Expanding the set of tools for investigating and improving vortex pinning in coated conductors

B. Maiorov, J. Mantei[1], H. Wang[2], S. Baily, F. Hunte[3], J.L. MacManus-Driscoll[4], H. Zhou, T. Holesinger, S.R. Foltyn, Q.X. Jia, P.N. Arendt and L. Civale

Superconductivity Technology Center, Los Alamos National Laboratory

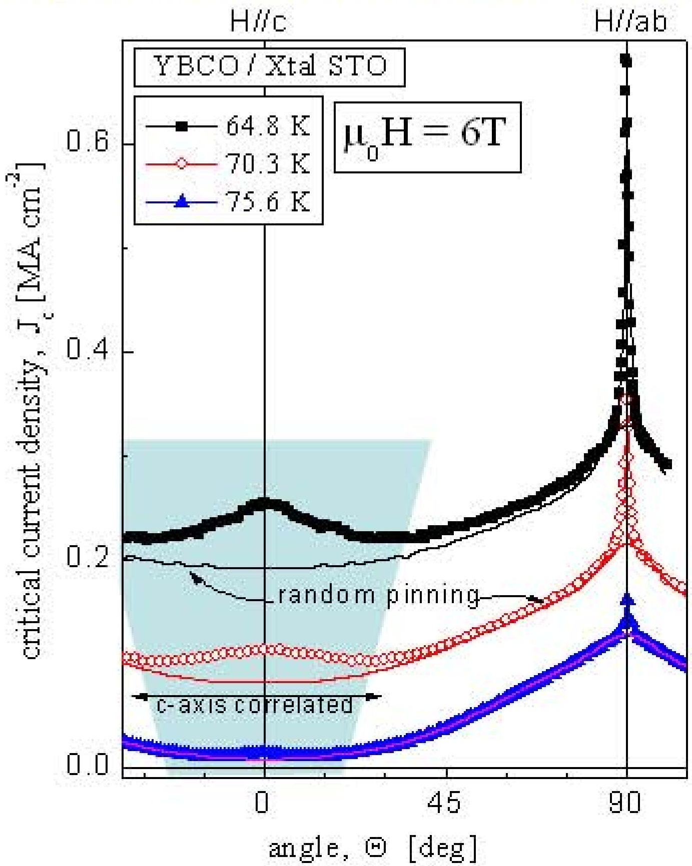
[1] *Univ. Wisconsin-Madison,* [2]*Texas A&M, TX,* [3]*NHMFL/FSU,* [4]*Univ. of Cambridge*

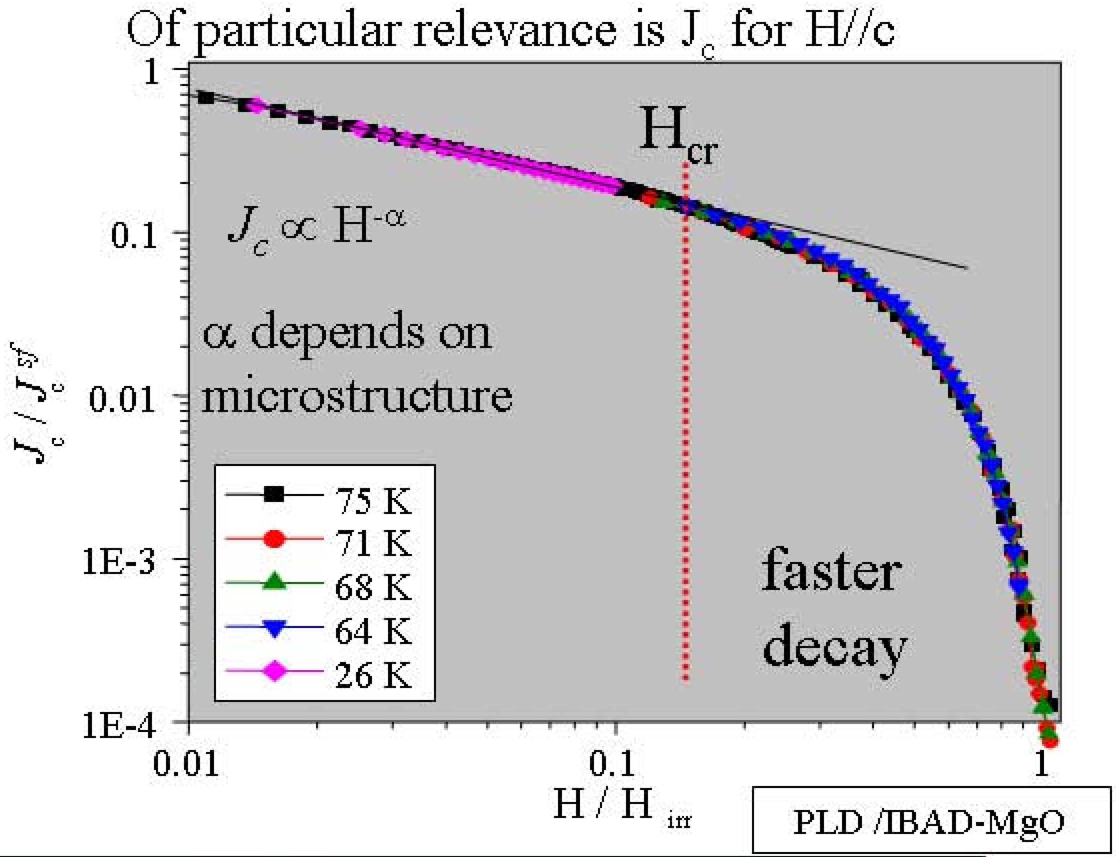
Cost: $ 200K

Outline

- **Pinning enhancement routes**
  - Angular and field regimes
  - Temperature regimes
- **Other field and current configuration (Variable-Force and Force-Free configurations)**

Angular, field and temperature dependences of J_c allows identification of different pinning mechanisms and regimes





Objectives

- Identify pinning responsible for high J_c
- Determine pinning mechanisms relevant for different field-angular-temperature ranges
- Increase the already high pinning in HTS coated conductors

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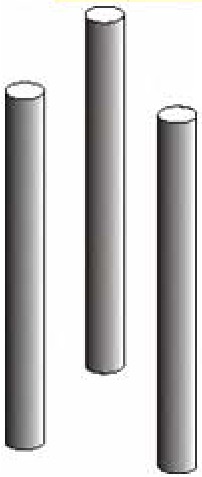
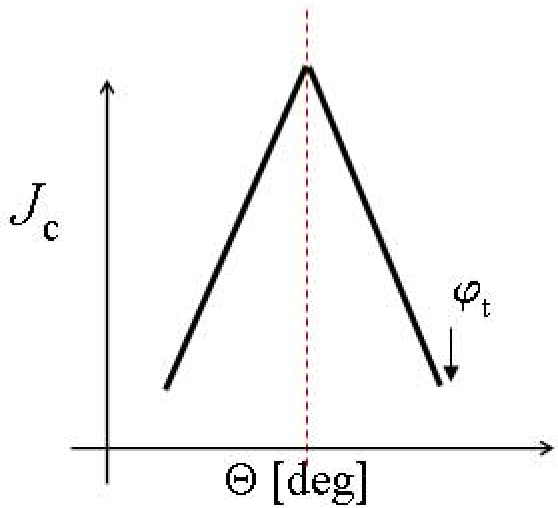
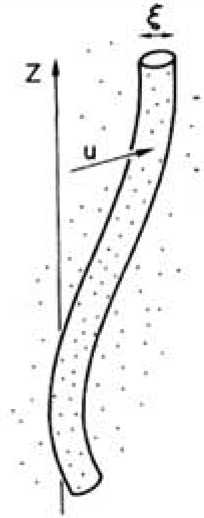
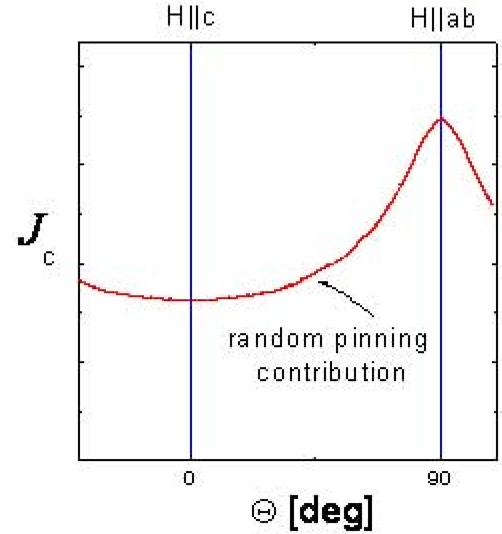
Motivation: Understand $J_c(H,\Theta)$ due to diverse pinning centers in different temperature regimes





- Correlated defects create $J_c(\Theta)$ peak centered at defect's orientation
- Higher irreversibility line
- Better high temperature behavior

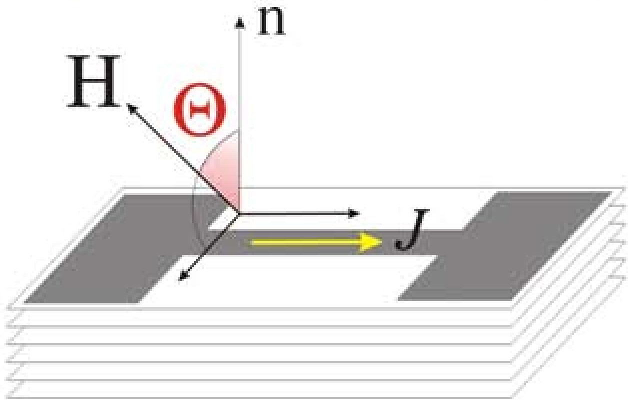




- Random defects + anisotropy, minimum H||c and maximum H||ab.
- Lower irreversibility line
- Better low temperature behavior

Questions:
- What type of pinning center is better in a certain field and temperature range?
- Is there a temperature of crossover from correlated to random?
- Can we add different types of pinning centers?

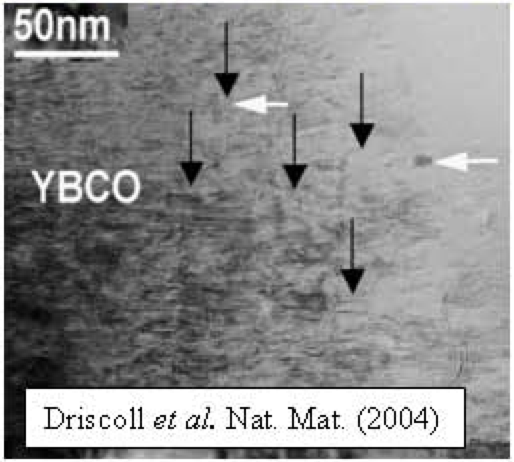
Comparison of different pinning routes: random *vs.* correlated?



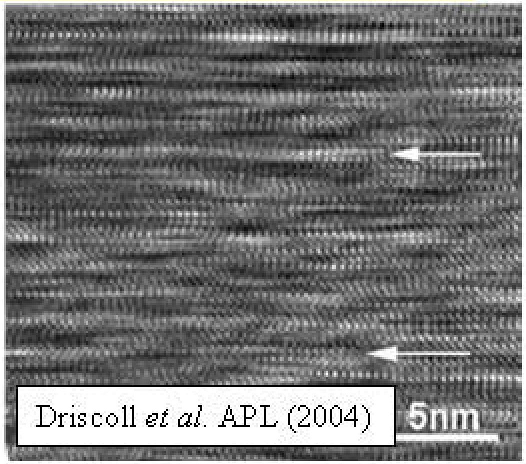
Random or correlated?

- Correlated defects in $BaZrO_3$+YBCO create a $J_c(\Theta)$ peak
- Better high field dependence

- RE-mixtures induce random disorder and overall increase in $J_c(\Theta)$
- Better at lower fields.

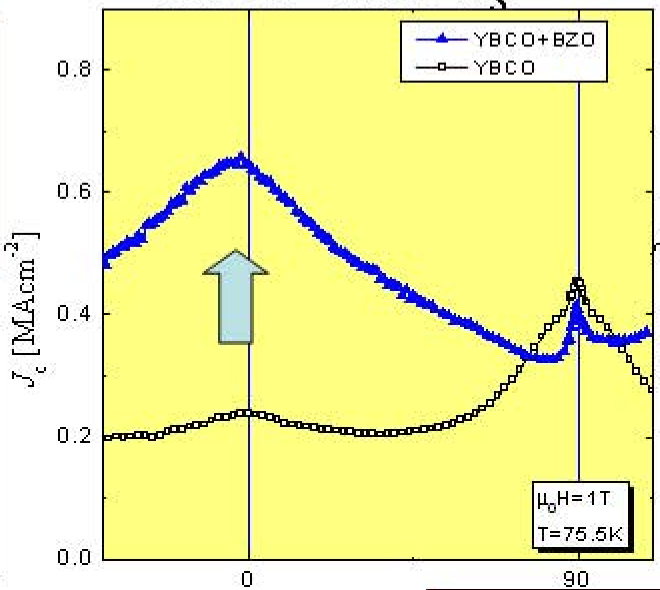


Driscoll *et al.* Nat. Mat. (2004)



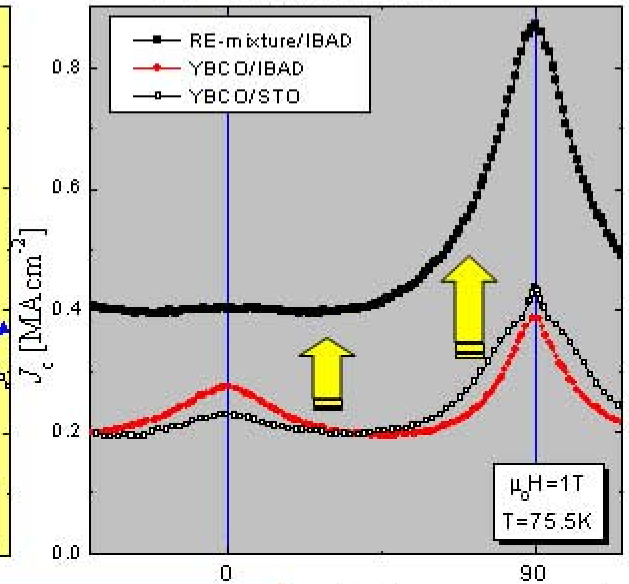
Driscoll *et al.* APL (2004)

YBCO+$BaZrO_3$



Θ [deg]

RE-mixtures



Θ [deg]

Driscoll-Civale PR04

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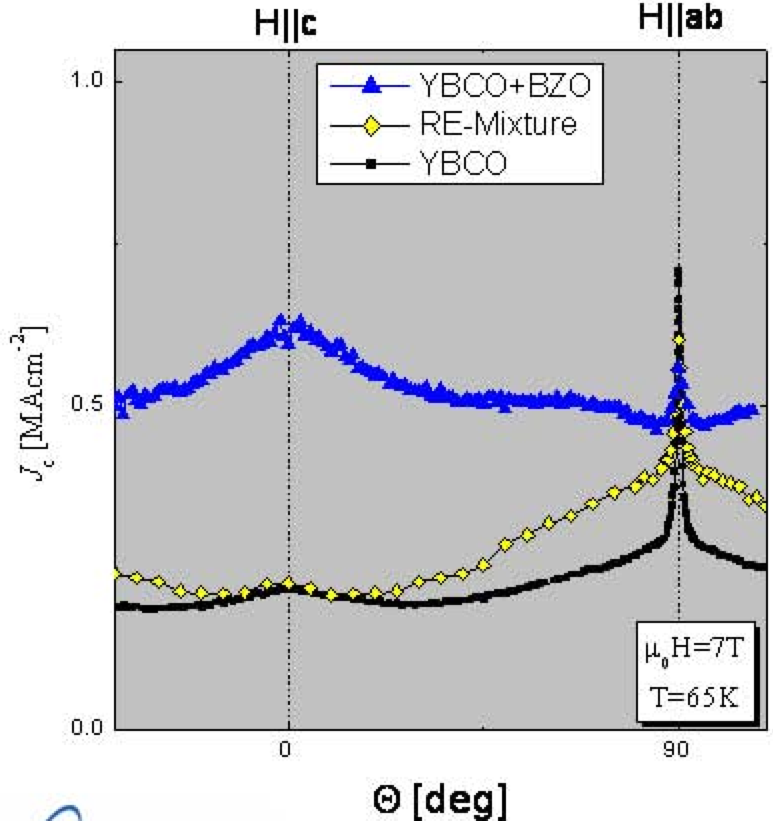
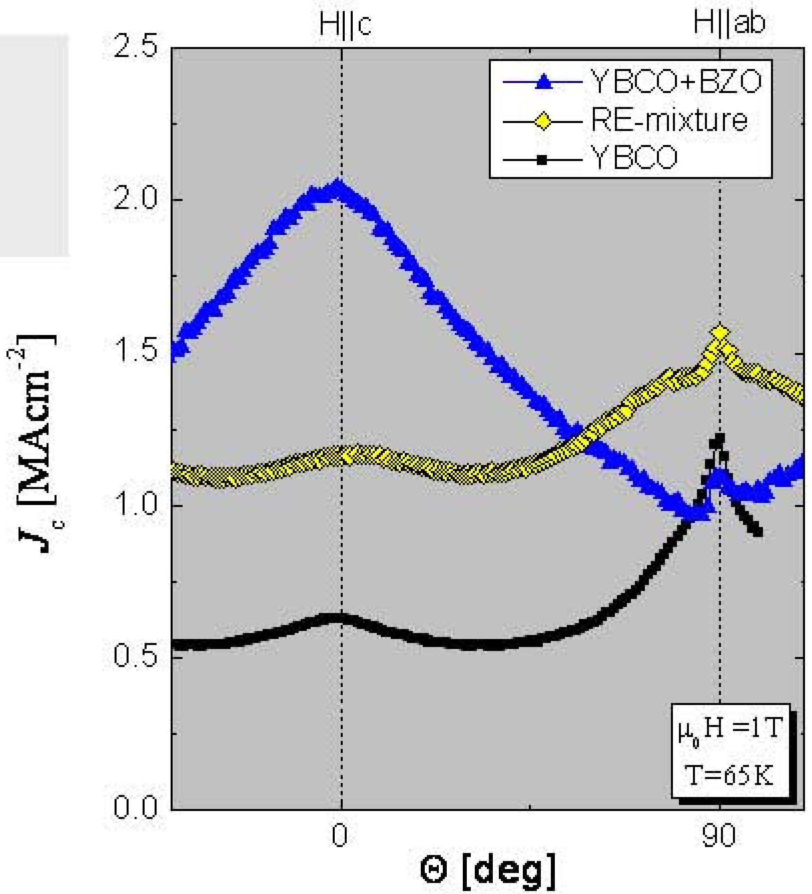
Explore pinning enhancement routes at lower temperatures: Correlated better than random at 65K

Low fields

- YBCO+BZO films better around c-axis.
- RE-mixture films better around ab-plane.





High fields

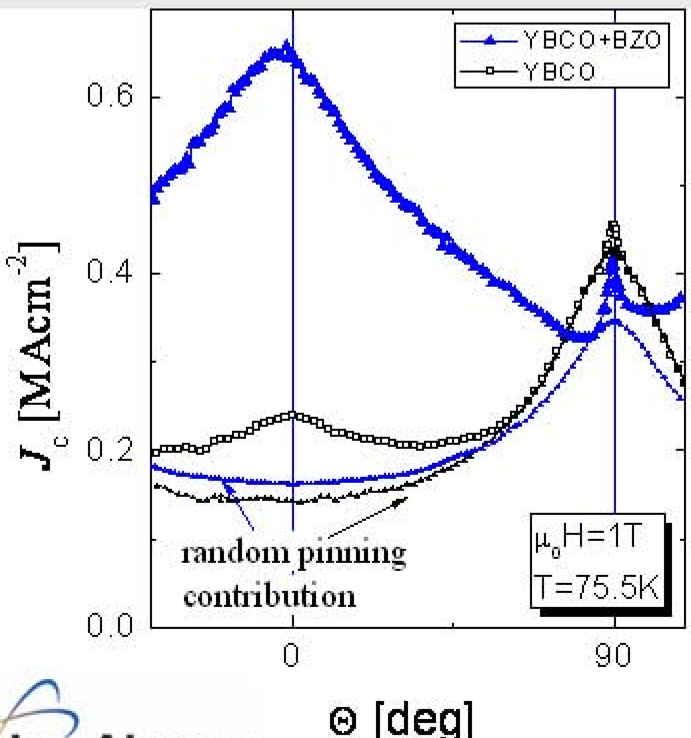
- YBCO+BZO films outperform RE-mixture ones

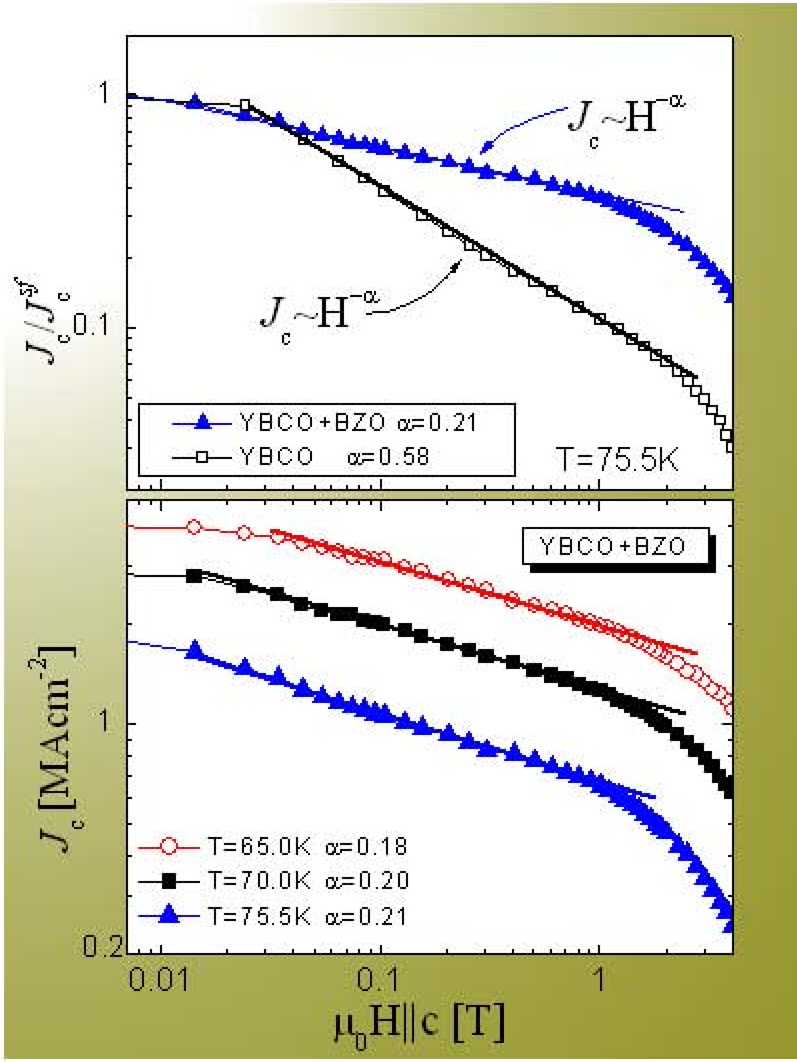
B.Maiorov *et al* AIP Conf. Proc. **824**, 763 (2006)

Record low α=0.20 constant in temperature

Foltyn-Civale PR05

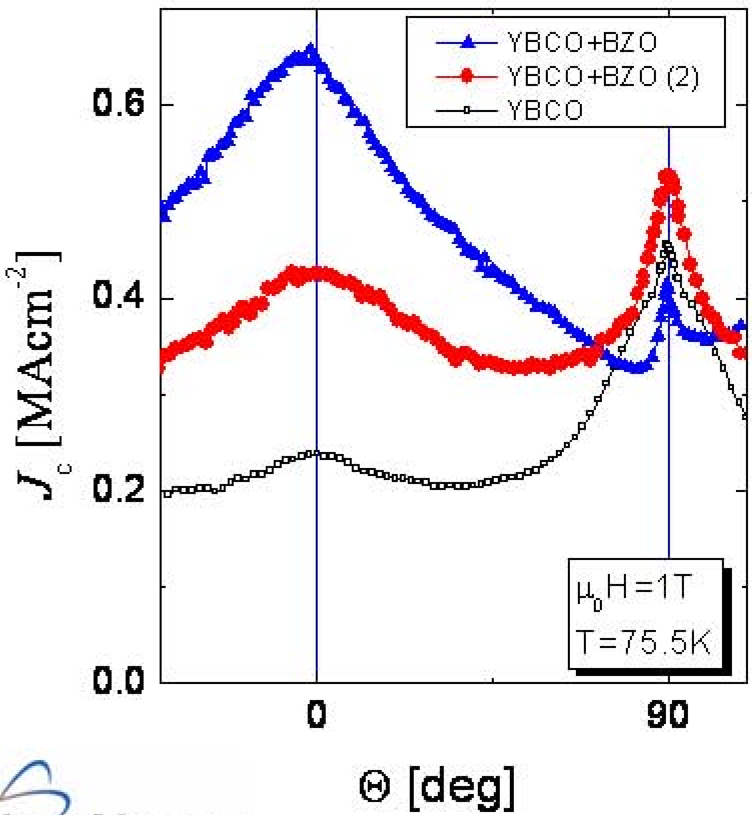
- α is smaller for samples with bigger c-axis peak.
- α is almost constant when correlated defects dominate (65K-75K)
- α temperature independent for plain YBCO
- Small pinning contribution from BZO particles by themselves

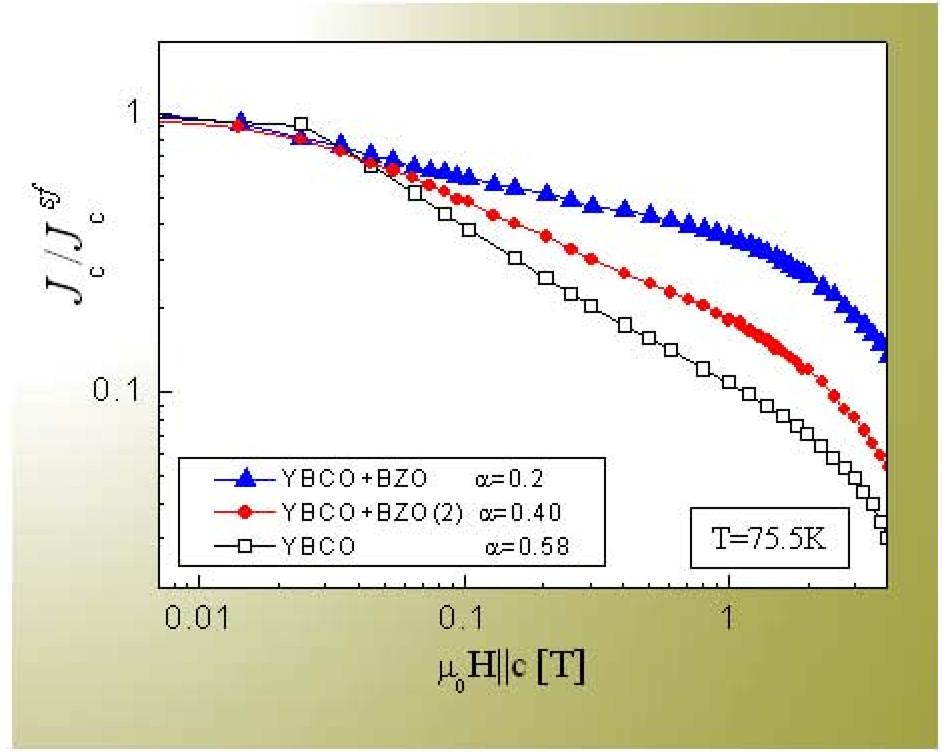




Study of interplay of random and correlated: Can we increase J_c with both, random and correlated?

- Select a YBCO+BZO film with higher random contribution at 75K; YBCO+BZO(2)
- Sample YBCO+BZO(2) has a less prominent c-axis peak
- Smaller c-axis peak → increase in α=0.40



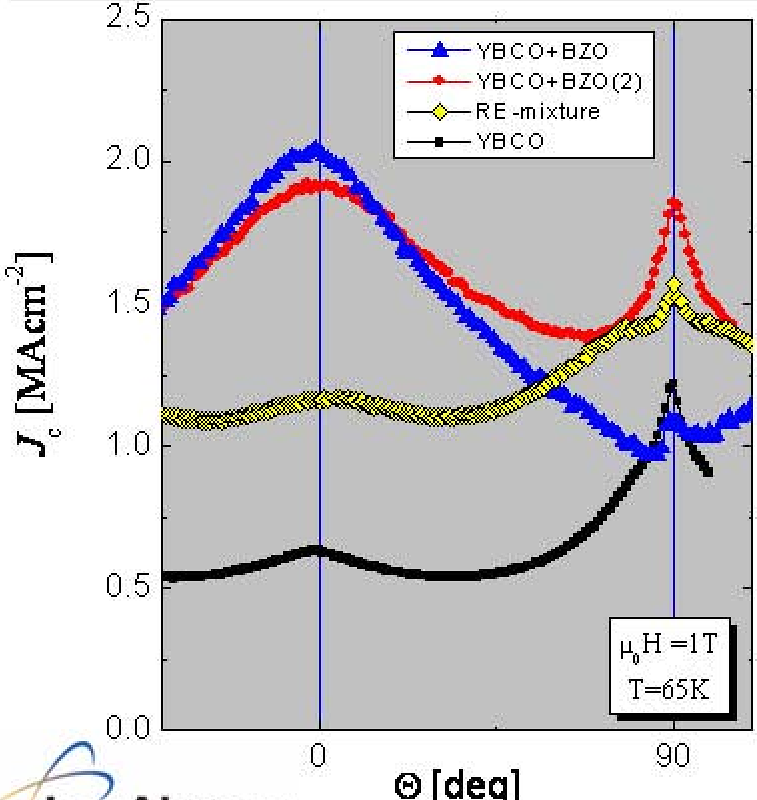


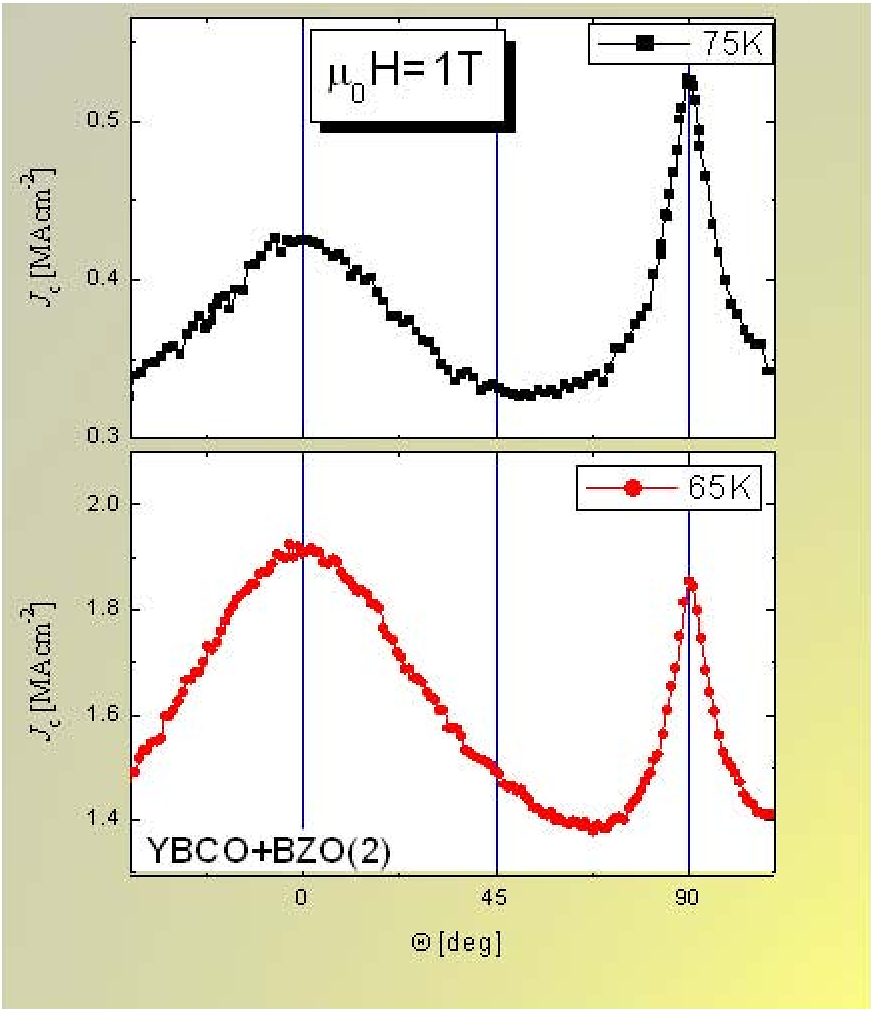
YBCO+BZO Strong Correlated only
YBCO+BZO(2) Strong Correlated + random

- Take advantage of strong pinning of correlated defects at low temperatures

YBCO+BZO(2) has the advantages of both types of pinning center

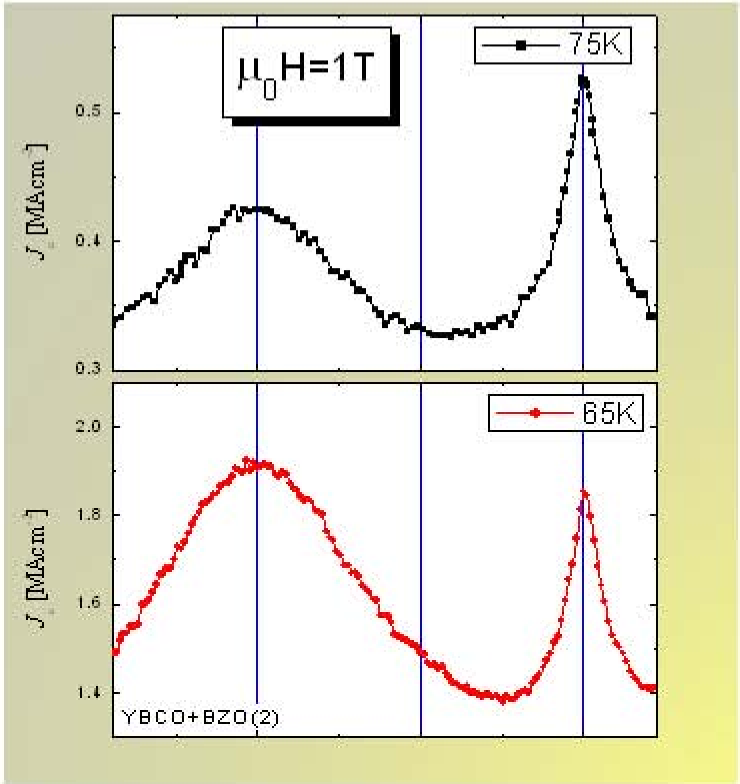
- Wider c-axis peak at T=65K
- J_c(H//c)>J_c(H//ab) for YBCO+BZO(2)
- Addition of random pinning improves $J_c(\Theta)$
- Captures benefits of both types of pinning centers

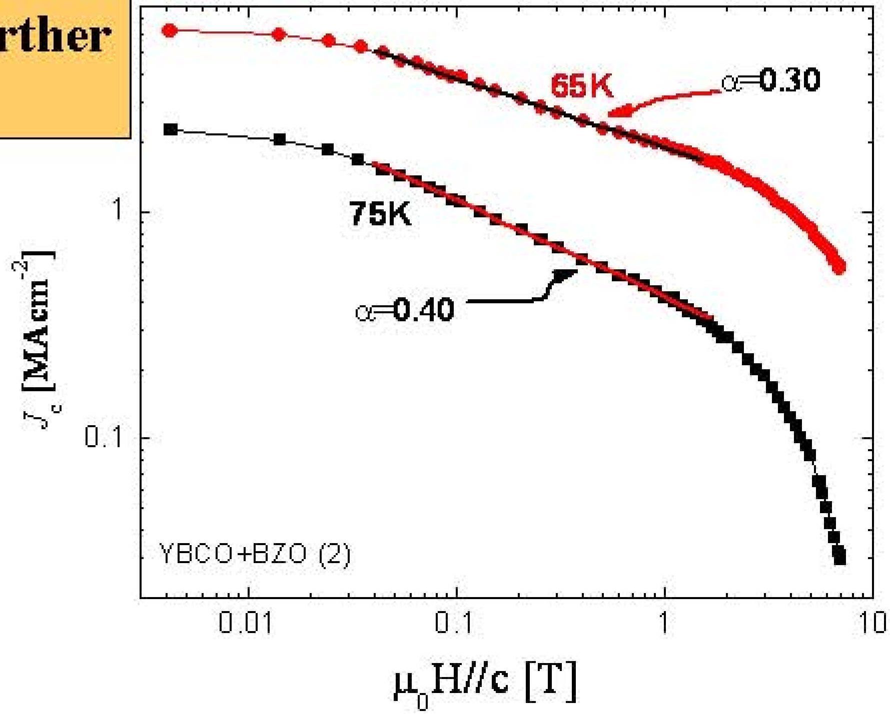




α improves at lower temperatures for YBCO+BZO(2)
Stronger correlated pinning centers

Lower Temp → correlate dominates further → smaller α

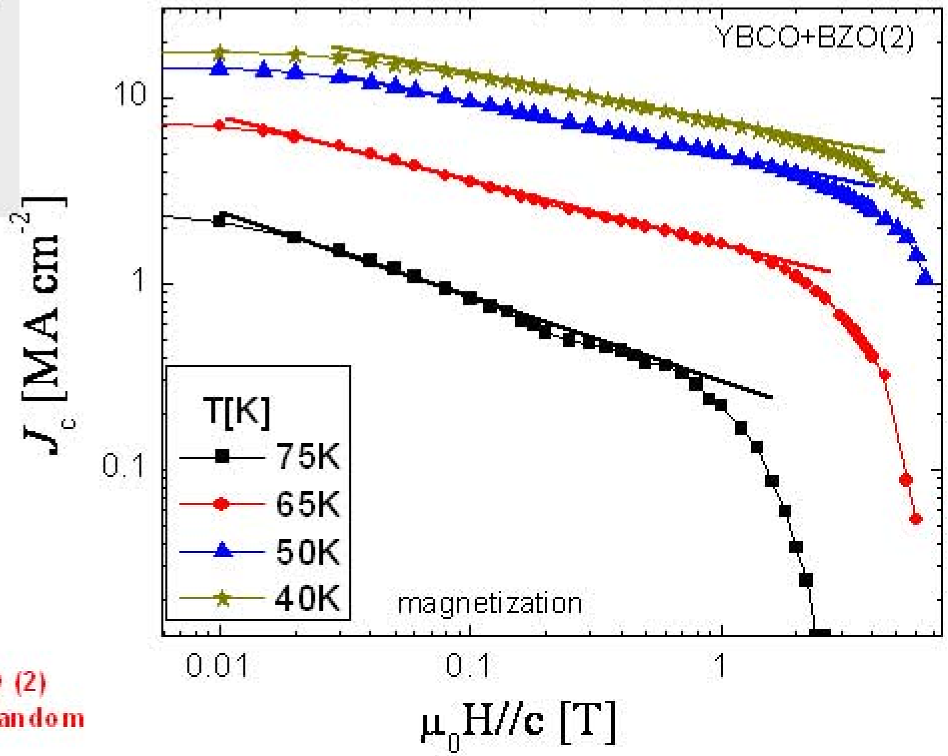


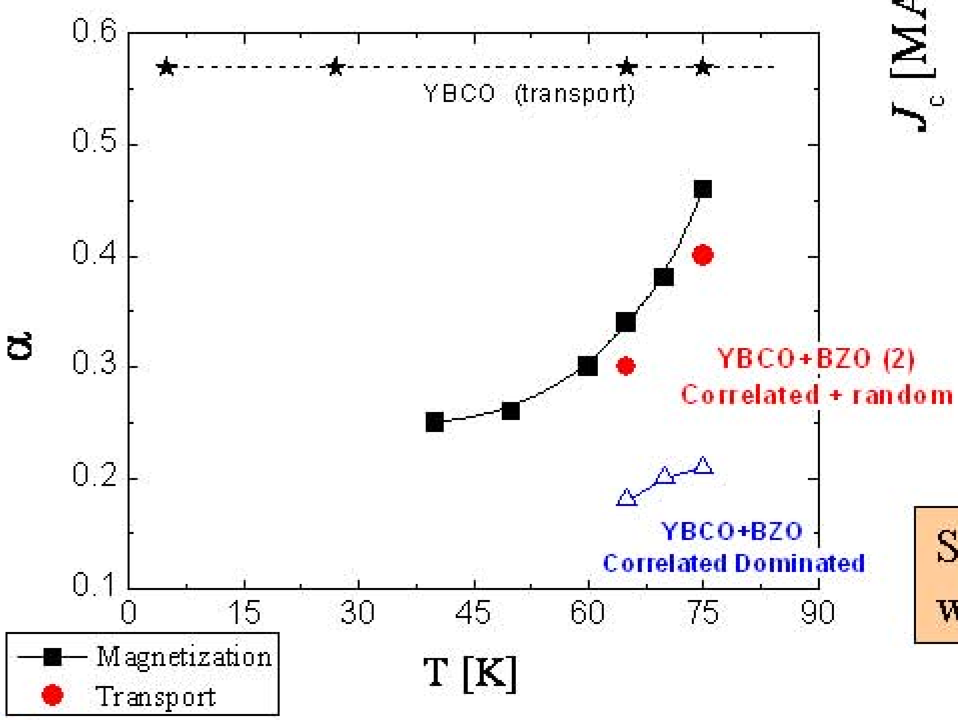


- α is a measure of the relative importance between correlated and random pinning.

α decreases at lower temperatures down to 40K: Stronger correlated pinning

- α decreases at lower temperatures (75-40K)
- Indicative of stronger correlated pinning
- Same trend in magnetization and transport
- α tends to α~0.20 (correlated dominated)





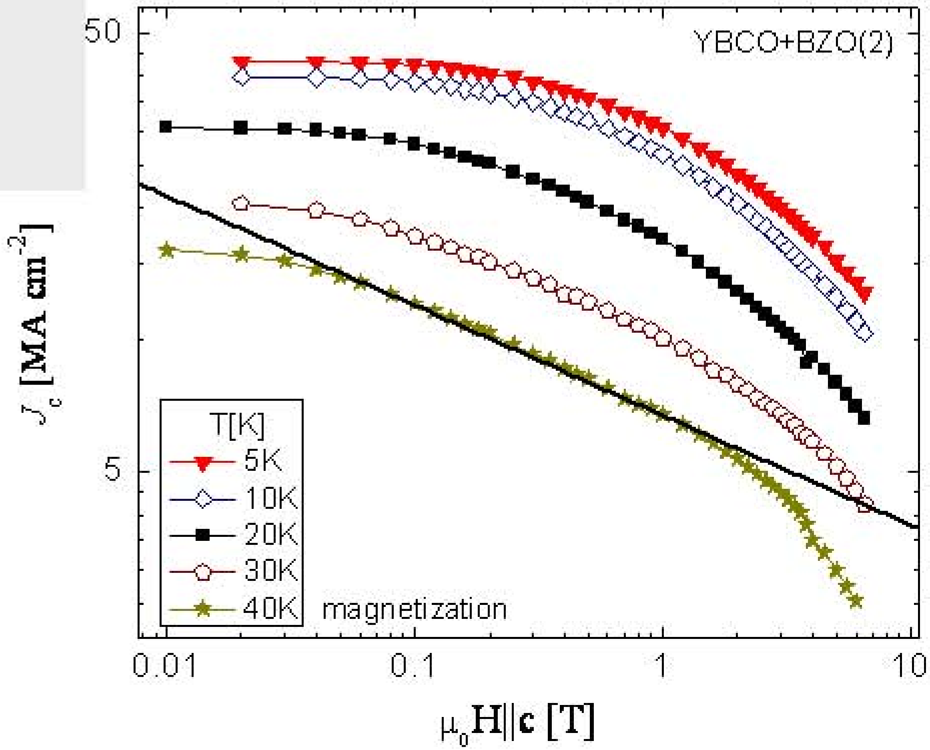
Same behavior found in different samples with thickness = 0.20 – 1.0μm

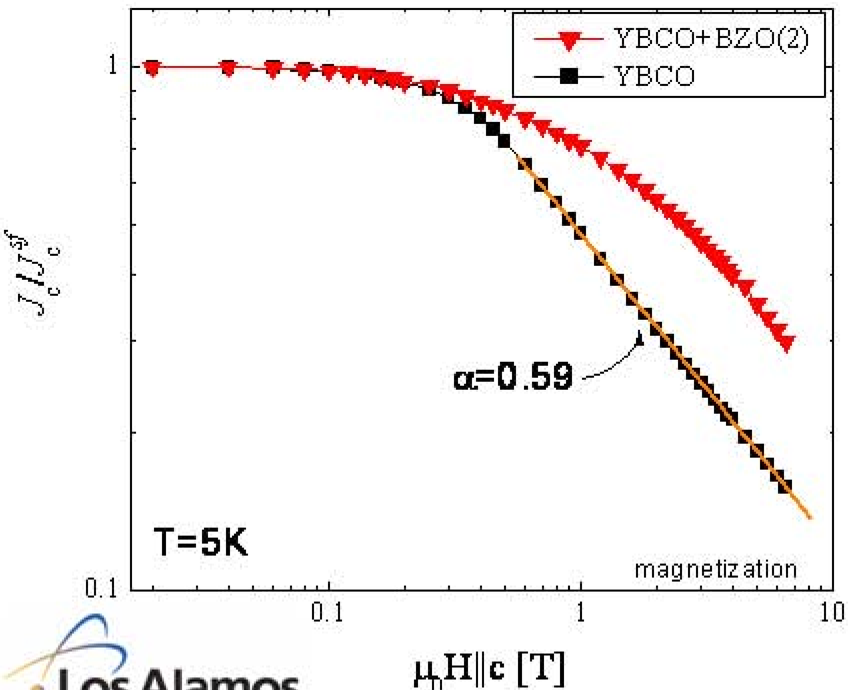
Non power-law J_c(H) for T<40K, in YBCO+BZO films

- Unexpected loss of power-law decay for T<40K
- Very slow J_c(H) decay
- Indication of change in pinning behavior

Foltyn-Civale PR05

YBCO samples retain power-law decay down to 5K

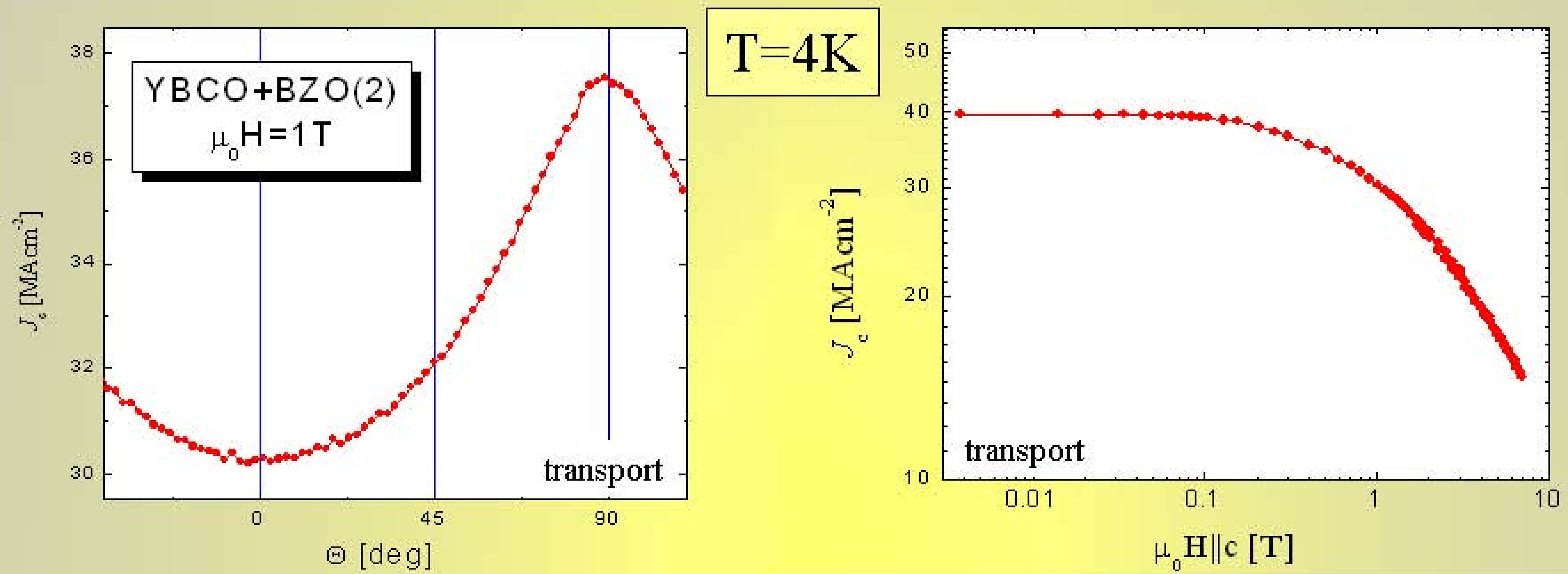




Same behavior found in different samples with thickness = 0.20 – 1.0μm

YBCO+BZO films show NO c-axis peak at 4K: No-power law J_c(H) fingerprint of NO c-axis peak

- Expanded measurement capability doing angular measurements at 4K.
- Very flat J_c angular dependence at 4K
- Non power-law decay



Consistent with previous knowledge (Theory & Experiment)

- Correlated pinning dominates at high temperatures (columnar defects by ion irradiation)
- Random pinning more important at lower temperatures (point like defects by proton irradiation)

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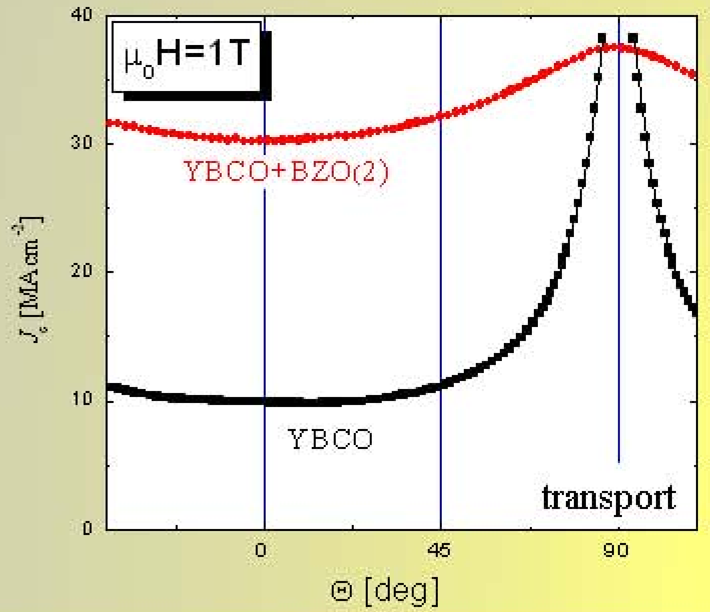
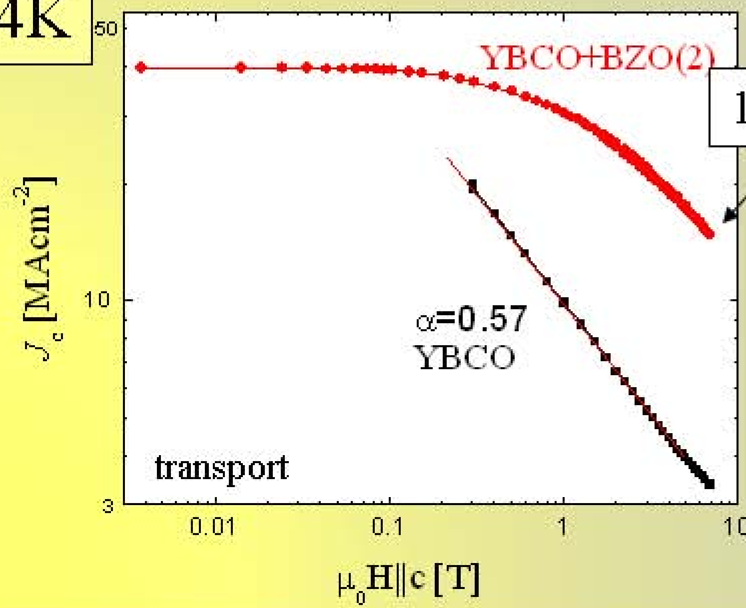
BZO–doped samples show NO c-axis peak at 4K

- Very flat J_c angular dependence at 4K
- Non power-law decay
- Marked improvement with respect to YBCO

BISSCO 2212 (round wire)*
J_c(4K,7T)=0.2MAcm^{-2}
* compiled by Peter Lee (FSU)



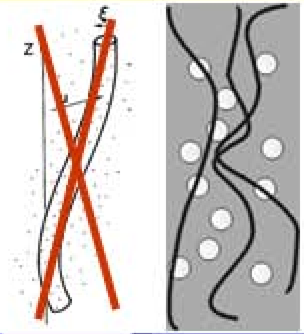
T=4K



Possible Pinning Mechanisms@4K

Point-like defects? **Not likely**
Plain YBCO retains power-law J_c(H) (α~0.6)

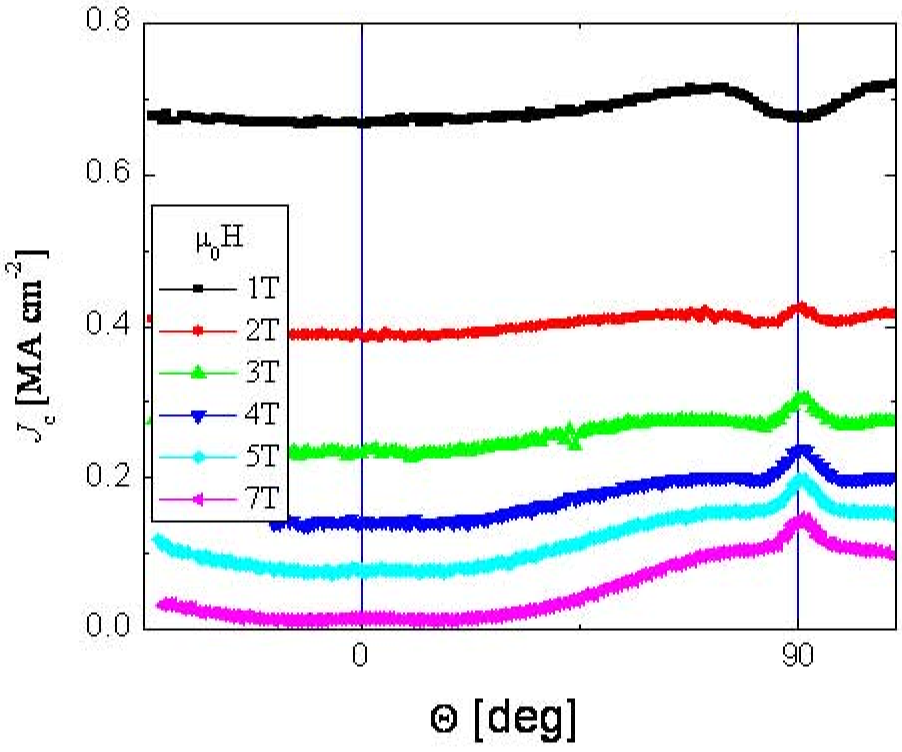
Random particles? ***Probably***

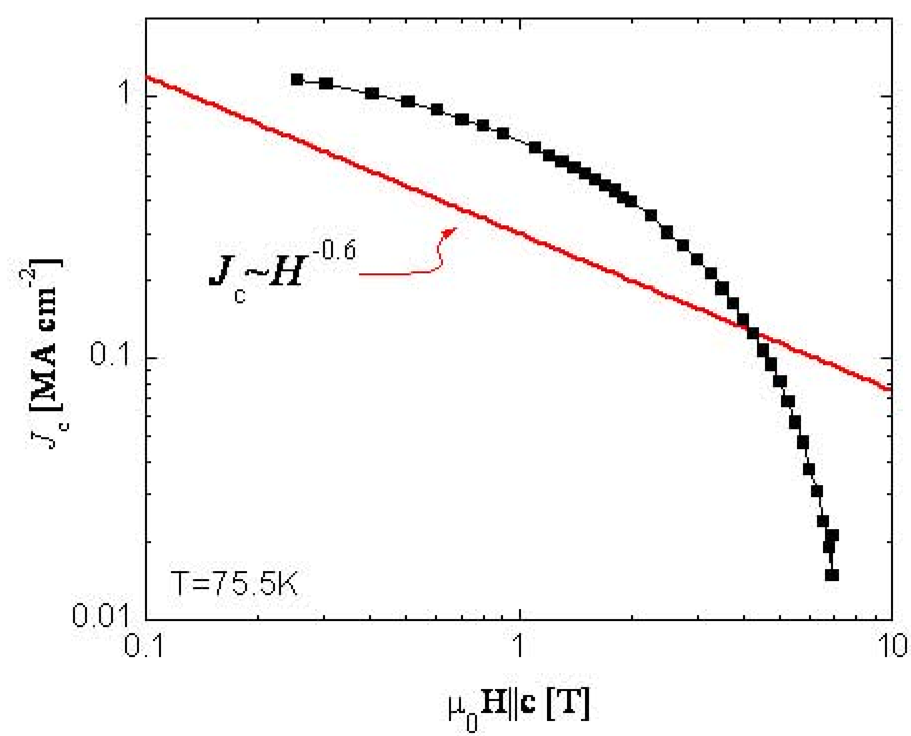


Absence of power-law decay in YBCO made by BaF_2-route

Brookhaven Nat. Lab. Collaboration

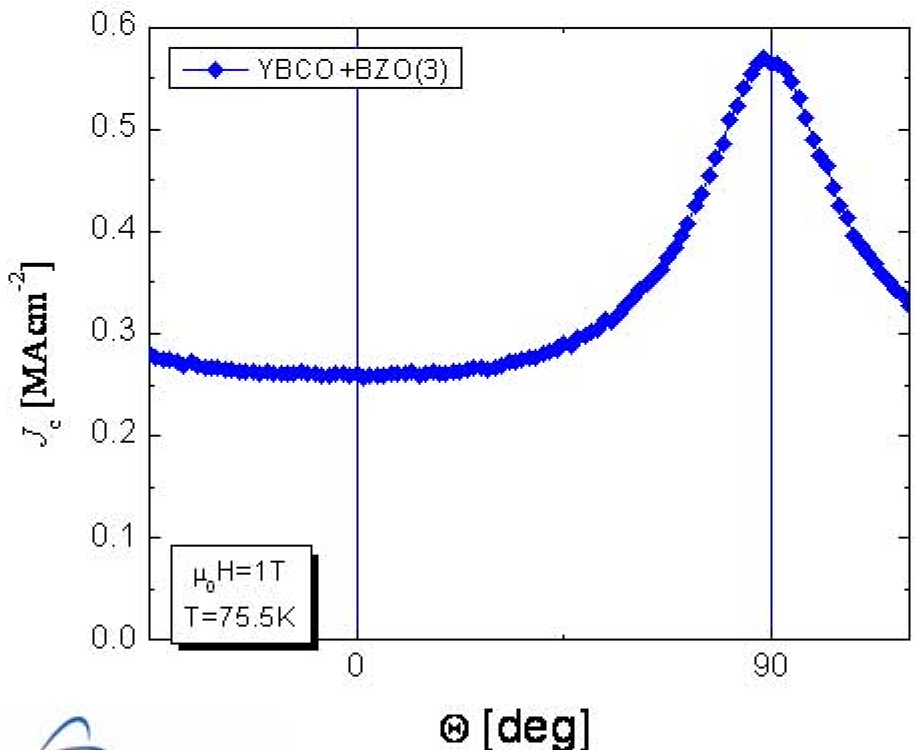
- No c-axis peak. Flat angular dependence
- No power-law decay at 75.5K
- Same phenomenology

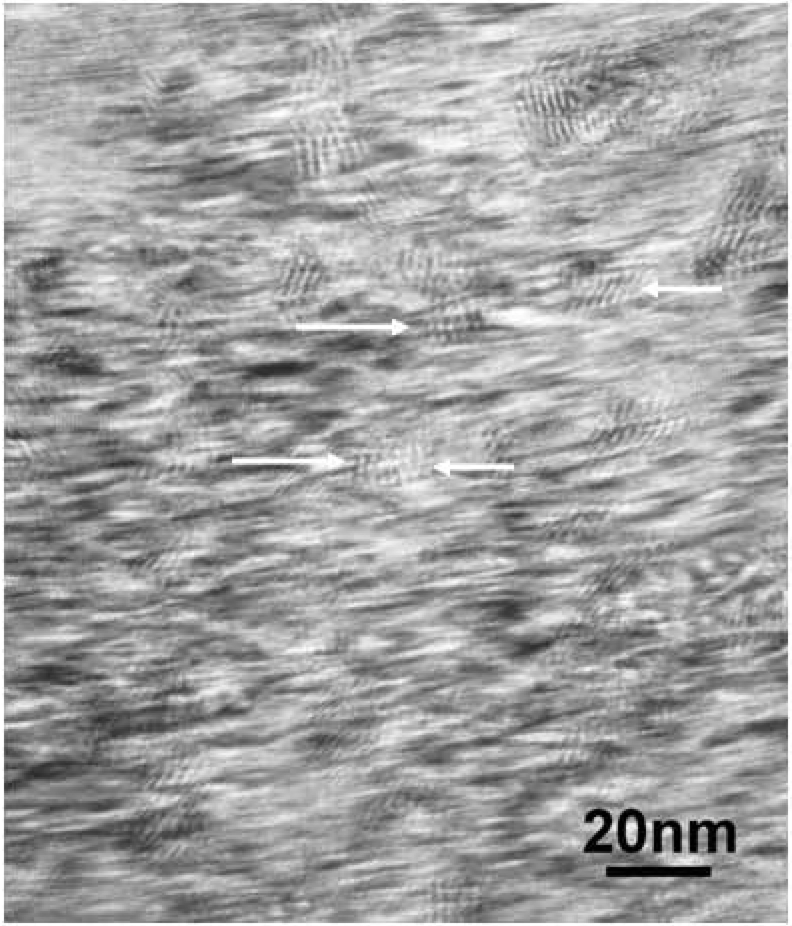




YBCO+BZO with no correlated defects, random BZO particles

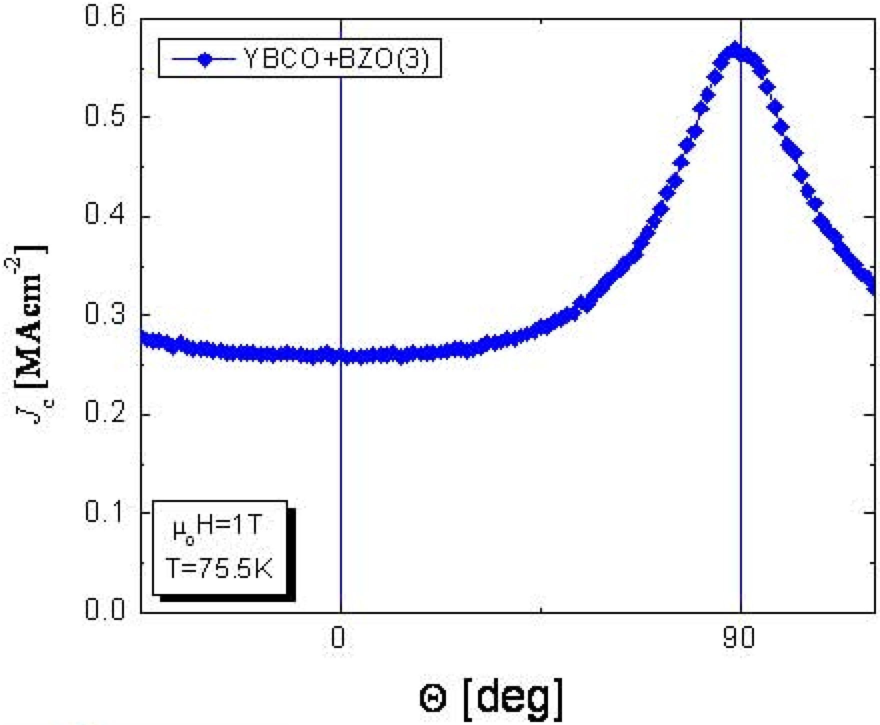
- Grown BZO-doped without c-axis correlated defects YBCO+BZO(3)
- Same chemical composition
- Randomly distributed particles ~10nm size
- No c-axis peak

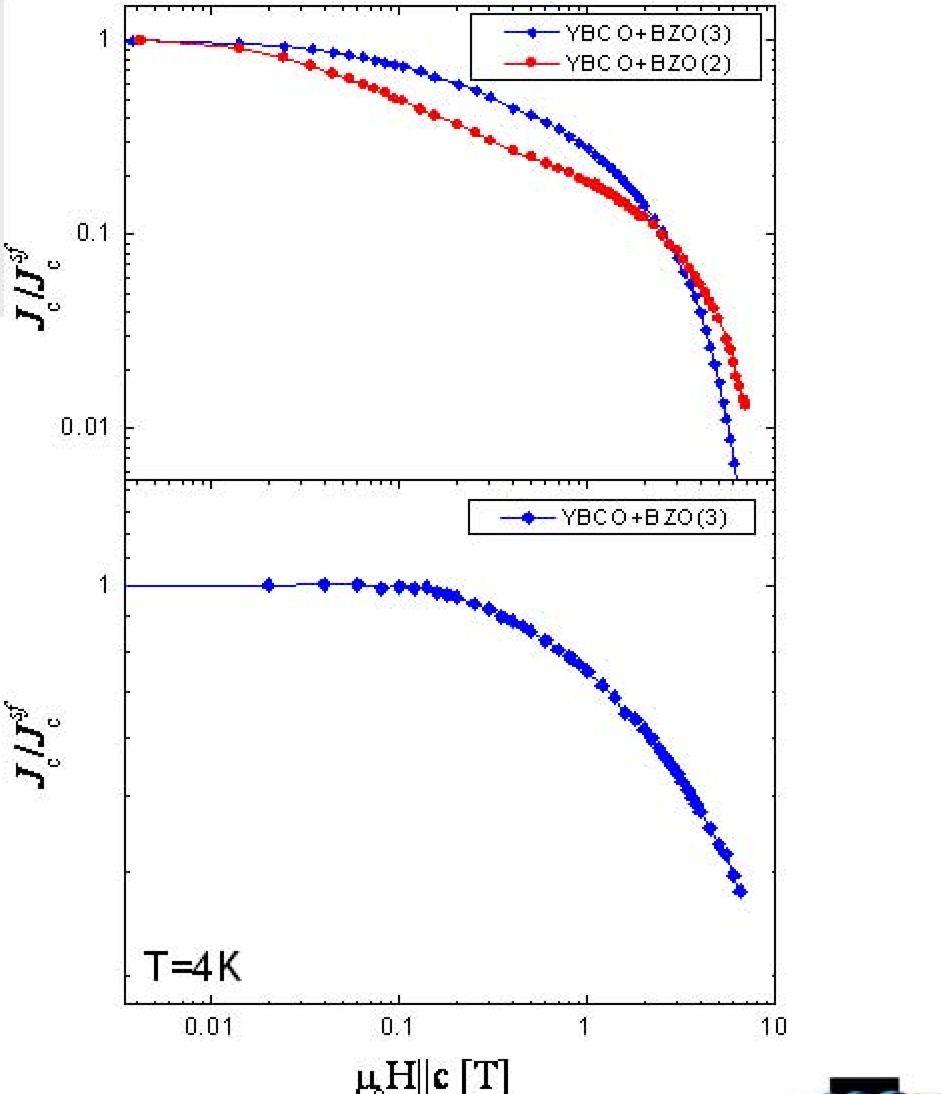




YBCO+BZO samples with no correlated defects: No power-law in $J_c(H)$ from 4-75K

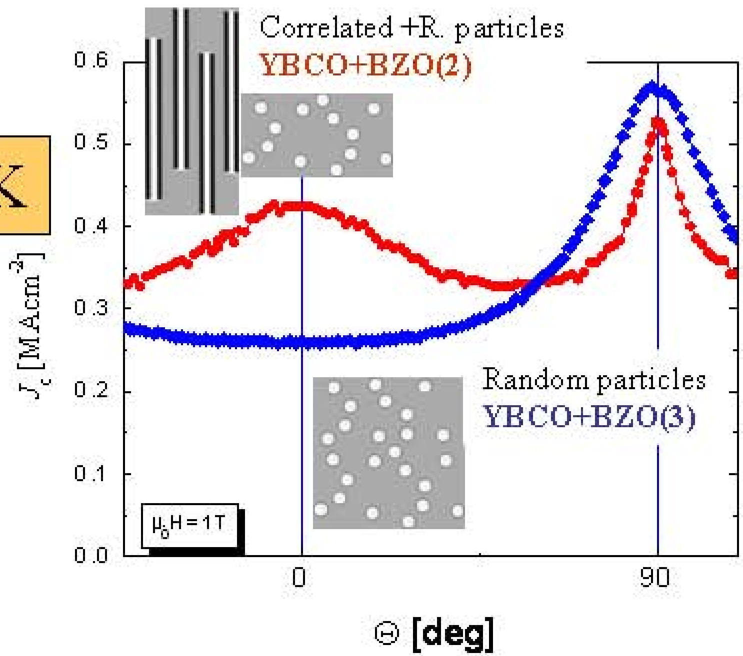
- Same chemical composition but $J_c(\Theta)$ does not show c-axis peak.
- Disperse particles ~10nm size
- No power-law decay at intermediate field region in all temperatures 5K-75K

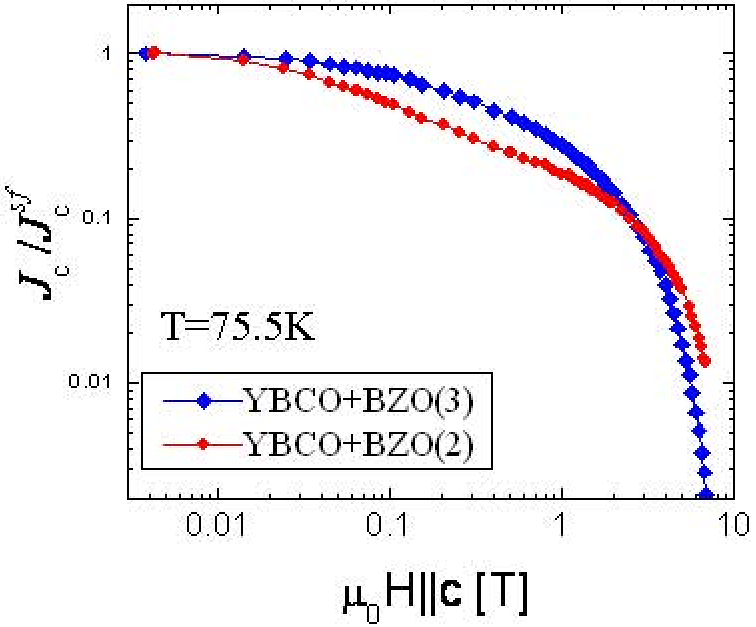




Summary of behavior of BZO-doped samples

T=75.5K



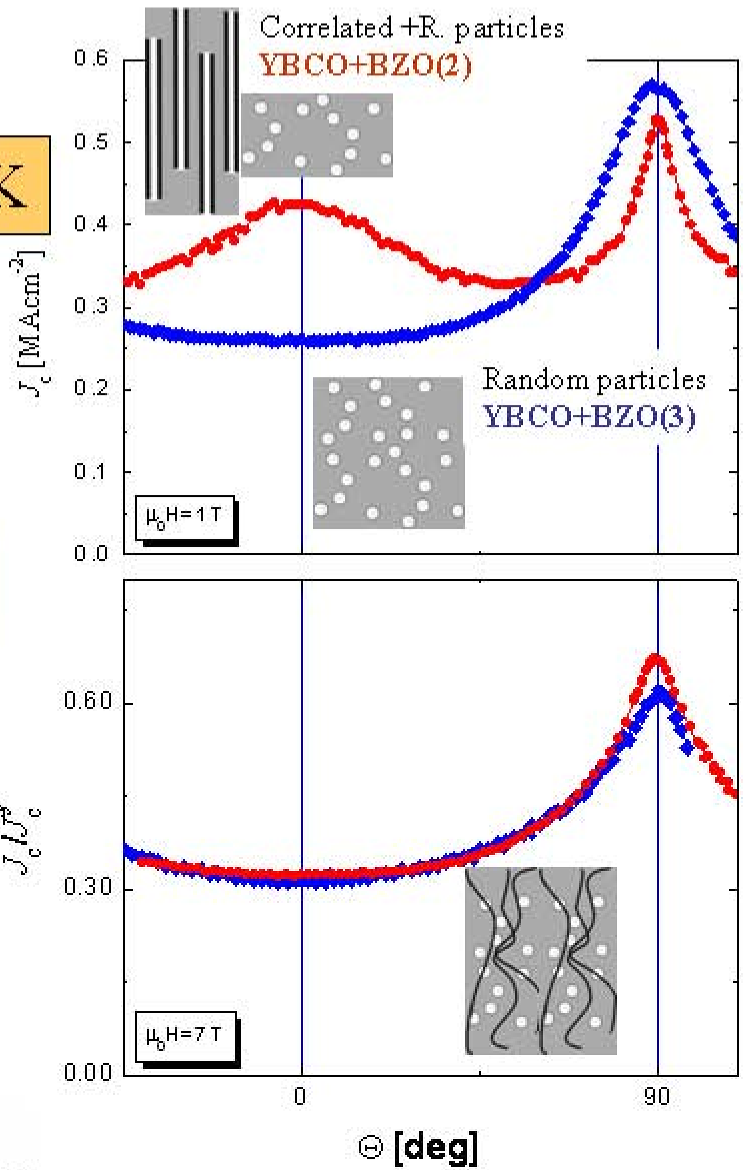


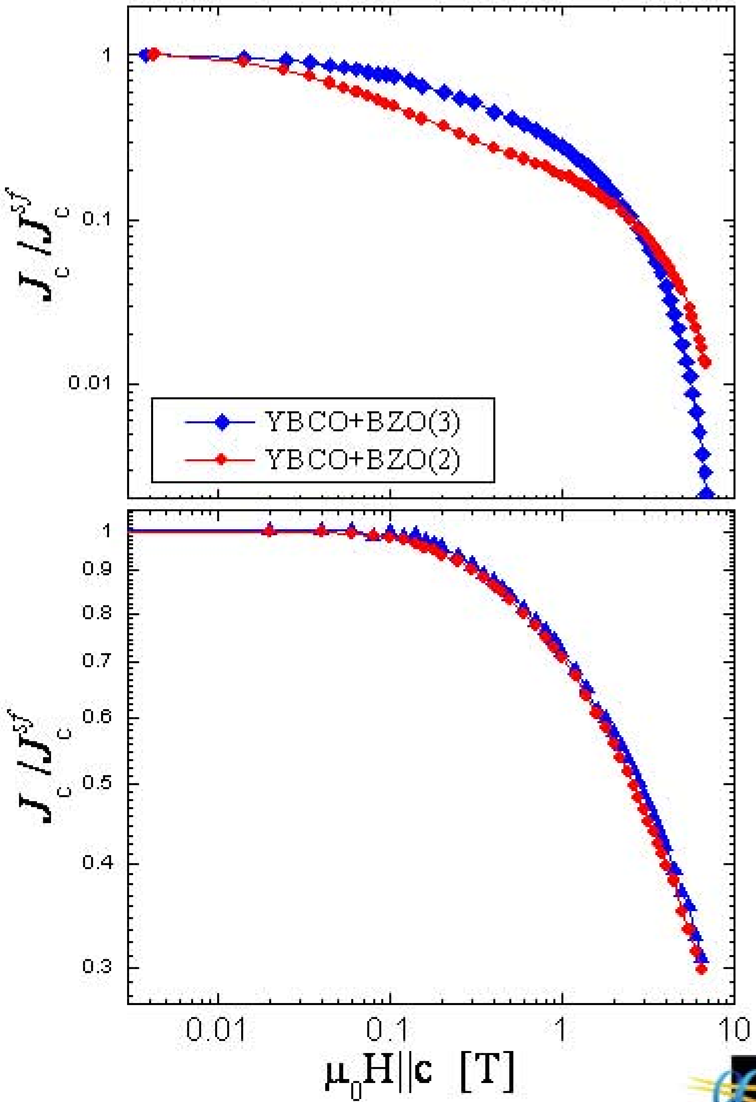
Summary of behavior of BZO-doped samples

T=75.5K

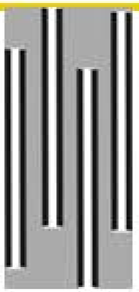
crossover T~40K

T=4K



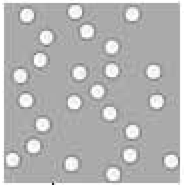


Identification of pinning mechanisms and microstructural defects in YBCO+BZO films



Correlated disorder (α~ 0.20)

- Correlated defects: Important at higher temperature
- Power-law exponent (α) with temperature (more important c-axis peak)
- Particles: More important at low temperatures. (T<40K)
- Correlated disorder is irrelevant against strong random pinning; Hwa *et al.* PRB **48**, (1993)

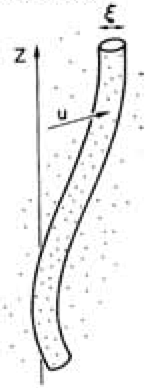


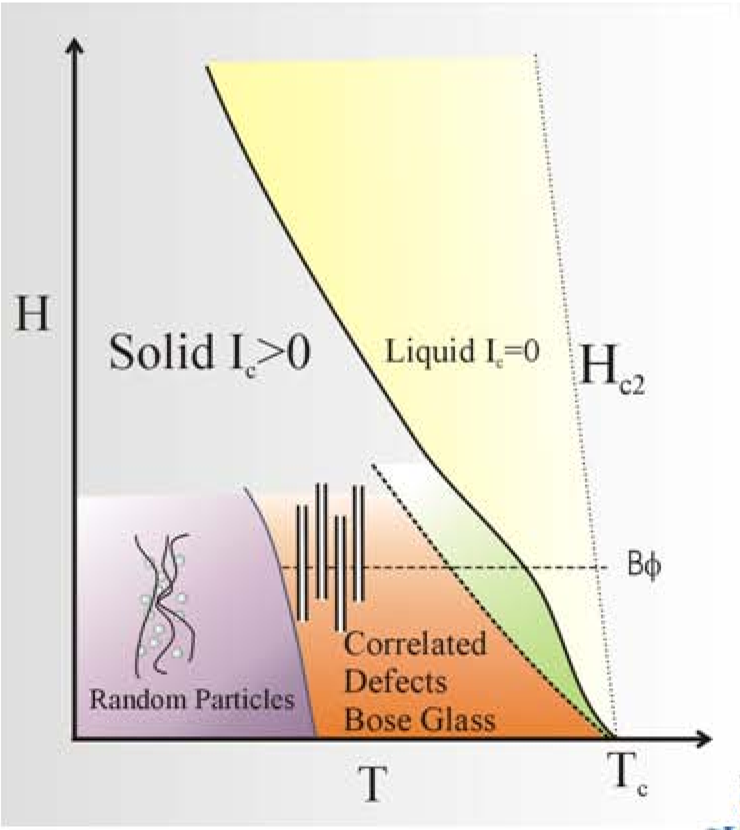
Random Particles

- Absence of correlated disorder
- Non-power law J_c(H) for all temperatures

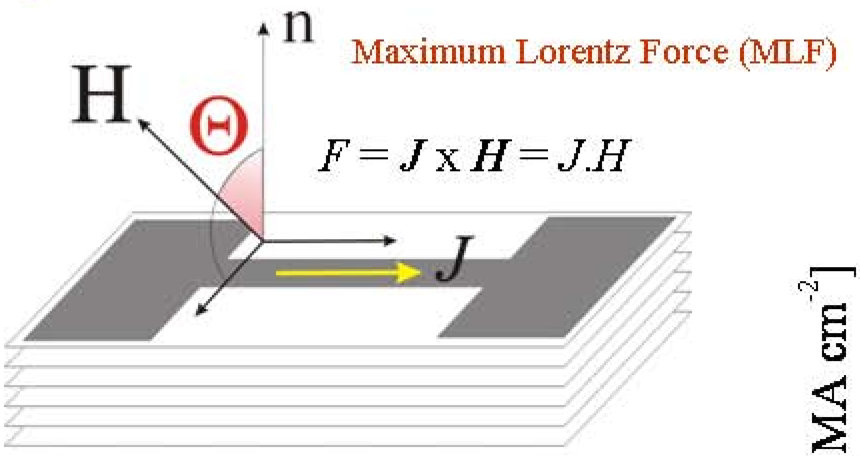
Random Point-like disorder (α~0.60)

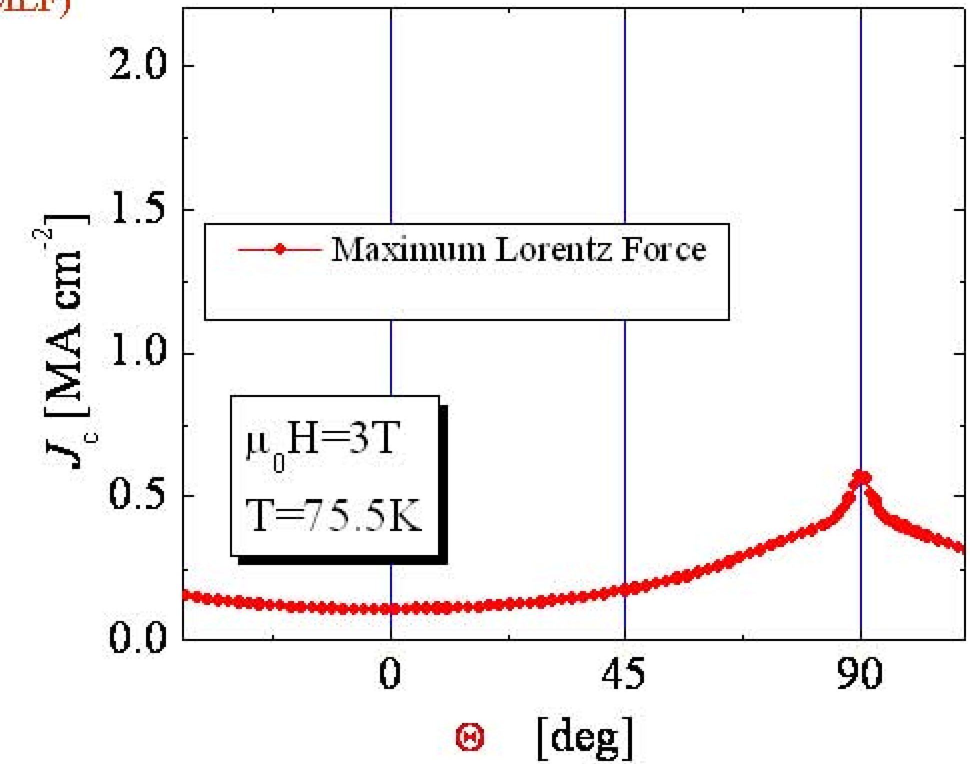
- Power law decay at all temperatures
- Important at low temperatures and Θ>>0





Motivation: understand vortex pinning in realistic current and magnetic field configurations





- Important to explore other field-current configurations where J is not perpendicular to H
- Determine influence of pinning

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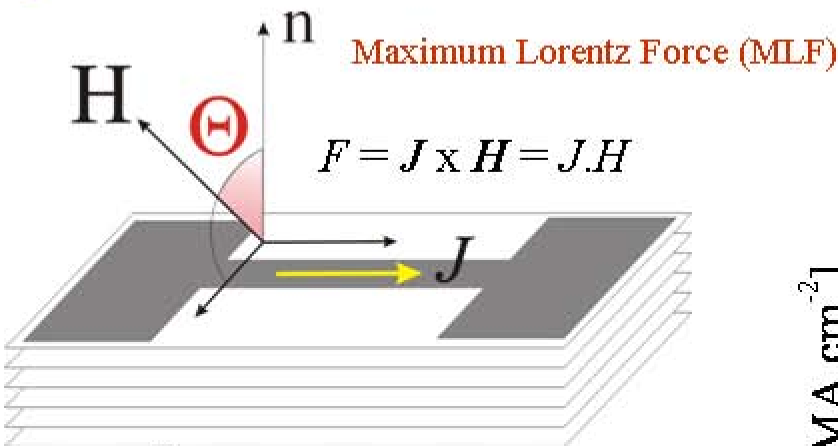
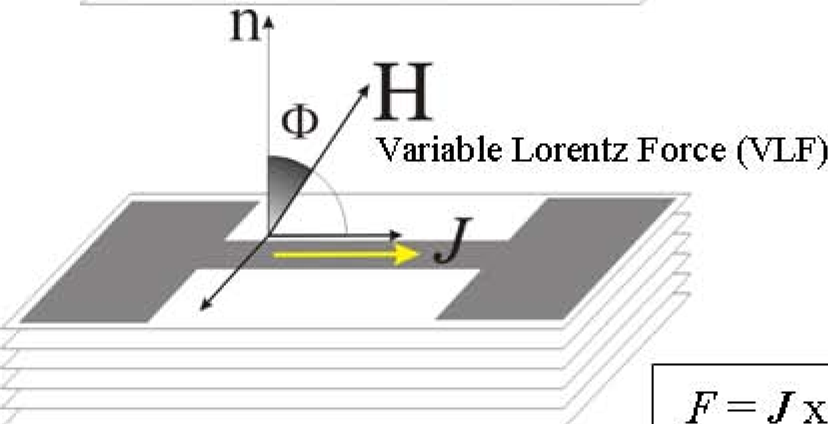
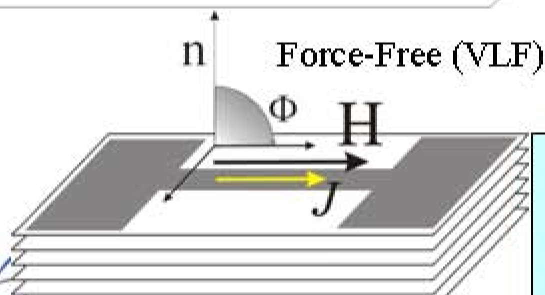
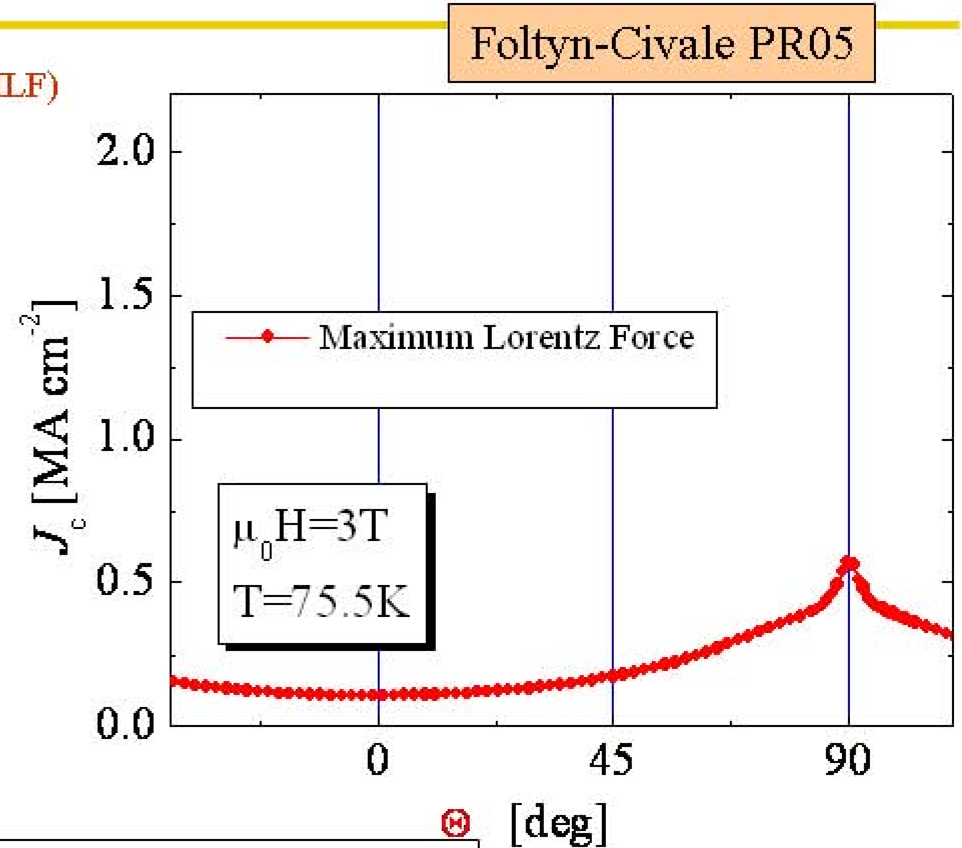
Variable Lorentz Force and Force-Free configuration







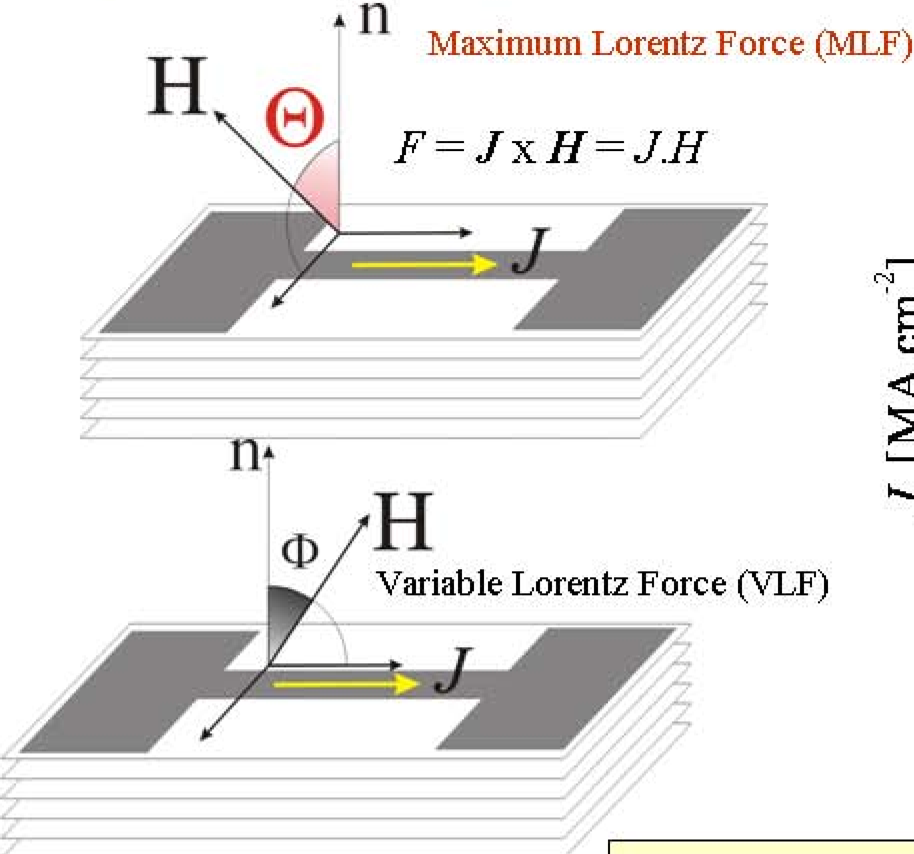


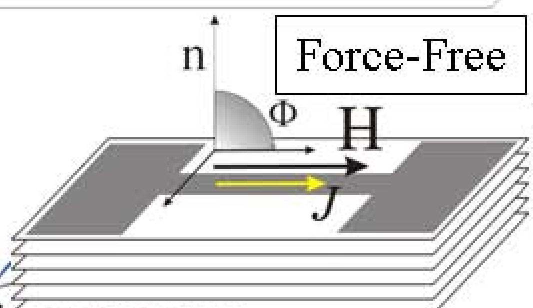
$F = J \times H = J.H \cos(\Phi)$

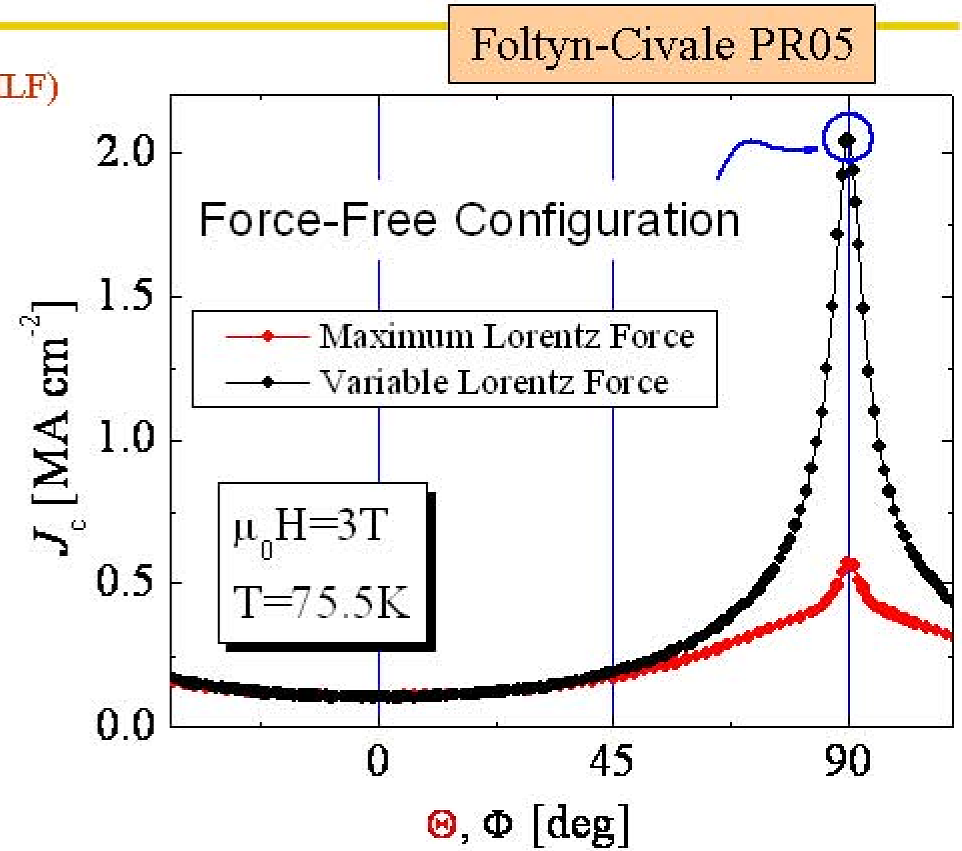
For $\Phi=90°$ $\rightarrow$ $F=0$ (Force Free)

- Important to explore other field-current configurations where *J* is not perpendicular to H
- Determine influence of pinning, how to improve it.

Variable Lorentz Force and Force-Free configuration







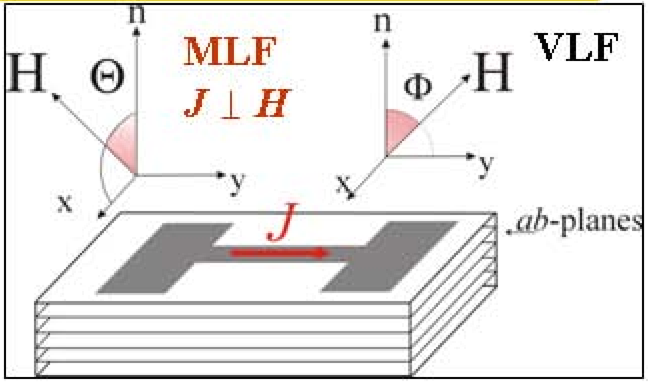
Vortex mechanism responsible for high-J_c

References: J.Clem PRL **38** (1977); E.H.Brandt JLTP **44** (1981); T.Matsushita *et al* Jap. J. Appl. Phys. **25** (1986)

- No theory for HTS.
- No studies in HTS of how pinning affects in Force-Free configuration

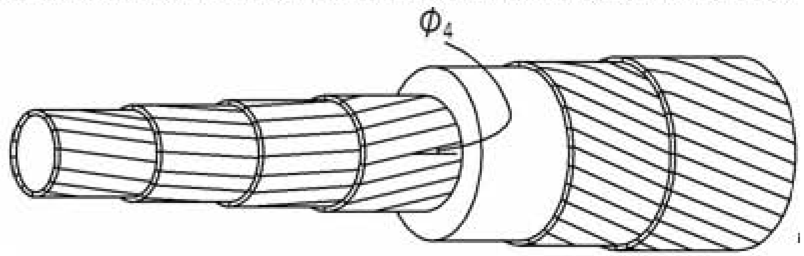
Realistic Current-Field configurations: Relevance of Variable Lorentz Force and Force-Free configuration

- J_c is higher when J is not perpendicular to H.
- Pitch in cables creates Variable Lorentz Force configuration.
- If $J_c(FF)$ high, design can take advantage of this configuration
- Relaxes condition for mechanical strength (net force).



$$F = J \times H = J.H \cos(\Phi)$$

J.Kondoh *et al IEEJ Trans. on Power and Energy*, **120** (2000)



Furth *et al* IEEE Trans. Magn **24,** 1467 (1988)

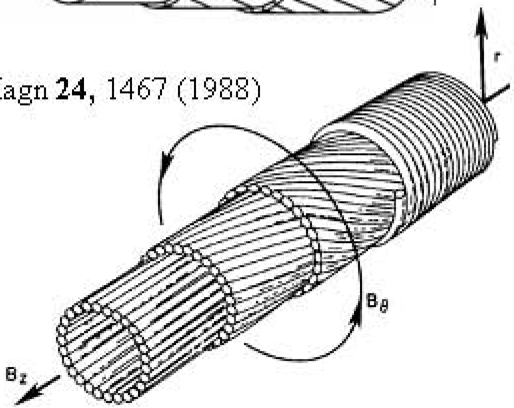
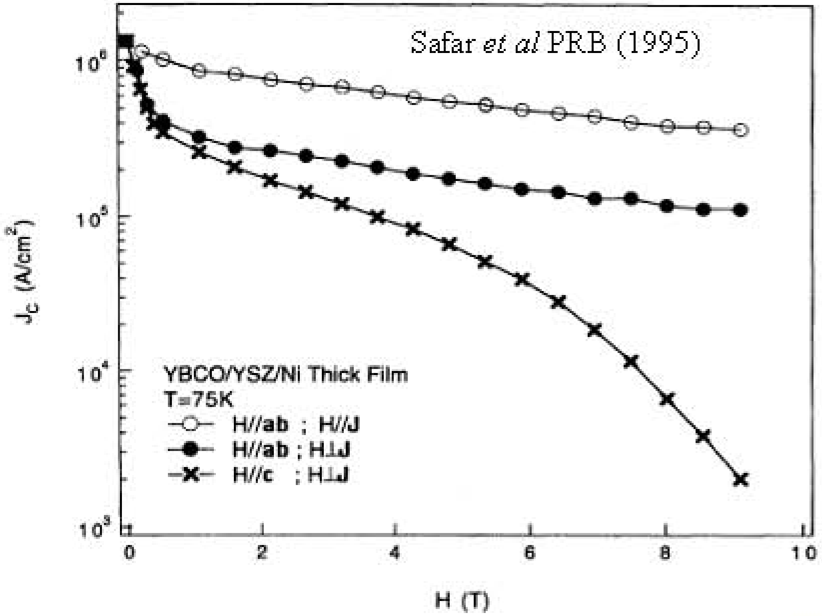
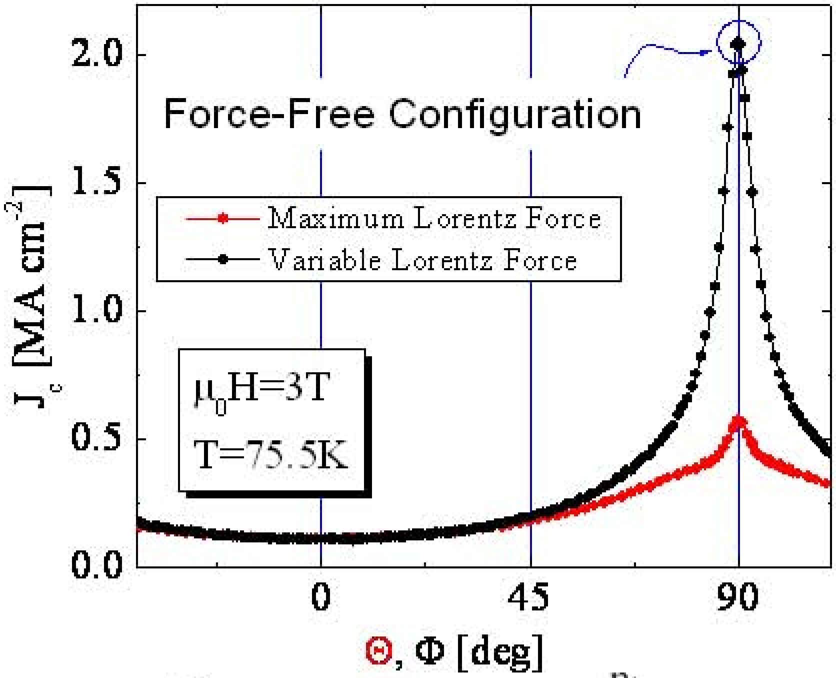
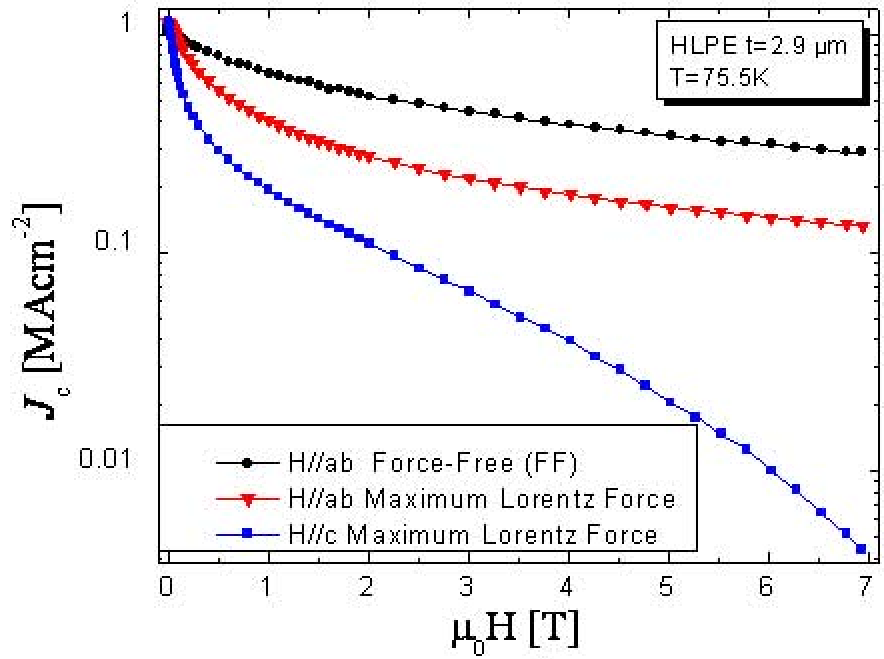


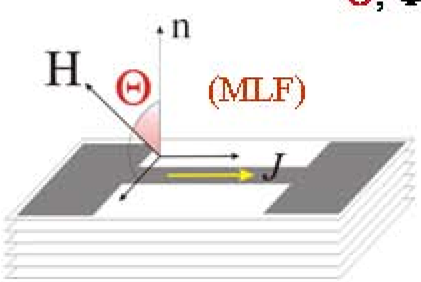
Fig. 1. Force-free cables use helical windings of varying pitch.

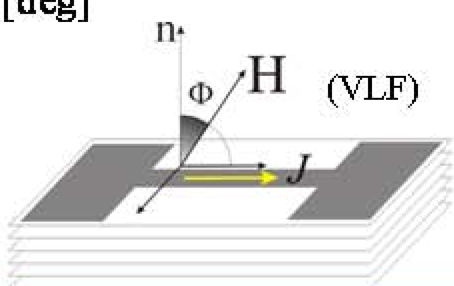


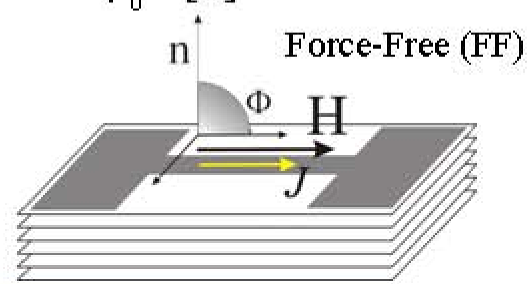
Set of tools to study Variable Lorentz Force and Force-Free configuration











GOALS

- Determine influence of pinning in J_c(Force-Free) in CC
- Increase J_c(Force-Free)

Los Alamos NATIONAL LABORATORY EST.1943

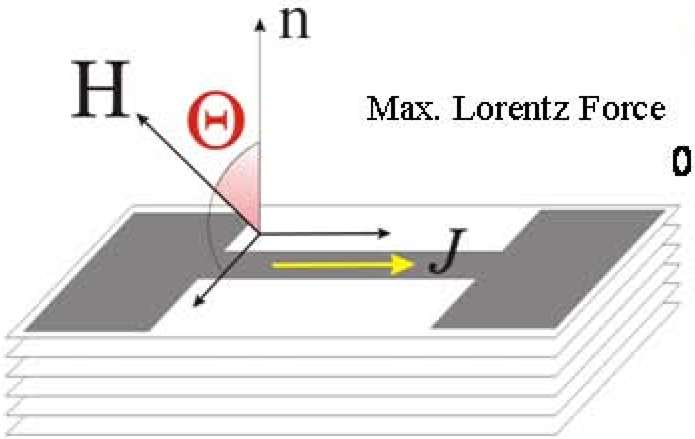
STC

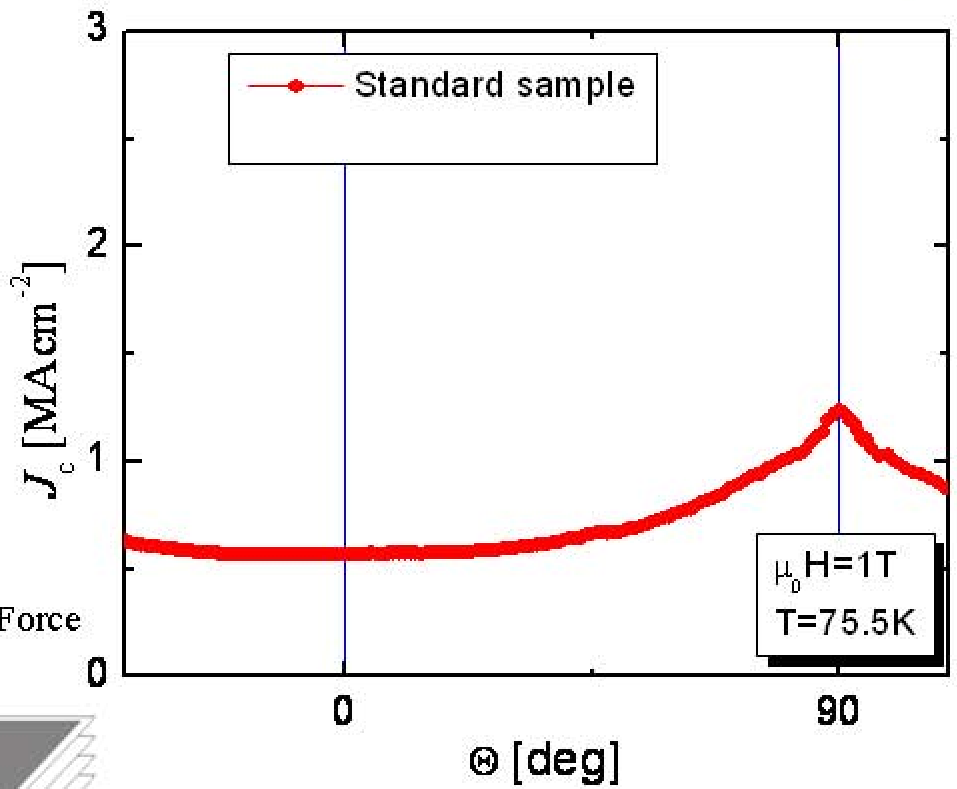
To study the influence of the pinning in J_c(FF) we select two samples with different pinning strength at H//ab

"Standard" sample, PLD YBCO/$SrTiO_3$

•thickness = 0.34 μm

•$J_c(sf)$=4.5 $MAcm^{-2}$





•Study samples on single crystals to isolate possible effects from grain boundaries.

•Samples with different microstructures and pinning characteristics

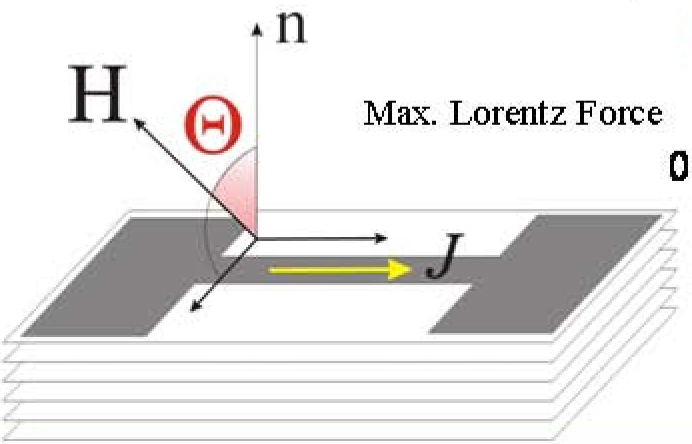
To study the influence of the pinning in J_c(FF) we select two samples with different pinning strength at H//ab

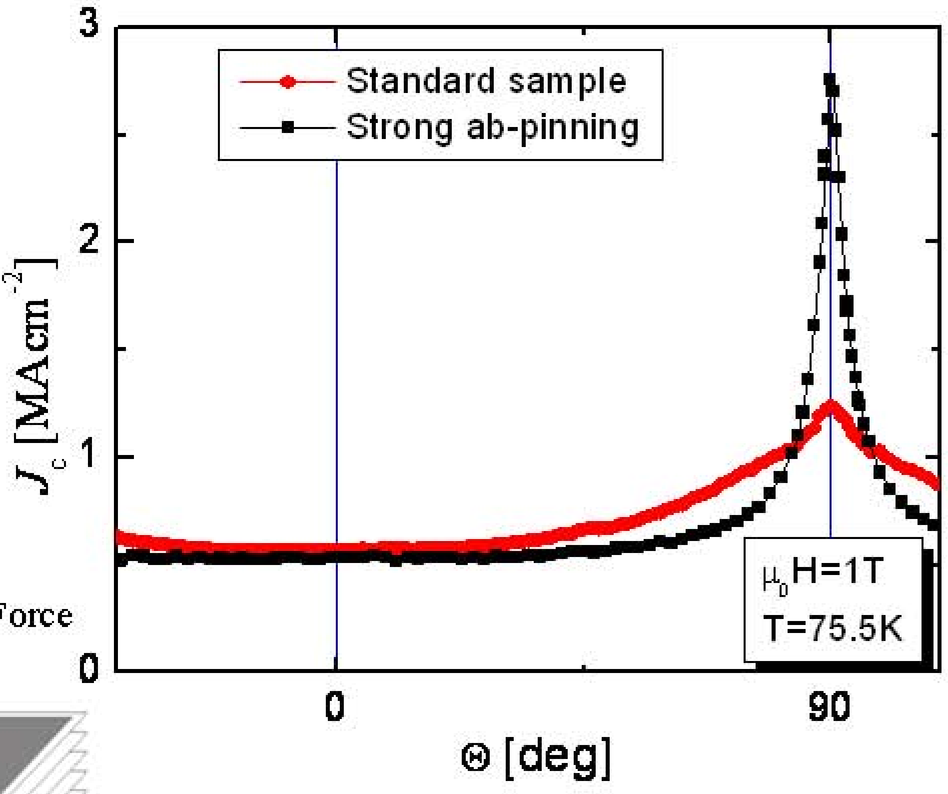
Standard sample, PLD YBCO/$SrTiO_3$

- thickness = 0.34 μm
- $J_c(sf)$=4.5 $MAcm^{-2}$

"**Strong**" ab-pinning, PLD YBCO/$LaAlO_3$

- thickness =0.30 μm
- $J_c(sf)$=4.85 $MAcm^{-2}$





- Higher peak in $J_c(\Theta \sim 90^\circ)$ indicates stronger pinning at ab-plane.

Higher ab-peak is reflected in smaller field decay

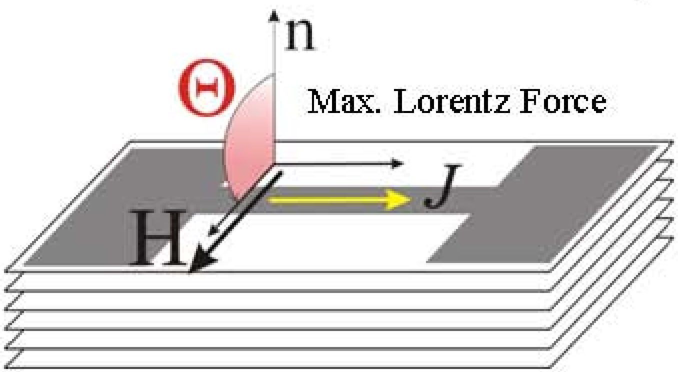
•The ratio of decay for J_c(7T)/J_c(sf) also quantifies the strength of pinning at the ab-planes

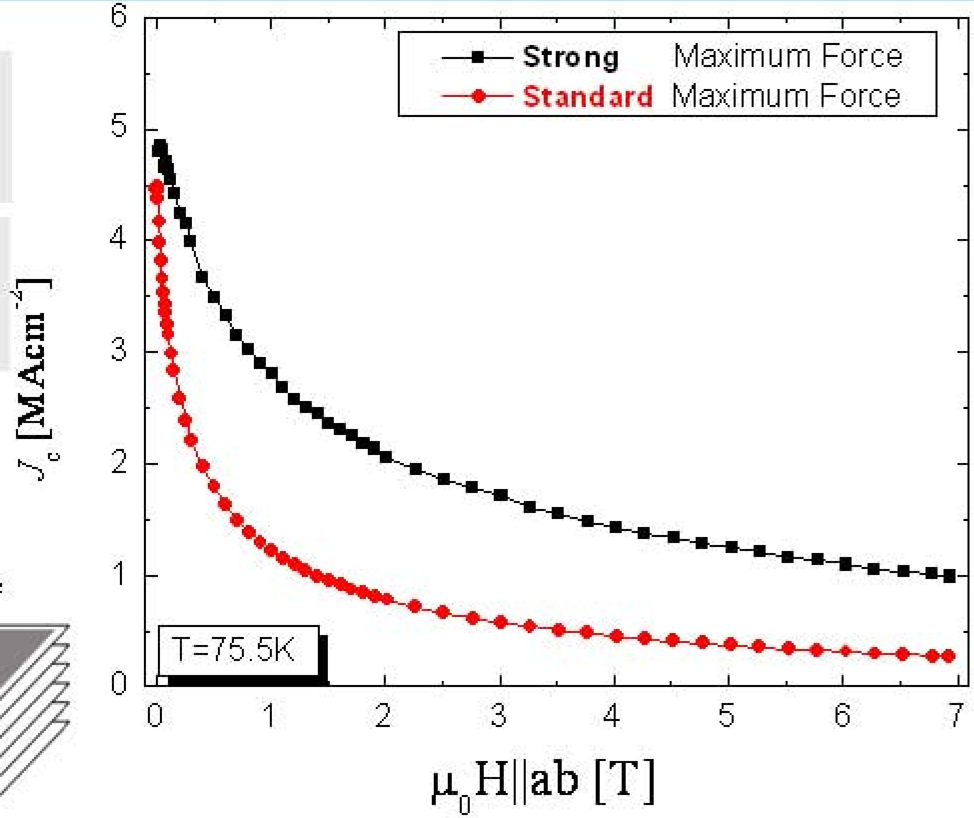
•"**Standard**" sample $J_c(7T)/J_c(sf)$=0.06

•$J_c(sf)$=4.5 $MAcm^{-2}$

•"**Strong**" ab-pinning $J_c(7T)/J_c(sf)$=0.20

•$J_c(sf)$=4.85 $MAcm^{-2}$



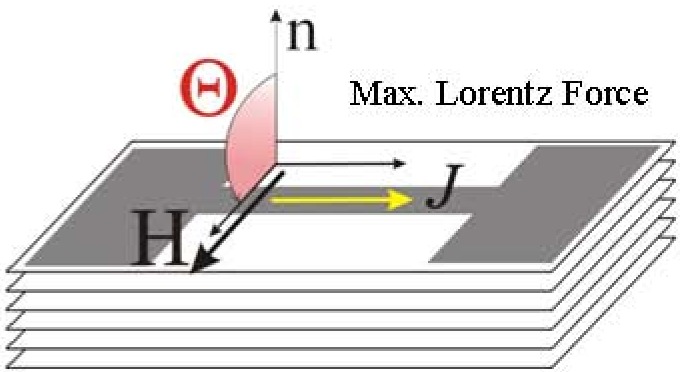


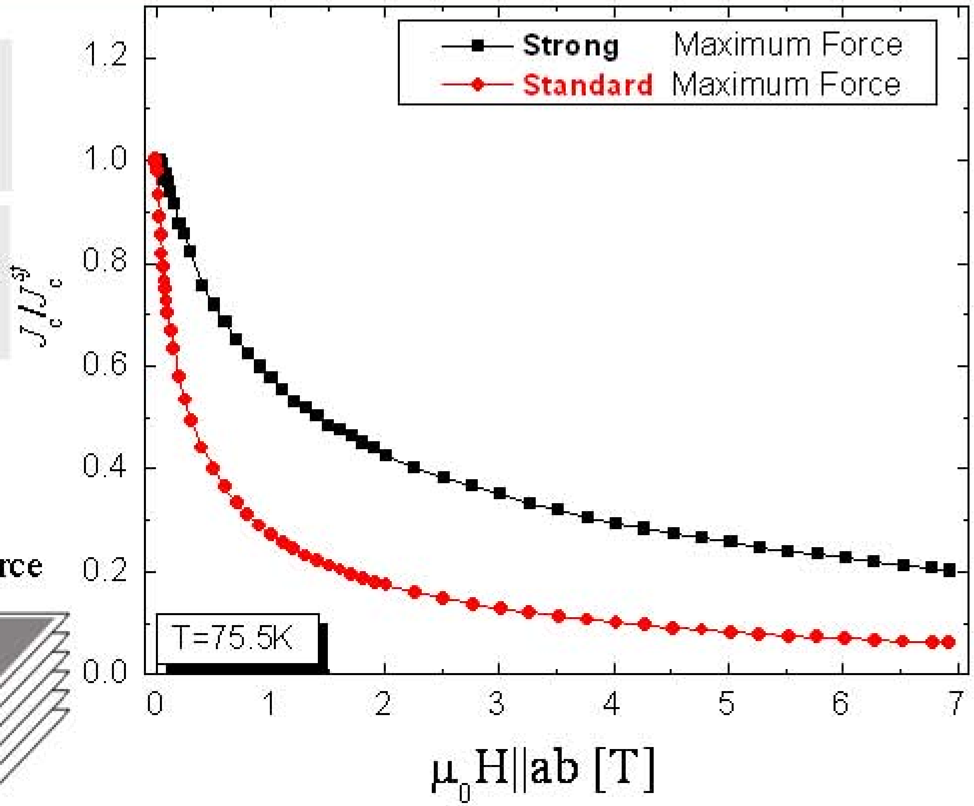
Higher ab-peak is reflected in smaller field decay

- The ratio of decay for $J_c(7T)/J_c(sf)$ also quantifies the strength of pinning at the ab-planes

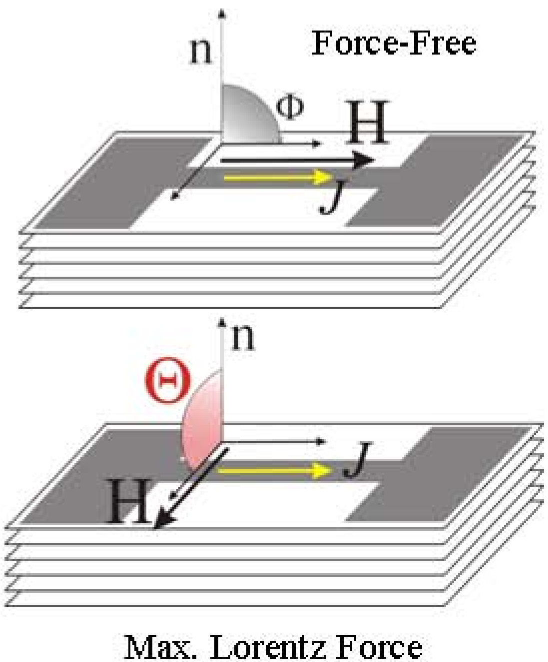
- "**Standard**" sample $J_c(7T)/J_c(sf)=0.06$
- $J_c(sf)=4.5$ $MAcm^{-2}$

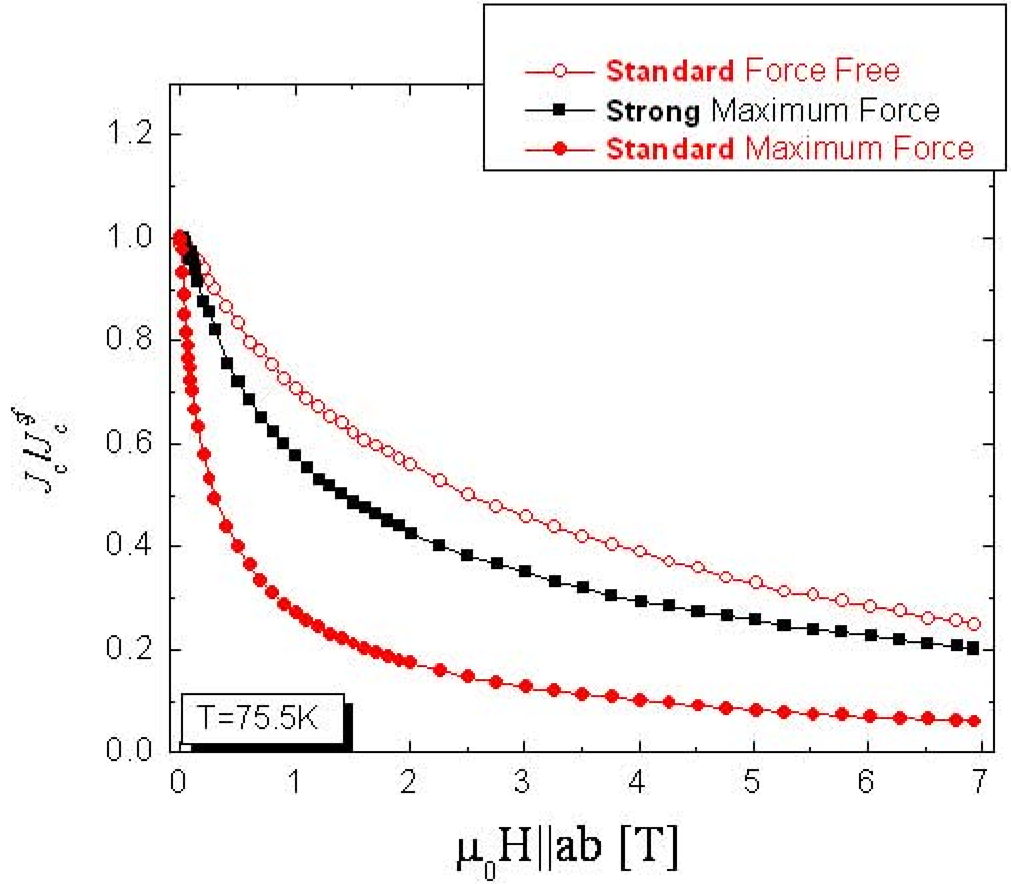
- "**Strong**" ab-pinning $J_c(7T)/J_c(sf)=0.20$
- $J_c(sf)=4.85$ $MAcm^{-2}$





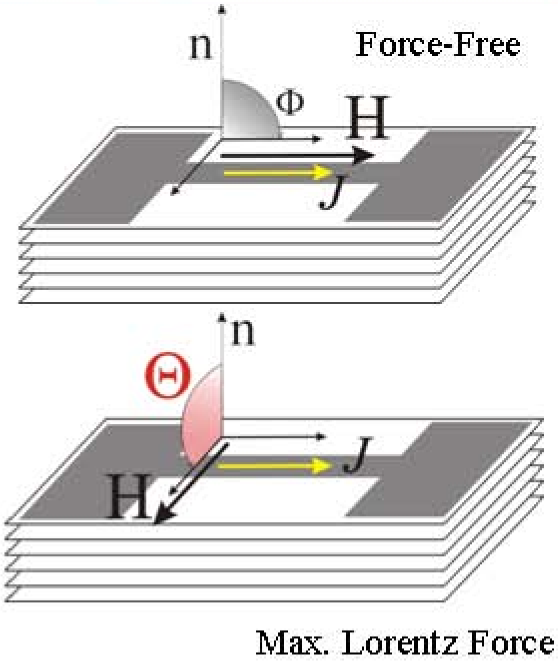
Samples with stronger pinning at ab-planes have much higher $J_c(FF)$

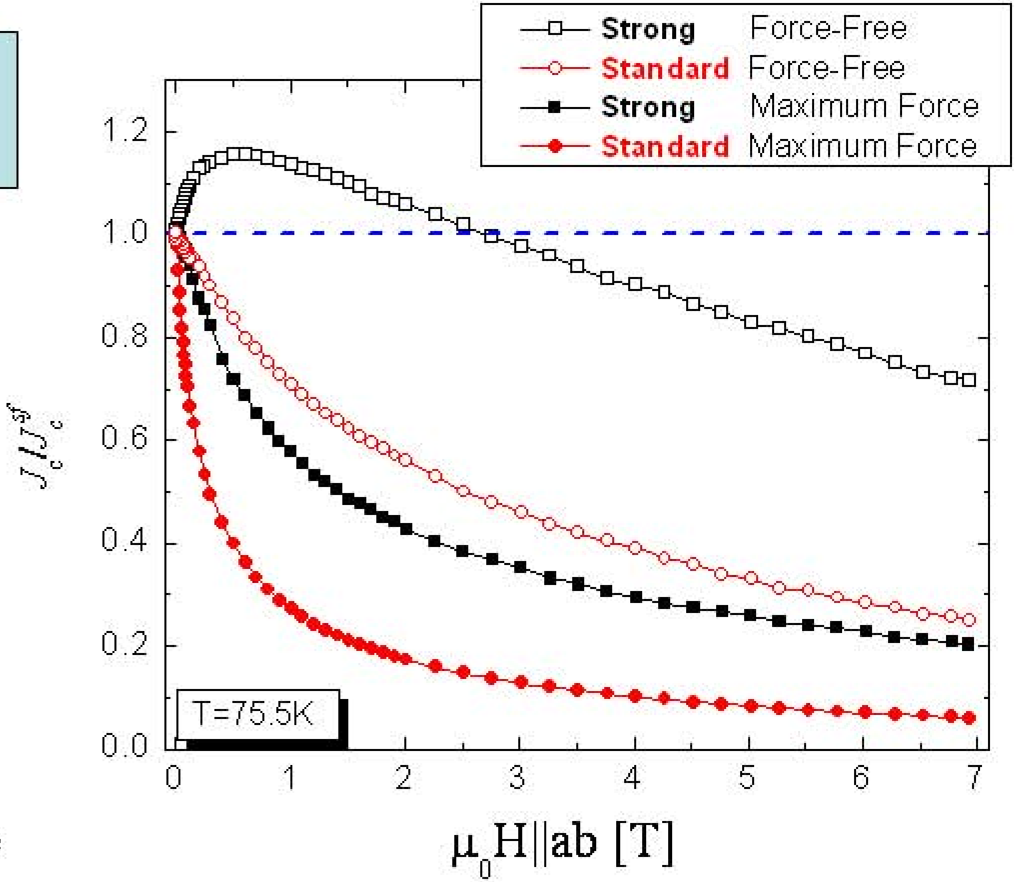




Samples with stronger pinning at ab-planes have much higher $J_c(FF)$

- "**Strong**" sample has $J_c(FF)>J_c(sf)$
- $J_c(FF)>J_c(sf)$ up to $\mu_0H=3T$!!





First observation of increasing $J_c(FF,H)$ in high J_c HTS

$J_c(FF)$ increase is well known in LTS

Sekula *et al* APL **2** (1963)

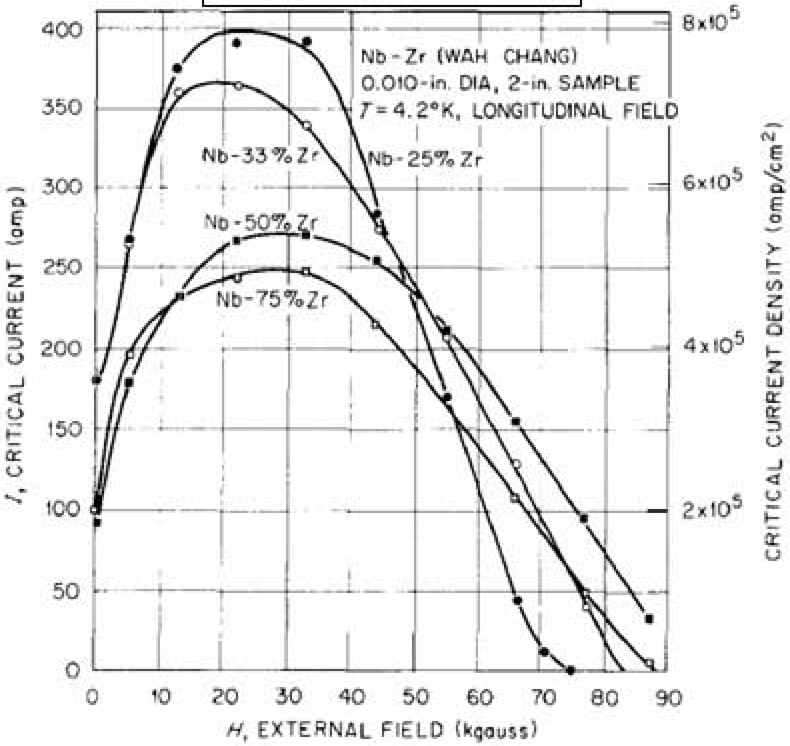
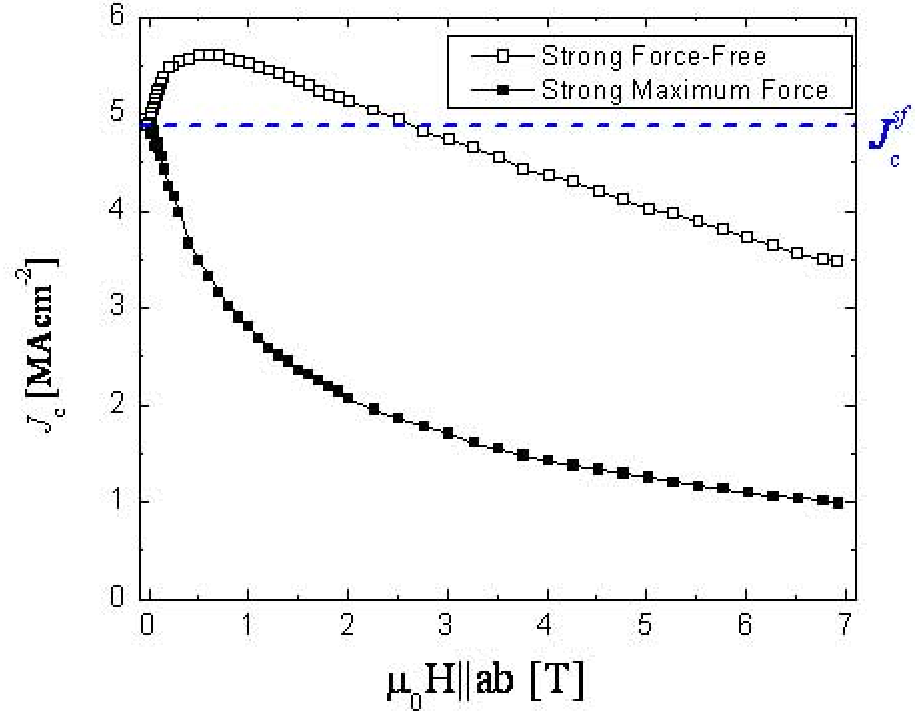


Fig. 1. Longitudinal critical current vs applied field for several cold-drawn Nb–Zr alloys.

• "**Strong**" ab-pinning



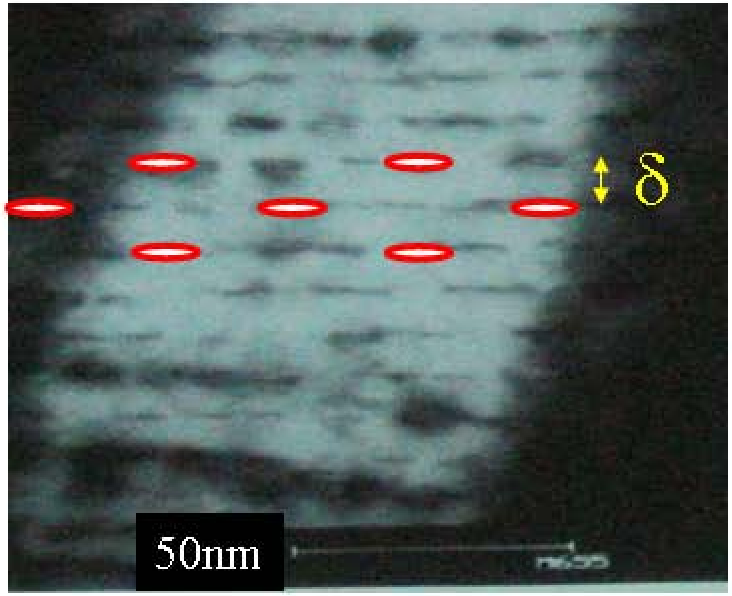
•Increasing J_c in Force-Free configuration was found in LTS wires

References: Cullen *et al*, APL **4** (1964) Nb_3Sn; Karasik & Vereshchagin, Zh. Eksp. Teor. Fiz **59**, (1970) Ti - 22 at.% Nb Gauthier *et al*, *Low Temp. Phys.* **3**,(1974) V, $Nb_{0.5}Ta_{0.5}$, Nb_3Zr, and NbTi.; Blamire & Evetts PRB **33** (1986) Pb-36%Tl; Matsushita *et al* Jap. J. Appl. Phys. **25** (1986) Pb+Bi;

Defects that affect pinning at the ab-plane: 211 inclusions with matching field for H//ab

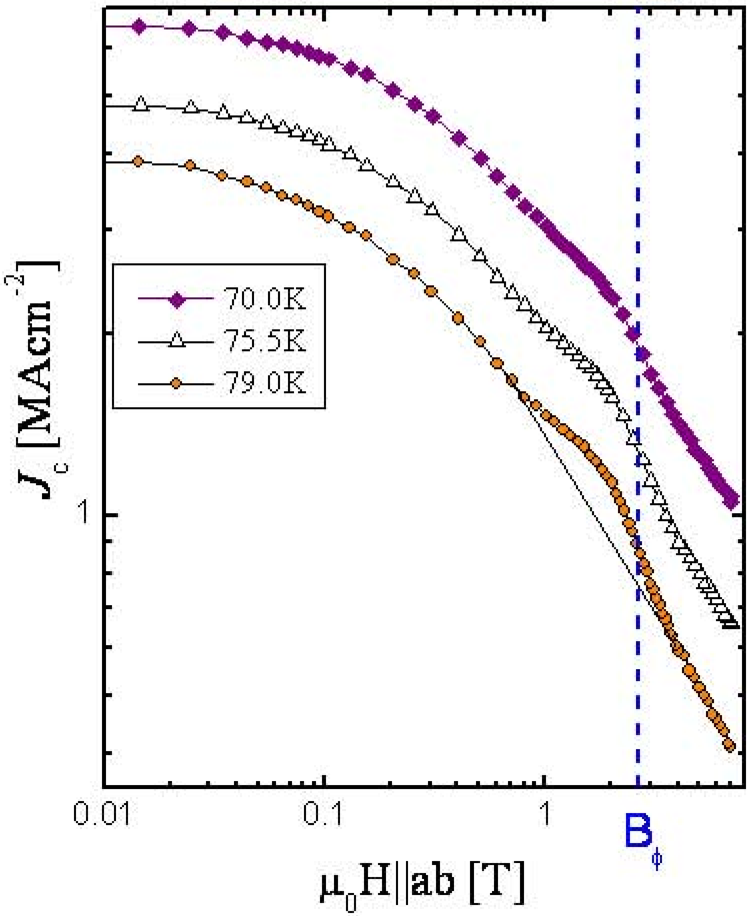
Wright-Patterson Air Force Lab. Collaboration

- Geometric matching field, bump in J_c(H).
- Position of B_ϕ Independent of temperature.
- Bump at slightly lower fields than expected.



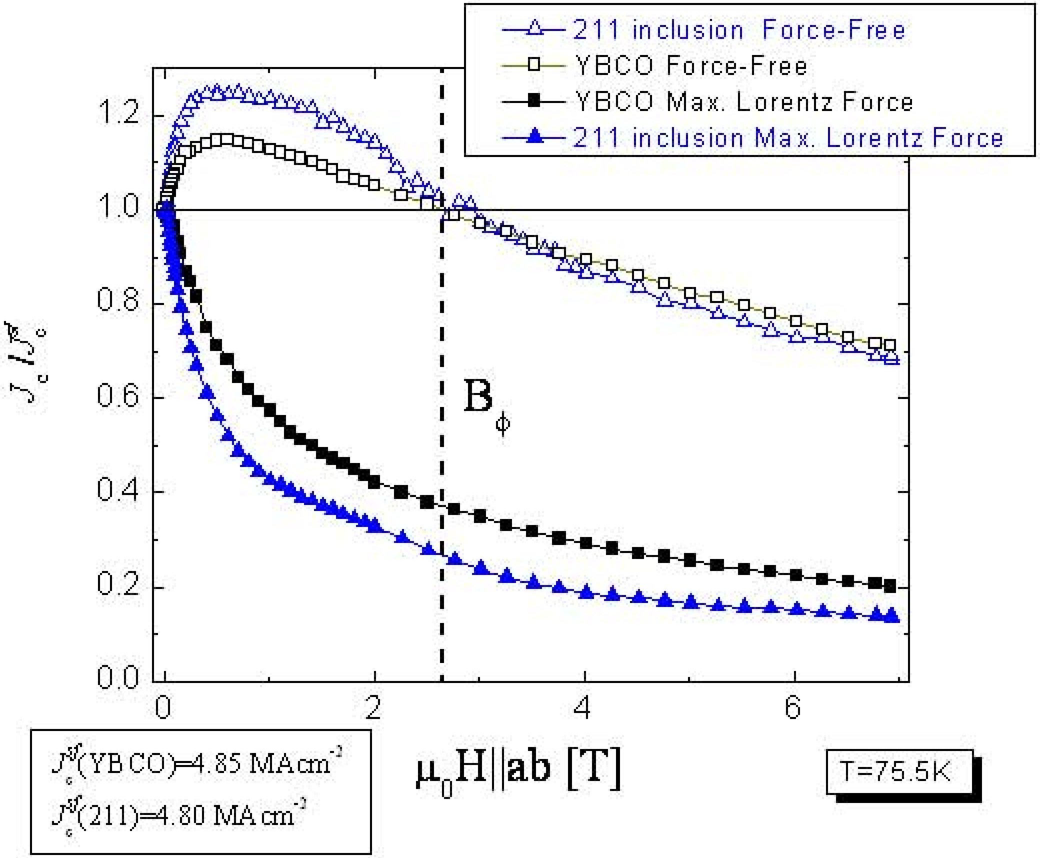
$$B_\phi = 3/(2\gamma)\phi_0 (1/\delta)^2 \quad (H||ab)$$

Driscoll-Civale PR04



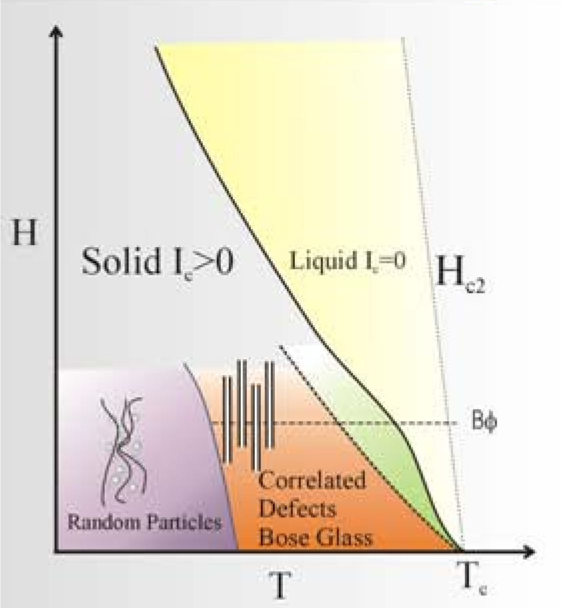
211 inclusions increase J_c(*Force-Free*) up to B_ϕ

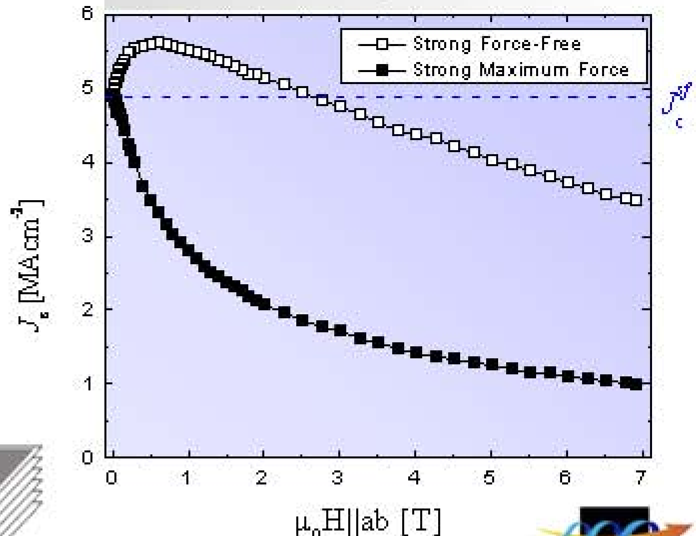
- Bigger enhancement of Force-Free with 211 inclusions
- Increase is sustained up to B_ϕ
- Clear indication of pinning center affecting J_c in Force-Free configuration

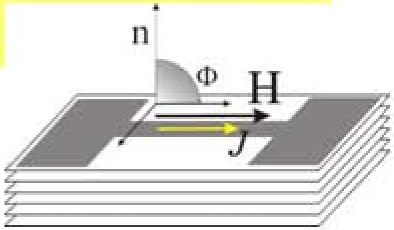


Scoring criterion -- Results

1. Explored $J_c(H,\Theta)$ temperature behavior of pinning enhancement routes. (BZO with and without c-axis peak, RE-mixtures).
2. Found change in pinning mechanism (T~40K) for YBCO+BZO with columnar defects. For T<40K c-axis peak and power-law decay are lost.
3. Combined tools (such as magnetization and transport) for further understanding of vortex pinning in coated conductors.
4. Explored Variable Lorentz Force and Force-Free configurations in films with diverse microstructures.
5. First observation of increasing $J_c(FF,H)$ in high J_c HTS films with naturally grown and artificially engineered defects.



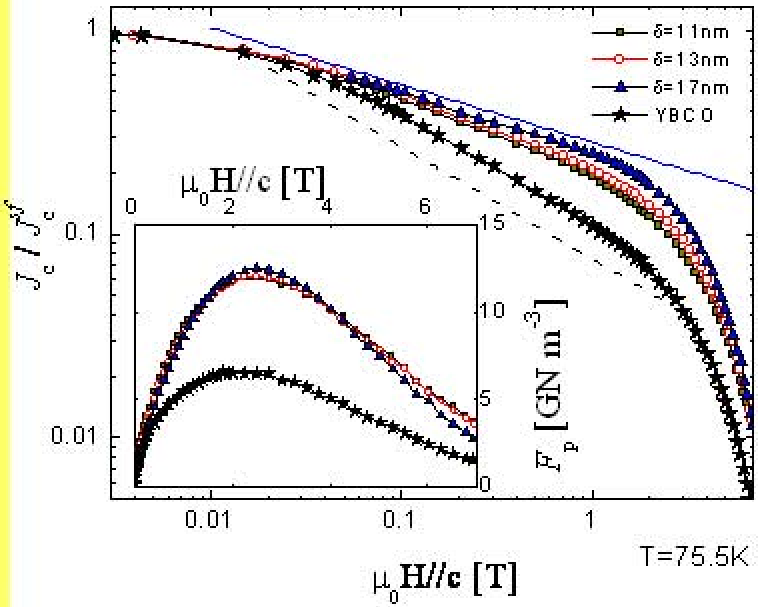




Scoring criterion – Results (continued)

…

6. Performed pinning studies of YBCO with 211 inclusions as a function of interlayer distance and at different temperatures (Wright Patterson Air Force Research Lab)
7. Studied the angular and field dependence in record J_c thick BaF_2–route films (Brookhaven National Laboratory)
8. Measured thickness dependence of MOD-TFA samples (ICMAB, Barcelona).
9. Performed pinning studies in Maximum and Variable Lorentz Force configuration in different Hybrid Liquid Phase Epitaxy samples (Cambridge).



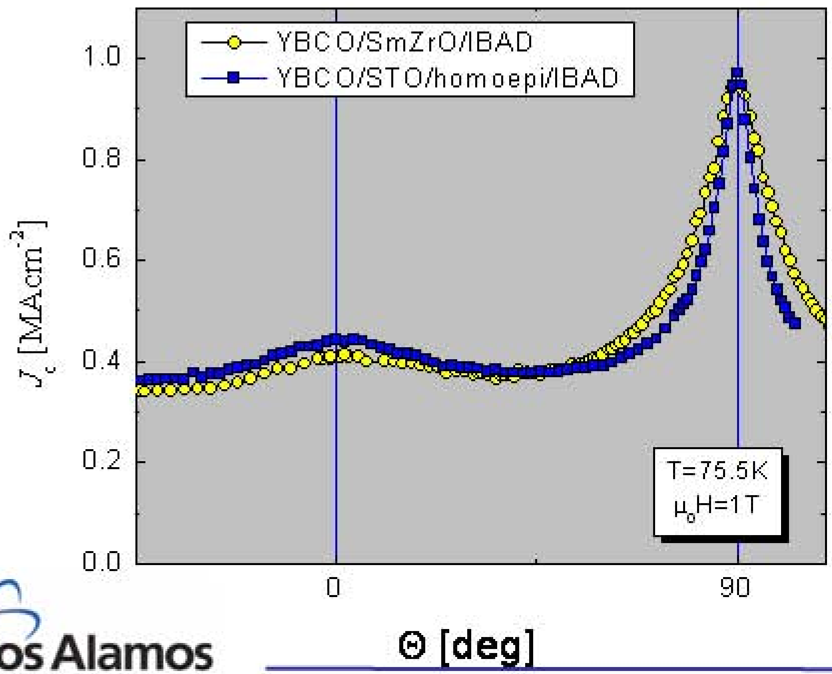
Scoring criterion -- FY2006 Performance

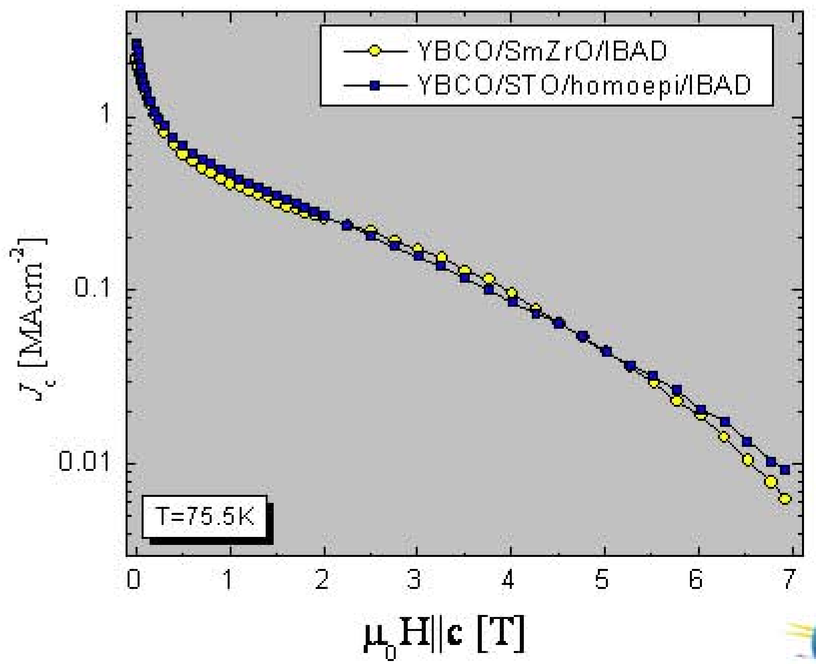
➔ Survey alternate interlayer or buffer layer materials.

Goal: Determine which properties are significant in producing high interfacial j_c.

Achievement: Studied field and angular dependence of YBCO on $SmZrO_y$ buffer layer, very similar to YBCO on $SrTiO_3$ buffer layer. Similar interfacial j_c

Advantage: Faster process and reduction of one layer in coated conductor stack (No need of homoepitaxial MgO)

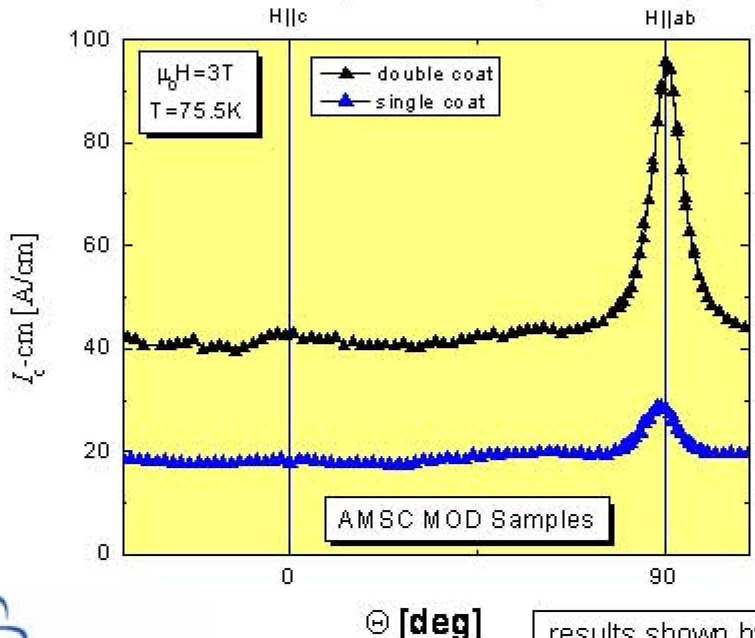




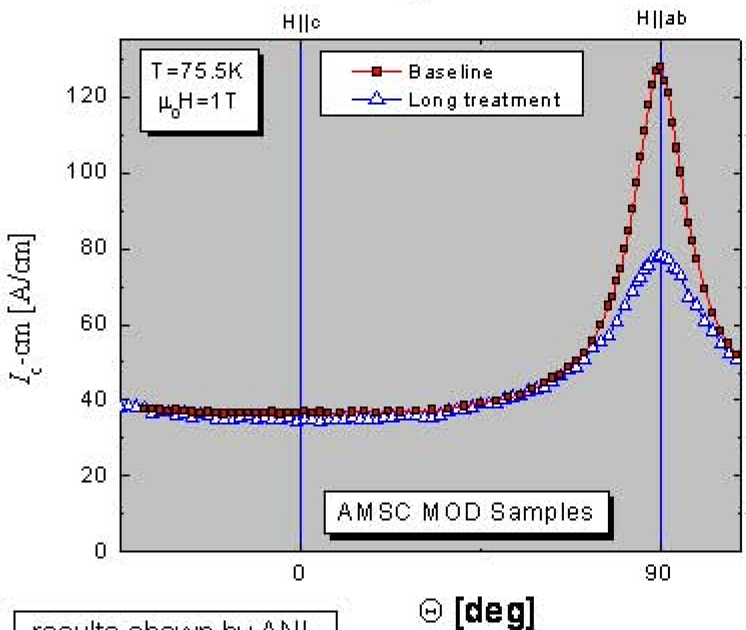
Scoring criterion -- FY2006 Performance (continued)

➔ Continue to work with American Superconductor in the understanding and enhancement of vortex pinning in ex-situ films.
Goal: To be coordinated with AMSC.

Achievement: Worked closely with AMSC in study of double-coating and pinning enhancement mechanisms. Also worked with Argonne National Lab studying the effects of thermal annealing.
Additional achievements: Performed studies in other ex-situ processes MOD-TFA (ICMAB,Barcelona) and BaF_2 route (Brookhaven National Laboratory)



results shown by WDG



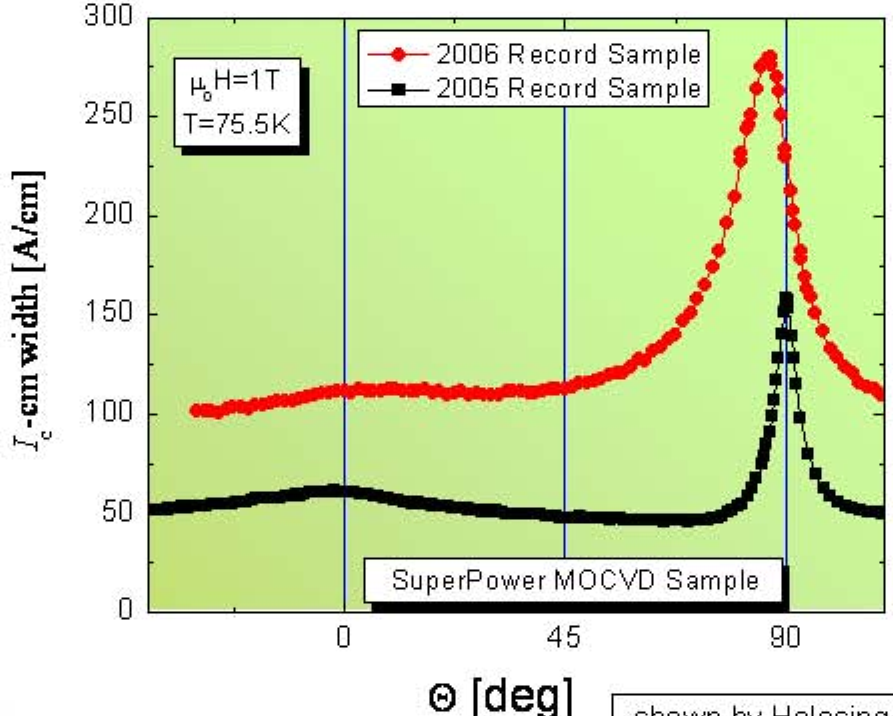
results shown by ANL

Scoring criterion -- FY2006 Performance (continued)

➔ Work closely with SuperPower to produce high-current multilayers on IBAD MgO using MOCVD.

Goal: Significant improvement over single-layer I_cs.

Achievement: Study record SuperPower samples as a function of angle, field, and temperature. Identify random pinning enhancement with respect to previous record samples.



shown by Holesinger-Civale

Scoring criterion -- Research integration

➔ We have worked closely with SuperPower with measurements and analysis of temperature, field and orientation dependence of J_c for pinning improvement in MOCVD CC. (Results shown by Holesinger-Civale).

➔ As part of the Wire Development Group, measure pinning performance of AMSC coated conductors with multiple coatings and pinning enhancement routes. Began lower temperature measurements (T<65K) to explore pinning mechanisms in MOD films (shown by T. Holesinger in WDG talk Tuesday).

➔ We continued our extensive collaboration with the Univ. of Cambridge, UK, in the exploration of pinning enhancement routes, vortex dynamics in variable Lorentz force configurations, and characterization of films grown by Hybrid Liquid Phase Epitaxy. (Results shown today).

➔ We continued our collaboration with the Air Force Research Lab. on the vortex pinning of YBCO with 211 layered inclusions in different Lorentz force configurations.

Scoring criterion -- Research integration (continued)

➔ We began a collaboration with Brookhaven National Laboratory to explore angular and field dependent pinning mechanisms in record J_c ex-situ films produced by BaF_2.

➔ We continued the collaboration with the Applied Superconductivity Center at Univ. of Wisconsin. (visits, samples exchange, joint presentations)

➔ Started a new collaboration with NHMFL/FSU (Tallahassee), to further explore performance and pinning properties of coated conductors at high magnetic fields. (NHMFL/FSU postdoc visit to LANL)

➔ Started working with John Clem analyzing results in Variable Lorentz Force and Force-Free configurations. Plan to work on theoretical model for HTS.

➔ We began a collaboration with Argonne National Laboratory to study the effect of thermal annealing in MOD pinning mechanisms.

➔ We began a collaboration with X.Obradors and T.Puig (ICMAB-Barcelona) studying thickness dependence of TFA-MOD. (visits, ICMAB student visiting at LANL)

Scoring criterion -- FY 2007 Plans

➔ Explore limit for adding random pinning to YBCO+BZO samples

<u>Goal</u>: *Grow and study pinning in samples with BZO combined with pinning enhancement routes to optimize pinning in different angular regions.*

➔ Continue research into the causes of the pinning crossover at T=40K.

<u>Goal</u>: *Measure samples with different microstructures from companies and other collaborators. Perform J_c relaxation measurement (creep) at different temperatures and fields.*

➔ Expand our set of measurement capabilities

Goal: *Extend angular measurement up to 60T at NHMFL-LANL.*

➔ Further study the J_c limits in Force-Free configuration.

<u>Goal</u>: *Perform measurements in Variable Lorentz Force and Force-Free configuration*

a) Samples on metal substrates (IBAD and RABiTS).

b) Explore maximum in F-F at other temperatures

c) Work on theoretical model for anisotropic HTS (J.R.Clem)

➔ Survey alternate buffer layer materials.

<u>Goal</u>: *Field and angular dependence of different concentration (x) of $Sm_xZr_{1-x}O_y$ buffer layer. (Initial results shown by Holesinger-Civale in wire session).*

Scoring criterion -- FY 2007 Plans

➔ Understand thickness dependence in other samples than PLD.
Goal: *Perform thickness dependence studies on BaF_2-route thick films from Brookhaven National Laboratory and HLPE from Cambridge.*

➔ Continue to work with American Superconductor in the understanding and enhancement of vortex pinning in ex-situ films.
Goal: *Work analyzing and studying MOD/RABiTS coated conductors, and in particular needs of AMSC. Expand pinning studies at lower temperatures and higher fields.*

➔ Work closely with SuperPower studying MOCVD YBCO on IBAD MgO.
Goal: *Study MOCVD coated conductors performance and work in particular needs of SuperPower. Expand pinning studies at lower temperatures and higher fields.*