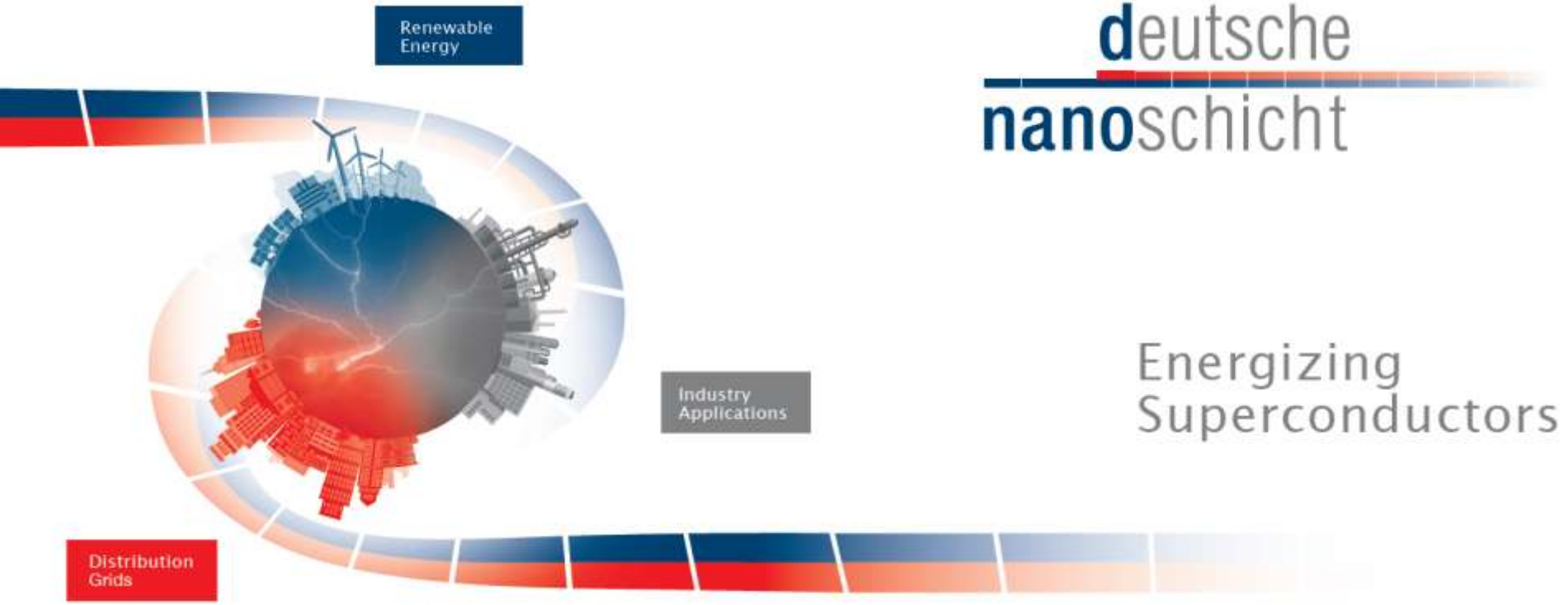


deutsche nanoschicht

Energizing Superconductors

Produktion supraleitender Drähte für die Energietechnik

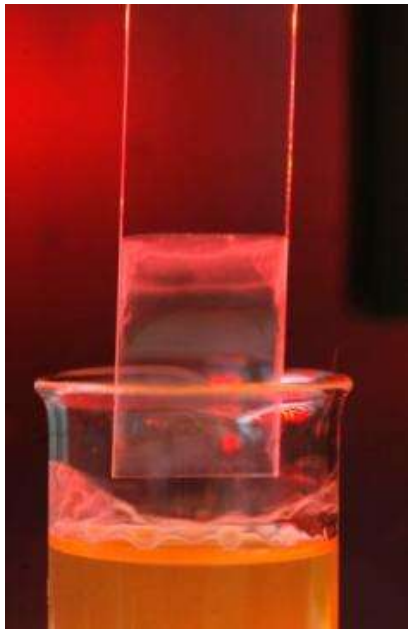
Michael Bäcker
Deutsche Nanoschicht GmbH

Hersteller supraleitender Drähte - Prozesstechnologien

deutsche nanoschicht

Schichtabscheidung

- Chemical solution deposition (CSD)
- Chemical vapour deposition (CVD)
- Physical vapour deposition (PVD)



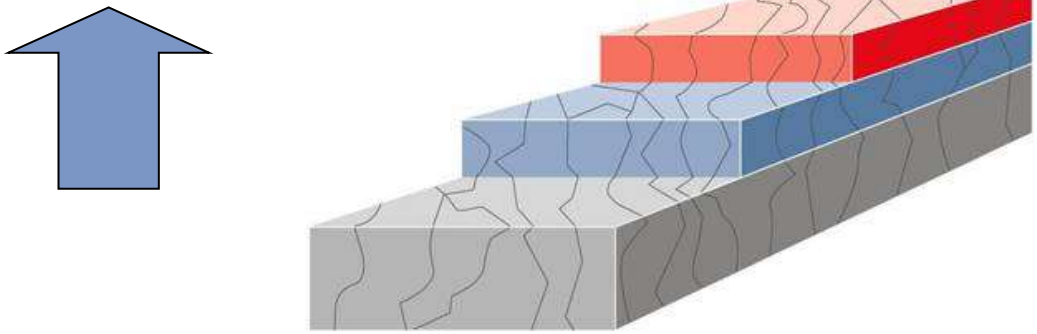
Hersteller supraleitender Drähte - Prozesstechnologien

deutsche nanoschicht

Schichtorientierung

- orientiertes epitaktisches Kristallwachstum

Orientierung der Pufferschicht während Beschichtung



Verwendung von orientiertem Metallsubstrat

IBAD: Ion-Beam assisted deposition
ISD: Inclined substrate deposition

RABiTS™: Rolling assisted biaxially textured substrate

Hersteller supraleitender Drähte

deutsche nanoschicht

Alle folgenden Folien wurden von den oben genannten Firmen zur Verfügung gestellt. Für den Inhalt sind die Firmen verantwortlich.
Sämtliche Rechte an den Folien liegen ausschließlich bei den einzelnen Firmen.

COATED CONDUCTORS ACTUAL STATUS

M. Bauer

THEVA Dünnschichttechnik GmbH

HTS – Production Line

Setting worldwide standards

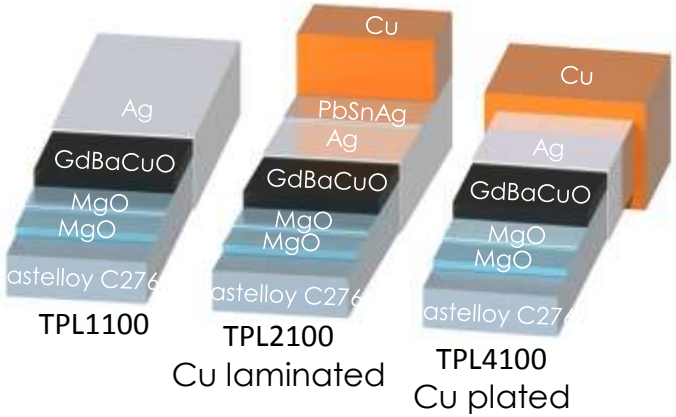
Pilot line features

- Modular, fully-automated
- Continuous vacuum tape locking
- Inline quality control
- Production capacity: 120 km/yr (@ 12 mm-width)
- Standard production wire length: 300 m
- Maximum demonstrated wire length: 600 m

Goals

- Cost efficient production
- Robust process allowing high yield
- Implementation of industrial standards

Stringent quality management

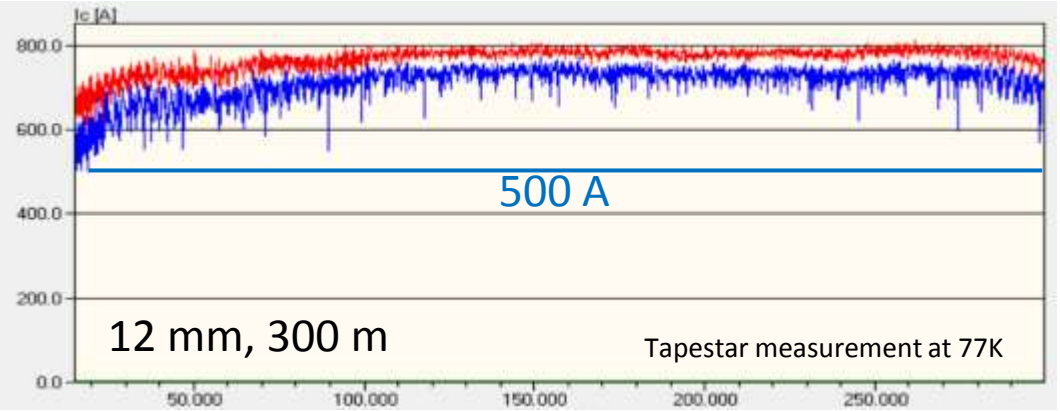


Pro-Line HTS wires

Increasing performance

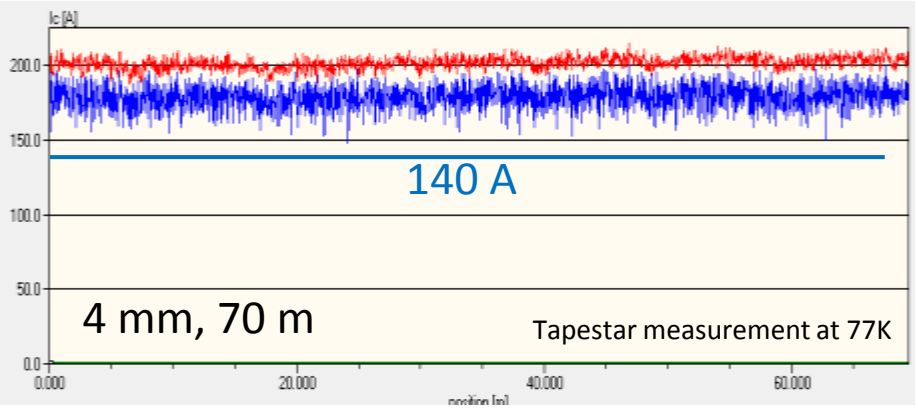
Quality of production improved

Ic > 500 A as new standard quality of 12 mm wide tapes



Development of 3 mm, 4 mm, and 6 mm wide wires

4 mm wide tapes with 150 A successfully demonstrated

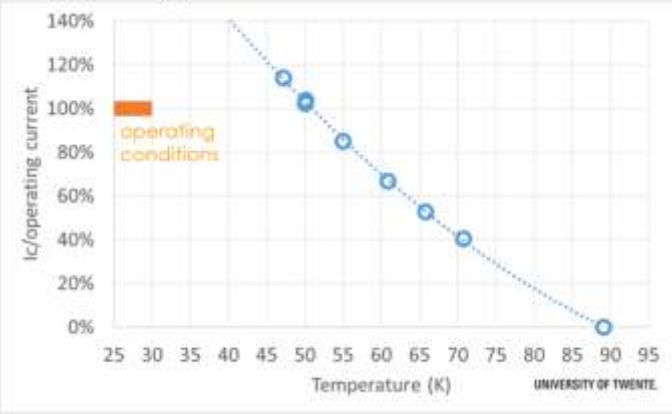


HTS coils

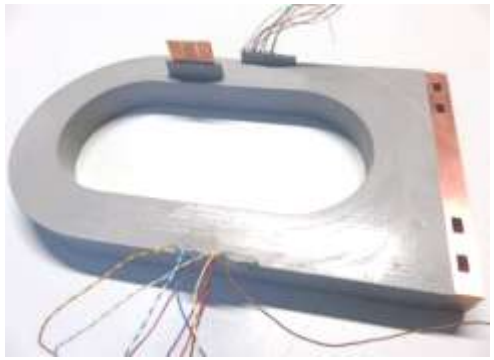
Coil winding and casting technology:

- Single or double pancake coils
- 200+ turns
- 10 cm…1,4 m in length
- Shape adaptable
- 20 K … 77 K
- Conduction or liquid cooling

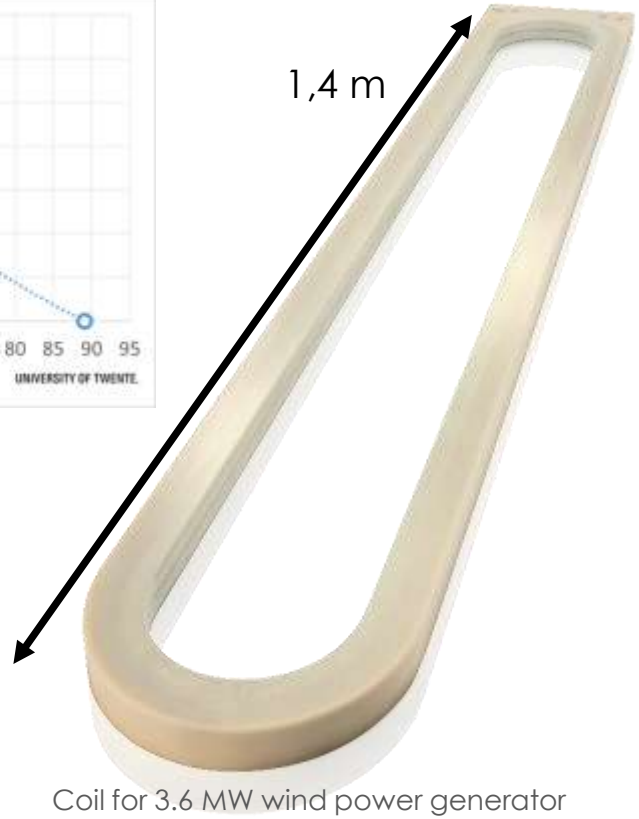
Proven technology successfully used for the production of 30+ coils for the 3.6 MW generator to be built within the EcoSwing project.



Type test result generator coil



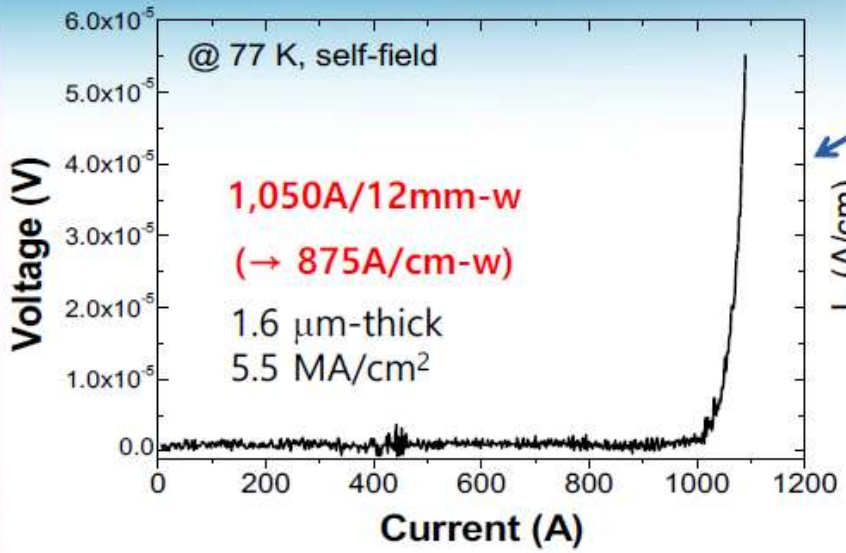
2 x 87 turn double layer coil including several voltage taps

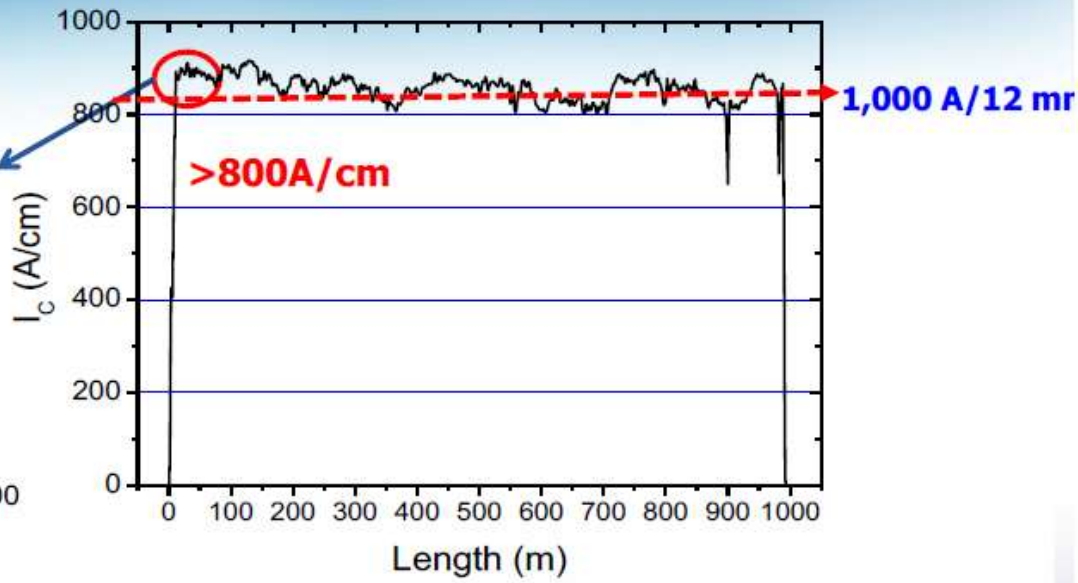


Coil for 3.6 MW wind power generator

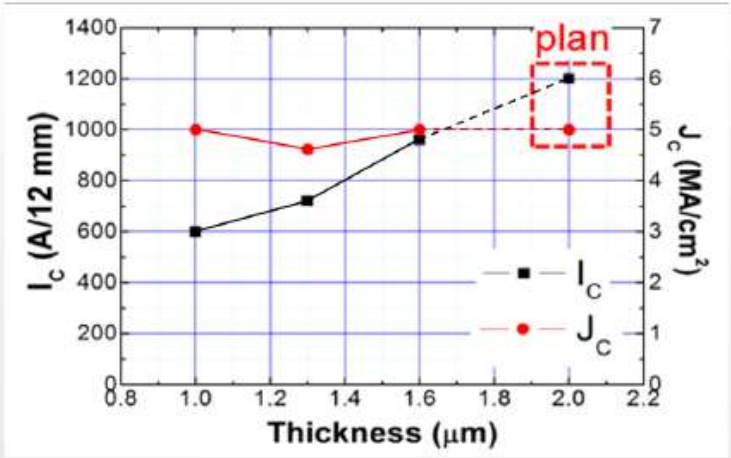
"EcoSwing has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 656024." "Herein we reflect only the author's view. The Commission is not responsible for any use that may be made of the information it contains."

RCE-DR results (with optimization deposition region)



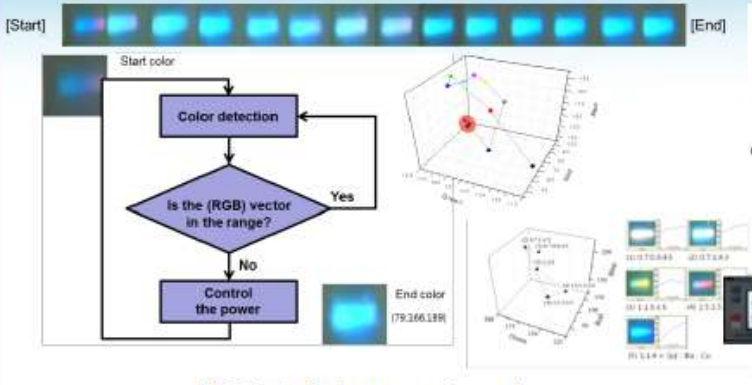


	Speed (m/min)	Turns	Thickness (μm)	I_C (A/cm)	J_C (MA/cm²)
results	2	14	1	500	5
	2	14	1.3	600	4.6
	2	14	1.9	400	2.1
	2	16	1.6	800	5
plan	2	> 20	2 ~ 2.5	> 1,000	> 5

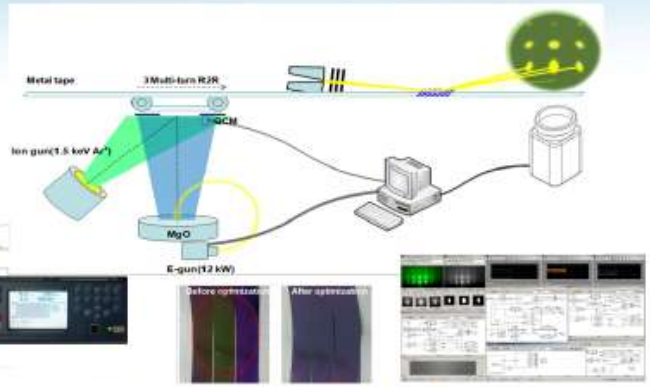


- The same process speed(120 m/hr).

Various quality control system



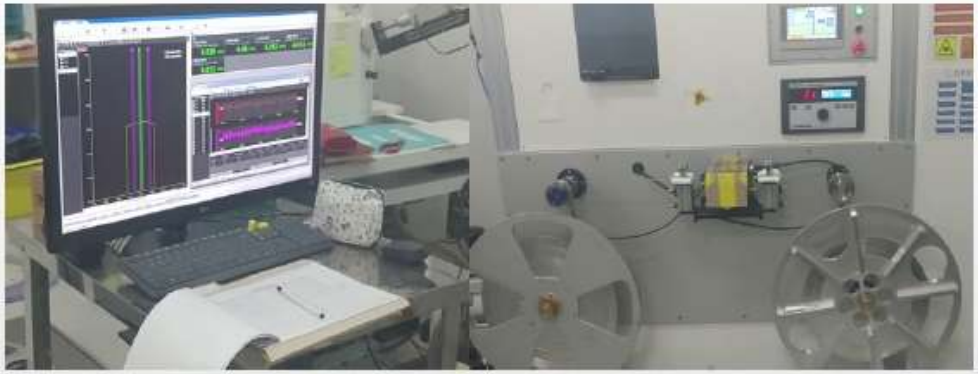
[RCE vision system]



[Rheed vision system]

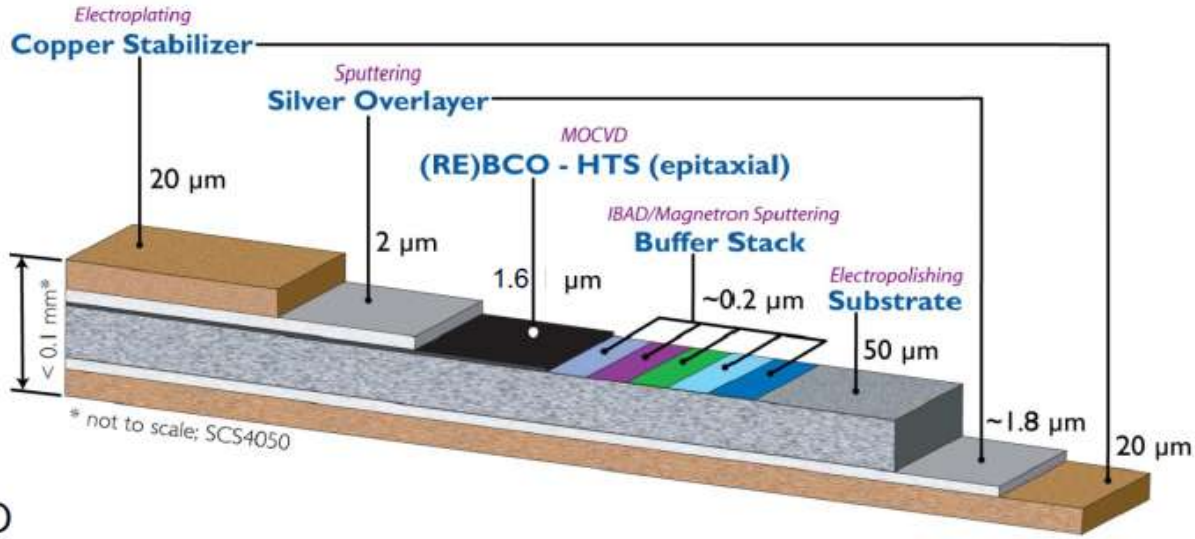
[Continuous void measurement system]

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

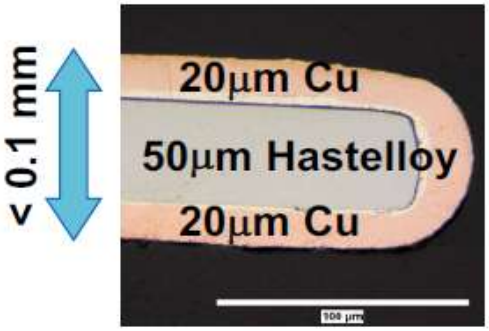


[Continuous dimension measurement system]

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



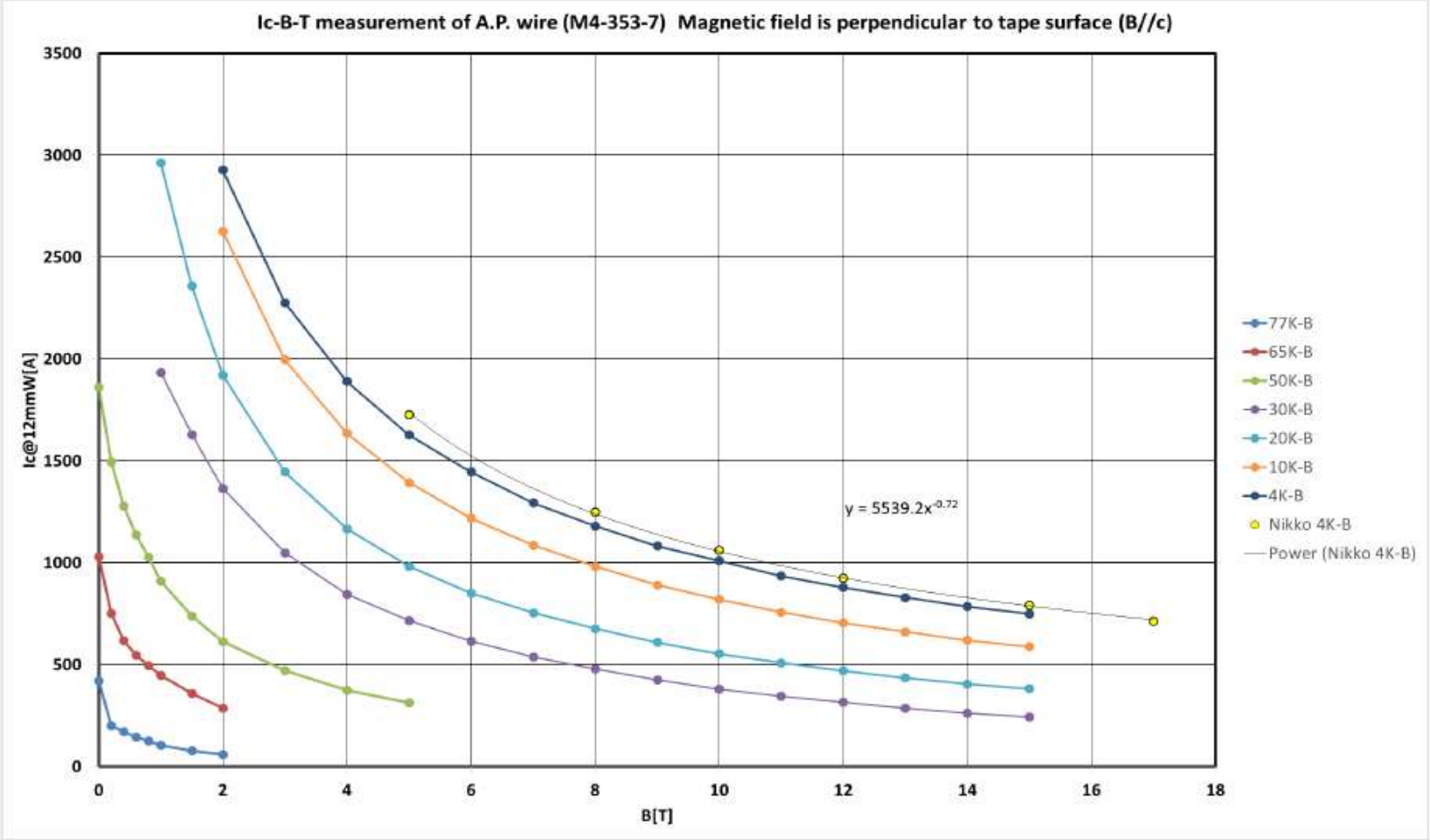
- Hastelloy® C276 substrate
  - high strength
  - high resistance
  - non-magnetic
- Buffer layers with IBAD-MgO
  - Diffusion barrier to metal substrate
  - Ideal lattice matching from substrate through REBCO
- MOCVD grown (RE)BCO layer with BZO nanorods
  - Flux pinning sites for high in-field I_c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



Recent step wise improvements to meet market challenges

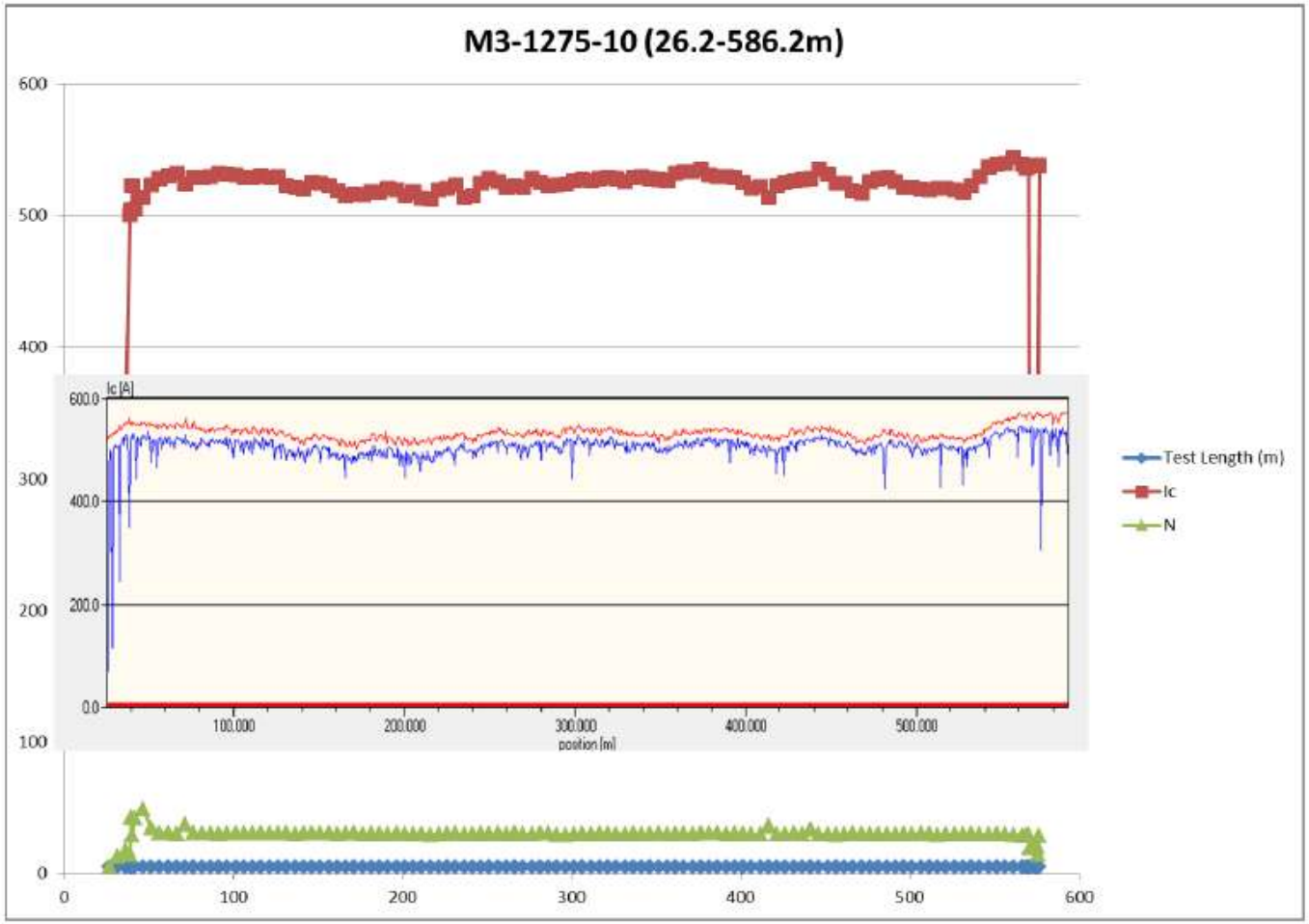
- ***Critical current***
  - Recent advances in processing have significantly increased the base I_c (77K, sf) of SP 2G HTS tapes into the 400-600 A/cm-w range
- ***Piece length***
  - Recent advances in processing have also increased the stable production piece length of SP 2G HTS tapes ~300m to 500 m
- ***Current density***
  - SP 2G HTS tapes have some of the highest conductor Je's in the industry
  - New initiatives will continue to improve performance
    - Thinner substrates (>30% Jc improvements)
    - Improved lift factors (2x +) with enhanced pinning
    - Focus on three operating regimes: 4K-high field, 20-50K – moderate field, 65-77K low field.
- ***Continuous improvement of uniformity and reproducibility within and between run***

Typical critical current vs. field of 7.5% Zr AP tape – recent production



Measured at Tohoku Univ, FEC Nikko

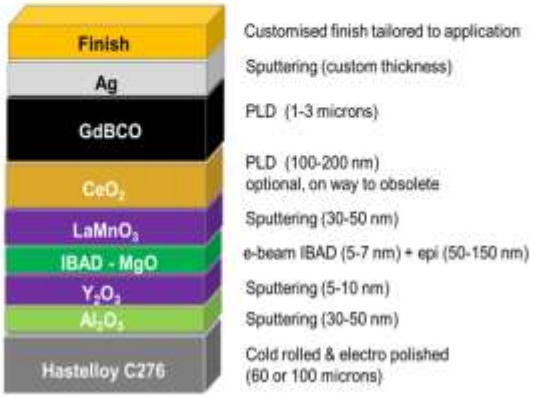
Recently delivered ~500m length w/ Ic >525A on 30 μm substrate



Production facility development in Tokyo and Moscow: 100 km/year at 12 mm

SuperOx

SuperOx 2G HTS wire architecture



Moscow buffer layer line commissioned Jan 2016

e-Polished Hastelloy substrate in
Ready buffered tape with $LaMnO_3$ on top out

SuperOx Japan LLC: in operation since Nov 2011

One-chamber sputtering/IBAD buffer system (R&D and production back-up)
Dual-chamber PLD-HTS system for CeO_2 and GdBCO

Moscow PLD-HTS line commissioned Dec 2016

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

SuperOx wire production: 100 km/year at 12 mm width in 2018

SuperOx

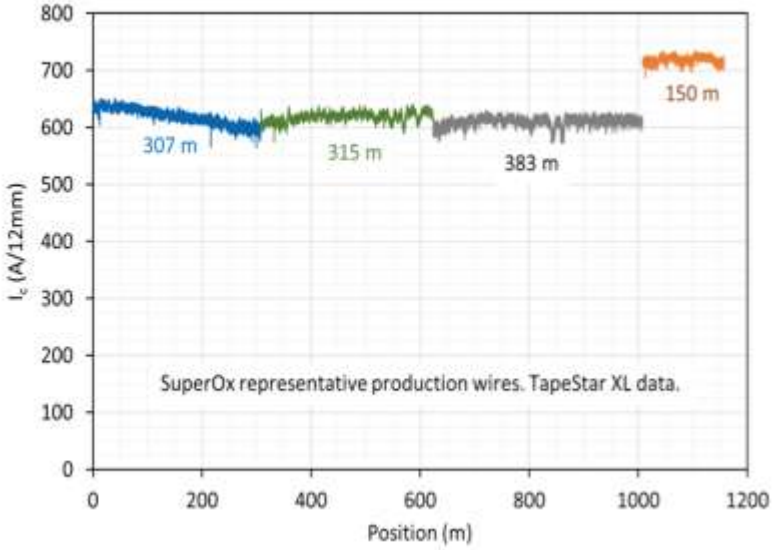
Quality management

	Substrate	Buffer	HTS	Ag	Cu	Finish
In-line	Optical	RHEED Optical	Optical			
Off-line, full length				Non-contact I_c	Non-contact I_c	Non-contact I_c
Off-line, segments	AFM	XRD	XRD SEM EDX	Transport I_c	Transport I_c	Specific tests

Rejection of defective material at early processing stages for cost optimisation

Real time closed-loop control for high yield

SuperOx wire: long length, high current, good uniformity



SuperOx wire specifications

Parameter	Value		
Substrate Thickness	60 or 100 µm		
Tape width	4 mm	6 mm	12 mm
Critical Current @ 77K, s.f.	80-150 A	120-250 A	300-600 A
J_e at 4.2 K, 20 T	> 400 A/mm²	> 400 A/mm²	> 400 A/mm²
Current Uniformity	±10%	±10%	±10%

Customisation:

+ Variable silver thickness
+ Variable copper thickness
+ Lamination
+ Insulation
+ Solder plating
+ Low resistance splices
+ Filaments
+ … just ask

SuperOx 2018 wire opportunity

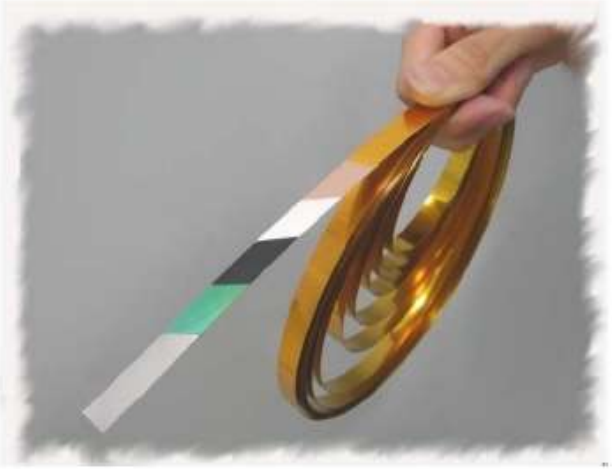
SuperOx expects to build temporary stock

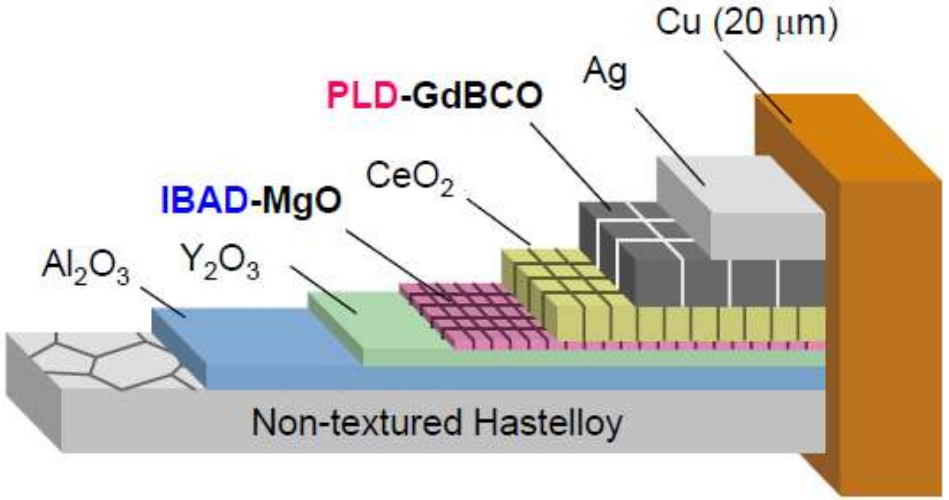
of few tens of km of wire

by the end of 2018

Now is good time to order

Fujikura's REBCO coated conductor (IBAD / PLD)





Ion Beam Assisted Deposition (IBAD)

R-to-R system
with large ion source

Pulsed Laser Deposition (PLD)

R-to-R system
with hot-wall heating

Fujikura

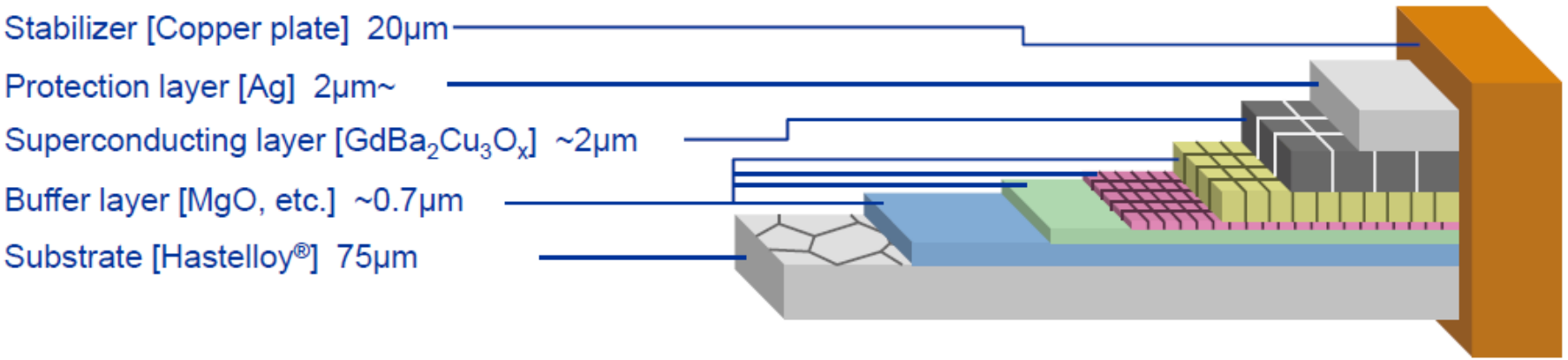
Fujikura's REBCO coated conductors

Typical Specification

Item	Width [mm]*	Thickness [mm]*	Substrate [μm]	Stabilizer [μm]	Critical Current (I_c) [A] (@77K, S.F.)
FYSC-SCH04	4	0.13	75	20 x 2	≧165
FYSC-SCH12	12	0.13	75	20 x 2	≧550

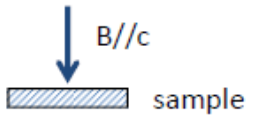
* Dimensions do not include thickness of insulating tapes.

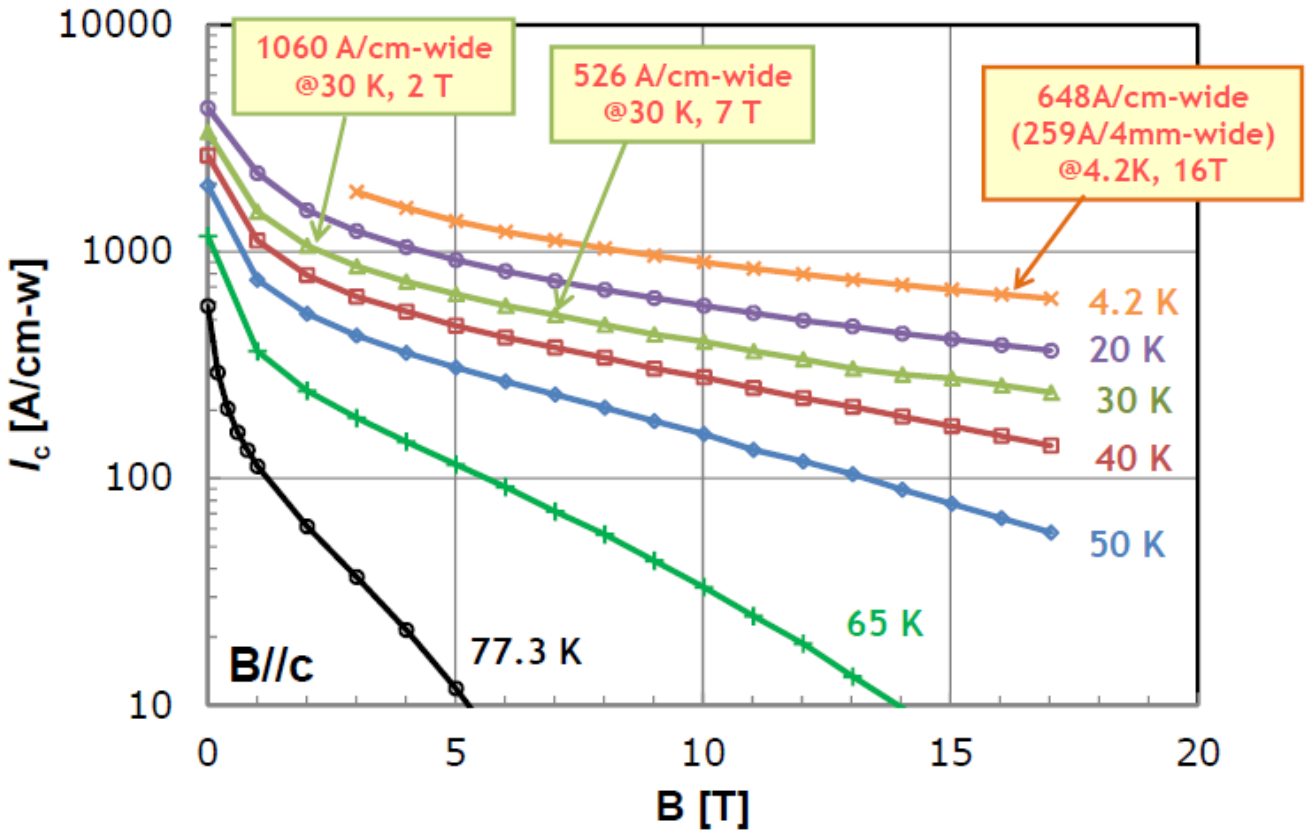
<Schematic of 2G HTS wire (FYSC-SCH04)>



Typical In-field I_c of a production wire

- Example data of typical production wire
- Sample : Ic = 573 A@77K,s.f. (cm-w)



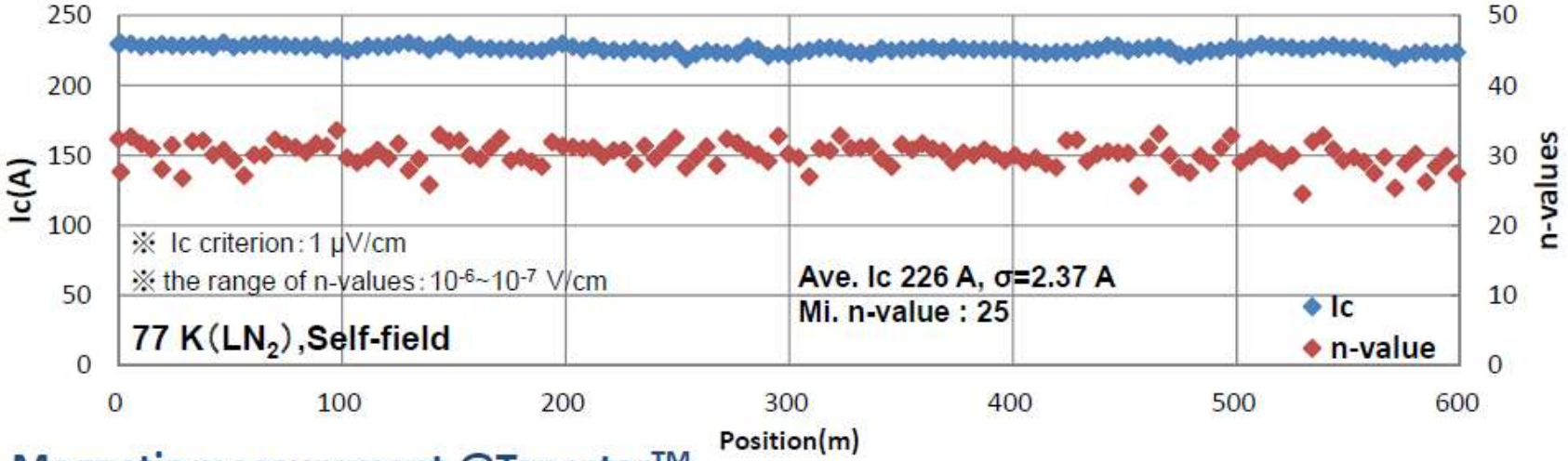


* This work includes some data measured at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

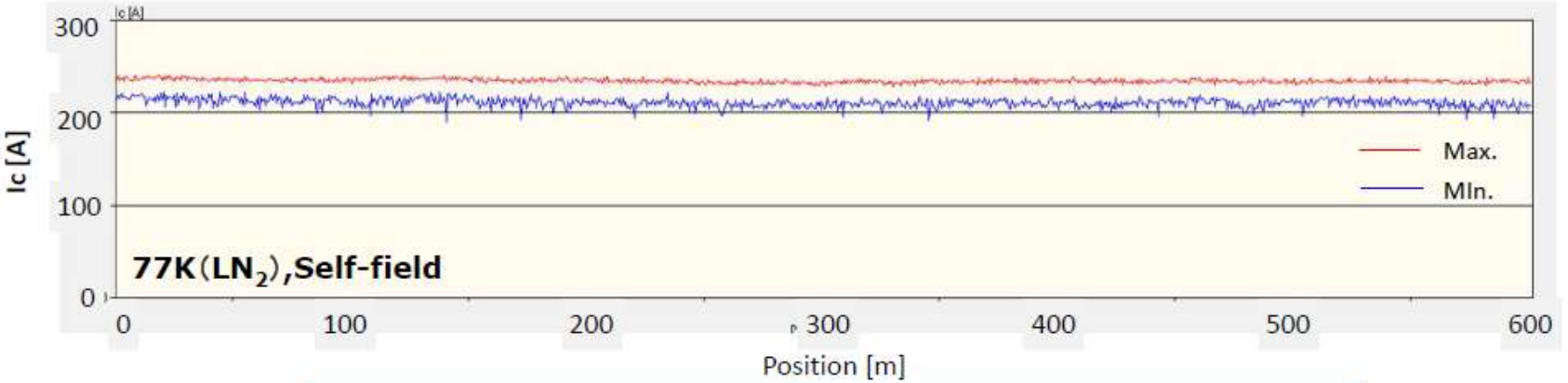
Example data of longitudinal I_c distribution

a production wire of 4 mm-wide

- **4-terminal method current conduction measurement at every 4.7 m**



- **Magnetic measurement @Tapestar™**



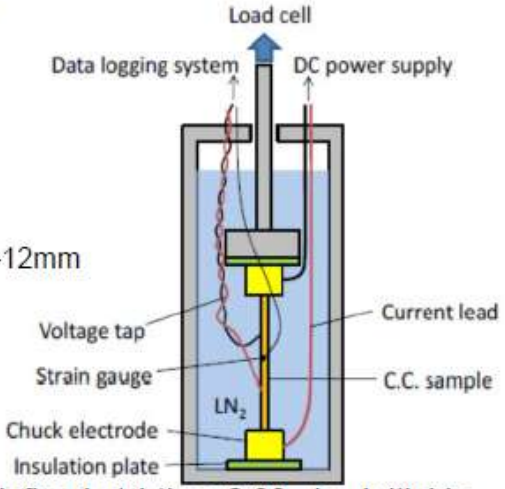
quite uniform I_c with 600m length are obtained

Evaluation of tensile characteristics of divided 4 mm-wide

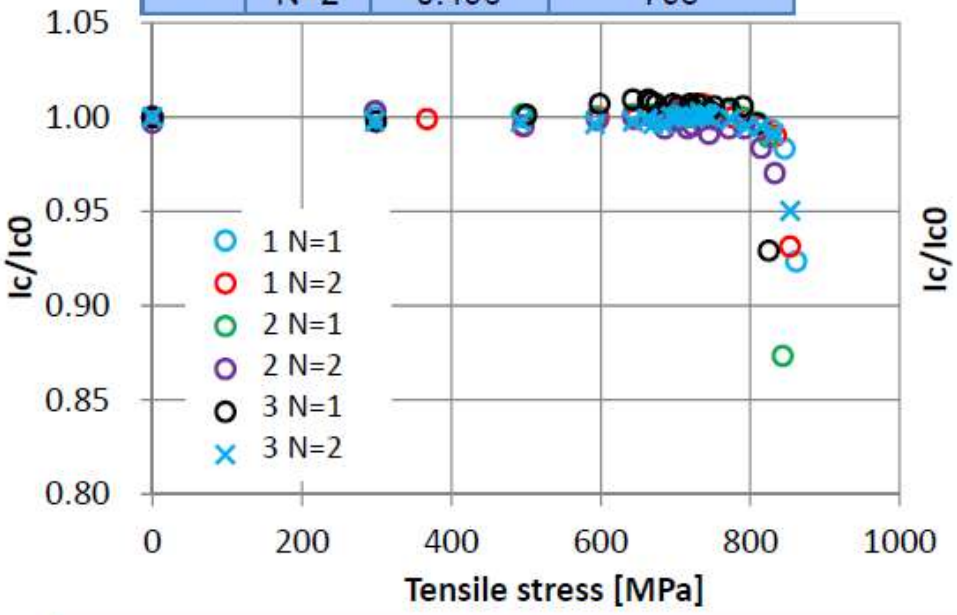
Tensile characteristics of 3 parts of 4 mm-wide conductors divided from 12 mm-wide coated conductor in LN2

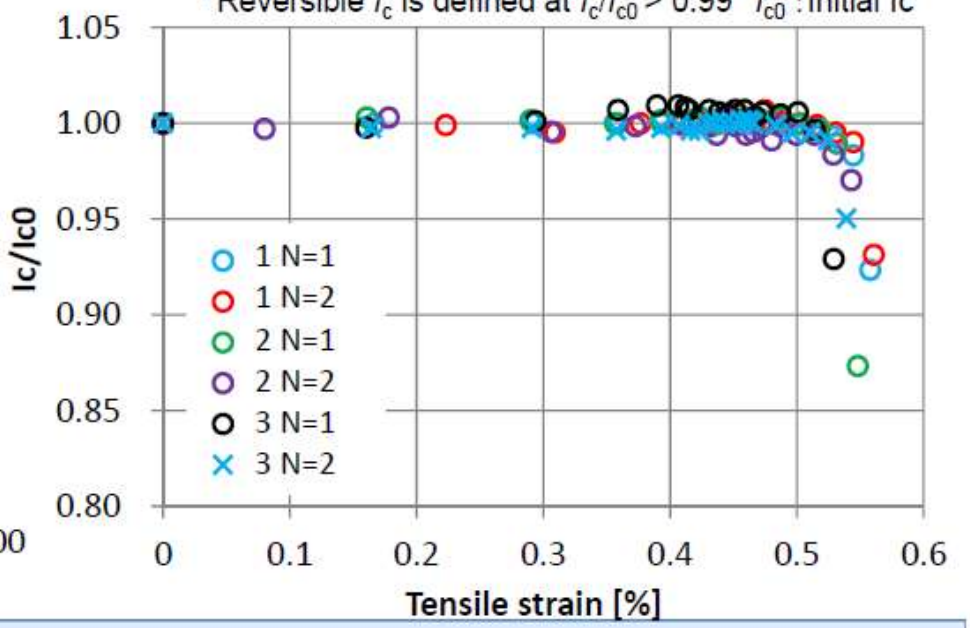
samples		reversible I_c	
		Strain [%]	Stress[MPa]
1	N=1	0.523	820
	N=2	0.513	817
2	N=1	0.521	813
	N=2	0.497	768
3	N=1	0.514	810
	N=2	0.496	795

4mm { 1 : one edge side
4mm { 2 : center side
4mm { 3 : the other edge side
} 12mm



* Reversible I_c is defined at $I_c/I_{c0} > 0.99$ I_{c0} : Initial Ic





Each divided 4 mm-wide conductors have shown equivalent tensile characteristics in LN2

BRUKER HTS

HTS COATED CONDUCTORS

Pilot-line production site

- BHTS pilot-line plant with more than 2000sqm operation area, located in the Industrial Park North of Alzenau, Germany
- Manufacturing of HTS coated conductors tailored for it's application at ultra-high magnetic fields at intermediate and low temperatures
- Processing route based on vacuum coating technology (e.g. Pulsed Laser Deposition), capability to process **4mm** wide HTS tapes with a max. single piece tape length of **600m** (12mm wide HTS tapes with a max. single piece tape length of 100m)

Processing Technology

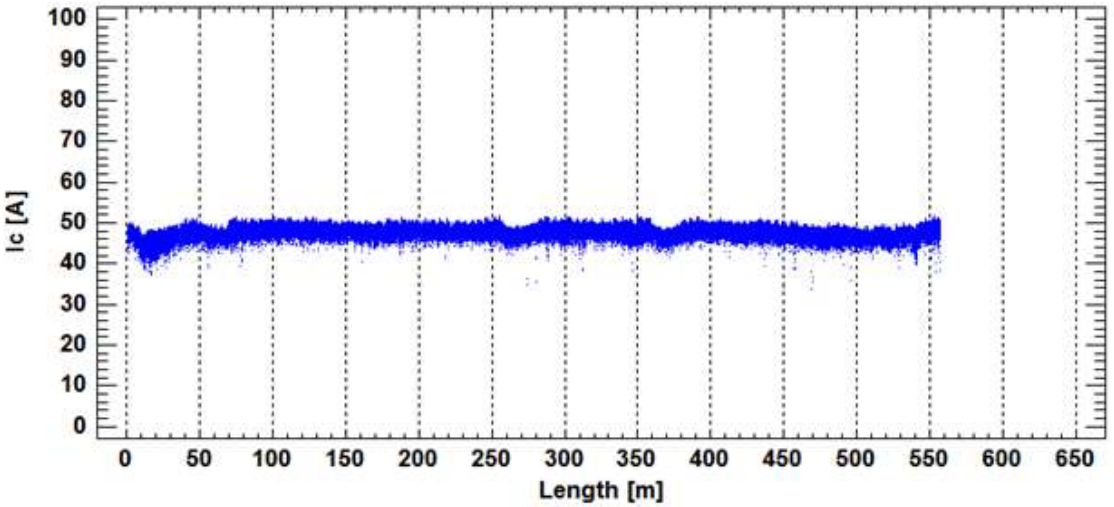
PROCESSING CHAIN OF HTS PILOT-LINE PRODUCTION
SUBSTRATE PREPARATION (SUB)
BUFFER LAYER COATING (ABAD)
HTS LAYER COATING (PLD)
METAL COATING (MET)
COPPER PLATING (PLA)
FINAL TAPE INSPECTION (INS)

- Wet chemical processes: SUB, CAP
- Vacuum coating processes: ABAD, PLD, MET
- Ic in-field measurements at 4.2K: INS

Pulsed Laser Deposition PLD production coater

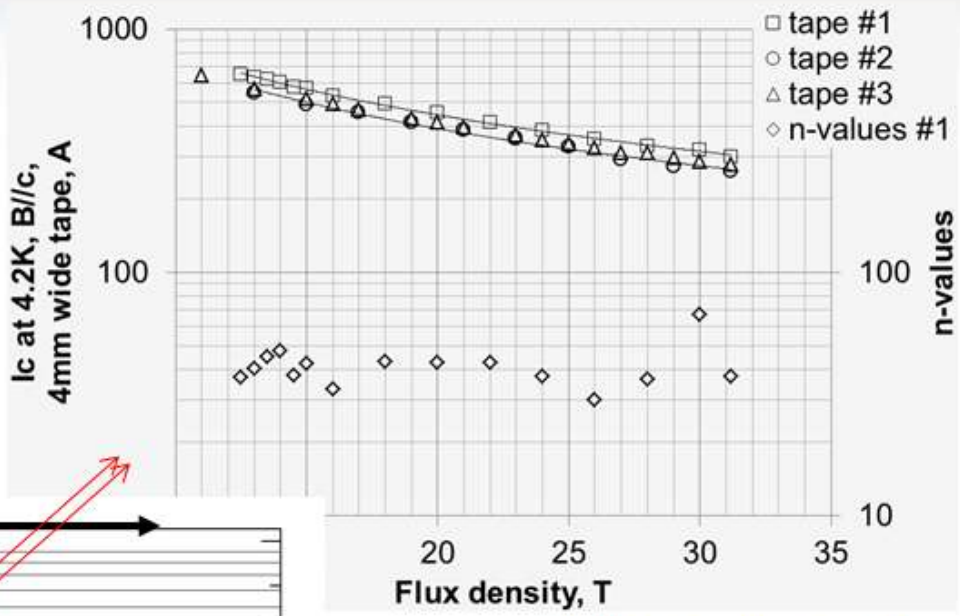
HTS tape capabilities

- Standard HTS tape configuration consisting of a stainless steel substrate, YSZ buffer layer, YBCO superconductor, Ag metal contact and Cu encapsulation
- Development of the single piece length capabilities of the 4mm HTS tape pilot-line production:
  - 2013: 100m
  - 2014: 200m
  - 2015: 600m
- Hall-probe measurements at 77K reveal the Ic drop-free single piece length of the HTS production tapes

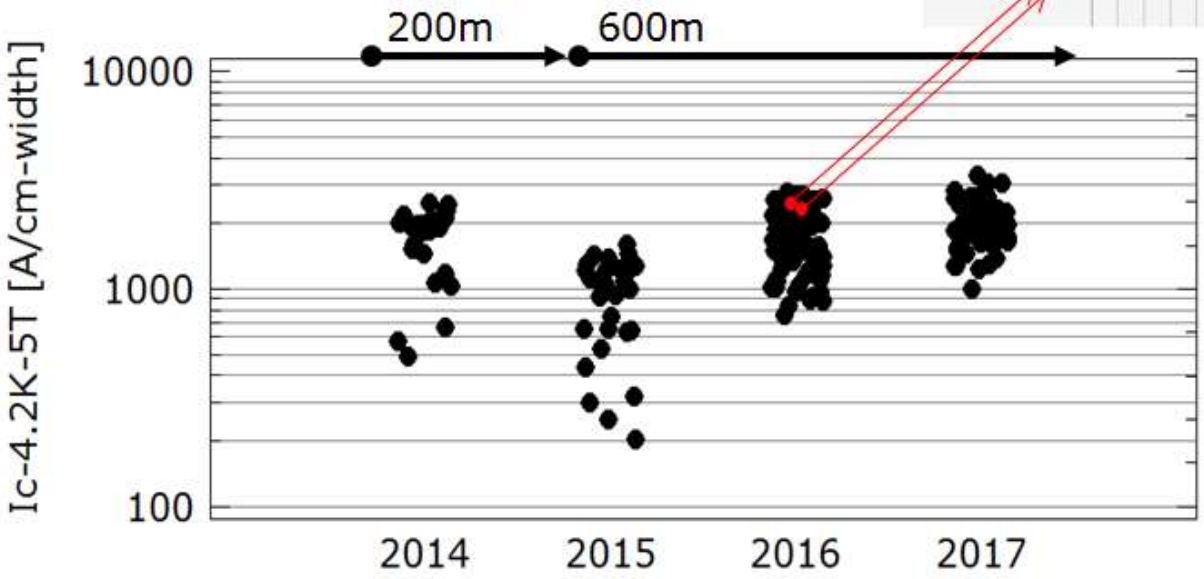


HTS tape performances

- Ic in-field performances of HTS production tapes during the ramp-up phase 2014 until 2017
- Superior Ic in-field performance of HTS tapes exceeding 750A/cm at 4.2K, **30T**, B//c, (n-values: >30, α-values: 0.85)



NHMFL measurements 2017



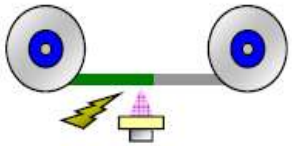
- Highest in-field engineering current density:
  Je > 1000 A/mm2
  at 18 T, 4.2 K, B//c,
  50µm thick substrate

In house manufacturing process (MOD process)

< Raw material >

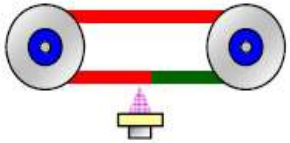
Metal sub　MOD solution

< 1st and 2nd intermediate layer>



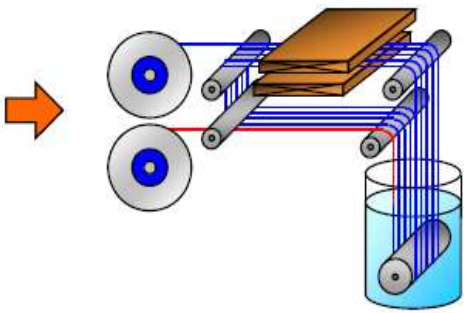
IBAD-sputtering

< 3rd intermediate layer>

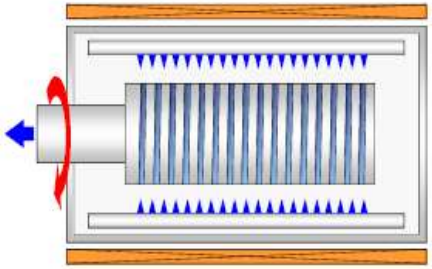


sputtering

< Calcination>

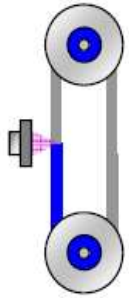


< Heat treatment>

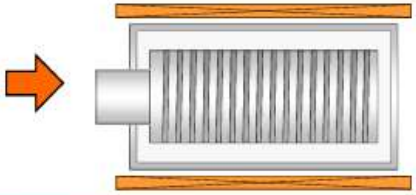


Bach process

< Ag sputtering >



< O2 annealing >



< Cu plating >

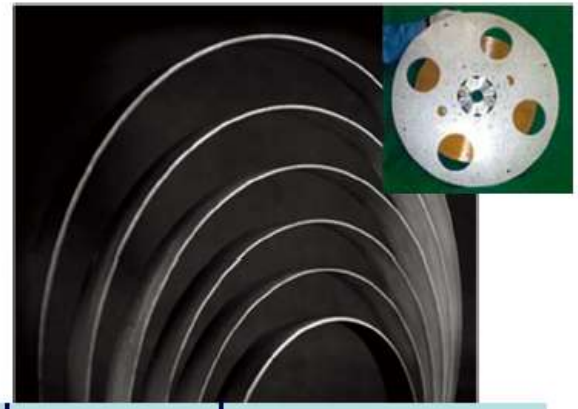
Electrical prating

MOD is inexpensive tape manufacturing process

Specifications of YBCO conductor

(1) Superior mechanical properties
min bending radius: 20 mm^{r}
tensile strength: 800 Mpa

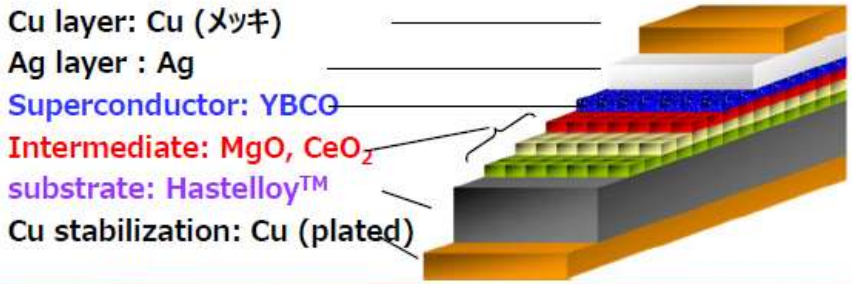
(2) Superior magnetic properties



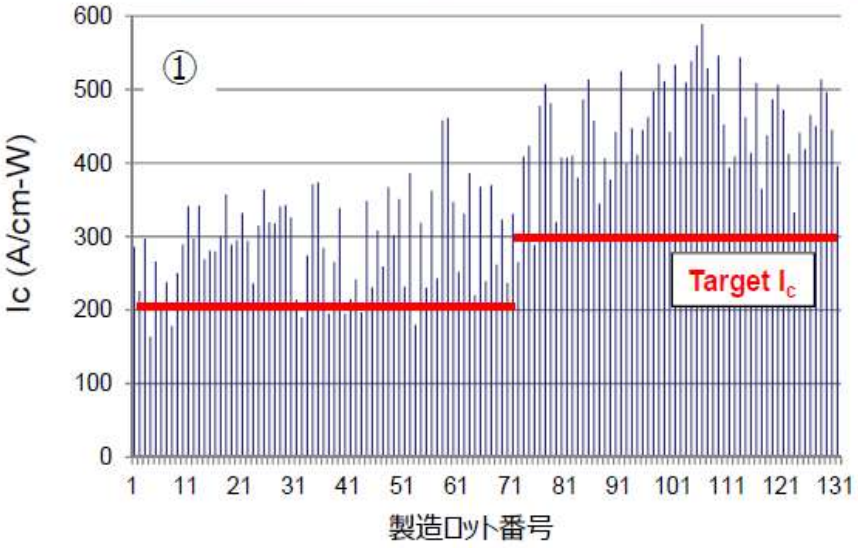
<spec.>

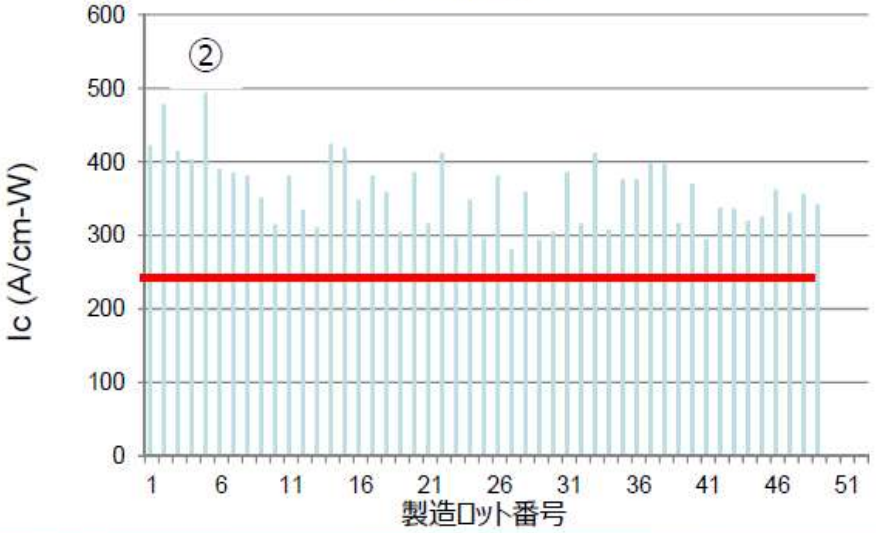
	width (mm)	Thickness (μm)	Thickness of Ag (μm)	Piece(m)	Ic (A) (@77K, self field)
SW2G04-N	4	85 ~110	> 5	200	> 100
SW2G05-N	5	85 ~110	> 5	200	>100

<Structure of our YBCO tape >



Production of in-house tape for cable





① FY 2014 15km

35kV-600A single phase 100mlong cable
piece length 150m、250m

② FY2015 8km

22kV-3000A triaxial cable 20m long
piece length 150m、250m

③ FY2017~2018 1Q 29km

11kV-3000A triaxial cable 250m long
piece length 150m
Ic>375A

Amperium®
Brass Laminated Wire
Type 8700

Second generation HTS wire for high-current cable applications.

Second generation HTS wire for high-current cable applications

Type 8700

Amperium® brass laminated HTS wire designed for cable manufacturing.

ELECTRICAL PROPERTIES

Minimum amperage (I_c)[ii]
Standard Product: 70 A - 100 A, 10 A increments
Beta Product: 140 A - 180 A, 10 A increments
Other minimum amperages available: Contact factory
Spliced wire available in long lengths
Insulation options: Contact factory
Certificate of Conformance provided. Certificate of Analysis optionally available. Contact factory. Leaders and trailers optionally available. Contact factory.

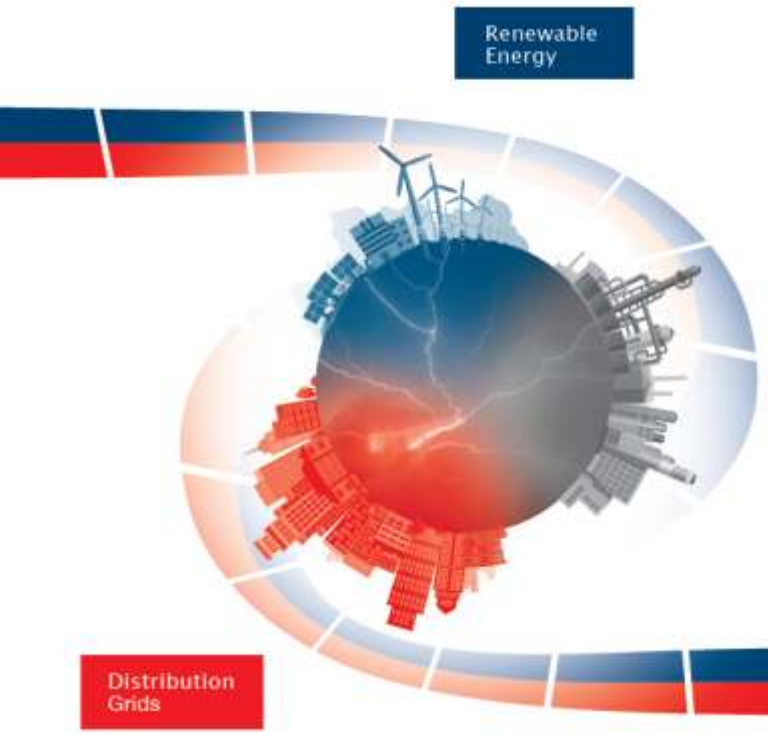
[i] Greater than 95% I_c retention
[ii] 77K, self-field, 1 μV/cm, 1 m resolution

MECHANICAL PROPERTIES

Average thickness:	0.36 mm - 0.44 mm
Minimum width:	4.24 mm
Maximum width:	4.55 mm
Minimum double bend diameter (RT):	35 mm[i]
Minimum double bend diameter for spliced wire (RT):	100 mm[i]
Maximum rated tensile stress (RT):	200 MPa[i]
Maximum rated wire tension (RT):	30 kg[i]
Maximum rated tensile strain (77K):	0.3%[i]

CABLING RELIABILITY:

Designed for cabling on a wide range of formers with tight pitch and large back tension. Durable in pressure cycled liquid nitrogen, including splices and joints.



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Energizing Superconductors

Development & production of HTS wires

Brygida Wojtyniak, Jan Kunert, Ron Feenstra, Mariusz Mosiadz, Oliver Brunkahl, Mark Rikel, Jan Bennewitz, Martina Falter, Oliver Thiems, Lisa Koliotassis, Tobias Betche, Michael Bäcker

CSD processing

- Chemical solution deposition for complete layer architecture
  - Best price performance ratio for large volume production
    - Length up to 500m
    - Width 4-40mm
    - Capacity >100km/a

HTS wires for applications

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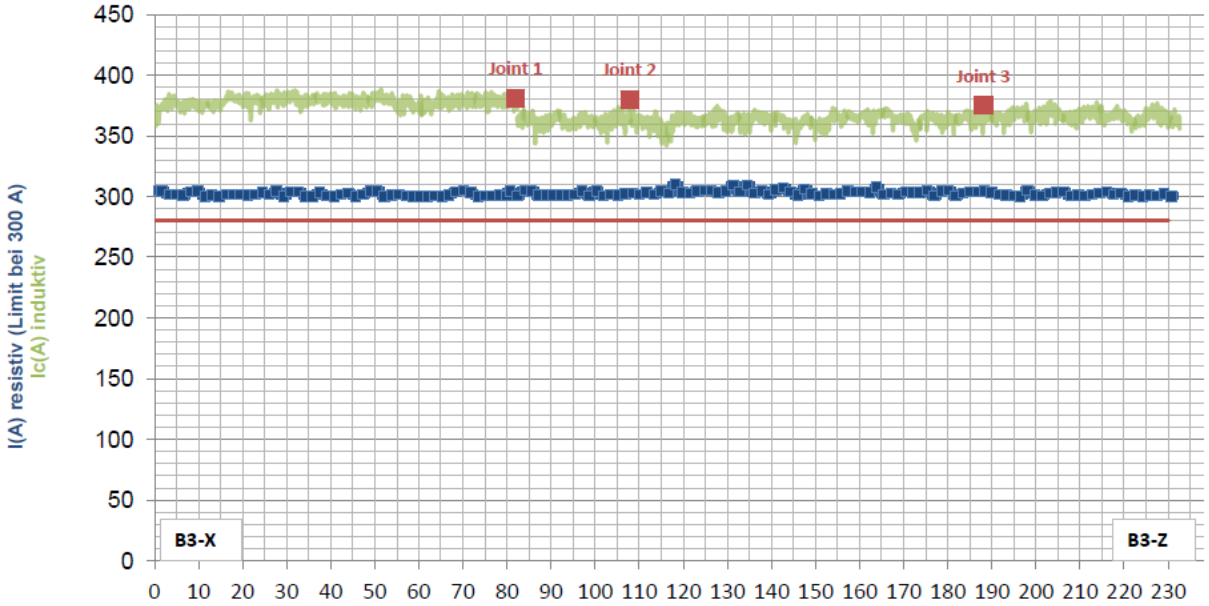
- single copper laminate - HTS neutral fiber
  - Upscaling: wide tapes and production devices

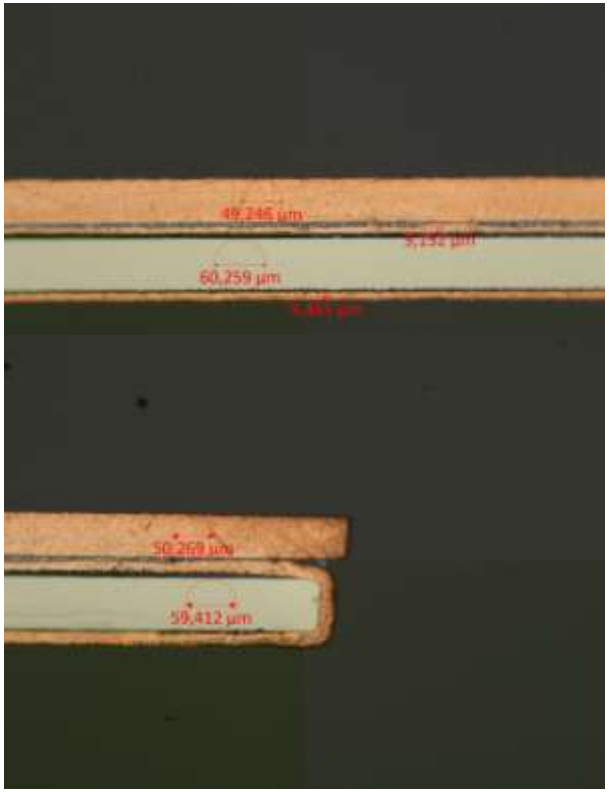
4x25m high temperature annealing furnace

40mm fully buffered tape

HTS wires for applications

- single copper laminate - HTS neutral fiber
  - Long length with high homogeneity
  - Mechanical and electrical stability with high J_e





50µm single copper laminate

Best HTS tapes > 800A @65K,sf

HTS wires for applications

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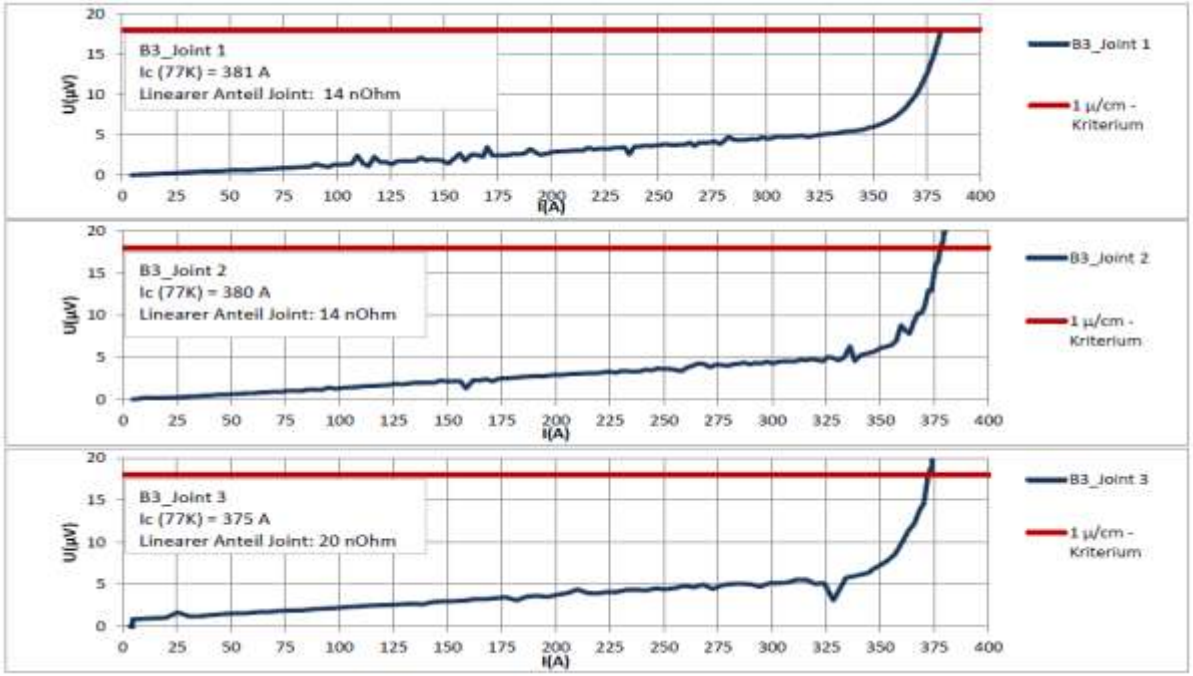
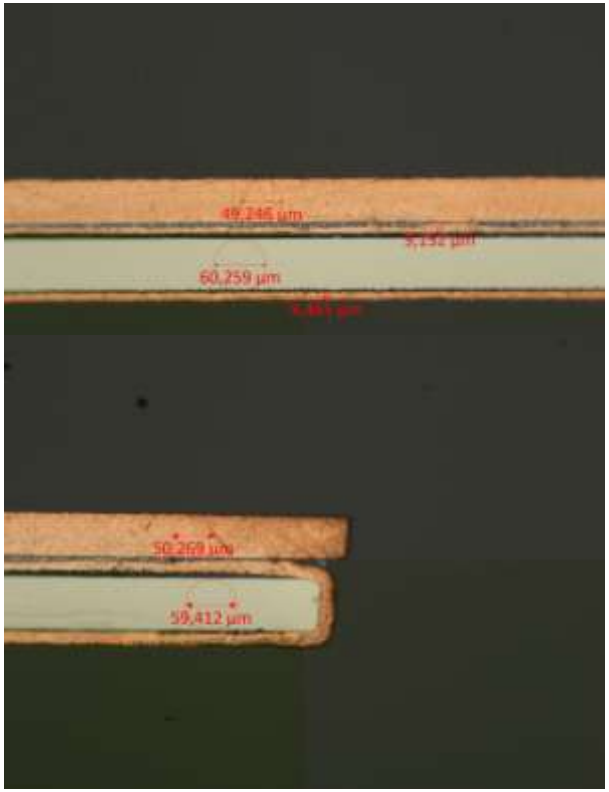
- single copper laminate - HTS neutral fiber
  - Long length with high homogeneity
  - Mechanical and electrical stability with high J_e
  - Low restance, high strength joints





50µm single copper laminate

HTS wires for applications

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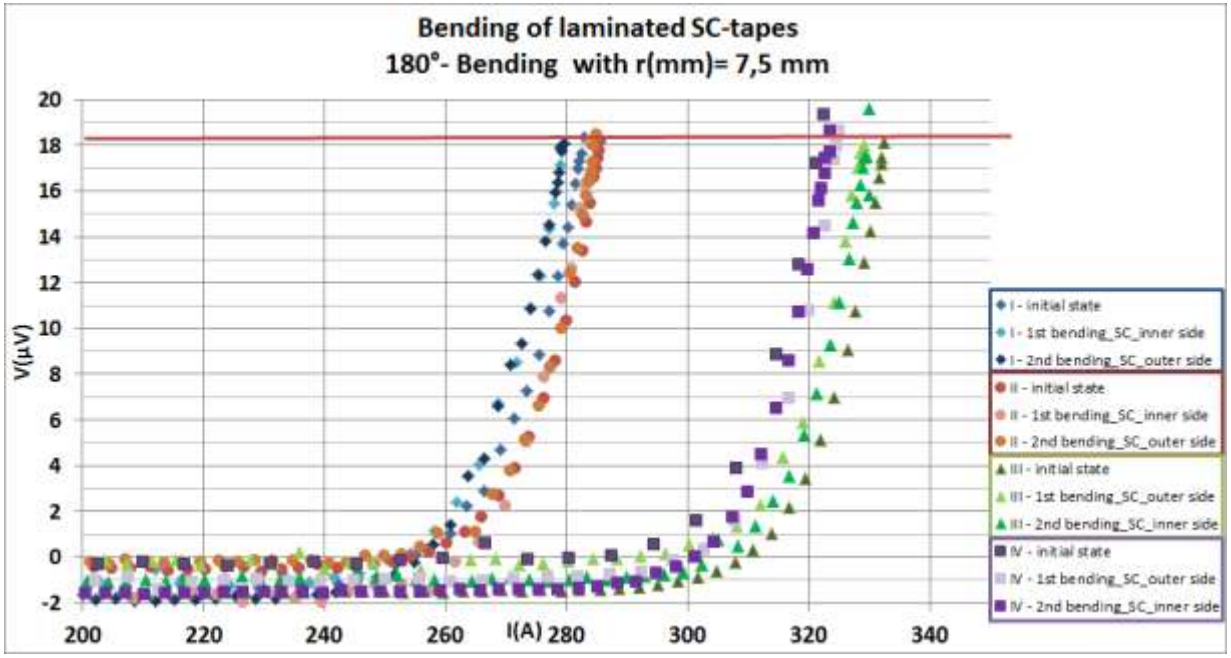
- Customized laminates
  - Small bending diameter possible



I_c degradation <2% for double bending on 15mm diameter

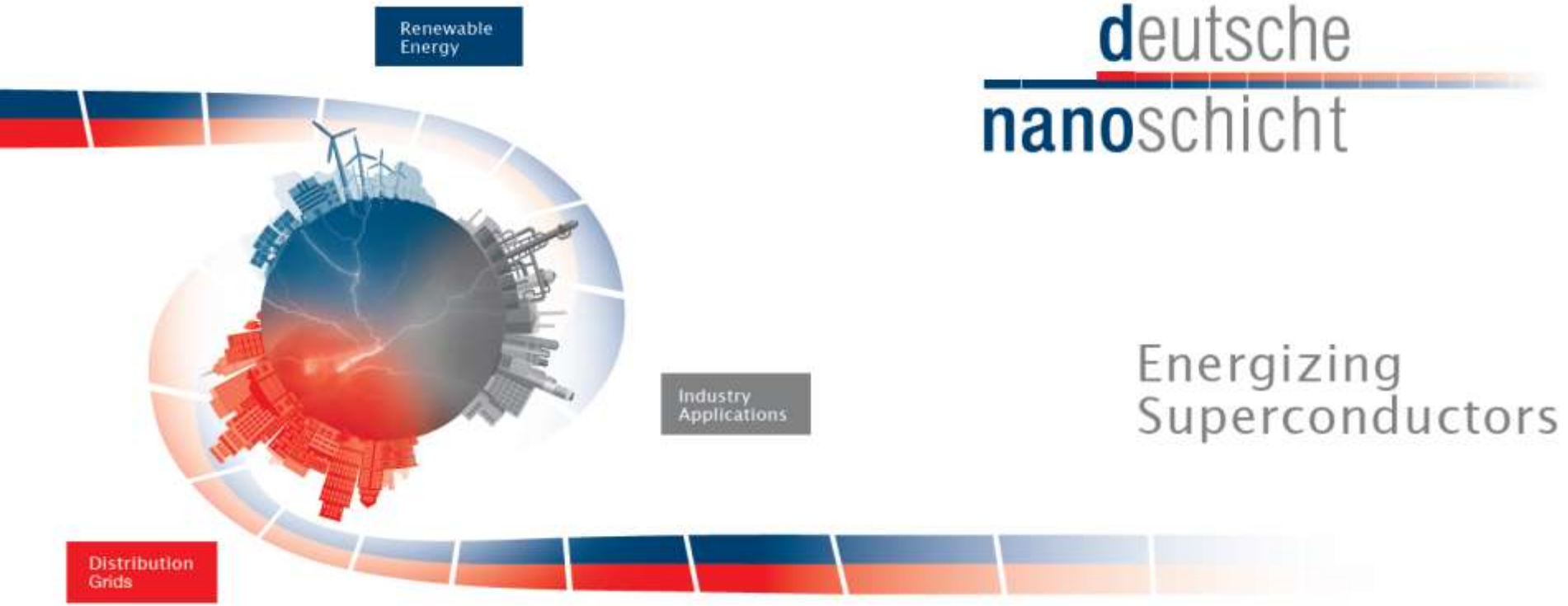
Zusammenfassung

deutsche nanoschicht

„Flexible Supraleiterbänder mit hoher Stromtragfähigkeit für energietechnische und industrielle Anwendungen werden heute kommerziell hergestellt.“

www.ivsupra.de /2016

- **Performance von Supraleiterbändern ist stabil und ausreichend für energietechnische Anwendungen.**
- **Mehrere Hersteller haben Produktionskapazitäten installiert, die ausreichend für Projekte nahezu jeder Größe sind.**
- **Die Hersteller stehen bei entsprechender Nachfrage bereit zur Aufskalierung.**
- **Preise werden bei steigender Nachfrage zukünftig deutlich sinken.**



Vielen Dank für Ihre Aufmerksamkeit

Dank an: M. Bauer, H. Lee, T. Hasegawa,
N. Sadakata, D. Hazelton, U. Betz, S. Samoilenkov