

CCA2025



UNIVERSITÉ  
DE GENÈVE

FACULTÉ DES SCIENCES



# High Temperature Superconductors

## PART I: From Materials to Conductors

**Carmine SENATORE**

Department of Quantum Matter Physics, University of Geneva, Switzerland

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

# Outline

**An introduction to high temperature superconductivity**

**The basics of HTS conductor fabrication with focus on REBCO**

**An overview of the properties of REBCO coated conductors**

- **Developments to improve performance**
- **Reversible and irreversible effects under mechanical loads**

**From REBCO coated conductors to REBCO-based cables**

# Outline

**An introduction to high temperature superconductivity**

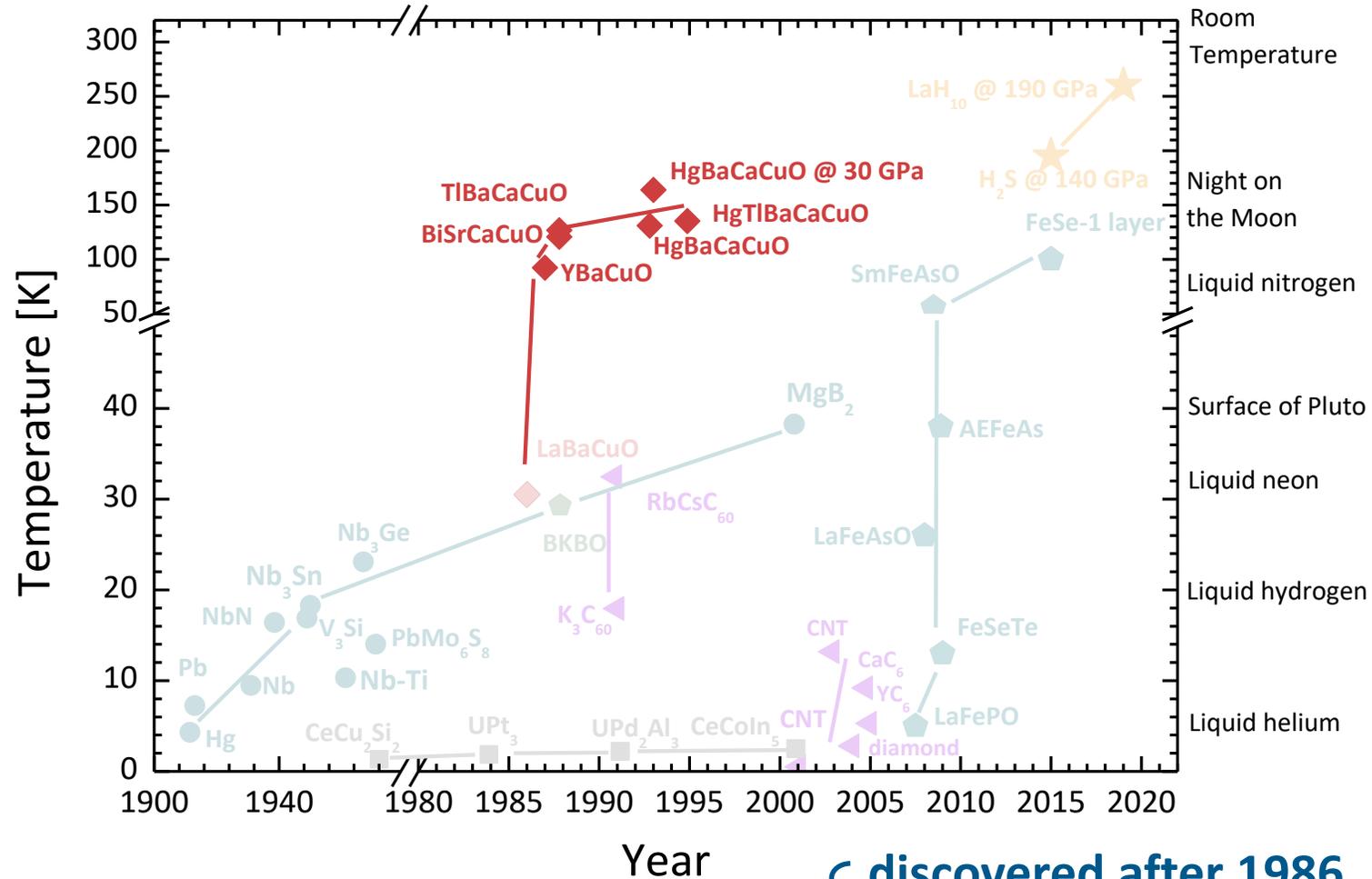
The basics of HTS conductor fabrication with focus on REBCO

An overview of the properties of REBCO coated conductors

- Developments to improve performance
- Reversible and irreversible effects under mechanical loads

From REBCO coated conductors to REBCO-based cables

# Timeline of Superconductivity



The course will focus on superconductors

discovered after 1986  
 with a T<sub>c</sub> above the LN<sub>2</sub> temperature  
 available as industrial conductors

# The cookbook for new superconductors before 1986

from a compilation of superconducting elements,  
binary compounds and solid solutions

## Matthias' Rules

- 0. Valence number per atom between 2 and 8 Favorable valence numbers: 3, 4.7, 6.9
- 1. Seek high symmetry Cubic is better
- 2. Seek peaks in density of state
- 3. Stay away from oxygen
- 4. Stay away from magnetism
- 5. Stay away from insulators

$$T_c = 1.14 \omega_{ph} \exp\left(-\frac{1}{N(E_F) V_{ph}}\right)$$

BCS, PR 108 (1957) 1175

B. Matthias et al., RMP 35 (1963) 1

**Record  $T_c = 23.2$  K in  $Nb_3Ge$**

**HTS are copper oxides**  
**The undoped parent compounds are**  
**antiferromagnetic Mott insulators**

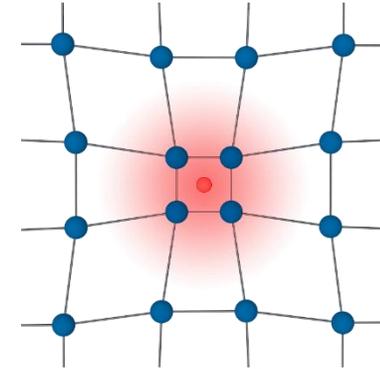
# 1986: Superconductivity in $\text{La}_{2-x}\text{Ba}_x\text{CuO}$ at $T_c \approx 30 \text{ K}$

In the 1980's Bednorz and Müller were looking for superconductivity in the oxides

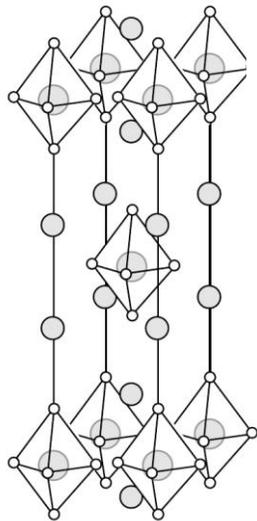
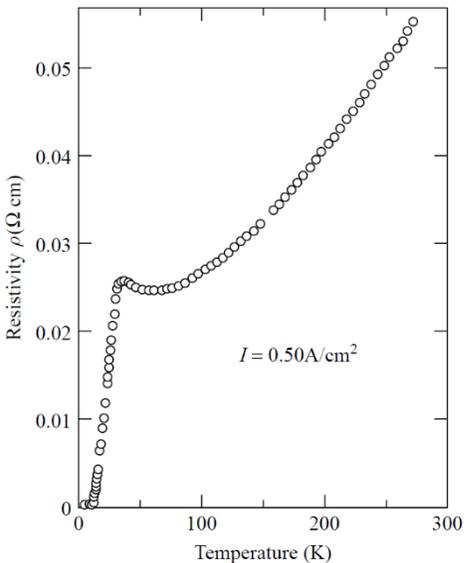
$$T_c = 1.14\omega_{\text{ph}} \exp\left(-\frac{1}{N(E_F)V_{\text{ph}}}\right)$$

$V_{\text{ph}}$  is rather strong  
Look for Jahn-Teller polarons

$N(E_F)$  is low  
Look for increased  $N(E_F)$  in mixed valence compounds



In particular, they investigated the 2 systems: ~~La-Ti-O~~ and La-Cu-O



Z. Phys. B – Condensed Matter 64, 189–193 (1986)

## Possible High $T_c$ Superconductivity in the Ba – La – Cu – O System

J.G. Bednorz and K.A. Müller

IBM Zürich Research Laboratory, Rüschlikon, Switzerland



- O
- La
- Cu

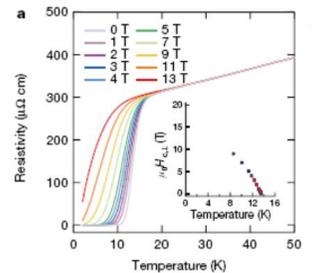
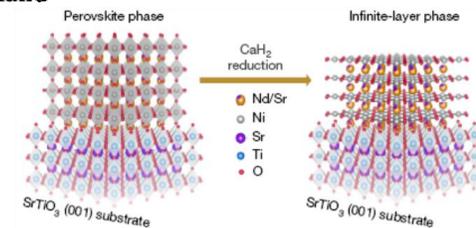
## LETTER

2019

<https://doi.org/10.1038/s41586-019-1496-5>

## Superconductivity in an infinite-layer nickelate

Danfeng Li<sup>1,2\*</sup>, Kyuho Lee<sup>1,3</sup>, Bai Yang Wang<sup>1,3</sup>, Motoki Osada<sup>1,4</sup>, Samuel Crossley<sup>1,2</sup>, Hye Ryoung Lee<sup>1,4</sup>, Yi Cui<sup>1,4</sup>, Yasuyuki Hikita<sup>1</sup> & Harold Y. Hwang<sup>1,2\*</sup>



# And only few months later...

VOLUME 58, NUMBER 9

PHYSICAL REVIEW LETTERS

2 MARCH 1987

## Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure

M. K. Wu, J. R. Ashburn, and C. J. Torng

*Department of Physics, University of Alabama, Huntsville, Alabama 35899*

and

P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu<sup>(a)</sup>

*Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004*

(Received 6 February 1987; Revised manuscript received 18 February 1987)

A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field  $H_{c2}(0)$  between 80 and 180 T was obtained.

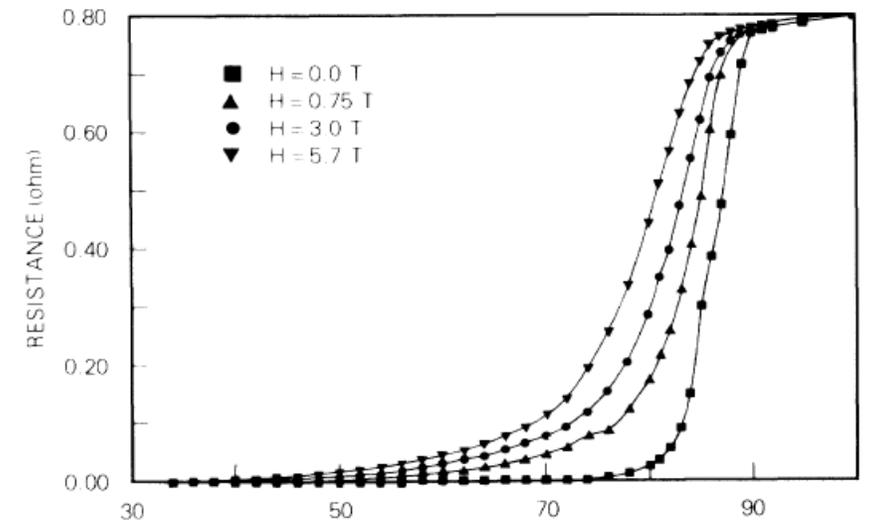
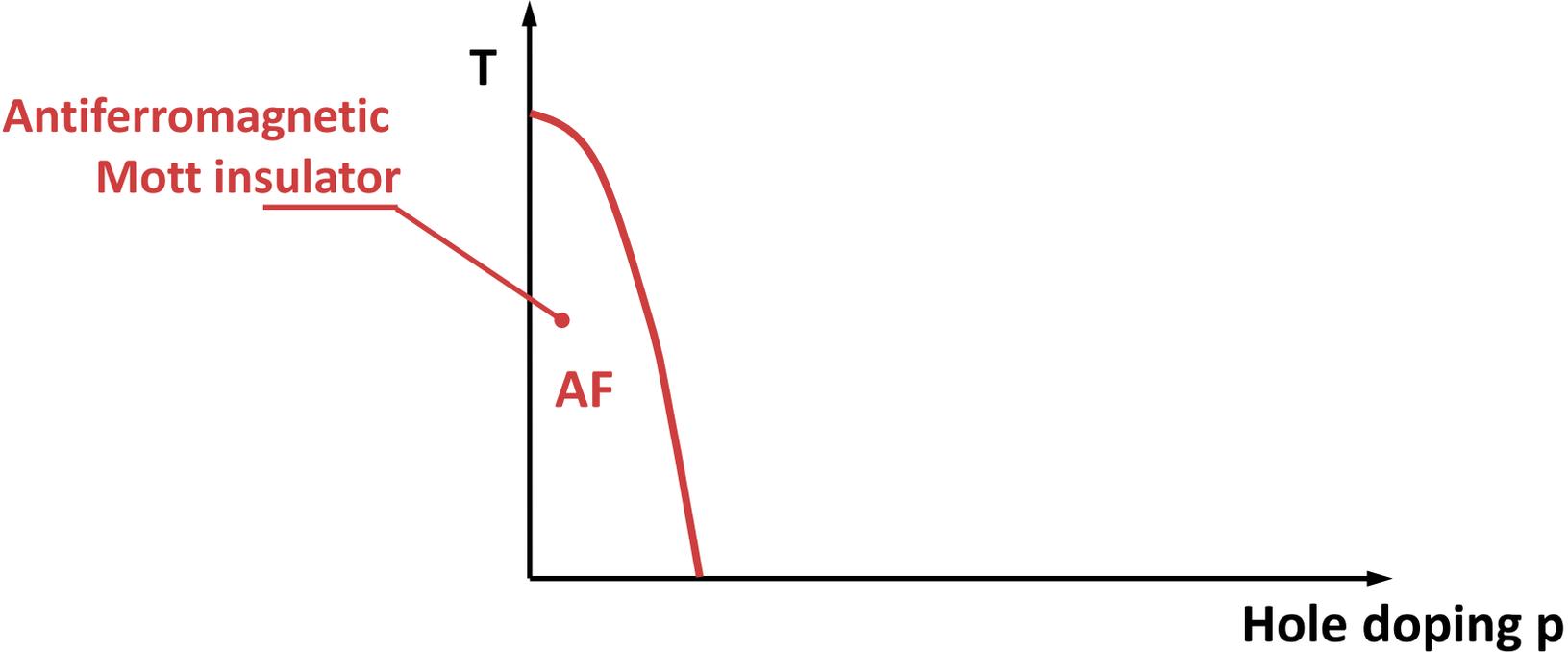


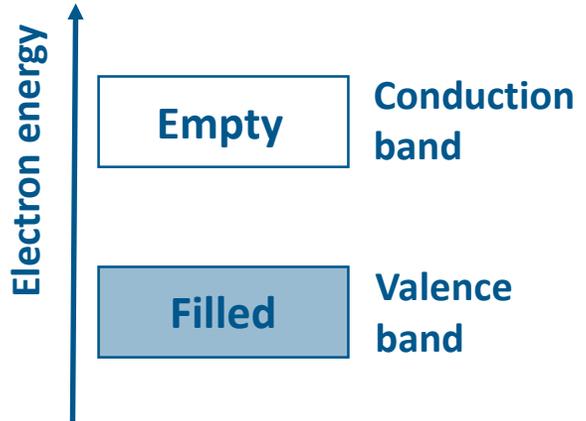
FIG. 1. Temperature dependence of resistance determined in a simple liquid-nitrogen Dewar.

**The 1<sup>st</sup> SC with  $T_c$  above the LN<sub>2</sub> temperature!  
And BSCCO came in 1988**

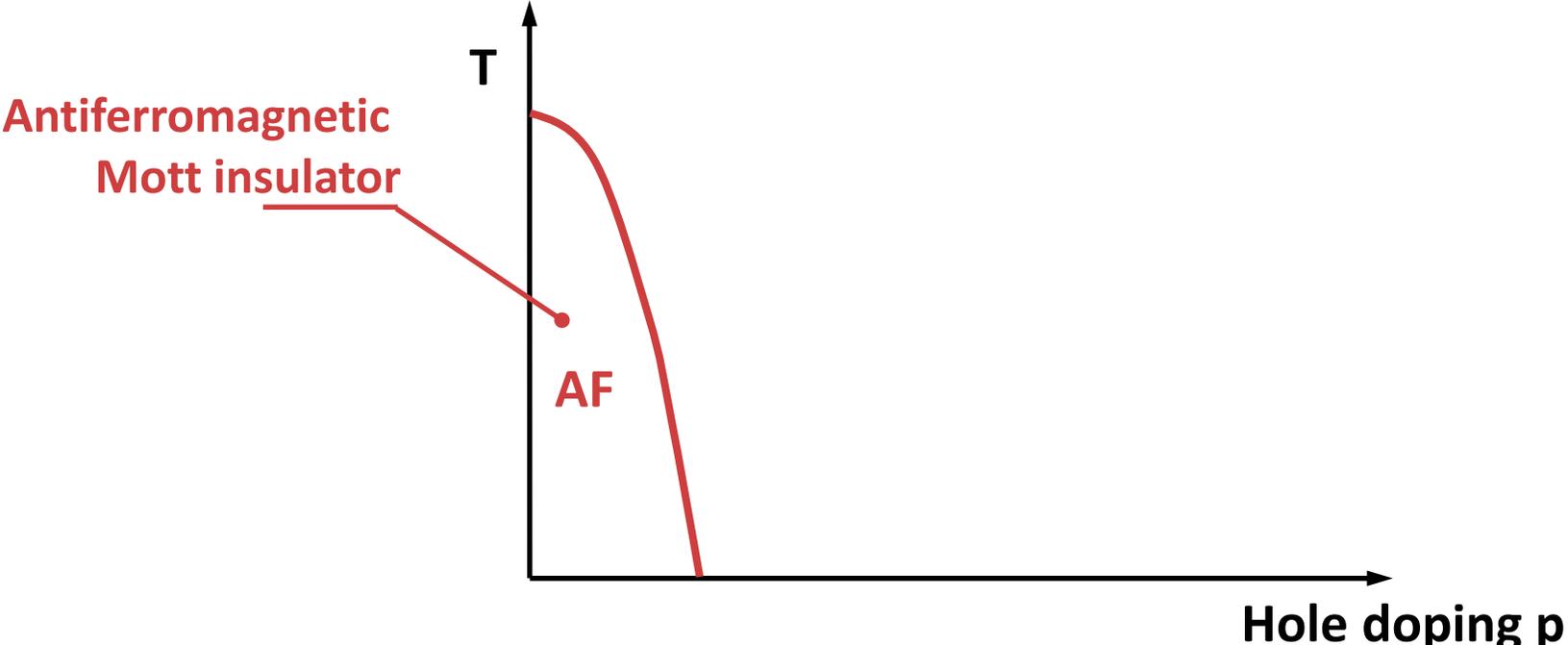
# A quick introduction to the HTS phase diagram



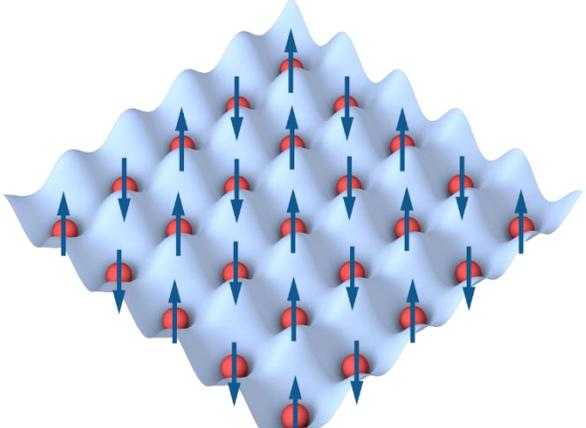
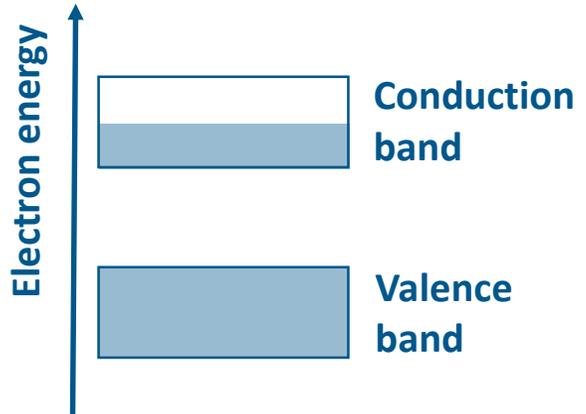
## Band (Bloch-Wilson) insulator



# A quick introduction to the HTS phase diagram



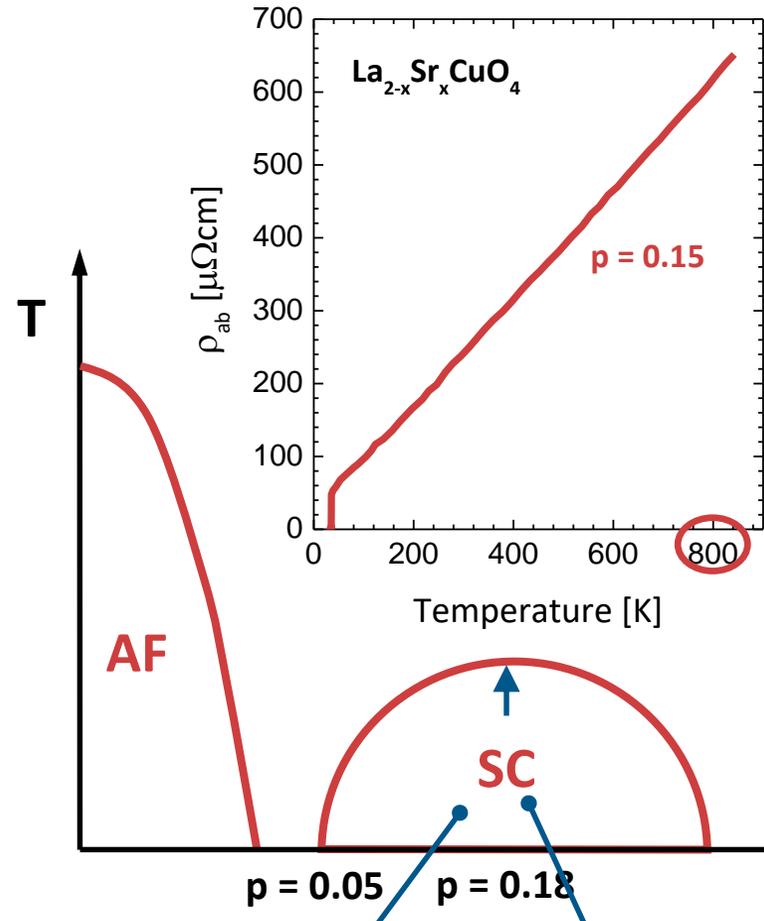
## Mott insulator



Only **one electron per site** but the **strong Coulomb repulsion** between the electrons impedes their flow

On the top of that the **antiferromagnetic interaction**

# A quick introduction to the HTS phase diagram



## Open questions

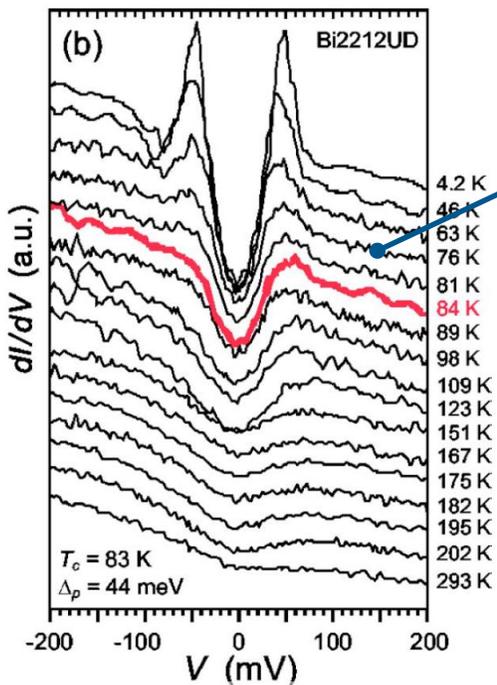
- T-linear resistivity at optimal doping  
B. Batlogg, SSC 107 (1998) 639
- $T_c$  variation with the number of  $\text{CuO}_2$  layers

<b>Bi2201</b>	$n = 1$	$T_c = 15$ K
<b>Bi2212</b>	$n = 2$	$T_c = 91$ K
<b>Bi2223</b>	$n = 3$	$T_c = 110$ K

Superconductivity arises in the  $\text{CuO}_2$  planes

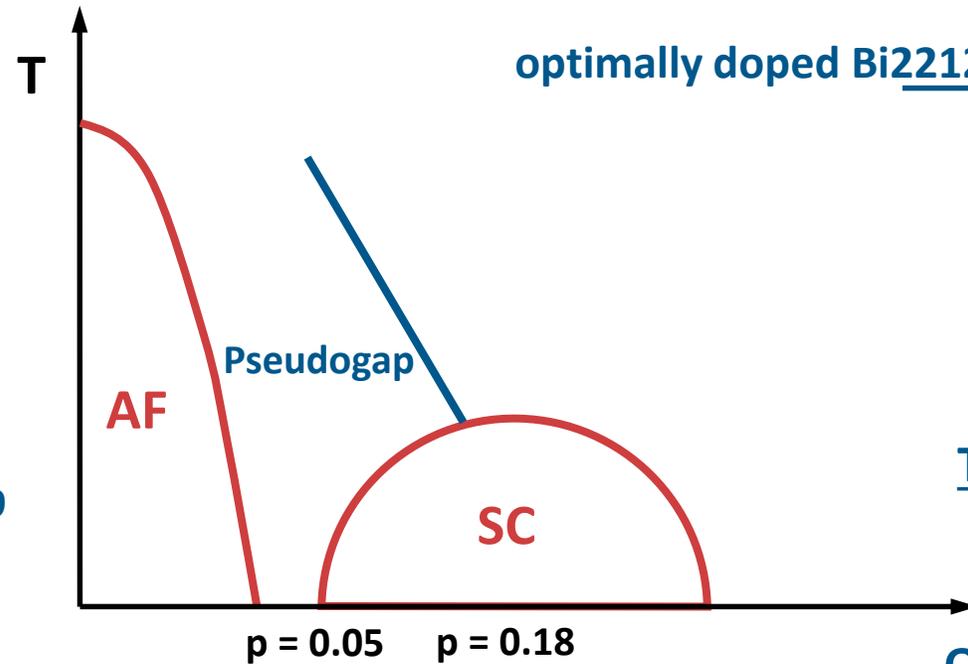
Macroscopic Ginzburg-Landau describes the electromagnetic properties

# A quick introduction to the HTS phase diagram



Renner et al., PRL 80 (1998) 149

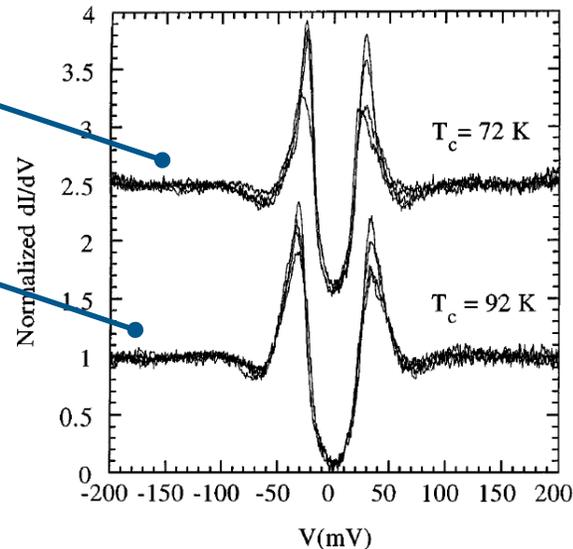
underdoped Bi2212



overdoped Bi2212

optimally doped Bi2212

## Tunneling spectra



DeWilde et al., PRL 80 (1998) 153

The energy gap  $\Delta$  goes to zero at  $T_c$

The energy gap  $\Delta$  does not go to zero at  $T_c$

The **pseudogap** exists only in the underdoped regime, up to  $T^*(p)$

Other phenomena take place in the underdoped regime

- Charge density waves
- Stripes
- Spin fluctuations

# Relevant HTS families

	Compound	T <sub>c</sub> [K]	Short name		
hole-doped	REBCO	La <sub>1.85</sub> Sr <sub>0.15</sub> CuO <sub>4</sub>	39	LaSCO	
		YBa <sub>2</sub> Cu <sub>3</sub> O <sub>7</sub>	92	Y123 or YBCO	
	Bi family		Bi <sub>2</sub> Sr <sub>2</sub> CuO <sub>6</sub>	15	Bi2201
			Bi <sub>2</sub> Sr <sub>2</sub> CaCu <sub>2</sub> O <sub>8</sub>	91	Bi2212
			Bi <sub>2</sub> Sr <sub>2</sub> Ca <sub>2</sub> Cu <sub>3</sub> O <sub>10</sub>	110	Bi2223 or BSCCO
	Tl families		Tl <sub>2</sub> Ba <sub>2</sub> CuO <sub>6</sub>	90	
			Tl <sub>2</sub> Ba <sub>2</sub> CaCu <sub>2</sub> O <sub>8</sub>	110	
			Tl <sub>2</sub> Ba <sub>2</sub> Ca <sub>2</sub> Cu <sub>3</sub> O <sub>10</sub>	125	Tl2223 or TBCCO
			TlBa <sub>2</sub> CaCu <sub>2</sub> O <sub>7</sub>	91	
			TlBa <sub>2</sub> Ca <sub>2</sub> Cu <sub>3</sub> O <sub>9</sub>	116	
			TlBa <sub>2</sub> Ca <sub>3</sub> Cu <sub>4</sub> O <sub>11</sub>	122	
		Hg family		HgBa <sub>2</sub> CuO <sub>4</sub>	95
			HgBa <sub>2</sub> CaCu <sub>2</sub> O <sub>6</sub>	122	
			HgBa <sub>2</sub> Ca <sub>2</sub> Cu <sub>3</sub> O <sub>8</sub>	133	Hg1223
electron-doped		Nd <sub>1.85</sub> Ce <sub>0.15</sub> CuO <sub>4</sub>	25	NCCO	

Record T<sub>c</sub> of ~165 K under high pressure

# Outline

An introduction to high temperature superconductivity

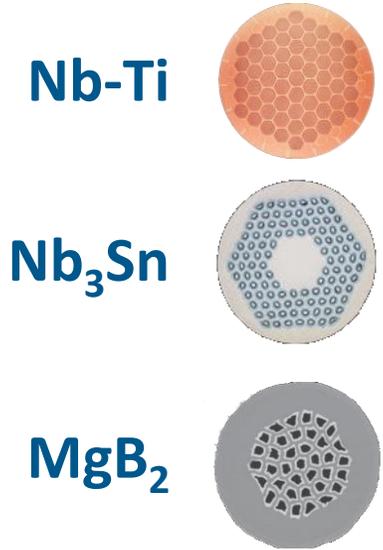
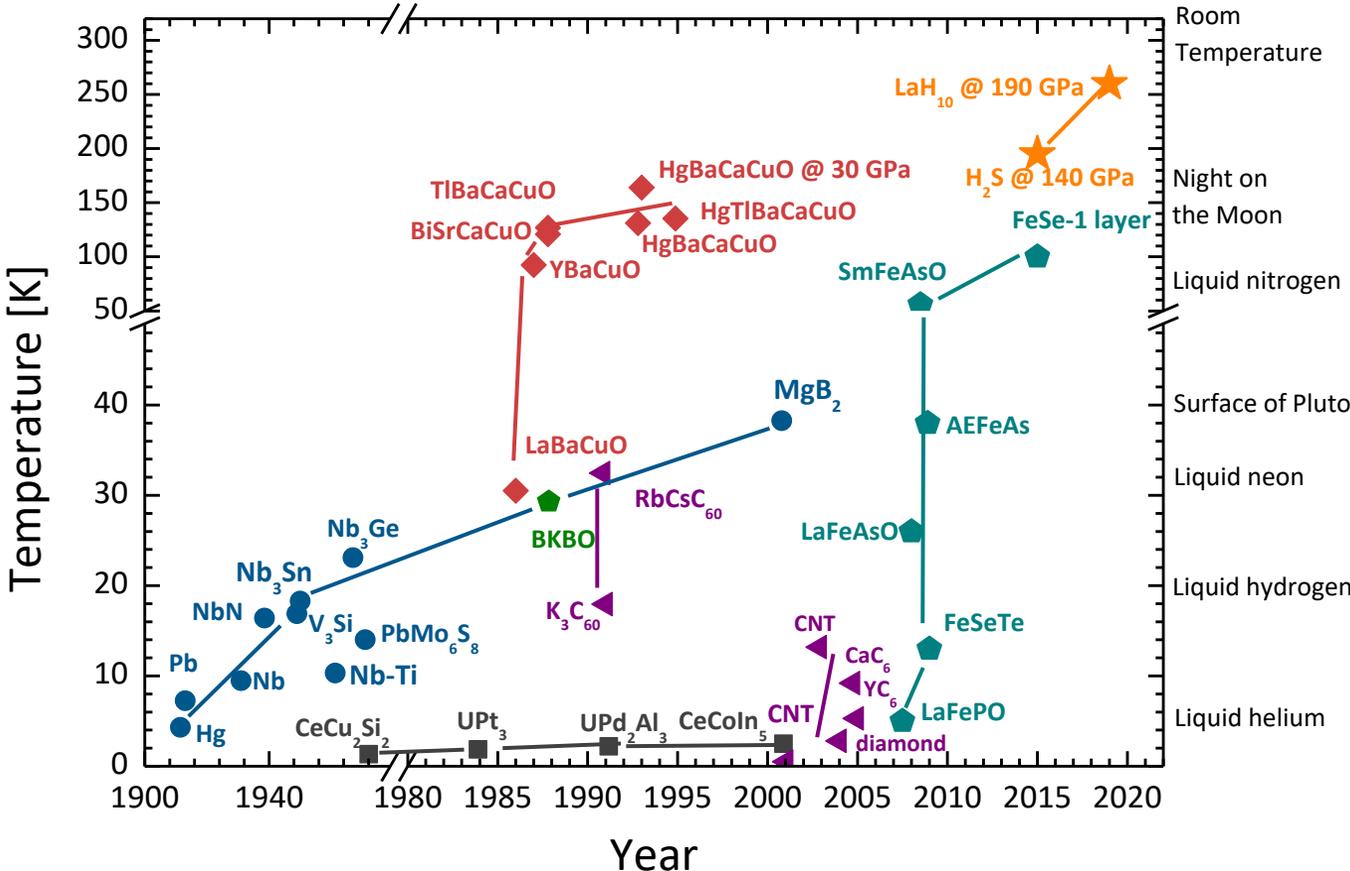
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- Developments to improve performance
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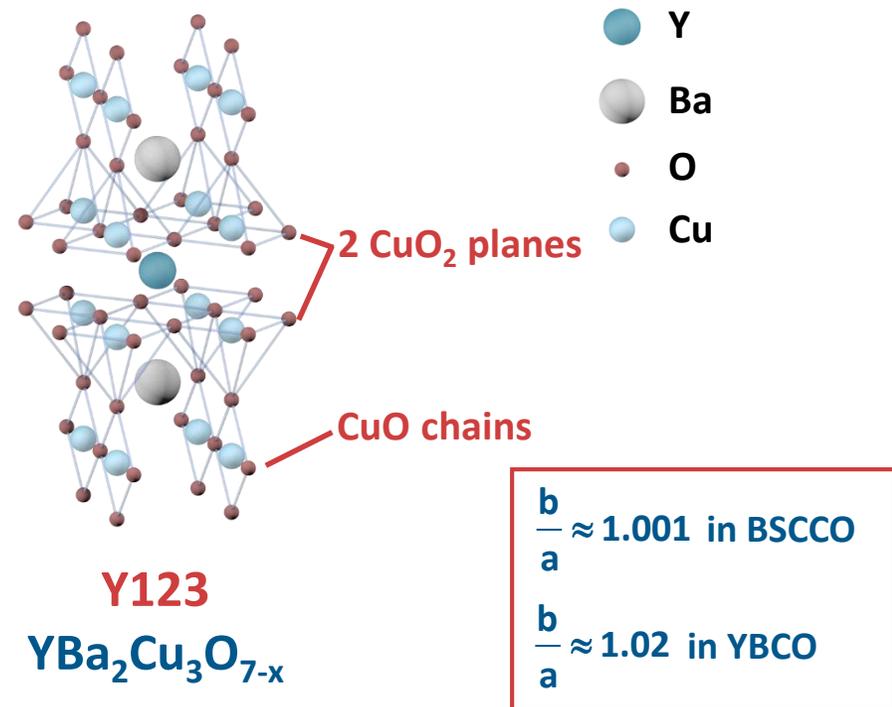
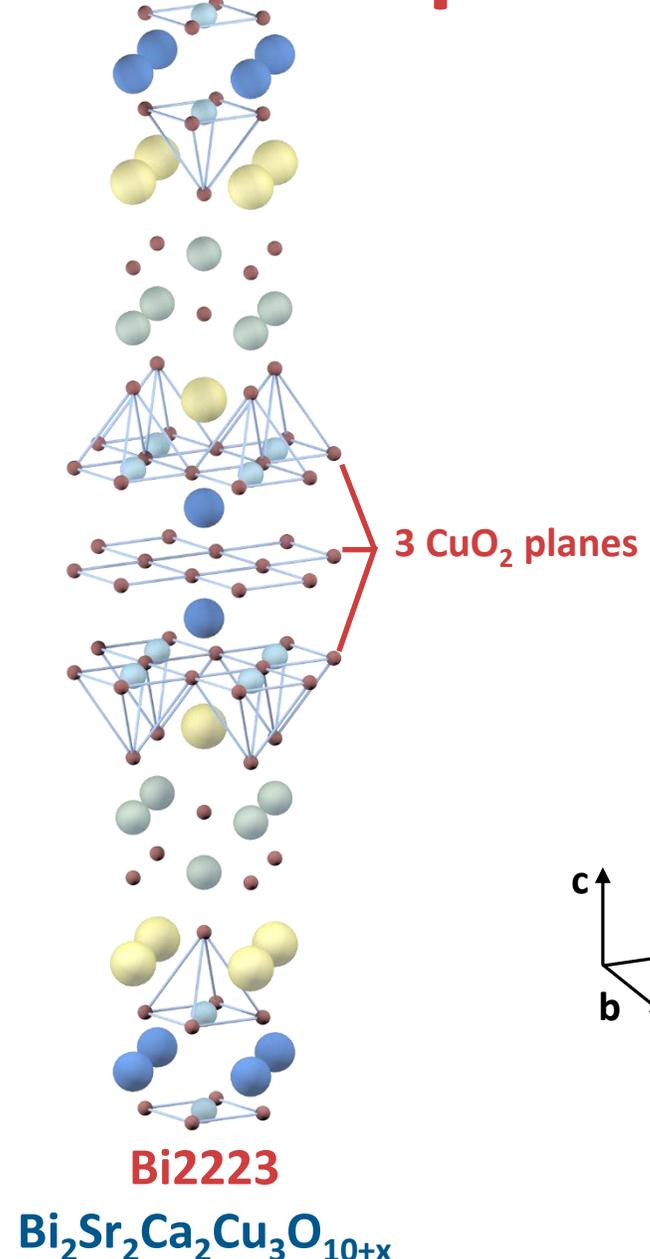
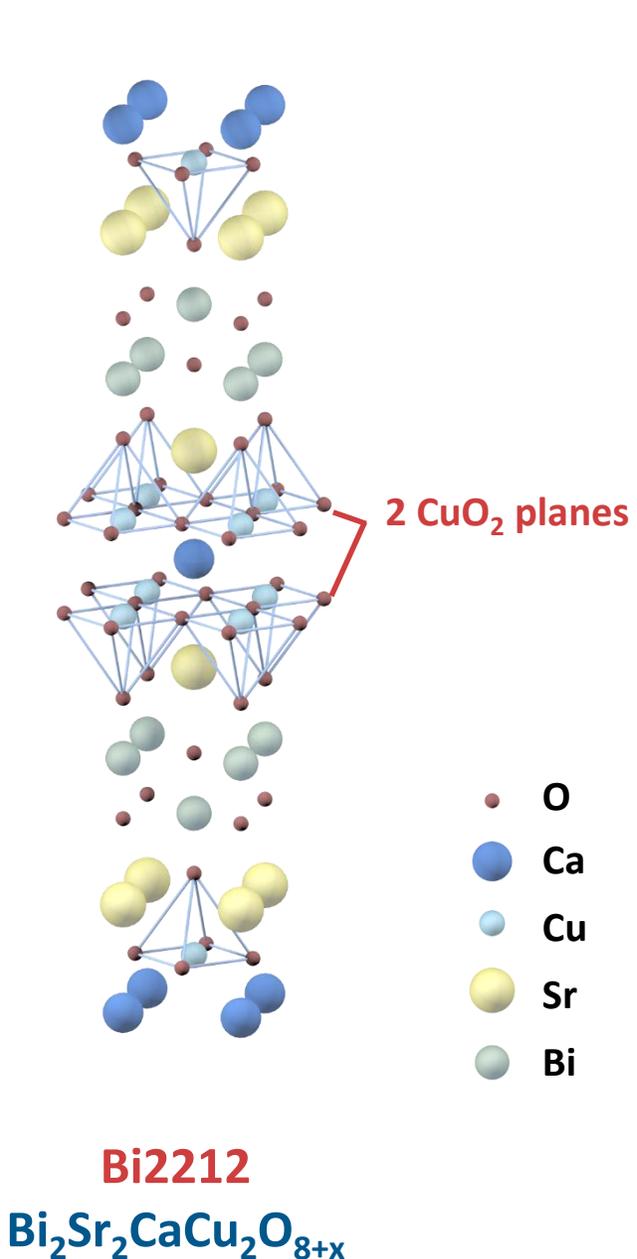
From REBCO coated conductors to REBCO-based cables

# From superconducting materials ... to technical superconductors

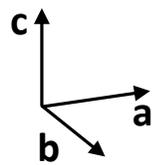


1. Superconducting ?	10'000
2. T <sub>c</sub> > 4.2K & B <sub>c2</sub> > 10T ?	100
3. J <sub>c</sub> > 1000 A/mm <sup>2</sup> ?	~10

# HTS materials for technical superconductors

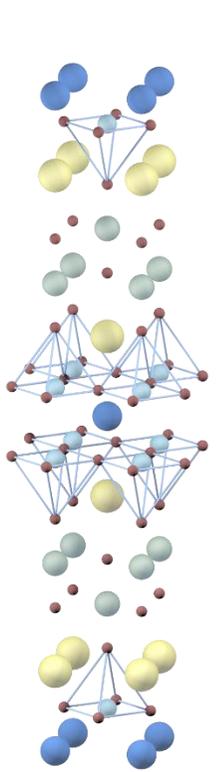


$\frac{b}{a} \approx 1.001$  in BSCCO  
 $\frac{b}{a} \approx 1.02$  in YBCO

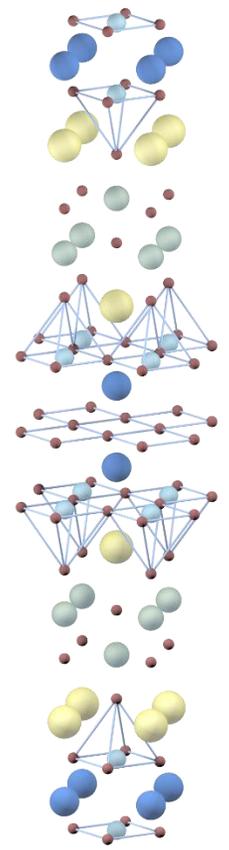


	Bi2212	Bi2223	Y123
a [Å]	5.415	5.413	3.8227
b [Å]	5.421	5.421	3.8872
c [Å]	30.880	37.010	11.680
# of adjacent CuO <sub>2</sub> planes	2	3	2
T <sub>c</sub> [K]	91	110	92

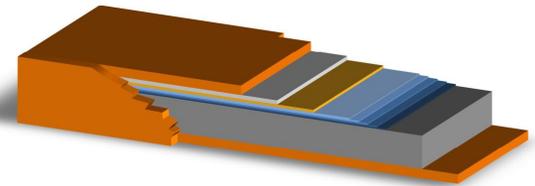
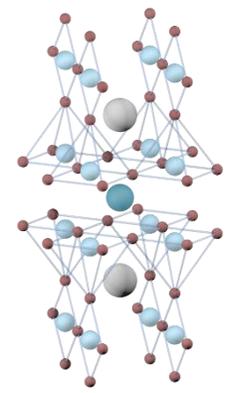
# The evolution to the present wires and tapes



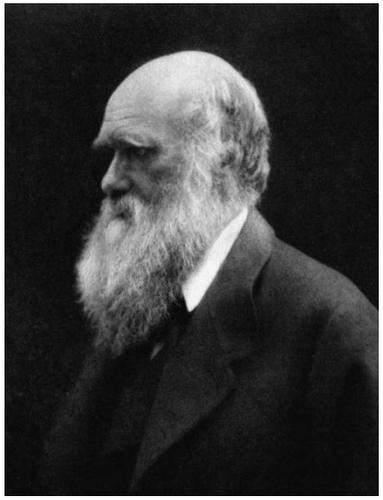
Bi2212 Powder-In-Tube wire



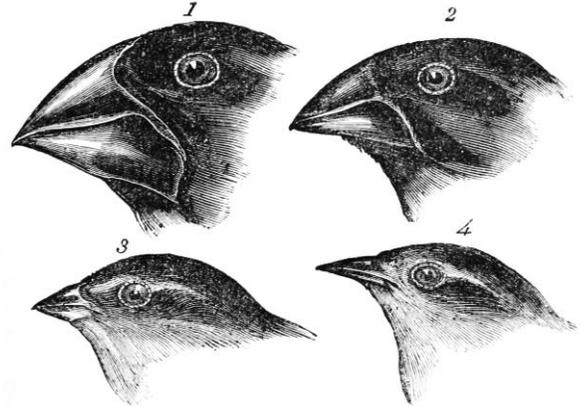
Bi2223 Powder-In-Tube tape



Y123 Coated Conductor



Darwin's finches



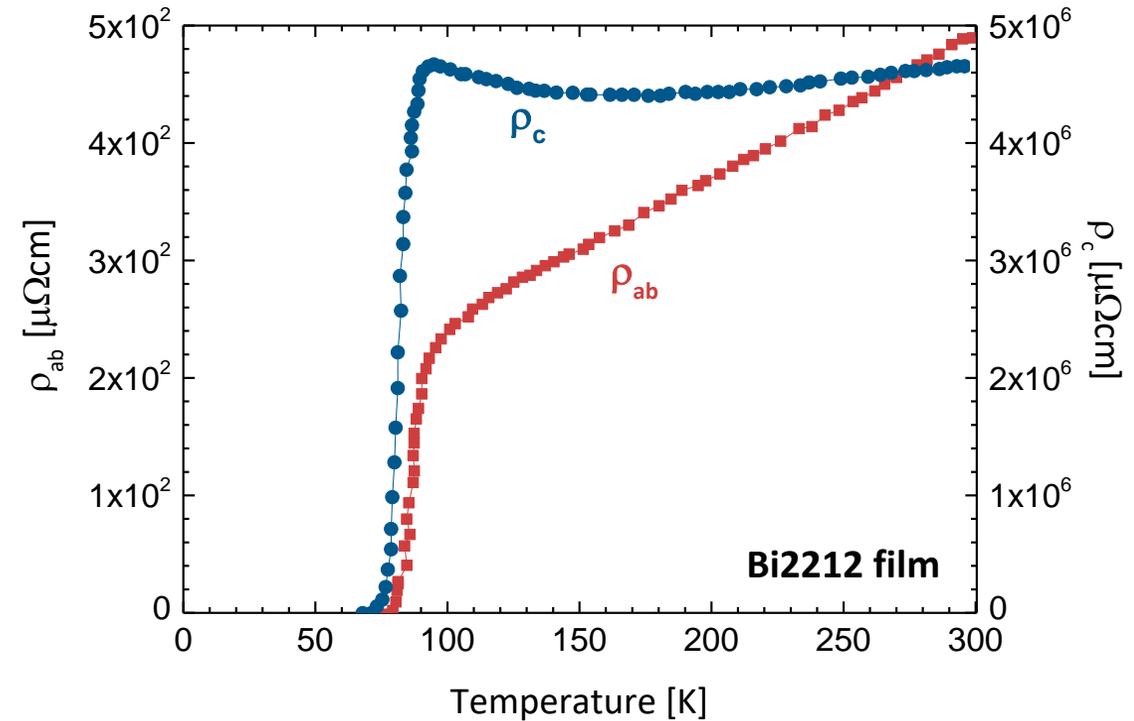
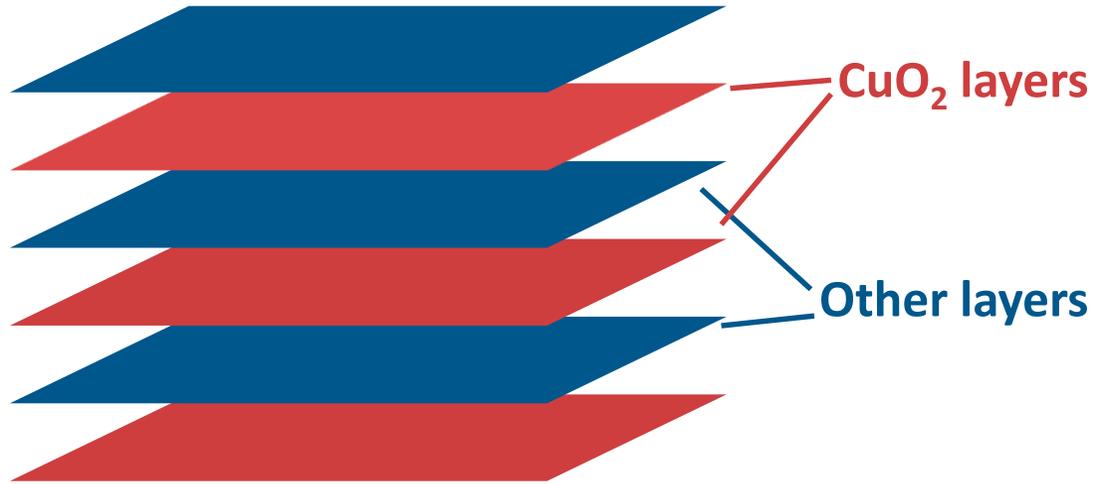
1. Geospiza magnirostris.  
2. Geospiza fortis.  
3. Geospiza parvula.  
4. Certhiidea olivacea.

**The basics of HTS conductor fabrication with focus on REBCO**

**1. How to deal with anisotropy**

$$\rho = \frac{m}{ne^2\tau}$$

# Layered structure and Anisotropy



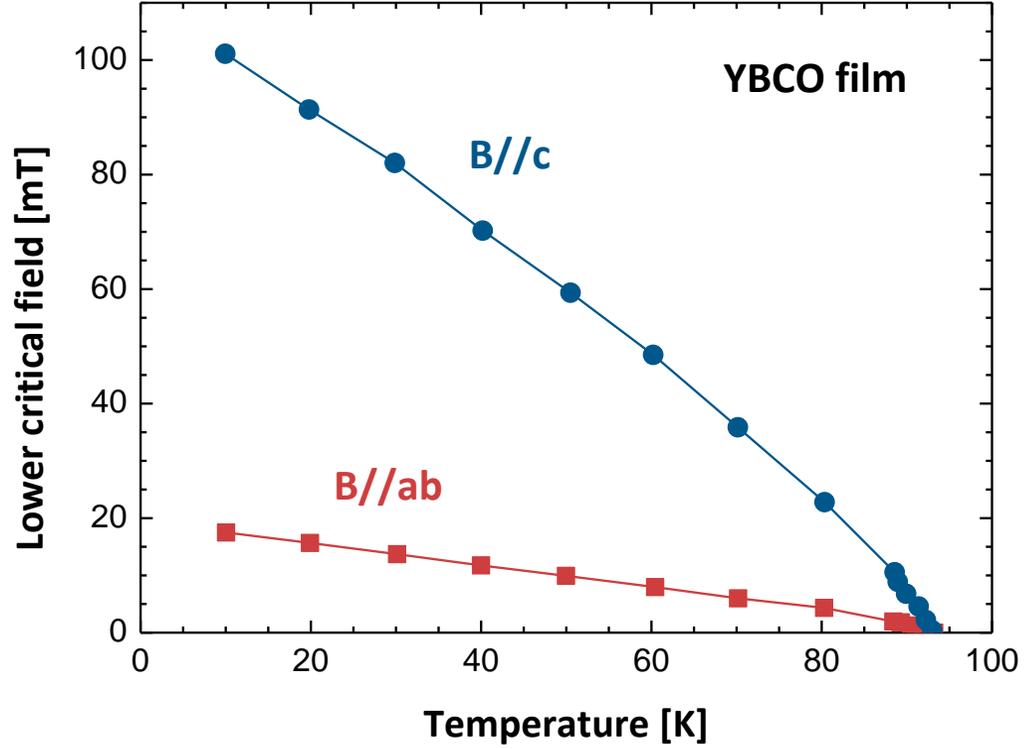
Raffy et al., Physica C 460-462 (2007) 851

Charge carriers have effective masses that depend on the crystallographic orientation

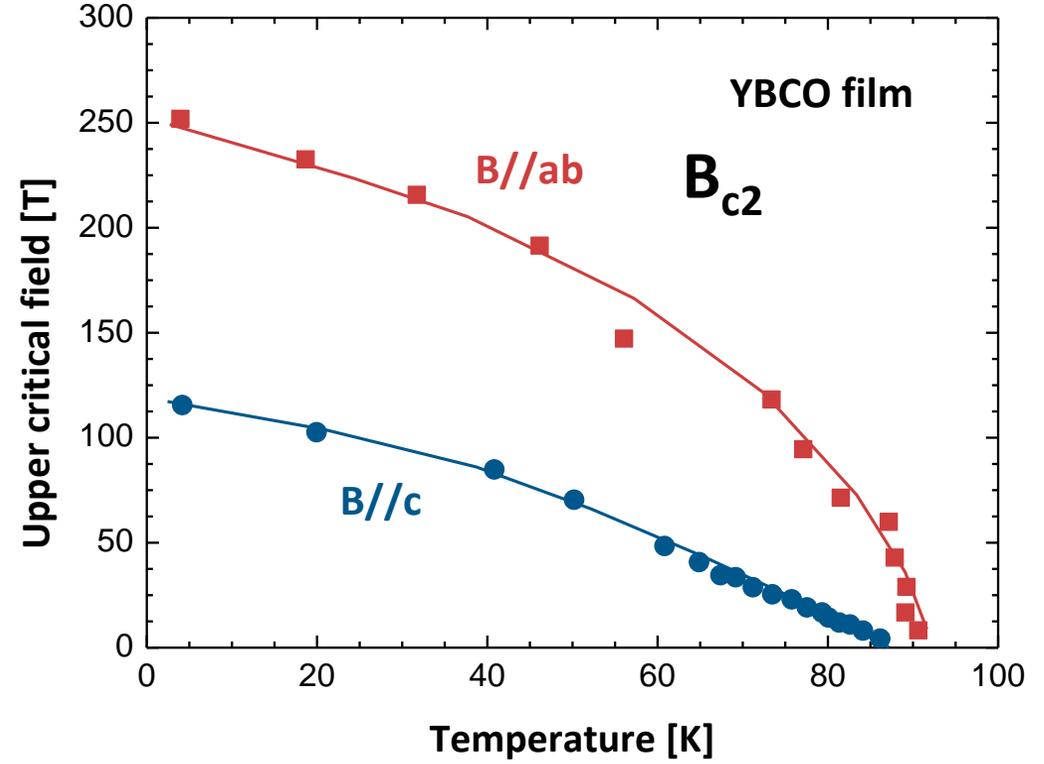
$\frac{m_c}{m_{ab}}$  ranges between 50 and 10'000 in cuprates

The superconductor lengths depend on the carrier mass:  $\xi \propto \frac{1}{\sqrt{m}}$  and  $\lambda \propto \sqrt{m}$

# Anisotropy of the critical fields $B_{c1}$ and $B_{c2}$



Liang et al., PRB 50 (1994) 4212



Nagakawa et al., JPCM 10 (1998) 11571

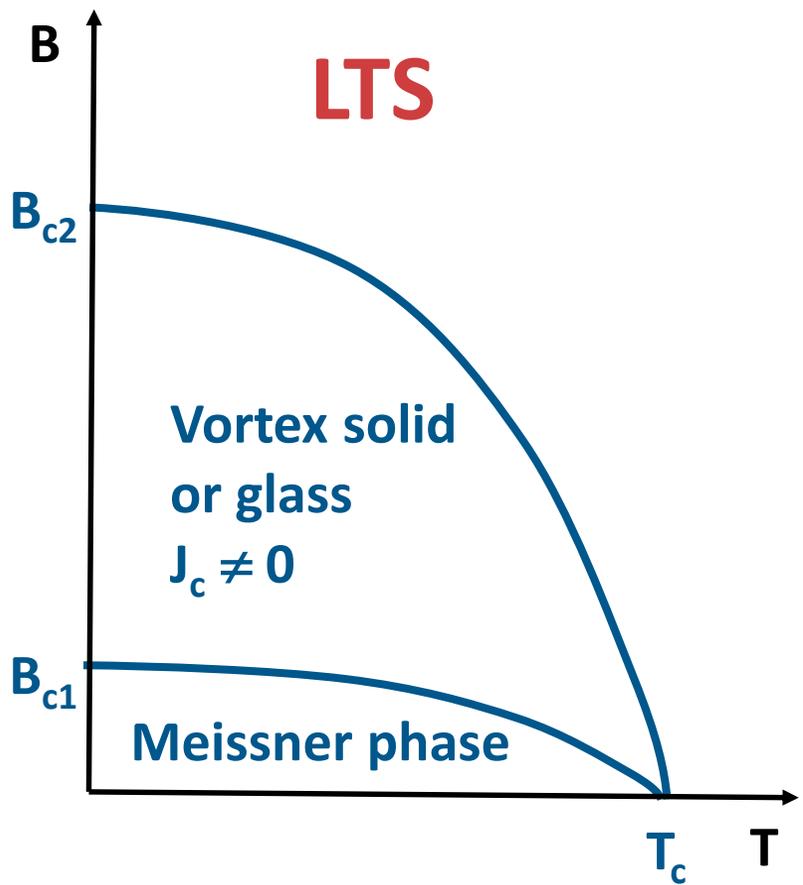
Sekitani et al., NJP 9 (2007) 47

## The superconductor anisotropy parameter

$$\gamma = \sqrt{\frac{m_c}{m_{ab}}} = \frac{\lambda_c}{\lambda_{ab}} = \frac{\xi_{ab}}{\xi_c} = \frac{B_{c2}^{ab}}{B_{c2}^c} = \frac{B_{c1}^c}{B_{c1}^{ab}}$$

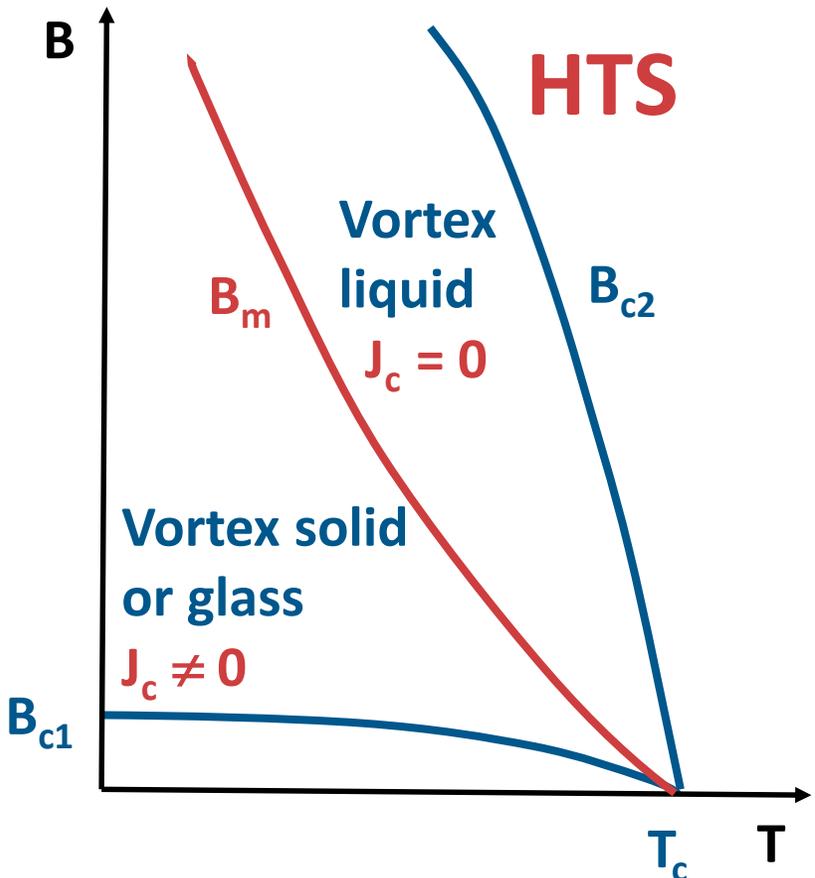
	Bi2212	Bi2223	Y123
$\gamma$	~150	~30	~7

# Anisotropy, magnetic phase diagram & critical current



LTS: in-field  $J_c \rightarrow 0$  close to  $B_{c2}$

# Anisotropy, magnetic phase diagram & critical current



In the case of a **anisotropic 3D** superconductor

$$\frac{B_m}{B_{c2}} \propto \frac{c_L^4 \Phi_0^4 \xi_{ab}^2}{(k_B T)^2 \lambda_{ab}^4 \gamma^2}$$

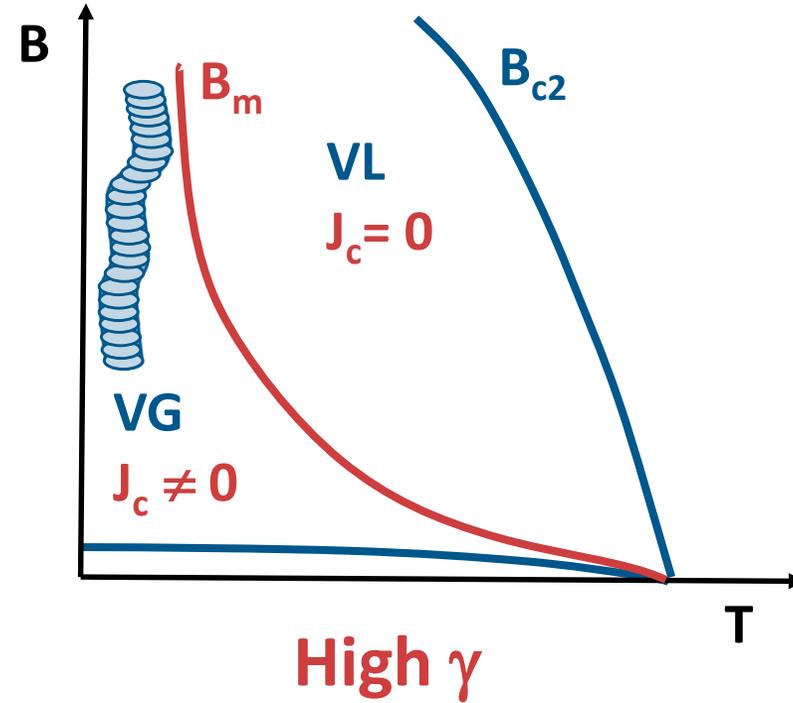
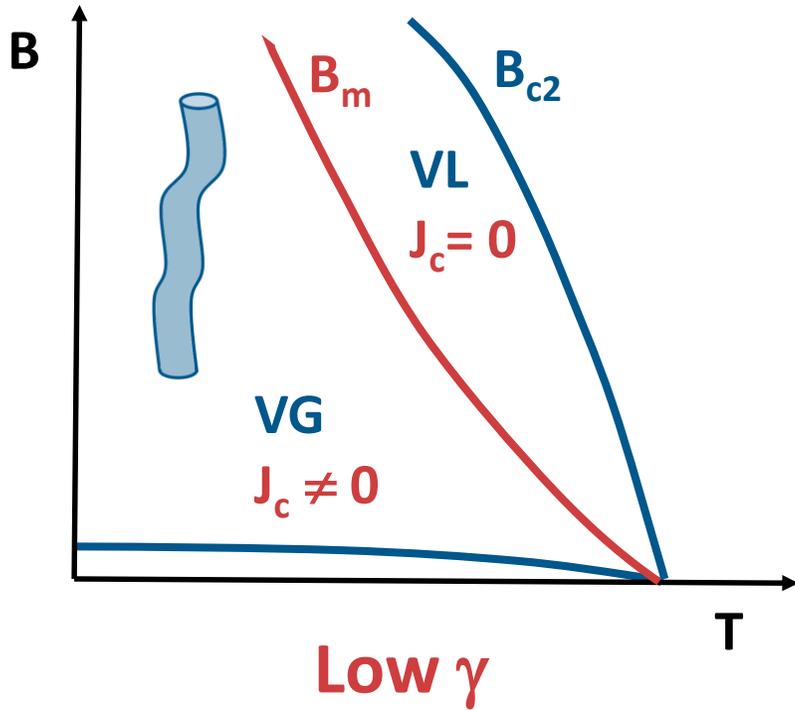
And high anisotropy makes the things worse

**HTS:** in-field  $J_c \rightarrow 0$  at the melting field  $B_m$

Anisotropy brings a field limitation in applications

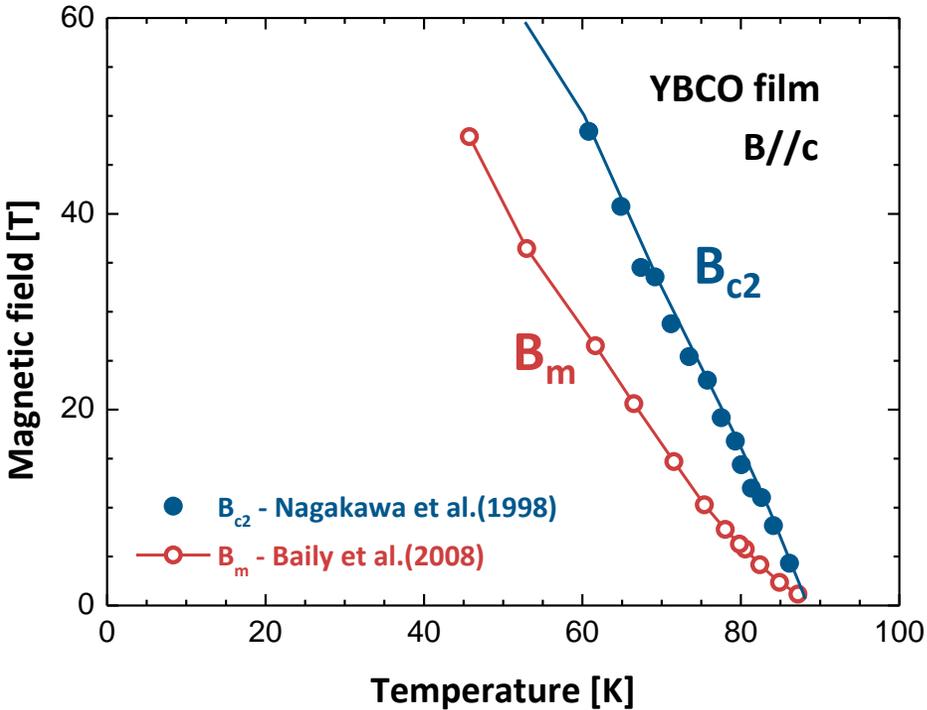
# 3-D melting vs. 2-D melting

Magnetic field perpendicular to the  $\text{CuO}_2$  planes



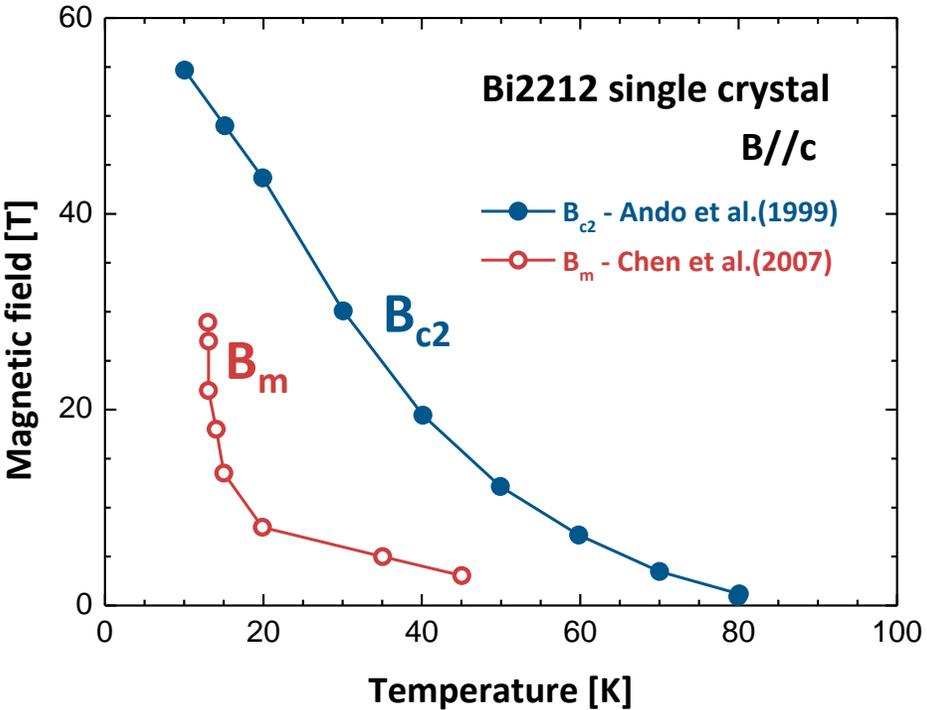
High  $\gamma$  : transition from **vortex lines in 3-D** to **vortex “pancakes” in 2-D**

# 3-D melting vs. 2-D melting



**Low  $\gamma$  : YBCO**

YBCO has in-field  $J_c \neq 0$  even at 77 K



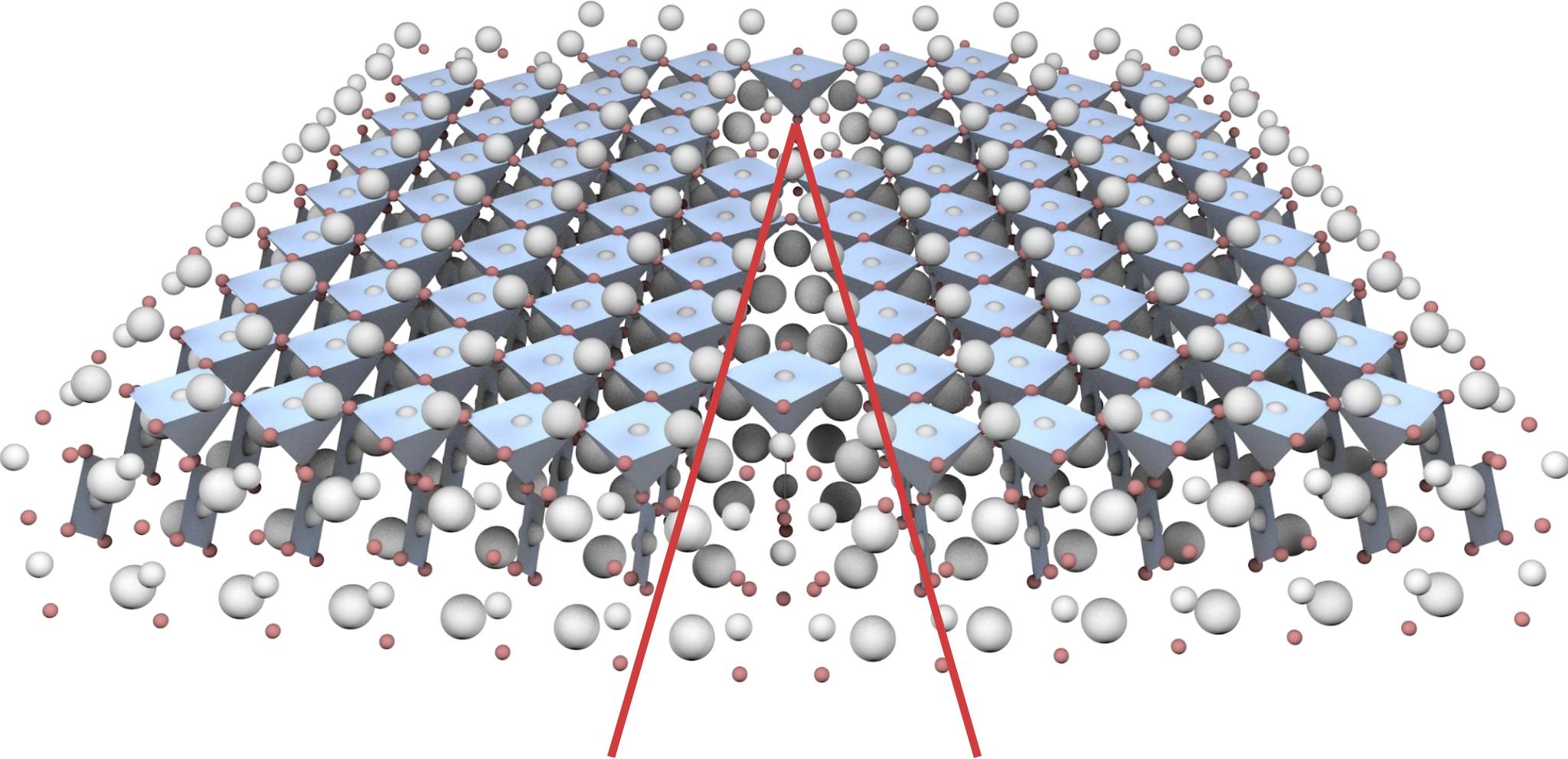
**High  $\gamma$  : Bi2212**

Bi2212 in-field  $J_c$  drops rapidly to zero with temperature

**The basics of HTS conductor fabrication with focus on REBCO**

## **2. How to deal with grain boundaries**

# Grain Boundaries in HTS



# Industrial fabrication of REBCO coated conductors



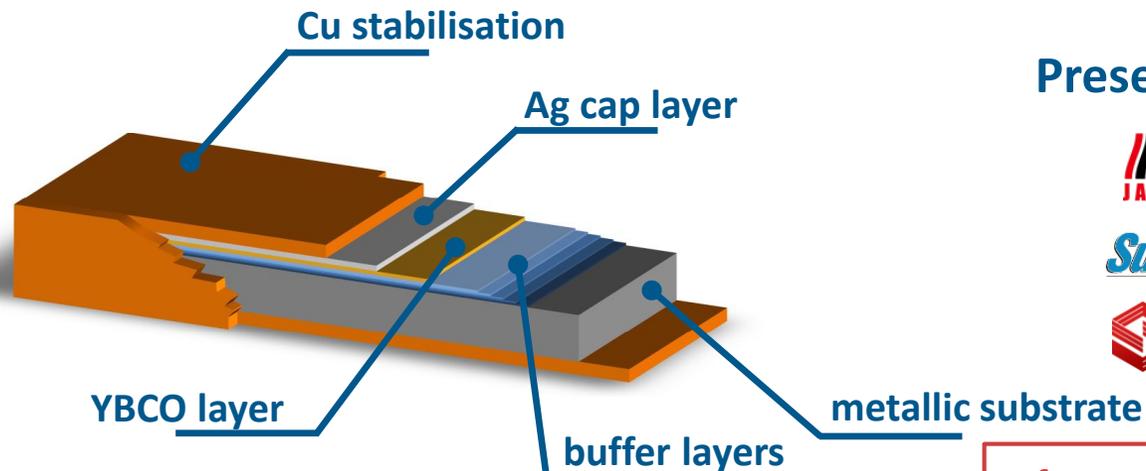
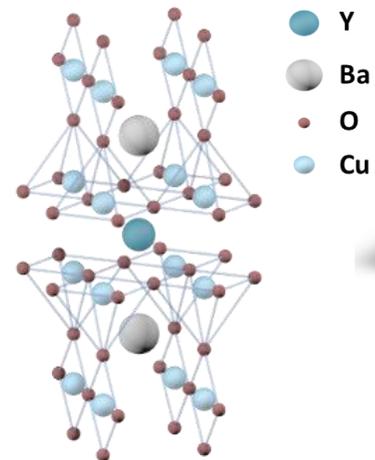
Iijima et al., APL **60** (1992) 769

DOI: [10.1063/1.106514](https://doi.org/10.1063/1.106514)

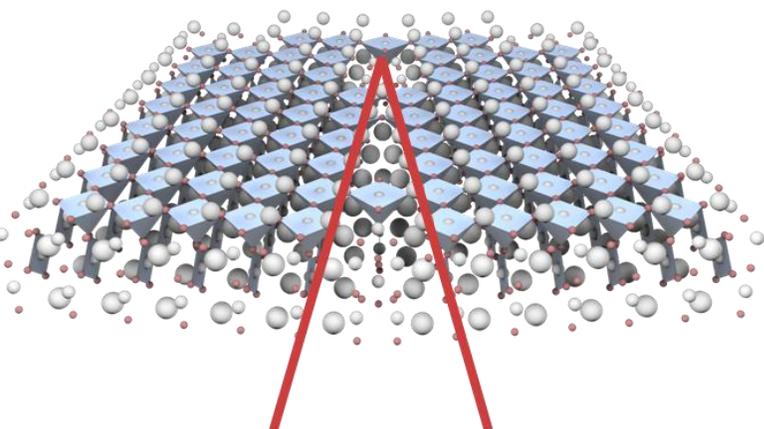
Goyal et al., APL **69** (1996) 1795

DOI: [10.1063/1.117489](https://doi.org/10.1063/1.117489)

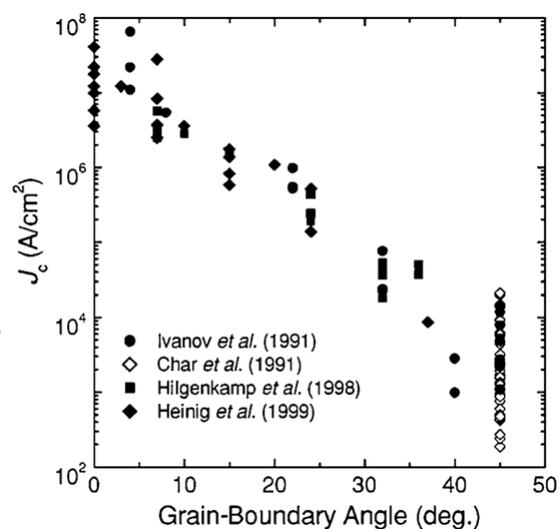
Presently produced by



**~1 μm of YBCO in a ~100 μm thick tape**



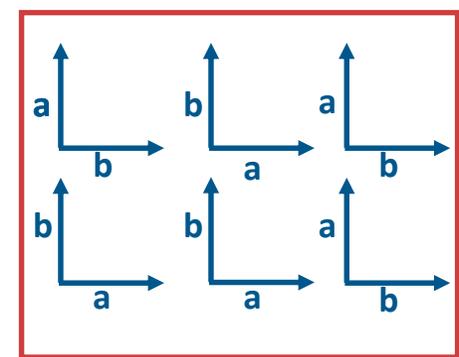
[001] tilt grain boundary



H. Hilgenkamp and J. Mannhart, RMP **74** (2002) 485

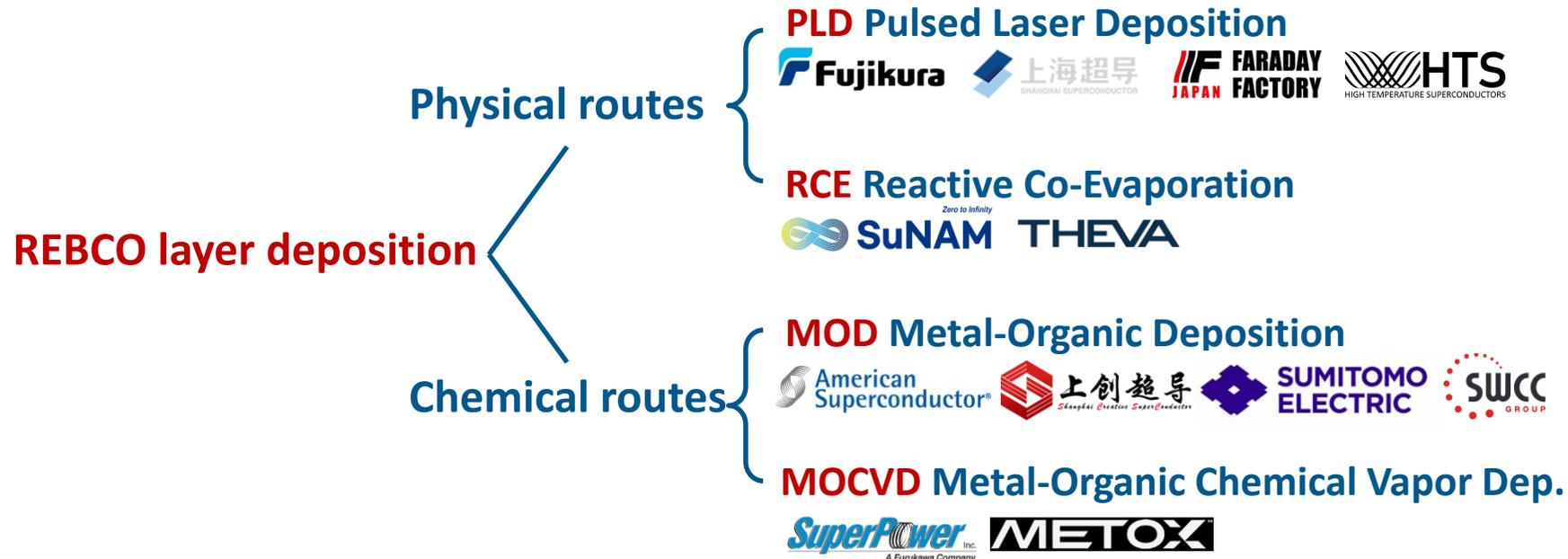
DOI: [10.1103/RevModPhys.74.485](https://doi.org/10.1103/RevModPhys.74.485)

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

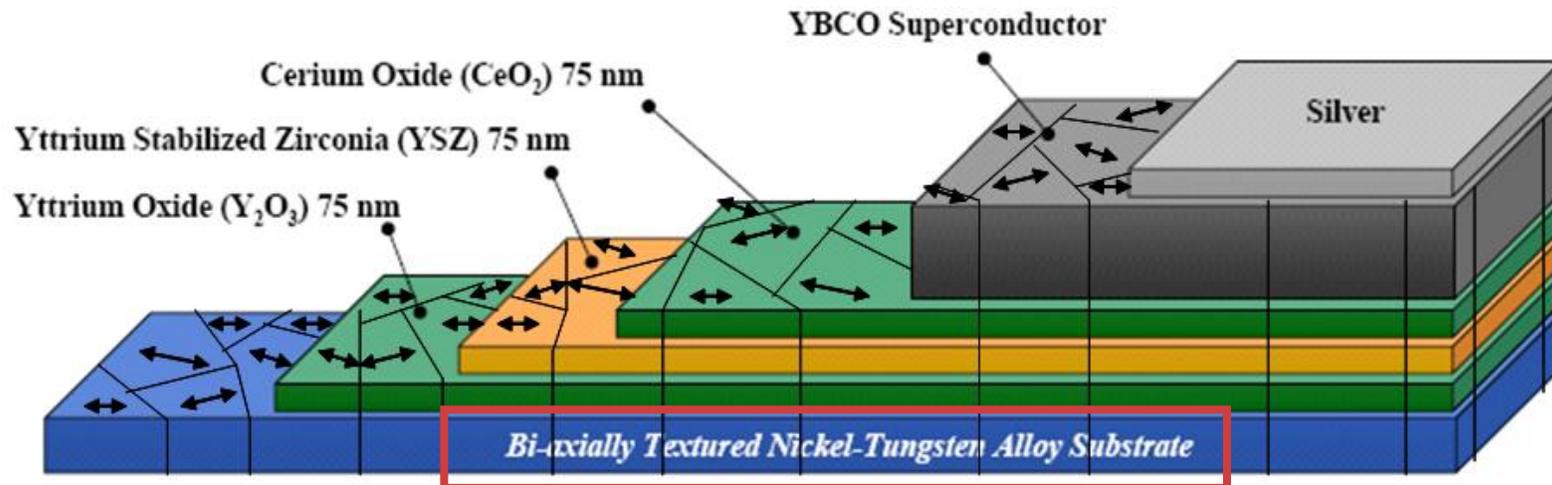
At least 4-5 medium-large companies using alternative approaches for growing epitaxial REBCO on flexible metallic substrates in km-lengths. Nowadays the **main driver** is **FUSION**



# REBCO conductor technology: RABiTS template

## RABiTS : Rolling-Assisted, Biaxially Textured Substrates

- [100] cube texture is created in the NiW substrate by a rolling-and-recrystallization process
- Several epitaxial buffer layers are needed to provide a lattice matched surface for growing the HTS layer

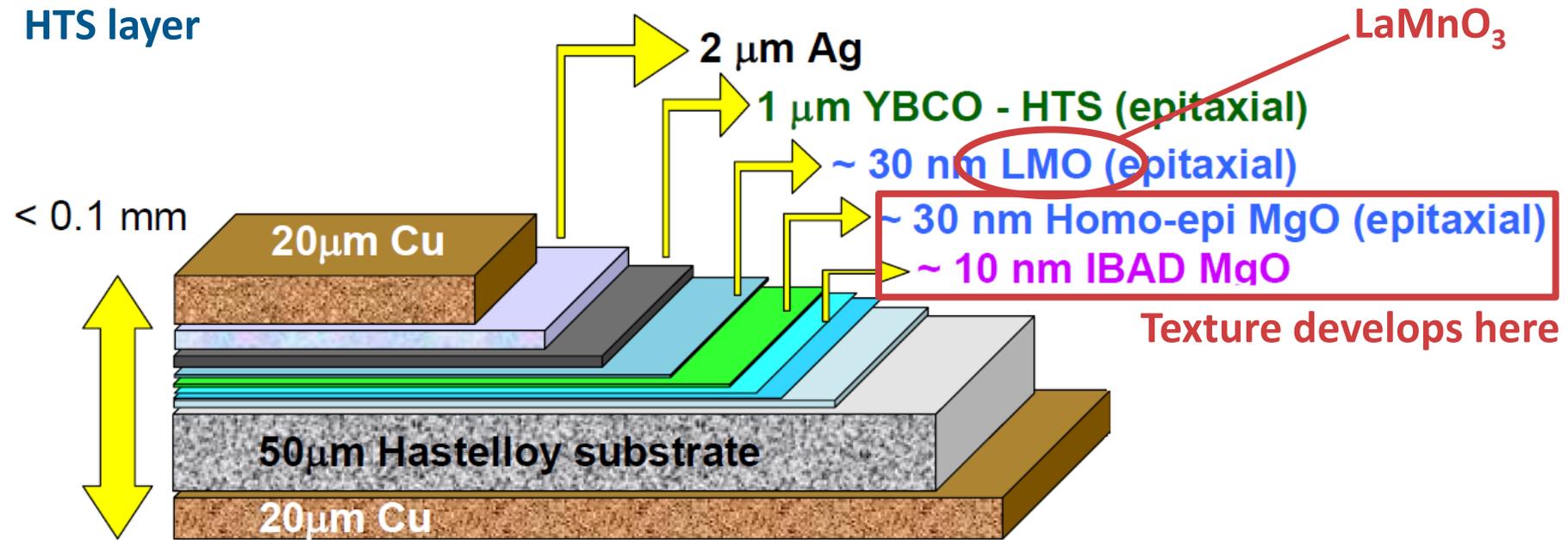


Texture develops here

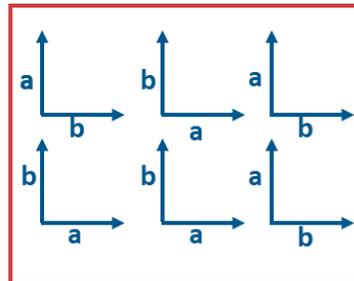
# REBCO conductor technology: IBAD template

## IBAD : Ion Beam Assisted Deposition

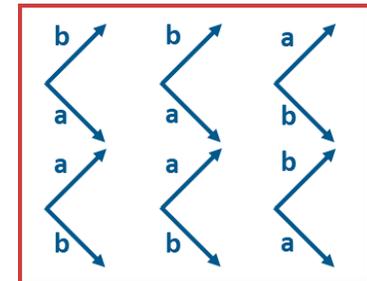
- A biaxially textured MgO layer is then grown on a polycrystalline Hastelloy tape
- Several other buffer layers are needed to provide a lattice matched surface for growing the HTS layer



REBCO with LMO buffer



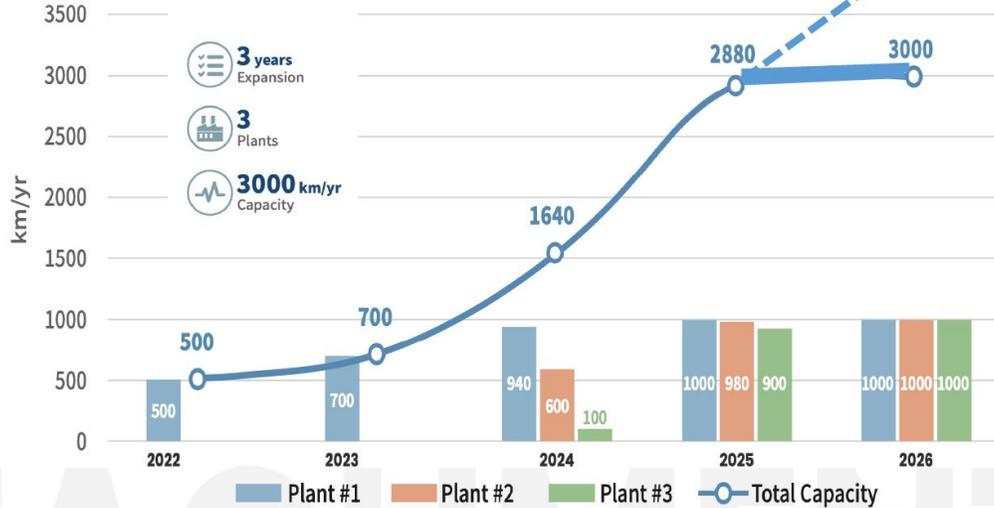
REBCO without LMO buffer



# Fusion-driven expansion of REBCO production capacity



SST Production Capacity Outlook



**1600 km<sub>12</sub>/yr (2024) → 3000 km<sub>12</sub>/yr (2026)**



**IF FARADAY JAPAN FACTORY**

**1300 km<sub>12</sub>/yr (2024) → 25000 km<sub>12</sub>/yr (2028)**



**SuperPower Inc. A Furukawa Company**

**200 km<sub>12</sub>/yr (2024) → 1200 km<sub>12</sub>/yr (2026)**

Tape width 12 mm  
Capacity: 100+ km<sub>12</sub>

Going wide  
25 ×

Tape width 4 × 80 -100 mm  
Capacity: 2500+ km<sub>12</sub>

**THEVA**

ALPHA  
2023

BETA  
2025

**100 km<sub>12</sub>/yr (2023) → 2500 km<sub>12</sub>/yr (after 2025)**

# Outline

An introduction to high temperature superconductivity

The basics of HTS conductor fabrication with focus on REBCO

**An overview of the properties of REBCO coated conductors**

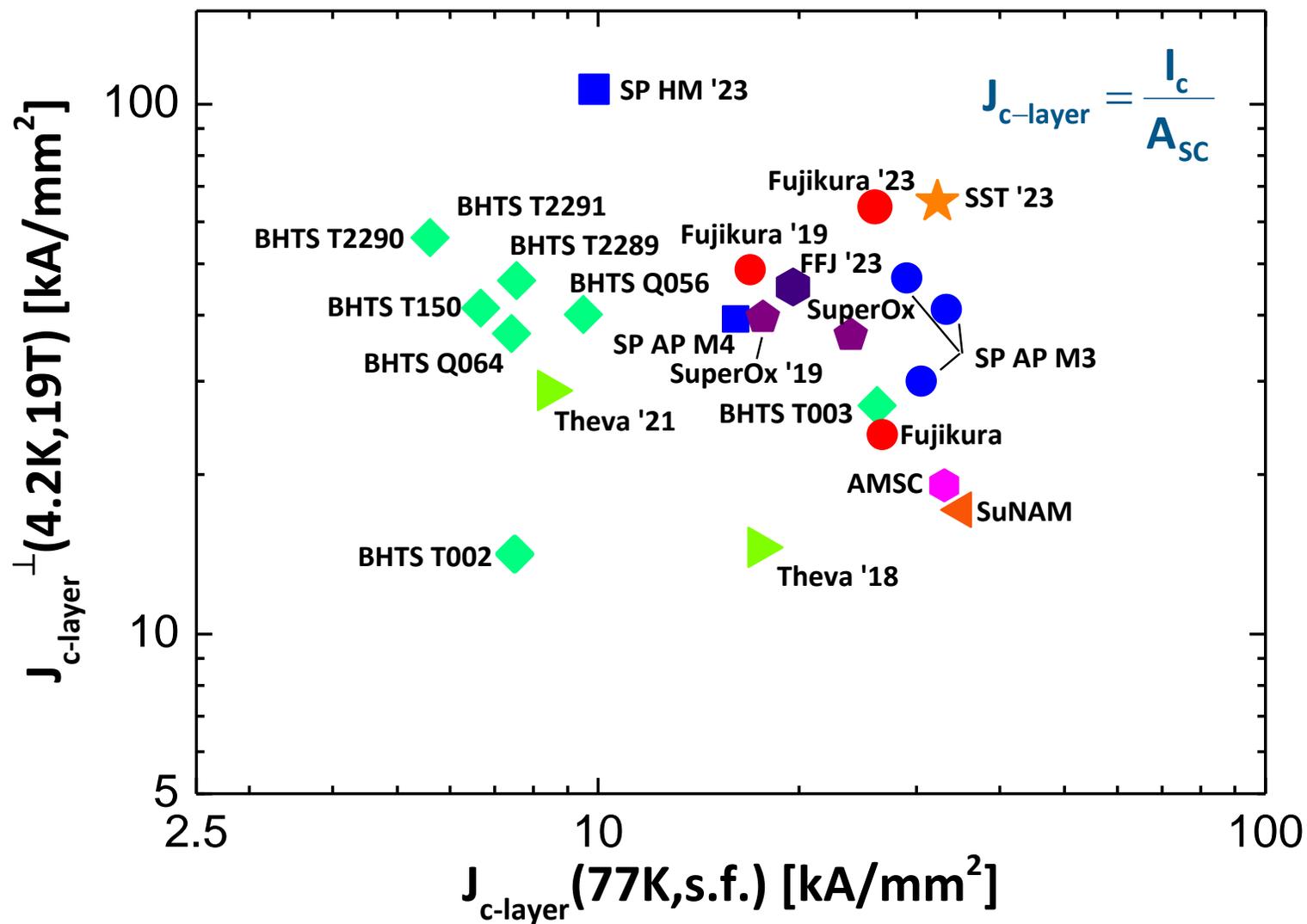
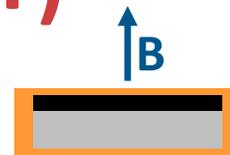
- **Developments to improve performance**
- **Reversible and irreversible effects under mechanical loads**

From REBCO coated conductors to REBCO-based cables



# Performance overview (2016): $J_c(77K, s.f.)$ vs. $J_c^\perp(4.2K, 19T)$

## Updated with recent results (2019-2024)

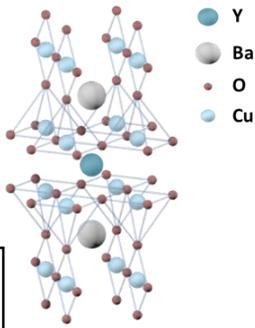


# Tailoring the critical current density of REBCO

## 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

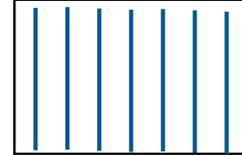
Tailored **artificial defects**, e.g. nanocolumns (1D) and nanoparticles (3D), can be introduced to reduce anisotropy and enhance performance



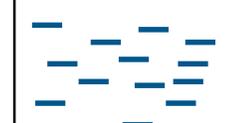
point defects



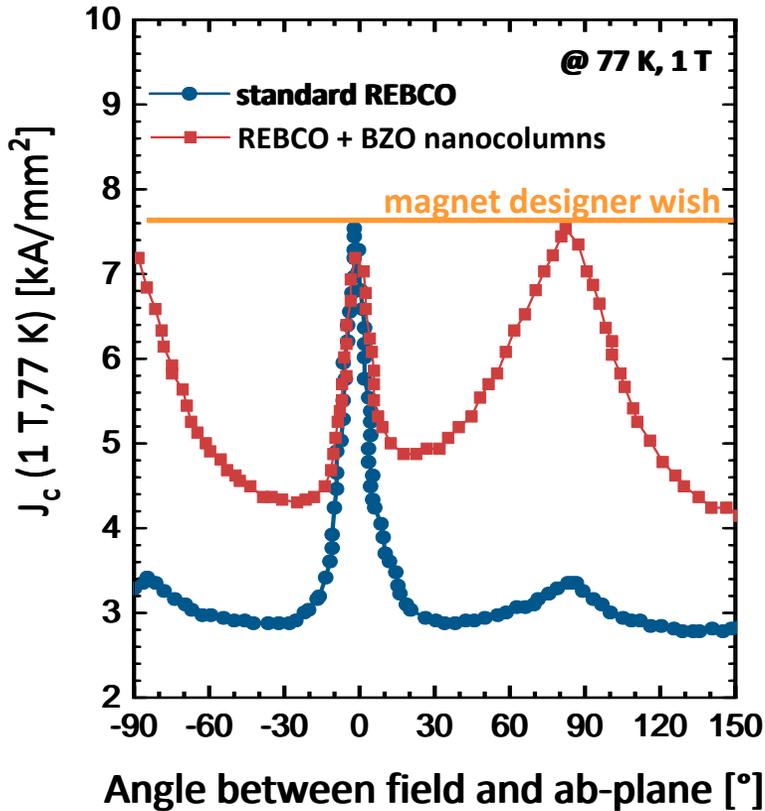
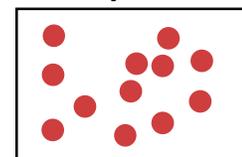
grain boundaries



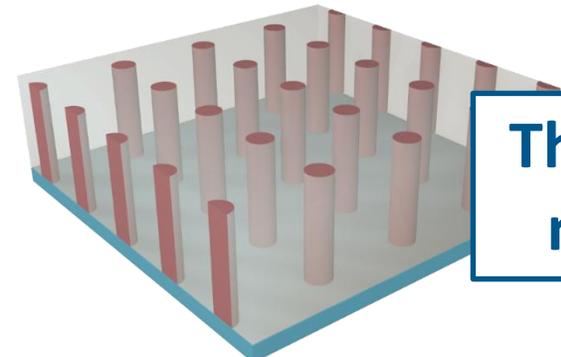
stacking faults



nanoparticles



BaZrO<sub>3</sub> (BZO) and BaHfO<sub>3</sub> (BHO) precipitate in the form of nanocolumns oriented along the c-axis of REBCO

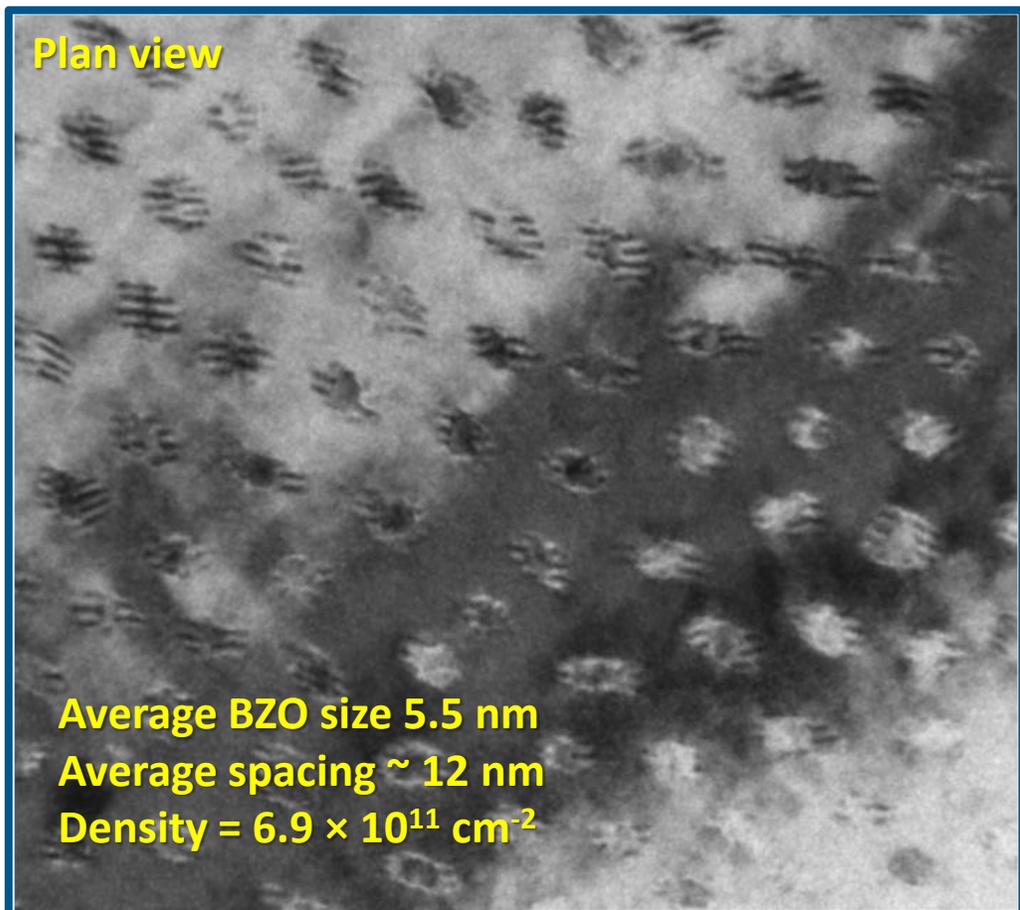


The approach varies from one manufacturer to the others

J. Driscoll *et al.*, Nat. Mat. **3** (2004) 439  
 DOI: [10.1038/nmat1156](https://doi.org/10.1038/nmat1156)  
 A. Goyal *et al.*, SUST **18** (2005) 1533  
 DOI: [10.1088/0953-2048/18/11/021](https://doi.org/10.1088/0953-2048/18/11/021)

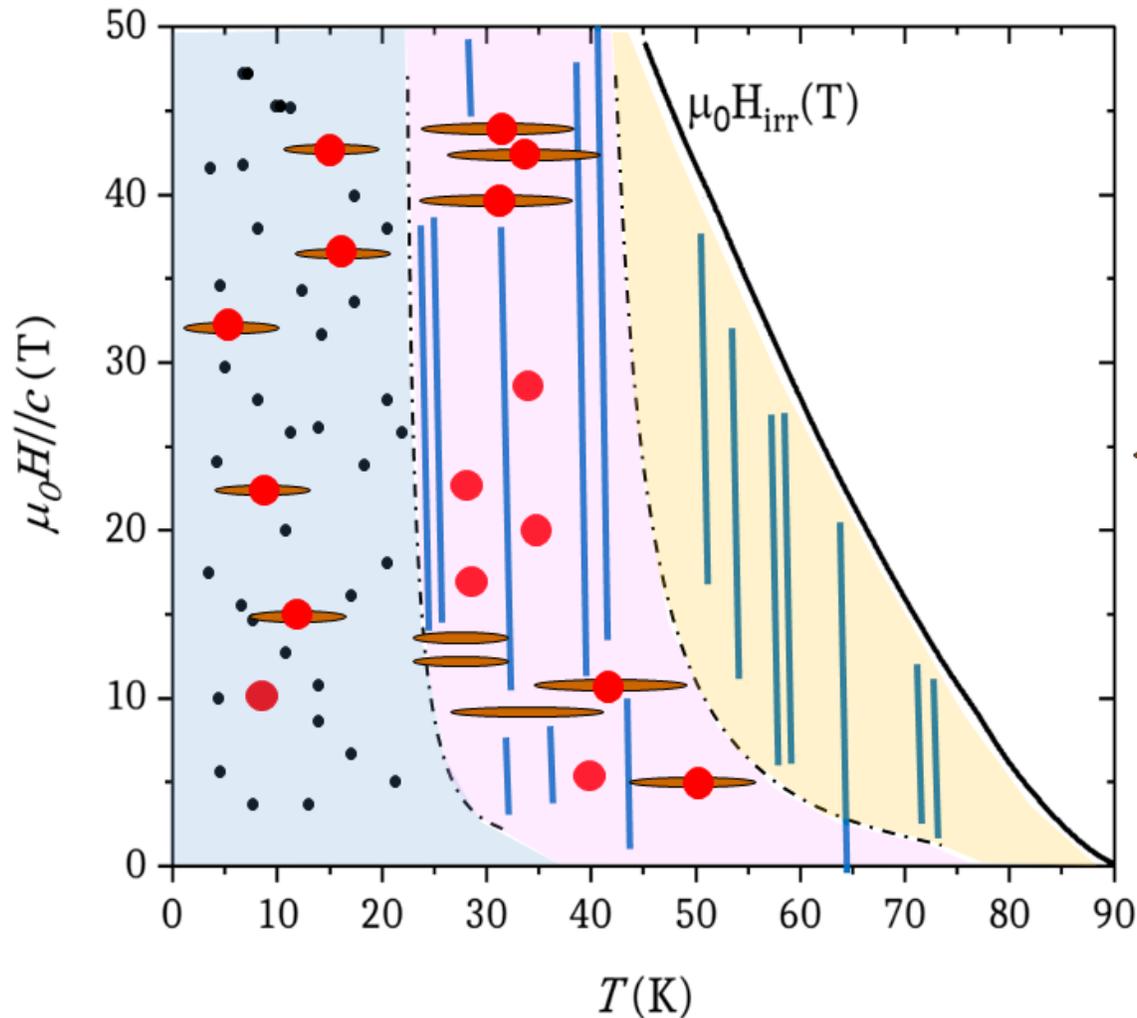
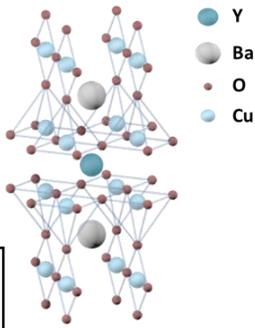
# Tailoring the critical current density of REBCO

## Morphology of the BZO nanocolumns

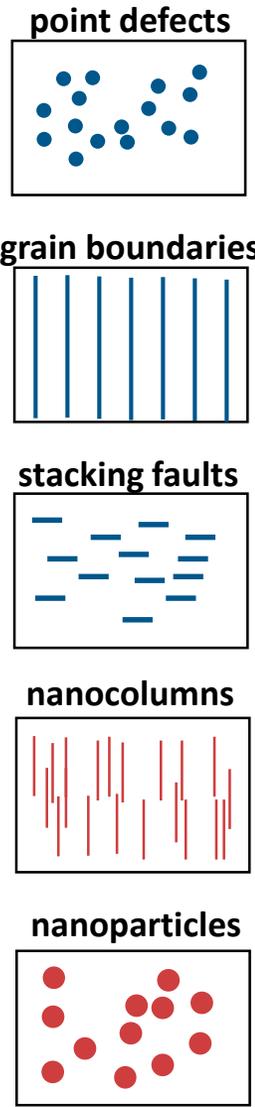


# Tailoring the critical current density of REBCO

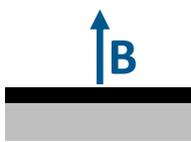
## Anisotropy, Intrinsic and Artificial defects and their Dimensionality



- Vacancy
- Nanorod or Twin boundary
- Intergrowth and dislocation (nanostrain)
- Nanoparticle

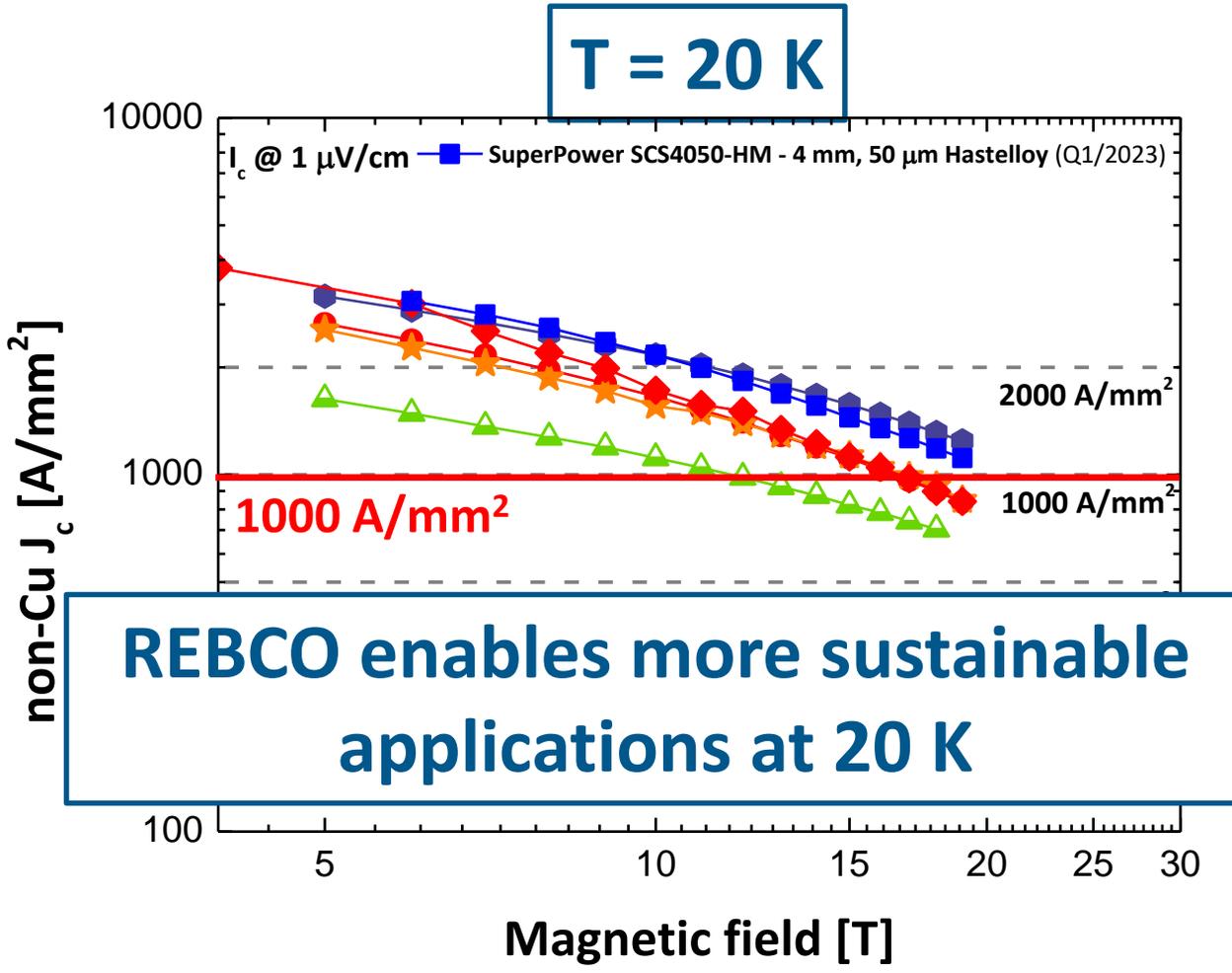
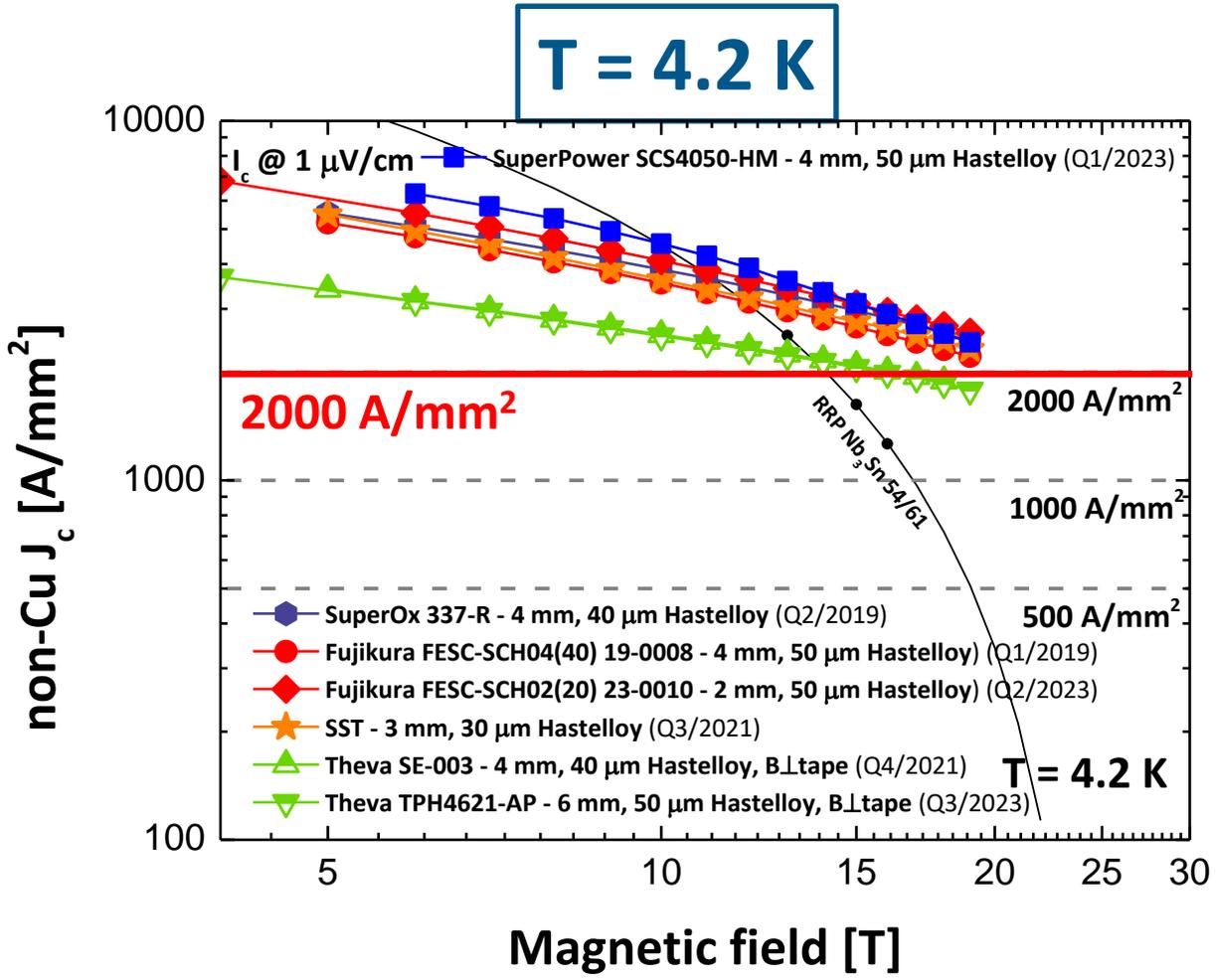


# Comparison of the performance: non-Cu $J_c$



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

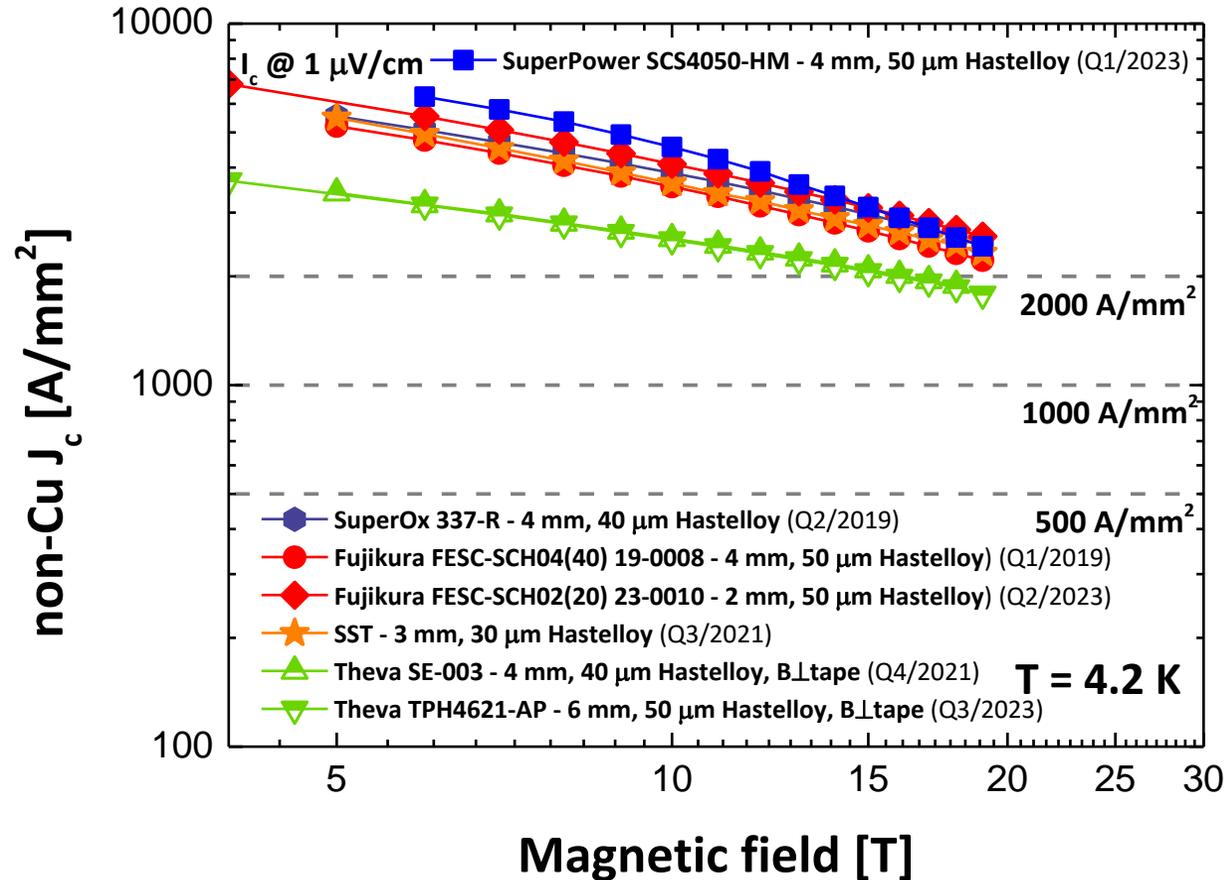
$$\text{non-Cu } J_c = \frac{I_c}{A_{\text{tot}} - A_{\text{Cu}}}$$



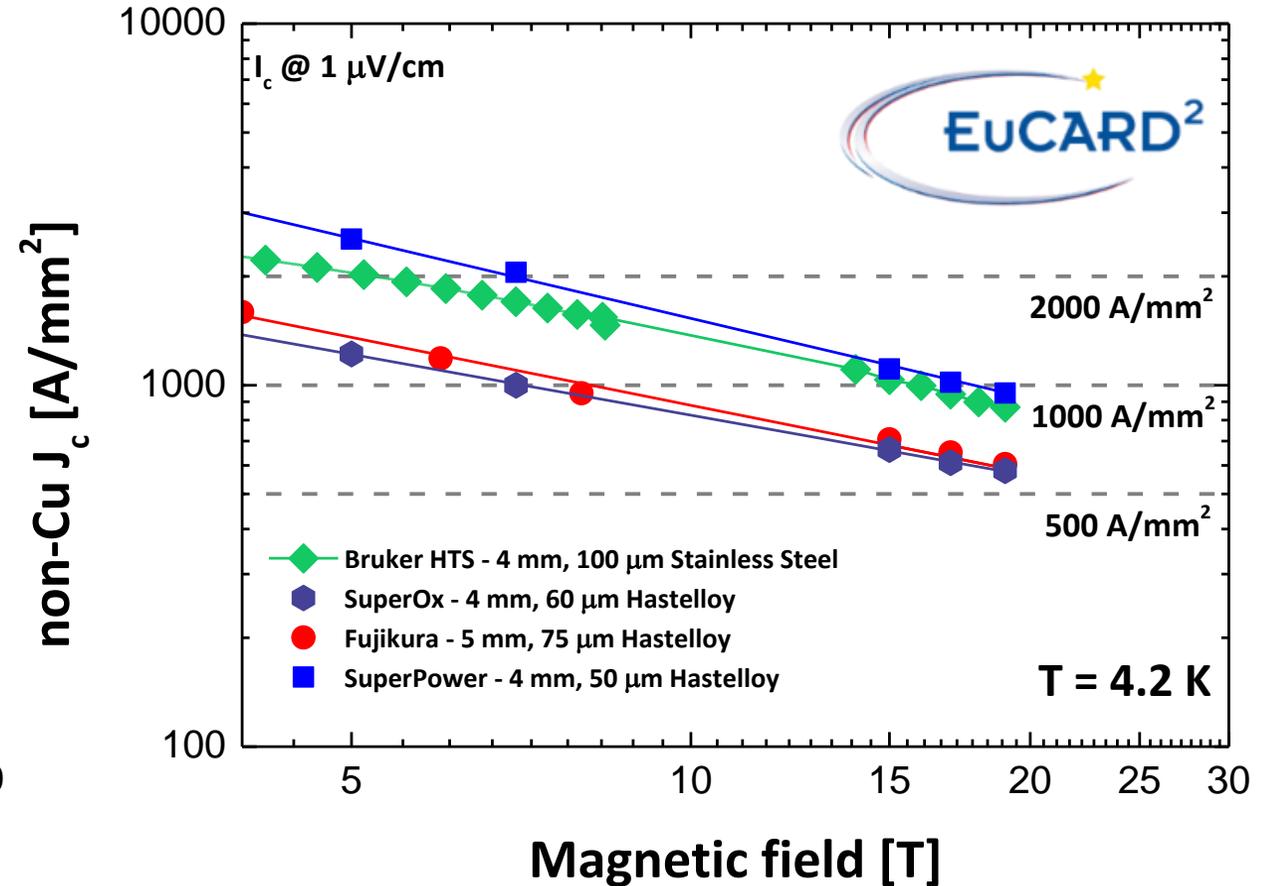
**REBCO enables more sustainable applications at 20 K**

# 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

 (2013-2017) is achieved and surpassed in modern tapes at 20 K !!

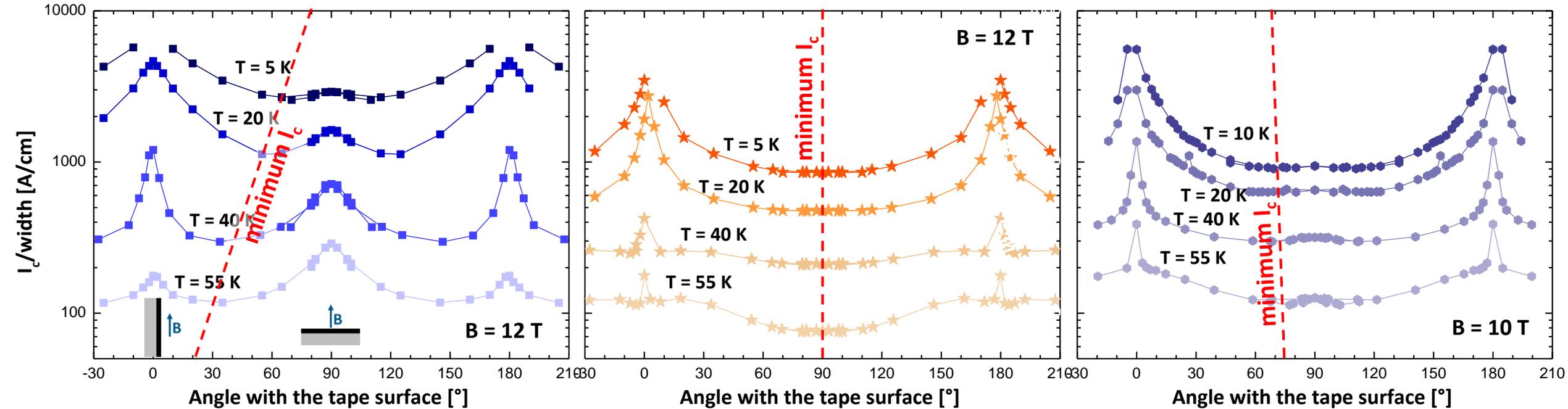
CS, [WAMHTS-2](#)

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

DOI: [10.3390/instruments5010008](https://doi.org/10.3390/instruments5010008)

# $I_c(B, \theta, T)$ does not exhibit universal behaviour

## Comparison of the results on tapes from three manufacturers



... and this has implications for magnet design

**Is the high  $J_c$  all you need ?**

Operate at **high current density** is a necessary condition, but it is **not sufficient**

Other crucial requirements:

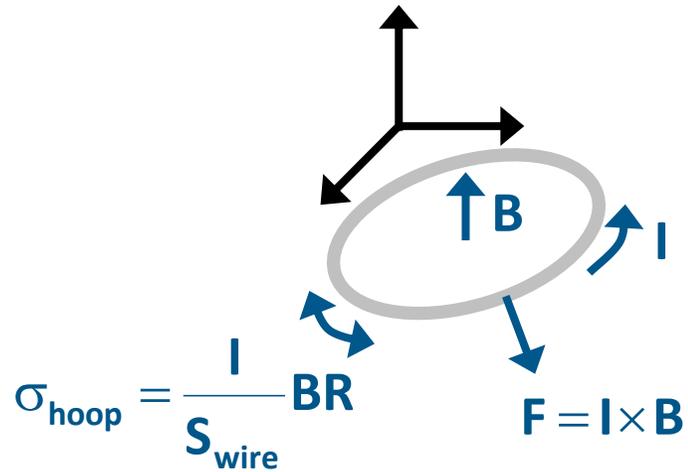
- ➔ • **Have high tolerance to stress** Magnetic forces
- **Be safe in case of magnet quench** Quench detection, NZPV
- **Have low magnetization** Applications to NMR, MRI, HEP magnets
- **Have a persistent joint technology** Applications to NMR, MRI

Operate at **high current density** is a necessary condition,  
but it is **not sufficient**

Other crucial requirements:

- **Have high tolerance to stress** Magnetic forces
- **Be safe in case of magnet quench** Quench detection, NZPV
- **Have low magnetization** Applications to NMR, MRI, HEP magnets
- **Have a persistent joint technology** Applications to NMR, MRI

# Magnetic stresses in the winding

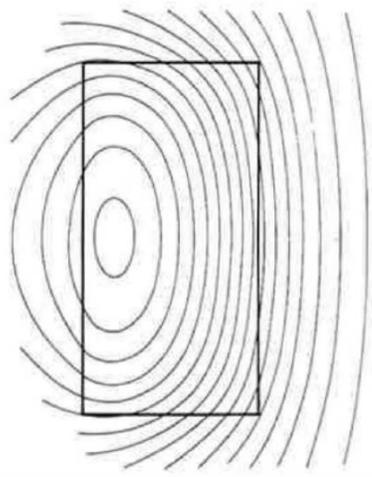


Hoop stress levels **above 100 MPa** are common

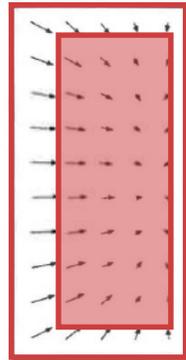
As an example, the NHMFL 32 T magnet operates at **400 MPa**

In a real winding adjacent turns press on each other and develop 3D stresses

## SOLENOID

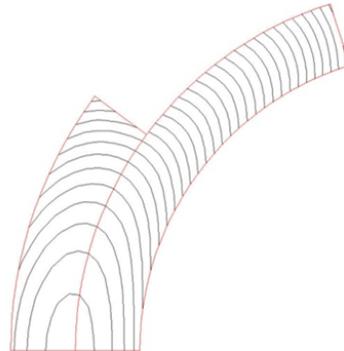


magnetic lines of force

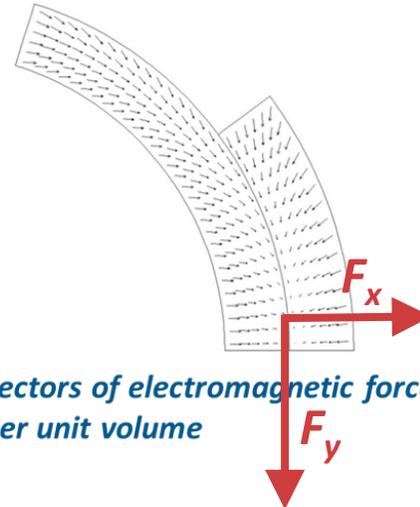


vectors of electromagnetic force per unit volume

## DIPOLE



magnetic lines of force



vectors of electromagnetic force per unit volume



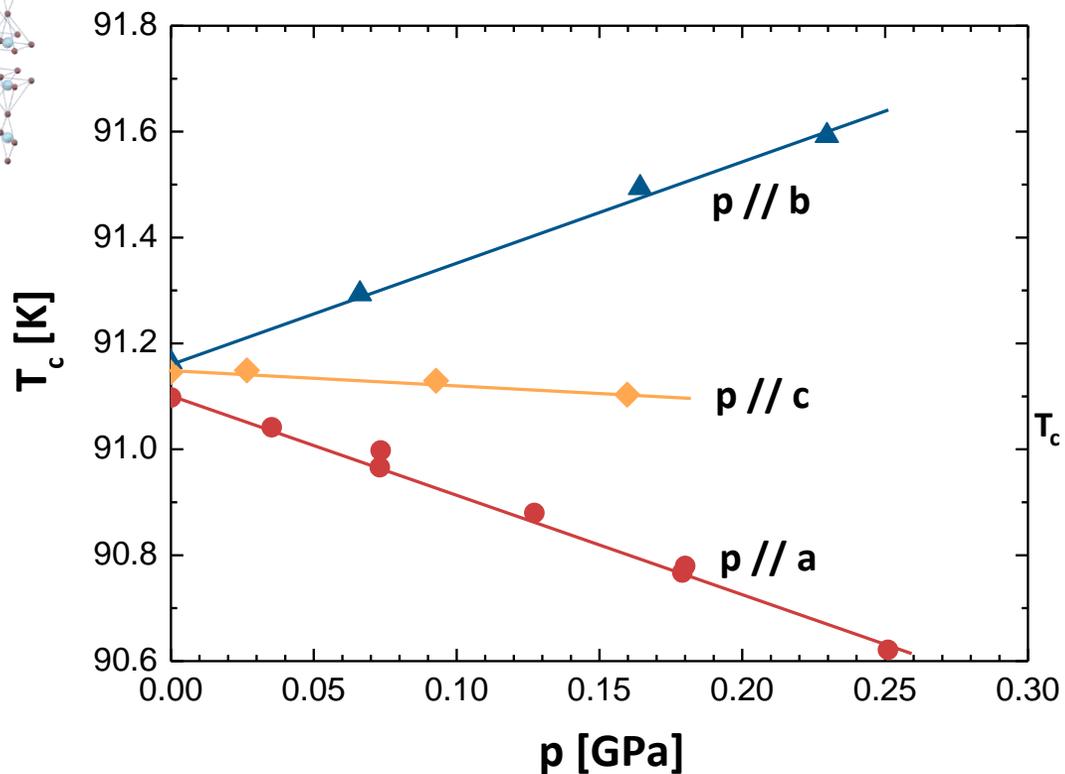
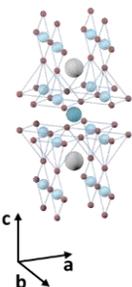
**What are the effects of stress/strain on REBCO coated conductors ?**

**1. Reversible effects**

2. Irreversible effects

# Reversible effects of strain on REBCO

## Axial loads

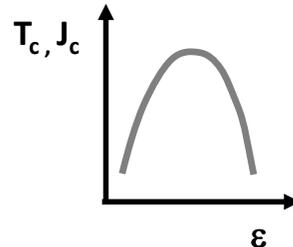
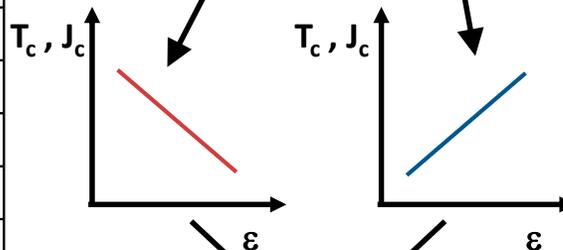
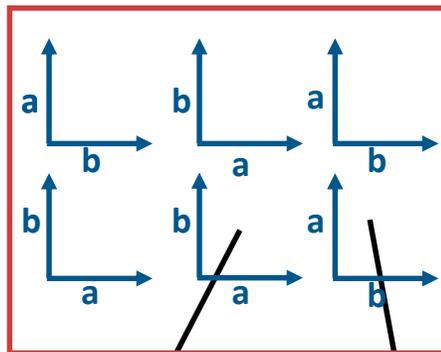


Critical temperature vs. uniaxial stress in single crystals

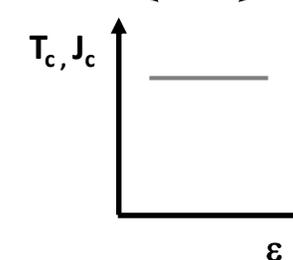
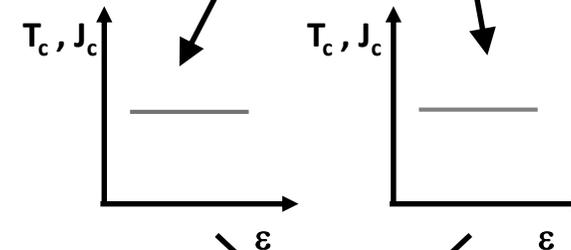
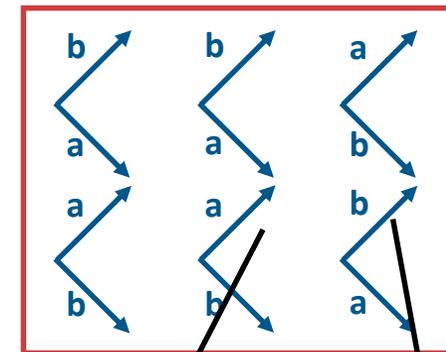
U. Welp *et al.*, PRL **69** (1992) 2130  
DOI: [10.1103/PhysRevLett.69.2130](https://doi.org/10.1103/PhysRevLett.69.2130)

## Critical current vs. uniaxial strain in coated conductors

### REBCO with LMO buffer



### REBCO without LMO buffer



D. van der Laan *et al.*, SUST **24** (2011) 115010  
DOI: [10.1088/0953-2048/23/1/014004](https://doi.org/10.1088/0953-2048/23/1/014004)

# Reversible effects of strain on REBCO

## Some good reads

P. Branch, K. Osamura, and D. Hampshire, *SUST* **33** (2020) 104006

*Weak emergence in the angular dependence of the critical current density of the high temperature superconductor coated conductor REBCO*

DOI: [10.1088/1361-6668/abaebe](https://doi.org/10.1088/1361-6668/abaebe)

P. Branch, Y. Tsui, K. Osamura, and D. P. Hampshire, *Sci. Reports* **9** (2019) 13998

*Weakly-Emergent Strain-Dependent Properties of High Field Superconductors*

DOI: [10.1038/s41598-019-50266-1](https://doi.org/10.1038/s41598-019-50266-1)

S. Awaji, T. Suzuki, H. Oguro, K. Watanabe, and K. Matsumoto, *Sci. Reports* **5** (2015) 11156

*Strain-controlled critical temperature in REBa<sub>2</sub>Cu<sub>3</sub>O<sub>y</sub>-coated conductors*

DOI: [10.1038/srep11156](https://doi.org/10.1038/srep11156)

D. C. van der Laan, T. J. Haugan, P. N. Barnes, D. Abraimov, F. Kametani, D. C. Larbalestier, and M. W. Rupich, *SUST* **23** (2010) 014004

*The effect of strain on grains and grain boundaries in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> coated conductors*

DOI: [10.1088/0953-2048/23/1/014004](https://doi.org/10.1088/0953-2048/23/1/014004)

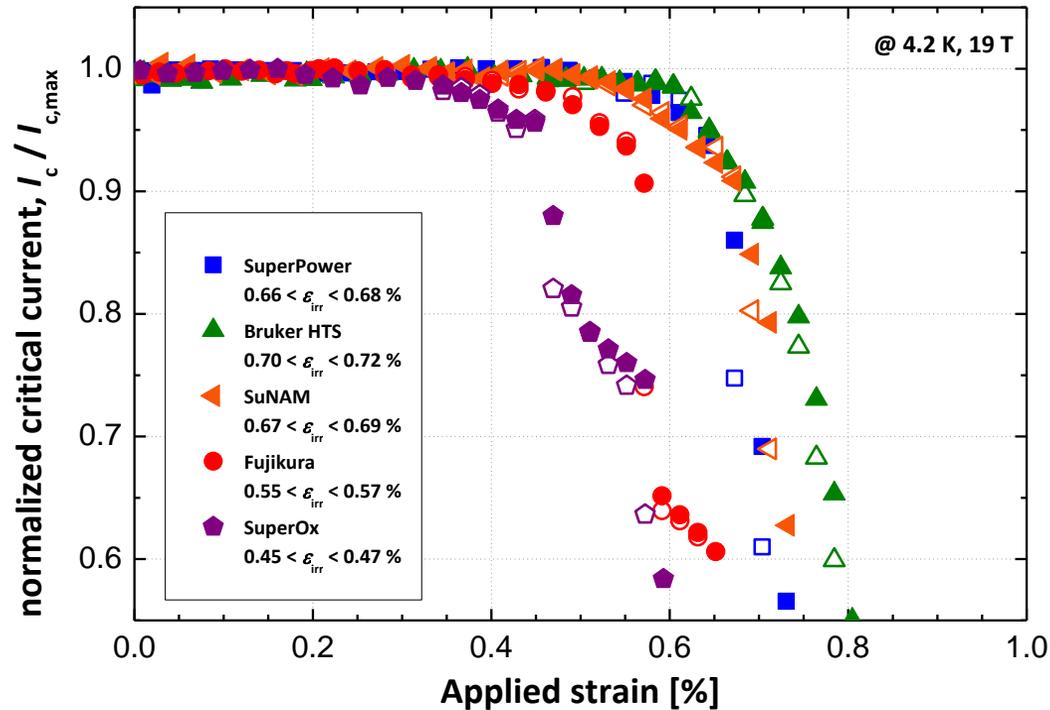
# What are the effects of stress/strain on REBCO coated conductors ?

1. Reversible effects

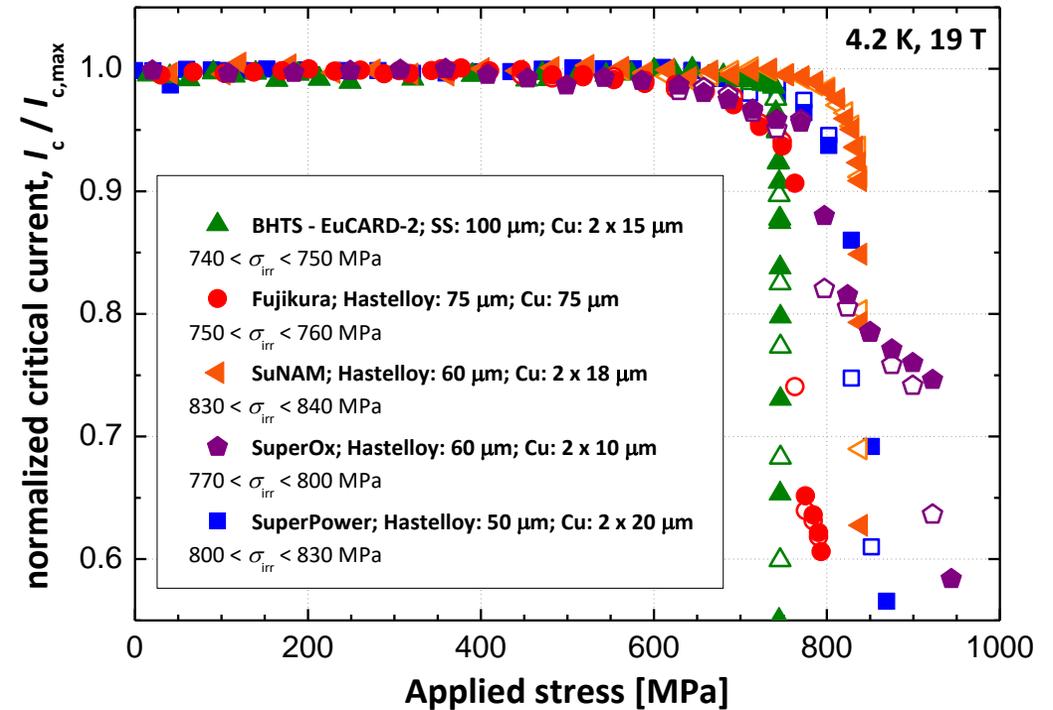
2. Irreversible effects

# Irreversible effects of strain on REBCO CCs

$I_c$  vs. longitudinal strain



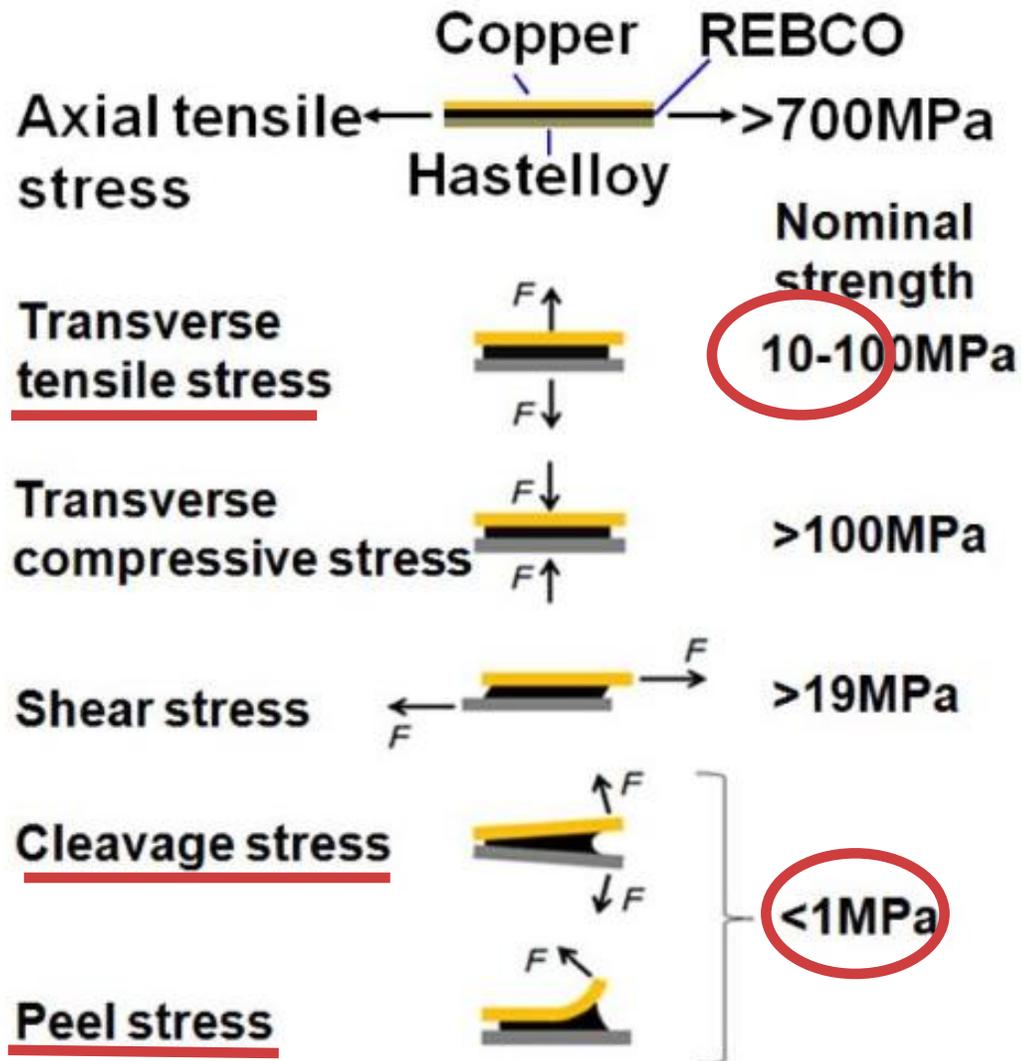
$I_c$  vs. longitudinal stress



- REBCO tapes are inherently strong, ~50% is a high strength alloy
- Very low stress effect and irreversible stress limit well above 500 MPa
- But mechanical properties are very ANISOTROPIC, tapes are prone to delamination

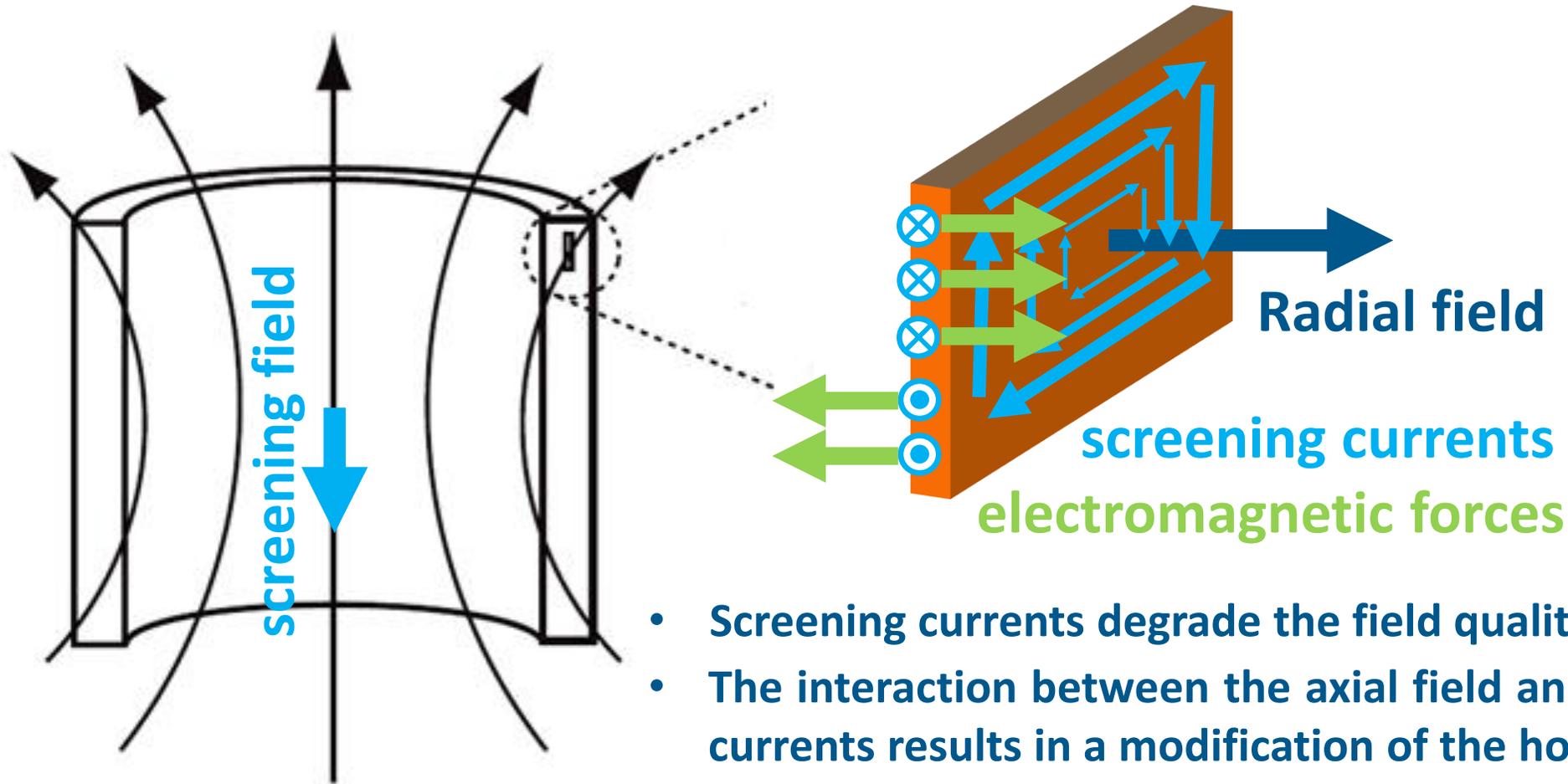


# Anisotropy of the mechanical properties of REBCO CCs



- REBCO tapes are inherently prone to delamination
- Adhesion between layers seems to be process dependent

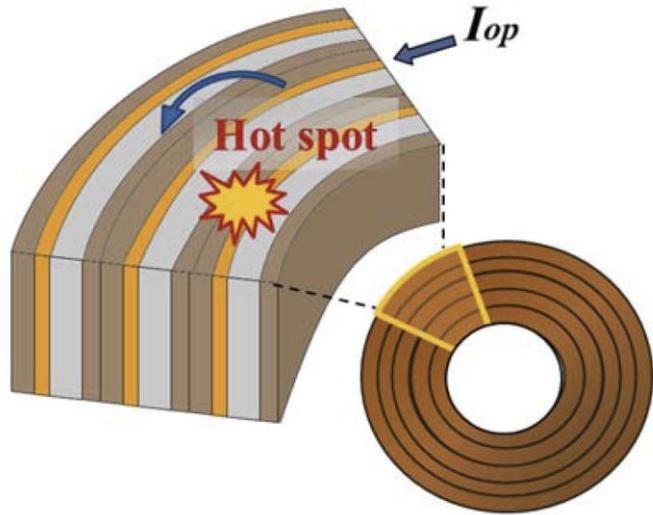
# Screening Currents, Field Quality and Conductor Degradation



- 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

# INTERMEZZO The No-Insulation (NI) winding technique

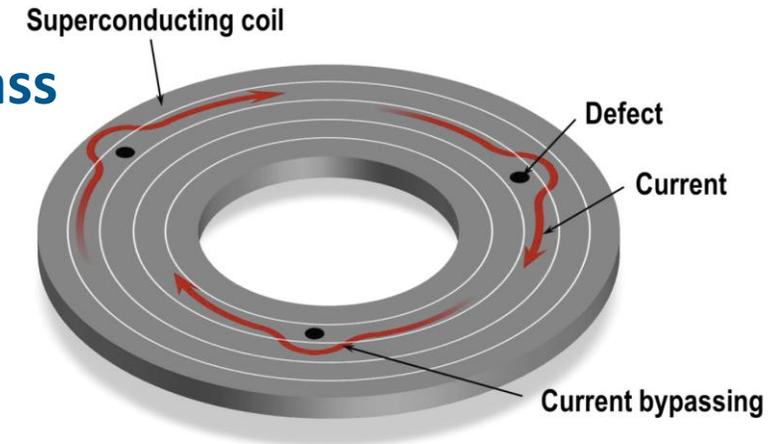
A new paradigm for REBCO coils with advantages and drawbacks



**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](https://doi.org/10.1109/TASC.2010.2093492)

U. Bong et al., *Supercond. Sci. Technol.* 34 (2021) 085003

DOI: [10.1088/1361-6668/ac0759](https://doi.org/10.1088/1361-6668/ac0759)

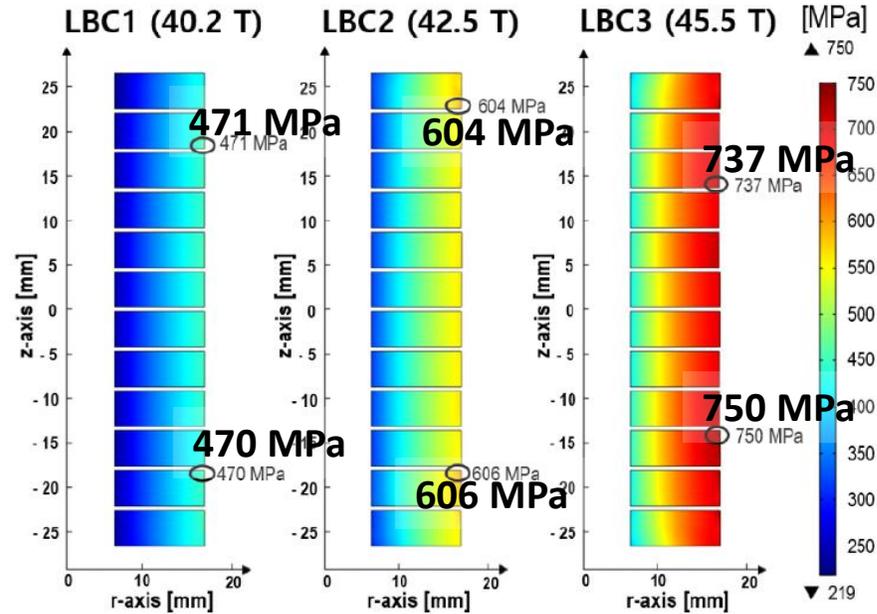
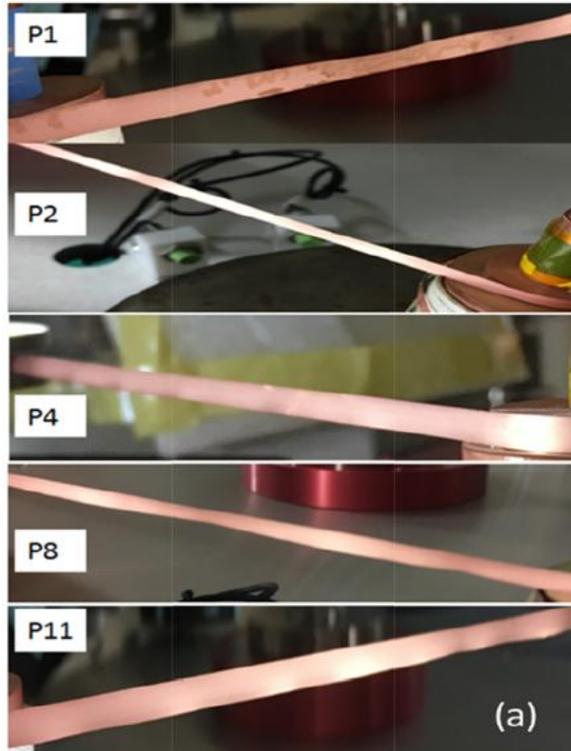
**A major drawback** comes from the **charging delays**, which can be **mitigated** by **Partial/Metal/Smart Insulation**

**Other known drawbacks:** **unbalanced forces**, induced overstresses

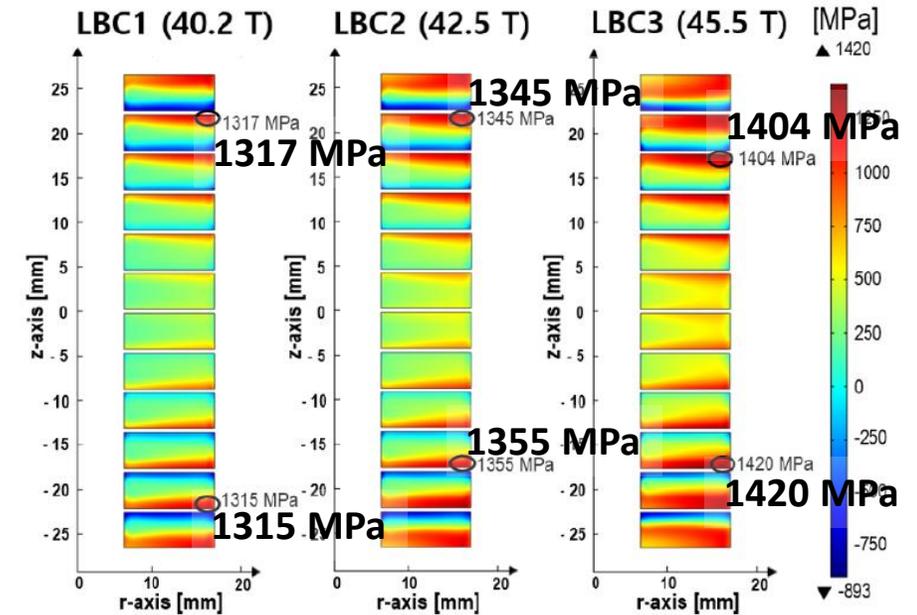
# Screening current stresses cannot be neglected

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



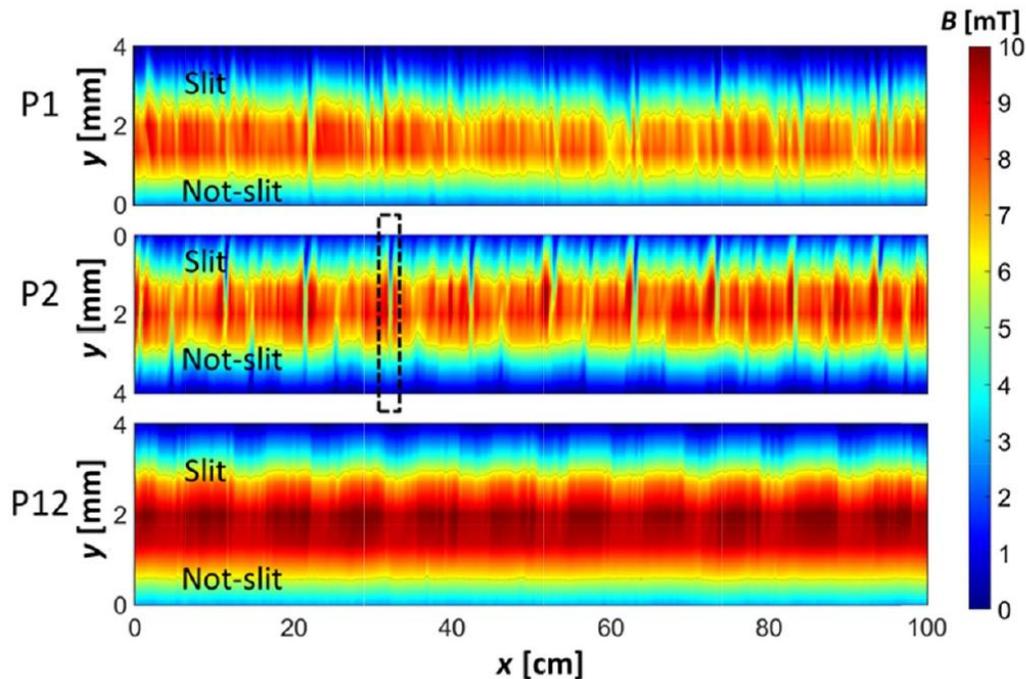
Calculated hoop stress distribution  
with screening currents

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

# Screening current stresses cannot be neglected

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

Three **no-insulation** 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



- $I_c$  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
- Screening current stresses play an important role, especially when the transport current is flowing along the slit edge

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

# Outline

An introduction to high temperature superconductivity

The basics of HTS conductor fabrication with focus on REBCO

An overview of the properties of REBCO coated conductors

- Developments to improve performance
- Reversible and irreversible effects under mechanical loads

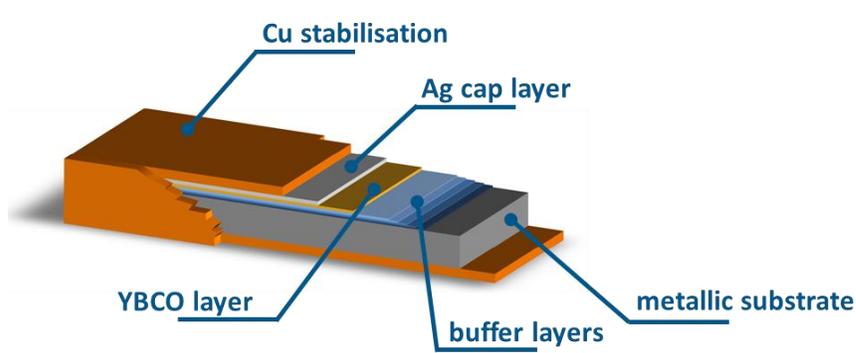
**From REBCO coated conductors to REBCO-based cables**

# From REBCO coated conductors to REBCO-based cables

Large magnets, like magnets for fusion and particle accelerator, are wound with cables instead of individual tapes. The main reasons are

- **Inductance control:** To increase operating current while keeping inductance low, ensuring reasonable voltage during charging and rapid discharges (e.g., during quenches)
- **Thermal stability and minimization of the AC losses:** Transposition of the individual tapes ensures uniform current distribution during ramping and minimizes coupling, reducing losses and thermal instabilities

# From REBCO coated conductors to REBCO-based cables



Promising R&D ongoing, not yet consolidated solutions

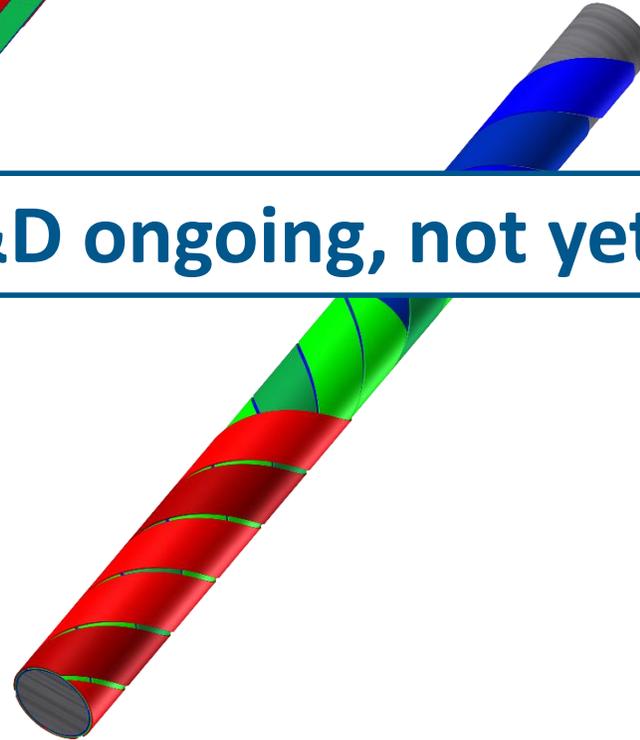
## Roebel cables

W. Goldacker et al., SuST 27 (2014 ) 093001  
DOI: [10.1088/0953-2048/27/9/093001](https://doi.org/10.1088/0953-2048/27/9/093001)



## CORC and STAR cables

D. Van der Laan et al., SuST 34 (2021) 10LT01  
DOI: [10.1088/1361-6668/ac1aae](https://doi.org/10.1088/1361-6668/ac1aae)  
E. Galstyan et al., SuST 36 (2023 ) 055007  
DOI: [10.1088/1361-6668/acc4ed](https://doi.org/10.1088/1361-6668/acc4ed)



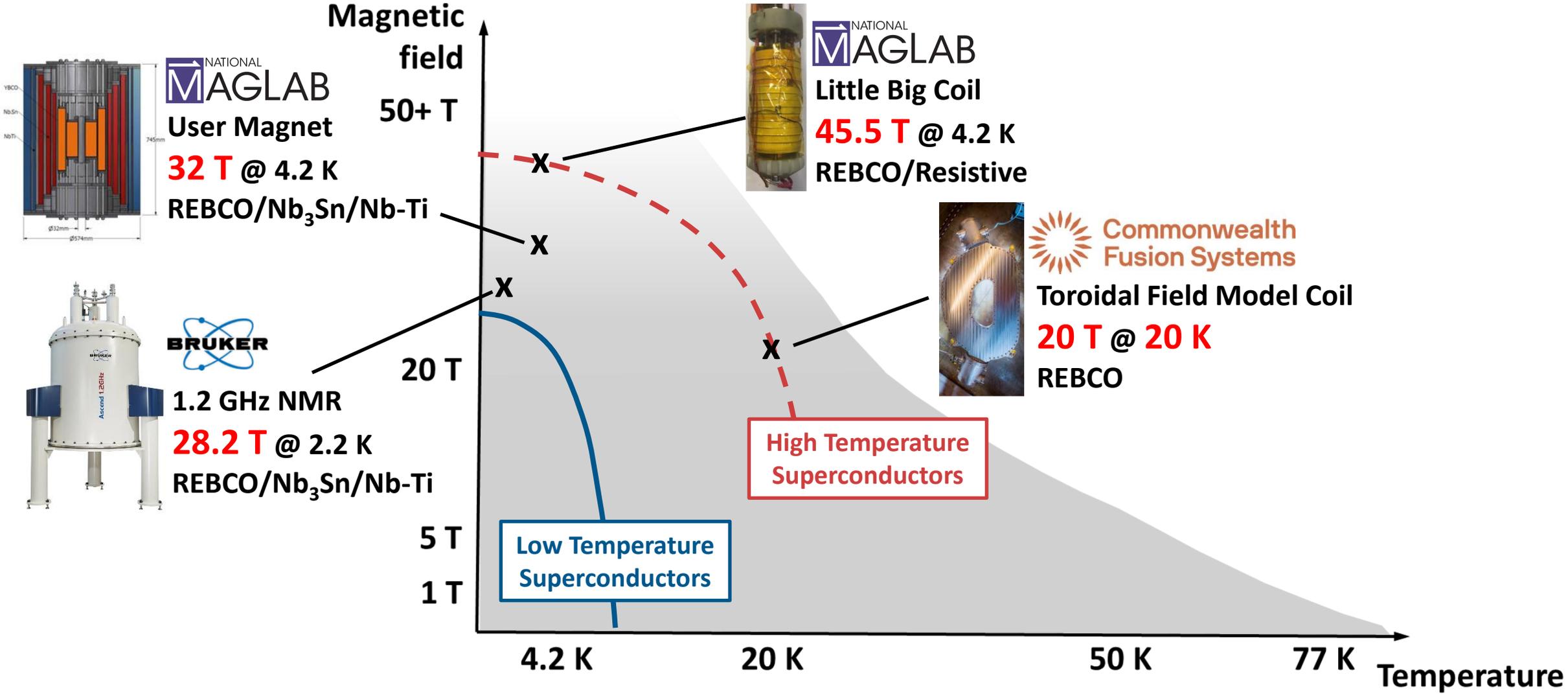
## Tape stacks

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



# High field applications of High Temperature Superconductors

## Field-temperature phase diagram of technical superconductors



# What we have learned

- **Unique Properties of REBCO: strengths and weaknesses**  
Anisotropy, grain boundaries, biaxial texturing, and artificial pinning
- **Importance of Electromagnetic Forces**  
Hoop stress, screening currents, and their impact
- **Degradation of  $I_c$  under Mechanical Loads**  
Distinguishing between reversible and irreversible effects



UNIVERSITÉ  
DE GENÈVE

FACULTÉ DES SCIENCES

Thank you for the attention !

...time for questions...

Carmine SENATORE

[carmine.senatore@unige.ch](mailto:carmine.senatore@unige.ch)

For more details about applied superconductivity in Geneva, please visit  
<http://supra.unige.ch>

The screenshot shows a web browser displaying the website <https://supra.unige.ch>. The page title is "Senatore Group - Applied super..." and the URL is "https://supra.unige.ch". The website header includes "APPLIED SUPERCONDUCTIVITY" and "Prof. Carmine Senatore". The navigation menu includes "Home", "About Us", "Research", "Publications", "Lectures", and "News". The main content area features a large image of a superconducting wire with the text "We are investigating superconductivity" and a sub-headline "Our research is driven by the challenge to understand and control the basic properties required for the practical implementation of superconducting materials. This includes all the material aspects that play a role in tuning the superconductor properties as well as innovative approaches to the processing of superconducting wires and tapes." Below this is a button labeled "Our research". The "Latest news" section includes three articles: "Congratulations to Tommaso Bagni for the Jan Evetts Award 2024" (7 September 2024), "Plenary talk of Prof. Carmine Senatore at ICEC29-ICMC2024" (7 September 2024), and "ASC2024 Conferer" (6 September 2024).