Wire Development Group (WDG)

Understanding and Engineering the Performance of 2G HTS Wire

2006 DOE Annual Peer Review

July 25, 2006

Washington DC

ARGONNE NATIONAL LABORATORY

Los Alamos NATIONAL LABORATORY EST. 1943

American Superconductor™

THE UNIVERSITY of WISCONSIN MADISON

UT-BATTELLE

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

WDG Mission

- Establishing material science underlying current carrying capacity and current limiting mechanisms of 2G HTS wire

- Transferring fundamental material science knowledge to commercial manufacturing of low-cost 2G wire

FY 2006 Performance: WDG Structure and Operation

- FY2006 Funding:

Organization	Source	Amount
LANL CRADA	DOE	$ 600 K
ORNL CRADA	DOE	$ 300 K
UW	DOE	$ 250 K ($65K allocated)
	AFOSR-MURI	$ 250K
ANL CRADA	DOE	$ 250 K
AMSC	AMSC	$ 1200 K

- Proprietary Information Agreement protects confidential ideas, enabling free exchange during meetings
- Trimesterly meetings, teleconferences, sample exchange, round robins
  - Over 150 samples exchanged and studied in FY2006
- AMSC invested over $3.4 M in 2G R&D in FY2006
  - Strong commitment to 2G HTS technology
- WDG research support AMSC's development of a low-cost 2G wire technology
- Core WDG group is expanding to include the University of Houston (K.Salama)

Research Integration: WDG Participants

American Superconductor

Xiaoping Li, Wei Zhang, Yibing Huang, Thomas Kodenkandath, Marty Rupich, and Alex Malozemoff

ARGONNE NATIONAL LABORATORY

Vic Maroni, Dean Miller, Ken Gray, Ulrich Welp, Helmut Claus, Vitalii Vlasko-Vlasov, Rachel Koritala, Alex Koshelev and Raul Arenal de la Concha

Los Alamos NATIONAL LABORATORY EST. 1943

Terry Holesinger, Leonardo Civale, Boris Maiorov, Yates Coulter, Jack Kennison, Brady Gibbons, Jonathon Storer, and Vlad Matias

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY

Ron Feenstra, Elliot Specht, Albert Gapud, Patrick Martin, Jim Thompson, Yifei Zhang, and David Christen

THE UNIVERSITY of WISCONSIN MADISON

Matt Feldmann, Dima Abraimov, Tolya Polyanskii, Zhijun Chen, Sang-II Kim, Nick Nelson, Alex Gurevitch, Xueyan Song, Kartik Venkataraman, Rasmi Das, K Choi, Chng Beom Eom, Eric Hellstrom, and David Larbalestier

Research Integration: WDG Expertise

American Superconductor	Wire process innovation, materials science expertise, Metal Organic Deposition, product development and manufacturing
ARGONNE NATIONAL LABORATORY	TEM, Raman, chemistry and reaction expertise
Los Alamos NATIONAL LABORATORY EST. 1943	Analytical Electron Microscopy, electrical characterization
UT-BATTELLE OAK RIDGE NATIONAL LABORATORY	PVD and Ex-situ YBCO processing, novel pinning development, electrical and analytical characterization
THE UNIVERSITY of WISCONSIN MADISON	Novel characterization and spatial imaging techniques, modeling of current limiting mechanisms

Premier program in the world dedicated to developing a comprehensive material science knowledge base focused on 2G HTS wire

WDG Research Strategy

- Focus on high I_c performance at temperatures and field ranges relevant for commercial and military applications
  - 77 K, self-field for cables, fault current limiters
  - 1-3 T at 35 – 65K for rotating machinery, magnets

- Develop a comprehensive understanding of epitaxial oxide film growth and current limiting mechanisms through detailed characterization and testing of diverse samples and growth techniques (both ex-situ and in-situ)
  - YBCO: MOD (AMSC, UH) PVD-BaF_2 (ORNL), PLD (UW, ORNL,LANL)
  - Templates: RABiTS (AMSC), IBAD (LANL)

Inter-related Collaborations Accelerate Progress

AMSC
Baseline Production

WDG
Fundamental Studies and Characterization

R&D Samples
(4 cm x 2 m)

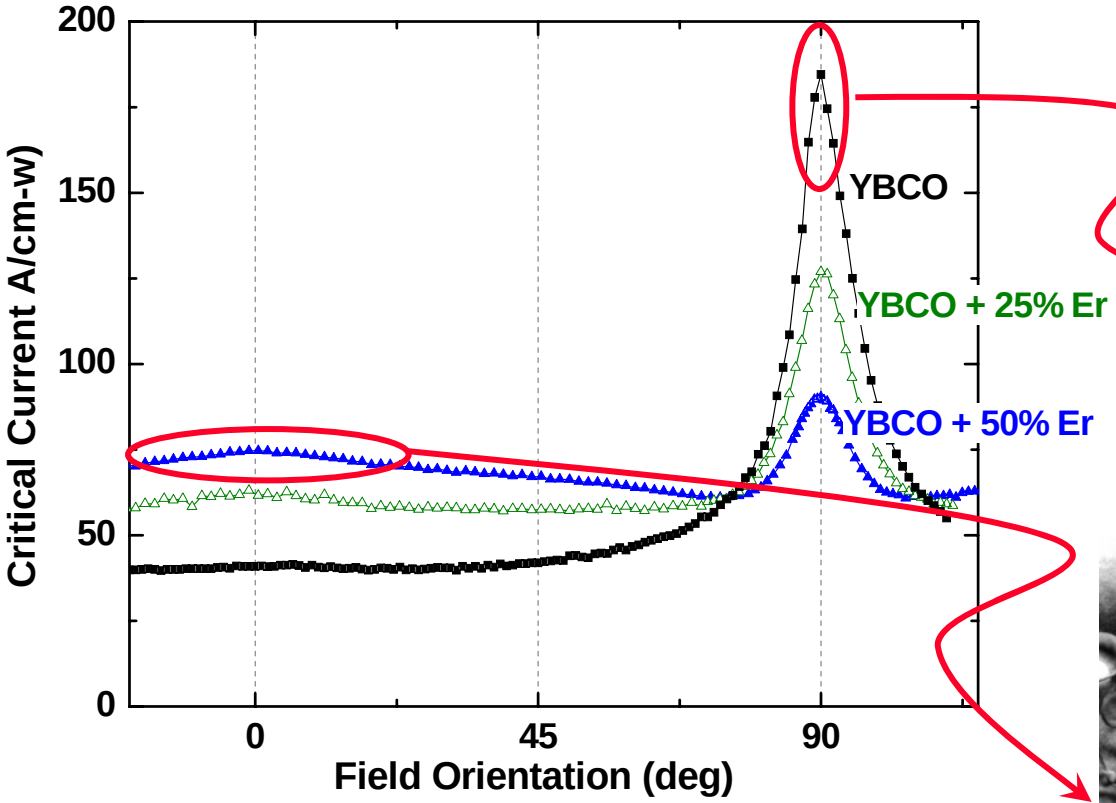
ORNL/AMSC CRADA
Long Length Baseline Development

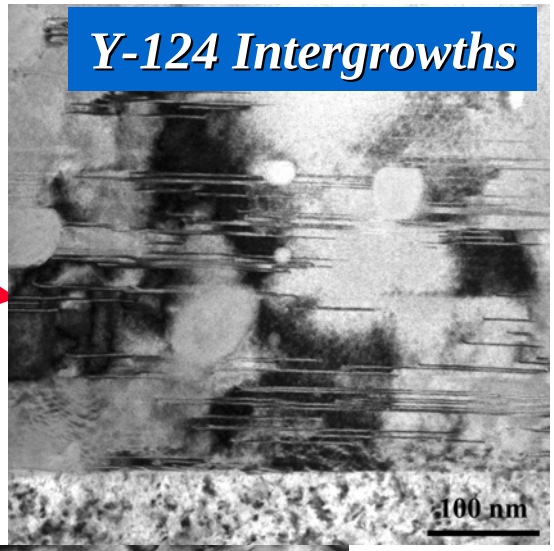
(4 cm x 20 – 100 meter)

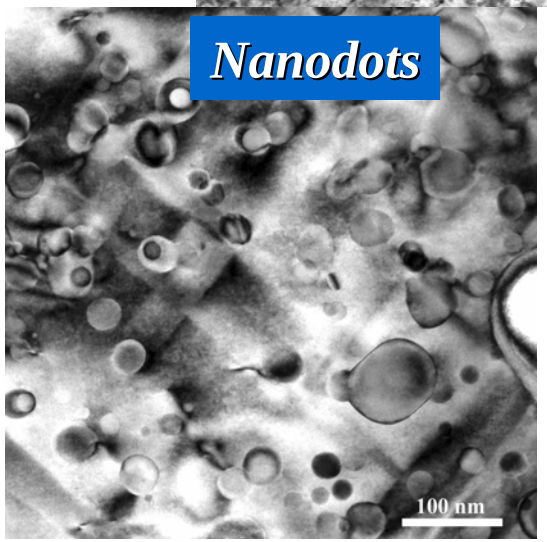
- Process Optimization
- Process Qualification
- Failure Analysis
- Cost Reduction

Special capabilities:
4 cm Ic measurements (LANL)
X-ray characterization (ORNL)

August 2005: Key Pinning Structures Identified in ex-situ Films



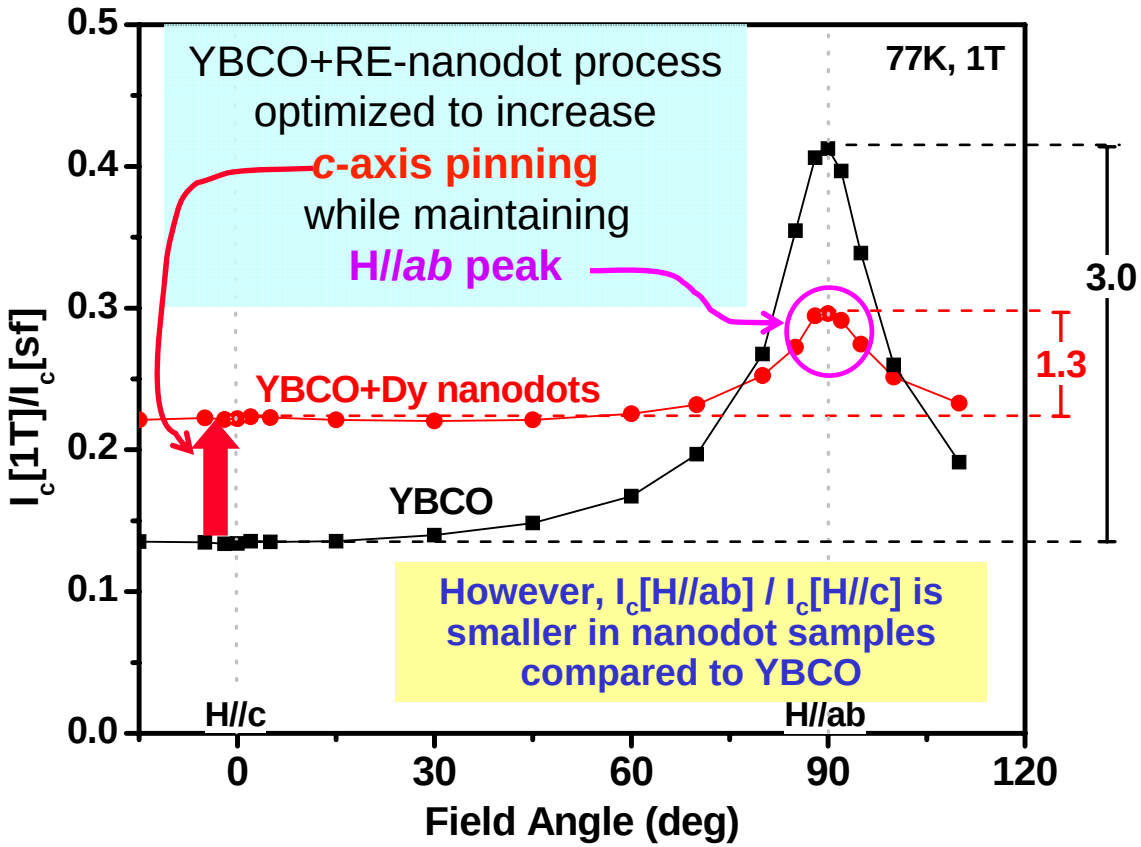




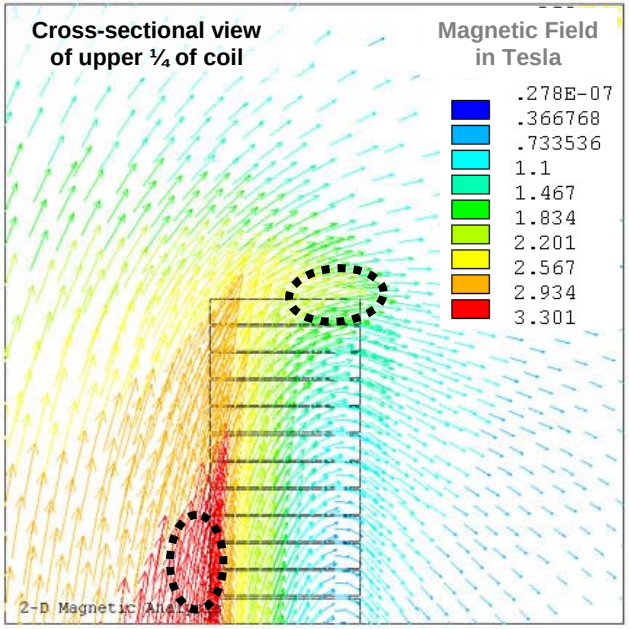
Addition of RE nanodots alters second phase composition, suppressing formation of 124 stacking faults and *ab*-plane pinning

American Superconductor™

WDG Challenges for FY2006



Magnetic field distribution in coils for rotating machines, solenoids, results in parallel fields ~ 2X the maximum perpendicular field



1) Understand process and control H//ab peak in presence of nanodots
2) Achieve I_c[H//ab] / I_c[H//c] ~2 at operating conditions
3) Develop thicker double-coat process (limit # layers to minimize cost)

Key Questions Examined in FY2006

Pinning

- What is the mechanism for formation of 124 intergrowths?
- Can the 124 intergrowth density and nanodot concentrations be independently controlled and I_c[H//*ab*] / I_c[H//*c*] be engineered for targeted applications in a practical 2G wire?

Thick *ex-situ* YBCO Films

- What causes observed decrease of J_c as YBCO thickness increases?
- Can constant and high J_c (>3 MA/cm^2) be maintained in thick (> 1 μm) YBCO films?

Grain Boundaries

- Do meandering grain boundaries benefit practical MOD/RABiTS wires?
- Do grain-boundary and bulk-pinning limited regimes vary for H//ab and H//c?

Technical Presentations

Dean Miller

- Origin and Control of *ab*-plane pinning in YBCO and RE nanodot-YBCO Films

Terry Holesinger

- Development of Thick (> 1μm) MOD YBCO Films for High Current Conductors

Matt Feldmann

- Deconstructing MOD YBCO films layer by layer and grain by grain

Marty Rupich

- FY2006 Results Summary
- FY2007 Plans

Controlling Pinning Defects in MOD Coated Conductors

Dean Miller

Argonne National Laboratory

Raul Arenal, Vic Maroni, Jon Hiller

Argonne National Laboratory

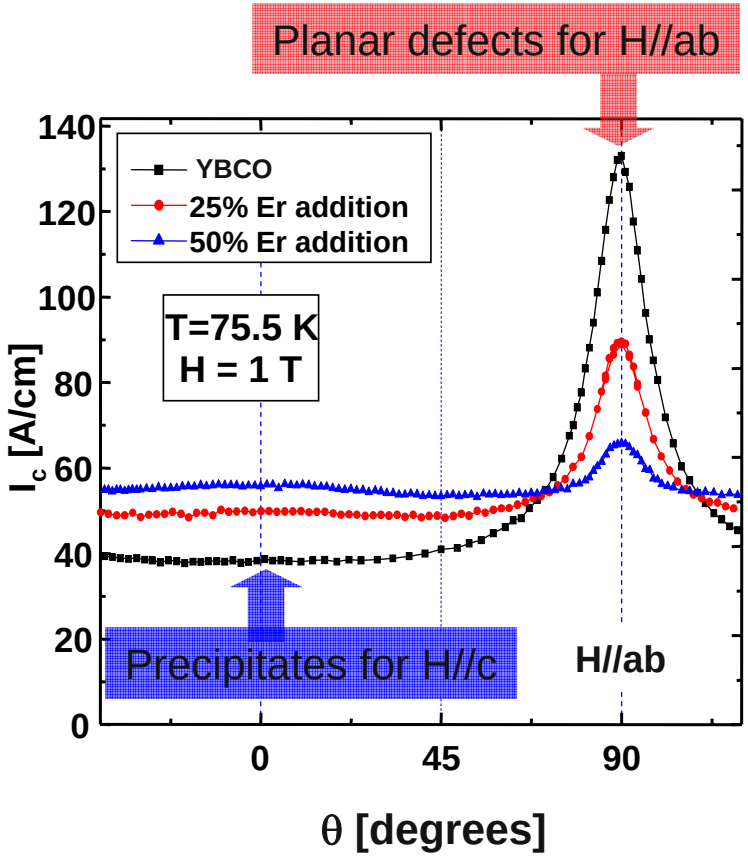
Marty Rupich, Wei Zhang, Xiaoping Li, Yibing Huang

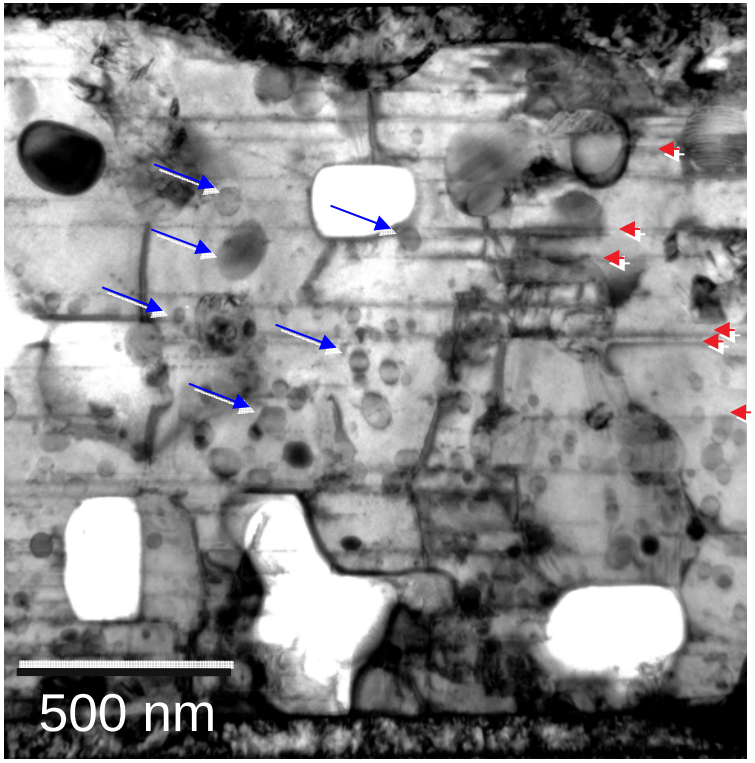
American Superconductor

Wire Development Group (WDG) members:

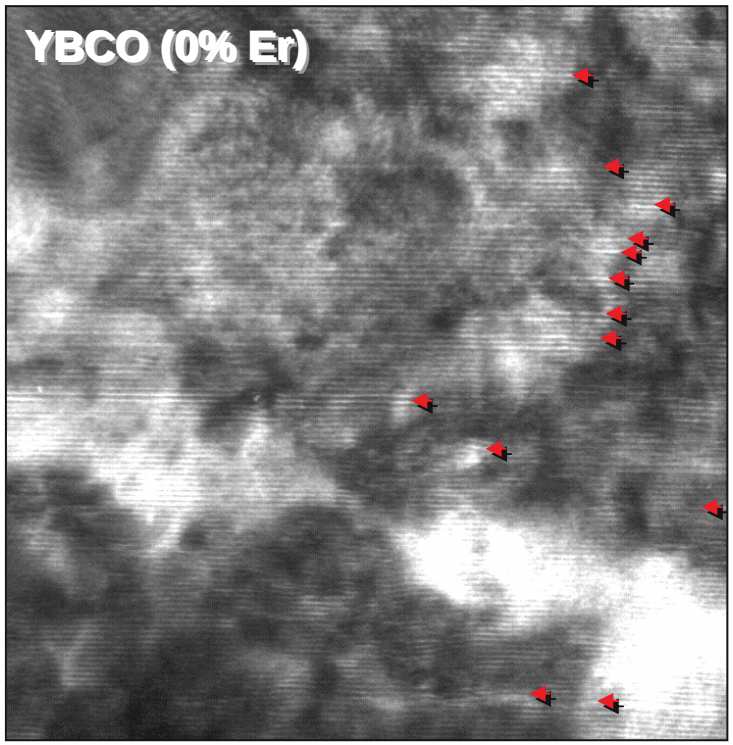
Relationship between defect types and pinning in AMSC coated conductors

- AMSC has developed approaches to introduce crystallographic defects to enhance pinning to meet the need for high I_C for all angles (θ) of field w.r.t c-axis



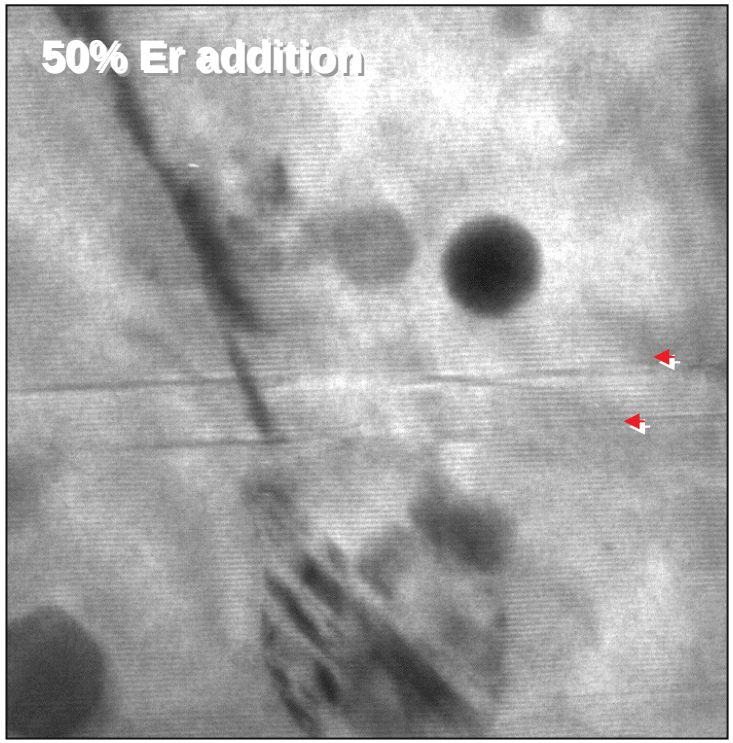


Key issue:
- interrelationship between defect types



50 nm

Planar defect spacing ≈ **16 nm**



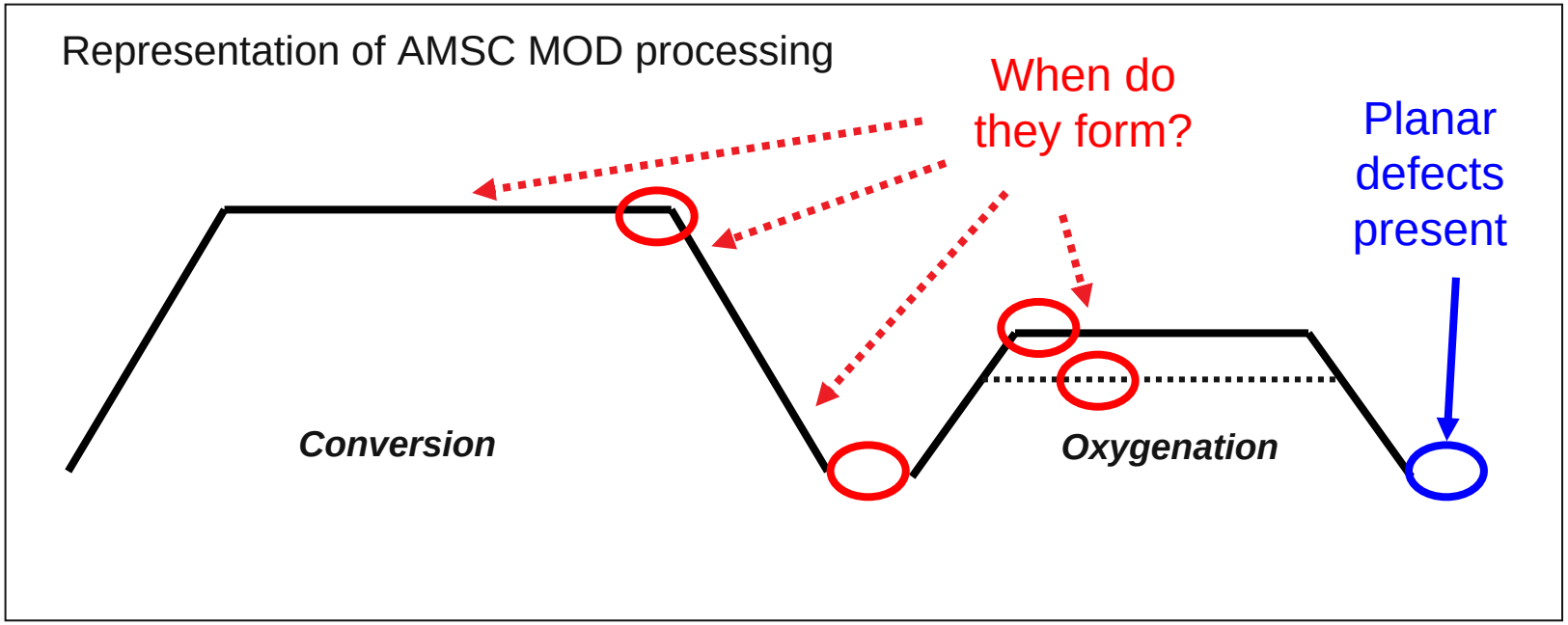
Planar defect spacing ≈ **111 nm**

50 nm

RE-additions:
- **⇑ in RE precipitates**
- **⇓ in planar defects**

- How do planar defects form?
- Why does the planar defect density decrease with RE-additions?
- Can we achieve high densities of both types of defects?

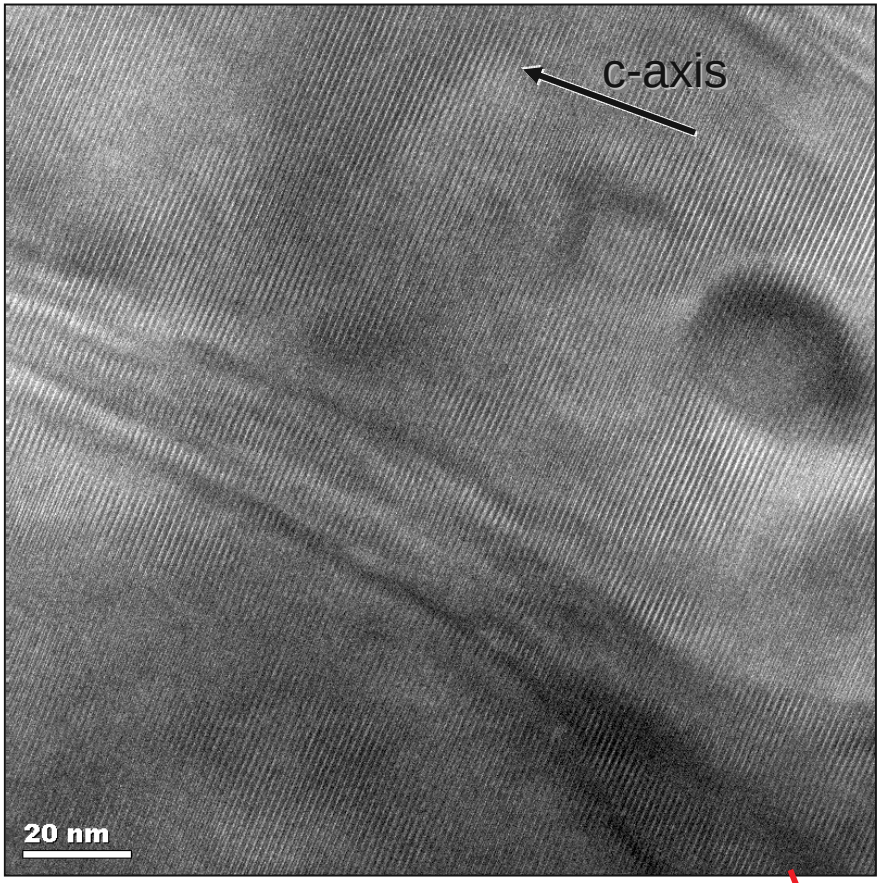
Origin and control of planar defects



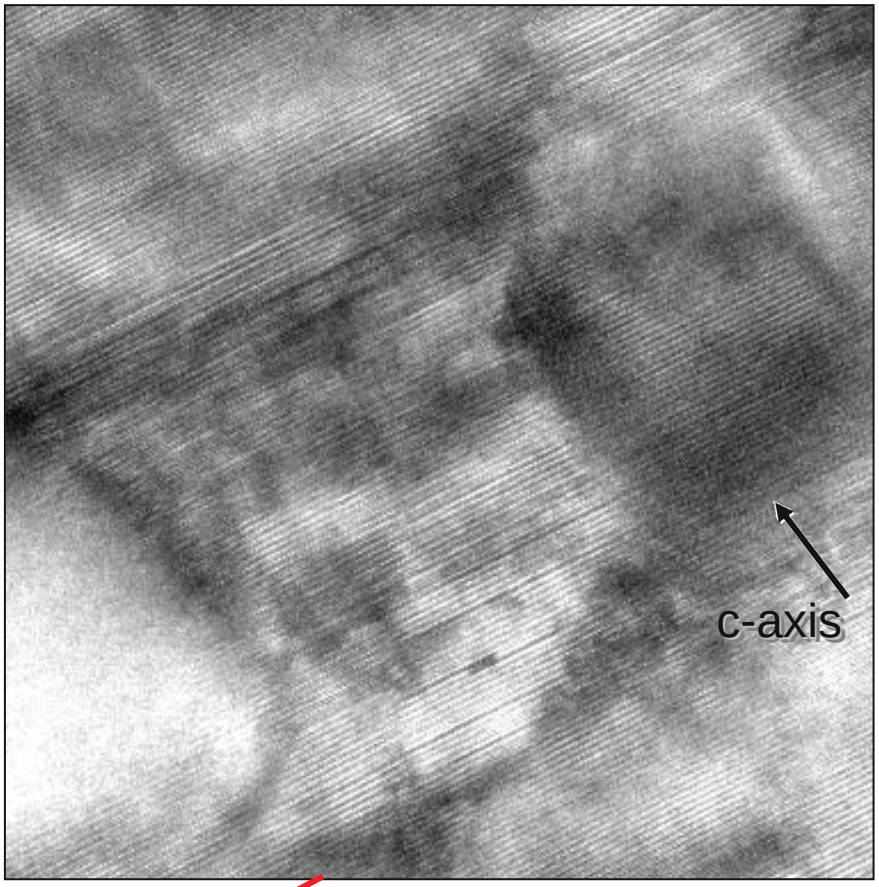
- Focus on standard YBCO composition (no RE-additions)
- Detailed characterization at key stages to elucidate evolution of planar defects

Goal: **Identify origin of planar defects**

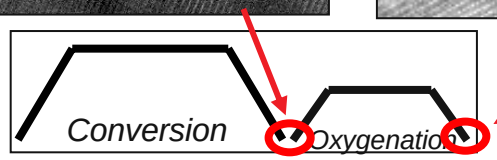
Origin of planar defects



As converted



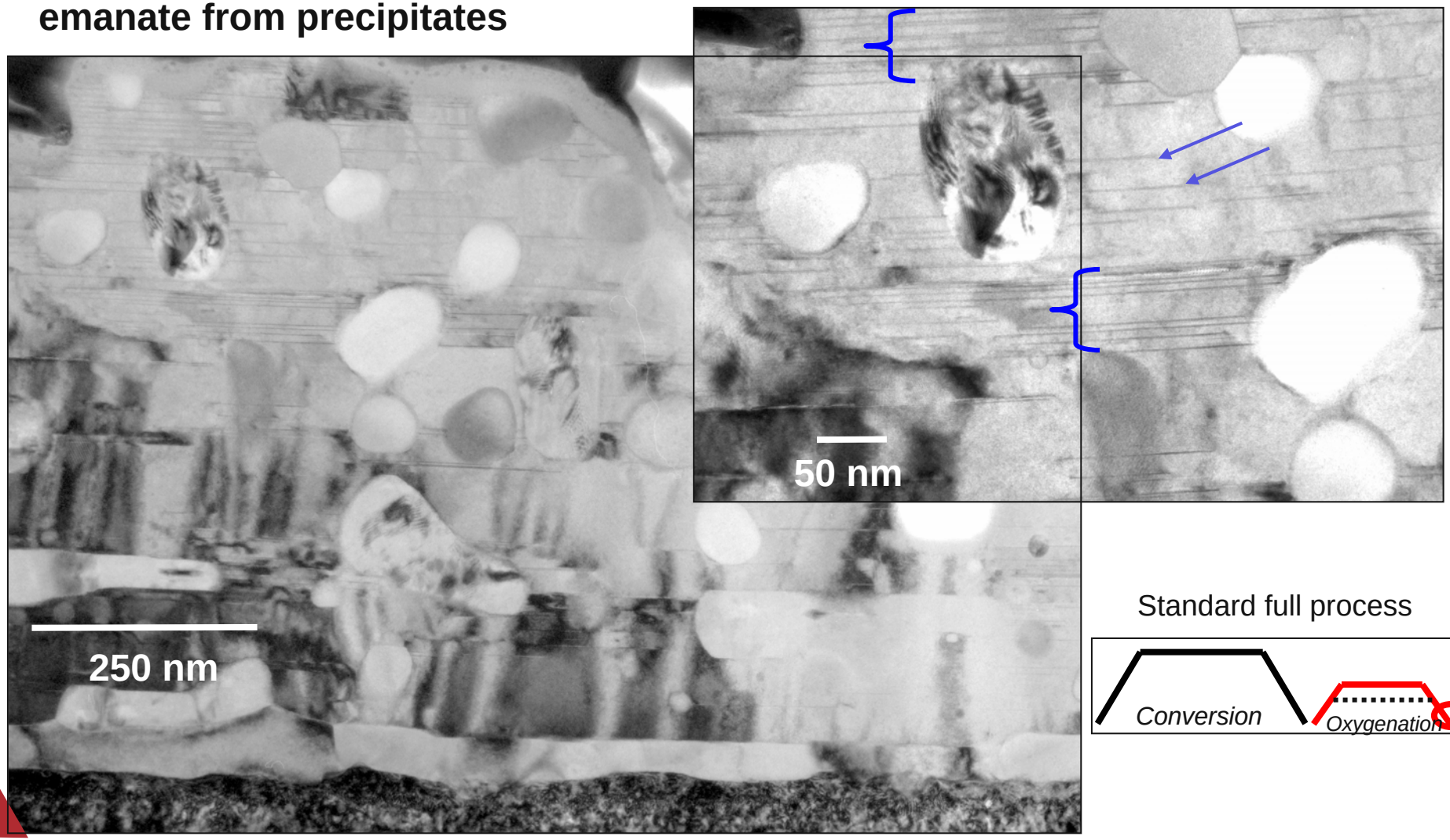
Oxygenated



Intergrowths form primarily during oxygenation treatment!

Growth mechanism of planar defects

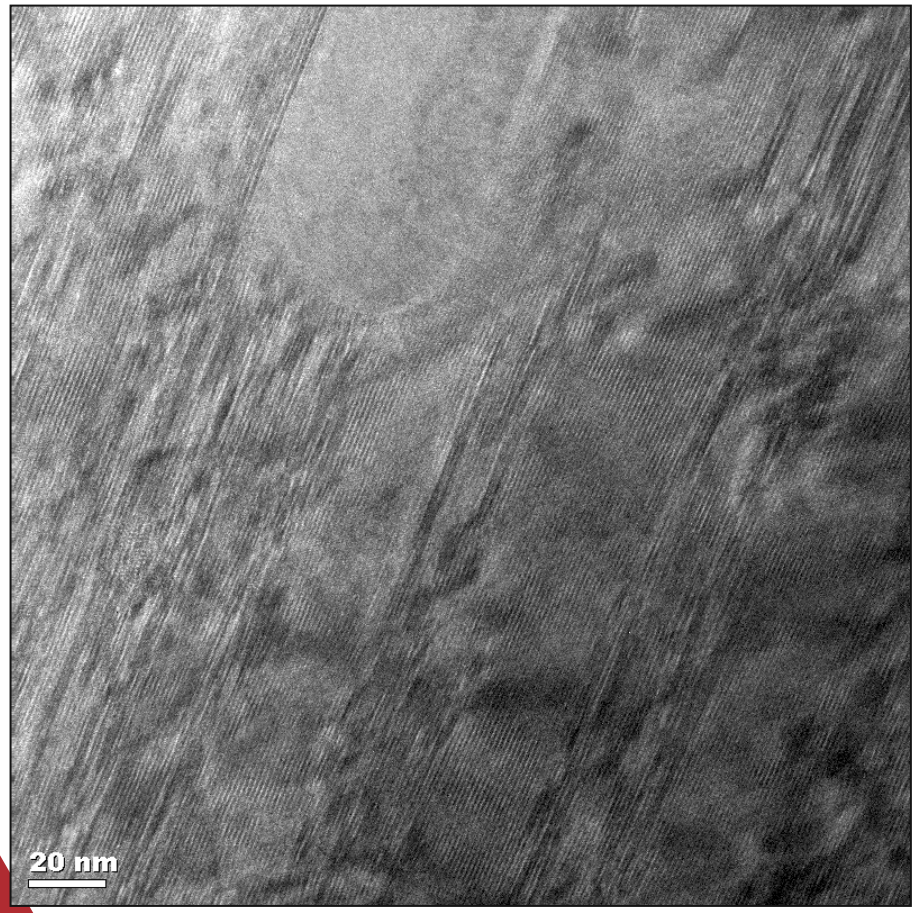
- **Microstructural evidence that planar defects emanate from precipitates**

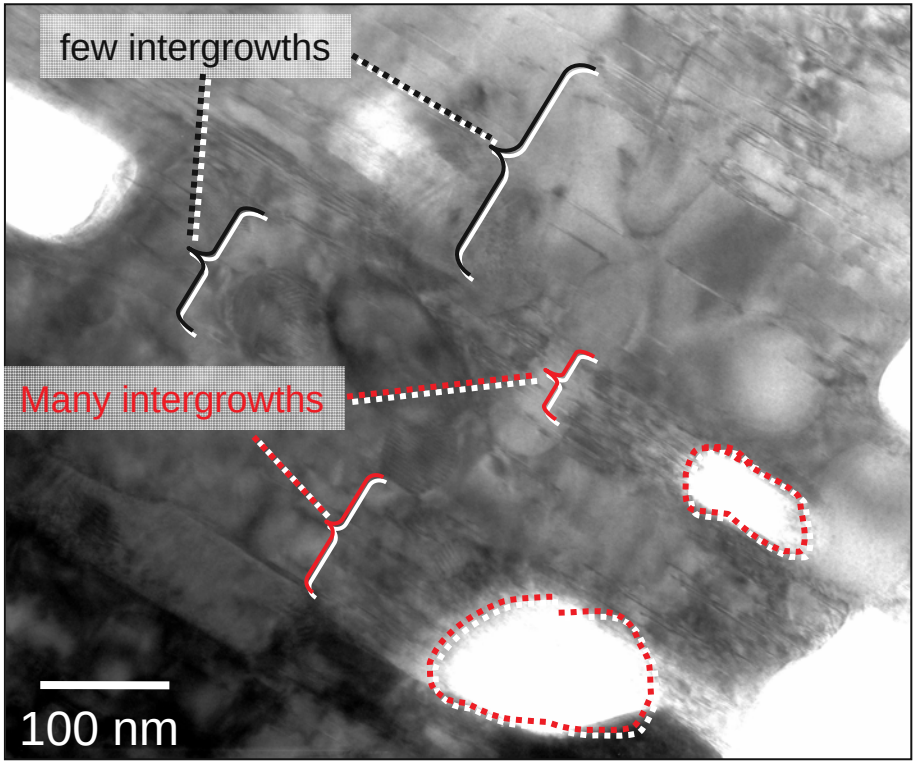


Standard full process

Growth mechanism of planar defects

- **Partial oxygenation provides further evidence of planar defect growth from precipitates** **- *but only some precipitates***





partial oxygenation

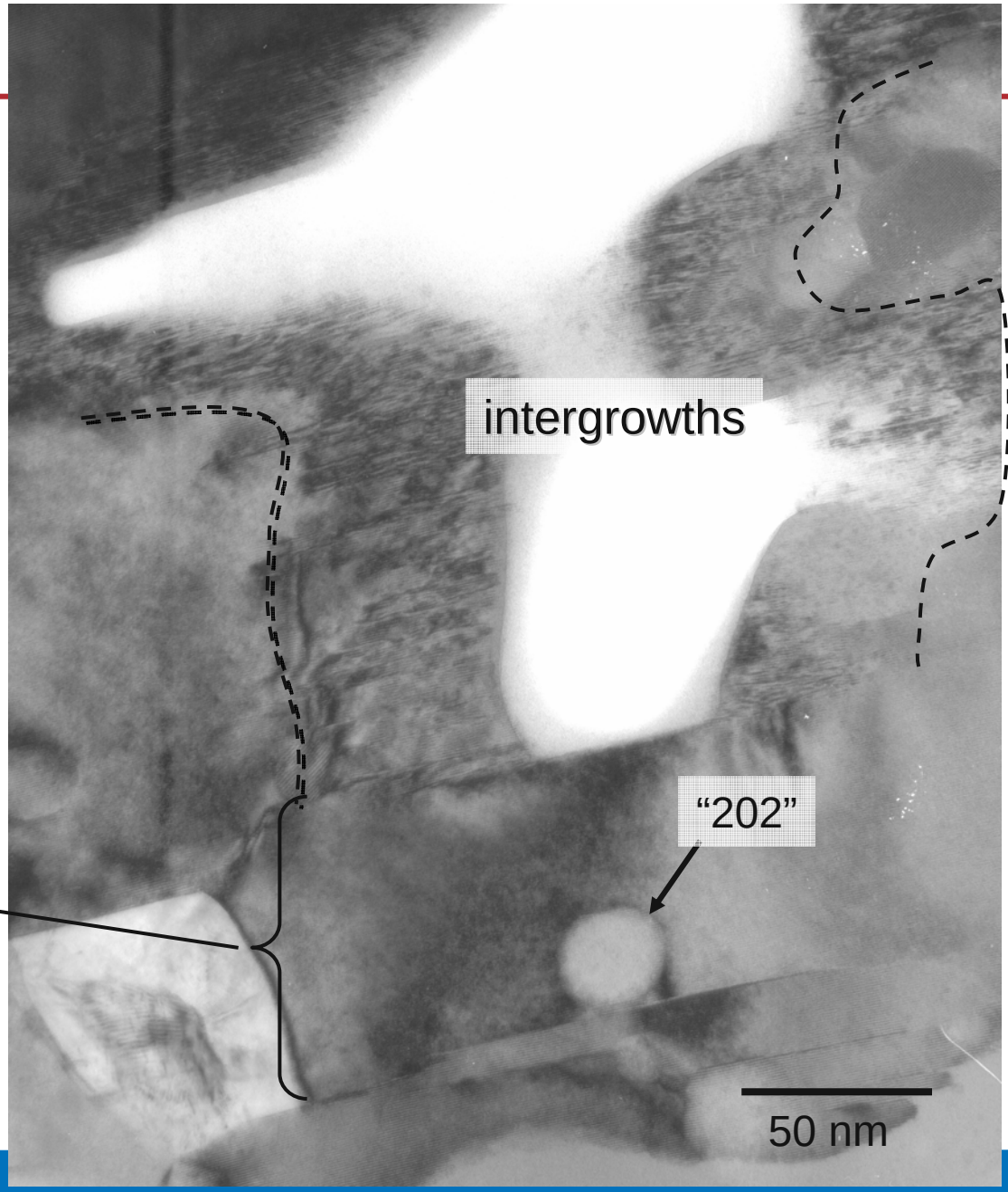
Origin of planar defects

- As-converted samples provide more insight

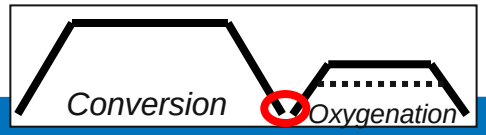
  - “snapshot” of initial growth process during cooling

What is special about the particles that yield the intergrowths???

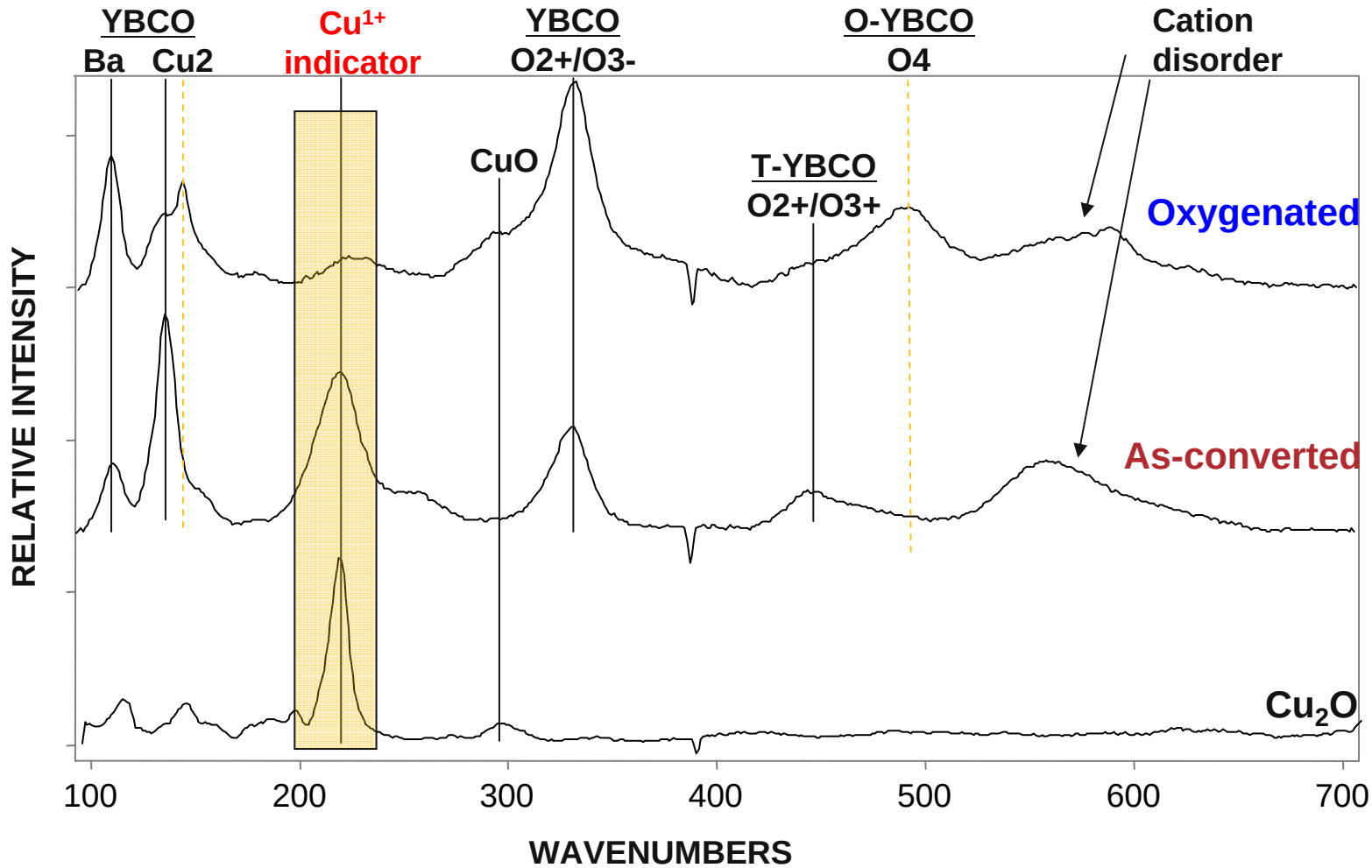
no intergrowths



As-converted

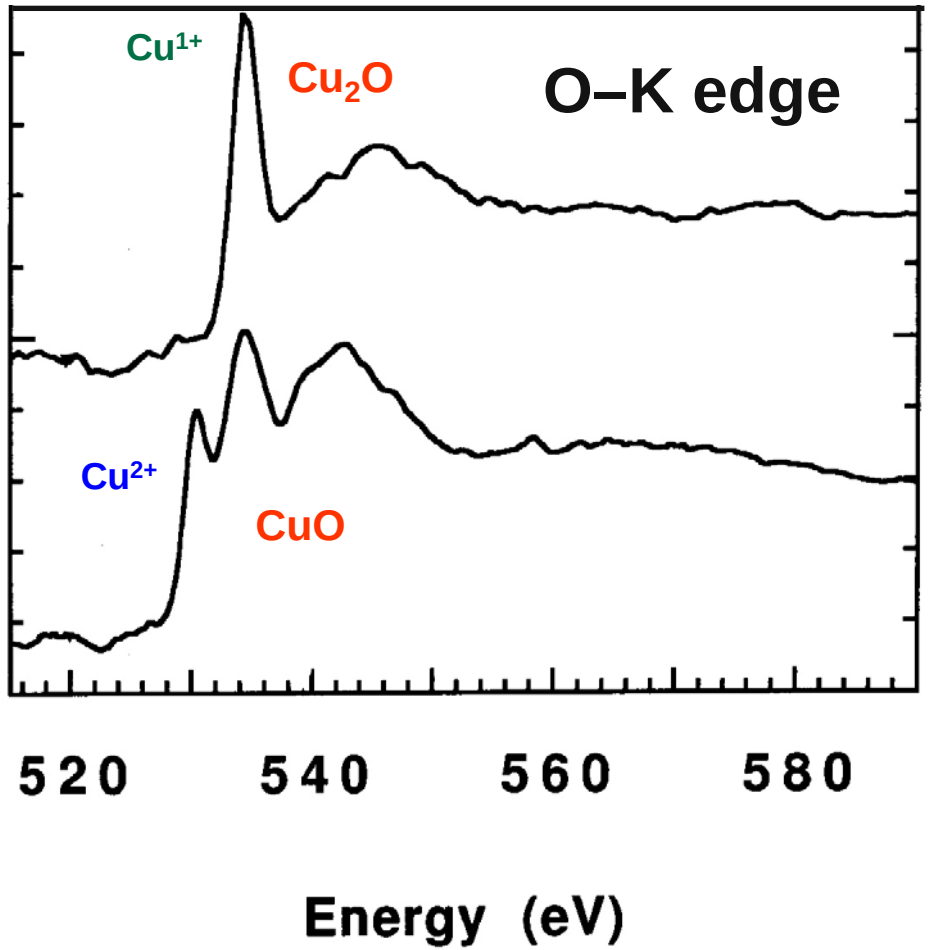


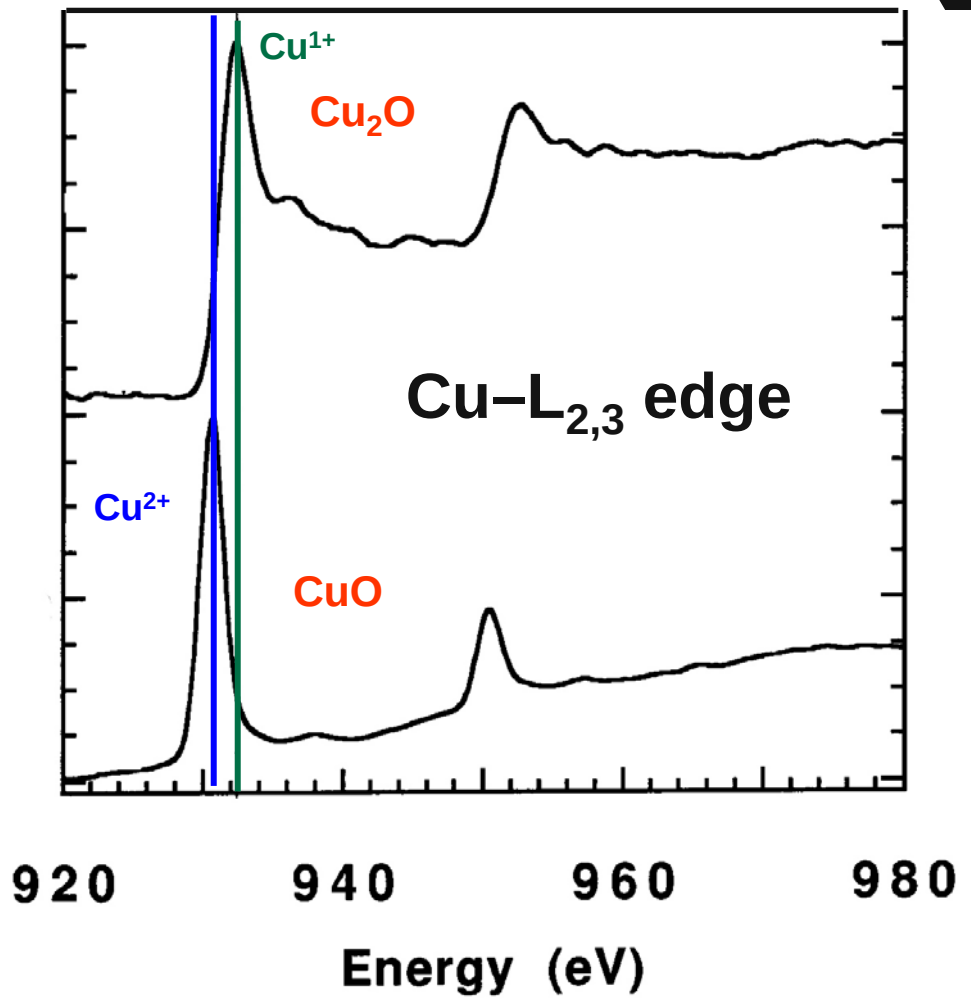
Raman spectroscopy provides a clue



- Raman shows evidence of **Cu^{1+}** states in as-converted samples

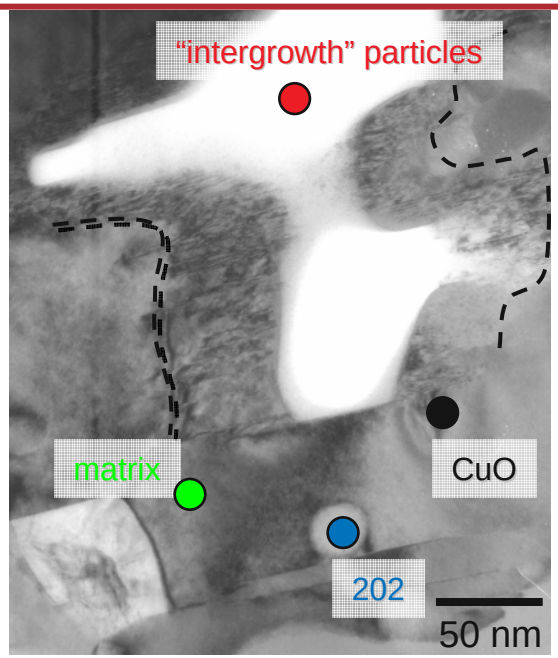
EELS analysis for spatially-resolved chemical valence - "fingerprinting"



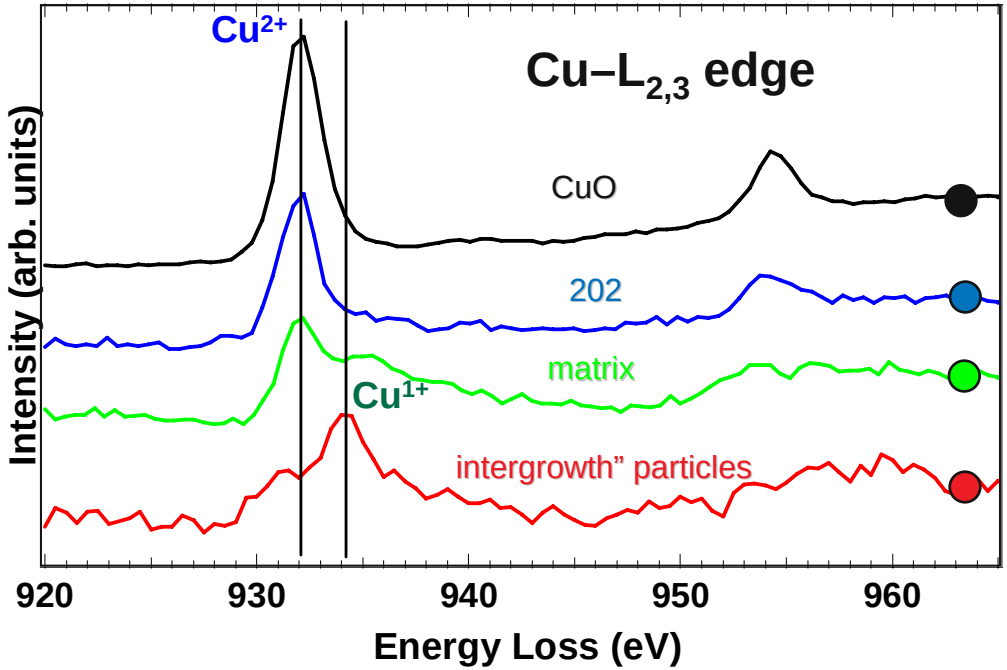


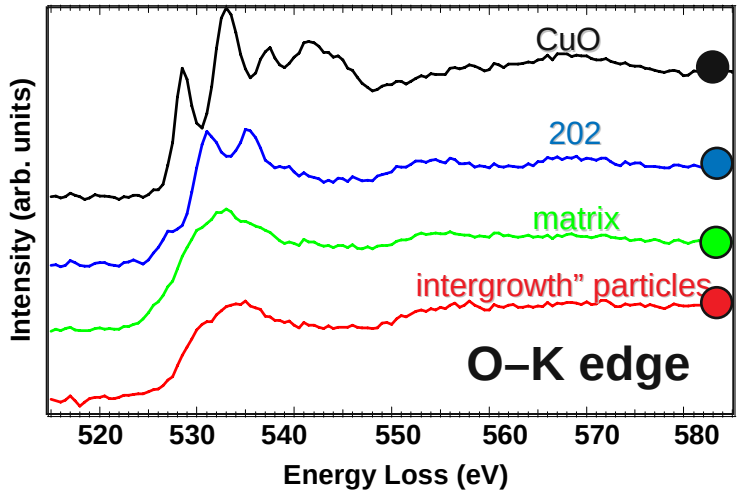
D. Imhof et al., Eur. Phys. Journal., AP 5, 9-18 (1999)

Cu valence is a key for effective intergrowth formation!



- Particles associated with intergrowths show **Cu^{1+}**.
- Particles with signature of Cu^{2+} do not form intergrowths.



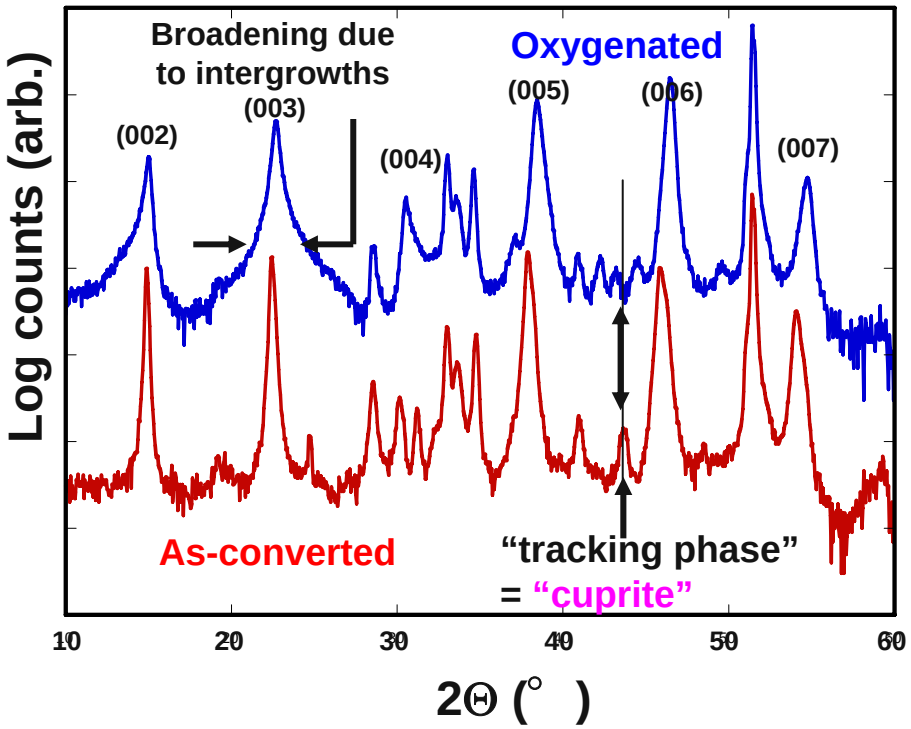


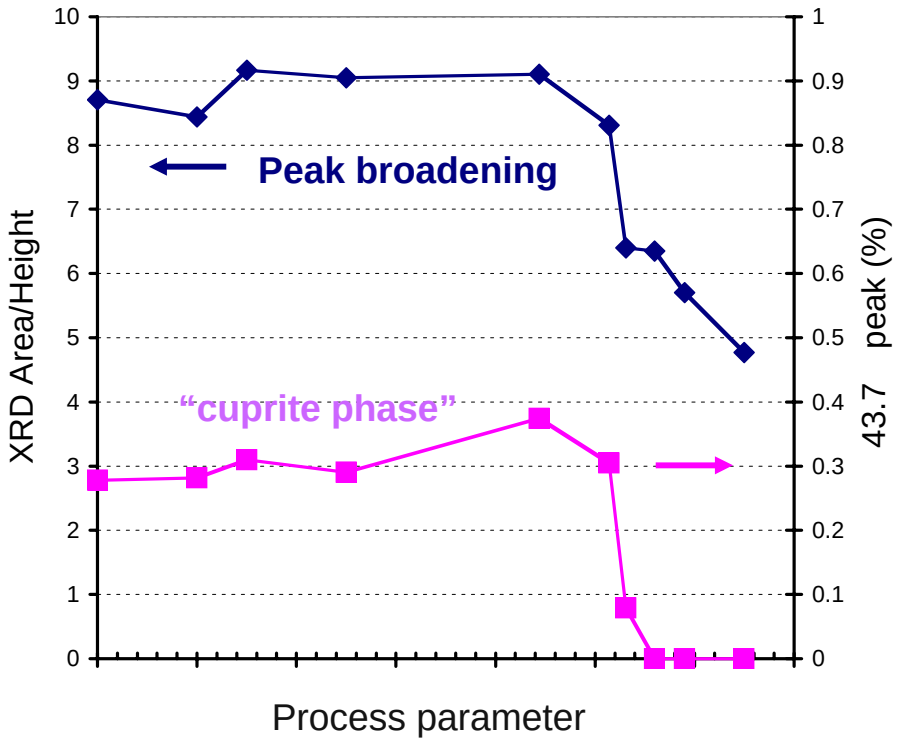
The particles that generate intergrowths are Cu-Ba-O in a Cu^{1+} oxidation state

- ***"barium cuprite"***

Correlation of "cuprite" phase with planar defects

- XRD data that shows phase that correlates with intergrowths



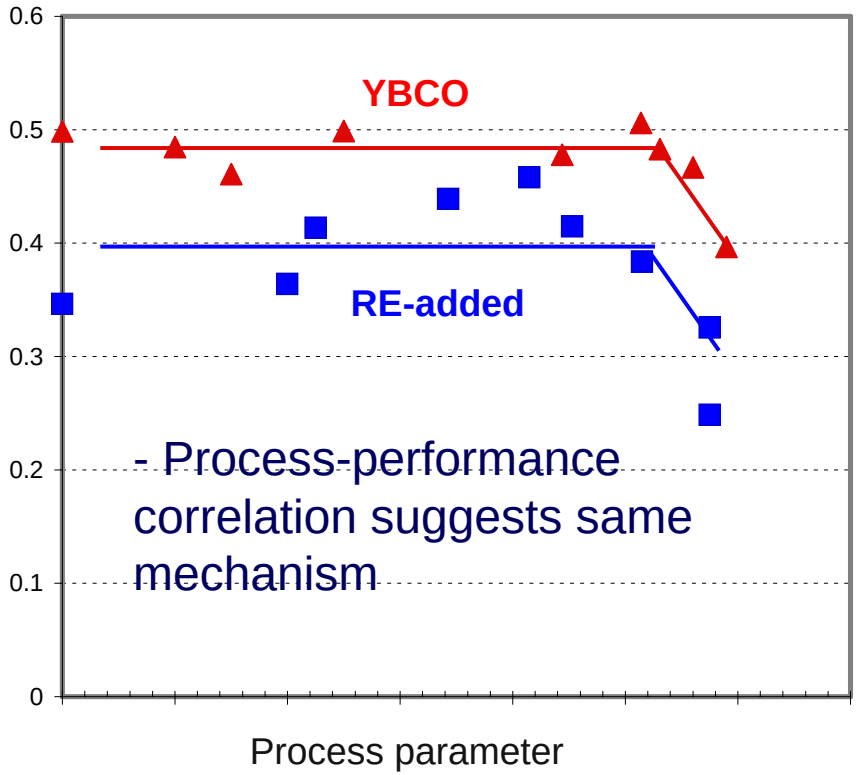


- phase identified by XRD that tracks with intergrowths correlates with "cuprite" phase based on Raman & TEM/EELS correlations

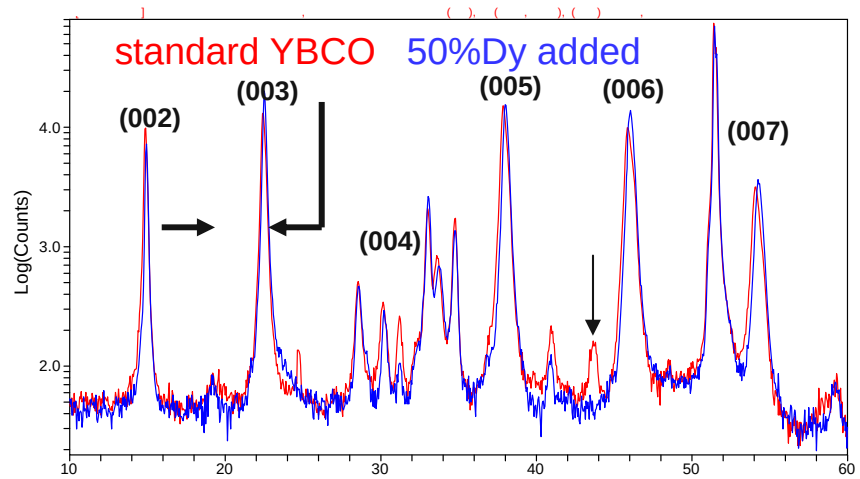
Origin of planar defects in RE-added samples

- Standard YBCO composition: strong evidence that intergrowths are generated from “cuprite” Cu-Ba-O particles

Is mechanism the same for RE-added samples?



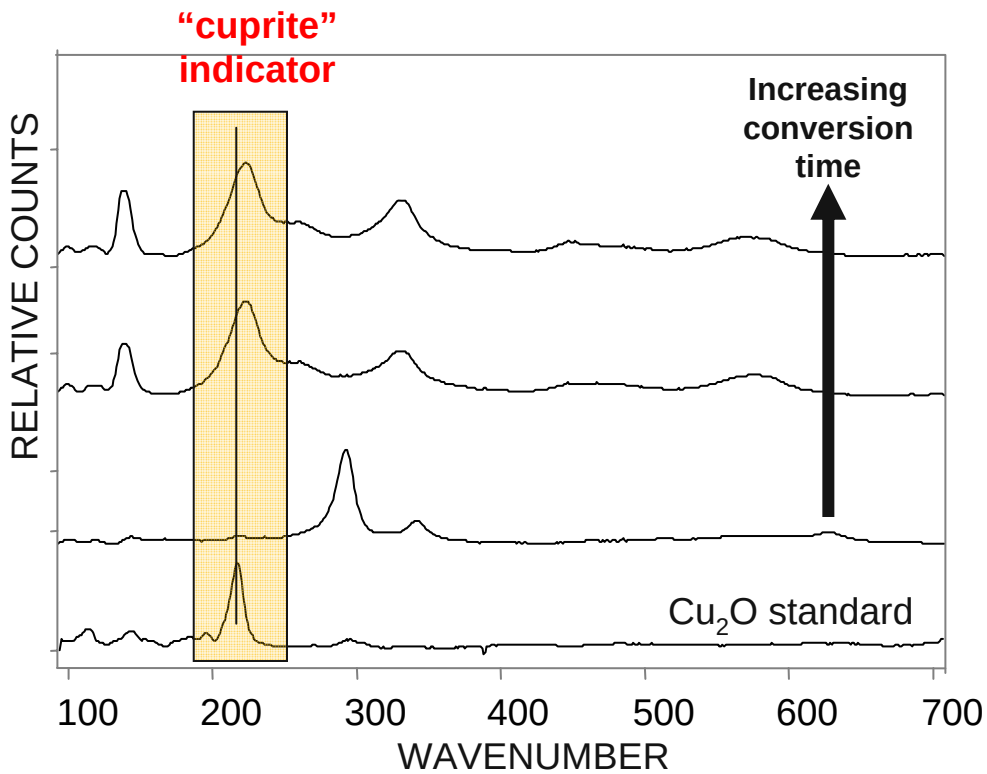
As reacted

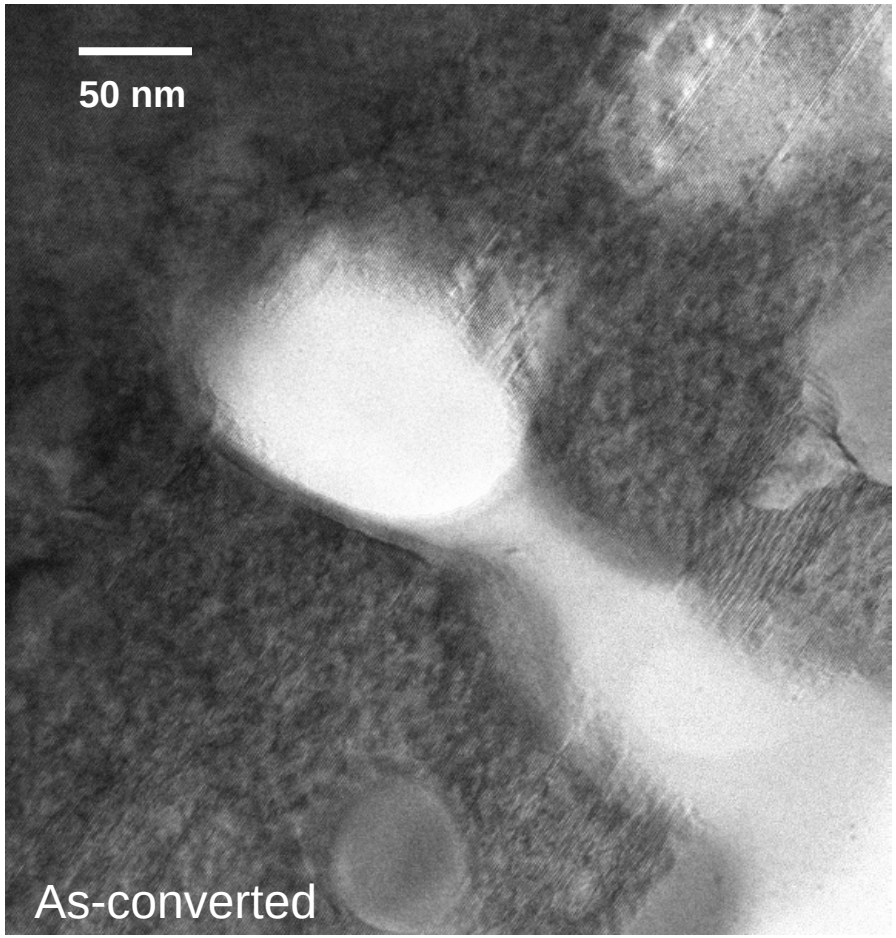


- “Tracking” phase not observed by XRD in RE-added samples

“Cuprite” phase also key in RE-added

Raman and TEM/EELS reveal presence of “cuprite” phase in RE-added samples





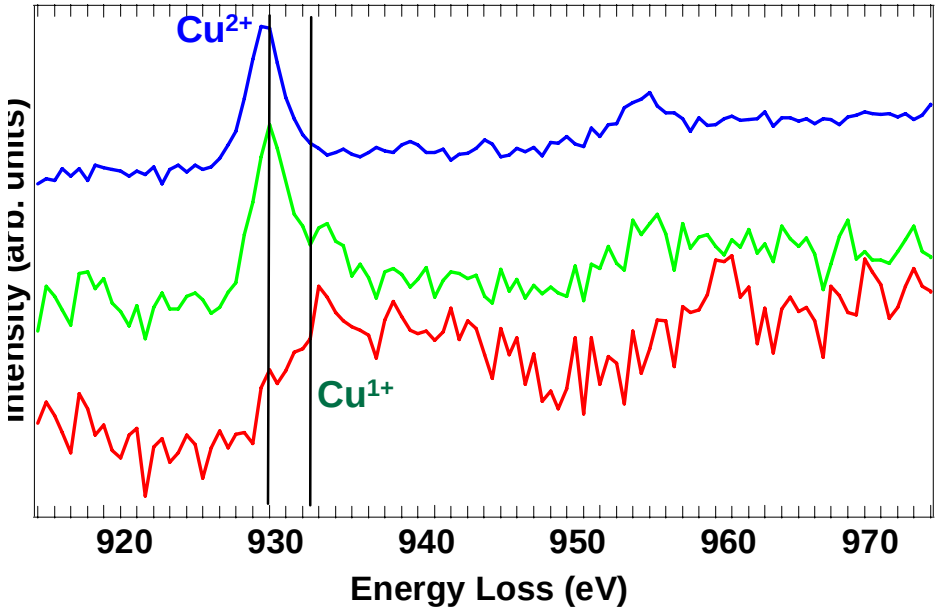
50% Dy-added

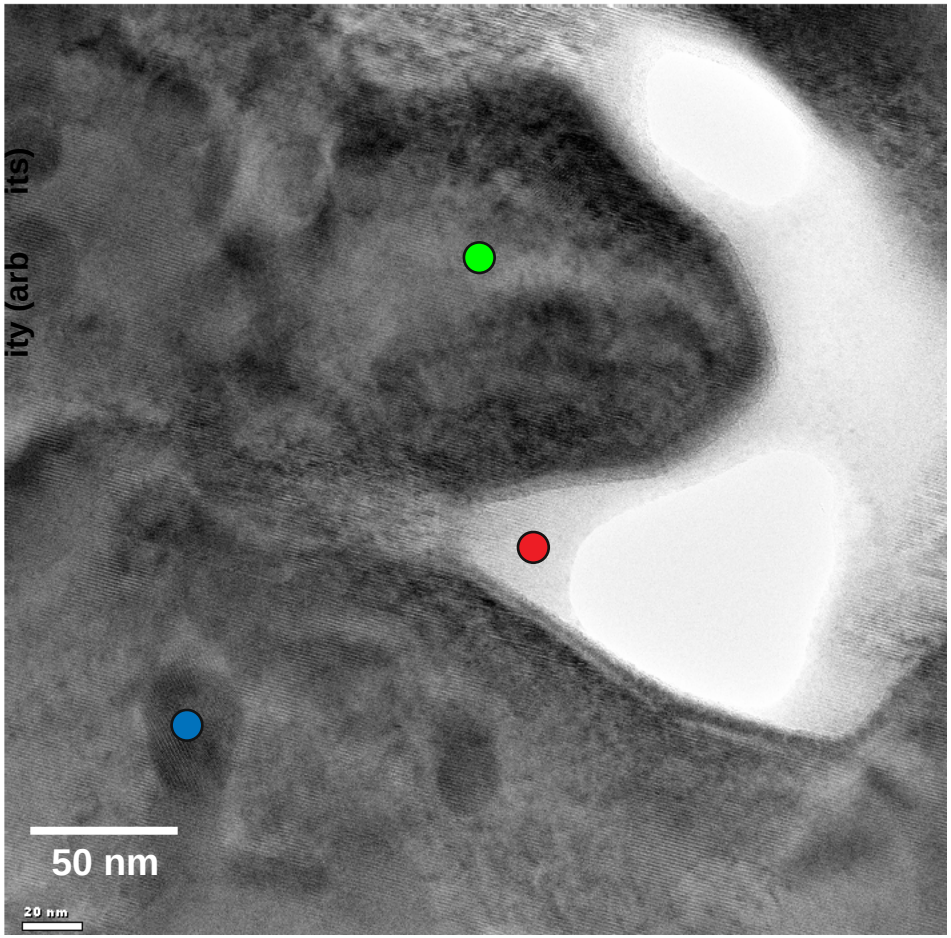
“202” = $(RE)_2Cu_2O_5$

Planar defect growth from cuprite phase in RE-added

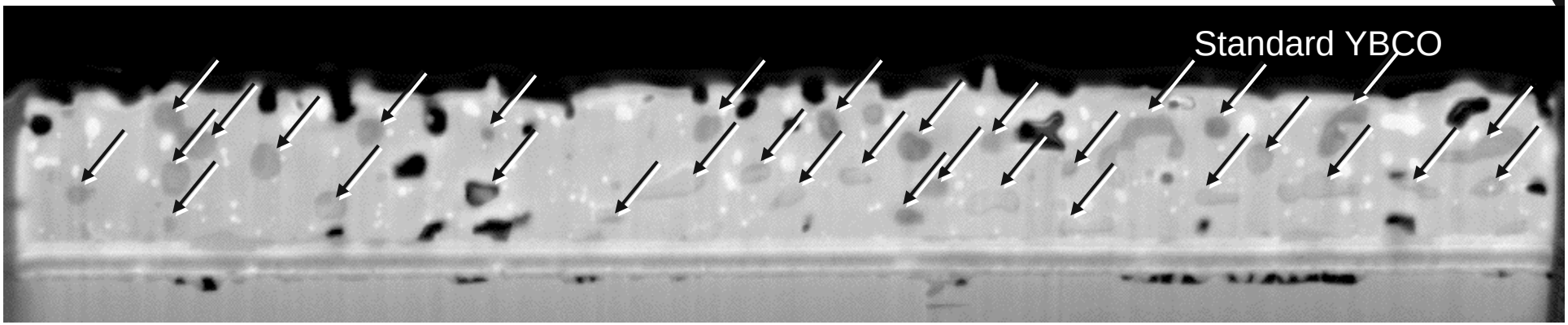
Raman and TEM/EELS reveal presence of "cuprite" phase in RE-added samples

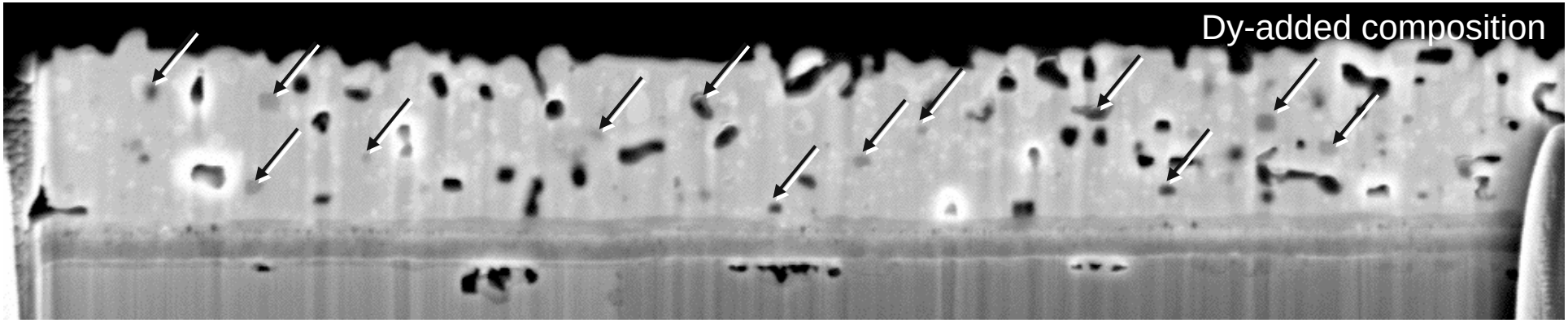
50% Dy-added





Basis for low planar defect density in RE-added



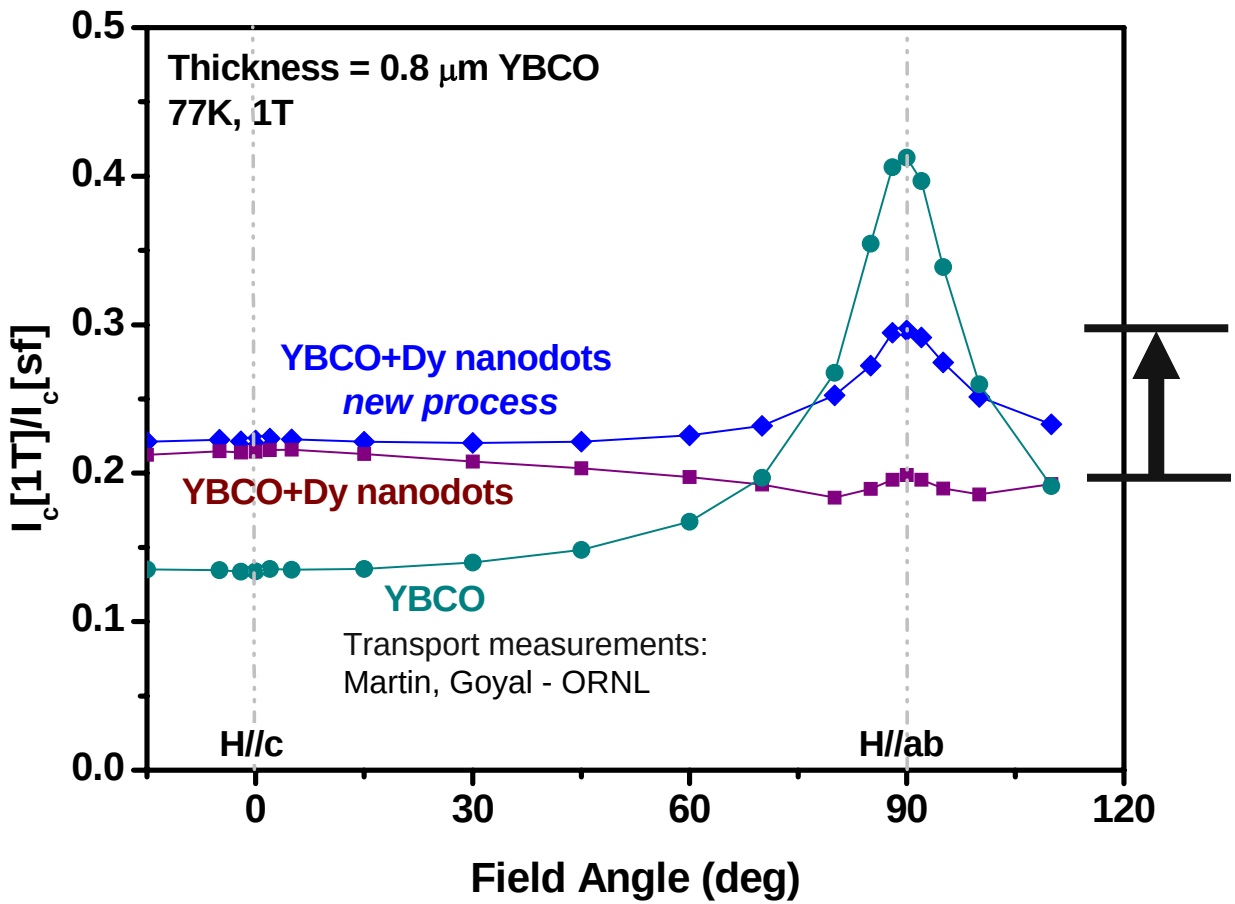


1 µm

- low volume fraction of key “cuprite” phase
- RE-additions drive reaction towards “202”

Controlling defects to improve properties

• based on these results, a new processing technique has been developed to retain a higher density of planar defects in RE-added samples!!



Summary, conclusions, future directions

Our goal was to identify the origin of planar defects

- ***a mechanism was established***

  - planar defects develop from Cu^{1+} "cuprite" precipitates present in the as-converted microstructure of both standard YBCO and RE-added compositions

- ***an explanation for the different behavior of RE-added samples was identified***

  - in RE-added samples, the higher RE content leads to more "202" and a lower "cuprite" content, yielding lower intergrowth density

- ***an improved process was developed***

  - a processing technique has been developed to retain a higher density of planar defects in RE-added samples

Development of Thick (> 1μm) MOD YBCO Films for High Current Conductors.

Terry Holesinger

Los Alamos National Laboratory

Boris Maiorov, Yates Coulter, and Leonardo Civale

Los Alamos National Laboratory

Matt Feldmann and David Larbalestier

University of Wisconsin

Xiaoping Li, Yibing Huang, and Marty Rupich

American Superconductor

Ron Feenstra

Oak Ridge National Laboratory

Wire Development Group

Los Alamos NATIONAL LABORATORY EST. 1943

American Superconductor™

Argonne NATIONAL LABORATORY

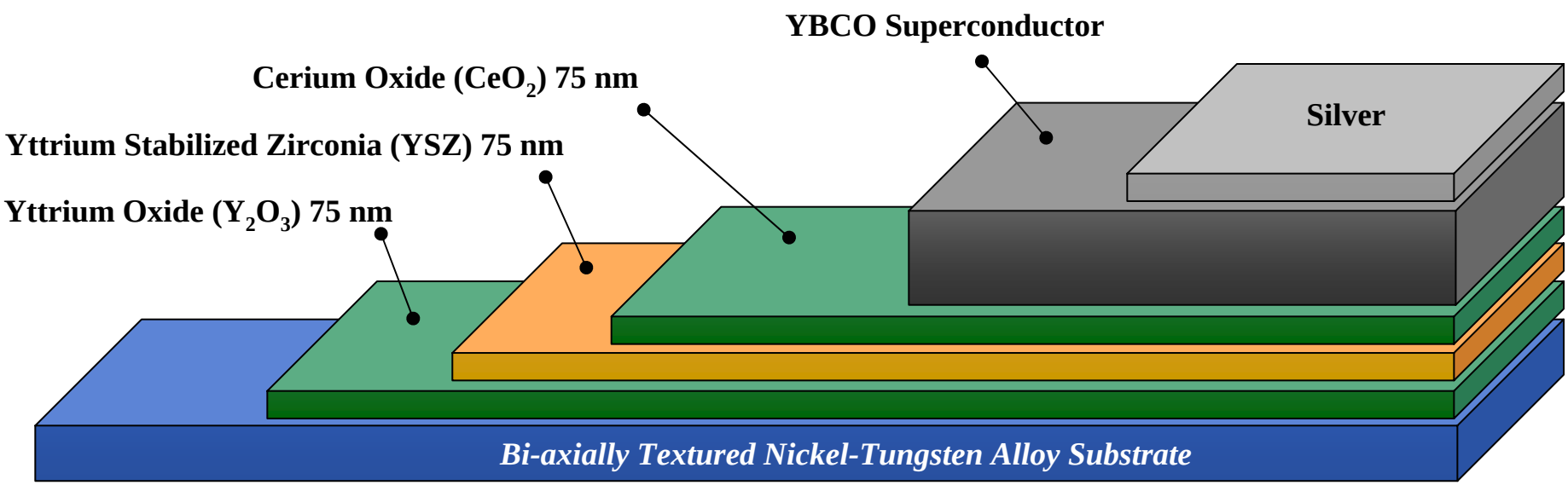
THE UNIVERSITY of WISCONSIN MADISON

UT-BATTELLE

OAK RIDGE NATIONAL LABORATORY

Overview

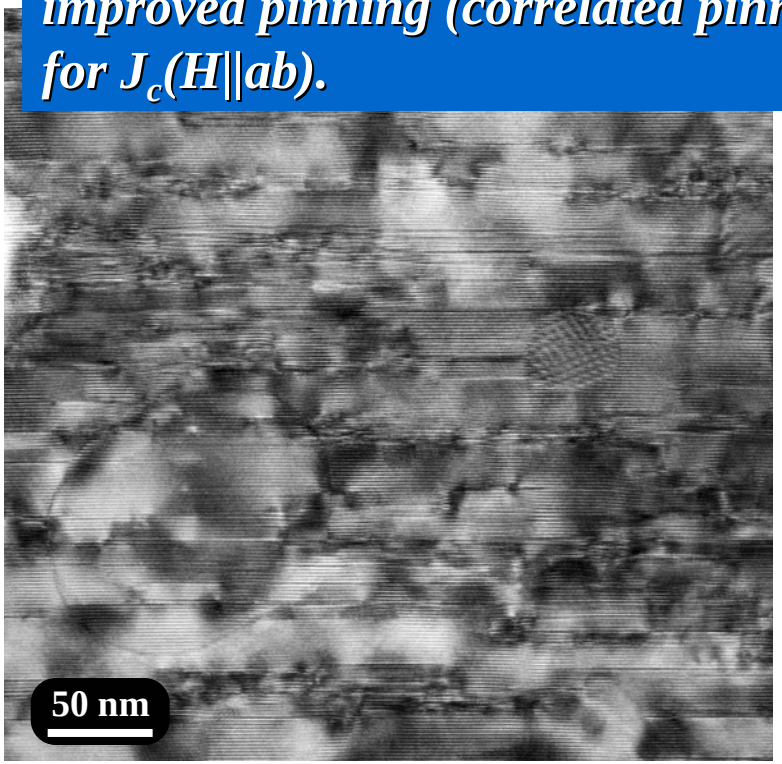
- Review of 0.9 μm MOD film microstructures and properties.
- Multi-coat development of thick, high-current (1-2.5 μm) MOD Films.
- Structure-Property-Chemistry characteristics of a 500 A/cm-w hybrid MOD YBCO film.
- I_c measurements of a thick hybrid MOD YBCO wire.



AMSC YBCO MOD *ex-situ* YBCO films are characterized by defects of various types and length scales.

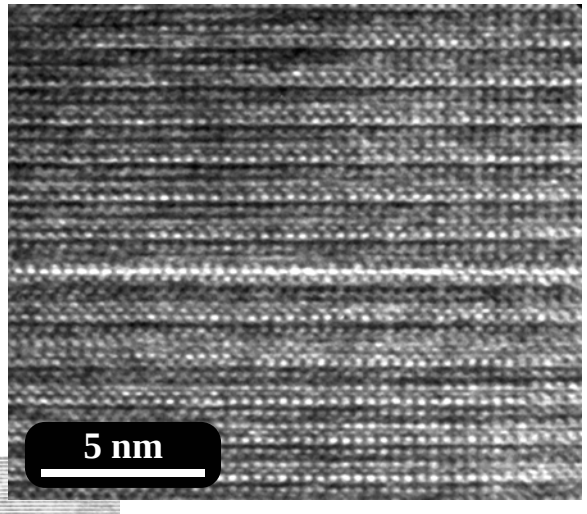
Review 2005

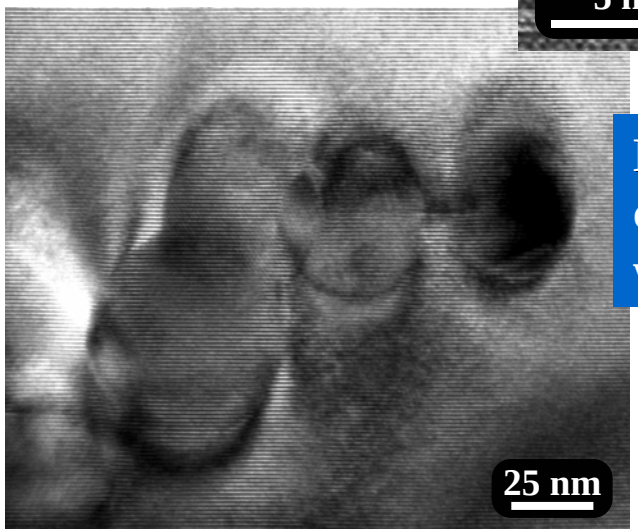
Y-124 intergrowths are responsible for improved pinning (correlated pinning) for $J_c(H||ab)$.



Y123 11.7 Å

Y124 13.7 Å (x 2)



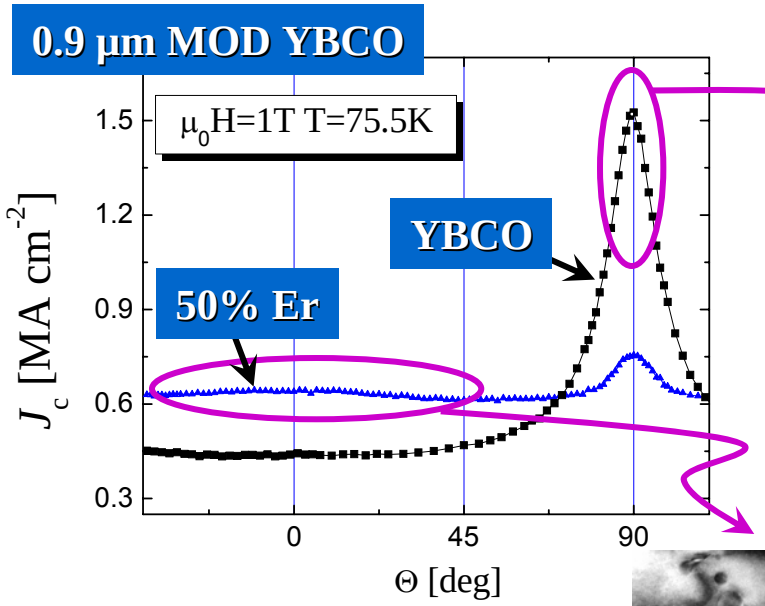


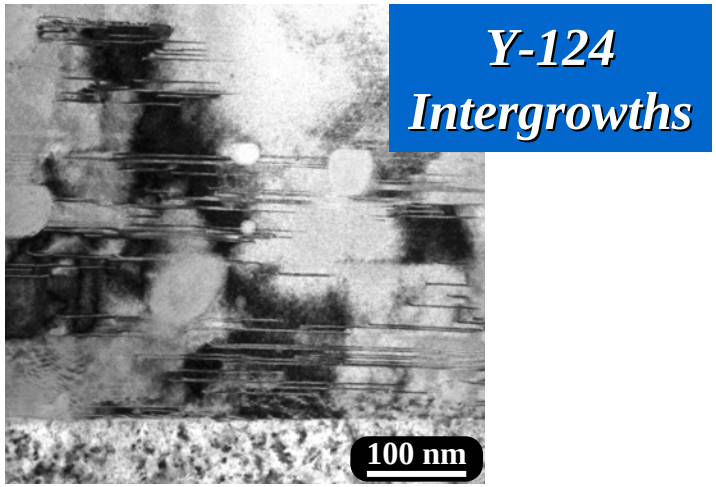
Low density of non-coherent inclusions with strain fields.

Variable porosity
Film tilting
Colony structure

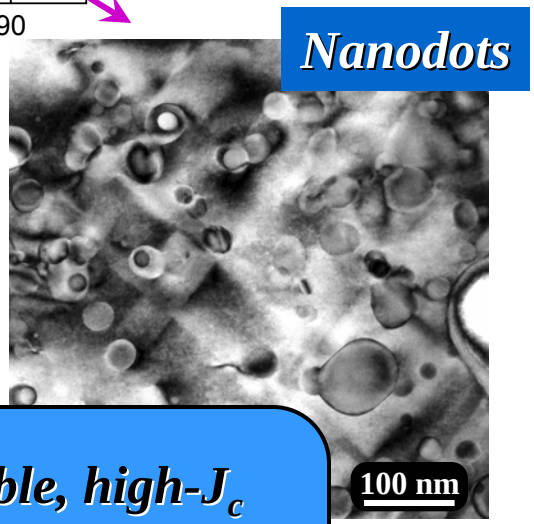
A tunable HTS wire technology was developed with the nano-engineering the pinning defects, Y124 intergrowths and nanodots.

Review 2005

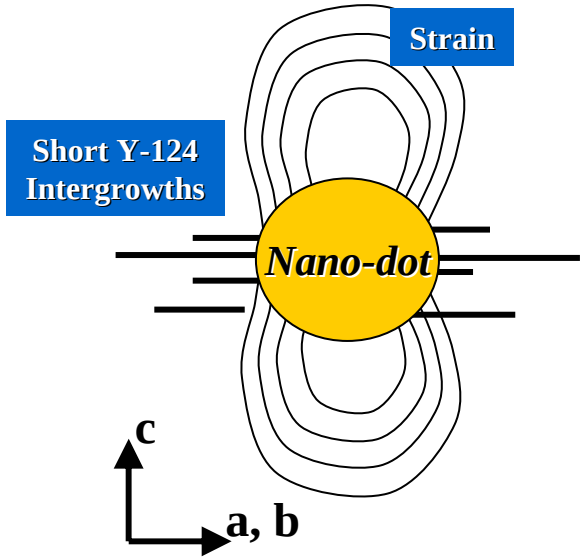




	I_c(sf,75K)
Baseline	250 A/cm
25%Er	260 A/cm
50%Er	260 A/cm



Defect Model



Goal 1: ***Maintain the tunable, high-J_c properties in thick, high-I_c MOD films.***

The development of thick MOD YBCO films for high current HTS wires involves double or triple coats of MOD precursor.

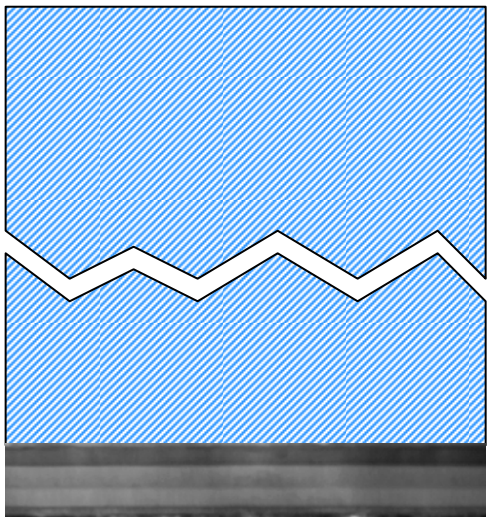
- **Challenge:** Develop optimized process conditions and MOD precursor chemistries for thick, epitaxial YBCO films with uniform, through-thickness J_c properties.

- The formation of thick (> 1.2 μm), high-J_c MOD YBCO films is a significant materials challenge.
  - Thick precursors with the standard high-J_c 0.9 μm MOD chemistry developed cracks during the decomposition step.
  - Precursor chemistry modification allowed for films > 1.5 μm; however, J_c was too low.

- **Alternative:** Deposit and decompose standard MOD precursors in two or more steps to produce a crack-free precursor that will convert to a thick, high-J_c film.

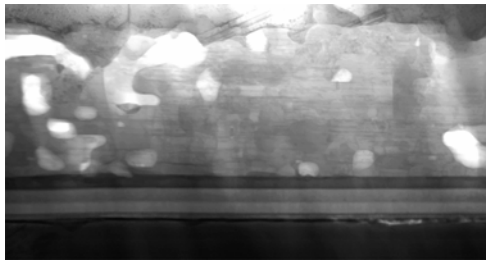
Stages of a 0.9 μm film

MOD Precursor (Liquid) **20 μm**



Decomposed Precursor **2.5 μm**

Superconducting Film **0.9 μm**



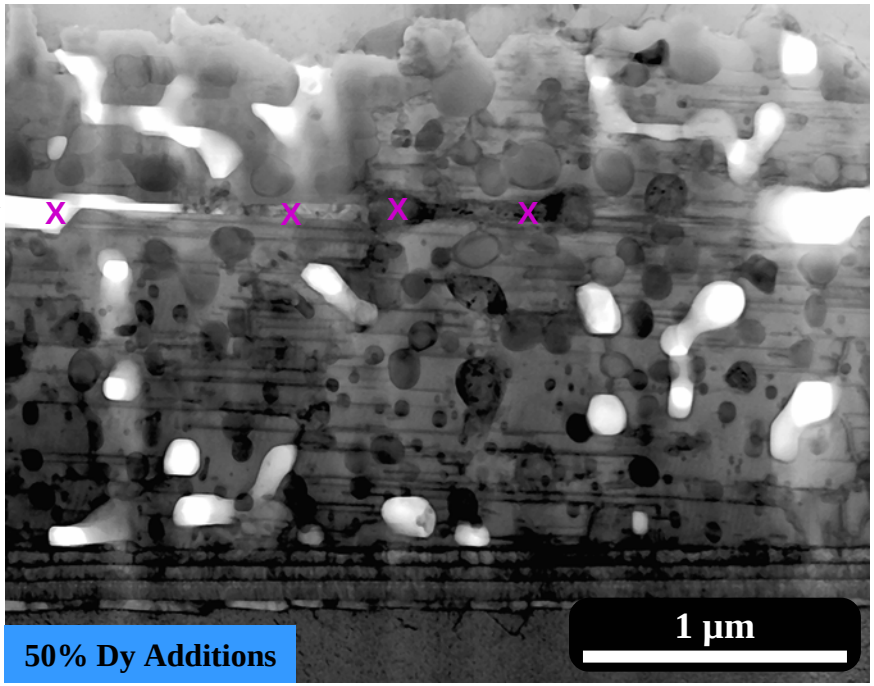
Goal 2: ***Minimize the number of coatings.***

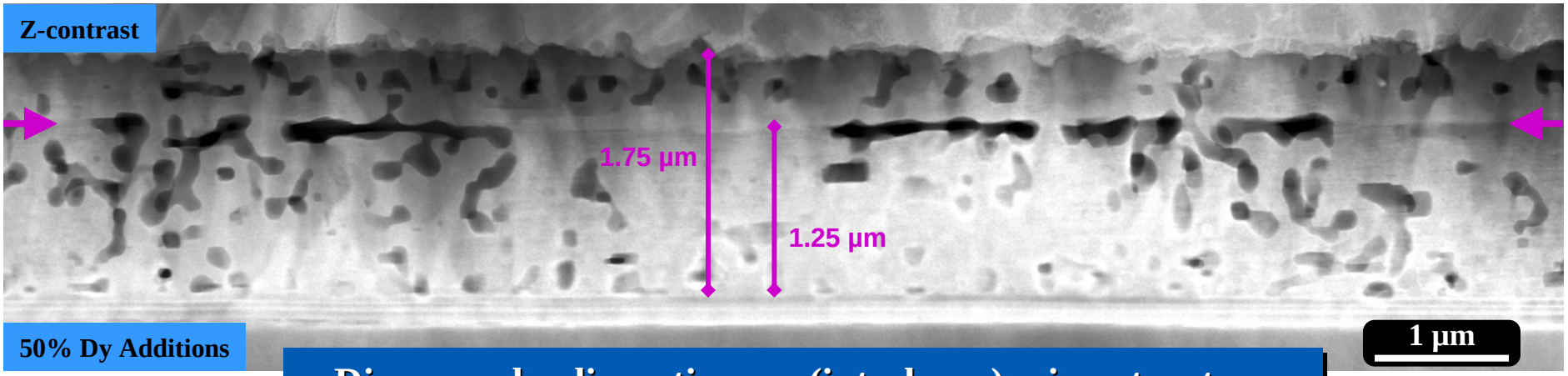
Over the past year, critical currents in excess of 350 A/cm-w were obtained in combinations of double or triple-coat films.

- YBCO / YBCO I_c = 360 A/cm-w
- 50% Dy Additions I_c = 403 A/cm-w
- Triple coat YBCO I_c = 492 A/cm-w
- Hybrid Double Layer I_c = 505 A/cm-w

- The actual film thickness is generally greater than nominal target thickness.
  - 1.6-1.8 µm measured in bi-layer films
  - 1.4 µm intended (0.8 µm / 0.6 µm)

X – Mix of porosity, Ba-Cu-O, and CuO



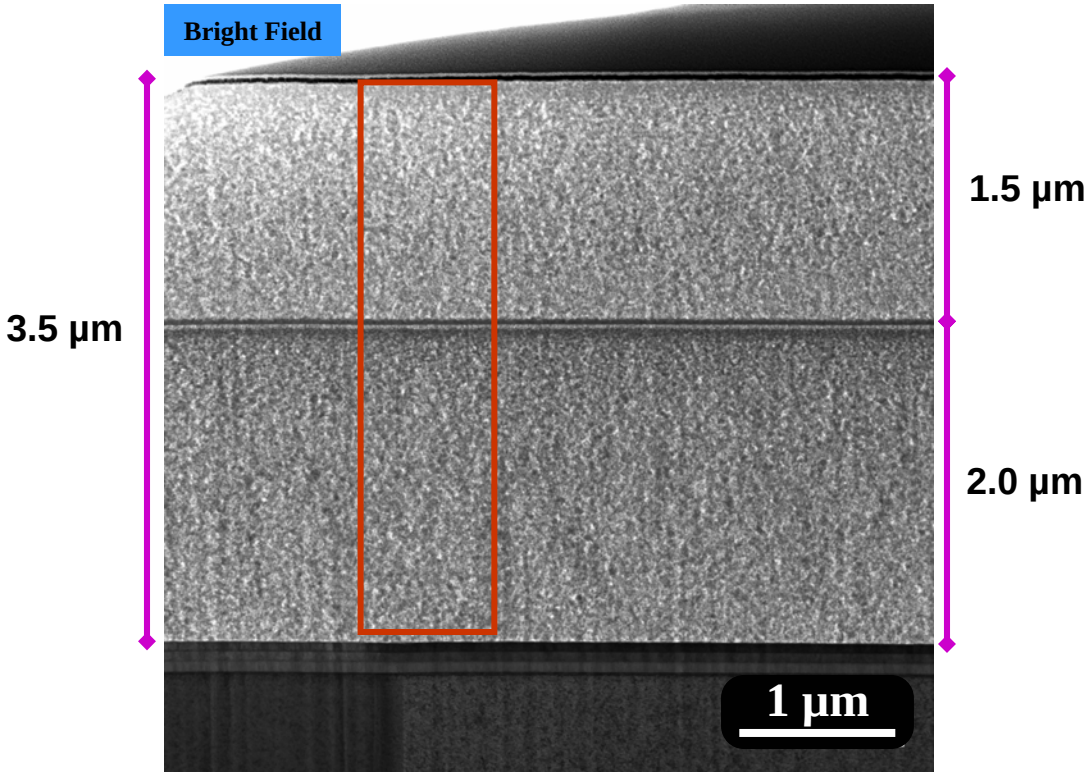


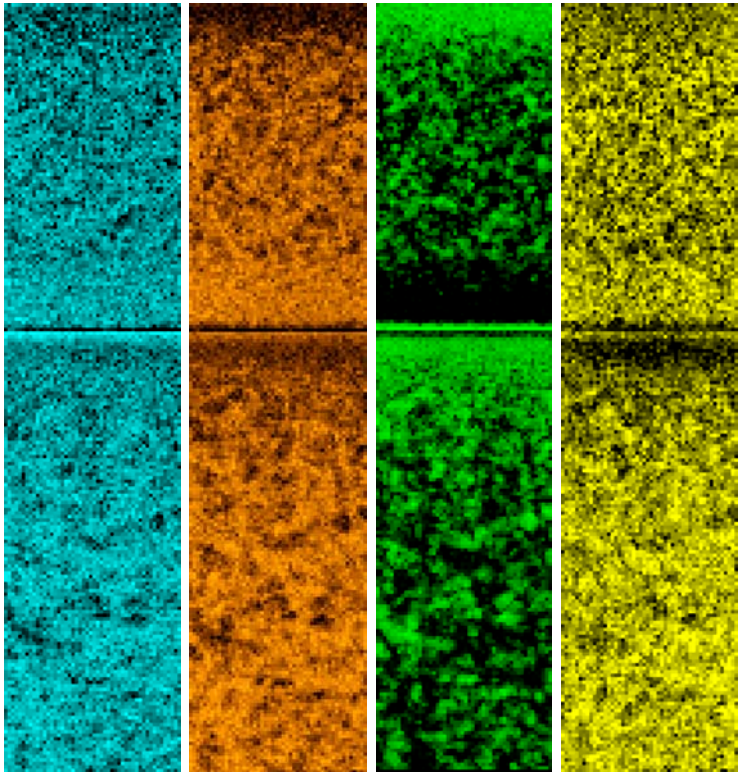
Discovered a discontinuous (interlayer) microstructure that doesn't directly coincide with the precursor layers.

The development of thick MOD films via a multi-coat process is hampered by phase segregation during processing.

- Previous layer is decomposed before the next layer is added.
- Phase segregation occurs during the decomposition of each precursor layer.
- Cu(O) segregates to the top of each layer; BaF_2 to the bottom.
- Segregation persists through the conversion process.

Example: Double-Coat process for a 1.4 µm MOD film; Precursor thicknesses designed for a 0.6 µm MOD film on top of a 0.8 µm MOD film.

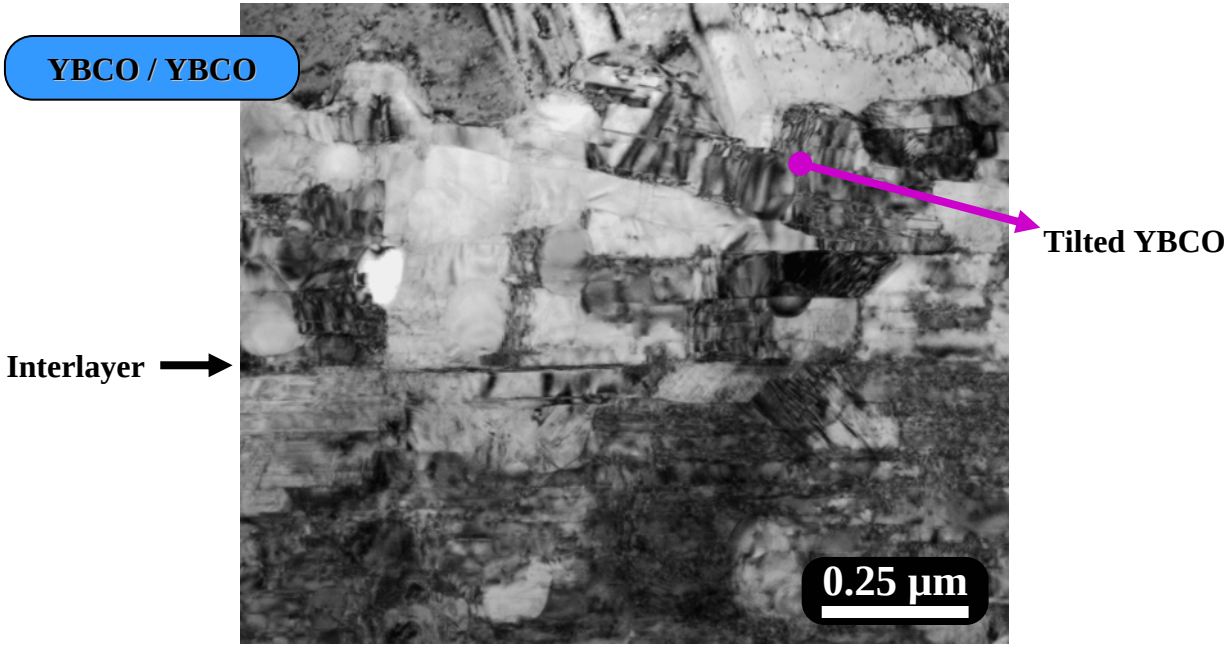


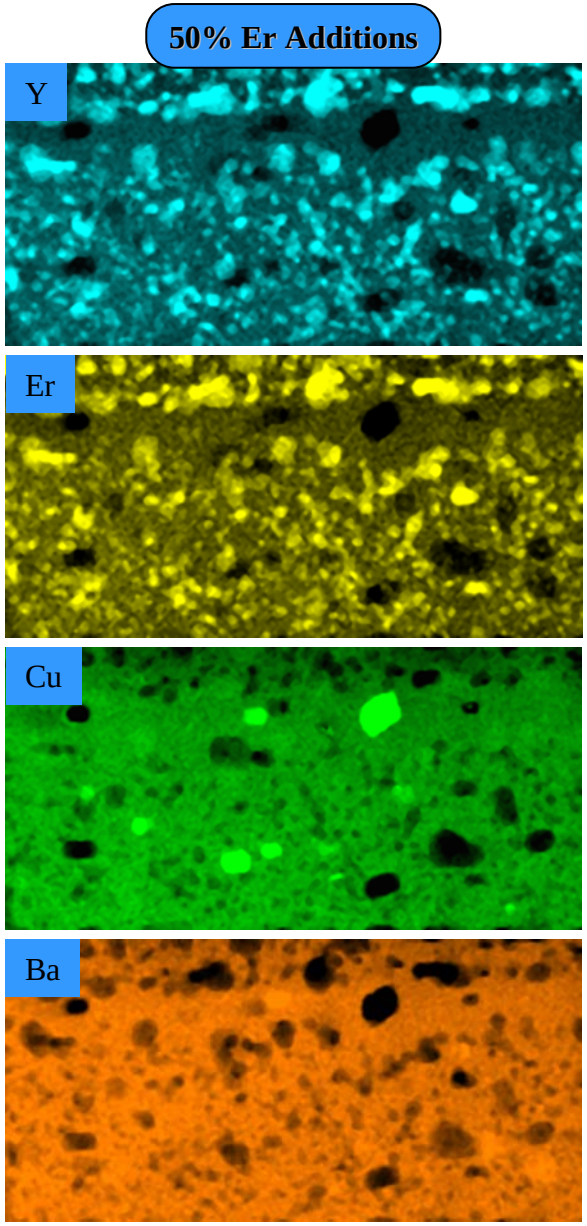


*Additional details on the conversion process to be shown in the LANL wire talk.

The presence of the interlayer structure poised some problems for tuning the properties of the multi-coat MOD films.

- Non-uniform microstructure through thickness.
- Interlayer consists of porosity, secondary phases (Ba-Cu-O, CuO), and inclusion-free YBCO.
- Top layer contained larger secondary phases and regions of misaligned YBCO; Out-of-plane tilted YBCO often observed in the YBCO / YBCO samples.

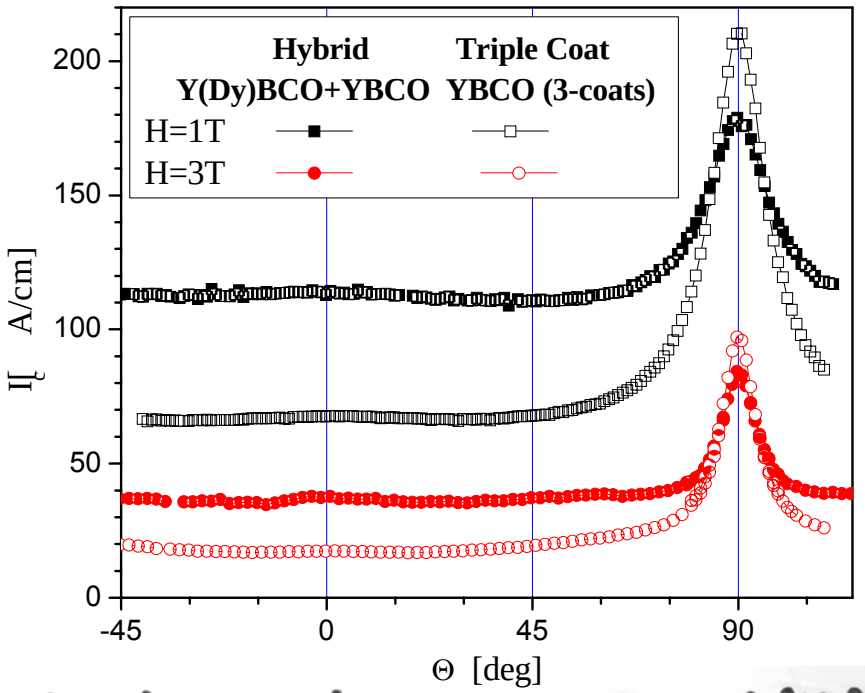




To balance high I_c and $J_c(H,\Theta,T)$, discovered best path forward was to vary the chemistry of each layer.

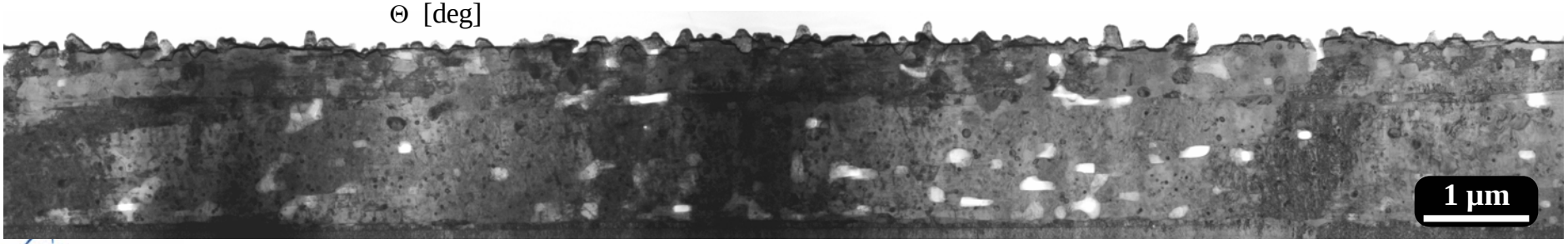
A 500 A/cm-w wire was obtained using a hybrid MOD double-layer film structure of 50% Dy additions in the bottom and a YBCO film on top.

- Comparison of 500 A/cm-w class samples, triple-coat (YBCO) and hybrid double-coat Y(Dy)BCO / YBCO.
- With the mixed chemistry, a much higher performance is obtained in fields oriented away from H||ab.



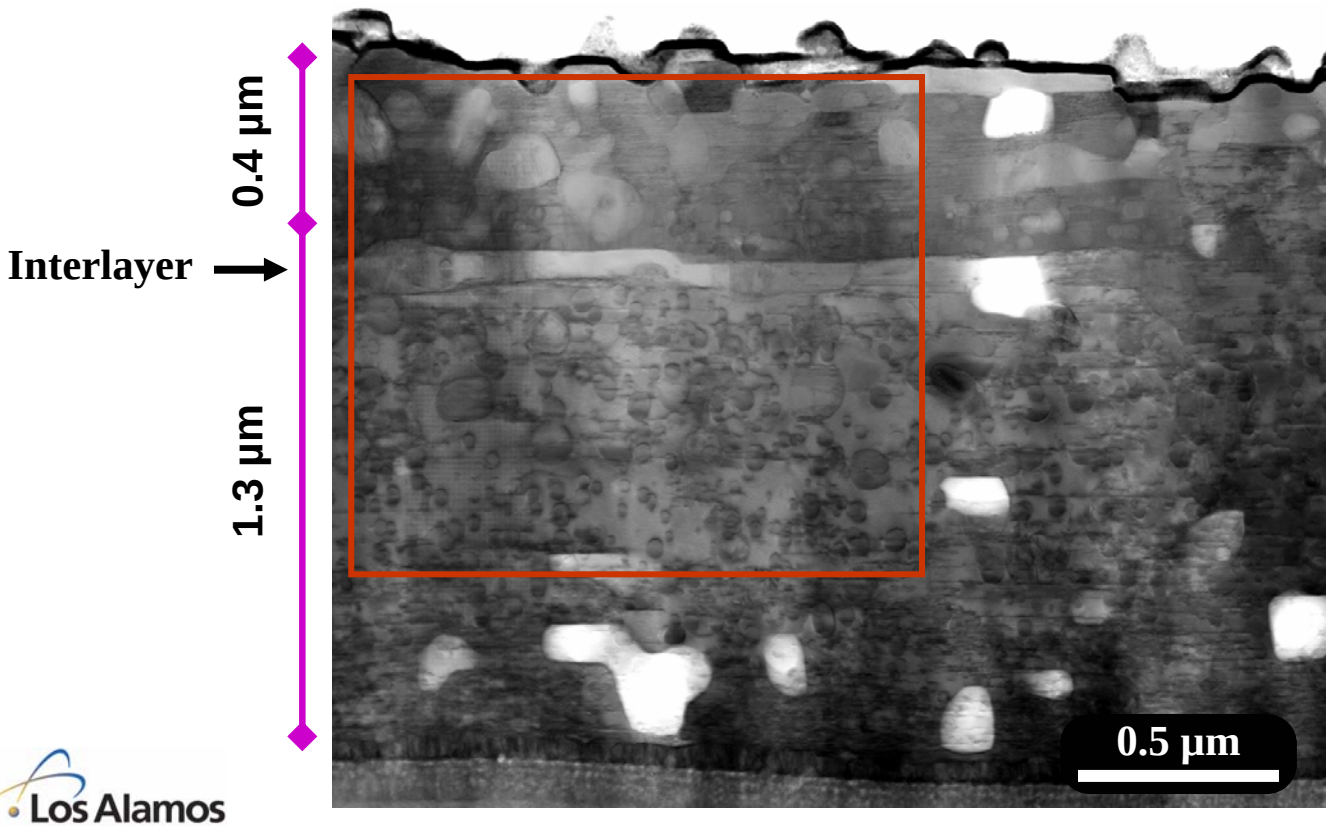
High I_c films could be obtained in double-coat, hybrid films that achieved the 500 A/cm-w goal.

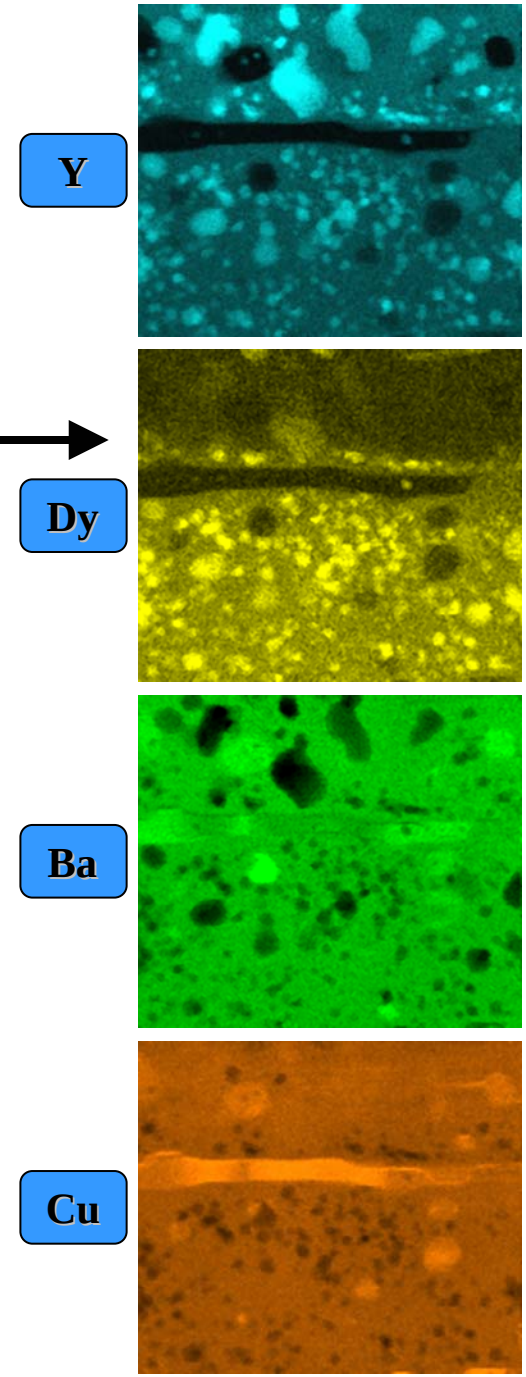
$t_{(YBCO)}$ = 1.7 µm
J_c(77K, SF) = 3 MA/cm^2



Spectral imaging confirms that the MOD film has two different chemistries.

- Spectral imaging showed a clear break in the Dy concentration in the double layer film.
- 1. 3 µm of film with Dy additions. (Nanodot microstructure)
  - Excess Dy additions actually extend past the interlayer.
- 0.4 µm of film at the top that has very little Dy. (Y124 planar defects).

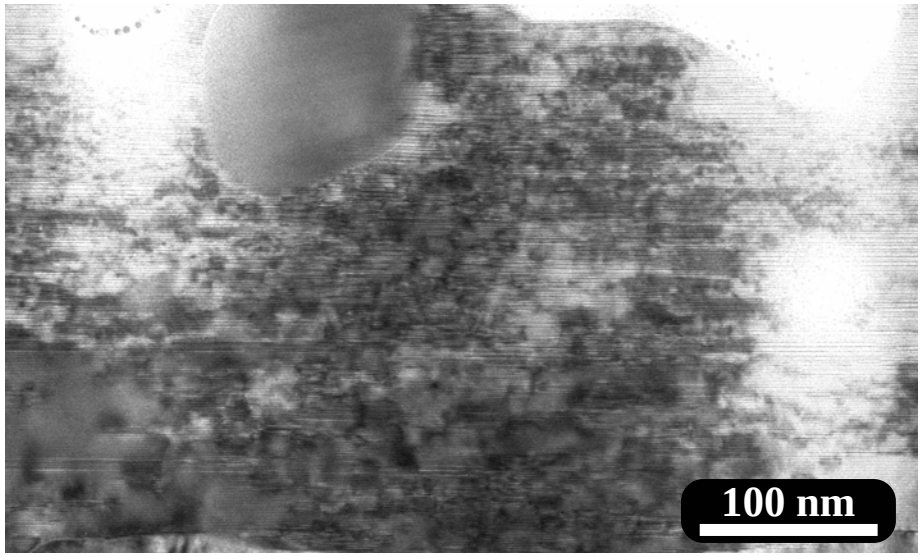


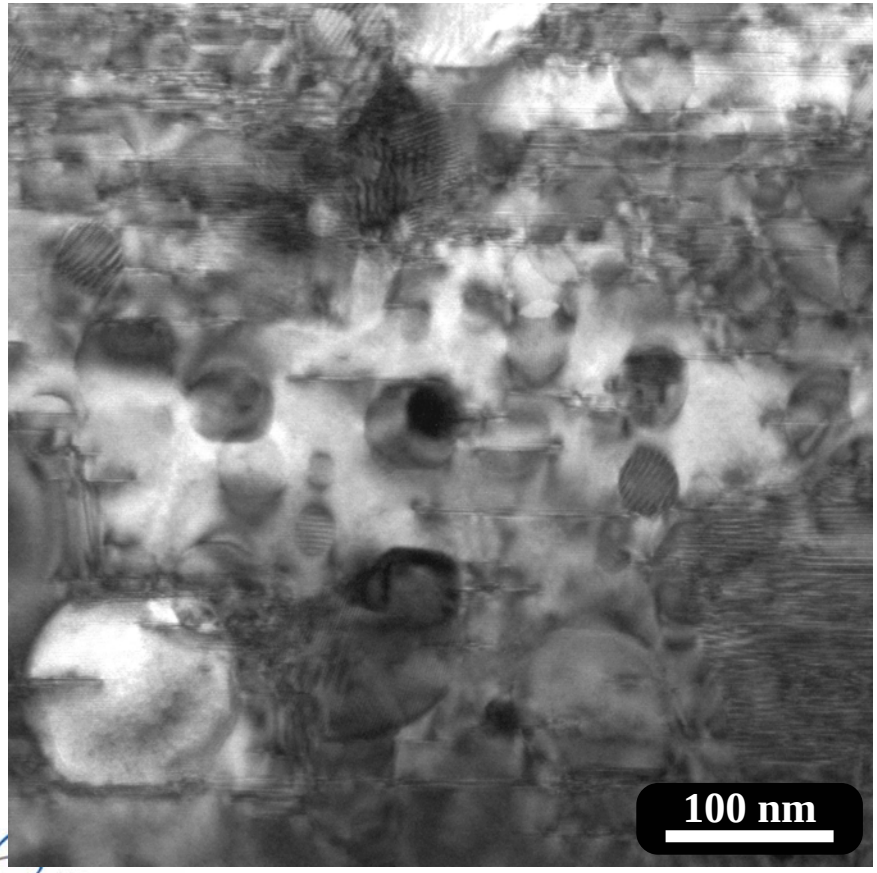


TEM imaging confirms the Y124 planar defect structure in the top portion and the nano-dot structure in bottom.

- For the most part, the transition from the nano-dot to planar defect structure is abrupt, in agreement with the spectral imaging.

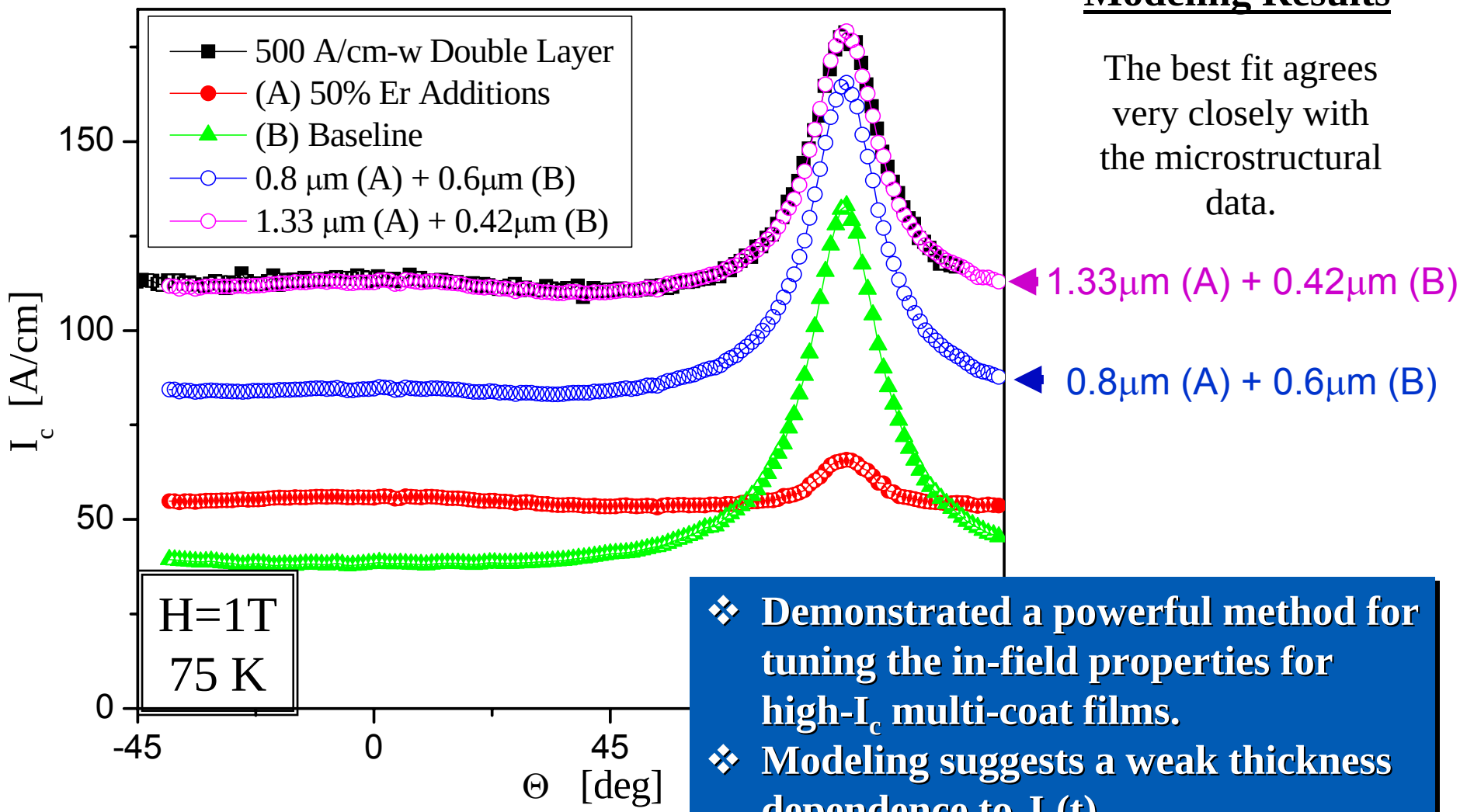
Y-124 planar intergrowth structure above the interlayer.





Nano-dot microstructure in the film below the interlayer.

The performance of the 500 A/cm-w film in applied fields can be modeled with the properties of (A) 50% Rare-Earth Additions or (B) YBCO 0.9 μm MOD films.



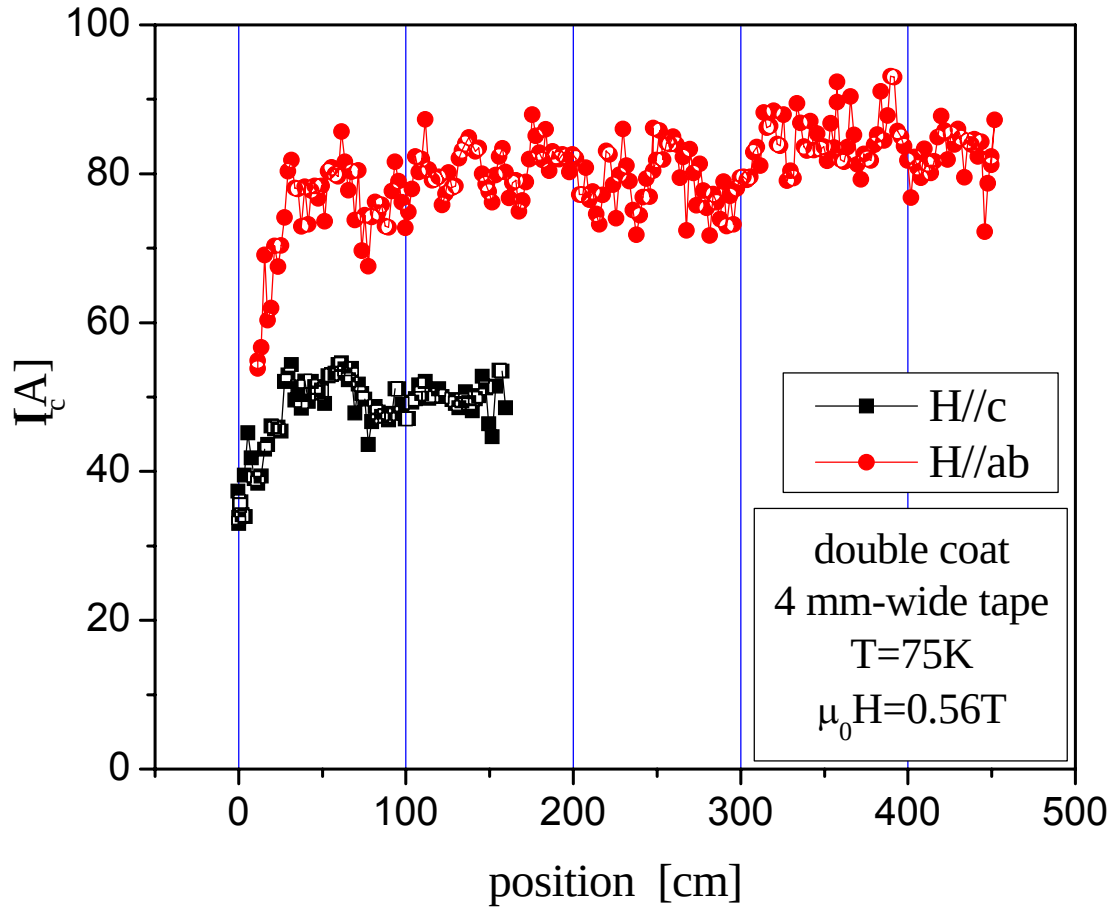
Modeling Results

The best fit agrees very closely with the microstructural data.

- **Demonstrated a powerful method for tuning the in-field properties for high-I_c multi-coat films.**
- **Modeling suggests a weak thickness dependence to $J_c(t)$.**

Wires made with the hybrid double-coat MOD process showed good uniformity in properties along the length of the wire.

- Continuous long length I_c measurements for H||ab and H||c.
- 344 Wire structure with 362 A/cm-w of insert at 75K, SF
  - Wire I_c(SF, 75K) estimated at 145 A.
  - Ratio of J_c(H||ab)/J_c(H||c) is 1.5



<u>Self-field I_c Estimation</u>

At 0.56 T, J_c(H||ab) is 55% of the self-field value as determined by bridge measurements on short samples.

*Additional details on the long length measurements to be shown in the LANL wire talk.

Summary

- Developed a successful thick MOD film technology
  - ✓ **Goal 1**: Reached 500 A/cm-w in a process that allows for tunable properties $J_c(H,\Theta,T)$ in applied fields.
  - ✓ **Goal 2**: Just two layers were used for a hybrid MOD YBCO film that reached the 500 A/cm-w goal.
- Developed an understanding of the microstructural evolution in multi-coat MOD films.
  - Discovered the development of a discontinuous microstructure (interlayers) that would prevent a uniform through-thickness microstructure.
  - Discovered that distinct chemistries can be maintained through processing in a multi-coat film with different layer chemistries.
- Demonstrated a powerful methodology for tuning the $J_c(H,\Theta,T)$ properties via chemistry modification of individual precursor layers.
  - Individual layers can be tuned like standard 0.9 μm single-layer films.
  - The modeling of the double-coat data with single-layer MOD film data implies a weak $J_c(t)$ dependence.
  - Demonstration of triple-coat films gives even more room for I_c and $J_c(H,\Theta,T)$ improvements.
- Demonstrated the hybrid double-coat technology in a practical wire.

Deconstructing MOD YBCO films
layer by layer and grain by grain

Matt Feldmann

University of Wisconsin

Terry Holesinger, Boris Maiorov, Leonardo Civale

Los Alamos National Laboratory

Zhijun Chen, Dima Abraimov, David Larbalestier

University of Wisconsin

Marty Rupich, Xiaoping Li, Wei Zhang

American Superconductor

Ron Feenstra, Claudia Cantoni

Oak Ridge National Laboratory

John Durrell

University of Cambridge

Wire Development Group (WDG) members:

THE UNIVERSITY of WISCONSIN MADISON

American Superconductor

Los Alamos NATIONAL LABORATORY EST. 1943

UT-BATTELLE OAK RIDGE NATIONAL LABORATORY U. S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

Overview

- **layer by layer**

  Hybrid double layer (YBCO / 50% Dy Additions):

  - Progress in $I_c(t)$ uniformity in double coat films
  - Additive nature of pinning mechanisms in the layers revealed by $J_c(\theta)$ through thickness

- **grain by grain**

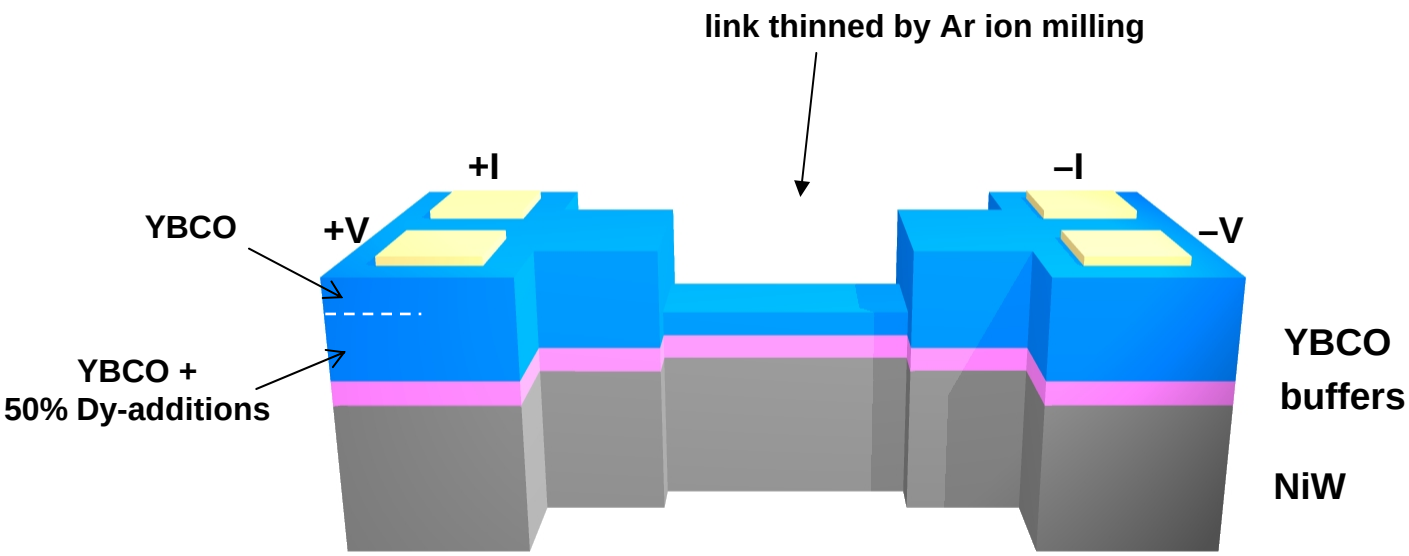
  Single coat films (0.8 μm)

  - LTLSM in high fields (5T) reveals local GB/grain limited regimes (New to WDG in 2006)
  - Enhanced J_c of meandering GBs revealed by single GB measurements in MOD/RABiTS
  - Enhanced $J_c(H||c,\phi)$ of single isolated GBs in MOD/RABiTS

$J_c(t,\theta)$ Properties in Hybrid Double Coat Film Studied Through-thickness by Thinning with Ion Milling

Top Layer: YBCO (high density of 124-intergrowths)

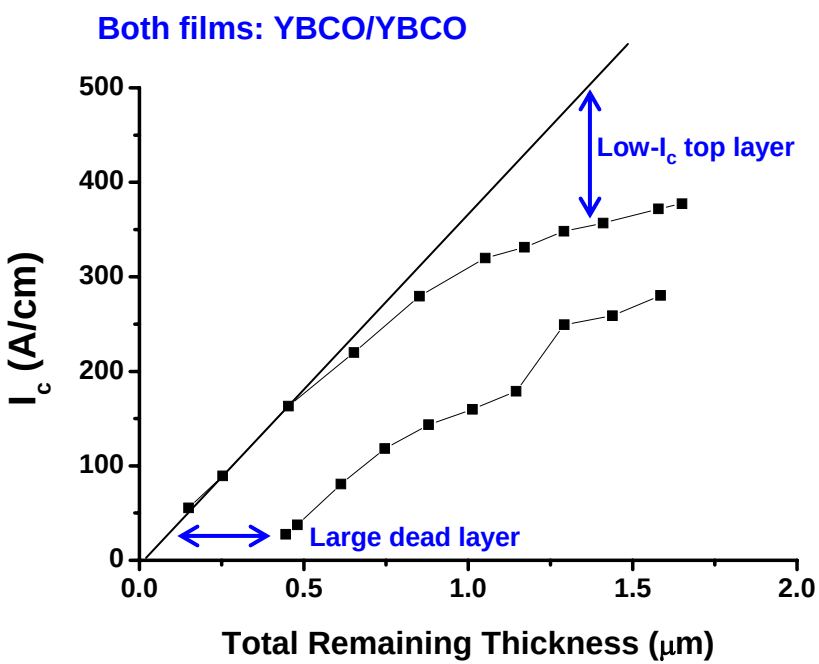
Bottom layer: YBCO + 50% Dy-additions (high density of nano-dots)

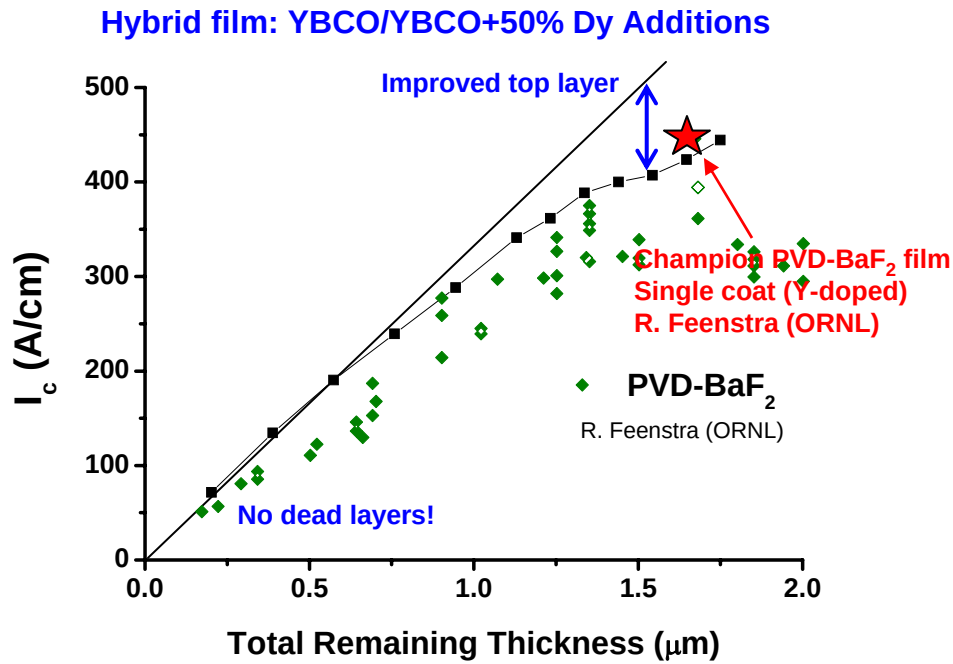


Process Improvements Over the Last Year Have Greatly Improved $I_c(t)$ Uniformity in Double Coat Films

❖ Previous double coat films exhibited significant low-J_c layers at the top or bottom of the films

❖ Process improvements have greatly improved through-thickness uniformity in new baseline double coat film



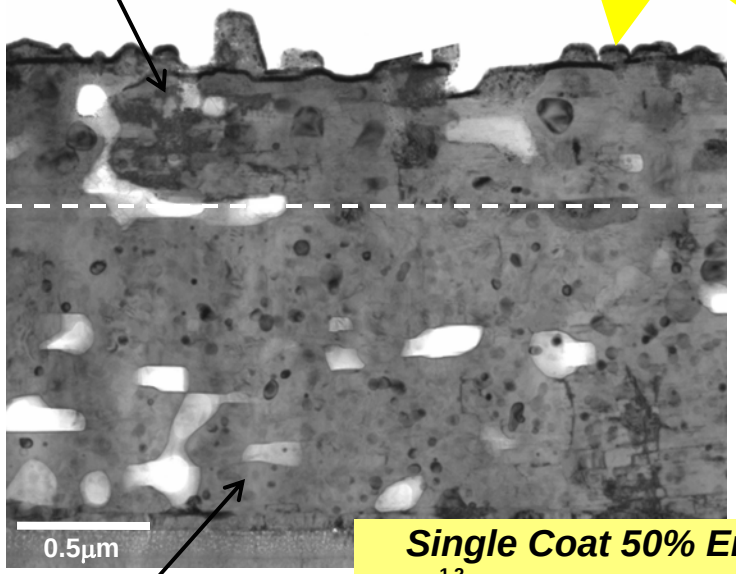


J_c Anisotropy Changes Through Thickness Due to Distribution of Pinning Defects

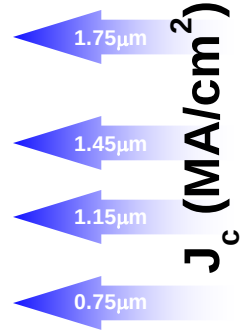
Effect of Dy nano-dots alone has been observed by isolating the bottom layer!

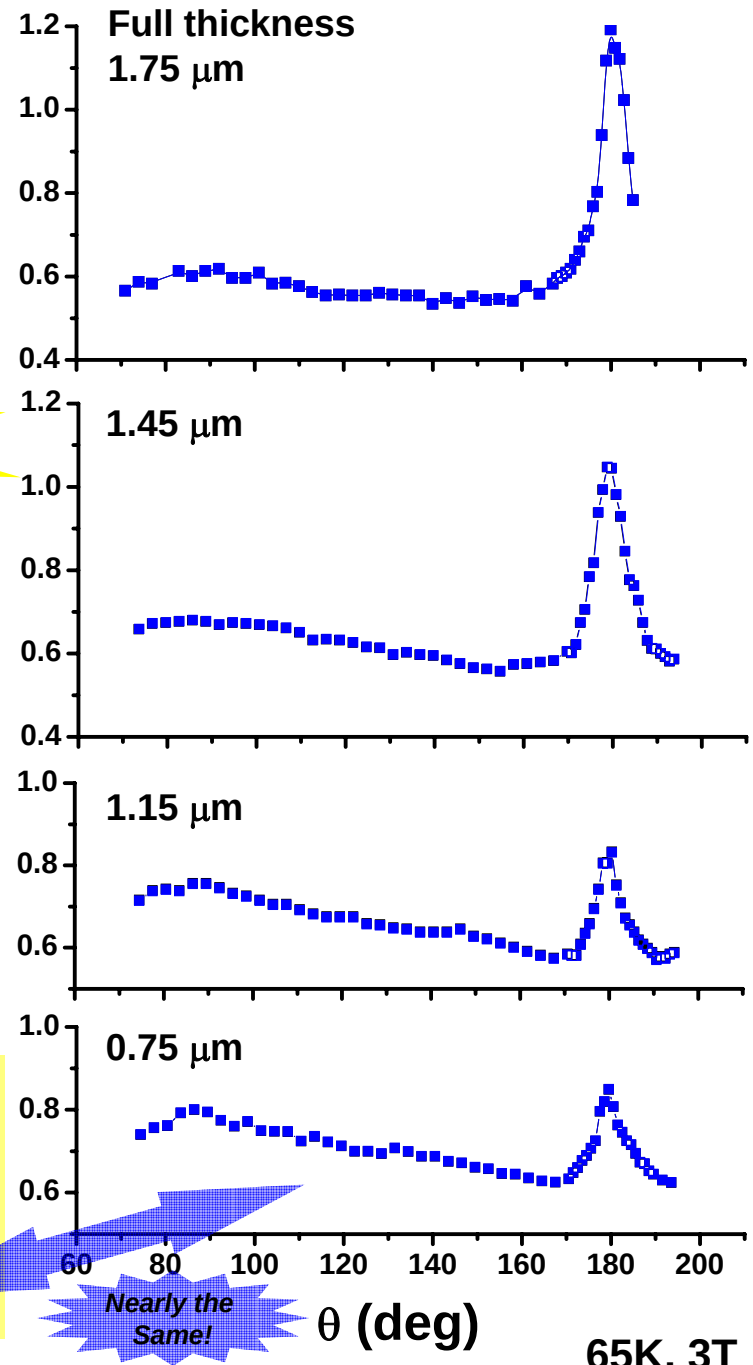
high density 124-intergrowths in top

inter-face



high density Dy nano-dots in bottom

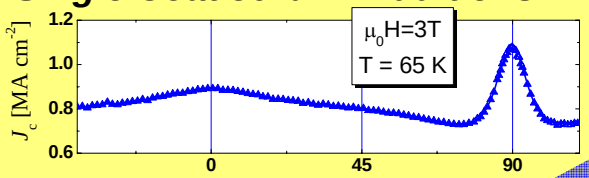




Nearly the Same!

65K, 3T

Single Coat 50% Er Additions

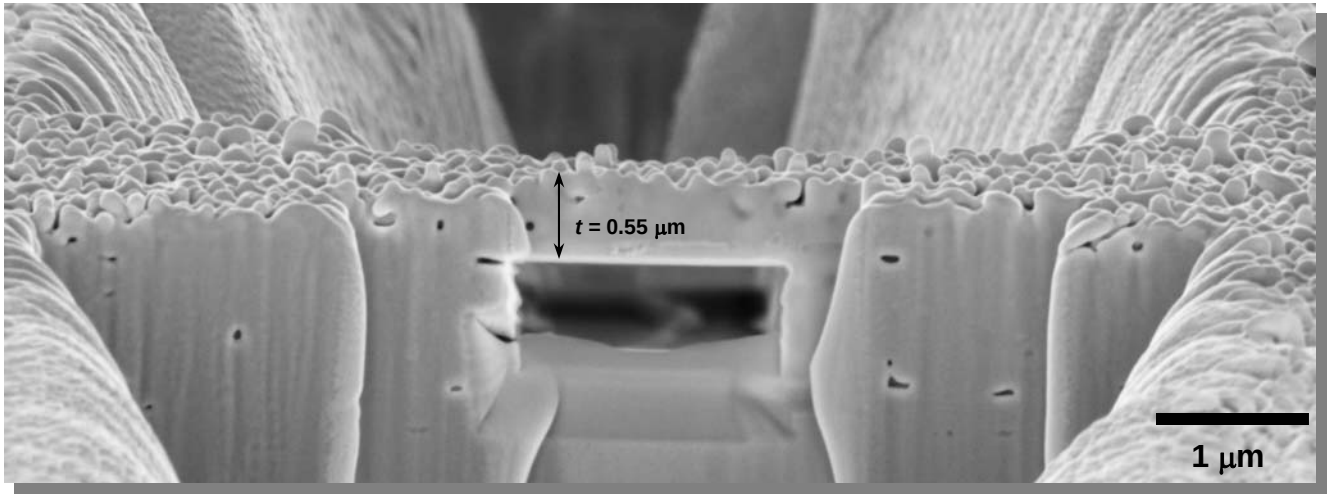


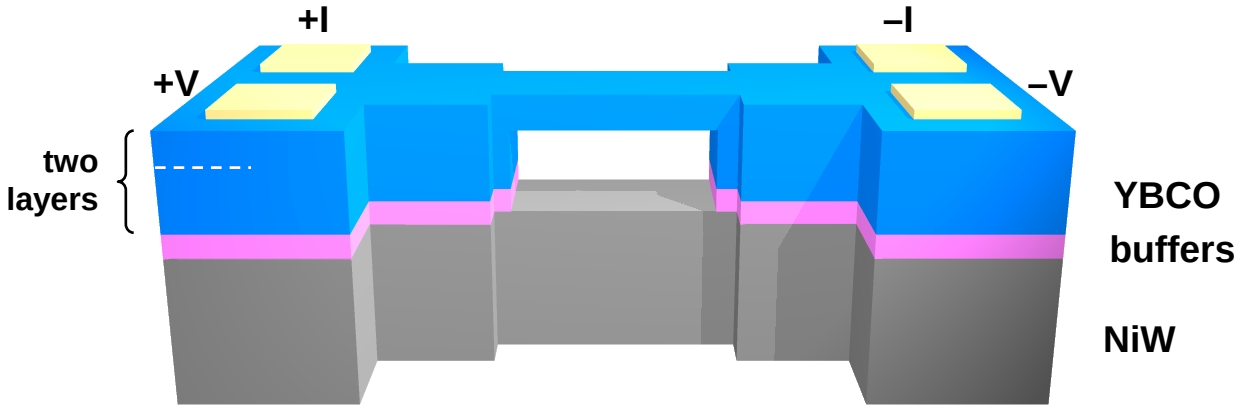
L. Civale
B. Maiorov (LANL)

Can We Study the Effect of the 124-intergrowths Directly? Yes.

Isolated Top layer: Effect of 124-intergrowths alone

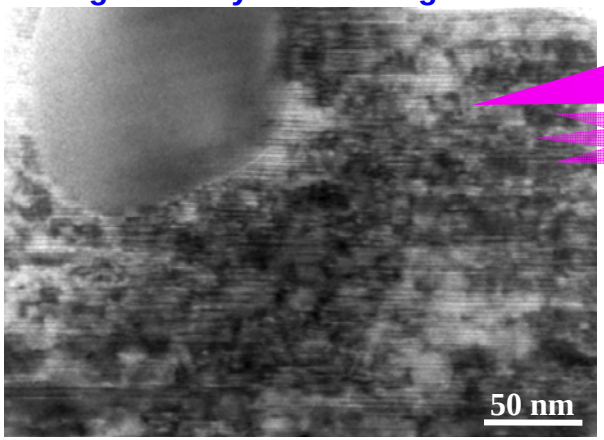
Top layer isolated with Focused Ion Beam (FIB)





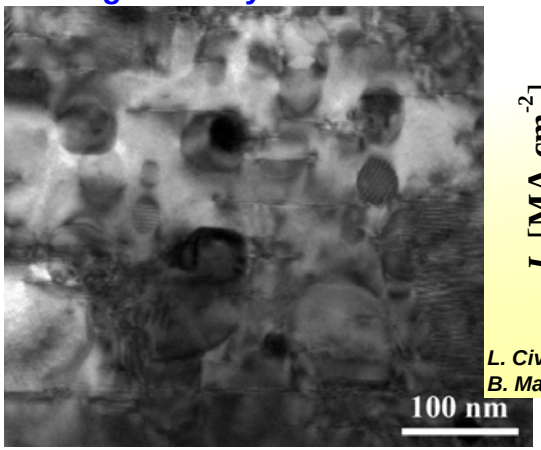
The Different Pinning Properties of the Layers are Additive!

Top layer (YBCO):
High density of 124-integrowths

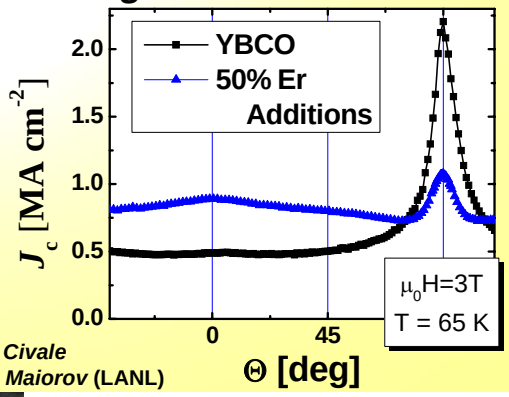


Effect of 124-intergrowths alone is clearly observed!

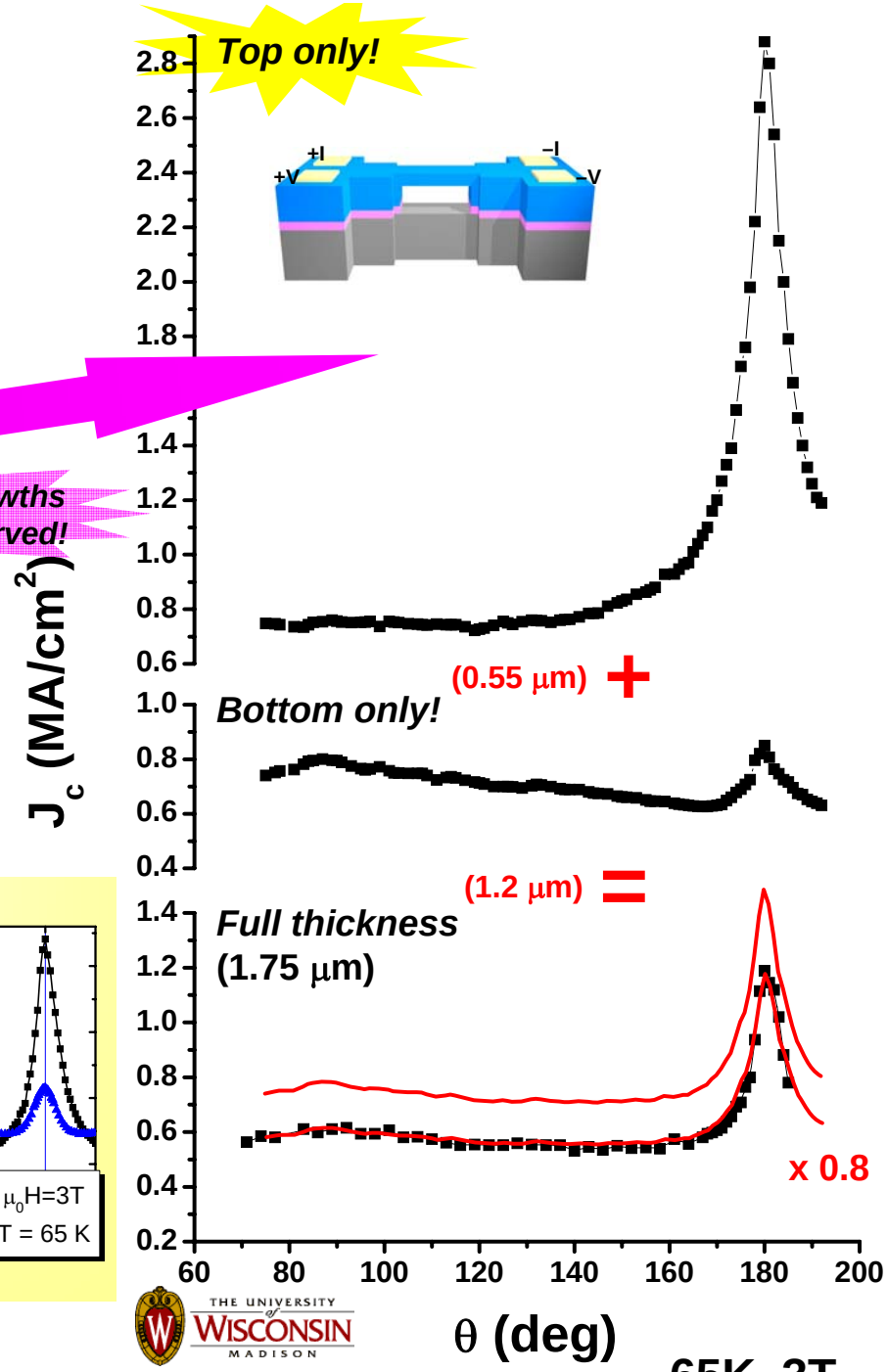
Bottom layer (50% Dy additions):
High density of nano-dots



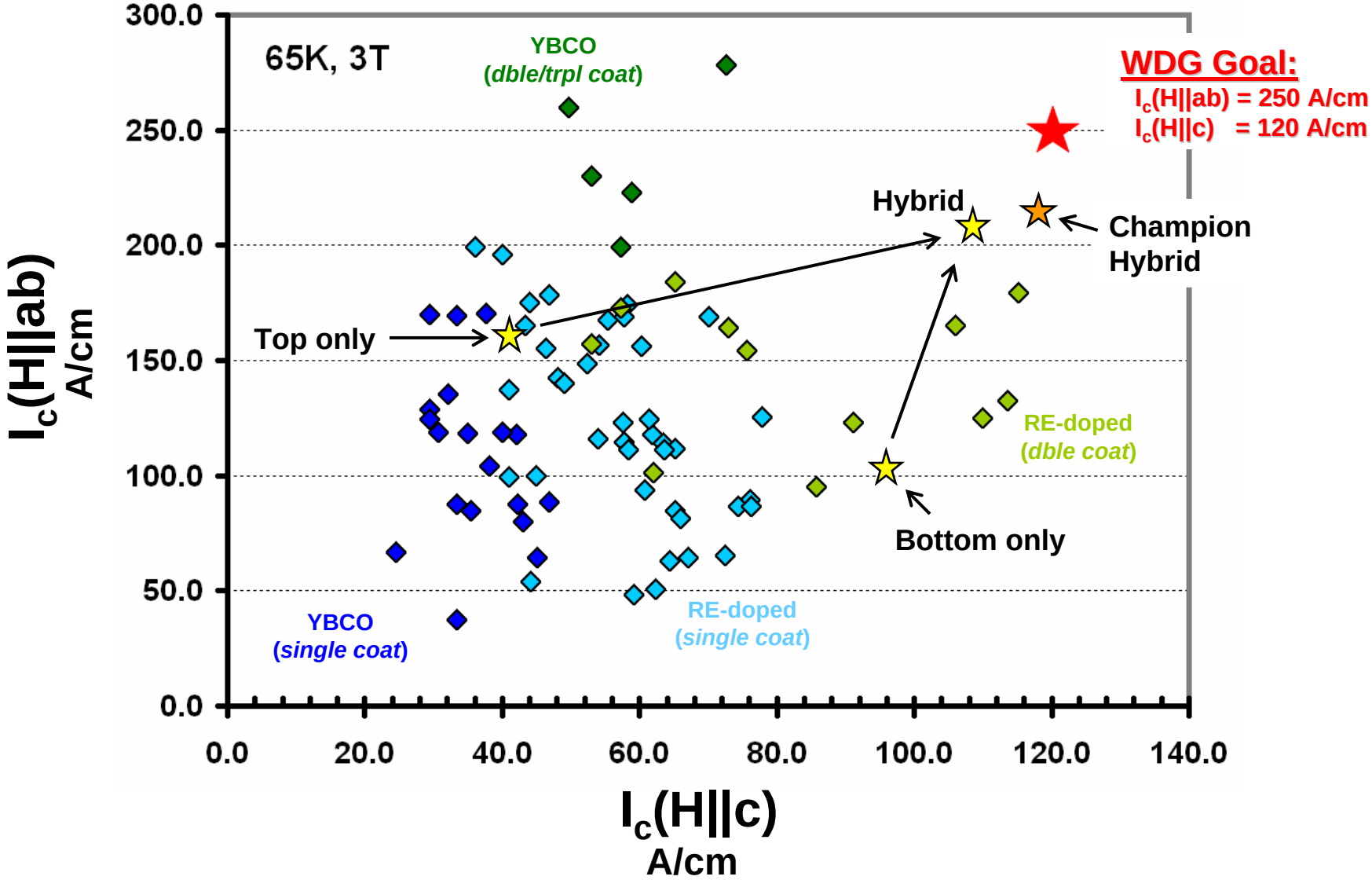
Single Coat Films:



L. Civale
B. Maiorov (LANL)



Hybrid YBCO/YBCO+Dy Double Coat Film Gets Very Close to FY2006 Goal



$J_c(t,\theta)$ Summary of Hybrid Film

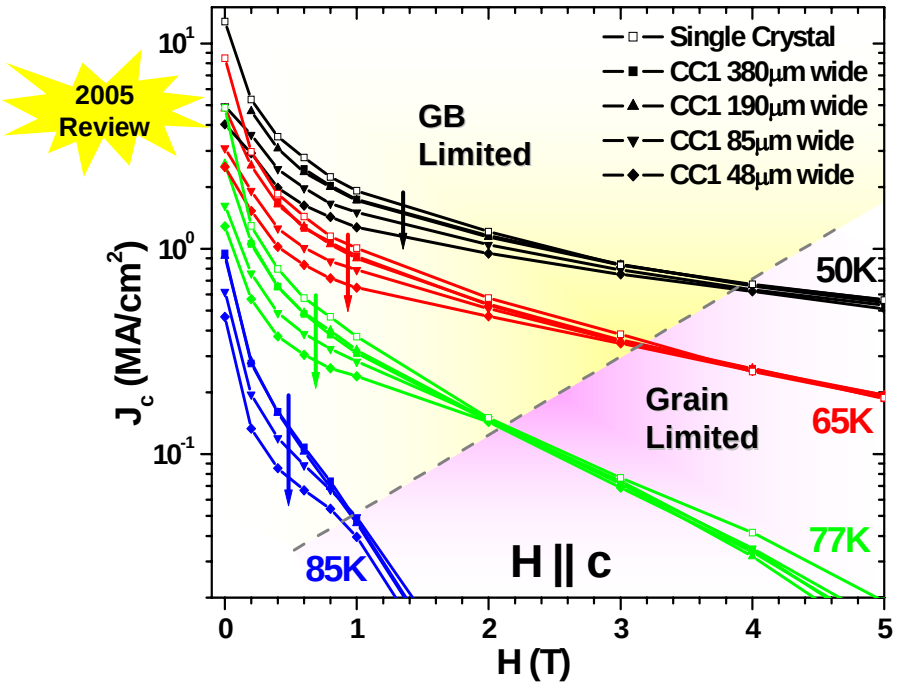
- Process improvements over the last year have greatly improved $I_c(t)$ uniformity in double coat films
- Gained an understanding of the individual contributions of the dominant pinning mechanisms in the film to the overall $J_c(\theta)$ properties of the 500 A/cm hybrid film
  - The isolated top and bottom layers each behave as their single layer counterparts
  - The $J_c(\theta)$ properties of the Hybrid film were shown to be a direct summation of the properties of the individual layers
- This implies that $J_c(\theta)$ properties can be tuned by the addition of multiple pinning mechanisms

- Further details of $J_c(t,\theta)$ will be presented in the UW talk tomorrow morning

New 5T LTLSM System Allows Local Mapping of GB Limitations as a Function of *H*

➢ ***In a CC local variations of the grain/GB limited regime exist***

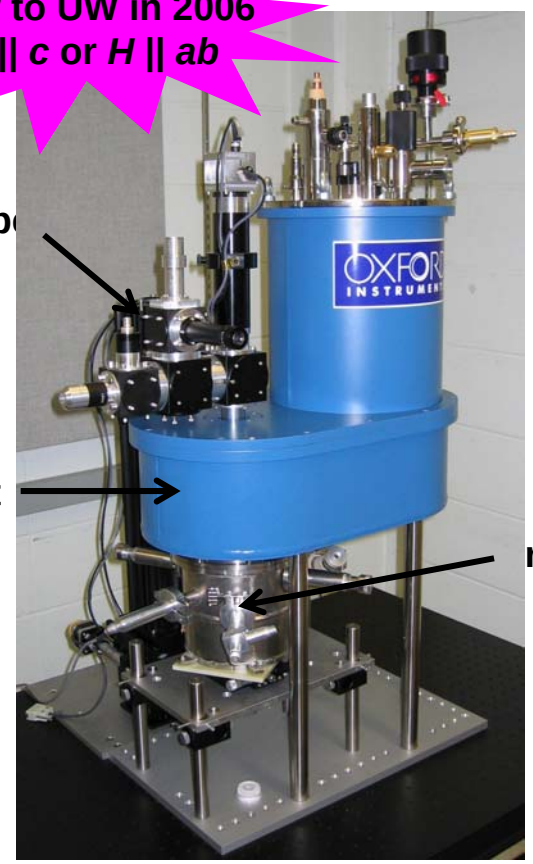
Transport measurements reveal macroscopic Grain/GB limited Regimes



Kim et al, PRB **71** 10, 104501 MAR 2005

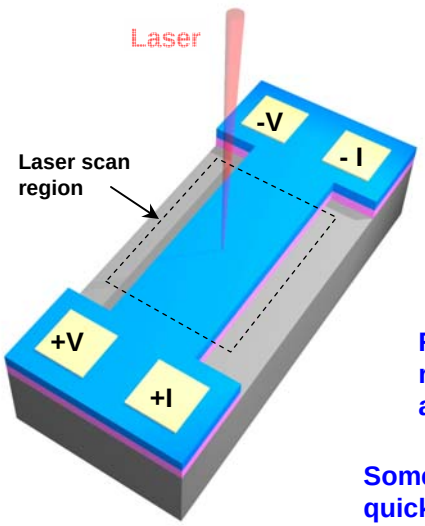
Low Temperature Laser Scanning Microscopy (LTLSM) can reveal local Grain/GB limited Regimes

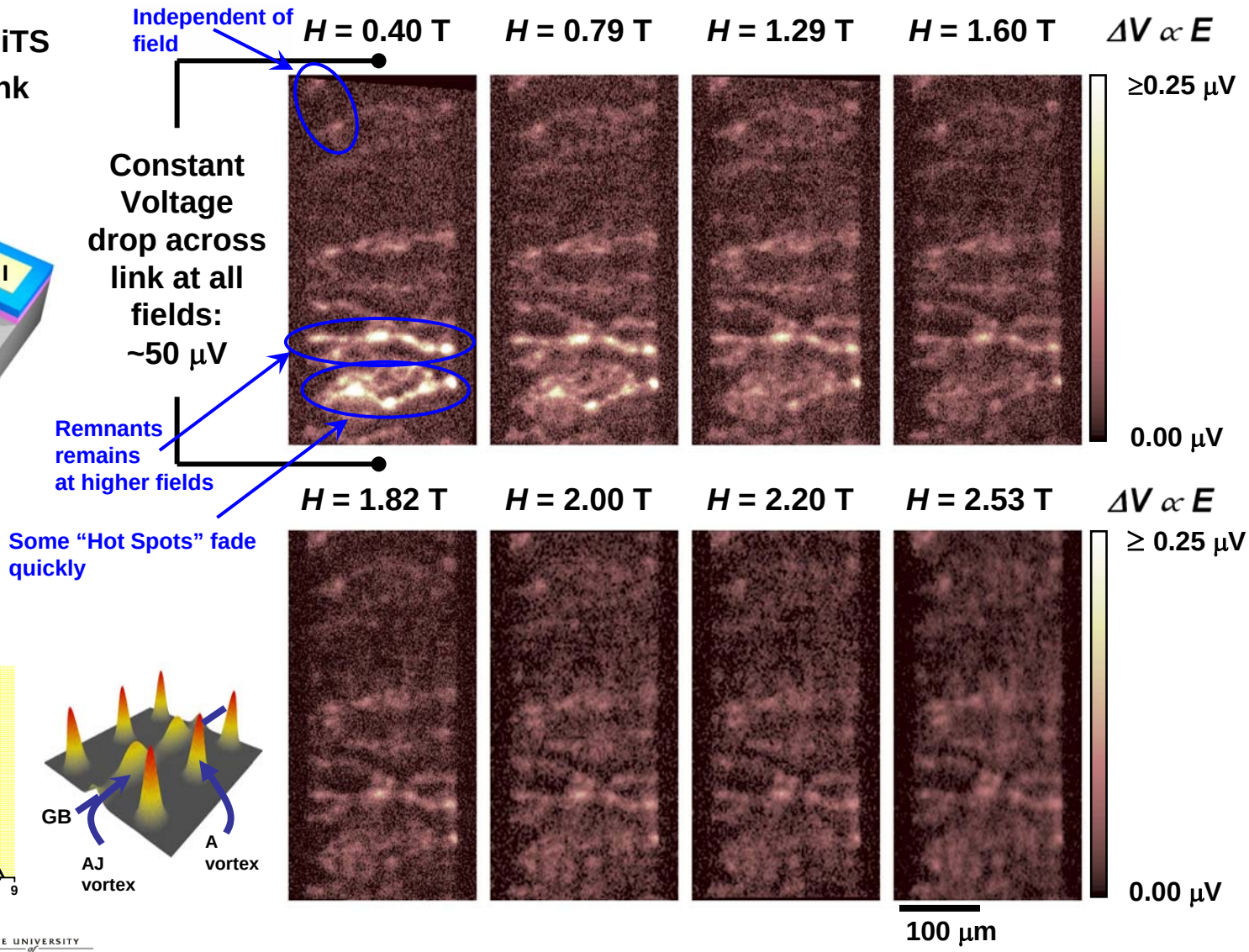
New to UW in 2006
H* || *c* or *H* || *ab

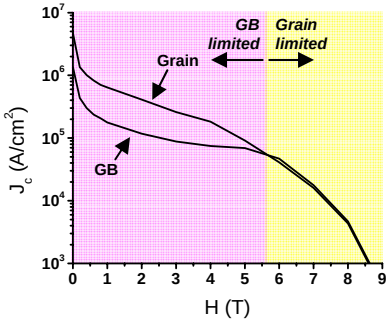


At higher fields dissipation within the link becomes more evenly distributed

Single-coat MOD (0.8μm)/RABiTS Laser patterned link







82 K

Different Microstructures of MOD, PLD Films Result in Different Behaviors of the YBCO GB Network

MOD/RABiTS show benefit of meander

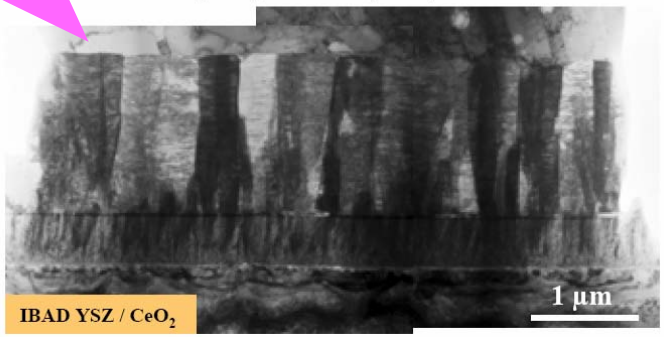
PLD

MOD

TEM, cross sections:

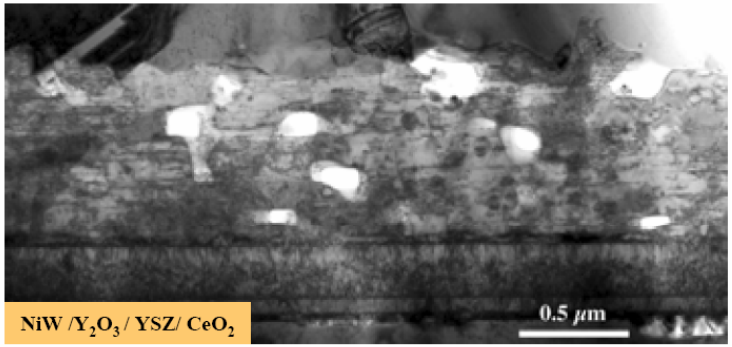
columnar microstructure

LD YBCO (Foltyn-LANL) 1.5 µm YBCO film



layered microstructure

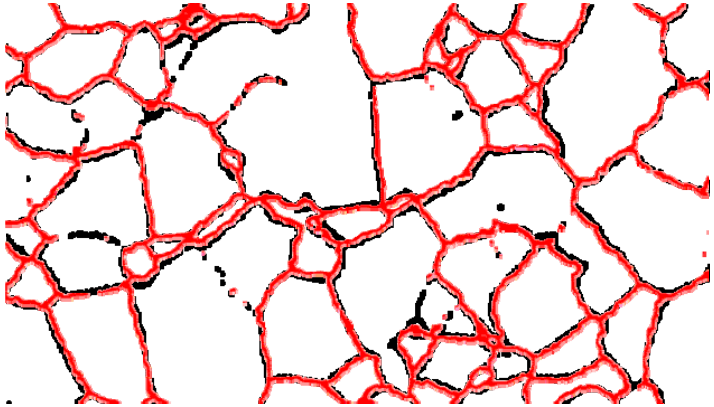
MOD YBCO (AMSC) 0.8 µm YBCO film



EBSD, plan view:

PLD/RABiTS replicates template GBs

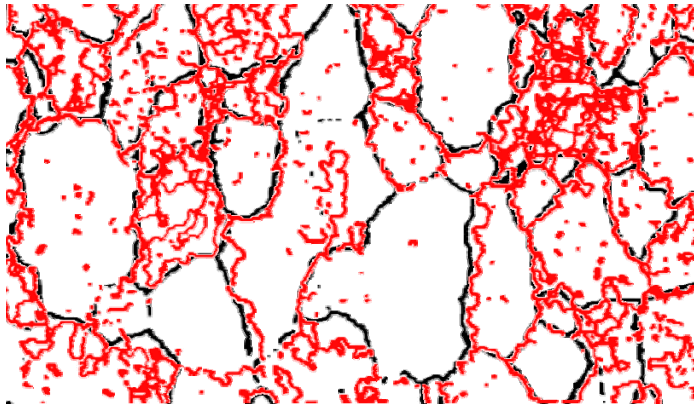
YSZ GBs + YBCO GBs



50 µm

MOD/RABiTS: meandering GBs

YSZ GBs + YBCO GBs



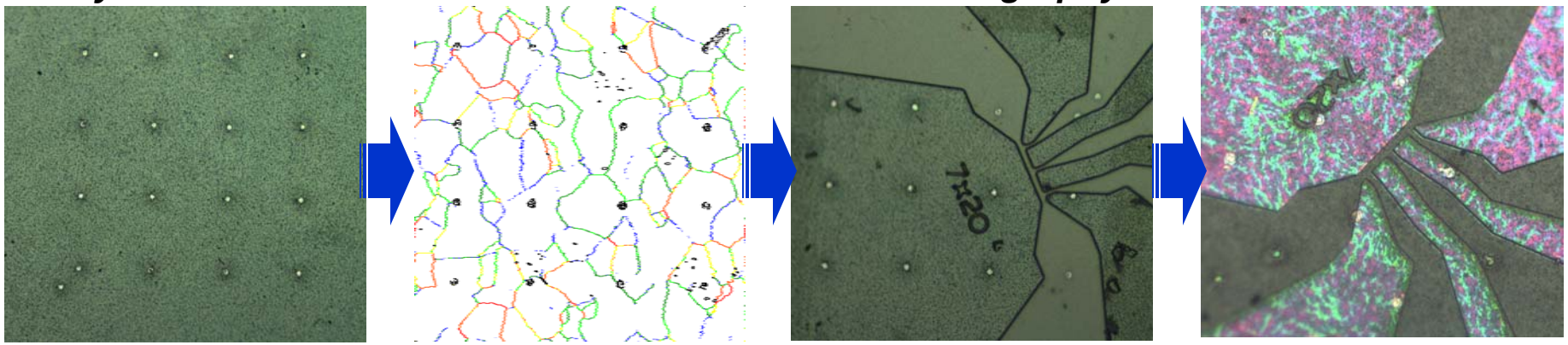
50 µm

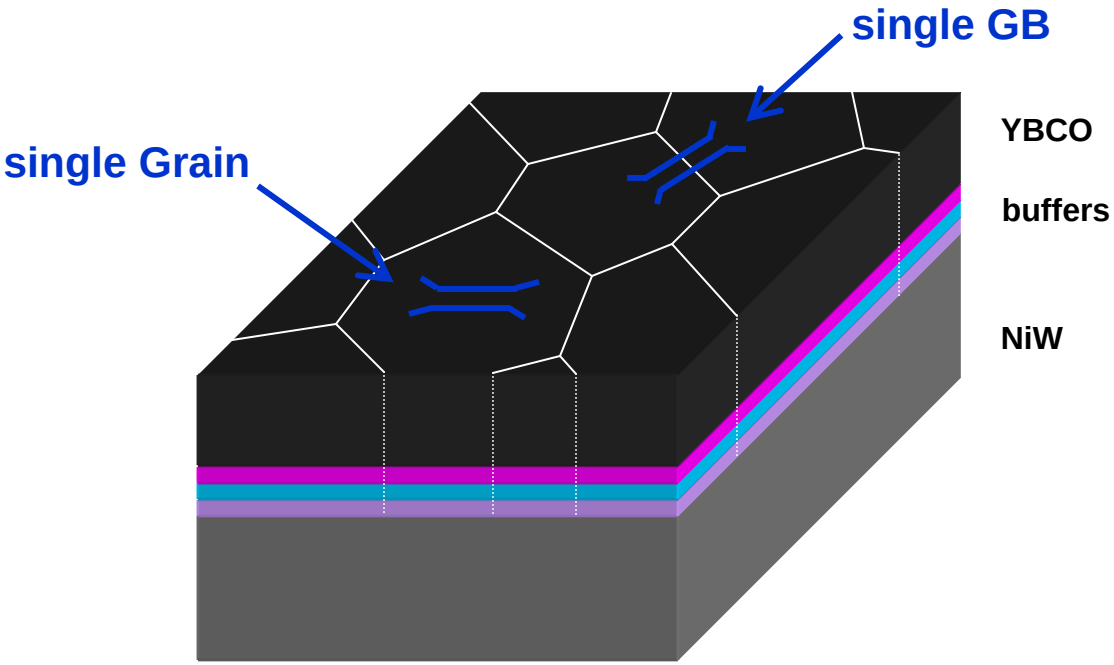
THE UNIVERSITY of WISCONSIN MADISON

TEM: T. Holesinger

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

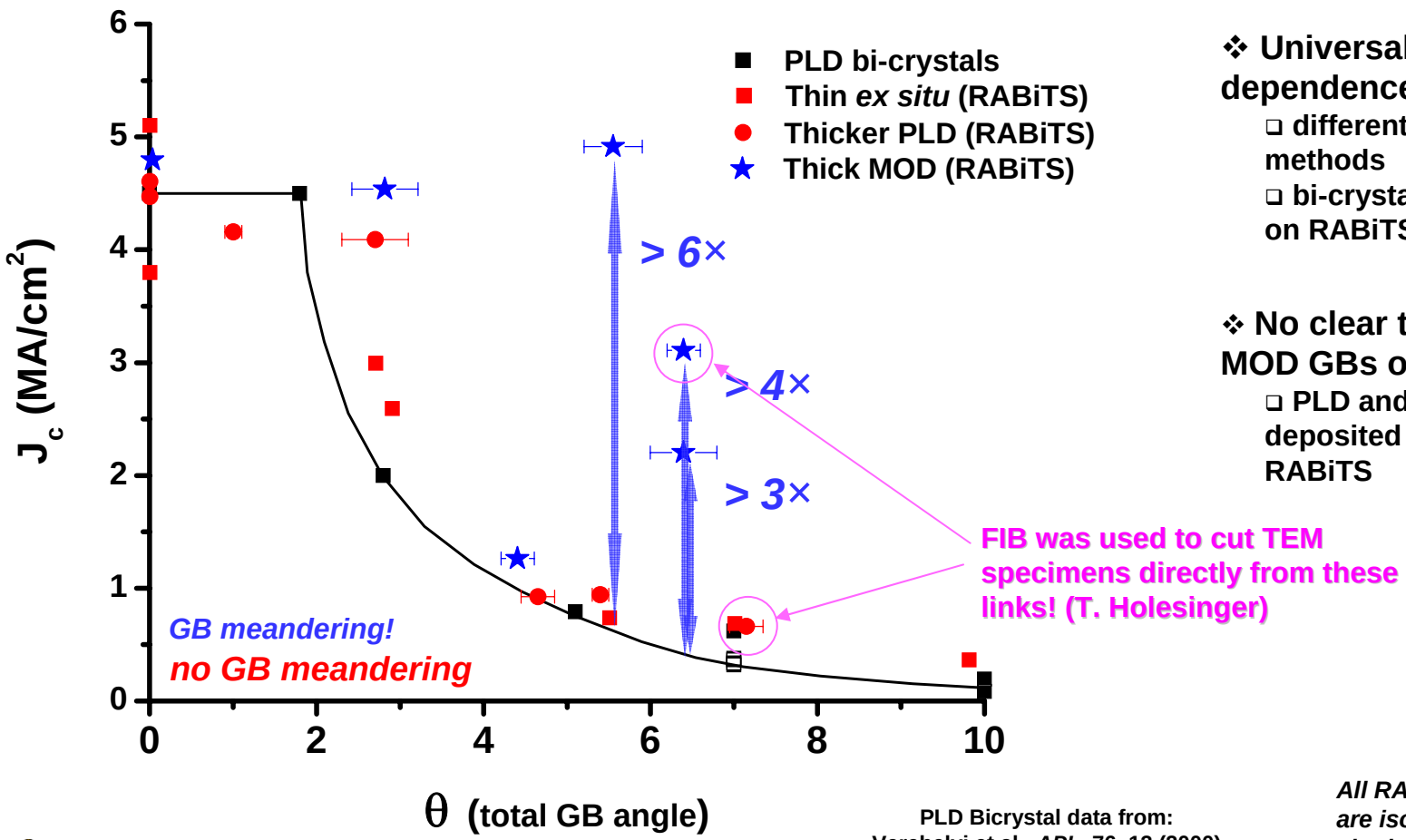
Array of laser cuts ***EBSD*** ***Photolithography*** ***Isolated Grain/GB***





Thick ex situ films (GB meandering) break trend!

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

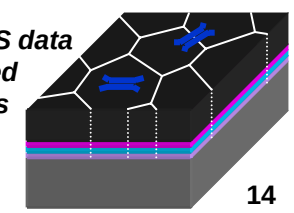


❖ **Universally observed $J_c(\theta)$ dependence**
- ❑ different YBCO growth methods
- ❑ bi-crystals and single GBs on RABiTS

❖ **No clear trend with θ for MOD GBs on RABiTS**
- ❑ PLD and MOD films were deposited on the same RABiTS

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

All RABiTS data are isolated single GBs

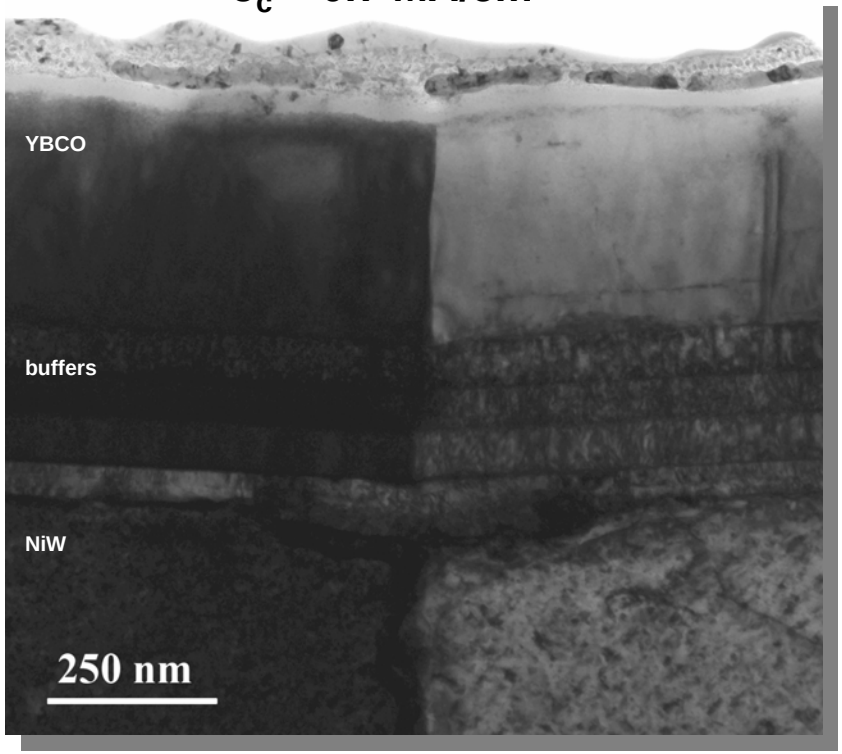


FIB Cut TEM Sections From Isolated GBs: PLD GB Straight; MOD GB Meandered

PLD

$\theta \sim 7°$

$J_c \sim 0.7$ MA/cm^2

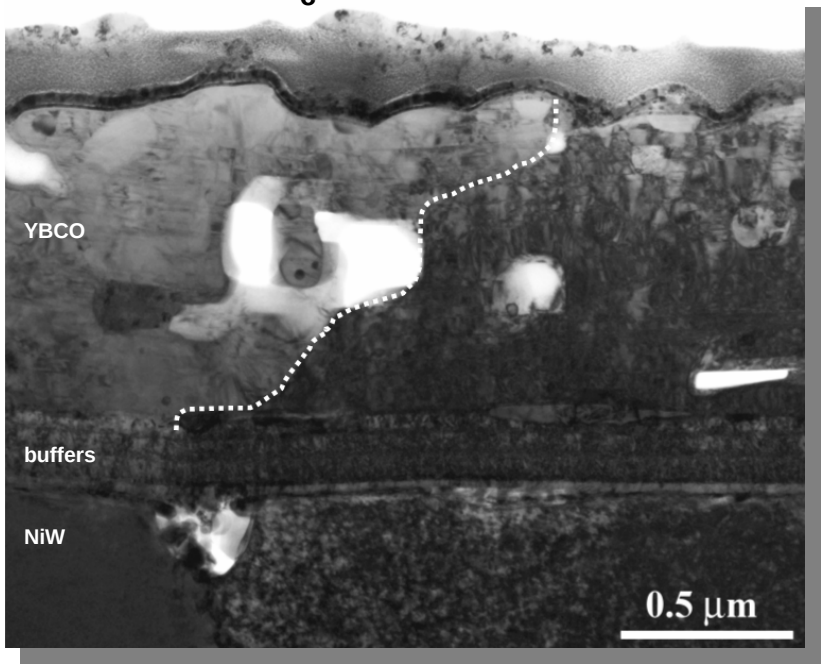


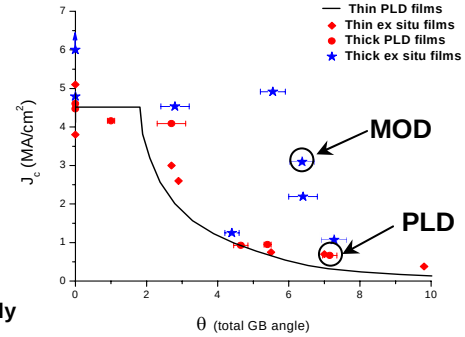
TEM: T. Holesinger

MOD

$\theta \sim 6.5°$

$J_c \sim 3.1$ MA/cm^2





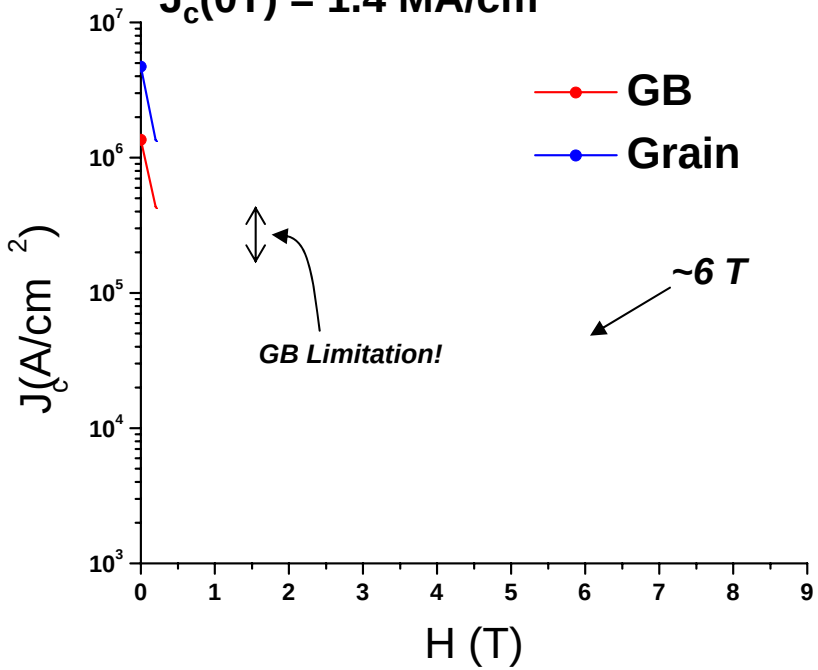
Meandering GBs result in higher J_c and improved magnetic field properties

❖ **Crossover to grain limited regime occurs at lower field for MOD GB**

Straight GB
PLD – *in situ*

$\theta \sim 5°$

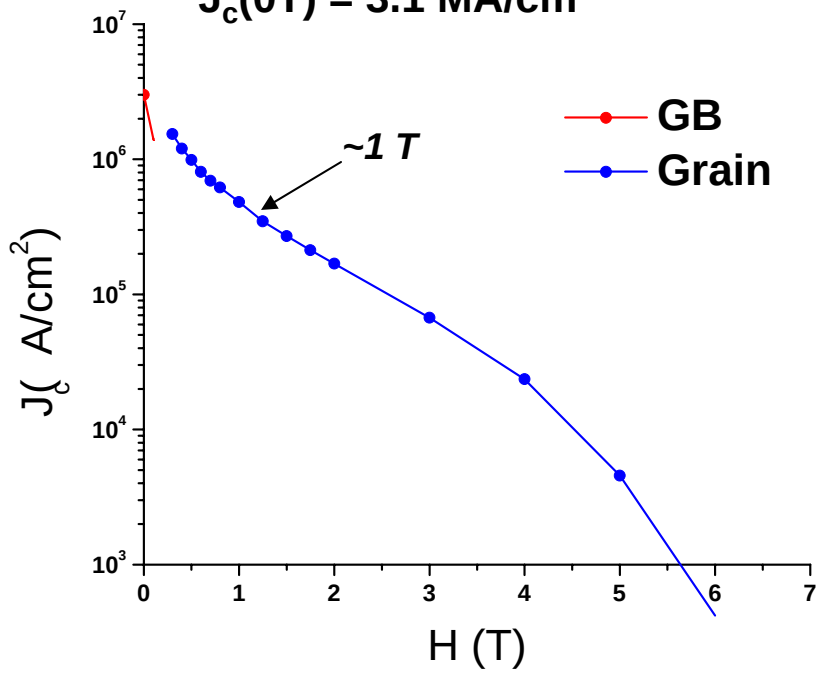
$J_c(0T) = 1.4\ MA/cm^2$



Meandered GB
MOD – *ex situ*

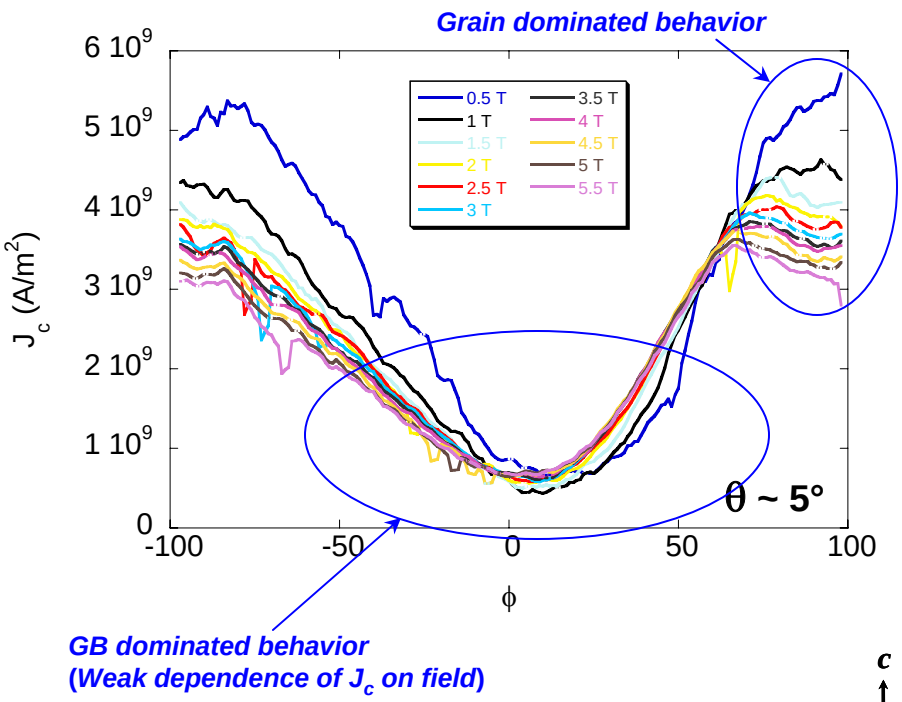
$\theta \sim 6.5°$

$J_c(0T) = 3.1\ MA/cm^2$

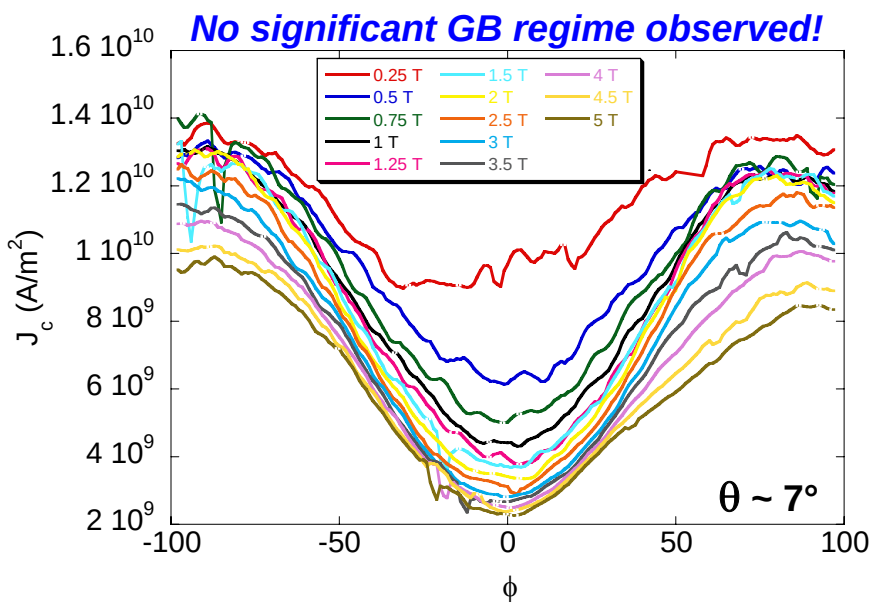


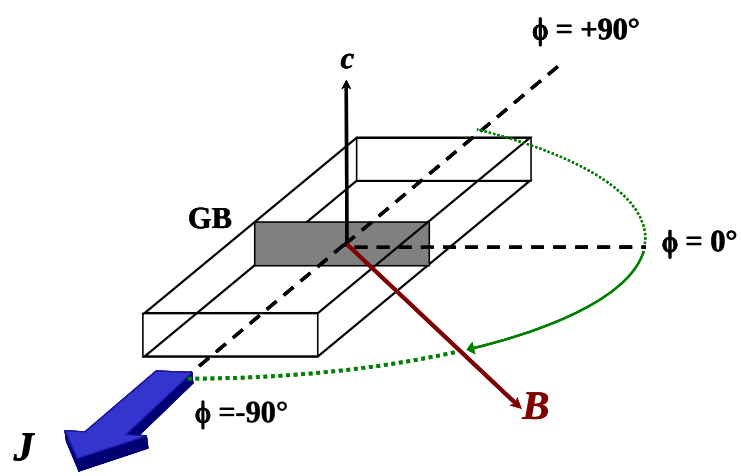
For *H* Rotated in the Plane of the Film, the MOD GB Exhibits no GB Limited Regime

Isolated GB from PLD/RABiTS

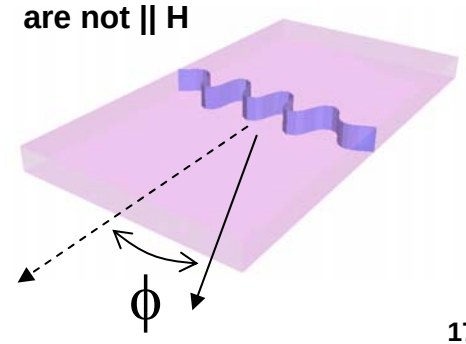


Isolated GB from MOD/RABiTS





There are always regions of a meandered GB that are not || H



J.H. Durrell et al., PRL 90, 247006 (2003)

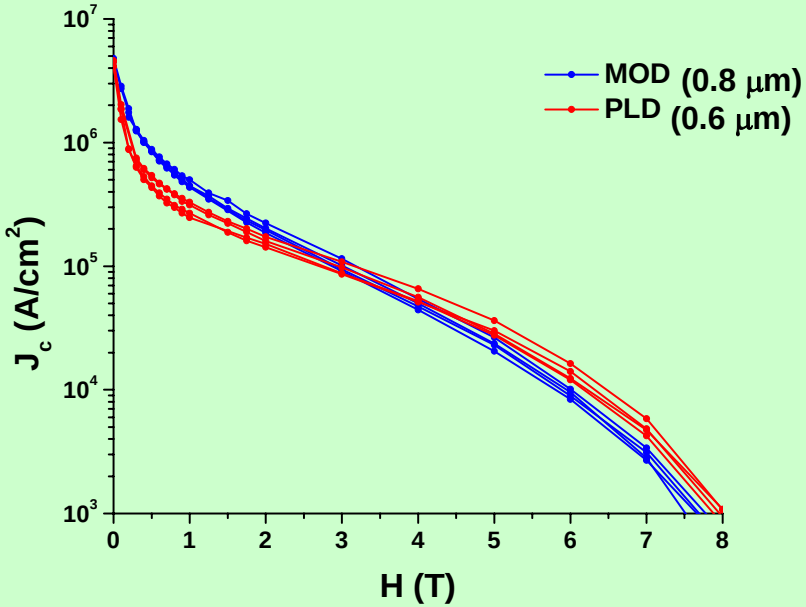
Enhanced Properties of MOD GBs Greatly Facilitate RABiTS Wire Technology

✓ **Full-width J_c of MOD/RABiTS 3x higher than PLD/RABiTS**

YBCO deposition method (on RABiTS)	J_c(77K, 0T) MA/cm^2 (intra-grain)	J_c(77K, 0T) MA/cm^2 (full-width, 5 – 10 mm)
PLD (0.6-0.8 μm)	4.2 – 4.6	0.9 – 1.3
MOD (0.8 μm)	4.8 – 5.1	3.1 – 3.4

2005 Review

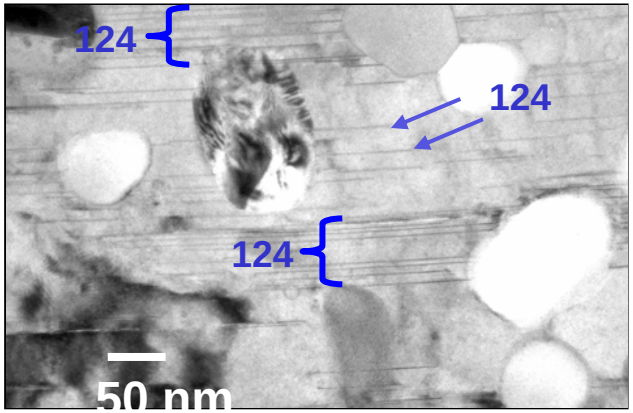
- 8 Intra-grain curves
  - 4 MOD
  - 4 PLD
- Similar intra-grain properties confirm high quality of PLD samples and support comparison



GB Summary

- 5T (H||ab or H||c) LTLSM system new to UW in 2006
  - Will be used to correlate local microstructure to $J_c(H)$ properties and grain/GB limited regimes
- Gained an understanding of and demonstrated the quantitative benefit of GB meandering by comparing MOD and PLD films of similar quality on the same RABiTS
  - MOD GBs perform better at 0T and in field
  - FIB prepared TEM cross sections from isolated GBs confirm meandered/straight nature of MOD/PLD GBs, respectively

FY2006 Results: Key Questions Answered



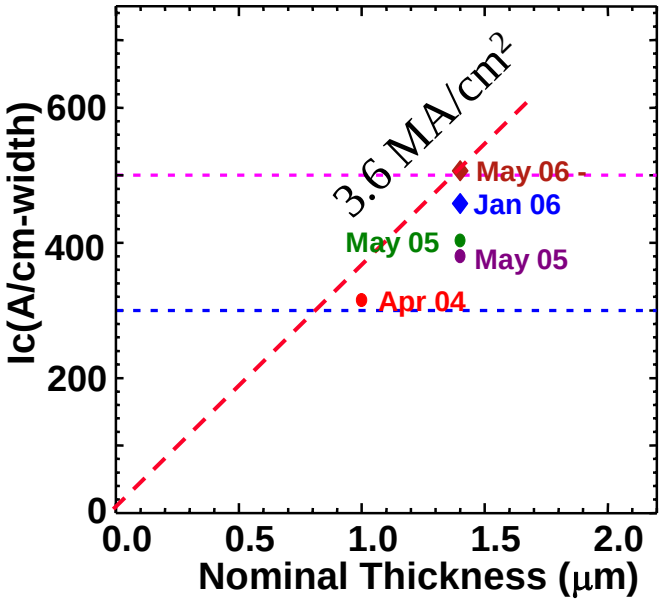
Pinning

- What is the mechanism for the formation of 124 intergrowths?
  - Growth from "cuprite" phase during oxygenation
- Can the 124 intergrowth density and nanodot concentrations be independently controlled?
  - Yes, through process and chemistry, and through novel hybrid two-layer HTS films
- How can I_c[H//ab] / I_c[H//c] be engineered for targeted applications in a practical 2G wire?
  - Yes, and targeted ratio of ~2 achieved

FY2006 Results: Key Questions Answered

High Critical Current 2G Wire

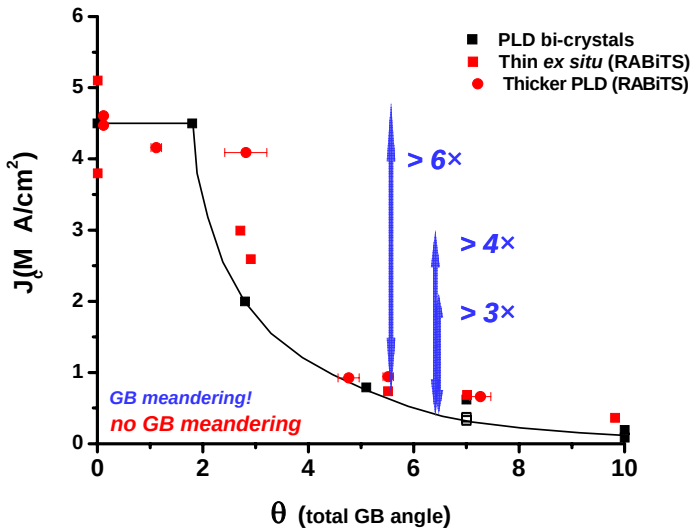
- What are causes for the observed decrease of J_c as YBCO thickness increases?
  - Loss of texture, second phase coarsening
- Can constant and high J_c be maintained in thick (> 1 μm) YBCO films?
  - Yes, and >3 MA/cm^2 achieved over 1.4 μm, 508 A/cm-width achieved in double-coat HTS layer



FY2006 Results: Key Questions Answered

Grain Boundaries

- Do meandering grain boundaries really benefit practical MOD/RABiTS conductors?
  - Yes, they actually enable uniform, high current performance



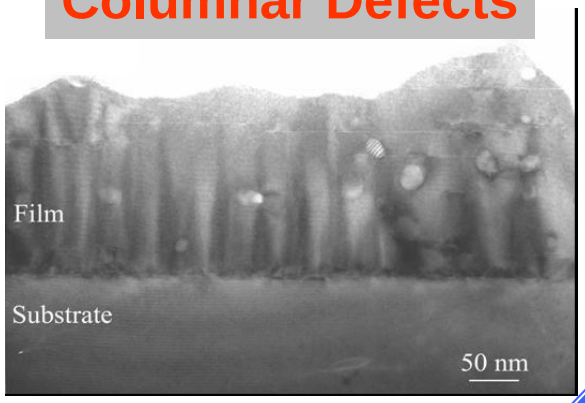
- Do grain-boundary and bulk-pinning limited regimes vary for H//ab and H//c?
  - First results show similar GB to bulk crossovers in both directions

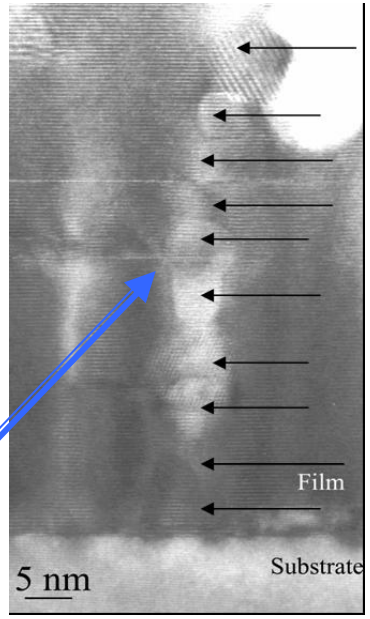
Texas Center for Superconductivity

A Center for Research and Development of Advanced Materials

Generation of Columnar Defects in MOD YBCO Film Doped with 5% $BaZrO_3$

Columnar Defects



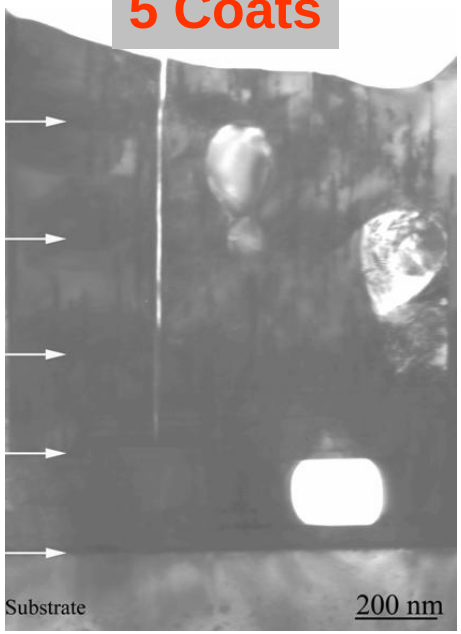


Columnar defects are formed by Zr-enriched nano particles.

Enlarged Column

Multi-Coat MOD YBCO Development

5 Coats



YBCO Film with 5 coats is achieved with Jc~1.5MA/cm^2 at 77K and self field.

2006 Performance Against Plans

1. Understand intra- and inter-grain Jc dependence with thickness to achieve a self field Ic of 500 A/cm-width

   - ✓ 508 A/cm-w achieved in 1.4 μm hybrid YBCO/Dy-nanodot + YBCO film
   - ✓ 492 A/cm-w achieved in a 2 μm YBCO film
   - ✓ Meandering grain boundaries in thick MOD YBCO films mitigate effect of high angle grain boundary mis-orientation
   - ✓ Non-meandering, columnar grain boundaries of PLD YBCO films limit J_c across high angle grain boundaries
   - ✓ Meandering grain boundaries in MOD-YBCO improve performance in magnetic fields

2006 Performance Against Plans

2. Engineer pinning in YBCO films through optimization of nanodot and intergrowth to achieve a performance of 250 A/cm-width H//ab) and 120 A/cm-width (H//c) at 65K, 3T

   - ✓ 213 A/cm-w for H//*ab*-plane and 118 A/cm-w with H//*c*-axis at 3T, 65K achieved in 1.4 μm hybrid YBCO+Dy-nanodot / YBCO film
   - ✓ H//ab-plane / H//c-axis I_c ratio of ~ 2
   - ✓ Multi-coat YBCO films allows Jc engineering for specific applications.
   - ✓ H//ab-plane / H//c-axis I_c ratio varied from ~ 1/1 in double YBCO+nanodot / YBCO+nanodot film to > 4 in YBCO/ YBCO film

2006 Performance Against Plans

3. Quantify grain boundary and bulk pinning limited regimes for H//c and H//ab

   - ✓ Transport measurements reveal macroscopic Grain/GB limited Regimes
   - ✓ Laser Scanning Microscopy (LTLSM) reveals first direct observation of transition from Grain to Grain Boundary Limited regime
   - ✓ LTLSM shows localized dissipation at GBs fades quickly with increased magnetic field

Context: The Last 3 Years - WDG Has Driven Major 2G Advances

- WDG research has driven steady and dramatic increase in I_c/width of ex-situ YBCO wires
  - 135A (2003) to 270A (2004) to 405 (2005) to 500A (2006)
- Key pinning centers identified and controlled, major increases in in-field I_c
  - 124 intergrowths for H//ab pinning
  - RE nanodots for H//c pinning
- Meandering grain boundaries discovered, found to enhance grain boundary current by up to 6 times
  - Key to the success of RABiTS/MOD technology
- Current limiting mechanisms – grain boundary, bulk pinning – charted vs. field and temperature
- Coordinated WDG efforts made major contributions to materials understanding and development of MOD-RABiTS pilot production
  - Long length, high Ic 2G wire so successful that AMSC could phase out 1G BSCCO production!

WDG contributions to materials science understanding of YBCO coated conductors key to rapid commercialization of the MOD-RABiTS technology

What Does the Future Hold?

- 2G HTS wire technology is poised to broadly impact the electric infrastructure and many other applications
- But much more technical progress needed to enable this vision:
  - Scaled up high-volume, low-cost 2G HTS wire manufacturing
  - Significantly higher performance

Why Do We Need More I_c Performance?

- **Isn't 500 A/cm-width in ex-situ YBCO wires enough?**
  - **No!**
  - Higher I_c allows greater design flexibility for cables, greater I_c for low-cost compact fault current limiters…
  - Higher I_c is the most effective way to reduce cable losses (which go as $\sim 1/I_c$)
    - This is tremendously important because of the huge size and cost of existing cable cryogenic plants
  - Much higher in-field performance required for compact, powerful coils in 65-77K range
    - Enables lower cost, more flexible rotating machinery, other magnet applications

We are in the midst of an exciting period of accelerating progress
The opportunity to drive the technology forward is NOW !

Vision for WDG

In low-cost, robust ex-situ YBCO wires:

- Achieve reproducibly
  - 1000 A/cm-width at 77 K, self-field
  - 500 A/cm-width in 3T//ab, 1.5 T//c, at ≥65 K
  - Pinning forces exceeding 20 GN/m^3
- Establish limiting mechanisms over the full range of fields and temperatures
- Understand and control pinning mechanisms
- Identify key defect mechanisms and conductor stabilization requirements
- Support full-scale commercialization of 2G HTS wire

An agenda for the remainder of the decade

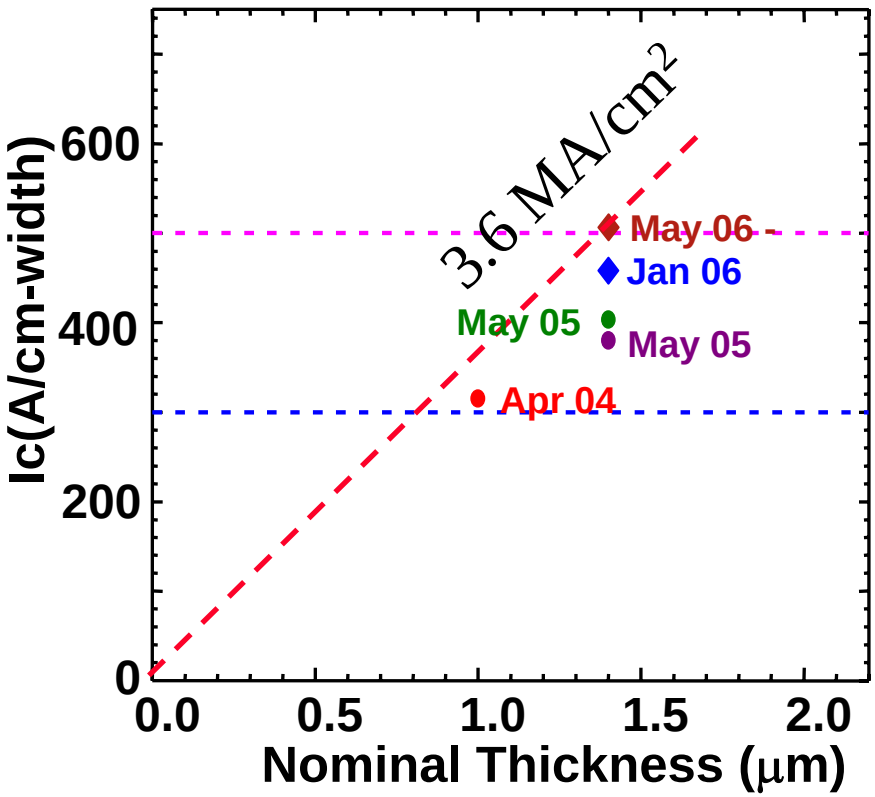
FY2007 Plans

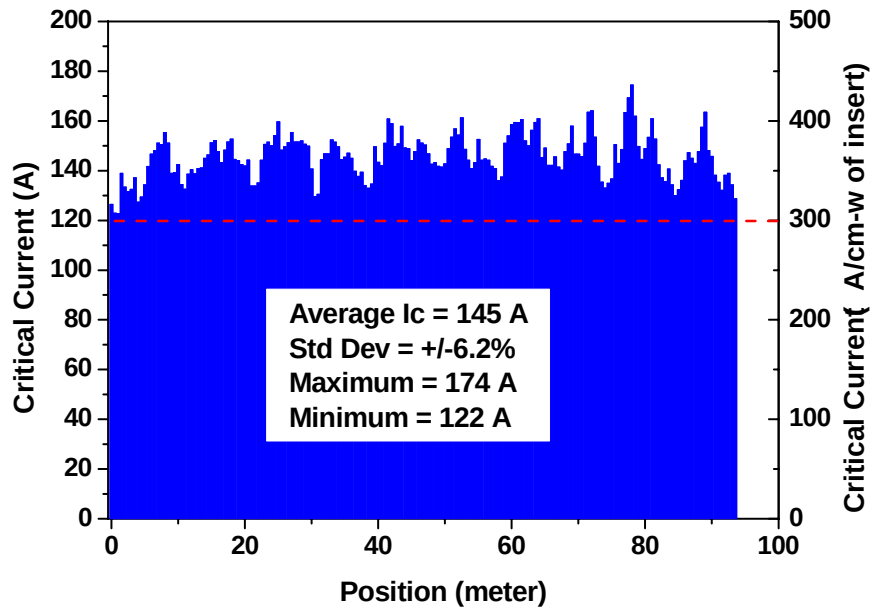
- Next step in I_c: 650 A/cm-width (77K, sf)
- Improved understanding of epitaxial growth of thicker HTS films
  - Achieve ≥3 MA/cm^2 over ≥ 2 μm
- Visualization of grain-boundary and bulk-pinning current limited regimes for both H//ab and H//c using new in-field LTLSM, and understand dissipation mechanisms
- Develop new and improved pinning techniques for ex-situ YBCO films
  - Confirm mechanism for Y-124 intergrowth formation and optimize H//ab-plane pining in RE-nanodot YBCO
  - Demonstrate improved hybrid HTS films engineered specifically for coil, FCL or cable applications

WDG will continue to play a critical role in driving commercialization of a broadly available, low cost 2G wire technology

WDG Material Science Advances Drive Commercialization Progress!

WDG science → 2G HTS wire scale-up

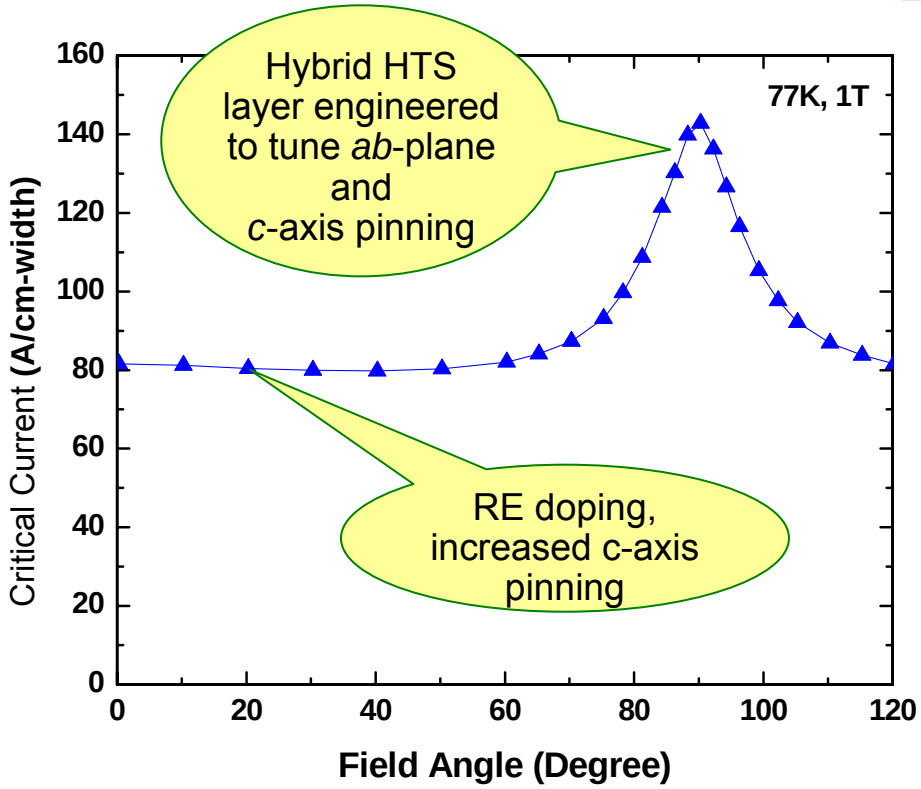




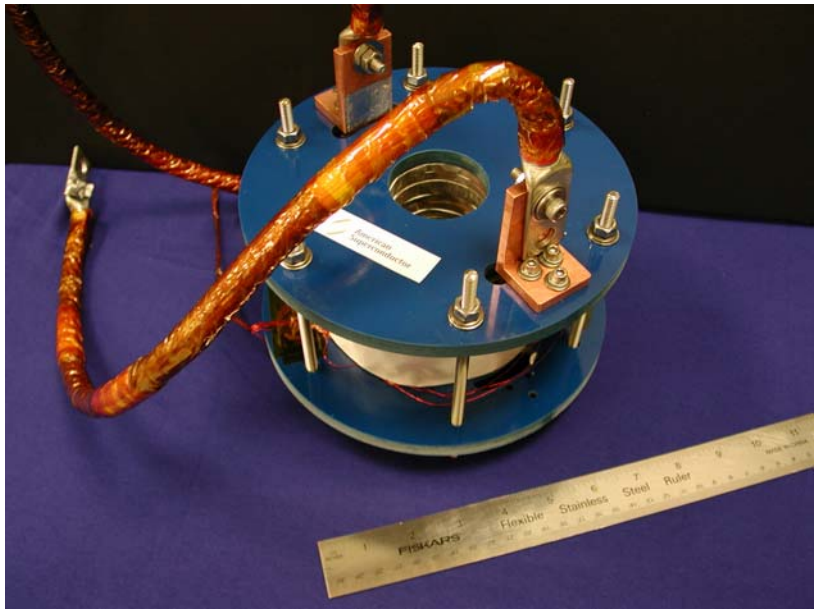
350 A/cm-width
over ~ 100 meters

WDG Material Science Advances Drive Commercialization Progress!

WDG science



2G HTS coil technology



1.5 T
in 5 cm dia. bore
at 64 K