# Pinning Properties and Thickness Dependence of $J_c$ in *ex-situ* PVD-$BaF_2$ Films

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# Overview

- Vortex pinning
  - controlled variations in the angular dependence of $J_c$

- Thickness dependence of $J_c$
  - role of meandering GBs

Study of PVD-$BaF_2$ YBCO and comparison to MOD reveals the common characteristics of *ex-situ* processes

- WDG enables this kind of study by broad expertise in different processing and coordinated effort
- Flexibility of PVD-$BaF_2$ technique enables study of a broader range of thickness

# ORNL *ex-situ* PVD-$BaF_2$ Process

- precursors deposited by e-beam evaporation (Y, $BaF_2$, Cu sources)
  - arbitrary thickness in range 30 nm – 3 µm

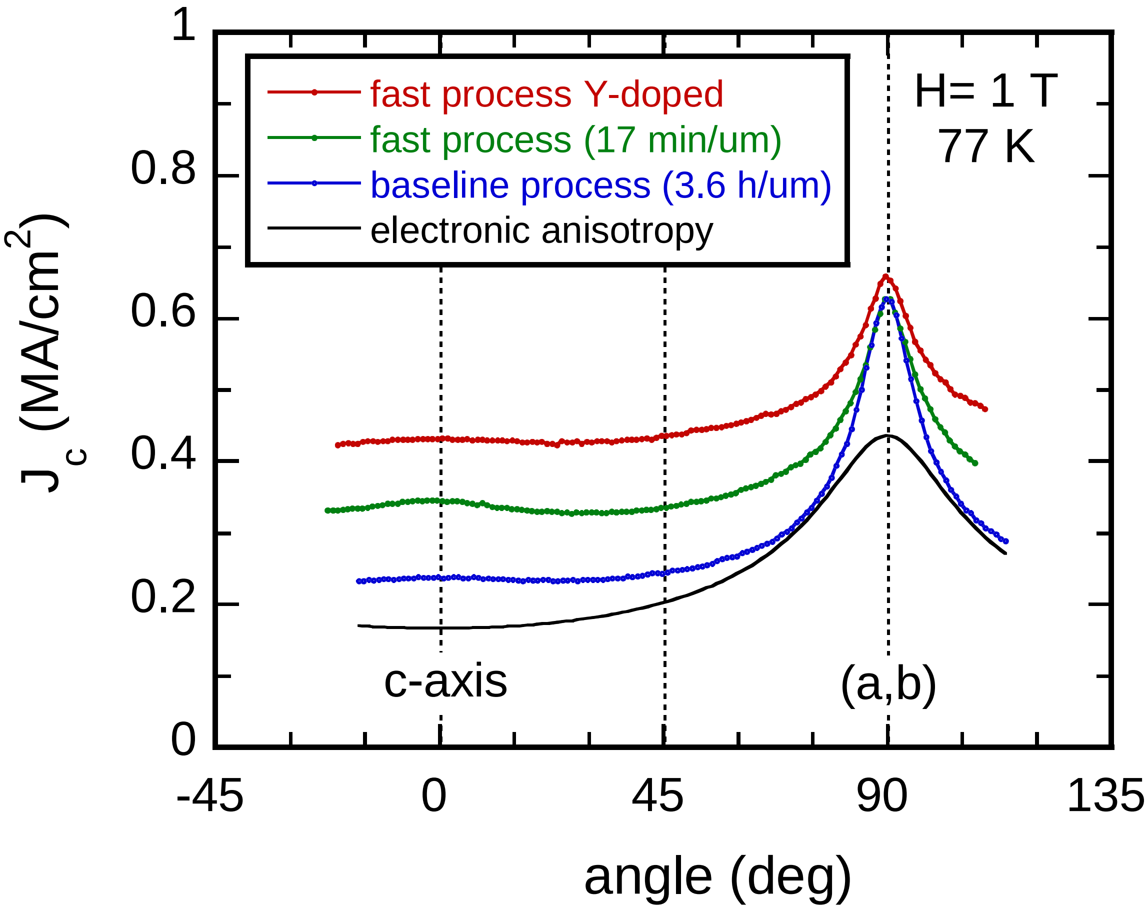
- *ex-situ* conversion in flowing gases at 1.0 atm total pressure

- alternative processes developed to modify microstructure and properties
  - “baseline” (conversion at ~ 1 Å/s)
  - “fast” (5-15 Å/s)
  - Y-rich compositions for enhanced pinning (H||c)
  - “alternative” processes (pinning modification)

- $I_c$ values on RABiTS are comparable to AMSC-MOD YBCO
  - best values ~ 400 A/cm at 77 K, sf.

# FY2004: Fast-processed Films Exhibit Strong Flux Pinning, Reduced Field-angle Anisotropy $J_c^{max} / J_c^{min}$

- pinning is enhanced in orientations away from (a,b)—no peak along c
- Y-doping (Y-rich precursors) further enhances $J_c$, pinning




YBCO: 0.7 μm

| sample | $J_c(0)$ ($MA/cm^2$) | ratio |
|---|---|---|
| standard | 1.6 | 2.6 |
| fast | 2.3 | 1.9 |
| fast-doped | 2.5 | 1.5 |
| electronic ($\gamma$ = 5) | | 2.6 |

$J_c^{max} / J_c^{min}$

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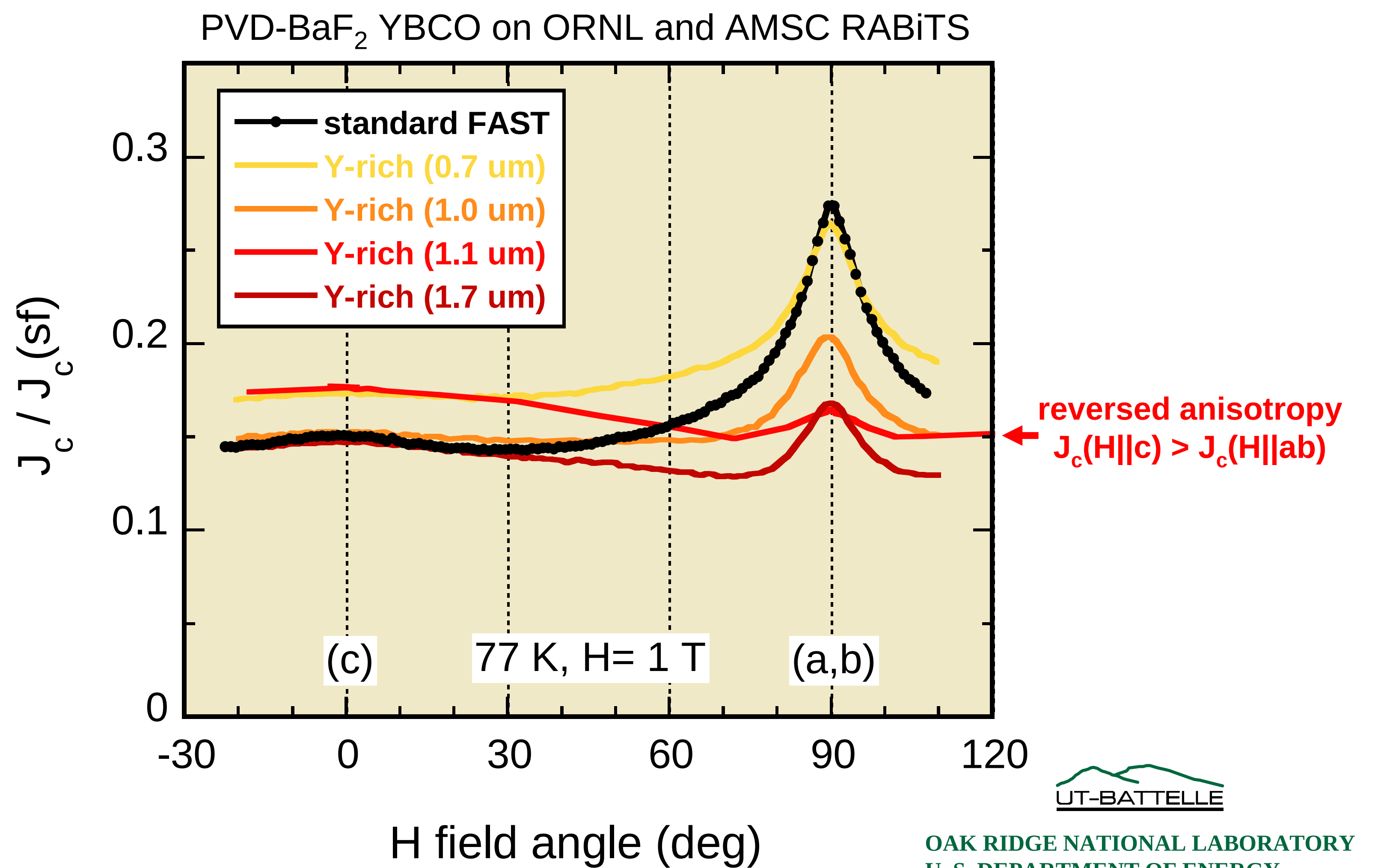
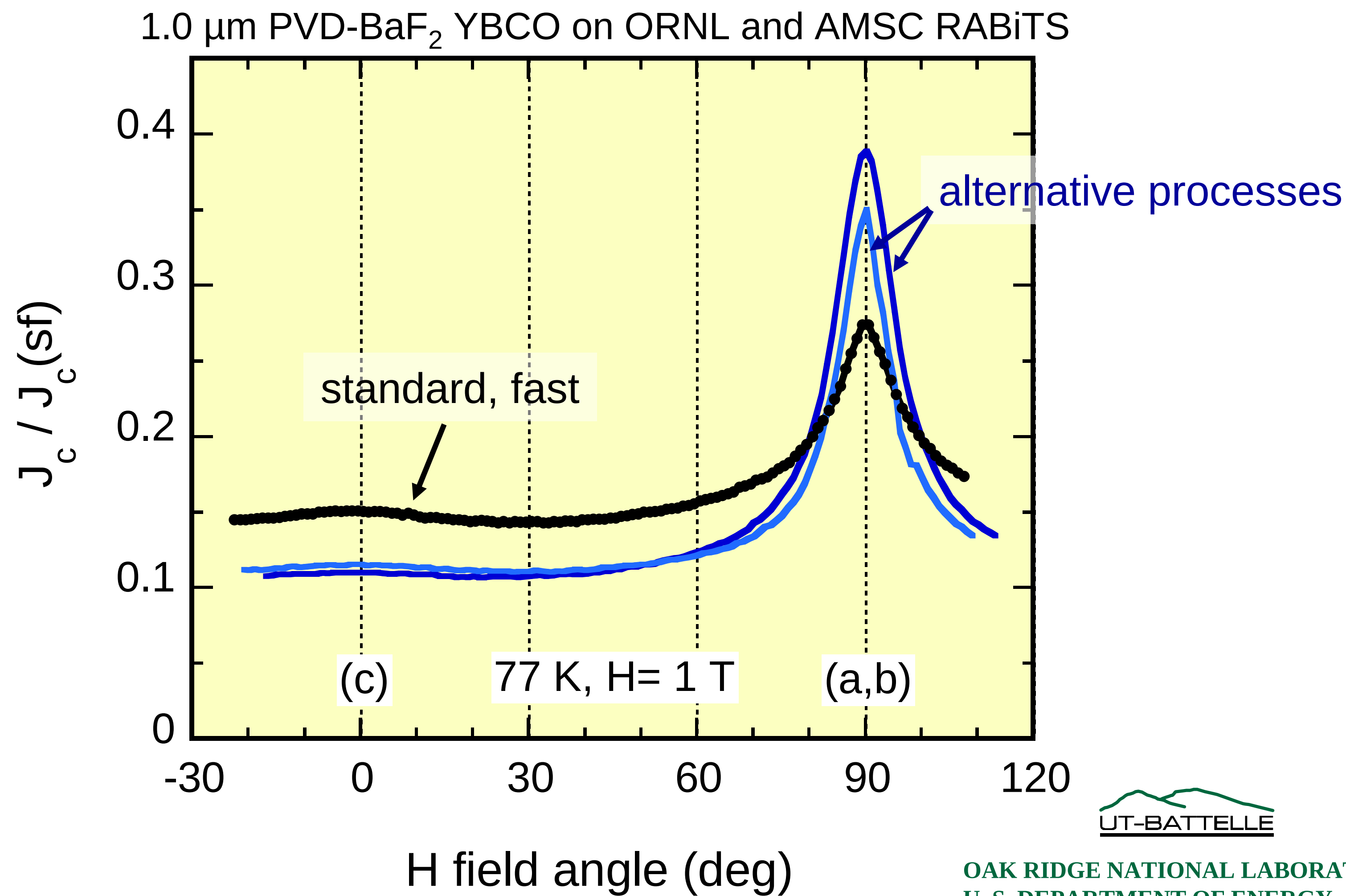
# FY2005: Y-doping Increases $J_c(H||c)$, $J_c(sf)$—Reduces $J_c(H||ab)$

- effects become stronger with increasing film thickness
- similar to MOD processed films: nanodot doping, HTOA



# Opposite Effects May Be Induced by Process Modifications

- faster $J_c$ drop-off for H||c, enhanced pinning for H||(ab)
- large (ab) peak is similar to baseline MOD films

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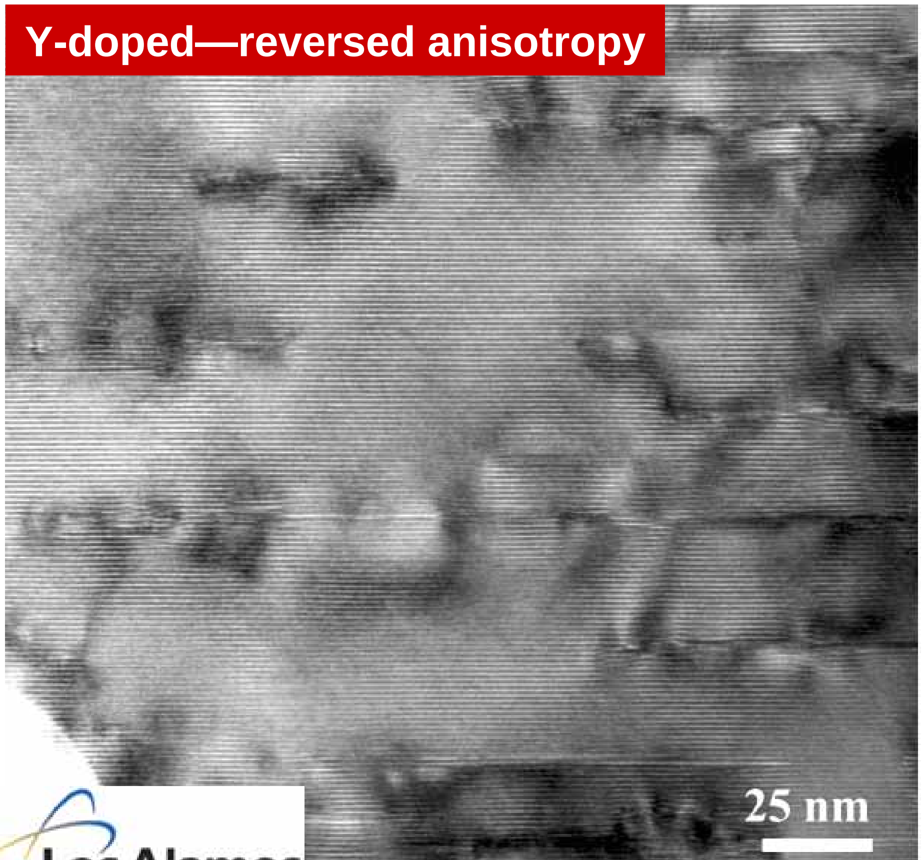
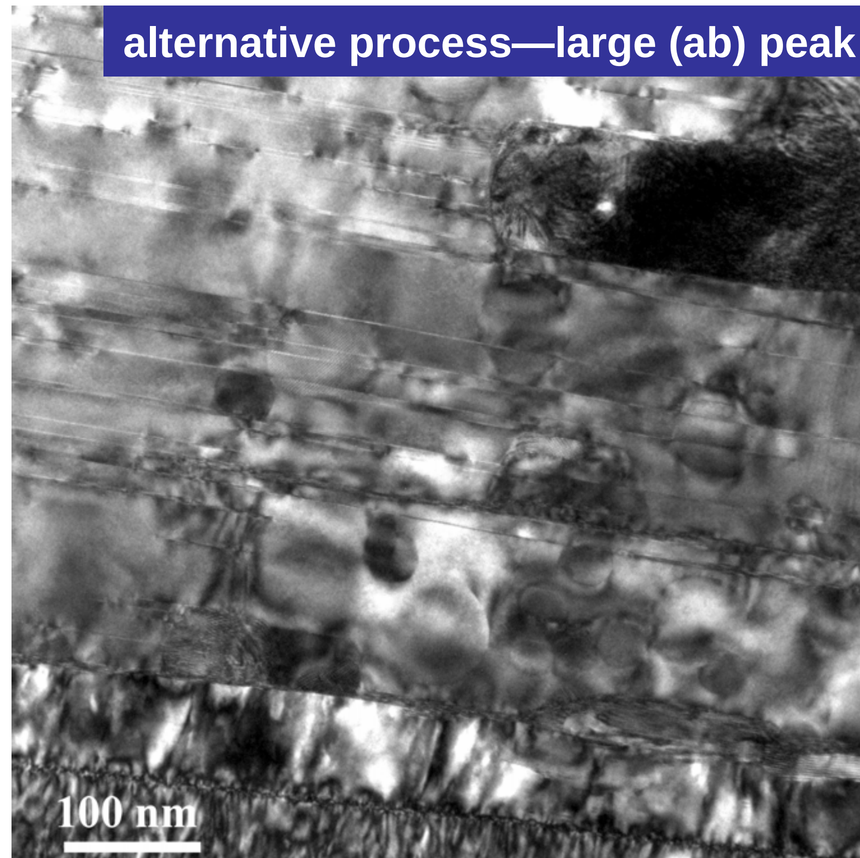
# TEM Reveals Different Defect Structures of Y-doped vis-à-vis Alternative-processed PVD-$BaF_2$ YBCO Films

- Y-rich precipitates
- short planar intergrowths terminated with strain fields ⊥ substrate

- reduced density of Y-rich precipitates
- extended planar intergrowths (medium density)

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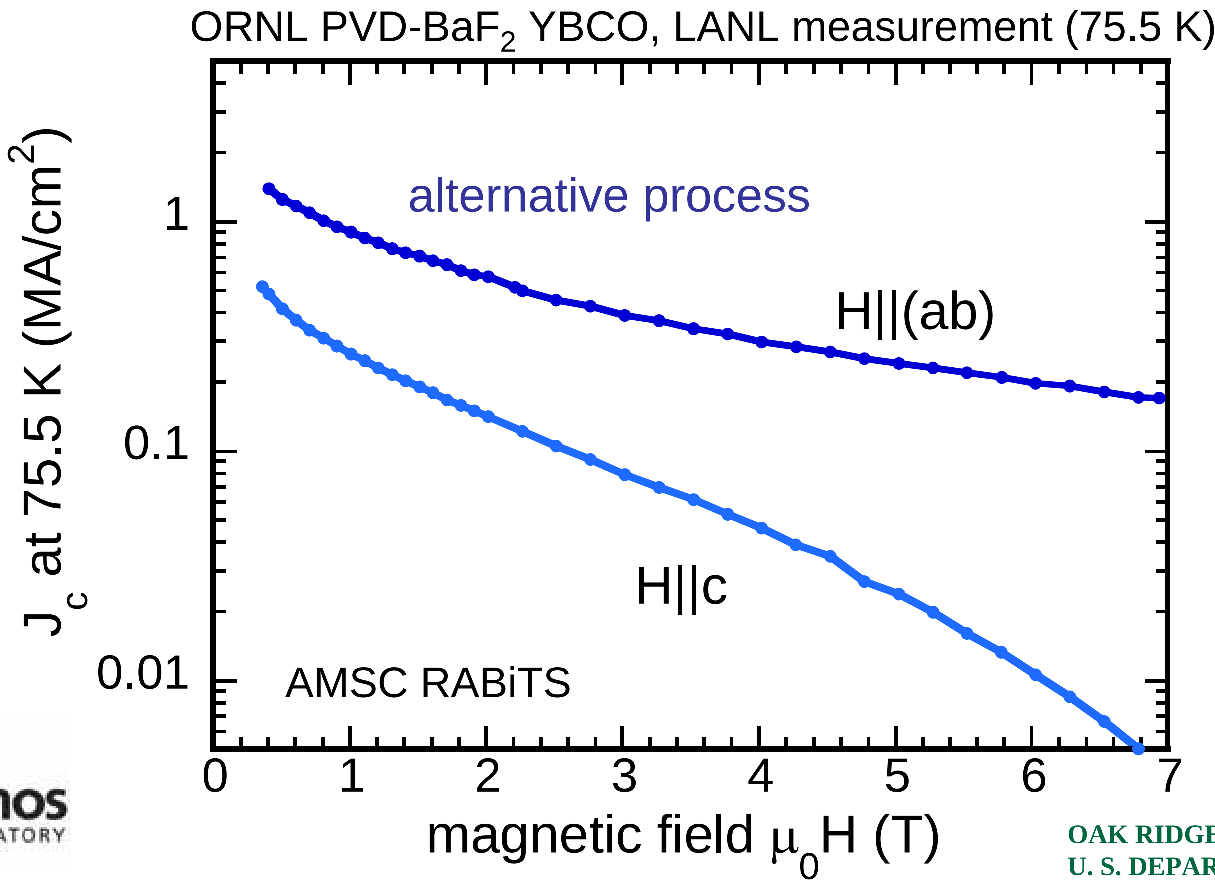
Terry Holesinger

# $J_c$ trends in Y-rich PVD-$BaF_2$ YBCO on RABiTS

- $J_c$(H||ab) drops while $J_c$(H||c) is enhanced—as in MOD YBCO
- note reversed anisotropy for H < 3.5 T

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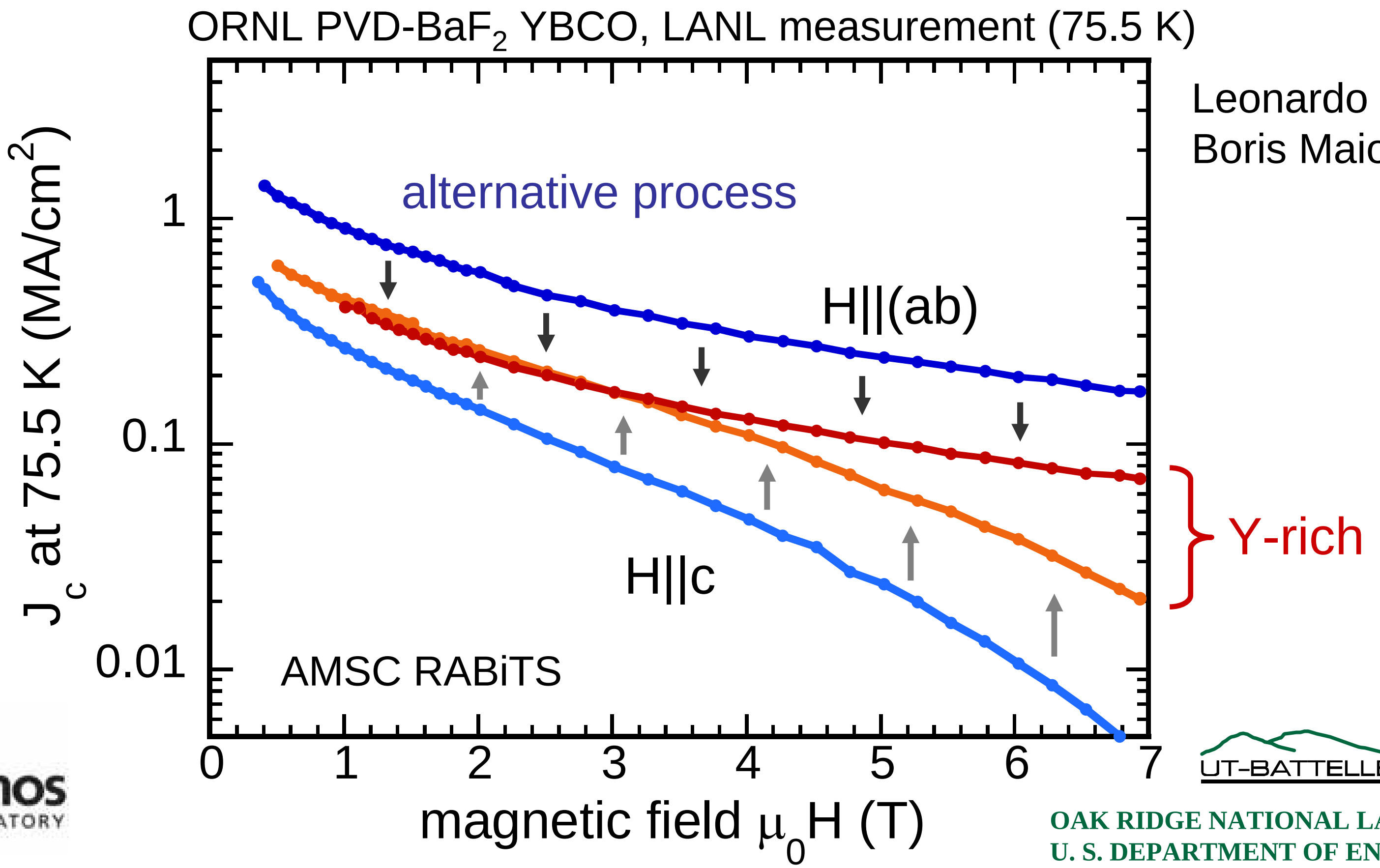
**Strong pinning for H||c resembling effects from correlated defects is not prevented by laminar growth mode in *ex situ* YBCO**

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# Summary: Pinning

- Angular dependence of $J_c$ in *ex-situ* PVD-$BaF_2$ films is influenced by the laminar microstructure—similar to MOD YBCO
  - planar intergrowths along (ab) direction
  - nano-scale precipitates

- Variations in $J_c(\theta)$ are enabled by process modifications and Y doping
  - Y-rich precipitates:
    - enhance pinning for H||c and related ⊥ orientations
    - reduce (ab) pinning by interruption or lowering planar defect density
  - process modifications can restore pinning along (ab) by increasing the length and density of Cu-rich planar defects (124 phase)

➢ Potential for engineering of $J_c(\theta)$ has been demonstrated

Comparison between MOD and PVD-$BaF_2$ processes within the WDG identifies general trends, accelerates path towards optimization

# Thickness dependence of $J_c$

# role of meandering GBs

# Background and Motivation

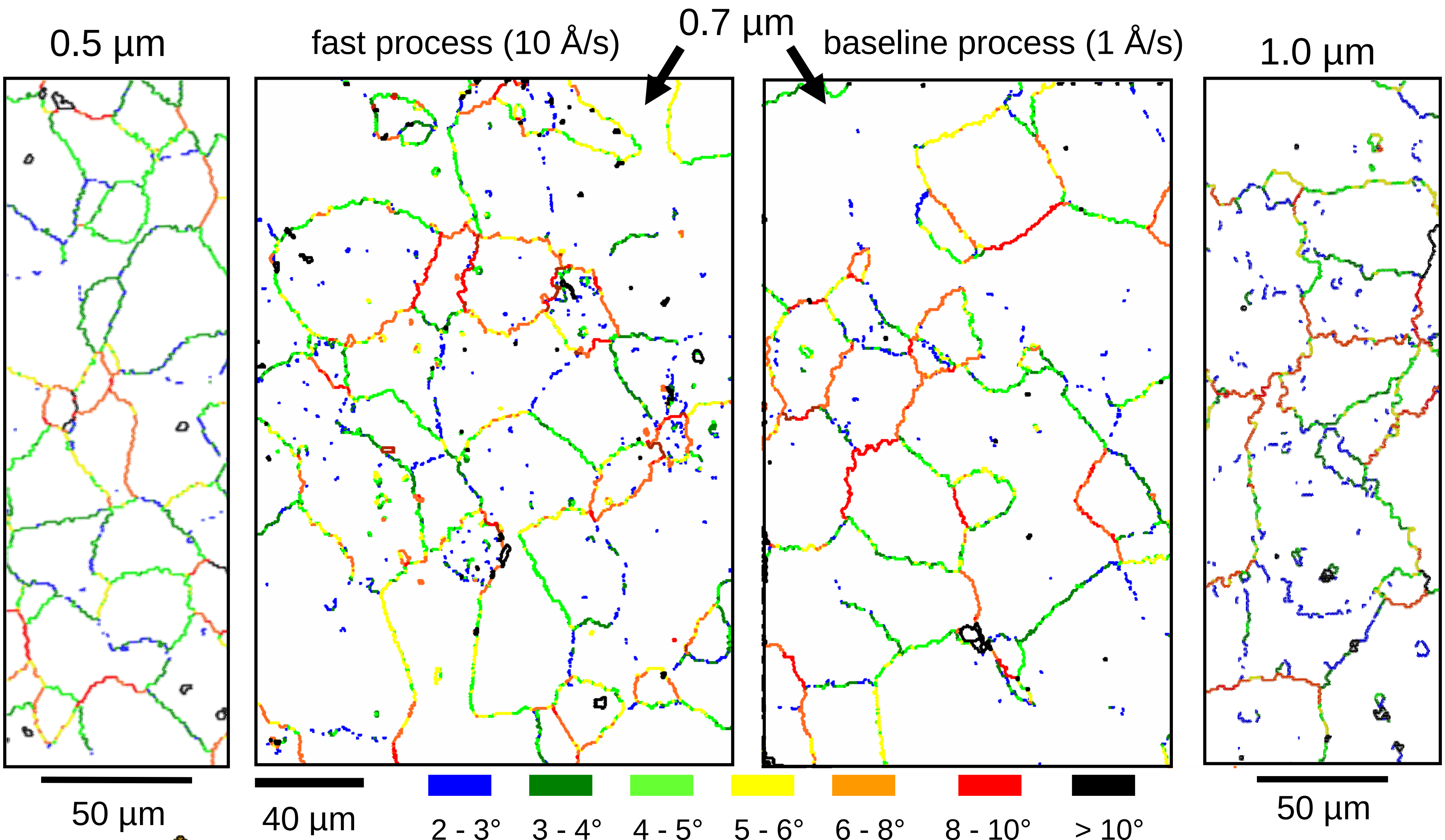
- meandering results from laminar growth mode of $BaF_2$ *ex-situ* films
- fast lateral growth leads to complete or partial GB overgrowth
  - possibly mediated by transient liquid phase(s)
- GB overgrowth depends on the YBCO (precursor) thickness:
  - thin films (< 0.5 µm) → YBCO GBs in registry with RABITS GBs
  - thick films ( > 2 µm) → disconnect between YBCO and substrate GBs
  - intermediate (1 µm) → meandering / tilted GBs

➢ What is the role of GB meandering on the thickness dependence of $J_c$?

➢ Does GB meandering contribute to high $J_c$ in 1 µm *ex-situ* YBCO?

# Strongest Parameter Controlling Meandering is YBCO Thickness

- no significant dependence on *ex-situ* conversion rate

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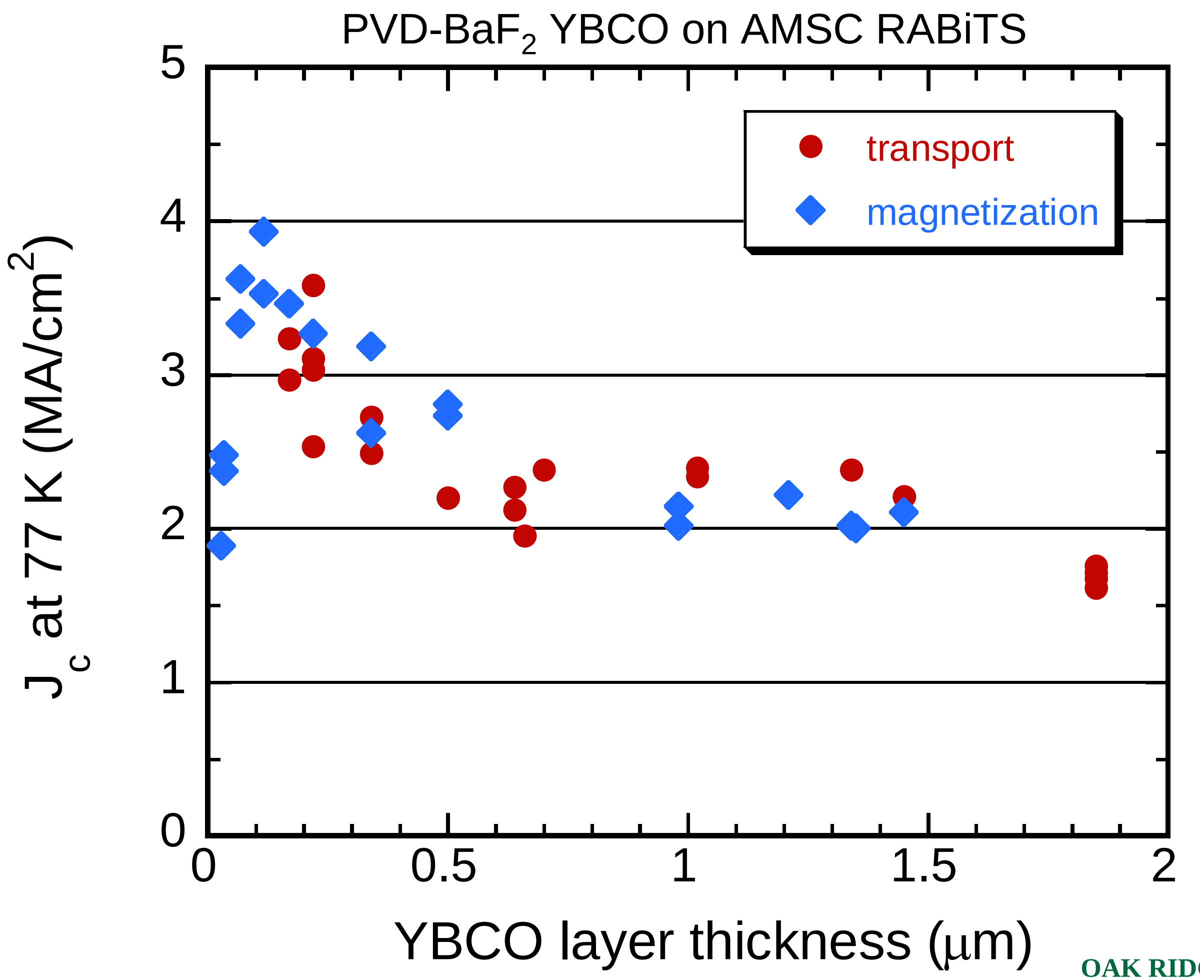
# $J_c$ as a Function of Thickness Shows Different Behavior Depending on Thickness Range

- constant $J_c$ in the range 0.5-1.5 µm

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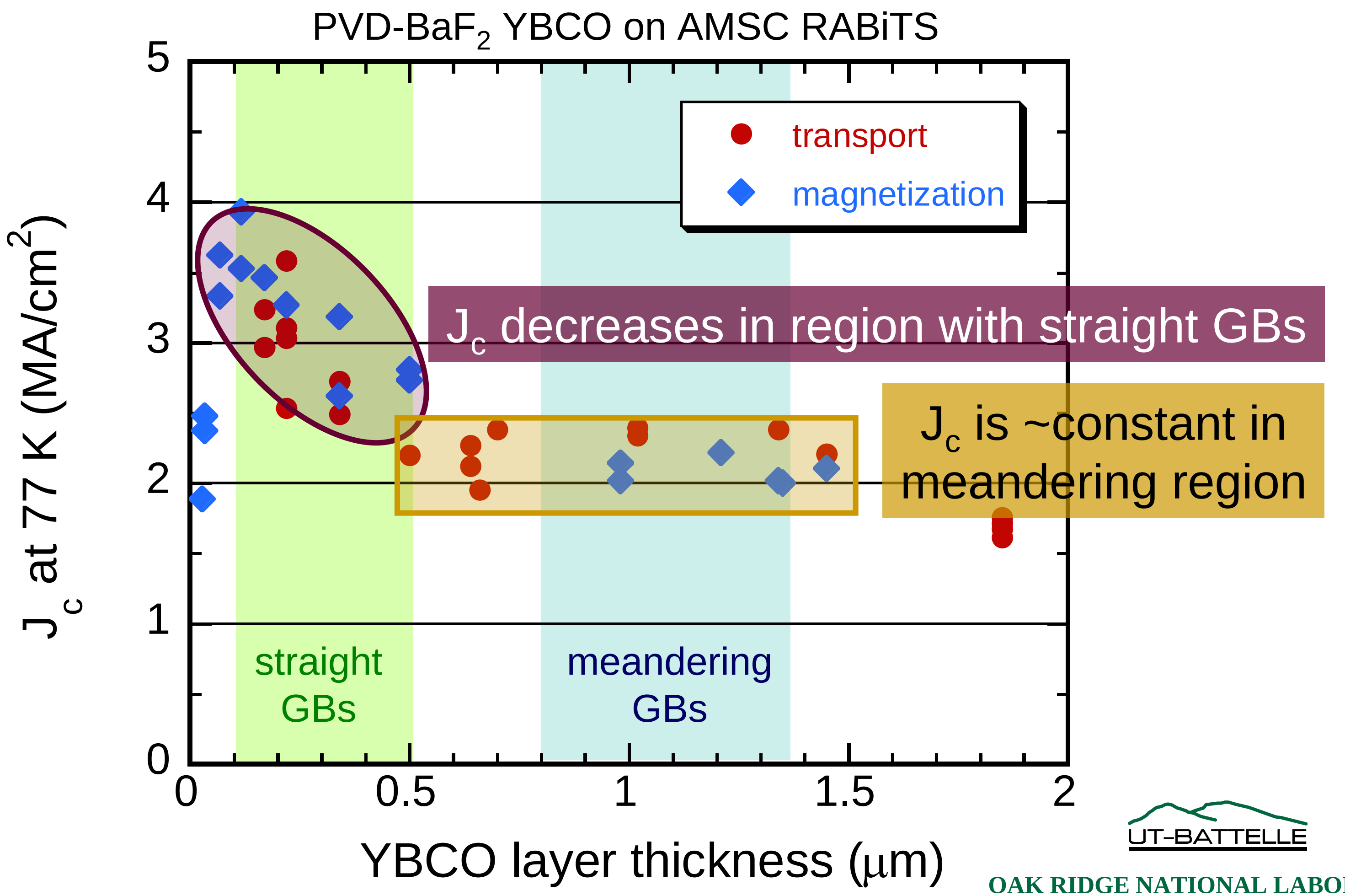
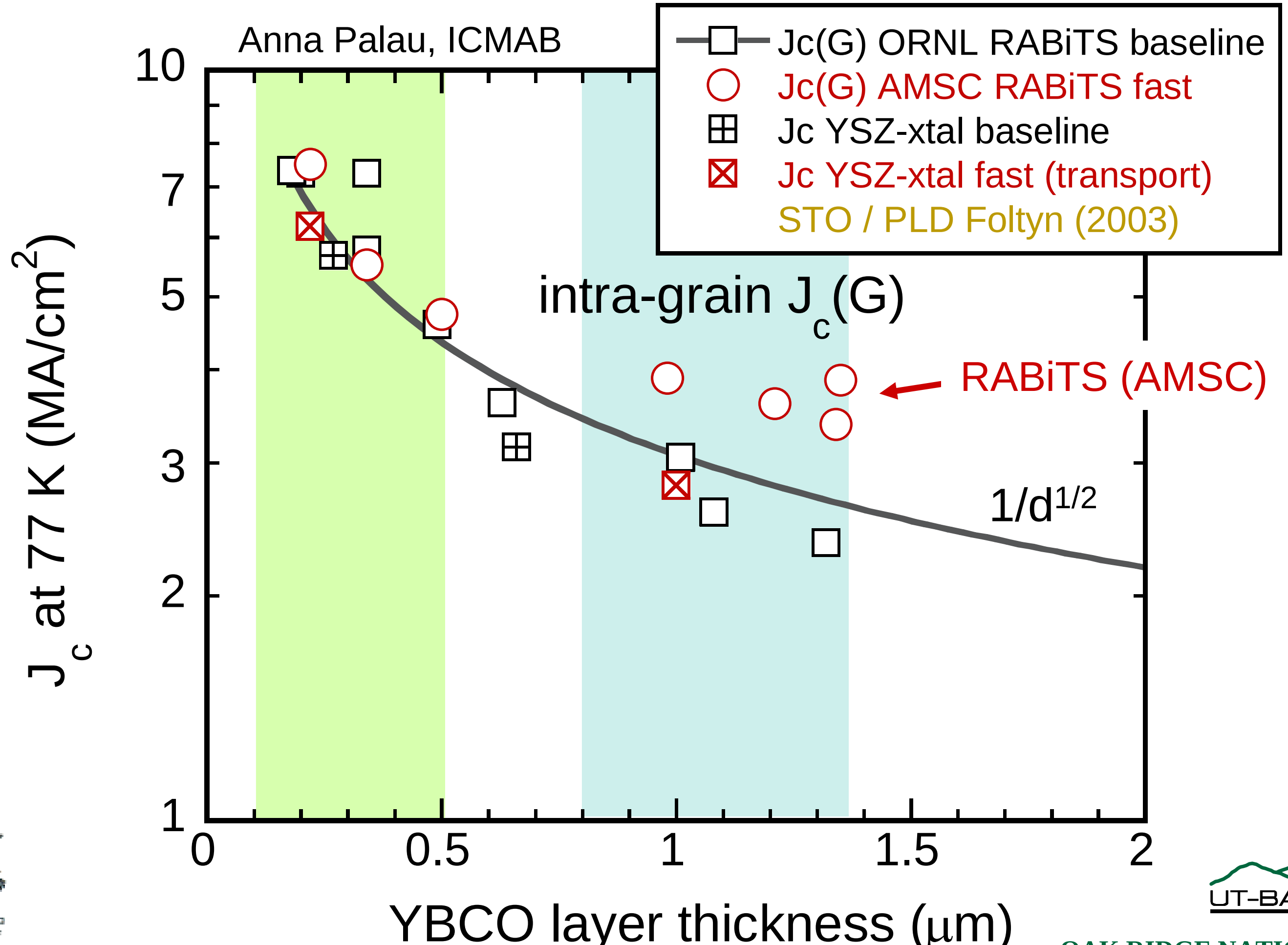
# $J_c$ as a Function of Thickness Shows Different Behavior Depending on Thickness Range

Is flattening of $J_c$ with thickness due to the meandering effect?



# Intra-grain $J_c$(G) Provides a Reference Point for Evaluating Role of Meandering as a Function of Film Thickness

$J_c$(G) of PVD-$BaF_2$ *ex-situ* YBCO on RABiTS determined by a magnetometer technique developed at ICMAB, Spain

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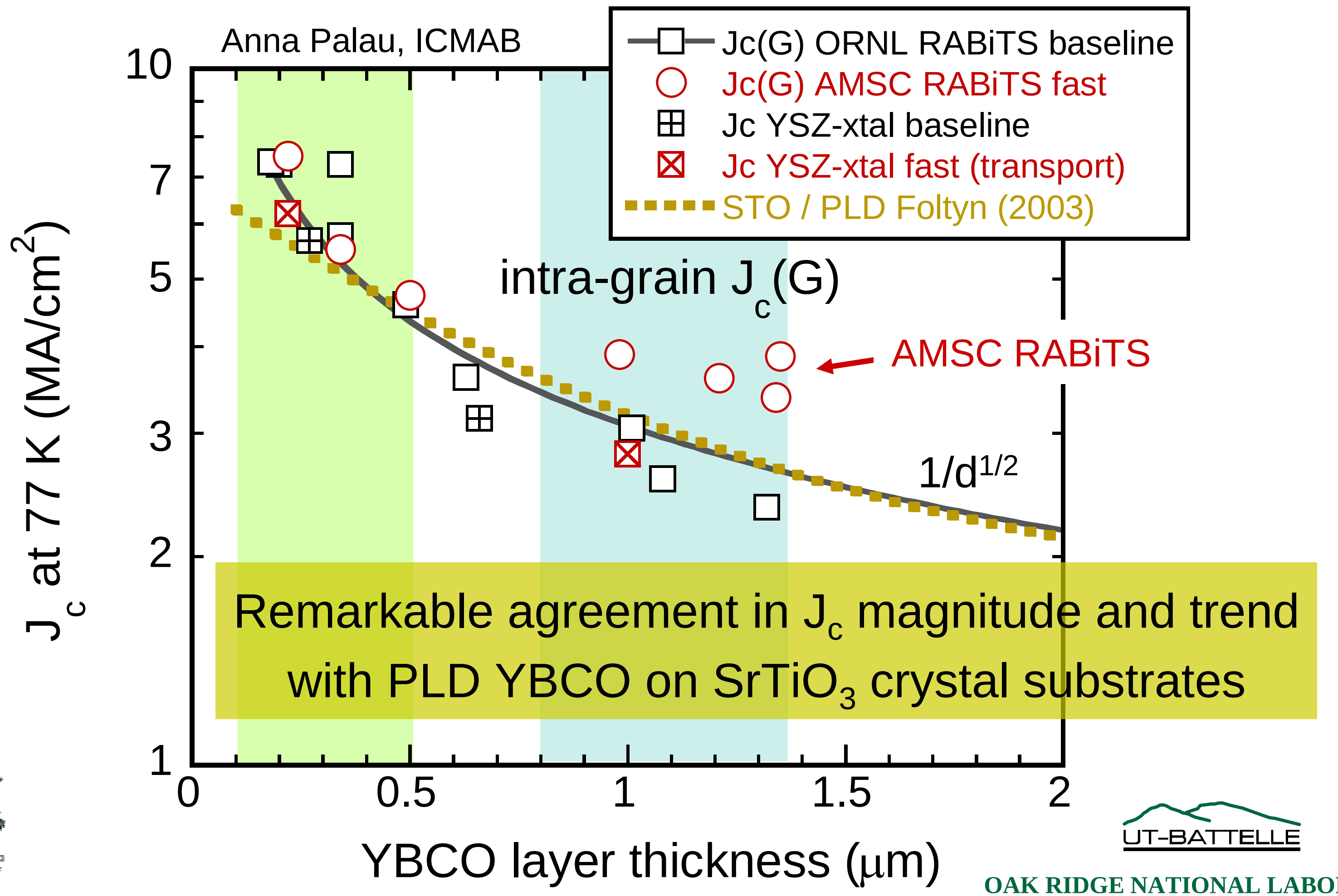


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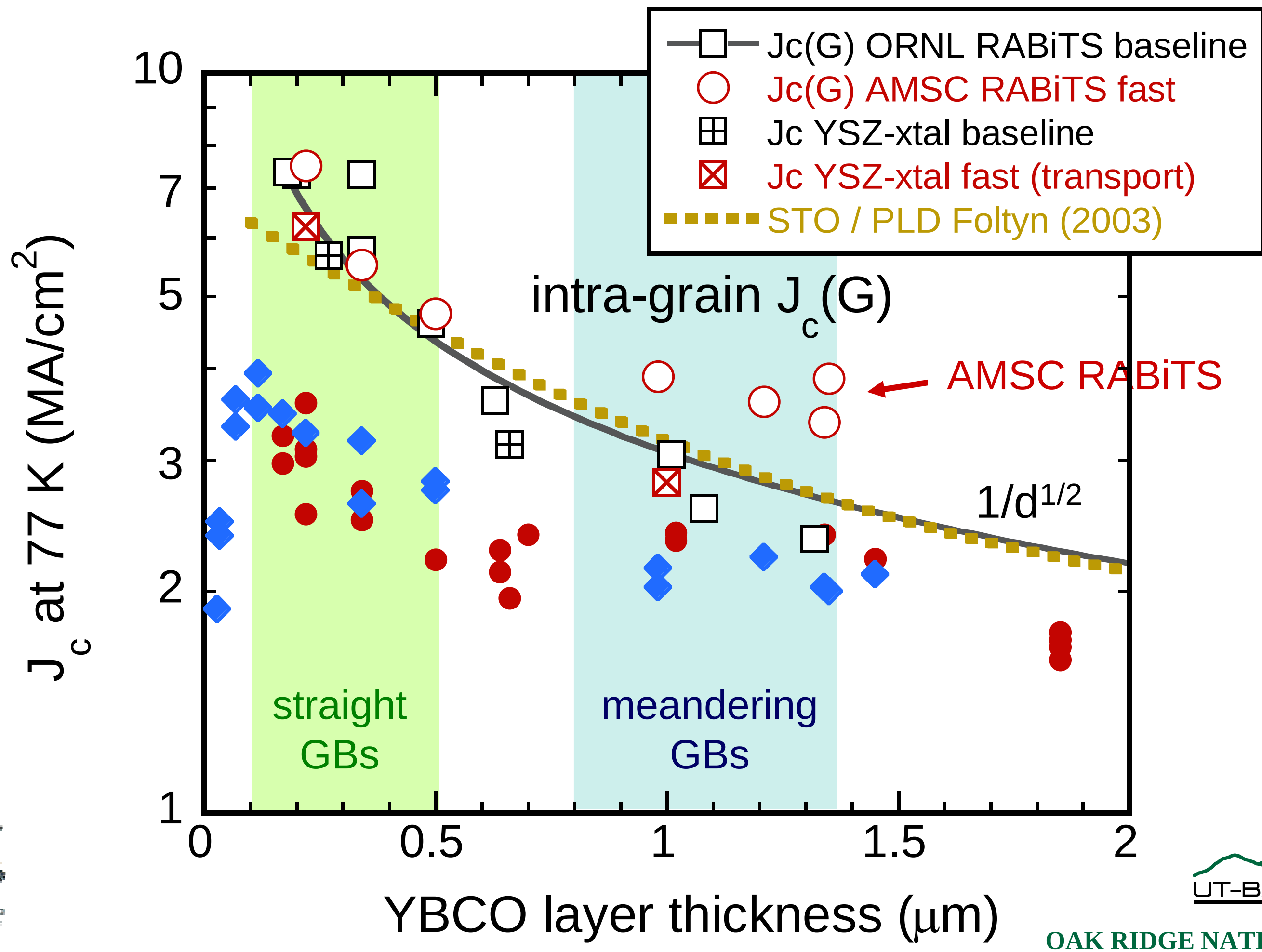
# Based on assumed scaling of $J_c$(GB) to $J_c$(G) for straight GBs, the role of meandering may be quantified

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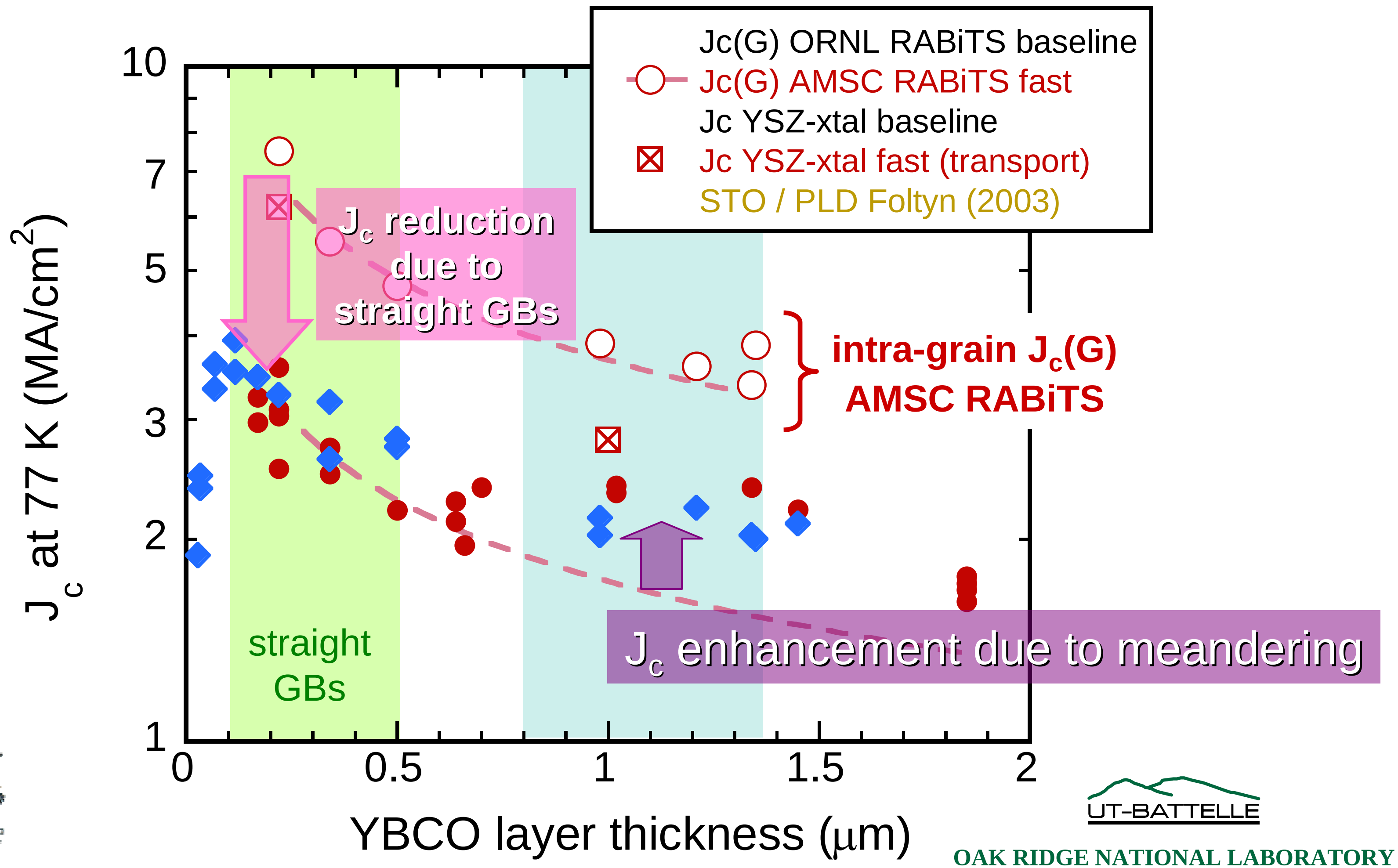
# Based on assumed scaling of $J_c$(GB) to $J_c$(G) for straight GBs, the role of meandering may be quantified

GB meandering enhances $J_c$ ~1.5x in the range 1-1.5 µm

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# Summary: thickness dependence

- intra-grain and inter-grain $J_c$'s for PVD-$BaF_2$ YBCO on RABiTS compared as a function of thickness

- magnitude and thickness dependence of the intra-grain $J_c$(G) agrees with reported data for PLD YBCO on STO crystal substrates

- results support hypothesis that GB meandering can substantially (~1.5x) enhance $J_c$ in 1.0-1.5 um thick PVD-$BaF_2$ *ex-situ* YBCO.