NC STATE UNIVERSITY

Applied (High Temperature) Superconductivity

Academic Training
Lecture 3

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CERN/Geneva
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SCHWARTZ GROUP

Department of Materials Science and Engineering

Outline for the week of training

- Lectures 1& 2: Introduction & “Just enough” physics
  - Brief introduction … what is superconductivity and why is it useful?
  - Basic physics of superconductivity and the superconducting state
  - Applications-relevant physics of superconductivity & superconducting state
- **Lecture 3: Technical superconductors**
  - What a magnet wants
  - A brief summary of NbTi and Nb_3Sn
  - HTS conductor options: Bi2212 & YBCO
- Lecture 4: Electromechanical behavior
  - A brief summary of NbTi and Nb_3Sn
  - HTS conductor options: Bi2212 & YBCO
- Lecture 5: Quench behavior and high field magnets
  - What is quench protection?
  - Quench protection in HTS magnets

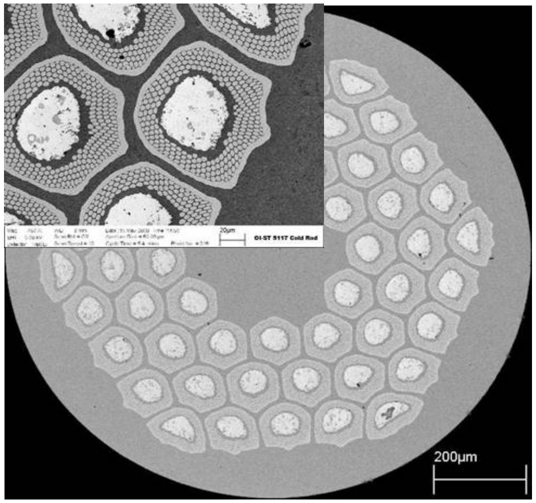
What a magnet wants… magnet engineering issues

- Conductor … the bridge from phenomenon to magnets
  - Availability & Cost
  - Processing & manufacturing (nano→ macro)
  - J_c at field, temperature, field orientation … application driven
  - Uniformity
  - Chemical compatibility with reinforcement and insulation
  - Conductor size and scalability
  - Multifilamentary
  - Cable-able
- *Stability & quench protection*
- Magnet fabrication
- *Electromechanical behavior*
- AC losses
- Turn-to-turn insulation
- Cooling
- Joints

Desirable Conductor Properties

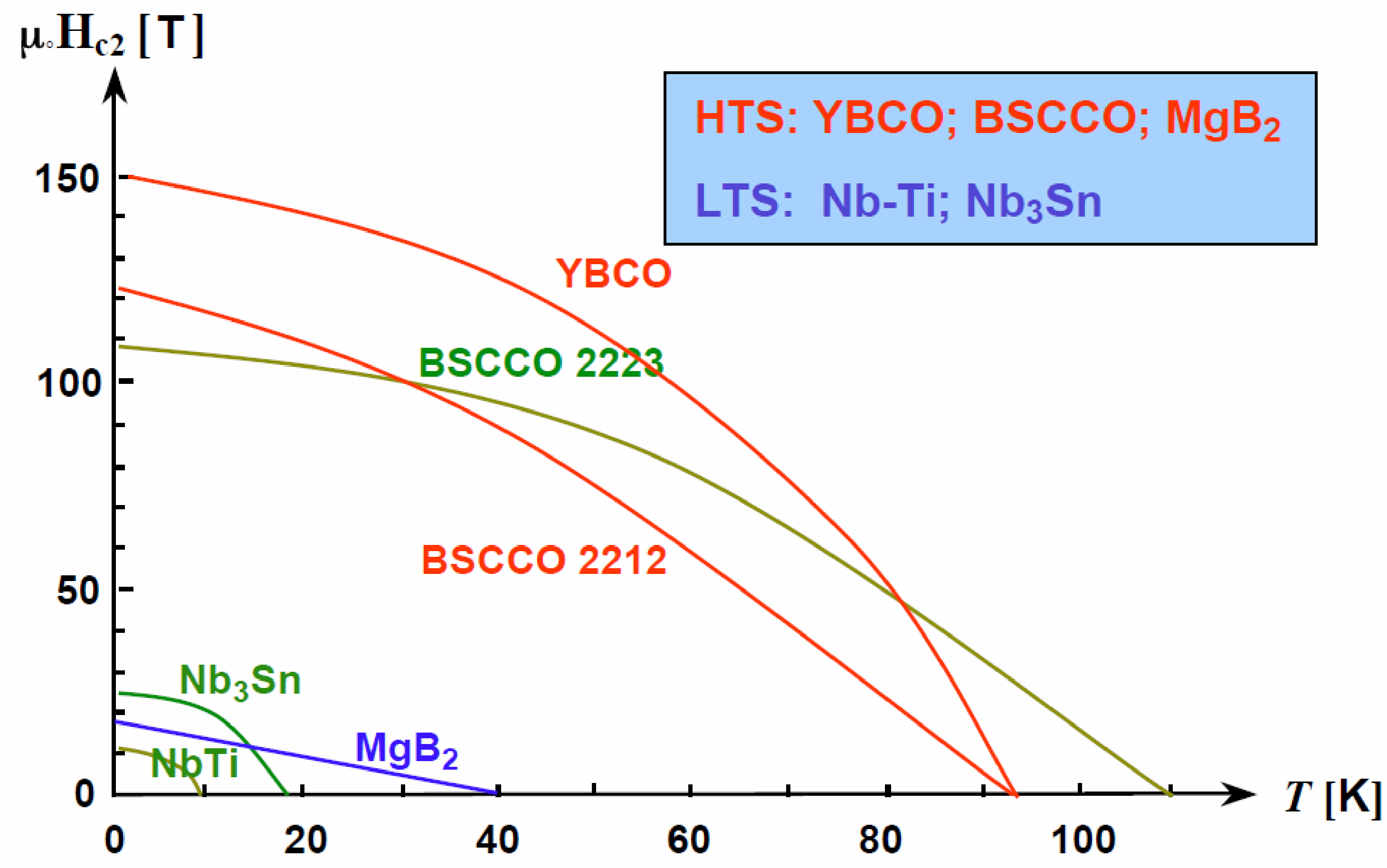
- $J_c(B)$ 1st & foremost; but other properties can be limiting
- Mechanical properties
  - High strength and modulus (strain tolerant)
  - Workability during processing (ductility)
  - Effect of strain on superconducting properties
- Environmental properties
  - atmosphere (H_2O, other components to magnet)
  - thermal contraction effects ($\Delta L/L$)
  - radiation effects (fusion and accelerator applications)
- Costs
  - much of cost is in processing, handling
  - NbTi ~ \$100/lb, Nb_3Sn ~ \$1000/lb, Ag/Bi2212 ~ \$20/meter, YBCO conductor ~ \$50/meter

Two (or three) types of Type II superconductors



- "Low-T_c superconductors" (LTS)
  - NbTi and Nb_3Sn
  - Commercially available
  - In most operating superconducting magnets
  - Conductors are predominantly Cu
- "High-T_c superconductors" (HTS)
  - Discovered from 1986-1993 with much fanfare
  - $Bi_2Sr_2CaCu_2O_{8+y}$ & $YBa_2Cu_3O_{7-x}$ are most technically interesting
  - ***more complicated than LTS in almost every way***
    - flux motion is thermally activated … now T-window is wider
    - complex multicomponent oxide
    - very small ξ → grain boundaries are weak-links
    - highly anisotropic structure & properties
- MgB_2 not quite LTS or HTS. Might become useful too.

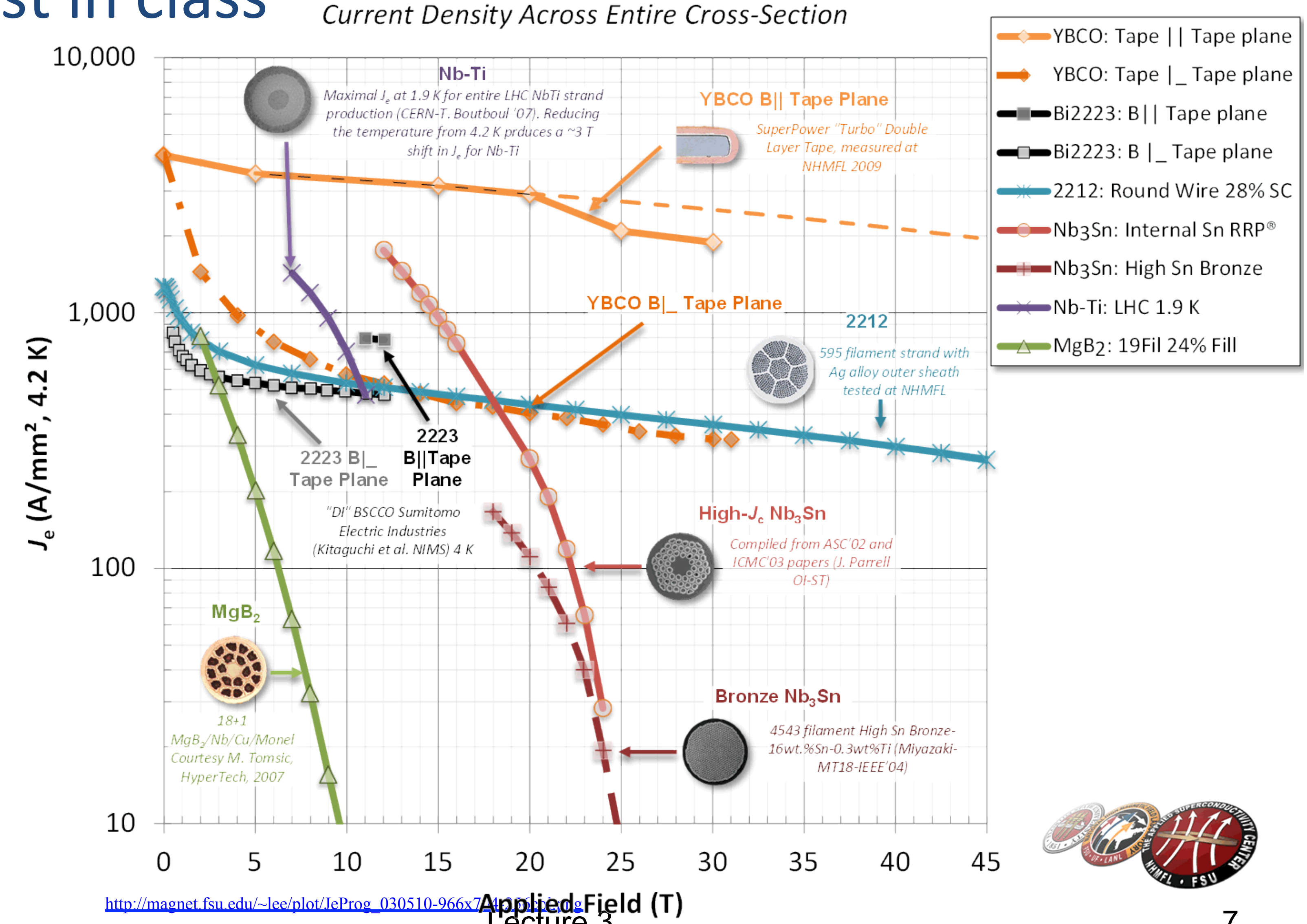
Upper critical field versus temperature



HTS: YBCO; BSCCO; MgB_2

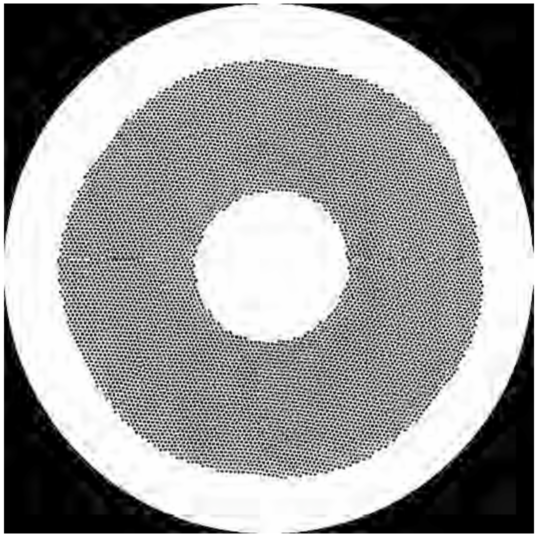
LTS: Nb-Ti; Nb_3Sn

Critical current density versus magnetic field "best in class"

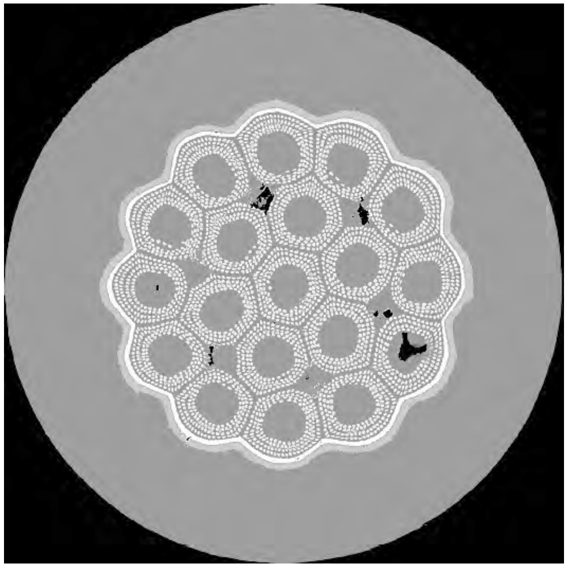


http://magnet.fsu.edu/~lee/plot/JeProg_030510-966x724-256cb.png

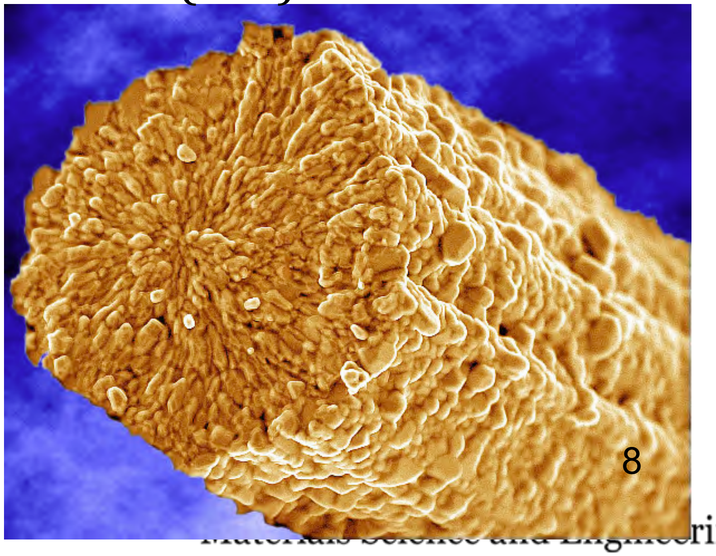
LTS conductors are highly engineered, complex composites



Typical SSC Nb-47wt.%Ti strand (OST)

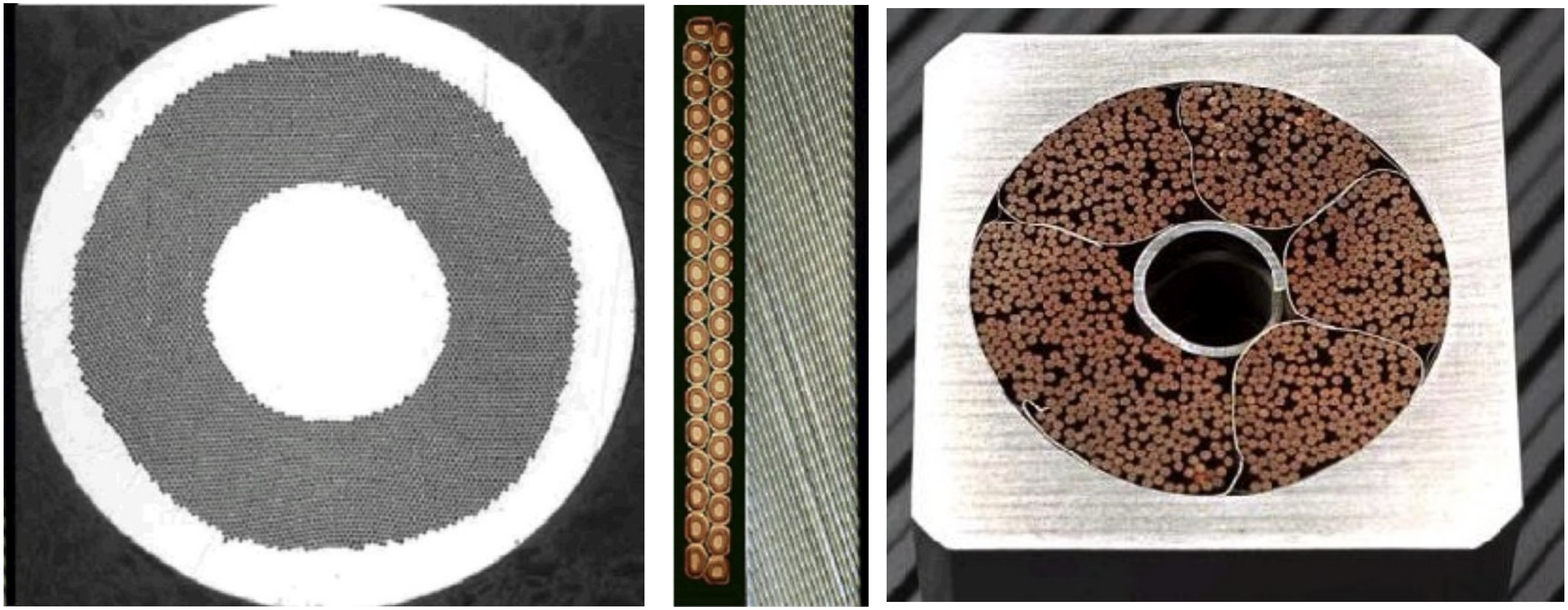


Typical reacted ITER Nb_3Sn strand (IGC)

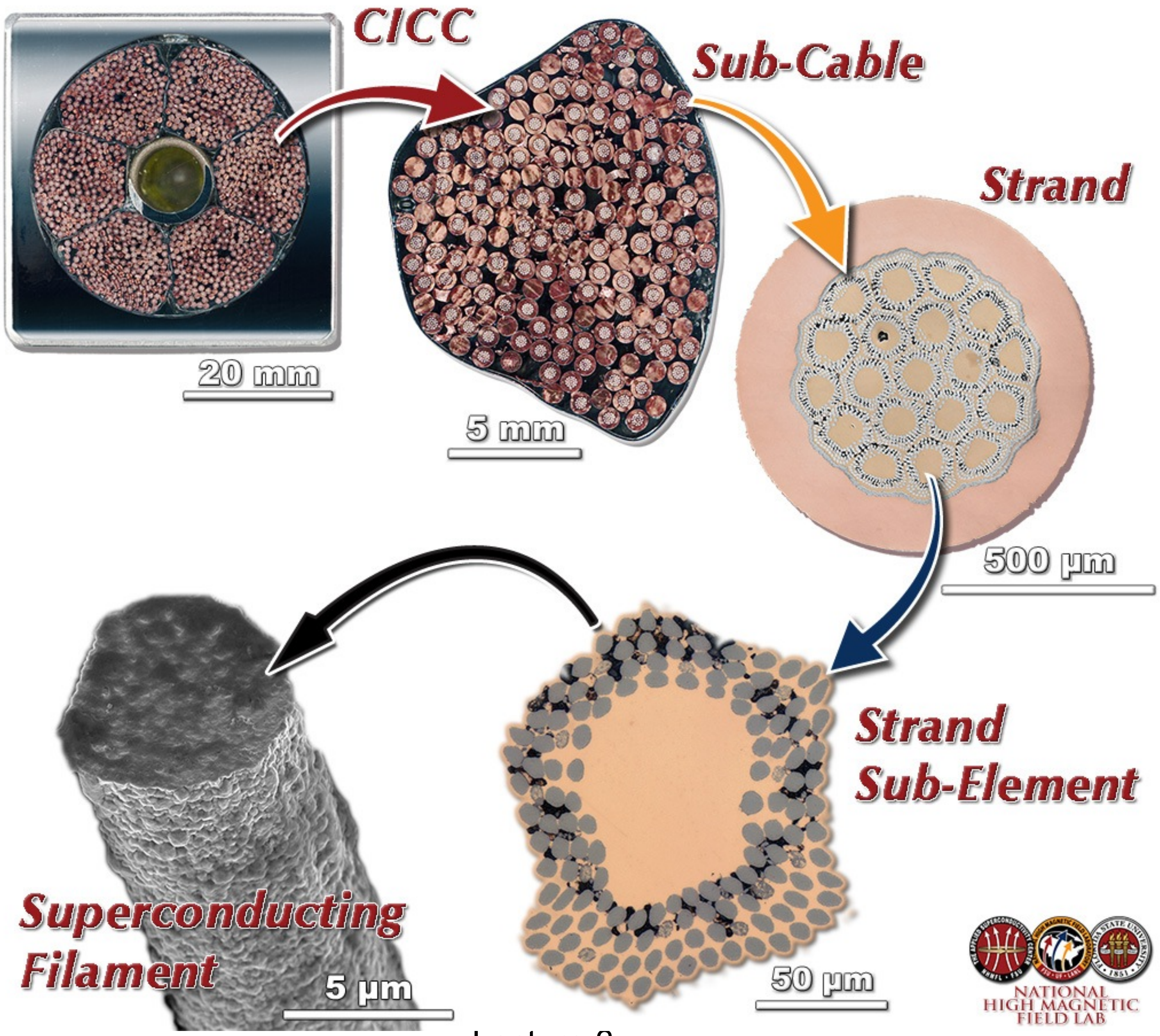


Conductors for magnets – strand and cable

- Magnets can be from strand (wire) or cable
- Decision driven by the demand of the application
- Cables vary greatly depending on what is required

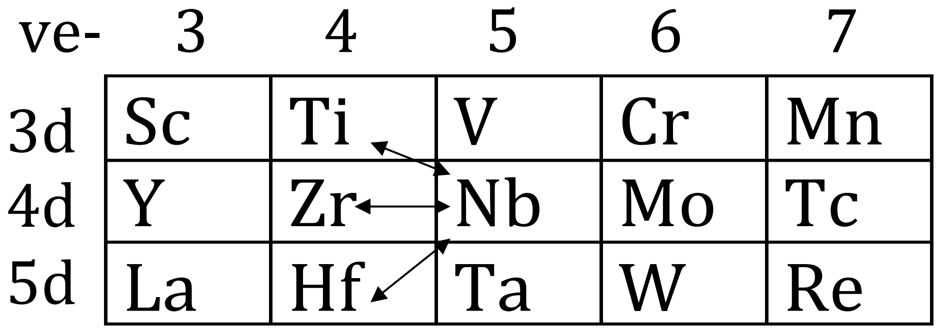


Length scales (this example is Nb_3Sn)



NbTi Alloys as Superconductors

- First discovered in early 1960s that Nb formed continuous solution alloy with Zr, other elements
- Technologically/commercially matured by the Tevatron
- Became "stock" material by medical MRI

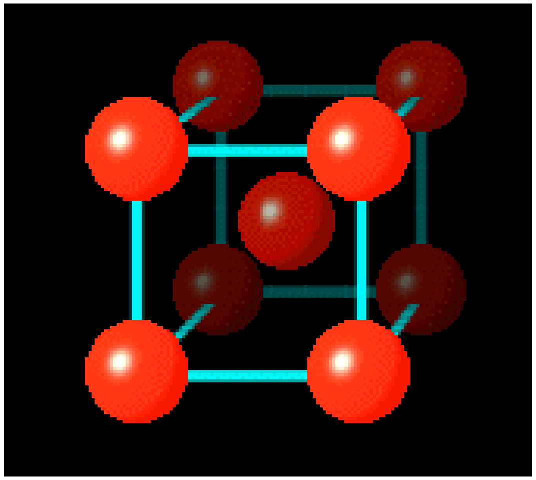


ve-	3	4	5	6	7
3d	Sc	Ti	V	Cr	Mn
4d	Y	Zr	Nb	Mo	Tc
5d	La	Hf	Ta	W	Re

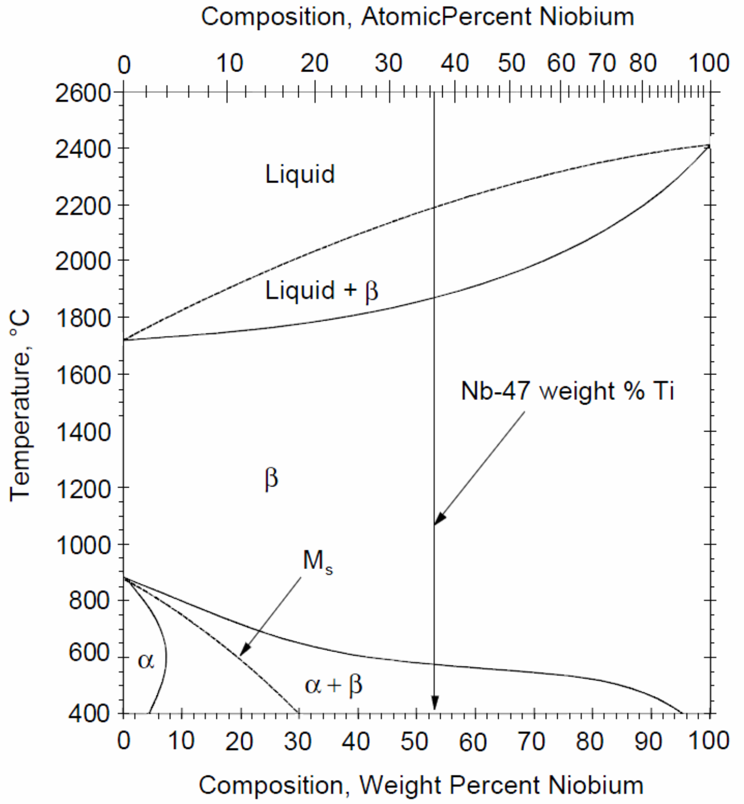
4-5 transition elements

NbTi wires

- Nb and Ti are soluble & at high temperature form a ductile alloy: β phase
- Cold work & heat treatment determines the formation of other phases
- α phase is used for flux pinning
- Easily processed by extrusion and drawing
- J_c depends on the microstructure
- Mature product: ~3 Ton per day for MRI, ~60,000 km/year
- Cost ~$1/kA·m (Cu ~$20/kA·m)

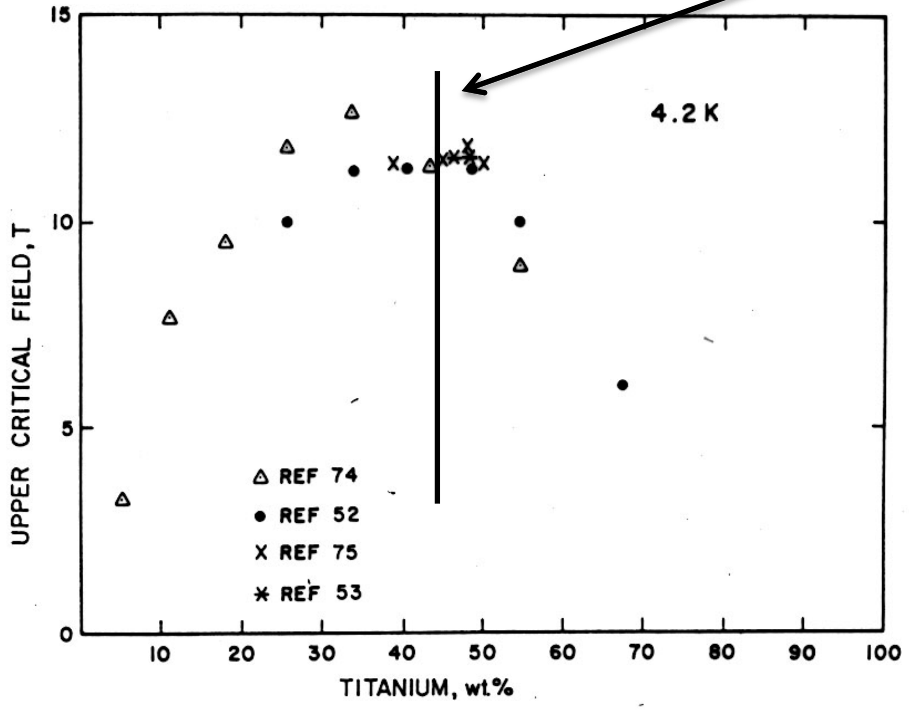


BCC crystal structure

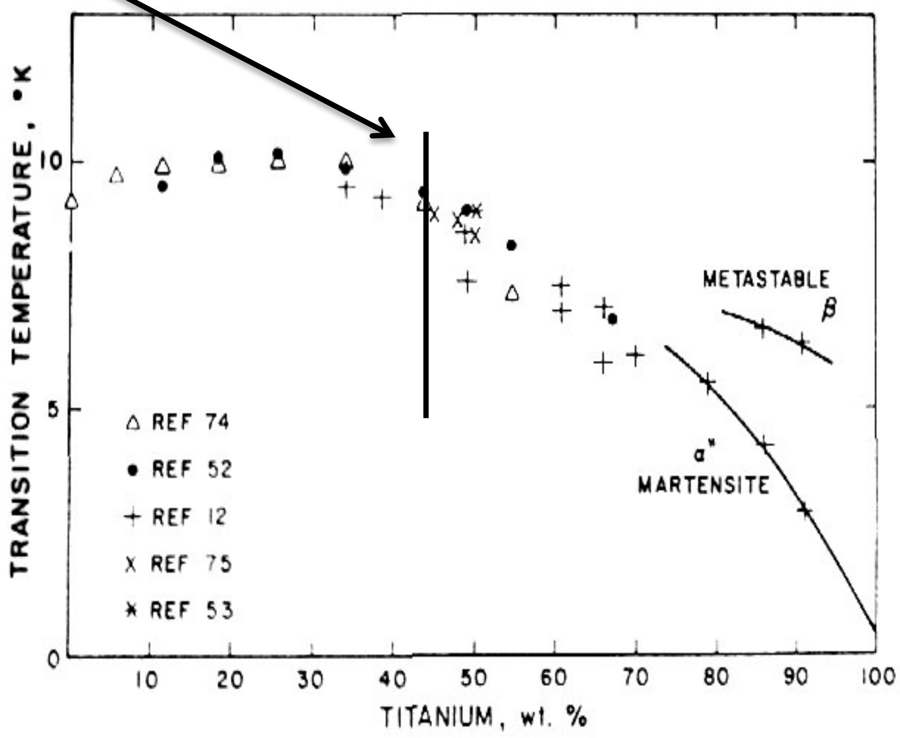


NbTi: H_{c2} and T_c vary with composition

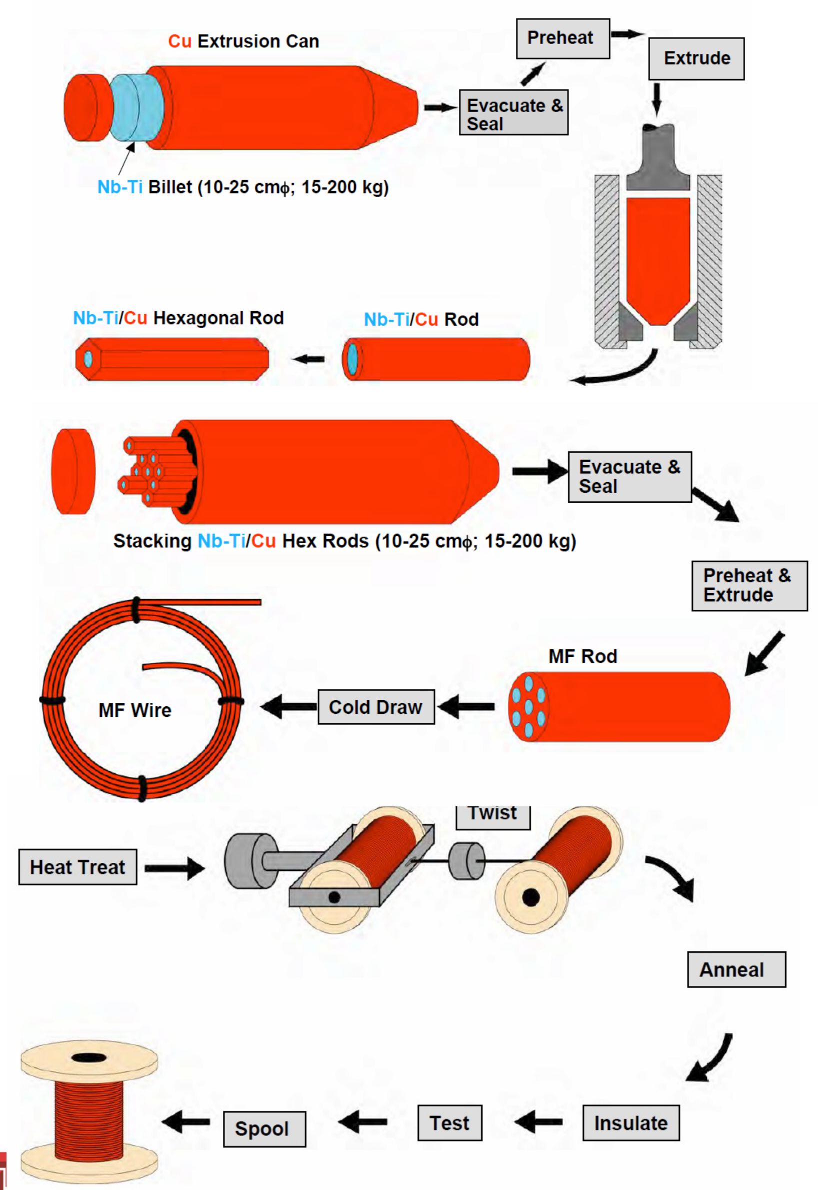
Commercial material not at either peak



Upper critical field of Nb-Ti alloys at 4.2 K.



Fabrication of NbTi wire



Stage I: Stacking & Hexagonal Nb-Ti/Cu Rod monofilament composite

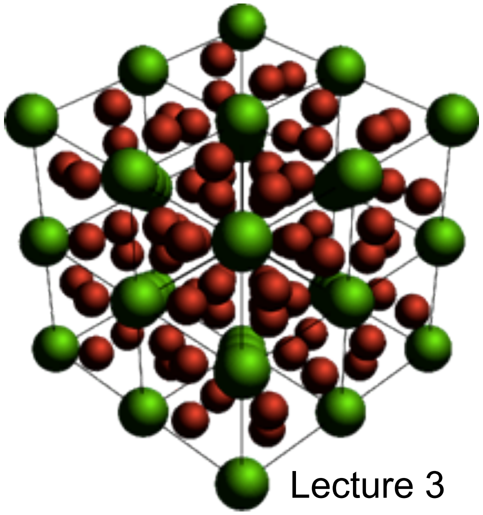
Stage II: Multifilamentary composite

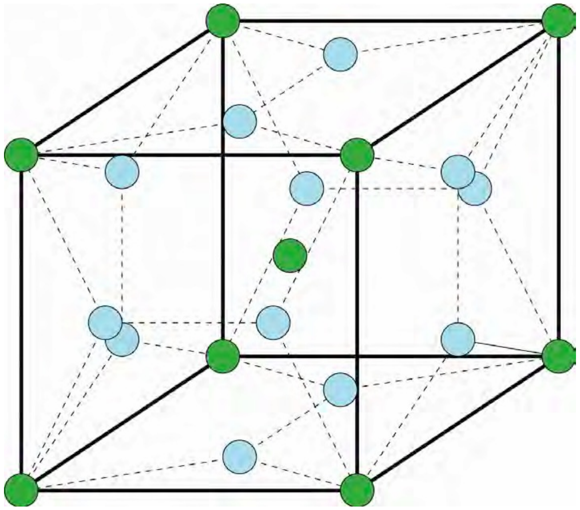
Stage III: Twisting and spooling

Nb_3Sn: the 1st "high field" conductor

- Nb_3Sn is an intermetallic compound with an "A15" structure
- A brittle composite that cannot be drawn after formation
- T_C & H_{C2} depend on Sn content: optimal is 20-25 weight%
- J_c depends on the microstructure (grain structure)
- Cost < $10/kA·m
- A number of processes have been developed for wires
- Nb (6/cube) Sn (2/cube): Nb_3Sn

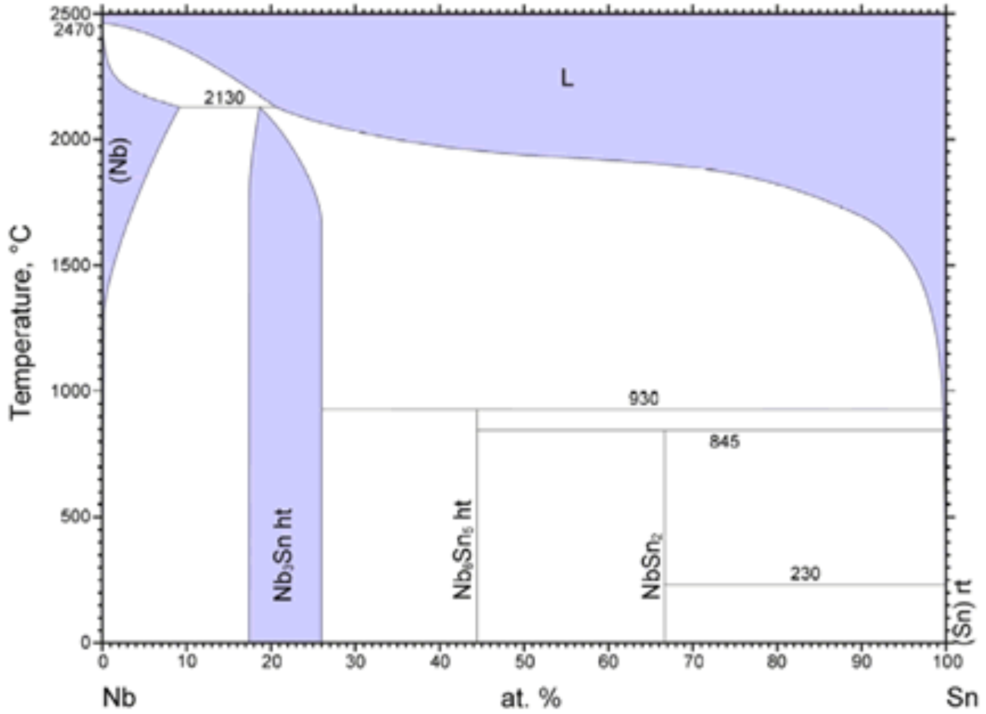
Sn on BCC lattice
Nb on orthogonal
chains across faces

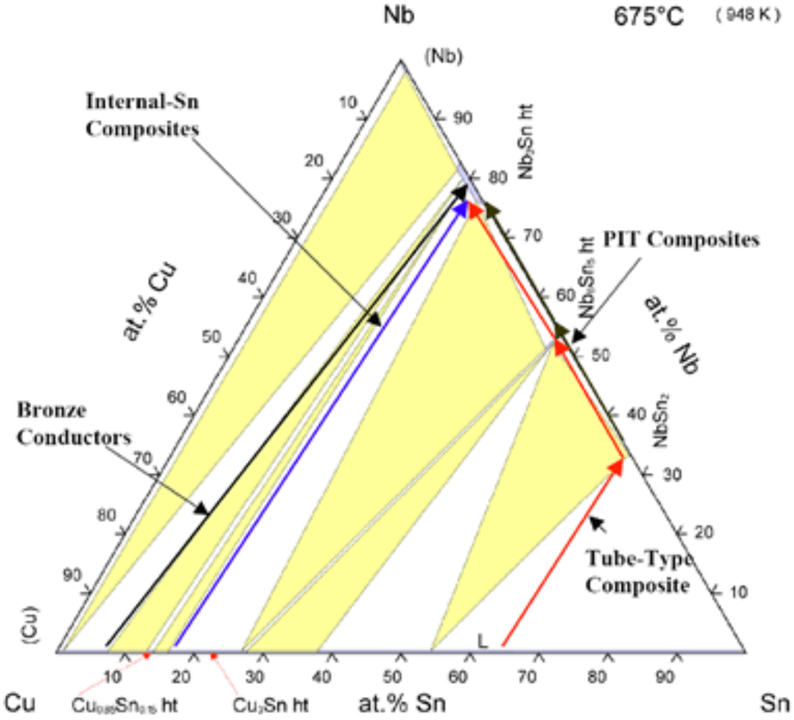




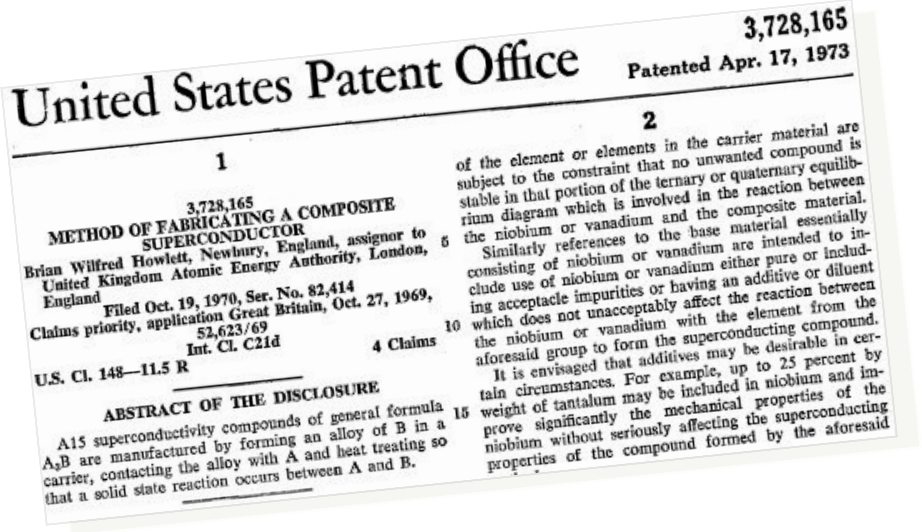
Nb_3Sn phase diagram – more complex than NbTi

- Reacting at 925 °C to 1050 °C was typically required to form Nb_3Sn from Nb and Sn – making it difficult to apply to the fabrication of multifilamentary strand.





Breakthrough . . . the Bronze Process … wires



United States Patent Office

3,728,165
Patented Apr. 17, 1973

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3,728,165
METHOD OF FABRICATING A COMPOSITE SUPERCONDUCTOR
Brian Wilfred Howlett, Newbury, England, assignor to United Kingdom Atomic Energy Authority, London, England
Filed Oct. 19, 1970, Ser. No. 82,414
Claims priority, application Great Britain, Oct. 27, 1969, 52,623/69
Int. Cl. C21d
U.S. Cl. 148—11.5 R
4 Claims

ABSTRACT OF THE DISCLOSURE

A15 superconductivity compounds of general formula A_3B are manufactured by forming an alloy of B in a carrier, contacting the alloy with A and heat treating so that a solid state reaction occurs between A and B.

2

of the element or elements in the carrier material are
subject to the constraint that no unwanted compound is
stable in that portion of the ternary or quaternary equilib-
rium diagram which is involved in the reaction between
the niobium or vanadium and the composite material.
Similarly references to the base material essentially
consisting of niobium or vanadium are intended to in-
clude use of niobium or vanadium either pure or includ-
ing acceptacle impurities or having an additive or diluent
which does not unacceptably affect the reaction between
the niobium or vanadium with the element from the
aforesaid group to form the superconducting compound.
It is envisaged that additives may be desirable in cer-
tain circumstances. For example, up to 25 percent by
weight of tantalum may be included in niobium and im-
prove significantly the mechanical properties of the
niobium without seriously affecting the superconducting
properties of the compound formed by the aforesaid

A15 compound layers (Nb_3Sn and V_3Ga) could be formed at the interface of Nb(V) and Cu-Sn(Ga) [bronze] without forming undesirable compounds *and* at less elevated temperatures, e. g., 700 °C, from composites of Nb(or V) and bronze mechanically co-reduced in size.

- Breakthrough made simultaneously by three groups ’69-70:

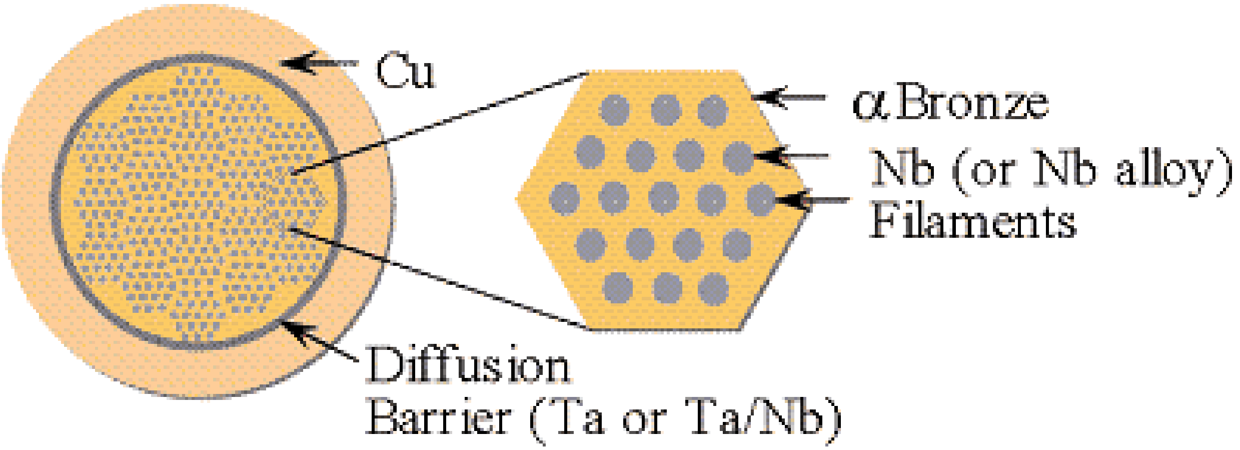
K. Tachikawa at the National Research Institute for Metals in Japan

A. R. Kaufman at the Whittaker Corporation in the USA

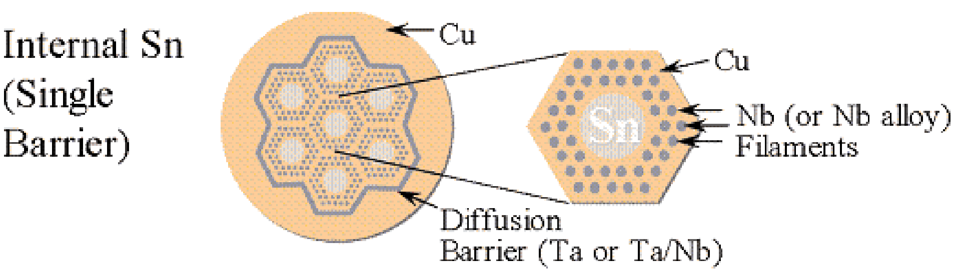
E . W. Howlett at the Atomic Energy Research Establishment at Harwell in Great Britain

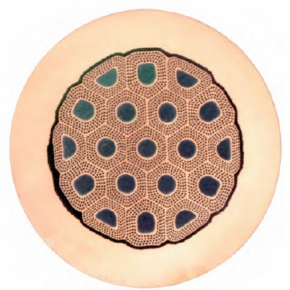
Bronze Process – historical breakthrough for wires

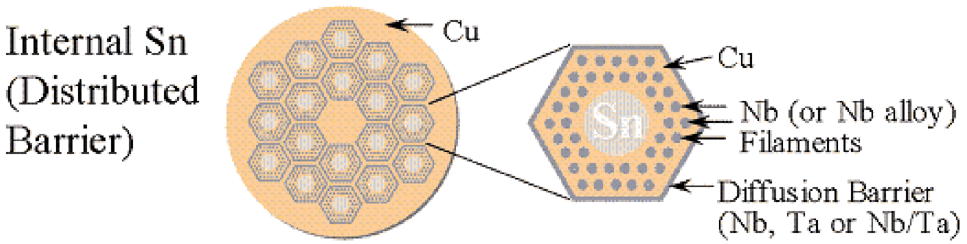
- Start with Nb filaments in a bronze matrix
- Diffusion of Sn into Nb
- Typical parameters: 700°C, 1-10 days (max. diff. 5-10 μm)
- Cu: prevents Nb_6Sn_5 from forming; a catalyst
- Temperature: good stoichiometry vs. small grains
- Bronze: 16wt.%Sn max.; >13% makes drawing difficult
- Maximum Nb_3Sn:~25wt.%
- Small filament size

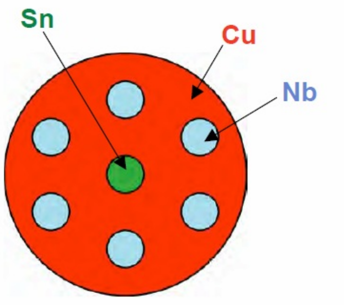


Internal Tin

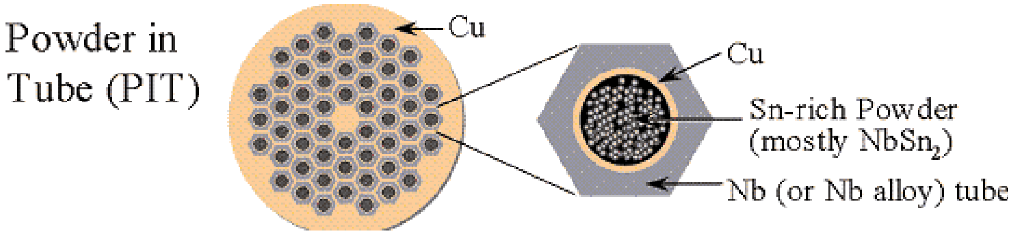


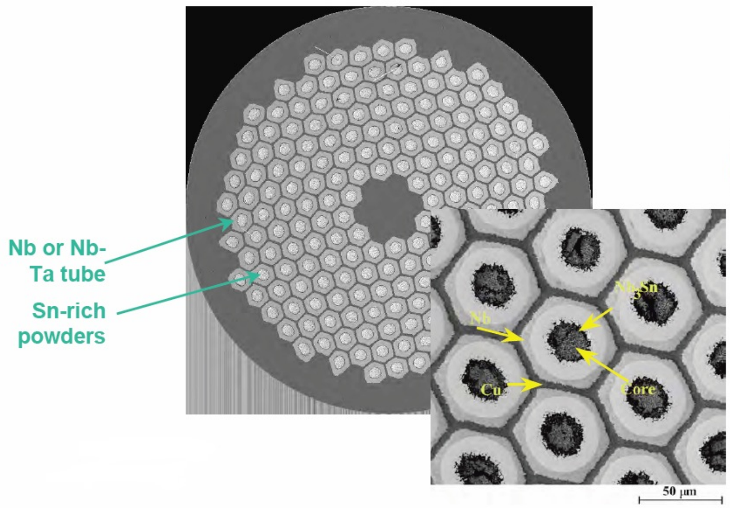


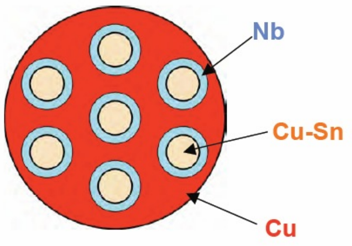




Powder-in-tube







HTS v Nb_3Sn for large, high field magnets

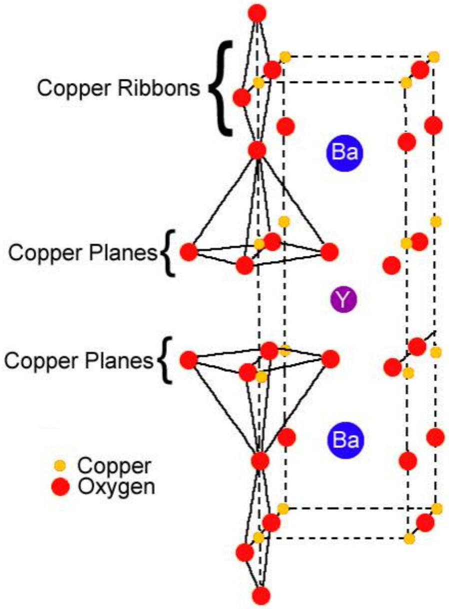
- Conductor $J_c(B,T)$, n-value, homogeneity
- Conductor I_c- strain
- Conductor scale-up
- Packaging (insulation & reinforcement)
- Coil manufacturing
- Stability, quench detection, quench protection
- Application specific issues field profile, homogeneity, heat & radiation resistance
- Overall materials complexity
- Costs; *systems pull not firmly established*
- Bi2212 & YBCO have conductor-specific challenges

HTS is enabling technology, not replacement technology

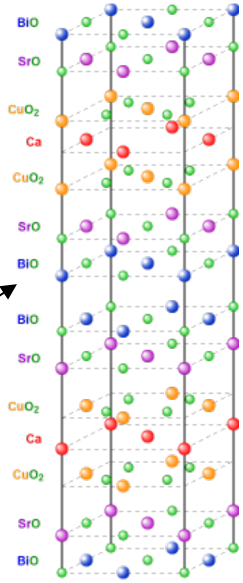
HTS crystal structures – anistropy dominates

- Each has highly anisotropic electro-magnetic behavior

YBCO



Bi2212

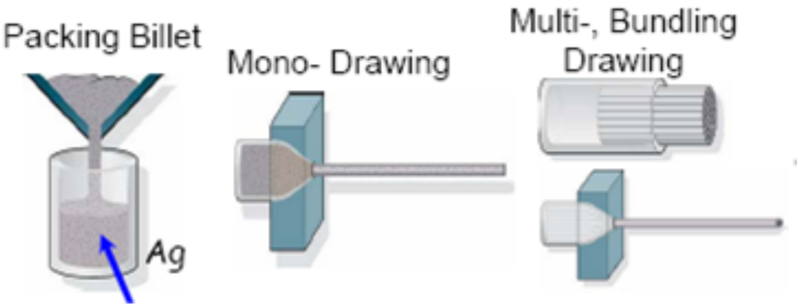


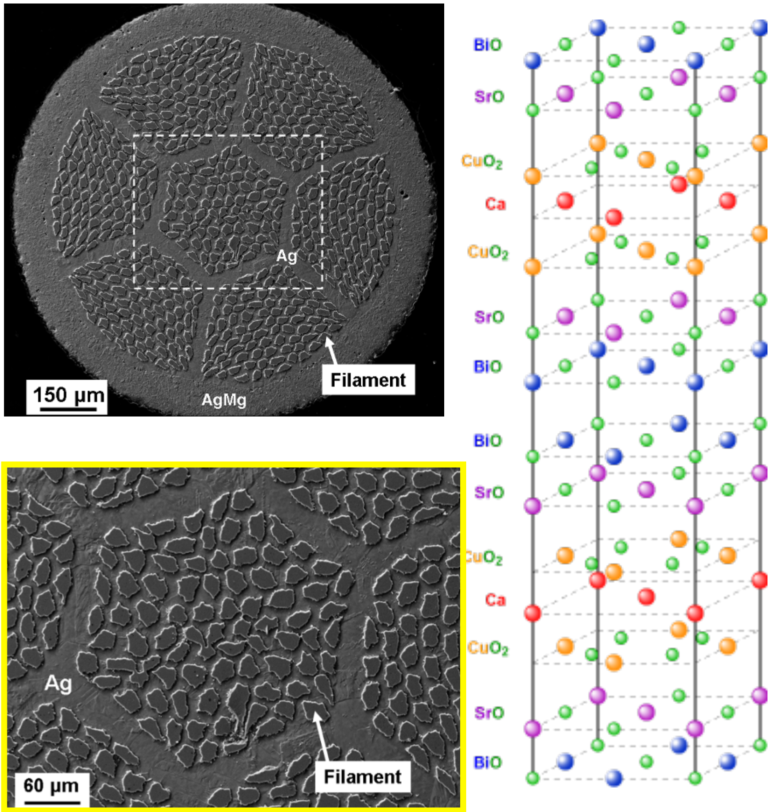
Micaceous double BiO layers; great for deformation

Bi-axial texture required for transport
Not AS anisotropic as Bi2212
(relatively) good flux pinning

c-axis texture required
VERY anisotropic
very weak flux pinning

Emerging conductor: $Bi_2Sr_2CaCu_2O_x$





- Formed by powder-in-tube process
- Requires Ag/AgX matrix
- Only HTS round wire option
- Only HTS conductor w/isotropic EM behavior, despite crystalline anisotropy

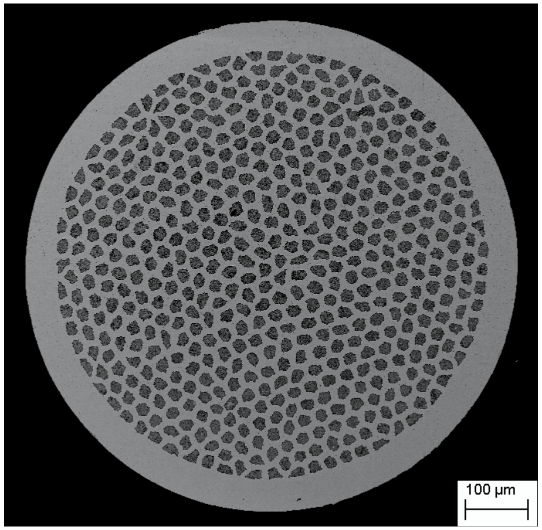
If Bi2212 wasn't the only material capable of generating >25 T in a round wire, one would never try to develop it

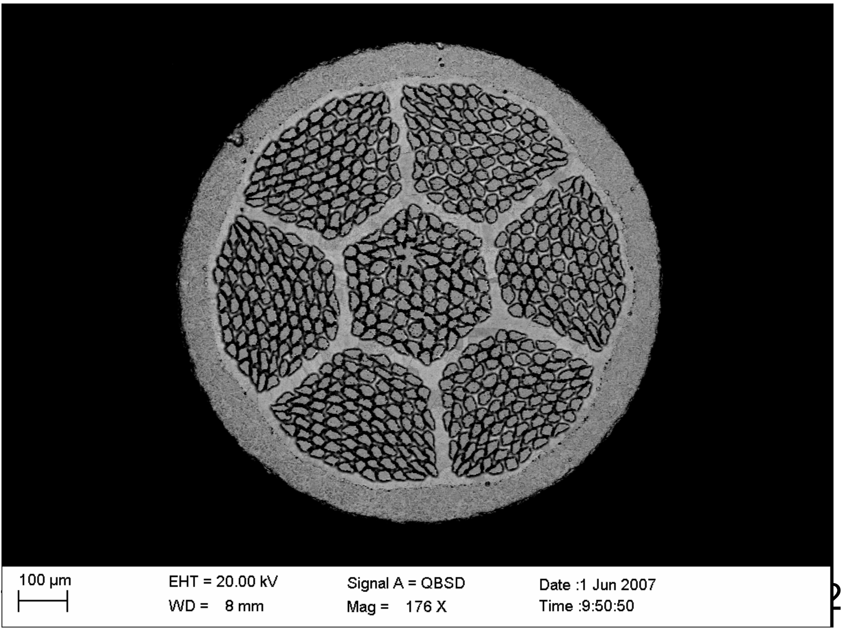
Bi2212 dogma … or why it is the way it is

- To form a multifilamentary wire, a ductile matrix is required
  - Powder-in-tube
- For grain-to-grain connectivity in a wire, the powder/grains must be well-bonded via heat treatment after wire-drawing
  - Connectivity only results if significant liquid phase is created during the heat treatment (due to small coherence length)
  - Bi2212 melts incongruently through a peritectic reaction
  - Solid (Bi2212) → liquid + solid (neither of which are Bi2212)
- Oxygen content in Bi2212 evolves during heat treatment and is important for final properties
  - Matrix must allow oxygen diffusion, not oxidize, and be chemically compatible with Bi2212
  - Therefore Ag is used → very limiting (and mechanically weak)
  - Ag used next to filaments, AgMg for "outer sheath"

Bi2212 challenges & the partial-melt process

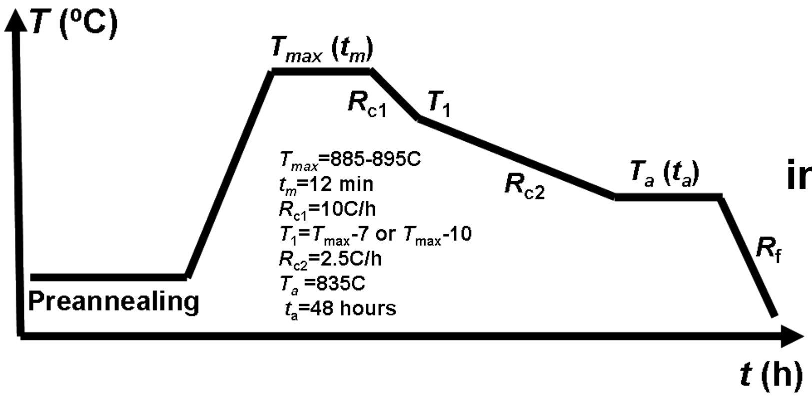
- To date, “partial-melt process” and its variants are that standard heat-treatments for Bi2212 wire
  - like Churchill’s description of democracy – it’s the worst possible option except for all of the others
- And while we now (somewhat) understand why it works, it is still rather surprising
- We start with:





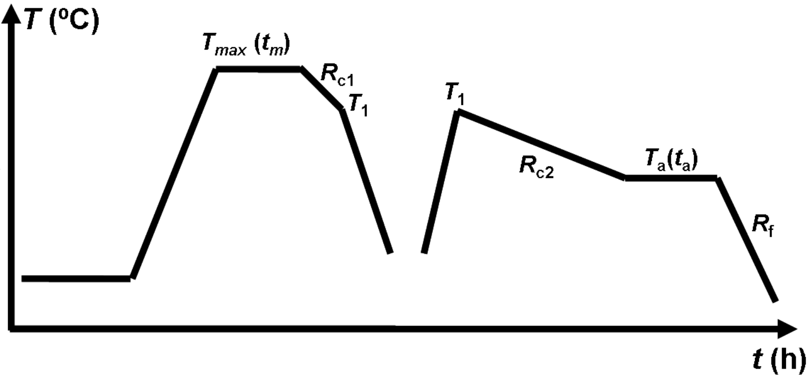
We process above the peritectic melt

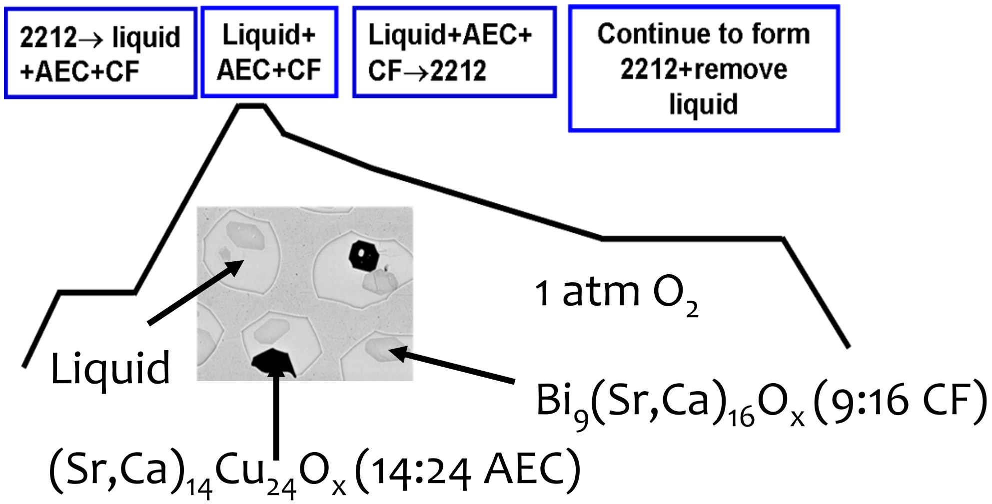
Standard partial-melt processing (PMP)

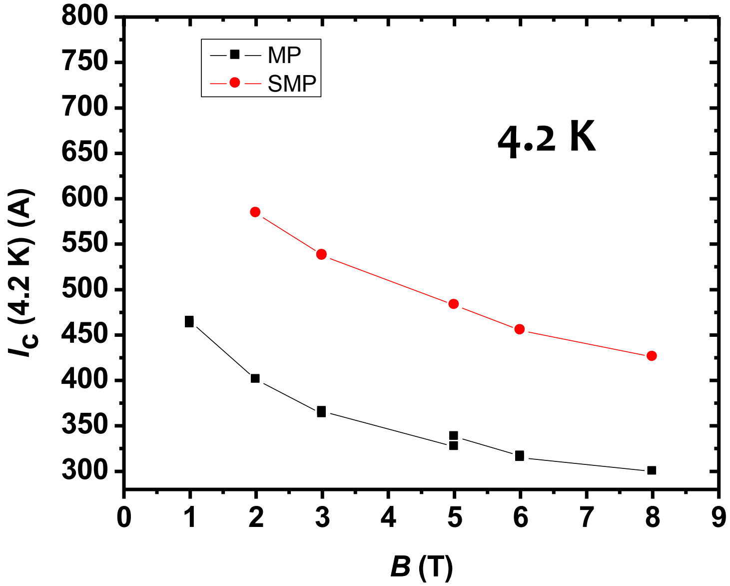


30-40% improvement

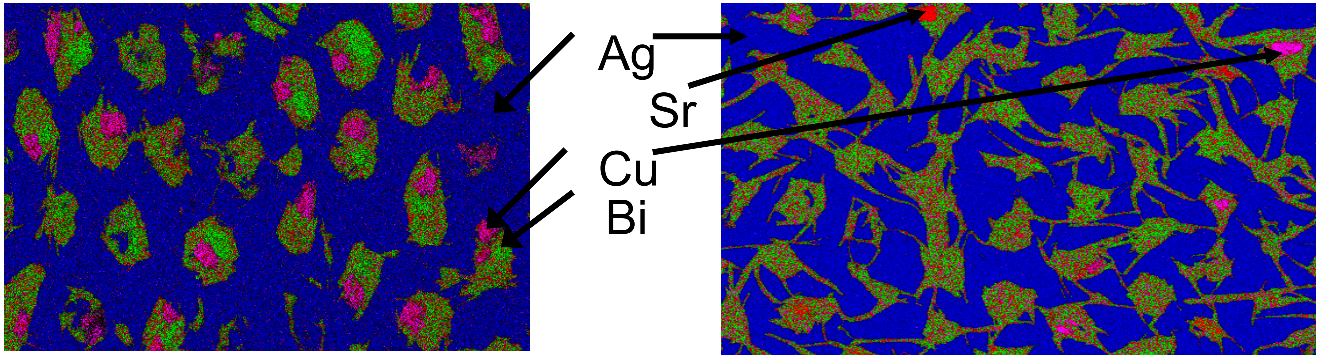
Split melt processing (SMP)





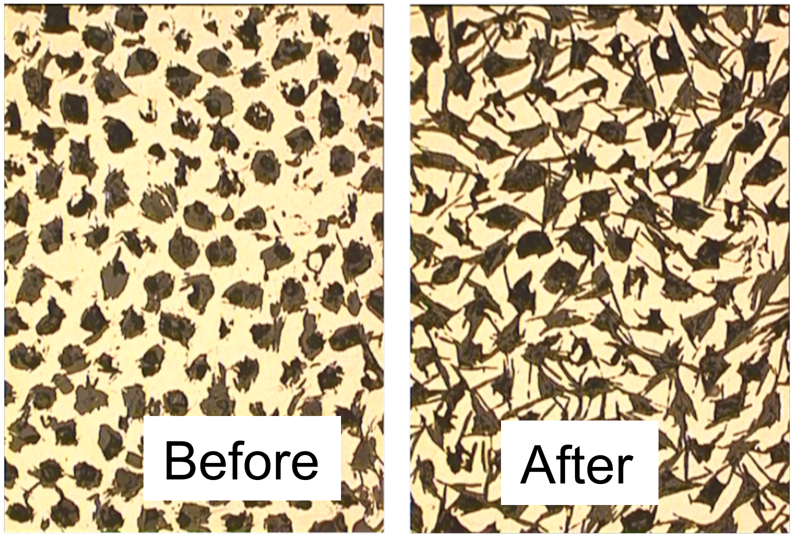


and we end up with … a complicated, inhomogeneous microstructure

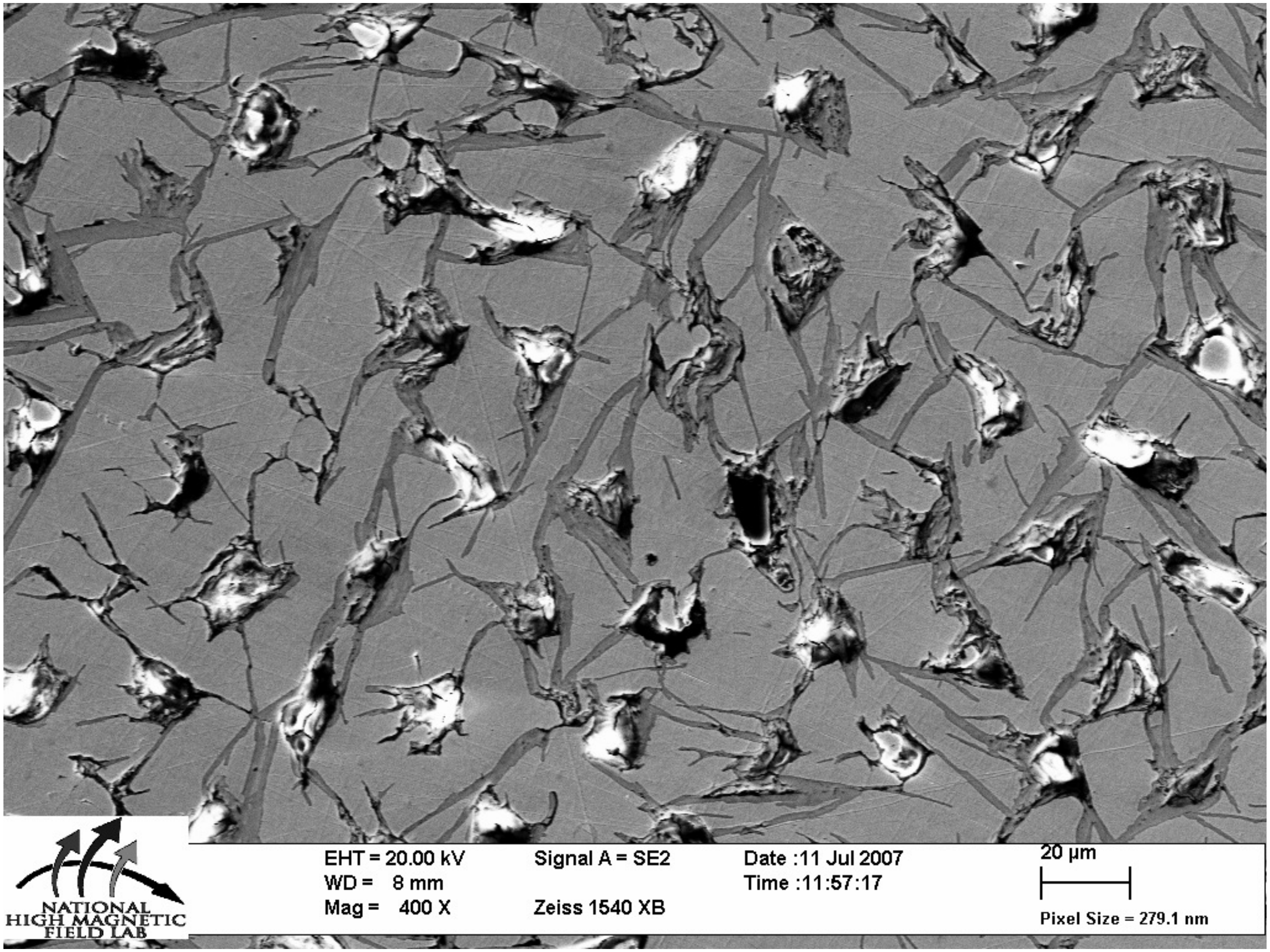


I_c~0
Second phases segregate in center (Bi2212 @ Ag interface);
No filament bridging

I_c~2 kA/mm^2
More uniform chemistry
Significant bridging



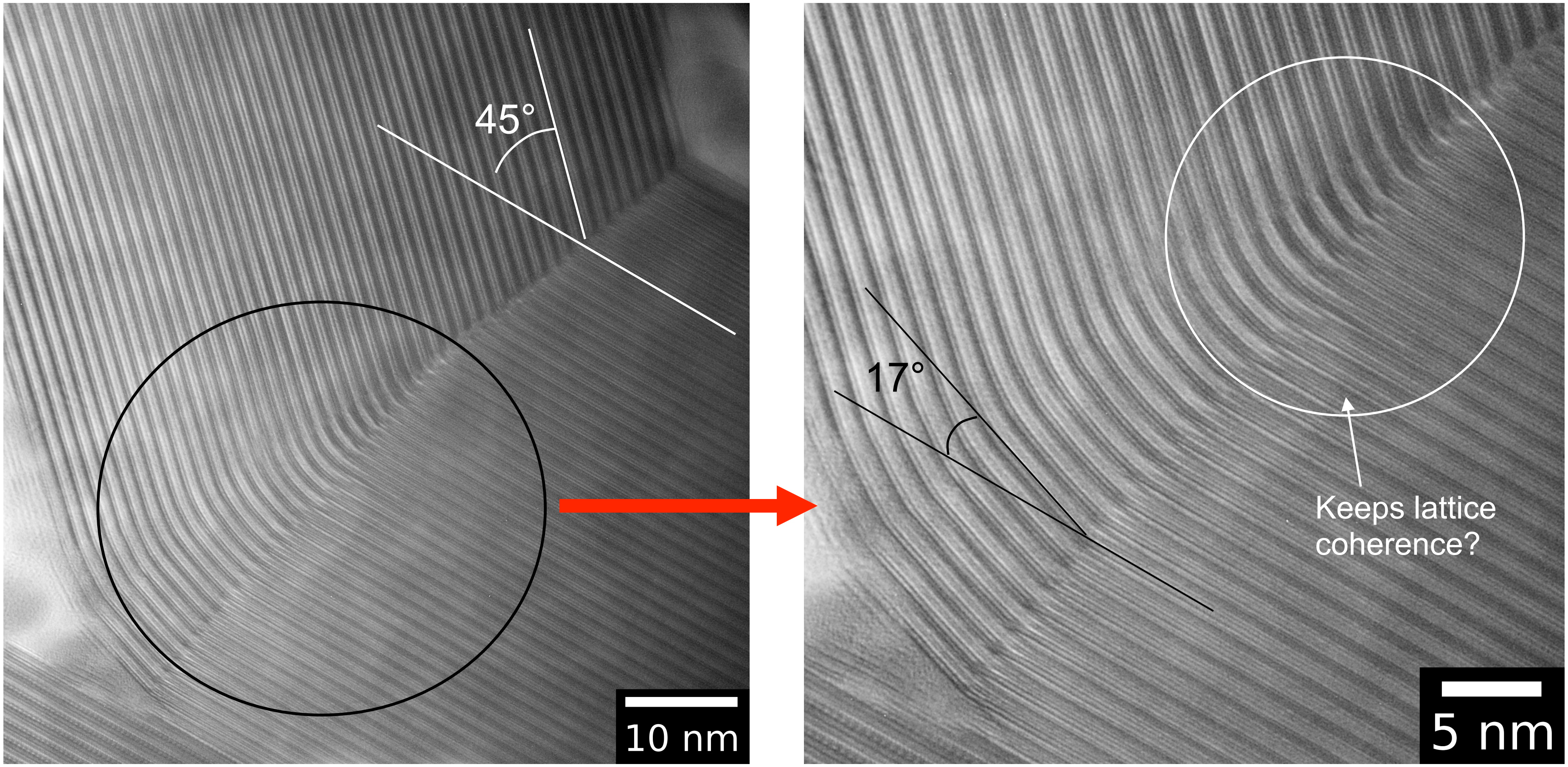
Bi2212 microstructure



Why does it carry current?

- How does microstructure evolve to produce high J_c?
- Why is there high J_c with poor texture?
- Do the interfilamentary bridges play a key role in transport?
- Which bridges? … microstructure is a statistical mess!
- What about the significant porosity that remains?
- Let’s look at different length scales

Bi2212 lattice planes change direction

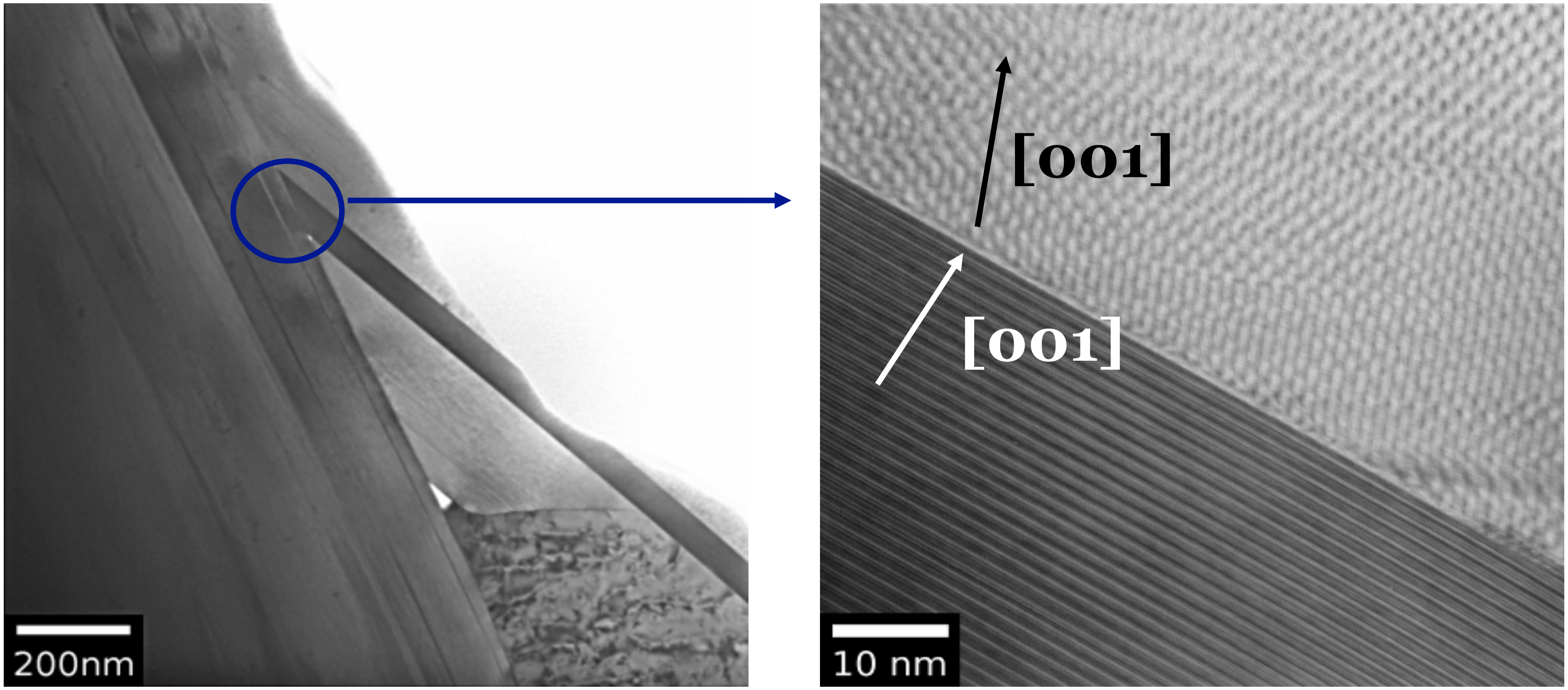


Keeps lattice coherence?

- The tilt angle between two grains is 45°
- Lattice planes bend to connect to the adjacent grain, reducing the tilt angle to 17°

F. Kametani, FSU

Transverse TEM of “small” bridge

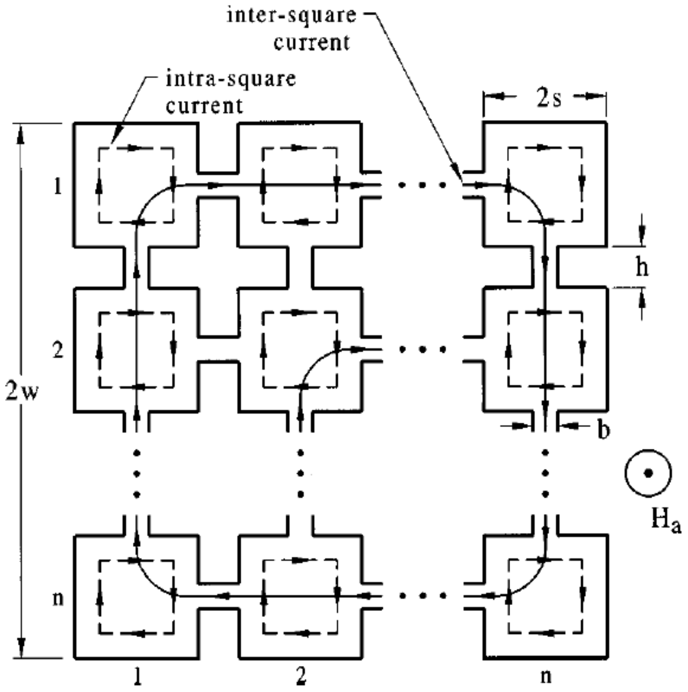


- Images of a junction of an outgrowth (bridge) and a filament
- Misorientation (not pure tilt) angle ~ 23°
- Grain boundary is clean but *should not* support transport … but does it?

F. Kametani

"Connectivity" and the role of bridges

- Grain flexibility overcomes lack of texture
- For connectivity, consider two-dimensional treatment based upon YBCO thin film grain-to-grain connectivity
- Bi2212 case is 3D, highly inhomogeneous extension
- Macroscopic approach?

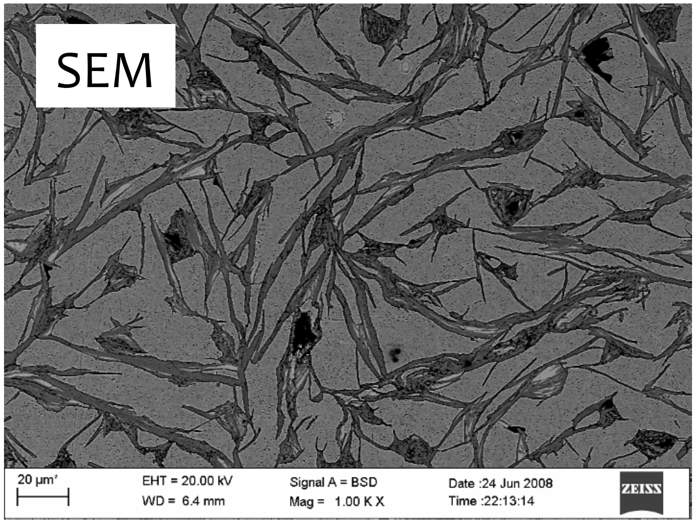


$$C = \frac{b}{2s+h}.\qquad J_c^I = \frac{b}{2s+h} J_c$$

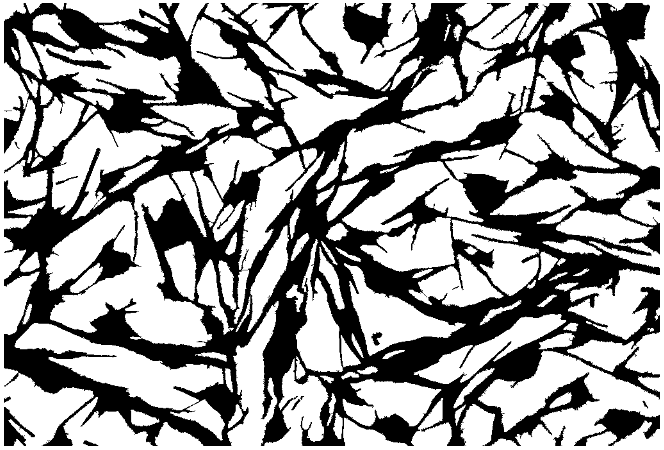
Muller, Andrikidis, Du, Leslie and Foley, PRB **60**(1) 1999 659

Develop quantitative image analysis

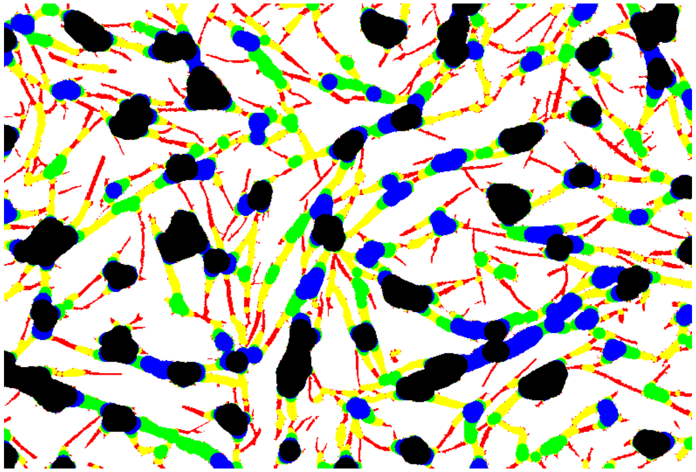
Do bridges correlate with properties?



Photoshop
+ Image J

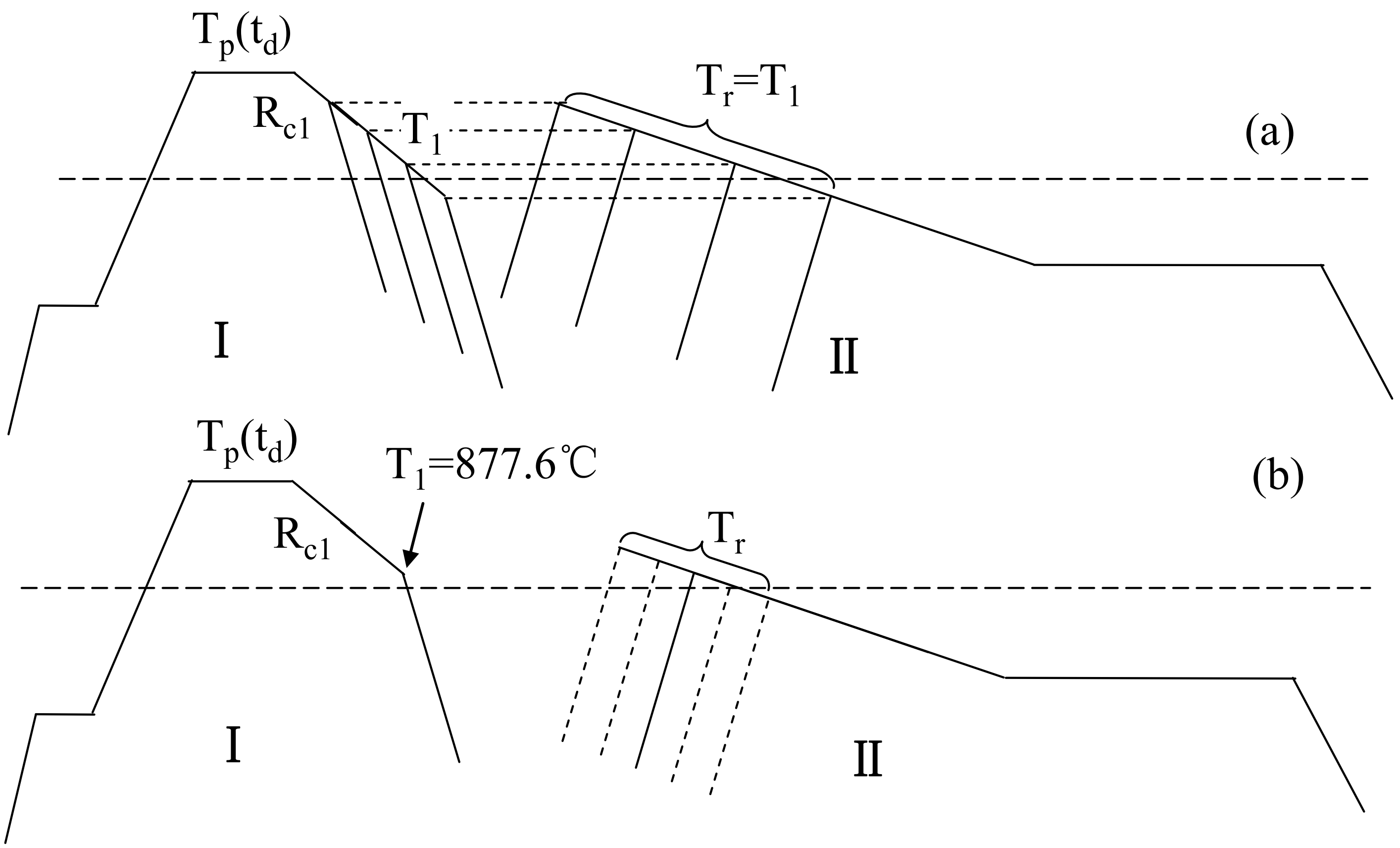


Matlab



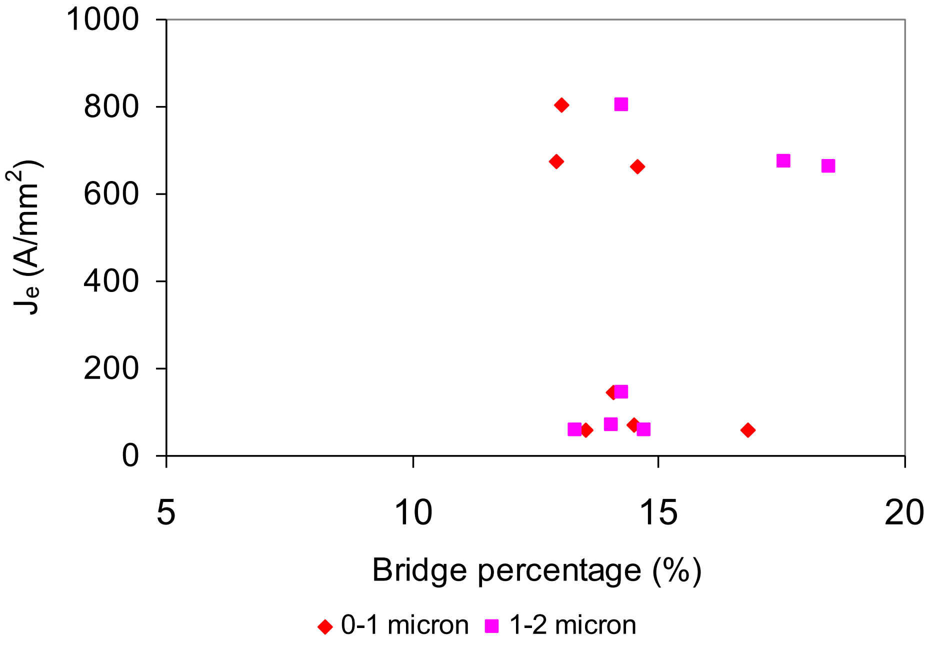
Ag-alloy	White, all
Oxide filaments	Black > 4 µm
Oxide bridges	4 µm > Blue > 3 µm
Oxide bridges	3 µm > Green > 2 µm
Oxide bridges	2 µm > Yellow > 1 µm
Oxide bridges	Red < 1 µm

Vary the processing, vary the microstructure

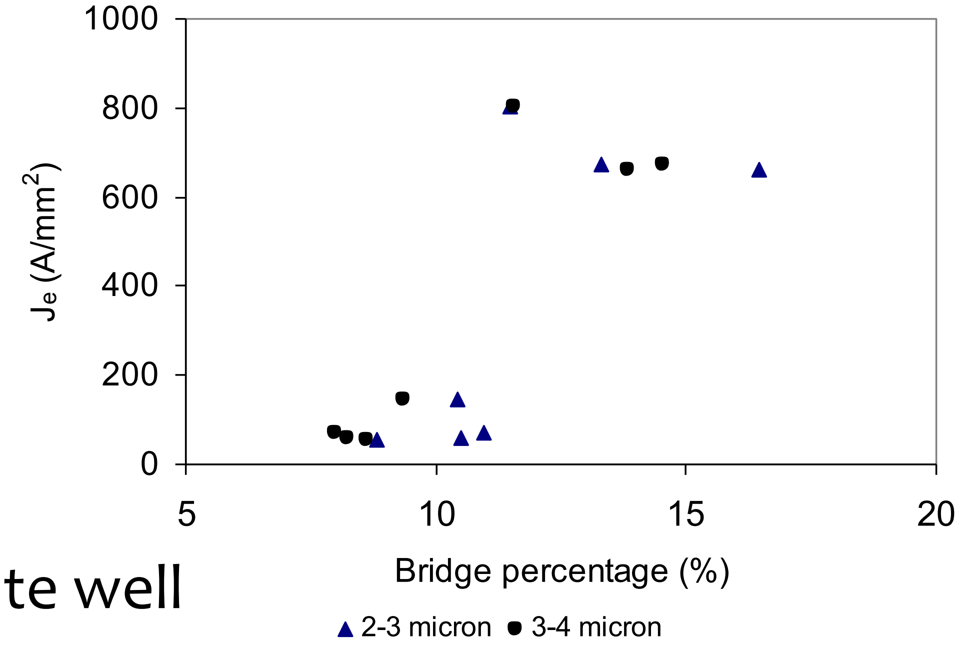


NC STATE UNIVERSITY

Do bridges correlate with J_c?

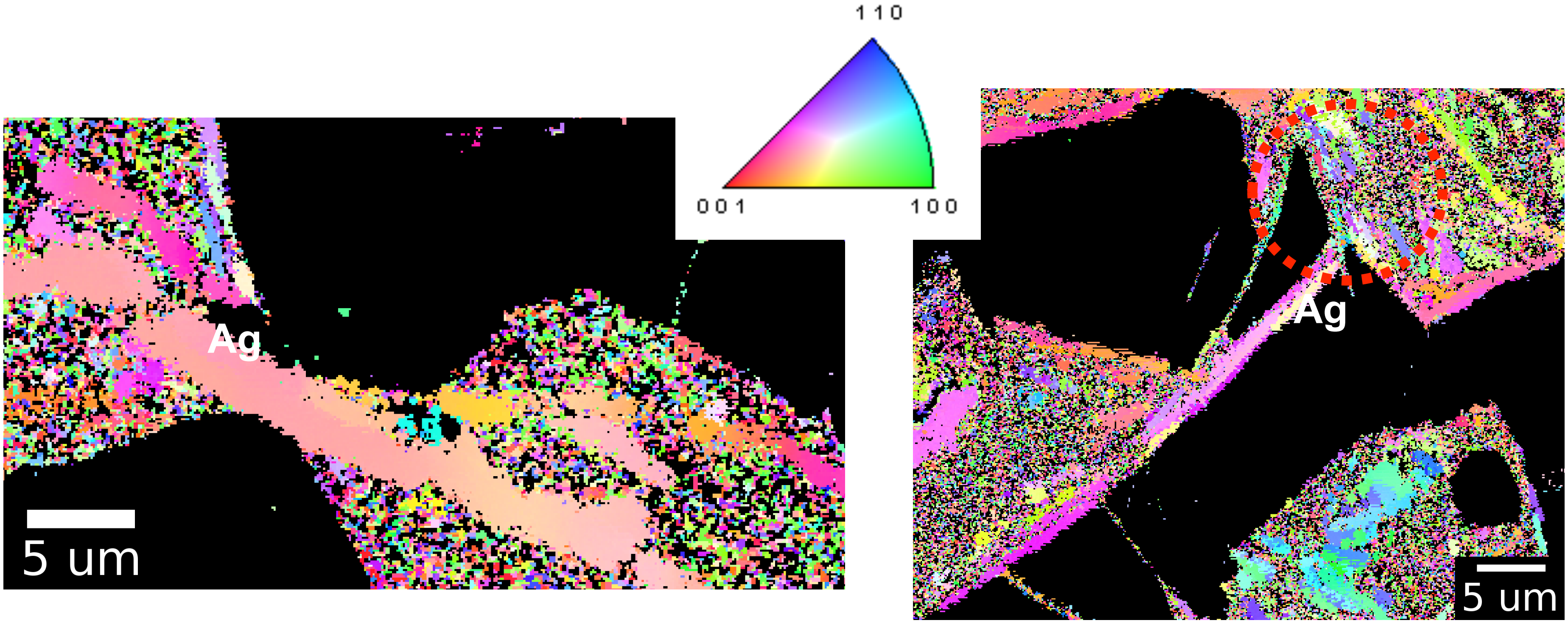


1-2 μm bridges do not correlate



2-4 μm bridges correlate well

Grain orientation mapping agrees!

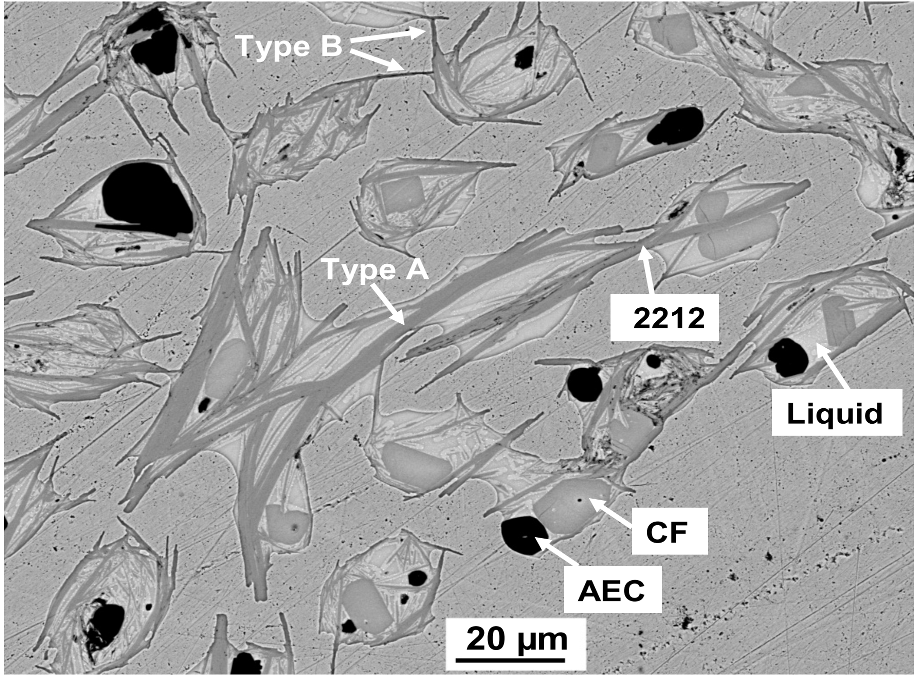


- LAGBs in some bridges; current can cross the bridge to the adjacent grain
- HAGBs are more typical than LAGBs in bridges; minimal current flow

F. Kametani, FSU

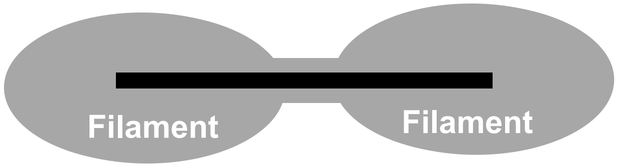
Why are there two types of bridges?

Samples quenched as Bi2212 nucleates

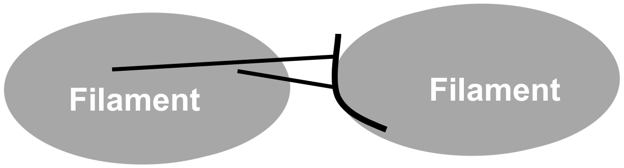


- Type-A bridges
  - Large, thick single Bi2212 grain/colony
  - Supercurrent crosses type-A bridges from one filament to another

Filament-filament bonding



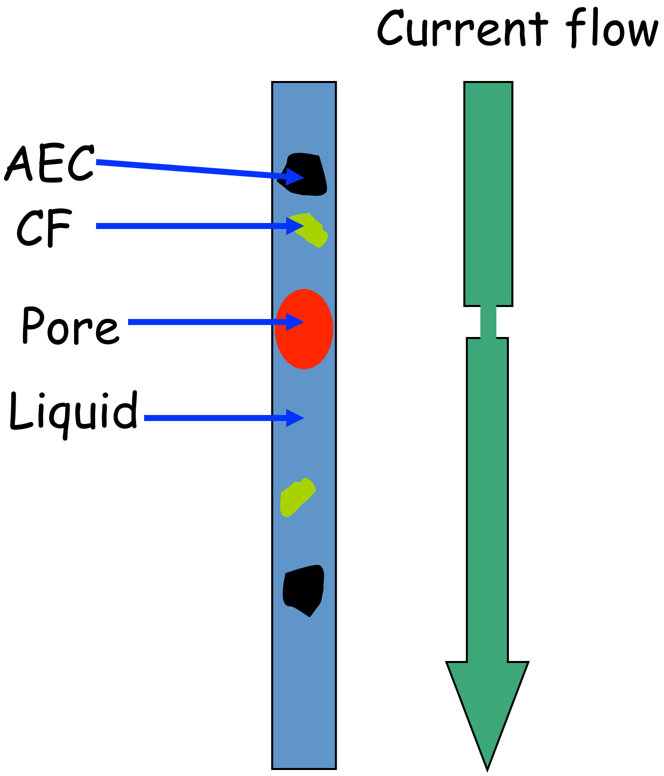
Isolated filaments



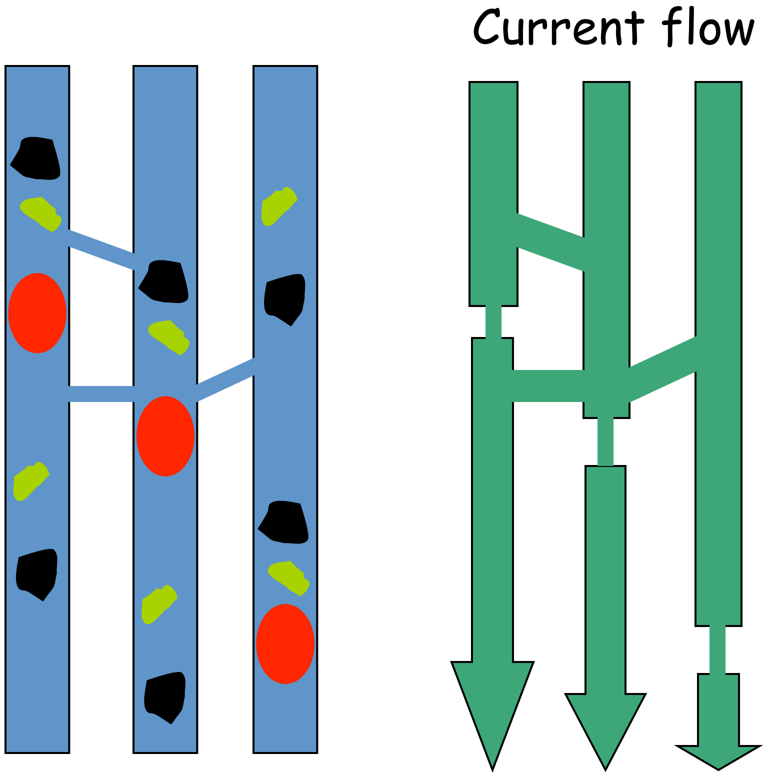
- Type-B bridges
  - Result from Bi2212 outgrowths
  - High angle grain boundaries
  - Low transport

T. Shen et al. & PhD dissertation

Interconnected 3-D current flow path … “walking in Venice” or “drunken electrons”



Monocore 2212



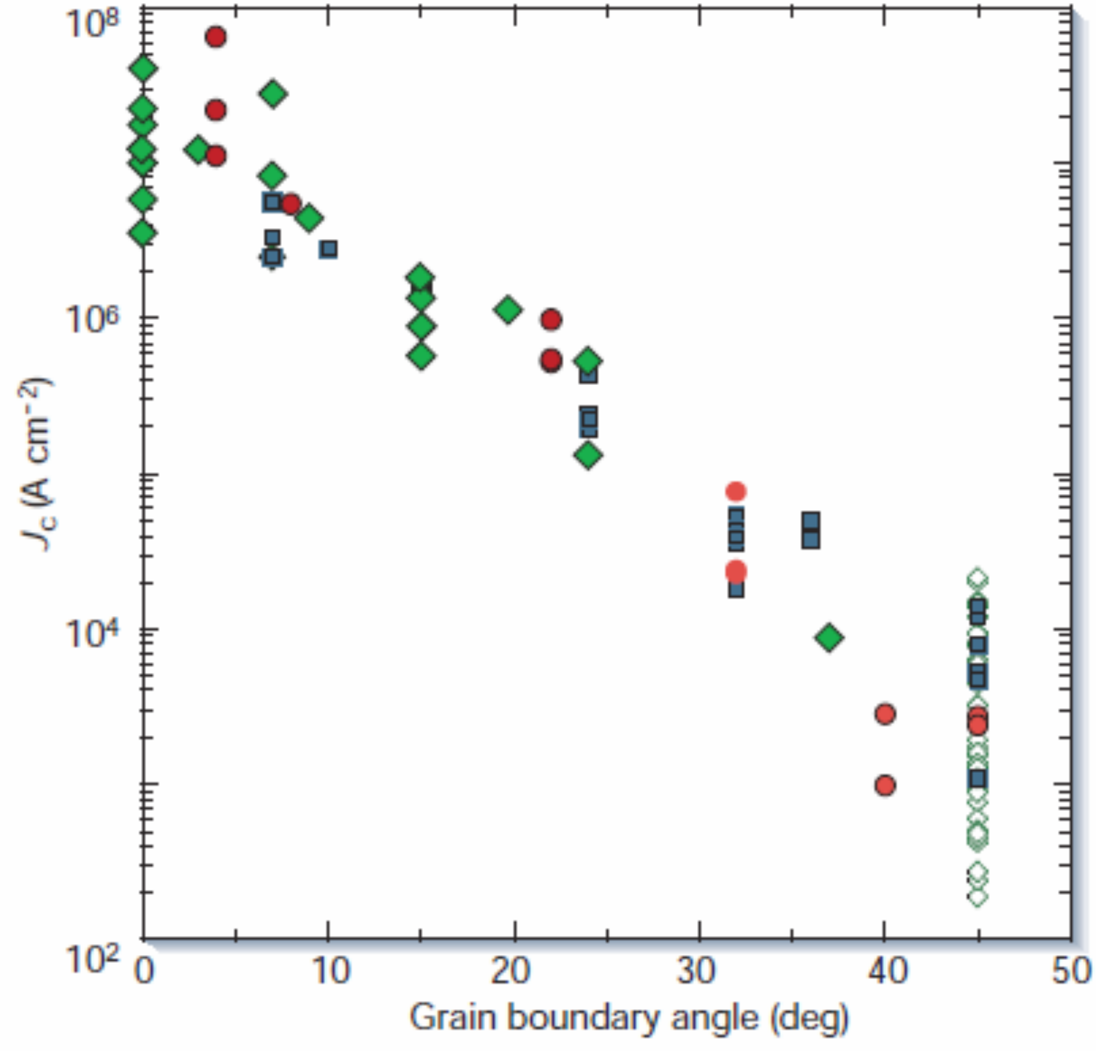
Interconnected Bi2212 filaments

So can Bi2112 improve significantly?

- Remarkable that Bi2212 microstructure carries high transport current
- Two primary obstacles to improvements (or, if you're an optimist – why it can get a lot better)
  - Porosity is significant; removing porosity in short samples shows significant increase in J_c
  - Reconversion to Bi2212 "nucleation site saturation limited" (split-melt processing shows that additional nucleation sites can be formed)
- Other unexplored opportunities
  - Varying Bi2212 composition … so many variables!

YBCO coated conductors & Dimos experiment

- Transport across a grain boundary in a bi-crystal



Weak-linked YBCO … the need for bi-axial texture

- J_b across the grain boundary drops exponentially below that of the grains, $J_b=J_0\ exp(-\theta/\theta_c)$, *as* a function of the misorientation angle θ, where θ_c ~2-5°
- This extreme sensitivity to misorientation, coupled with the intrinsic anisotropy, demands bi-axial texture in YBCO to minimize grain-boundary misorientation
- The "weak-link" behavior of grain boundaries is in effect a combination of this anisotropy and small coherence length

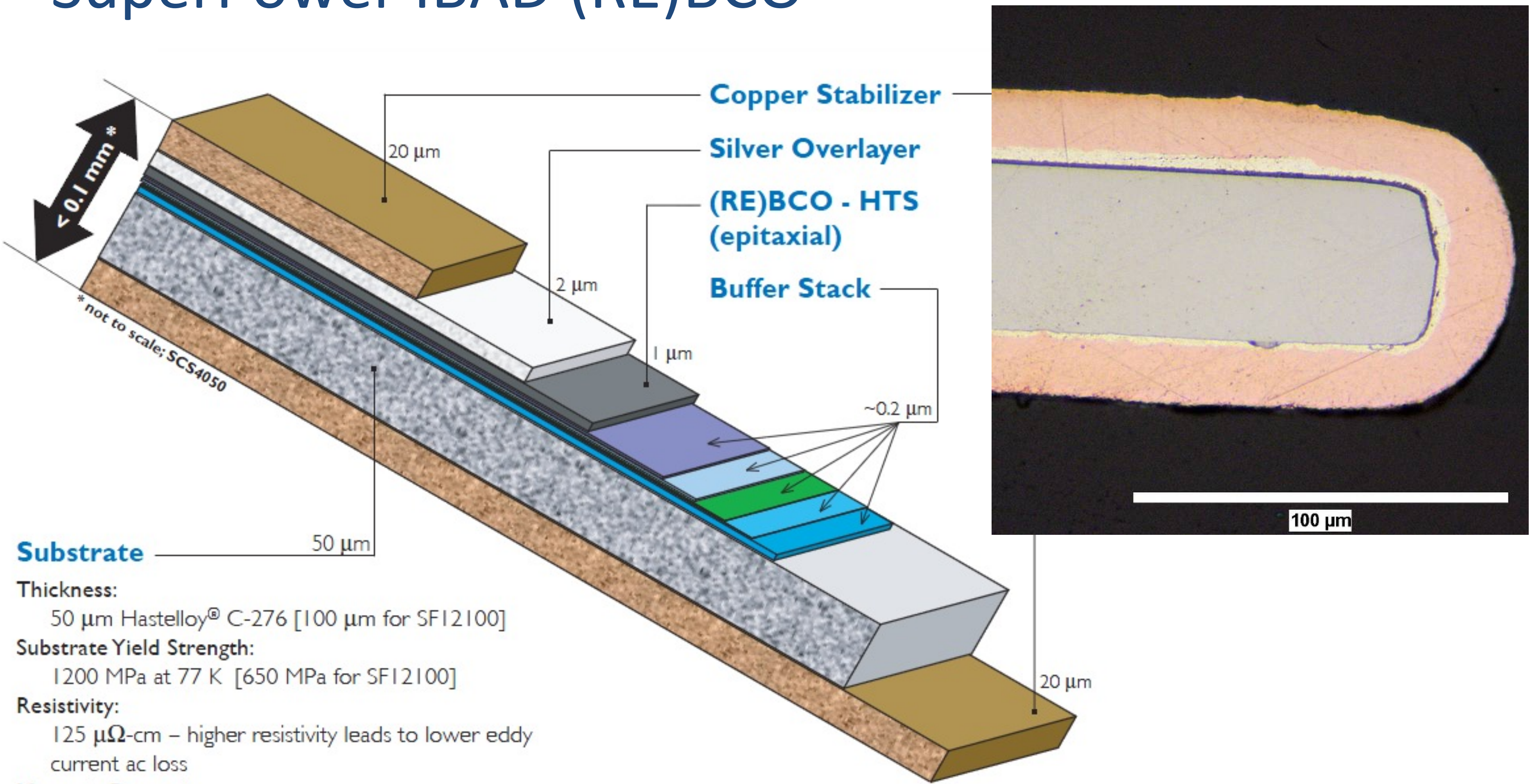
Emerging conductor: (RE)BCO coated conductor

- **ANY** method of making a conductor requires biaxial texturing; three approaches have emerged
- Rolling Assisted Bi-axial Textured Substrates (RABiTS)
    - Textured metallic substrate (NiW) serves as template
    - Requires buffer layers to separate Ni from YBCO chemically while "transmitting" texture information
- Ion Beam Assisted Deposition (IBAD)
    - Randomly oriented substrate (Hastelloy)
    - IBAD to deposit textured buffer layers which provide the template for YBCO growth
- Inclined Substrate Deposition (ISD)
    - Texture induced in buffer layers

What do (RE)BCO CCs share?

- Wide, thin tapes with very high $J_c(B)$
  - E.g., SuperPower IBAD is 12 mm wide, then slit to 4 mm
- **1-2% “fill factor” (%conductor that is superconductor)**
- Specialized buffer layers
  - Transmit/provide textured template
  - Chemical barrier between YBCO and Ni
  - Y_2O_3, YSZ, MgO, CeO_2, STO, are common buffer layers
- **A strong Ni-alloy substrate**
- A thin Ag cap-layer atop the (RE)BCO for environmental protection
- Cu enclosure
- Very anisotropic $J_c(B)$
- **“Engineerable” microstructure: flux pinning optimization**

SuperPower IBAD (RE)BCO

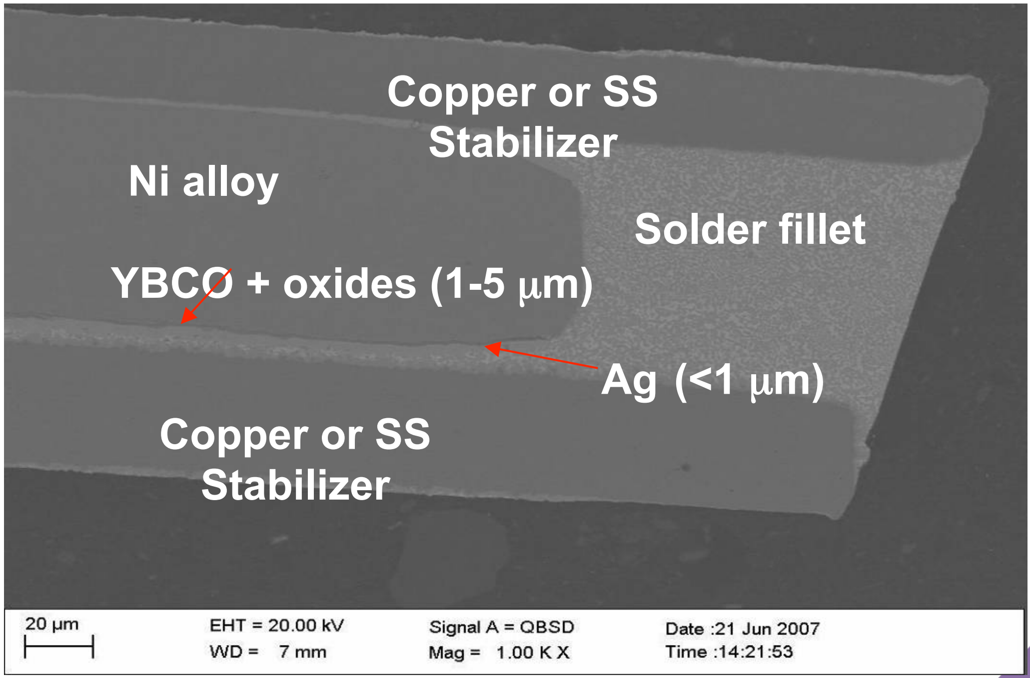


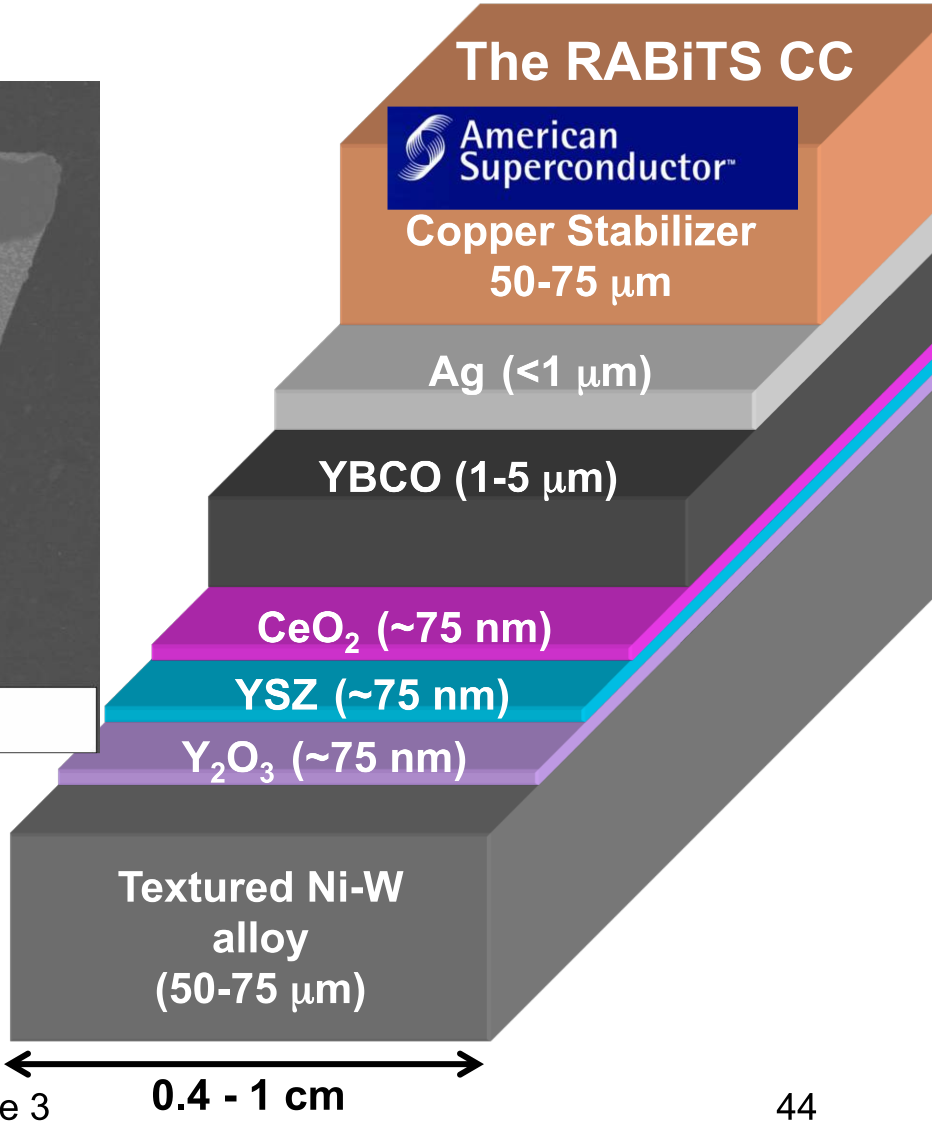
Substrate

Thickness:
50 µm Hastelloy® C-276 [100 µm for SF12100]
Substrate Yield Strength:
1200 MPa at 77 K [650 MPa for SF12100]
Resistivity:
125 µΩ-cm – higher resistivity leads to lower eddy current ac loss
Magnetic Properties:
non-magnetic, leads to lower ferromagnetic ac loss

- Cu is electroplated

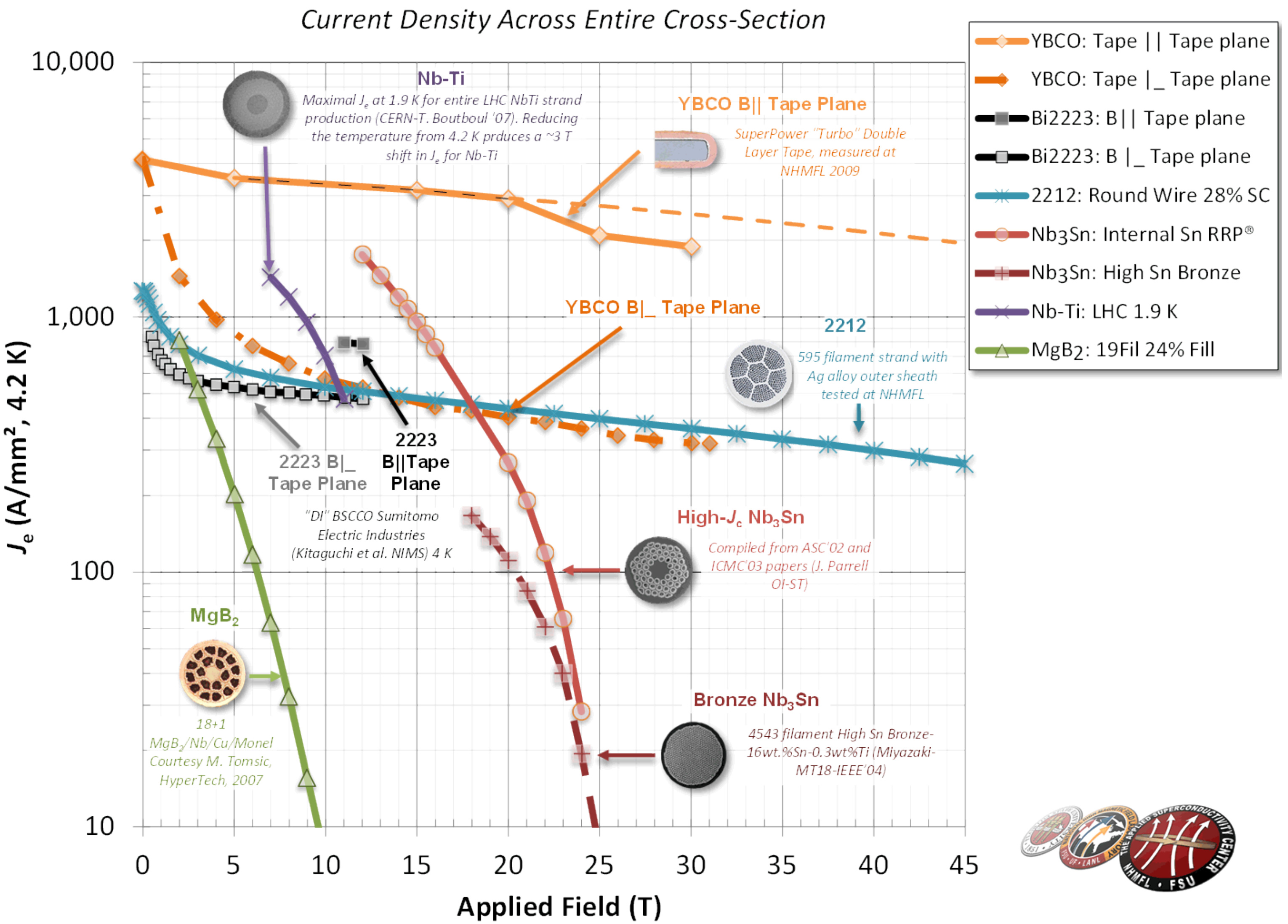
American Superconductor (RE)BCO Coated Conductor





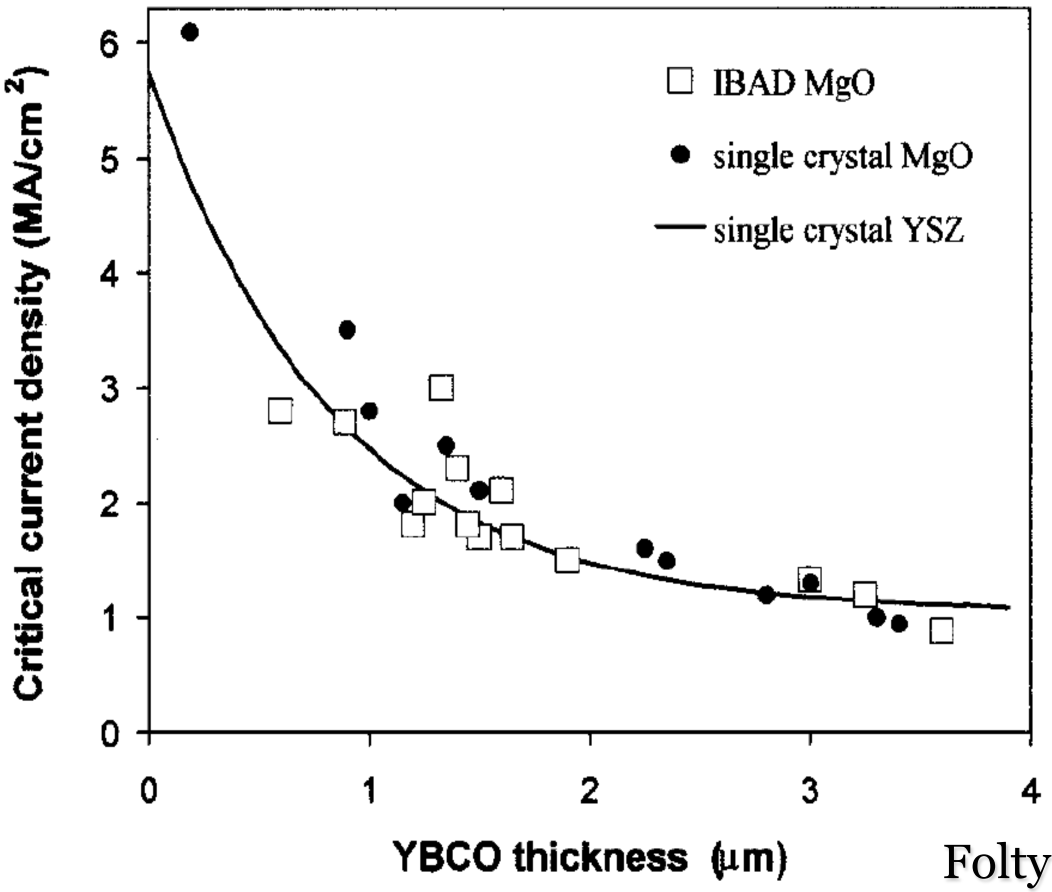
Cu is soldered – easy to use other materials, but bonding not as strong as electroplating

Recall J_c(B) plot … *two YBCO curves*



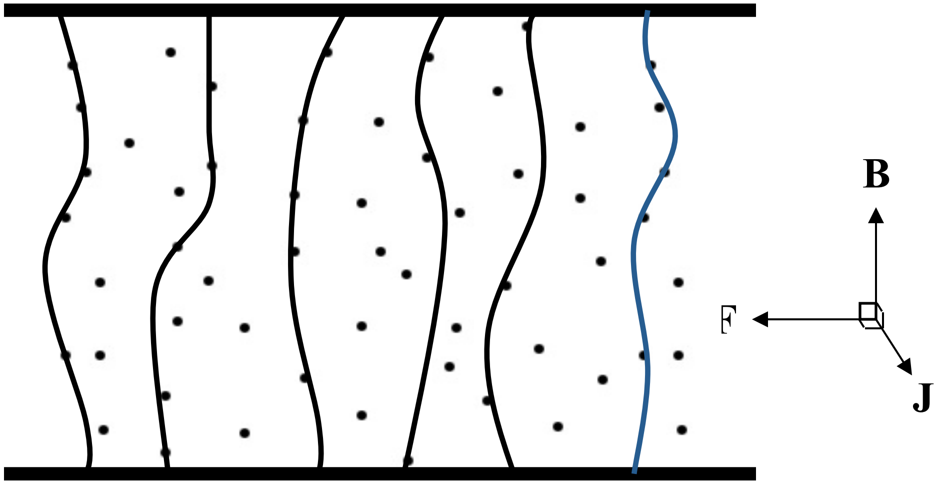
Thickness dependence of J_e

- Attempts to increase fill factor have diminishing return



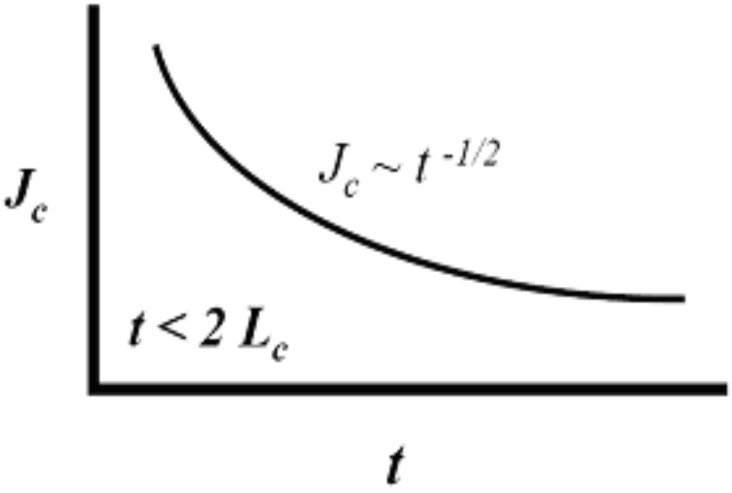
Foltyn et al. APL 2003

Two-dimensional flux pinning



2D Collective Pinning Theory shows that weak flux pinning & thermal fluctuations can lead to thickness dependence

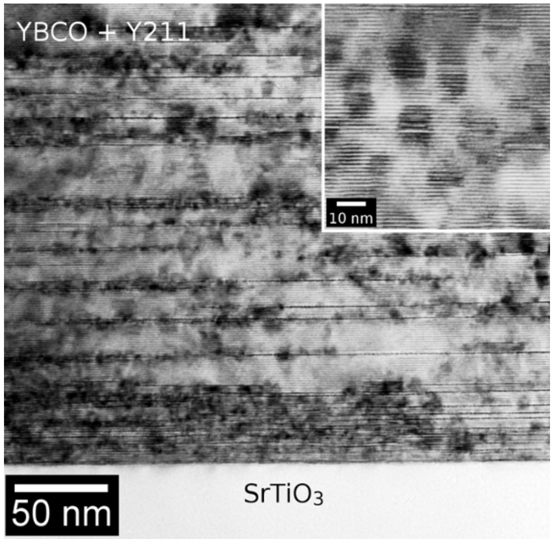
$$J_c \cong \frac{\pi^{1/2} f_p r_p}{\phi_0 d^{3/2} t^{1/2}} \approx \frac{J_d r_p \xi}{d^{3/2} t^{1/2}} \propto t^{-1/2}$$

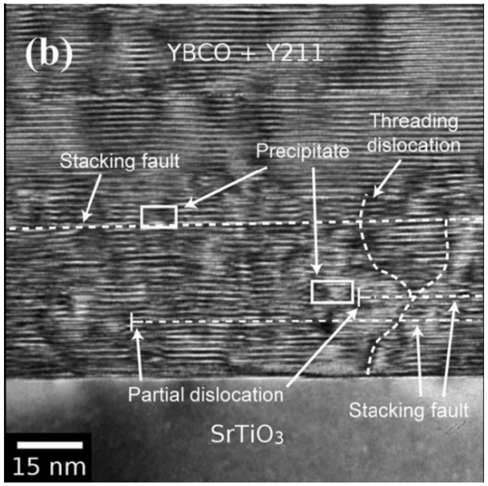


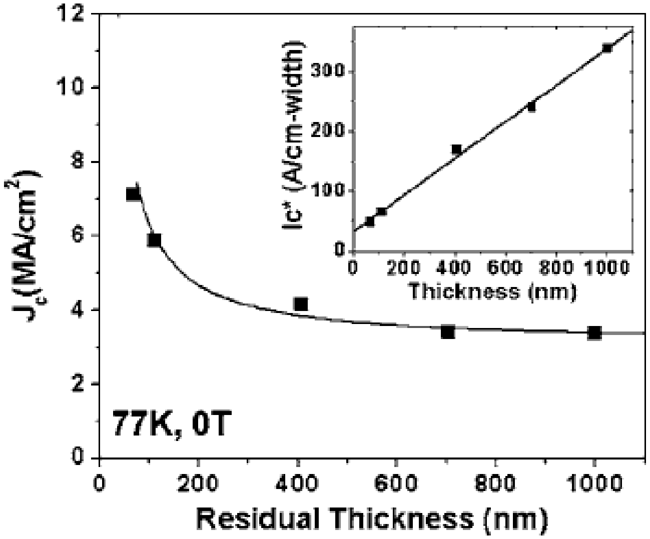
What can be done?

Gurevich; Kim

Three-dimensional flux pinning with nanoinclusions



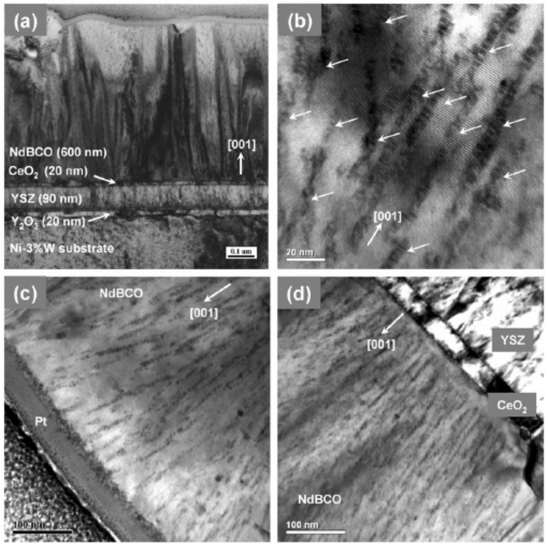




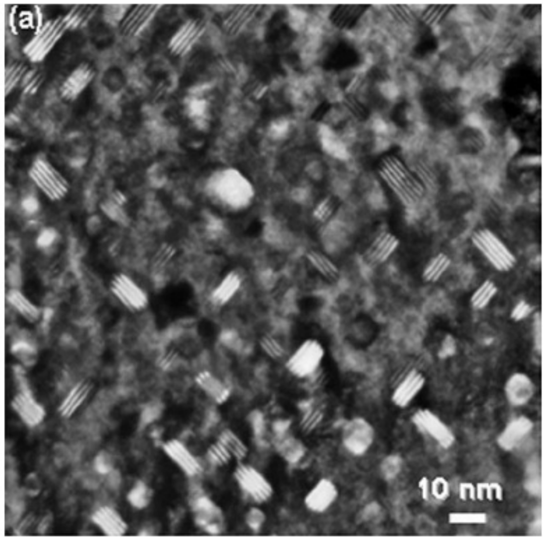
- Flux pinning inclusions reduce thickness dependence … *but not totally*
- Multiple mechanisms in concert

Kim et al., APL 90 2007

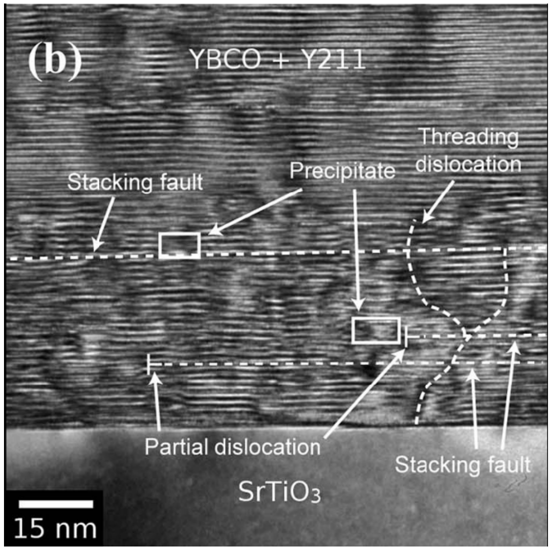
Flux pinning nanoinclusions



Columnar $BaZrO_3$
Wee et al., SuST 20 2007



(Y,Sm) O_3
Song et al., APL 88 2006

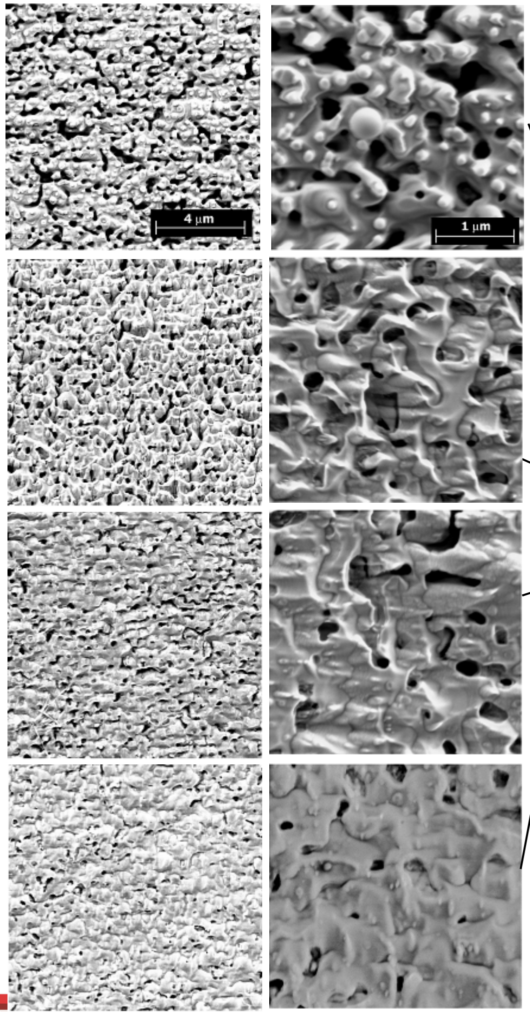


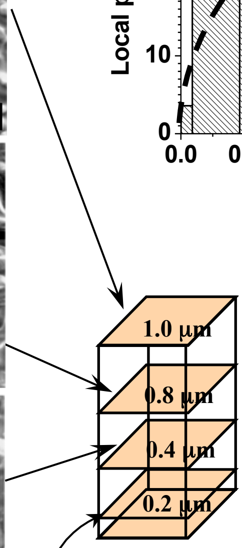
Y211
Kim et al., APL 2007

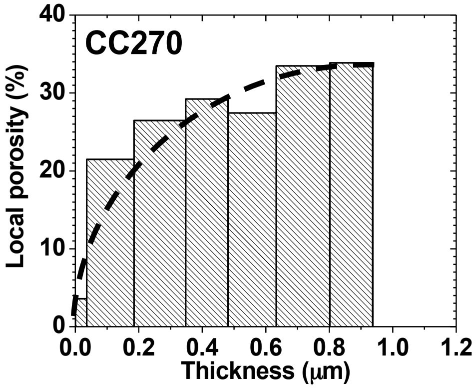
- YBCO CC chemistry facilitates wide variety of nanoinclusions for flux pinning… can high field conductor be engineered? An isotropic conductor?

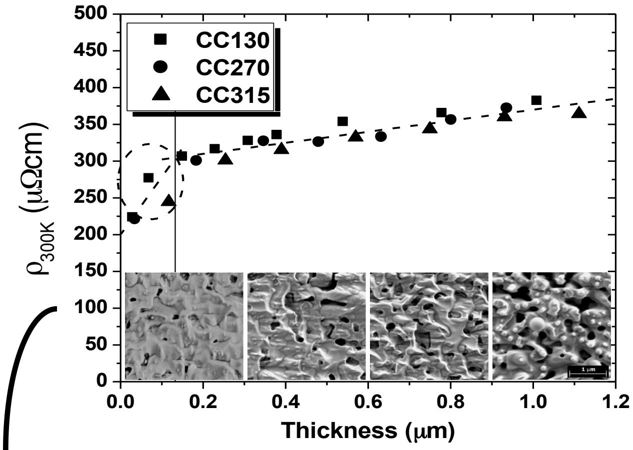
Inhomogeneous porosity

Kim, Feldmann, Gurevich, Larbalestier

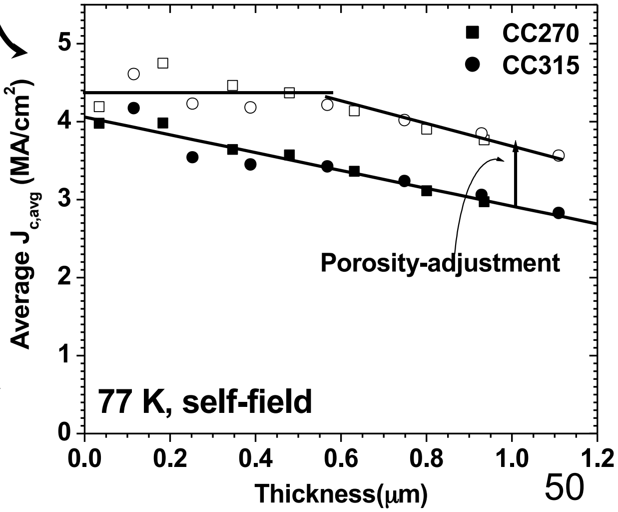








Effective Medium Theory



Pore sizes: 50-500 nm
Can pin flux or block
current depending on size

SCHWARTZ GROUP

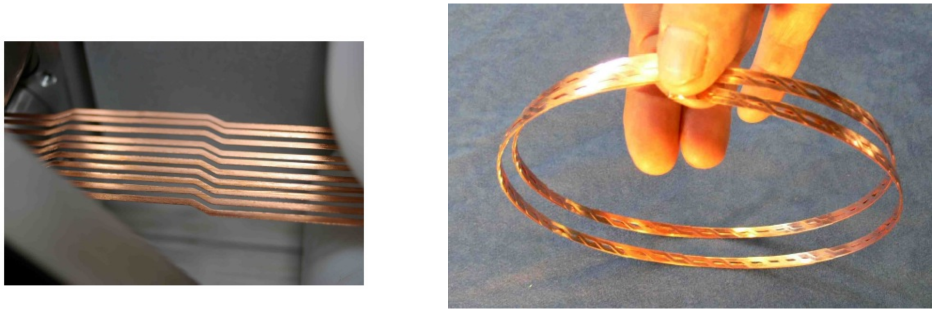
Department of Materials Science and Engineering

Transport in YBCO CCs

- Three factors can destroy transport in YBCO CCs
  - Grain boundaries & other connectivity blockers
    - Can be improved with Ca, Nd, … , other dopants
  - Flux pinning
    - Can be improved/engineered by plethora of nanoinclusions
  - Porosity
    - Can be improved via better processing
- Solving these simultaneously may
  - Reduce anisotropic electromagnetic behavior
  - Provide flexibility in operating current
  - Improve J_e
  - Result in a conductor that can be engineered

What about cables made from wide, thin tape?

Roebel cable

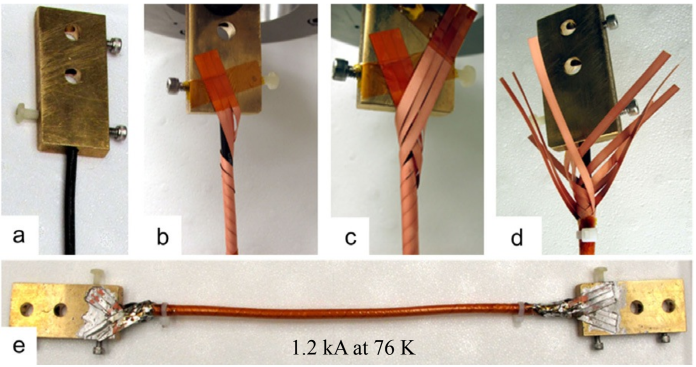


N J Long, R Badcock, P Beck, M Mulholland, N Ross, M Staines, H Sun, J Hamilton, R G Buckley, Journal of Physics: Conference Series 97 (2008) 012280

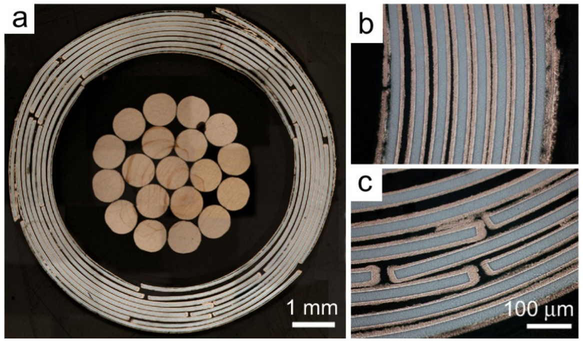
Twisted stacked tape cable

M. Takayasu et al., “Cabling Method for High Current Conductors Made of HTS Tapes”, ASC 2010

Compact cable



1.2 kA at 76 K



2.8 kA at 76 K

D C van der Laan, X F Lu and L F Goodrich, “Compact GdBa2Cu3O7–δ coated conductor cables for electric power transmission and magnet applications”, Supercond. Sci. Technol. 24 (2011) 042001

Summary of potential magnet conductors

	Conductor manufacture	**MF?**	**Shape**	**Isotropic**	**n-value**	**Coil manufacture**	**Material class**
Bi2212 ~80 K >50 T	Powder-in-tube	Pseudo	Tape & Round 300 m	Yes or no	Low	R&W or W&R	Oxide
Bi2223 ~110 K >50 T	Powder-in-tube	Pseudo/ yes	Tape 1.4-2 km	No	Mid	R&W	Oxide
YBCO ~90 K >50 T	Deposition processing	No	Tape 1 km	No	High	R&W	Oxide
MgB_2 ~39 K 12-40 T	Powder-in-tube	Yes	Round 1 km	Yes	High	R&W or W&R	Boride

“YBCO, Bi2212, … *what needs to be improved?”*

- Bi2212 (>22 yrs of PIT)
  - Is porosity intrinsic to PIT?
  - Are non-Bi2212 phases avoidable with peritectic melting?
  - Narrow temperature window challenge ***in large systems***
  - Lack of strain tolerance
    - Are 100%-dense, 100%-phase pure filaments the answer?
    - AgX needs a better “X”
- YBCO (>15 yrs of CCs)
  - Can we manage the high J_c?
    - Very different J(x,y)
    - Particularly in light of drop-outs
  - High J_e cable? What price?
  - Can high current cable bend?
  - Joining (conductors & cables)