UNIVERSITY OF TWENTE.

High-Temperature Superconductors
- state of the art -

Herman ten Kate

Content
1. HTS superconductors history
2. Bi-2212 & Bi-2223
3. *Re*BCO
4. Iron Based Superconductors
5. High current conductors - cables
6. Conclusion

1. History of superconducting materials

- Textbooks show pages-long tables with superconducting materials, more than 1000
- However only a few can be shaped as practical conductors, makeable in long length, robust, uniform, strain resistant, etc. and for an acceptable price.

Discovery milestones:

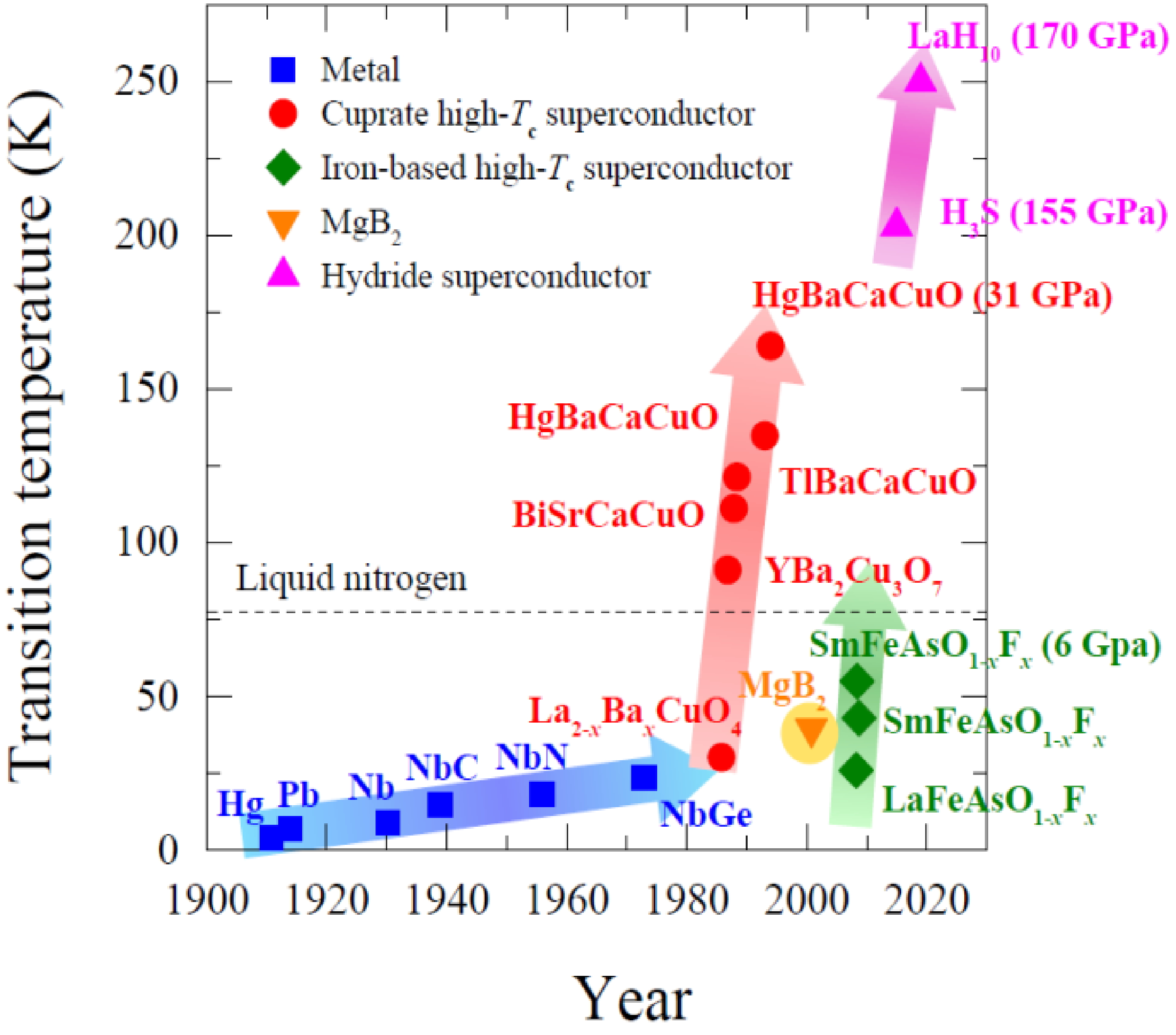
✓ **1911**: Superconductivity in Hg

✓~ **1960:** {LTS} **Nb_3Sn** and **NbTi**, 1st practical wire and magnets

✓~ **1986:** {HTS} Cuprates, **BiSrCaCuO** and **YBaCuO**

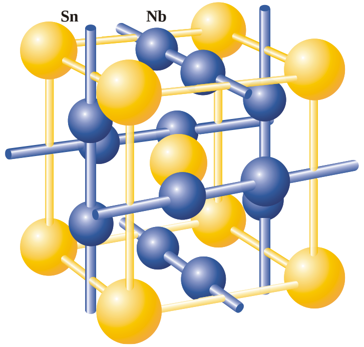
✓ **2001:** {MTS} **MgB_2** (not further discussed here)

✓ **2008:** {HTS} Iron **FeAs-Based** Superconductors (IBS)



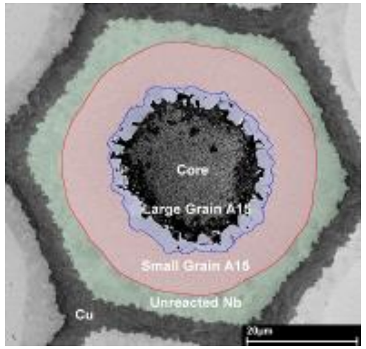
From material to magnet

Lattice



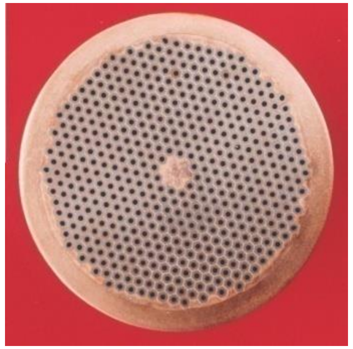
50 nm

Filament



20 µm

Wire

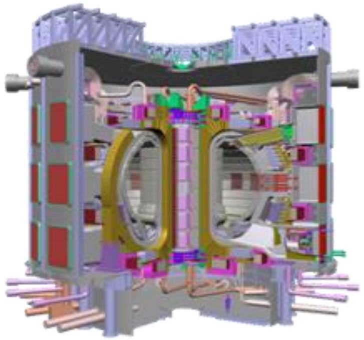


1 mm

Cabled conductor

50 mm

Magnet

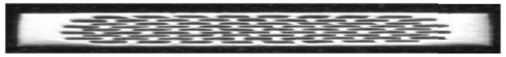


35 meter

- Often we need a high current for a large scale magnet
- How to make cabled conductors from vulnerable wires and tapes without degradation ?
- Key area of research, to avoid surprises and degraded magnets
- **Need to understand and control the entire chain for magnets to work**
- Striking examples exist of missing understanding putting large projects at risk !

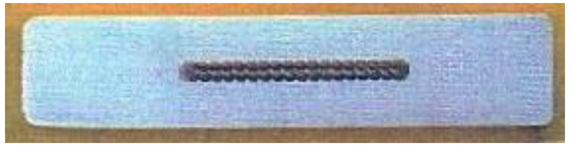
For large-scale magnets - Cables are what we need!

200 A HTS tape



X

65000 A@5T Al-NbTi/Cu



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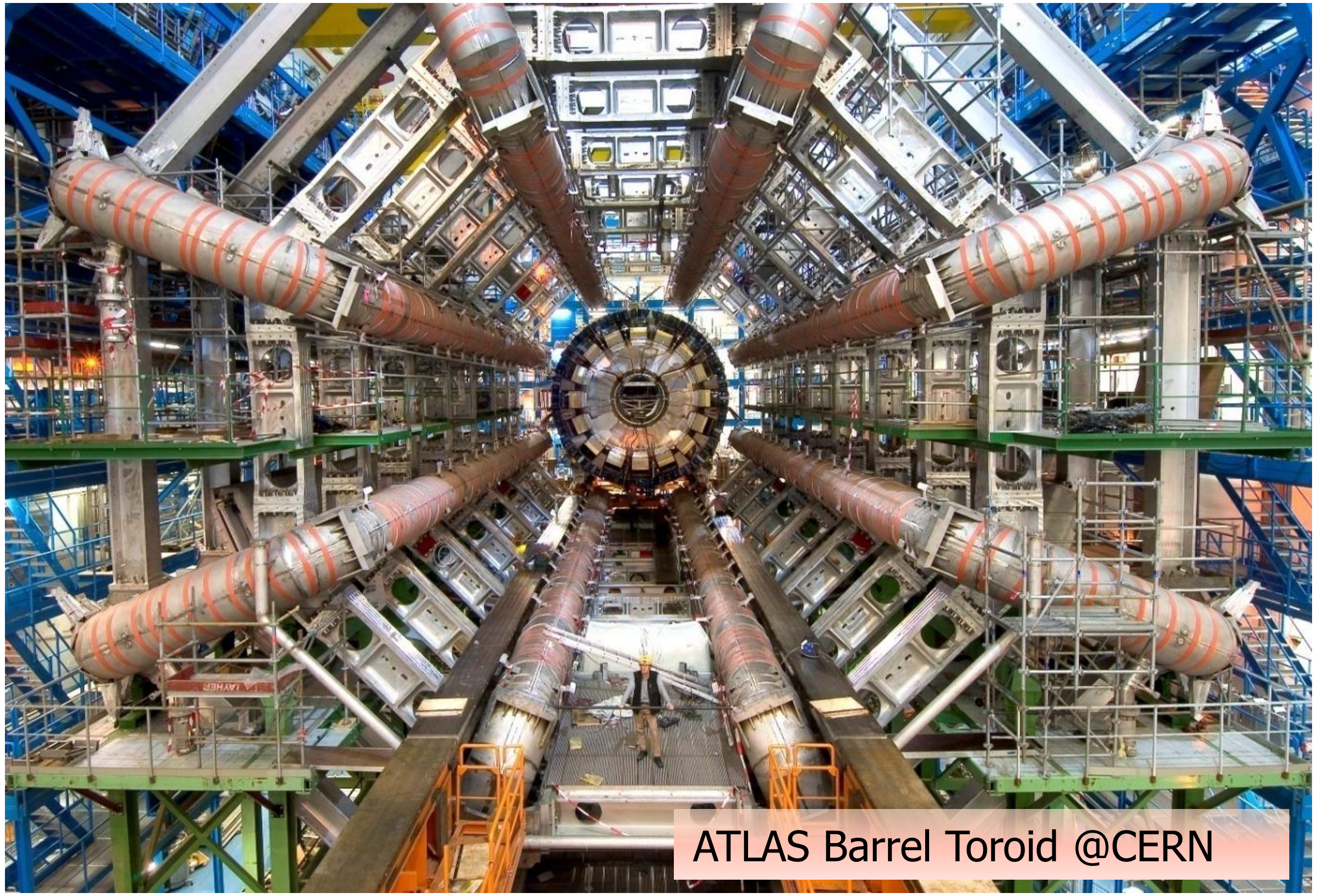

ATLAS Barrel Toroid @CERN

- Can not build **large scale magnets** from single NbTi, Nb_3Sn, B2212 wires, or ReBCO tapes
- Superconductors are required **that can be put in parallel, be cabled and still perform**!

Essential properties

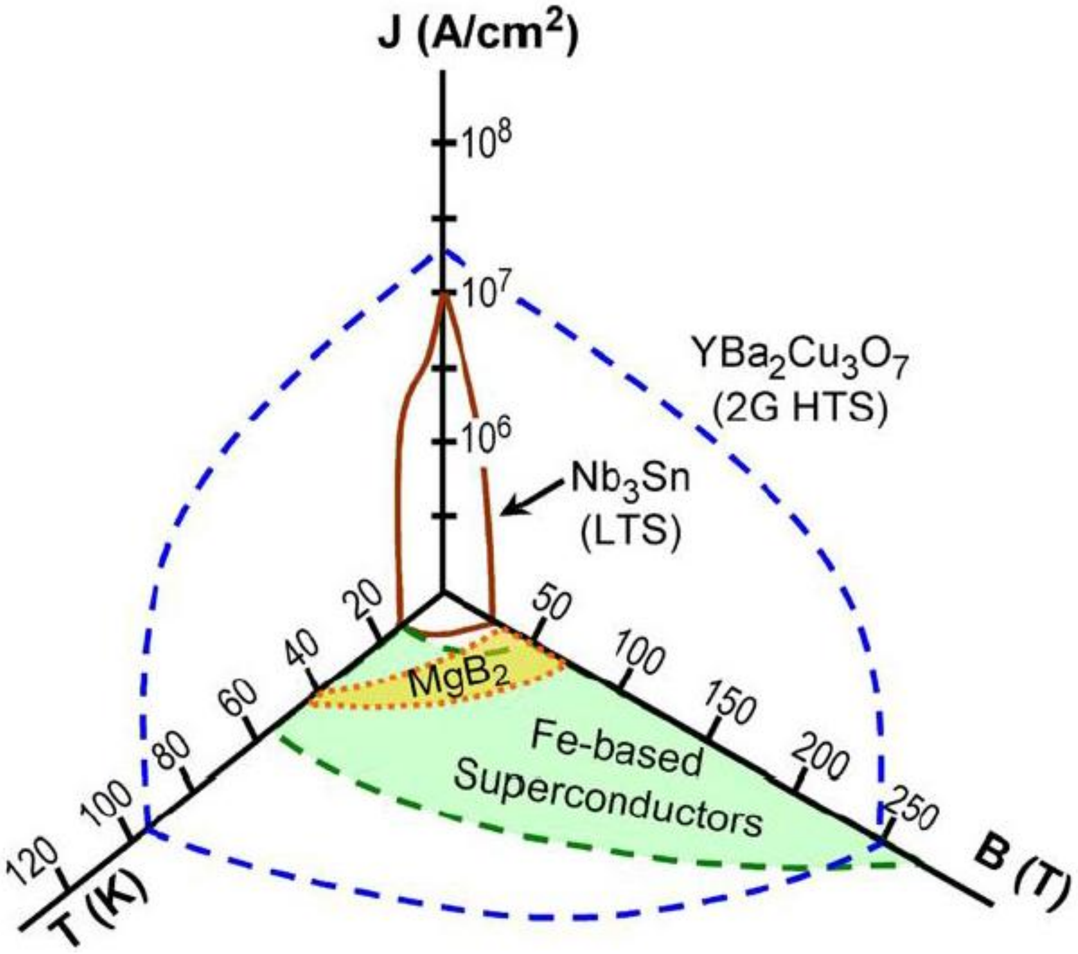
Three key properties enabling applications

- T_c : transition temperature
- B_{c2}: upper critical field
- J_c : critical current density

For applications we need:
a large J_c, a high B_{c2}, and for stability and minimum cooling a high T_c

Practical superconductors today are :

- **LTS:** NbTi, Nb_3Sn,
- **HTS:** MgB_2, ReBiCuO, BiSrCaCuO
- **IBS:** (may be, coming up): **FeAs-based**



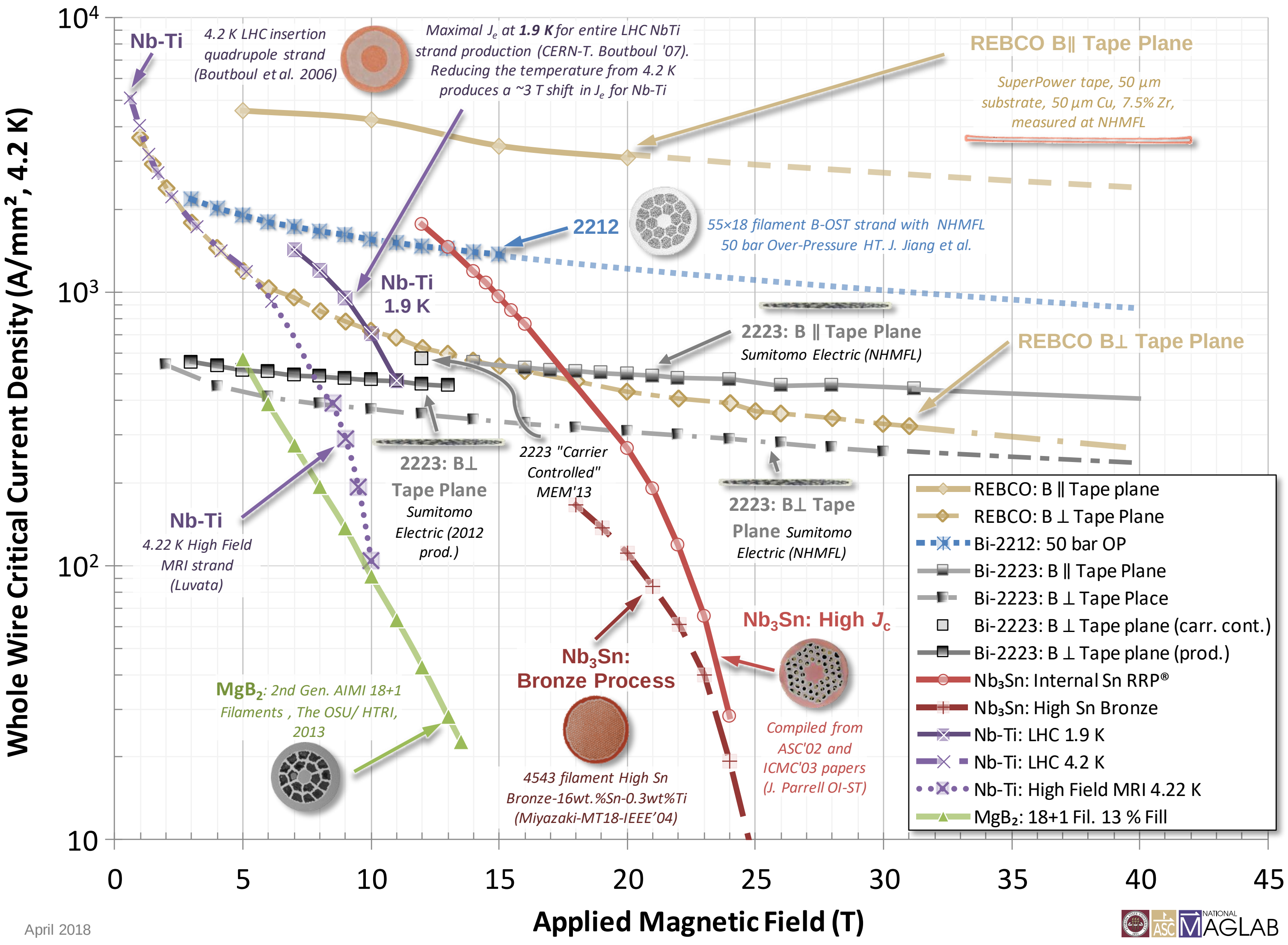
Li et al., *Rep. Prog. Phys.* 74 (2011)

Whole wire current density is what counts…..

For suitable applications, it is the whole-wire current density that counts!

Assuming a threshold of 300 A/mm² @1.9-4.5K, we see:

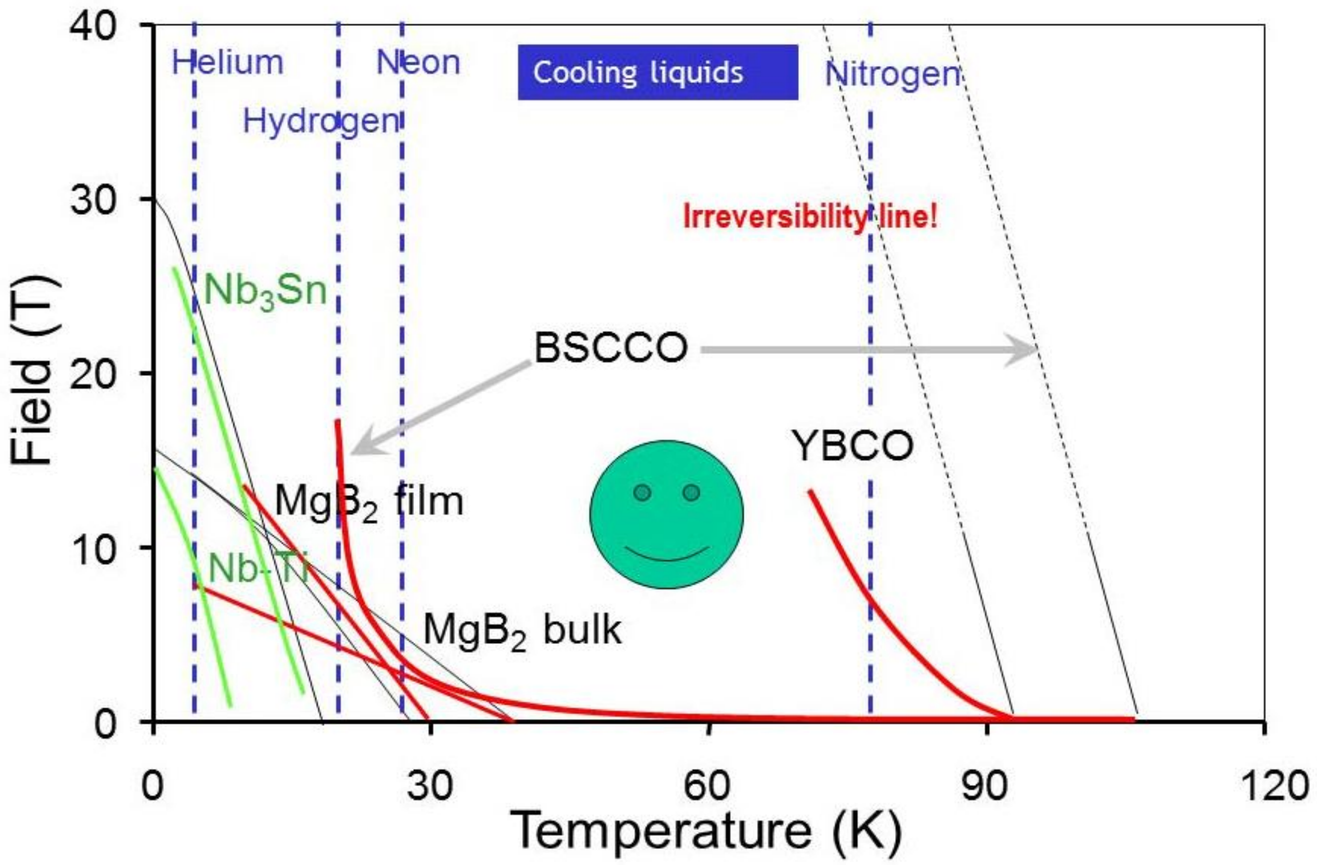
- MgB_2 up to 5 T
- NbTi up to 10-11 T @1.9 K
- Nb_3Sn up to 20 T @1.9 K
- **Only HTS: Bi-2212, Bi-2223 and ReBCO can go >>20 T up to the conductor YS limit!**



Courtesy P. Lee

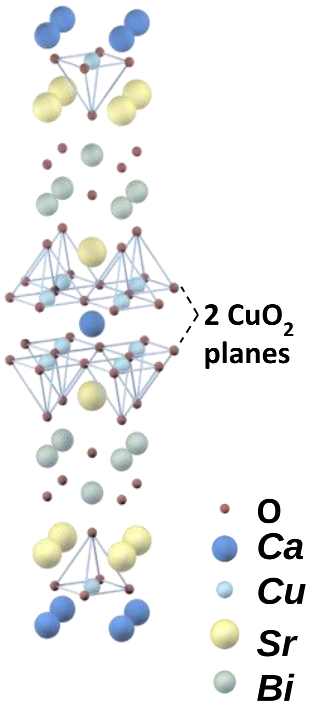
Unbeatable beauty of ReBCO, teslas at 30 – 50 K

At higher temperatures?



✓ **ReBCO is the only superconductor that allows us to generate high magnetic fields without using liquid helium in the temperature range 20-50 K. No other conductor can do this!**

3. Three maturing practical cuprate HTS conductors

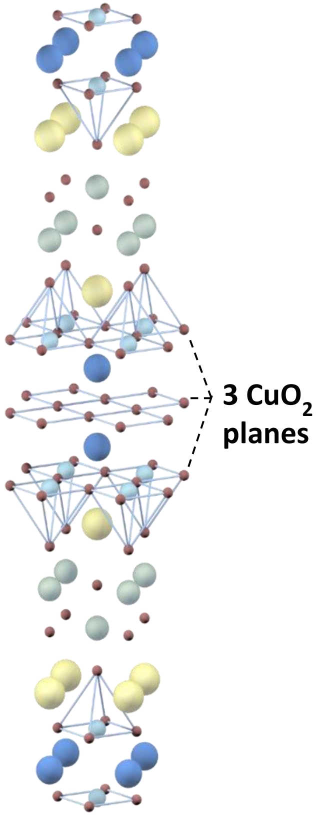


Bi-2212 [T_c = 91 K]

$Bi_2Sr_2CaCu_2O_{8+x}$

Bi-2212

Powder-In-Tube **round wire**

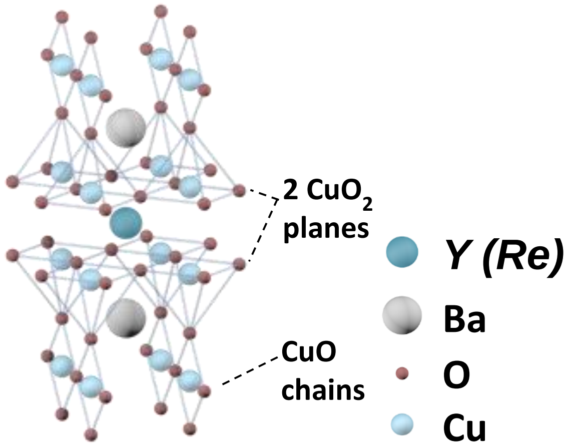


Bi-2223 [T_c = 110 K]

$Bi_2Sr_2Ca_2Cu_3O_{10+x}$

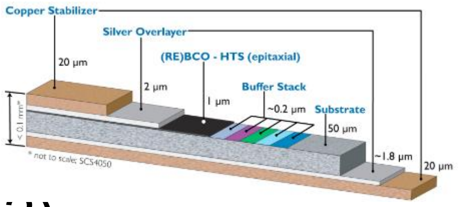
Bi-2223

Powder-In-Tube **tape**



Y123 (*Re*BCO) [T_c = 92 K]

$YBa_2Cu_3O_{7-x}$



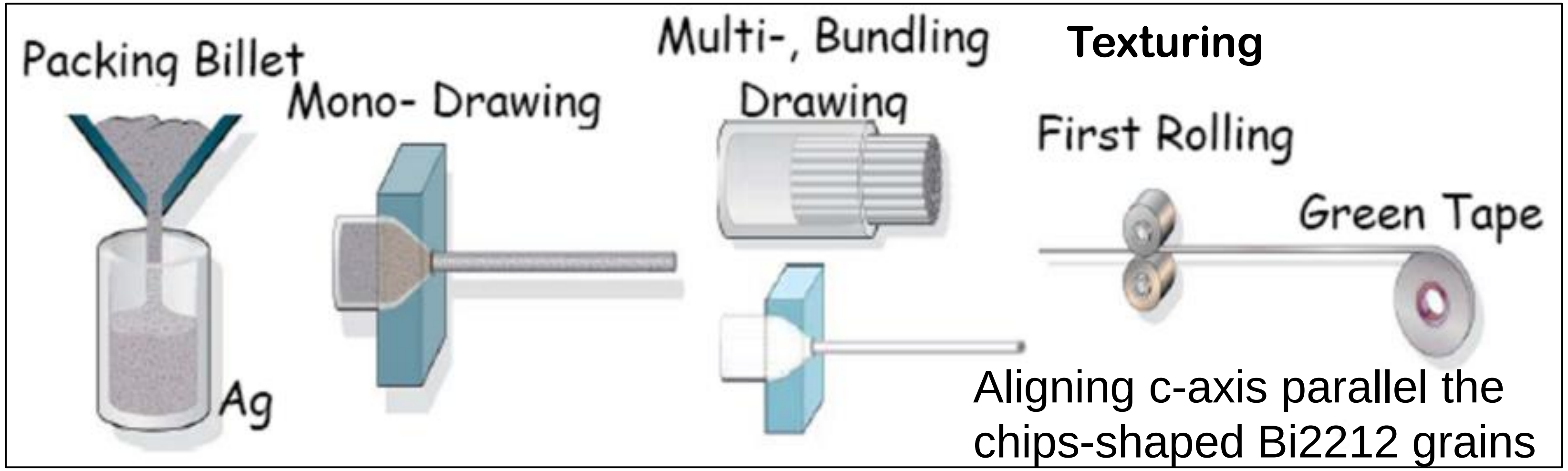
***Re*BCO** (Y123)

Coated Conductor **tape**

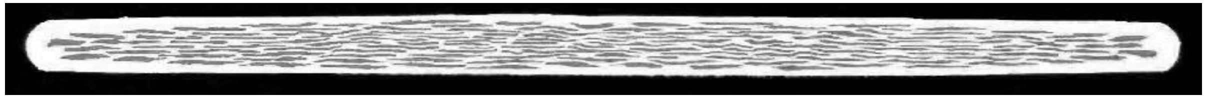
Bi-2223 conductor manufacturing

Bi-2212 (75-80%)
+ Bi-2201 (~5%)
+ Ca_2PbO_4 (10%)
+ CuO in a **Ag** tube

Ag is permeable for O_2



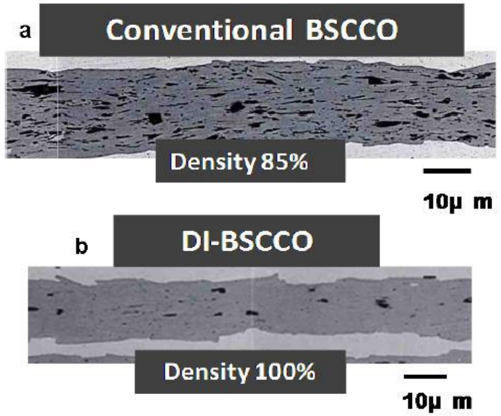
Bi-2223 formation:
Heat treatment @ 830 - 850°C in ~7.5% O_2

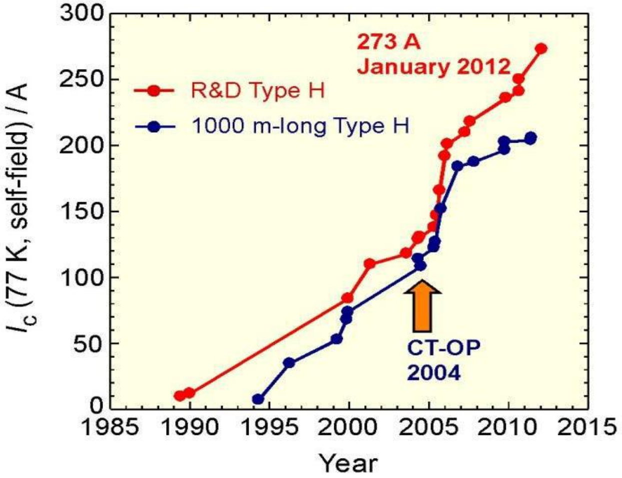


Weak Ag matrix, superconductor filling factor ~40%

Typically ~4 x ~0.4 mm^2

- Heat treatment releases $C0_2$ --> 'voids'.
- Densification needed to enhance I_c.
- In the past many groups and few companies were making Bi-2223.
- **Today essentially only Sumitomo!**

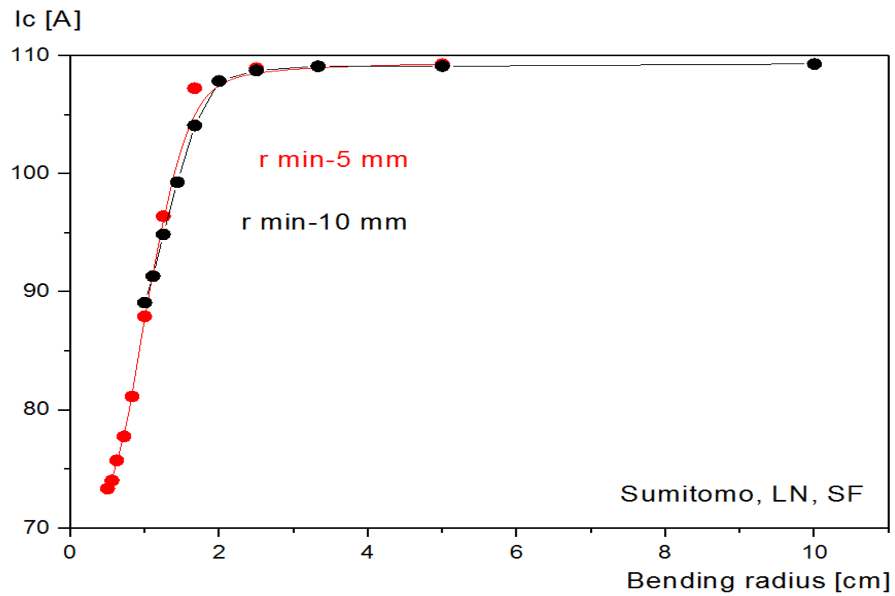


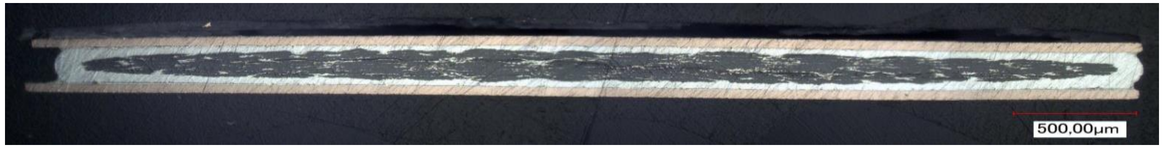


Bi-2223 tape, reinforced, suitable for magnets

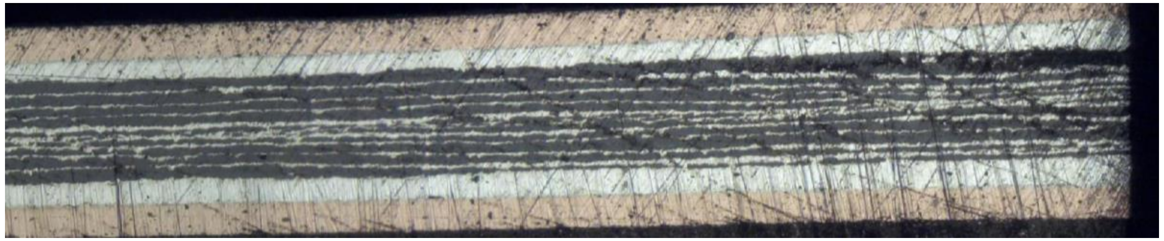
- **Sumitomo turned this weak Bi-2223/Ag tape into a strong magnet conductor**

- CT-OP BiPb2223 high strength tape
- Copper sheath 2x50 µm
- Ic in self-field at 77 K: 150 to 200 A
- Minimum bending radius 20 mm
- Stainless Steel or Ni (HT-NX) alloy sheet reinforcement
- Can withstand 400 MPa before degradation is noticed





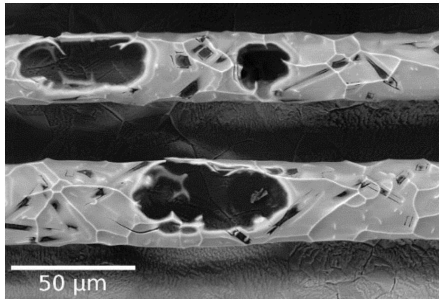
SUMITOMO ELECTRIC



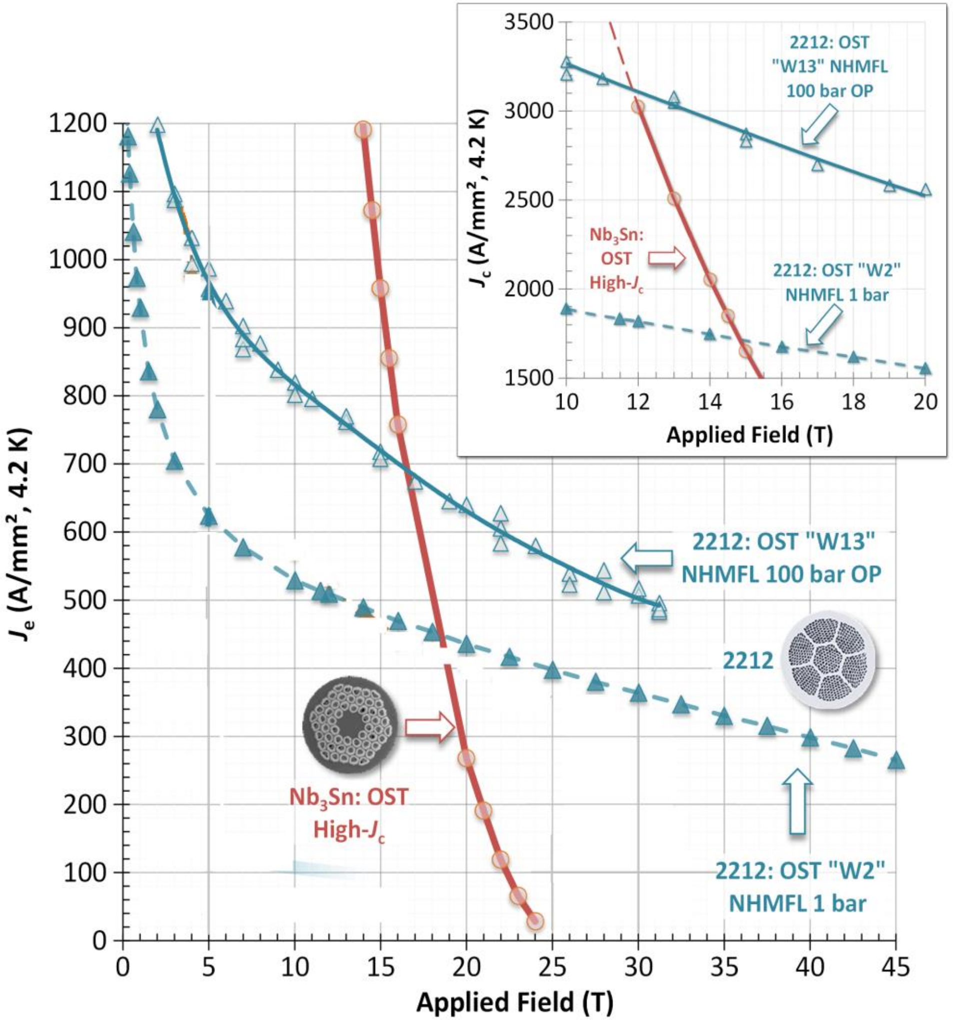
✓ This **Bi2223** conductor is a **fully developed, mature and commercial high-strength conductor**, ready for coil winding, somewhat 'forgotten' with all focus on ReBCO, **may be deserves a revival….**

Bi-2212 round wire - quasi isotropic

0.8-1.0 mm round wire
Bi-2212, some 30% filling factor in Ag tube



Large voids present in tube-like filaments due to long heat treatment, obviously heavily limiting critical current!



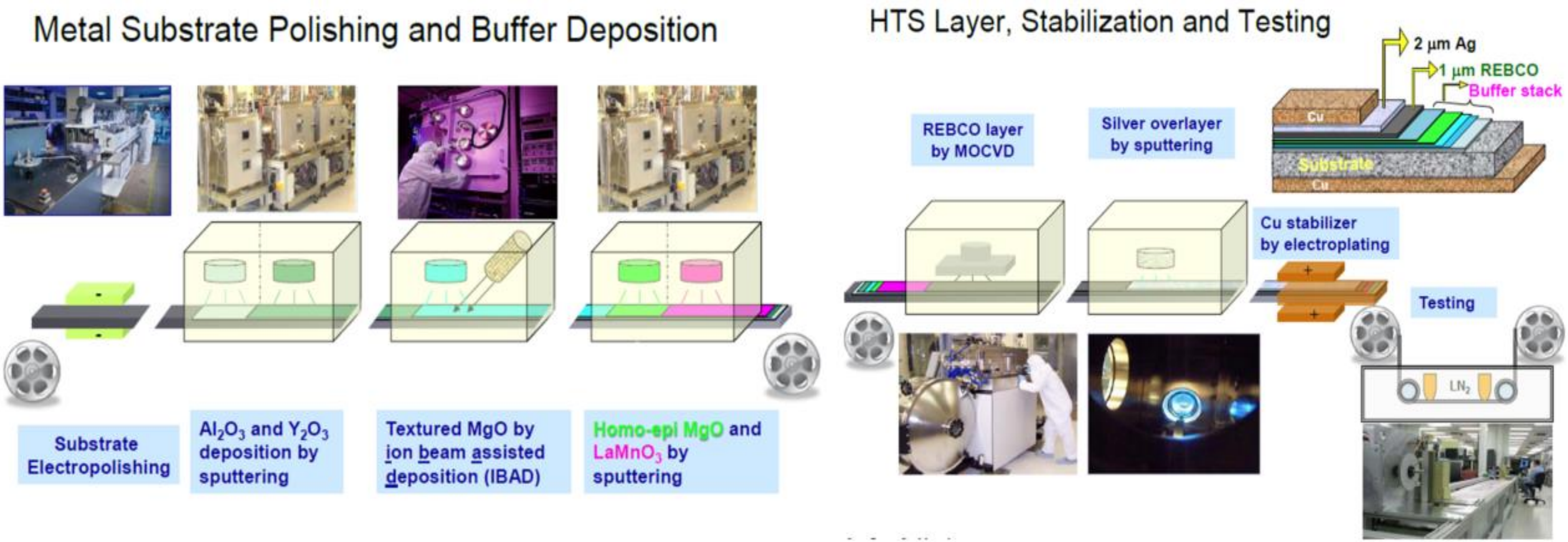
- Cure: do reaction in overpressure up to 100 b
- ---> Some 30 - 100% I_c enhancement demonstrated
- May be acceptable for special magnets
- Not very practical for large scale series production though….
- Momentarily supported by 1 lab and (still) made by one supplier

D. Larbalestier et al., Nat. Mat. 13 (2014) 375

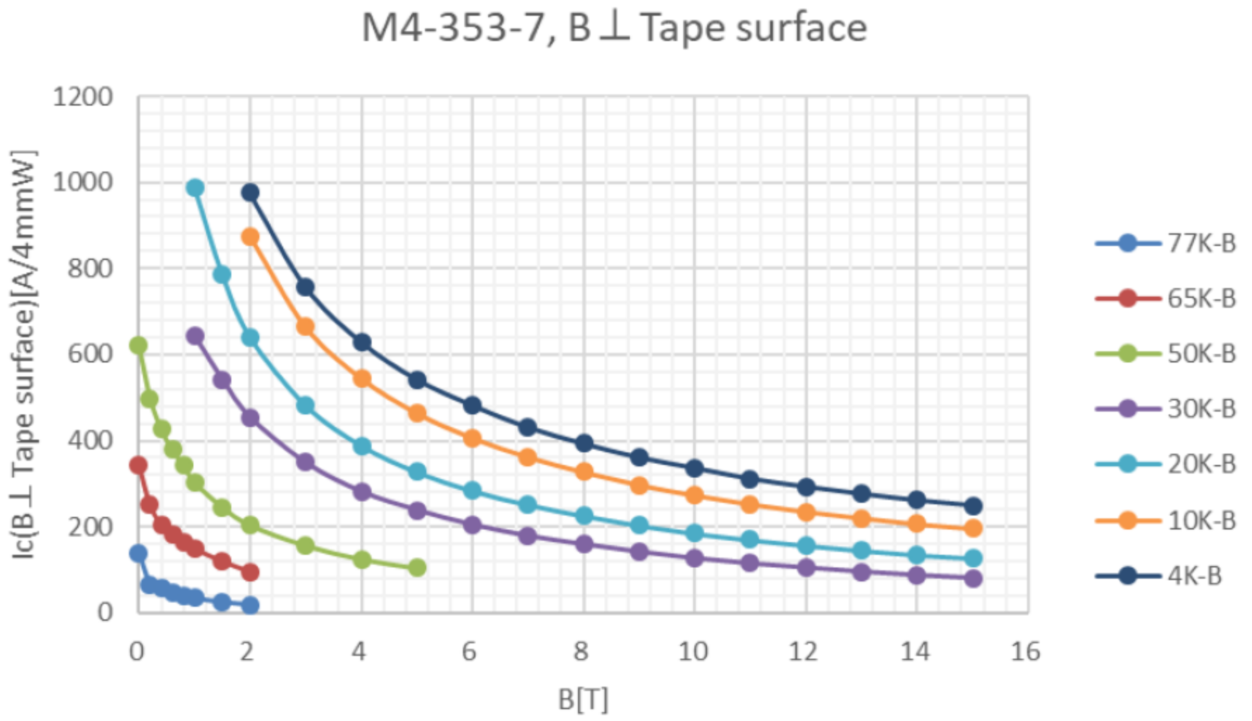
4. Example of Coated Conductor Manufacturing

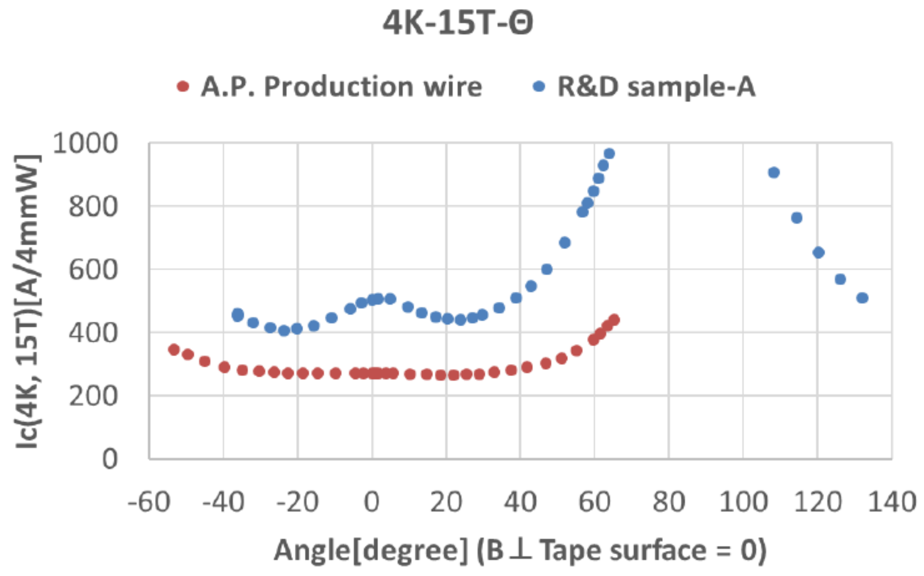
Three techniques needed, various methods developed and chosen by manufacturers:

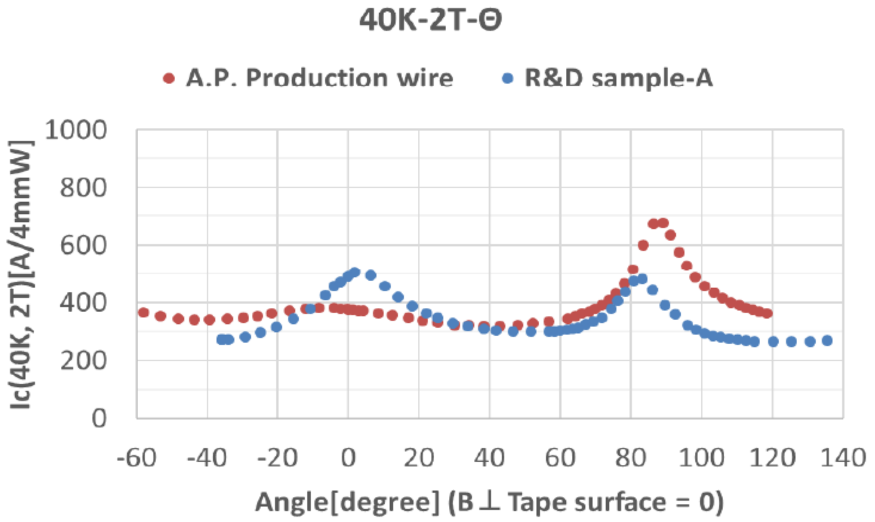
- Preparing the substrate with proper buffer layers
- Deposition of the ReBCO layer & surface closing
- Adding stabilizing copper.



Example Superpower tape properties







- 12 mm wide using 50 µm substrate
- Ic as function of temperature and field
- Reduction angular dependence, towards isotropic behaviour
- Optimisation for low temperature and high magnetic field
- New manufacturing plant ready

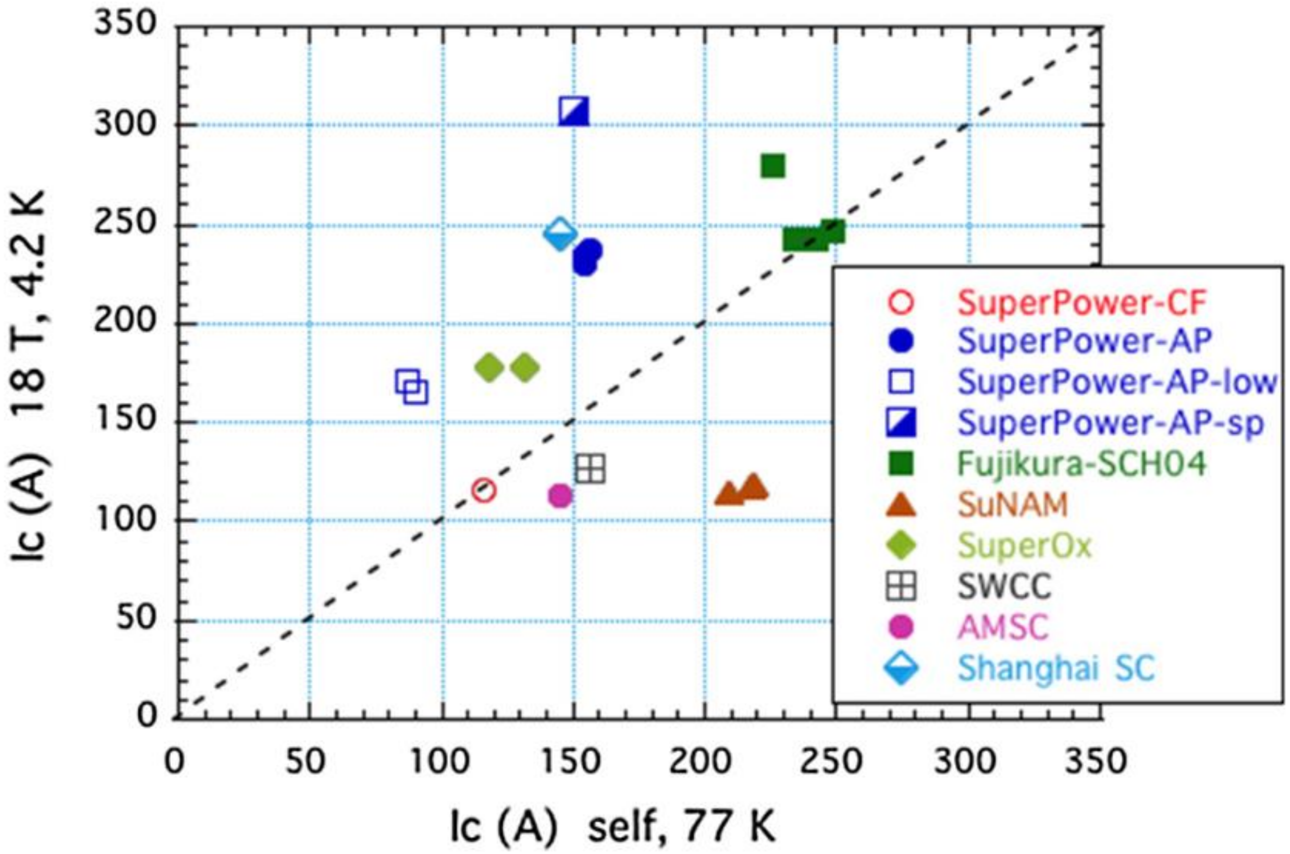
D. Hazelton et al, MT26 Vancuver

Flavor of ReBCO tape suppliers

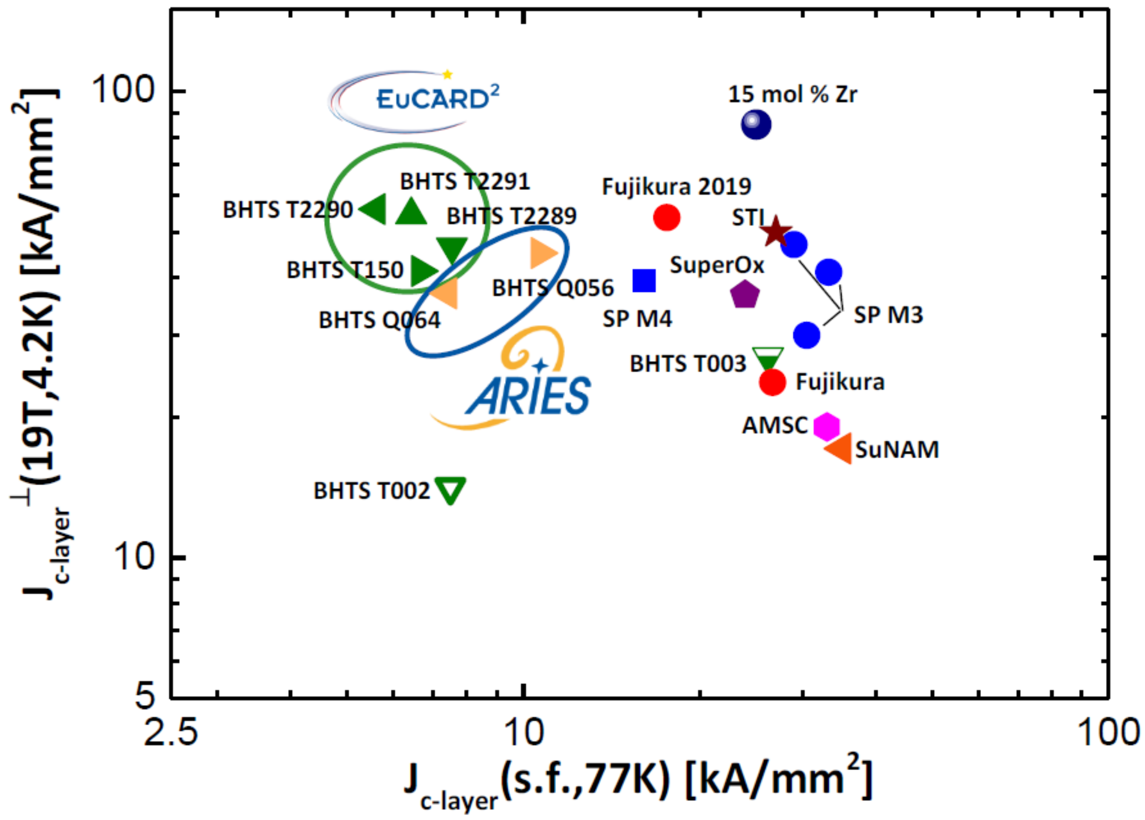
Manufacturer	Technology	Substrate (material/thickness) µm	Cu stabiliser (type, thickness) µm	*Re*BCO thickness µm	Size (w x t) mm^2
American Superconductor	RABiTS MOD	NiW 75	Laminated 50 per side	0.8	4.4 x 0.20
Bruker HTS	ABAD PLD	Stainless steel 100 / 50	Electroplated 20 per side	1-2	4.1 x 0.15 12 or 4 x 0.09
Fujikura	IBAD PLD	Hastelloy 75	Laminated 75 on 1 side	2.0	5.1 x 0.16
SuNAM	IBAD RCE	Hastelloy 60	Electroplated 20 per side	1.4	4.0 x 0.11
SuperOx	IBAD PLD	Hastelloy 60	Electroplated 10 per side	1.2	4.0 x 0.09
SuperPower	IBAD MOCVD	Hastelloy 100 / 50 / 25	Electroplated 20 per side	1.4	4.0 x 0.10 12.0 x 0.10
Shanghai Superconductor	IBAD PLD	Hastelloy 50	Electroplated 5-35 or Laminated 50-125	1–2.5	4.0 x 0.1 10.0 x 0.35
THEVA	ISD	Hastelloy 100 / 50	Laminated 50 or 100 Electroplated 20	3.5	4.0 or 12.0 x 0.15 or 0.1
Dnano	CSD	Ni5W 60	Electroplated or laminated 20 per side		4.0 x 0.10

Comparing tapes

Tape Ic 18 T @ 4.2 K vs Ic sf @ 77 K



Tape Jc 19 T @ 4.2 K vs Jc sf @ 77 K



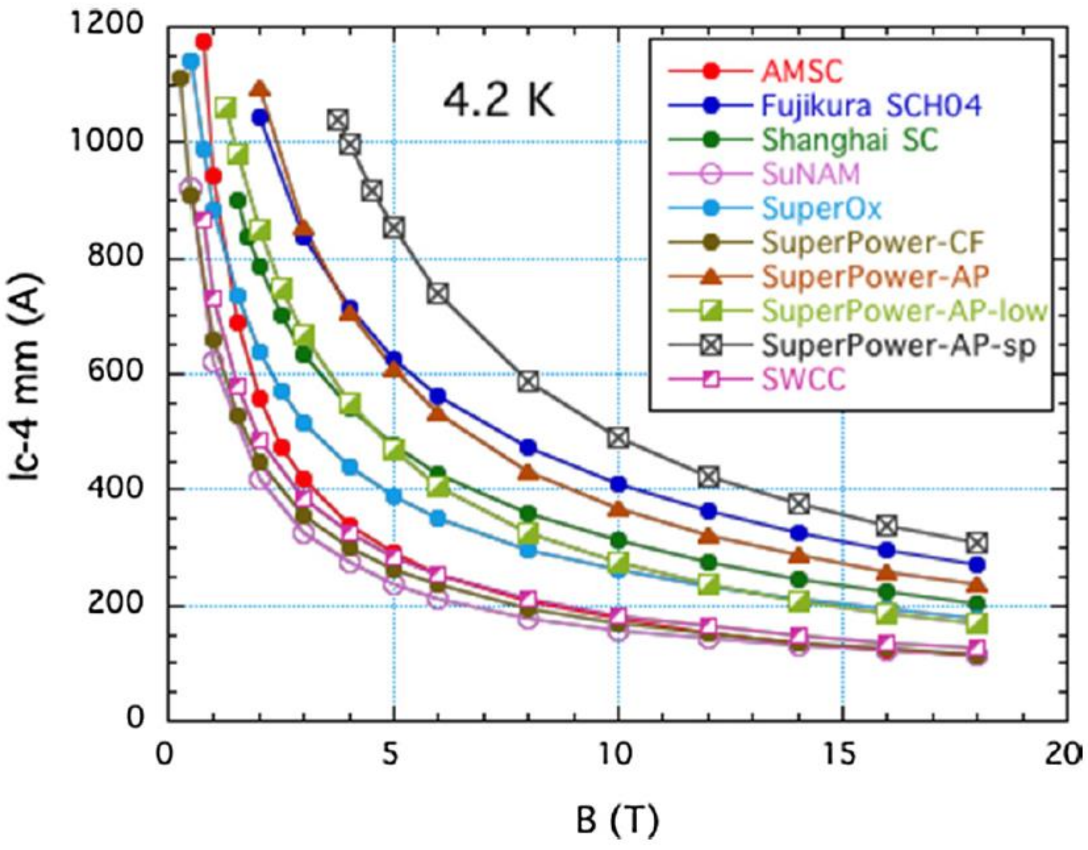
- Some tapes are optimized for low T and high B, most of them for 77 K and low B (energy appl.)

K. Tsuchiya et al., Cryogenics 85, 1-7, 2017

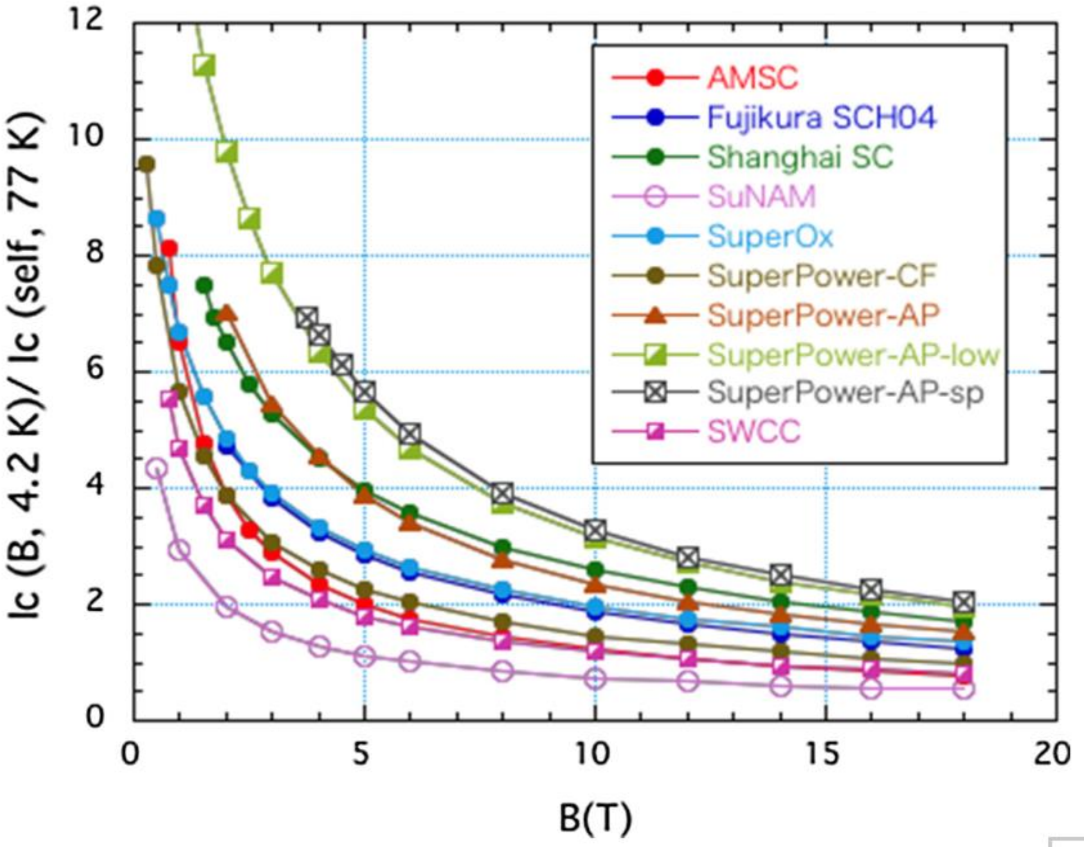
C. Senatore et al., WAMHTS-5 Budapest, 2019

Comparing tapes

Tape Ic per 4 mm width vs field @ 4.2 K



Ic @ 4.2K / Ic @ 77 K-sf



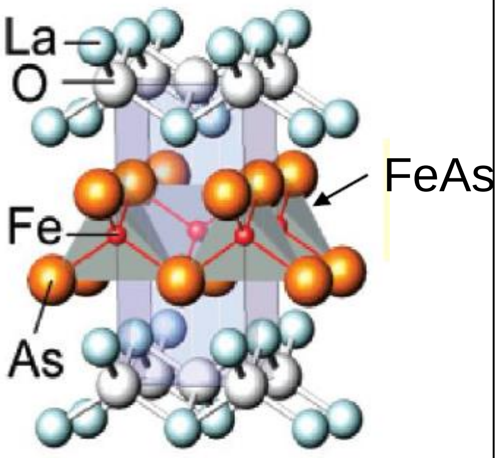
K. Tsuchiya et al., Cryogenics 85, 1-7, 2017.

Summary coated conductors

- Most manufacturers now optimize for low temperatures / high field use of the tapes (now focussing on core business of superconductors, rather than energy applications use at 77 K.
- Reducing the €/kAm by increasing ReBCO layer thickness (1 > 5 or 8µ); reducing substrate thickness (100 > 50 > 30 > 20 >10µ); applying Zr doping and APC….
- Lengths of 300 m available, still long delivery times, some deliver up to 1000 m, need more!
- Homogeneity of longer lengths depends on producer, usually measured magnetically at 77 K.
- Geometrical and mechanical inhomogeneity's over long length to be controlled.
- In recent years accelerator EU Programs like EuCARD & Aries successfully pushed Coated Conductor manufacturers for 'better tape'.
- Now a days a strong push is from enterprises aiming to build 20 T type tokamaks, requiring large volumes of tape in short time for aggressive coil technology program, a very welcome support.
- Properties of Coated Conductor need to be tunes and optimized 'application specific'.

5. Iron Based Superconductors (IBS) types

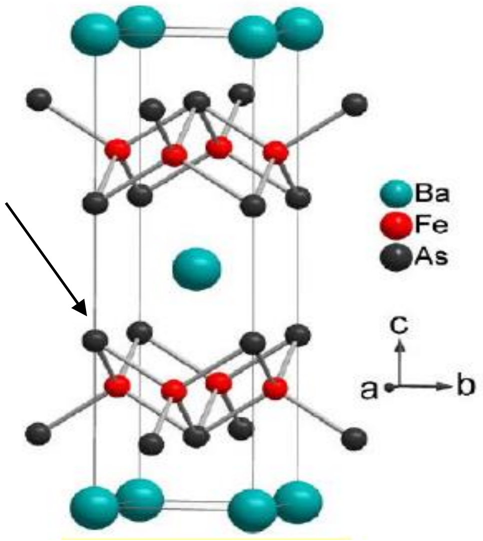
1111 Phase LnOFeAs



Z.A. Ren et al., Chin. Phys. Lett. 25 (2008)

T_c ~ 55 K

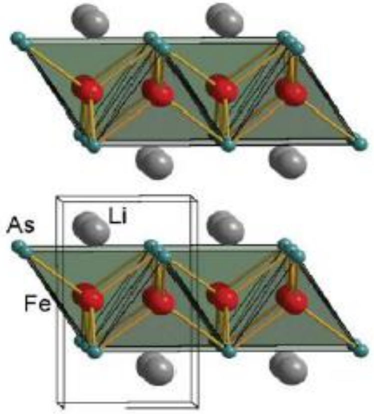
122 Phase AFe2As2 (A=Ba, Sr, Ca)



M. Rotter, et al., Phys. Rev. Lett. 101 (2008)

T_c ~ 38 K

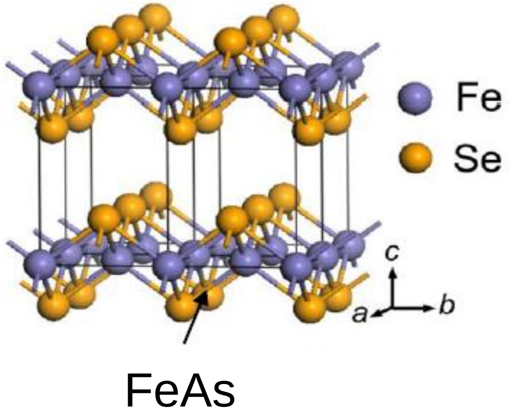
111 Phase LiFeAs



X. C. Wang, et al., Solid State Commun. 148 (2008)

T_c ~ 18 K

11 Phase FeSe



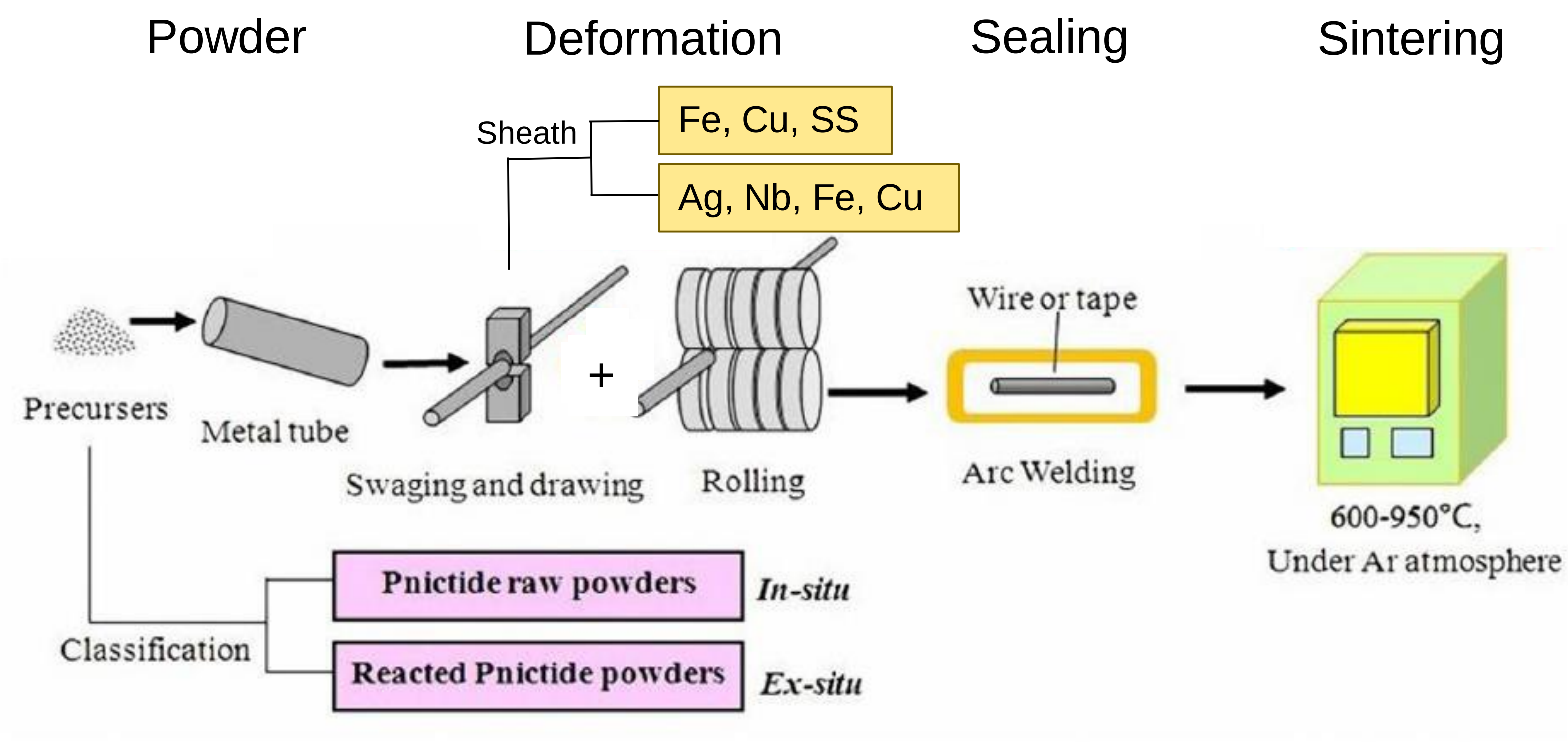
F. C. Hsu, et al. Proc. Natl. Acad. Sci. USA 105 (2008)

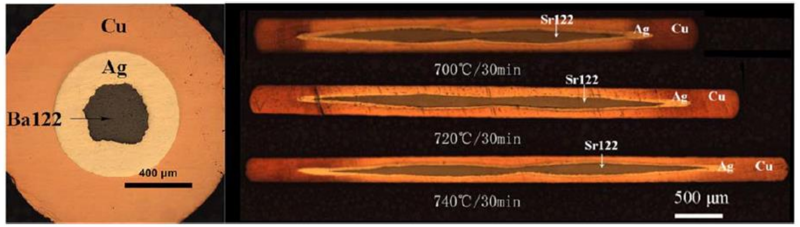
T_c ~ 8 K

* Y. Ma et al., @EUCAS2019

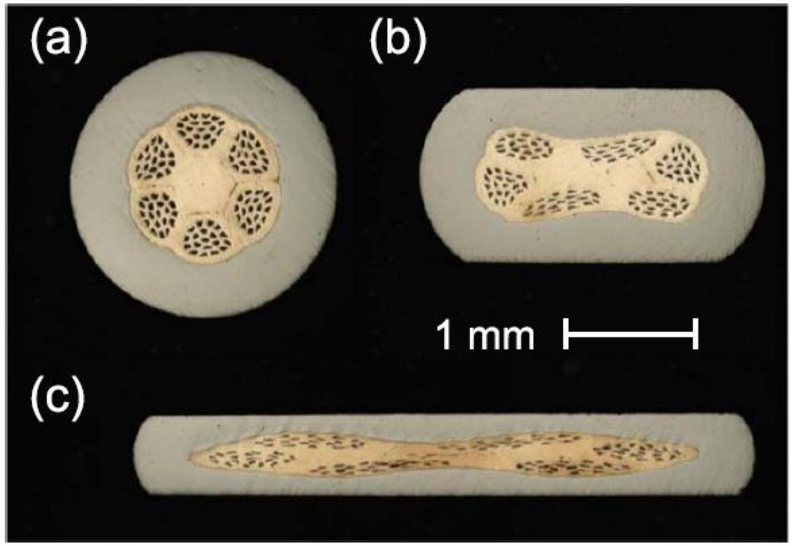
- IBS materials shows a layered structure of FeAs layers, in a similar way as CuO_2 in ReBCO/BSCCO (toxicity of As may become an issue preventing large scale application)

Iron Based Superconductors – manufacturing





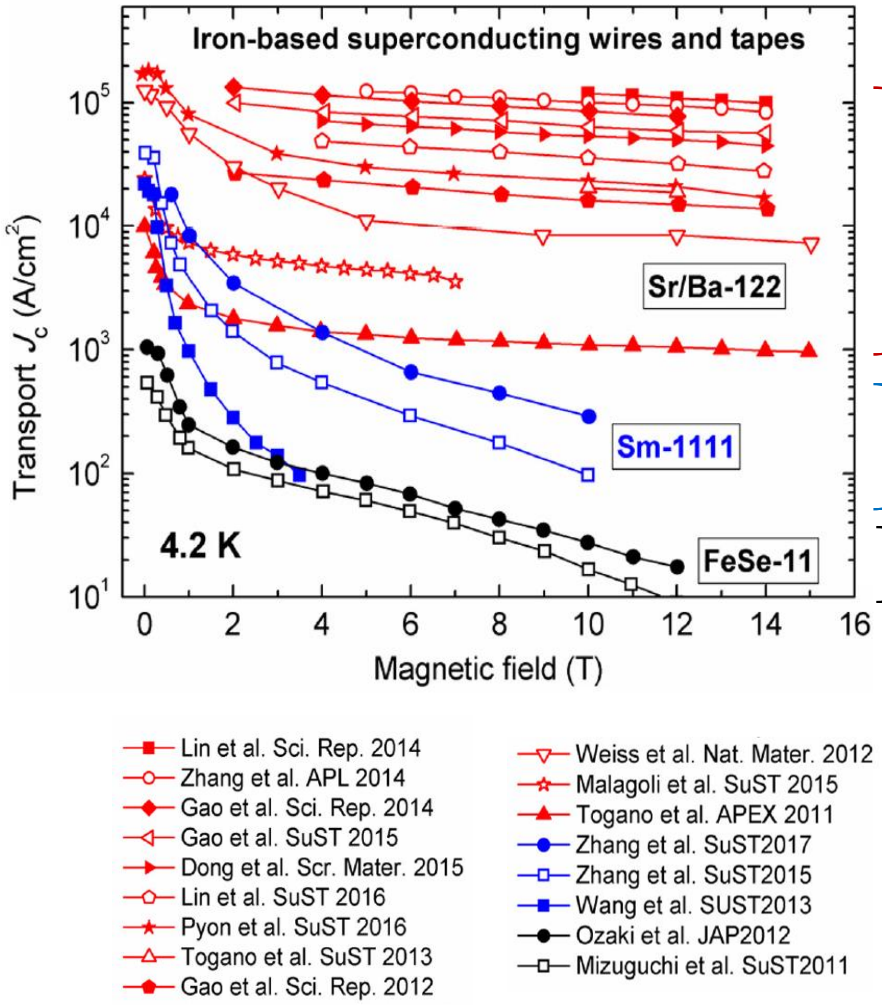
hot isostatic pressed Ba-122 wires and Sr-122 tapes



114-filament Sr-122/Ag/Fe

* H. Hosono, A. Yamamoto, H. Hiramatsu, Y. Ma, Materials Today, in press
C. Yao et al., SUST 32 (2019)

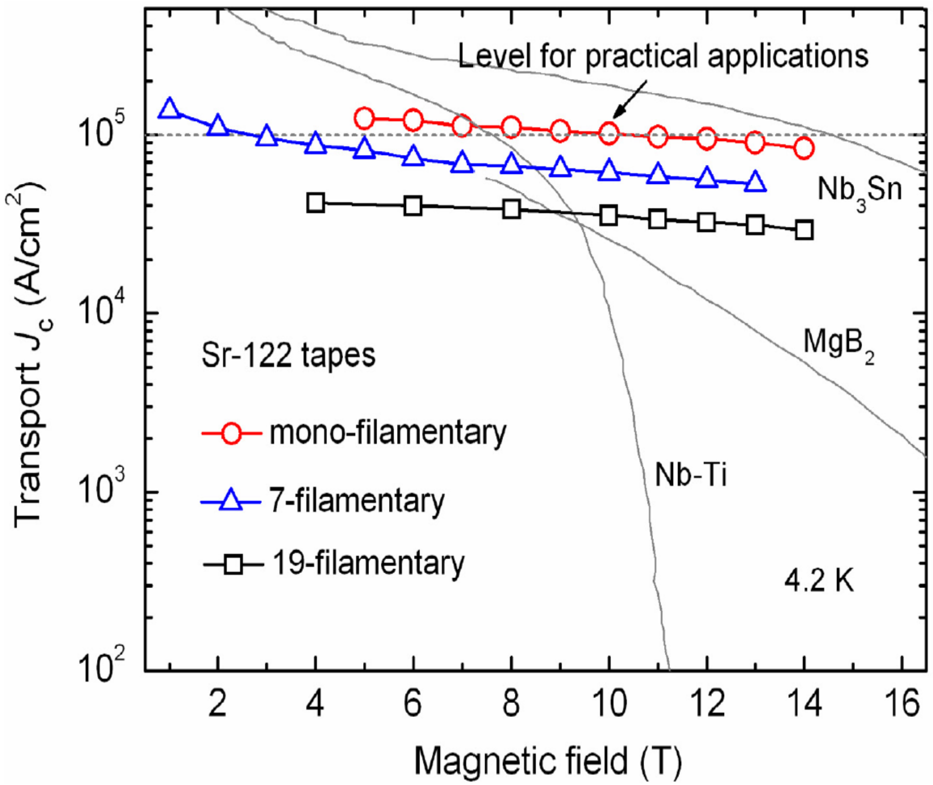
Iron Based Superconductors – applicable materials



potential for high-field applications

difficulty controlling the fluorine content during sintering

difficulty in removing excess of Fe

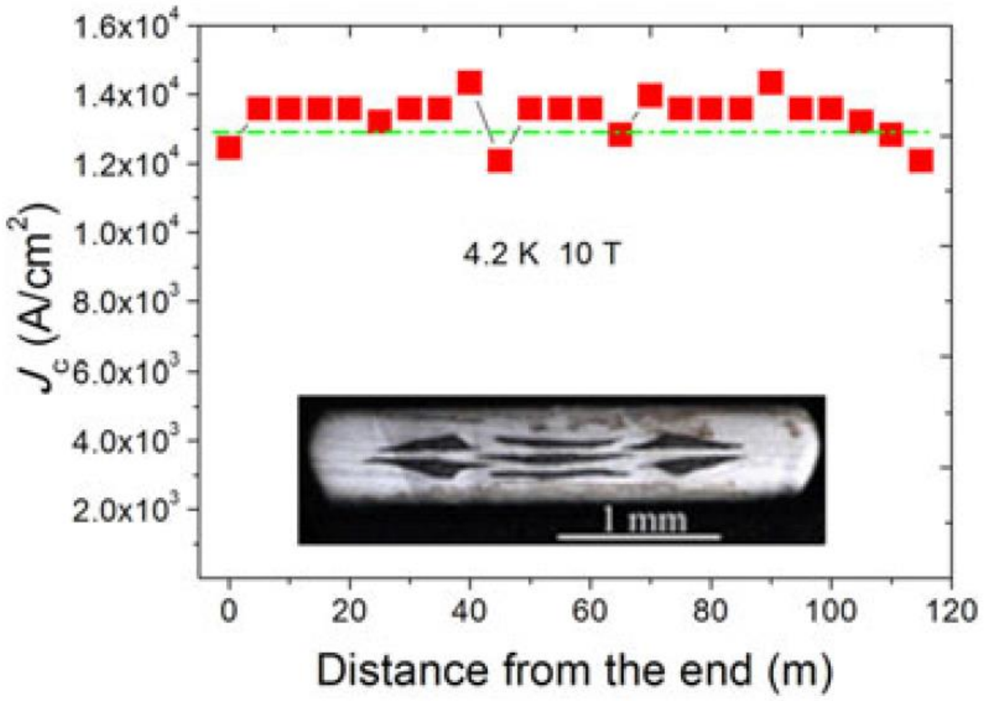


- **Roughly missing a factor 10 in wire current density…**
- **Still long development route ahead but worth doing!**

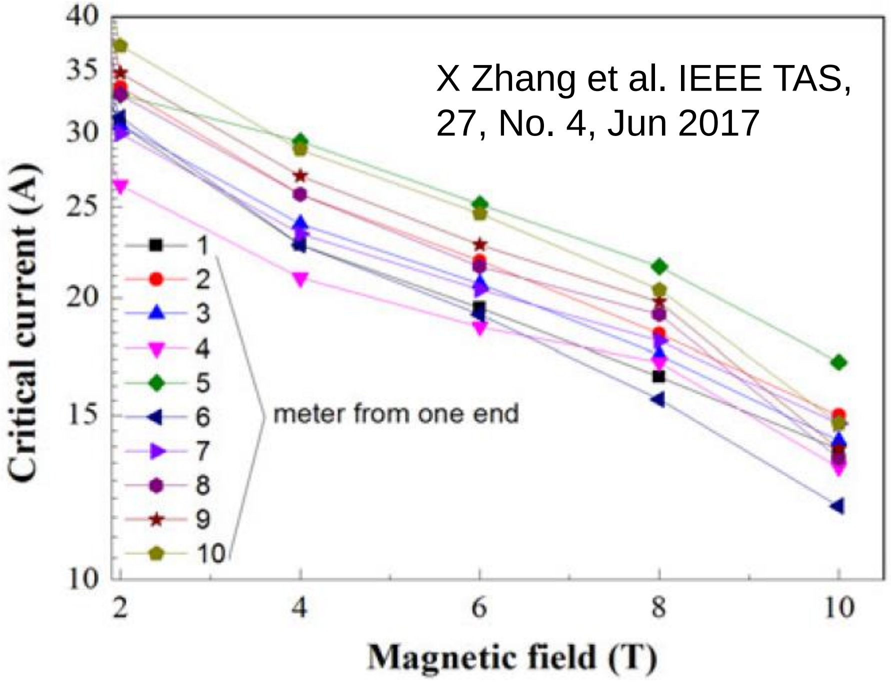
* H. Hosono, A. Yamamoto, H. Hiramatsu, Y. Ma, Materials today, article in press

Iron Based Superconductors – long length

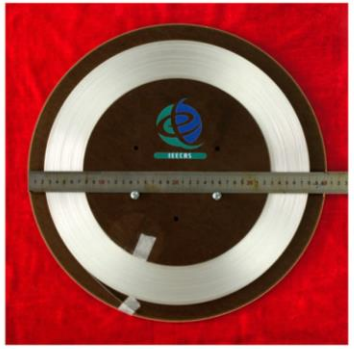
J_c of the 115 m long 7-filamentary Sr122 tape



I_c of short samples, 10 m 7-filamentary Sr122 tape



- PIT, Ar atmosphere, Nb tube, synthesis at 900 °C for 35 h
- Sr0.6K0.4Fe2As2 + 5 wt.% Sn to improve grain connectivity
- Mono-filament tape with Ag ～0.35 mm in thickness
- 7-filament Sr122/Ag wires



Up to some 150 m tape made

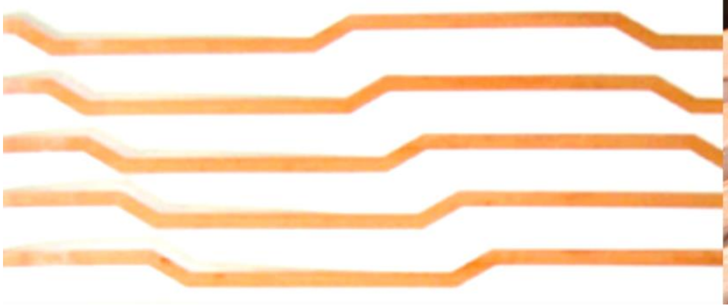
6. ReBCO multi-tape conductors

ReBCO Multi-Tape Cables:

- Large magnets require currents beyond the capacity of a single ReBCO tape.
- Multiple tapes combined to a high-current ReBCO cable.
- Increased stability, single tape defects are less pronounced.
- Reduction of inductive and coupling losses.
- Three main designs: Roebel, Twisted Stacked Tape Cable (TSTC) and Conductor on Round Core (CORC).

TSTC:

- Tape stack with high current density.
- Difficult to bend and long twist pitch.
- Copper shell for practical handling during magnet winding.
- Mainly designed for large-scale magnets for fusion reactors.



Roebel:

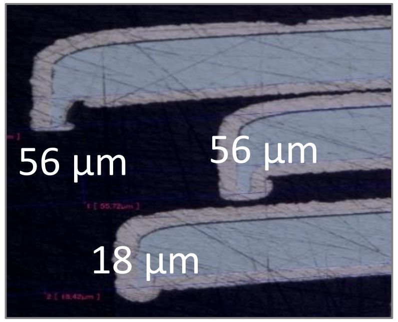
- High current density.
- Flexible in the 'out-of-plane' bending direction.
- Fully transposed.
- Designed for compact high-field magnets.

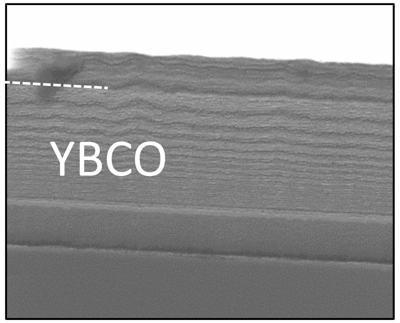
ReBCO Roebel Cables

Developed for highest current density in a flat cable, 'ideal for racetrack-like coils for motors, generators, FCL, transformers……., and HEF accelerator coils

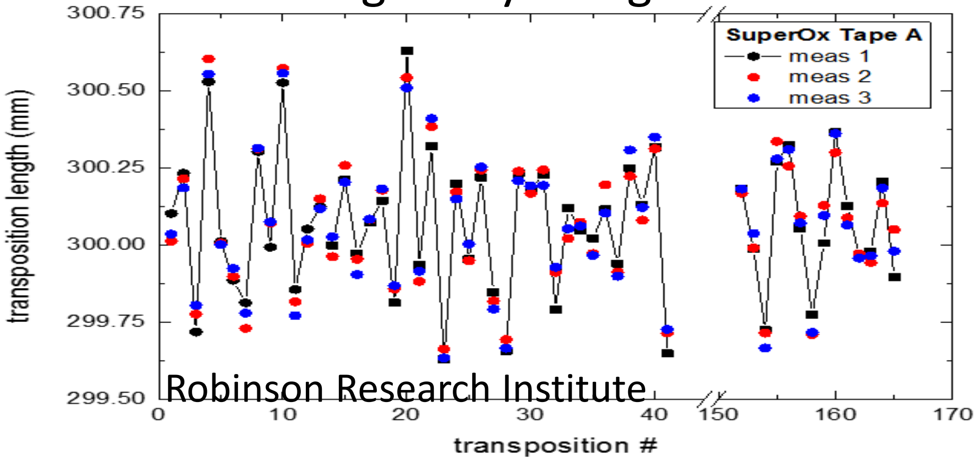
Further optimization required for strand cutting techniques and making long lengths:

Punching or Laser cutting

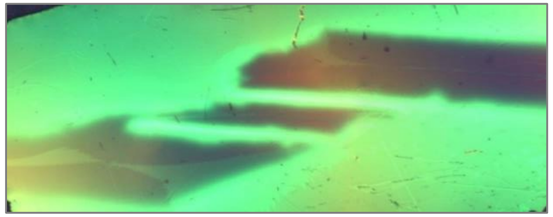




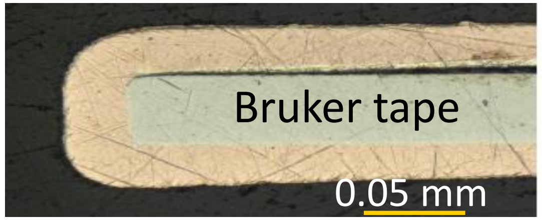
Homogeneity along strand:



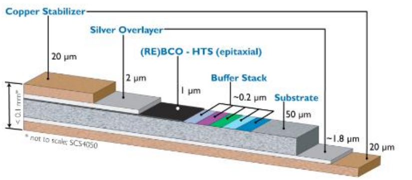
Magneto-optical imaging showing broken strands

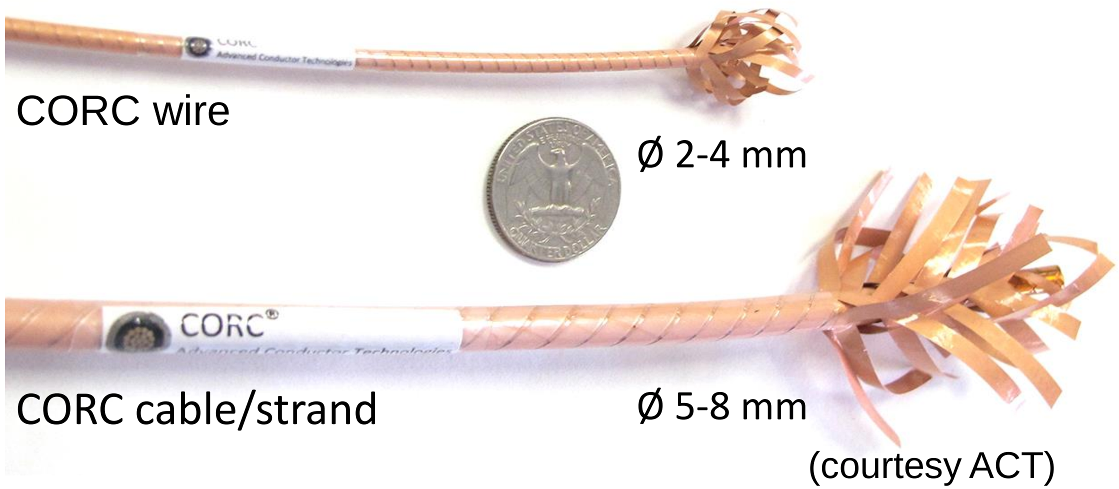


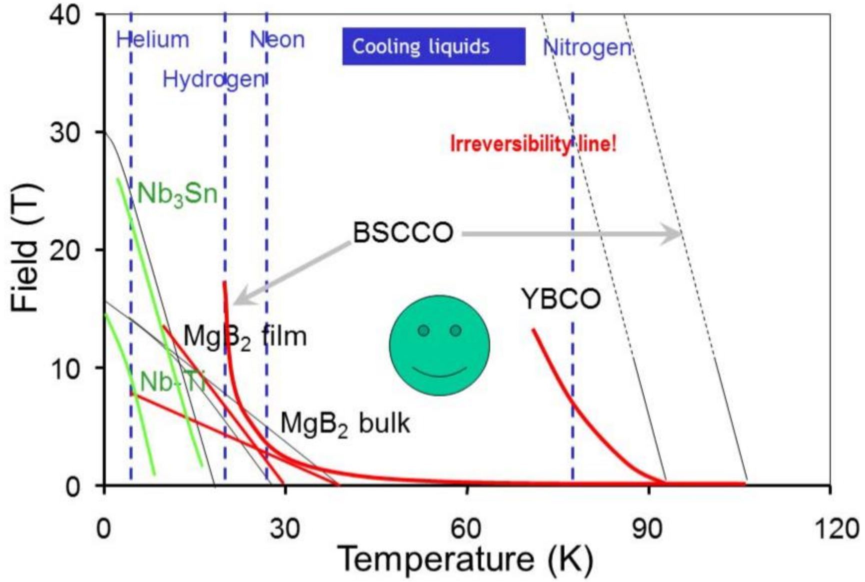
Punch & coat technique



ReBCO CORC – cables and wires







Dreamed conductor: easy to make, off the reel, ready to use, no-heat treatment, ‘isotropic’, flexible, cab used like a thick NbTi wire but much better

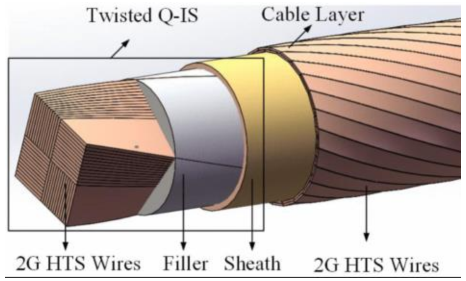
- Truly opening up massive magnet applications running at 30-50 K
- Today the only thin-round wire solution is CORC-’cable’ (and variants)
- Multi layers of ReBCO tapes spiraled around a core
- Quest for thinner wire: thinner substrate > thinner core, 100>50>30>20 μm

ReBCO CORC - *Cable-in-Conduit conductors*

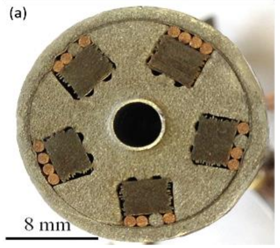
- **Cable-In-Conduit Conductors (CICCs),** designed for large-scale, high-current magnets as for large outsert coils, fusion magnets and particle detectors
- *NbTi* and *Nb_3Sn* conductor development close to their limits, also quest for higher temperature & no-helium operation **---> Development of *Re*BCO based CICCs**
- Dramatic increase in stability due to high T_c enables training-free operation at 20 to 50 K

Demonstrators of several *Re*BCO based CICCs are being developed around the globe:

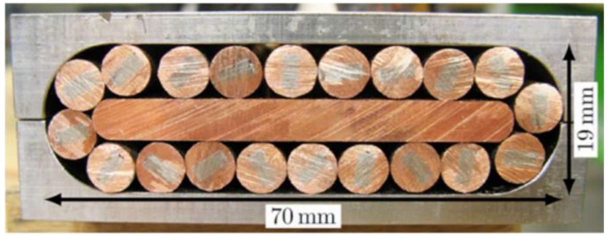
CERN & ACT:
CORC 6-a-1 CICC



North China Electric Power
University Quasi-Isotropic Conductor



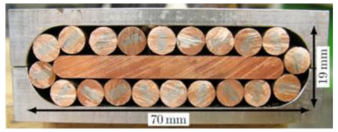
ENEA: Twisted Stacked
Round CICC



Swiss Plasma Center:
Twisted Stacked Rectangular CICC

Conclusion

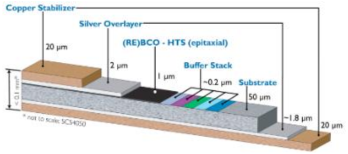
- ✓ Understanding electromagnetic, thermal & mechanical behaviour of HTS, as well as cables is key to the success of magnets.



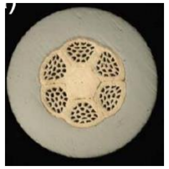
- ✓ Bi2212, a round quasi isotropic wire, still developed for achieving higher critical current density by high pressure during heat treatment, but not so practical.

- ✓ Bi2223 reinforced tape, mature and strong conductor for magnets, however, presently overruled by ReBCO, may be needs to be reconsidered.

- ✓ ReBCO development in full swing, massive low-field @77K energy applications are not supported, re-orientation towards high field magnets.



- ✓ IBS development is trendy (in China), results are coming, but still long way to go to achieve compatible current densities, however, deserves a serious effort.



- ✓ HTS cabling technology still in an early stage. More long demonstrators are needed for exercising the technology and to develop mature magnet technology.