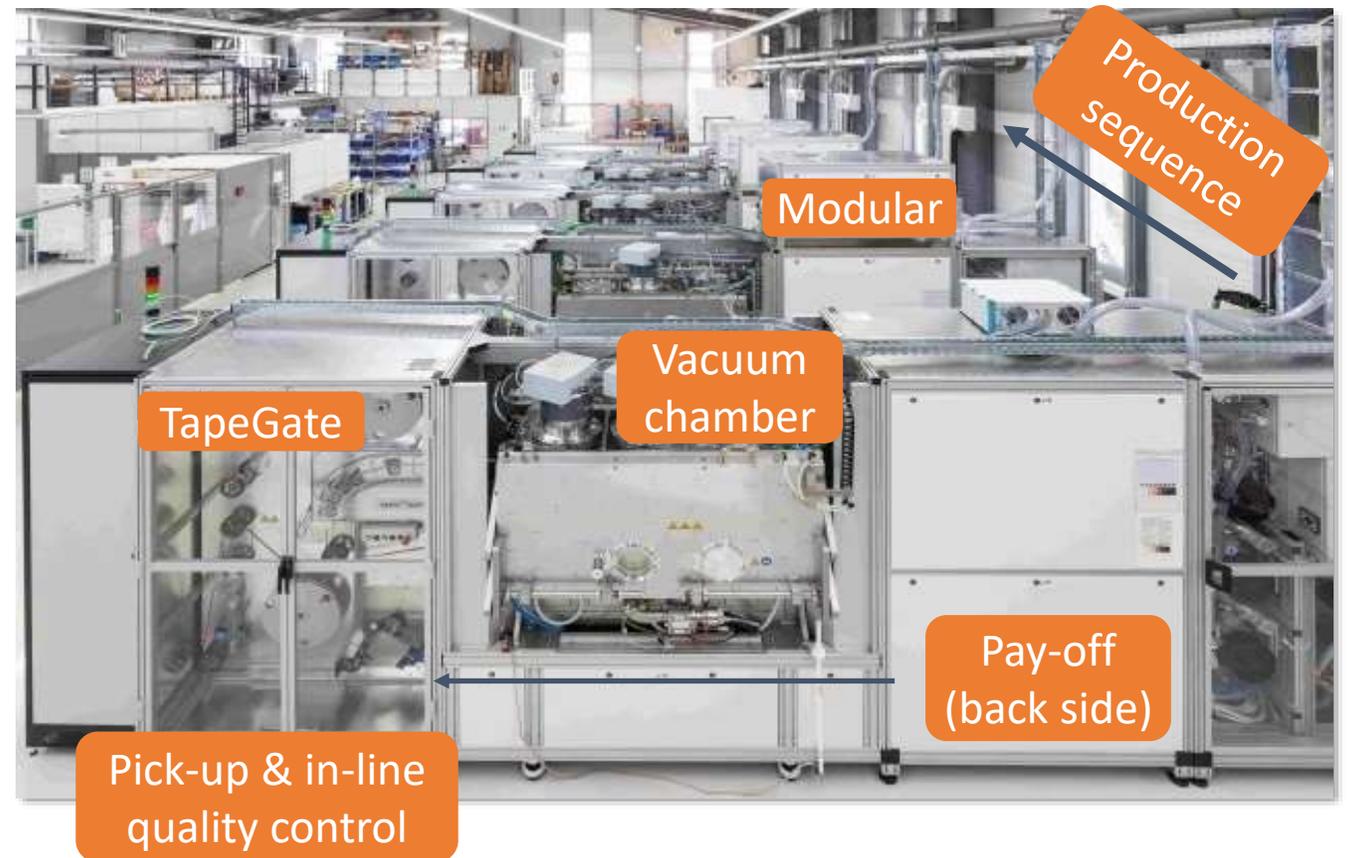
@ 12 mm-width

Production wire length:

300 m – 600 m (1000 m possible)

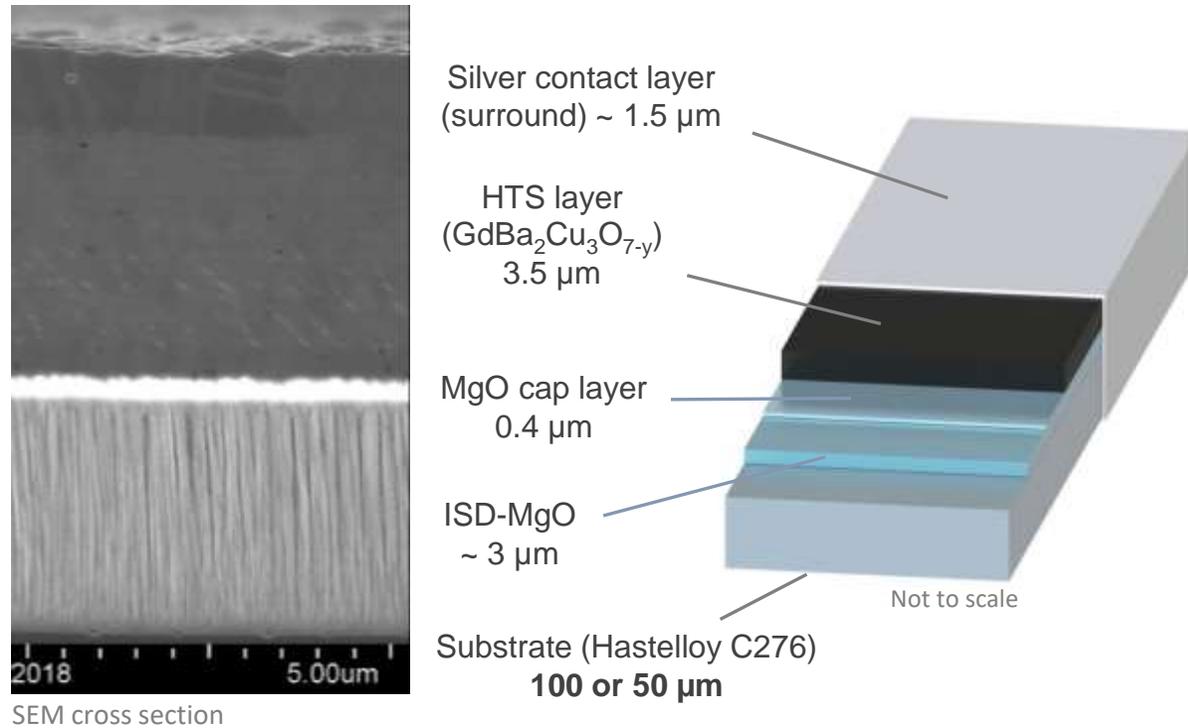
Physical vapor deposition using  
scalable e-beam evaporation

Integrated QC for highest quality



## THEVA Pro-Line HTS Wire

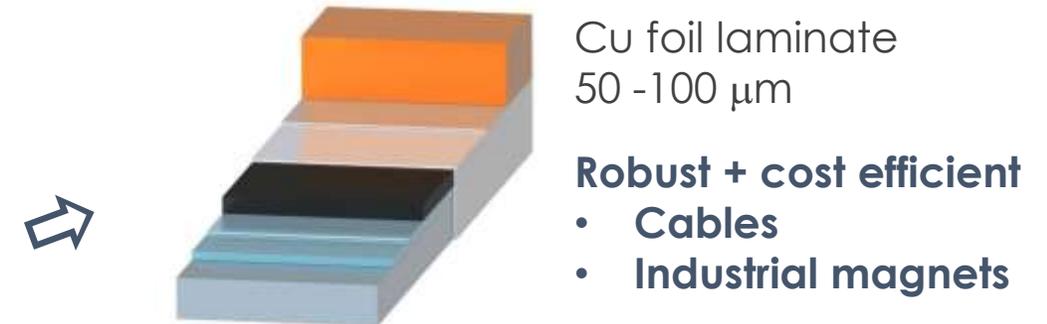
### Basic wire



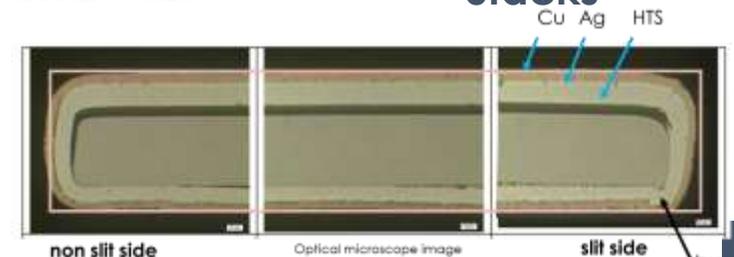
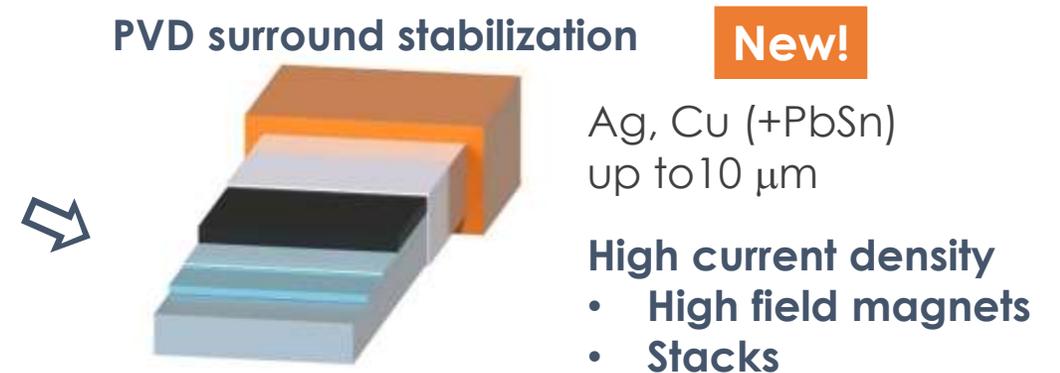
**Simple, cost efficient, and robust**

### Customized wire

#### Laminated stabilization



#### PVD surround stabilization

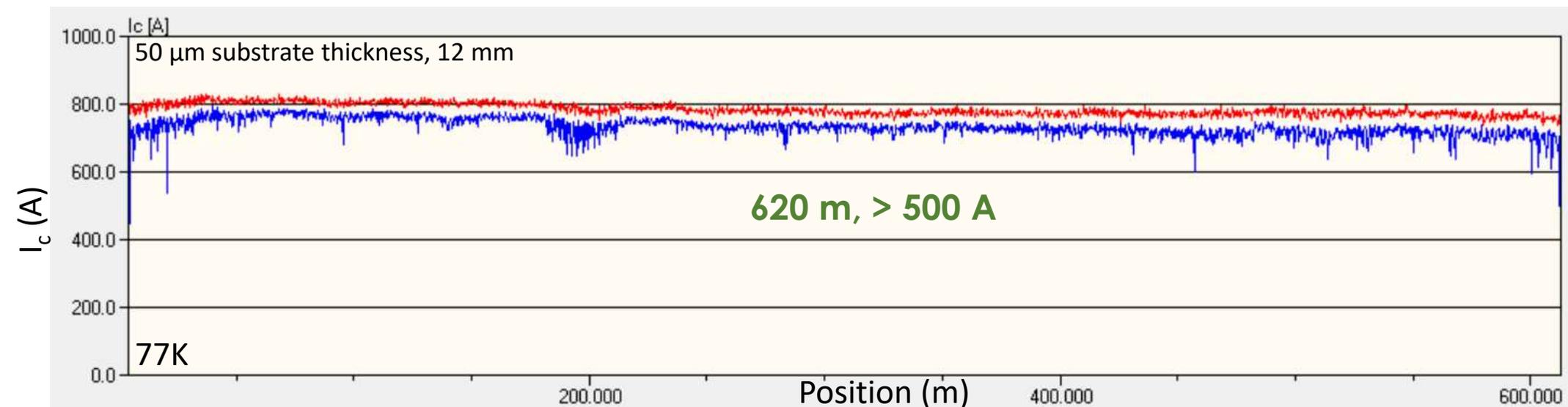
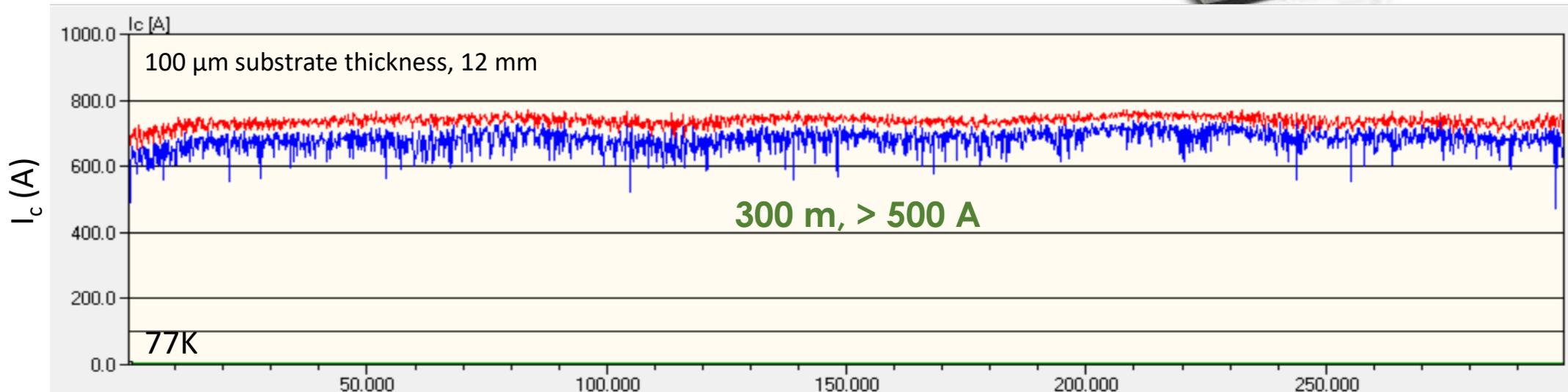


# Typical performance of THEVA Pro-Line

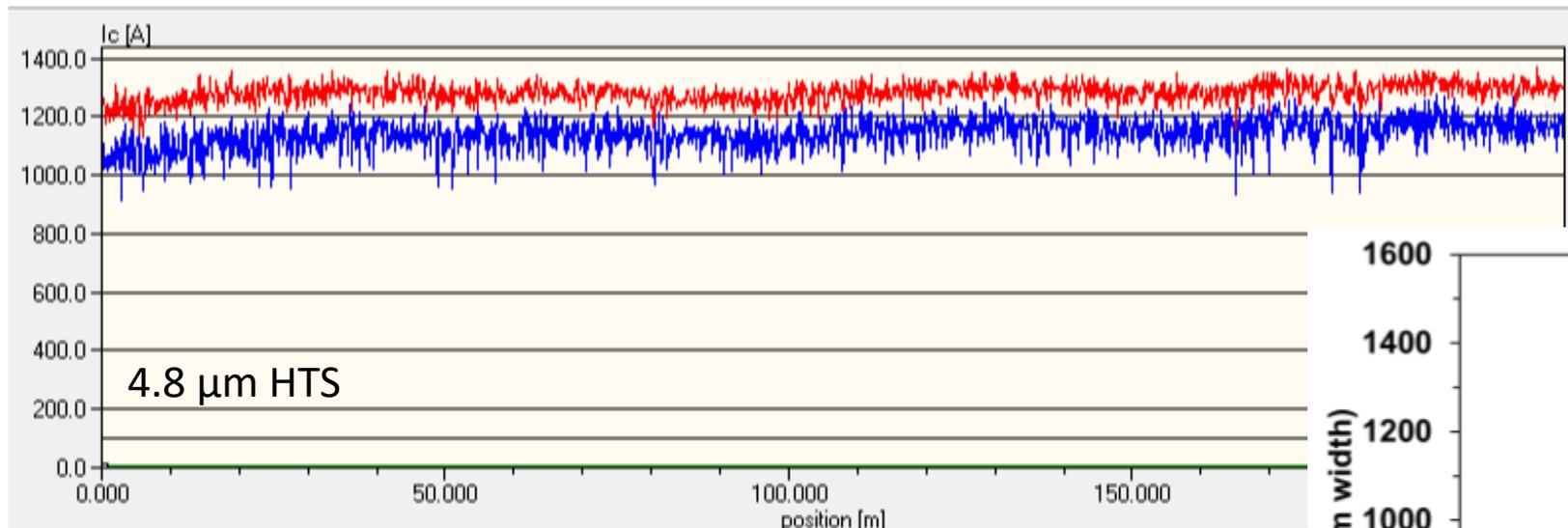


THEVA

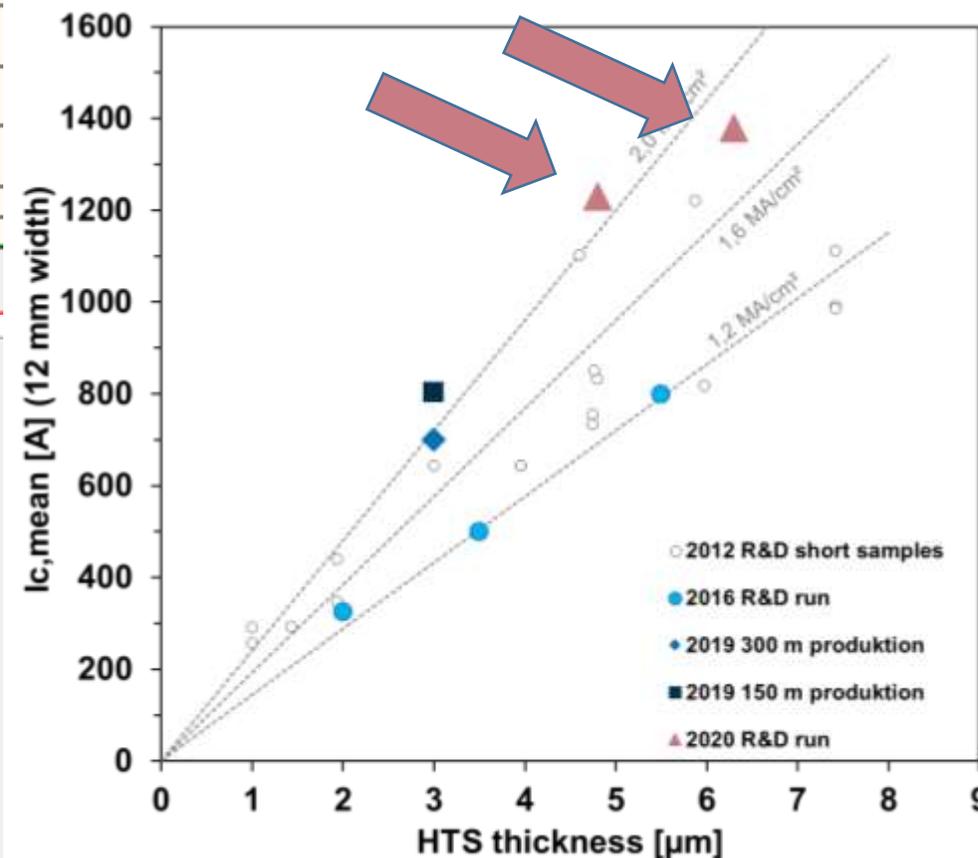
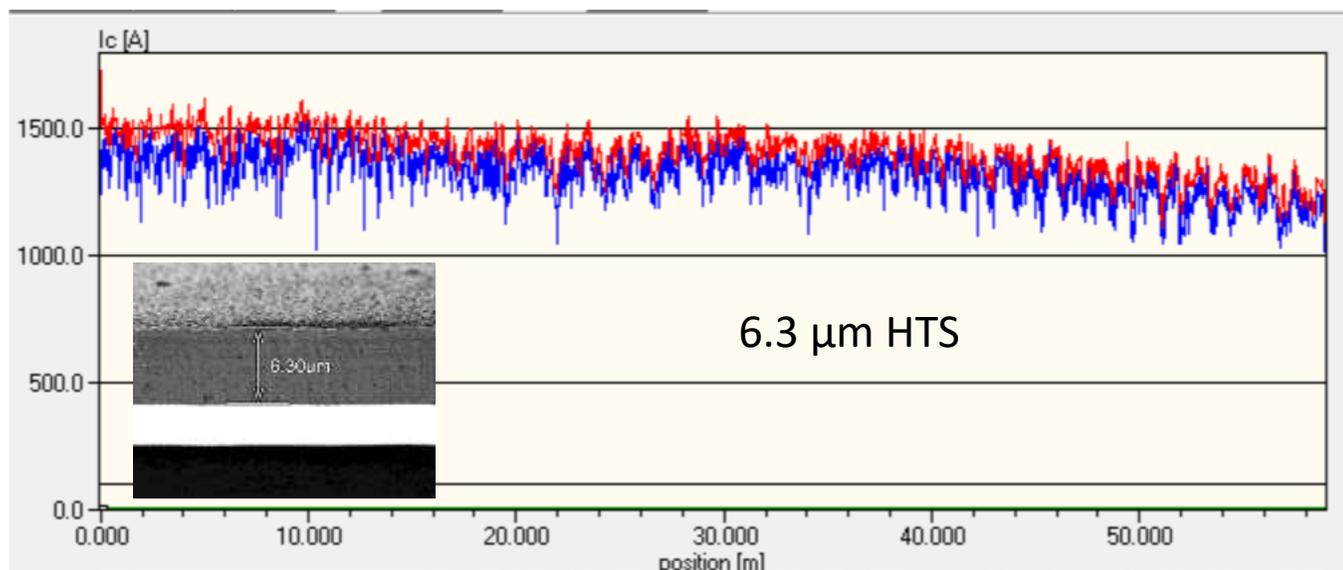
Tapestar



# Development: Increasing HTS thickness in production length



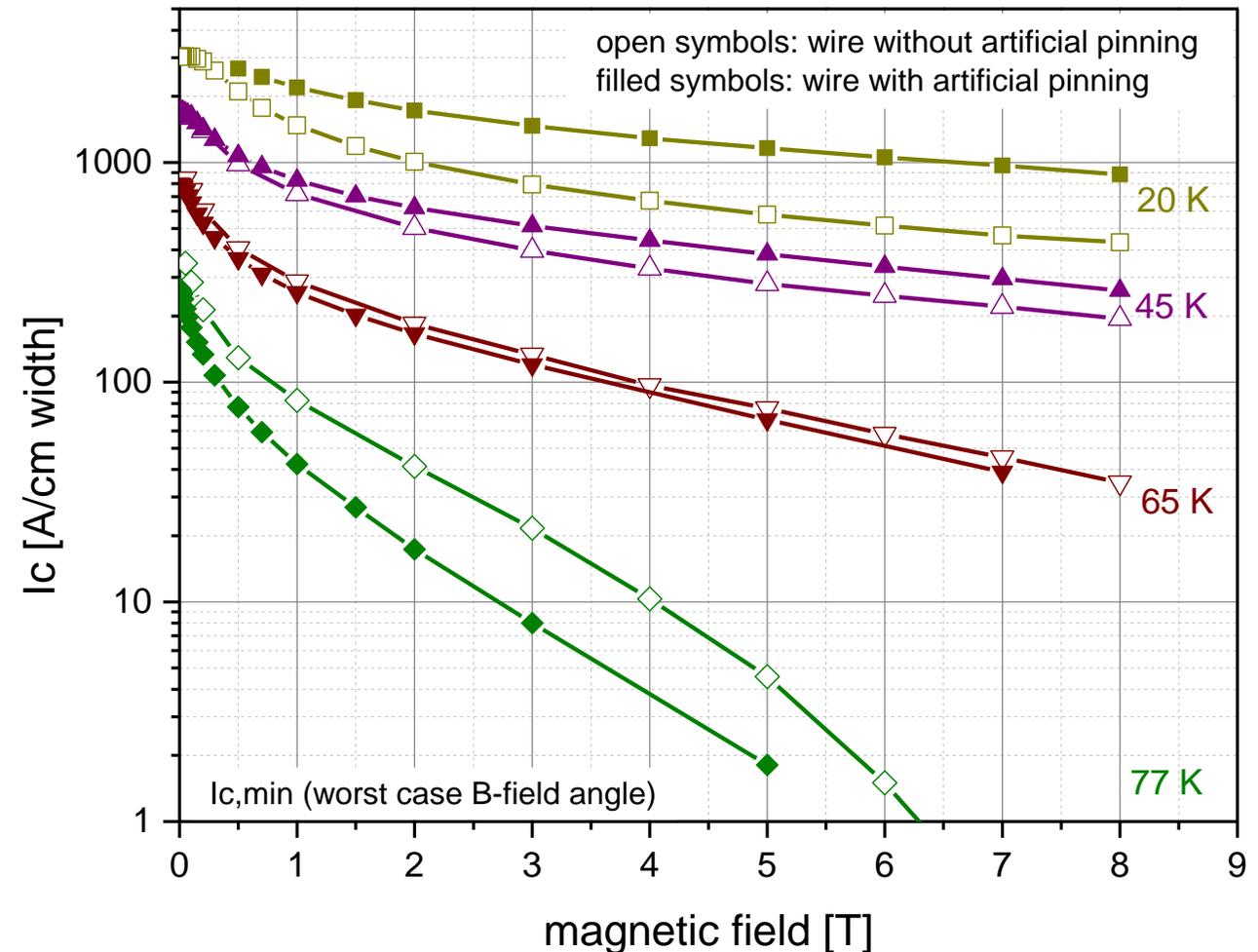
Record  $I_c$  on long HTS wires!  
 $I_c > 1000$  A



# Development: Increasing performance in magnetic field

- Development of HTS wire for low temperature and high field applications
- Deposition on 300 m piece length with regular production systems
- Increase of  $I_c$  by factor 2 at 20 K and  $B > 3$  T

$I_c$  doubled at 20K and high field compared to standard wire



# Zusammenfassung

Mehr als 10 Hersteller weltweit können HTS Drähte mit guter oder sehr guter Performance und relevanten Längen herstellen.

Mehrere Hersteller haben Produktionskapazitäten aufgebaut, die für Projekte in fast jeder Größenordnung ausreichend sind.

Eigenschaften werden laufend verbessert:

- $I_c$
- Magnetfeldabhängigkeit
- Stücklänge
- Mechanische Eigenschaften

Fertigungskapazitäten werden aufgrund der steigenden Nachfrage ausgebaut.

Vielen Dank an: S. Meuer, U. Betz, V. Petrykin, Y. Yamada (SEI), Y. Iijima, H. Lee, Y. Yamada (SST), C. Chai, D. Hazelton

Vielen Dank!

**THEVA**



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