Progress in REBCO Conductor Technologies for Ultra-High Field Applications

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Department of Nuclear and Particle Physics, University of Geneva, Switzerland

Outline

- Magnet applications of High Temperature Superconductors
  - Where we stand and what we aim to achieve – Focus on applications *beyond colliders*
- A brief introduction to REBCO coated conductor technology
- Performance overview of commercial REBCO coated conductors
  - Transport properties at low temperature/high field
  - Anisotropy, uniformity over the length and batch-to-batch variability
  - Electromechanical properties
- Lessons learned so far from magnet R&D
- Conclusions

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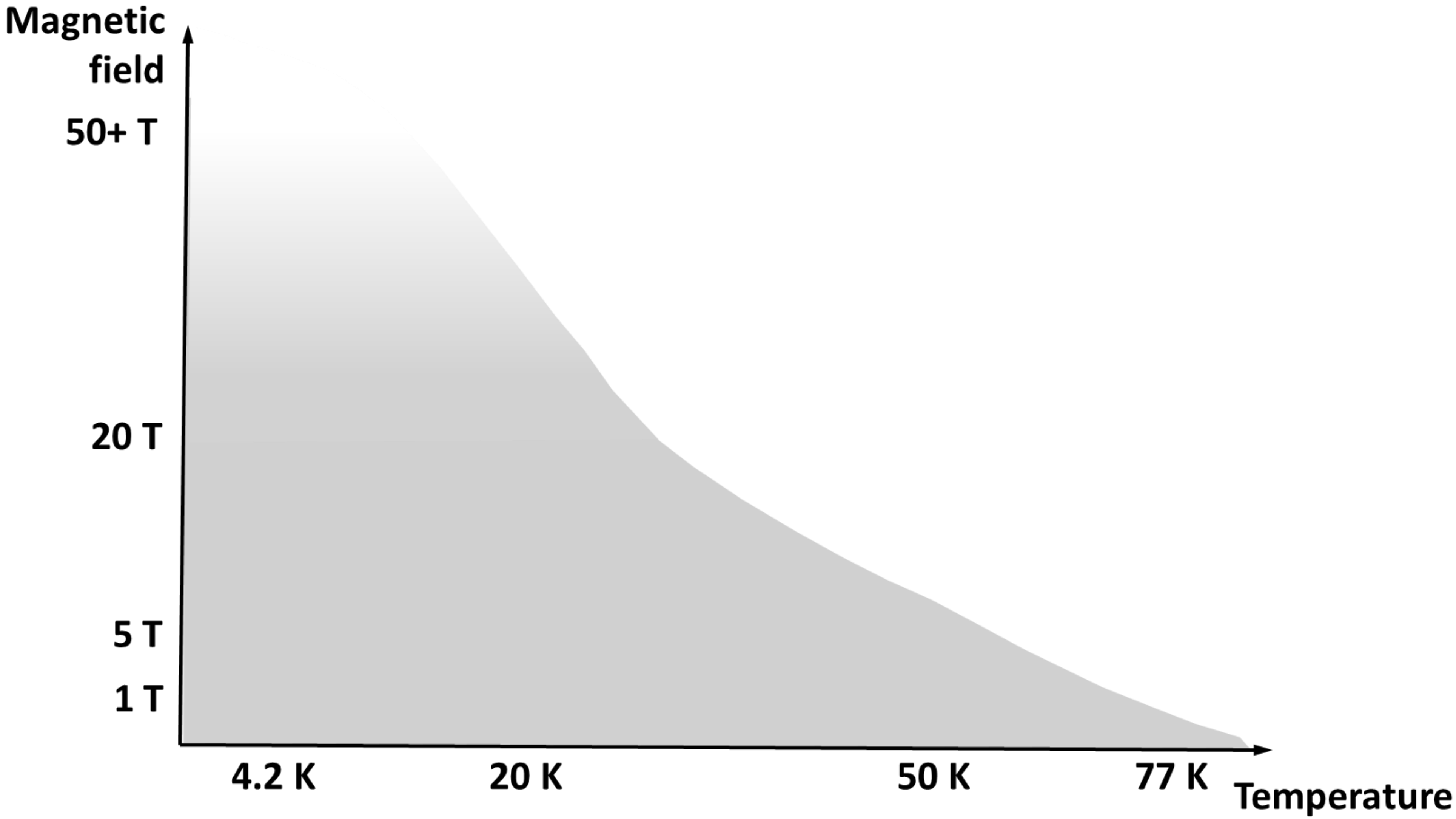
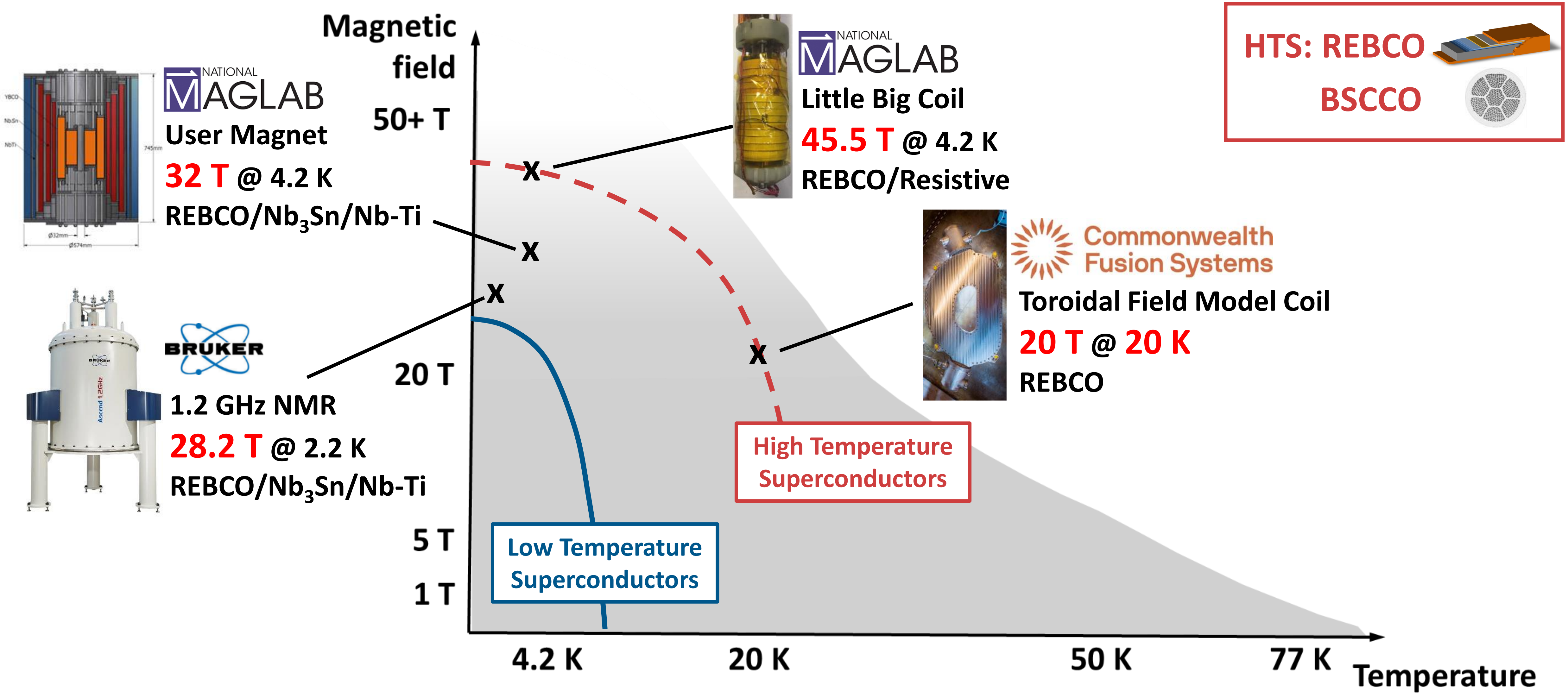
Field-temperature phase diagram of technical superconductors



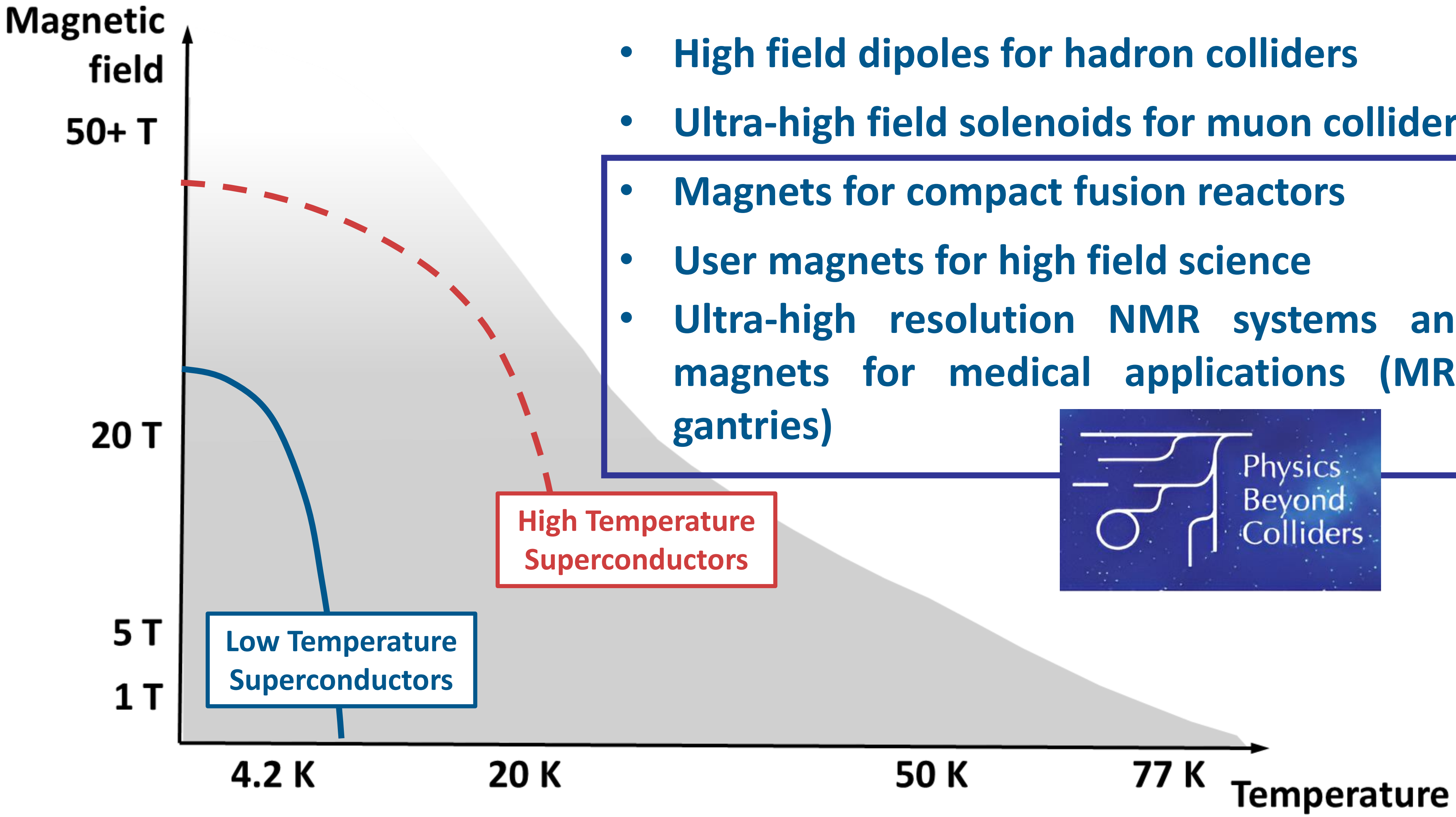
High field applications of High Temperature Superconductors

Field-temperature phase diagram of technical superconductors



The application's pull towards higher magnetic fields

Field-temperature phase diagram of technical superconductors

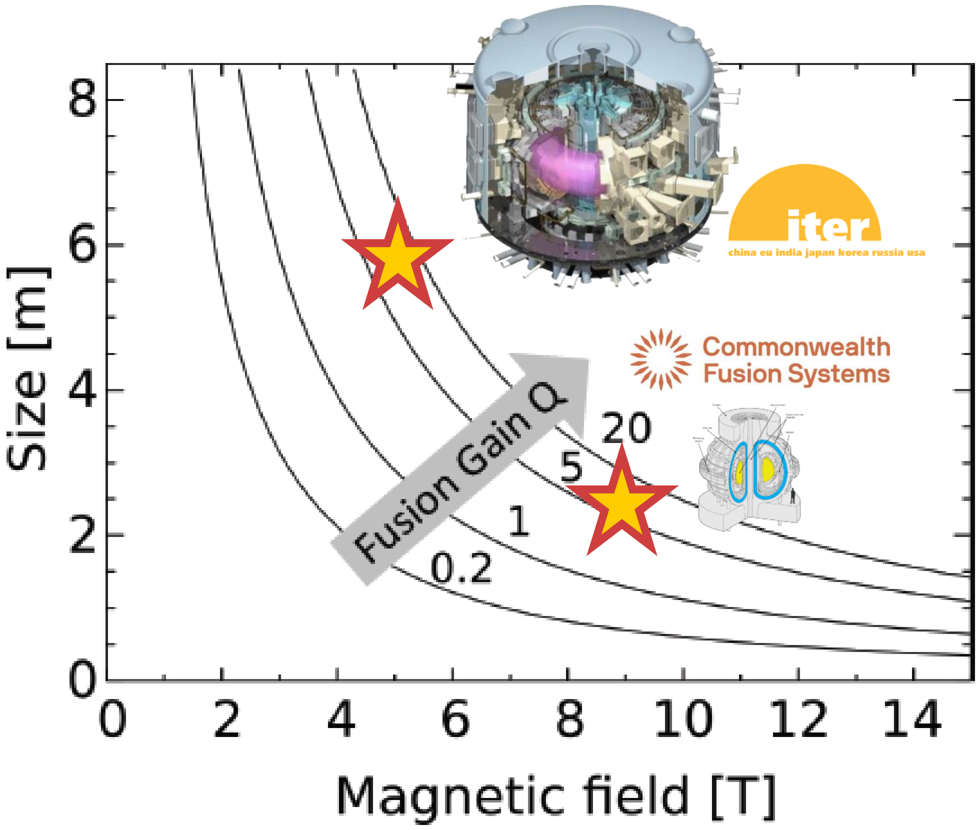


- High field dipoles for hadron colliders
- Ultra-high field solenoids for muon colliders
- Magnets for compact fusion reactors
- User magnets for high field science
- Ultra-high resolution NMR systems and magnets for medical applications (MRI, gantries)

Physics Beyond Colliders

The call for High Field Magnets from Fusion

Towards high-gain small-size fusion reactors



HTS are making possible new designs of compact fusion reactors because of **two technical advantages** with respect to LTS

1. **Higher critical fields**, as the **fusion power density** in a tokamak is **proportional to B^4**
2. The possibility to **operate at higher temperatures**, > 4 K, with a large margin that would allow withstanding the neutron heating and lower the cryogenic costs

Two examples: Commonwealth Fusion Systems and Tokamak Energy are both developing magnets for plasma confinement with **peak fields at 20 T** on the superconductor and operation in the **20 K range**

Energy from Fusion: an emerging industrial business

FUSION INDUSTRY ASSOCIATION

ABOUT Members https://www.fusionindustryassociation.org/

Commonwealth Fusion Systems, Type One Energy, Thea Energy, Renaissance Fusion, nT-tao Compact Fusion Power, Proxima Fusion, Tokamak Energy, Gauss Fusion, Stellarex, Helical Fusion

With growing competitors in China

ENN 新奥, Neo Fusion, 能量奇点 ENERGY SINGULARITY, STARTORUS FUSION 星环聚能

Funding for Fusion Companies

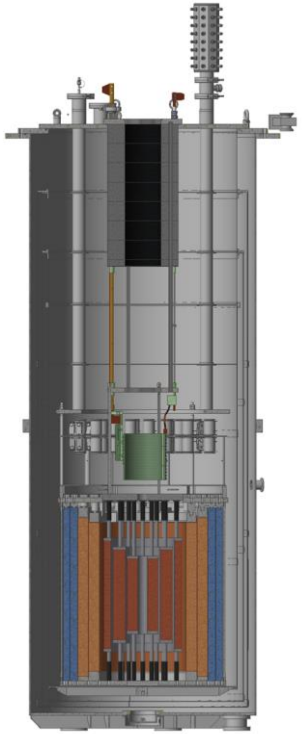
Total 2024	>$900,000,000 (900m)
Total to date	~$7,122,435,000 (7.1bn)
Total public	~$426,000,000 (426m)

Companies adopting magnetic fusion confinement systems

The call from High Field Science

Superconducting magnets for sustainable user facilities

High Magnetic Field Laboratories have as a goal to develop all-superconducting user magnets in the 40 T range. These magnets are intended to replace the current resistive ones, leading to a significantly lower energy consumption and to new scientific possibilities



NATIONAL MAGLAB

U.S. National Science Foundation

LNCMI

anr agence nationale de la recherche

A common strategy towards 40 T

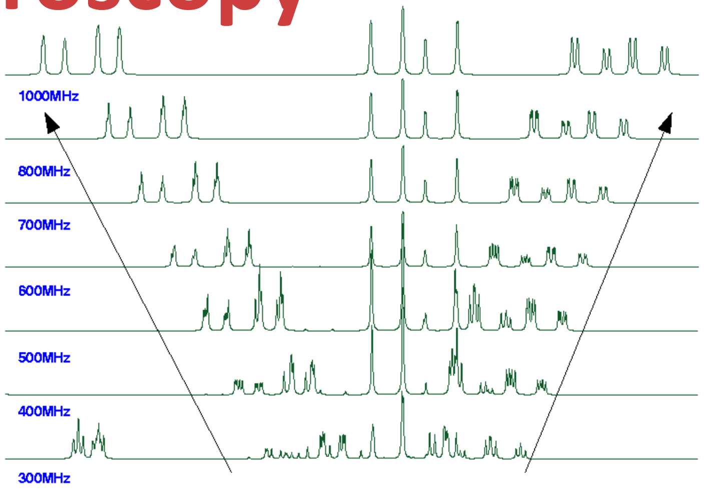
- REBCO high field insert
- commercial LTS outsert 12-15 T

I. Dixon, IMCC Annual Meeting 2022
K. Amm, FCC Week 2024

F. Debray, HiTAT Workshop 2023

The call for higher resolution in NMR spectroscopy

A commercial application of ultra-high fields



Higher fields in NMR magnets lead to

- better resolution, i.e. better peak separation in the NMR spectra
- better signal to noise ratio

REBCO is the enabling technology for NMR magnets up to 28.2 T (HTS/LTS hybrid, 2.2 K)

proton resonance frequency of 1.2 GHz

Next target is 1.3 GHz, 30.5 T

REBCO enables also NMR systems with reduced footprint compared to all LTS solutions

1 GHz / 23.5 T
LTS @ 2.2 K

1 GHz / 23.5 T
HTS/LTS @ 4.2 K

P. Vonlanthen, ASC 2022

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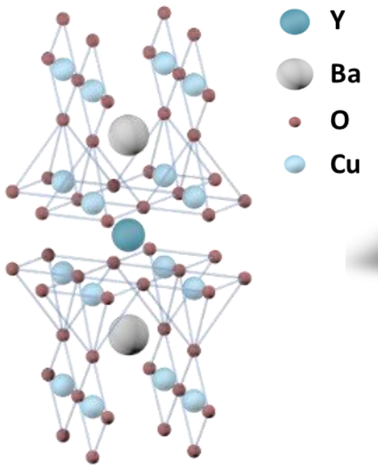
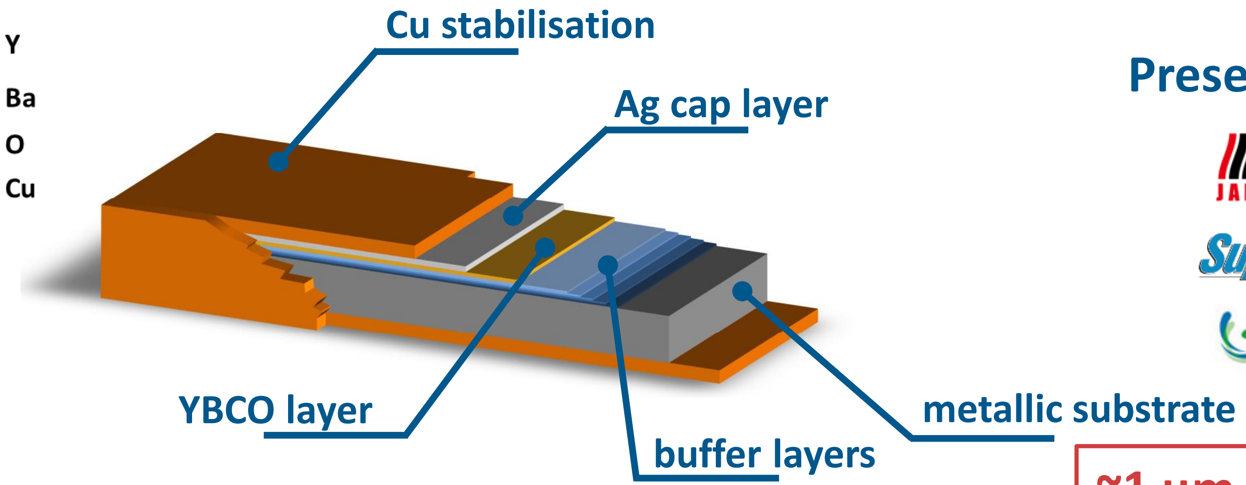
Industrial fabrication of REBCO coated conductors

$REBa_2Cu_3O_{7-\delta}$, RE = Y, Gd, Eu, Nd, Sm, Yb, …

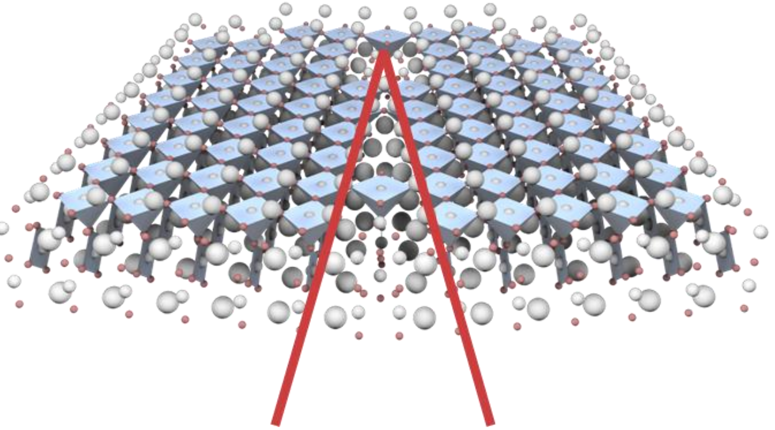




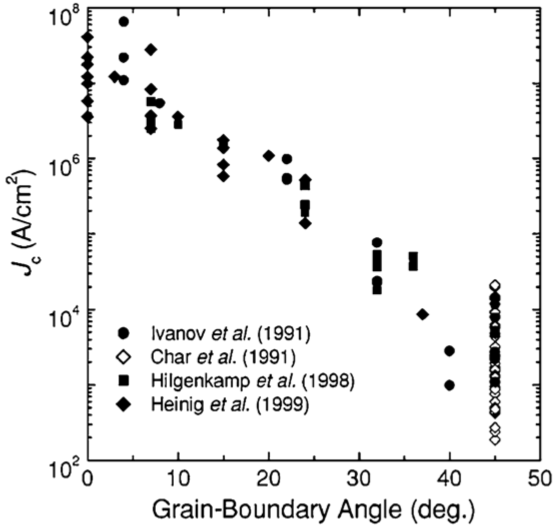
Presently produced by

FARADAY FACTORY JAPAN, Fujikura, 上海超导 SHANGHAI SUPERCONDUCTOR, SuperPower Inc. A Furukawa Company, SuNAM Zero to Infinity, THEVA, Shanghai, METOX, American Superconductor®

~1 µm of YBCO in a ~100 µm thick tape

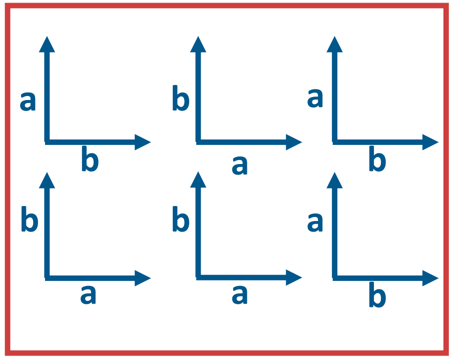


[001] tilt grain boundary



H. Hilgenkamp and J. Mannhart, RMP 74 (2002) 485
DOI: 10.1103/RevModPhys.74.485

A metallic substrate coated with a multifunctional oxide barrier is the template to grow biaxially textured REBCO with in-plane alignment within 5°



The technology of REBCO coated conductors

At least 4-5 medium-large companies using alternative approaches for growing epitaxial REBCO on flexible metallic substrates in km-lengths. Nowadays the main driver is FUSION

Substrate texturing

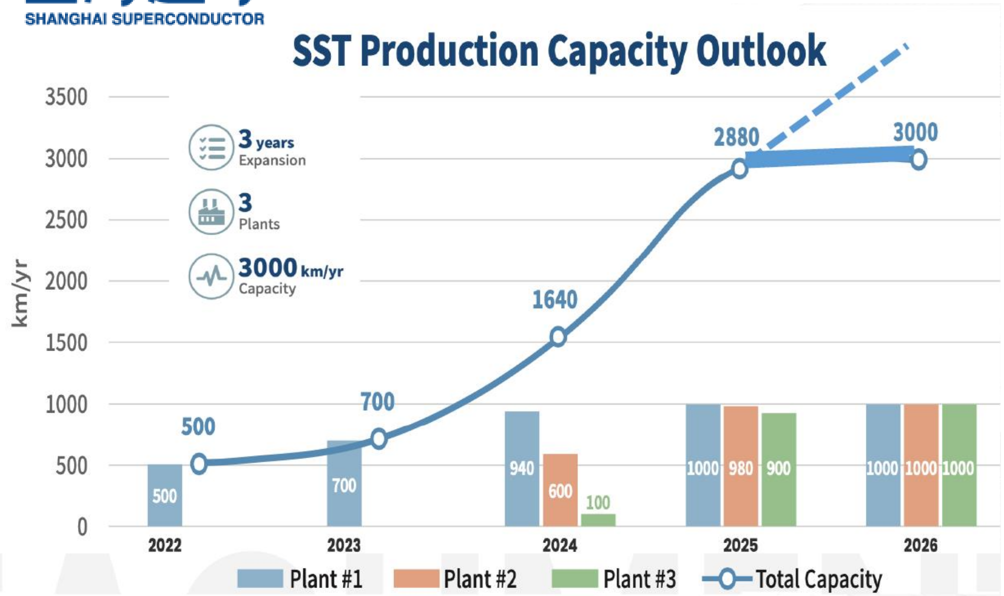
- **RABiTS (Rolling-Assisted, Biaxially Textured Substrates)** American Superconductor
  Texture is created in NiW by a rolling-and-recrystallization process
- **IBAD (Ion Beam Assisted Deposition) or alternatives**
  A biaxially textured MgO layer is grown on polycrystalline Hastelloy

REBCO layer deposition

- **Physical routes**
  - **PLD Pulsed Laser Deposition**
    Fujikura, 上海超导 SHANGHAI SUPERCONDUCTOR, FARADAY FACTORY JAPAN
  - **RCE Reactive Co-Evaporation**
    SuNAM (Zero to Infinity), THEVA
- **Chemical routes**
  - **MOD Metal-Organic Deposition**
    American Superconductor, Shanghai
  - **MOCVD Metal-Organic Chemical Vapor Dep.**
    SuperPower Inc. (A Furukawa Company), METOX

Fusion-driven expansion of REBCO production capacity

上海超导™
SHANGHAI SUPERCONDUCTOR



1600 km_{12}/yr (2024) → 3000 km_{12}/yr (2026)

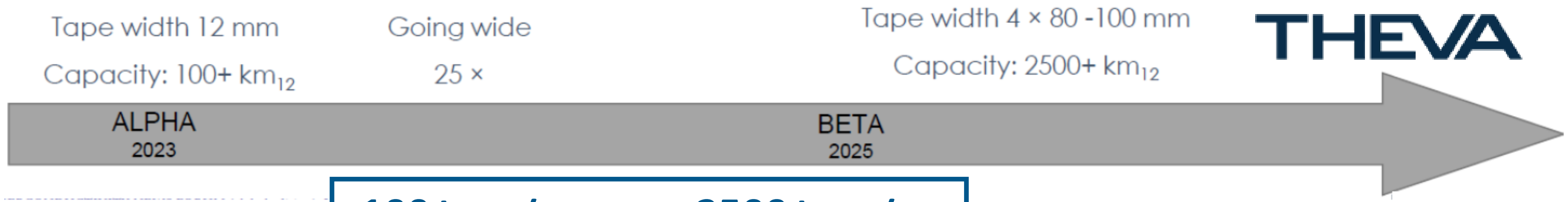
FARADAY FACTORY JAPAN

1300 km_{12}/yr (2024) → 25000 km_{12}/yr (2028)

SuperPower Inc.
A Furukawa Company

200 km_{12}/yr (2024) → 1200 km_{12}/yr (2026)

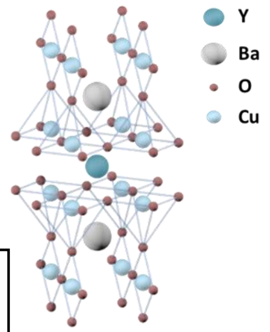
THEVA



100 km_{12}/yr (2023) → 2500 km_{12}/yr (after 2025)

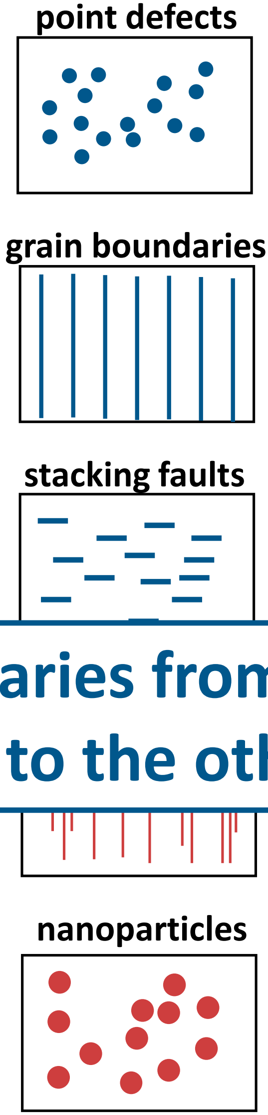
Tailoring the critical current density of REBCO

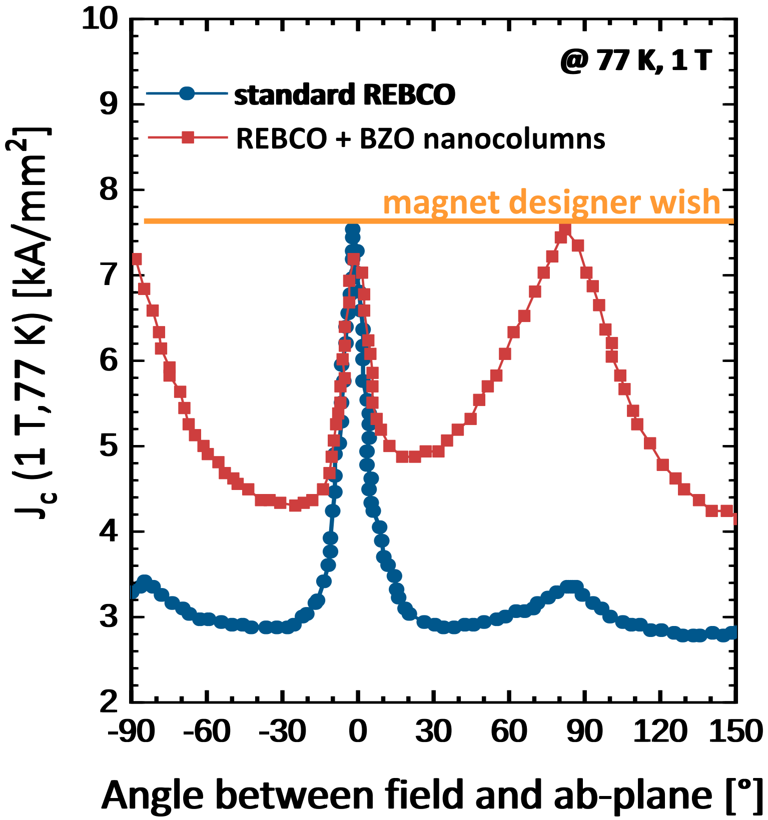
Anisotropy, Intrinsic and Artificial defects and their Dimensionality



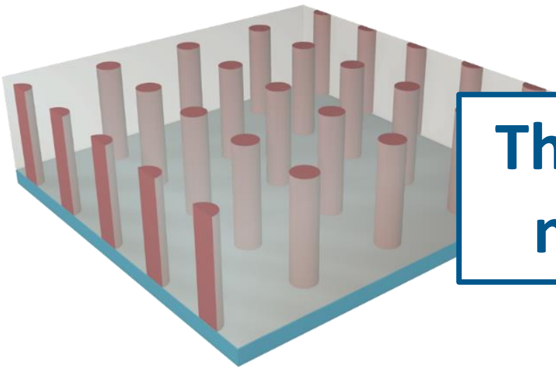
Intrinsic defects, e.g. point defects (0D), grain boundaries (2D), stacking faults (3D), are native pinning centers

Tailored **artificial defects**, e.g. nanocolumns (1D) and nanoparticles (3D), can be introduced to reduce anisotropy and enhance performance





$BaZrO_3$ (BZO) and $BaHfO_3$ (BHO) precipitate in the form of nanocolumns oriented along the c-axis of REBCO



J. Driscoll *et al.*, Nat. Mat. 3 (2004) 439

DOI: 10.1038/nmat1156

A. Goyal *et al.*, SUST 18 (2005) 1533

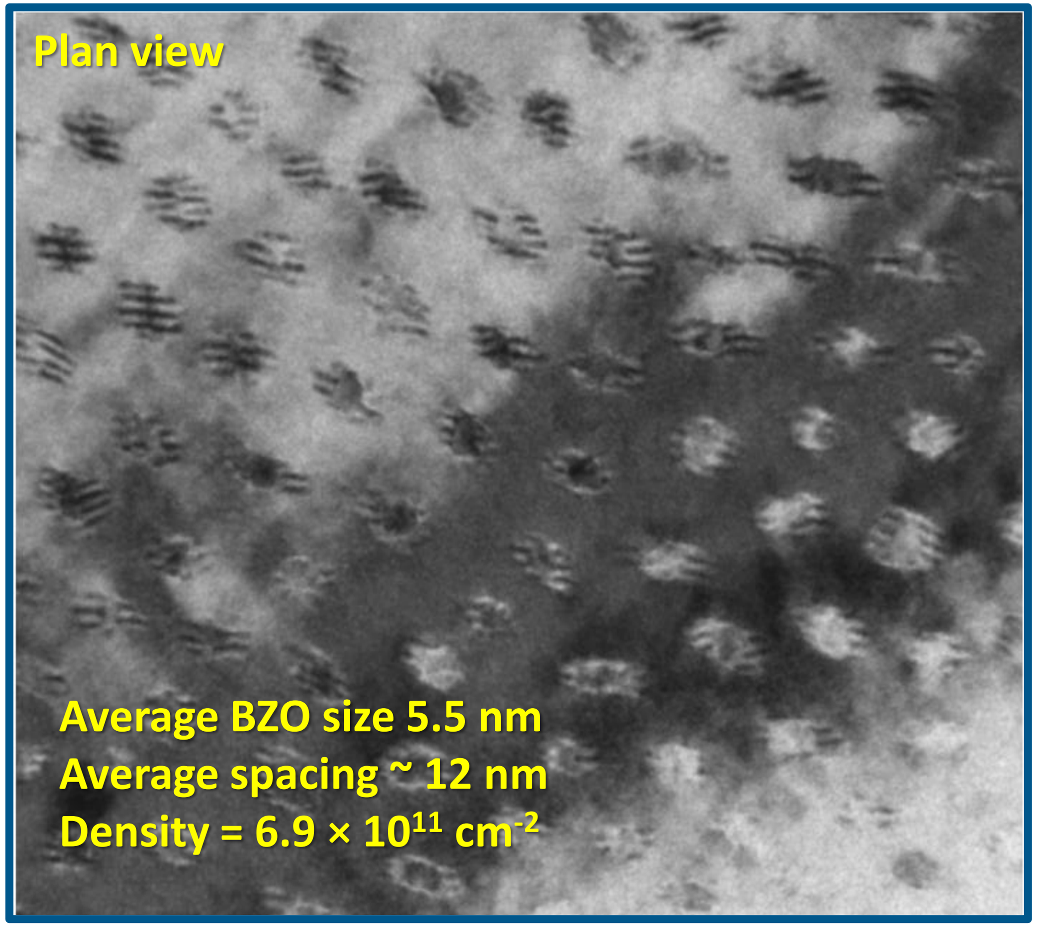
DOI: 10.1088/0953-2048/18/11/021

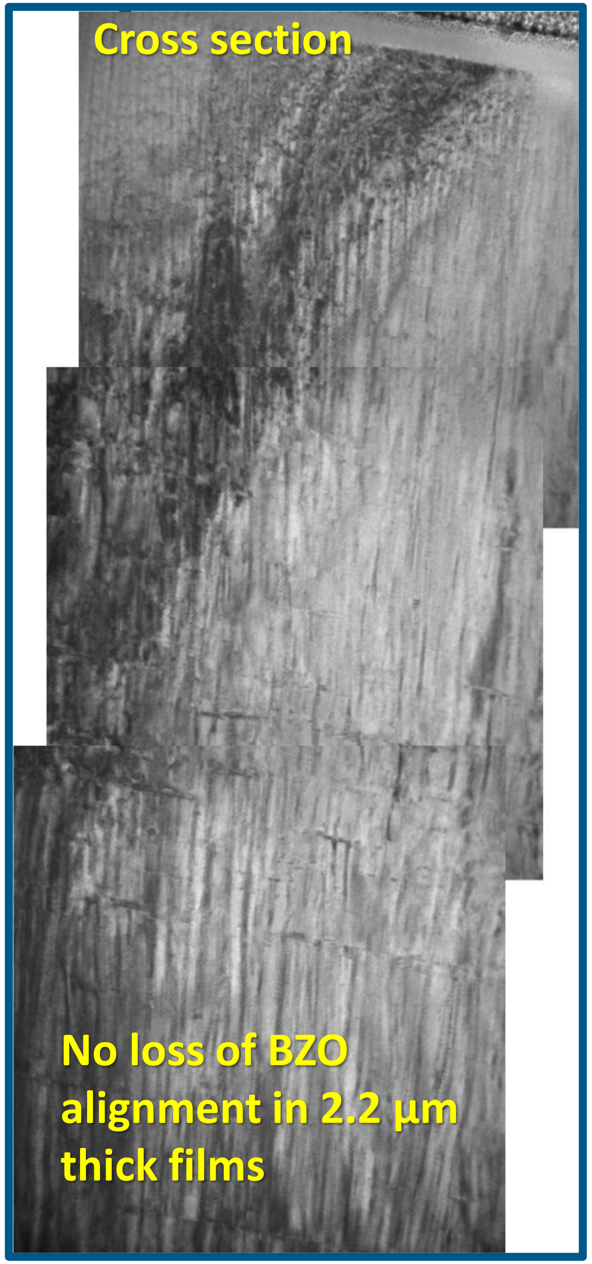
The approach varies from one manufacturer to the others

V. Selvamanickam *et al.*, IEEE TAS 21 (2011) 3049 – DOI: 10.1109/TASC.2011.2107310

Tailoring the critical current density of REBCO

Morphology of the BZO nanocolumns





V. Selvamanickam *et al.*, Appl. Phys. Lett. 106 (2015) 032601
DOI: 10.1063/1.4906205

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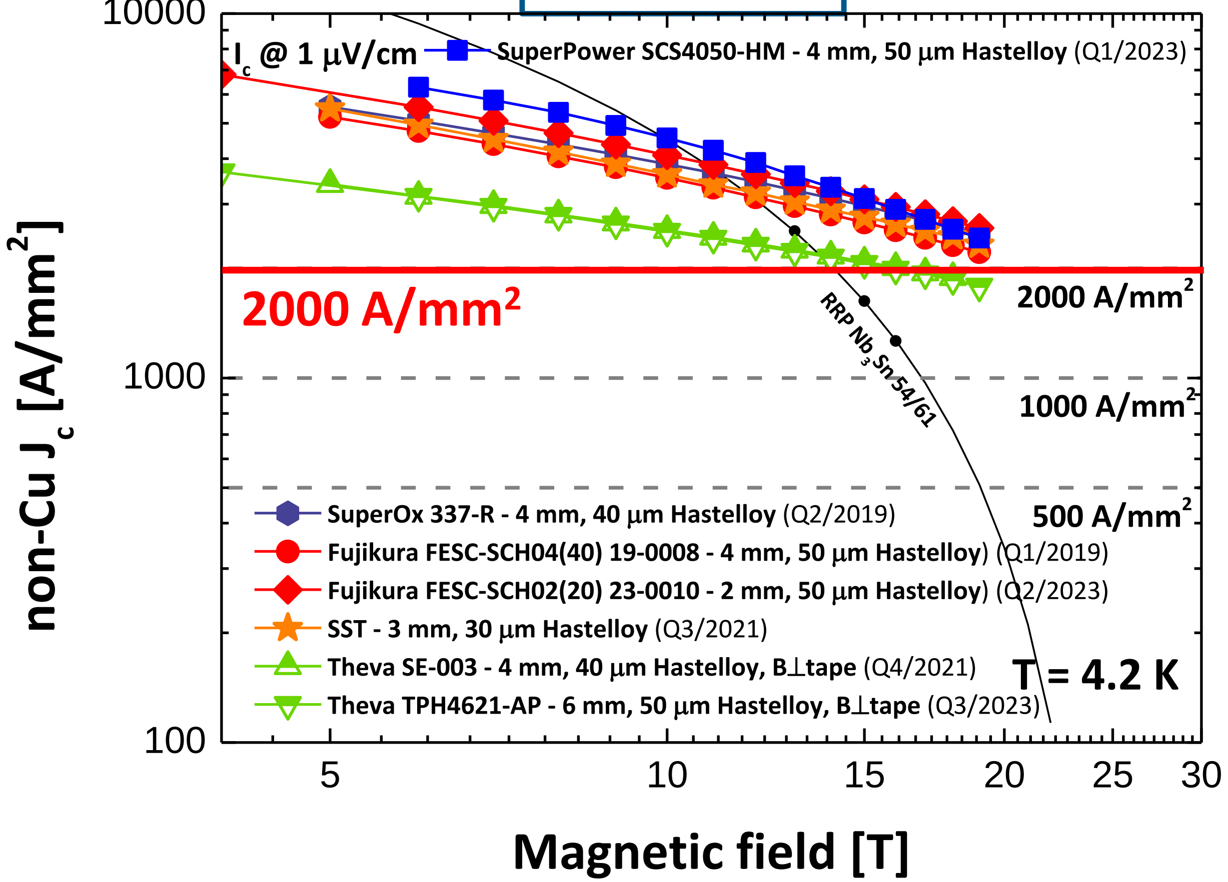
Comparison of the performance: non-Cu J_c

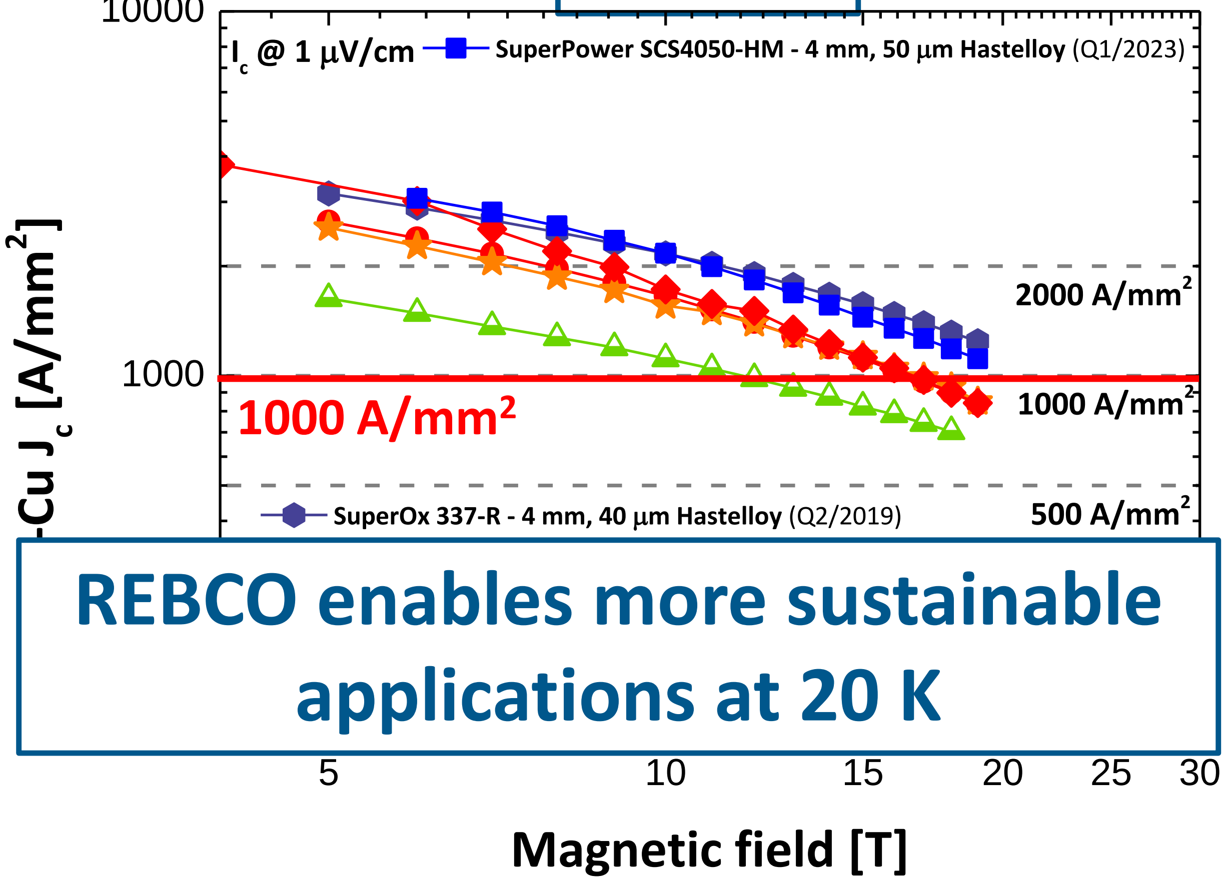
The non-Cu J_c corresponds to the critical current divided by the tape cross-section area minus the Cu area

$$\text{non-Cu } J_c = \frac{I_c}{A_{tot} - A_{Cu}}$$

T = 4.2 K



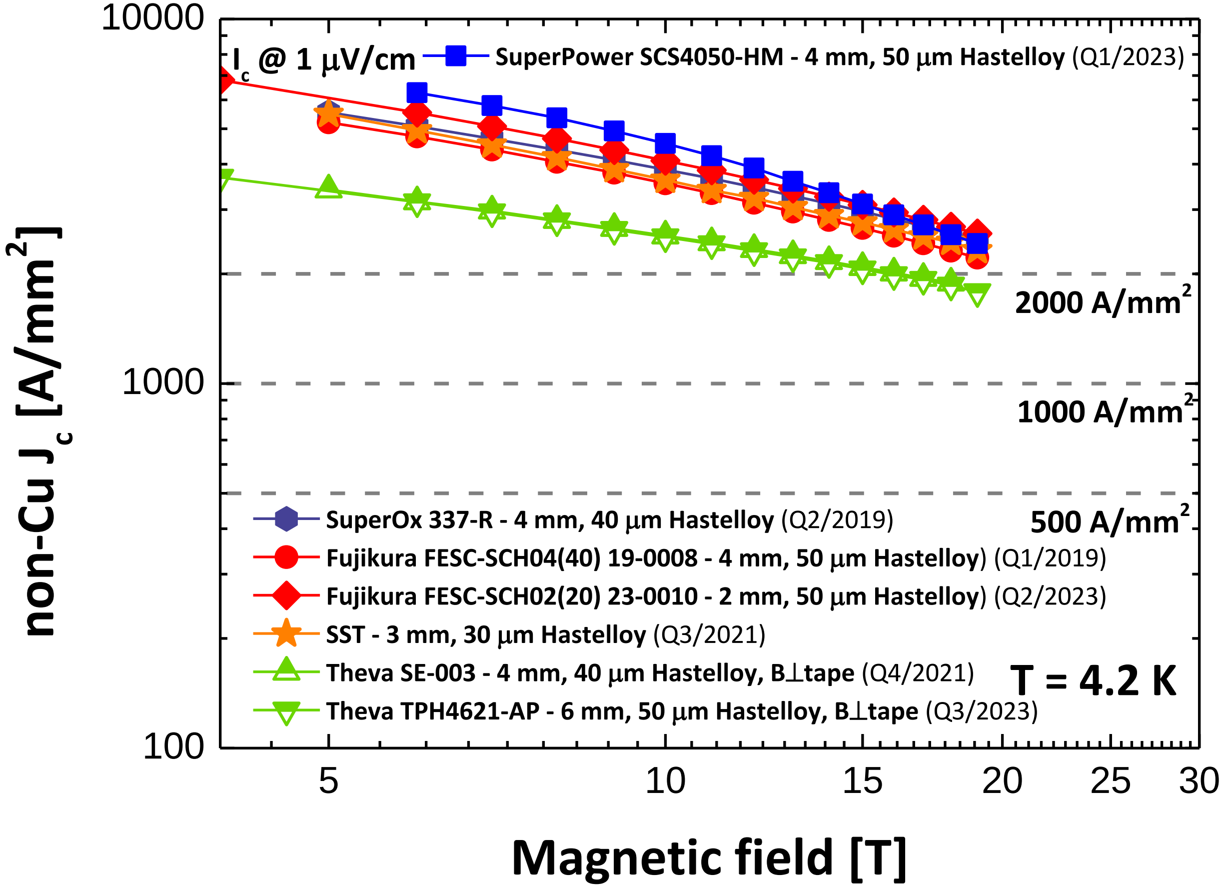
T = 20 K



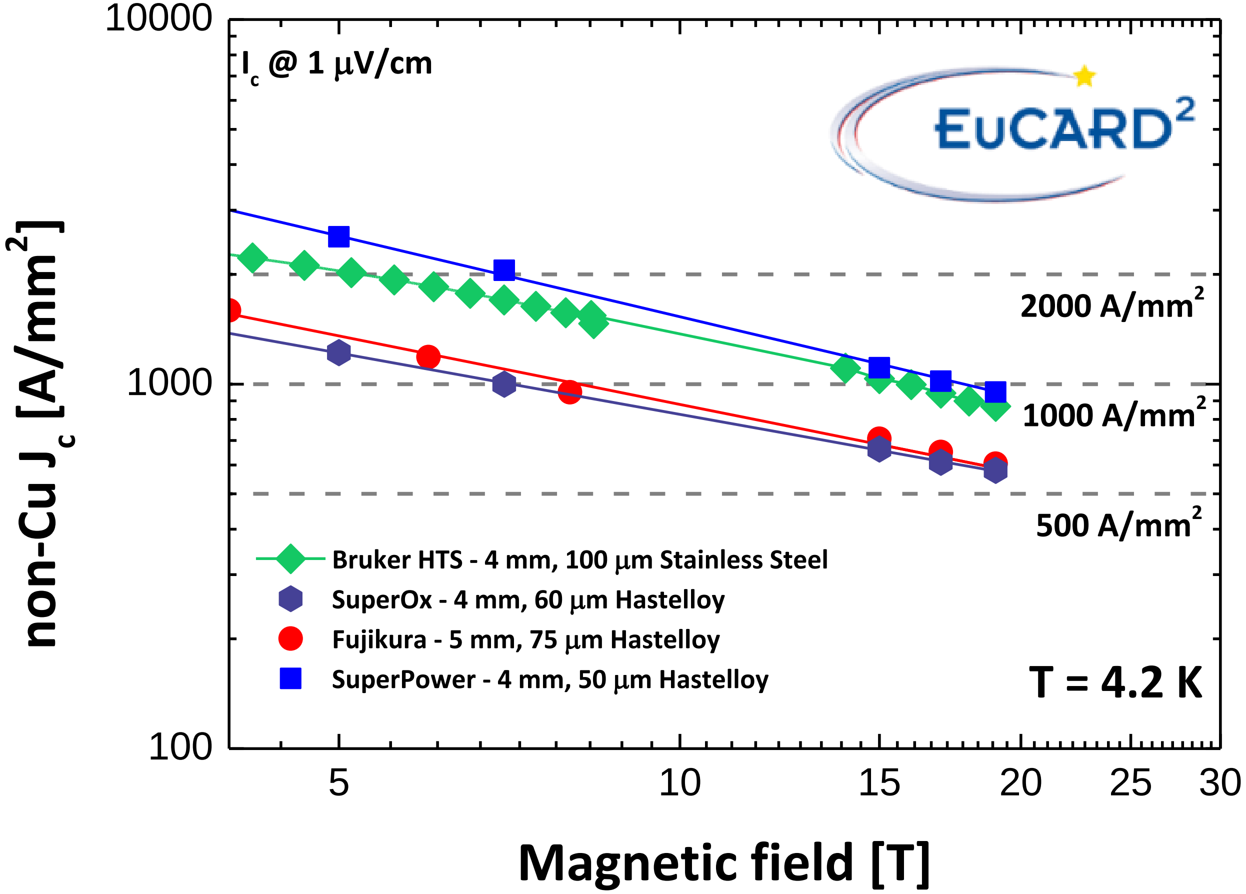
REBCO enables more sustainable applications at 20 K

Evolution of the performance: non-Cu J_c

Tapes procured between 2019 and 2023



Tapes procured between 2013 and 2017



The performance at 4.2 K of the tapes procured during EuCARD² (2013-2017) is achieved and surpassed in modern tapes at 20 K !!

CS , WAMHTS-2

L. Rossi and CS, Instruments, 5 (2021) 8

DOI: 10.3390/instruments5010008

Angular dependence of I_c: very fresh results

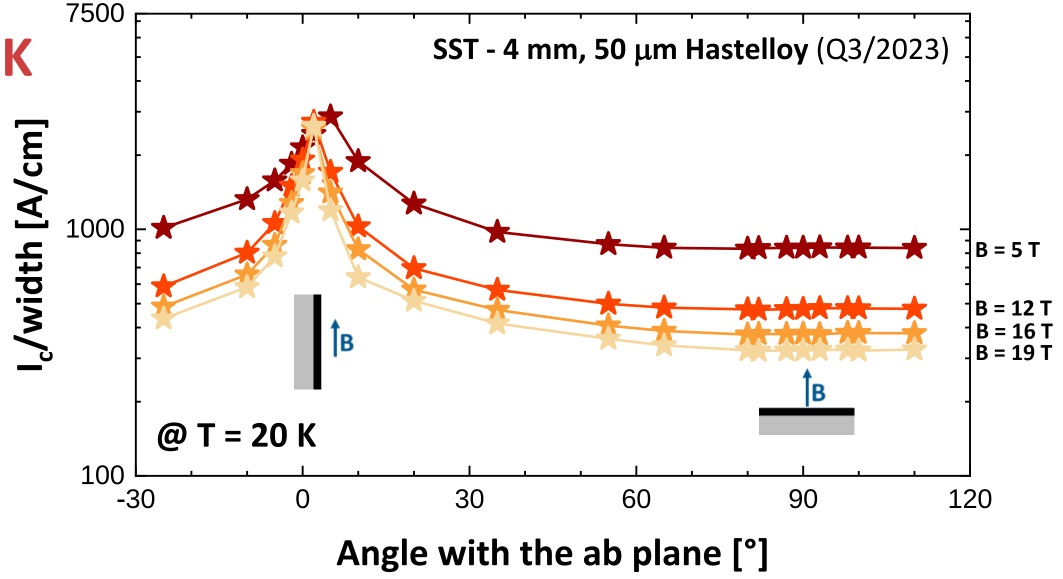
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
TOHOKU UNIVERSITY

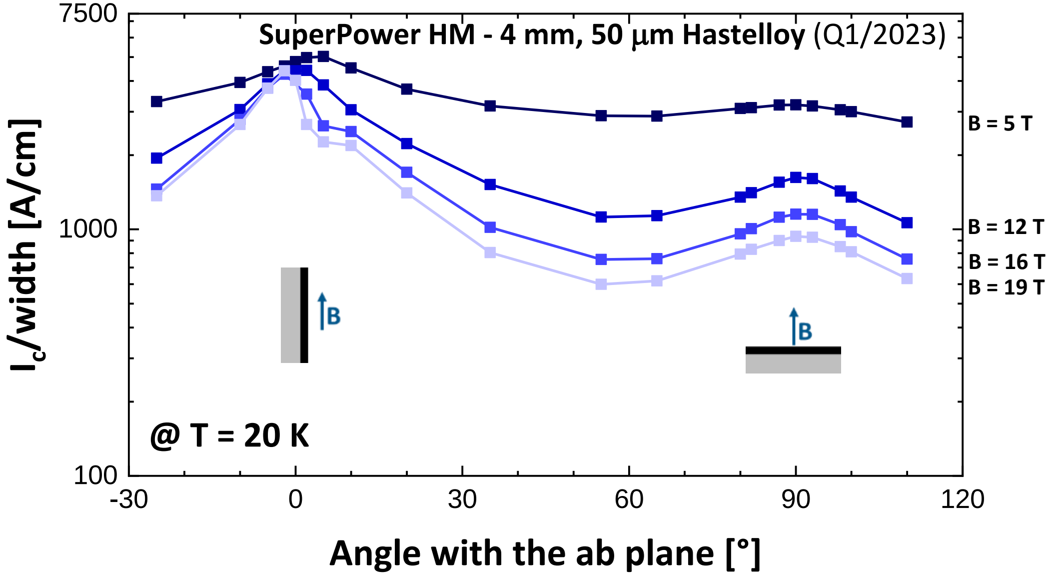
上海超导™ SHANGHAI SUPERCONDUCTOR EuBCO + BHO nanocolumns

SuperPower Inc. A Furukawa Company YBCO + BZO nanocolumns

T = 20 K

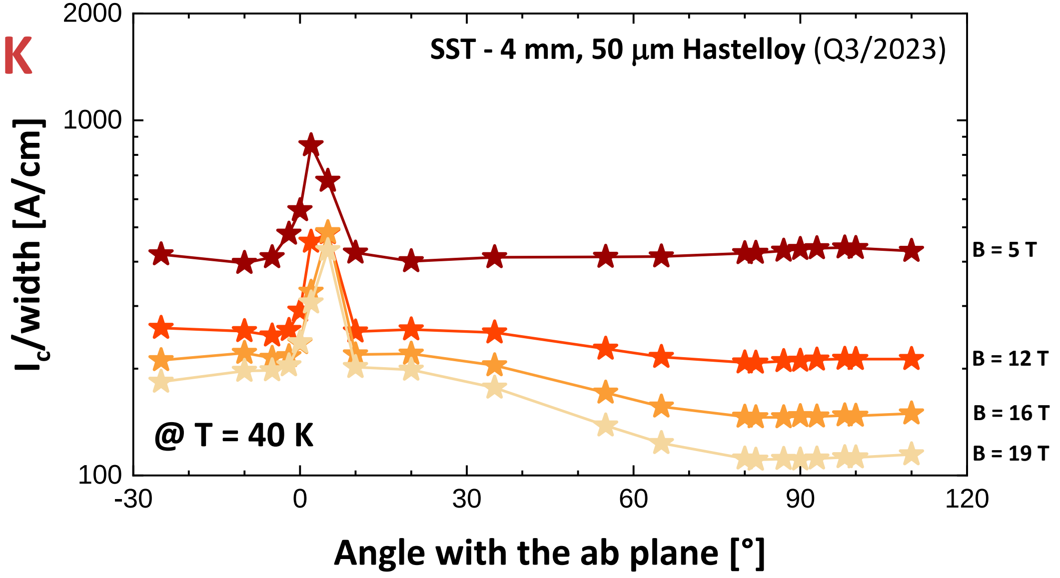
5 T → 19 T

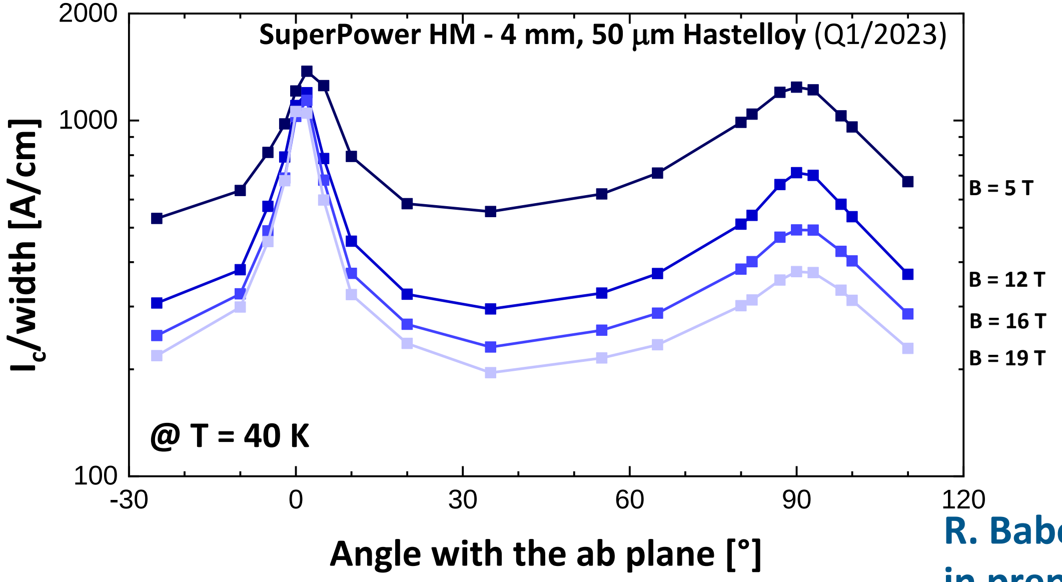




T = 40 K

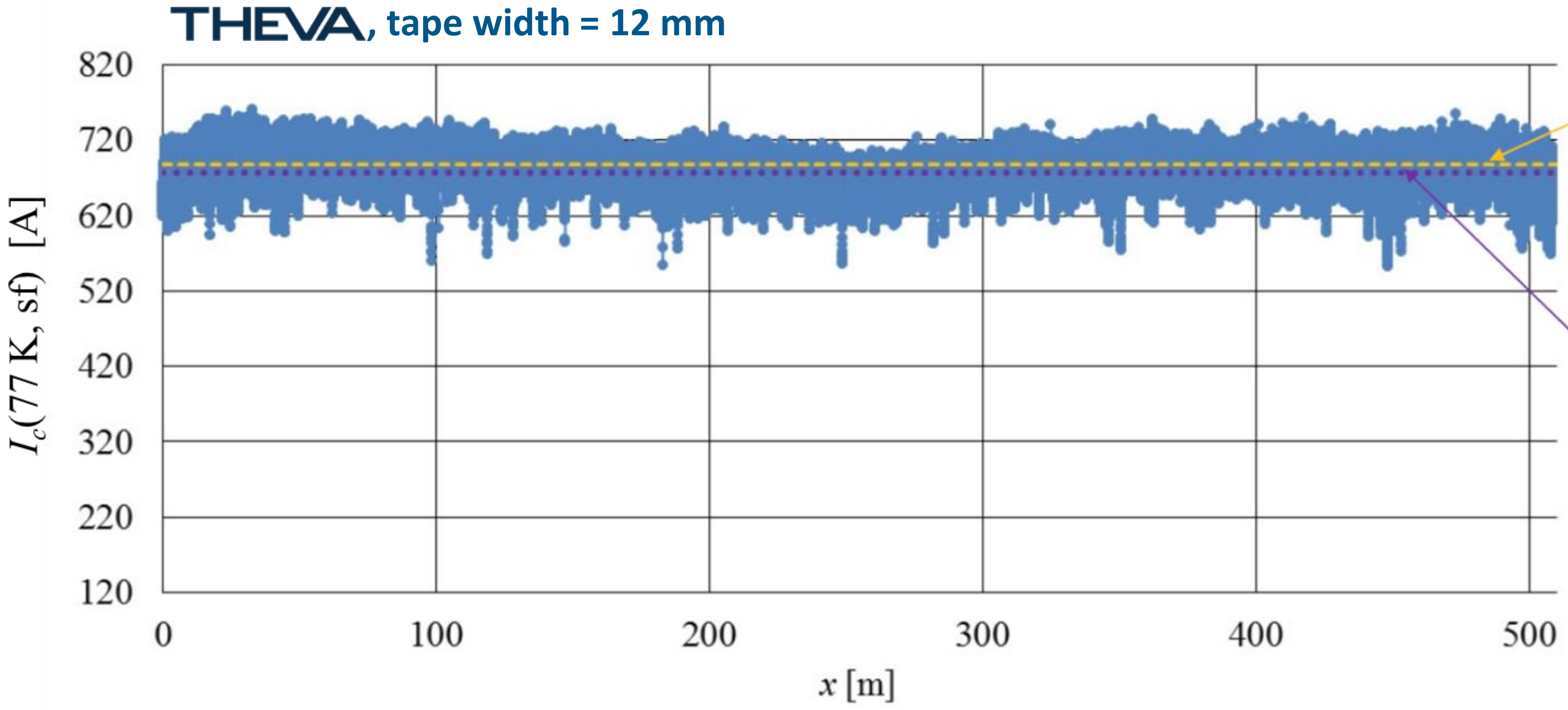
5 T → 19 T





R. Babouche et al., in preparation

(Non-)uniformity of I_c over the length



average value of critical current

$$I_{c,aver} = \frac{\sum_{i=1}^{N} I_{c,i}}{N} = 687\ \text{A}$$

σ = 19 A

overall critical current generating 1 μV/cm on all the tape length

$$I_{c,ovrl} = \left[\frac{N}{\sum_{i=1}^{N}\left(\frac{1}{I_{c,i}}\right)^{n}}\right]^{\frac{1}{n}} = 678\ \text{A}$$

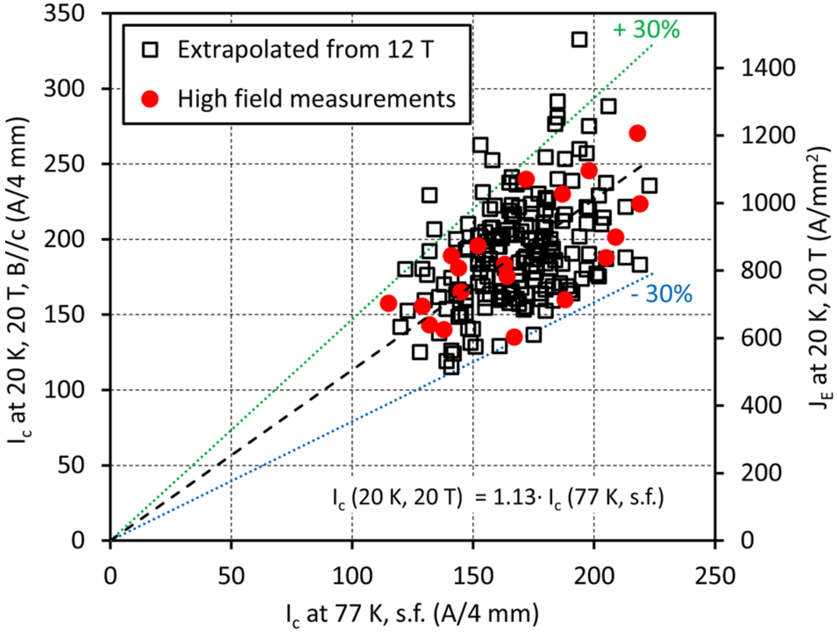
A variation of I_c(77 K,sf) by ± 10% along the length is common, but larger drops may occur locally

F. Gömöry, et al., SuST 36 (2023) 054001
DOI: 10.1088/1361-6668/acb73f

Batch-to-batch variability of REBCO performance

I_c distributions of tapes produced for fusion and for the 32 T magnet at MagLab

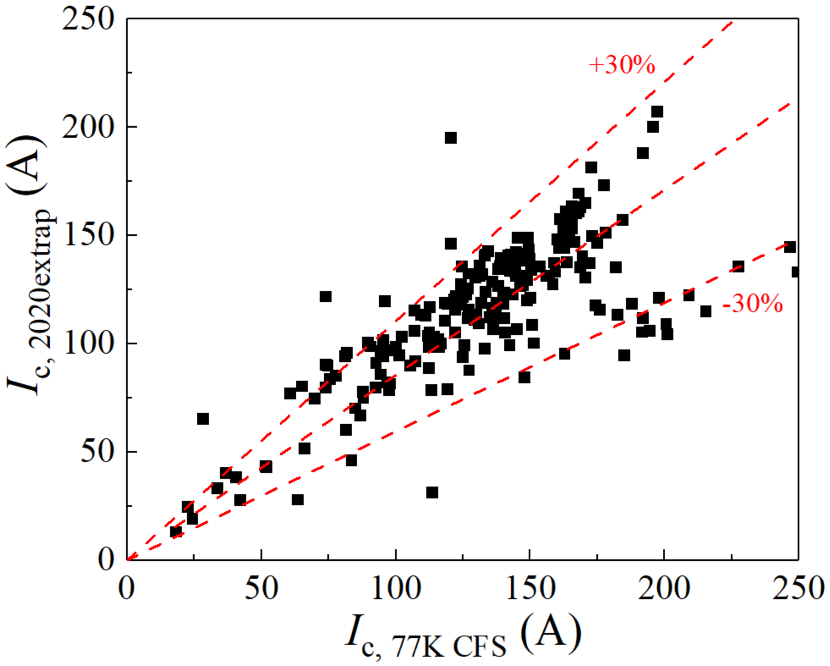
SuperOx FARADAY FACTORY JAPAN



A. Molodyk, et al., Scientific Reports, 11 (2021) 2084

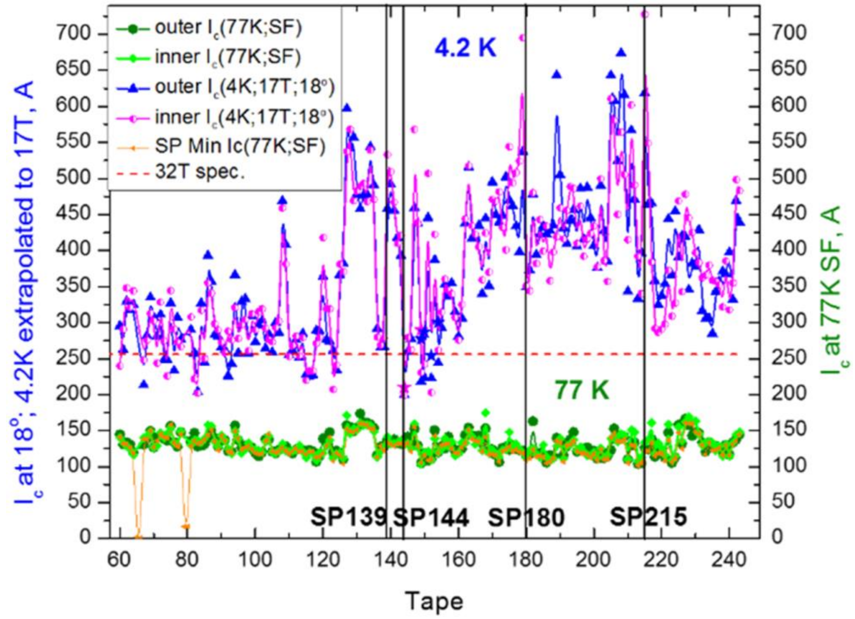
DOI: 10.1038/s41598-021-81559-z

上海超导™ SHANGHAI SUPERCONDUCTOR



B. Song, private communication

SuperPower Inc. A Furukawa Company



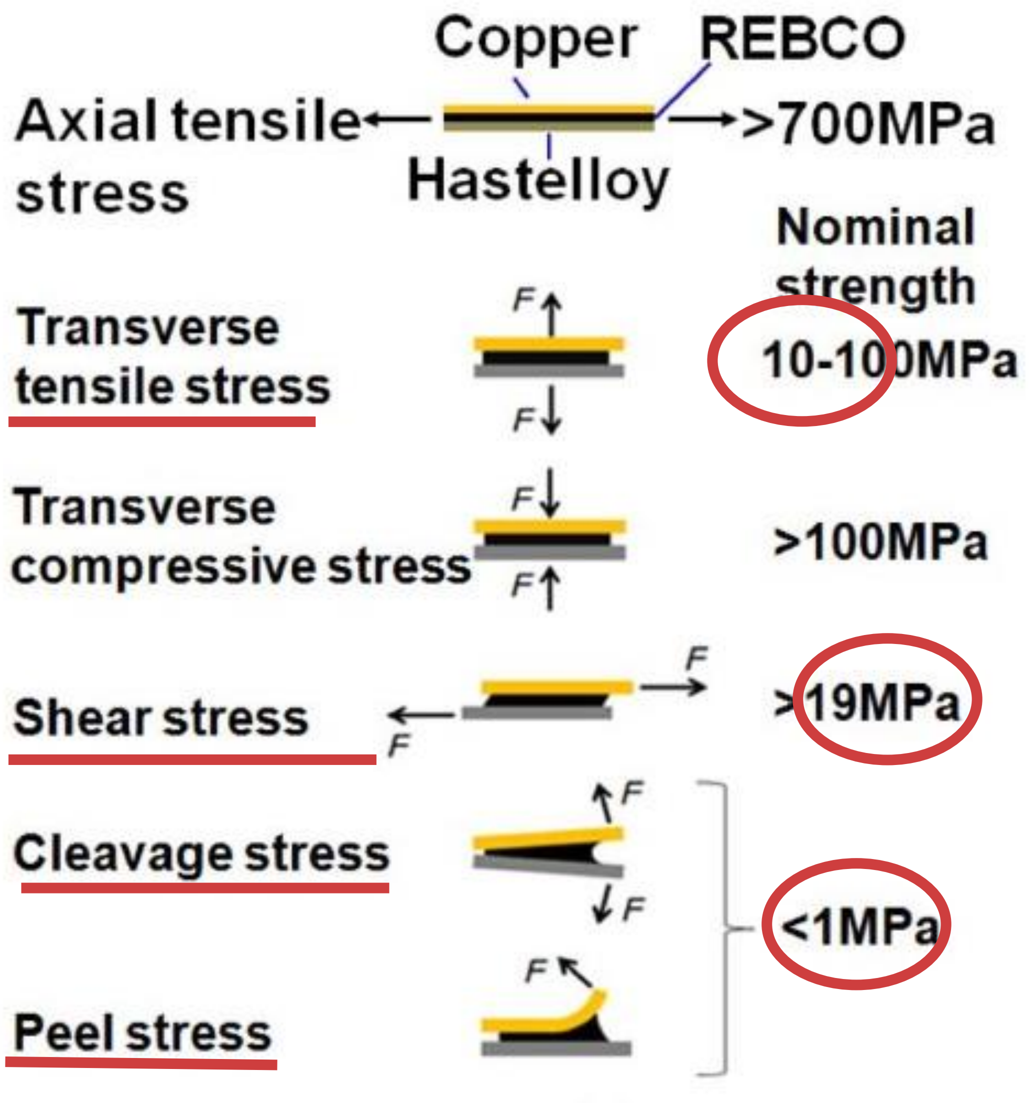
A. Francis, et al., SuST 33 (2020) 044011

DOI: 10.1088/1361-6668/ab73ee

A large variability of the performance at low temperature/high field, about ± 30%, is observed for a given I_c at 77 K, self-field

High in-field J_c is not sufficient for UHF magnets

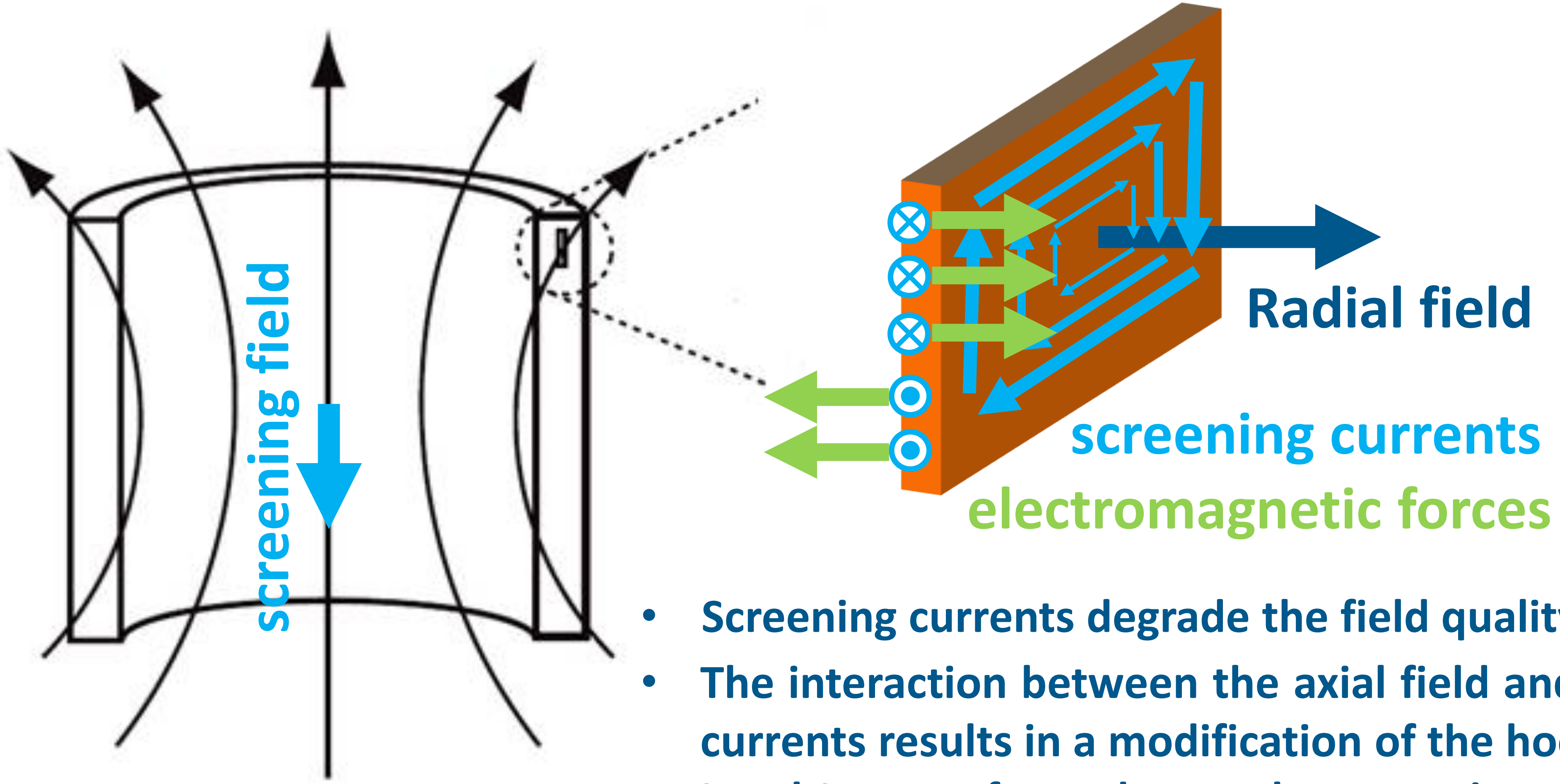
A short note on the mechanical properties



- REBCO tapes are inherently prone to delamination
- Adhesion between layers seems to be process dependent
- A standardized process to determine the properties of the tapes is missing

H. Maeda, and Y. Yanagisawa, IEEE Trans. Appl. Supercond., 24 (2014) 4602412
DOI: 10.1109/TASC.2013.2287707

Screening Currents, Field Quality and Conductor Degradation



- Screening currents degrade the field quality
- The interaction between the axial field and the screening currents results in a modification of the hoop stress
- Local Lorentz force due to the screening currents can be source of delamination force

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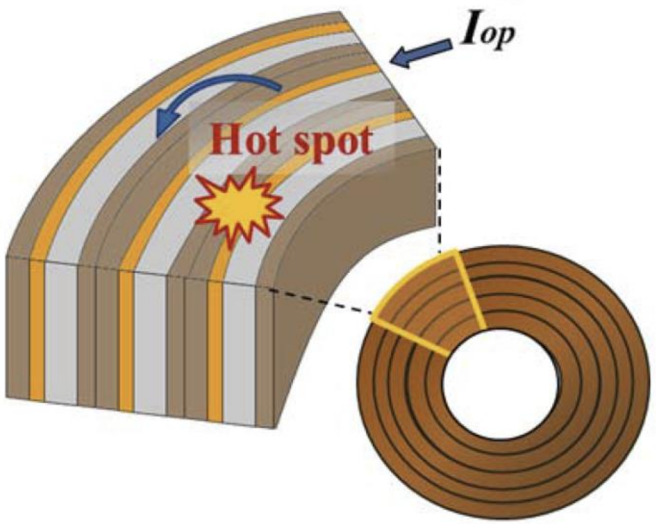
The No-Insulation (NI) winding technique of REBCO coils

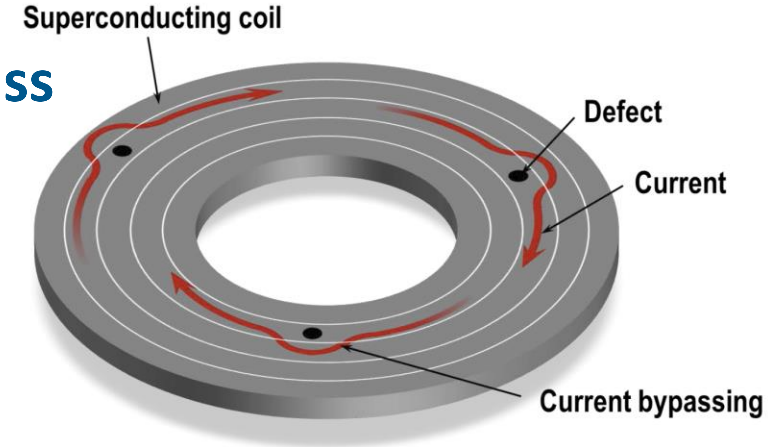
A new paradigm with advantages and drawbacks



Compact winding → very high current density in the winding

Self-protecting → turn-to-turn bypass of quench current
(in principle)

Defect-tolerant → turn-to-turn bypass of current in case of local I_c drop



S. Hahn et al., *IEEE Trans. Appl. Supercond.*, 21 (2011) 1592
DOI: 10.1109/TASC.2010.2093492

U. Bong et al., Supercond. Sci. Technol. 34 (2021) 085003
DOI: 10.1088/1361-6668/ac0759

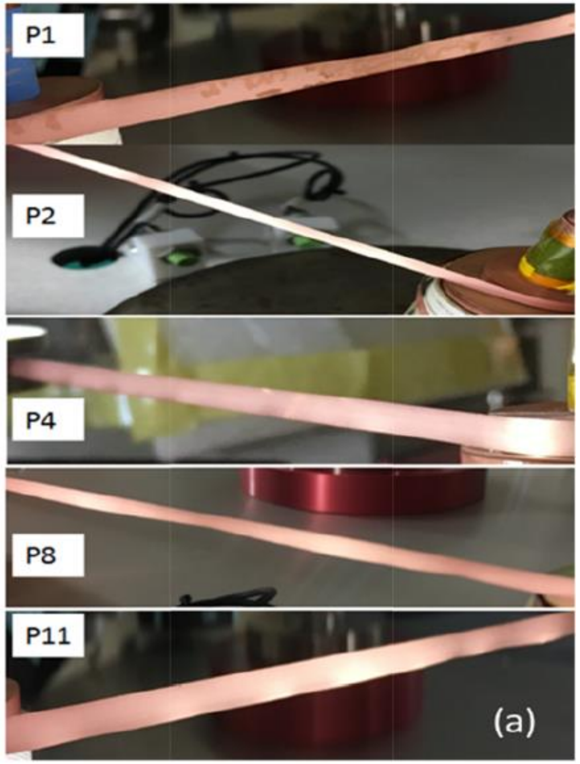
A major drawback comes from the charging delays, which can be mitigated by Partial/Metal/Smart Insulation

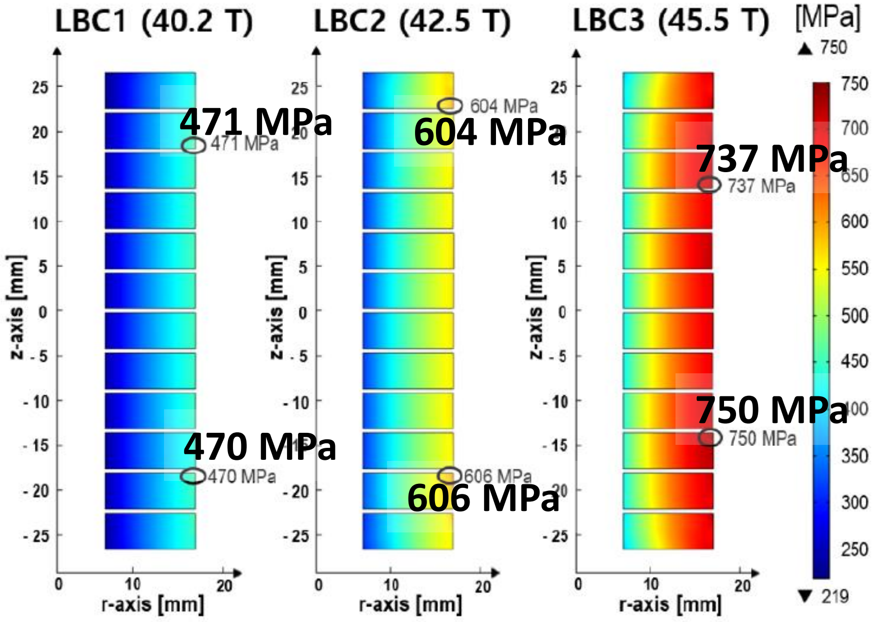
Other known drawbacks: unbalanced forces, induced overstresses

Lesson learned from REBCO magnet R&D

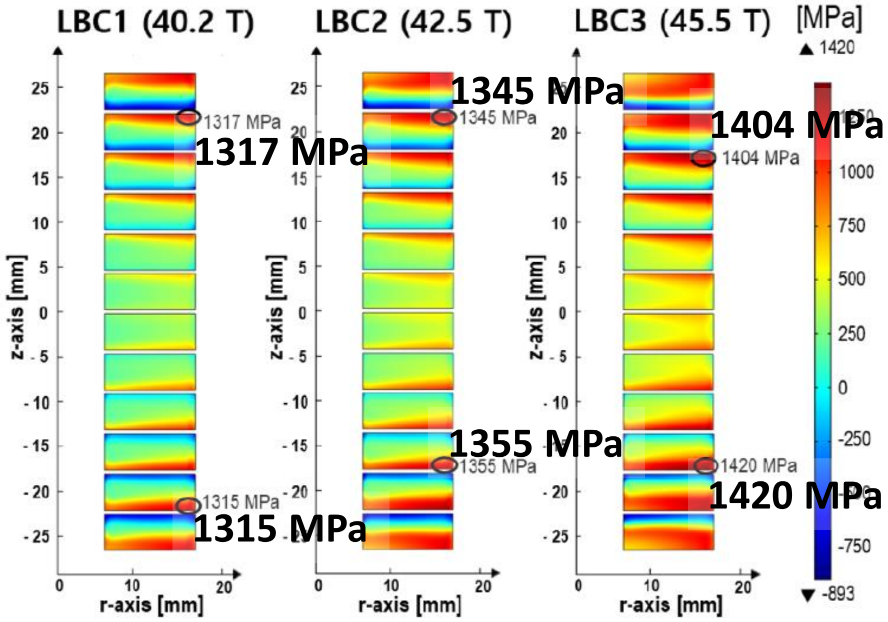
Post-mortem analysis of REBCO tapes from ultra-high field test coils at NATIONAL MAGLAB

Three non-insulated Little Big Coils (35 mm OD, 14 mm ID and 50 mm length) tested in the 37 mm diameter cryostat of the 31 T Bitter magnet at NHMFL





Calculated hoop stress distribution
without screening currents



Calculated hoop stress distribution
with screening currents

Conductor plastic deformation occurs at nominal JBR stress levels below the yield stress of Hastelloy, ~1 GPa @ 4 K

X. Hu *et al.*, SuST 33 (2020) 095012
DOI: 10.1088/1361-6668/aba79d

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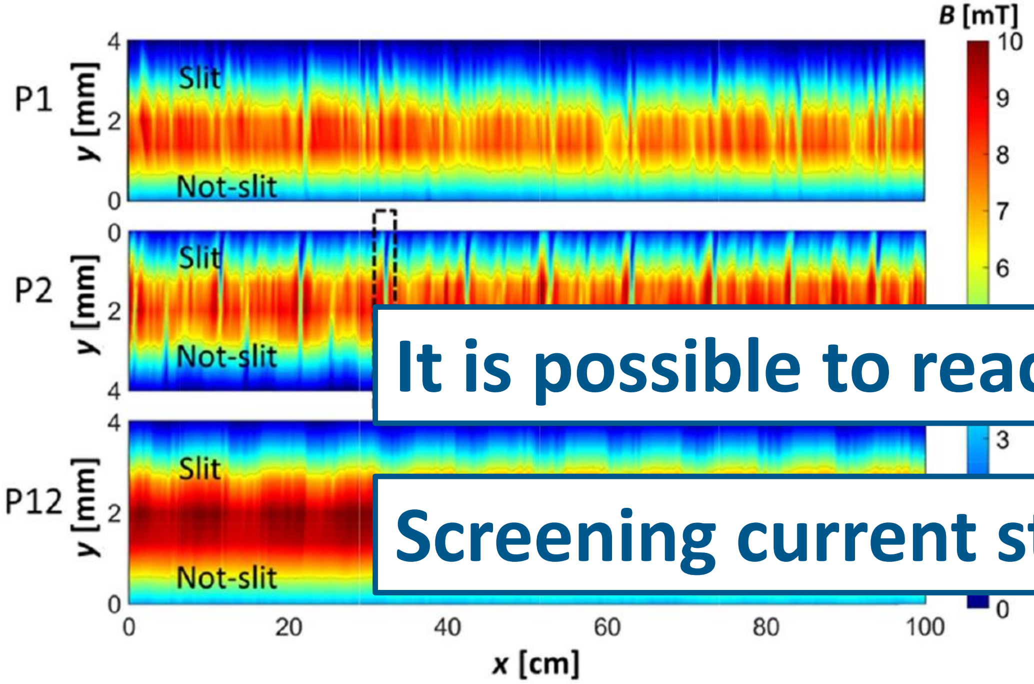


Magnetization maps of tapes extracted from LBC2 with evident signs of degradation

- I_c degradation due to plastic rippling occurs at coils edges
- All degraded edges occur at slit edges containing pre-existing micro-cracks
- Delamination of the REBCO buffer interface is also observed especially when the transport current is flowing along the slit edge

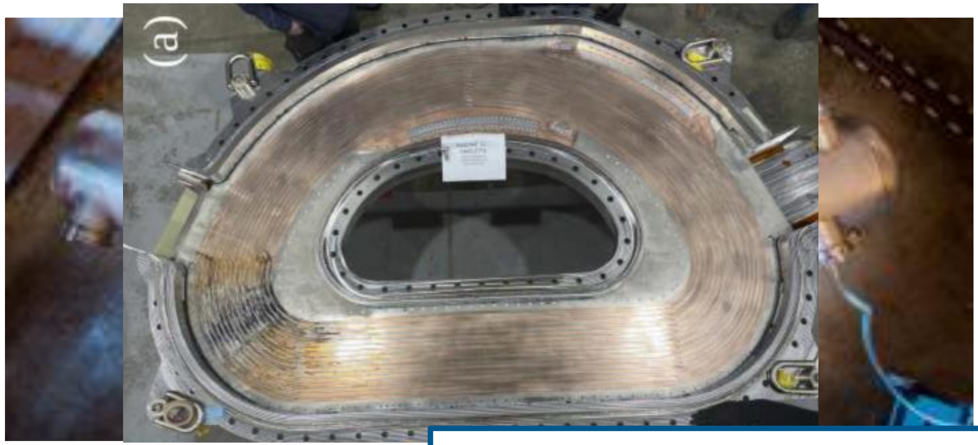
It is possible to reach and exceed 40 T with REBCO

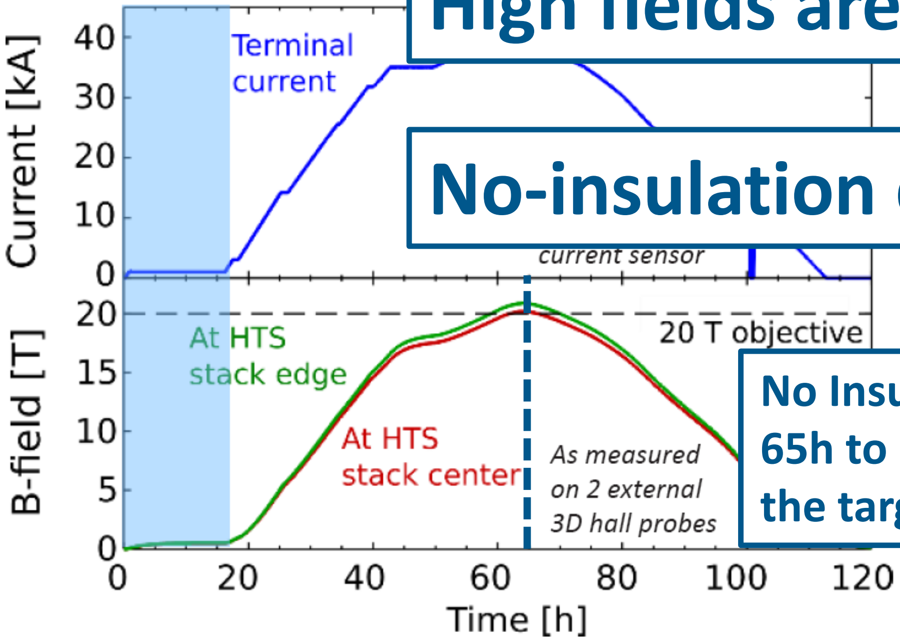
Screening current stresses cannot be neglected

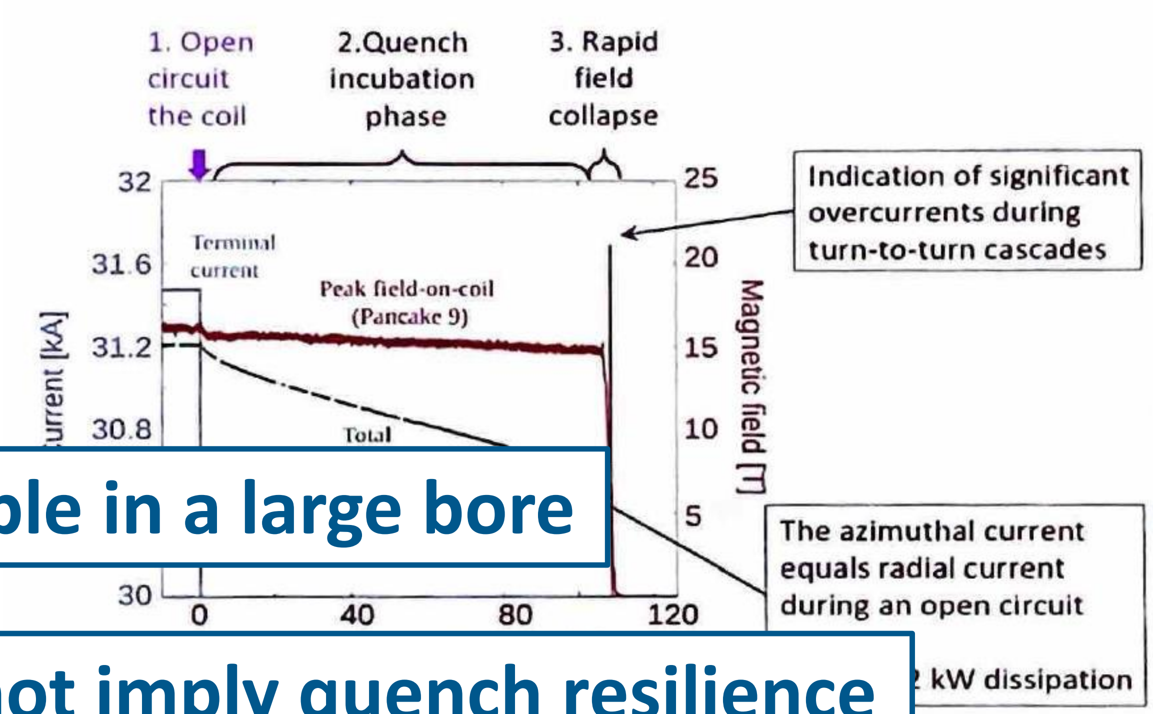
X. Hu *et al.*, SuST 33 (2020) 095012
DOI: 10.1088/1361-6668/aba79d

Lesson learned from REBCO magnet R&D

The quench test of the 20 T/ 20 K no-insulation SPARC Toroidal Field Model Coil







High fields are possible in a large bore

No-insulation does not imply quench resilience

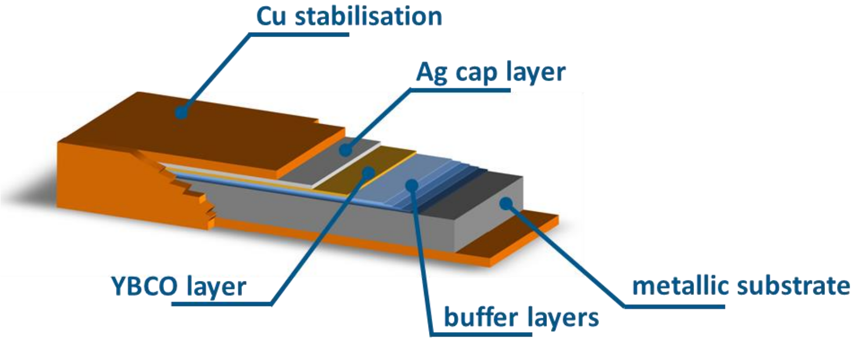
No Insulation: 65h to reach the target field

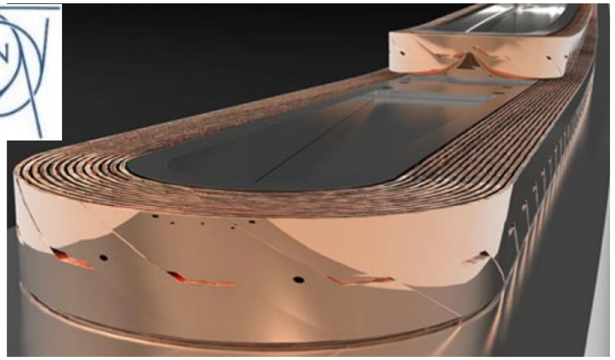
Quench test **at 31.3 kA** in open-circuit conditions

- **Coil did not survive**
- **Localized energy deposition at levels high enough to damage the coil**

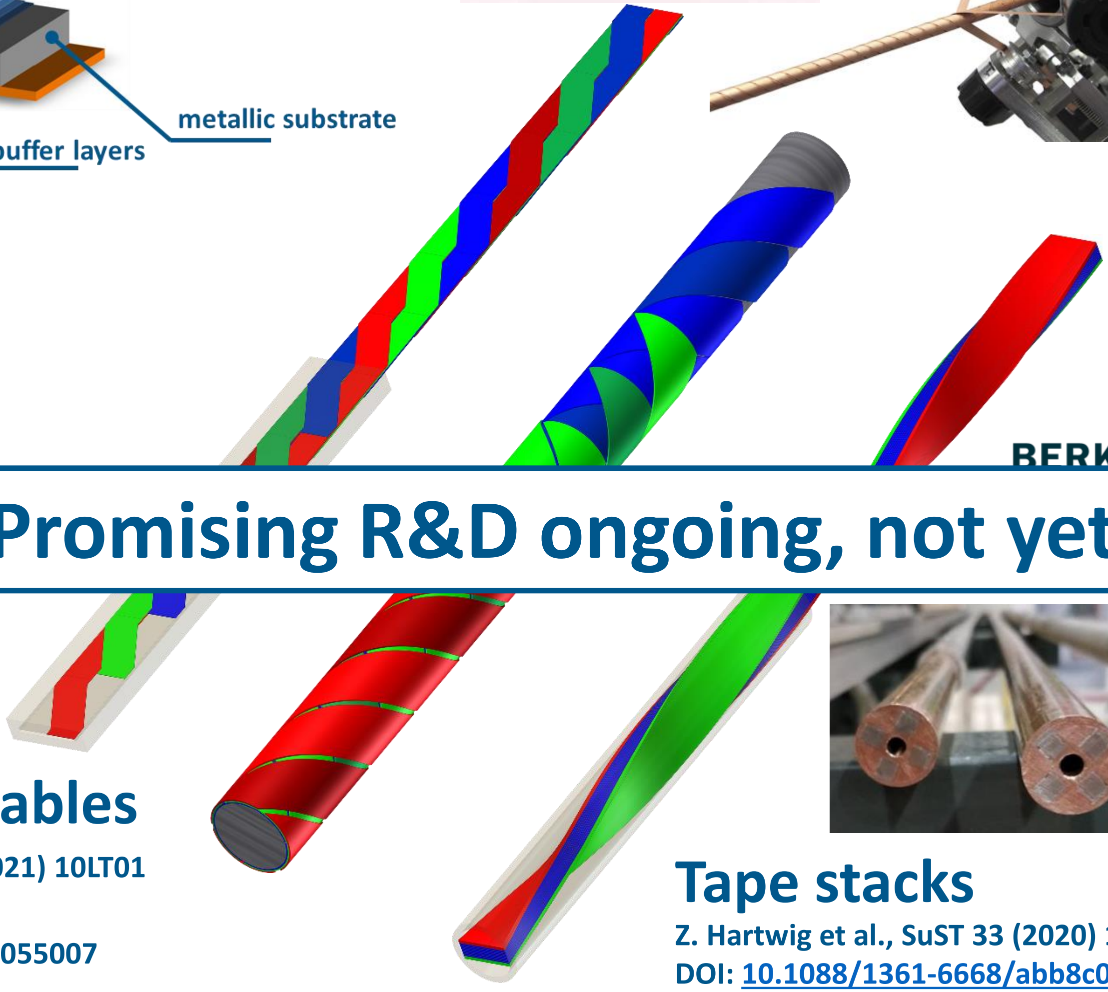
Z. Hartwig et al., IEEE TASC 34 (2024) 0600316
DOI: 10.1109/TASC.2023.3332613

From REBCO tapes to REBCO-based dipole magnets





Aligned block with Roebel cables



Roebel cables

W. Goldacker et al., SuST 27 (20
DOI: 10.1088/0953-2048/27/9/

Promising R&D ongoing, not yet consolidated solutions

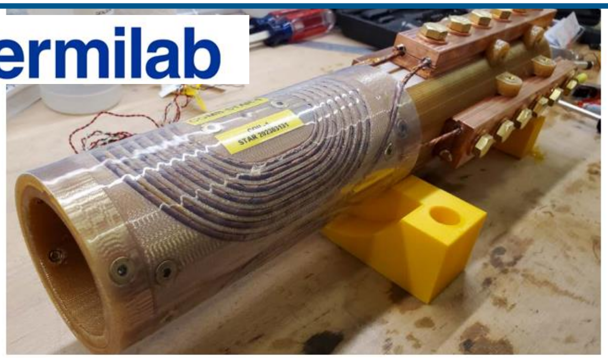
CORC and STAR cables

D. Van der Laan et al., SuST 34 (2021) 10LT01
DOI: 10.1088/1361-6668/ac1aae

E. Galstyan et al., SuST 36 (2023) 055007
DOI: 10.1088/1361-6668/acc4ed

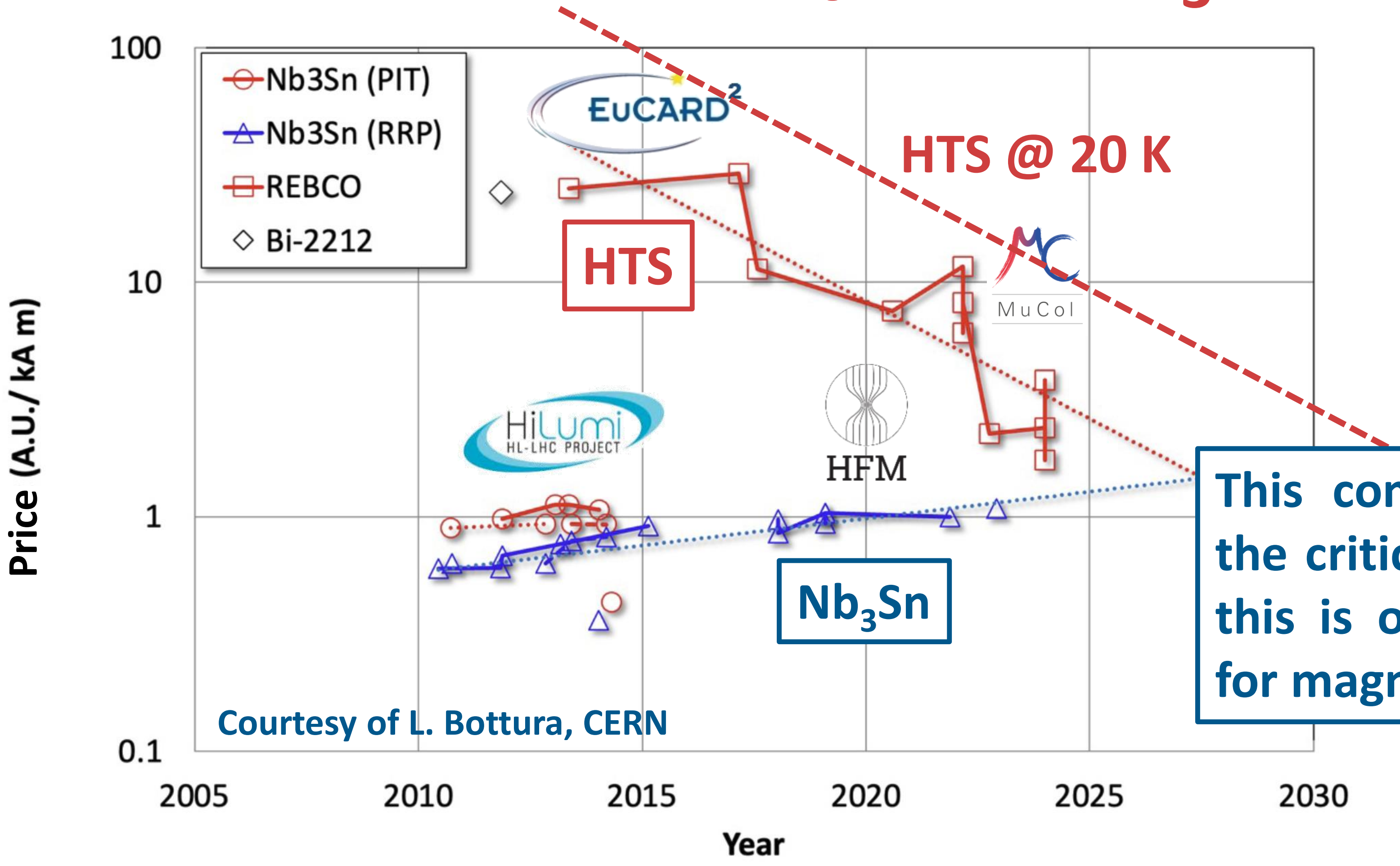
Tape stacks

Z. Hartwig et al., SuST 33 (2020) 11LT01
DOI: 10.1088/1361-6668/abb8c0



COMB with CORC cables

Some considerations on price: Nb_3Sn vs REBCO



This comparison is based only on the critical current performance but this is only one of the parameters for magnet applications

Price (arbitrary units) per unit length and current for Nb_3Sn and HTS (mainly REBCO), based on CERN orders and requests

The normalization is done for B = 12 T (// c-axis for REBCO) and T = 4.2 K

Conclusions

- HTS have a proven potential for higher operating fields and/or higher operating temperatures compared to LTS
- REBCO is becoming available at affordable prices from multiple sources, driven by private fusion programs.
- The performance gap between various manufacturers is relatively small in spite of the differences in process, composition and pinning landscape.
- There is no urgent need for further developments of the transport properties. R&D efforts should be oriented towards other properties: homogeneity, delamination strength, internal resistance, ac loss.
- There is still much to learn about using REBCO in magnets. Challenges include tape geometry, intrinsic anisotropy, mechanics, and large filament size.
- No major roadblocks have emerged so far, but there is still a long way to close the technology gap with LTS magnets. If we maintain momentum, breakthroughs will come.

Thank you for the attention !

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DOI:

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IEEE Trans. Appl. Supercond., 33 (2023) 8800106

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M. Bonura, C. Barth, A. Joudrier, J. Ferradas Troitino , A. Fête, and C. Senatore

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IEEE Trans. Appl. Supercond., 29 (2019) 6600305

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DOI: 10.1021/acsaelm.2c00065

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Instruments, 5 (2021) 8
DOI: 10.3390/instruments5010008

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IEEE Trans. Appl. Supercond., 28 (2018) 9500206

DOI: 10.1109/TASC.2018.2794199