Some Basic Superconductivity for Accelerator Builders – Lecture 2 Irreversible properties

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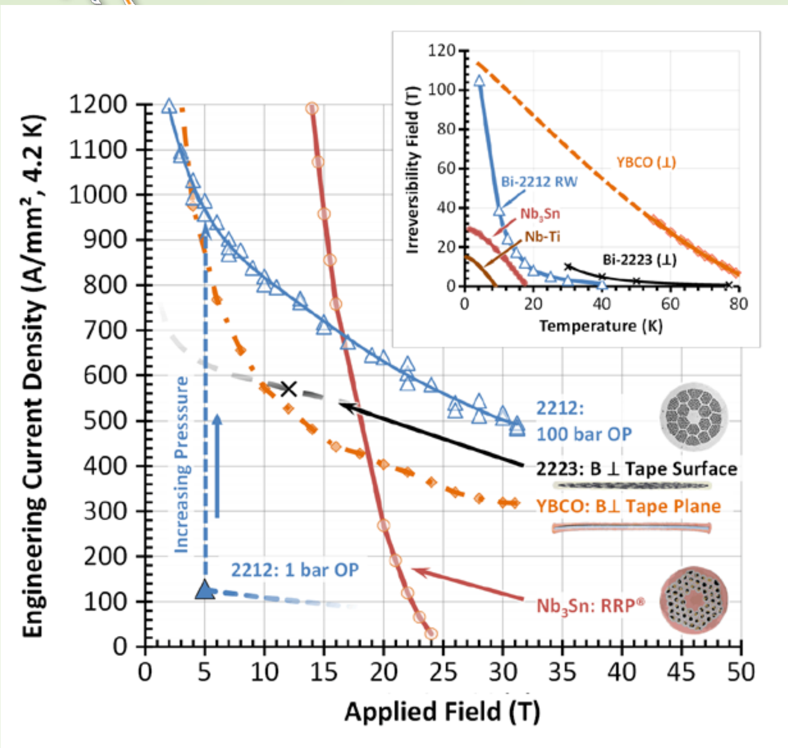
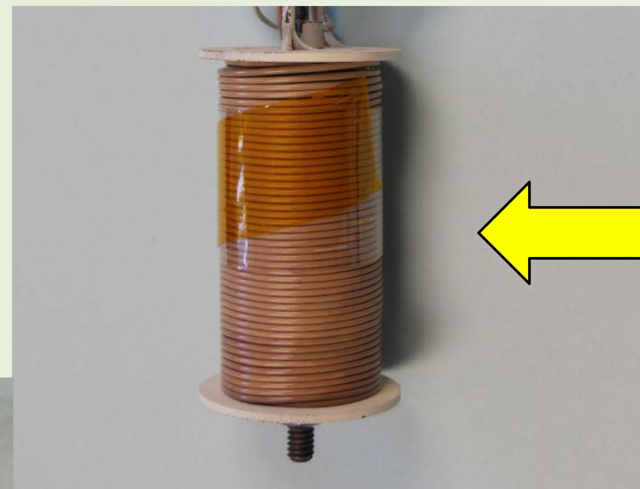
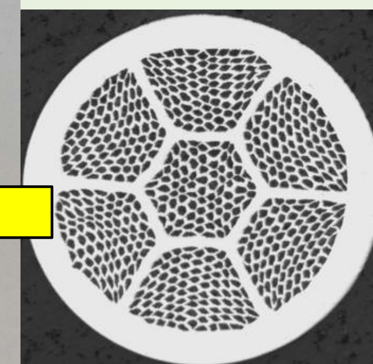
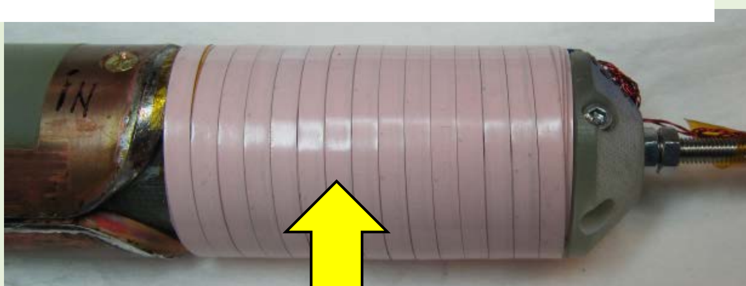


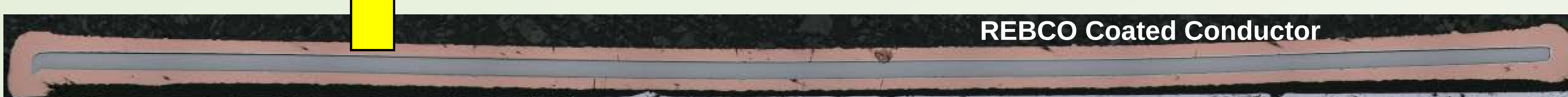




34T (in 31T) – Bi-2212



35T (in 31T) – REBCO coated conductor



My/our point of view

- The "**killer app**" for superconductors is magnets –
  - Onnes described this clearly in 1913 (in Chicago)
  - Only **by accident** did the path to magnet conductors emerge.. (Kunzler *et al.* Bell Labs 1960)
- Magnet builders want:
  - Conductors of **varying I_c**
  - Small lab magnets can operate at 100 A, big ones like ITER or LHC may need 20-60 kA – requires cables of many strands
  - Conductors with many **small** filaments to minimize charging losses, field errors and to avoid single-defect flaws
  - Conductors with good normal metal around each filament
- Magnet builders need high **conductor** current density (J_e)
  - Demands high J_c, high H_{irr} and high H_{c2}
  - High J_e demands either exceptional J_c or sc fill factors of 20-40vol.%
- High strength, km lengths, affordability ($/kA.m), ….

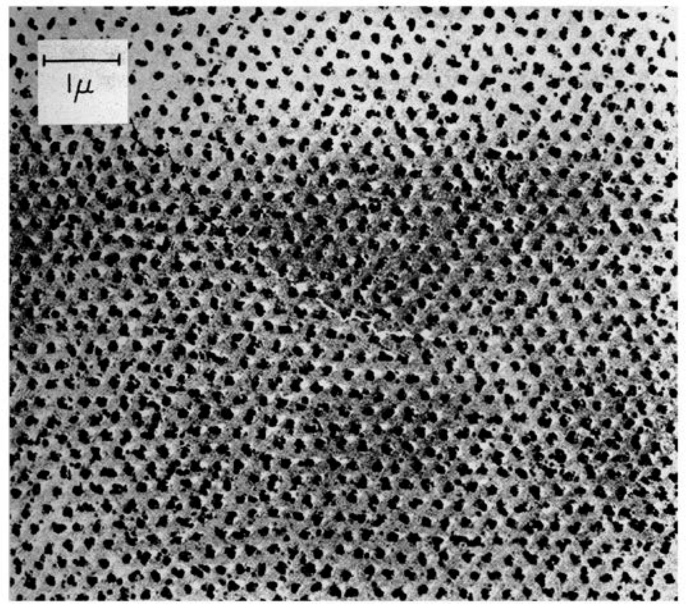
Transparent grain boundaries are critical for all above requirements…..

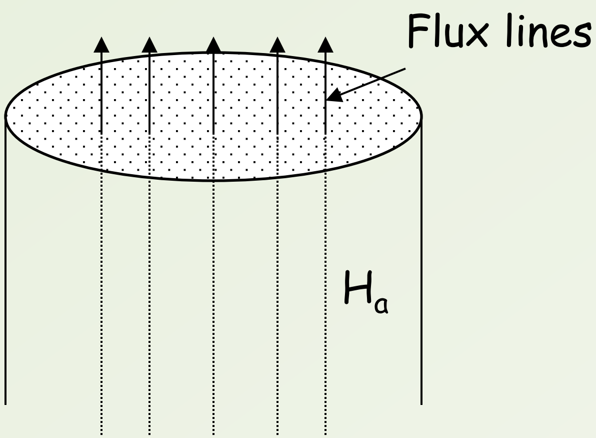
Lecture 2 outline

- Vortex pinning and high Jc
- Grain boundary effects
- Conductor outlook taking account of the huge advantages of Nb-Ti and Nb_3Sn (see Flukiger talks on Monday)

Type II Superconductivity

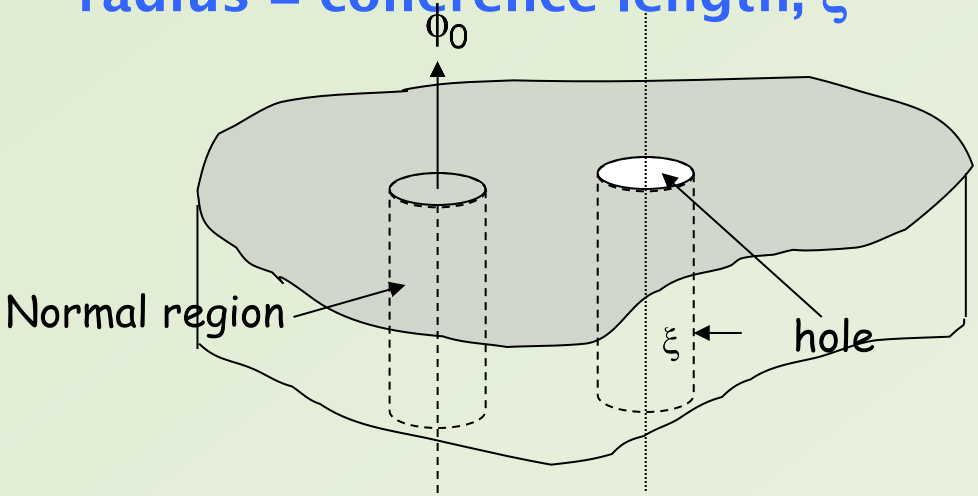
- For $H_{c1} < H < H_{c2}$, Type II superconductors enter the mixed state
- Experimental observation
  - Magnetic particles on SC
  - Triangular pattern of normal regions w/I SC regions
  - Number of lines a B_a
- Materials of interest
  - Nb-Ti ($T_c \approx 9$ K)
  - Nb_3Sn ($T_c \approx 18$ K)
  - BSCCO ($T_c \approx 85$ to 105 K)
  - YBCO ($T_c \approx 95$ K)





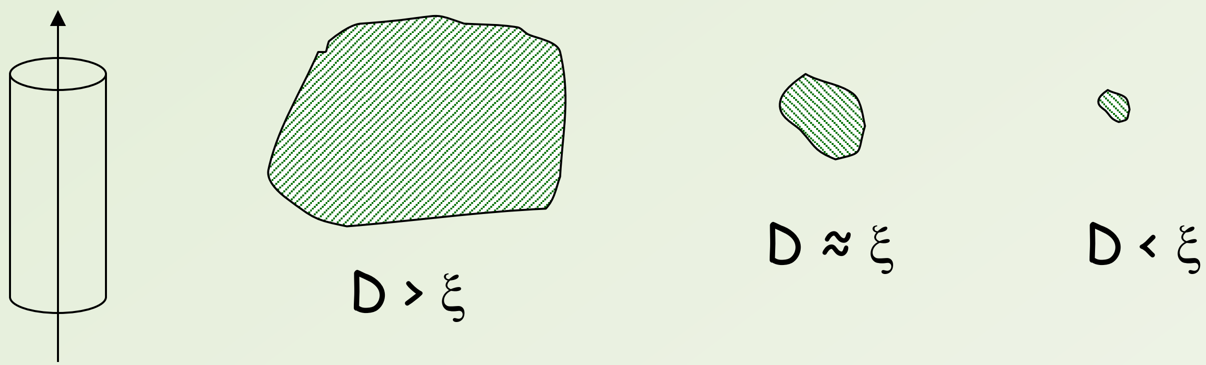
Vortex pinning basics

- Ideal pinning site is an normal, insulating or void region of radius = coherence length, ξ



Energy/length = $1/2\mu_0 H_c^2 \pi \xi^2$
$\approx 10^{-11}$ J/m

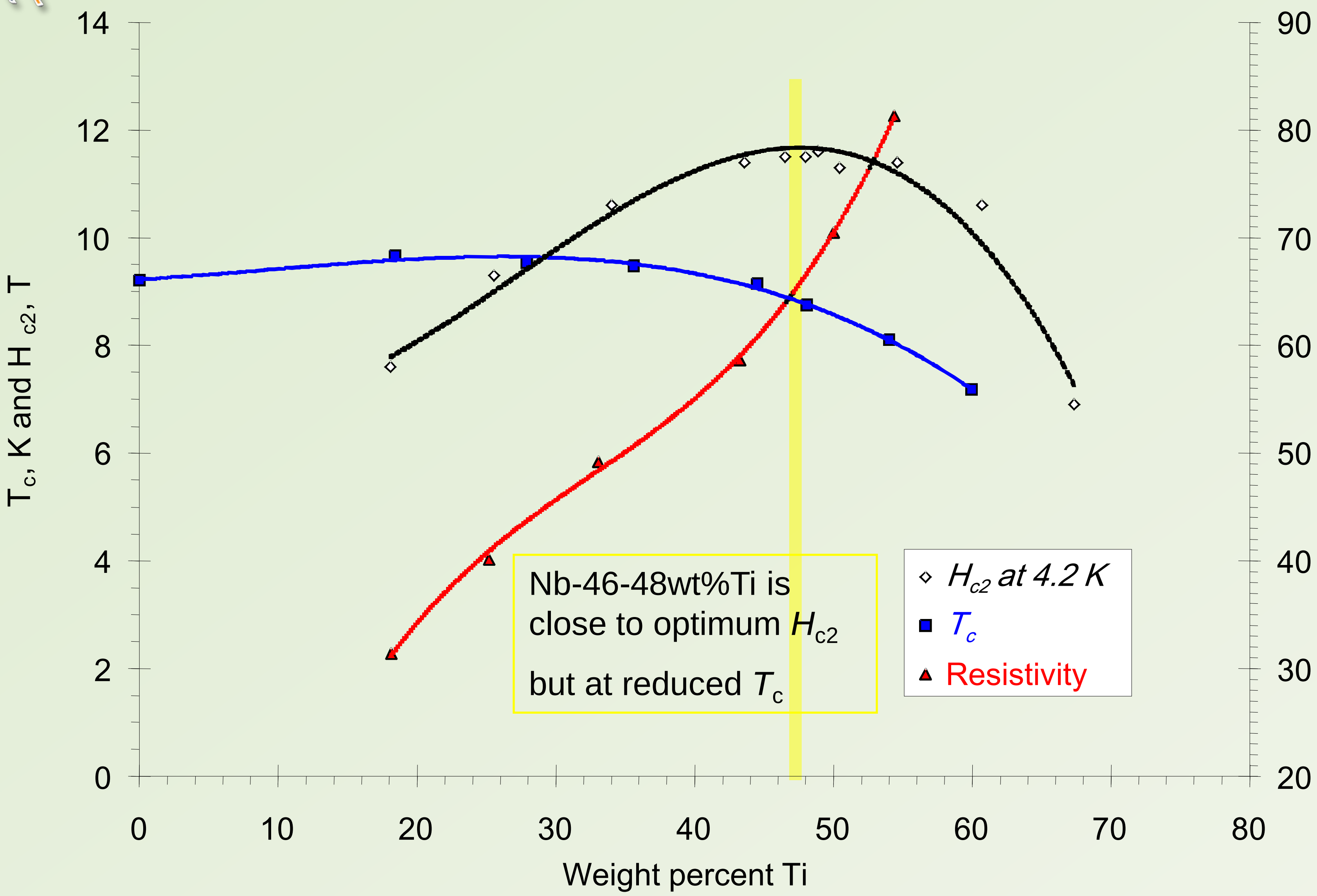
- Artificial pinning centers approximate ideal pinning sites while normal precipitates only pin portion of flux line



Two case studies

- Nb-Ti
  - Pins are a-Ti ribbons that are generally about 20% by volume in the superconducting b-phase matrix
  - At optimum Jc, ribbons are < x in thickness and the nanostructure transforms from a distinct S-N-S structure when formed into a coupled S-S’-S nanostructure
- YBCO
  - All sorts of nanoscale pin can be put into YBCO, leading to 10 years of exciting designer pinning work
  - Most are insulating

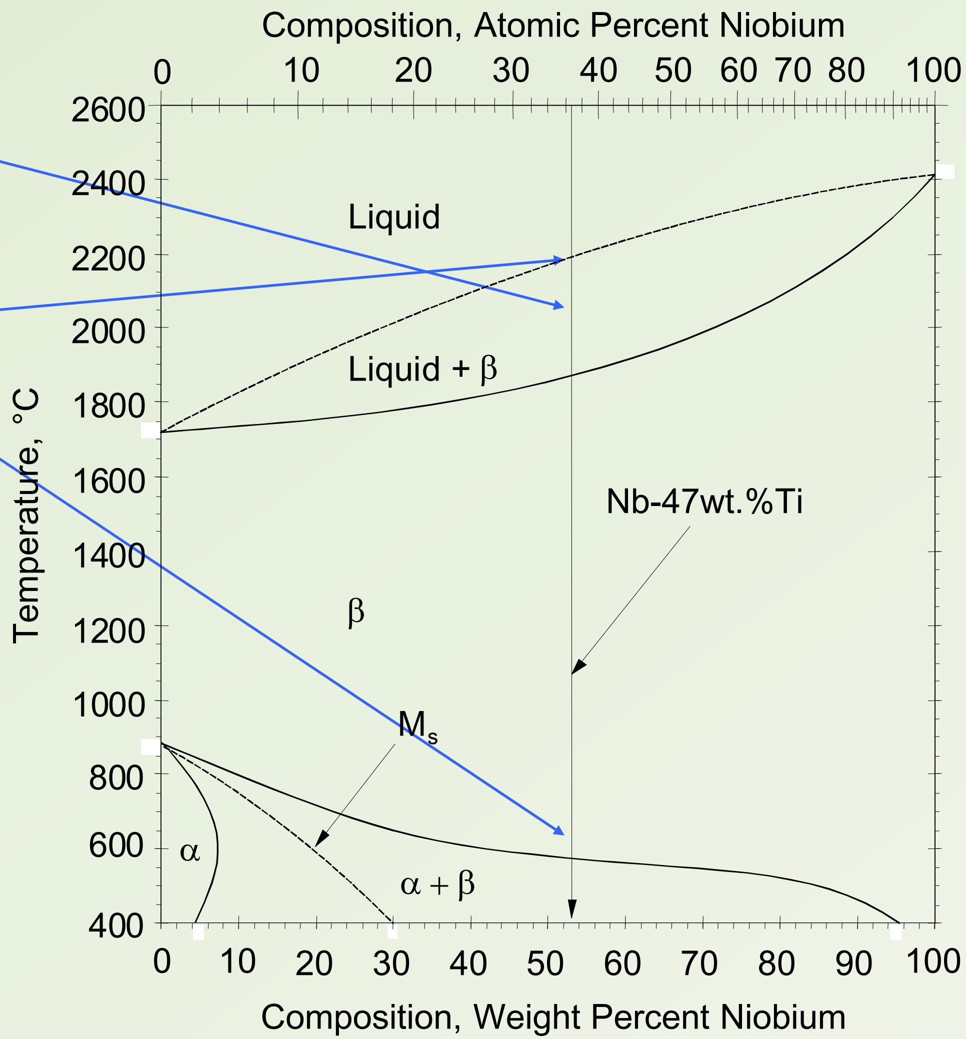
Nb-Ti Superconductivity



Nb-Ti Metallurgy

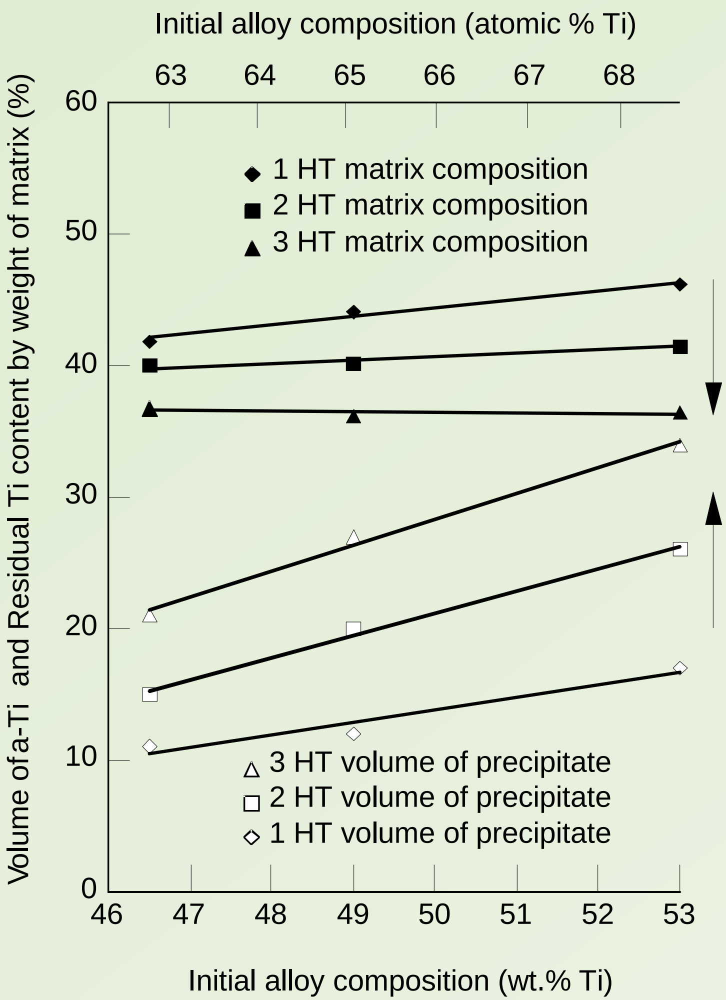
Large phase separation produces coring in alloy

High melting point produces low diffusion rates at precipitation temperatures



A hybrid equilibrium phase diagram for Nb-Ti combining the experimentally determined high temperature phase boundaries of Hansen et al with the calculated low temperature phase boundaries of Kaufman and Bernstein modified by Moffat and Kattner. Also shown is the martensite transformation curve (M_s) of Moffat and Larbalestier.

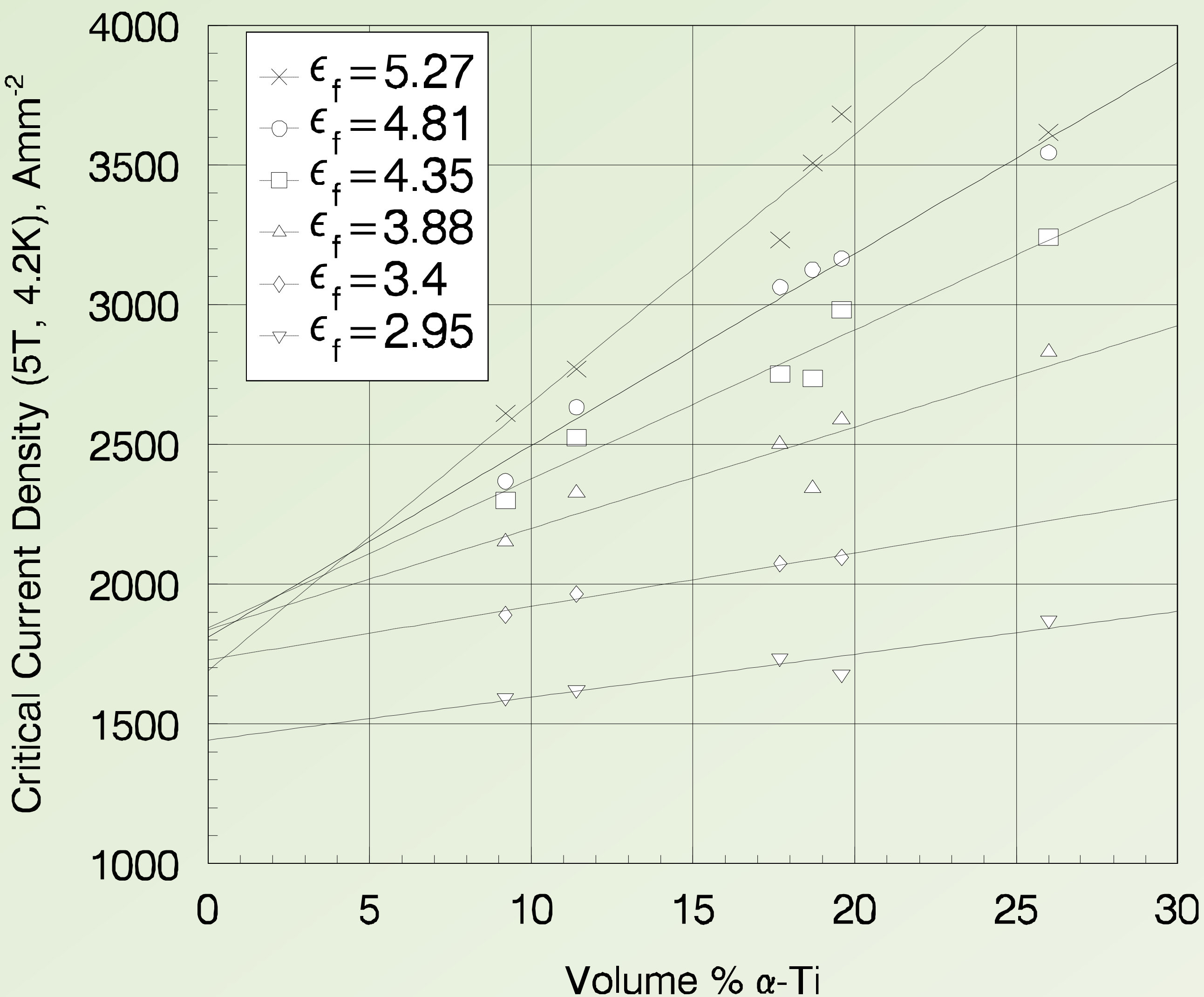
Increasing the volume of precipitate by multiple strain/heat treatment cycles.



The precipitation rate in Nb-Ti increases strongly with Ti content in Nb-Ti alloys. Additional heat treatments further increase the amount of precipitate. As additional heat treatment and strain cycles are applied, and more precipitate is produced, the residual Ti content of the β-Nb-Ti matrix drops until insufficient Ti is left to drive further precipitation. In this graph data from one and two heat treatments are combined data from three heat treatments of 80hr at 420 °C. The average residual matrix composition is calculated assuming an α -Ti composition of Nb-3.75 atomic % Ti.

Increasing Ti % increases precipitation rate > 46 wt % is needed, but too high %Ti depresses T_c and H_{c2}.

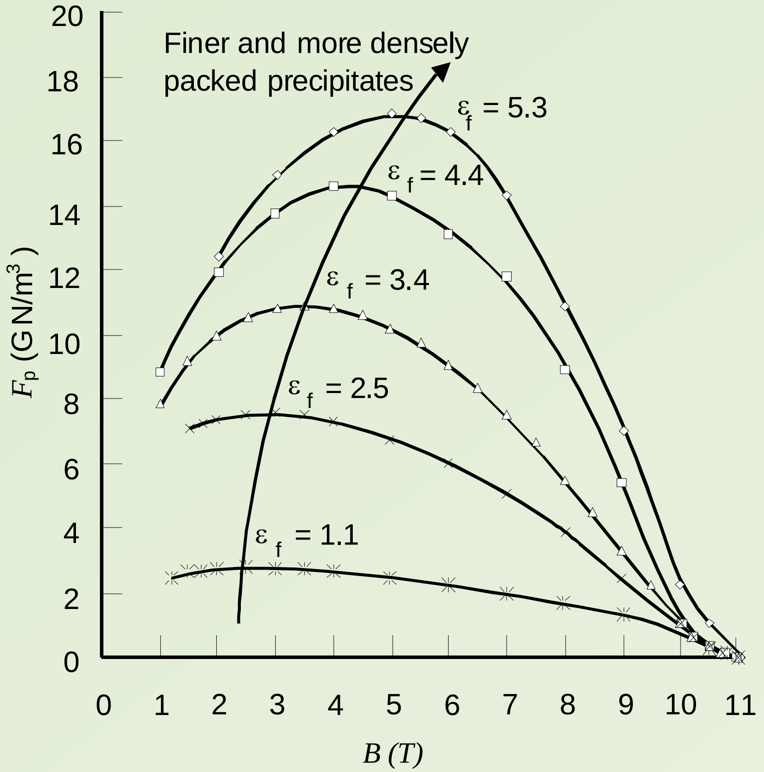
Final Drawing Strain effectively increases J_c by increasing vortex-pin interaction density

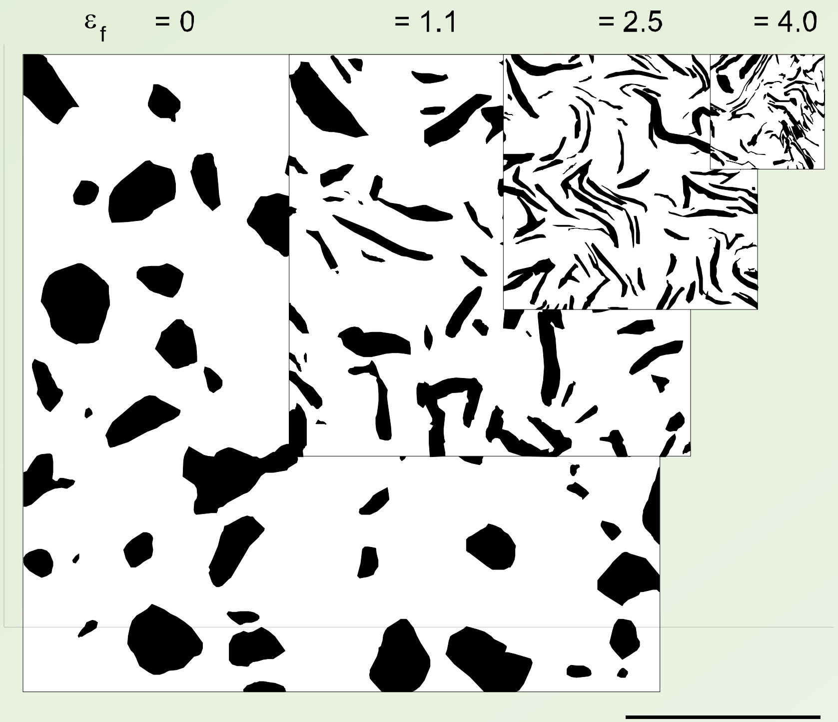


Nb-47wt% Ti, 5 T, 4.2 K

More precipitate and more final strain means more J_c

Bulk Pinning Force and nanostructure





For conventionally processed Nb-Ti the bulk pinning force increases in magnitude with drawing strain after the last heat treatment. The increase occurs at all fields as the precipitate size and spacing are reduced to less than a coherence length in thickness. The refinement of the microstructure with increasing strain for the same strand is shown schematically in transverse cross-sections with the α-Ti precipitates in black. [Meingast, Lee and DCL JAP 1989]

Nb-Ti

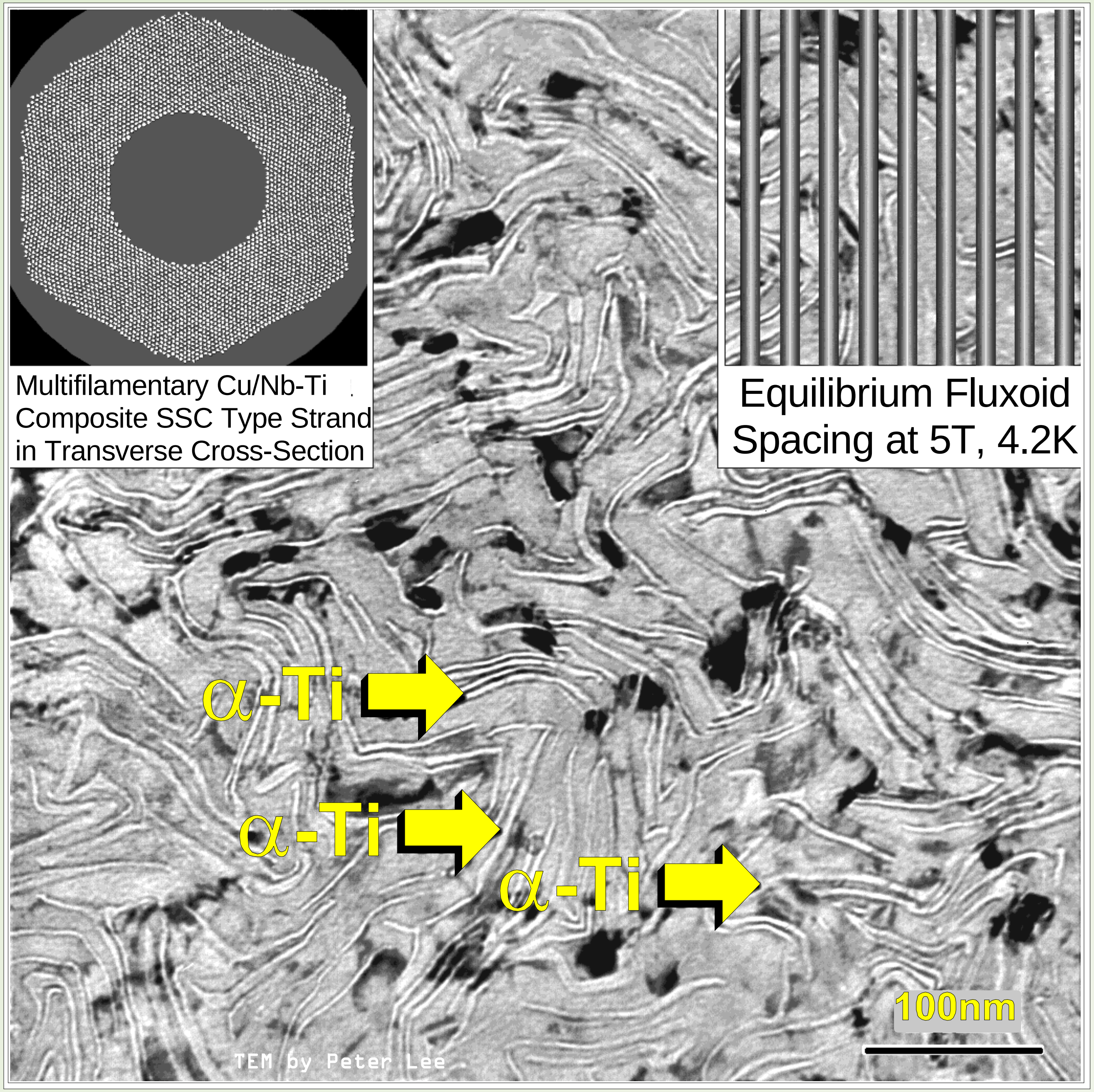
Optimized Nb-Ti strands have:

~25% α-Ti

More precipitates than fluxons (full summation)

Very strong flux pinning 5-10% J_d

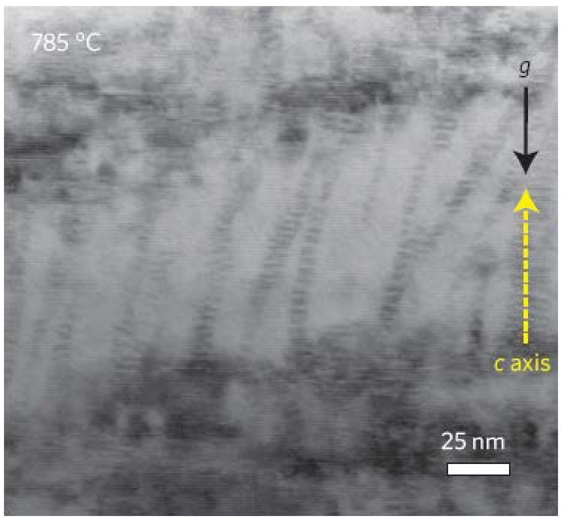
Laminar, proximity-coupled N pins become S'

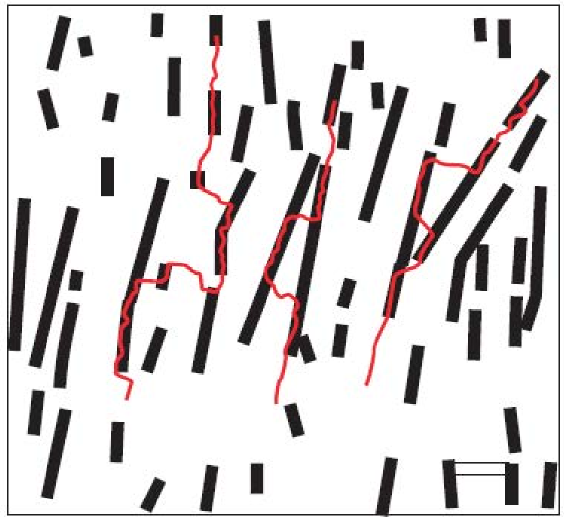


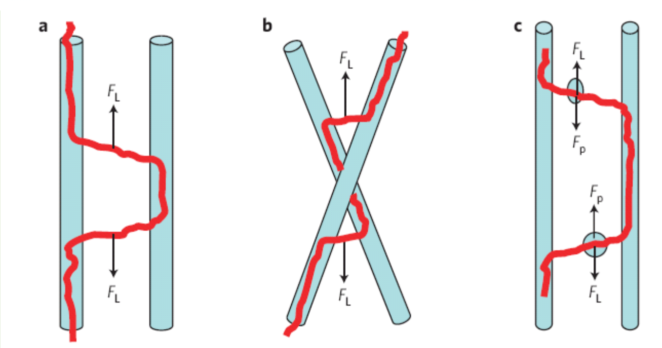
Designer nanoparticle structures in YBCO

J.L. McManus-Driscoll, Nature Materials 3, 439 (2004) (BZO); S.A. Harrington et al, SUST 22, 022001 (2009)
T. Haugan et at, Nature 430, 867 (2004) (Y_2BaCuO_x nanoparticles in PLD YBCO films)
Y. Yamada et al, APL 87, 132502 (2005); K. Matsumoto et al, JJAP, 44, L246 (2005).
J. Gutierrez et al, Nature Materials, 6 367 (2007); X. Obradors et al, SUST 19, S1 (2006)
S. Solovyev et al, SUST, 20, L20 (2007).
M.W. Rupich et al, MRS Bull., 29, 572 (2004)

Combination of nanoparticles and columnar pins



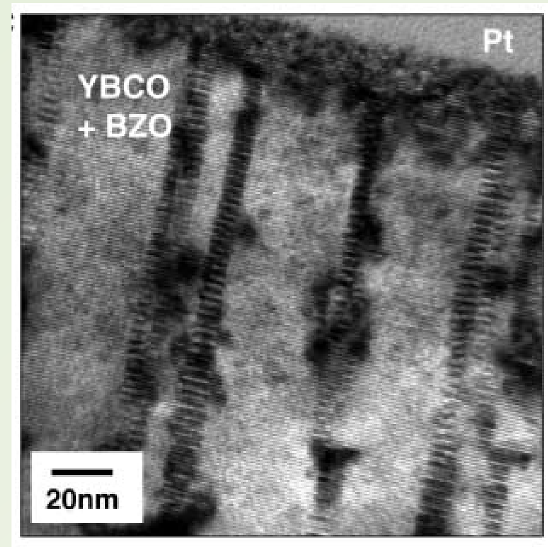




B. Maiorov et al,
Nature Materials 8, 398 (2009)

Self assembles BZO nanpparticles

S. Kang et al, Science 311, 19111 (2006)

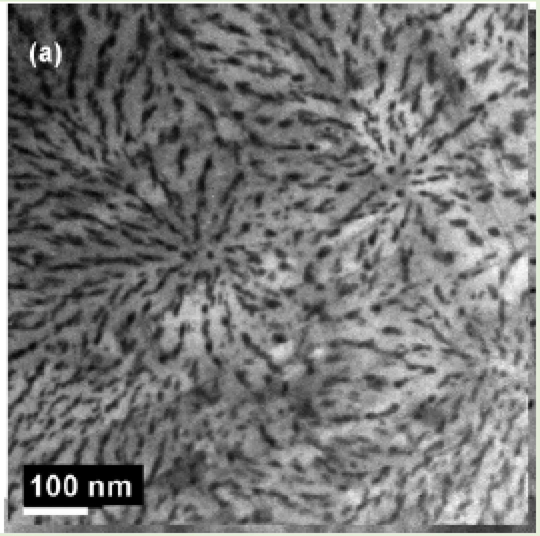


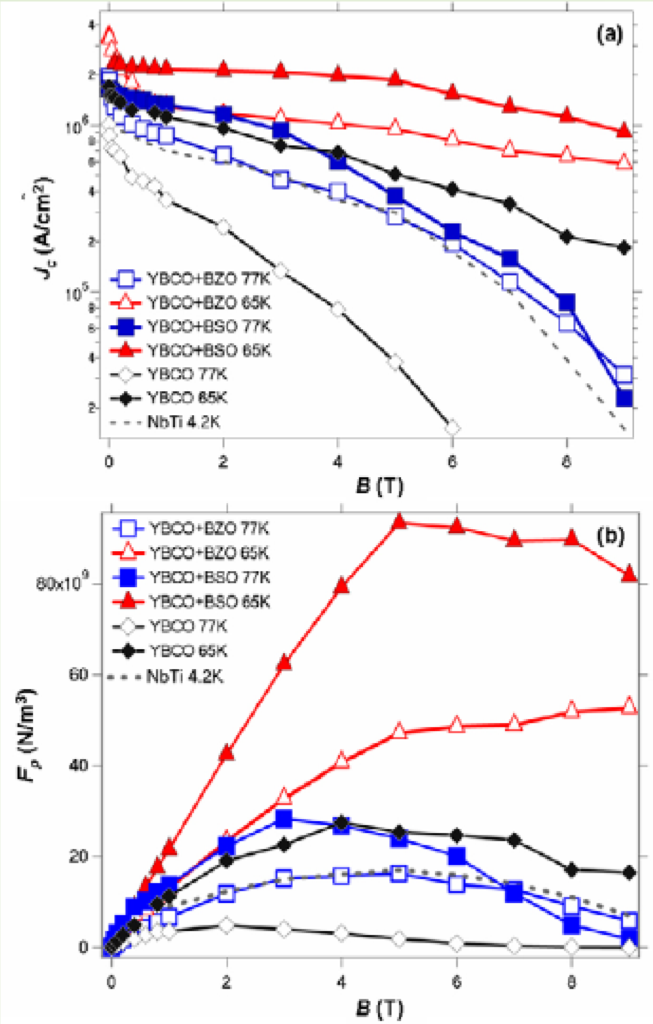
- weaker flux creep at high fields
- weaker field dependence (reduced α in $J_c \propto H^{-\alpha}$)

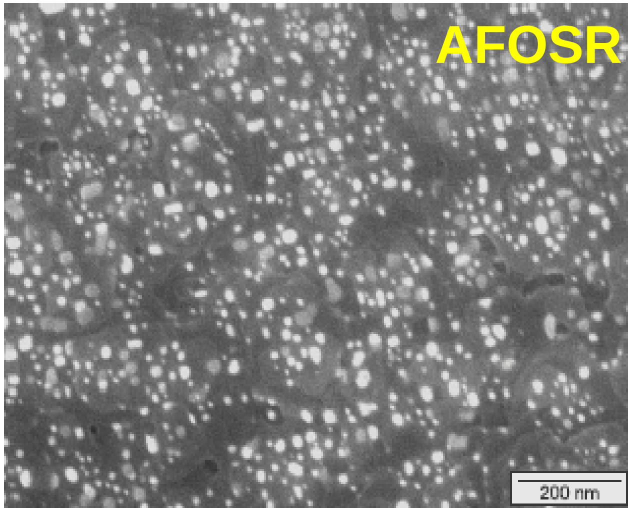
Enhancement of Jc by "designer" nanoparticle structures

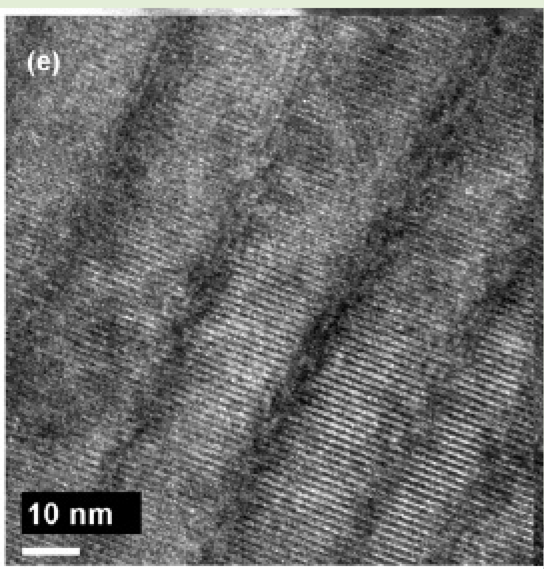
Self-assembled chains of BZO nanoparticles

8 nm YBa_2CuO_5 nanoparticles

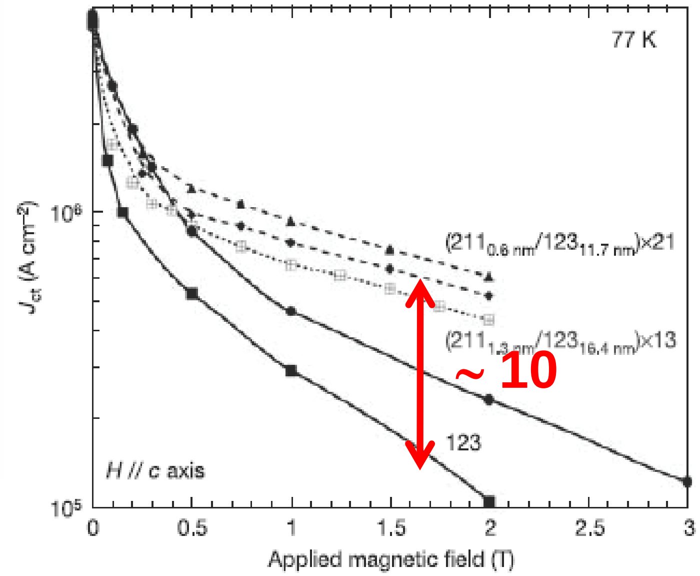








P. Mele, K. Matsumoto, T. Horide, A. Ichinose, M. Mukaida, Y. Yoshida, S. Horii, R. Kita
SUST 21, 032002 (2008)

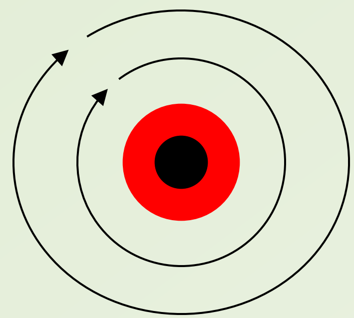


T. Haugan, et al. Nature 430, 867 (2004)

Strong pinning basics

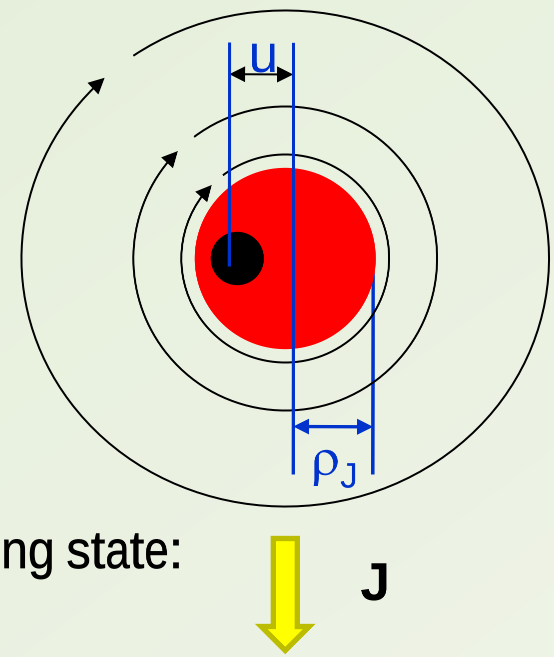
- Pins chop vortices into short, weakly coupled segments Labusch (1967); T. Hylton and M. Beasley (1990). Low-field J_c comparable (20-30%) to the depairing current density circulating near the vortex core (J_c ~ 10 MA/cm^2 and J_d ~ 40 MA/cm^2 YBCO at 77K)

$$J_d = \frac{c\phi_0}{12\sqrt{3}\pi^2\lambda_a^2\xi_a}$$



J=0 vortex core appears at

$J(\rho_0) = c\phi_0/8\pi^2\lambda^2\rho_0 \sim J_d$



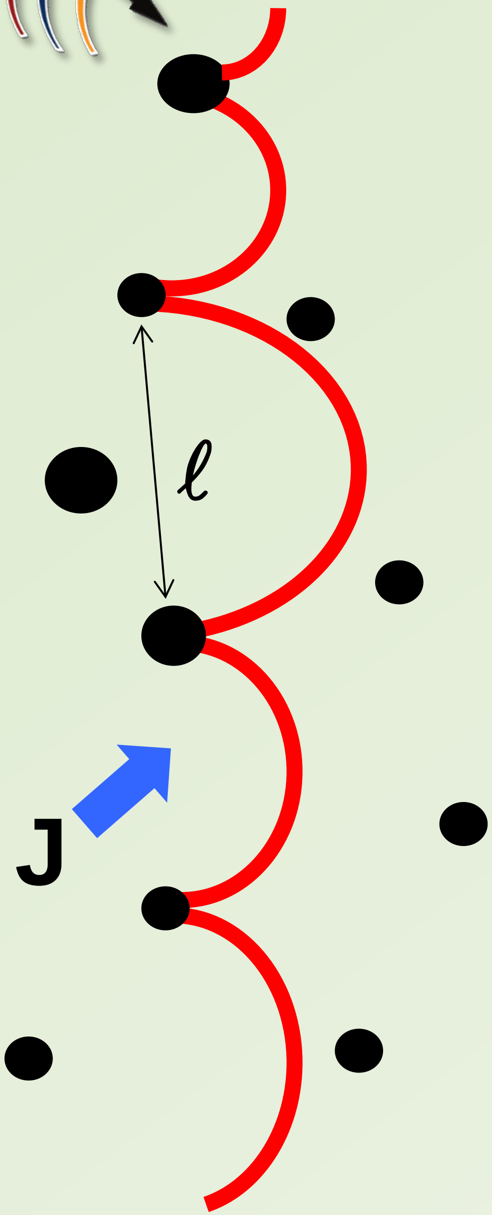
The core radius ρ_J and displacement u in the current carrying state:

$[J_x(x,y) + J]^2 + J_y^2(x,y) \sim J_d^2$

$$\rho_0 \cong \xi, \qquad \rho_J \cong \frac{\rho_0 J_d^2}{J_d^2 - J^2}, \qquad u \cong \frac{\rho_0 J J_d}{J_d^2 - J^2}$$

- Depinning: $u \sim \rho_J$, $J \sim J_d r_0/\rho_0$

Strong 3D pinning by insulating nanoprecipitates



- Elliptic critical vortex loops: **$L_{||}L_{\perp} = \ell^2$, $L_{||} = \Gamma L_{\perp}$**

- Analog of the Frank-Reed dislocation source with the effective
  loop width $L_{\perp} \sim \ell\Gamma^{-1/2}$, **$\varepsilon/R = \phi_0 J/c$**

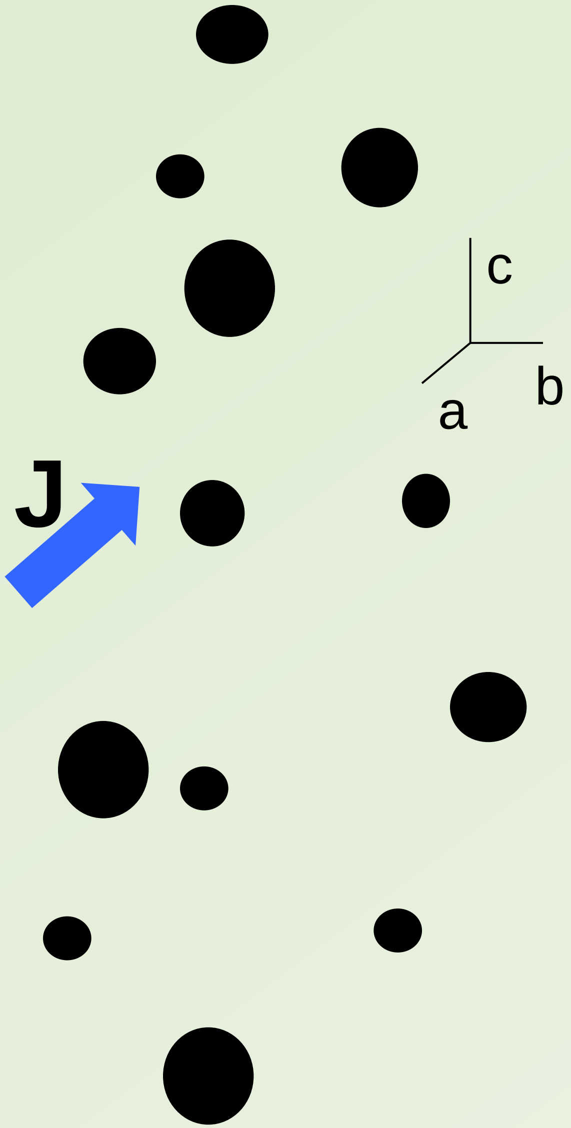
- Depinning due to reconnection of parallel vortex segments: the
  smaller the pin spacing the higher J_c:

$$J_c \cong \frac{c\phi_0}{8\pi^2\lambda^2\Gamma^{1/2}\ell}\ln\frac{\ell}{\xi_c}$$

- To get J_c(77K) ~ 9 MA/cm^2 in YBCO, an average pin spacing
  should be $\ell \sim 30$ nm

- Too many pins result in T_c suppression and current blocking

Too many pins block the Current-carrying cross section



- Effective medium theory for an anisotropic matrix with dielectric precipitates of volume fraction x

$$\rho = \rho_0 \frac{A}{A_{eff}}, \qquad A_{eff} = \left(1 - \frac{x}{x_c}\right) A$$

- The current-carrying cross section $A_{eff}(x)$ vanishes at the percolation threshold x_c
- $x_c = 0.5$ in 2D
- x_c □2/3 in isotropic 3D

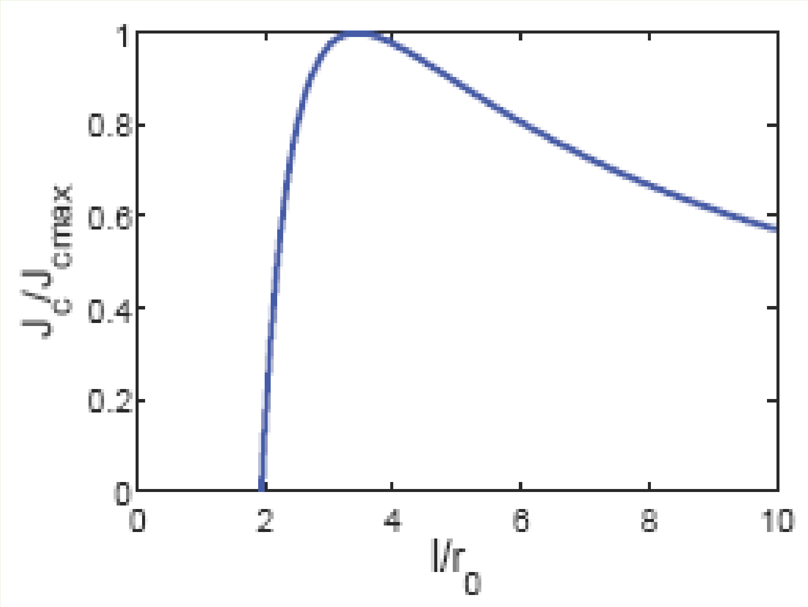
Optimum pin density: pinning vs. current blocking (Gurevich)

- J_c due to random insulating precipitates of radius r_0 spaced by ℓ

$$J_c(l) \cong J_0 \frac{\xi}{\ell} \ln\frac{\ell}{\xi_c}\left(1 - \frac{4\pi r_0^3}{3x_c\ell^3}\right)$$

Pinning

Cross-section



- Optimum pin spacing and volume fraction:

$$\ell_m \approx 3-4r_0, \qquad x_m = \frac{4\pi r_0^3}{3\ell_m^3} \approx 8-12\%$$

- Optimum critical current density:

$$\frac{J_{c\max}}{J_d} \approx \frac{9\sqrt{3}\xi_a}{8\Gamma^{1/2}\ell_m} \ln\frac{\ell_m}{\xi_c}$$

For $\Gamma = 7$, $J_{cmax} \approx 0.5J_d$ for $r_0 = \xi$, and $J_{cmax} \approx 0.25J_d$ for $r_0 = 3\xi$

Upper limit for small pins, no fluctuatio
and no proximity effect T_c suppression

Bean Model

- Bean (1962) and London (1963) introduced the concept of the critical state in which the bulk currents of a type II superconductor flow either at $+J_c$, $-J_c$ or zero.

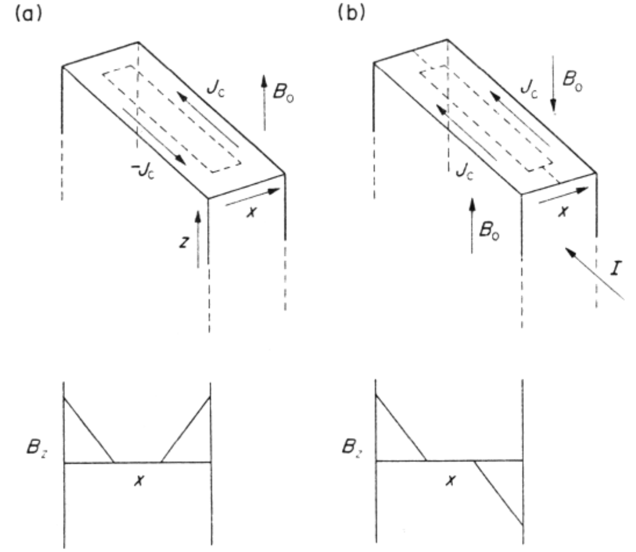


Figure 1
Schematic of the flux profile and current flow for (a) a slab in an applied field B_0 and (b) a sample with similar dimensions carrying a total current I sufficient to generate a field B_0 at the surface of the sample

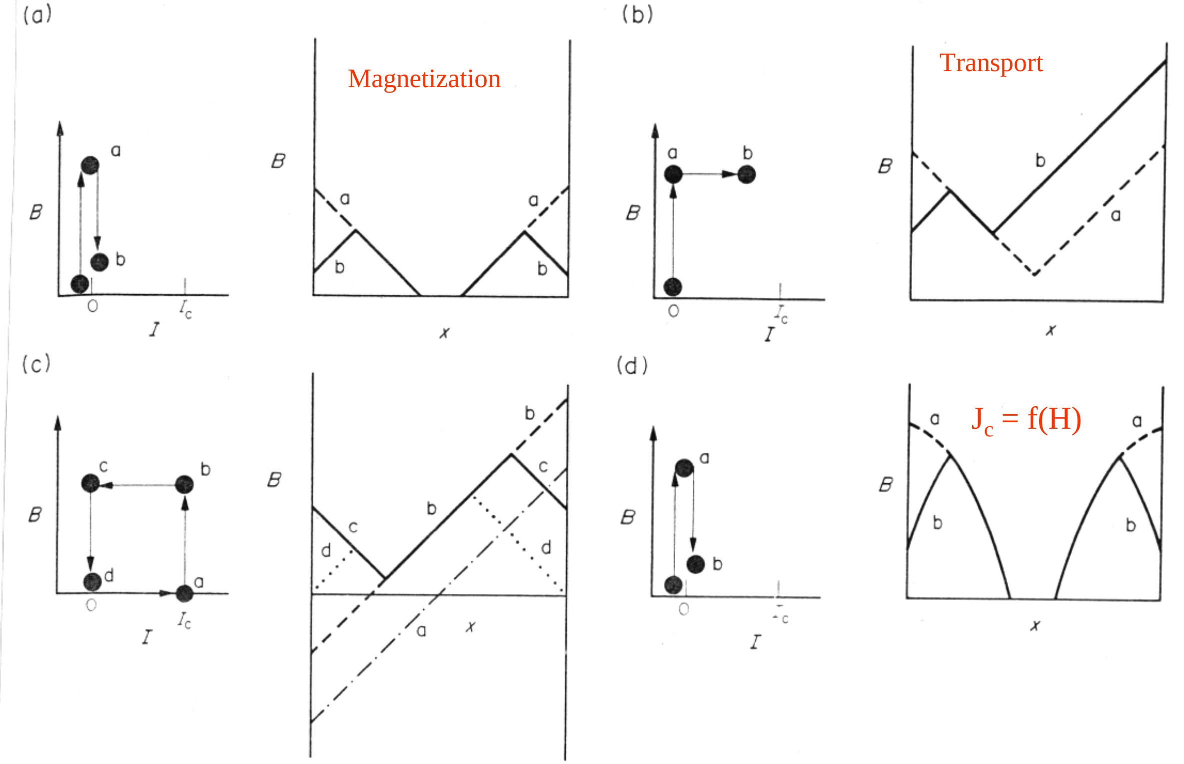


Figure 2
Schematic of the critical state flux profile; the different current–applied field trajectories are indicated in the IB diagrams: (a–c) Bean model with J_c constant; (d) as (a) but $J_c(B)$ decreasing strongly with increasing B

Superconducting Materials, Ed J. Evetts Pergamon 1991

Magnetization and the Bean Model

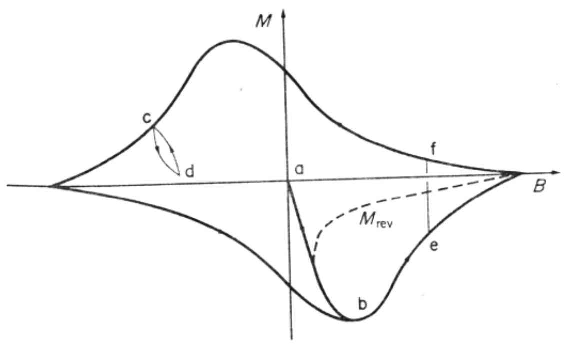
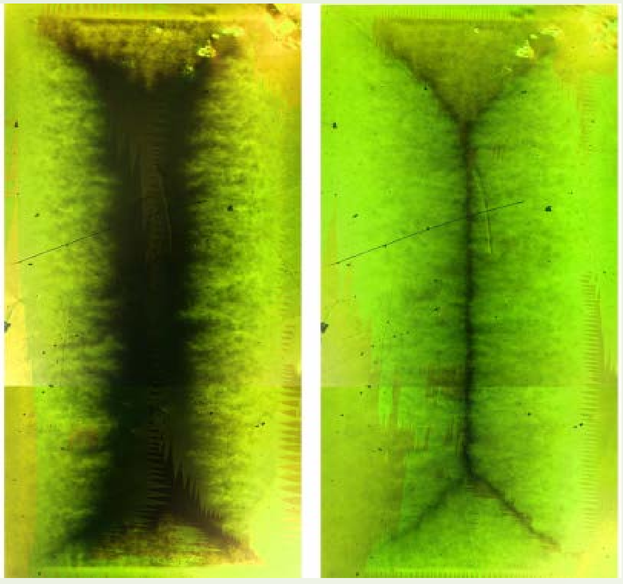


Figure 4
A typical hysteretic magnetization loop including the reversible magnetization M_{rev}. The figure also indicates the initial curve from zero induction (ab), a minor loop excursion typically experienced by a superconductor under low amplitude ac conditions (cdc) and a pair of magnetization values used to extract $J_c(B)$ information as described in the text (ef)

Table 1
The magnetization for a full critical state established in the samples indicated for different applied field directions

Sample shape and field orientation	M (A m^{-1})
Cylinder diameter $2a$	
$B \parallel$ axis	$J_c a/3$
$B \perp$ axis	$4 J_c a/3\pi$
Infinite slab, thickness d	
$B \parallel$ face	$J_c d/2$
Square section bar ($d \times d$)	
$B \parallel$ axis	$J_c d/6$
$B \perp$ face	$J_c d/4$
Sphere radius a	$3\pi J_c a/32$
Disk, $2a$, thickness d	
$B \perp$ face	$J_c a/3$
Rectangular section bar ($b \times d$ with $b > d$) $B \parallel$ axis	$\frac{3b-d}{12b} J_c d$

- $m = MV = 0.5 \int (r \times j)\, dV$
  - where $j = (1/\mu_0)\nabla \times B$ or $m = MV = \sum I_i \times S_i$
- Slab geometry is very simple
  - $dB/dx = \pm J_c(B)$



Magneto optical image of current flow pattern in a BSCCO tape. The "roof" pattern defines the lines along which the current turns.

Summary of Vortex Pinning Issues

- Enormous J_c can be obtained in some systems
  - ~10% of depairing current density (~H_c/λ) in Nb-Ti and for many HTS at low temperatures
  - HTS suffer from thermal activation and lack of knowledge about what are the pins
- Practical materials want full summation to get maximum J_c
- To compute F_p a priori in arbitrary limit is so far beyond us
- Useful materials tend to be made first and optimized slowly as control of nanostructure at scale of 0.5-2 nm is not trivial

What about 2D defects that might block current – e.g. grain boundaries?

- The big problem of HTS materials is that their GBs may block current
- Classic behavior seen for simple [001] tilt GBs in YBCO

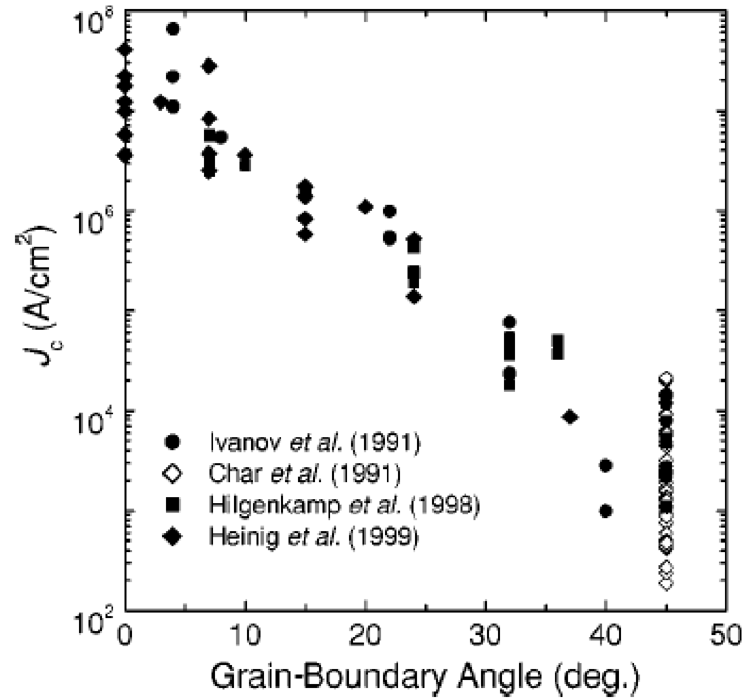
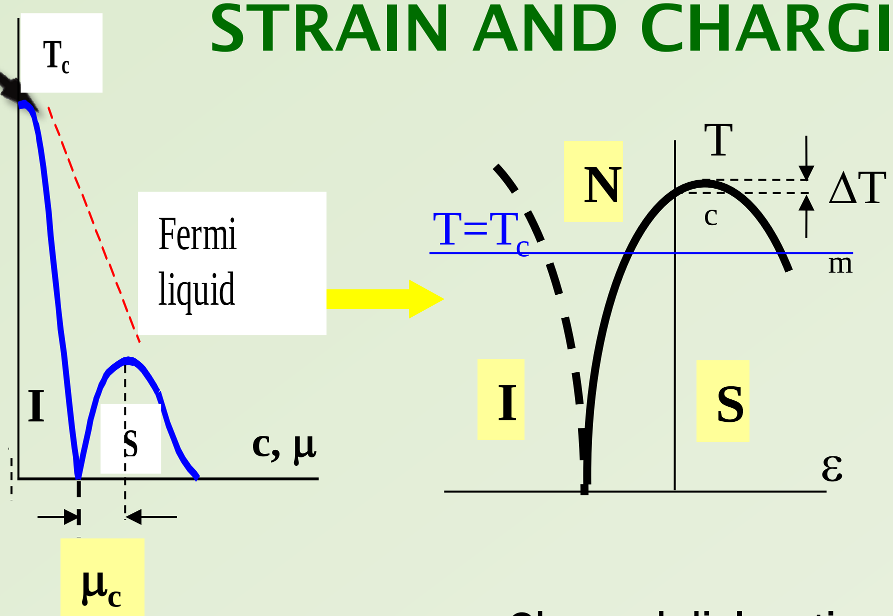


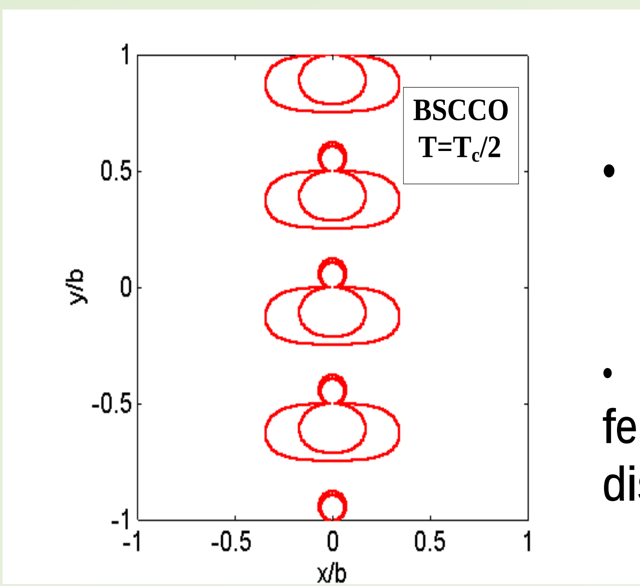
FIG. 30. Critical current densities of [001]-tilt grain boundaries in $YBa_2Cu_3O_{7-\delta}$ films as a function of tilt angle. The data, compiled from the literature as indicated, were measured at 4.2 K, except for those of Ivanov *et al.* (1991). As the latter were measured at 77 K, these current densities were multiplied by a factor of 10.9, which was obtained from the temperature dependence of I_c (see Fig. 36). The data of Char *et al.* were measured with biepitaxial junctions, the others with bicrystalline junctions.

STRAIN AND CHARGING EFFECTS AT GB



Strain-induced dielectric and normal regions near dislocation cores

$$T_c = T_{c0} - C_a\varepsilon_a - C_b\varepsilon_b - R_{iklm}\varepsilon_{ik}\varepsilon_{lm}$$



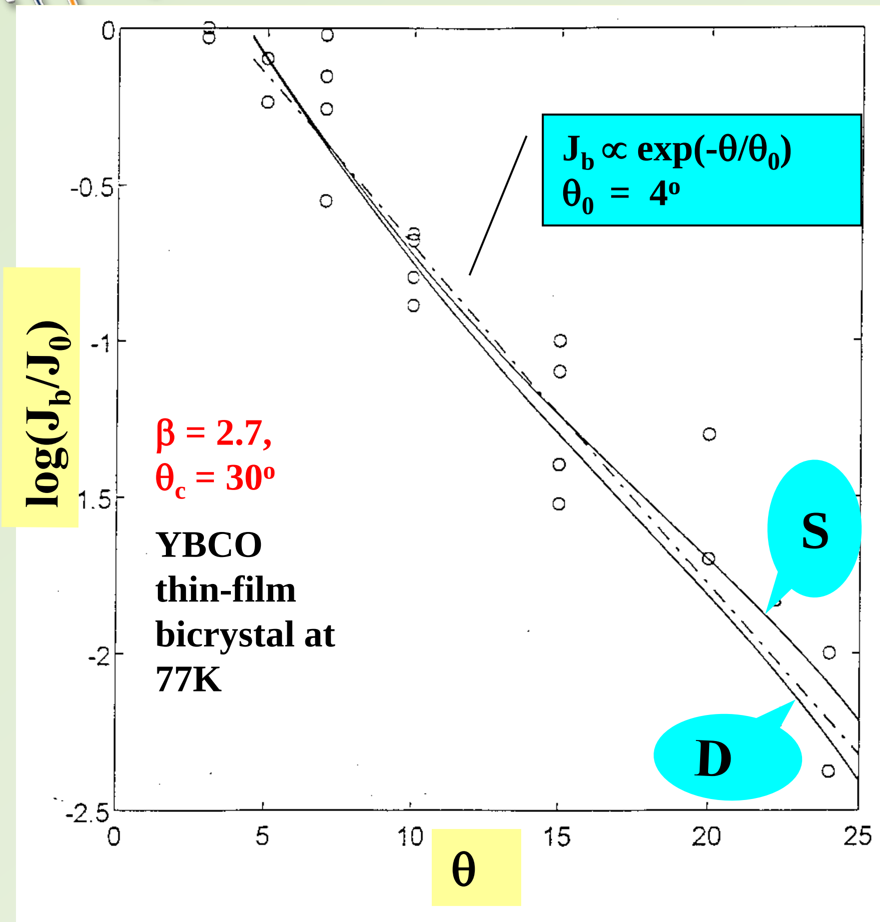
- Charged dislocation cores (broken bonds, variable valence, and lattice anharmonicity). Lattice expansion near GB:

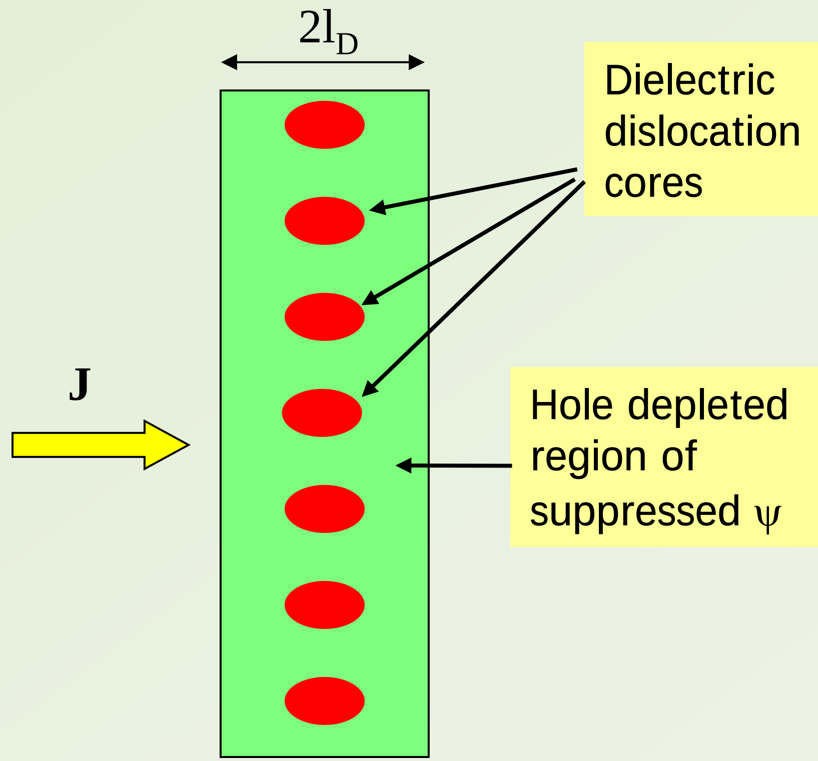
- "Transistor model" of the zone bending near GB
  J. Mannhart and H. Hilgenkamp, APL 73, 265 (1998)
  A Gurevich and E.A. Pashitskii, PRB 57, 13875 (1998);

- Shift of superconducting state at GB towards an anti-ferromagnetic state induced by charge imbalance and GB dislocation strains

- Suppression of order parameter ψ in dislocation channels.

Microscopic calculation of Jc(θ)





Experiment: N.F. Heinig et al., APL 69, 577 (1996), PRB (1997)

Theory: A Gurevich and E.A. Pashitskii, PRB 57, 13875 (1998);

Summary of GB problem

- Widely recognized as limiting application of all HTS materials
  - High texture believed essential to all cuprate conductors
  - Tapes of Bi-2223 and YBCO are the only conductor form.
- Contaminated GBs (typically amorphous B or MgO) obstruct some GBs
- Some Nb GBs may become degraded by strong polishing procedures

Outlook for new accelerator materials

- All accelerators so far have been built from Nb-Ti
  - Hi-lumi upgrade requires Nb3Sn
  - High energy LHC would require HTS in addition
- Anisotropic superconductors pose challenges
  - Especially because GBs may be blocking
- Are there new possibilities?
  - Recent talk to EMA January 2013

A Round Wire Multifilament HTS conductor for High Field Magnet Use : what stands in the way?

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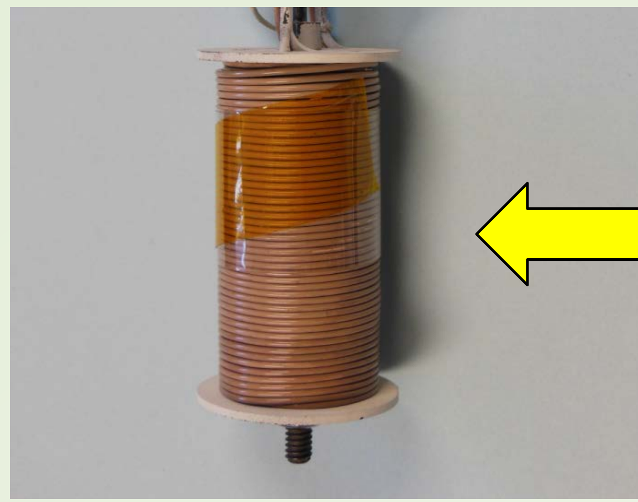
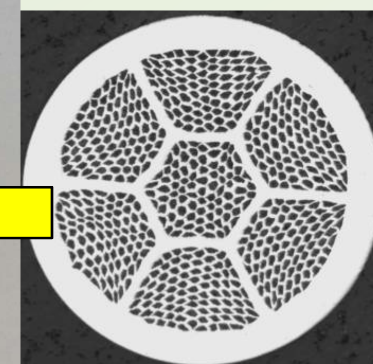
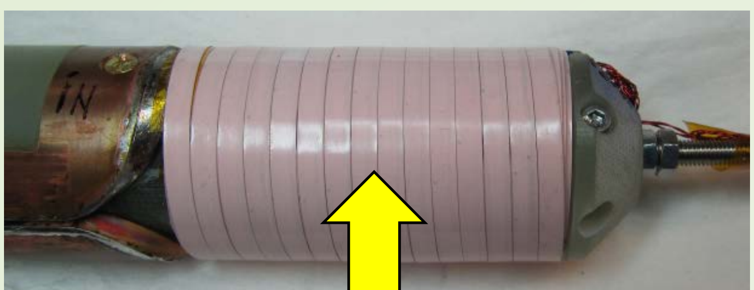
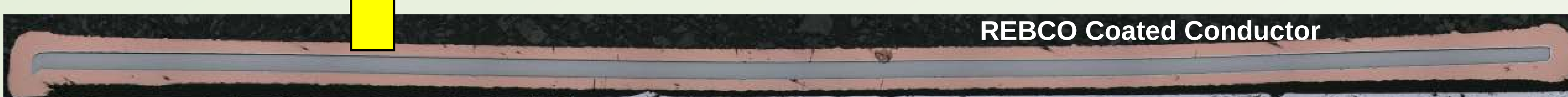




34T (in 31T) – Bi-2212

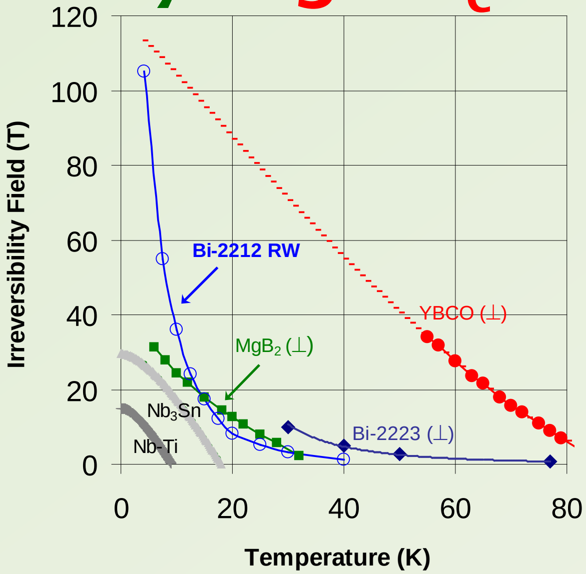


35T (in 31T) – REBCO coated conductor

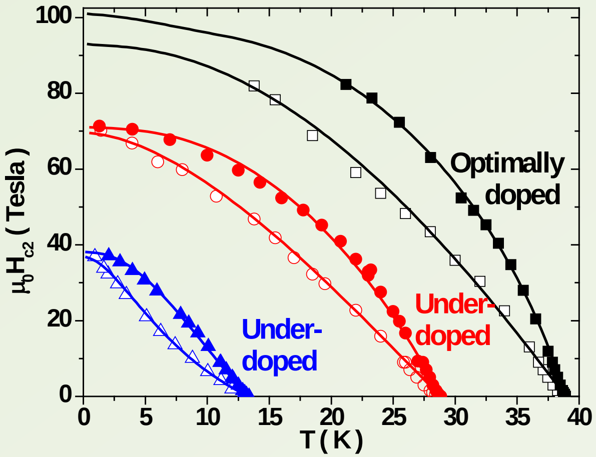


Applications are determined by high J_c, J_e and H_{irr} rather than by high T_c

- What constitutes a useful superconductor?
  - High $H_{irr}(T)$ defines where $J_c > 0$
  - J_c must be $>10^5$, better $>10^6$ A/cm^2 at field
    - Strong vortex pinning AND
    - Transparent GBs that do NOT block supercurrent
- Nb47Ti and Nb_3Sn still control the market
- HTS has been banging on the door for 20 years
  - Bi-2223, recently YBCO, most recently Bi-2212
  - Pnictides are intriguing too
    - ~100 T H_{c2} and almost no anisotropy in K-doped Ba122 (Tarantini et al. PRB 84,184522 (2011))

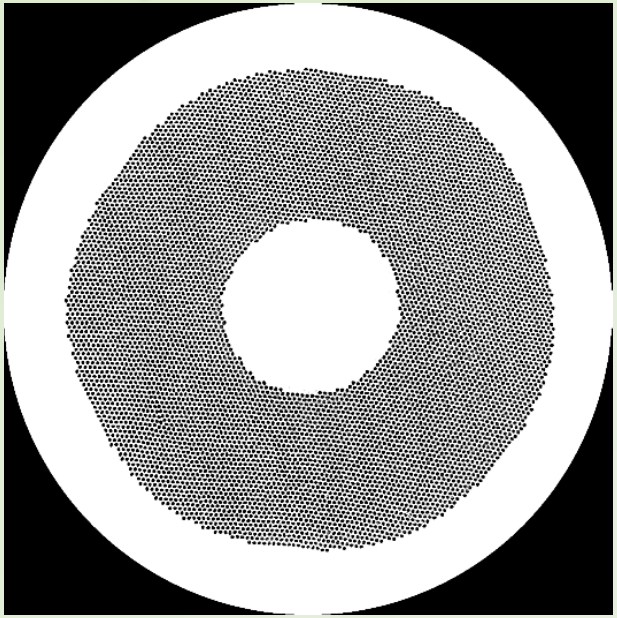


Cuprates vs. LTS

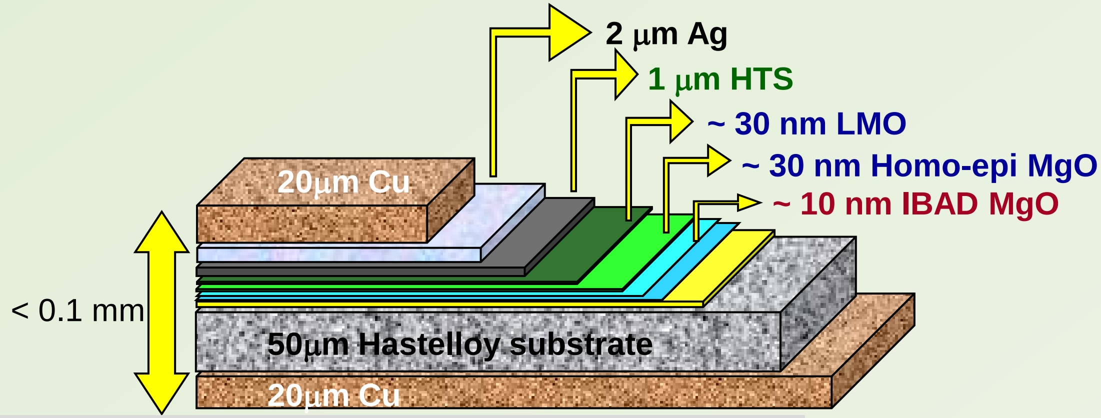


H_{irr} and H_{c2} for K-Ba122

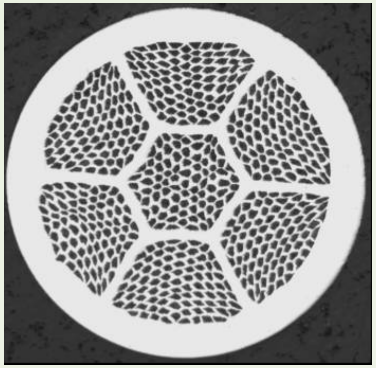
Magnet Conductors so far….



1. Nb47Ti conductor- thousands of 8 μm diameter Nb47Ti filaments in pure Cu (0.8 mm dia.), easily cabled to operate at 10-100 kA



3. REBCO coated conductor – extreme texture (single crystal by the mile) – for maximum GB transparency

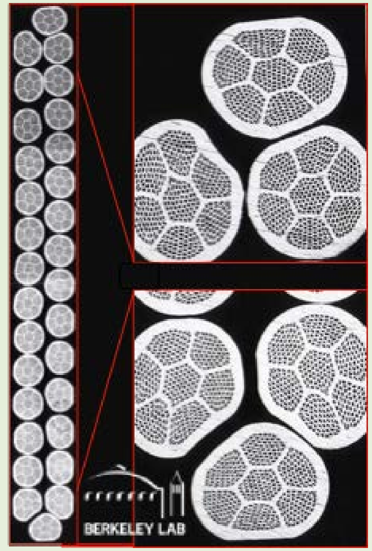


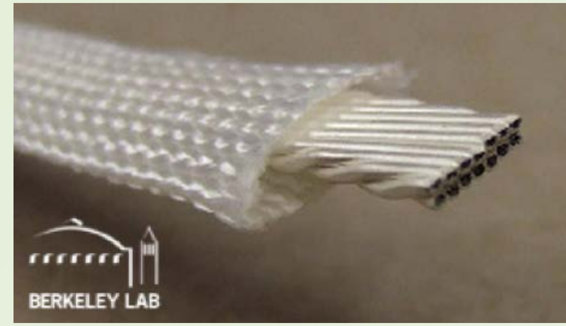
4. Bi-2212 – high J_c without macroscopic texture!

2. Bi-2223 – the first HTS conductor – uniaxial texture developed by deformation and reaction

Large magnets are better protected when operated at high currents – cables!

- Easy path to 2212 cables through the standard Rutherford cable
- REBCO cables are harder (**Coated Conductor is a single filament**) – but possible (IRL, KIT, CORC, twisted stack (MIT)
- Cables vital for 60 T hybrid at the NHMFL, an LHC energy upgrade and a neutrino machine based on a Muon Collider at Fermilab





Bi-2212 Rutherford cables (Arno Godeke LBNL) with mullite insulation sleeve

REBCO coated conductor cable wound in many layers helically on a round form

Other variants too: e.g. Roebel cable

The path to HTS cuprate conductors and applications…………

- Avoid grain boundaries (GBs)
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- Avoid grain boundaries (GBs)
  - Based largely on the original IBM bicrystal experiments……….

Planar GBs all seem to show the exponential fall off of $J_c(\theta)$

- But are all GBs the same?
  - θ_c is only 3º for epitaxial, planar YBCO
- What happens in real coated conductors?
  - In situ (straight GBs) like PLD or MOCVD?
  - Ex situ (meandered GBs) like MOD?

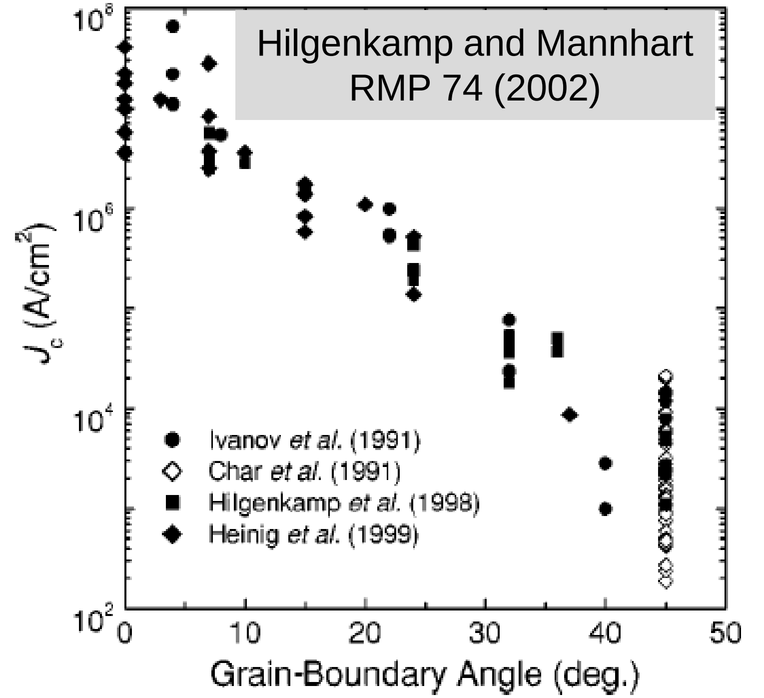
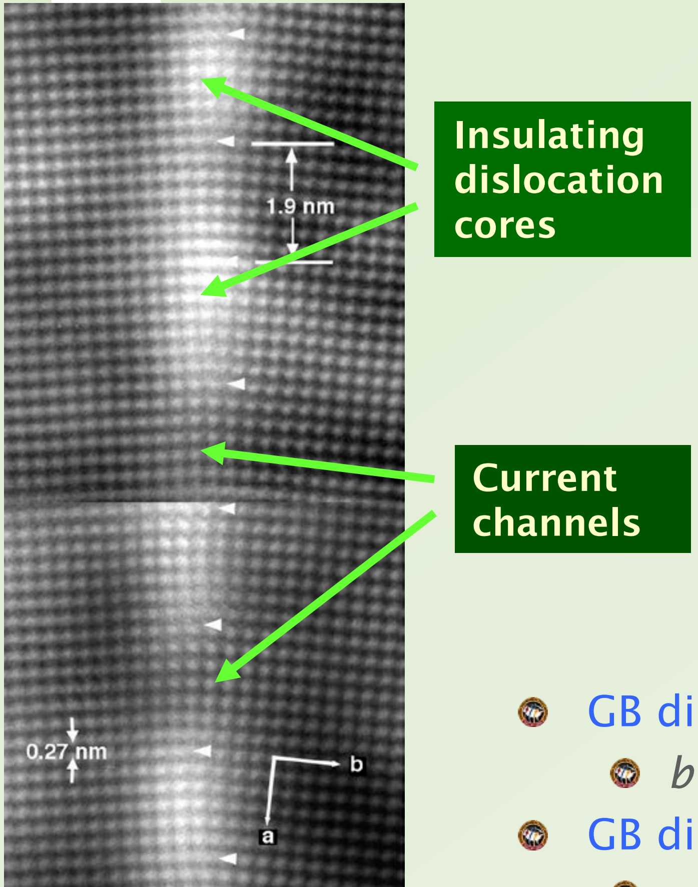
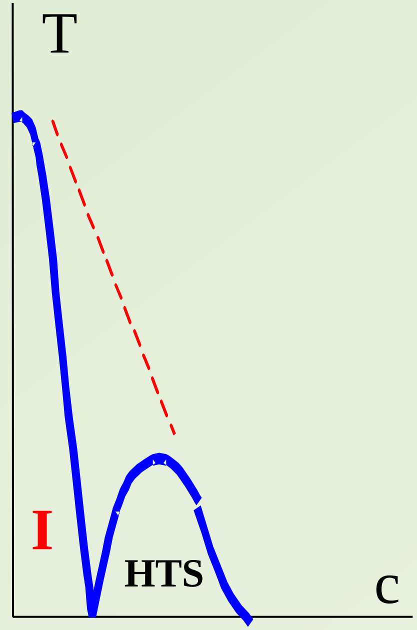


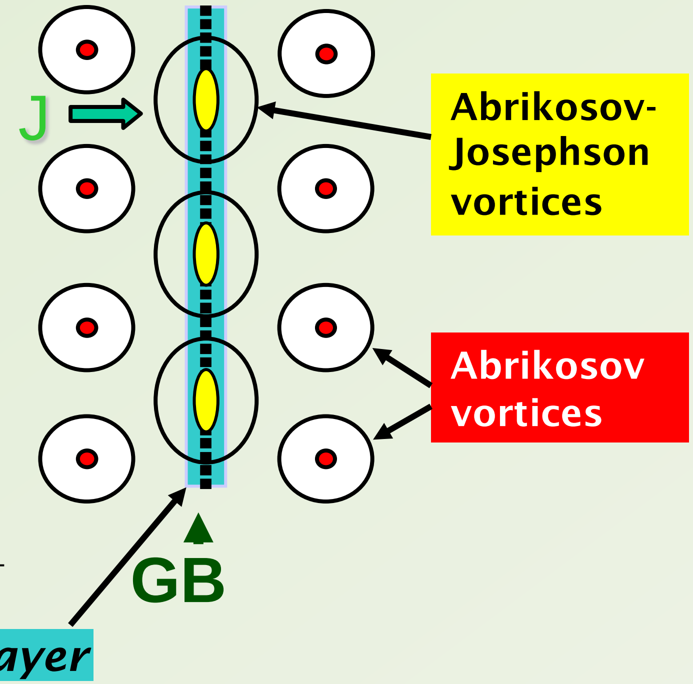
FIG. 30. Critical current densities of [001]-tilt grain boundaries in $YBa_2Cu_3O_{7-\delta}$ films as a function of tilt angle. The data, compiled from the literature as indicated, were measured at 4.2 K, except for those of Ivanov *et al.* (1991). As the latter were measured at 77 K, these current densities were multiplied by a factor of 10.9, which was obtained from the temperature dependence of I_c (see Fig. 36). The data of Char *et al.* were measured with biepitaxial junctions, the others with bicrystalline junctions.

Vortices in planar Low-Angle GB



HRTEM image of 8°[001] tilt GB in $Bi_2Sr_2CaCu_2O_x$



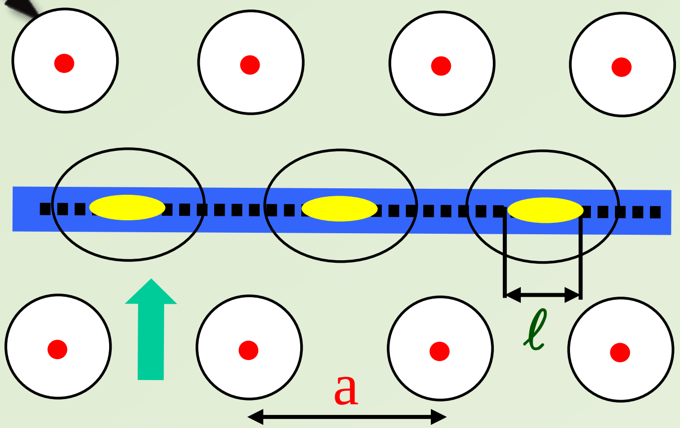


- GB dislocations enable the misorientation
  - *but produce **strains** which destroy superconductivity*
- GB dislocations cause **charge imbalance**, thus
  - *suppress the superconducting gap in the current channels*

A Gurevich and E.A. Pashitskii, PRB 57, 13875 (1998)
J. Mannhart and H. Hilgenkamp, APL 73, 265 (1998)

Planar GBs can be (marginally) improved by increasing the GB hole density….

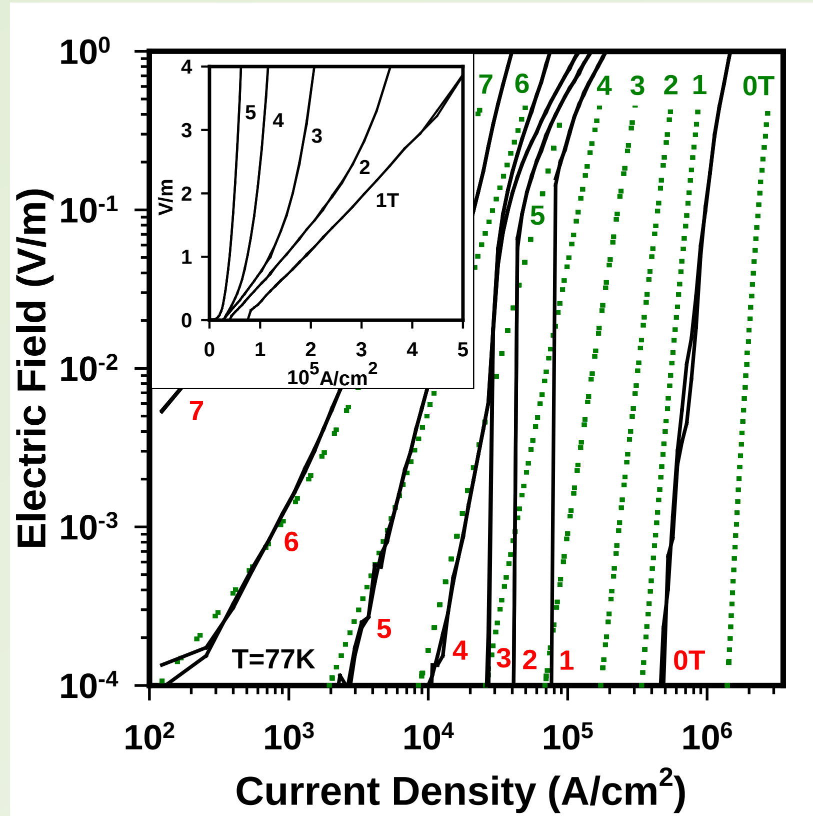
Single vortex-row motion along planar YBCO GB



- Josephson core size $\ell = \lambda_J^2/\lambda = \xi J_d/J_b$
- The Josephson cores overlap if $\ell > a$
  (Gurevich, PRB48, 12857 (1993); PRB46, R3187 (1992)):

$$H > (J_b/J_d)^2 H_{c2}$$

- Viscous flux motion $V = (I - I_b)R$
- R(B) is independent of B, if a single vortex chain moves along GB, while $\ell > a$

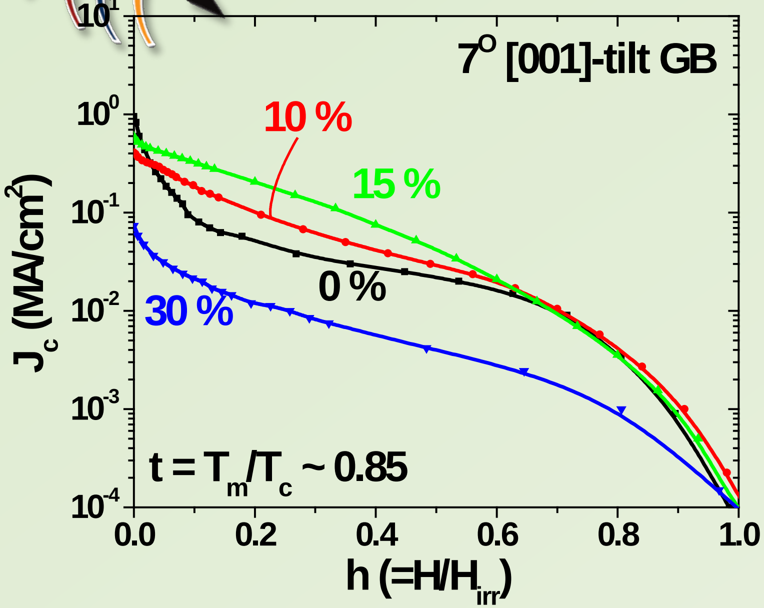


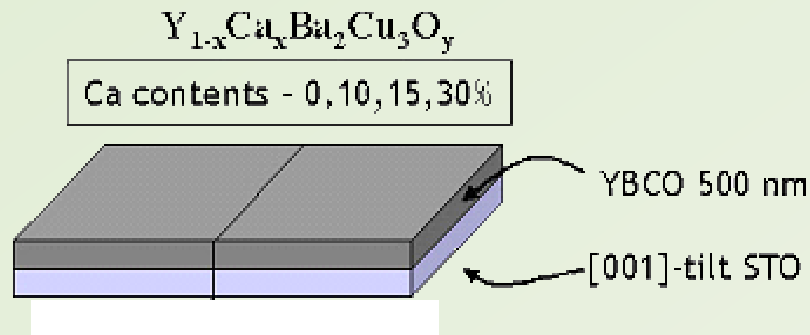
Collective depinning of multiple vortex rows along GB:

$$R(B) = w(B)\rho_n B/B_{c2}$$

Gurevich et al. PRL 88, 097001 (2002)

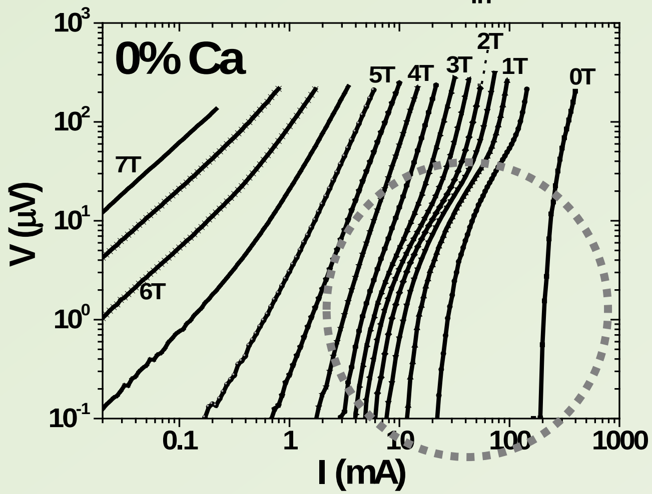
Varying Ca content for a 7° [001]-tilt $Y_{1-x}Ca_xBa_2Cu_3O_{7-\delta}$ improves J_c(GB) but only marginally

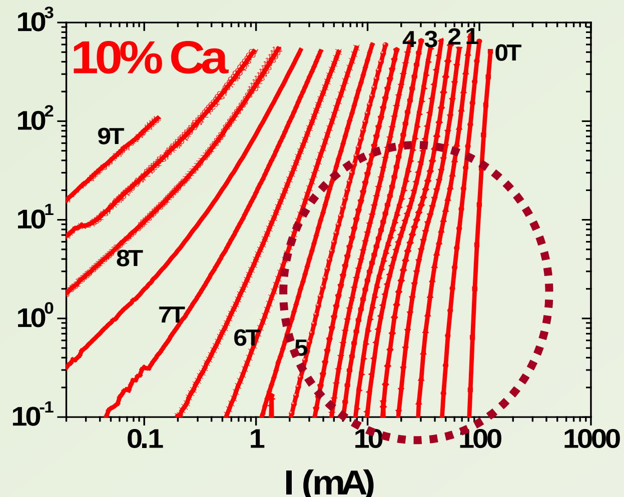


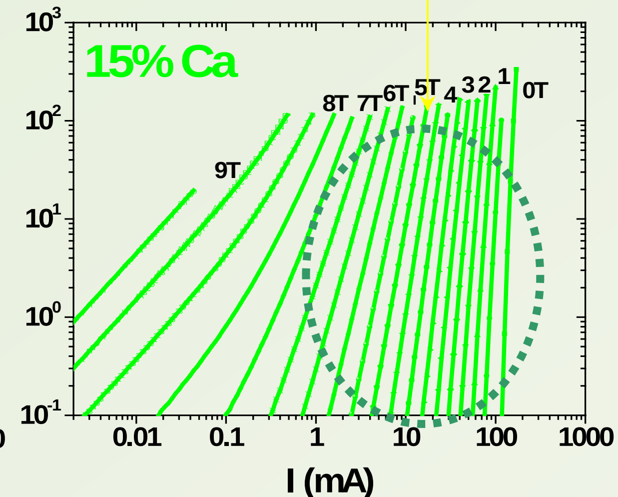


Ca%	0%	10%	15%	30%
T_c	**90.2K**	**76.6K**	**70.8K**	**65.4K**

Elimination of GB signature







Reduction of GB signature in V-I characteristics

Sang-Il Kim PhD thesis U. of Wisconsin 2007

Planar GBs of Co-doped Ba122 are very similar to YBCO

APPLIED PHYSICS LETTERS 95, 212505 (2009)

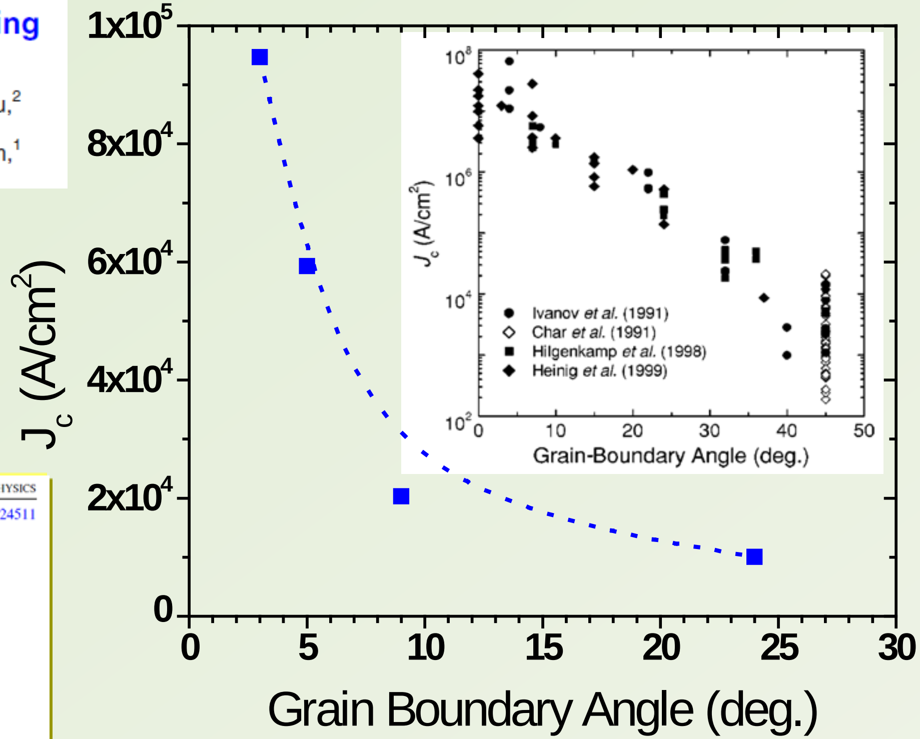
Weak-link behavior of grain boundaries in superconducting $Ba(Fe_{1-x}Co_x)_2As_2$ bicrystals

S. Lee,[1] J. Jiang,[2,a)] J. D. Weiss,[2] C. M. Folkman,[1] C. W. Bark,[1] C. Tarantini,[2] A. Xu,[2] D. Abraimov,[2] A. Polyanskii,[2] C. T. Nelson,[3] Y. Zhang,[3] S. H. Baek,[1] H. W. Jang,[1] A. Yamamoto,[2] F. Kametani,[2] X. Q. Pan,[3] E. E. Hellstrom,[2] A. Gurevich,[2] C. B. Eom,[1] and D. C. Larbalestier[2]

IOP Publishing — Reports on Progress in Physics
Rep. Prog. Phys. 74 (2011) 124511 (23pp) doi:10.1088/0034-4885/74/12/124511

The behavior of grain boundaries in the Fe-based superconductors

J H Durrell[1], C-B Eom[2], A Gurevich[3], E E Hellstrom[4], C Tarantini[4], A Yamamoto[5] and D C Larbalestier[4]



- **Greater opportunity has appeared recently for random polycrystals however……**
  - Weiss et al. "High intergrain critical current density in fine-grain $(Ba_{0.6}K_{0.4})Fe_2As_2$ wires and bulks, " Nature Materials 11, 682 (2012)

Planar GB summary

- A planar GB, especially with H parallel to the GB plane generates:
  - Abrikosov vortices in grains
  - Hybrid Abrikosov-Josephson vortices in the GB
    - Hybrid AJ vortices depin before the intragrain Abrikosov vortices – Jc is lowered……….
- Pnictide GBs approximate cuprate GBs
  - Not quite as large a suppression of GB superconductivity for same θ (Eom-Hellstrom-Pan-DCL) and Hosono group (Katase et al.)

What about non-planar GBs?

- YBCO coated conductors with meandered GBs have higher Jc
  - Feldmann *et al*. JMR 2006, JAP 102, 083192 (2007)
- Macroscopically untextured Bi-2212 round wire, multifilament conductors can have very high J_c
  - Shen *et al*. APL 2009
  - Kametani *et al*. SuST 2011
  - Jiang *et al*. SuST 2011
  - Malagoli *et al*. SuST 2011
  - Scheuerlein *et al*. SuST 2011
- Fine-grain (100 nm) untextured Co- and K-doped Ba122 can have high J_c
  - Weiss *et al*. Nature Materials 2012

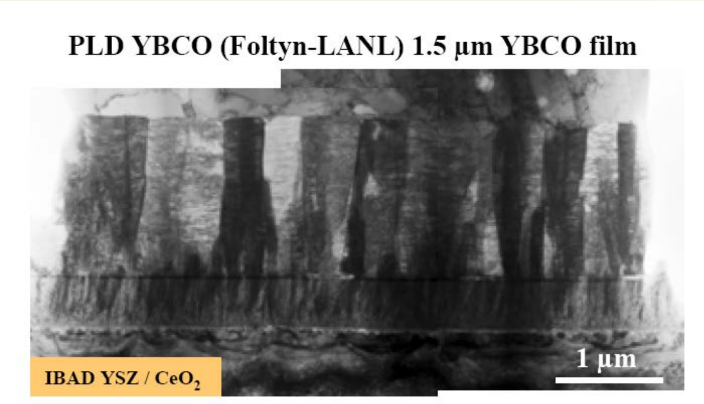
PLD (*in situ*) and MOD (*ex situ*) YBCO result in quite different YBCO GB networks

PLD - planar

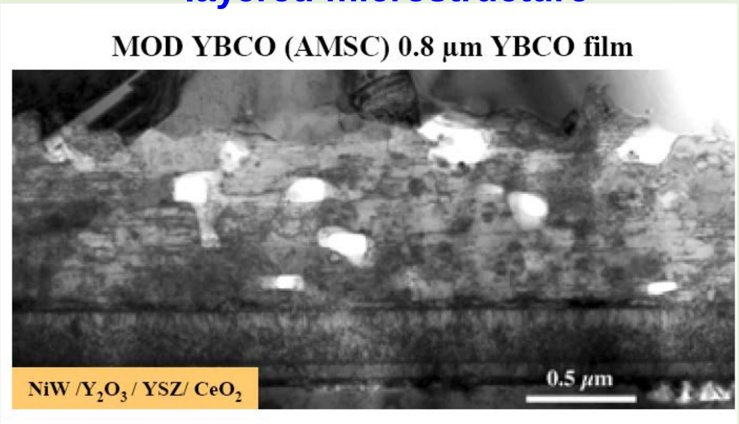
MOD - meandered

TEM, cross sections:

columnar microstructure



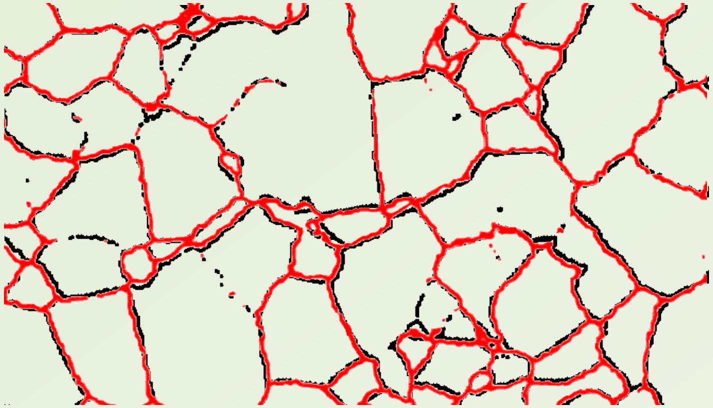
layered microstructure



EBSD, plan view:

PLD/RABiTS replicates template GBs

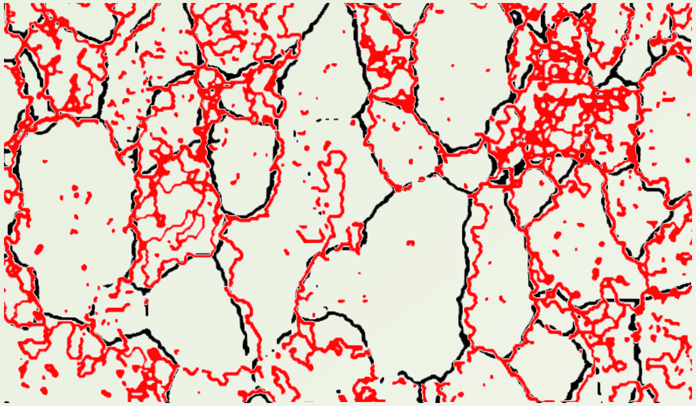
YSZ GBs + YBCO GBs



50 µm

MOD/RABiTS: meandered GBs

YSZ GBs + YBCO GBs

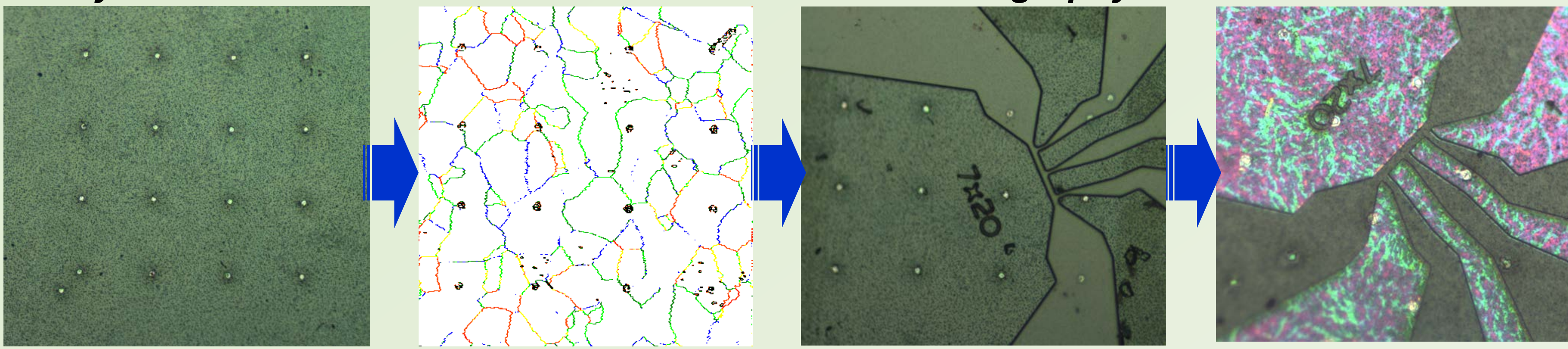


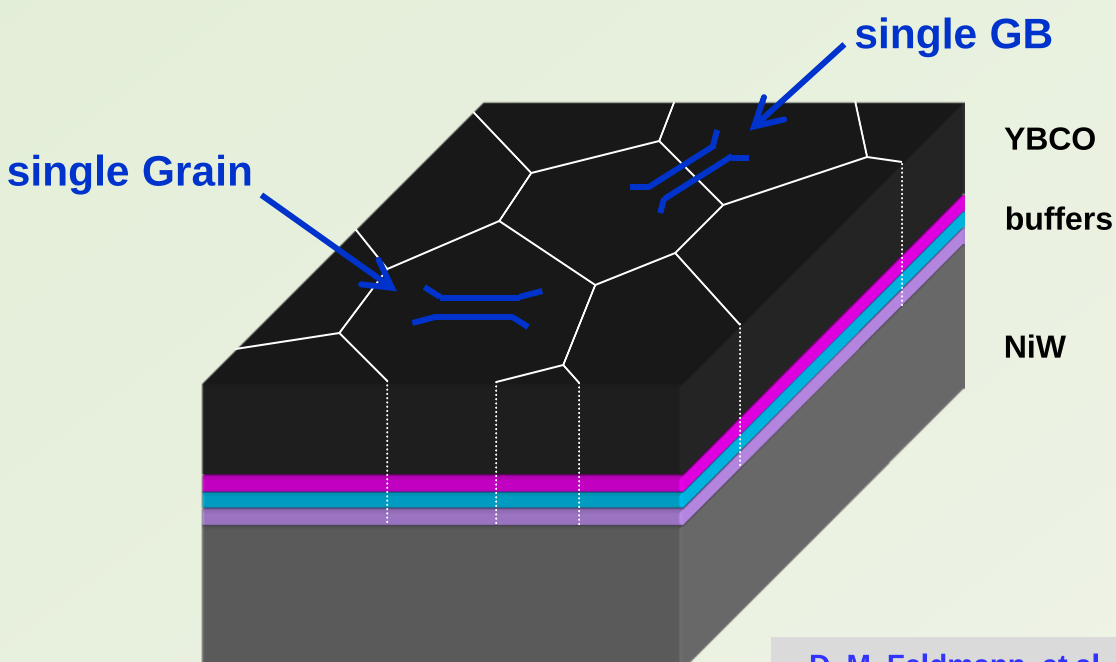
50 µm

D. M. Feldmann et al. JMR 21, 923 (2006)

Single grains/GBs in RABiTS identified with EBSD and isolated with photolithography

Array of laser cuts ***EBSD*** ***Photolithography*** ***Isolated Grain/GB***

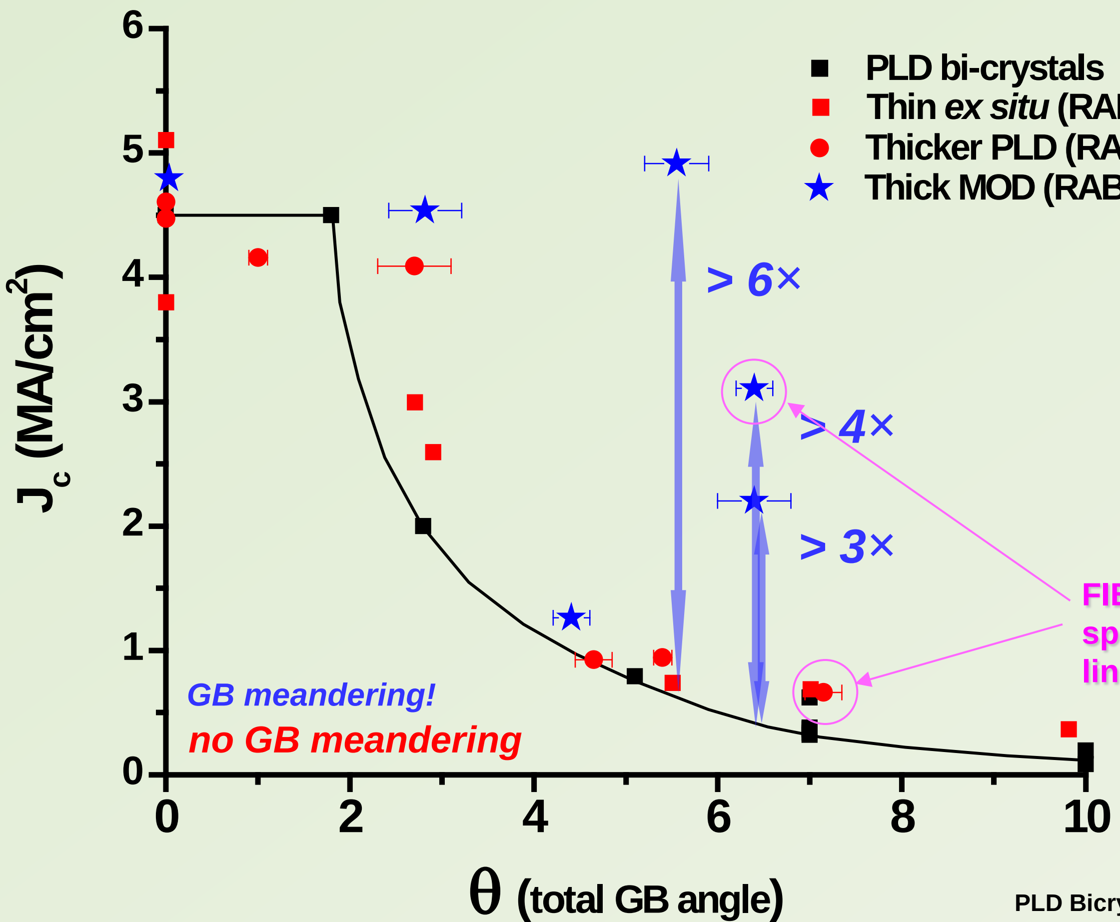




D. M. Feldmann et al. JAP 102, 083192 (2007)

Thick *ex situ* films with meandered GBs break IBM "Law"

❖ **Large J_c enhancements across meandered GBs!**



❖ **Universally observed $J_c(\theta)$ dependence**

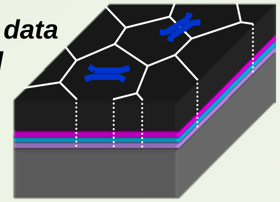
- ❑ different YBCO growth methods
- ❑ bi-crystals and single GBs on RABiTS

❖ **No clear trend with θ for MOD GBs on RABiTS**

- ❑ PLD and MOD films were deposited on the same RABiTS

FIB was used to cut TEM specimens directly from these links! (T. Holesinger)

All RABiTS data are isolated single GBs

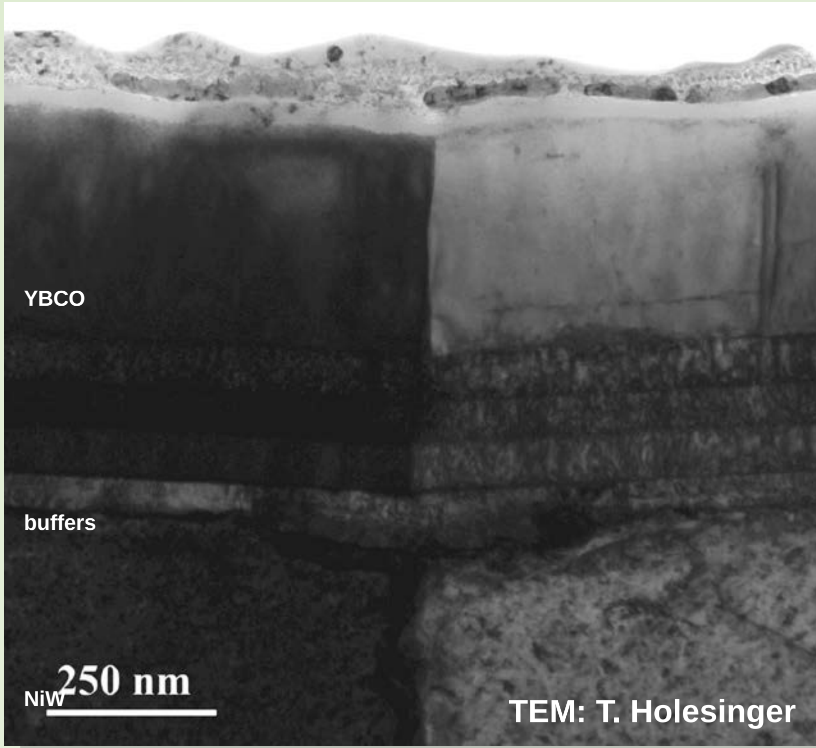


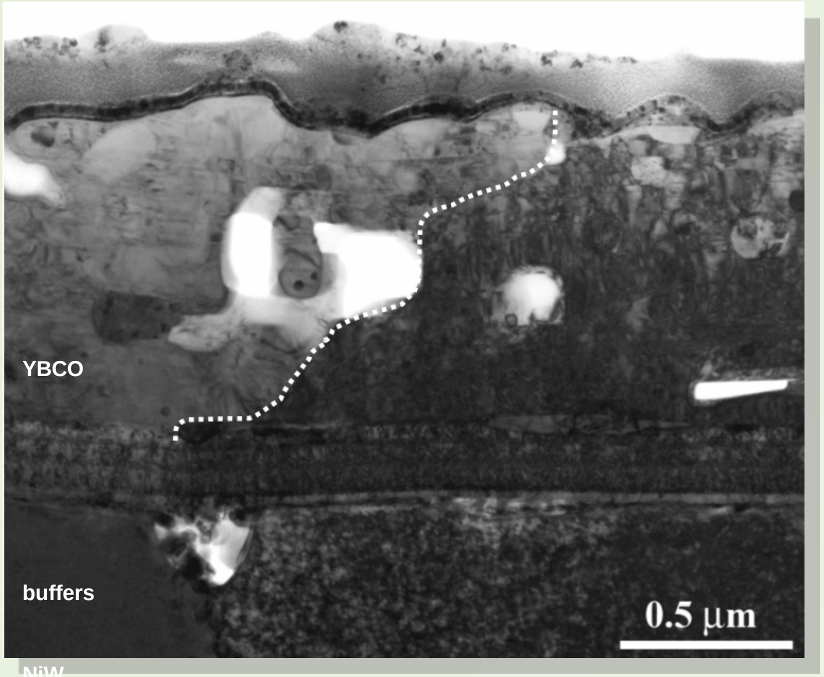
PLD Bicrystal data from:
Verebelyi et al., *APL*, 76, 13 (2000)
and private communication

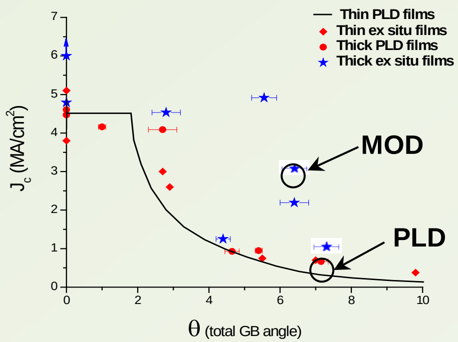
D. M. Feldmann et al. JAP 102, 083192 (2007)

J_c depends vitally on GB morphology

PLD - ~ 7° J_c ~ 0.7 MA/cm² — **MOD - ~ 6.5°, J_c ~ 3.1 MA/cm²**





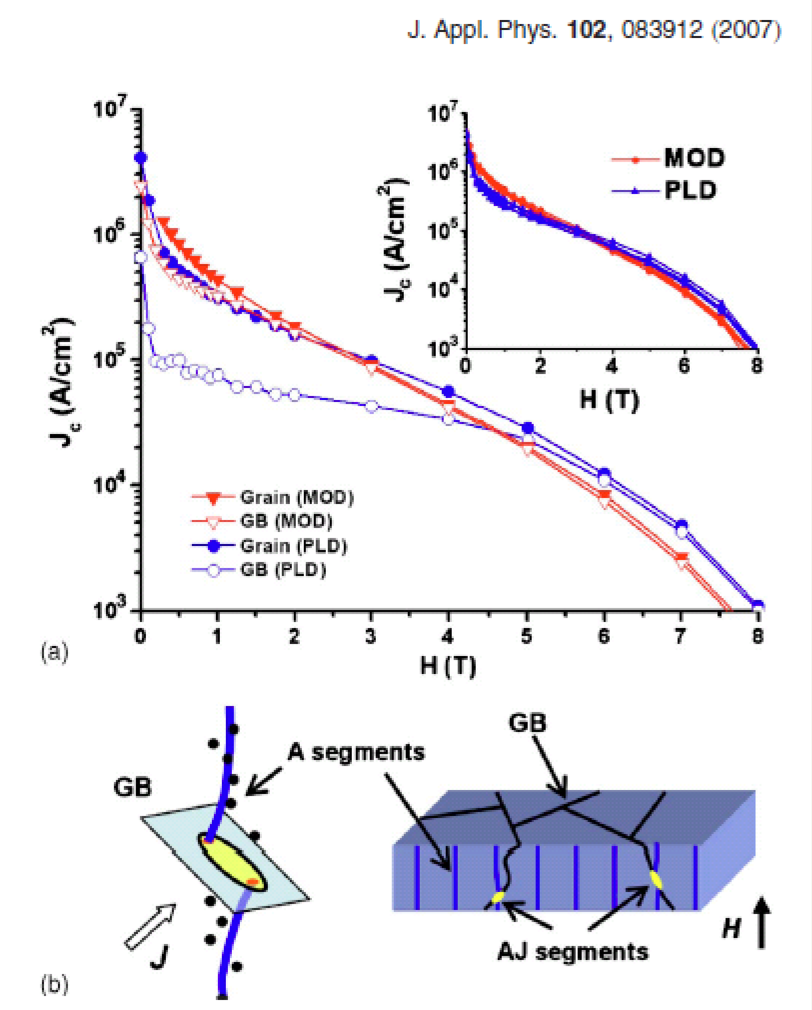


FIB Cut TEM Sections From Isolated GBs: PLD GB Straight; MOD GB Meandered

M. Feldmann …. DCL JAP 102, 082912 (2007)

J_c(H) of meandered GBs is also enhanced

- **Meandered, *ex situ* GBs, have no unique GB plane**
  - whatever orientation of H, there are no AJ vortices to depin before A vortices
  - AJ vortex segments may be pinned by vortex line tension and strong intra-grain pinning



D. M. Feldmann et al. JAP 102, 083192 (2007)

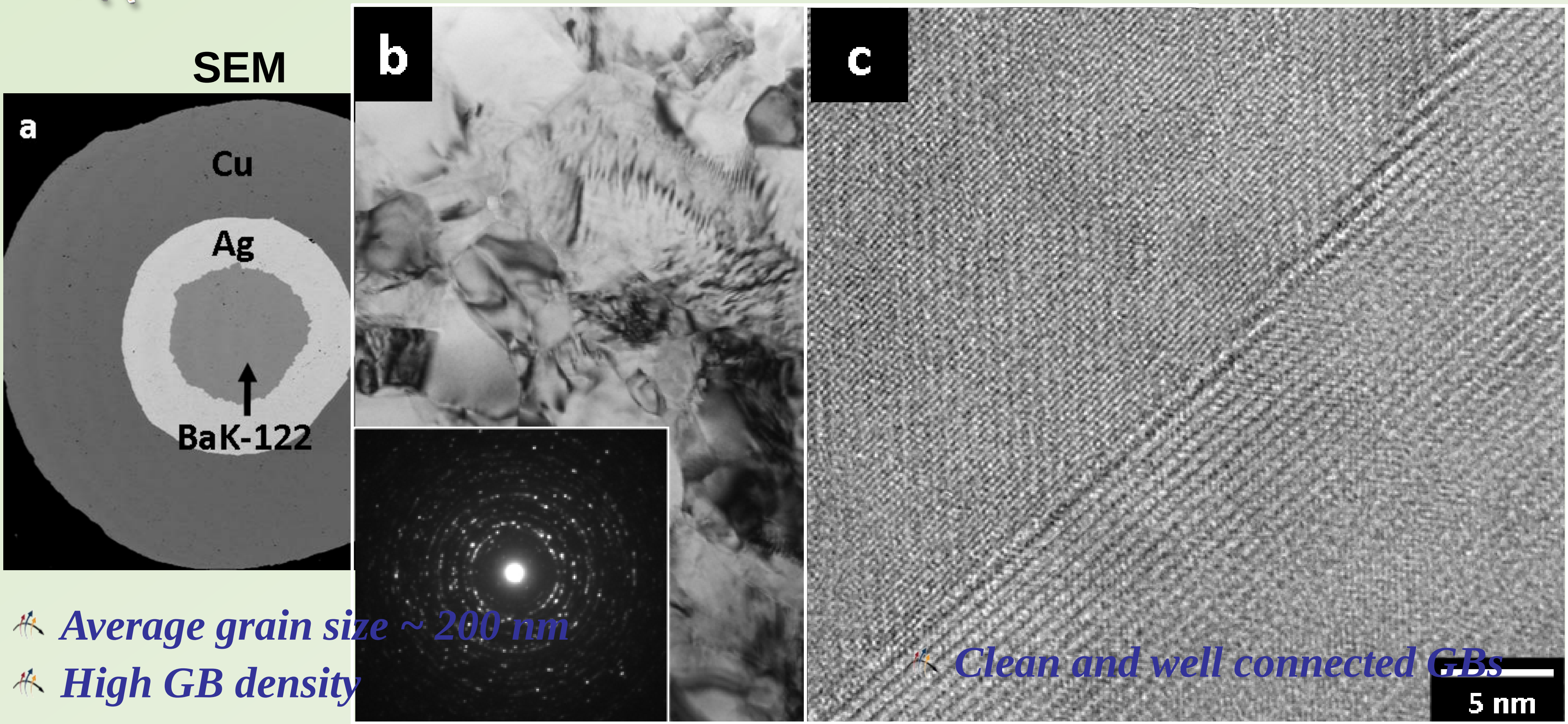
Summary: GB meandering

- Meandering is essential to the viability of RABiTS route to coated conductors in comparison to IBAD routes
  - J_c on RABiTS is not viable with the planar GBs produced by *in situ growth*
  - *Only ex situ* routes like MOD with meandered GBs allow high Jc on RABiTS
- Meandering is good – but does not remove the need for a high biaxial texture
  - Critical misorientation is enhanced from 2-3° to perhaps 4-6°
- Important lesson: ONE class of vortex is much better than TWO

What happens for HTS without macroscopic texture?

- Fine-grain polycrystalline Co-doped and K-doped Ba122 bulks and wires…….
- Round wire Bi-2212……….

Fine grain (many GBs!) K-doped Ba122 polycrystals without texture



- *Average grain size ~ 200 nm*
- *High GB density*
- *Randomly oriented polycrystalline structure with many high-angle GBs*
- *Clean and well connected GBs*

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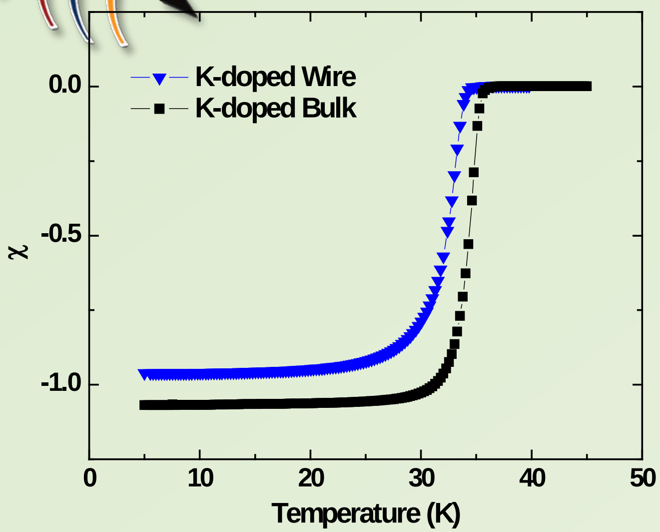
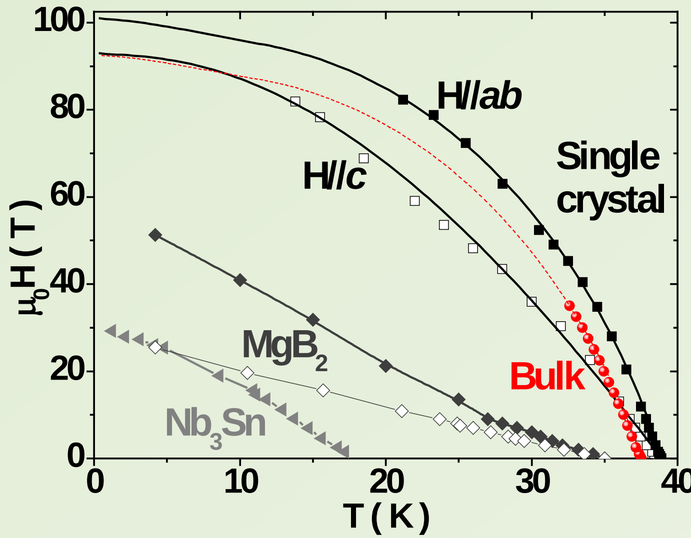
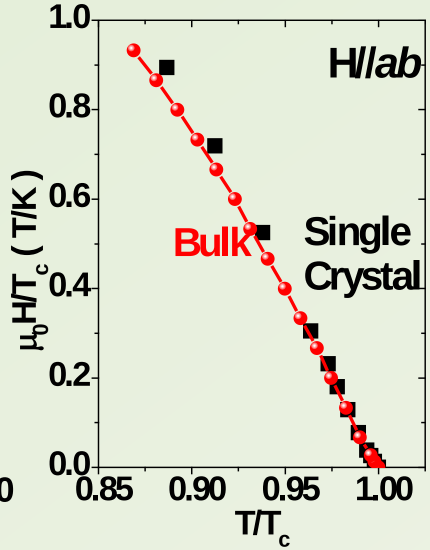
- *High GB density*
- *Randomly oriented polycrystalline structure with many high-angle GBs*
- *Clean and well connected GBs*

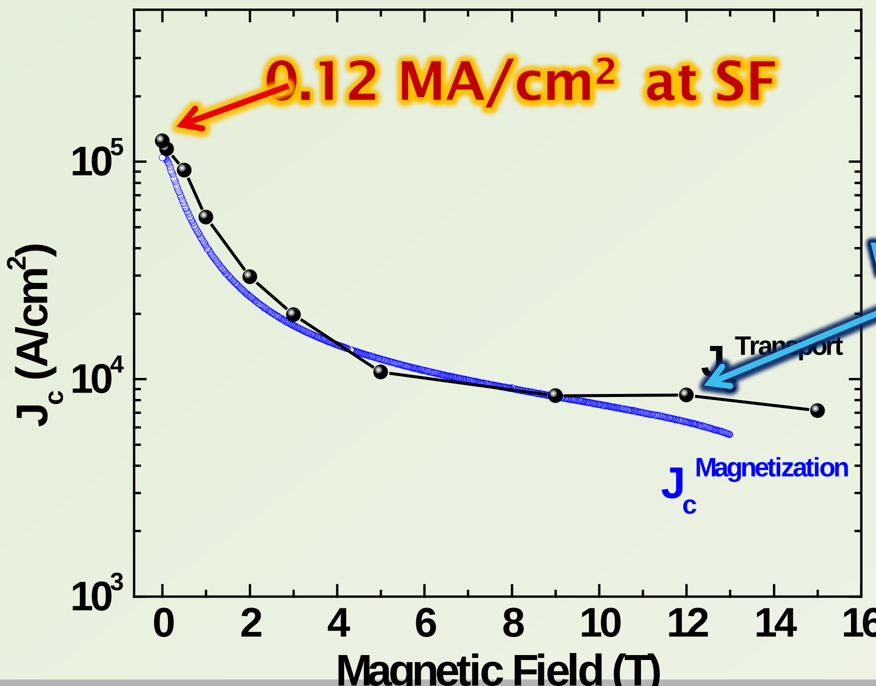
J. Weiss, C. Tarantini et al. Nat. Mater. 11, 682 (2012)

K-doped Ba122: Bulk and Wire Properties







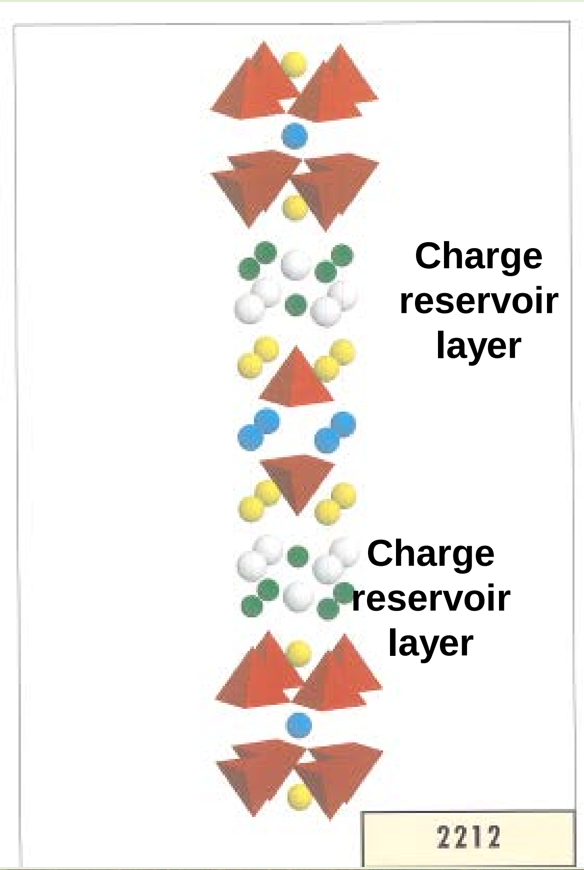


Weak field dependence
J_c(12T) ~ 10 kA/cm^2

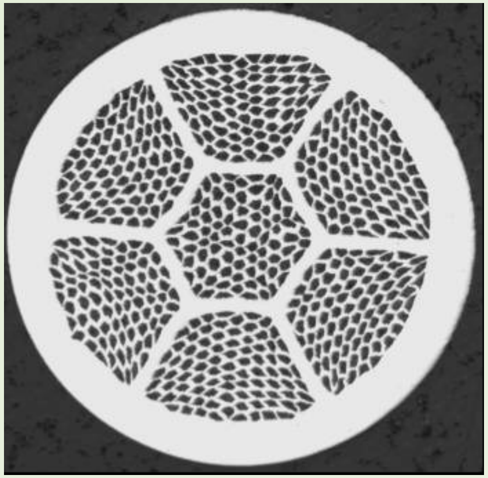
J. Weiss, C. Tarantini et al.
Nat. Mater. 11, 682 (2012)

Round wire vs. tape BSCCO Technology

- How can 2212 and 2223 be so different as conductors when they are so similar as structures?

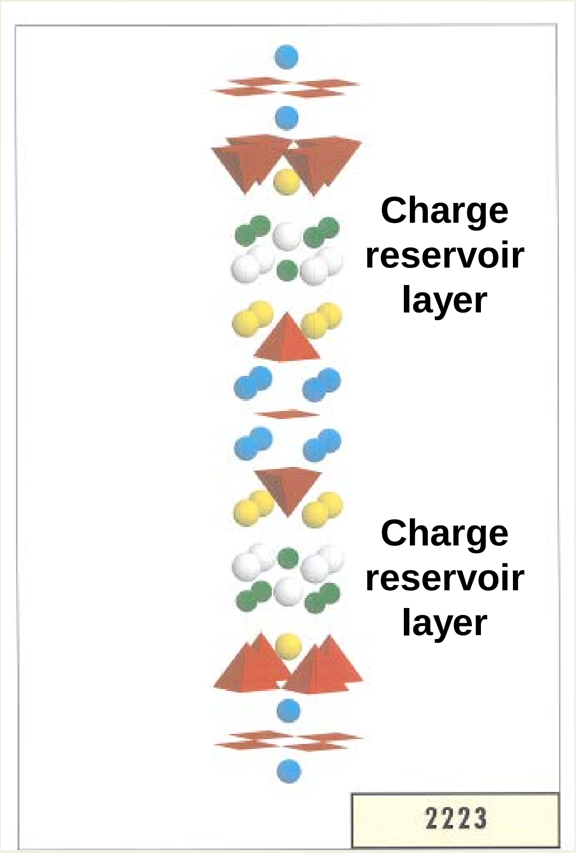


RW - 2212



Versus

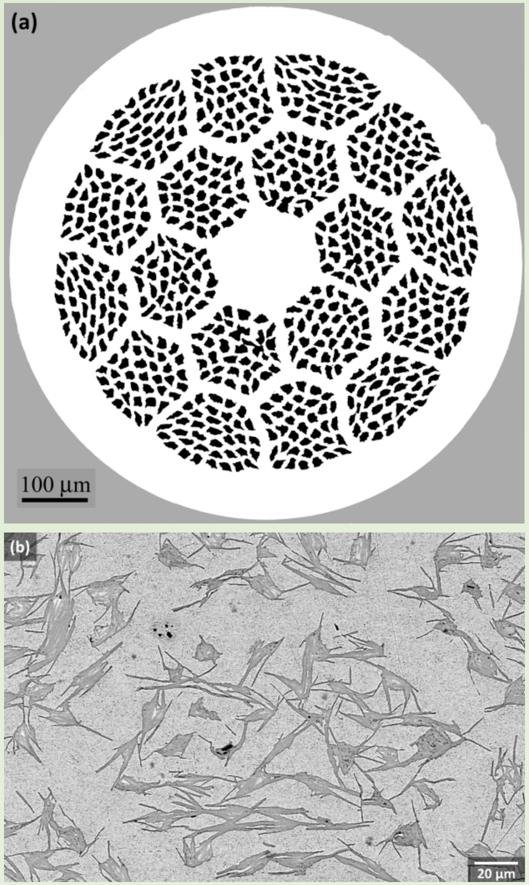
tape 2223



Multifilamentary 2212 has been made for years without much interest

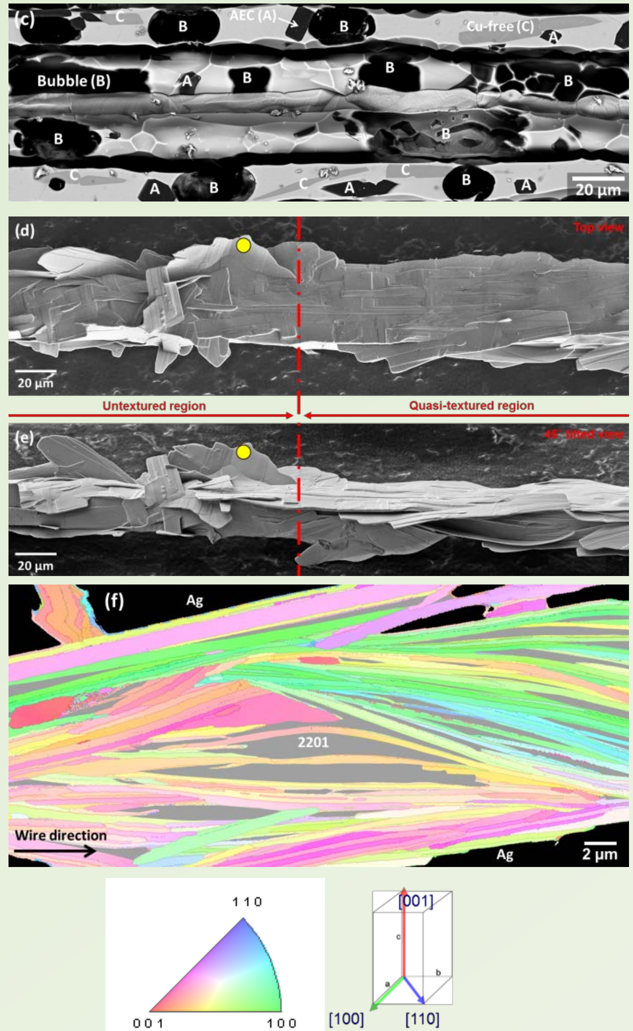
- Why was 2212 round wire ignored?
  - Because, being untextured, it was **obvious (!)** that high angle GBs were producing a connectivity-compromised current path of low Jc……
- ARRA support for a multi-lab collaboration (VHFSMC – DOE-HEP support) in 2010-2012 enabled a much fuller understanding
  - **Principal current limitation is by agglomerated void space in the filaments (bubbles of residual gas) not HAGBs!**
  - Overall conductor J_c of Bi-2212 now exceeds that of any coated conductor when 100 bar overpressure is used to eliminate bubbles

2212 Filaments contain many HAGBs – and (without bubbles) have high Jc



Kametani and Jiang unpublished

Transverse section images



Longitudinal section images

Polished sections of filaments in their surrounding Ag

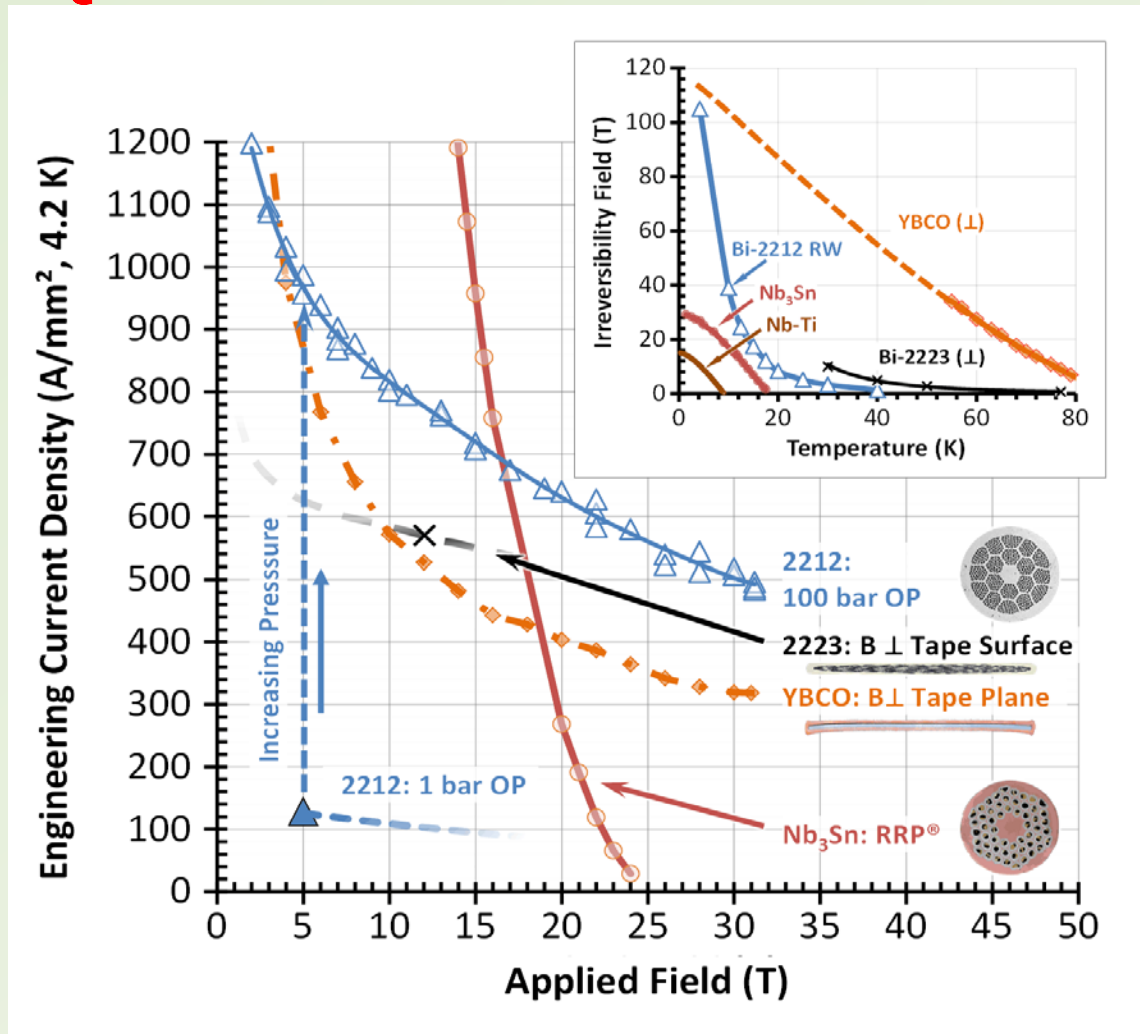
Exposed filaments show their plate-like nature and frequent strong misalignments.

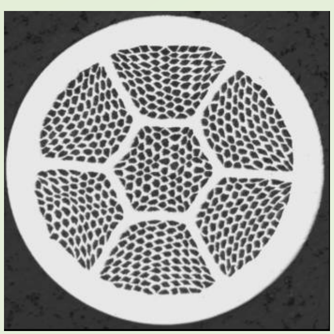
EBSD images show some local texture and significant 2nd phase content within filaments

The filaments cannot be fully connected – yet do have high Jc

Isotropic, multifilament 2212 has higher conductor J_c than coated conductor!

- Requires ~100 bar 890˚C processing
- High J_c, high J_e and high J_w has been demonstrated in a coil already (2.4T in 31T)
- Much less field distortion from 2212 than from coated conductors – better for high homogeneity coils
- 7 times increase in long length J_e by removing bubbles





2212

REBCO coated conductor

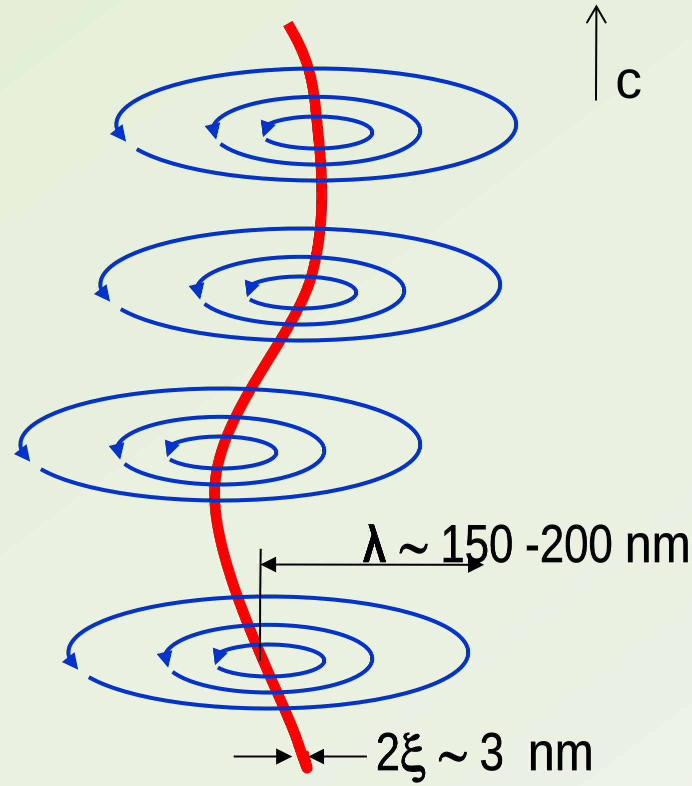
Vortex stiffness matters (Gurevich)

- **Elastic energy of a distorted vortex line**
  Brandt, Rep. Prog. Phys. 58, 1465 (1995);
  Blatter et al, RMP 66, 1125 (1994)

- **Dispersive line tension of a single vortex**

$$\varepsilon_l = \frac{\varepsilon_0}{\Gamma^2} \ln \frac{1}{\xi_c k_z}, \qquad \lambda k_z >> 1$$

$$\varepsilon_0 = \left(\frac{\phi_0}{4\pi\lambda} \right)^2 = \frac{\pi \hbar^2 n_s}{4 m_*}, \qquad \Gamma = \left(\frac{m_c}{m_{ab}} \right)^{1/2}$$



- **Anisotropy strongly reduces bending rigidity of the vortex:**

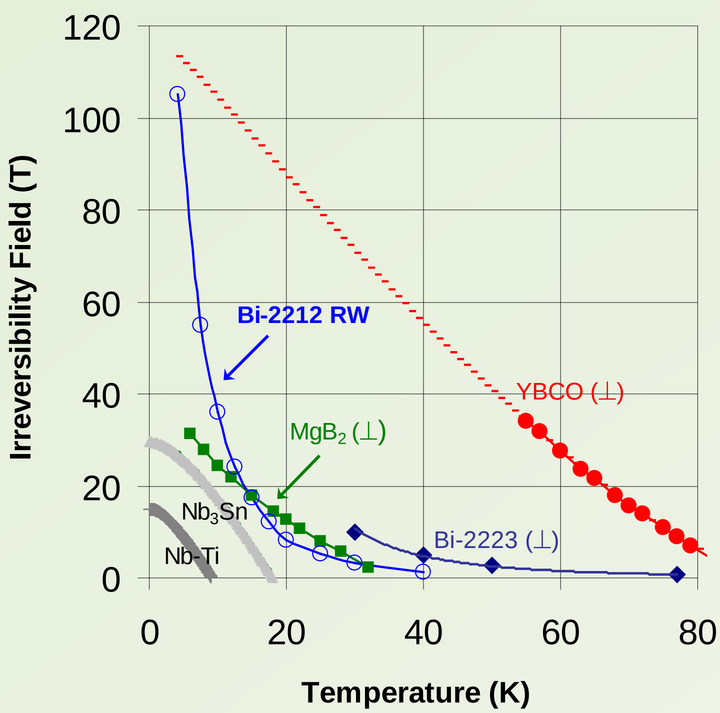
$\varepsilon_\ell \sim 10^3$ K/Å for LTS → rigid rods

$\varepsilon_\ell \sim 3$ K/Å (YBCO @ 0K)
$\varepsilon_\ell \sim 0.5$ K/Å (YBCO @ 77K) → soft filaments

Stiffness mostly determined by superfluid density and mass anisotropy!

Let's dream: applications really need round wire multifilament YBCO

- The best $H_{irr}(T)$ performance of any known superconductor
- The possibility to provide 10 T fields up to about 60K
- Tape geometry is valuable for high strength
  - But detrimental in almost all other aspects in comparison to round wires of Nb-Ti, Nb_3Sn, MgB_2 and Bi-2212
- The best of 2212 in YBCO – why not?



If non-planar GBs work so well in Bi-2212 and K-doped Ba-122, why not in YBCO too?

"Real" vs. "science" grain boundaries – they are different and real is often better!

- Non-planar GBs avoid a separate population of AJ vortices
  - Non-planar GBs have lower strain too – good for J_c
  - Generally have larger area too – good for J_c
- Order parameter at GB is (presumably) still depressed by local charge imbalance and strain whether planar or non-planar
  - Higher carrier density can screen such charges and provide carriers for pairing – overdoping is good
  - YBCO and Bi-2223 can hardly be overdoped!
  - Ca-doped YBCO and especially O-overdoped Bi-2212 show the advantages of overdoping – some loss of T_c is a valuable trade for a more user-friendly conductor architecture
  - None of this obviously explains the much larger J_c of untextured Bi-2212
- Pnictide bicrystal results again suggest the disconnect between planar and untextured polycrystalline GBs
  - Perhaps the variability of properties in FBS is much larger than in cuprates - low anisotropy (γ~1-10) is positive (cuprates 5-100)

Summary points

- Superconductors are enormously useful for magnets
  - High enough H_{c2} is essential – Nb-Ti and Nb_3Sn have satisfied this demand for 50 years now
  - A new era of high fields OR high temperature use might open with cuprates or Fe-based superconductors
  - Grain boundary properties will control
- There are reasons for optimism!

Special thanks to may colleagues in the community for many challenging questions and explanations over the years – especially Alex Gurevich, Peter Lee and Eric Hellstrom