Materials and intrinsic properties in the J_c dependence on thickness of ex situ YBCO coated conductors

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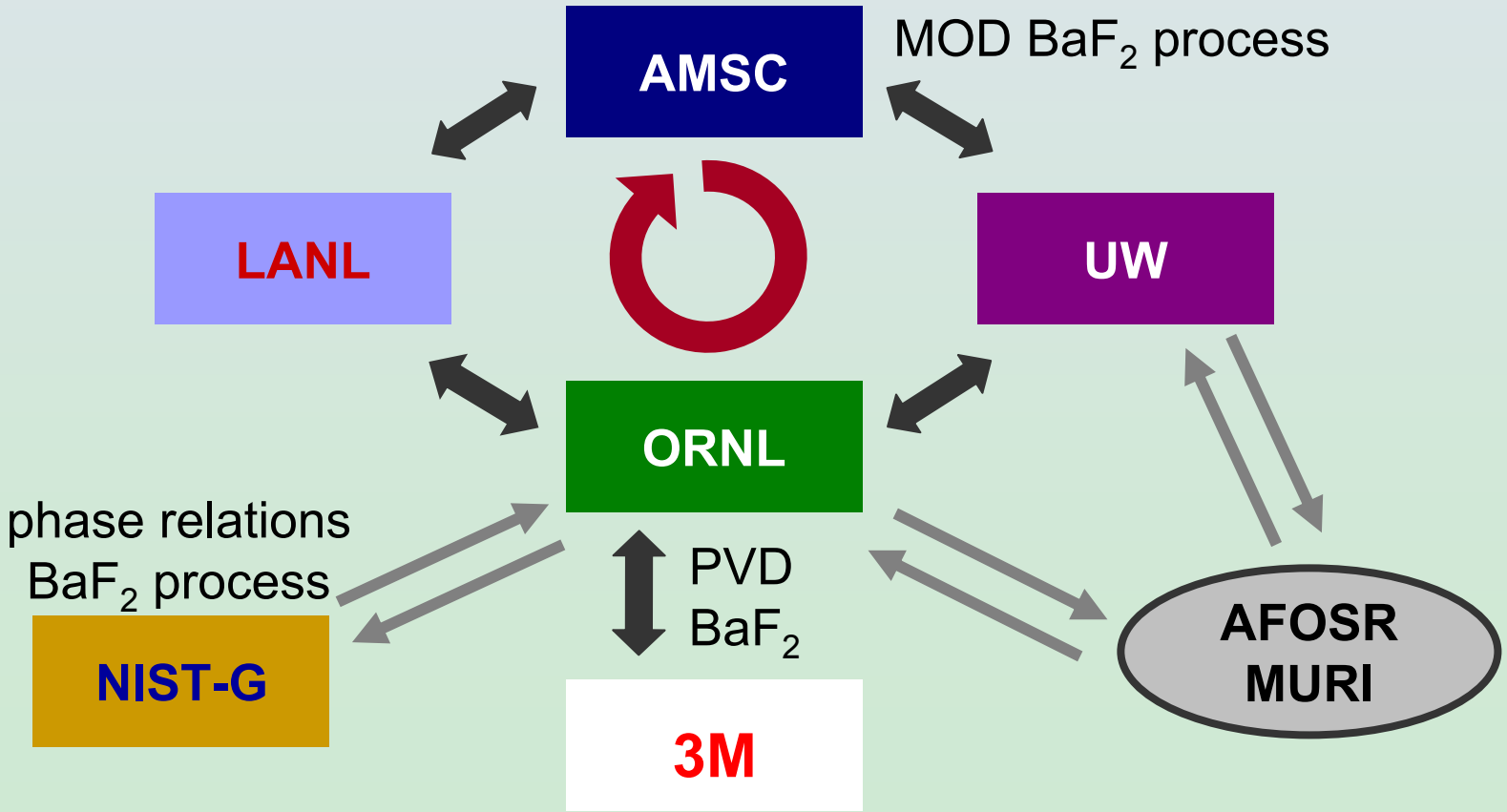
A new multi-institutional collaboration was formed in FY03 to bring together complementary capabilities

- focus: YBCO--growth and properties
- existing two-way collaborations were expanded
- triggered by termination of 3M-ORNL-LANL crada
- impetus from AFOSR - MURI project



Purpose and objectives

- To advance a materials science background for development of high-performance ReBCO coated conductors

- Long-term objectives are to develop understanding of:
  - fundamental epitaxial growth mechanisms (ex situ BaF_2 process)
  - thickness dependence of J_c
  - origin of flux pinning in high J_c in ReBCO coated conductors

- Specific performance objectives:
  - I_c > 500 A/cm (77 K)
  - in-field operation in liquid N_2 temperature range (65-77 K)

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Outline

- **Thickness dependence of J_c in ex situ YBCO** — **Ron Feenstra**
  "Intrinsic vs. materials"

- **Through-thickness J_c measurements** — **Matt Feldmann**
  spatially correlated J_c and microstructure

- **Microstructural development from e-microscopy** — **Terry Holesinger**
  liquid-mediated growth

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Outline

- **Thickness dependence of J_c in ex situ YBCO** **Ron Feenstra**
  - "Intrinsic vs. materials"
  - analysis of J_c-d results—role of texture
    $\rightarrow$ indications of "intrinsic" J_c-d effects
  - FY03 results: YBCO on reel-to-reel RABiTS
    $\rightarrow$ new processing directions (faster, YF_3 source material)
  - "fruits" from the collaboration
    $\rightarrow$ recent results from improved, modified processing
- **Through-thickness J_c measurements** **Matt Feldmann**
  spatially correlated J_c and microstructure
- **Microstructural development from e-microscopy** **Terry Holesinger**
  liquid-mediated growth

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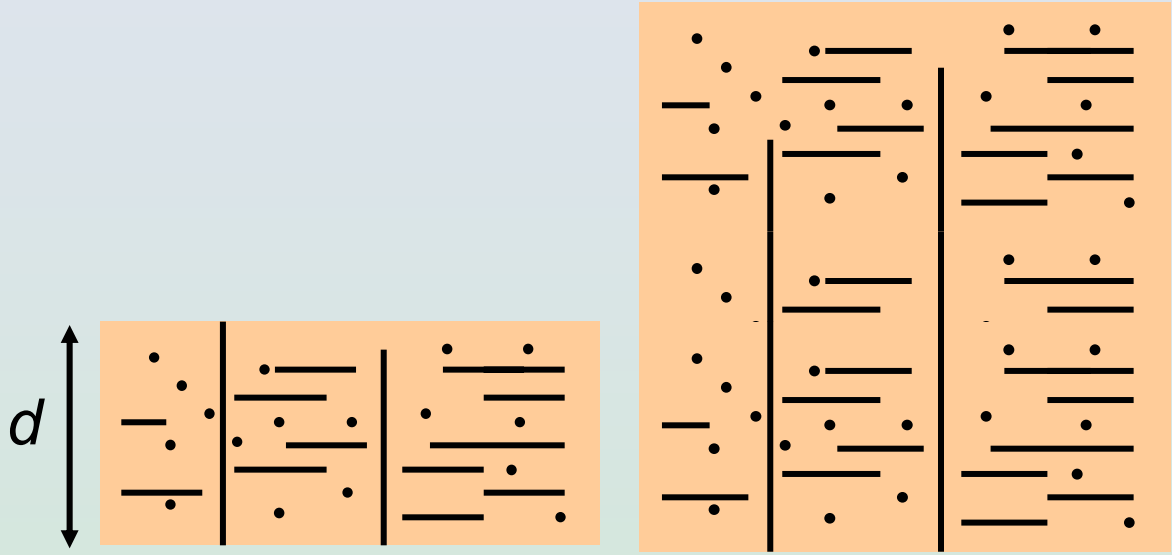
Thickness-independent pinning microstructure

bridge between physics ("intrinsic") and processing



defects in YBCO:

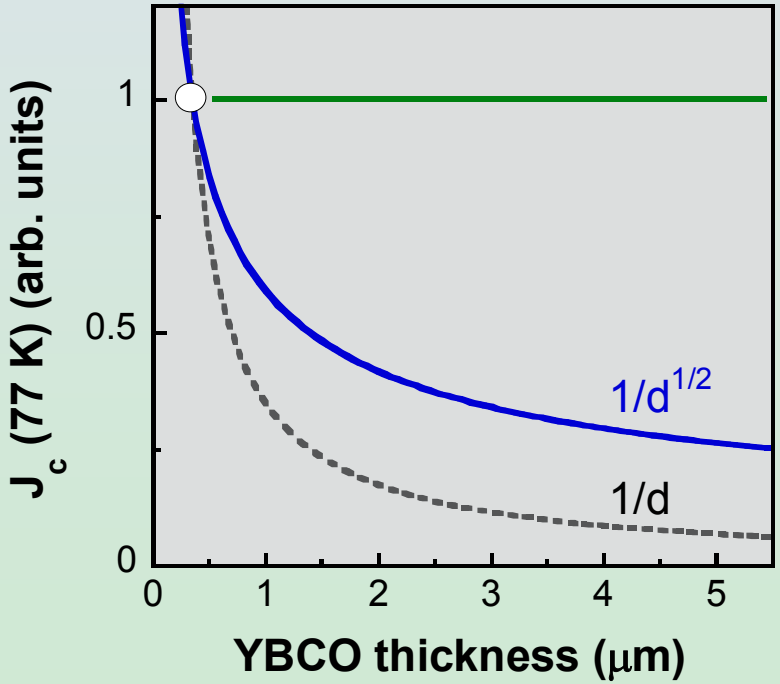
- CuO stacking faults
- anti-phase boundaries
- twin boundaries
- GB dislocation cores
- O vacancies (chains)
- O vacancies (planes)
- anti-site defects (Ba-Y)

....

- J_c is controlled by pinning → microstructure--processing dependent
- **Materials**—aim: replicate thin-film, high-J_c structure to produce **d-independent pinning microstructure**
- **Physics**: does d-independent enable **constant J_c?**
  - answer depends on origin of pinning, dominant defect type

For optimization of high-I_c YBCO coatings: distinguish between current-limiting and flux pinning defects

- both defect types result from processing
- theoretically predicted behavior provides reference framework (absent current-limiting defects, d-independent pinning microstructure)
- **usual assumption of ideal constant J_c-d may not be valid !**



large surface/volume ratio
→ surface pinning $\mathbf{J_c \propto 1/d}$

point defects—collective pinning
2D (d<L_c) $\mathbf{J_c \propto 1/d^{½}}$
3D **J_c is constant**

threading dislocations $\mathbf{J_c \propto 1/d}$ (?)

✓ **need to understand origin of flux pinning for J_c-d**

PVD BaF_2 process

- precursors deposited by e-beam evaporation of Y, BaF_2, and Cu
- ex situ anneal in flowing gas mixtures at 1.0 atm total pressure
  - *reduced pressure processing—discussed by D. F. Lee, F. A. List*

➢ **closely related to MOD BaF_2 (TFA) process**

+ similar conversion chemistry (reaction of BaF_2 with H_2O)
+ differences in "detail"
  - excess F in MOD precursor because of presence of YF_3
  - starting microstructure (MOD—result of calcination anneal)

➢ **added flexibility of PVD BaF_2 process**

- unlimited precursor thickness

- microstructure control through evaporation process
- freedom to insert any desired intermediary anneal

- typical sample size in this study: length: 1.5-2 cm x width 0.5 cm
- J_c measured full width, where needed: extrapolated from J_c-H

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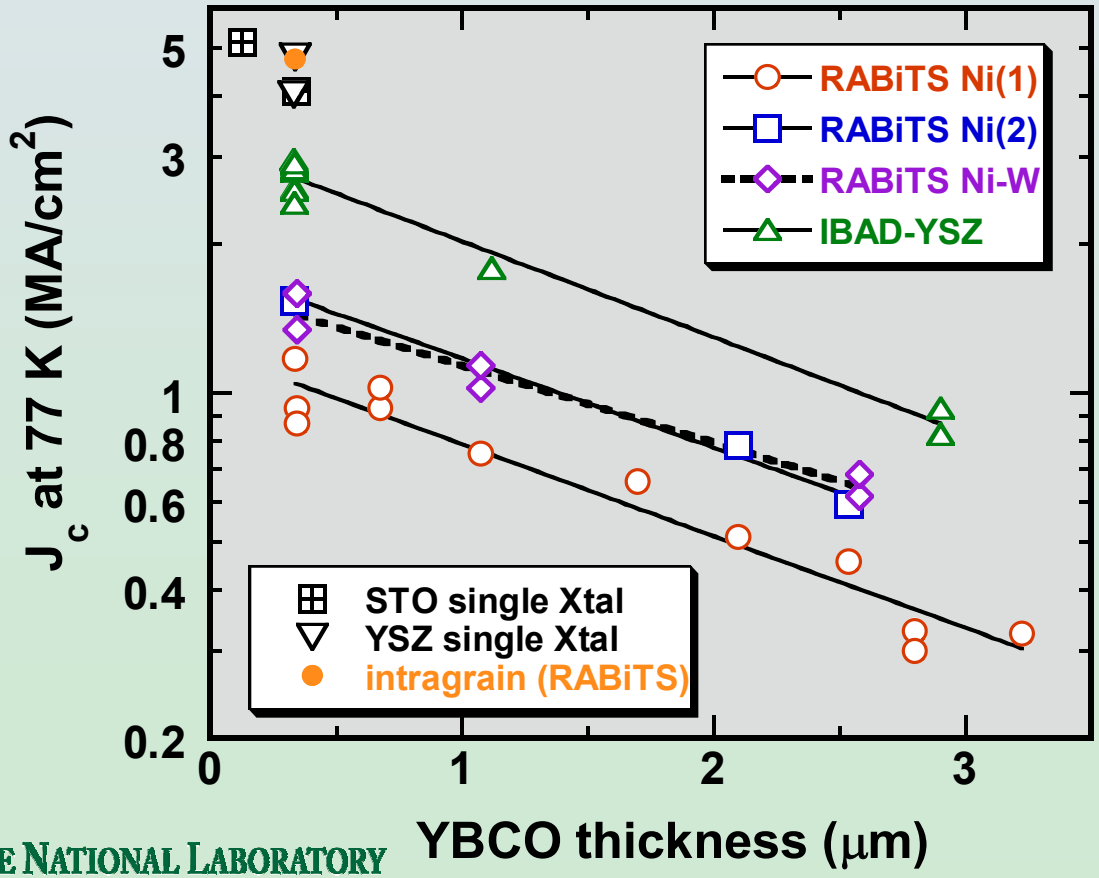
J_c is grain boundary limited for all values of the YBCO thickness

- substrate texture controls J_c level (for all d)
- J_c is GB limited → $J_c^{intra} > J_c^{GB}$ <u>for all values of d</u>

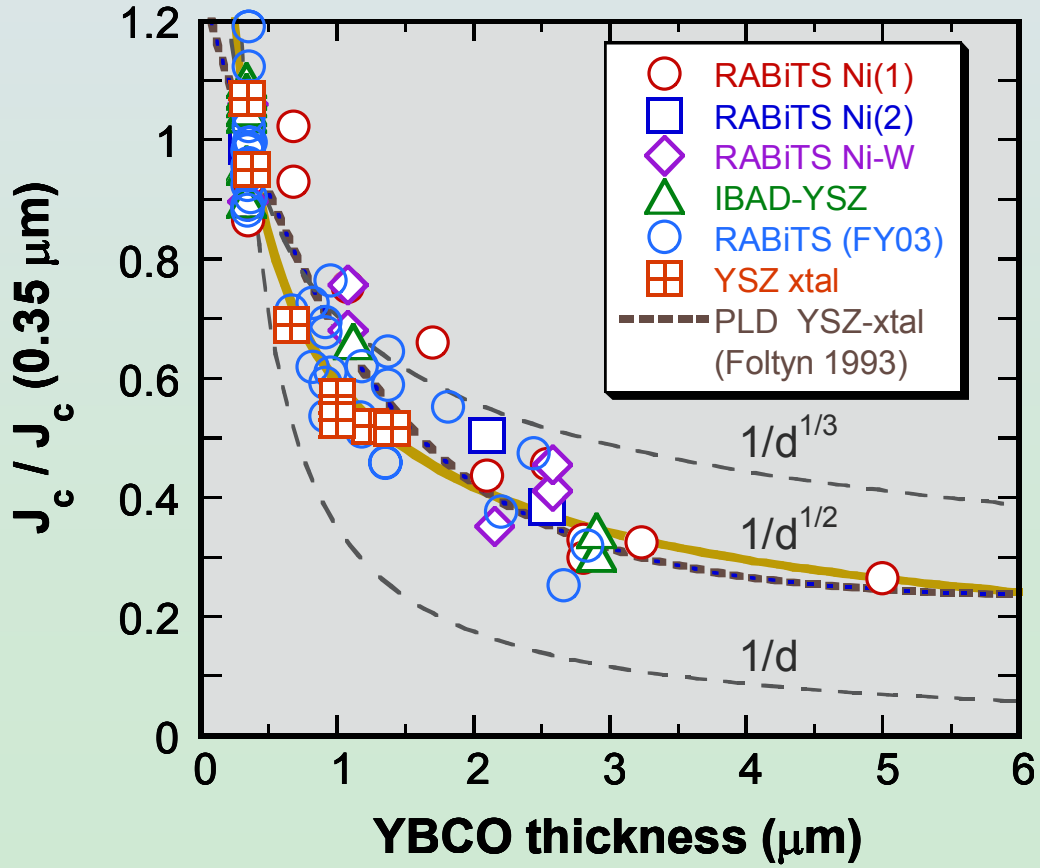


- exponential fit
  $J_c = J_0 \exp(-d/d_0)$
- best available data from initial optimization ("baseline process")

improved texture

Functional dependence of J_c on YBCO thickness is substrate independent

- exponential fit: predicts maximum I_c for $d = d_0 \cong 2.2\ \mu m$—not observed
- physics-based function $1/d^{1/2}$ accurately describes range of J_c variation
  - collective pinning (2D)—random distribution of small pins (Gurevich)



J_c observations suggest "intrinsic"

- ✓ substrate independent
- ✓ intra-grain J_c is origin
- ✓ uniform scaled behavior:

$$J_c = J_\Phi \cdot j(d)$$

J_Φ texture dependent, not d

$j(d) = 1/d^{1/2}$ ← intra-grain

- ✓ PLD and ex situ: same J_c-d columnar vs laminar structure
- ❑ point defects provide weak pinning—realistic for films?

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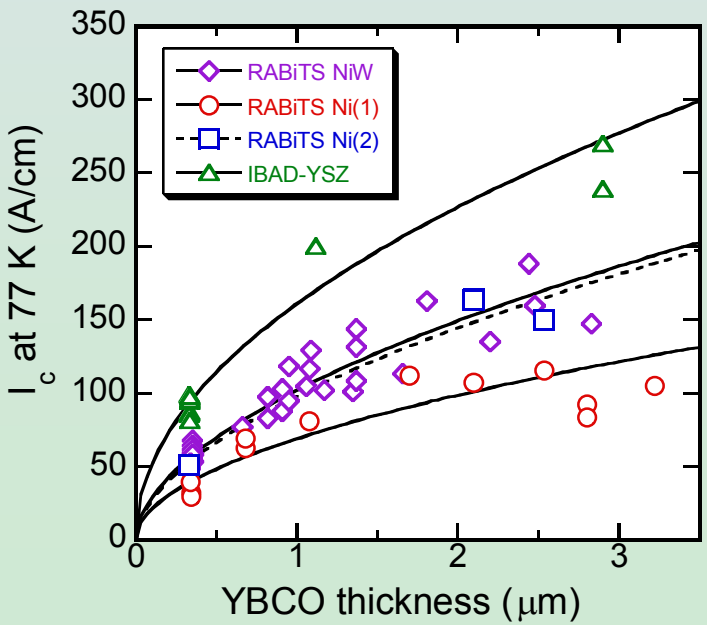
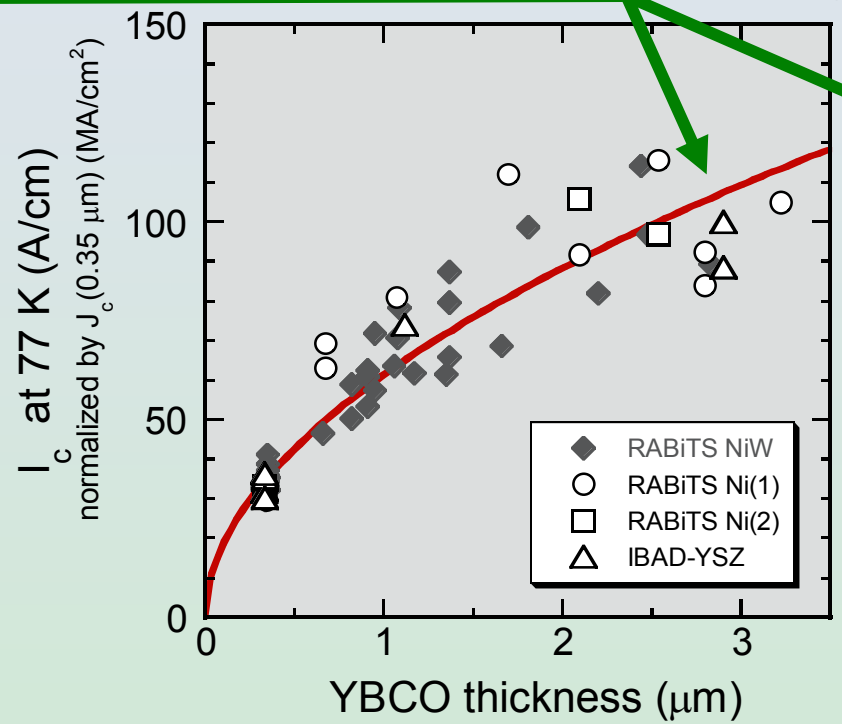
Substrate texture and YBCO thickness provide independent "handles" to increase I_c

I_c > 400 A/cm (77 K) appears feasible in PVD BaF_2 YBCO

$$J_c = J_{\Delta\Phi} \cdot 1/d^{1/2}$$

➢ $$I_c = d \cdot J_c = J_{\Delta\Phi} \cdot d^{1/2}$$





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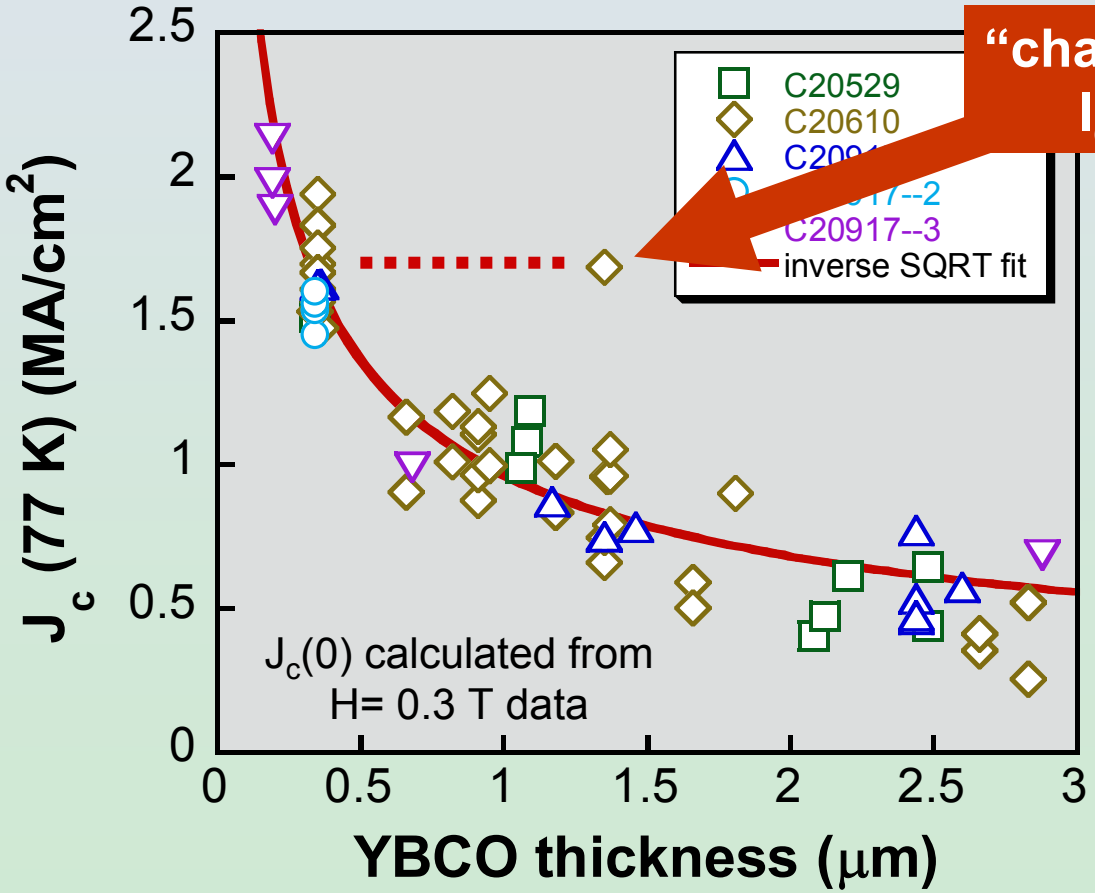
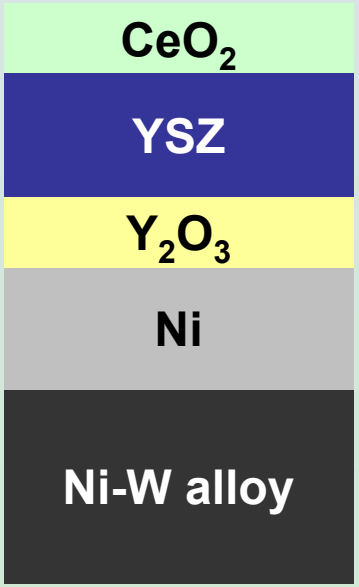
FY03: systematic study of J_c- d dependence was enabled by consistent substrate availability

- ORNL RABiTS—produced by reel-to-reel processing
- consistent quality—high J_c obtained on several tapes

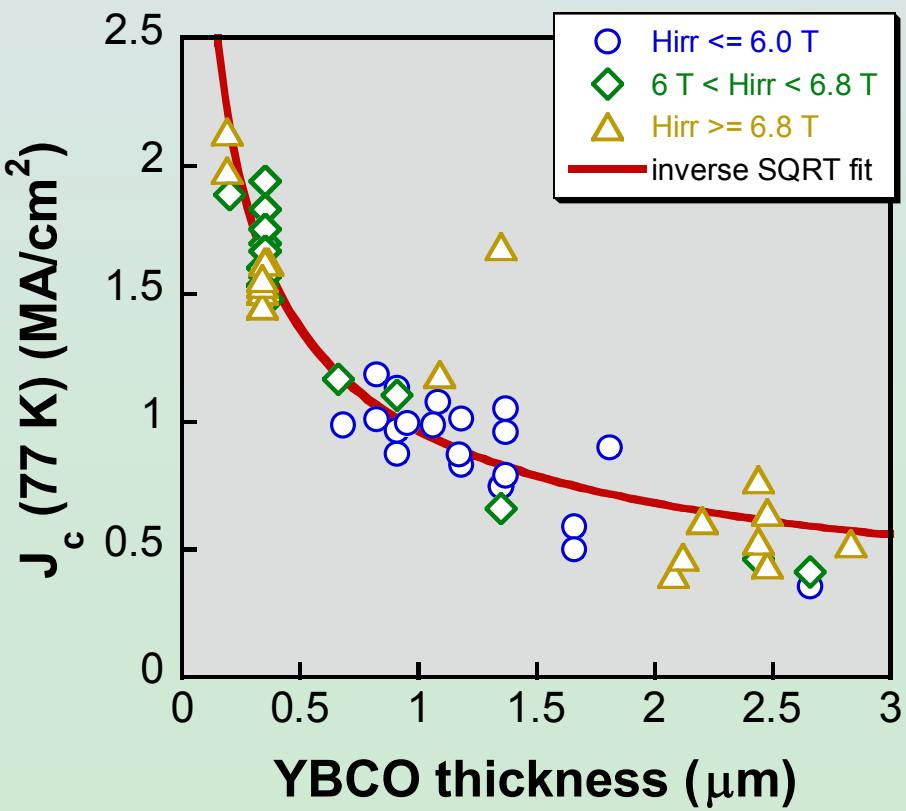


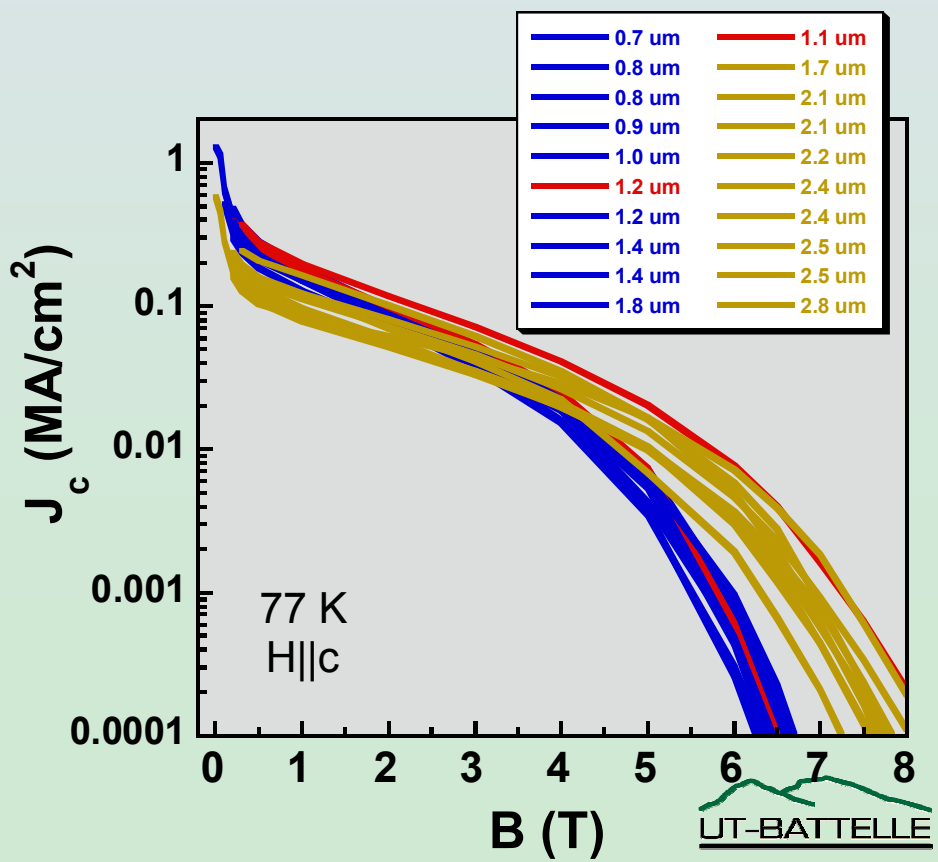
"champion" sample
I_c = 228 A/cm



YBCO films of various thickness exhibit dissimilar properties in H field

- systematic trend: $d \cong 1\ \mu m \rightarrow$ low H_{irr}; $d \cong 2\ \mu m \rightarrow$ high H_{irr}
- J_c-H curves intersect—tradeoff: $H_{irr} \leftrightarrow J_c(H=0)$
- thickness dependent defect/pinning structure
- J_c-d at 77 K is H-field dependent





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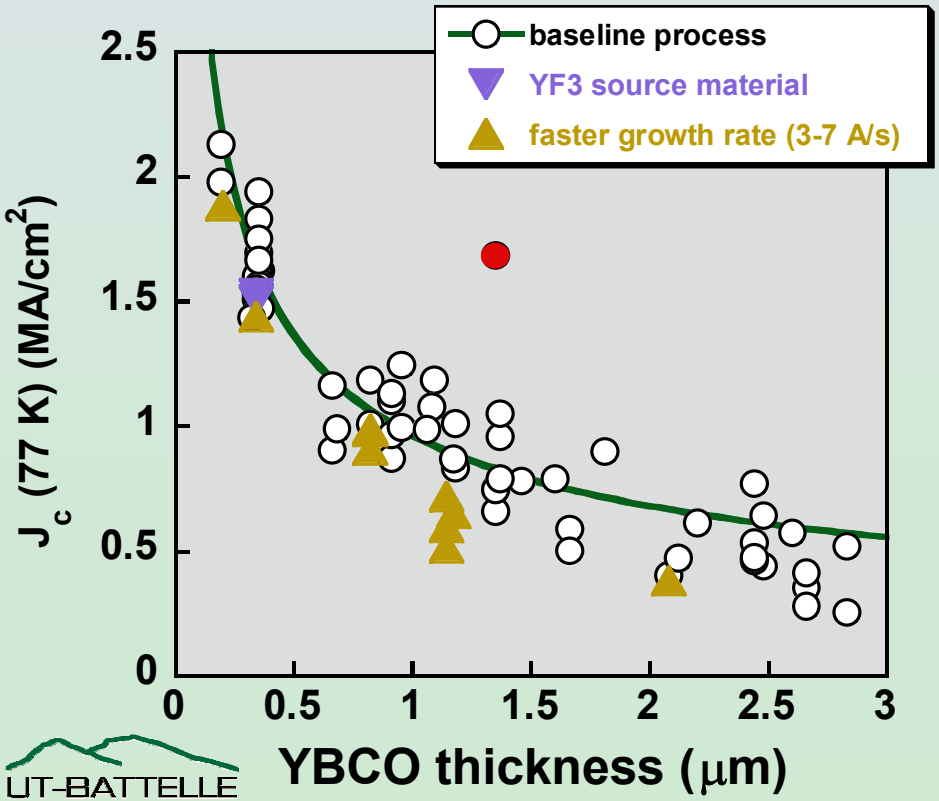
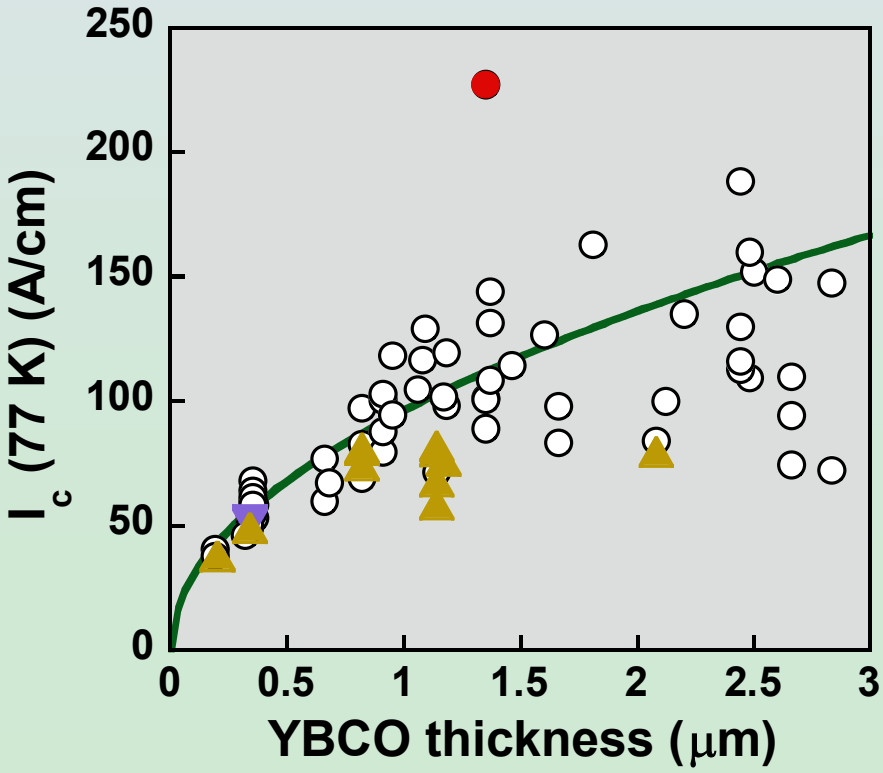
Alternative processing directions were tested

- **replace Y metal with YF_3 as the source material**
  - F/Ba= 2 → 3.5 with YF_3 —similar to MOD-TFA process
  - samples sent to NIST-G for study of low-T melting phases
- **test of faster conversion rates**
  - encouraging first results—high J_c, H_{irr} ↑
  - new growth mode? (TEM study is underway)





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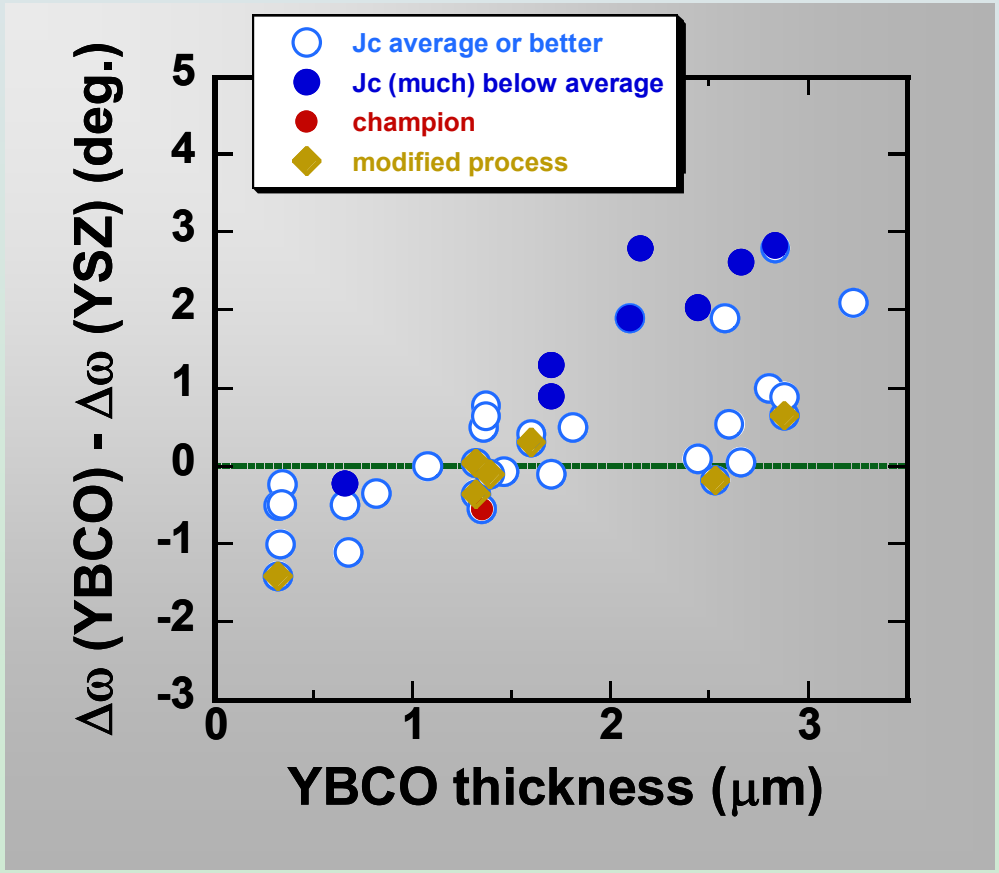
Materials aspects of J_c-d

The quality of the YBCO epitaxy was observed to decrease with increasing layer thickness

- identification of the role and effects of a **liquid-mediated growth mode**, *recently**, has enabled improved processing → better epitaxy
- input from TEM and through-thickness J_c



- Similar correlation observed for in-plane texture ($\Delta\Phi$)
- RABiTS and IBAD-YSZ
- epitaxial quality correlates with J_c

texture improvement relative to substrate

*first films with new procedure were processed 1 month before the review.

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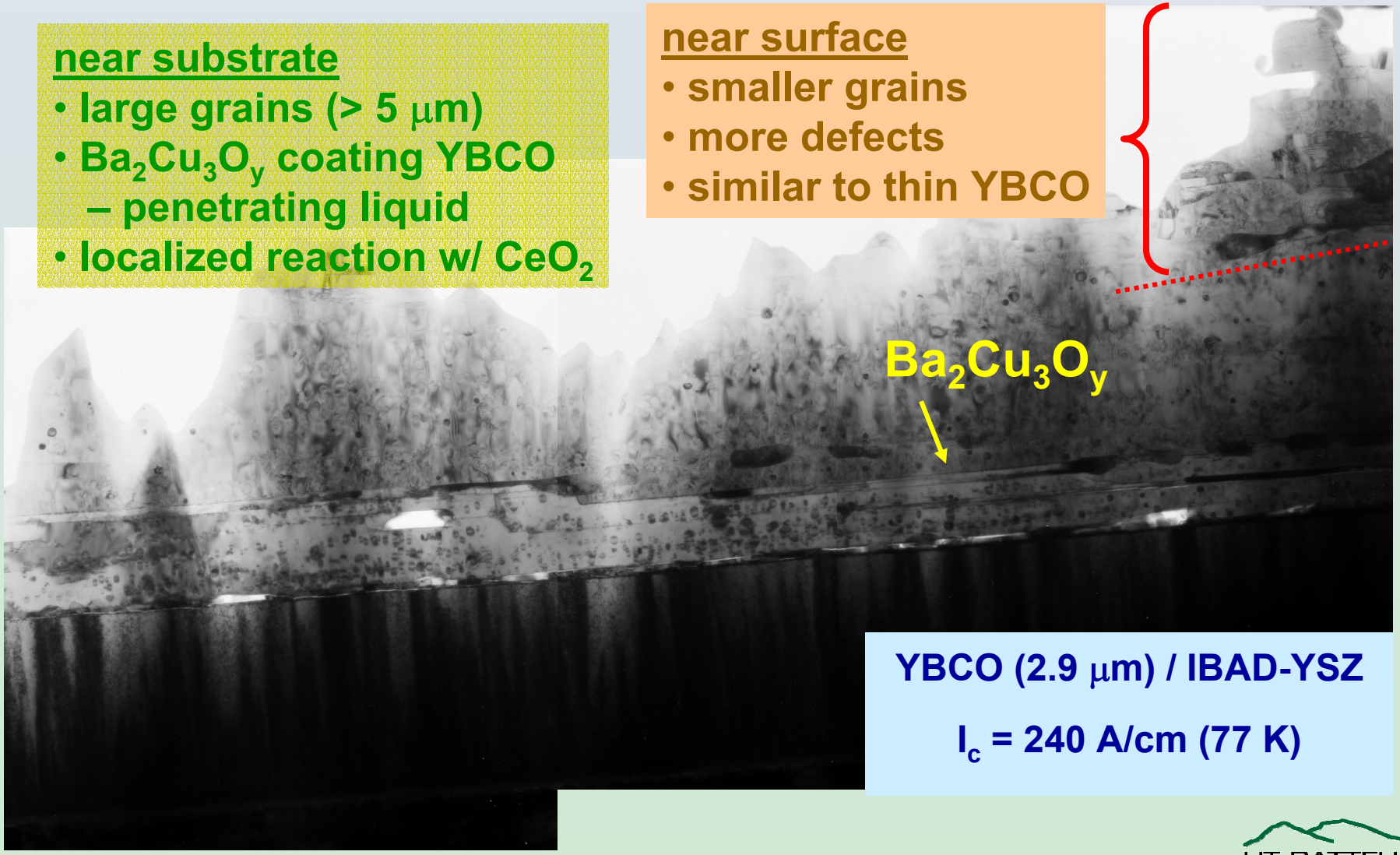
TEM shows dense, “bimodal” layered structure

- no “dead” layers
- time-dependent growth modes during conversion process

near substrate
- large grains (> 5 μm)
- $Ba_2Cu_3O_y$ coating YBCO – penetrating liquid
- localized reaction w/ CeO_2

near surface
- smaller grains
- more defects
- similar to thin YBCO



YBCO (2.9 μm) / IBAD-YSZ

I_c = 240 A/cm (77 K)

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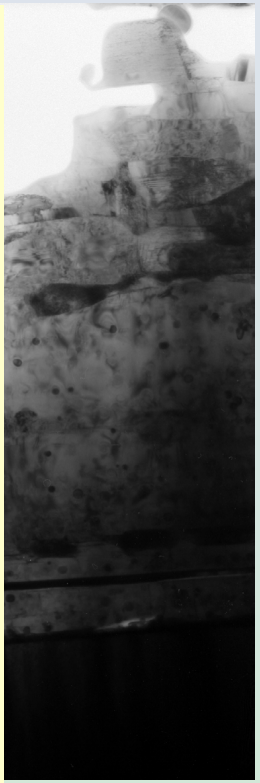
Team interaction leads to improved I_c performance

Critical observations

- ✓ through-thickness J_c study
  → reduced J_c in bottom, large-grained YBCO
- ➢ suppress liquid-mediated growth mode of bottom layer
- ✓ TEM of champion sample
  → feasibility of alternative growth mode
- ➢ process modifications were introduced, enabling higher I_c
  - modifications involve precursor layer



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modified process yields higher I_c

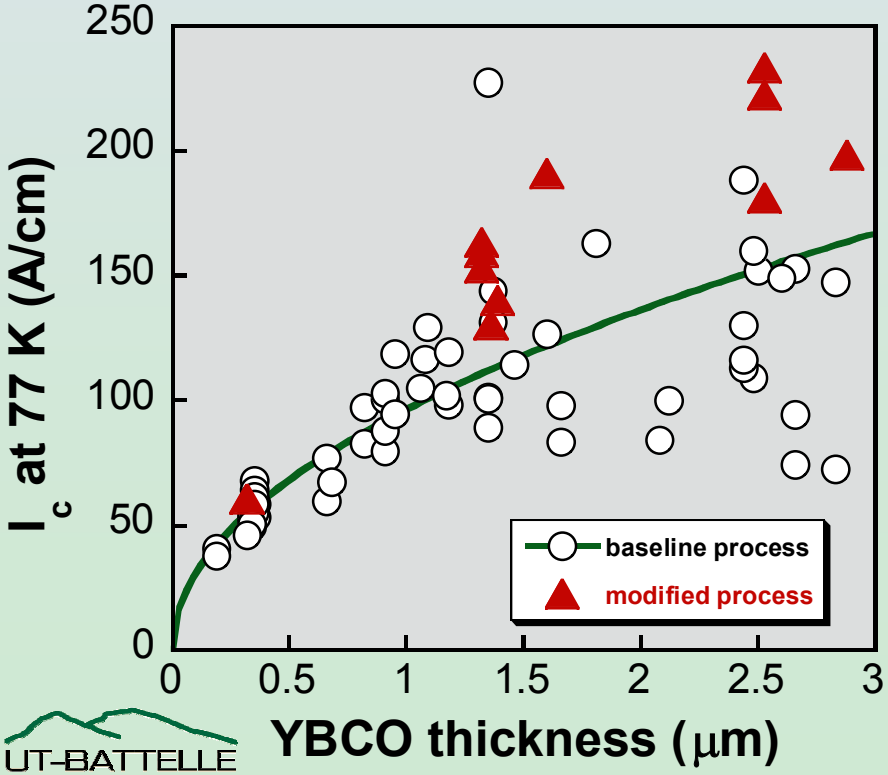
✓ **best I_c on ORNL RABiTS: 233 A/cm** (FY02: 160 A/cm)

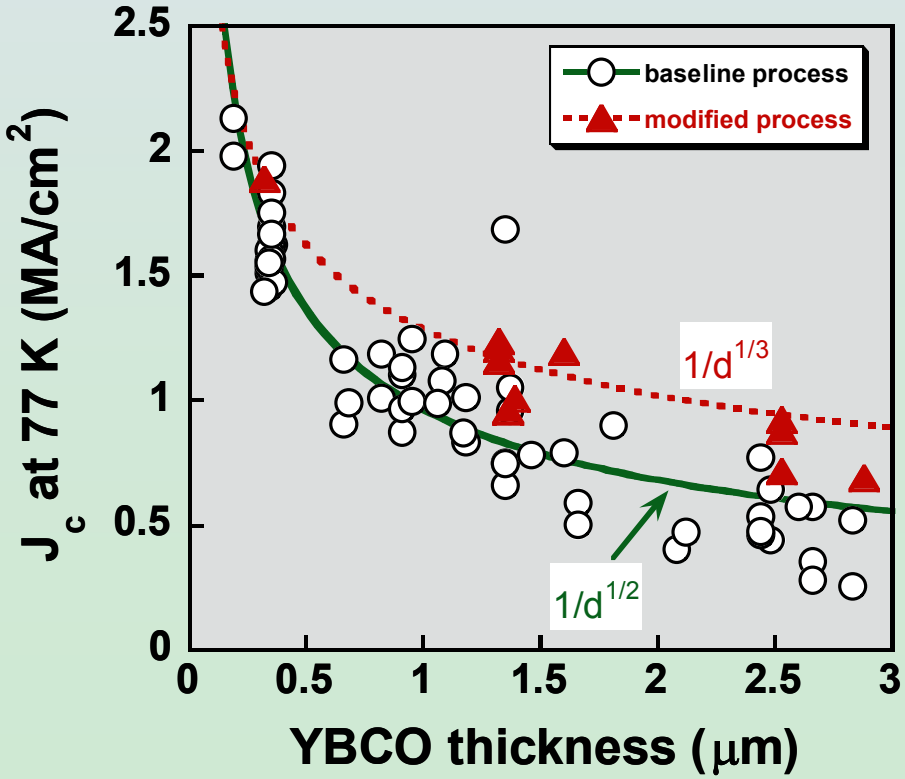
- higher I_c expected on better textured substrate (thin J_c = 1.6–2 MA/cm^2)

- **process modification is effective at all thickness values**

➢ data suggest weaker J_c-d dependence is feasible for ex situ YBCO

- modification is gradual—**parameters still being optimized**





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Outline

- **Thickness dependence of J_c in ex situ YBCO** — **Ron Feenstra**
  "Intrinsic vs. materials"

- **Through-thickness J_c measurements** — **Matt Feldmann**
  spatially correlated J_c and microstructure

- **Microstructural development from e-microscopy** — **Terry Holesinger**
  liquid-mediated growth

Through-thickness properties of thick film *ex situ* $YBa_2Cu_3O_{7-x}$ coated conductors

- Experimental: through-thickness J_c measurements
- do ex situ films have dead layers?
- Correlation with through-thickness microstructure
- “intrinsic vs materials”: evidence against “intrinsic” model

Through-thickness J_c studies performed on a variety of samples

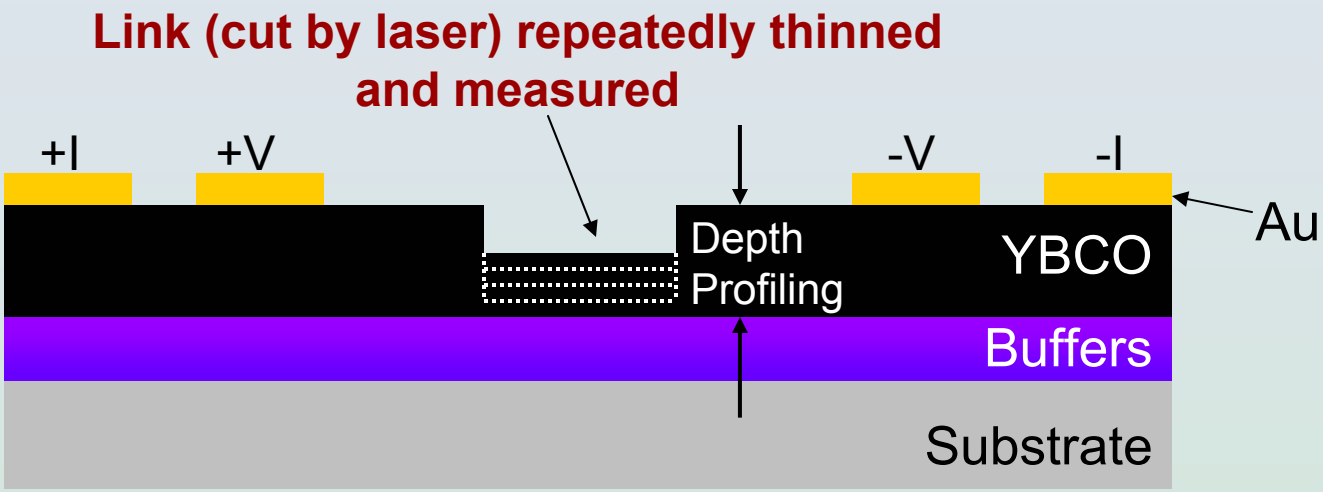
PVD BaF_2 process (ORNL)

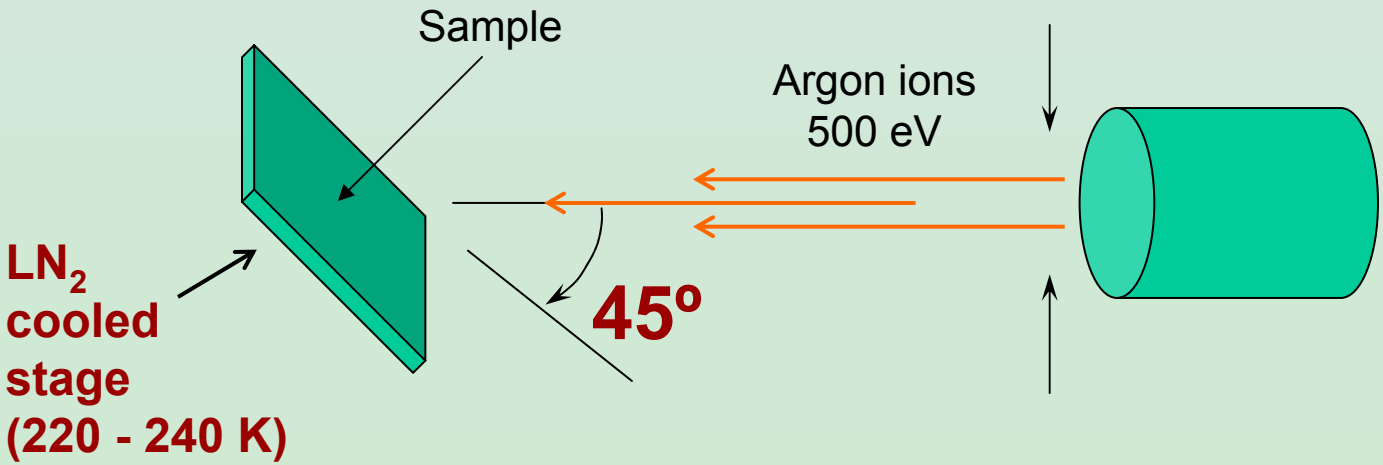
YBCO thickness	texture template	J_c(77K,SF)	$\Delta\Phi$(YBCO)
2.9 μm	IBAD	0.94 MA/cm^2	5.9°
2.0 μm	IBAD	0.73 MA/cm^2	6.9°
0.9 μm	RABiTS	0.96 MA/cm^2	7.5°

MOD BaF_2 process (AMSC)

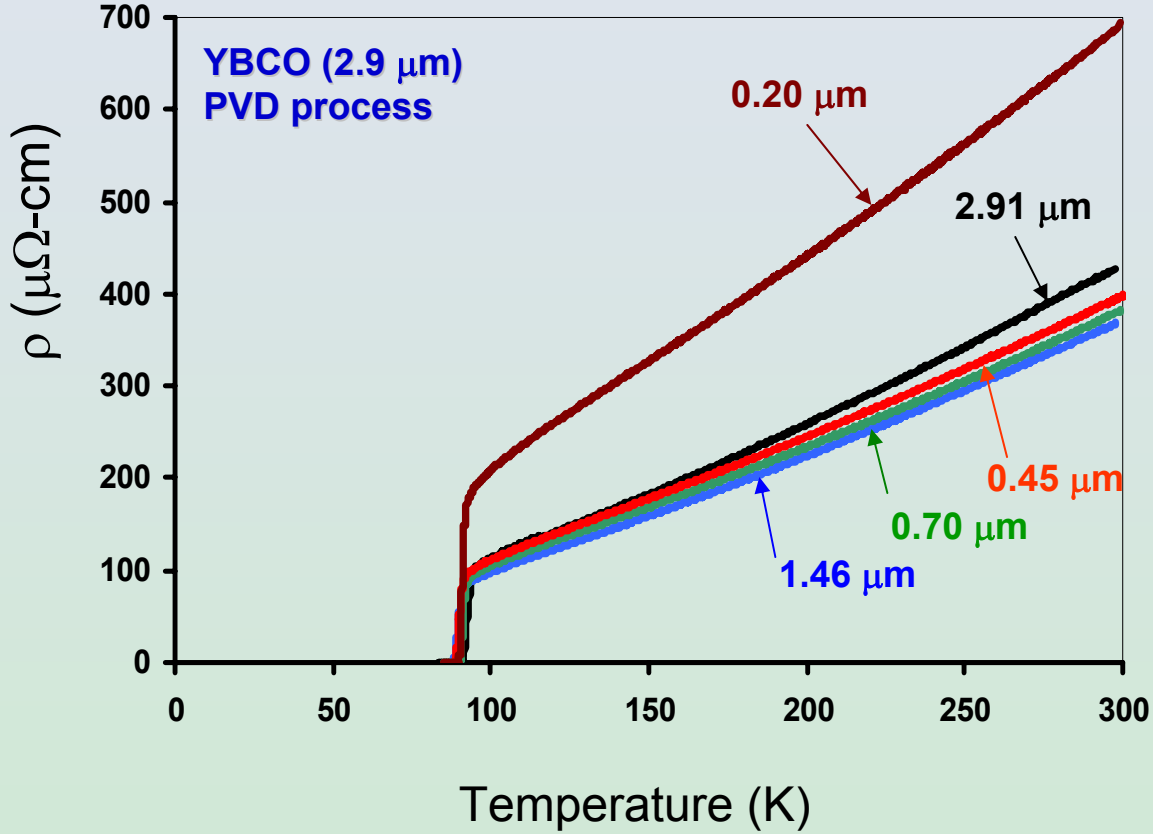
YBCO thickness	texture template	J_c(77K,SF)	$\Delta\Phi$(YBCO)
1.1 μm	RABiTS	1.2 MA/cm^2	6.4°
1.0 μm	RABiTS	2.8 MA/cm^2	4.6°

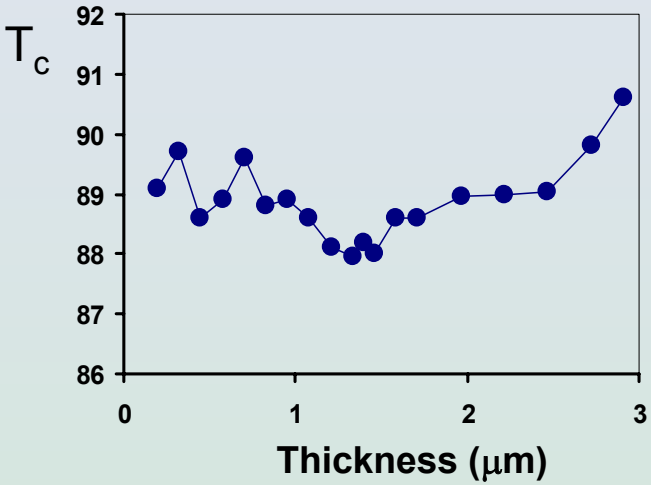
Experimental Setup for Through-thickness J_c measurement and Ion Milling





$\rho(T)$ and T_c show repeated ion milling did not induce damage





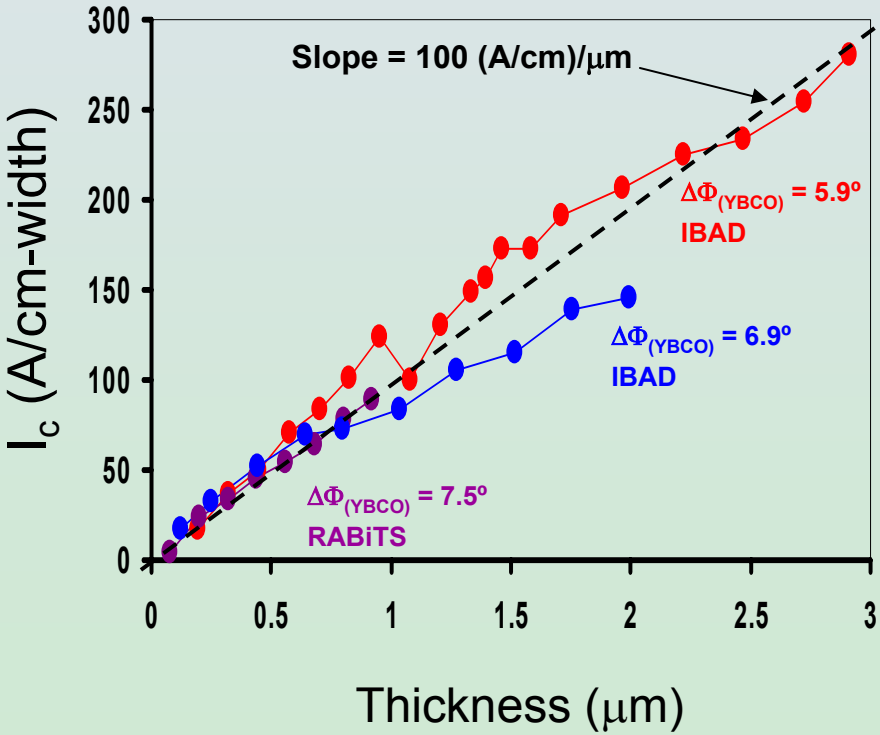
- $\rho(T)$, T_c measured on all samples

- Constant curvature of $\rho(T)$ → Oxygenation state not changing
- T_c stays relatively constant : $T_c > 88K$
  - **Observed for all samples studied**

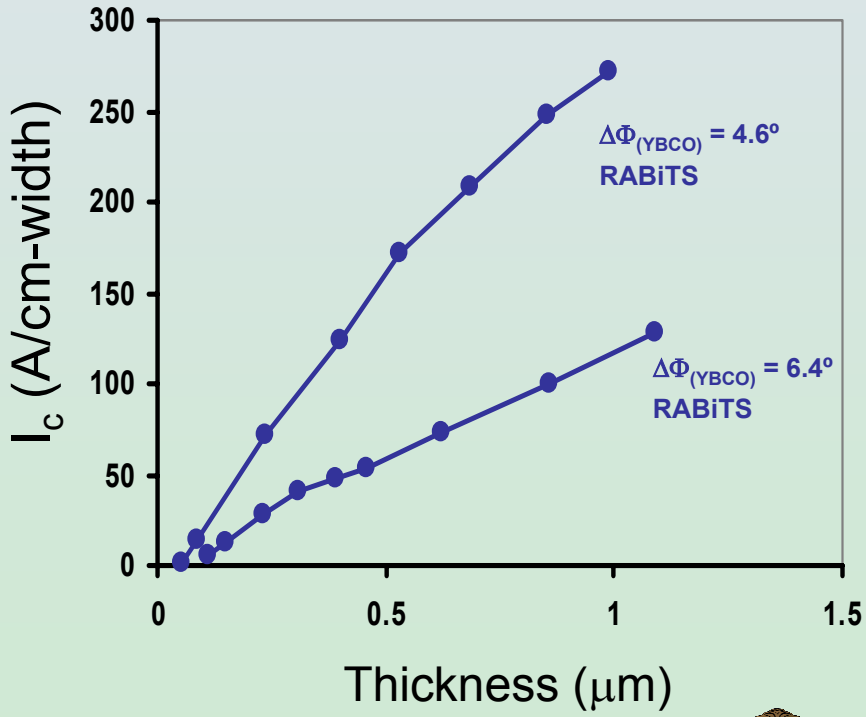
Linear $I_c(t)$ observed for both PVD and MOD processed films

- **No dead layer near surface**
  - **→ thicker YBCO layers should yield higher I_c**

PVD BaF_2 process (ORNL)



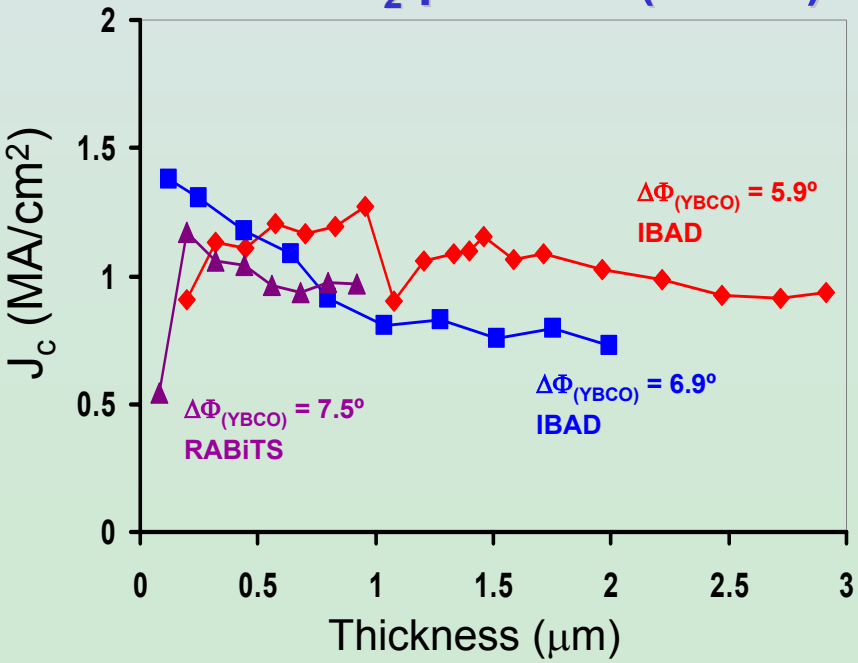
MOD BaF_2 process (AMSC)



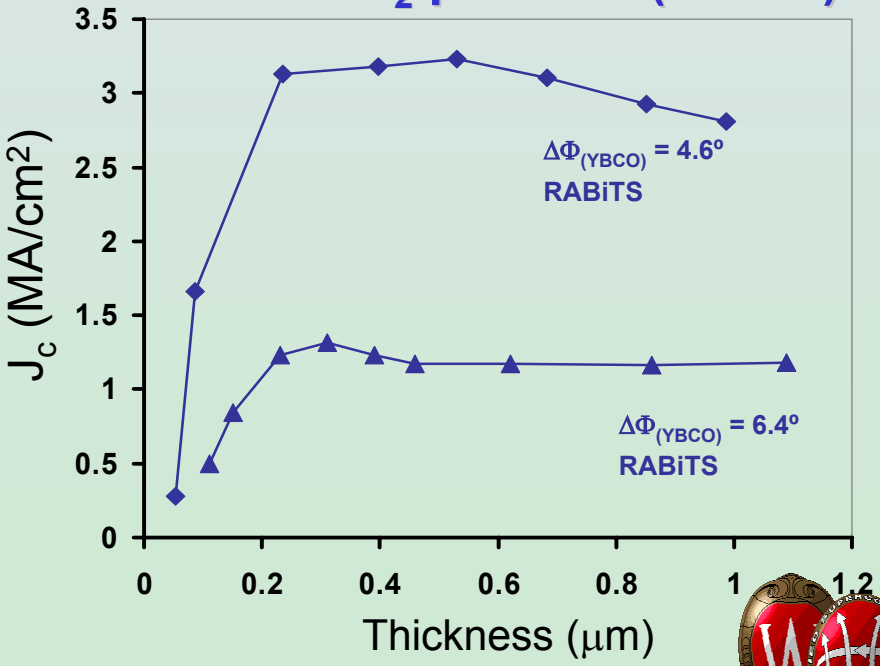
PVD, MOD *ex situ* films show constant J_c through thickness

- Thin "dead" layer near substrate in some films - has small effect on overall performance
  - — effective thickness of "dead" layer in MOD films may be exaggerated due to high porosity (connectivity issue)
- ***Indicative of a homogeneous through-thickness microstructure?***

PVD BaF_2 process (ORNL)



MOD BaF_2 process (AMSC)

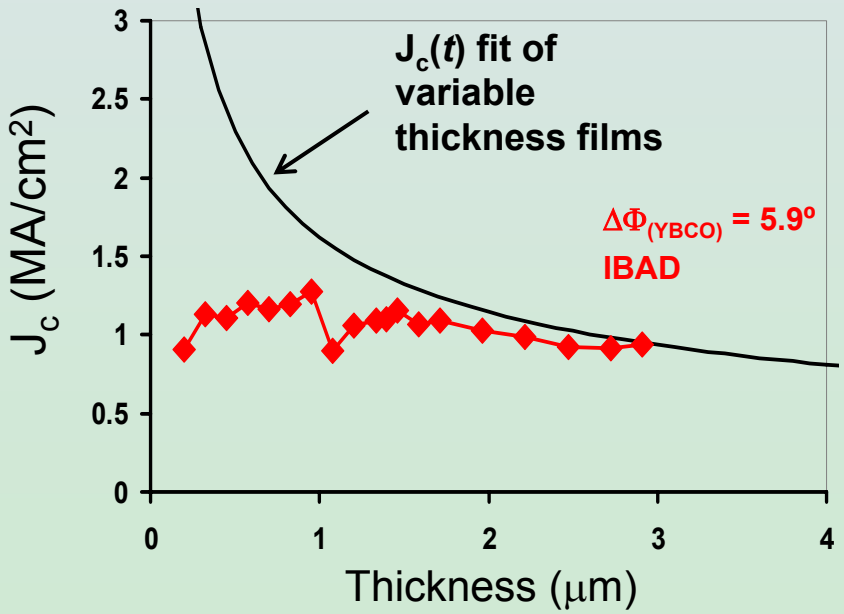


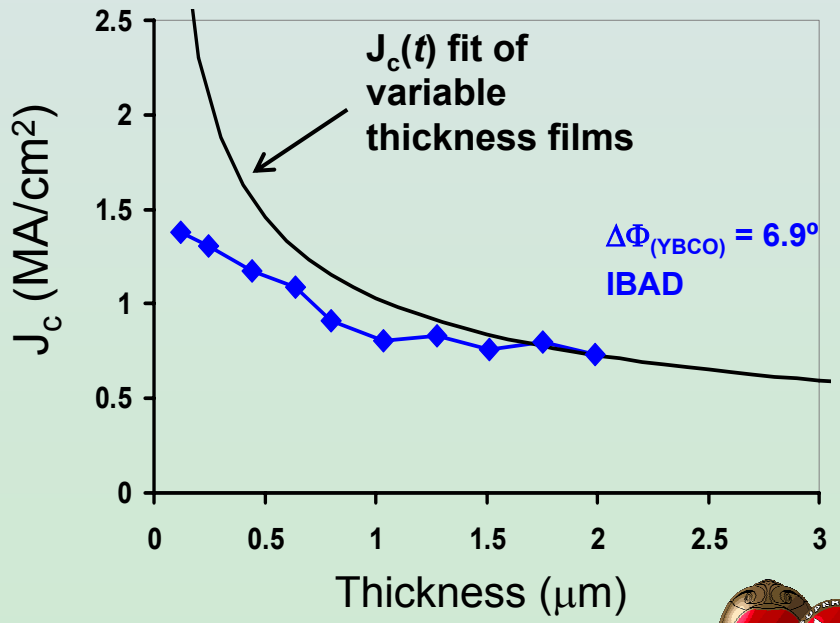
"thin film" J_c not recovered as samples are thinned (PVD BaF_2 process)

- Higher J_c values of films reacted from thin precursors are not recovered as these thick films are milled thinner

Conclusion: Bottom layer contains current blocking defects or a reduced density of pinning defects

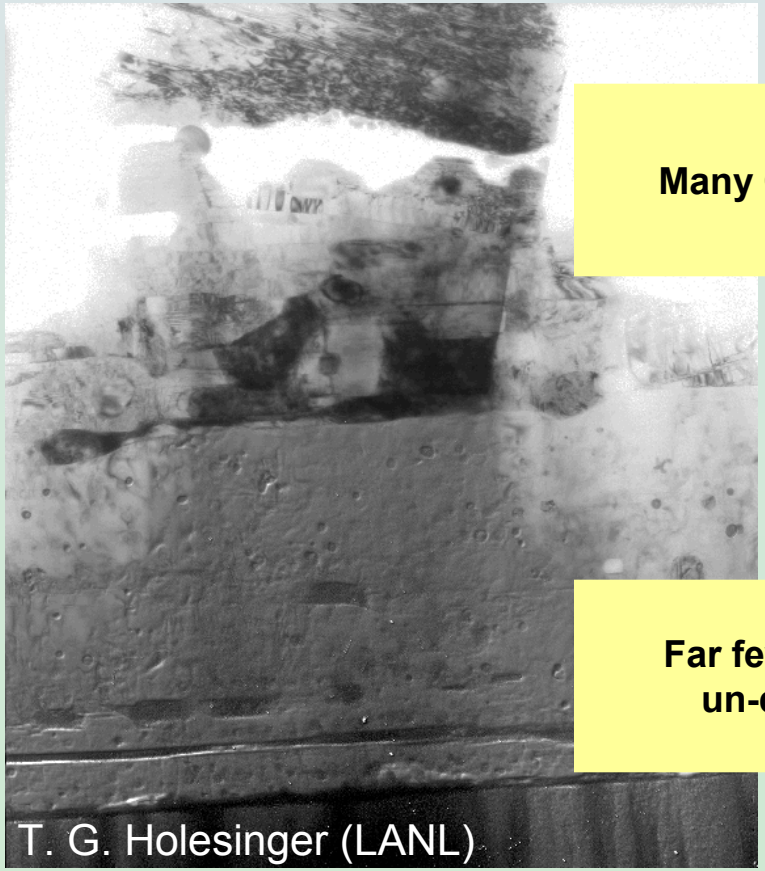
✓ lower J_c is NOT due to oxygen deficiency (inferred from T_c, ρ data)





Through thickness TEM for 2.9 μm thick YBCO (PVD-BaF_2) shows 'bi-modal' structure

- **Crystal-like nature of bottom layer is consistent with a reduced defect density → reduced J_c**



2.9 μm

Ag

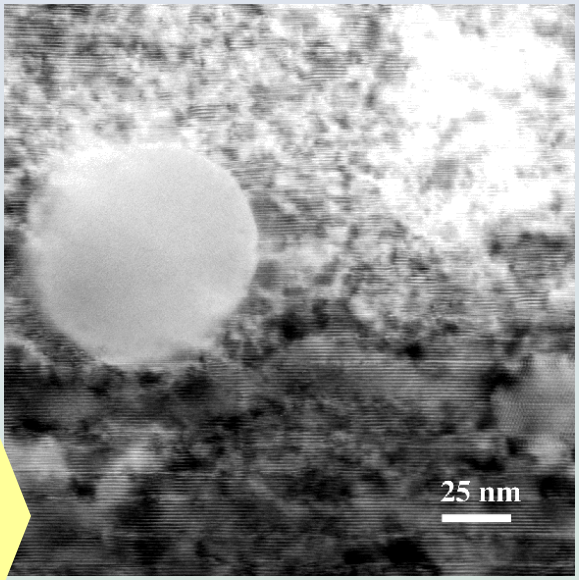
tilted grains

Large, un-defected, well-aligned

YBCO

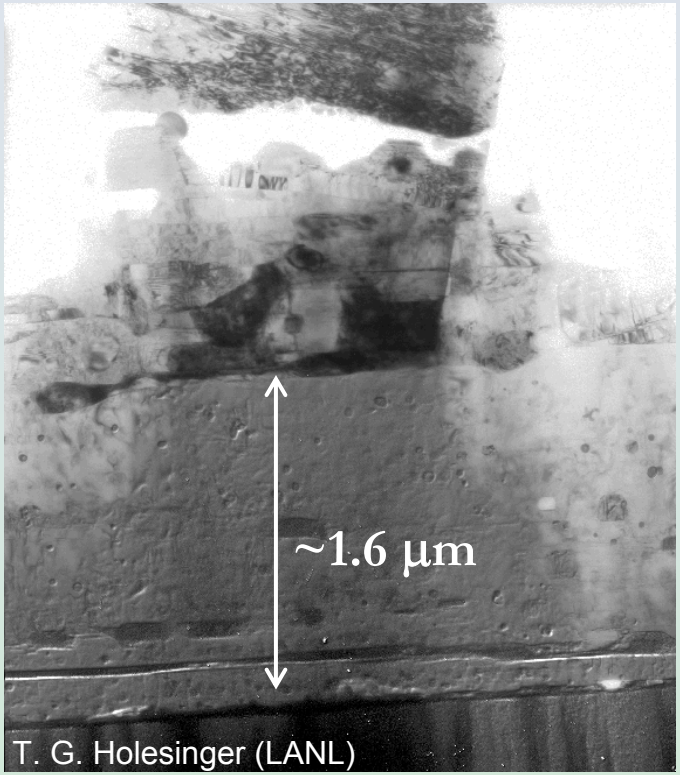
YSZ

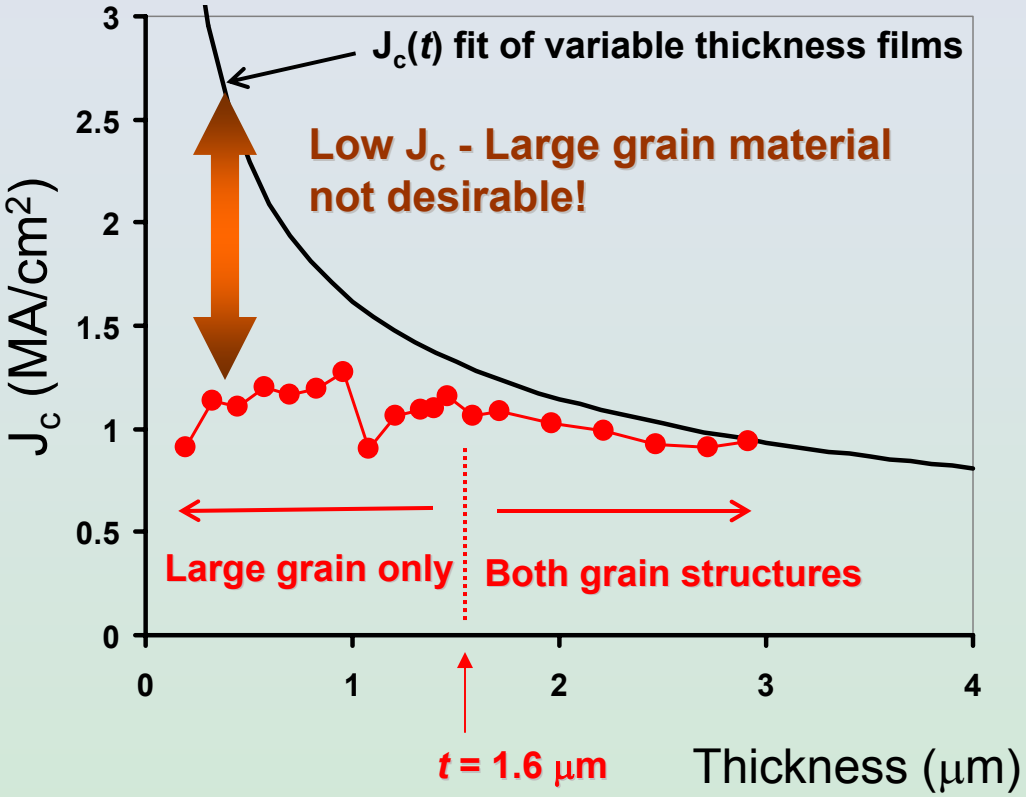
Many Cu-O stacking faults



Far fewer stacking faults, un-defected structure

Surprising result: difference in microstructure is NOT reflected in the through-thickness $J_c(t)$





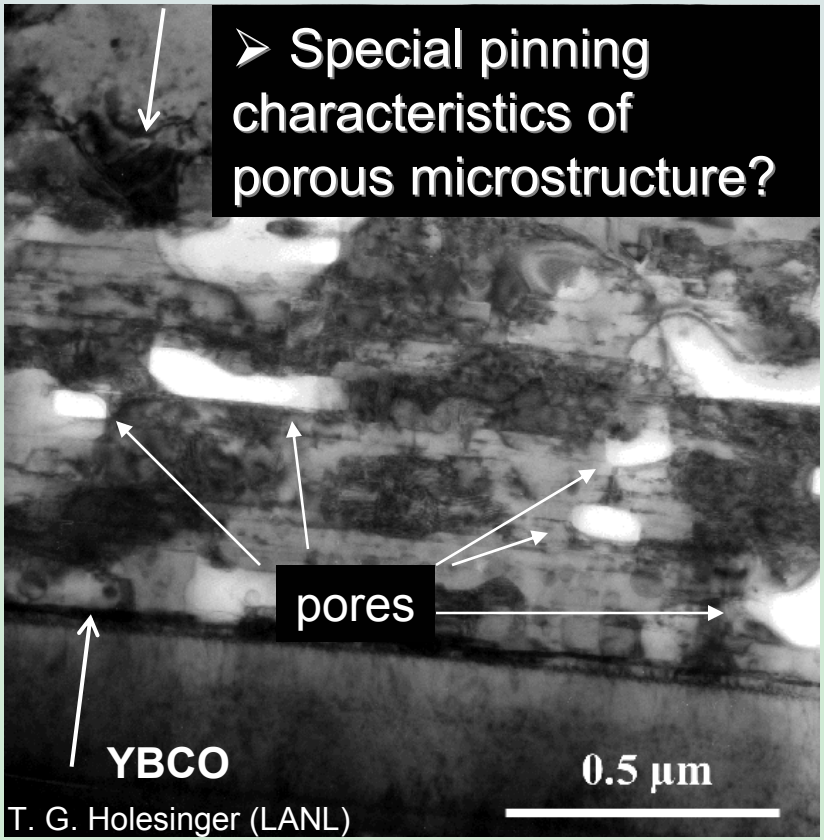
- TEM shows different defect densities (top vs. bottom), but flat $J_c(t)$ suggests these defects aren't controlling J_c

OR

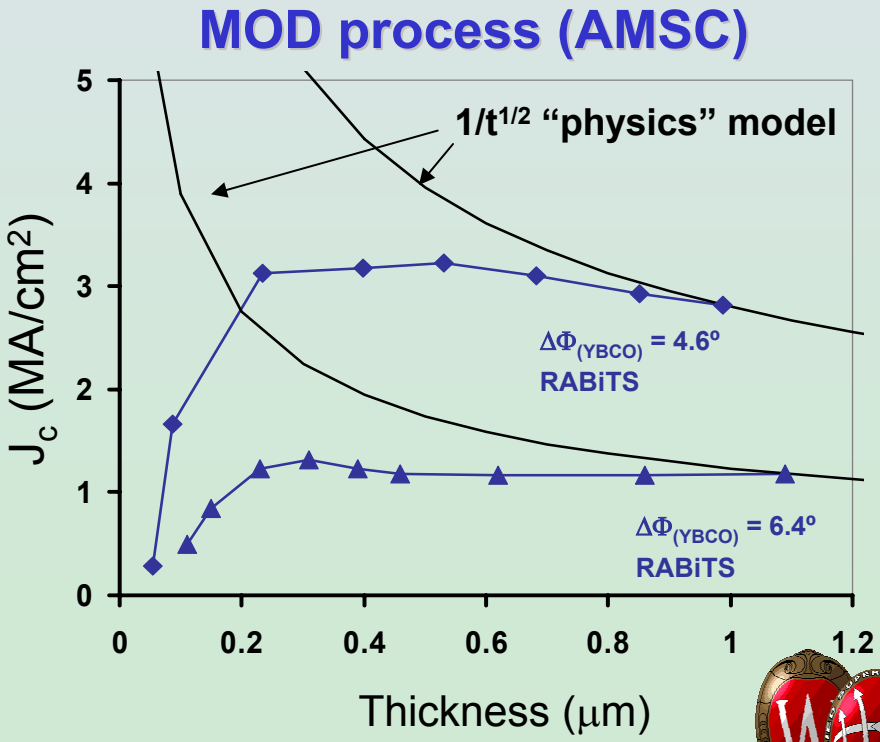
- Compensating effects between current limiting features and pinning defects → <u>Coincidence</u>: J_c(top) ~ J_c(bottom)

Constant through-thickness $J_c(t)$ for MOD YBCO contradicts intrinsic model predictions

- Constant J_c appears consistent with homogeneous microstructure
- **In context of physical model, either**
  - ✓ collective pinning model holds, but defect density decreases towards substrate (TEM: appears unlikely) **or**
  - ✓ pinning in MOD films is NOT dominated by point defects



T. G. Holesinger (LANL)



Outline

- **Thickness dependence of J_c in ex situ YBCO** — **Ron Feenstra**
  "Intrinsic vs. materials"

- **Through-thickness J_c measurements** — **Matt Feldmann**
  spatially correlated J_c and microstructure

- **Microstructural development from e-microscopy** — **Terry Holesinger**
  liquid-mediated growth

Microstructural Development from Electron Microscopy

- Microstructural development in ex-situ BaF_2 YBCO films.
  - ✓ Laminar vs. columnar structures
  - ✓ PVD-BaF_2 and MOD-BaF_2 ex-situ films
  - ✓ The role of liquid phases in phase development
- Current limiting microstructures
- The "porous microstructure"
- Wrapup

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→ PVD-BaF_2: Physical vapor deposition of precursors

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→ MOD-BaF_2: Metal organic deposition of precursors

High current YBCO coated conductors can have different film morphologies that are process dependent.

- Laminar vs. columnar growth (Does it matter??)
- Laminar growth is characteristic of the MOD and PVD-BaF_2 conversion processes.

IBAD YSZ / CeO_2 / BaF_2 YBCO (Feenstra-ORNL)
J_c(77K) = 1 MA/cm^2 / 2.7 µm YBCO film

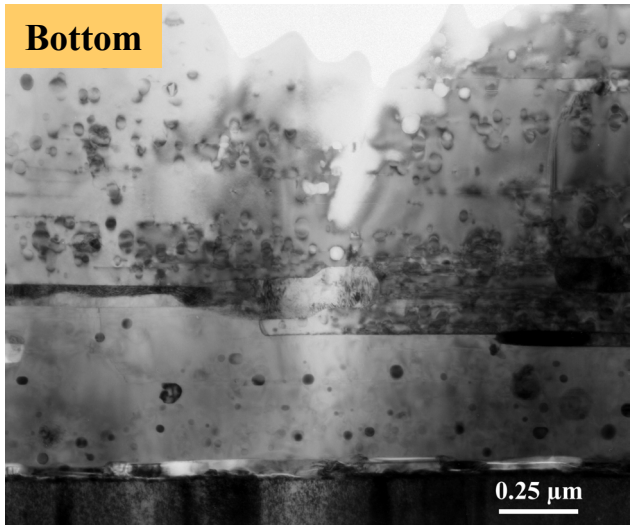
IBAD YSZ / CeO_2 / PLD YBCO (Foltyn-LANL)
J_c(75K) = 1.7 MA/cm^2 / 1.5 µm YBCO film

MOD YBCO / CeO_2 / YSZ / Y_2O_3 / Ni / NiW RABiTS™
0.84 µm YBCO J_c(77K) = 2.0 MA/cm^2 (Rupich - AMSC)

The "standard" conversion of PVD-BaF_2 YBCO films on IBAD YSZ templates produced high-J_c films with a bi-modal microstructure.

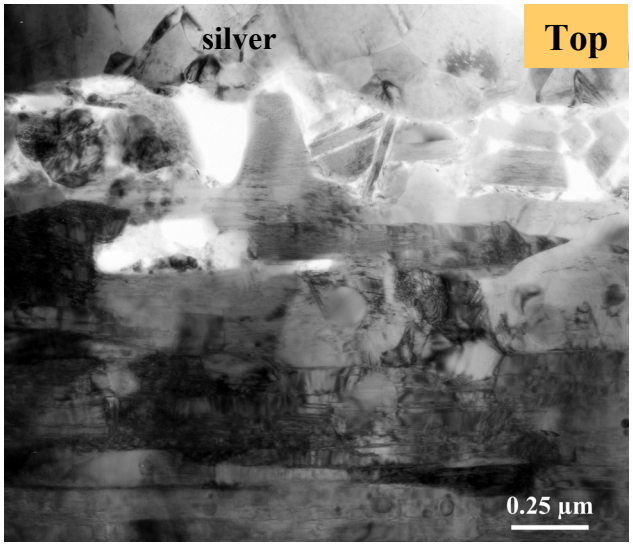
- **Bi-modal:** Large, well formed, low J_c YBCO grains in bottom half of film and smaller, faulted YBCO grains in the top half.
- Two different growth modes indicated by different grain morphologies and phase assemblages.

IBAD YSZ (LANL) / CeO_2 / BaF_2 YBCO (ORNL)
J_c(77K) = 1 MA/cm^2 / 2.7 µm YBCO film / 270 A/cm-width



Large, low-J_c, YBCO grains (> 10 µm)

Y_2O_3 precipitates, large Ba-Cu-O secondary phases, minor amounts $YCuO_2$, CuO.

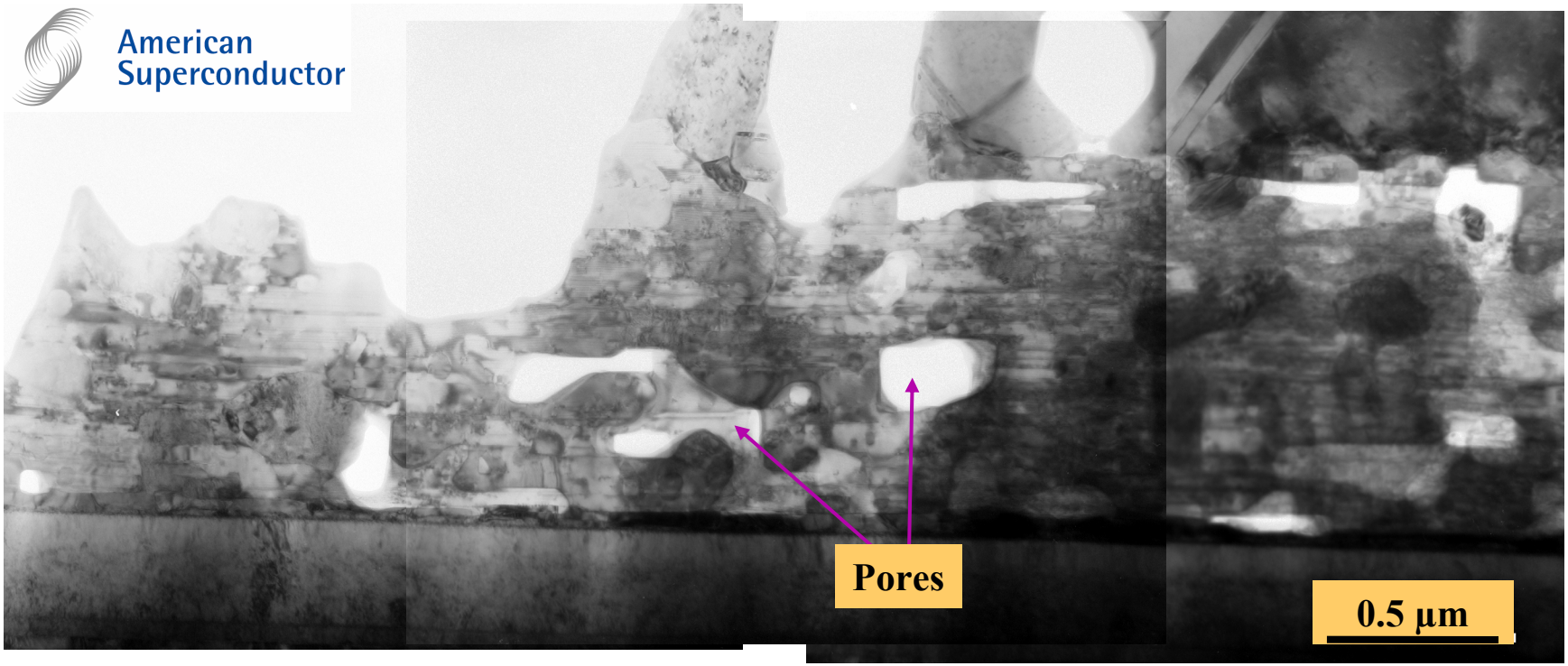


Small YBCO grains

<u>Multiple secondary phases</u>
$YCuO_2$, Y_2O_3, $Ba_2Cu_3O_y$, and $BaCu_2O_y$

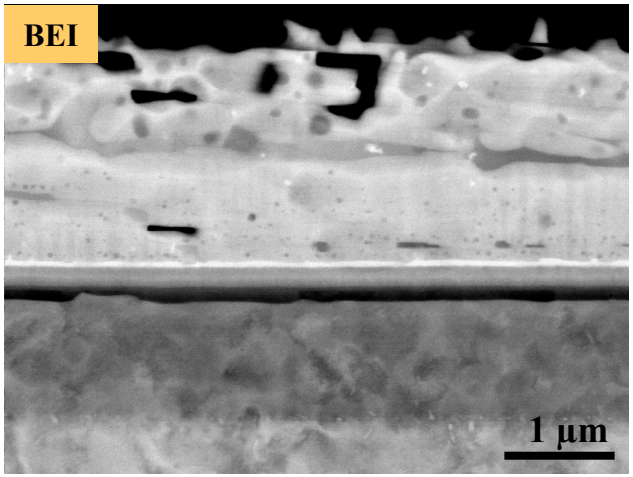
The ex-situ conversion of MOD-BaF_2 YBCO precursors on RABiTS produced very high J_c films that did not have a bi-modal structure.

- 0.8 µm YBCO / CeO_2 / YSZ / Y_2O_3 / Ni / NiW (RABiTS)
  - ✓ I_c = 270A/cm width. (Full width measurement!)
  - ✓ $J_c \approx 3.4$ MA/cm^2 (≈0.8 µm YBCO)
- "porous microstructure" - small-grain, faulted YBCO structure that is uniform thru thickness in spite of all the porosity.

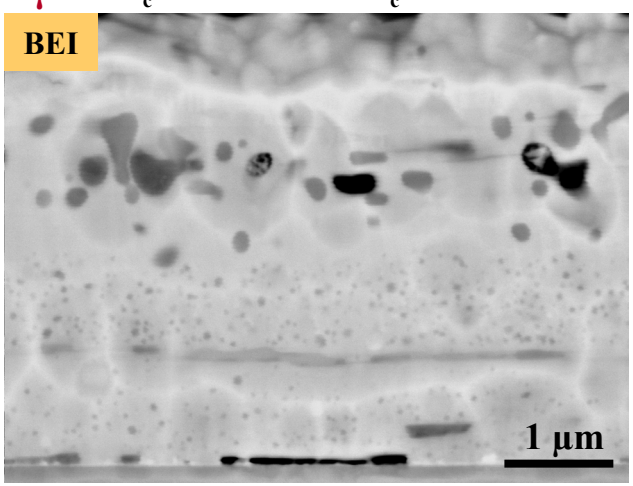


The "standard" ex-situ conversion of PVD-BaF_2 films on RABiTS™ produced the bi-modal structure over a wide range of film thicknesses.

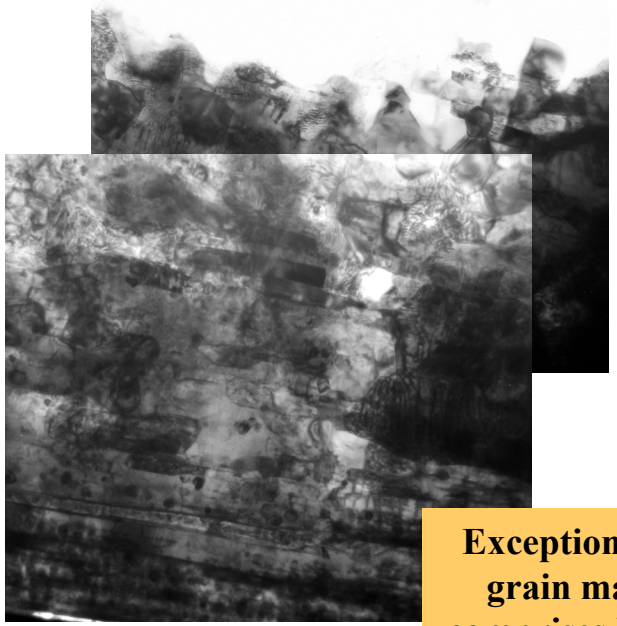
2.1µm $J_c = 0.44$ MA/cm^2 $I_c = 93$ A/cm-width



5µm $J_c = 0.31$ MA/cm^2 $I_c = 155$ A/cm-width



- The bi-modal structure is process, not substrate, dependent.
- Rule-of-thumb: Large grain material comprises ≈ 1/2 of the film thickness.



Small-grain YBCO

Large-grain YBCO

Buffer layers NiO

Ni

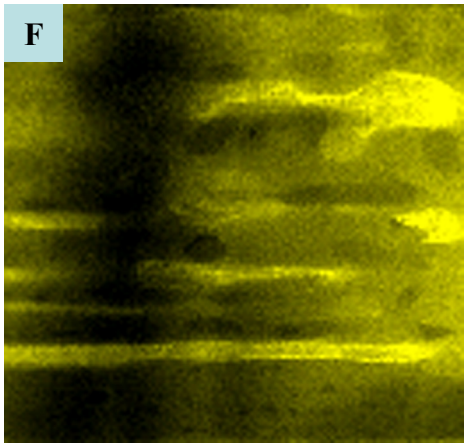
Exception: Large grain material comprises less than half of the film.

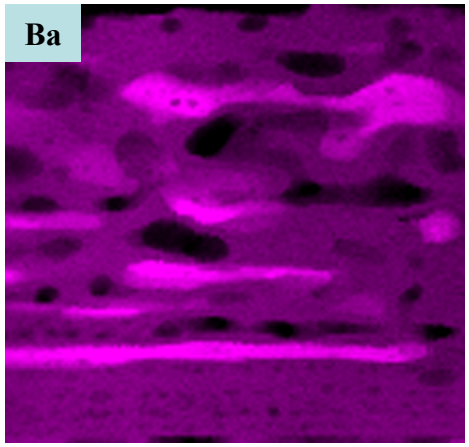
0.5 µm

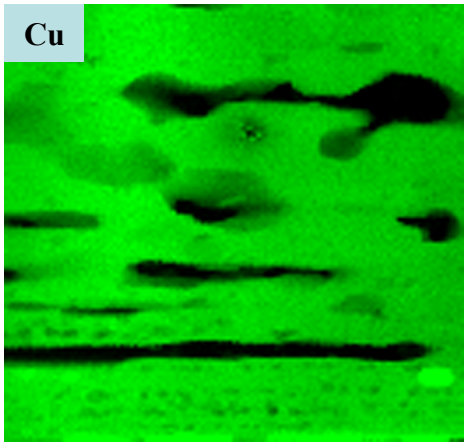
2.5µm J_c=0.75 MA/cm^2 I_c=186 A/cm-width

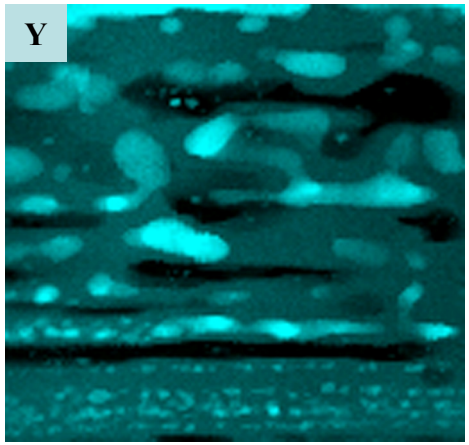
The bi-modal structure is a process dependent structure derived from the presence of excessive amounts of liquid phases during conversion.

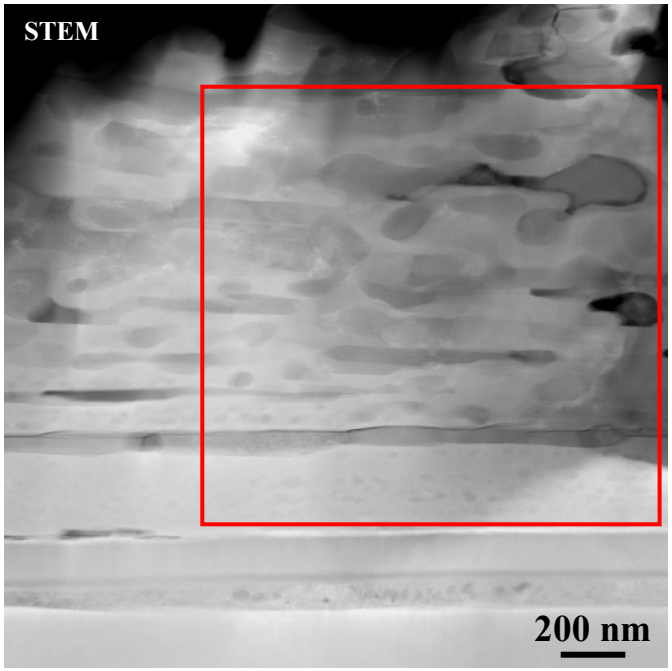
- Remnants of the liquid phase (Ba-O-F) can be found in some of the fully processed films.
- Typically, the Ba-Cu-O phase takes the place of the Ba-O-F.
- Spectral images (below) show the distribution and extent of the secondary phases.









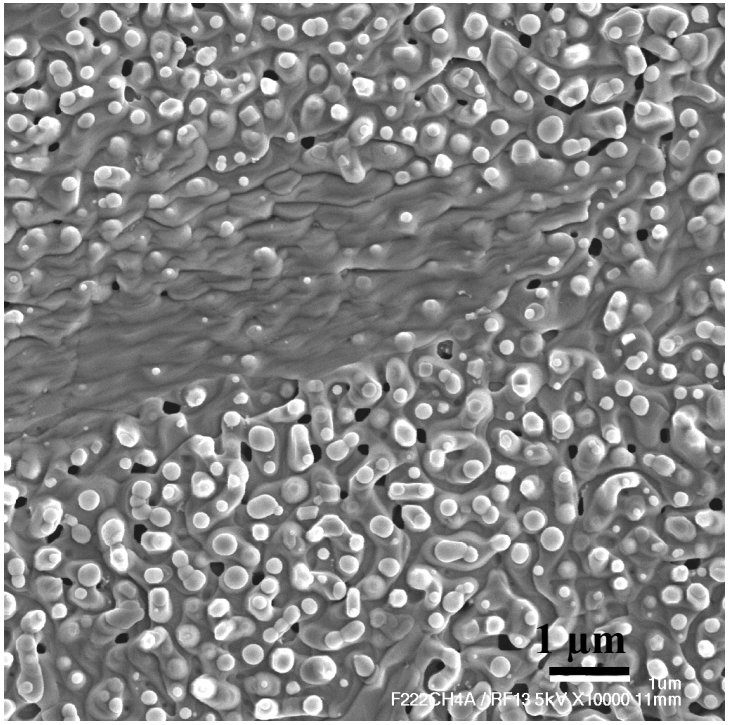


bi-modal structure

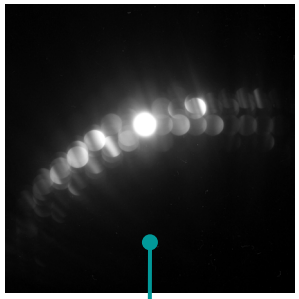
2.5µm J_c=0.75 MA/cm^2 I_c=186 A/cm-width

Too much liquid phase during processing can also cause the formation of YBCO colonies tilted out-of-plane.

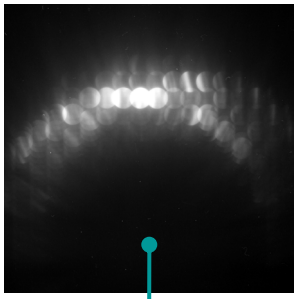
- Colonies of tilted grains (not a-axis) can form above layers of liquid phase; their intersections with the film surface are easily viewed by SEM.
- Tilted grains can have both out-of-plane and twist components.



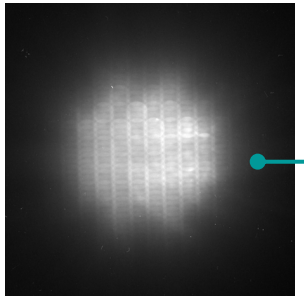
Out of plane tilt with a twist component.

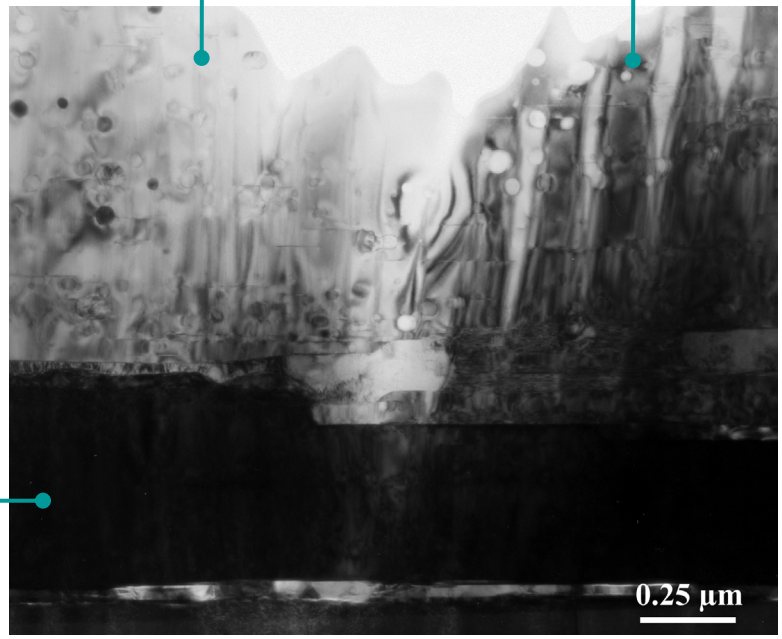


Out of plane tilt



YBCO on zone axis

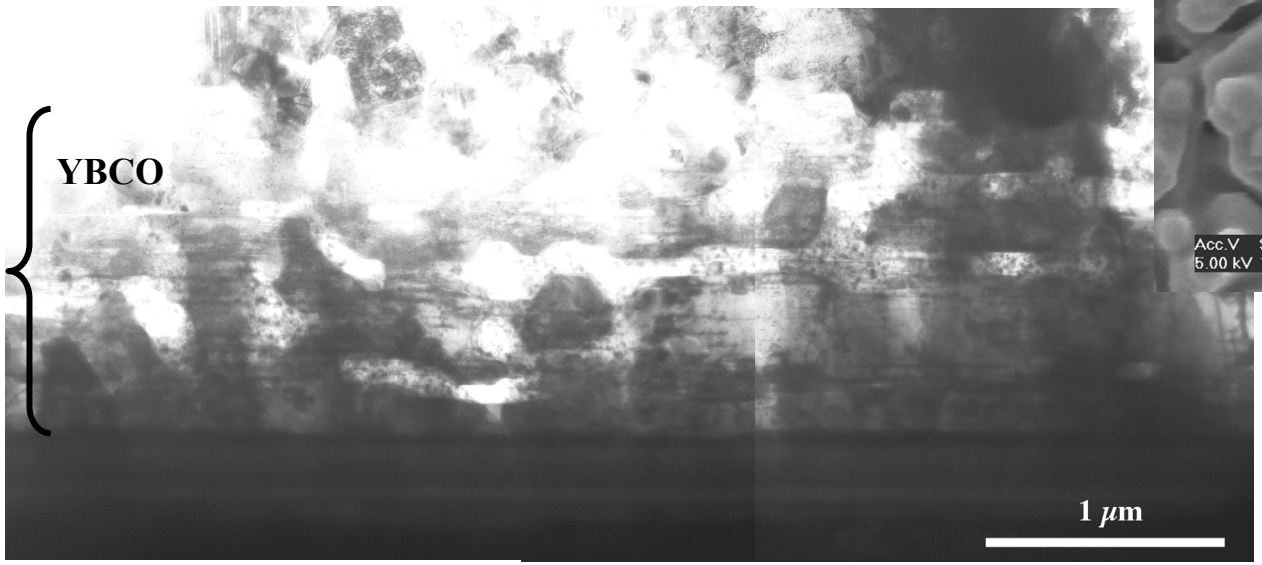


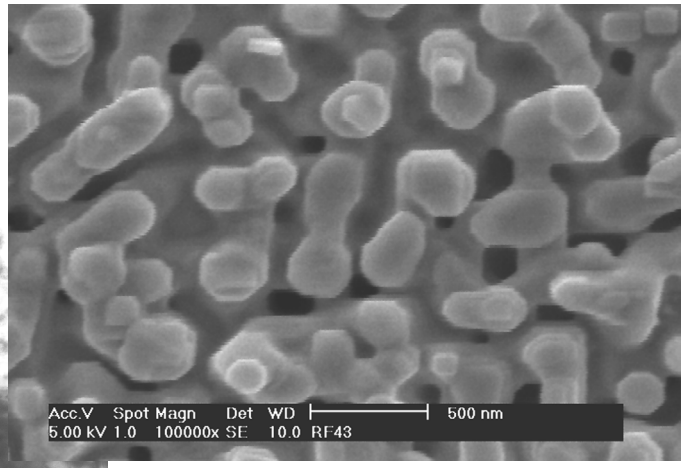


IBAD YSZ / CeO_2 / BaF_2 YBCO (Feenstra-ORNL)
J_c(77K) = 0.9-1 MA/cm^2 / 2.7 µm YBCO film

A “champion” PVD-BaF_2 film on RABiTS™ did not contain the bi-modal structure.

- 1.35µm YBCO J_c = 1.69 MA/cm^2; I_c = 228 A/cm-width
- An exception to the norm in the “standard processing” provided insight into how the microstructure and superconducting properties can be improved.
- The high-J_c “porous microstructure” can be obtained from a PVD-BaF_2 conversion process.

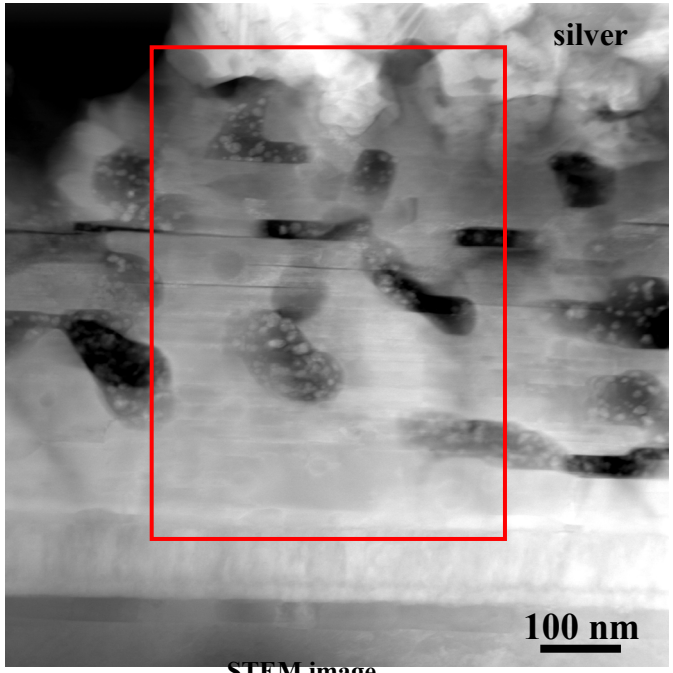




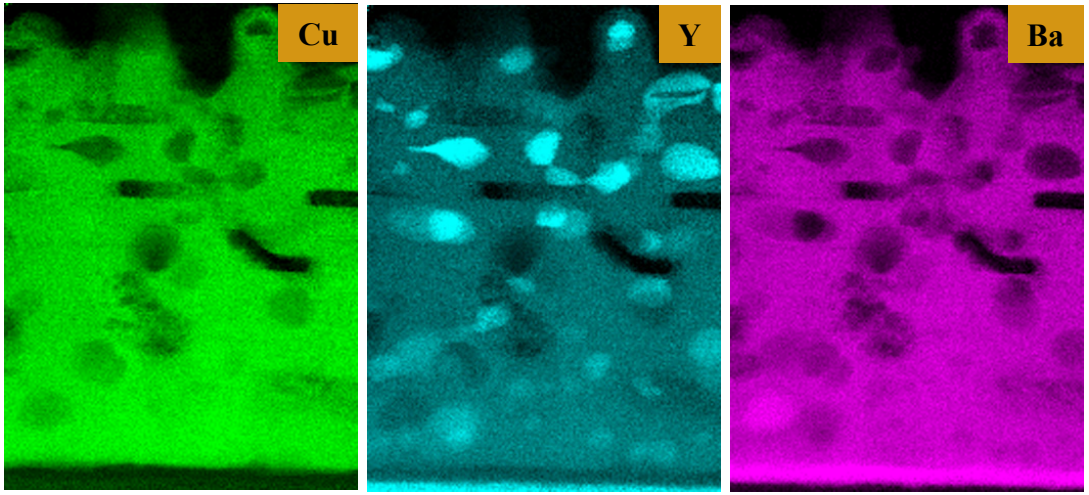
YBCO / CeO_2 / YSZ / Y_2O_3 / Ni / NiW

The microstructure and phase assemblage of the "champion" PVD-BaF_2 sample suggested a reduced amount of liquid phase during conversion.

- Spectral imaging shows a uniform distribution of secondary phases within the porous microstructure.
  - ✓ Very few, large Ba-Cu-O phases
  - ✓ Very few Y_2O_3 precipitates within grains
  - ✓ Random mix of "round" Y_2O_3, $YCuO_2$, and Ba-Cu-O phases



STEM image



Residual fluorine was found in the high-J_c (3.4 MA/cm^2) AMSC MOD-BaF_2 YBCO coated conductor.

- Not necessary to remove all F from the films. (shorter processing times!)
- Residual F (Ba-Cu-O-F or BaO_xF) suggests an important role for liquid phase assisted growth in the conversion process.

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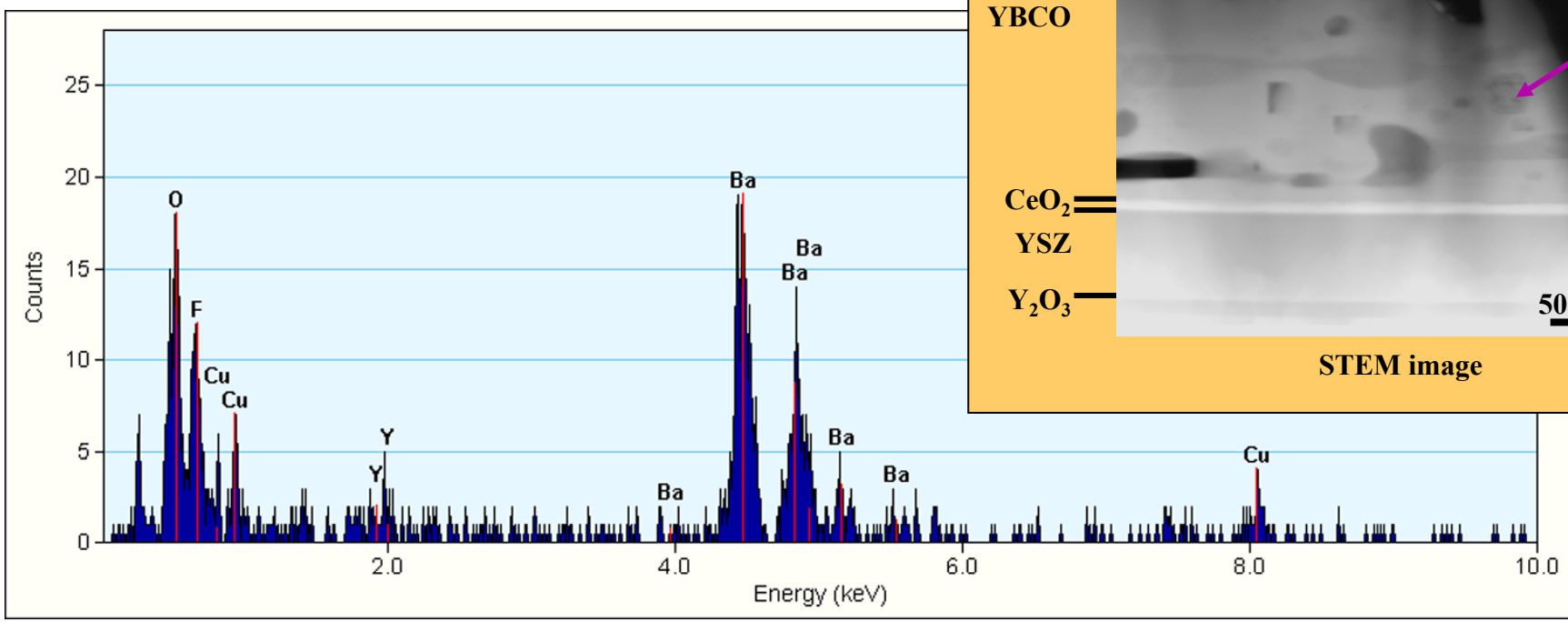
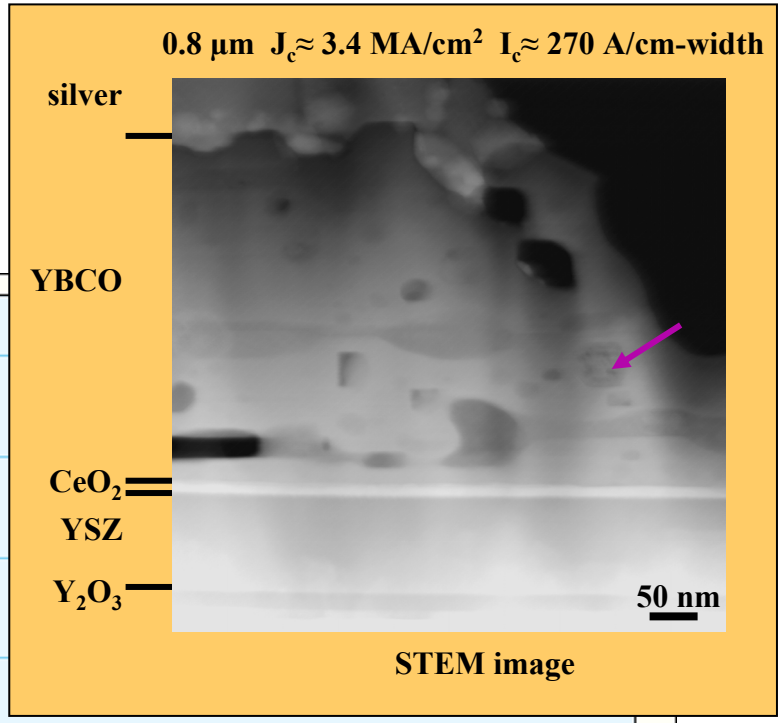
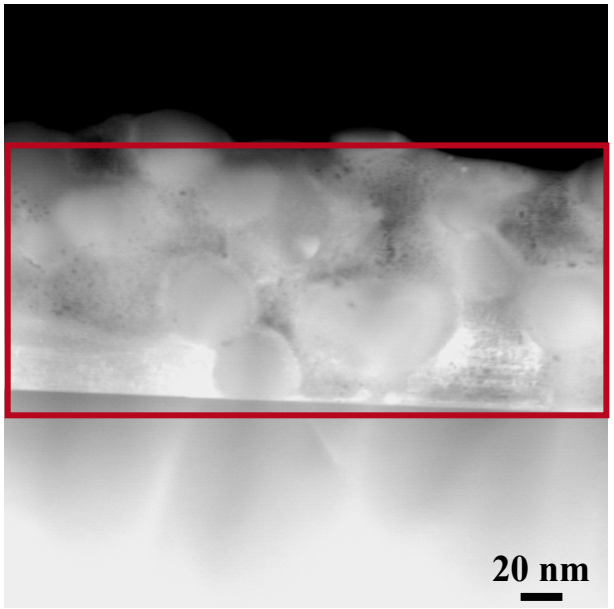


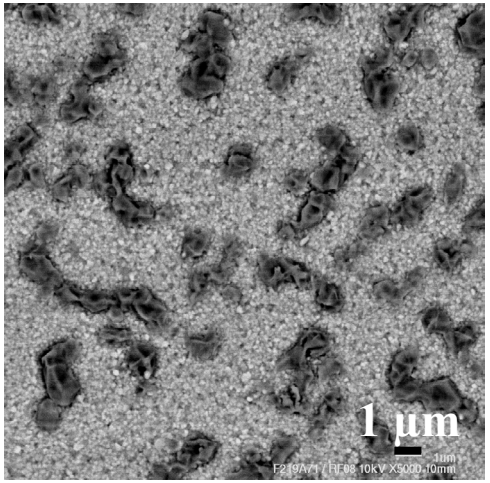


Understanding the role of the liquid phase in the *ex-situ* conversion of the BaF_2 precursors is a key area for obtaining a high-J_c microstructure.

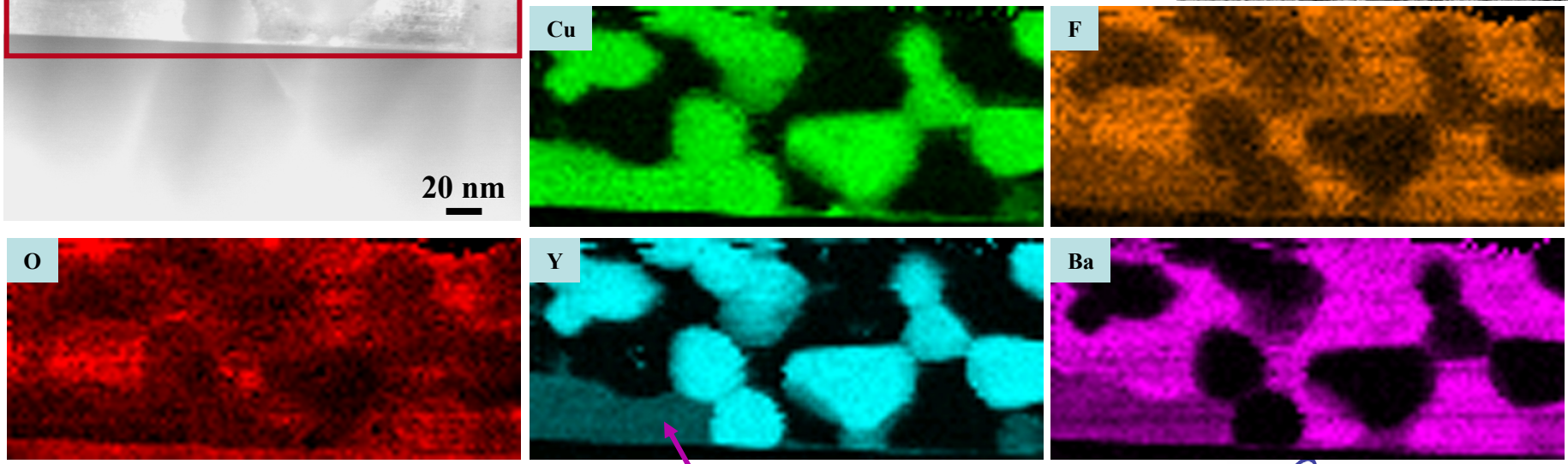
- In the thin films, a segregation of the precursor into Ba-O-F (liquid phase?) and $YCuO_x$ occurs. (what happens to the rest of the copper?)
- Laminar YBCO growth starts at the substrate interface.



SEM image - CuO segregation



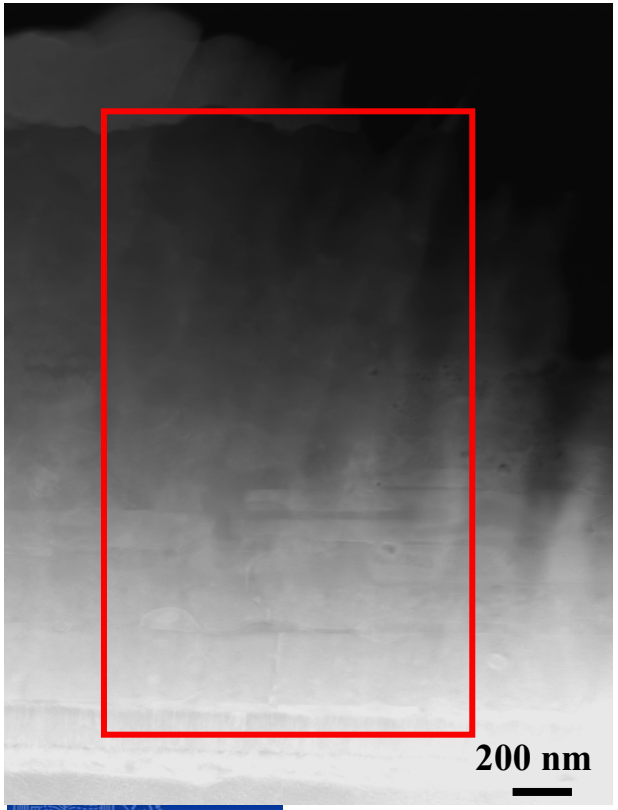
0.3 µm precursor on (100) $SrTiO_3$
Quenched after 0.3 hours



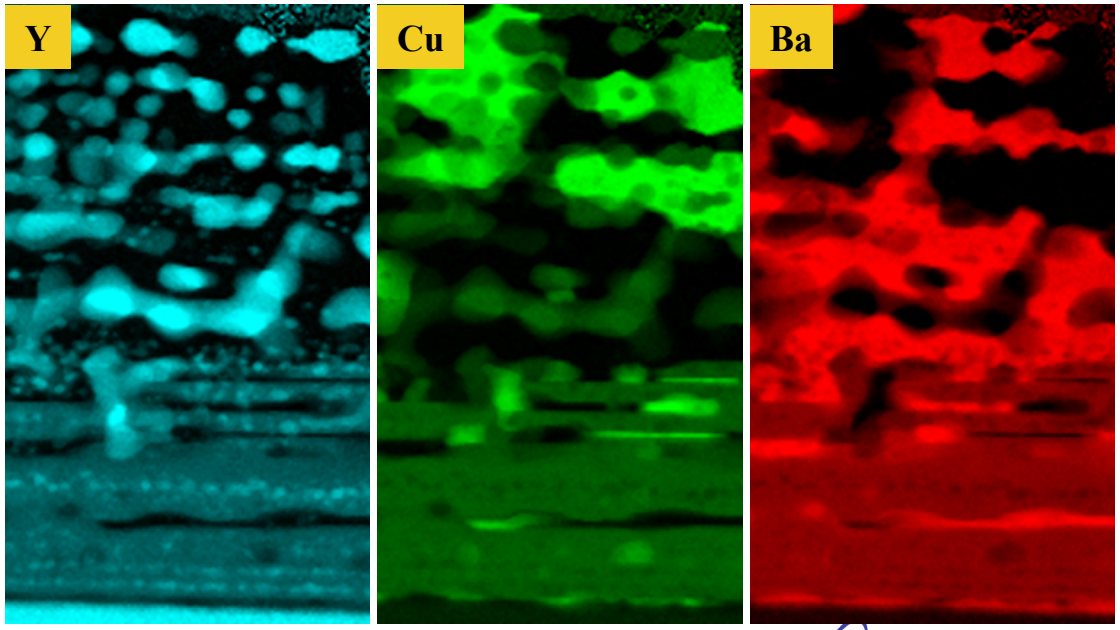
YBCO grain growing on the substrate.

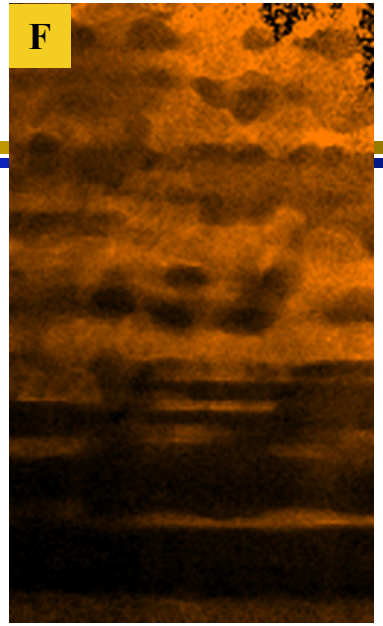
The starting thickness of the precursor film also affects the conversion process.

- CuO segregation
- Ba-O-F and $YCuO_x$ again associated with precipitation of YBCO.
- Y_2O_3 particles floating in the Ba-O-F near growth front.
  - ✓ (3) $YCuO_x$ + (2) Ba-O-F $\rightarrow$ $YBa_2Cu_3O_y$ + Y_2O_3
  - ✓ Layered Y_2O_3 structure within the large YBCO grains.
- Start of small grain YBCO nucleation in top half of film.



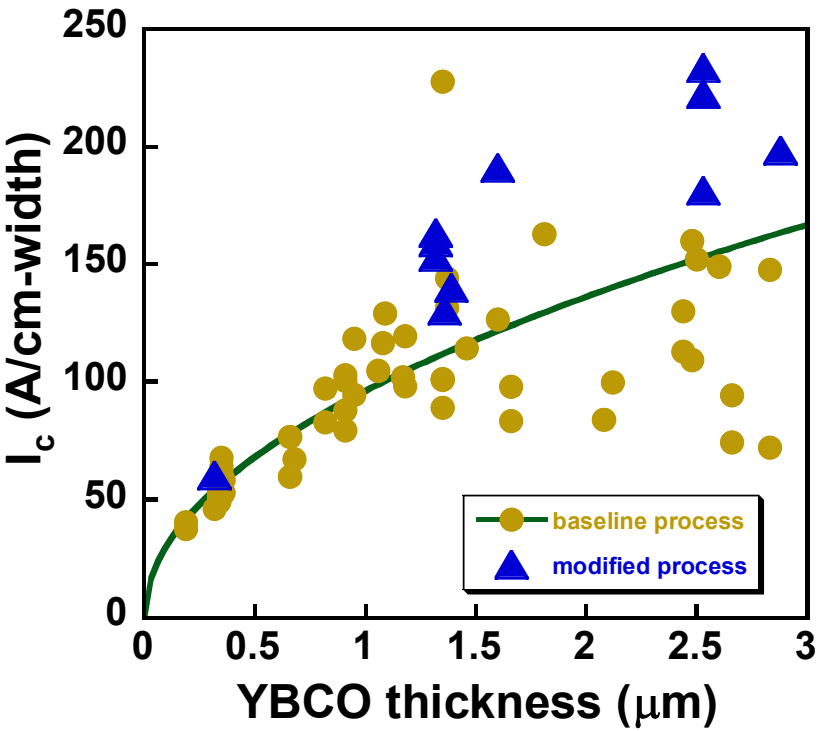
2.66 µm film on RABiTS quenched after 1.5 hours total processing time

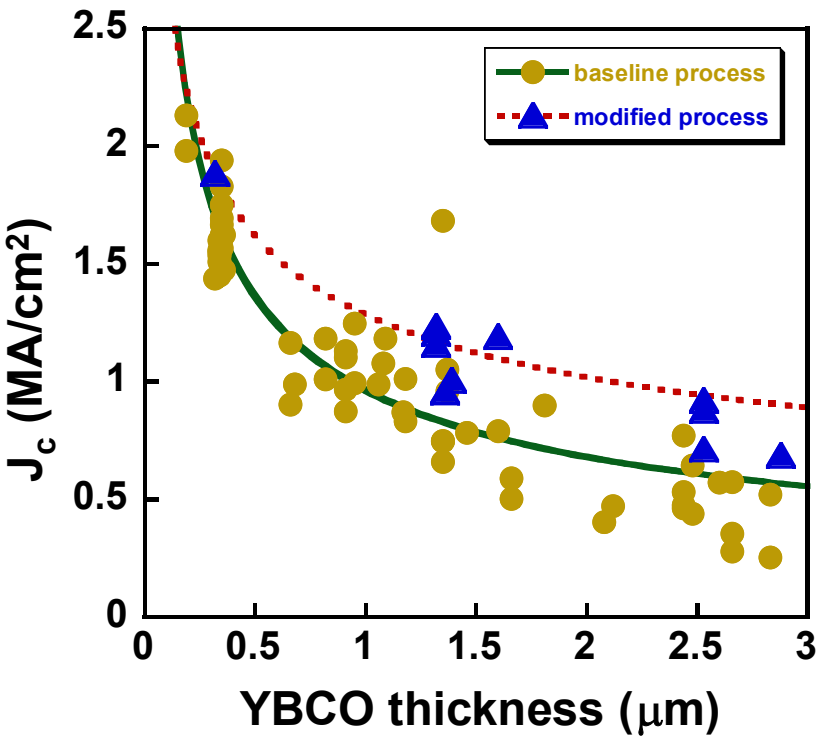




New process methodologies developed from microscopy and ion-milling insights resulted in improved transport properties for PVD-BaF_2 films.

- PVD-BaF_2 YBCO films of various thickness on RABiTS.



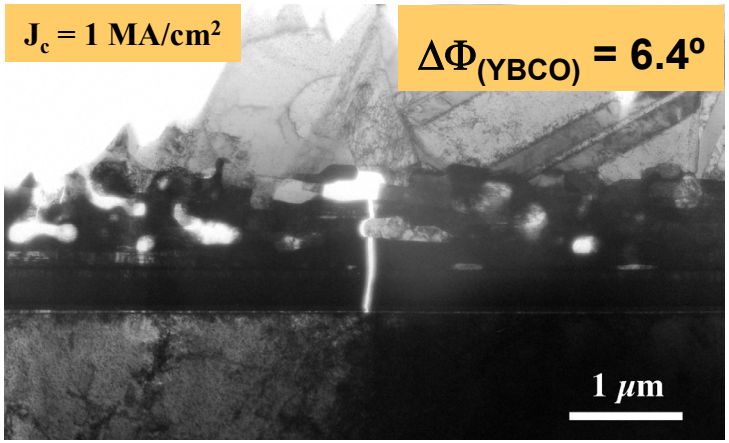


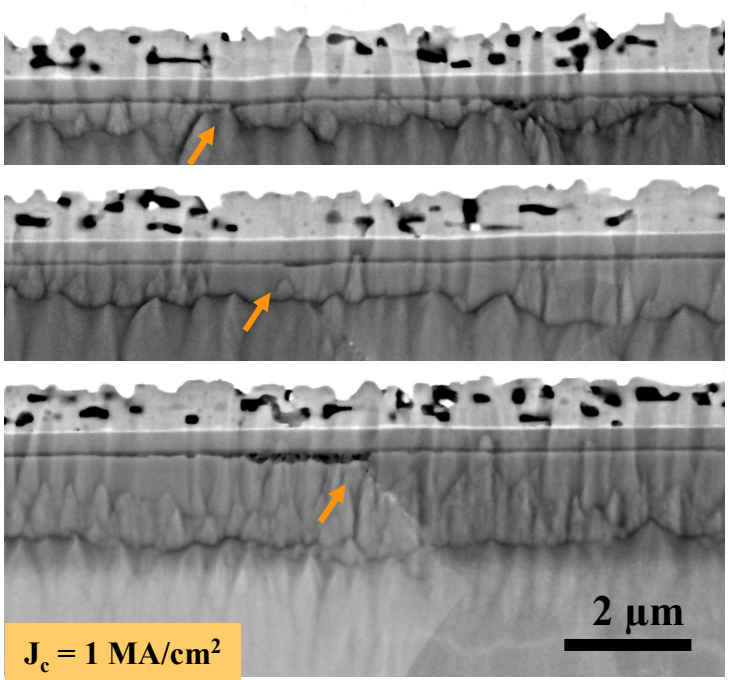
$1/d^{1/2}$ baseline process

Modified process

$(1/d^{1/3})$

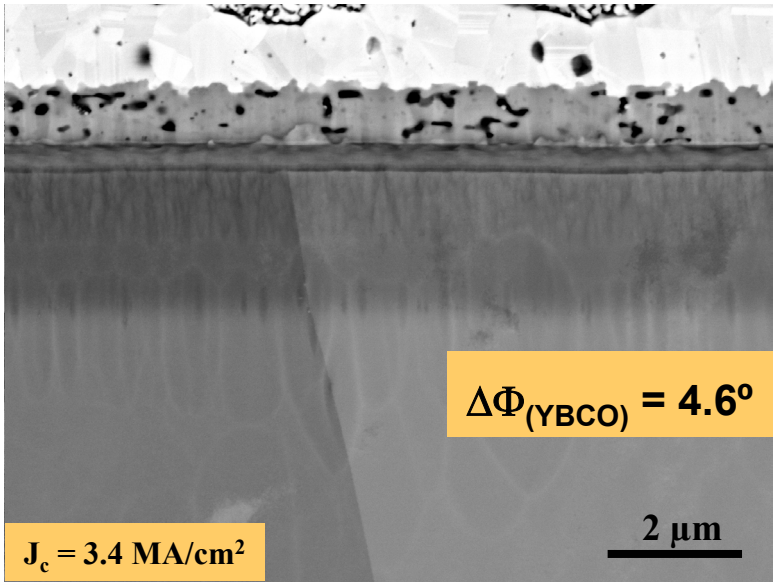
Control of the liquid phases is but one area for I_c improvement as evidenced by AMSC's recent advances in MOD-BaF_2 YBCO films on RABiTS.





- Cracks were observed in early AMSC MOD BaF_2 films.
- Early films also had non-planar surfaces and grain boundary grooving.
- J_c values for 0.8 μm MOD-BaF_2 YBCO films on RABiTS have been raised to the level of 3.4 MA/cm^2.

Process Improvement



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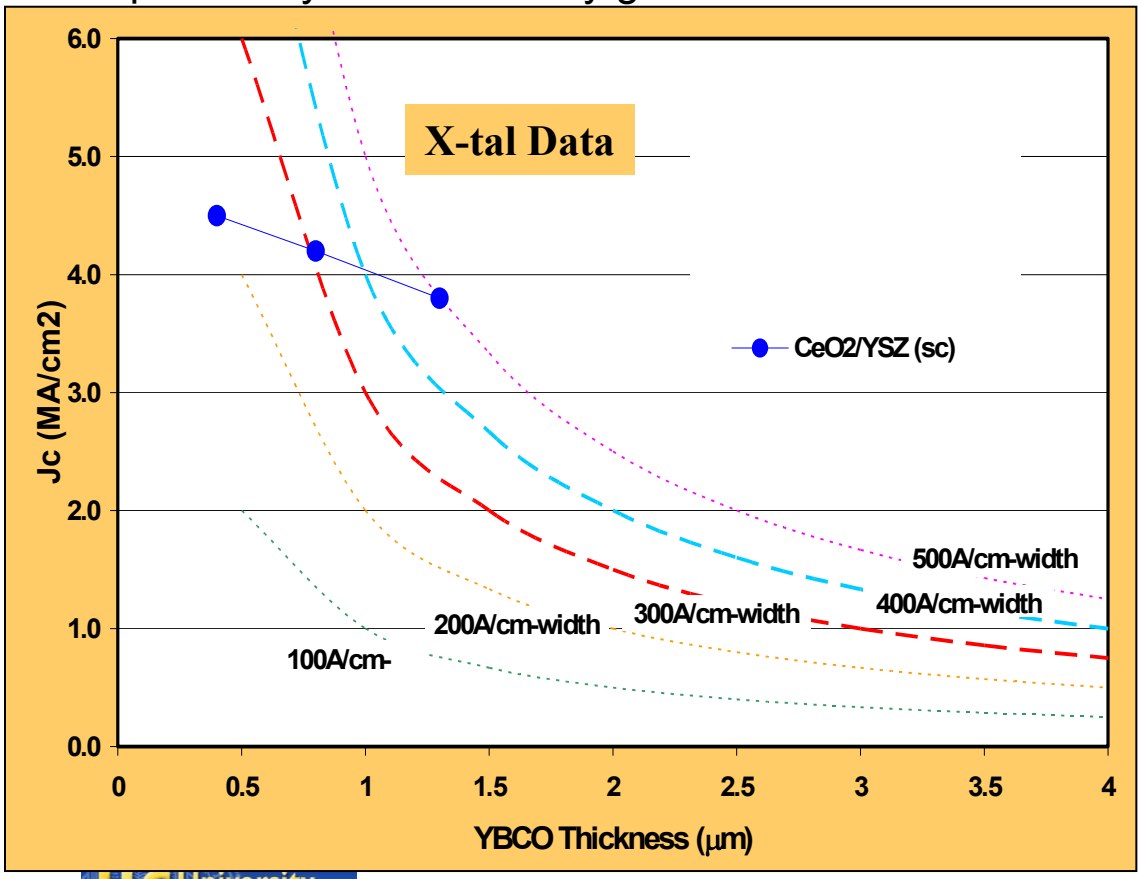
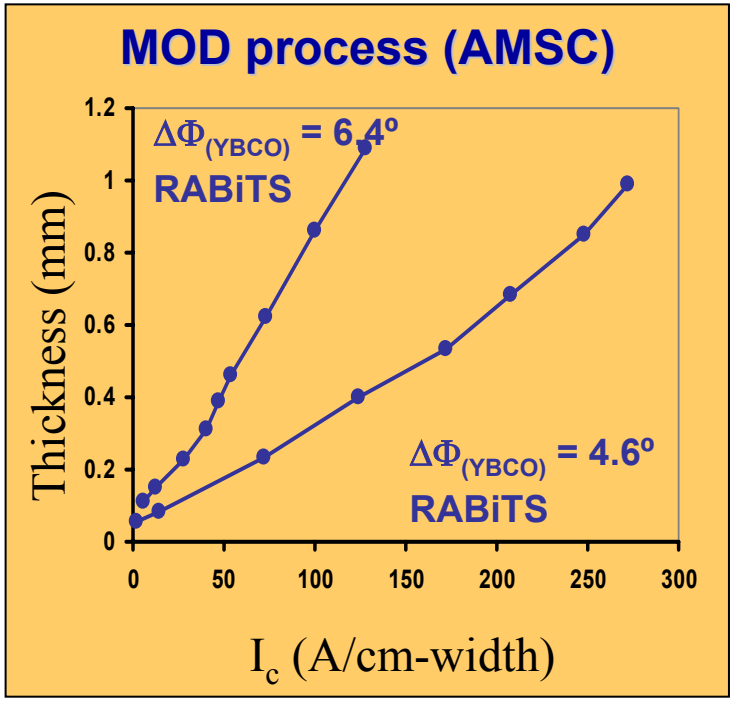
The "porous microstructure" is the structure associated with the high-J_c, ex-situ BaF_2 YBCO films.

- ? Better structure (minimal out-of-plane tilt)
- ? Better pinning by small, faulted YBCO grains
- ? Better flux pinning via increased surface area
- ? Formation of a pseudo multi-layer microstructure; periodicity determined by grain size





MOD BaF_2 YBCO / CeO_2 / SC YSZ

0.4 µm	J_c = 4.4 MA/cm²
0.8 µm	J_c = 4.2 MA/cm²
1.3 µm	J_c = 3.8 Ma/cm²

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FY2003 Results (Scoring Criterion)

- Goal - Determine the dependence of J_c on YBCO film thickness.
- Results
  - Films up 3 μm thick on RABiTS, IBAD-YSZ, and x-tal YSZ
  - Functional dependence of J_c on d is template independent
  - Substrate (texture) controls level of J_c and I_c
  - $J_c(d)$ of PVD-BaF_2 films with "standard" conversion conditions fitted to $J_c = J_\Phi * J(d)$ where J_Φ is texture dependent scaling factor and $J(d) = 1/d^{1/n}$ where n=2
  - TEM correlations show a non-uniform structure in PVD-BaF_2 films suggesting an extrinsic dependence for $J_c(d)$
  - Improved processing of PVD-BaF_2 films leads to higher J_c values and suggests a weaker $J_c(d)$ dependence.
  - $J_c(t)$ dependence of homogeneous, 1 μm thick, MOD-BaF_2 films is almost linear in thickness contradicting the "intrinsic" model for point defect pinning.
  - Absence of dead layers in ex-situ YBCO films.
  - Linear $I_c(t)$ implies higher I_c's for thicker YBCO films.

FY2003 Results (Scoring Criterion)

- Goal –Correlation of the microstructure with the superconducting properties.
- Results
  - ✓ Identified process dependent, laminar growth modes in the ex-situ conversion of BaF_2 films
    - Bi-modal structures
    - "porous microstructure"
  - ✓ Identified current limiting structures in both PVD and MOD BaF_2 films
    - Tilted colonies
    - Cracks, grain boundary discontinuities
    - Bi-modal structure
  - ✓ Showed relationship between the "porous microstructure" and high-J_c films.
    - MOD BaF_2 film J_c = 3.4 MA/cm^2; 270 A/cm-width
    - PVD BaF_2 film J_c = 1.7 MA/cm^2; 228 A/cm-width
  - ✓ Constant $J_c(t)$ typically observed from ion-milling, but doesn't necessarily reflect a homogenous microstructure.

FY2003 Results (Scoring Criterion)

- Goal - Understand the BaF_2 conversion process and develop methodologies for process improvement.
- Results
  - ✓ Identified the role of liquid phases in microstructural development
  - ✓ Showed an early phase evolution of $YCuO_x$ and Ba-O-F in thin films; deviations occur in the conversion of thicker films.
  - ✓ Improved the PVD-BaF_2 processing with microstructural and ion milling J_c information.
  - ✓ Faster conversion speeds obtained (3-7Å/s)
  - ✓ Showed that the "porous microstructure" can be obtained with both MOD-BaF_2 and PVD-BaF_2.
  - ✓ Showed that the size of the YBCO grains is independent of the substrate type (process dependent).

FY2003 Results (Scoring Criterion)

- Goal - Produce high current YBCO coated conductors with ex-situ conversion of PVD-BaF_2 based films.
- Results
  - ✓ Showed that PVD-BaF_2 ex-situ conversions can produce the MOD-BaF_2, high-J_c "porous microstructure."
  - ✓ Exceeded 200 A/cm-width for PVD-BaF_2 films on both IBAD YSZ and RABiTS.
    - 1.4 μm 228 A/cm-width ("champion")
    - 2.5 μm 233 A/cm-width (modified process)
  - ✓ Obtained J_c = 2 MA/cm^2 for thin PVD-BaF_2 film on an IBAD MgO template.

FY2003 Performance (Scoring Criterion)

- Goal - Determine the dependence of J_c on YBCO film thickness.
- Performance
  - ✓ Correlated the thickness dependence of J_c with spatially correlated, process dependent microstructure
    - -variable thickness films
    - -through-thickness J_c by ion milling
  - ✓ Intrinsic and extrinsic issues pertaining to $J_c(d)$ were identified

- Goal –Correlation of the microstructure with the superconducting properties.
- Performance
  - ✓ Identified process dependent laminar growth modes in the ex-situ conversion of BaF_2 films
  - ✓ Compared spatially correlated microstructural data with transport and ion milling data to understand potential current limiting mechanisms and to determine an optimal structure for ex-situ films.

FY2003 Performance (Scoring Criterion)

- Goal - Understand the BaF_2 conversion process and develop methodologies for process improvement.
- Performance
  - ✓ Started the investigation of the role of liquid phases in microstructural development.
  - ✓ Developed improved PVD-BaF_2 processing routes using the microstructural and ion milling J_c information.

- Goal - Produce high current YBCO coated conductors with ex-situ conversion of PVD-BaF_2 based films.
- Performance
  - ✓ Exceeded 200 A/cm-width for PVD-BaF_2 films on both IBAD YSZ and RABiTS.
  - ✓ Obtained J_c = 2 MA/cm^2 for thin PVD-BaF_2 film on an IBAD MgO template.
  - X Unsuccessful in optimizing the conversion process for thick PVD-BaF_2 films on IBAD MgO.

FY2004 Plans (Scoring Criterion)

- Determine by how much the established baseline $J_c(d)$ can be improved upon with an optimized PVD-BaF_2 process.
  - ✓ Produce films on single crystal substrates up to 5 μm with optimized process.
  - ✓ Spatially correlate the through-thickness J_c determined by ion milling with the microstructure for films grown with the modified process
- Investigate the initial stages of liquid phase formation and YBCO precipitation at different rates of the conversion process.
  - ✓ Determine the liquid phase composition
  - ✓ Determine the reaction sequence to form Y-123.
  - ✓ Obtain 10Å/s growth rate with PVD BaF_2

FY2004 Plans (Scoring Criterion)

- Develop a compatible buffer layer architecture for the PVD BaF_2 process on the IBAD-MgO template.
  - ✓ Investigate the morphology of intermediate buffer layers and propagation of epitaxy and roughness through the buffer layer stack
  - ✓ Research to be led by LANL, performed at LANL and ORNL
  - ✓ Grow YBCO films of various thickness on qualified buffer layer stacks

- Correlate the microstructure and through-thickness J_c on partially and fully converted MOD BaF_2 YBCO films and compare the results to PVD BaF_2 YBCO films.

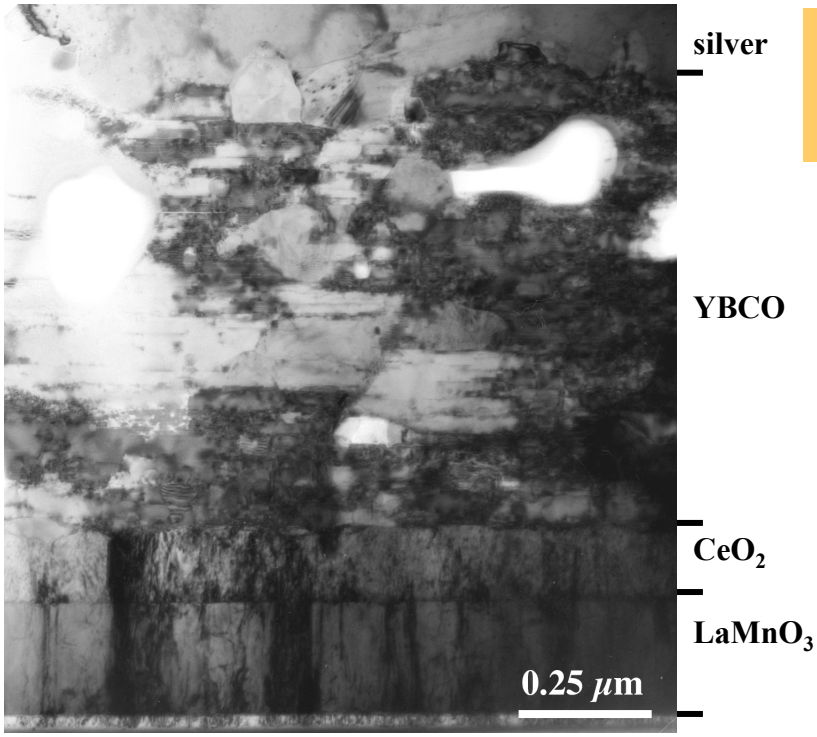
- Increase I_c in PVD BaF_2 YBCO films on CC substrates to values > 400 A/cm-width (77 K).

Research Integration (Scoring Criterion)

- This research group represents an synergistic effort between two national labs, a leading university research group, and an industry leader in coated conductor research and development.
- Each partner brings unique expertise to the collaboration.
- Focused support of American Superconductor in its effort to commercialize coated conductors using the ex-situ YBCO process.
- Multiple interactions at the individual level further leverage the research
  - ✓ NIST-Gaithersburg (phase development) and NIST-Boulder (strain effects)
  - ✓ ANL (Raman spectroscopy)
  - ✓ SNL (Buffer layers)
  - ✓ Collaboration / Information exchange with Stanford University and other participants of the MURI project
  - ✓ Institute de Ciencia de Materials de Barcelona, Spain (granularity effects)
  - ✓ Kyushu University, Japan ($J_c(H,T)$)

High-J_c, I_c films were obtained on IBAD MgO by MOD-BaF_2 at AMSC; PVD-BaF_2 *ex-situ* processing has not yet been optimized for reproducible results.

- The "single-crystal-like" textures obtained in IBAD MgO templates provides a compelling reason to continue working with them. (See Paul Arendt and Steve Foltyn-Friday 8:30 a.m.)
- The YBCO grain size is the same on all substrates. (process, not substrate dependent).



AMSC YBCO / ORNL $LaMnO_3$ / LANL IBAD MgO
MOD-BaF_2 YBCO / CeO_2 / $LaMnO_3$ / IBAD MgO
t(YBCO) = 0.89 µm -- J_c(170A/cm-width, 77K) = 1.9 MA/cm^2

PVD-BaF_2 results with MgO and IBAD MgO

PVD-BaF_2 YBCO / $LaMnO_3$ / single crystal MgO
t(YBCO) = 0.3 µm; J_c (77K, SF) = 4.4 MA/cm^2

PVD-BaF_2 YBCO / $LaMnO_3$ / IBAD MgO
t(YBCO) = 0.3 µm; J_c (77K, SF) = 2.2 MA/cm^2