Laboratoire de
Supraconductivité et
Magnétisme

POLYTECHNIQUE
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High Temperature Superconductor (HTS) magnets for particule accelerators

Prof. Frédéric Sirois and collaborators

Laboratory of Superconductivity and Magnetism (LSM)

Polytechnique Montréal, Montréal, QC, Canada

CAP Conference, Ottawa, June 21-26, 2026

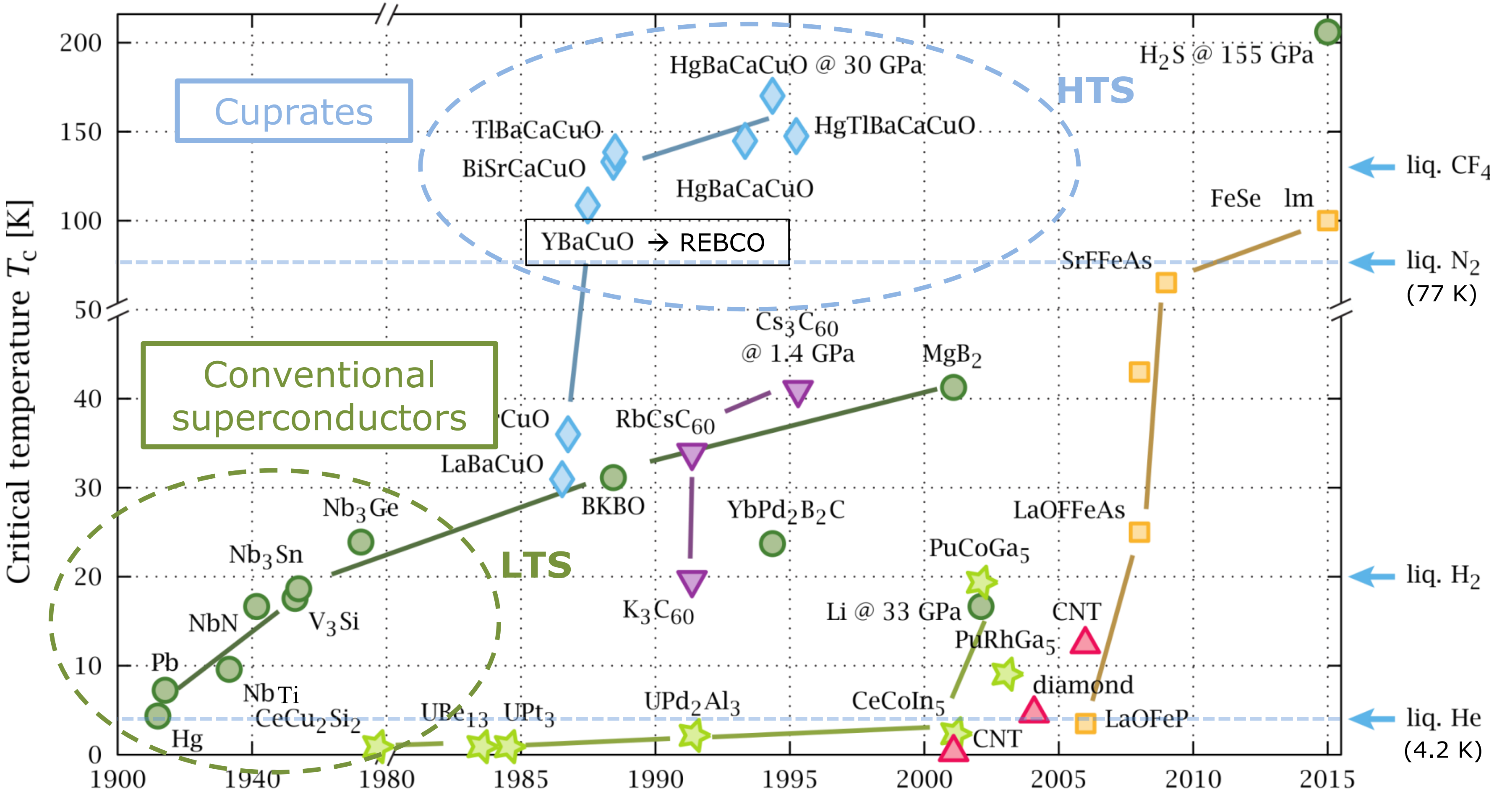
INTRODUCTION

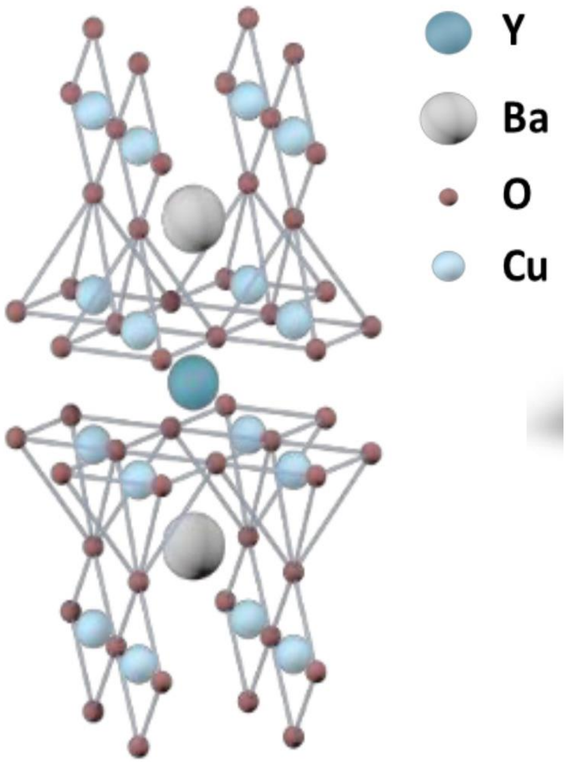
- Particle accelerators: essential tool in modern physics research
- Magnets (copper or superconductor): essential components of particle accelerators
- High-energy beams require **high-field magnets** for reasonable accelerator footprint
  - Low Temperature Superconductor (LTS) technology has nearly reached its limits
    - NbTi technology: fully mature and industrialized, **rely on LHe**, **field <8 T**
    - Nb_3Sn technology: mature but limited industrialization, **rely on LHe**, **field <16 T**
  - High Temperature Superconductor (HTS) technology
    - **REBCO[*] tape technology**: industrialization ramping up, **magnet technology still in its infancy**
    - **Immense potential for very high-field magnets (>16 T) and LHe-free magnets**
- **Energy efficiency** and **helium supply** are key aspects to consider in future projects

[*] REBCO = Rare-Earth-Barium-Copper-Oxide

FAMILIES OF SUPERCONDUCTORS

Source: https://commons.wikimedia.org/wiki/File:Timeline_of_Superconductivity_from_1900_to_2015.svg



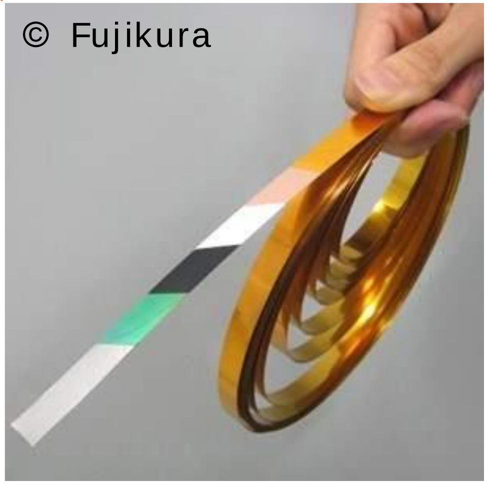


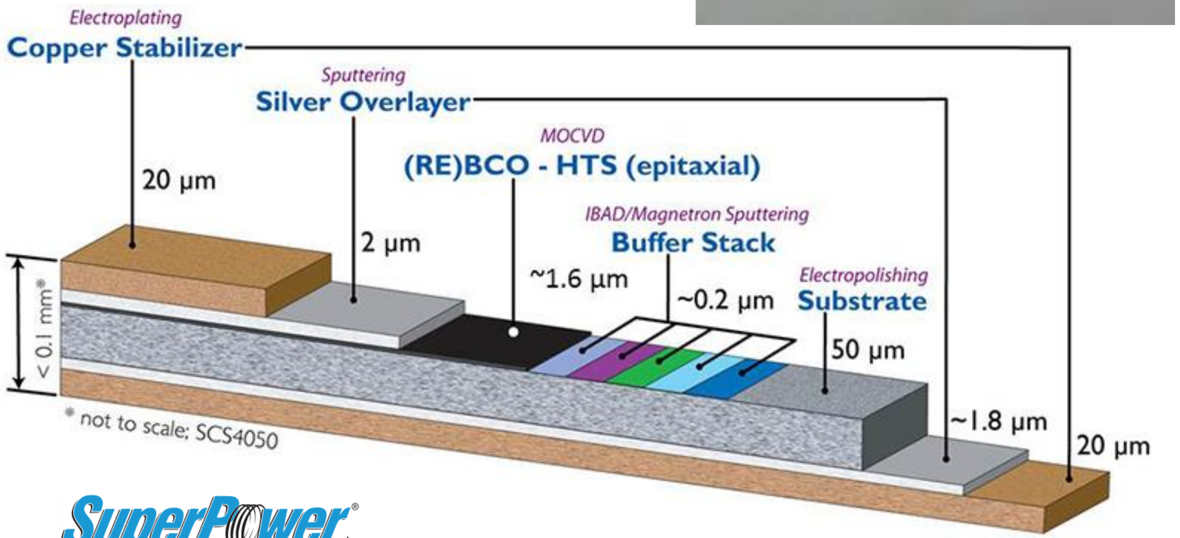
RE: Rare Earth (Y, Sm, Dy, Gd, …)

LTS/HTS: Low/High Temperature Superconductor

SUPERCONDUCTING WIRES: HOW DO THEY LOOK LIKE?

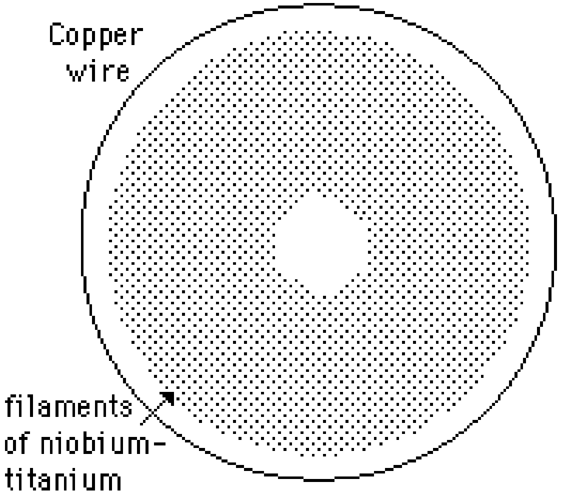
- REBCO technology (HTS tapes)
  - Flexible but anisotropic ribbon
  - Sophisticated thin film deposition techniques (PLD, MOCVD, …)

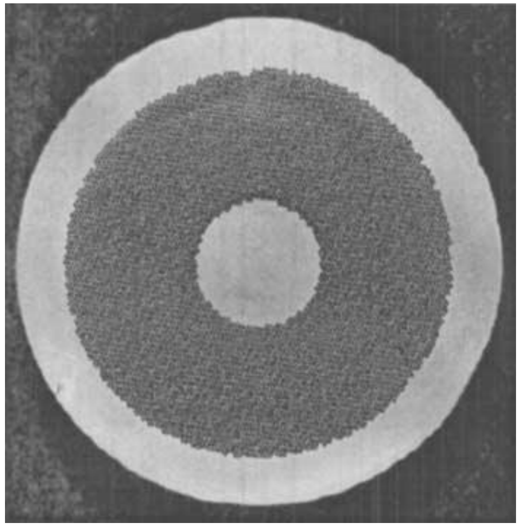




SuperPower Inc.

- NbTi technology (LTS wires)
  - Flexible multifilamentary metallic wire
  - Produced by conventional drawing methods





Source: http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/scmag.html

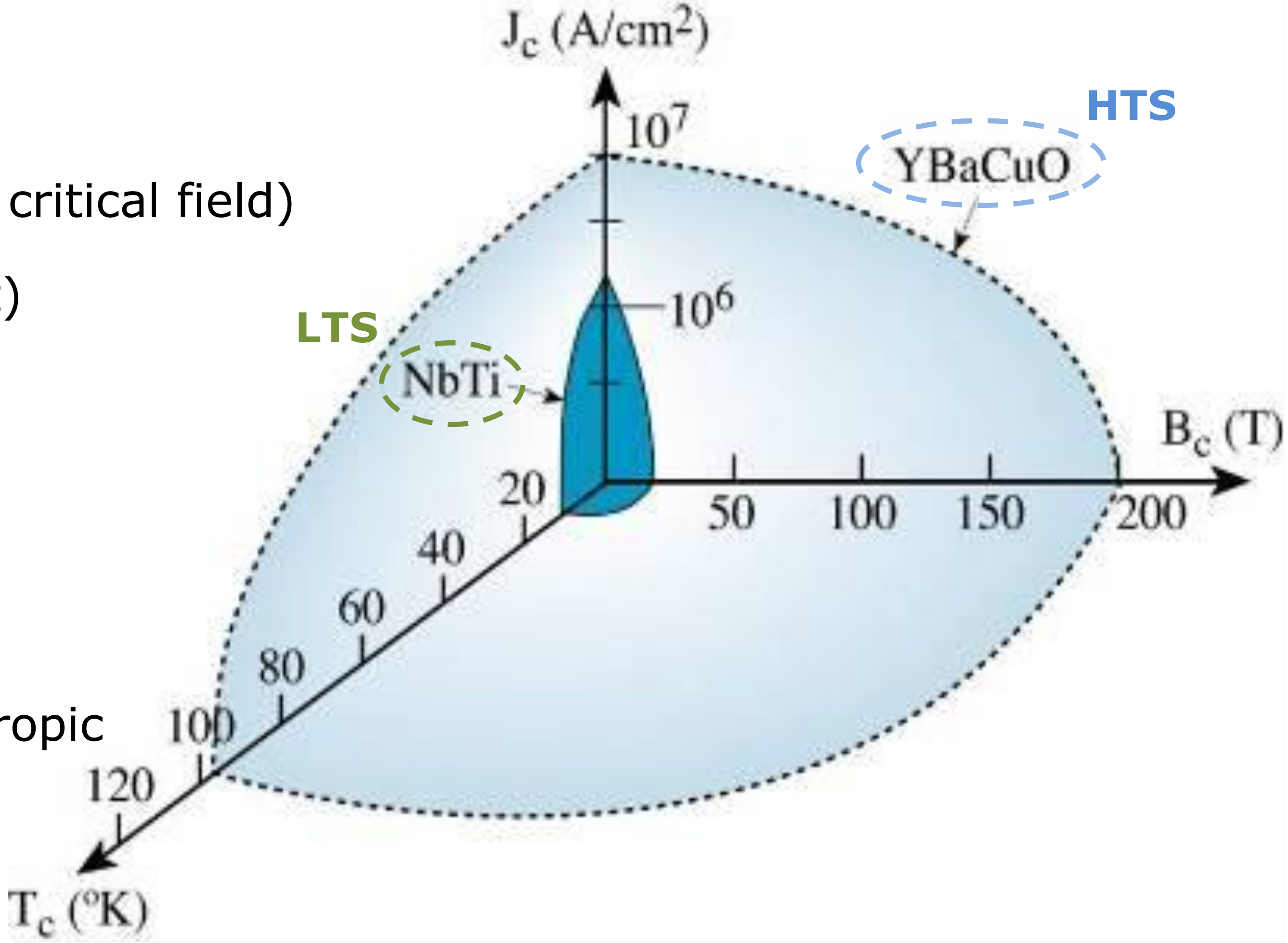
CRITICAL SURFACES (J_c = CRITICAL CURRENT DENSITY)

- Superconductivity is lost when
  - ***T* > *T*$_c$** (this is what everyone knows)
  - $B > B_{c2}$ (B_c = flux density, B_{c2} = upper critical field)
  - $J > J_c$ (reality is more subtle than that)

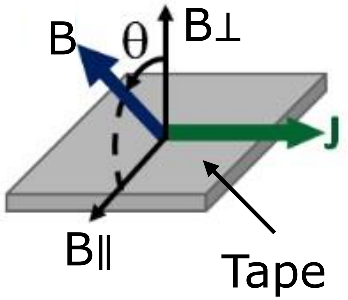
- Note that
  - J_c = f(B,T)

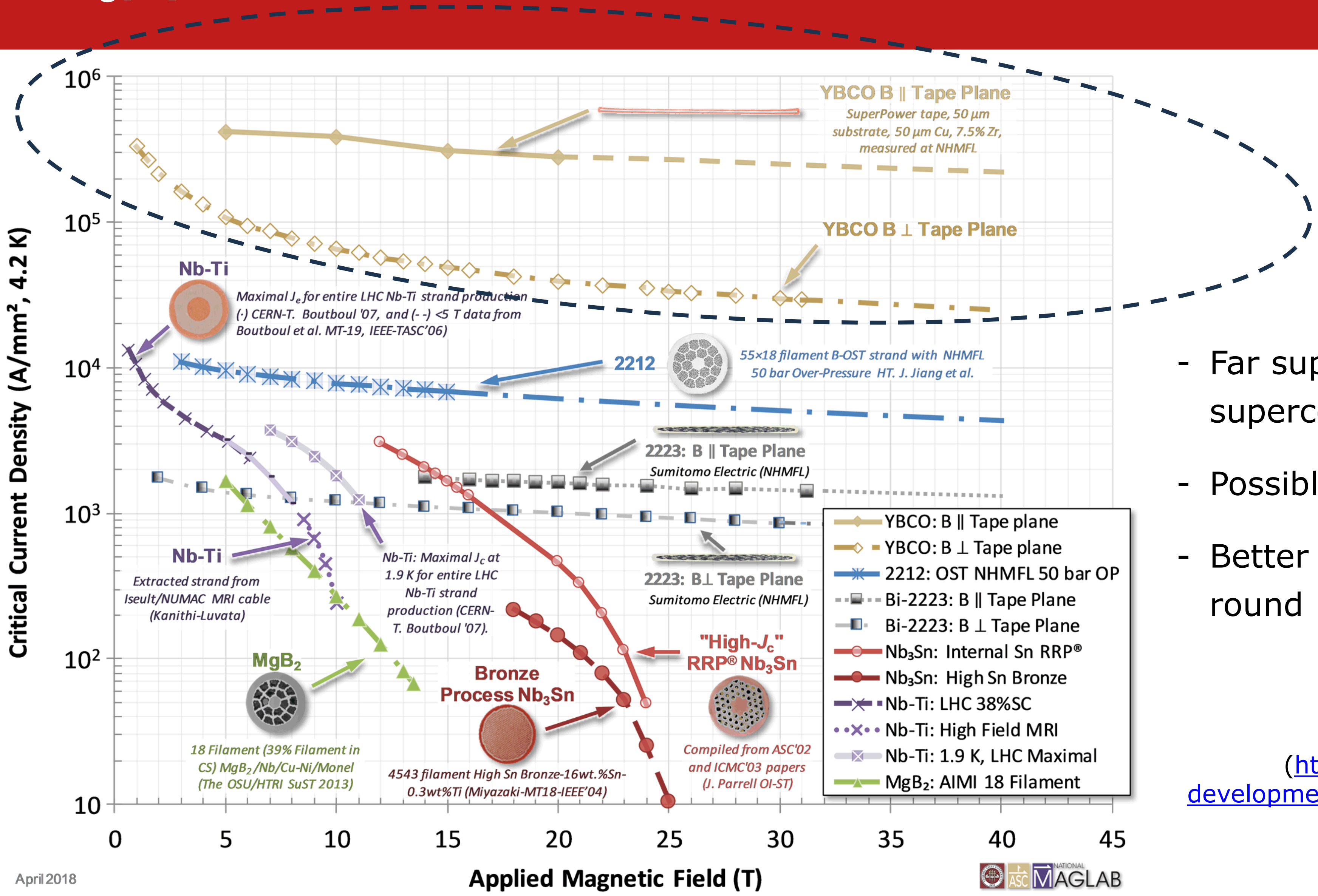
    → J_c decreases with B and T
  - B dependence of REBCO is very anisotropic

    → angle between B and J matters



$J_C(B)$ FOR DIFFERENT SUPERCONDUCTOR MATERIALS AT 4.2 K





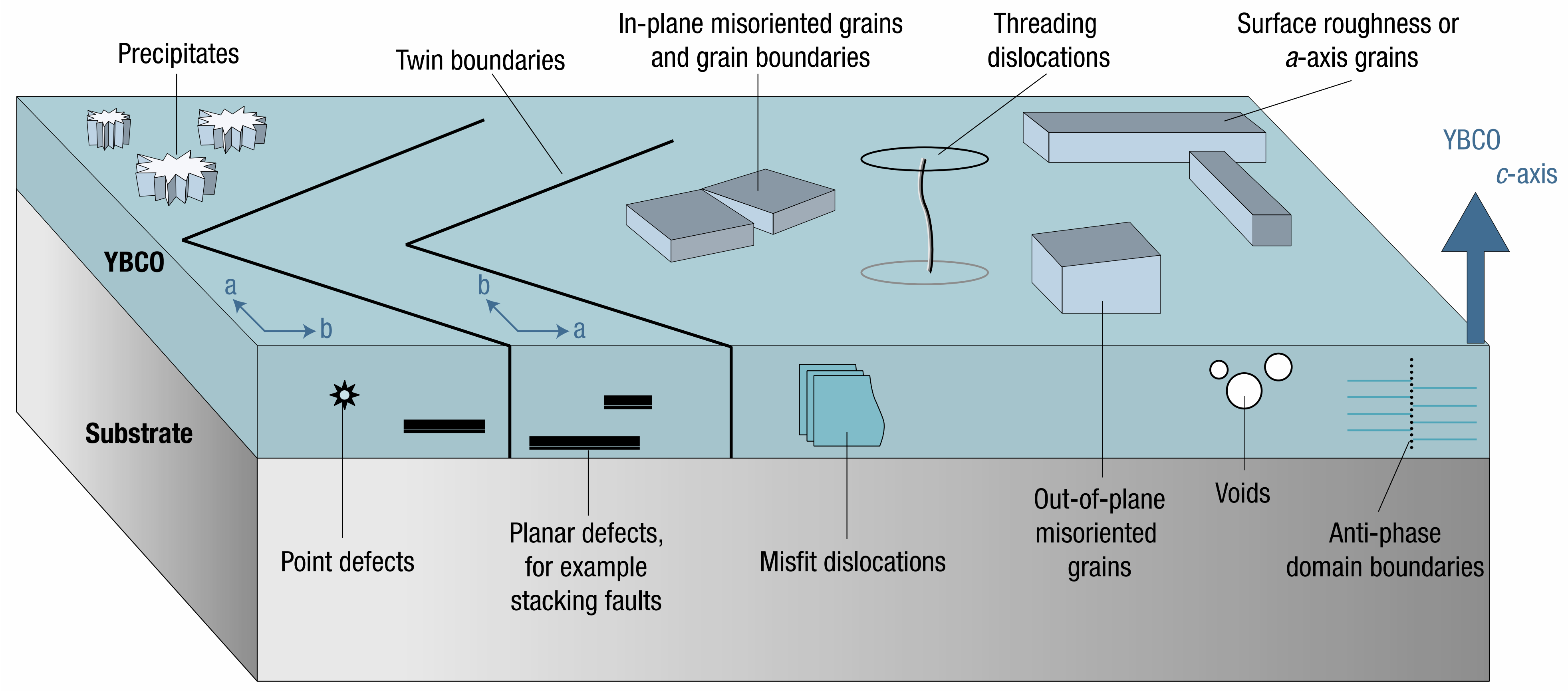
Intrinsic properties of REBCO tapes:

- Far superior to that of any other superconducting material
- Possible to go beyond 20 T with high J_c
- Better than Bi-2212 (Ag-based isotropic round HTS wire)

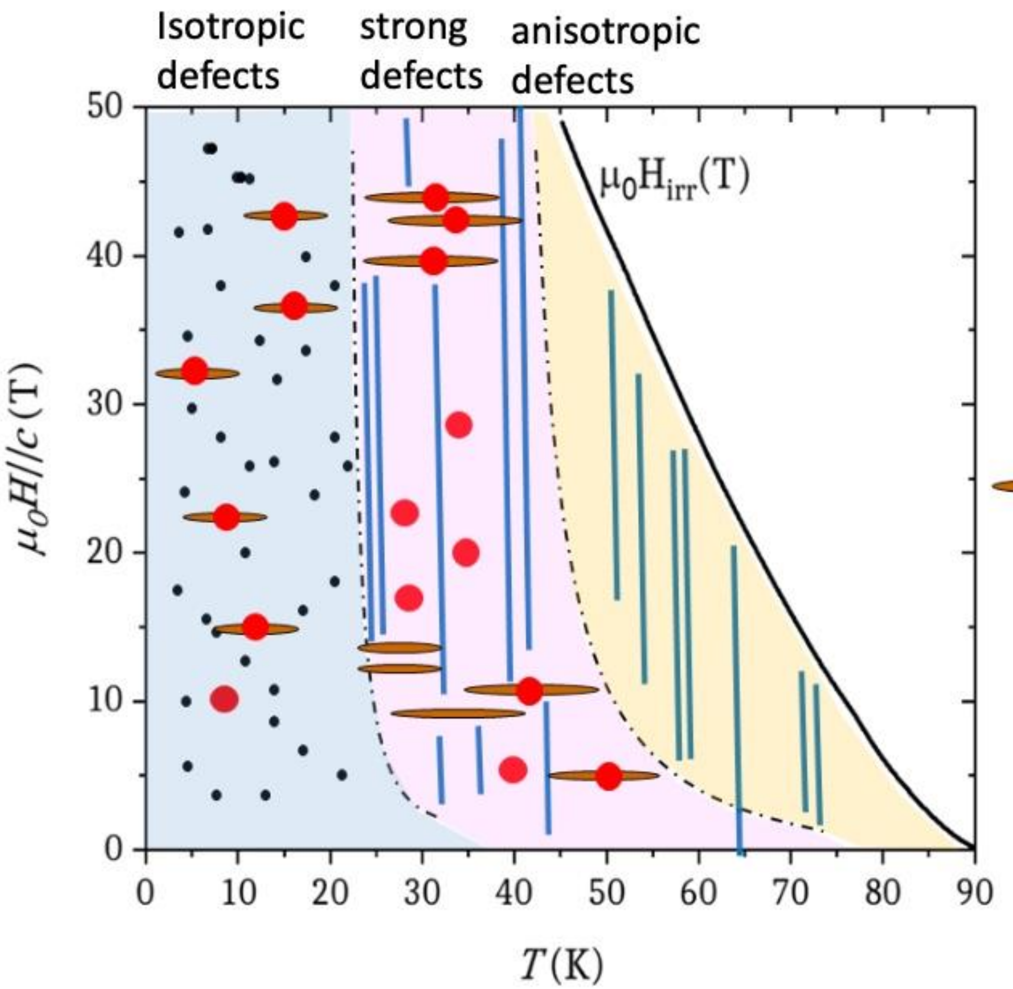
Source: NHMFL (https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots)

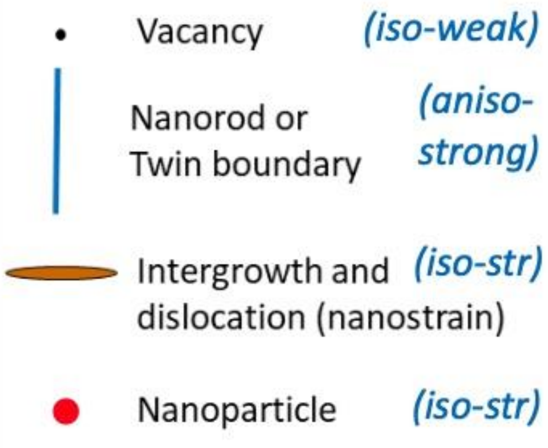
DEFECTS IN EPITAXIALLY GROWTH HTS LAYER

- Typical defects in REBCO tapes (some of them are beneficial if well controlled)

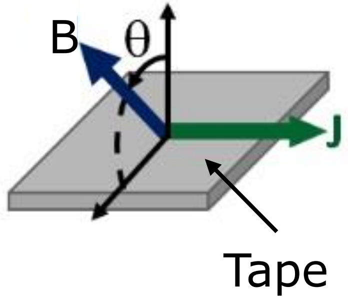


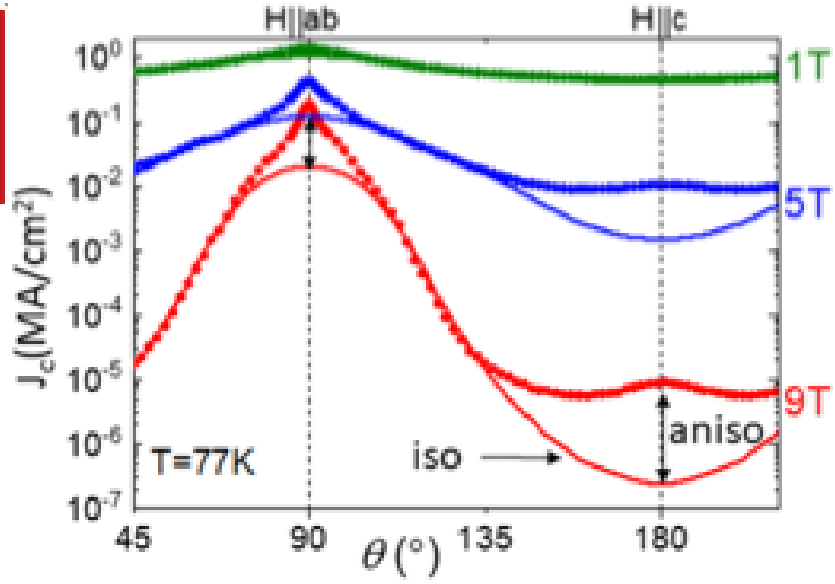
DEFECT ENGINEERING: THE ART TO TAILOR $J_C(B)$

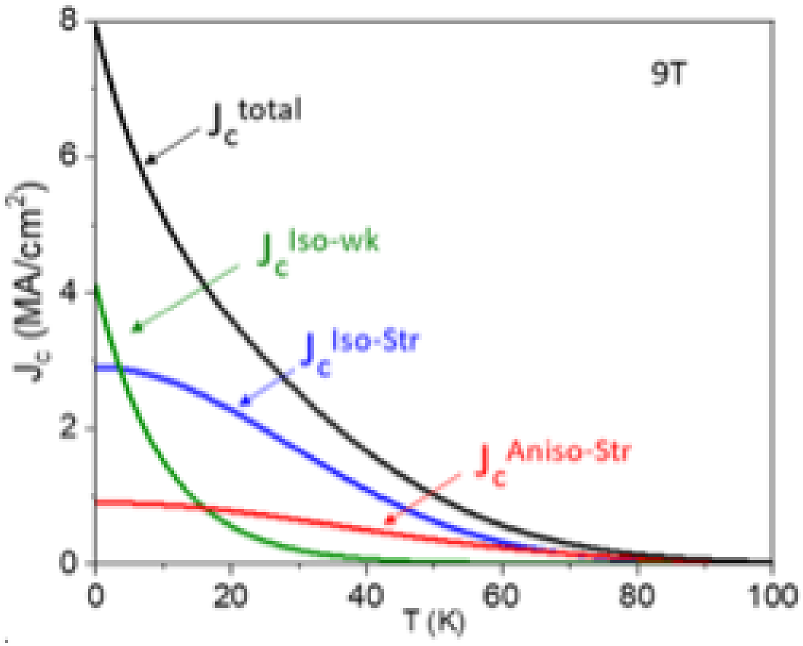




T. Puig *et al.,* Nature Physics Reviews 6, 132-148, 2024.



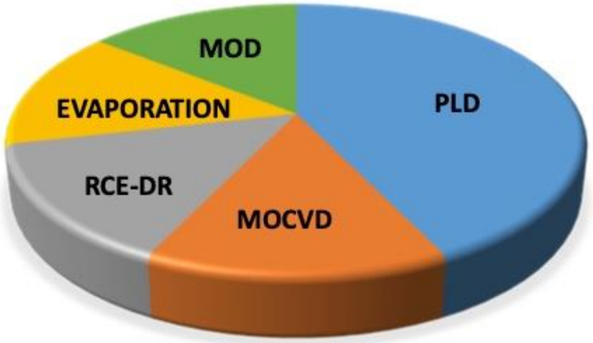




F. Valles *et al.,*
Comm Mat 3, 2022.

REBCO TAPE MANUFACTURERS (A DOZEN WORLDWIDE, NONE IN CANADA)

Consolidated product	Growth method	Textured substrate	REBCO materials	Main APC
FARADAY FACTORY JAPAN	PLD	IBAD	YBCO	Y_2O_3 nanoparticle
			GdBCO	
"Tsunagu" Technology Fujikura	PLD	IBAD	EuBCO	BHO nanorod
			GdBCO	
Shanghai Superconductor Technology 上海超导	PLD	IBAD	YBCO	BZO nanorod
SuperPower Inc.	MOCVD	IBAD	(Y,Gd)BCO	BZO nanorod
			HM prod.	
THEVA	ME	ISD	GdBCO	
SuNAM	RCE-DR	IBAD	GdBCO	
上创超导 Shanghai Creative Superconductors	CSD	IBAD	YBCO	BZO nanoparticle



R&D product

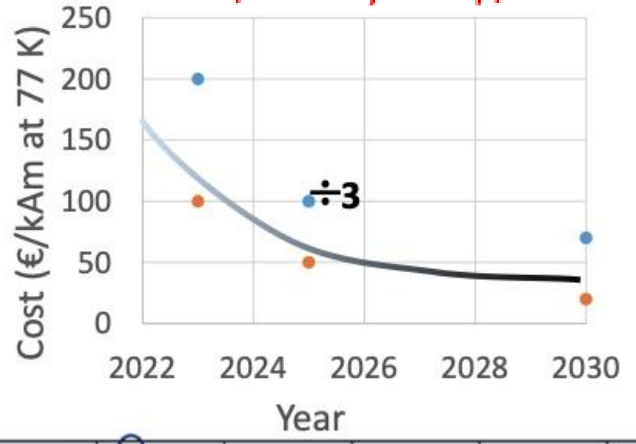
HTS HIGH TEMPERATURE SUPERCONDUCTORS	PLD
SuNAM	PLD
SWCC GROUP	CSD
SUMITOMO ELECTRIC	CSD
METOX™	MOCVD

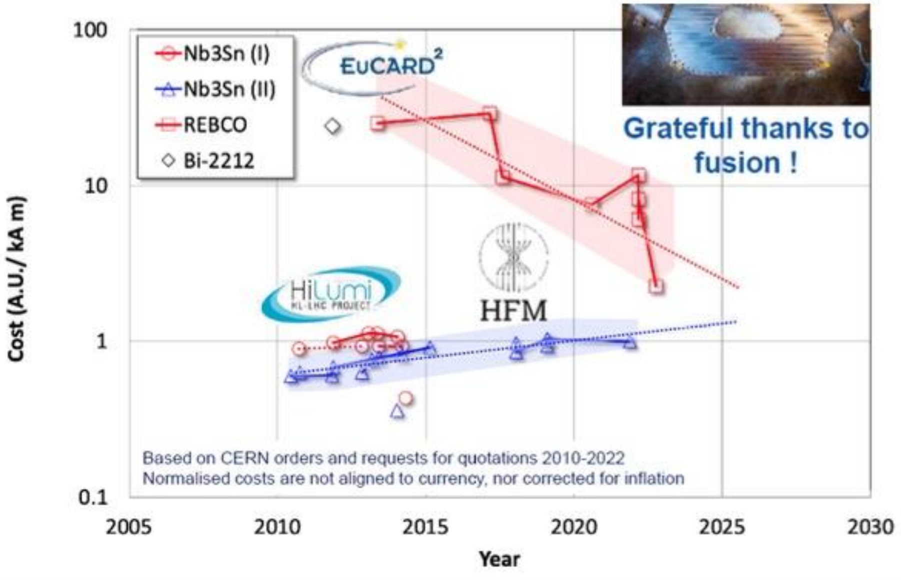
Source: X. Obradors, Applied Superconductivity Conference, Salt Lake City, Sept. 2024

PRODUCTION RATE VS. COST OF REBCO TAPES (X2 EVERY YEAR)

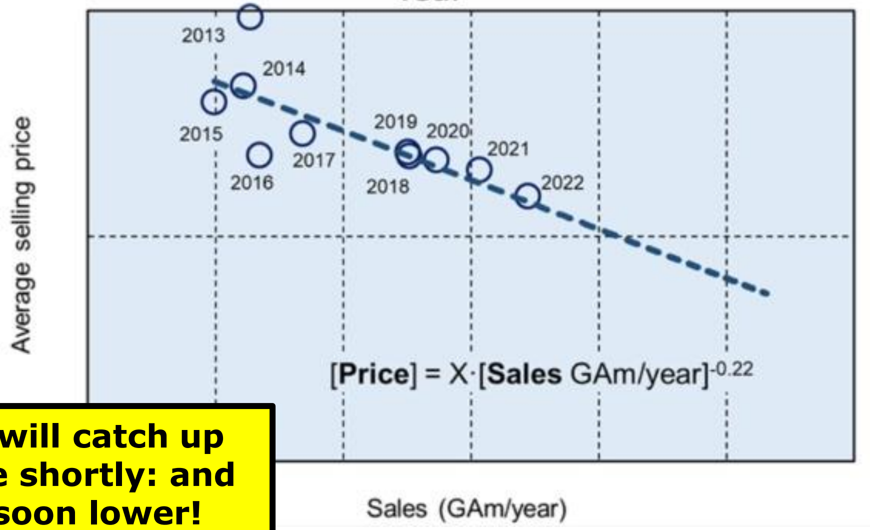
Magnitude	At present	Target for 2025	Target for 2028
Length (km)	0.5 – 1	1 – (5)	
Width (mm)	2, 3, 4, 6, 12	40, 80, 100, 125	
Production (km/yr) *12 mm equiv.*	3000 - 5000	6000 -10000	+40000 (+25000 Faraday)

S. Lee, Faraday Group, SNF Issue 53





L. Bottura, CERN, SNF Issue 52

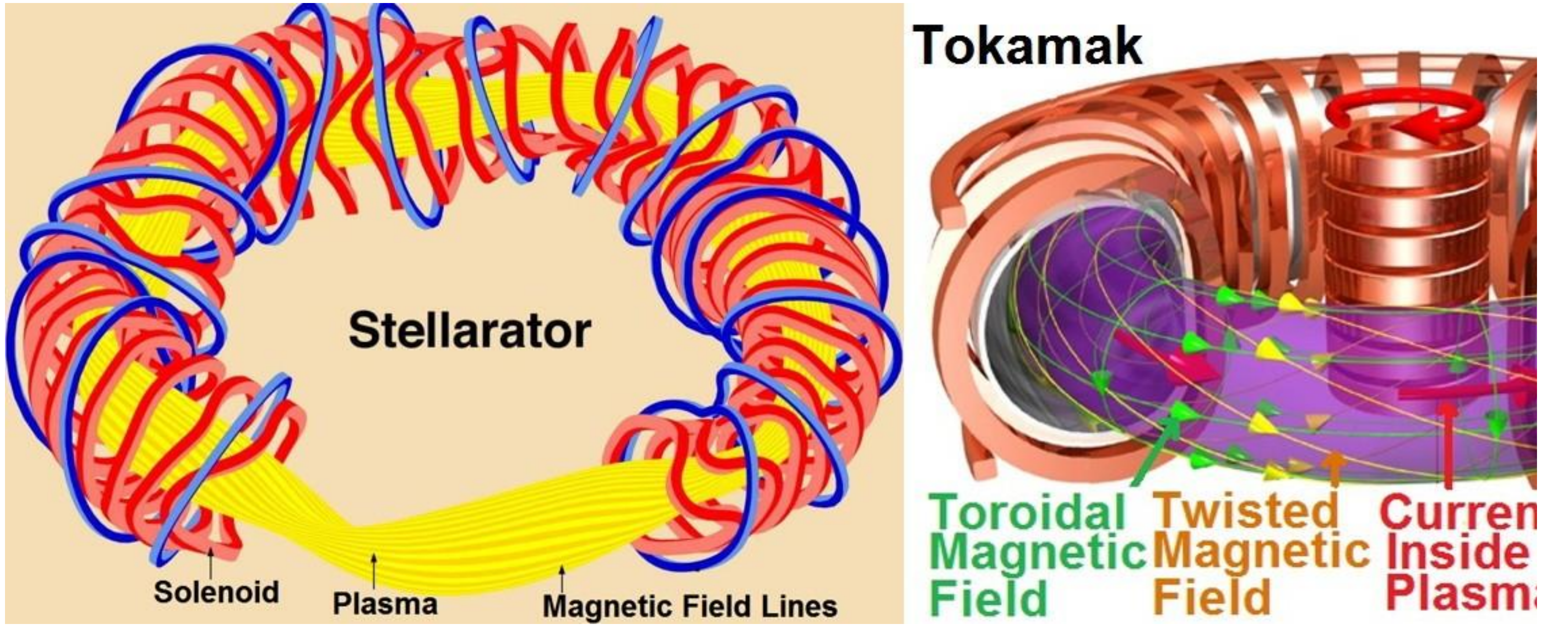


REBCO price will catch up with LTS price shortly: and it might be soon lower!

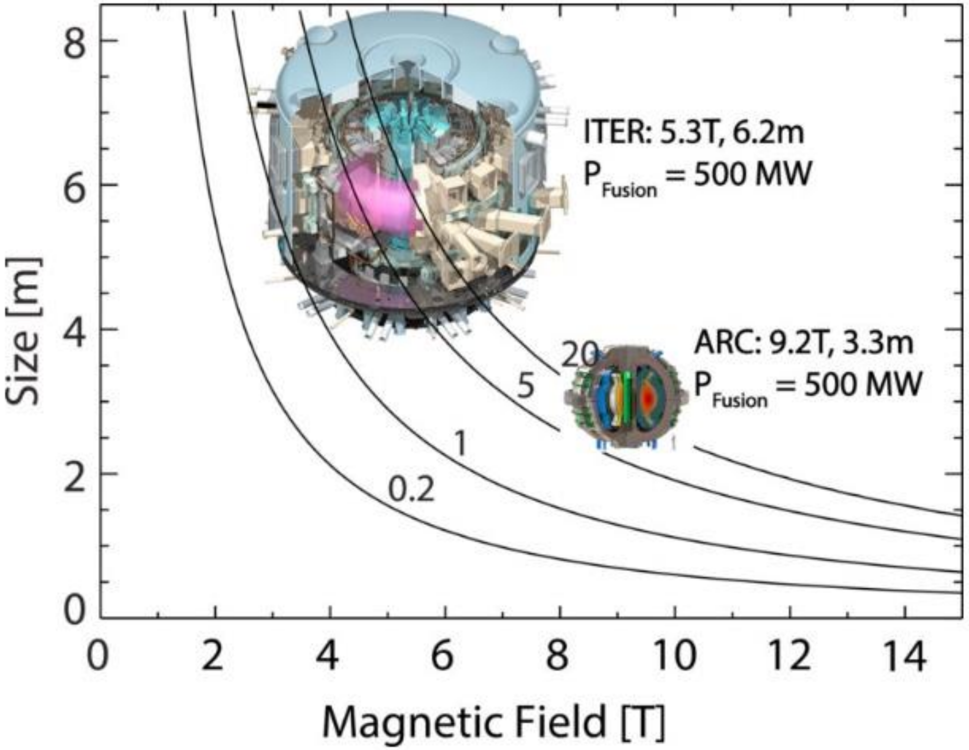
Source: X. Obradors, Applied Superconductivity Conference, Salt Lake City, Sept. 2024

WHY IS THE WORLD PRODUCTION OF REBCO TAPES BOOMING?

- Fusion reactors require many huge high-field magnets (~10 T at 20 K)



Two types of magnetic confinement fusion reactors



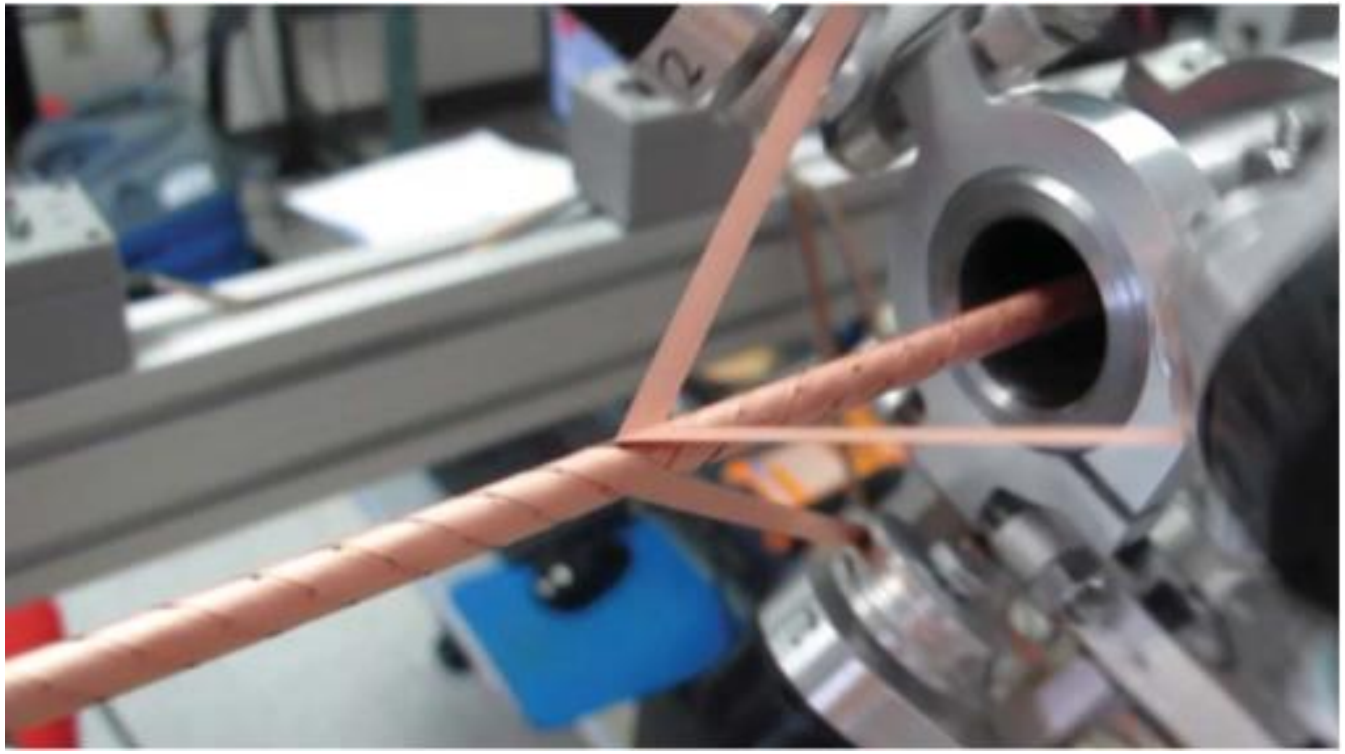
- ~12 private fusion companies worldwide based on REBCO tape technology
- **Fusion is THE DRIVER for REBCO tapes (>90% of world purchases)**

BACK TO HTS ACCELERATOR MAGNETS…

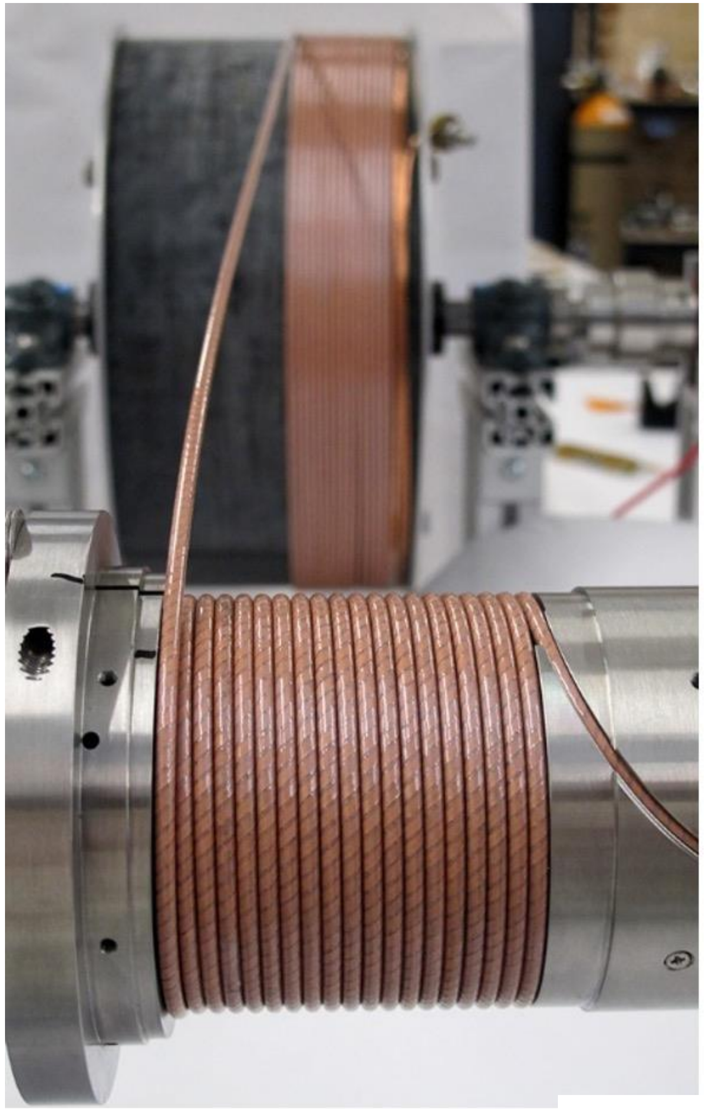
- Some challenges to overcome to develop REBCO-based magnet technology
  - Anisotropy of REBCO tapes to make cables and coils
  - Understand the behaviour of REBCO under various types of radiations
  - Higher magnetic fields = high forces and new types of mechanical failures under
  - Completely new magnet designs: lots of experience to acquire + lots of models to produce
- Two very fundamental questions to address in the short term
  - **How to deal with magnetization currents** and their impact on field homogeneity?
  - **How to handle quench protection**, provided that
    - Higher-field magnets store a lot of magnetic energy
    - REBCO tapes have a very different thermal behaviour than LTS wires (slower hot spot propagation)

EXAMPLE OF CABLE AND COIL WINDING

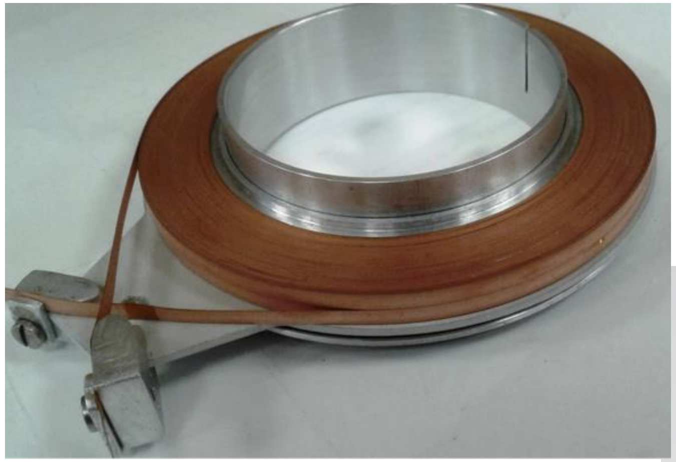
- Conductor On Round Core (CORC) cables and coils
  - Allow making kA-class REBCO cables (below)



Source: https://www.advancedconductor.com

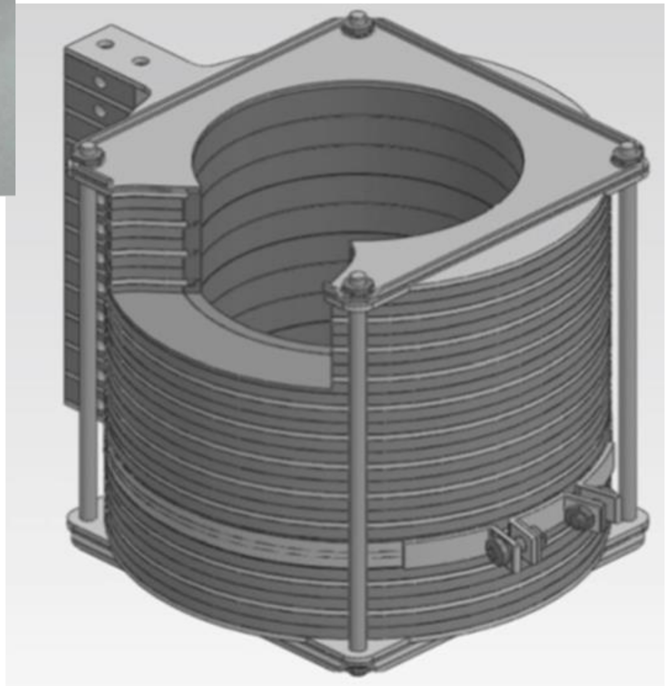


MAGNETIZING (SCREENING) CURRENTS AND FIELD QUALITY



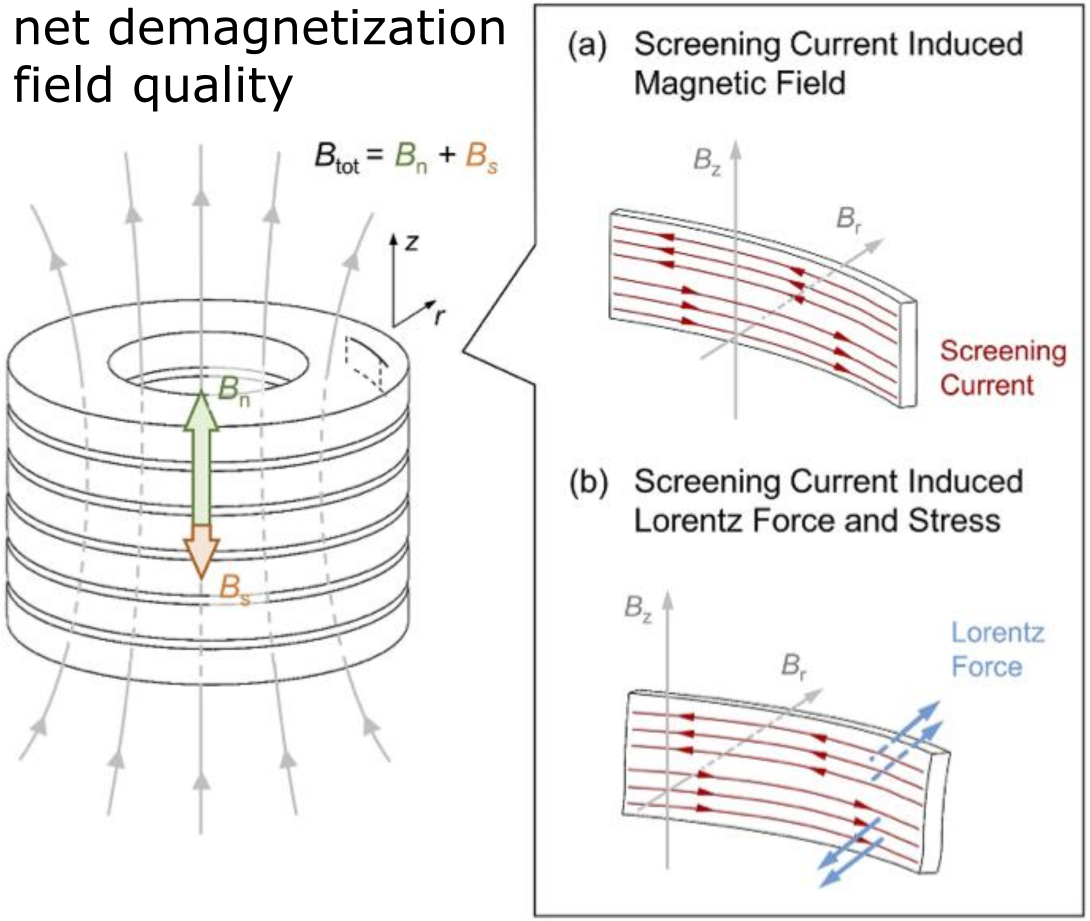
Screening currents create a net demagnetization field (B_s), affecting field quality

Top: example of HTS pancake coil (top)



Right: solenoid made by stacking pancake coils

E. P. Krasnoperov et al., Electrical Engineering (2020), 102:1769–1774

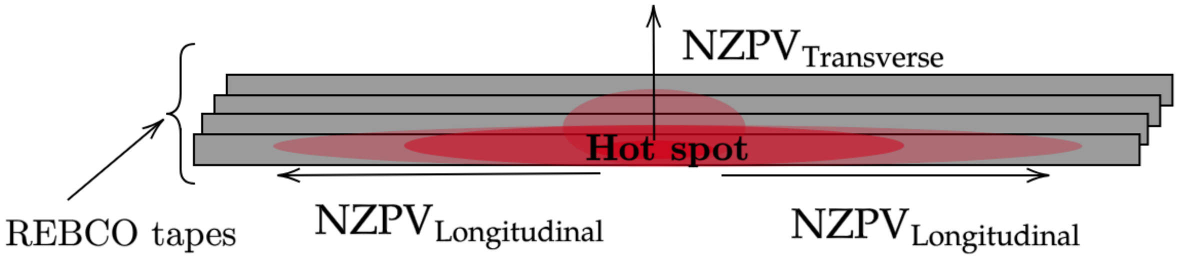


Y. Yan et al., Supercond. Sci. Technol. (2022), 35:014003

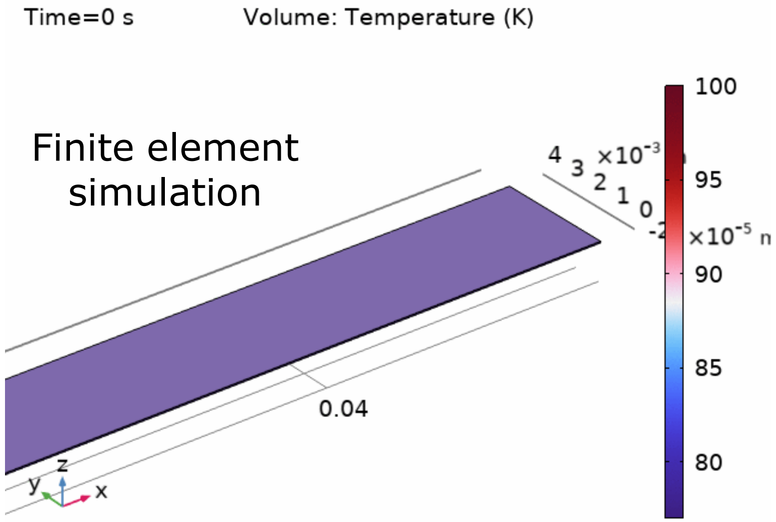
QUENCH PROTECTION OF REBCO-BASED MAGNETS

- REBCO-based devices are prone to HOT SPOTS and QUENCH PROPAGATION
  - A hot spot can destroy a 2 M$ magnet in a matter of seconds!

Hot spot nucleation and quench propagation



(NZPV – Normal Zone Propagation Velocity)



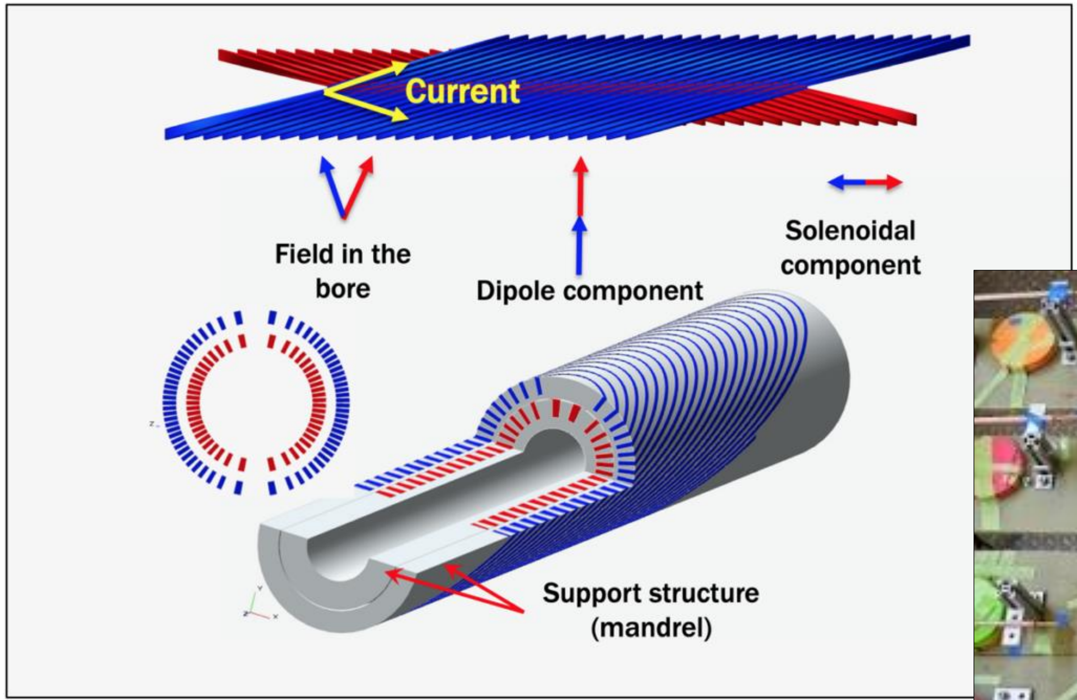
- Hot spots in REBCO tapes propagate up to 2 orders of magnitude slower than in LTS devices → **Much harder to detect**
- **Finding robust quench protection systems is currently <u>THE PRIMARY CONCERN</u> of the HTS magnet community → Many strategies under test**

- Subscale model of an REBCO accelerator magnet (CCT dipole) damaged by a quench

Courtesy of Lawrence Berkeley National Lab – Project carried out within the U.S. Magnet Development Program

C3 MAGNET: A 6 T REBCO MAGNET (65 MM APERTURE)

Schematic first 2 layers

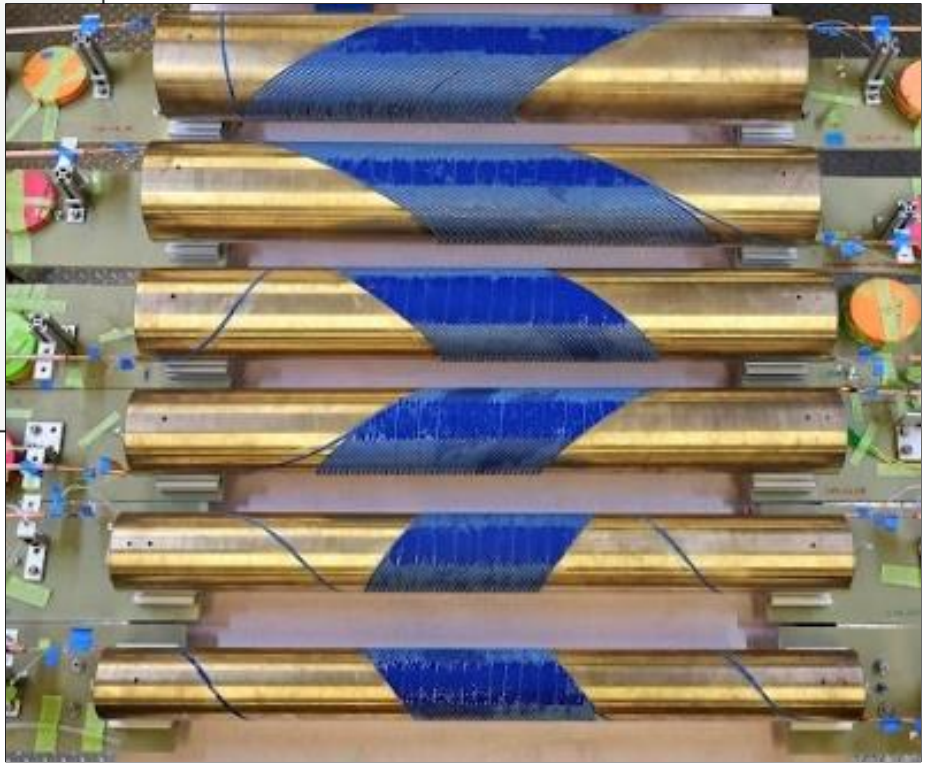


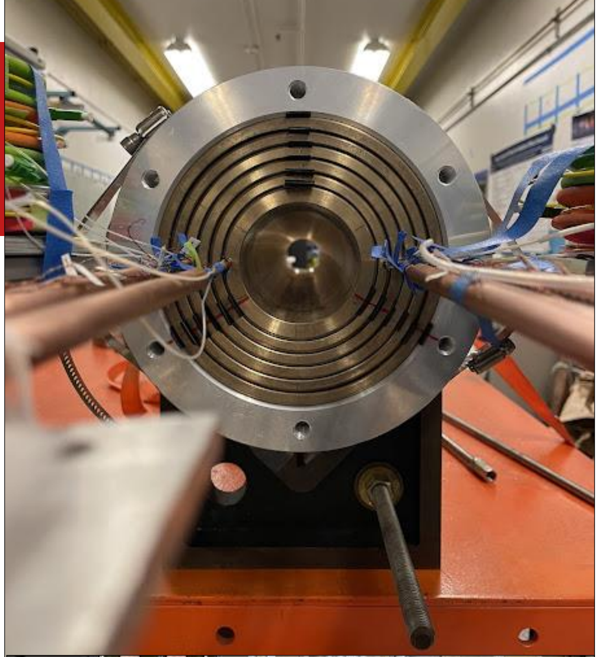
Source: https://atap.lbl.gov/news/a-blueprint-for-more-powerful-superconducting-magnets

Courtesy of Lawrence Berkeley National Lab
Project carried out within the U.S. Magnet Development Program

Right: Complete magnet assembly

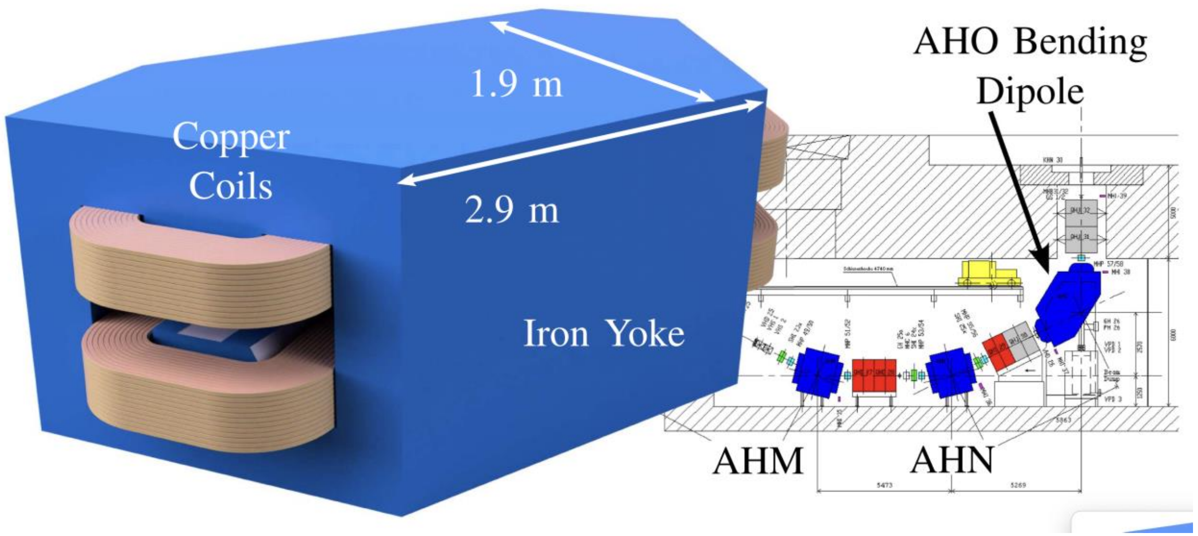
Picture of the whole 6 layers

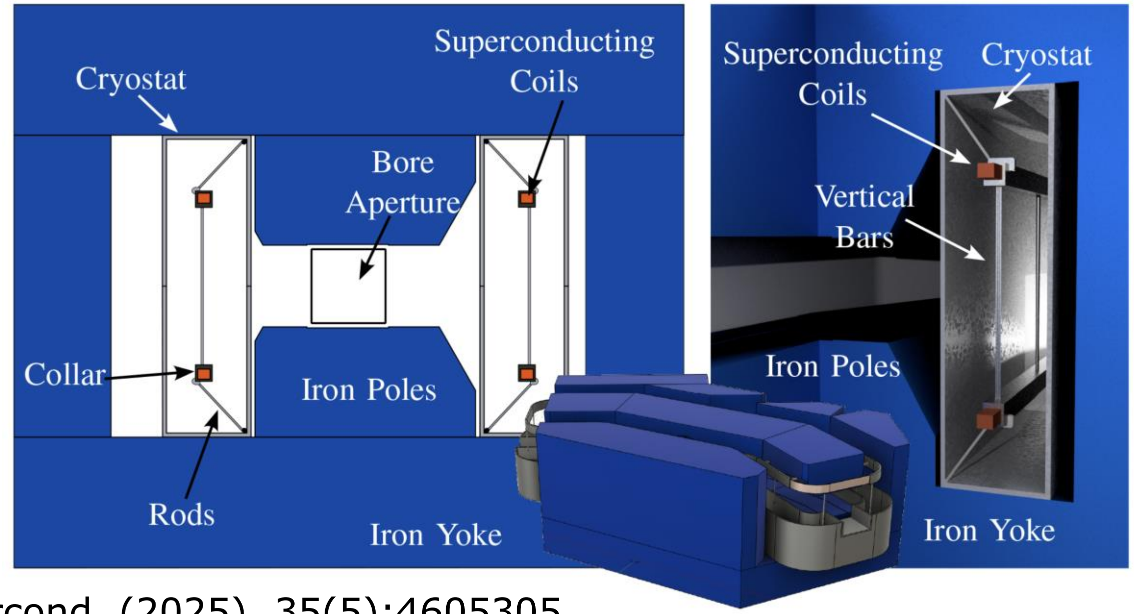




IS THERE ROOM FOR LOW-FIELD REBCO MAGNETS? (WITH NO LHe)

- Concept of retrofit HTS magnet to replace a copper dipole at PSI (Paul Scherrer Inst.)
  - T_{op}=50 K (low cryogenic cost) → **Power: from 190 kW to 6 kW (3-year payback)**





S. Mariotto *et al.*, IEEE Trans. Appl. Supercond. (2025), 35(5):4605305

- Applicable to any beamline using copper magnets (In Canada: TRIUMF, CLS)
- NSERC SAP Discovery project awarded (April 2026, Poly-TRIUMF-UVic)

CONCLUSION → TOWARDS A CANADIAN MAGNET STRATEGY?

- HTS (REBCO) magnets can benefit many sectors
  - Accelerators, Fusion reactors, Medical magnets, High-field research magnets, etc.
- **REBCO magnet technology is still in its infancy, but it is here to stay**
  - U.S.A., Europe, Japan, China, Korea, etc.
- **Canada has missed the LTS magnet technology…**
  - **… but it is still time to catch the train of HTS magnets (REBCO technology)**
- Exchanges between stakeholders are required to establish a **Canadian Magnet Strategy**
- Canadian efforts should be coupled with other national/international efforts, e.g.
  - The US Magnet Development Program (US MDP)
  - Various Horizon 2020 European projects (now that Canada is an associated member of EU)
  - etc.

Thank you for your attention!

Fonds de recherche Nature et technologies Québec

NSERC CRSNG