Technical Superconductors: HTS

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CAS course on "Normal- and Superconducting Magnets“
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Outline

- Introduction
  - Physical parameters of superconductors
  - High Temperature Superconductors (HTS)
- The Cuprates: REBCO, BSCCO 2211, BSCCO 2223
  - Properties
  - Pinning
  - Manufacturing Processes
- MgB_2
  - Properties
  - Wire and tapes
- Iron Based Superconductors
  - The IBS family
  - Ba-122
- HTS technical superconductors: overview
- Applications
- Summary

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Superconductors classification (1/2)

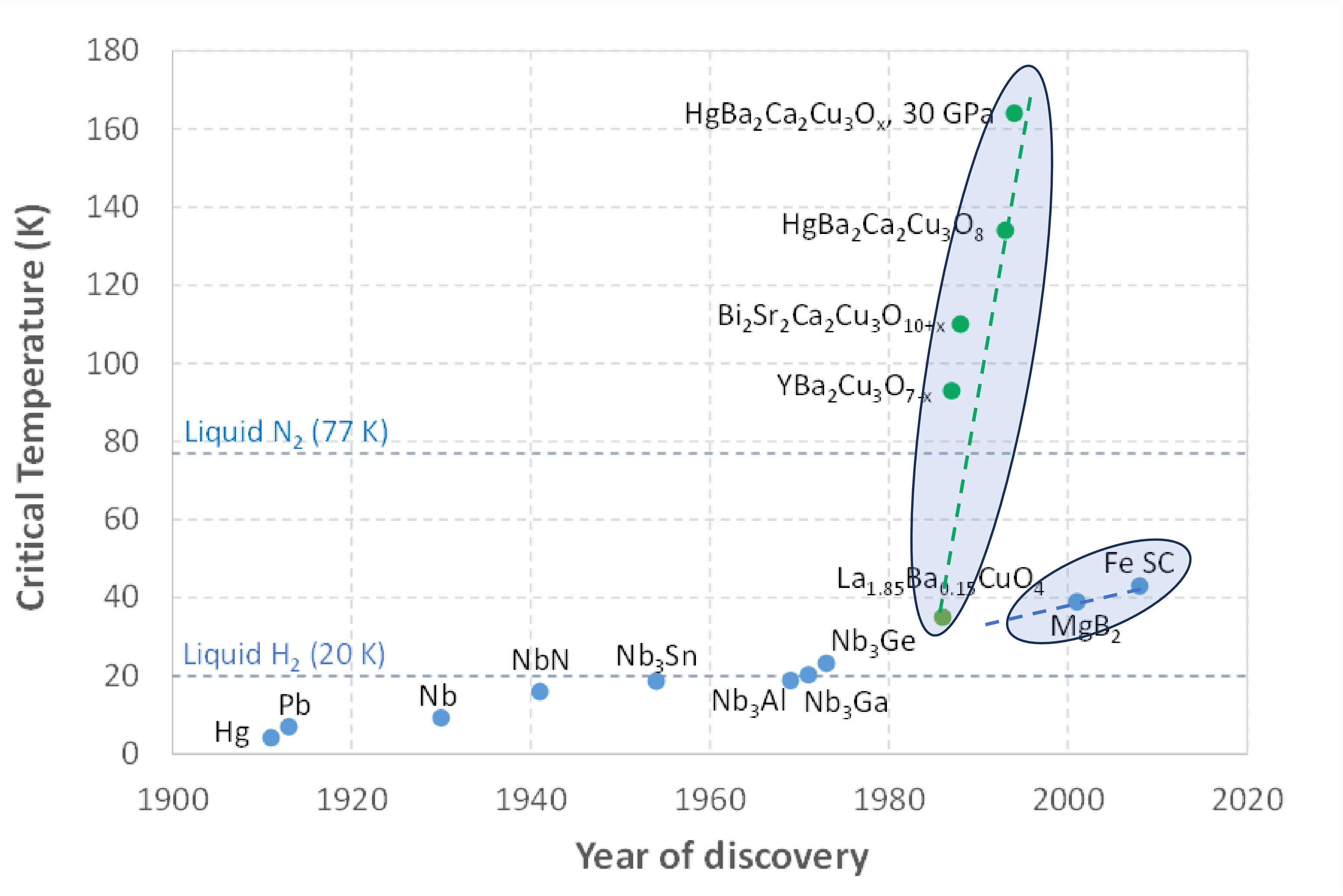
- **Response to magnetic field**
  - Type I, Bc1
  - Type II, Bc1 and Bc2
- **Theory to explain them**
  - Conventional (BSC theory)
  - Unconventional (not conform to BCS theory)
- **Material**
  - Chemical element (Hg, Pb, Sn…)
  - Alloy (Nb-Ti)
  - Compound (Nb_3Sn, MgB_2…)
  - Ceramic (REBCO…)
- **Family**
  - Cuprates, Iron Based
- **Geometry (and manufacturing process)**
  - Bulk (REBCO, BSCCO…)
  - Multifilamentary wire or tape (Nb-Ti, MgB_2…)
  - Coated conductor (REBCO…)
- **Critical temperature**
  - Low temperature Superconductor
  - High Temperature Superconductor

Superconductors classification (2/2)

- **Technical superconductors:** superconducting materials - **Type II** - with properties that enables their use in electrical applications
  - High current capability at the operational temperature and field
  - Good/appropriate and homogeneous properties (mechanical, electrical,….)
  - Available in long unit lengths
  - The focus of this lecture is on wires and tapes

- **High Temperature superconductors**: superconductors with **high critical temperature** - Tc exceeding $\sim$ 30 K (record in Tc, before the discovery of HTS, was in Nb_3Ge films with Tc = 23.2 K)

Critical Temperatures

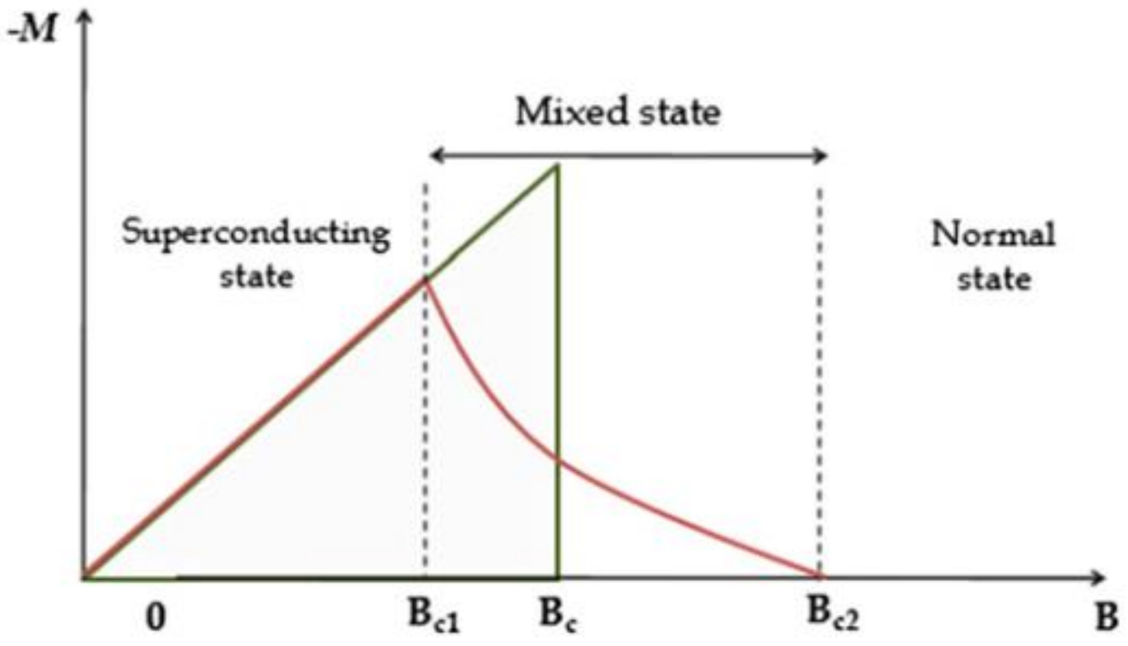


Green: cuprates

Physical parameters of Superconductors - Recap

- **Critical Temperature**, **Tc**, temperature at which superconductivity is suppressed
- **Lower critical field**, **Bc1**, magnetic field at which the magnetic flux starts to penetrate the superconductor
- **Upper critical field**, **Bc2**, magnetic field at which superconductivity is suppressed
- **Coherence length,** ξ (a few nm): spatial dimension of a superconducting pair, i.e., the minimum length over which superconductivity can vary until it disappears
- **Penetration depth,** λ (10-100 nm): length over which an applied field penetrates in a superconductor
- $k_{GL} = \lambda/\xi$: response of a superconductor to a magnetic

Type I and Type II Superconductors - Recap



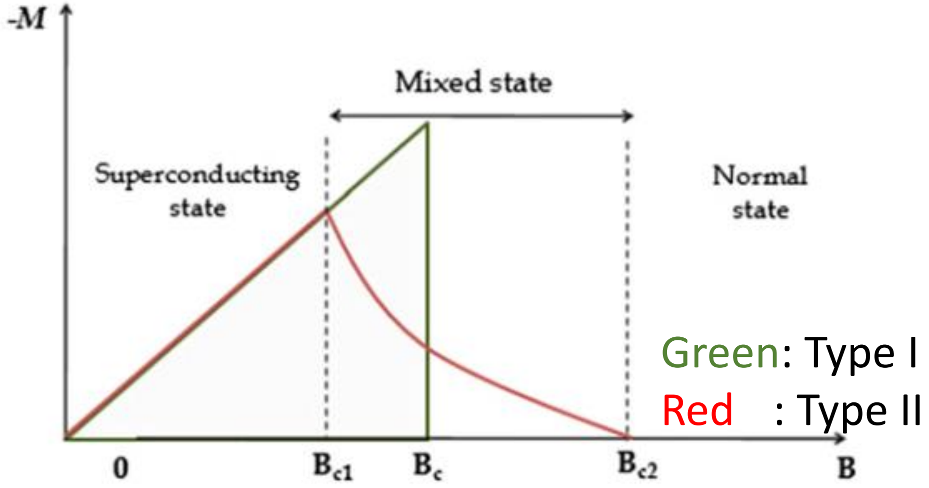
Green: Type I
Red : Type II

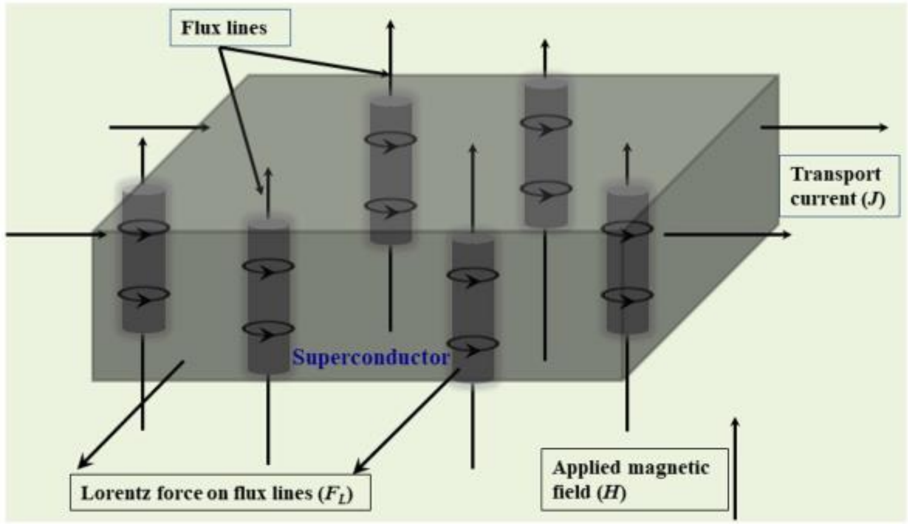
Bc : Type I Superconductor
Bc1, Bc2: Type II Superconductor

	Bc (T)	Tc (K)
Al	0.011	1.3
Pb	0.090	7.2
Sn	0.031	3.7
Zn	0.0053	0.87

Type I : $\kappa_{GL} < 1/\sqrt{2}$
Type II: $k_{GL} > 1/\sqrt{2}$
$1/\sqrt{2} \sim 0.707$

Type II Superconductors





REVIEW
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- **Type II superconductor**: mixed state between Bc1 and Bc2 $\rightarrow$ flux penetrates in the form of **vortices,** i.e. normal regions of cylindrical magnetic tubes containing a magnetic flux quantum **$\Phi o = h/2e$**, where h = Planck's constant and e = electronic charge
- The **vortex core has $\Phi = 2\xi$**
- Superconductivity disappears at **Bc2 = $\Phi_0/2\pi\xi^2$** because vortex cores overlap
- When a superconductor carries a current I, **$F_L = J \times B$**
- To avoid vortices motion, **vortices** must be **pinned at microstructural defects**. Manufacturing processes of superconducting materials shall optimize "**flux pinning**"

Characteristics of HTS (1/2)

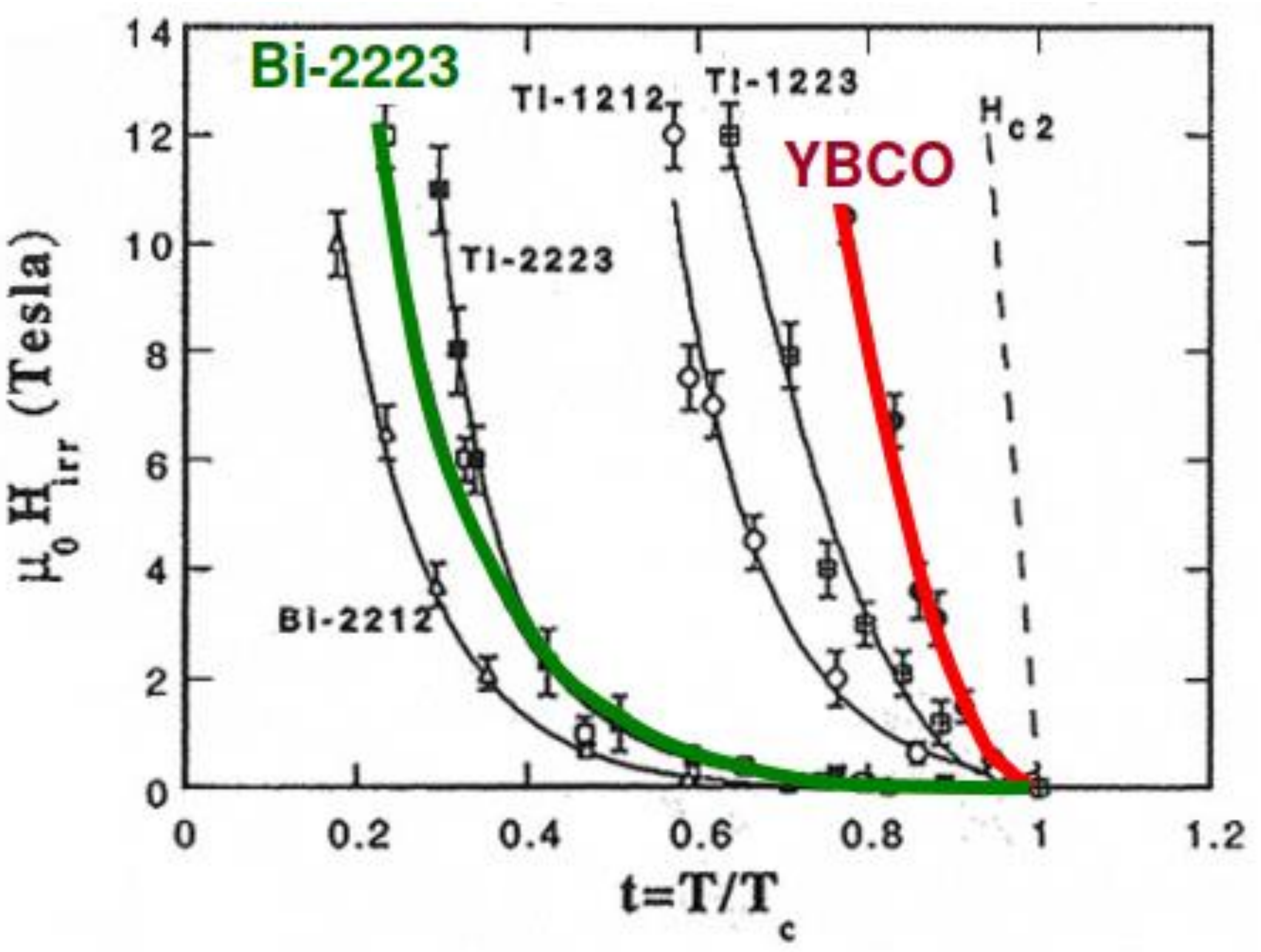
- **Extreme Type II superconductors** ($\lambda >> \xi$, $k_{GL} \sim 100$ for YBCO)

  $\lambda \sim 100$ - 1000 nm, $\xi \sim 1$ nm
- **Small coherence length** (a few interatomic spacings), $\xi \propto 1/Tc \rightarrow$ high Tc
  - Sensitive to defects like grain boundaries: coherence length is often shorter than the grain boundary width - current flow from one grain to the next is strongly impeded
- **High upper critical field**, $Bc2 = \Phi_0/2\pi\xi^2$
- **Large penetration depth**, λ (several thousand interatomic spacings), $Bc1 = (\Phi_0/4\pi\lambda^2)(\ln\lambda/\xi + 0.497)$
- **Large anisotropy**, with properties different in different crystalline direction (including ξ and λ)

$\Phi_0 = 2.07 \cdot 10^{-15}$ Wb, magnetic flux quantum

Characteristics of HTS (2/2)

- **Irreversibility field**, Birr, above which there is not flux pinning and energy is dissipated by the unpinned flux lines. Birr < Bc2



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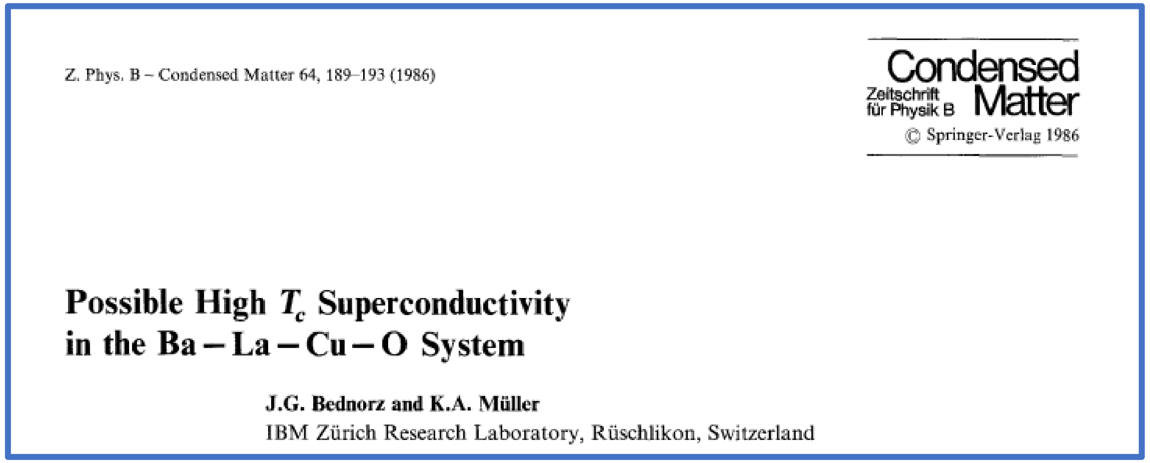
Cuprates – Discovery of HTS

- **1986**, **Johannes Bednorz** and **Karl Müller,** researchers at IBM - Zurich, demonstrated superconductivity in a copper-oxide compound (**LaBaCuO**, a ceramic material) at a temperature of **35 K**, 12 K above the then previous record Tc (Tc ~ 23 K in Nb_3Ge**). Tc higher than what predicted by fundamental science perspectives**
- **1987**, **superconductor at 92 K** (*above liquid nitrogen*): **YBCO**, copper-oxide compound
- **1988**, **superconductor at 108 K**: **BSCCO**, copper-oxide compound


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

Condensed Matter
Zeitschrift für Physik B
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Possible High T_c Superconductivity in the Ba–La–Cu–O System

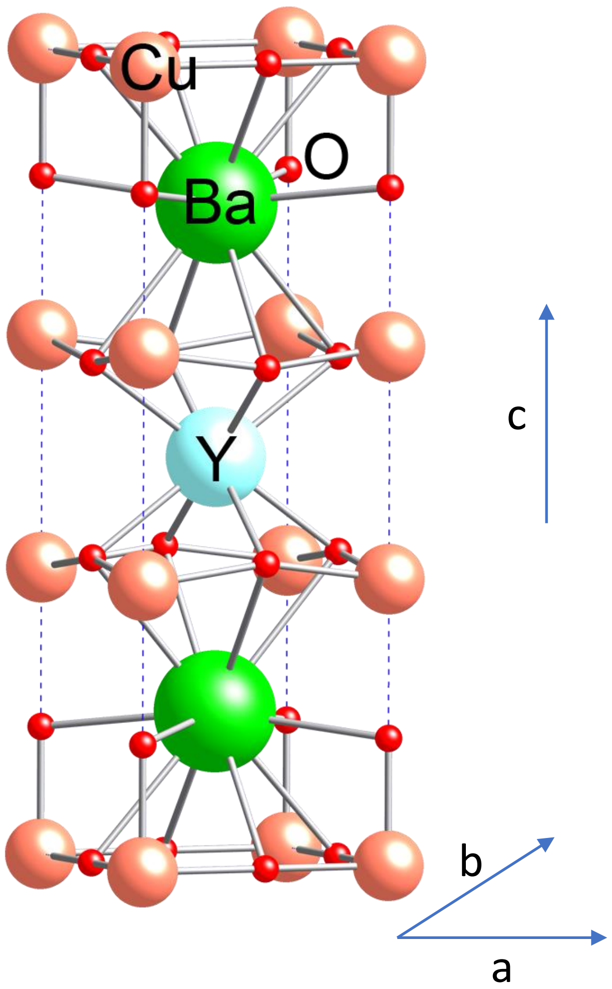
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Nobel prize in Physics in 1987 "*for their important break-through in the discovery of superconductivity in ceramic materials*"

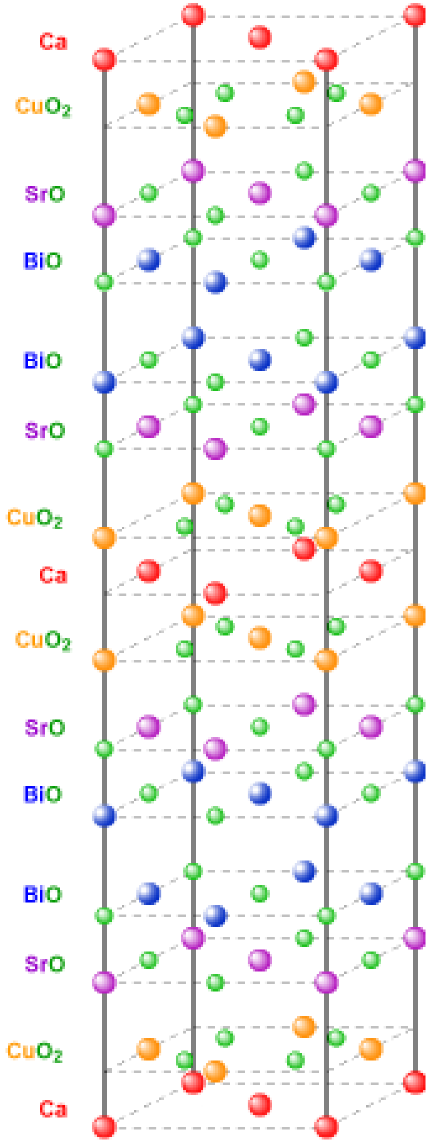
Still today the only superconducting materials with Tc ≥ 77 K

Cuprates – REBCO and BSCCO

- Perovskite structure
- Layered crystal structure consisting of one or more CuO_2 layers – called **ab planes**
- Various layers are stacked together in the c-direction – called **c axis**
- The Cu-O planes are the superconducting layers
- REBCO/ReBCO/2G HTS
  - REBCO: Rare-Earth Barium-Copper-oxide
  - RE/Re: Rare-earth element, e.g. yttrium, gadolinium, lanthanum
  - $YBa_2Cu_3O_{7-x}$ or Y123 (molar ratio for yttrium, barium, and copper is 1 to 2 to 3)
- BSCCO
  - Bismuth Strontium Calcium Copper Oxide
  - BSCCO 2212/Bi-2212/$Bi2Sr_2CaCu_2O_{8+x}$
  - BSCCO 2223/B-2223/$Bi_2Sr_2Ca_2Cu_3O_{10+x}$



Unit cell of YBCO



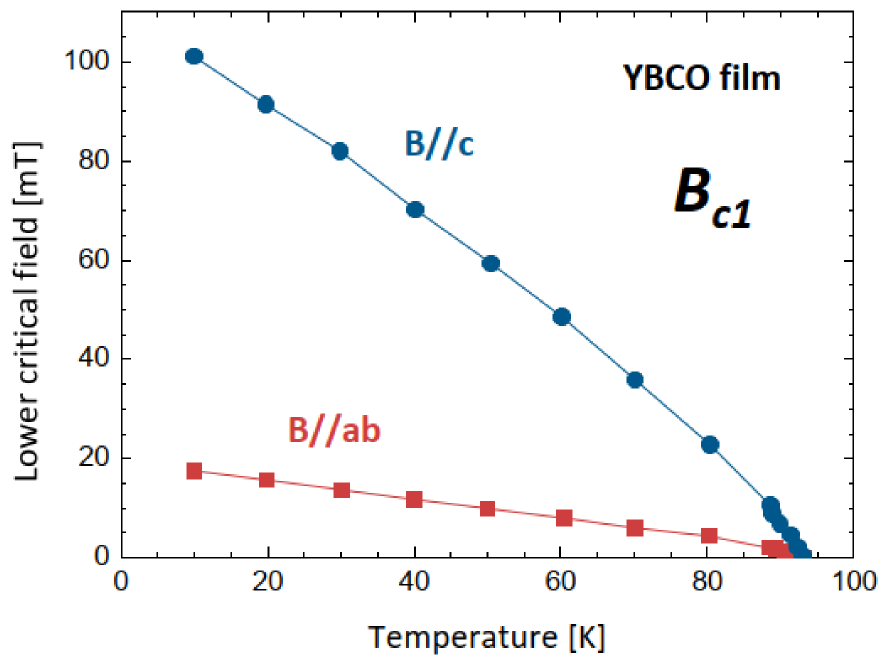
Unit cell of BSCCO 2212

Anisotropy of Superconducting Properties (1/3)

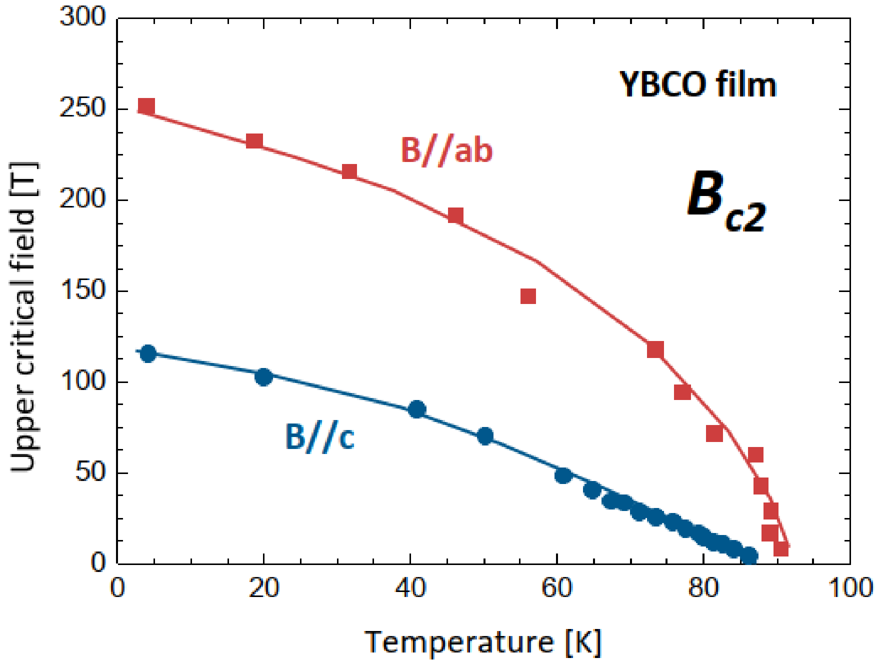
- The layered crystal structure leads to **high anisotropy of the superconducting properties**, e.g. $\xi ab > \xi c$, $\lambda c > \lambda ab$

Charge mass anisotropy: $\boldsymbol{\gamma = (mc/ma)^{1/2} = \lambda c/\lambda ab = \xi ab/\xi c}$

$\gamma \sim 7$ for YBCO



Liang et al., PRB 50 (1994) 4212



Nagakawa et al., JPCM 10 (1998) 11571

Sekitani et al., NJP 9 (2007) 47

Anisotropy of Superconducting Properties (2/3)

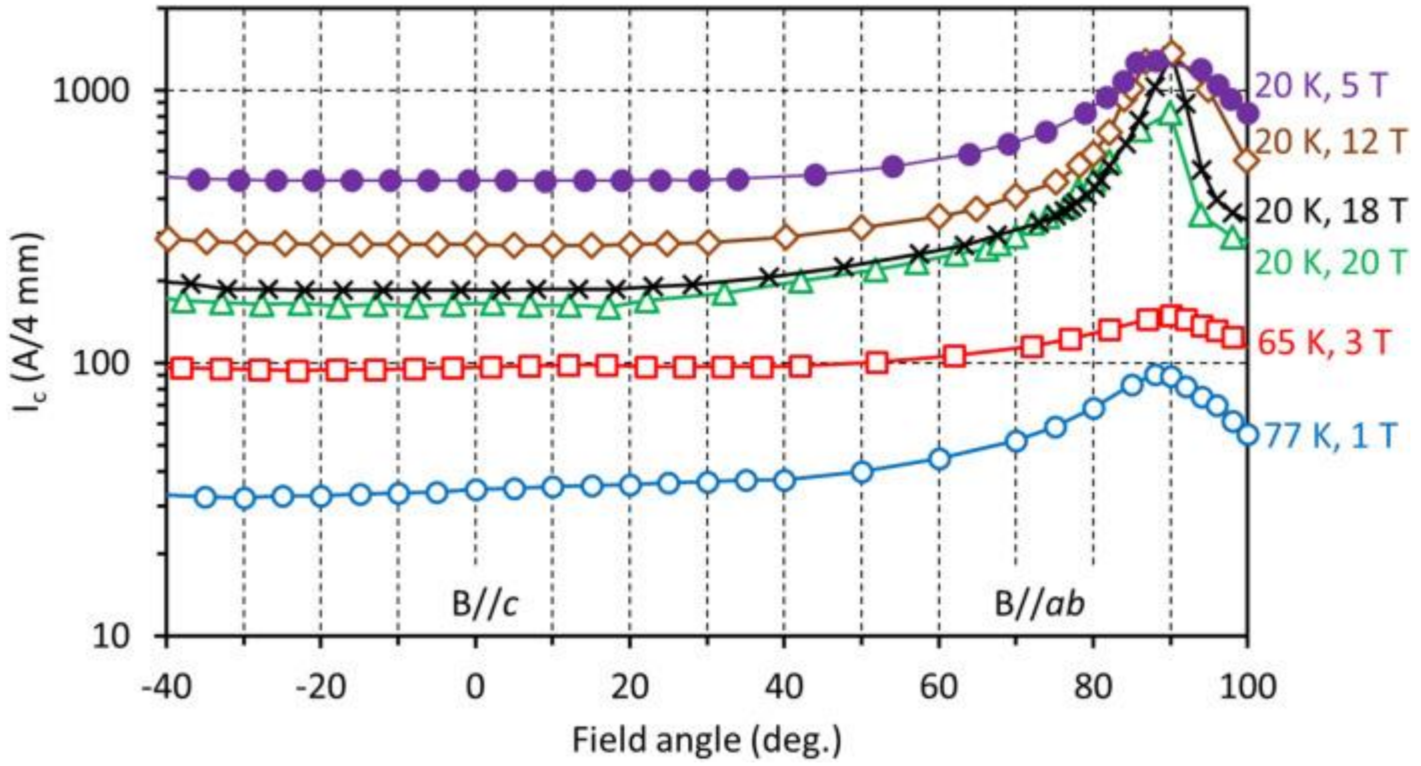
	ξ_{ab} (nm)	ξ_c (nm)	λ_{ab} (nm)	λ_c (nm)
YBCO	~1.6	~0.2	~140	~900
BSCCO 2223	~2.9	~0.1	~150	> 1000
	ξ (nm)		λ (nm)	
Nb-Ti	~4		~60	
Nb_3Sn	~4		~80	
Nb	~40		32-44	

ξ and λ at T = 0 K

ξ and λ have different values in the different crystallographic directions

Anisotropy of Superconducting Properties (3/3)

Critical current (**Ic**) - at a given temperature and field - depends on the **magnetic field orientation.** Magnetic field direction has to be specified wrt to the crystallographic axes



0° corresponds to the *B//c* orientation and 90° corresponds to the *B//ab* orientation

Grain alligment

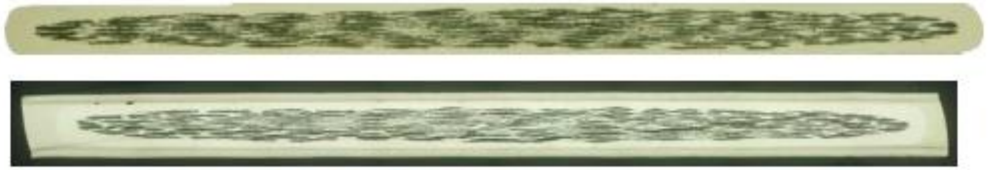
- Weak link behavior: current that passes through a non superconducting region. **Grain boundaries** act as insulating layers. Both impurities and grain misalignment are problematic
- This is a consequence of the small ξ in HTS. In LTS impurities at the grain boundaries are small when compared to ξ; in HTS ξ is comparable to the grain boundary thickness
- In addition, these **layered HTS conductors** have properties that depend on the crystalline direction: $\xi c < \xi a$ (or ξb) $\rightarrow$ in HTS, grain alignment is important to obtain good transport properties
- Individual REBCO grains need to be aligned with a very low relative angle
- Manufacturing processes have to take into account the need of optimizing current across grain boundaries

HTS Cuprates: Manufacturing Processes

- REBCO **tape**: **thin film deposition** for coated tape conductor

Width: 2-3-4-6-12 mm **Thickness ~ 0.1 mm**

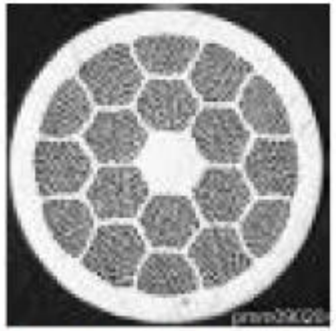
- BSCCO 2223 **tape**: **Powder in Tube Technology** (PIT) for multi-filamentary tape in a **silver matrix**



Sumitomo DI-BSCCO tape

~ 4.3 mm × 0.23 mm

- BSCCO 2212 **round wire**: **Powder in Tube Technology** (PIT) for multi-filamentary round wire in a **silver matrix**



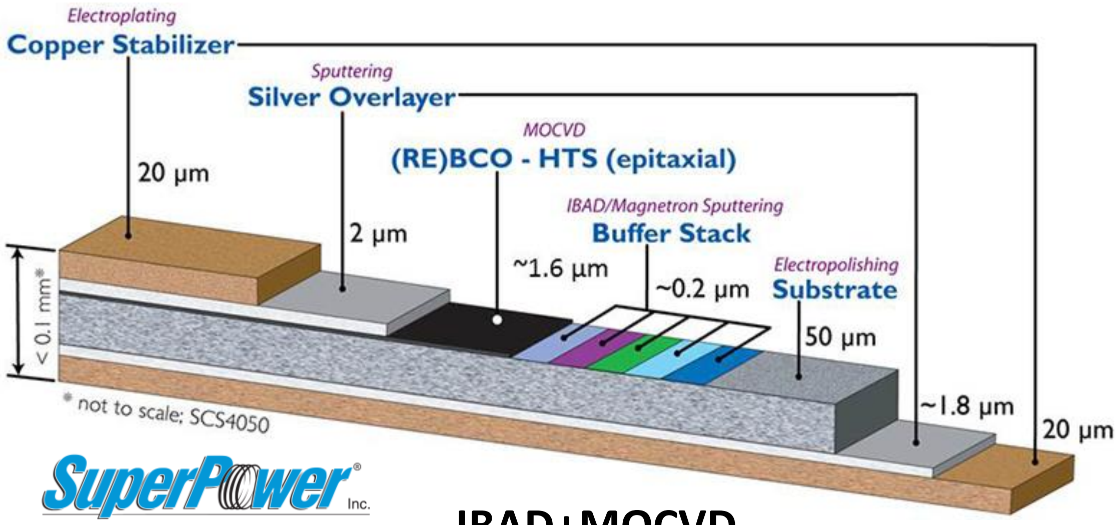
OST BSCCO 2212 wire

Φ = 0.8-1.4 mm

Manufacturing Process: REBCO Coated Conductor

IBAD: A biaxially textured MgO layer is grown on **untextured Hastelloy** substrate. Several **buffer layers** are needed to provide a lattice matched surface for growing the HTS layer

RABiTs: Texture is created in **Ni-W** by a rolling-and-recrystallization process. Several epitaxial **buffer layers** are needed to provide a lattice matched surface for growing the HTS layer



IBAD+MOCVD

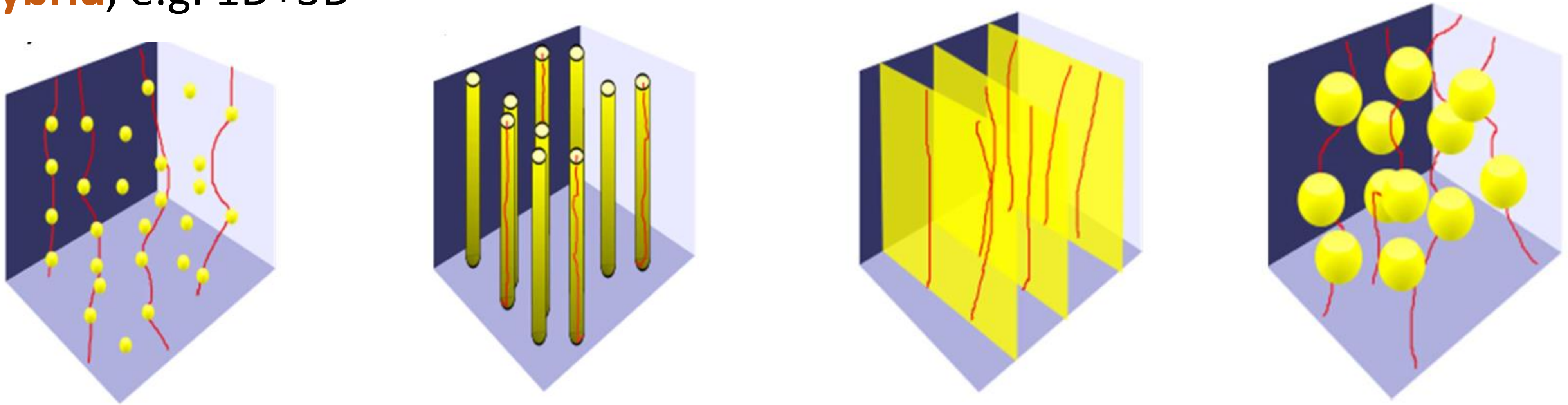
- Required **biaxial texturing** with grain misalignment < ~ 3°
  - **Textured <u>buffers</u>**: IBAD (Ion Beam Assisted Deposition)
  - **Textured <u>substrates</u>**: **RABiTs** (Rolling-Assisted Biaxially Textured Substrates)
- **REBCO** epitaxial layer **deposition**
  - **Chemical routes**, e.g. Metal Organic Deposition (**MOD**), Organic Chemical Vapor Deposition (**MOCVD**);
  - **Physical routes**, e.g. Pulsed Layer Deposition (**PLD**), Reactive Co-Evaporation (RCE)

Artificial Pinning in REBCO Coated Conductor (1/4)

- **Natural pinning centres**: point defects, e.g. impurities and vacancies or interstitials, voids, precipitates, grain boundaries (if the angle between adjacent grain boundaries is small),…Their pinning efficiently is not sufficient for high Jc in high fields
- **Artificial Pinning Centers** (**APCs**) are introduced in the REBCO superconducting layer in the form of non-superconducting nanoparticles and nanorods to enhance performance
- The goal is to generate **nanometric** non-superconducting **defects** - the size of the pinning centres should be in the order of magnitude of ξ of the superconductor. These defects generate a strong pinning force **Fp**, i.e. the force that resist to the motion of vortices under the Lorentz force - if $F_p > F_L$, flux lines remain stationary
- APCs are also used to **adjust anisotropy**

Artificial Pinning in REBCO Coated Conductor (2/4)

- **APCs** can be classified on the basis of their **dimensional structure**:
  - **0D**, **atomic level** point like defects, e.g. vacancies, atomic substitutions,…
  - **1D**, **linear** defects, e.g. columnar shaped secondary phases (columns, short rods) . Ex: introduction of $BaZrO_3$ (BZO) secondary phase in the YBCO film
  - **2D**, **planar** defects, e.g. deposition of multi-layer films via PLD, e.g. Ag, Y_2O_3,…
  - **3D**, **large size** defects in the from of spherical pinning centers, e.g. modification of substrates by growing nano-particles to create interfacial defects
  - **Hybrid**, e.g. 1D+3D



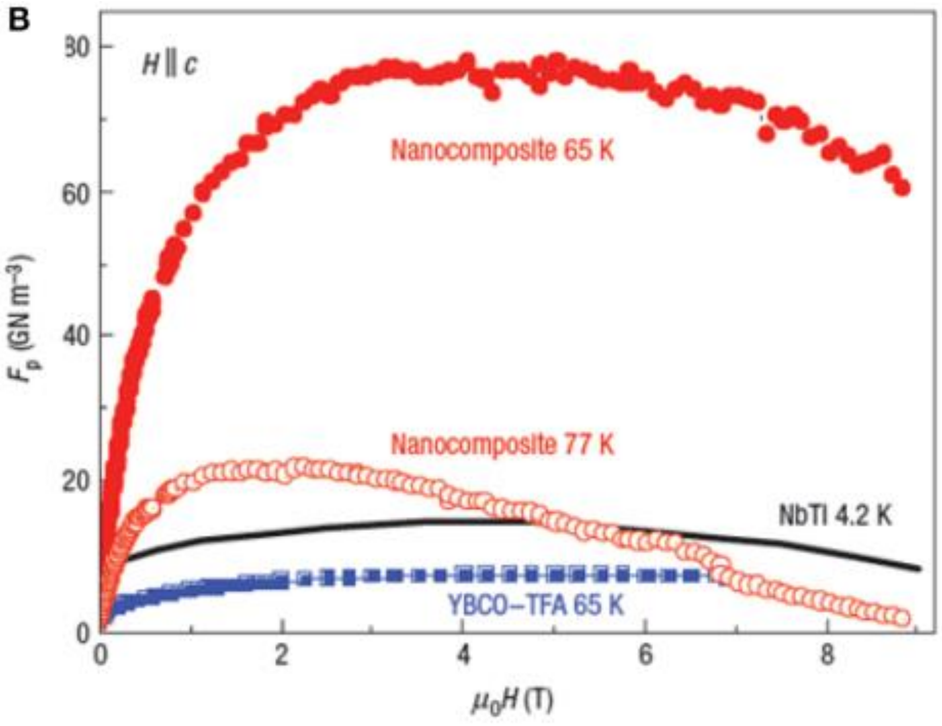
0D **1D** **2D** **3D**

Supercond. Sci. Technol. **30** (2017) 123001

Artificial Pinning in REBCO Coated Conductor (3/4)

- There is not a definitive way to predict the pinning from a specific microstructure. However, more than a decade of **experimental work to optimize the pinning centers distribution and morphology**, both in academia and industry, has enabled huge progress in enhancing critical current density (Jc)
- The **method for introducing the pinning centers** depends on the method of this film preparation.
  - PLD: pinning centers are present in the original target in a suitable form, e.g. $BaZrO_3$ (BZO)
  - MOCVD: the precursors for the pinning centers are added to the raw material and transported, with the material, to the film

Artificial Pinning in REBCO Coated Conductor (4/4)



YBCO with BZO nanodots

nature materials | VOL 6 | MAY 2007 | www.nature.com/naturematerials

Microstructures that produce the best Jc performance **are not the same at high** (~ 65 K - 77 K) **and low** (LHe, < 30 K) **temperatures**

- Sub-nanometers defects **(0 D)** are identified and the dominating pinning effect at **low temperature** and high fields. Lower temperature: less thermal energy and decreased ξab and ξc (from ~ 5 nm and ~ 0.7 nm at 77 K to ~ 2 nm and ~ 0.3 nm at 10 K) – even atomic sized defects can act as pinning centers
- Long columnar defects **(1 D)**, e.g. BZO, are desired for **higher temperatures** and lower fields

Industrial REBCO tapes

- **REBCO**: YBCO, EuBCO, GdBCO

Company	REBCO	Deposition Method
SuperPower	Non disclosed	IBAD/MOCVD
Theva	GdBCO	ISD/EB-PVD
SuperOx	YBCO	IBAD/PLD
Fujikura	EuBCO	IBAD/PLD
Shangai Superconductors	EuBCO	IBAD/PLD

- Most common types of **APCs in industrial REBCO tapes**: $BaHfO_3$ (BHO) particles, BHO columns, $BaZrO_3$ (BZO) columns
- Native pinning: Y_2O_3, Gd_2O_2

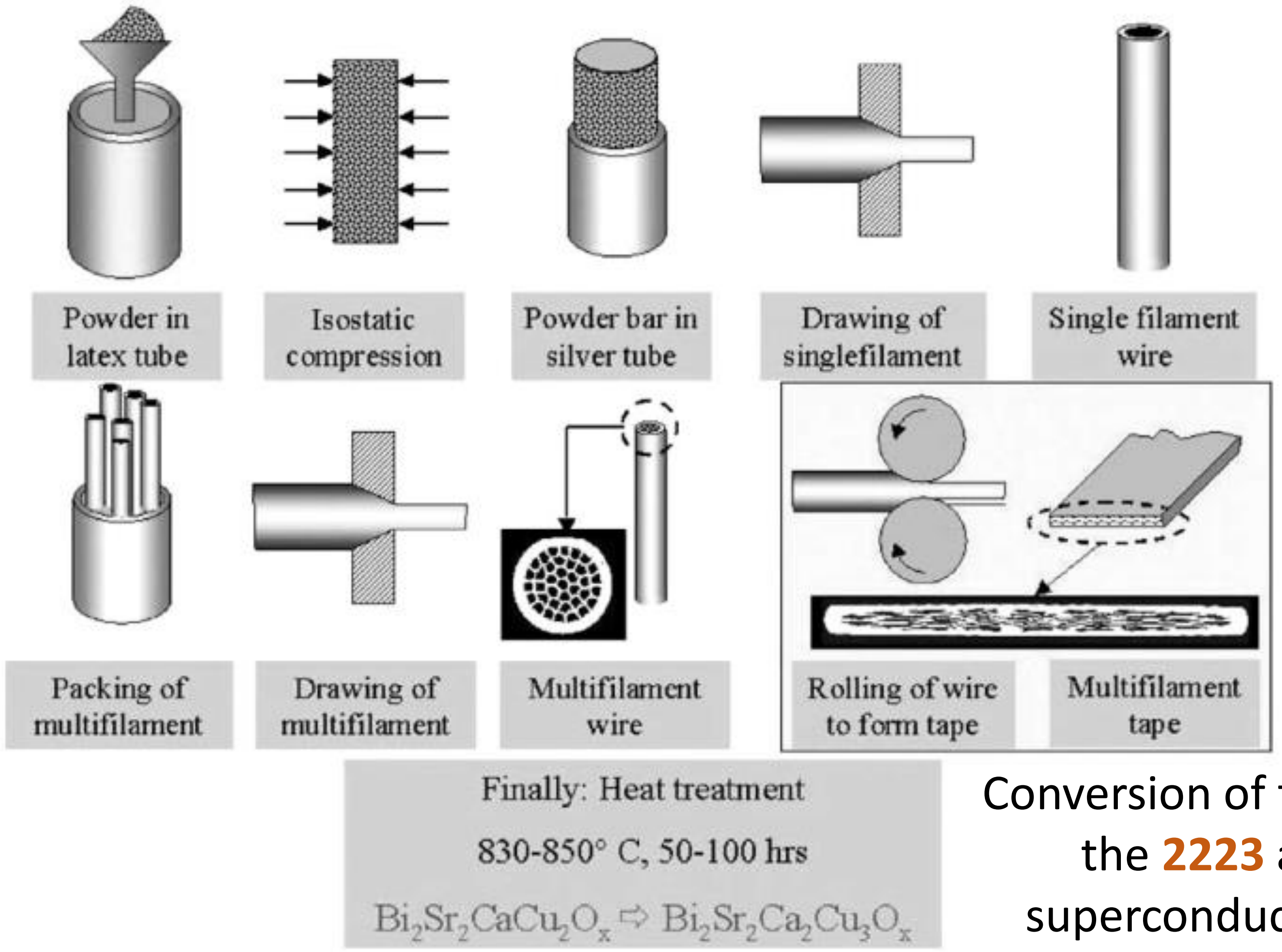
Filling factor of REBCO tape

- **Critical current (Ic)** is a combination of **Jc**, superconducting layer **width** and superconducting layer **thickness**
- **Filling factor, f*,** in a REBCO tape is ~ **1 %**
- Limitations have been found when trying to increase the thickness of the superconducting layer. **Thickness of REBCO** is typically **< 3 μm**: Jc decreases when thickness increase beyond this level
- Effort on **Ic** focuses on **increase of Jc via pinning**

*f = ratio of the superconductor area to the total area of the wire/tape

Manufacturing Process: Powder In Tube BSCCO

Silver: inert to BSCCO and permeable to oxygen at the annealing temperature



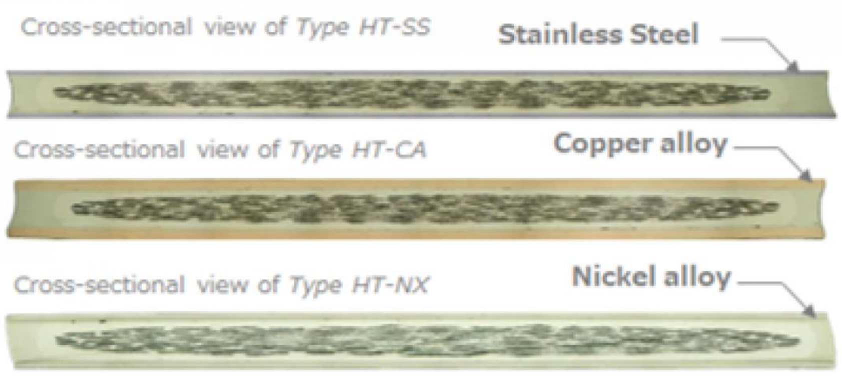
N. Bay, M.S. Nielsen / Journal of Materials Processing Technology 151 (2004) 18–26

Conversion of the powder in the **2223** and **2212** superconducting phases

BSCCO 2212 and BSCCO 2223

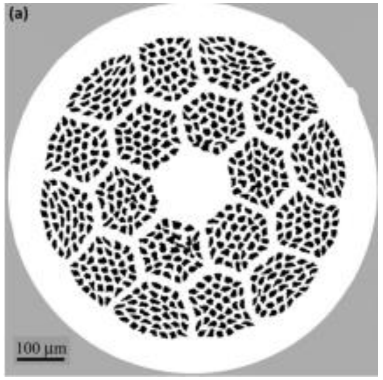
BSCCO 2223 multi-filamentary tape

- **Deformation-induced** (rolling and sintering) **texture** process. Uniaxial texture of ~ 15° (to be compared with ~ 2°-5°in REBCO)
- Silver matrix
- **External mechanical reinforcement** can be implemented
- **Filling factor ~ 40 %**



BSCCO 2212 multi-filamentary round wire

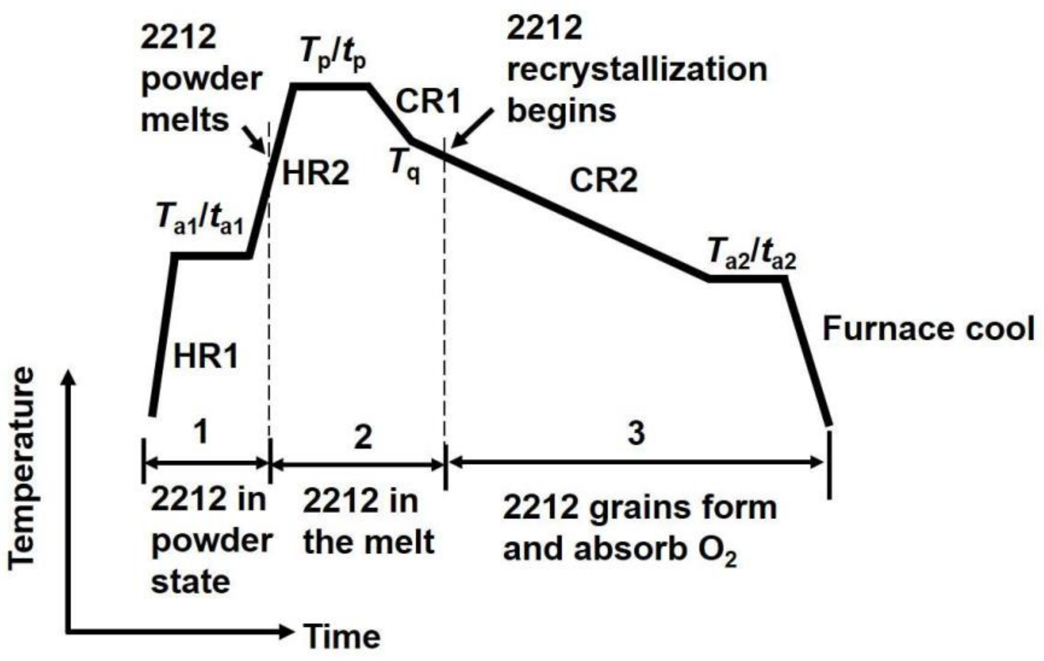
- **Texture formation** during the **melt process** (partial melt texturing): the process melts the superconducting phase, which during cooling reverts to the 2212 phase in such a way as to produce an aligned structure
- Partial melt processing that requires heat treatment in **oxygen atmosphere at ~ 900 °C**
- Silver matrix
- **No** appreciable **anisotropy** in magnetic fields
- **Filling factor ~ 30 %**



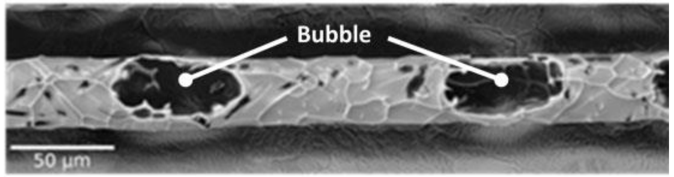
Transverse cross section of **BSCCO 2212 wire** with 0.8 mm diameter, D. Larbalestier et al, https://arxiv.org/abs/1305.1269

React & Wind – Wind & React

- **REBCO** and **BSCCO 2223**: tape superconducting after manufacturing process. **React & Wind** technology
- **BSCCO 2112**: brittle material. Reaction after production of cables and coils. **Wind & React** technology (as Nb_3Sn)



- **Overpressure** partial melt processing (**15-20 bar**) - to avoid bubbles - in a mixed gas of $\mathbf{O_2}$ at @ **900 °C**



Single filament with bubbles

- Complex dependence of **Jc properties** on **heat treatment** (Tp, tmelt, solidification rate, …)

https://www.sciencedirect.com/science/article/pii/S0011227517301534

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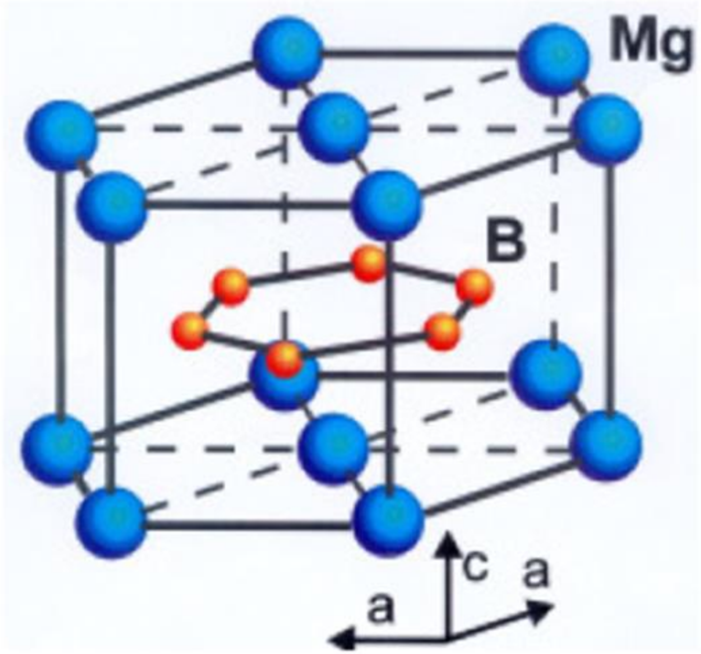
MgB_2

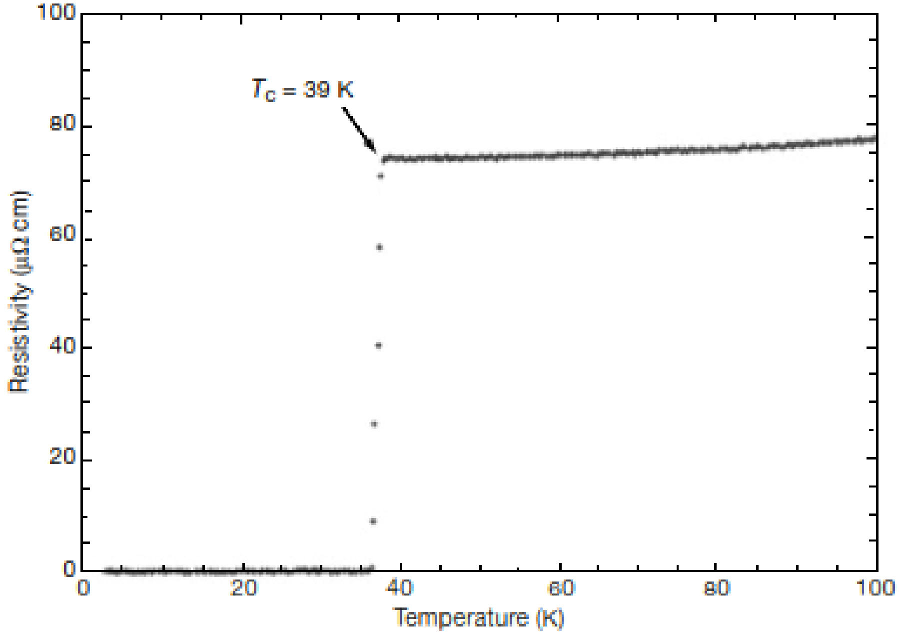
MgB_2: **binary inter-metallic** compound known since the 50s, but discovered to be **superconducting** only in **2001** – by Akimitsu and coworkers, Japan



Simple layered structure

Hexagonal **magnesium layers** sandwiched between **B layers**

NATURE | VOL 410 | 1 MARCH 2001 | www.nature.con



Superconductivity at 39 K in magnesium diboride

Jun Nagamatsu*, Norimasa Nakagawa*, Takahiro Muranaka*, Yuji Zenitani* & Jun Akimitsu*†

** Department of Physics, Aoyama-Gakuin University, Chitosedai, Setagaya-ku, Tokyo 157-8572, Japan*
† CREST, Japan Science and Technology Corporation, Kawaguchi, Saitama 332-0012, Japan

MgB_2

- **Exceptional** in MgB_2:
  - **Tc exceeds the highest BCS Tc** (~ 23 K in Nb_3Ge) – **as in cuprates**, but:
  - **Two band superconductivity:** two different superconducting energy gaps coexist below Tc. Anisotropic superconducting properties
  - **It is not the first member of a new class** (the "borides" or "diborides") of superconductors
- **Tc ~ 39 K**. Highest Tc for a binary superconductor
- **No weak link behaviour** at the grain boundaries – in contrast to the cuprates. **Grain boundaries in MgB_2 are transparent to current**: complex fabrication processes aiming at minimising grain misalignment and eliminate high angle grain boundaries are NOT required for MgB_2

MgB_2

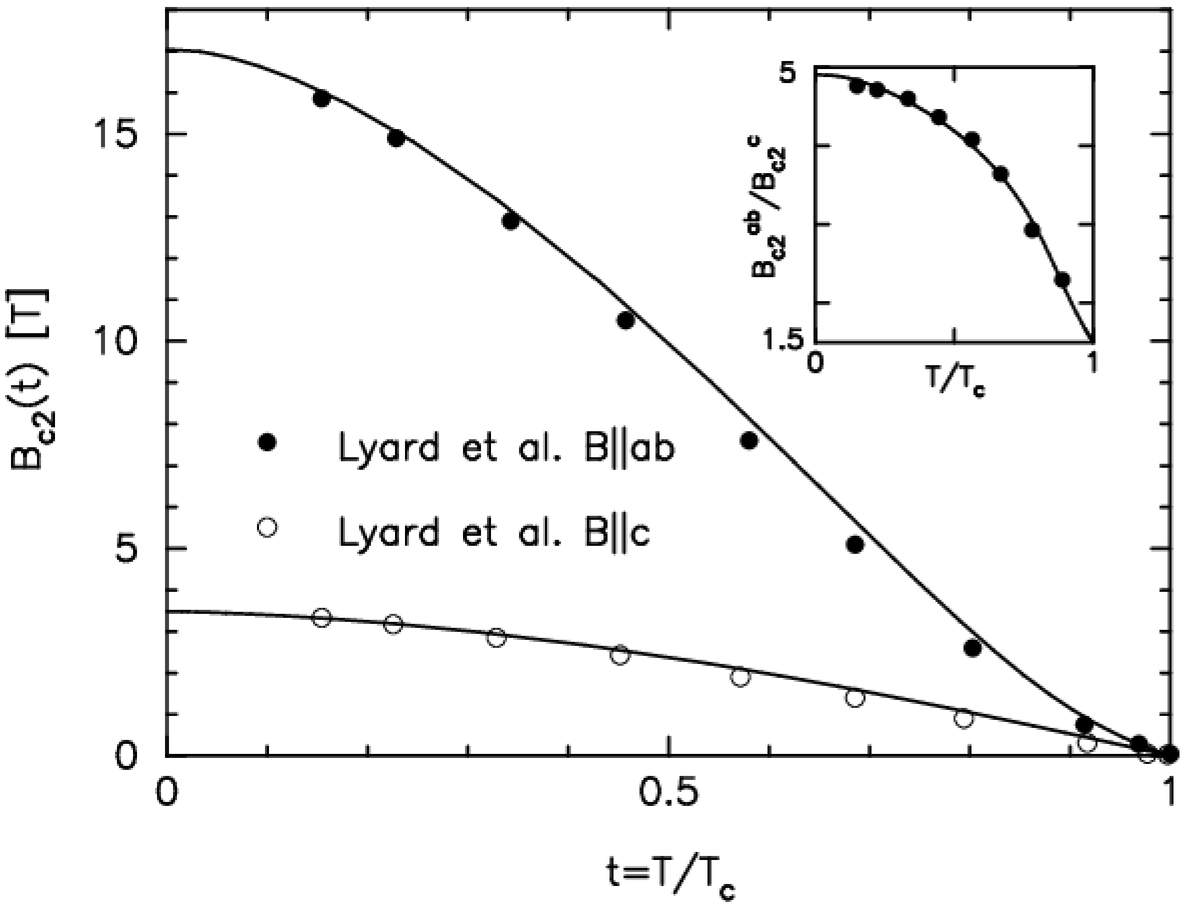
	ξab (nm)	ξc (nm)	λab (nm)	λc (nm)
YBCO	~1.6	~0.2	~140	~900
BSCCO 2223	~2.9	~0.1	~150	> 1000
MgB_2	~ 39	~ 35	~ 107	~120
	ξ (nm)		λ (nm)	
Nb-Ti	~4		~60	
Nb_3Sn	~4		~80	
Nb	~40		32-44	

ξ and λ at T = 0 K

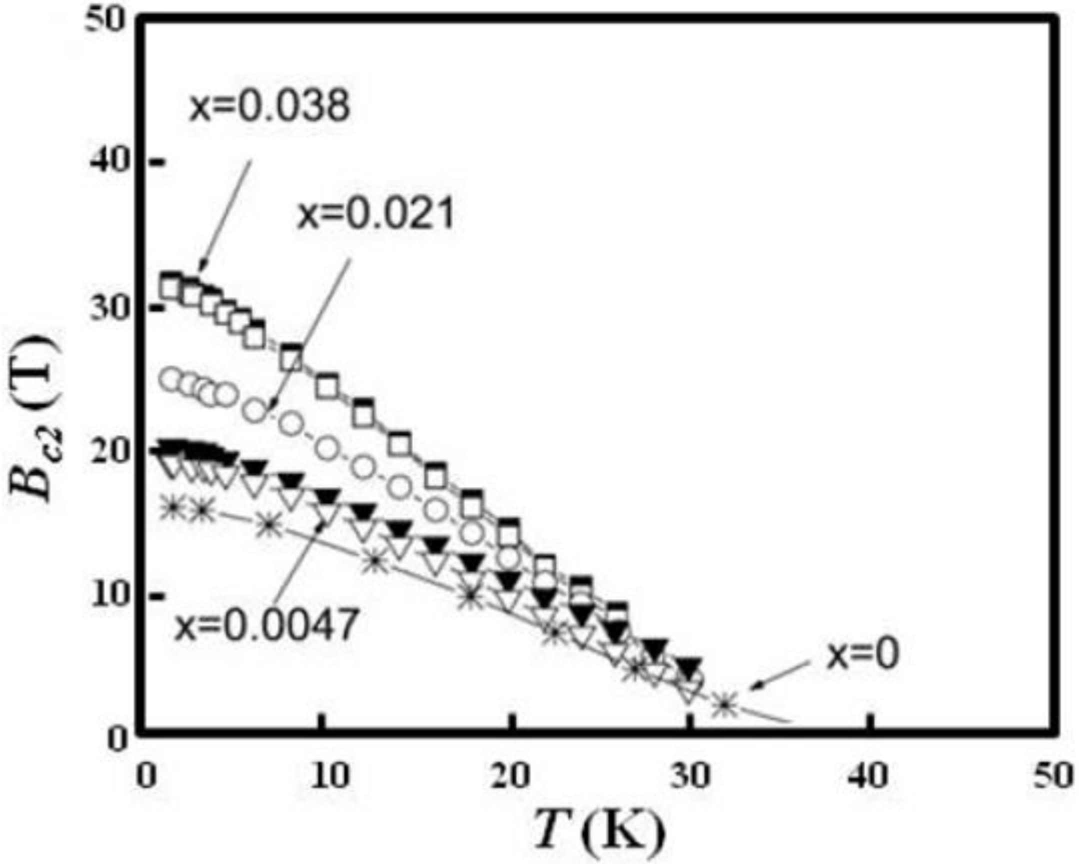
ξ is **large** wrt unit cell dimensions: isolated vacancies, substituents, interstitials, etc., contribute little to pinning → extended defects are required

MgB_2

Bc2 of MgB_2 single crystal



Doping to enhance Bc2
C and C-related compounds

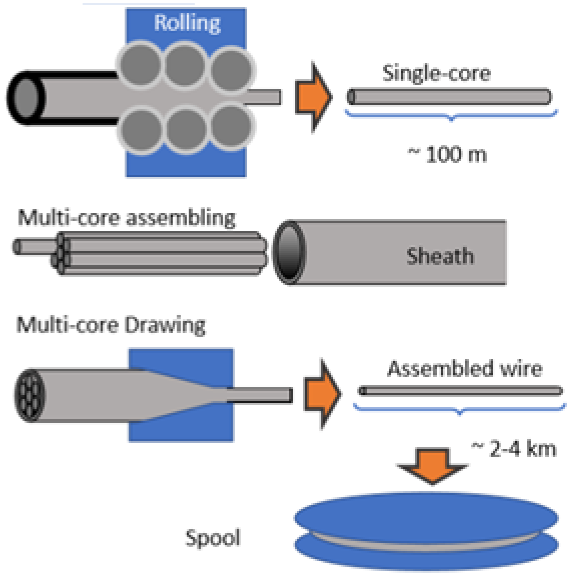


Doping with C shortens the mean free path and therefore increases B_{c2} and B_{irr}

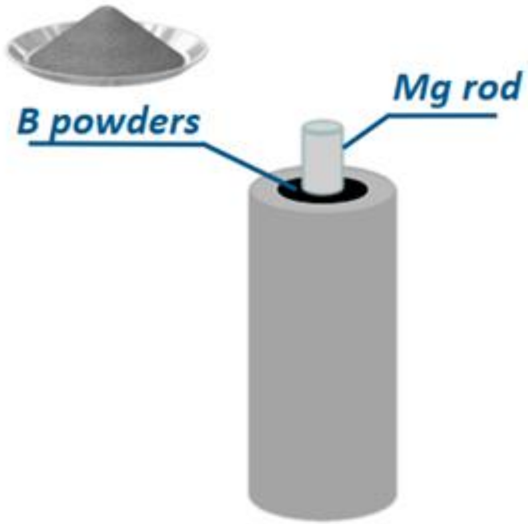
MgB_2 Wires via Powder Metallurgy

- **In-situ Powder in Tube**: it starts from a mixture of **B** and **Mg powders.** Rection to MgB_2 takes place after the deformation process. Higher filling factor and easier nanoparticles doping. Wind & react technology
- **Ex-situ Powder in Tube**: it starts from already **reacted MgB_2 powders.** Better control of purity and granulometry of the powder. More robust wire. React & Wind technology

Powder In Tube



Internal Magnesium Diffusion



MgB_2 Powder In Tube Industrial Wire

Ex-situ process

ASG SUPERCONDUCTORS columbus mgb2 unit

Powders clean synthesis

Multistep rolling machine

High power straigth drawing machine

4 meter furnace for annealing HT

Multistep drawing machine

20 m long in-line furnace

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Iron based Superconductors

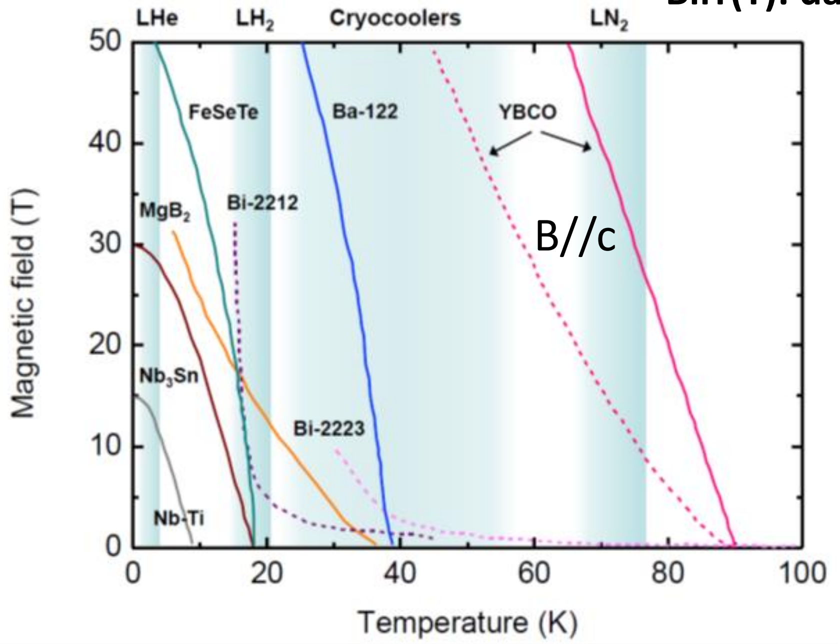
- **Iron Based Superconductors** (FeSC): **discovered in 2008** by the Hosono group in the Tokyo Institute of Technology

- **Layered structure**
- **Small ξ → High Bc2**

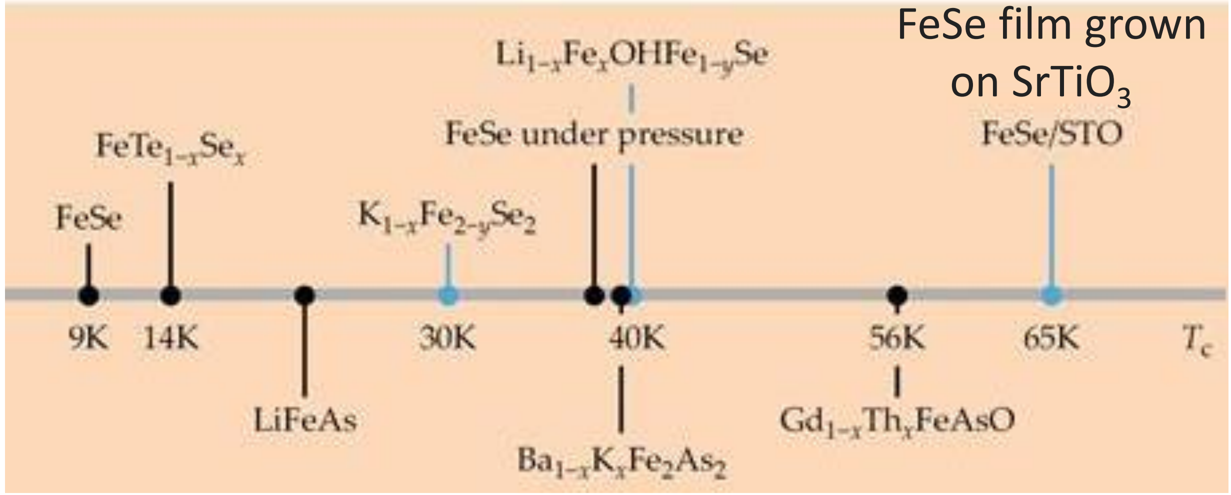
- Categorized in **different types** according to chemical composition and crystal structure:

1111 Type, e.g., LaFeAsO1-xFx and SmFeAsO1-xFx
122 Type, e.g., Ba1-xKxFe2As2 and Sr1-xKxFe2As2
111 Type, e.g. LiFeAs
11 Type, e.g. FeSe, FeSe1-xTex

Bc2(T):solid line
Birr(T): dashed line



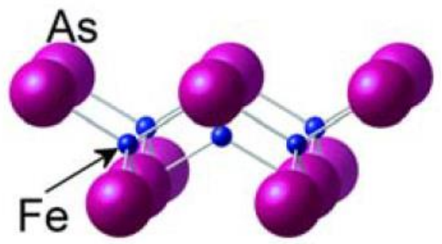
A Gurevich, Ann. Rev. Cond. Matt. Phys **5** (2014) 35



https://pubs.aip.org/physicstoday/article/76/5/34/2886761/

Iron based Superconductors: Crystal Structure

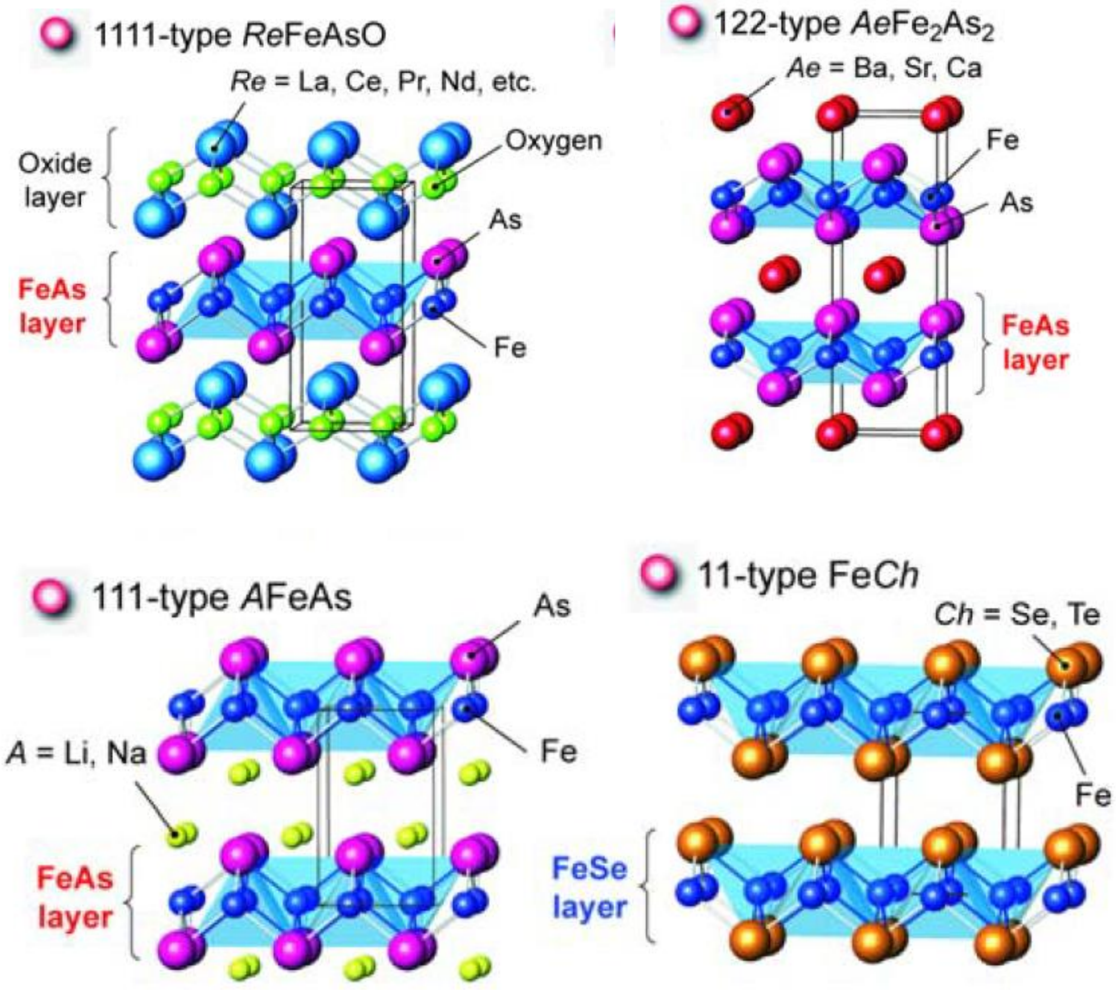
- **Layered** structure. **IBS** primarily comprises **iron pnictides** and **iron chalcogenides**
- Simplest structure: FeSe (11-type, Tc ~ 9 K)
- **Crystal structure**: common structural unit of **FePn or FeCh** (*Pn = pnictogen, **Ch = chalcogen) with ions and/or building blocks – **FeSe/FeTe** or **FeAs/FeP**



Se = Selenium
Te = Tellurium
As = Arsenic
P = Phosphorus

*__Pnictogen__: **nitrogen group** of elements in the periodic table (nitrogen, phosphorus, **arsenic**, antimony, bismuth, and ununpentium)

__Chalcogen__: chemical elements in the **group 16 of the periodic table (oxygen, sulfur, **selenium**, tellurium, polonium, and livermorium)



Iron based Superconductors vs Cuprates

		Iron based	Cuprates
Tc	K	55 (1111 type) 38 (122 type)	93 (YBCO) 110 (BSCCO 2223)
Bc2(0)	T	> 100 (111 type) 50 – 100 (122 type) ~ 50 (11 type)	> 100
Birr(T)	T	> 50 (4.2 K)	> 10 (77 K, B//c)
γ		4 - 5 (111 type) 1 -2 (122 type and 11 type)	5- 7 (YBCO)
Critical GB angle	deg	~ 9	~ 3 (YBCO)

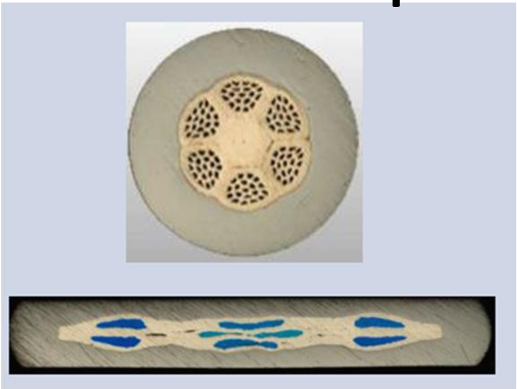
Iron based Superconductors: Manufacturing Processes

Produced in the form of **wires** and **tapes: laboratory research – not yet industrialized**

- Dependence of Jc on grain misalignment lower than REBCO: **PIT** technology for wires and tapes Differently from cuprates, **Ag** is **not the only choice** as sheath material (as for the cuprates): Cu, Fe, silver based composites (Ag/Fe, Ag/Cu,…)

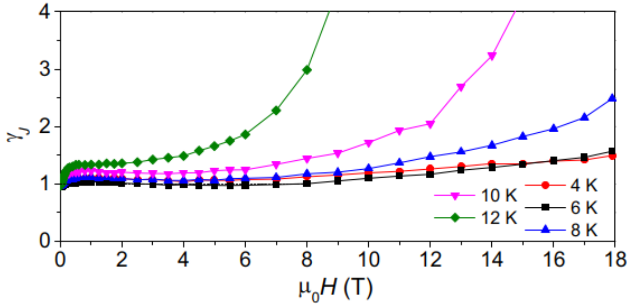
- **Coated conductors.** Coated conductors produced with IBAD and RABiTS. Well aligned metal tape substrates are not necessary

PIT Wire and Tapes



iScience 24, 102541, June 25, 2021 © 2021

Fe(Se,Te) films grown via PLD on a SeO_2 buffer layers. Ni-W substrates



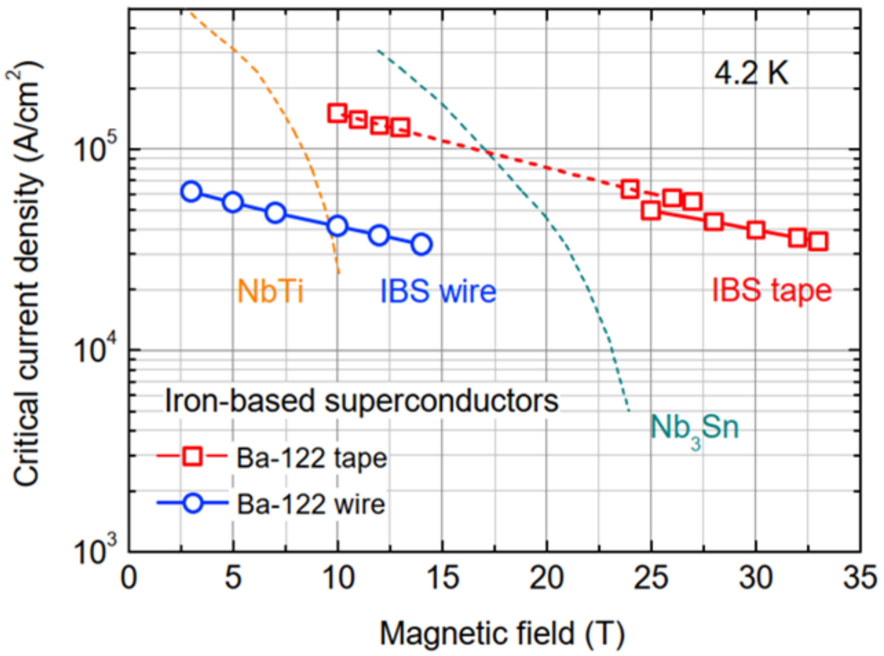
J_c anisotropy $\gamma_J = J_c\,(H//ab)/J_c\,(H//c)$ as a function of applied field in the 0–18 T field range

https://doi.org/10.1038/s41598-022-24044-5

Iron based Superconductors: Ba-122

Ba-122 ($BaFe_2As_2$)

- **High B_{c2}** (> 70 T @ 20 K)
- **H_{irr} close to H_{c2}**
- **$T_C \simeq$ 38 K**
- **Low anisotropy** (γ< 2)
- Processable by **PIT**
  - Multifilamentary architecture
  - Round wires and tapes (first 100 m length of tape in 2016 in China (Jc ~ 1.3×10^4 A/cm^2 at 4.2 K and 10 T). At present, Jc ~ 1.5×10^4 A/cm^2 at 4.2 K and 10 T



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- Ba-122 **tapes/wires** have been developed mainly in China and Japan. **Wind & React Technology** presently adopted (sintering temperature ~ 850 °C)

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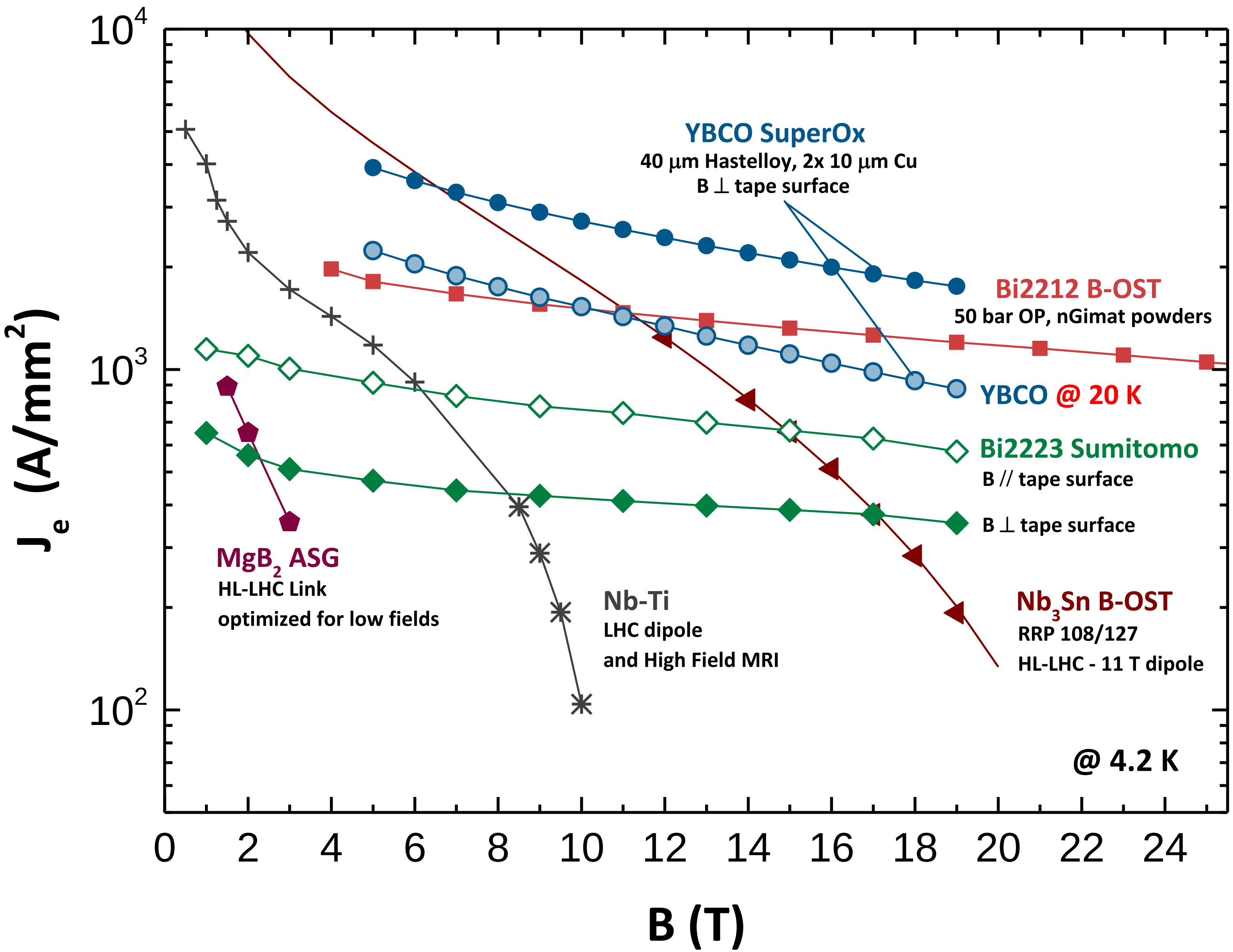
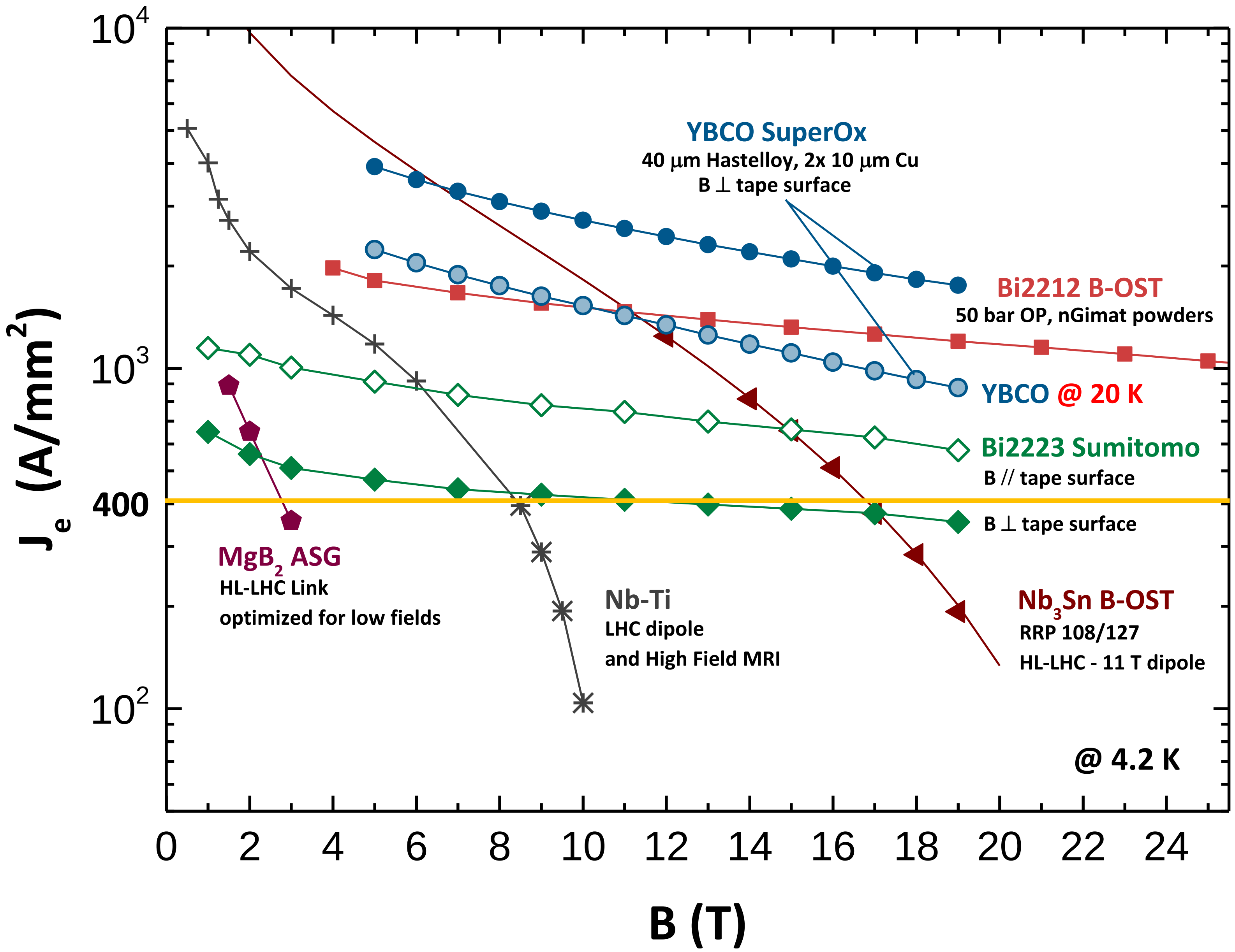
Technical Superconductors – The Present Landscape



Technical Superconductors – The Present Landscape



REBCO: several industrial manufacturers (see previous slide)

BSCCO 2223: Sumitomo (Japan), InnoST (China)

BSCCO 2212: Bruker OST (USA)

MgB$_2$: ASG Superconductors for ex-situ (Europe), Hypertech for in-situ (USA). Development at Hitachi (Japan)

Iron Based: development work – mainly in China

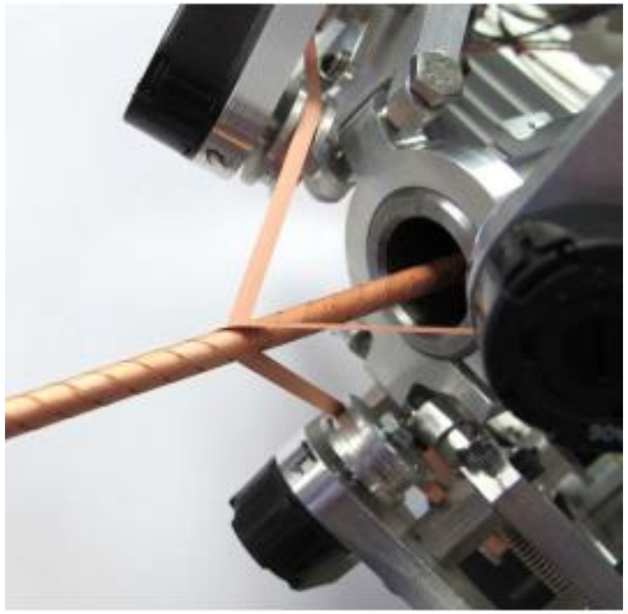
HTS Technical Superconductors - Advantages

- **Higher operating temperature**
  - Temperature margin
  - Thermal stability – high specific heat
  - Reduced cryogenic cost
- **Enabling technology for magnetic fields higher than ~ 16 T**
  - Nb-Ti up to ~ 10 T
  - Nb_3Sn up to ~ 16 T
  - HTS > 16 T

Superconducting cables: REBCO and BSCCO 2212

REBCO

Round cable



Stacks of Tapes

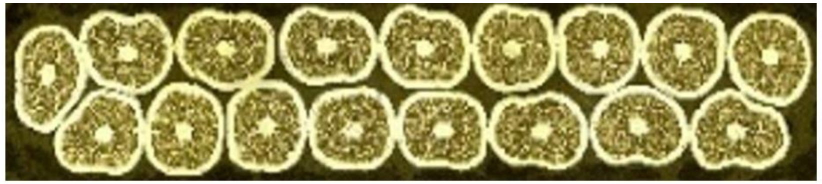
12 mm x 12 mm CICC (copper diameter 9.5 mm)

40 YBCO tapes in a copper diameter 9.5 mm.

20 YBCO tapes in each helical groove in a copper diameter 9.5 mm.

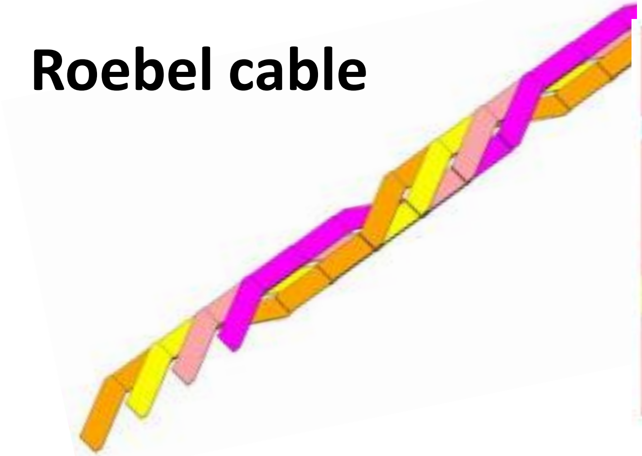
BSCCO 2212

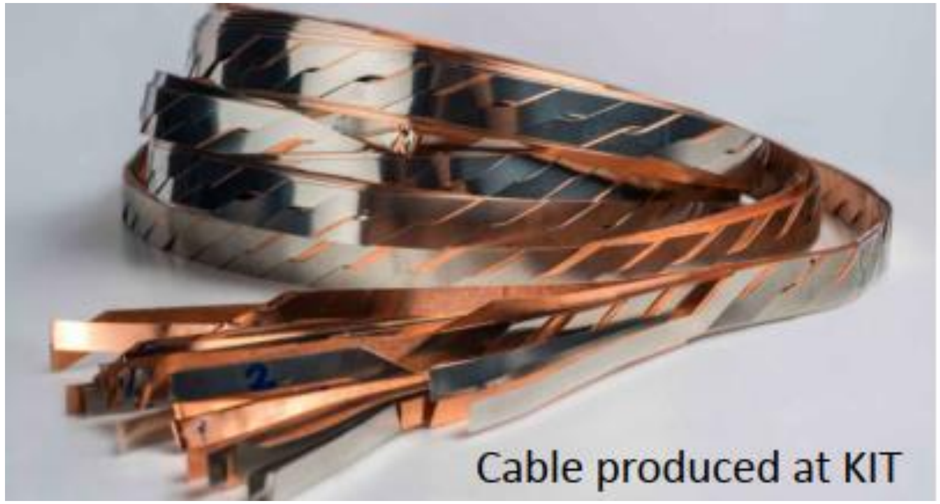
Rutherford cable



Instruments **2020**, *4*, 29; doi:10.3390/instruments4040029

Roebel cable





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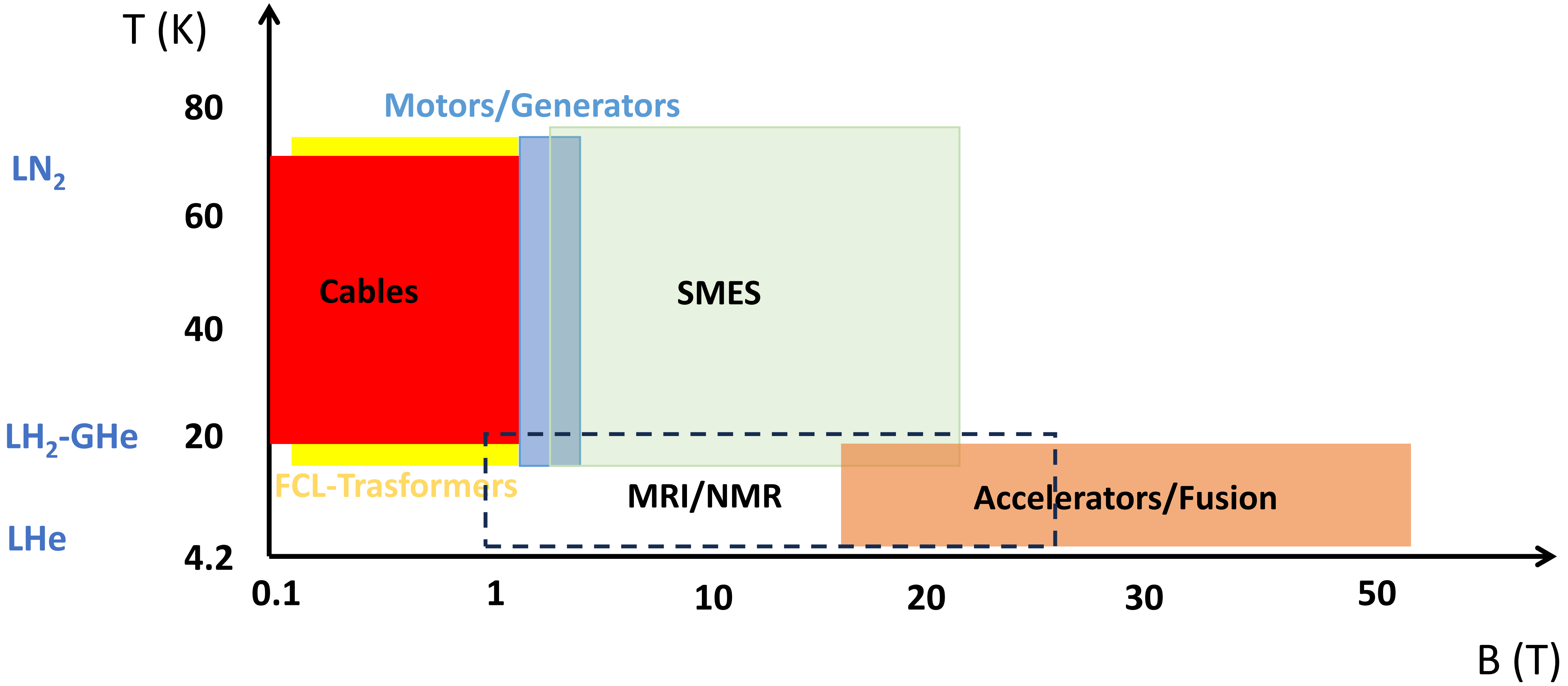
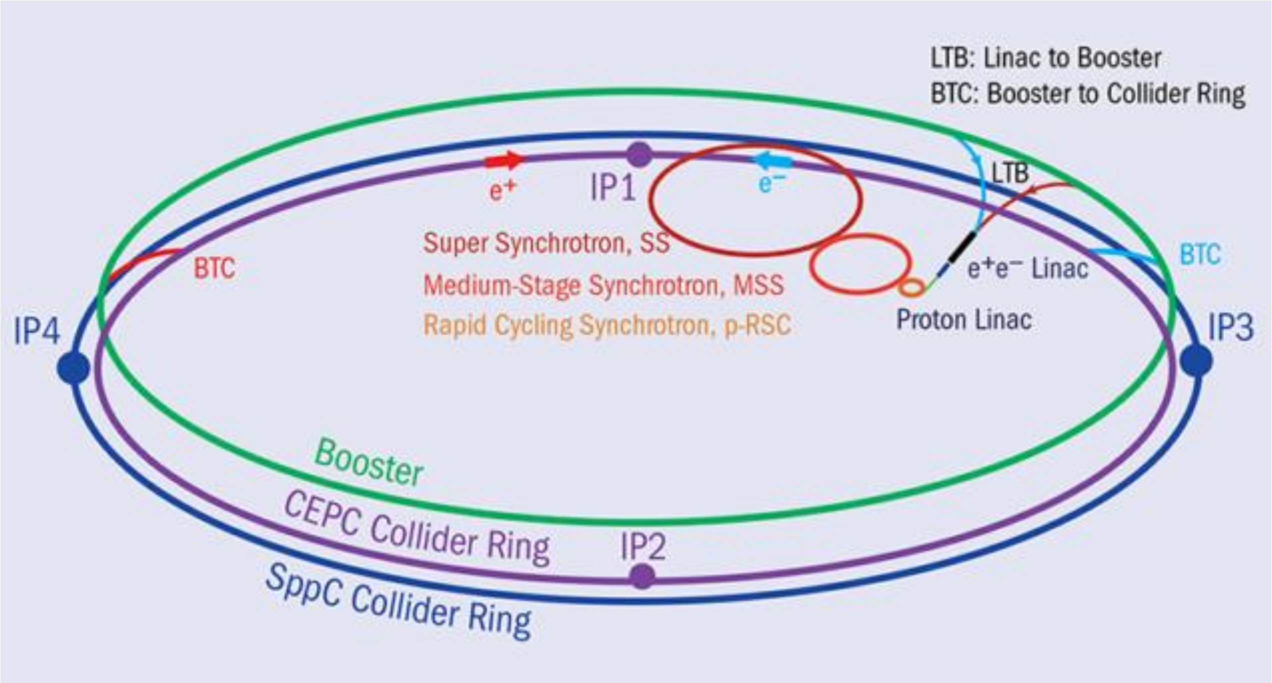
Application of HTS Superconductors



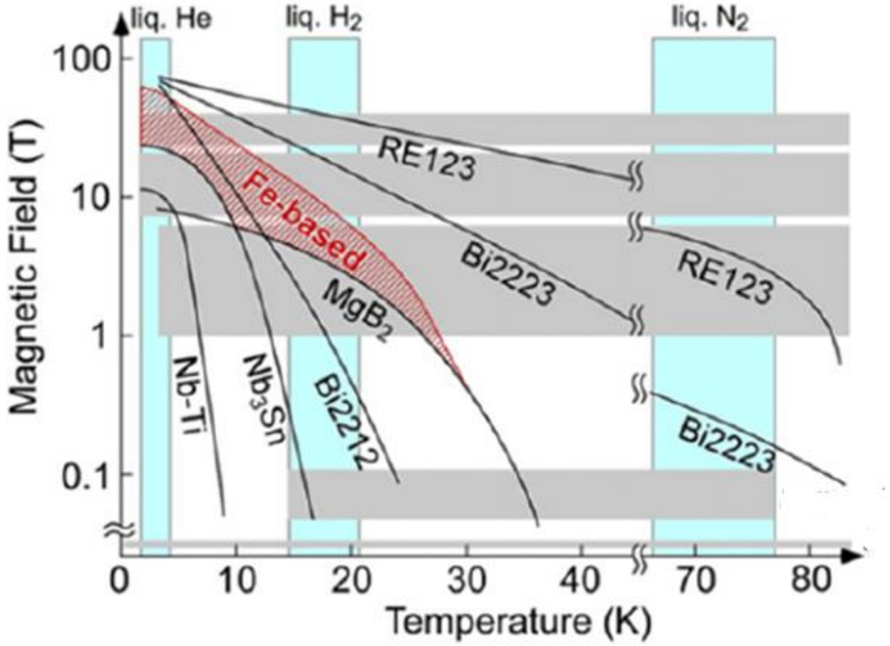
High Field Magnets for FCC-hh

LHC	FCC-hh	FCC-hh
27 km, 8.33 T	100 km, 16 T	80 km, 20 T
14 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1200 tons Nb-Ti	6000 tons Nb_3Sn	9000 tons LTS
200 kg HTS	3000 tons Nb-Ti	2000 tons HTS

IBS in High Field Magnets for SppC - China



https://cerncourier.com/a/chinas-bid-for-a-circular-electron-positron-collider/

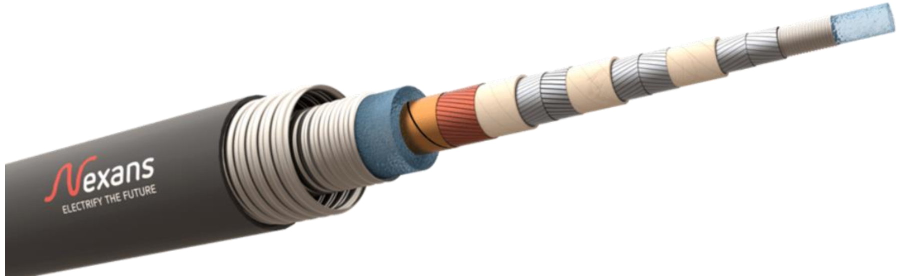


J. Shimoyama, ***SuST*** 27 (2014) 044002

12 T Dipoles: Iron based as replacement of Nb_3Sn – potentially lower cost

Low field: Power Transmission Lines

REBCO ~ 70 K



Recent Superconductor Projects			
2013	Nexans	Ampacity, Essen	1km, 40MVA, 10kV, AC
2018	Best Paths	EU Horizon's 'Best Paths' Project	30m, 3.2GW, 320kV, DC
2019	KEPCO	Shingal, Seoul	1km, 50MVA, 23kV, AC
2021	amsc	REG, Chicago	62MVA, 12kV, AC
2023	NKT	Superlink, Munich	12km, 500MVA, 110kV, AC

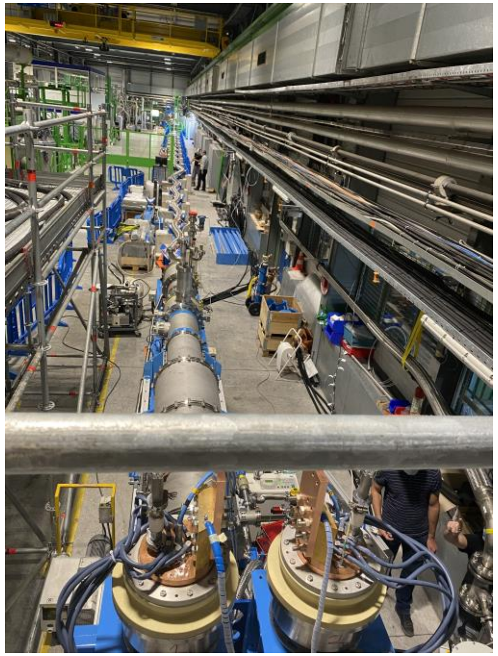
SUPERNODE

Paris Montparnasse, 2023

5/3 MW, 3.5 kA , 1.5 kV DC

Nexans and SNCF Resau

MgB_2 ~ 25 K



CERN, HL-LHC, 2021

120 kA , 3.5 kV DC

MgB_2 up to ~ 25 K: lower cost than REBCO, availability in unit length exceeding 3 km

Summary

- We went through physical properties and technical properties of High Temperature Superconductors: REBCO, BSCCO 2212, BSCCO 2223, MgB_2 and Iron Based Superconductors
- We have correlated technical properties with physical properties
- We have discussed manufacturing processes, industrial availability and maturity for applications
- HTS includes different materials with different properties in the wide range of operation (temperature and field). High field today implies operation at lower temperatures and cuprates while low field enables choice among different superconductors and/or operation at higher temperature
- HTS is an interesting and challenging field, with many applications both for society and for accelerator technology. It is still an evolving field, and use in applications will help in optimizing conductor performance

Thanks for your attention !