SuperPower Inc.
A Furukawa Company

Superior performance. Powerful technology.

REBCO HTS Wire Manufacturing and Continuous Development at ***SuperPower***

Yifei Zhang, Satoshi Yamano, Drew Hazelton, and Toru Fukushima

- *2018 IAS-HEP*
  Mini-Workshop on High Temperature Superconducting Materials and Magnets
- *The Hong Kong University of Science and Technology*
- *January 18, 2018*

FURUKAWA ELECTRIC GROUP

Outline

- Introduction to SuperPower Inc.
- REBCO wire and its manufacturing
- Applications of REBCO wire
- Performance and quality of REBCO wire
- Development and challenges
- Summary

Introduction to SuperPower

Superior performance. Powerful technology.

- Formed in 2000
- Location: Schenectady, New York
- Number of employees: 30
- President & CEO : Dr. Toru Fukushima
- Product: REBCO 2G HTS wire
- A subsidiary of Furukawa Electric Co. Ltd. Since 2012

古河電工

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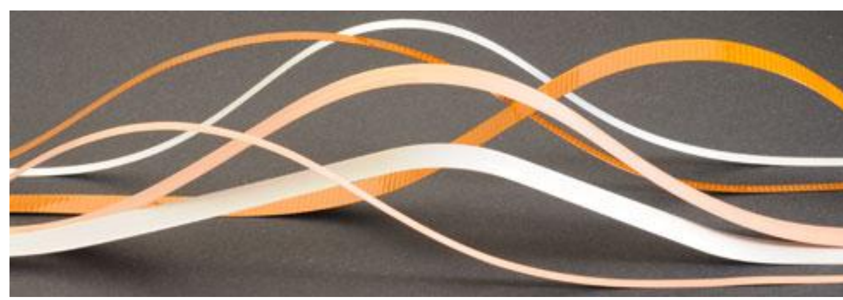
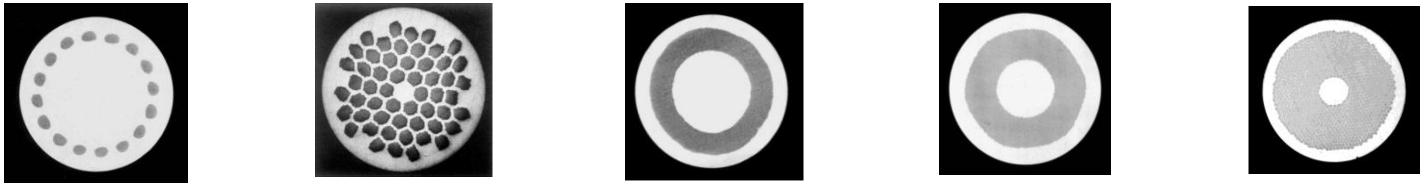


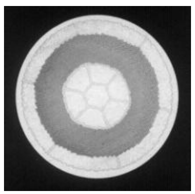
A brief history of SuperPower

- ***2000-2006:*** The Intermagnetics Years
  - SuperPower formed under IGC (Intermagnetics General Corporation)
  - 2G HTS wire technology research & development
  - Demonstration projects – electric power applications
- ***2006-2012:*** The Philips Years
  - Production scale-up
  - Market exploration
  - Performance improvements, flux pinning enhancement
- ***From 2012 onward:*** The Furukawa Years
  - Steady expansion of production capacity
  - Continuous performance improvements
  - Continuous R&D, customization
  - Processing optimization for quality and yield enhancement

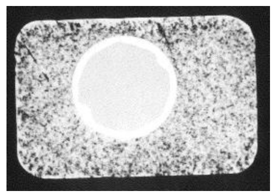
Furukawa has a long history in LTS



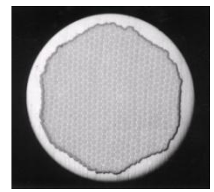
Nb-Ti wire with various Cu ratio & filament sizes



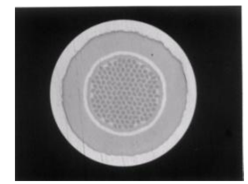
Low ac loss
Nb-Ti wire



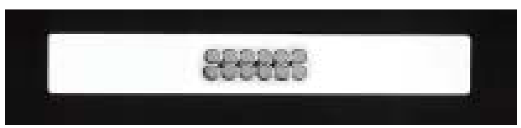
Al-stabilized
Nb-Ti wire



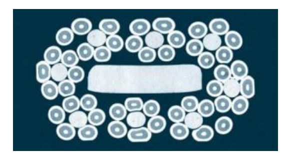
High Jc
Nb_3Sn wire



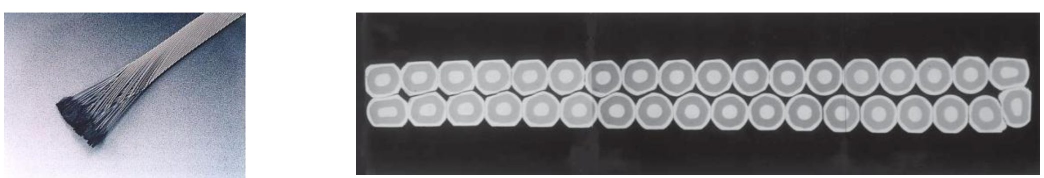
High strength
Nb_3Sn wire



Al-stabilized Nb-Ti Rutherford cable



Nb-Ti Rutherford cable with cored bar



Nb-Ti Rutherford cable with high-precision

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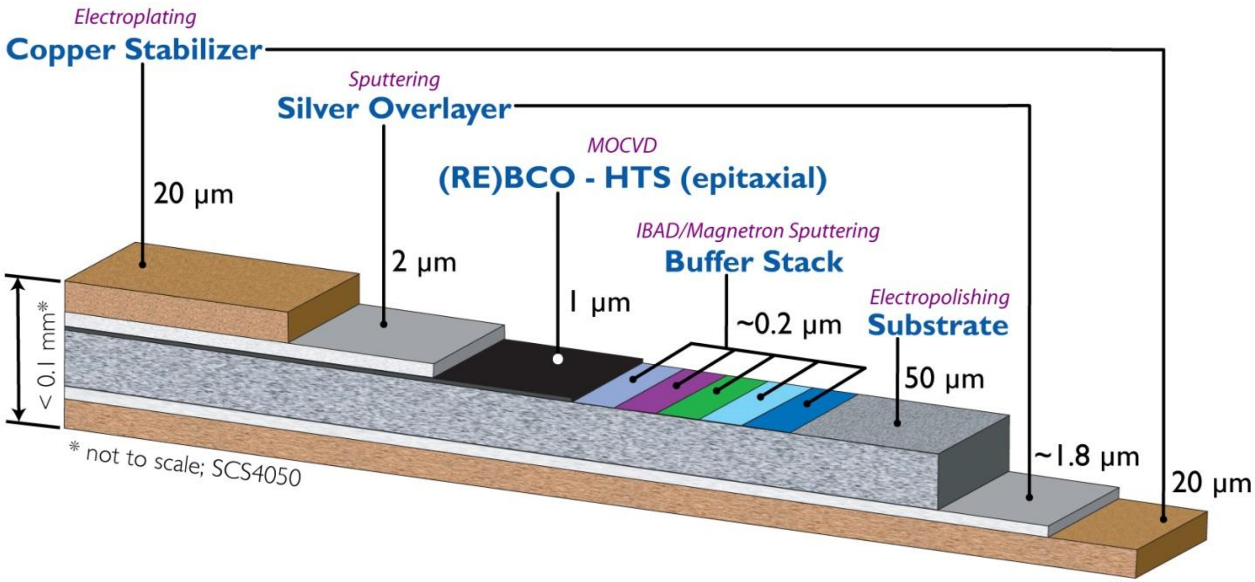
REBCO wire manufacturing at SuperPower

Electropolishing



IBAD

Buffer Deposition

MOCVD

Electroplating

IBAD-MOCVD based technologies

REBCO wire – basic information

Item	Value	Note
Composition	REBa2Cu3O7-δ	RE=Rear Earth
Width (mm)	(1), 2, 3, 4, 6, 12	
Substrate Thickness (μm)	30, 50, 100	Hastelloy
Ag Thickness (μm)	1~5	Sputtered
Cu Thickness (μm)	10~115 total	Electroplated
Insulation	Polyimide tape	Wrapped
Piece Length (m)	300~500	
Joint resistance (nΩ)	<20	Soldered
Ic(77K, s.f.) (A/12mm)	300~600	at 1μV/cm
σc,0.95 (MPa)	~550	γs dependent
εc,0.95 (%)	~0.4	
Min Bending D (mm)	5, 11, or 25	Substrate dependent

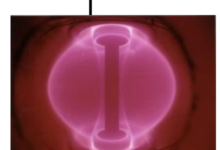

Cross-sectional image of a Cu-plated wire

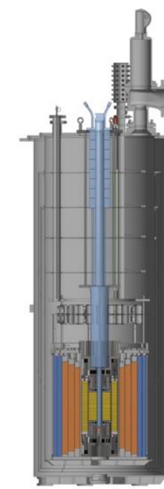
Targeted applications of REBCO HTS wires

Energy	Defense	Transportation	Industrial	Medical	Science/ Research
• Cables • FCLs • Generators • Transformers • SMES • Fusion Reactors	• Motors • Cables	• Maglev • Motors	• Induction Heaters • Motors • Generators • Magnetic Separation • Bearings	• MRI • Particle Therapy • Current Leads	• HF Magnets • NMR • Accelerators • Neutron and X-ray Scattering • Undulators







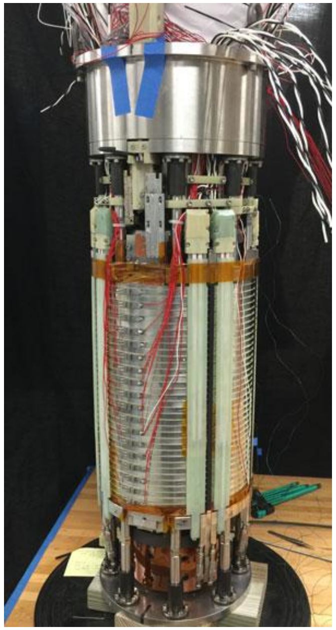
32T hybrid user magnet by NHMFL

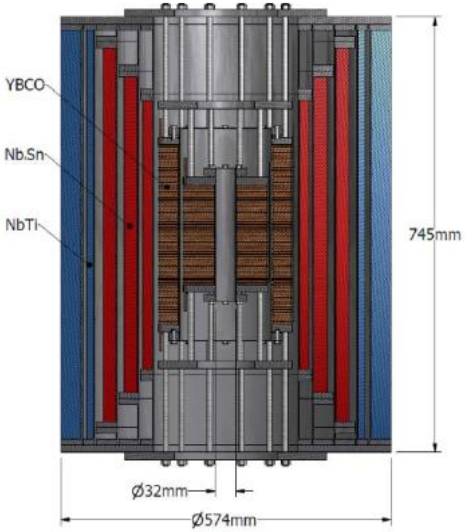
HTS/LTS hybrid magnet

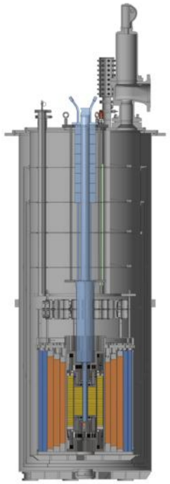
- LTS 15T
- HTS 17T
- Uniformity 1 cm DSV $5{\cdot}10^{-4}$
- Total inductance 254 H
- Stored energy 8.6 MJ
- Ramp to 32 T 1 hour
- Cycles 50,000

HTS conductor

- Wire width 4mm
- Wire thickness <0.170mm
- Ic at 17T, 18°, 4.2K >256A
- n-value at 17T, 18°, 4.2K >25
- Stabilizer RRR >50
- Iop 180A







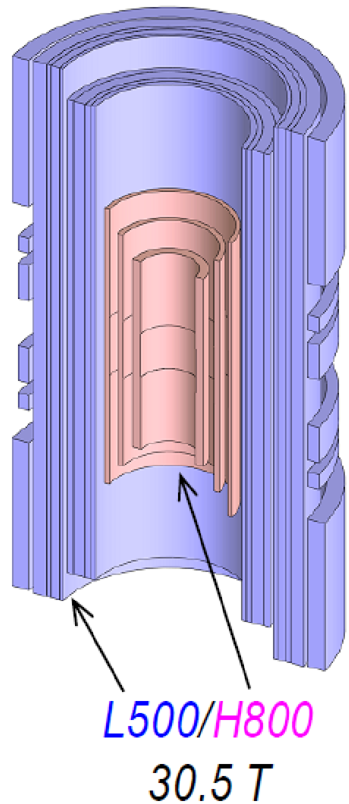
NATIONAL HIGH MAGNETIC FIELD LABORATORY

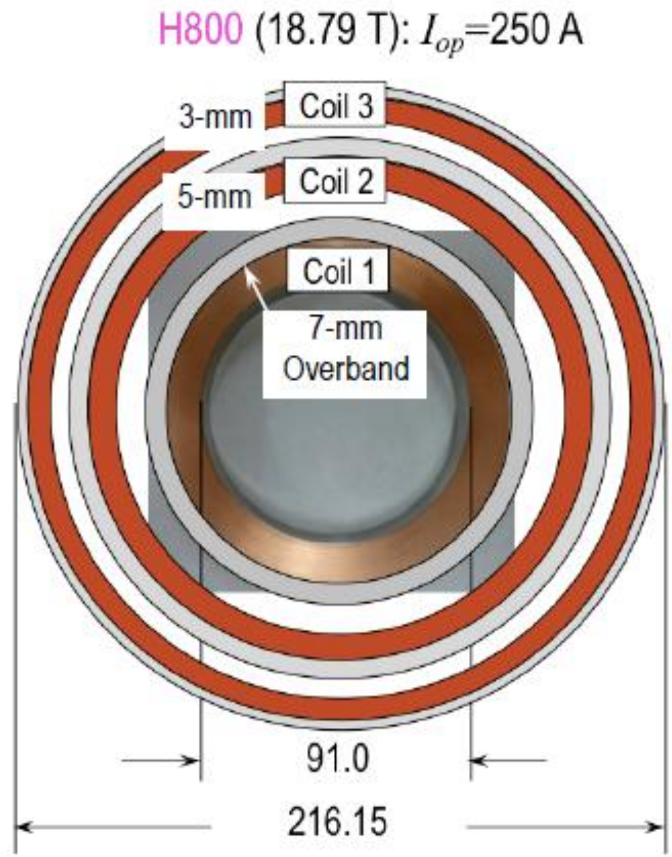
OXFORD INSTRUMENTS

1.3 GHz hybrid NMR by MIT

H800

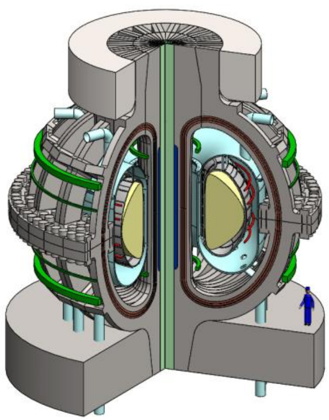
- Top=4.2K, Iop=251A
- 3-nested-coil formation
- NI DP coils
- Tape width 6mm
- Tape total thickness 75µm
- Cu stabilizer 10µm per side
- Coil 1: 26 DP, 369MHz, 8.66T
- Coil 2: 32 DP, 242MHz, 5.68T
- Coil 3: 36 DP, 189MHz, 4.44T
- HTS contribution: 61.5% of 30.5T



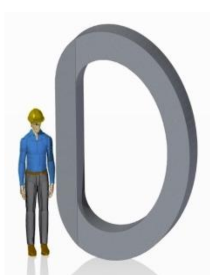


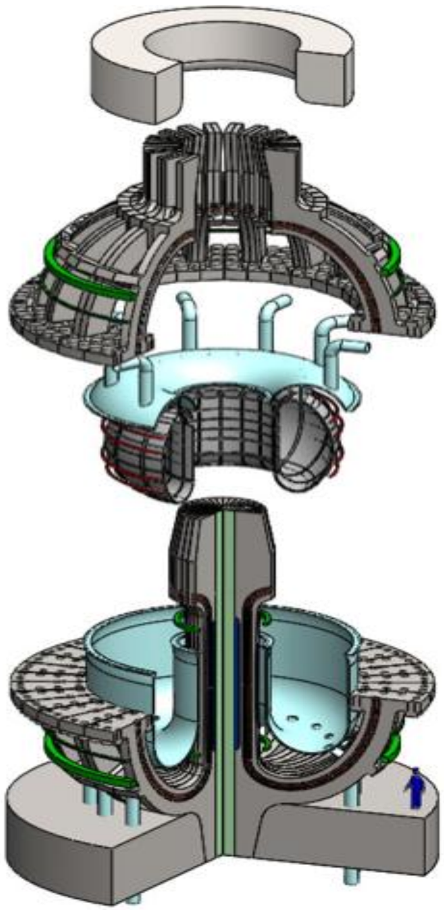
Y. Iwasa

ARC fusion reactor – proposed by MIT (Affordable, Robust and Compact)



9.2 T, 500MW, Q=10



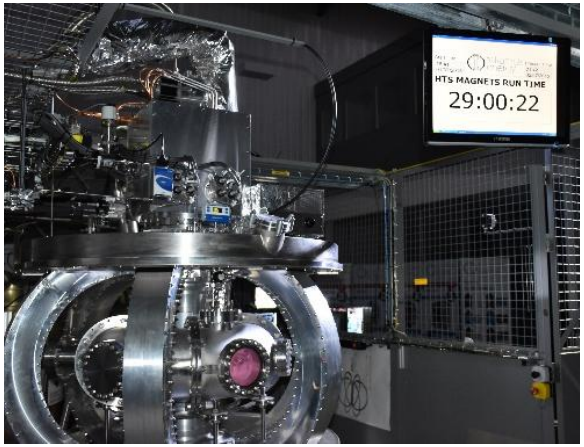


- HTS magnets at 9.2T on axis, 23T on coil
- Much smaller than ITER
  - 1/10th the volume
  - same gain
- 5,000 tons
- 60,000 kAm of HTS
- Demountable joints for maintenance

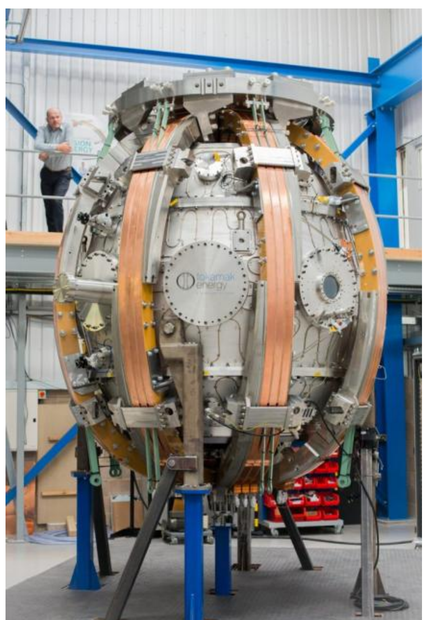
MIT PSFC

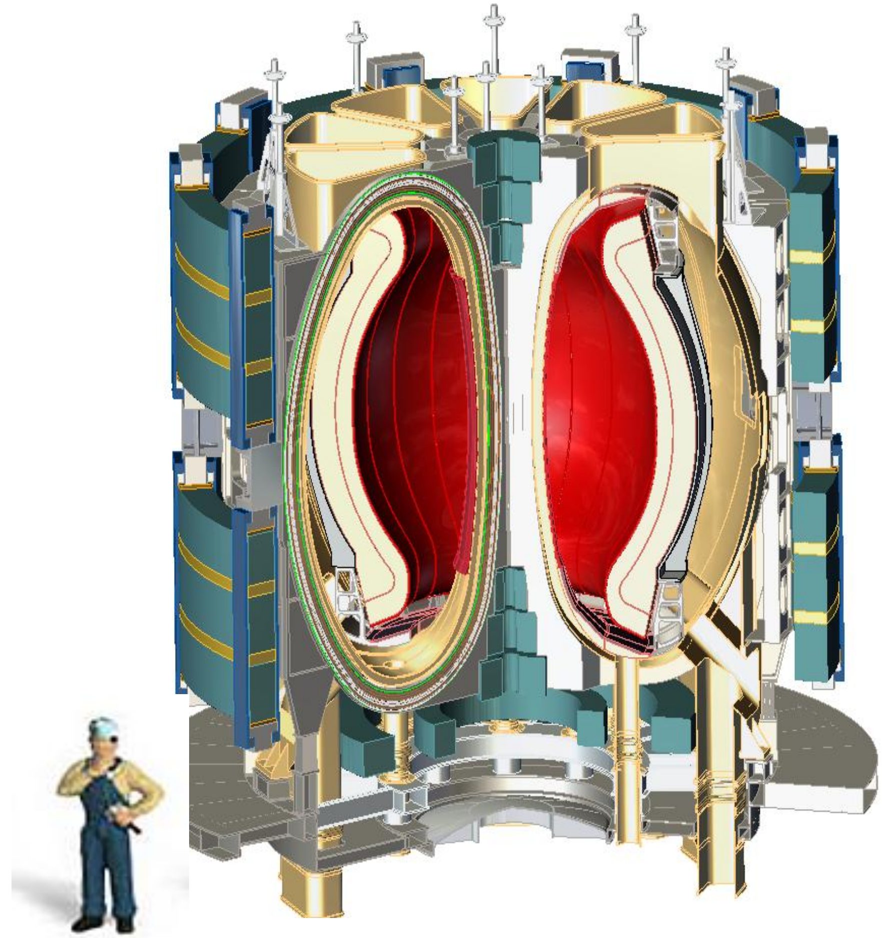
Spherical fusion reactor by Tokamak Energy

ST25 (HTS)



ST40 (LN2 cooled Cu)





ST140 (HTS)

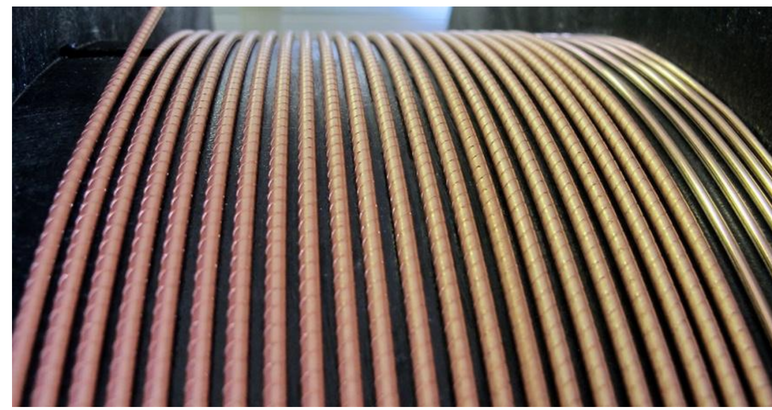
tokamak energy
a faster way to fusion

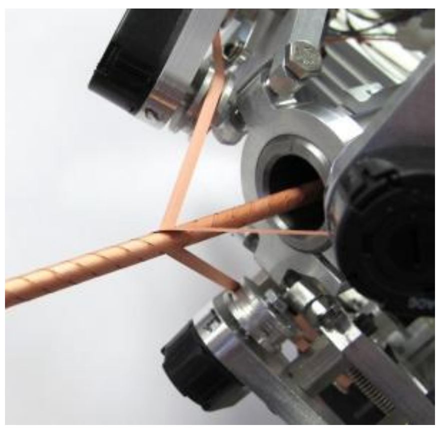
REBCO HTS high current cables

CORC ® (Conductor on Round Core) Cable

- Fabricated by winding multiple wires in a helical way around a small round former
- High currents and current densities
- Mechanically strong
- Flexible
- High level of conductor transposition

Advanced Conductor Technologies LLC
www.advancedconductor.com





First commercial sale (CERN)

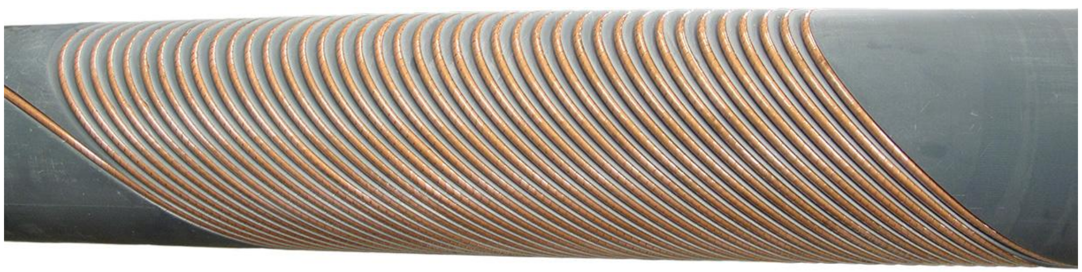
- 12 meter CORC® cable (38 tapes)
- Cable for detector magnets
- Delivered August 2014

Courtesy of D. van der Laan, ACT LLC

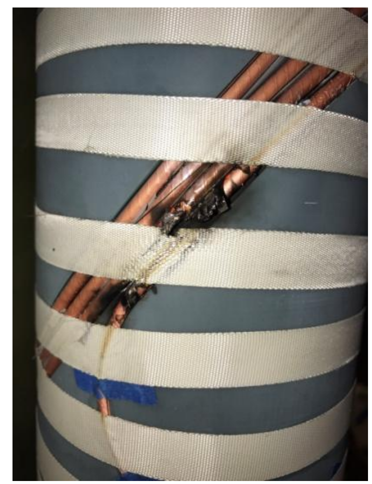
Canted-Cosine-Theta magnets wound from CORC® wires

CORC® CCT magnet program goals

- Reach 5 T in CORC® CCT insert with 10 T (15 T) LTS CCT outsert
- Develop the CORC® CCT magnet technology in several steps
- C1: 1 T 4.2 K, self-field, low-Je CORC® wire
- C2: 4-5 T 4.2 K, self-field, 2-3 T in 10 T, high-Je CORC® wire
- C3: 5 T in 15 T background, advanced CORC® wires



CCT C1



CCT C2-0

Advanced Conductor Technologies LLC
www.advancedconductor.com

Courtesy of D. van der Laan, ACT LLC

BERKELEY LAB

REBCO HTS high current cables

Twisted Stacked-Tape Cable (TSTC)

32 YBCO tape Twisted Stacked-Tape Cable (TSTC) with 200 mm twist pitch

For example:

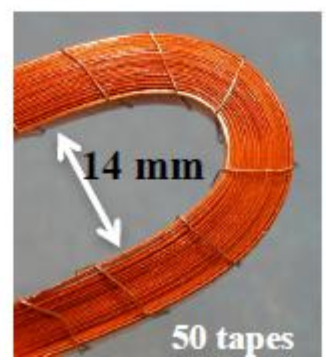
1. REBCO tapes are **stacked** between two thick copper strips.
2. The stacked-tapes with the copper strips are loosely **wrapped** with a fine stainless steel wire.
3. Then the stacked-tape cable is **twisted**.

Stacked-Tape Twist-Winding (STTW)

Method for 3D Magnets

Stacked tape cable is twisted during winding.

A curved saddle winding of 50 YBCO tapes on a 50 mm diameter tube.



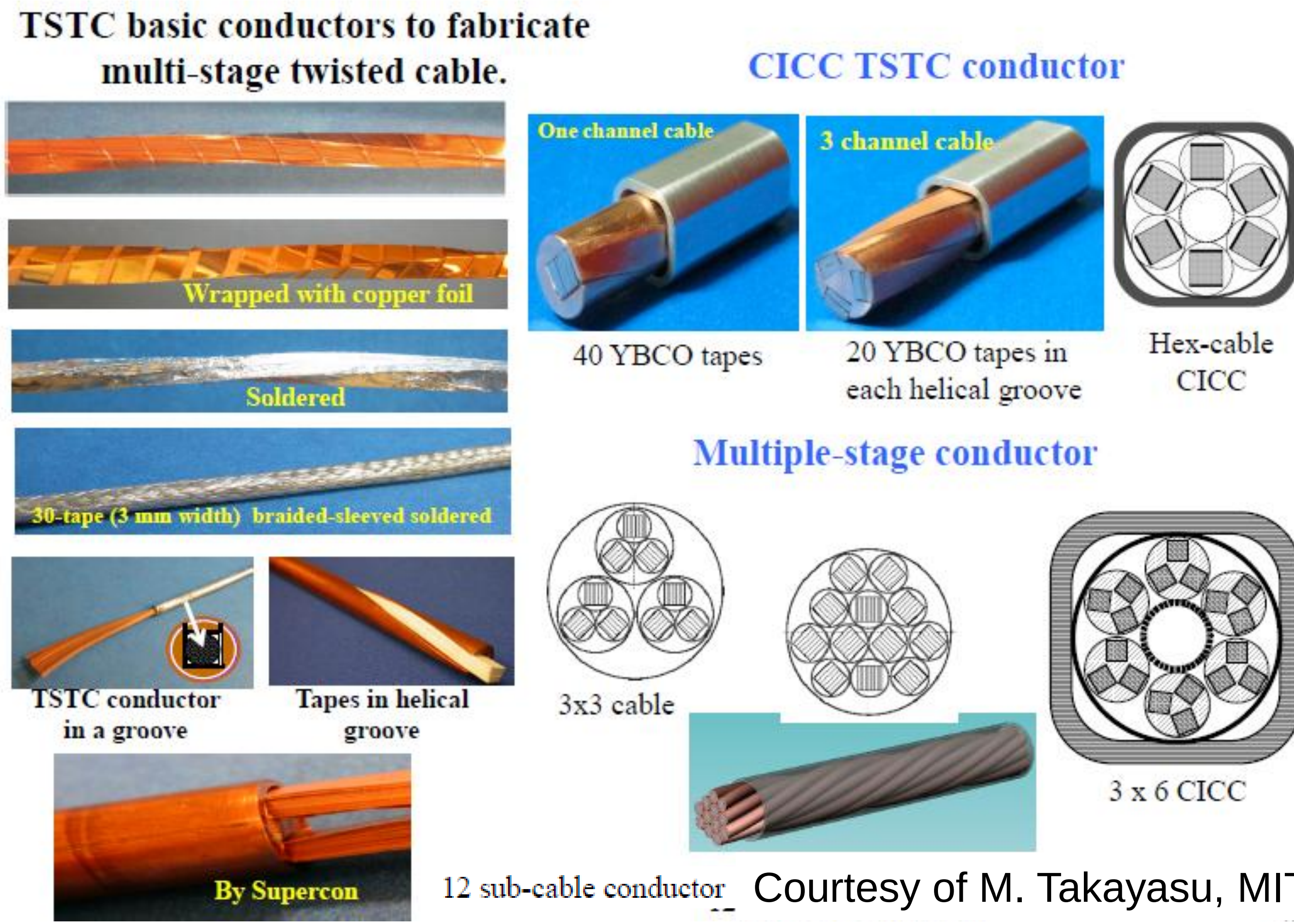
Courtesy of M. Takayasu, MIT-PSFC

MIT PSFC

SuperPower Inc. A Furukawa Company

REBCO HTS high current cables

Twisted Stacked-Tape Cable (TSTC) Conductor Scale-up



Courtesy of M. Takayasu, MIT-PSFC

REBCO HTS high current cables

Roebel Cable

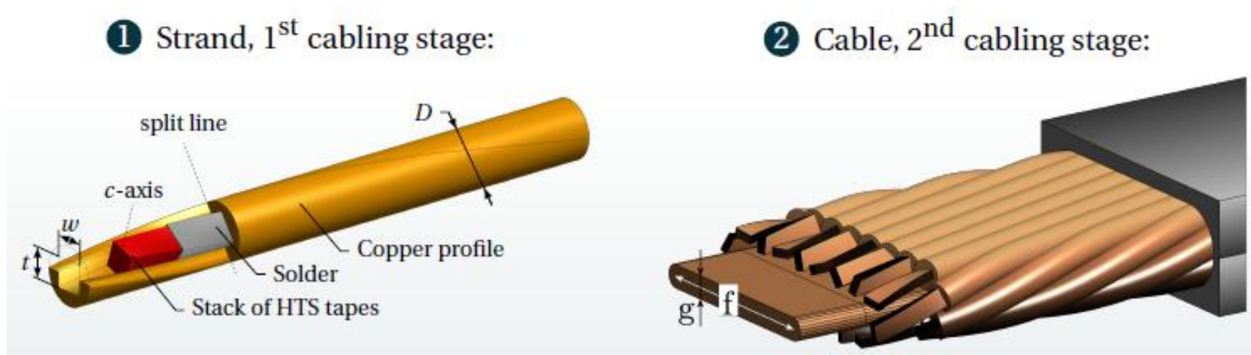
- Fabricated by winding mechanically punctured meandering tapes
- High current and low AC loss

Source: KIT Karlsruhe Institute of Technology

Stacked-tape Cable

- Two-step cabling
- 16 tapes per strand, twisted at 32 cm. 20 strands per cable, twisted at 100cm
- 60kA at 12T

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

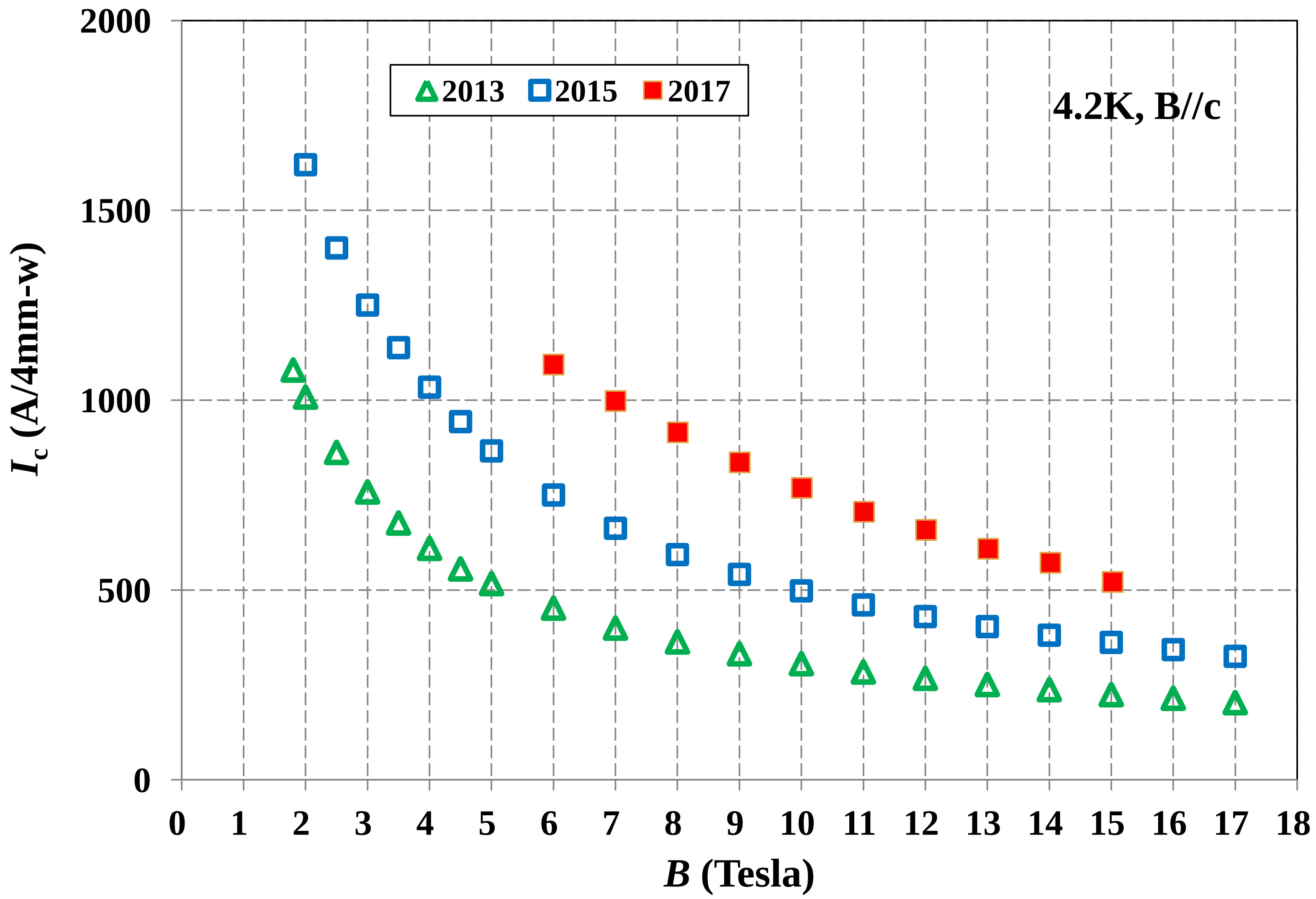


Nikolay Bykovsky et al, EUCAS 2017

Performance and quality of REBCO wire

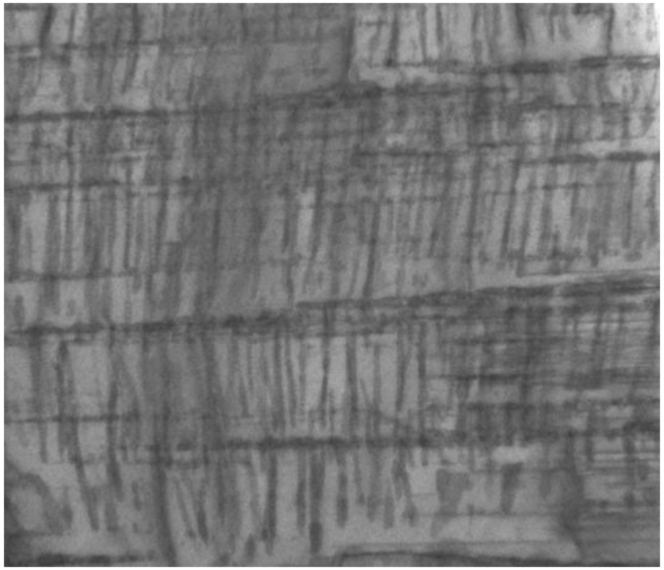
- ***I_c(B, T, θ)***
  - Field dependence
  - Angular dependence
  - Minimum $I_c(\theta)$
  - Engineering current density, Je
- **Uniformity along length (piece length) and consistency**
- **Electromechanical properties (stress and strain limits)**
  - Critical stress and strain
  - Irreversible stress and strain
  - Fatigue (in various stress states)
- **Overcurrent stability**
- **Joint**
  - Geometry
  - Resistance (resistivity)
  - Electromechanical strength (stress and strain limits)
- **AC losses**
- **Insulation**

In-field performance

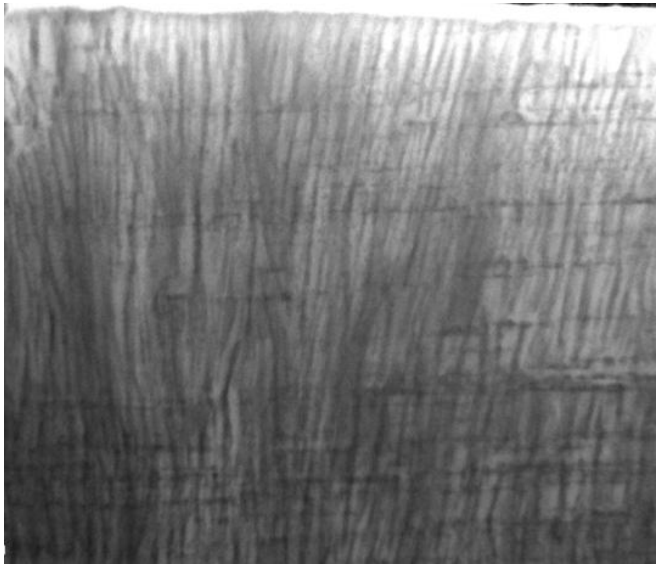


In-field performance – tailored structure

- Effect of Zr doping level on Ic(BTθ)
  - 7.5%Zr, 15%Zr, or higher
  - Field, temperature and angular dependence
- Wire classification – optimized for various applications
  - High-temperature low-field
  - Intermediate-temperature intermediate-field
  - Low-temperature high-field

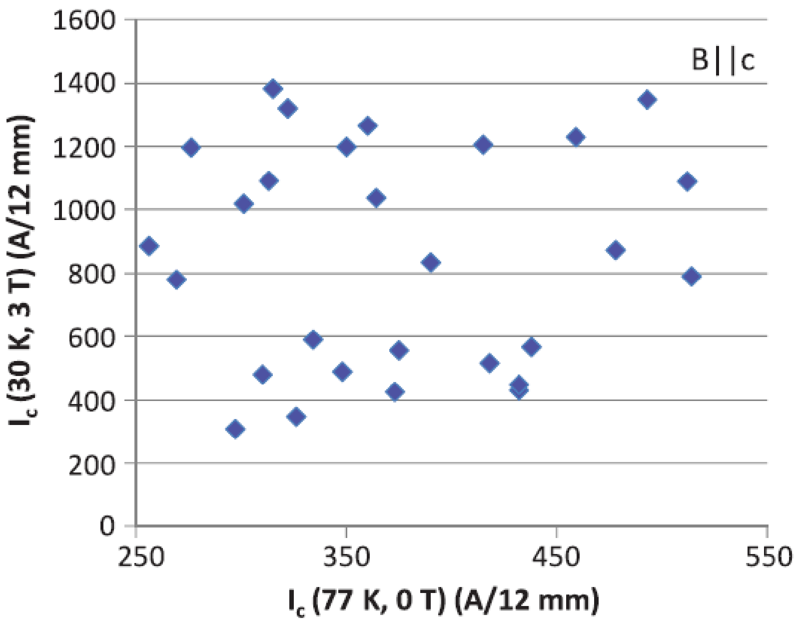


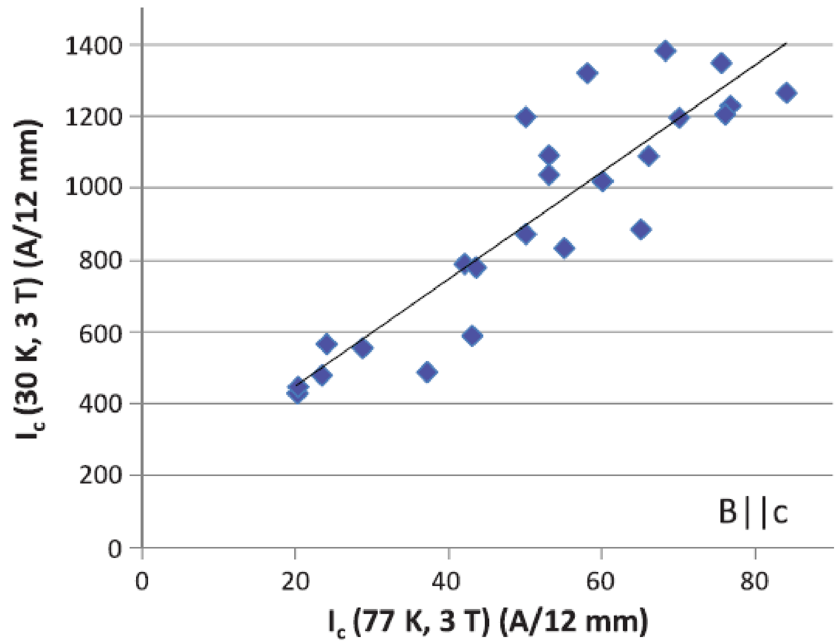
Cross-section, TEM, 7.5%Zr



Cross-section, TEM, 15%Zr

In-field performance – correlation



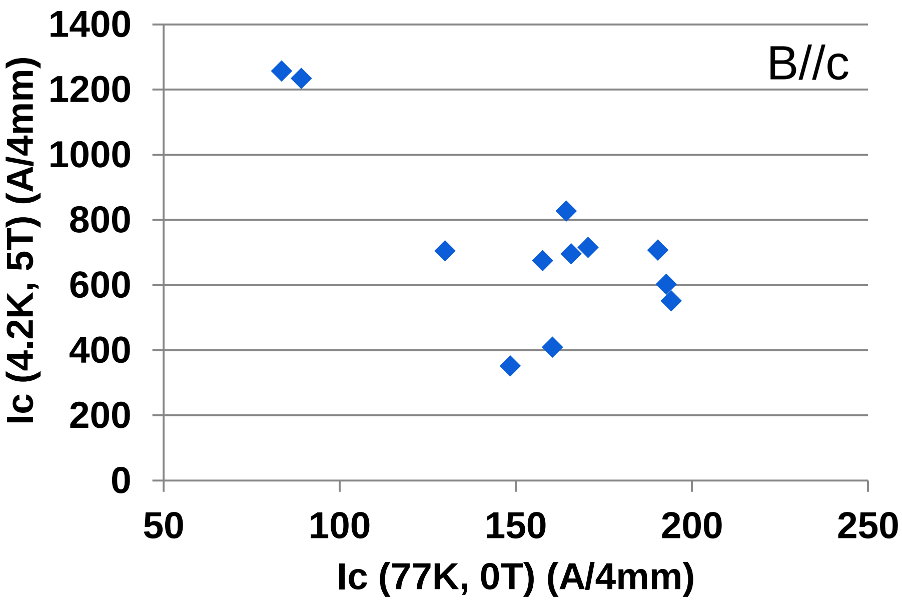


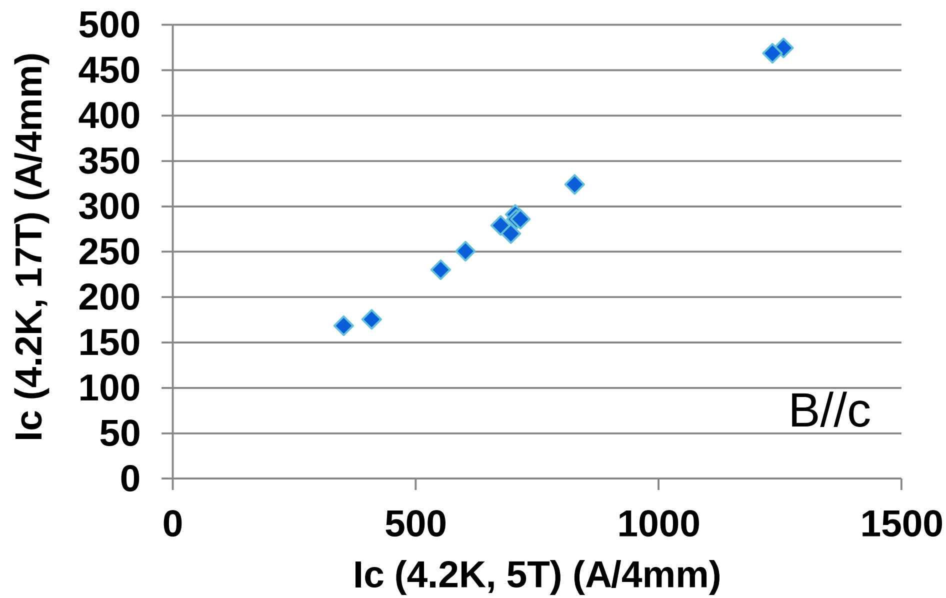
Earlier work at University of Houston suggested

- There is no correlation between Ic(30K, 3T//c) and Ic(77K, 0T)
- There is a fairly good correlation between Ic(30K, 3T//c) and Ic(77K, 3T//c)

V. Selvamanickam, et al, SUST, 27(2014)055010

In-field performance – correlation



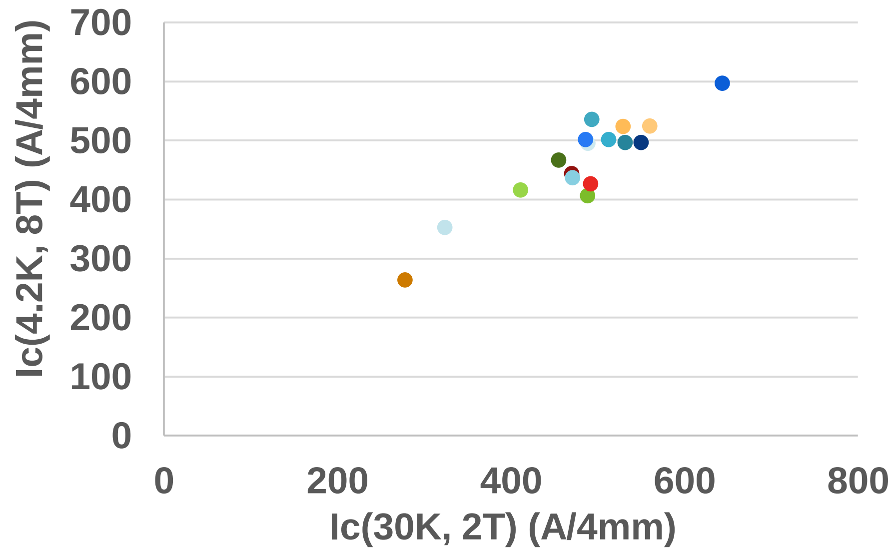


Our recent data suggested

− There is a loosely inverse correlation between Ic(4.2K, 5T//c) and Ic(77K, 0T)

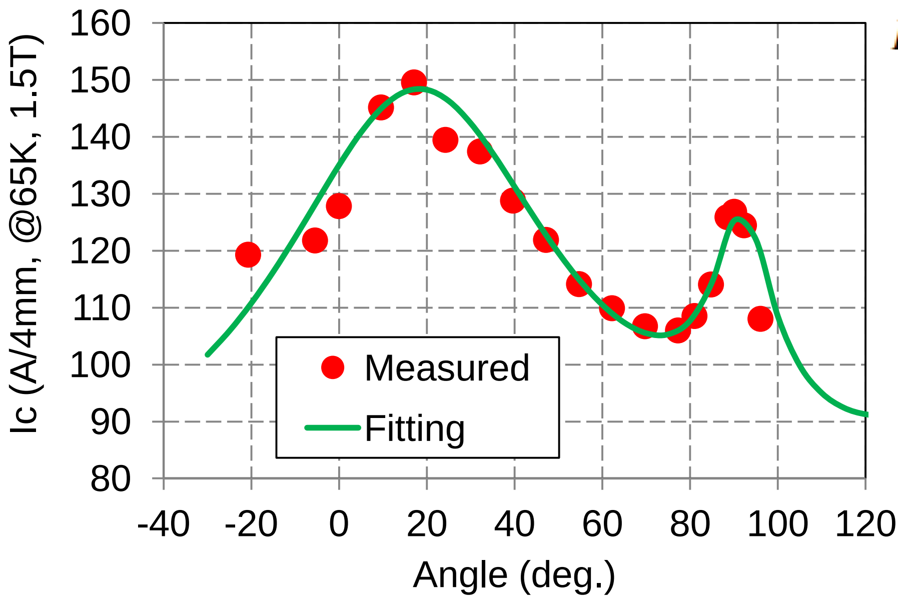
− There is a fairly good correlation between Ic(4.2K, 17T//c) and Ic(4.2K, 5T//c)

− There is a fairly good correlation between Ic(4.2K, 8T//c) and Ic(30K, 2T//c)



Angular dependence and anisotropy

- Biaxially textured REBCO film is essentially highly anisotropic material – Ic is dependent on magnetic field orientation
- The anisotropy is determined by the pinning landscape
- C-axis oriented BZO nano columns effectively enhance the pinning when B//c, therefore change the anisotropy
- The pinning effect from BZO is temperature and field dependent



$$I_c(B,\theta) \equiv b_0 + F_n\left(b_k \middle| \omega_k, \varphi_k; \theta\right), \quad b_k = b_k(B), \quad \omega_k = \omega_k(B).$$

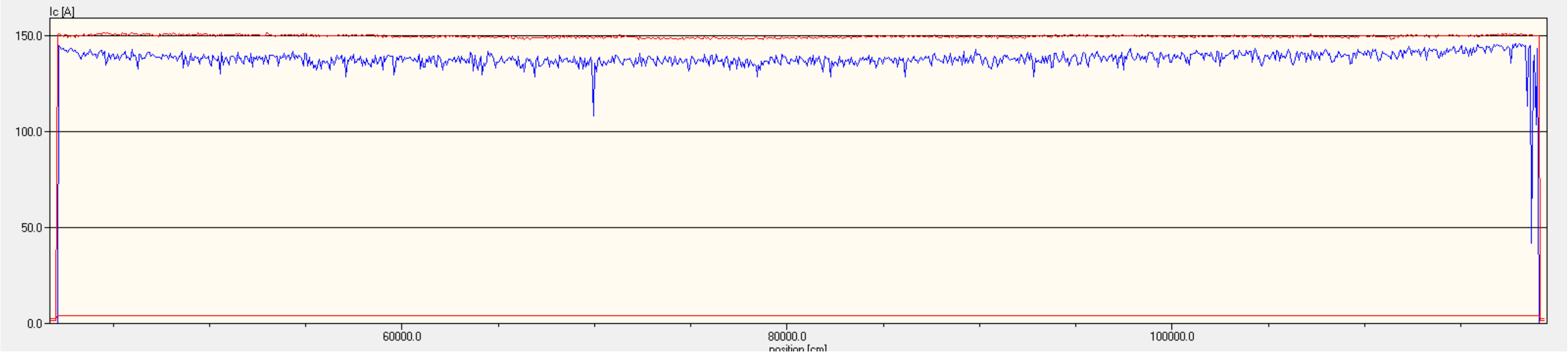
Where

$$F_n\left(b_k, \omega_k, \varphi_k; \theta\right) = \sum_{k=1}^{n} b_k f_2\left(\omega_k, \theta - \varphi_k\right).$$

$$f_p(\omega, \theta) = \left[\omega^2 \cos^2(\theta) + \sin^2(\theta)\right]^{-1/p} = \frac{1}{\left[\omega\, \varepsilon(\omega, \theta)\right]^{2/p}}, \qquad p \in \{1, 2\}.$$

D. K. Hilton, et al, SUST, 28(2015)074002

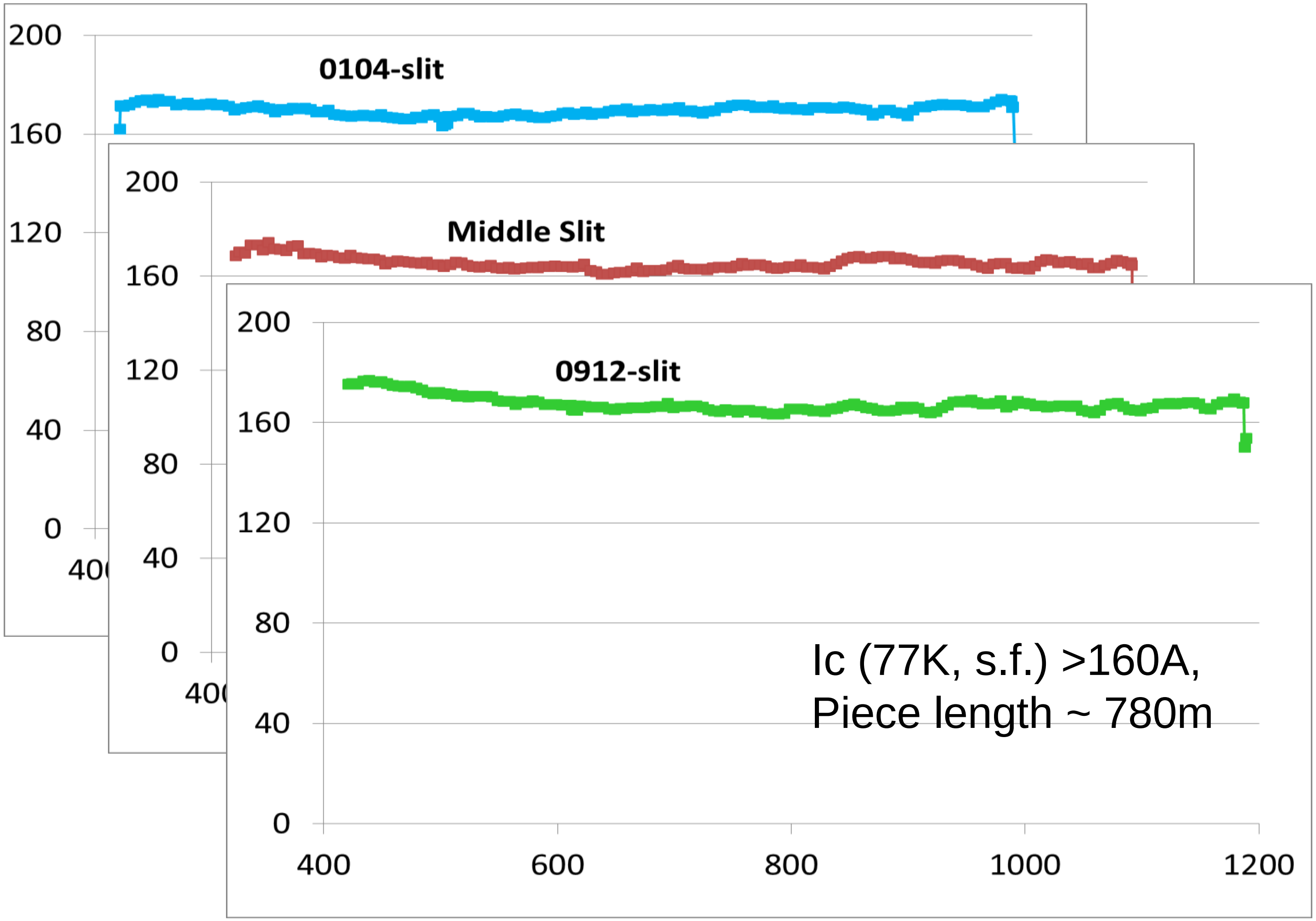
I_c uniformity along length – magnetic measurement



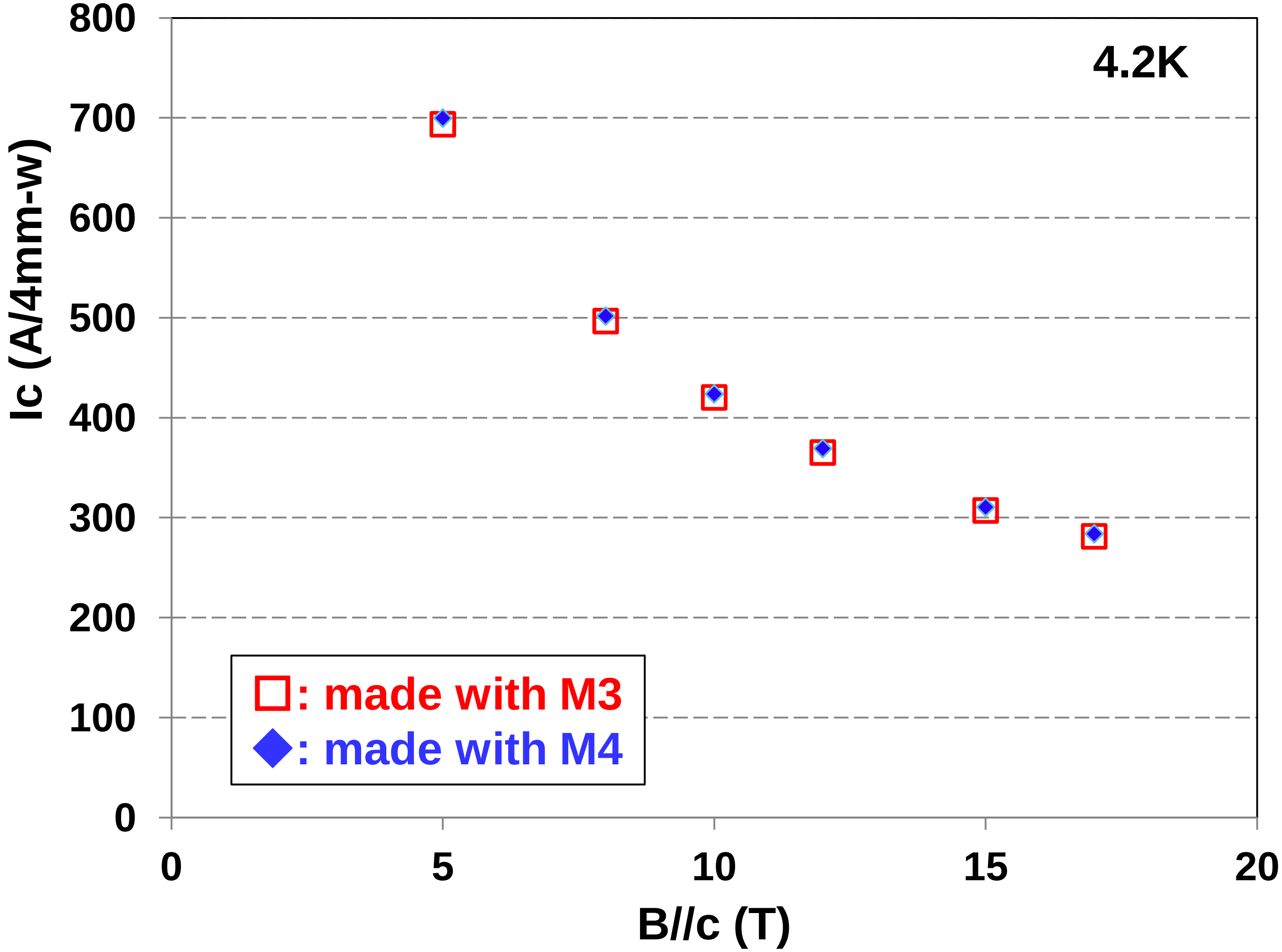
Position (cm)(on a 4 mm wide wire)

- Non-contact measurement
- High spacial resolution, high speed, and reel-to-reel
- Monitoring I_c at multiple production points after MOCVD
- Capable of quantitative 2D uniformity inspection

Ic uniformity along length – transport measurement

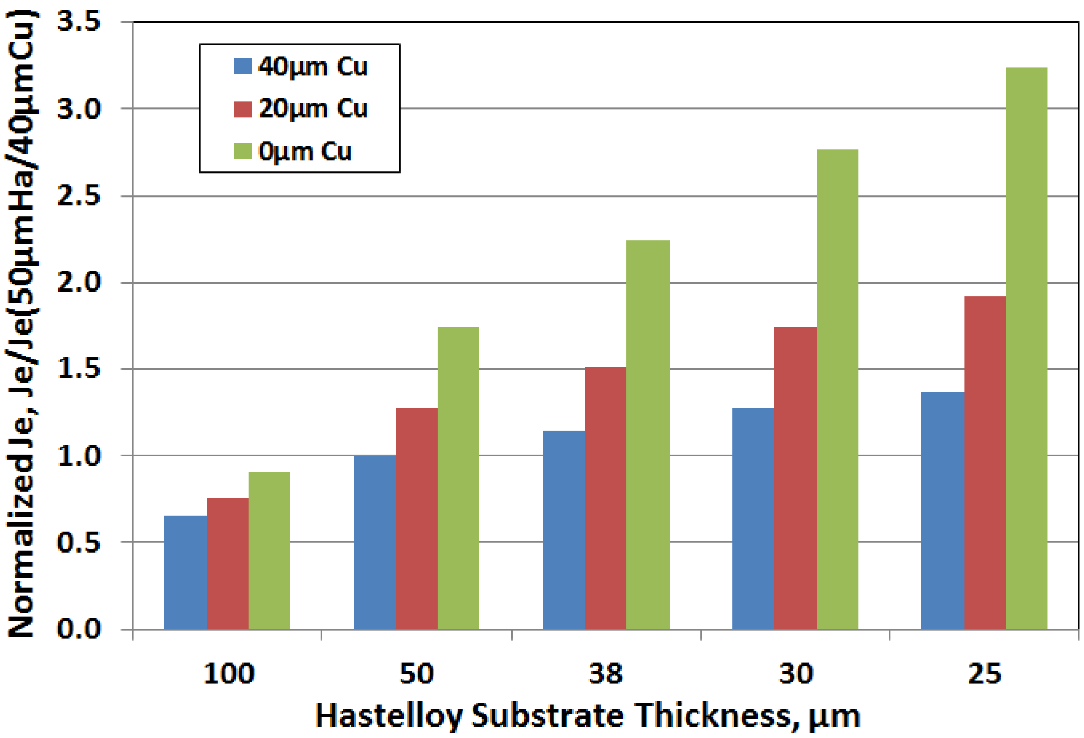


Consistent in-field performance



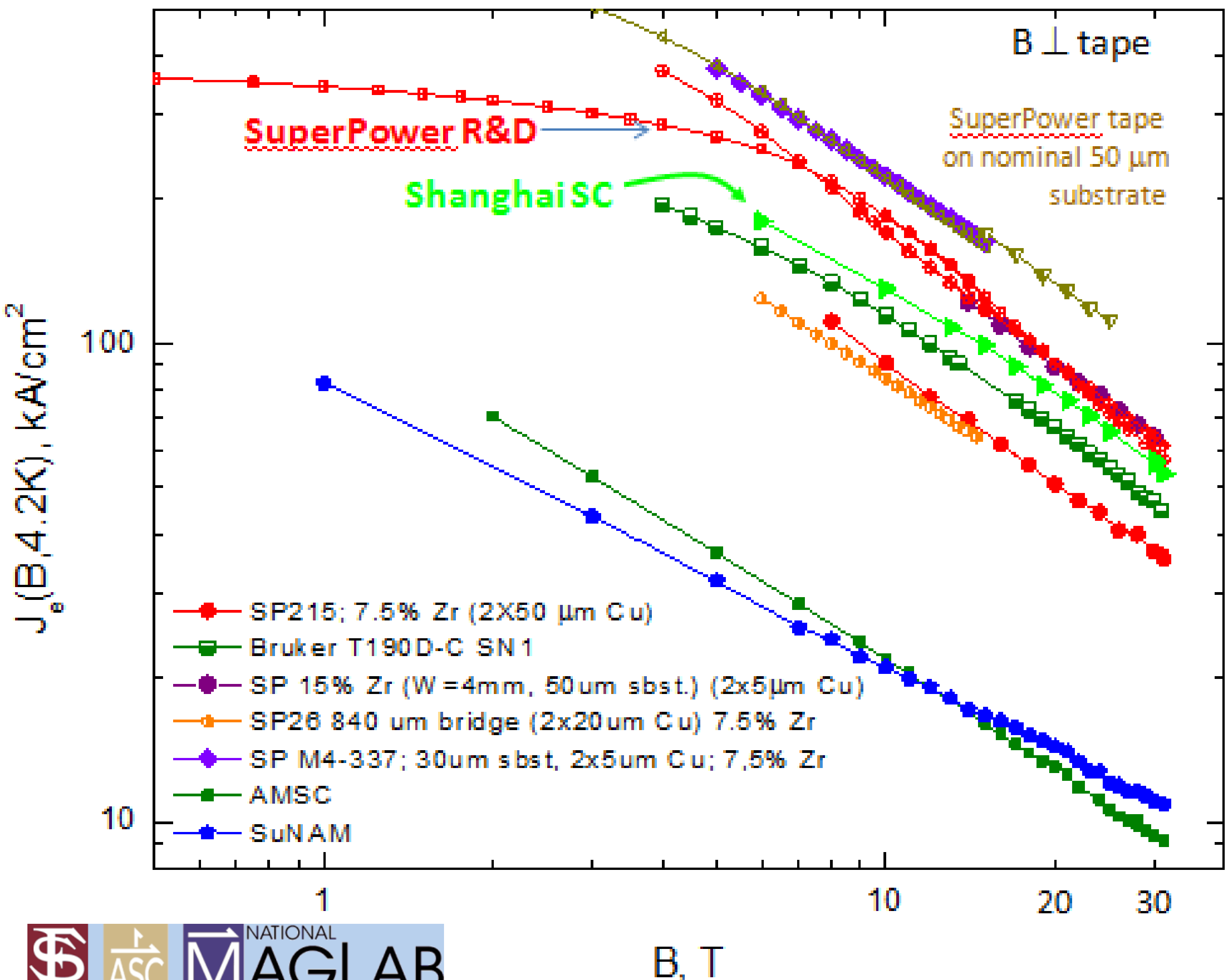
Higher J_e (engineering current density) wire with thinner substrate

- Thinner substrates (30μm or thinner) lead to higher Je without compromising the functionality of stabilizer that needs to be of certain thickness
- Higher J_e and the flexibility of thinner wire facilitates fabrication of high current cables



A. Sundaram, et al, SUST, 29(2016)104007

Higher J_e (engineering current density) wire with thinner substrate



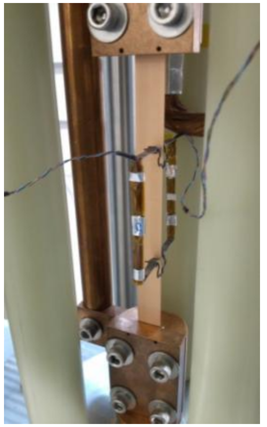
Courtesy of D. Abraimov, NHMFL

LBC3 HTS insert in 31T resistive magnet reached 45.46T

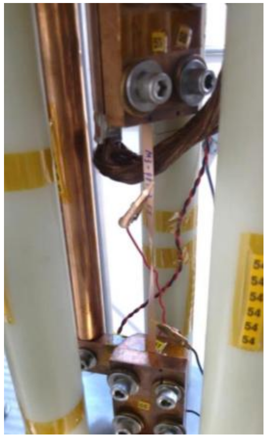
Hahn, et al EUCAS 2017

Mechanical and electromechanical properties and testing

- Axial tensile test at room temperature or at 77K (with I_c)
  - Measurement of elastic modulus and yield stress
  - Determination of critical stress and irreversible stress (strain)
- Torsion-tension test at 77K (with I_c)
  - Measurement of critical tensile stress under twist
- Transverse (c-axis) compressive test at 77K (with I_c)
  - Measurement of critical compressive stress
- Bending test at 77K (with I_c)
  - Measurement of minimum bending diameter
- Measurement of delamination strength – various testing methods
  - Peel test: at room temperature
  - Pin-pull (c-axis tensile) test: at room temperature
  - Anvil (c-axis tensile) test: at room temperature or at 77K (with I_c)



Uniaxial tension

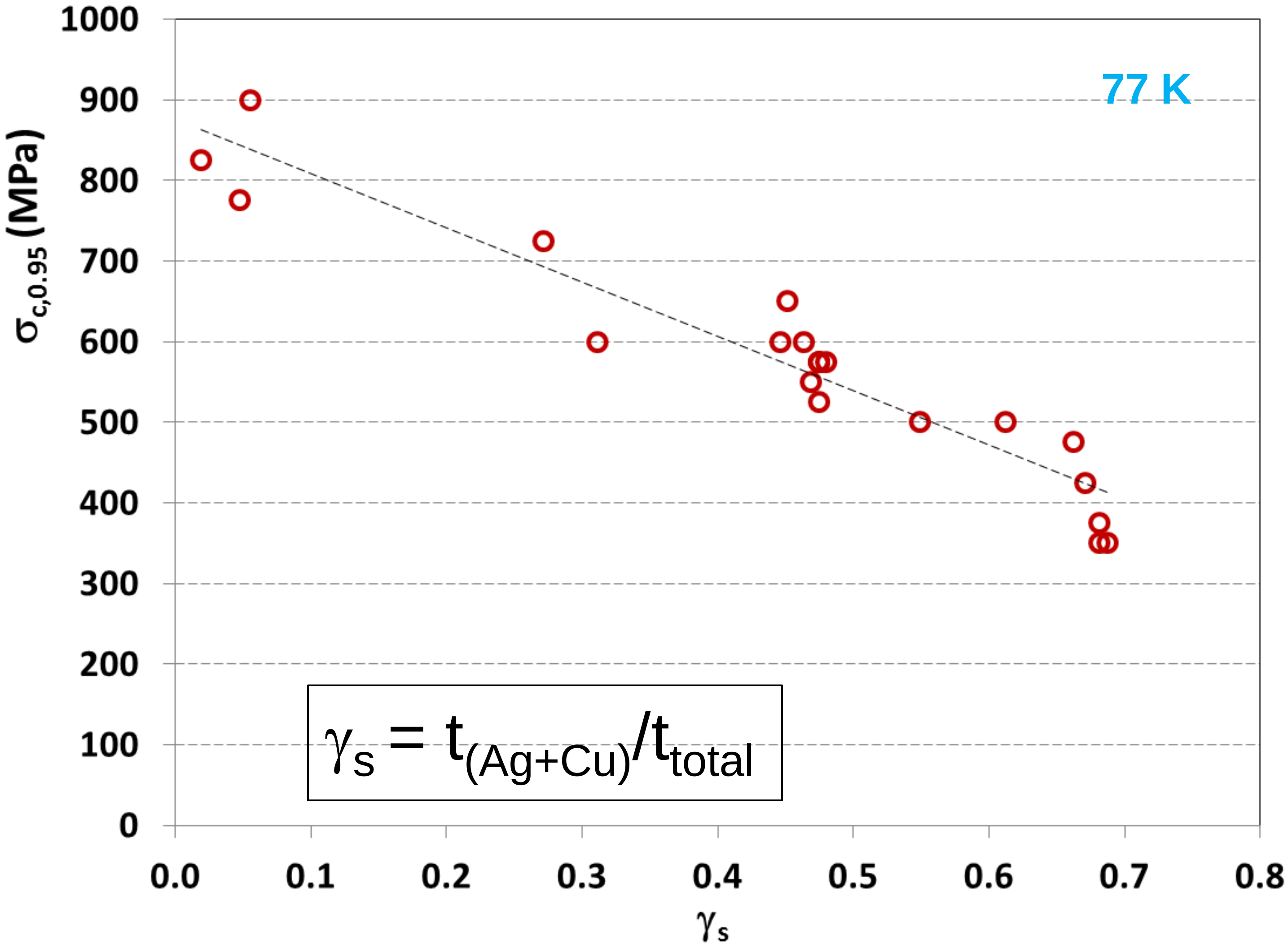


Torsion + tension

Transverse Compression

Peel Test

Effect of stabilizer thickness ratio on critical stress under uniaxial tension



Continuous development and engineering

- Wire on thinner substrates
  - Higher engineering current density and enhanced mechanical flexibility
  - For fabrication of high current cables and high-field magnets
- Different REBCO formula tailored for various operating conditions
  - Intermediate-temperature (30-50K) and intermediate-field (2-4T) applications
  - Low-temperature (4.2K) high-field (>10T) applications
- Bonded wires
  - Enhanced performance and specific functionality
- Wire filamentization
  - Reduction of AC loss
  - Mitigation of screening effect
- Alternative insulation
  - Thinner and more uniform
- Current Leads
  - AgAu instead of pure Ag
- Solder Coating
  - Facilitate cabling

Summary

- In a longer term REBCO HTS wire holds a great promise for electric power, transportation and medical applications (high reliability required)
- REBCO HTS wire has the advantages over other superconducting wires and its Ic level is high enough for many high-field magnet applications
- Different types of high-current /low-AC-loss cables are being developed, which will facilitate the adoption of REBCO HTS wire for magnet applications
- Continuous development efforts are focused on
  - Further reduction in wire price and increase in wire production capacity
  - Further improvements in wire performance and quality
  - Technology advancements in AC loss reduction, joint and termination fabrication, insulation, quench detection/protection