RABiTS Substrates Research & Development

OAK RIDGE NATIONAL LABORATORY

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FY 2003 EE/RE Funding: $700K: 2.0 FTE Staff
2.0 FTE Post-Doctoral Fellows

Relevance to DOE Superconductivity Program and technical targets

"R&D Needs/Knowledge gaps" identified in the DOE Coated Conductor Technology Development Roadmap *and* addressed in this project:

- Understanding of microstructural factors affecting critical current density
- Develop rolling technology and tools to produce long and wide substrates
- Understanding interfaces between epitaxial layers
- Non-Ni substrate development
- Grain boundary studies
- Uniformity of J_c in long tapes
- Development of methods to characterize physical properties

Overall Objective: To explore fundamental issues relating to the RABiTS process and to advance the technology in this area to enable commercial fabrication of YBCO/RABiTS by our industrial partners

Approach: Address important issues as identified by our industrial partners and the broader technical community relating to the two main steps of the RABiTS process – biaxially textured metal fabrication and buffer layer deposition

Specific Objectives/Milestones:

- Develop methodology for characterization of texture in RABiTS type substrates (what is the true phi versus measured phi?)
- Correlate texture and critical current - are present J_c levels primarily limited by degree of texture attained in the substrate?
- Fabricate long and wide metal/alloy substrates with homogeneous textures
- Fabricate a more robust, oxidation-resistant buffer stack on RABiTS
- Develop Cu-based RABiTS: Achieve a high degree of texture in Cu, deposit high quality epitaxial buffer layers and YBCO
- Address outstanding percolation issues in long lengths of YBCO on RABiTS
- Experimentally verify the developed percolation models

Industrial Collaborators

- American Superconductor Corporation (AMSC)
  - M. Rupich, D. Verebelyi, C. Thieme, U. Schoop, X. Li, T. Kodenkandath, J. Scudiere
- MicroCoating Technologies (MCT)
  - Todd Polley, Shara S. Shoup, Marvis White
- Oxford Superconducting Technology (OST) - Ken Marken
- Neocera - K. Harshavardhan
- SuperPower - V. Selvamanickam, J. Reeves
- MetOx - L. Castellani, L. Fritzemeier
- Ametek Corporation - C. Scorey, J. Easley
- Hamilton Precision Metals – M. Robinson, R. Crawford

National Laboratory Interactions:

- **NIST:** N. Cheggour, J. Ekin, W. Wong
- **ANL:** V. Maroni
- **LANL:** T. Holesinger
- **SNL:** P. Clem, M. Siegel
- **NREL:** R. Bhattacharya; **WPAFB:** P. Barnes, T. Haugan, R.Nekkanti

University Interactions:

- **University of Tennessee:** J. R. Thompson / H. Weinstock (AFOSR)
- **University of Houston:** K. Salama / H. Weinstock (AFOSR)
- **University of** [illegible] R)
- **University of** [illegible]
- **University of** [illegible] n
- **U. of Cincinnati:** Dongli Shi
- **University of Kansas:** Judy Wu
- **Embry-Riddle Aeronautical University:** John Mathis
- **University of Missouri-Rolla:** Jay Switzer
- **University of Augsburg:** J. Mannhart
- **SUNY Buffalo:** David Shaw
- **North Carolina State University:** J. Narayan
- **California State University:** Chuhee Kwon

All substrates fabricated at ORNL come from this project

OUTLINE

- **FY 2003 Results:**
  - True in-plane texture considerations
  - Fabrication of NiW substrates: 3at% and 5at% W
  - Texture homogeneity along width in wide substrates
  - Modification of standard RABiTS structure
  - Development of Cu-based RABiTS
  - Development of improved percolation model and current flow in RABiTS coated conductors
- **FY 2003 Performance and FY 2004 Plans**
- **Research Integration**

Characterization of texture in RABiTS-type Substrates

Issues:

a) What is the "true" in-plane texture of the substrate?

- should be independent of reflection used characterize the texture
- should be independent of the out-of-plane texture
- a true in-plane FWHM is necessary to distinguish if texture of buffer layer is really improving/deteriorating

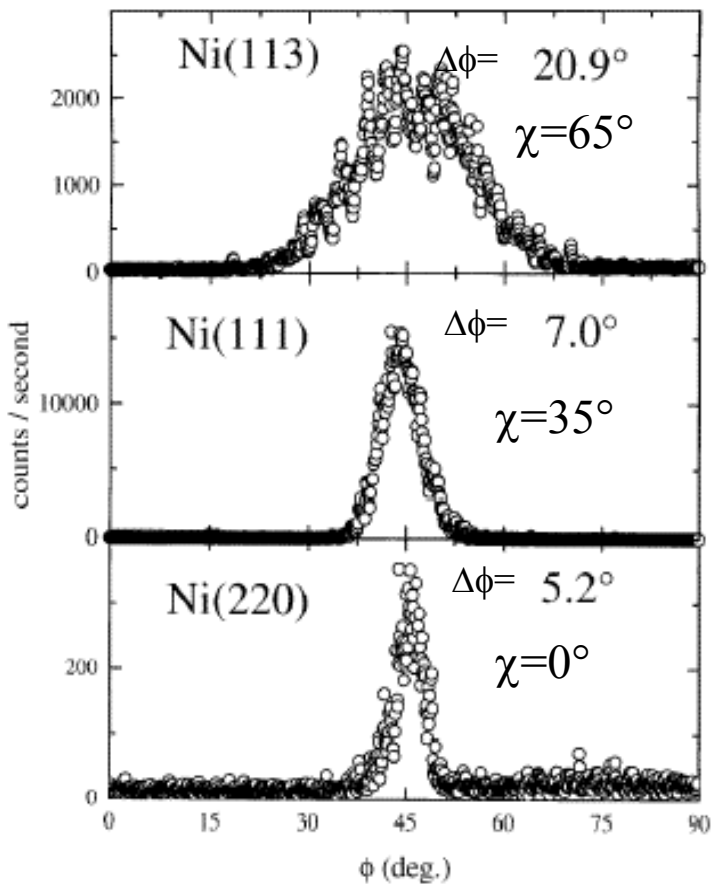
b) Is the degree of texture in RABiTS-type substrates primarily limiting the J_c levels attained so far?

- "true" in-plane FWHM is currently at 3-4°
- how much will we gain by improvement in the out-of-plane texture?

Phi Scan Width Depends On The Reflection and on the FWHM of the Omega Scans

True in-plane FWHM is:

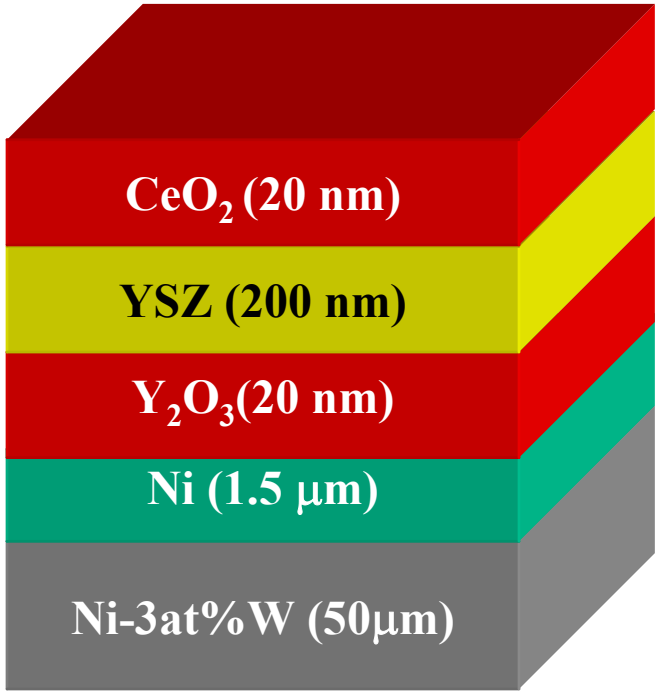
$$\Delta\Phi_{\text{true}} = \sqrt{\Delta\phi^2_{\text{observed}} - \tan^2\chi\left(\Delta\omega^2_{\phi=0}\cos^2\phi + \Delta\omega^2_{\phi=90}\sin^2\phi\right)}$$

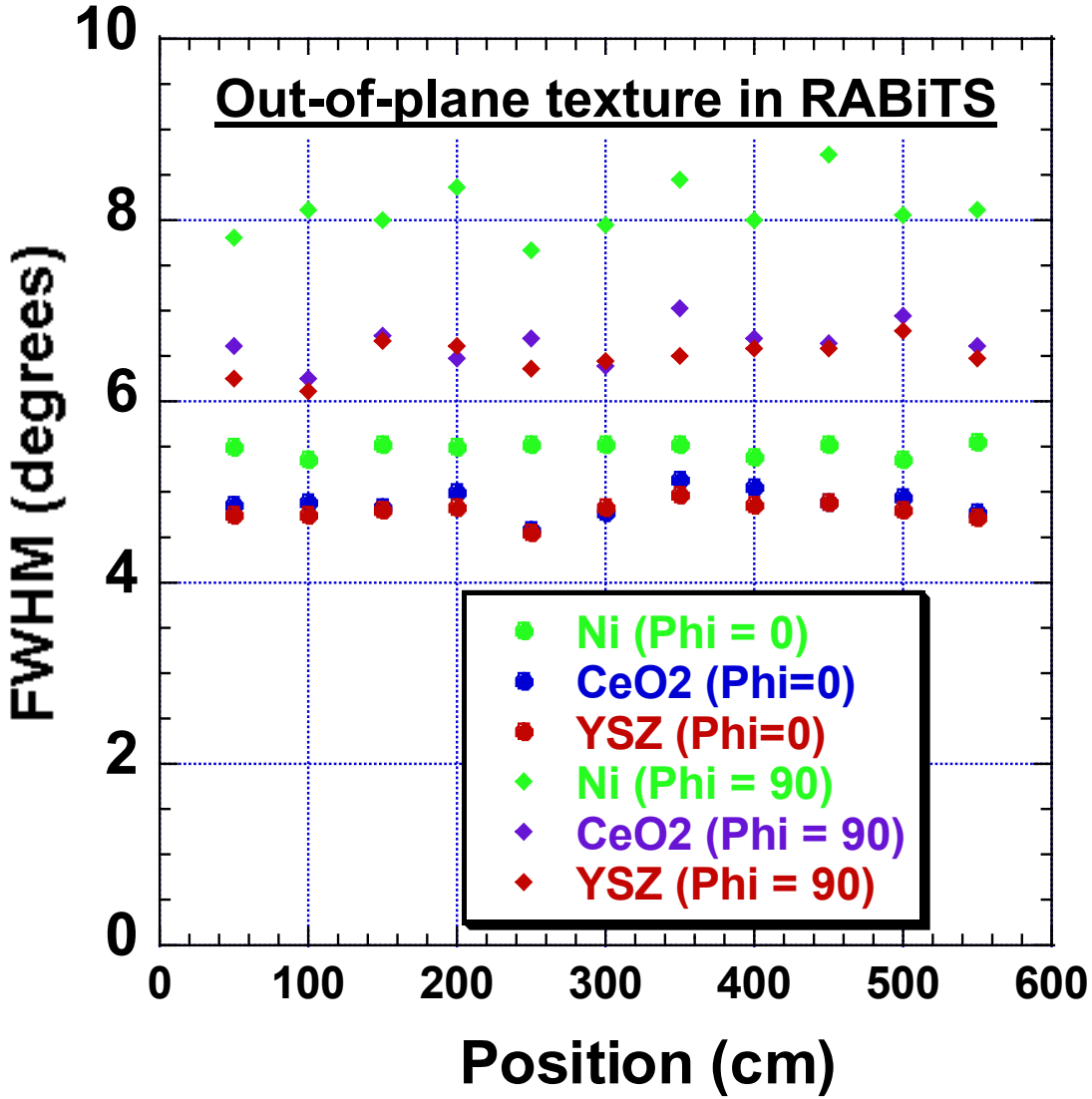


Note the big difference in the measured phi-scan FHWM

Out-of-plane texture in RABiTS tapes is typically 4-8° FWHM

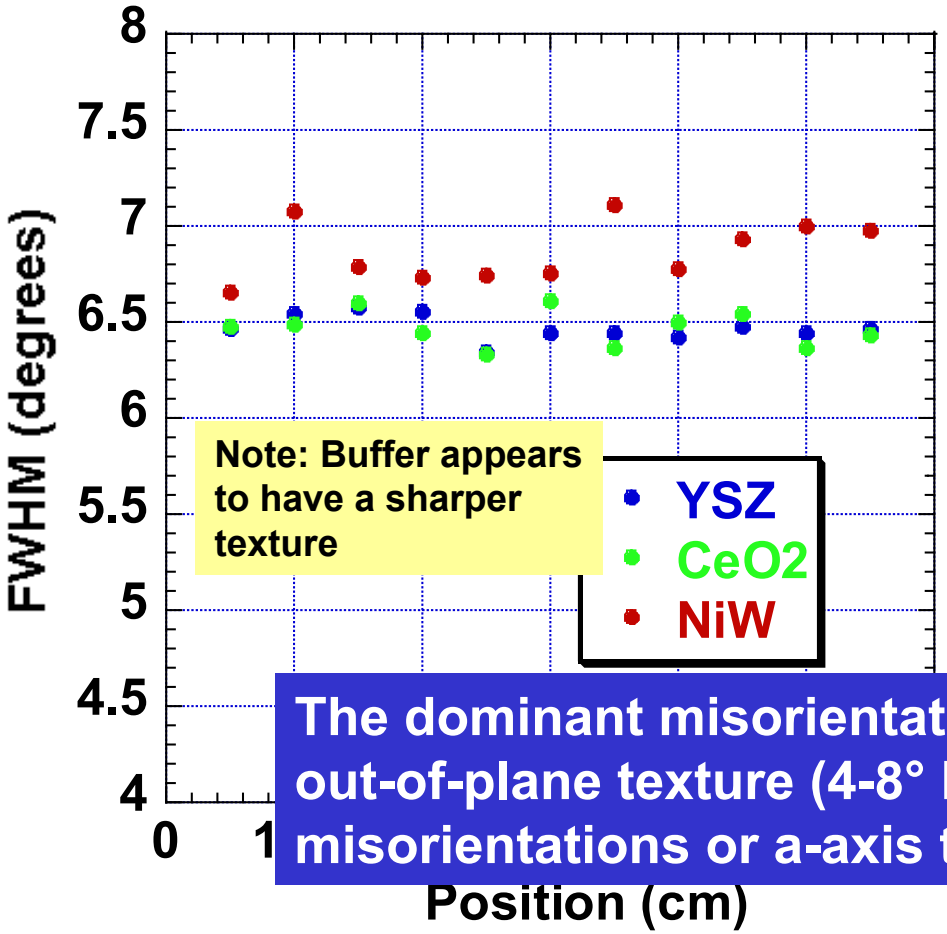
FY 2002 standard RABiTS configuration for process development



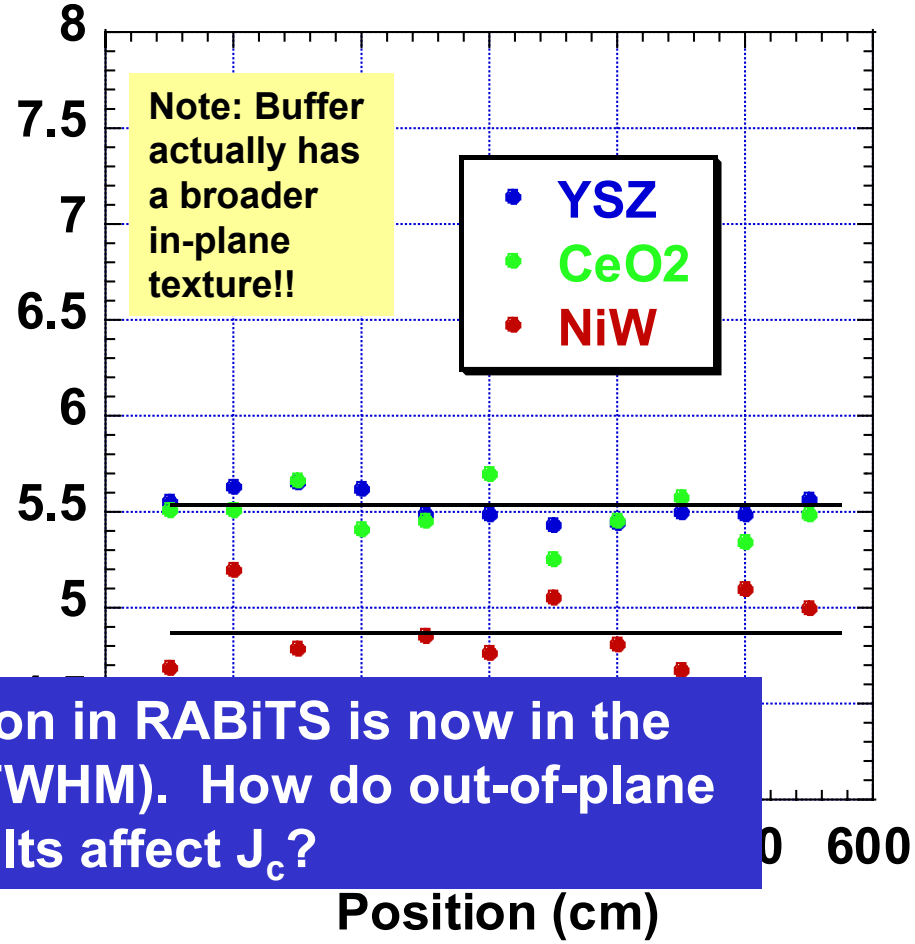


Measured and "True" In-plane Of Standard RABiTS Tape

Measured (111) Phi-Scans

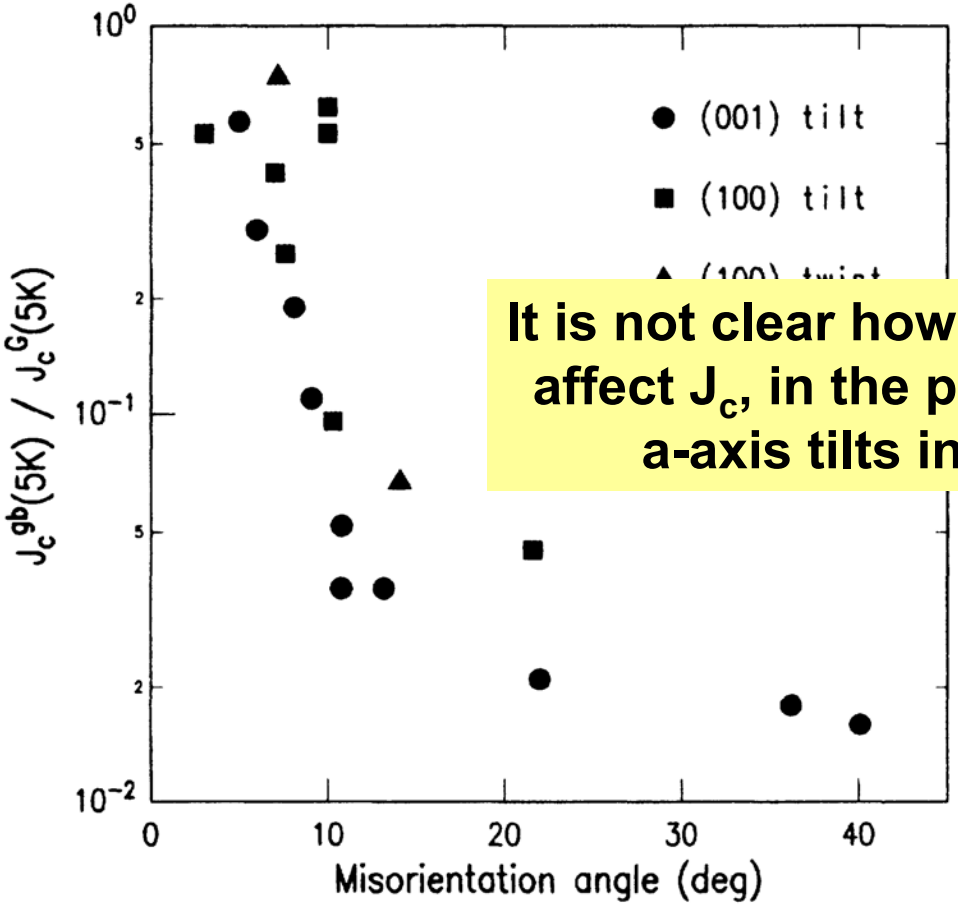


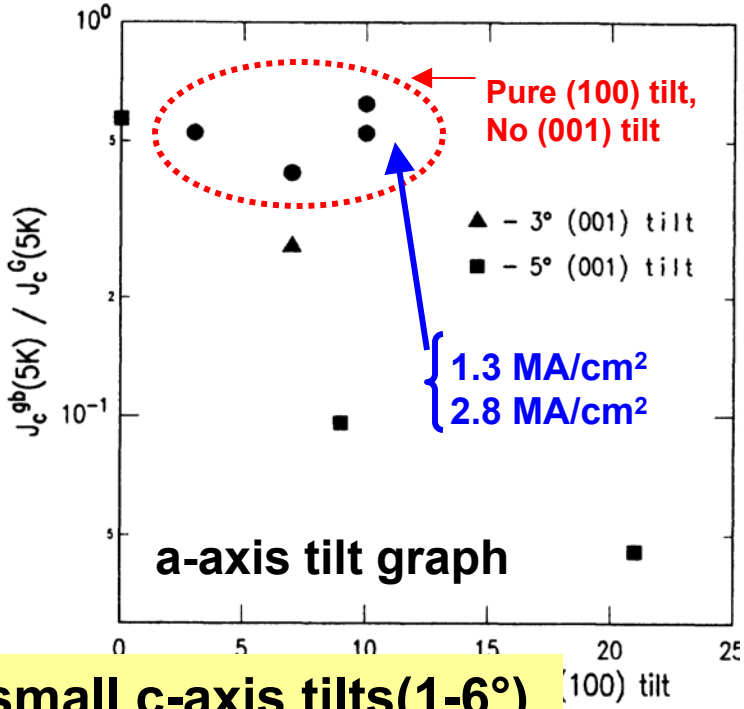
True Phi-Scans



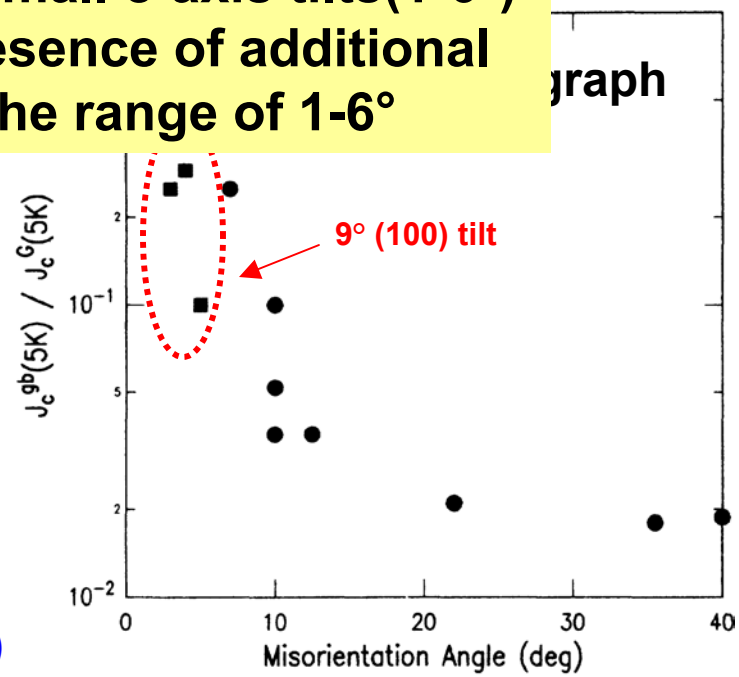
The dominant misorientation in RABiTS is now in the out-of-plane texture (4-8° FWHM). How do out-of-plane misorientations or a-axis tilts affect J_c?

How do a-axis tilts or out-of-plane misorientations affect J_c?



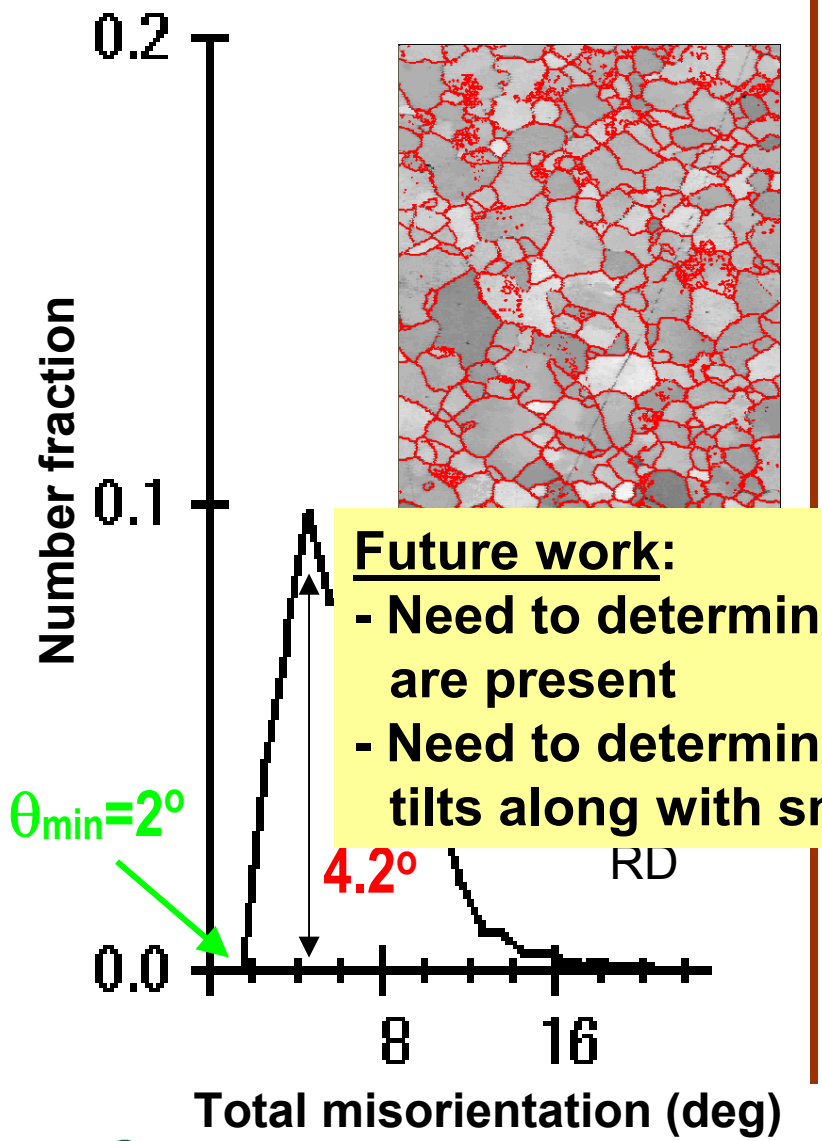


It is not clear how small c-axis tilts(1-6°) affect J_c, in the presence of additional a-axis tilts in the range of 1-6°

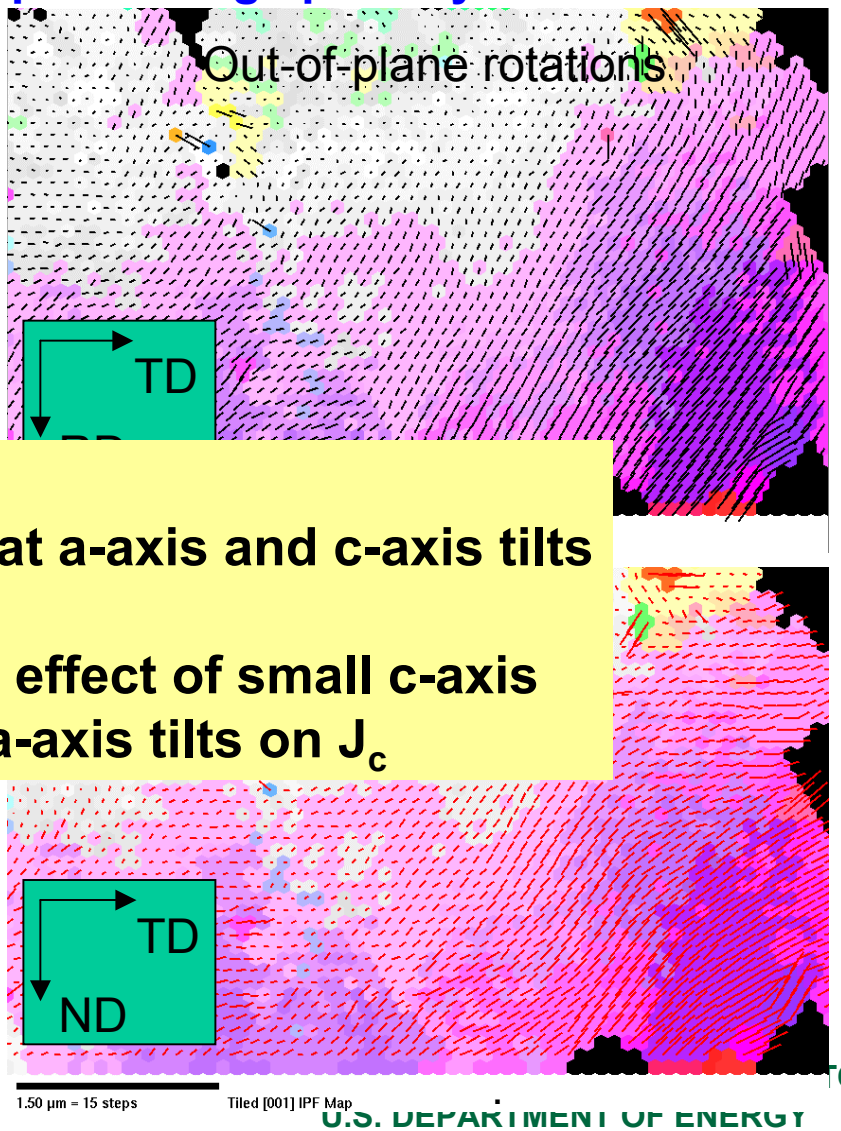


Ref: Dimos et al., Phys. Rev.B, 41, 4038 (1990)

What c-axis & a-axis tilts are present?



Could possibly be done in Rodrigues space using specially defined vectors



Future work:

- Need to determine what a-axis and c-axis tilts are present
- Need to determine the effect of small c-axis tilts along with small a-axis tilts on J_c

Is the degree of texture in RABiTS-type substrates primarily limiting the J_c levels attained so far?

Lets examine four YBCO/RABiTS samples from AMSC

- all have same buffer layer configuration: Y_2O_3/YSZ/CeO_2
- all
- diff

J_c is still improving
n processing!

For the presently achieved texture in long lengths of ~ 4-5°, the J_c continues to increase with improvements in buffer and YBCO deposition technology!

				MA/cm² A
YBCO	$\Delta\phi$ = 7.1° $\Delta\omega$ = 4.9°; 6.8°	$\Delta\phi$ = 5.4° $\Delta\omega$ = 6.5°; 6.6°	$\Delta\phi$ = 5.4° $\Delta\omega$ = 4.7°; 5.2°	$\Delta\phi$ = 4.8° $\Delta\omega$ = 4.5°; 5.6°
Buffer				° 7°; 7.1°
NiW	$\Delta\phi$ = 6.2° $\Delta\omega$ = 5.4°; 8.4°	$\Delta\phi$ = 4.3° $\Delta\omega$ = 7°; 9.6°	$\Delta\phi$ = 5.16° $\Delta\omega$ = 6.1°; 8.1°	$\Delta\phi$ = 5.3° $\Delta\omega$ = 5.5°; 8.1°

Present levels of J_c are 70-80% of what is possible on single crystal substrates!!

YBCO/CeO_2/SC YSZ J_c = 4.3 MA/cm²
I_c = 344 A

Estimated Total Error: ± 0.5°

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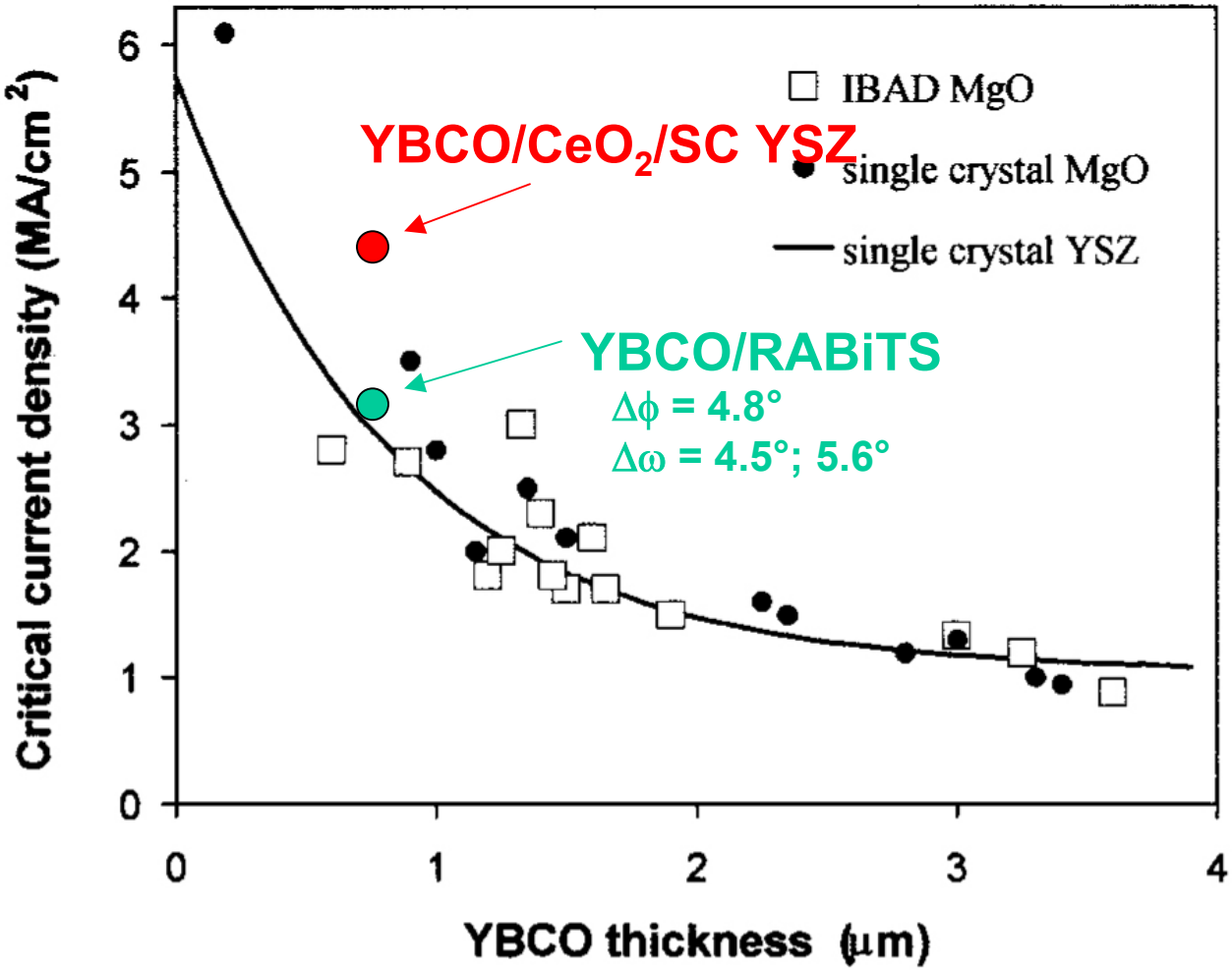
Strongly coupled J_c in near single-crystal-like substrates



S. R. Foltyn et al., APL, 82, 4519 (2003)

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Can we make long and wide metal/alloy substrates with homogenous textures ?

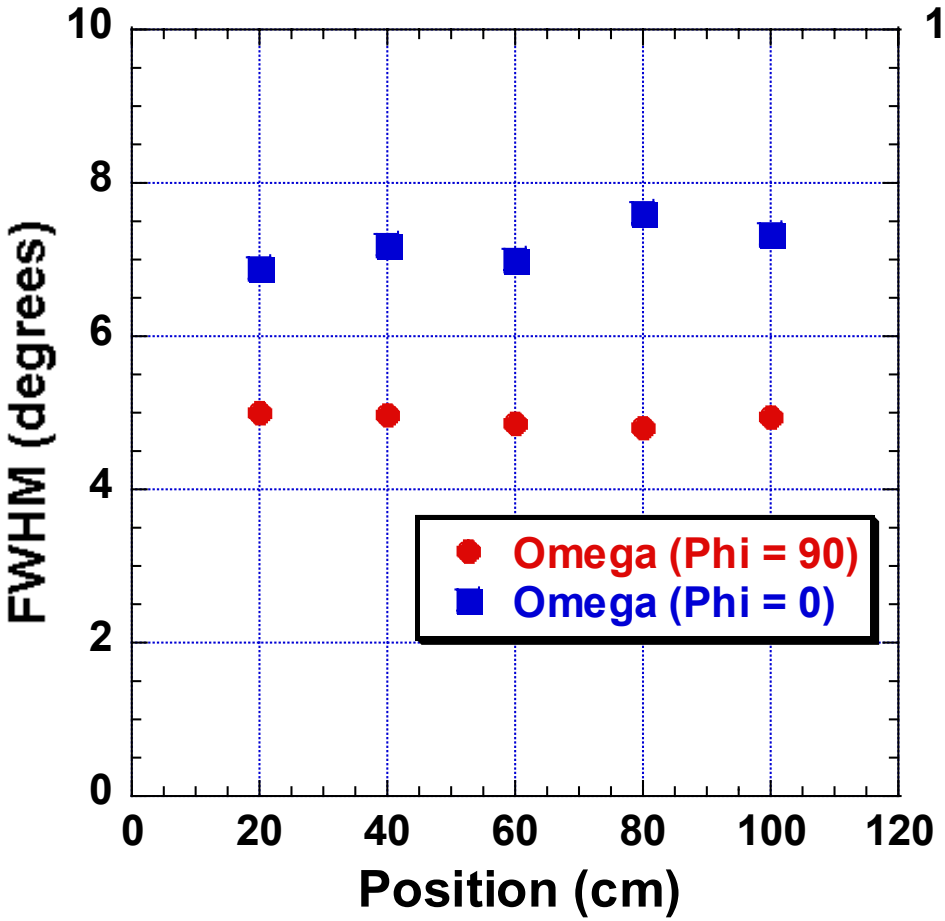
Fabrication of 1.2 km of Ni-3at%W Tape

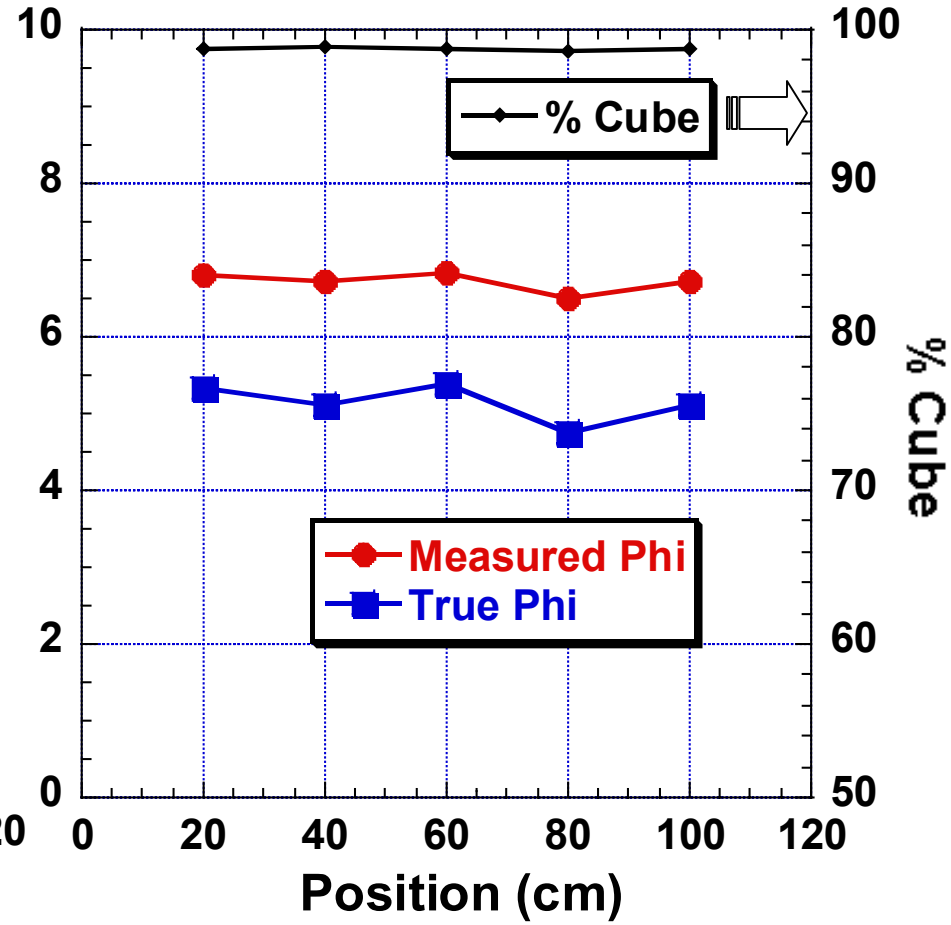
- Powder metallurgy based Ni-3at%W coil fabricated to ORNL specifications at Ametek Specialty Metals
  - significant optimization still needs to be done to obtain defect free and homogeneous coils (surface flaws, holes, density variations, compositional inhomogeneities)
- Rolling of coil done at Hamilton Precision Metals to ORNL specifications - significant work still needs to be done to optimize forward and back tensions during rolling, to minimize entrapment of particles in rolled tape, to minimize camber in rolled tape
- A 120 meter long, 10 cm wide tape was fabricated (only one third of the starting material was usable due to the combined problems with the coil and problems during rolling)
- 10, 1 cm wide, 120 meter long coils resulting in a total length of 1.2 km was successfully fabricated

ROLLING MILL WITH CLEAN ROOM FACILITY IN ACCI

The rolling mill facility is expected to be heavily subscribed in FY 2004, with industrial users and national laboratory research each sharing the facility

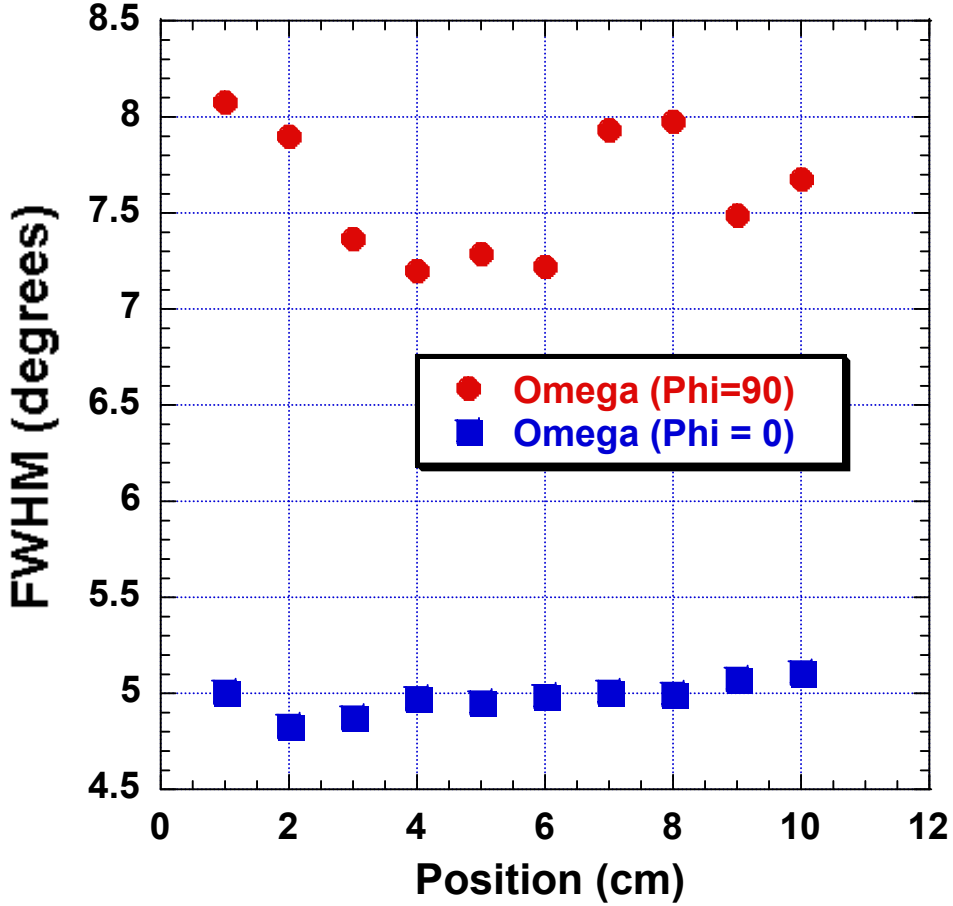
Texture along the length in *latest* Ni-3at%W tape

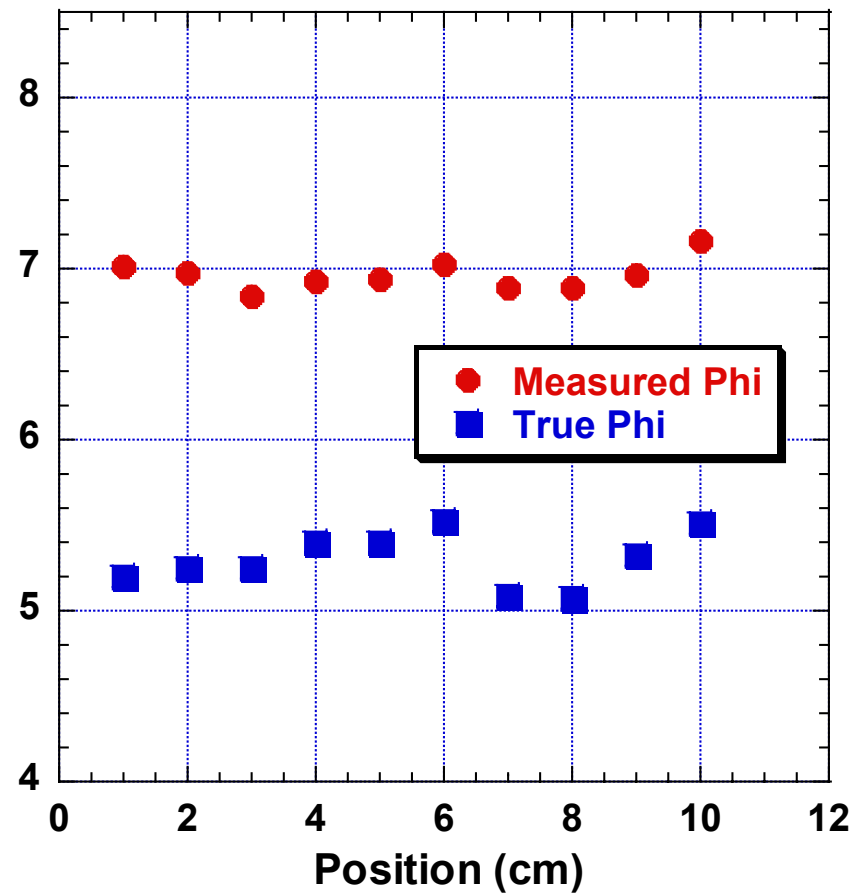




- Texture along the length is within 0.5 degrees

Texture homogeneity in 10 cm wide Ni-3at%W tape is quite good

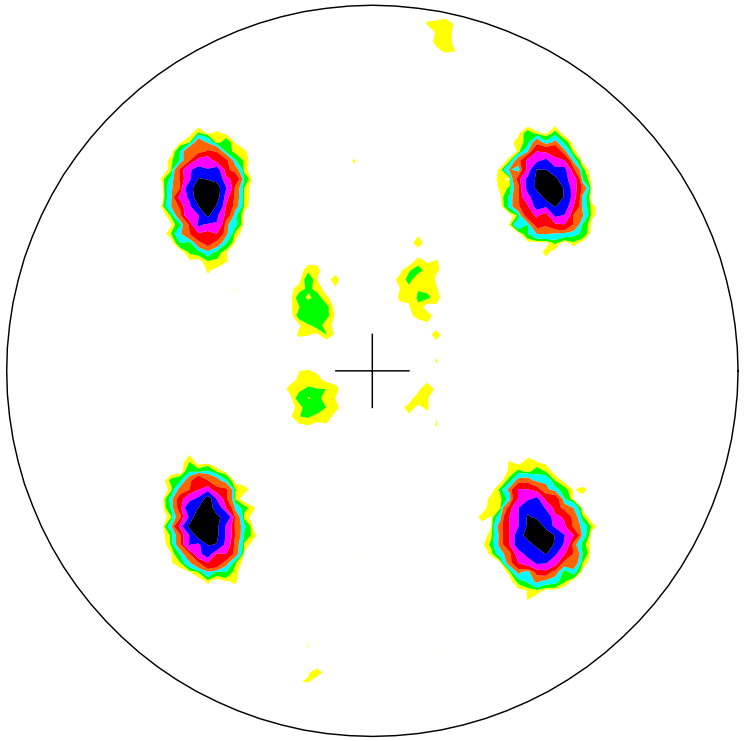




- **True in-plane texture along the width is within 0.5 degrees**

Results on Ni-5at%W via Powder Metallurgy

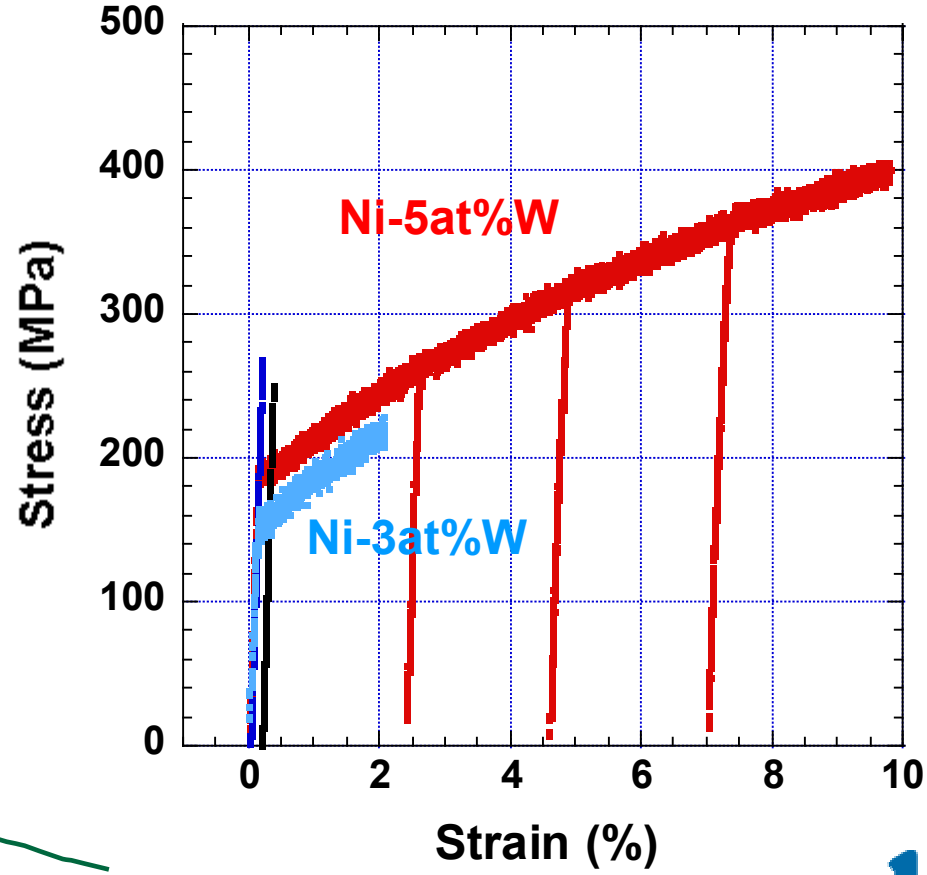
% Cube ~ 98%



Measured Phi: 7.4°
True Phi: 5.2°
Omegas: 4.06°; 9.8°

Yield Strength

Ni-5at%W: 195 MPa
Ni-3at%W: 145 MPa



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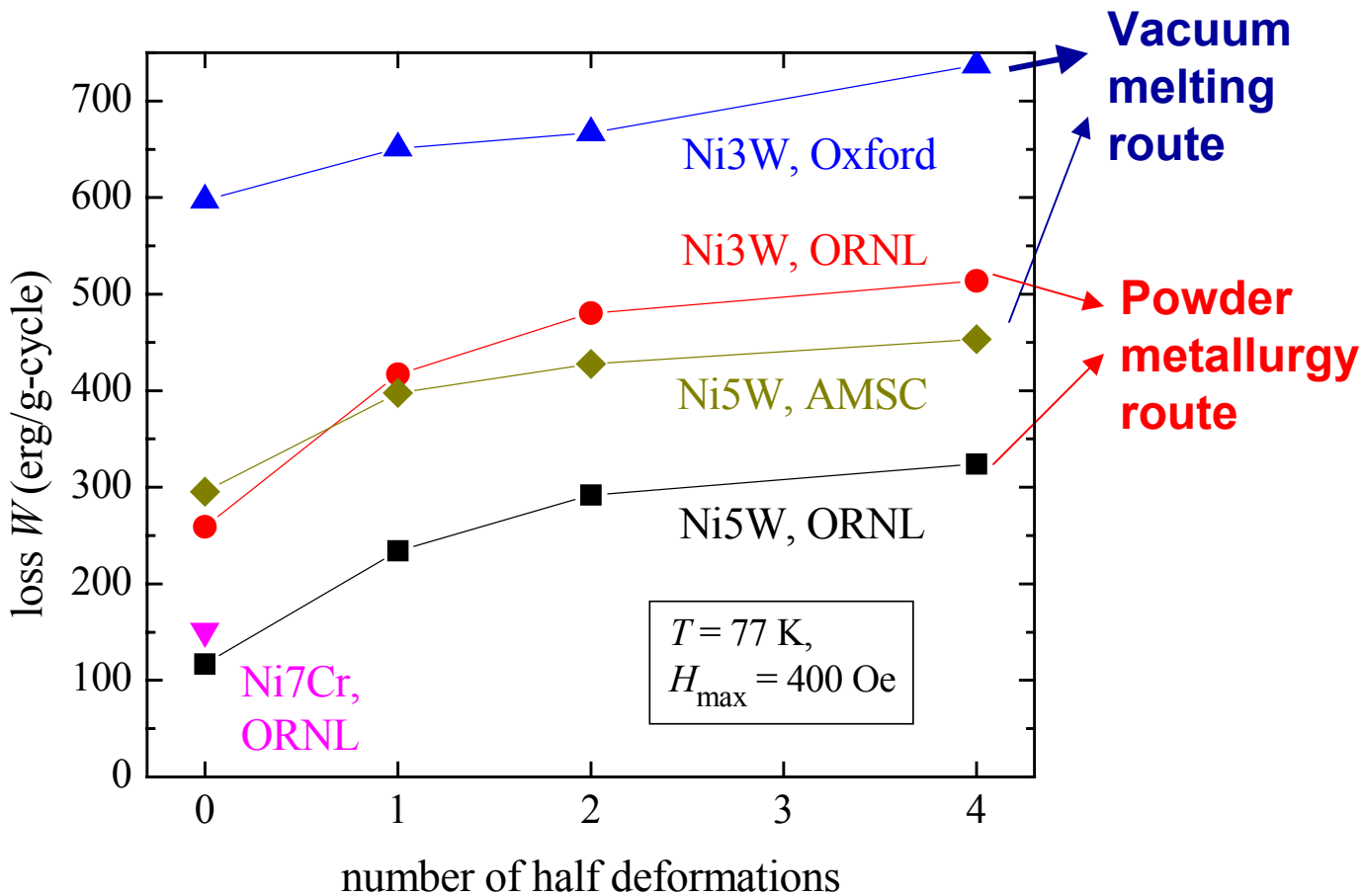
ornl

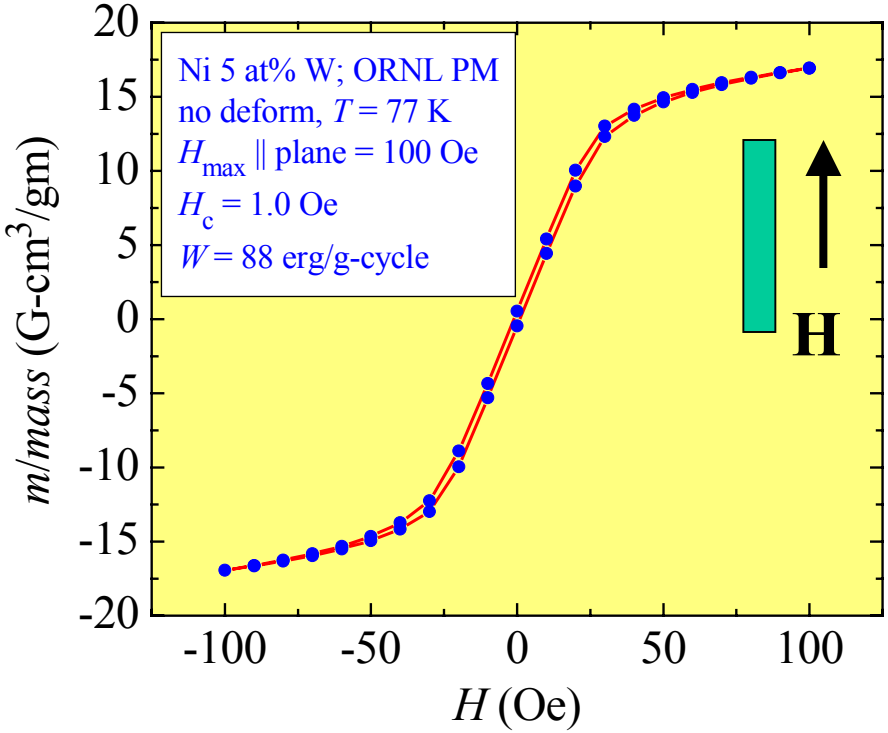
FM loss *W* vs damage due to number of bending deformations



one half-deformation: | ⇒) ⇒ | ; second half-deformation | ⇒ (⇒ |

half-deformation = 0.5 % bending strain

Illustration: relative losses for YBCO / Ni-5at%W



- **HTSC and FM power losses scale very differently with I_0/I_c**
- **Fraction of total losses arising from FM losses increases with decrease in I_0/I_c**

Loss in HTSC (10 mm × 2 μm):
for $J_c = 1\times10^6$ A/cm^2, I_c = 200 A
If $I_0 = I_c$, Norris gives ac loss
⇔ power = **2400 mW/(kA-m)**
For $I_0 = I_c/2$ = 100 A,
⇔ power loss = **270 mW/(kA-m)**

==========

Substrate Loss (10 mm × 50 μm):
0.5 cm^3 of alloy/m × 0.078 mJ/cm^3 ⇒

$L_{c,\,FM}$ = 0.039 mJ/m-cycle (Ni-5%W)

⇔ power loss = **23 mW/(kA-m)**
assuming $I_0 = I_c/2$ = 100 A
(and 83 mW/kA-m for pure Ni)

⇔ power loss = **30 mW/(kA-m)**
assuming $I_0 = I_c$ = 200 A

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Reduced magnetism and non-magnetic alloys have also been cube textured

AC losses are significantly reduced

Alloy	YS (0.2%)	Curie Temp.
Ni * (* Vacuum melted)	34 MPa	627 K
Ni-7at%Cr *	64 MPa	250 K
Ni-9at%Cr *	87 MPa	124 K
Ni-11at%Cr *	102 MPa	20 K
Ni-13at%Cr *	164 MPa	Non-magnetic
Ni-3at%W	150 MPa	> 400 K
Ni-5at%W *	165 MPa	335 K
Ni-6at%W * (98%)	197 MPa	?
Ni-9at%W * (93%)	270 MPa	~25K

ORNL/AMSC CRADA

Ni-13at%Cr-4%Al *	228 MPa	Non-magnetic
Ni-10at%Cr-2%W	150 MPa	Non-magnetic
Ni-Cr-W (2)	202 MPa	Non-magnetic

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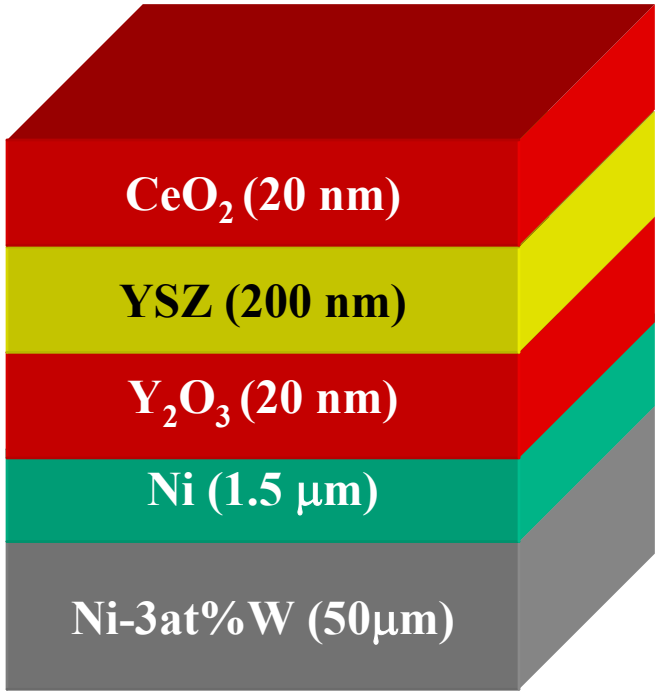
Modification of Standard RABiTS Buffers

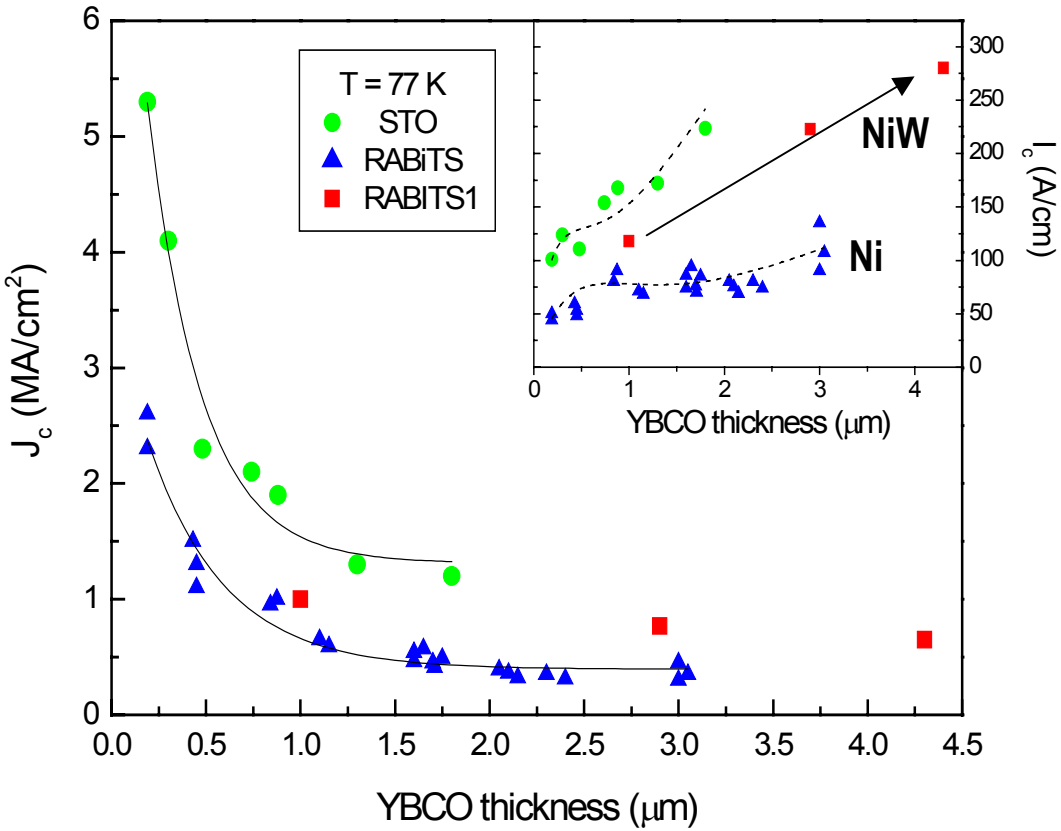
FY2002: Standard RABiTS

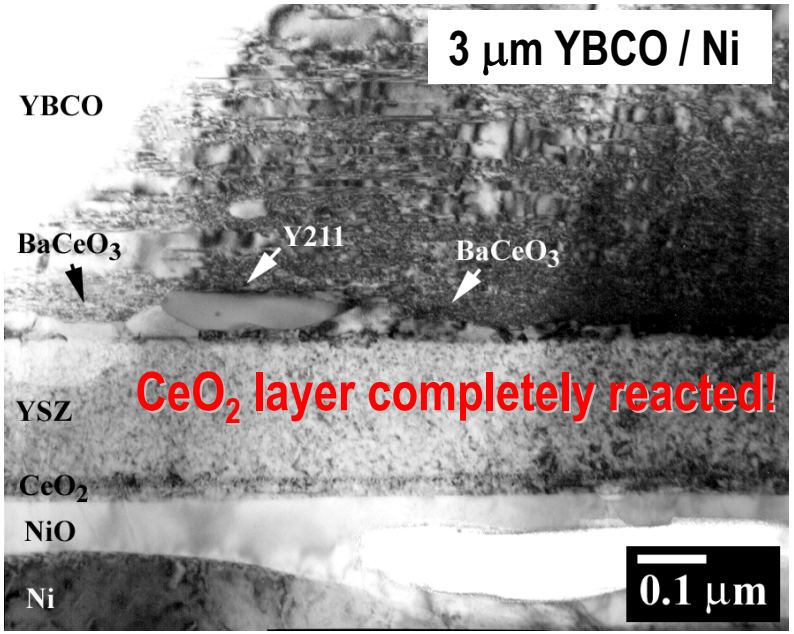


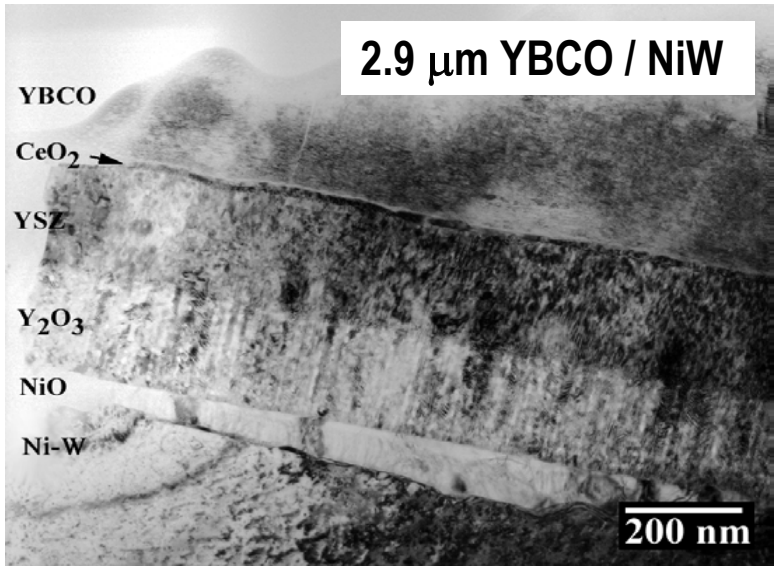
- **Removal of Ni overlayer**
- **Formation of a self-passivating oxide layer at interface of NiW and Y_2O_3**

<u>Why is this of interest?</u>
Need a robust template to form thick YBCO in the range of 1-6 μm

J_c vs. Thickness for YBCO films by PLD

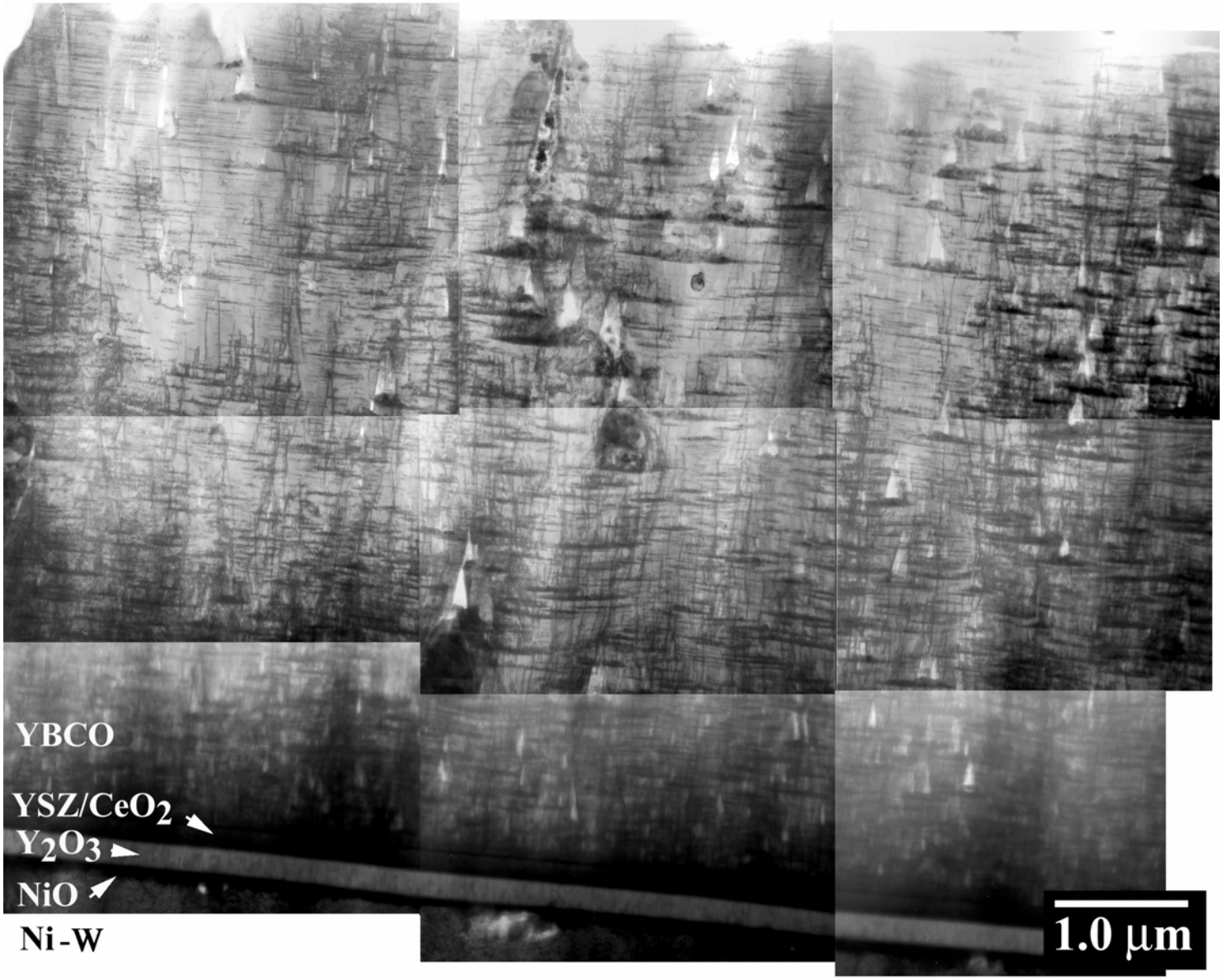




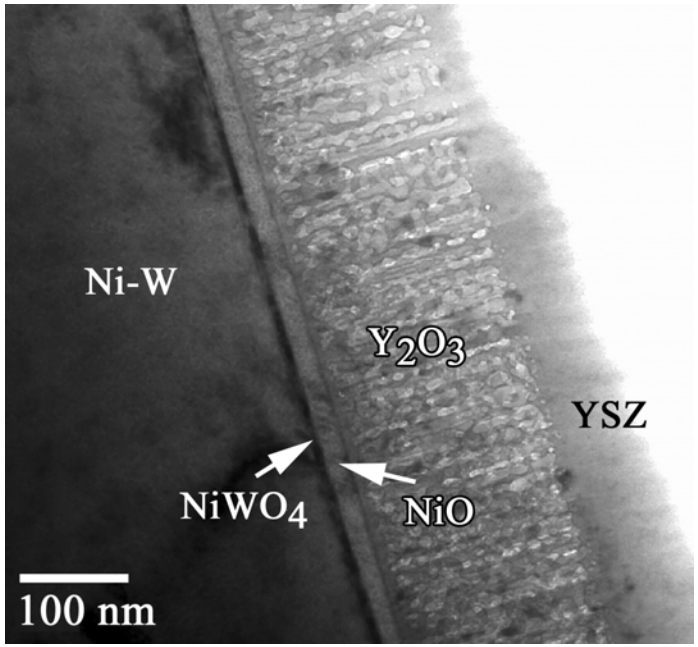


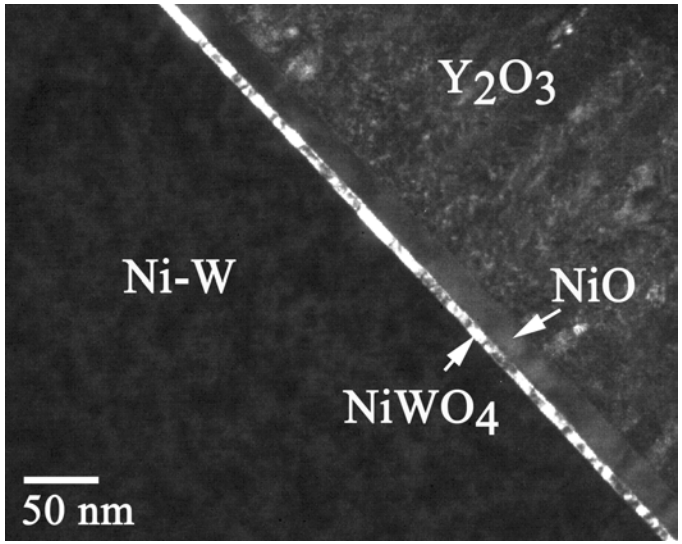
RABiTS: Ni/CeO_2(20nm)/YSZ (250nm)/CeO_2(20nm)
RABiTS1: Ni3at%W / Y_2O_3(150nm)/YSZ (150nm)/CeO_2(20nm)

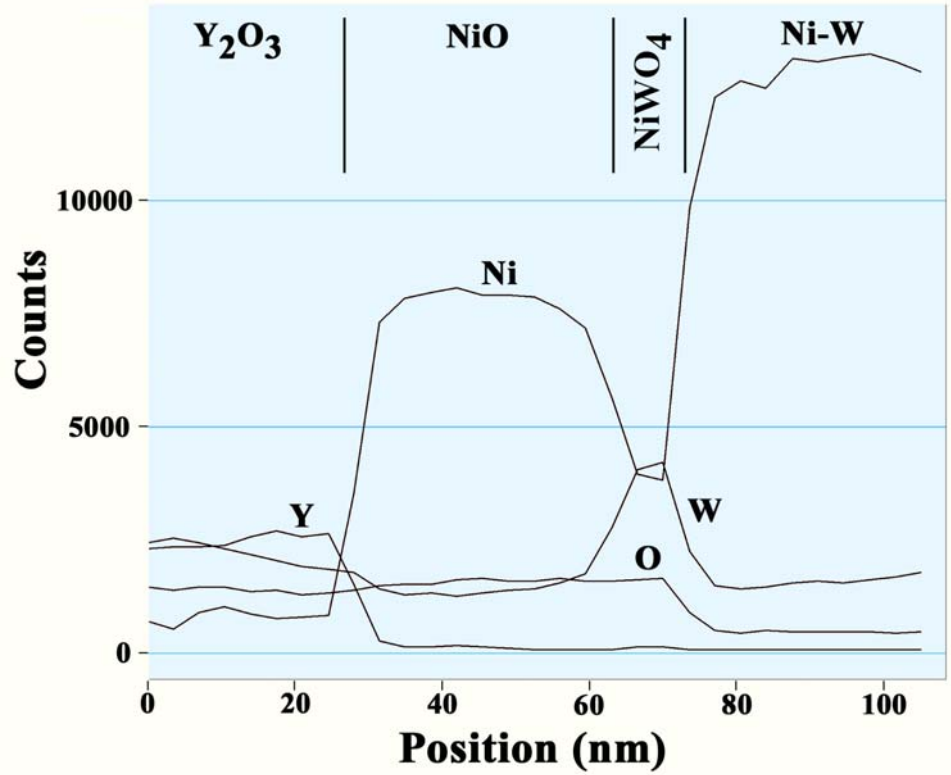
YBCO film looks homogeneous through the entire cross-section of 6.4 μm



Passivating tungsten oxide layer



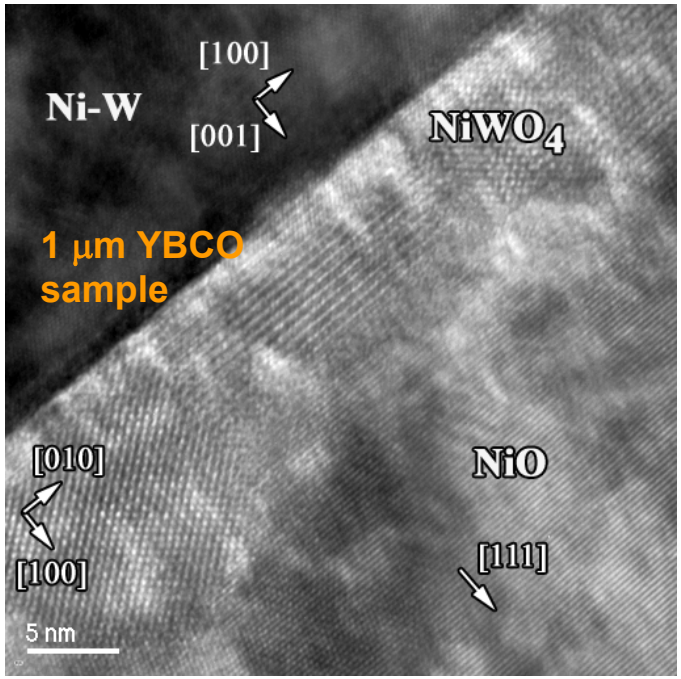


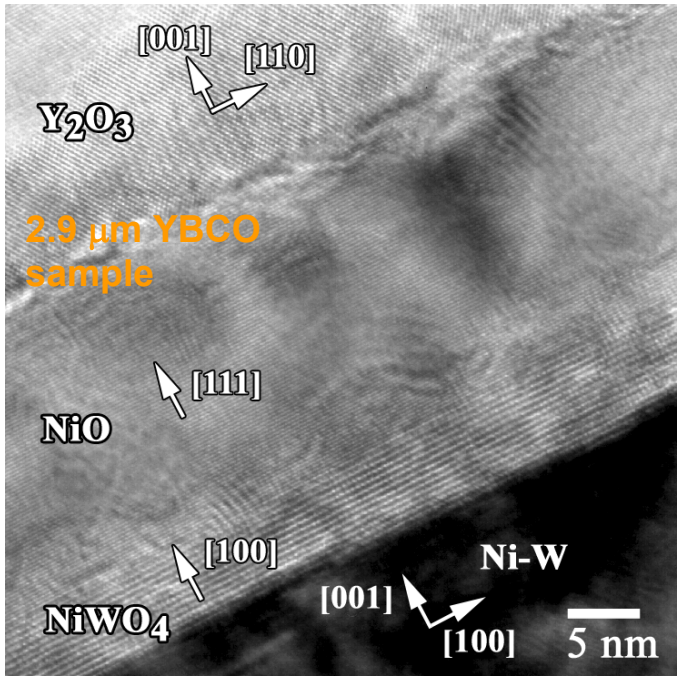


For YBCO samples ranging in thickness from 1-6.4 μm:

- **NiO: 35-40 nm**
- **$NiWO_4$: 8-10nm**
- **$NiWO_4$ is 20-25% the thickness of NiO**

Tungsten oxide layer is epitaxial





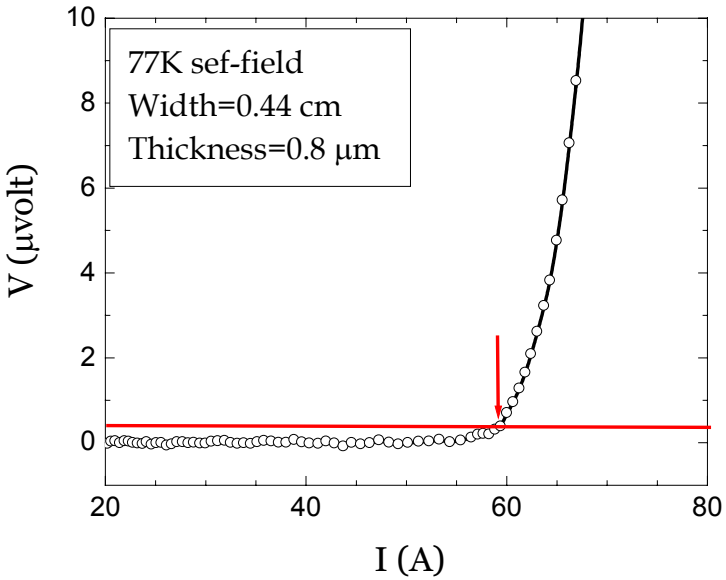
Multiple orientations are possible, but $NiWO_4$[100] is always be normal to the film interface. In other words, **$NiWO_4$(100) // Ni-W(001)**

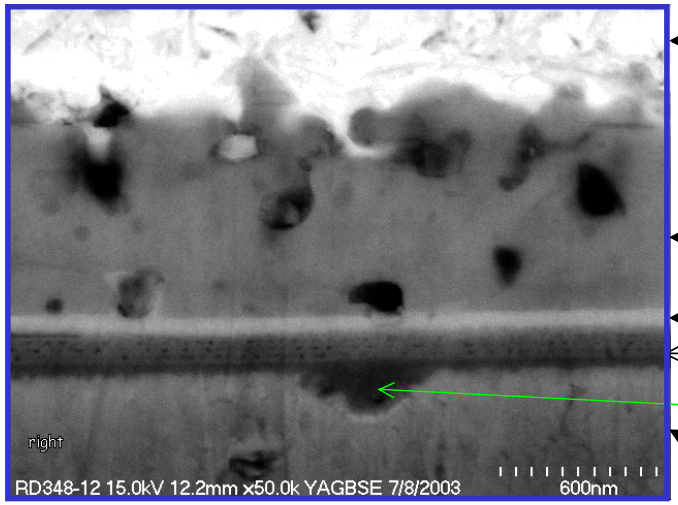
Sample Normal
Ni(W) <200> || $NiWO_4$ <100>|| NiO <111>

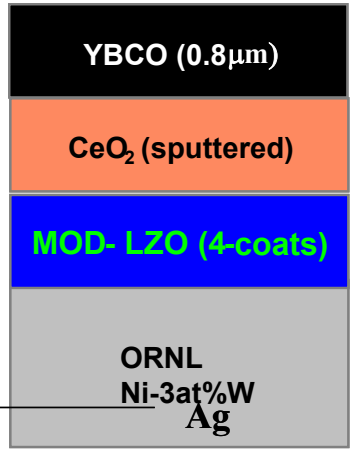
We will focus on buffers deposited directly on Ni-3at%W and Ni-5at%W substrates for developmental work and form a self-limiting $NiWO_4$ layer at the interface

Solution buffers via sol-gel processing are being developed in conjunction with industry

77K, SF: J_c=1.68 MA/cm^2, I_c=135 A/cm-w







YBCO

CeO_2 ($BaCeO_3$)

MOD LZO)

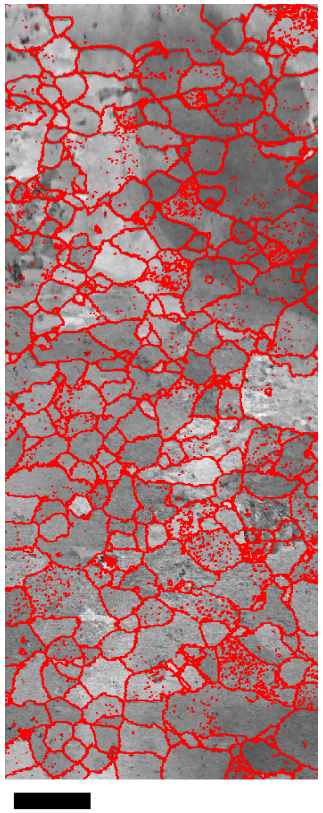
$NiO/NiWO_4$

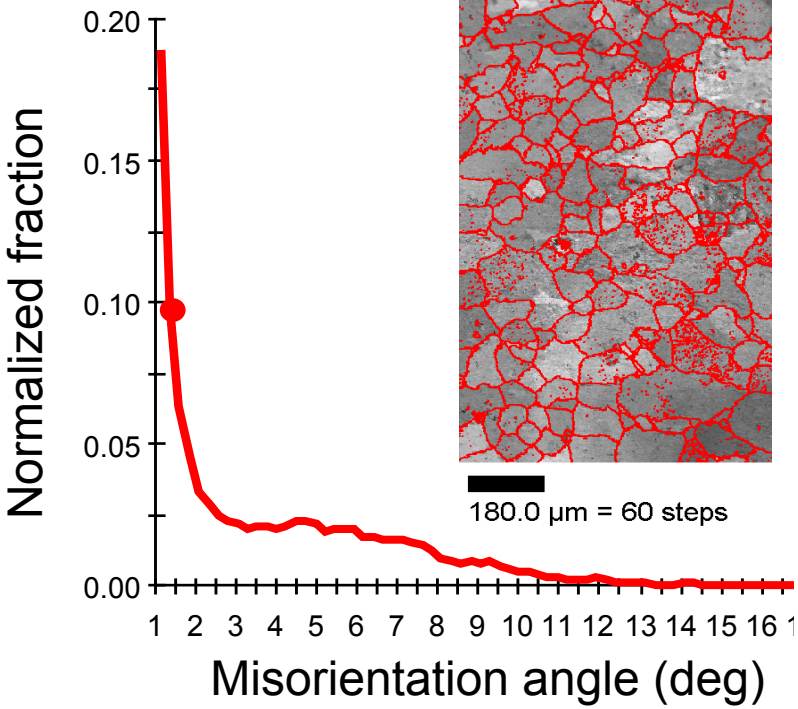
Ni-W

YBCO films with an I_c of 135 A/cm were achieved indicating that may be possible to replace both PVD Y_2O_3 and YSZ layers with MOD LZO

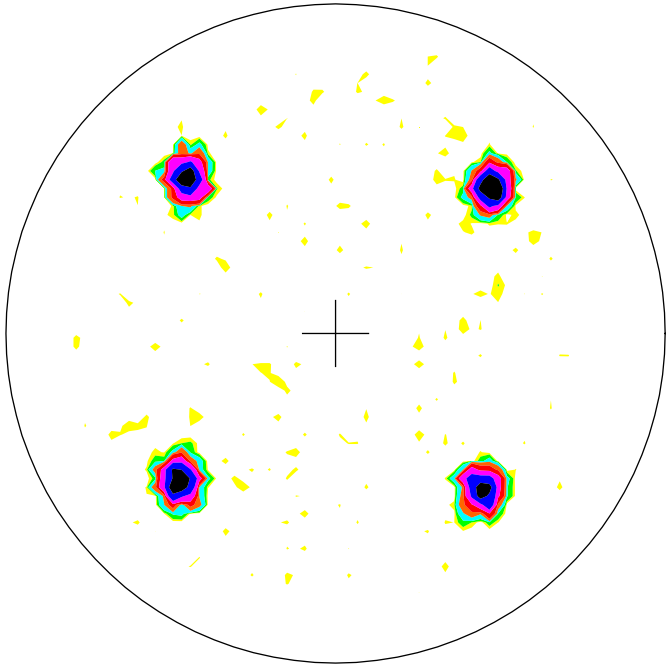
Cu-based Substrates: Potentially Inexpensive Substrates for CC's

Substrates are well textured



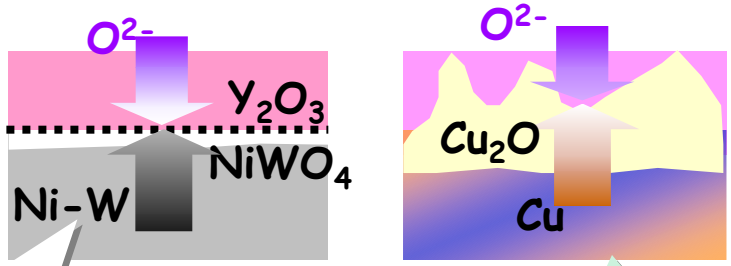


Log-scale Cu(111) pole figure



Measured Phi: 5.3°
True Phi: 4.1°
Omegas: 4.1°; 5.5°

Challenges



Ni diffusion barrier limits NiO growth

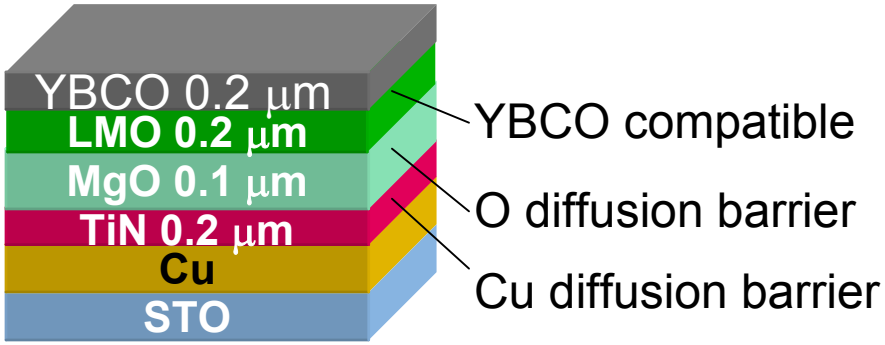
High Cu diffusion leads to detrimental Cu-O growth

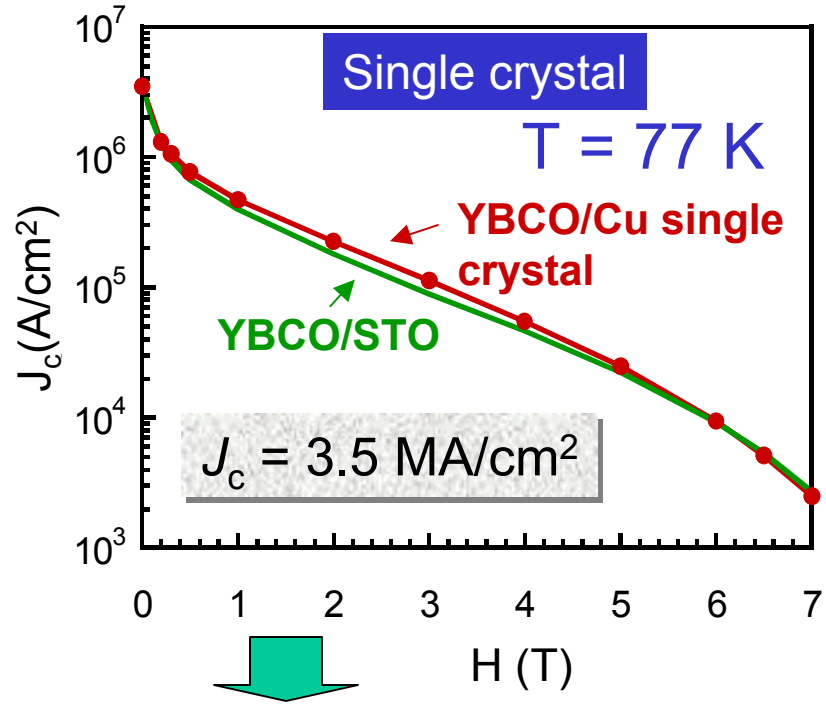
- ☹ rapid oxidation
- ☹ high ionic diffusion
- ☹ high thermal expansion
- ☹ mechanically soft
- ☹ direct epitaxy only with NaCl type structure on clean surface (TiN, MgO)

- *Alternative approach: metal overlayers*

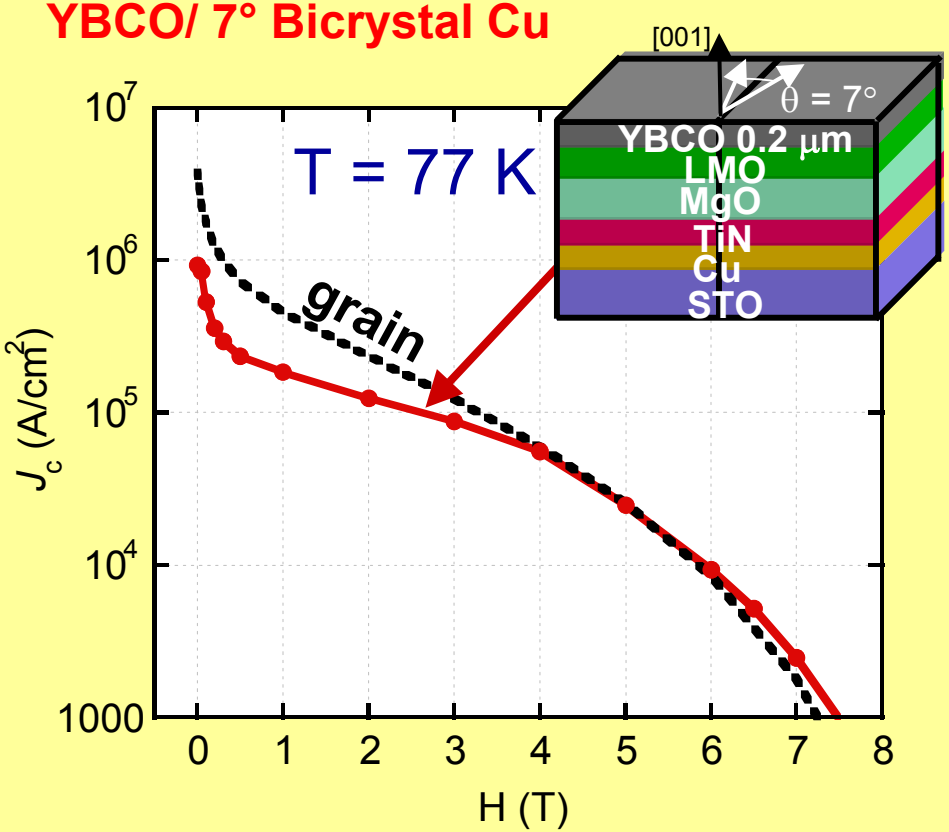
Buffer layers for Cu-based substrates

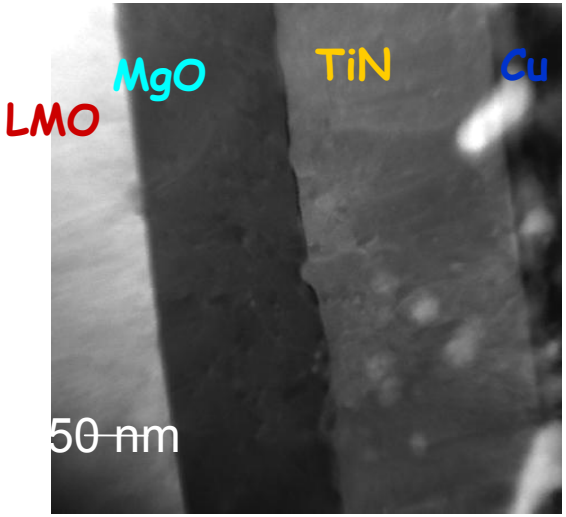
YBCO/ Single Crystal Cu





YBCO/ 7° Bicrystal Cu

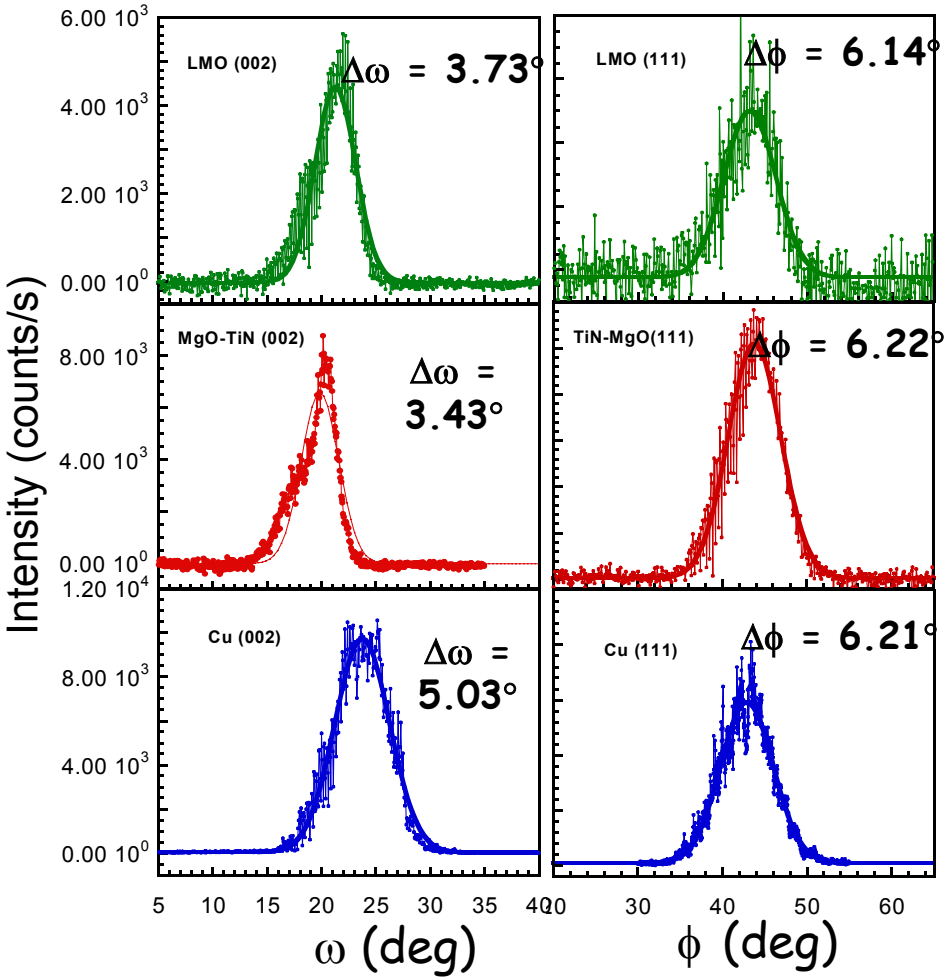




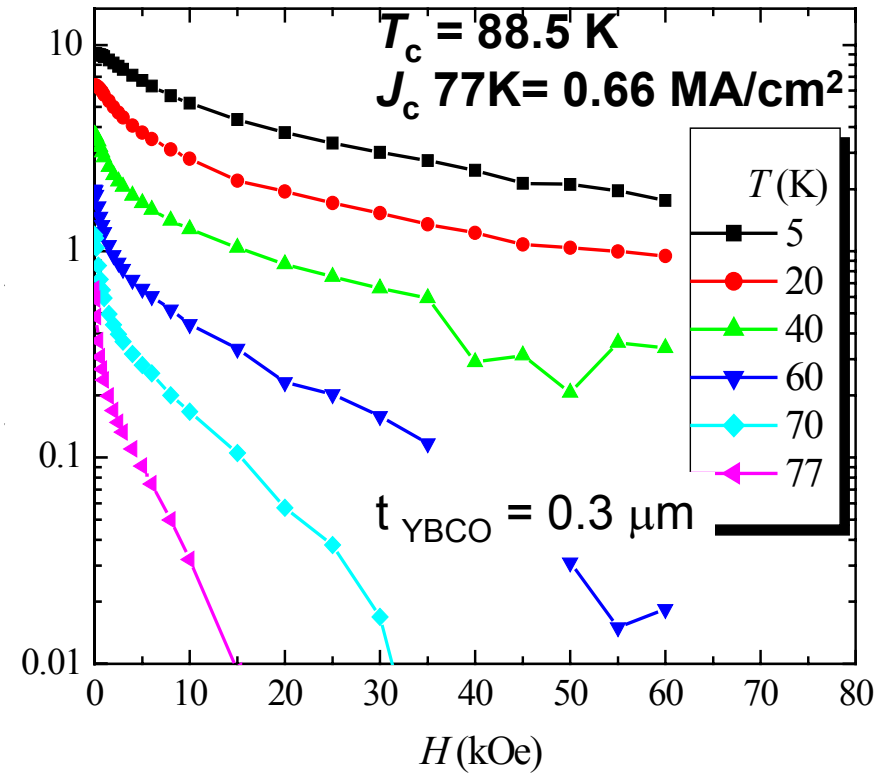
Z-STEM image

EELS detects no oxygen at the Cu/TiN interface

YBCO on LMO/MgO/TiN/textured Cu



Magnetic measurements

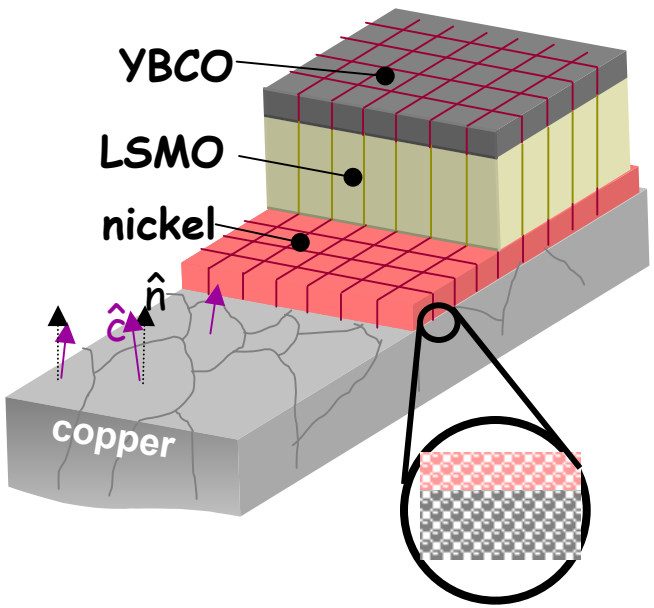


Need a stronger Cu substrate

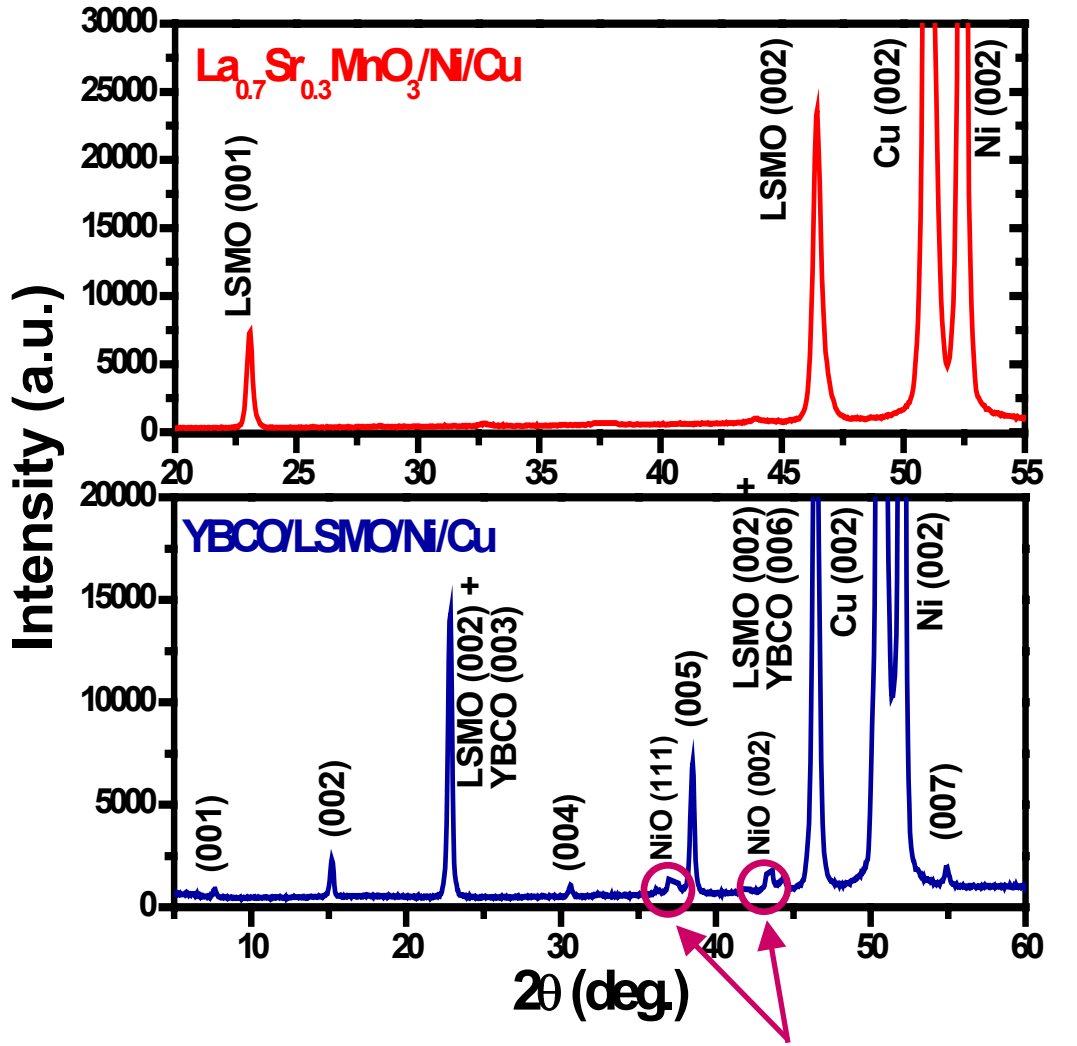
Epitaxial Conductive Architecture Achieved on Ni/Cu

YBCO = 200 nm, LSMO = 200 nm, Ni = 1.6 μm

Cube-on-cube epitaxy

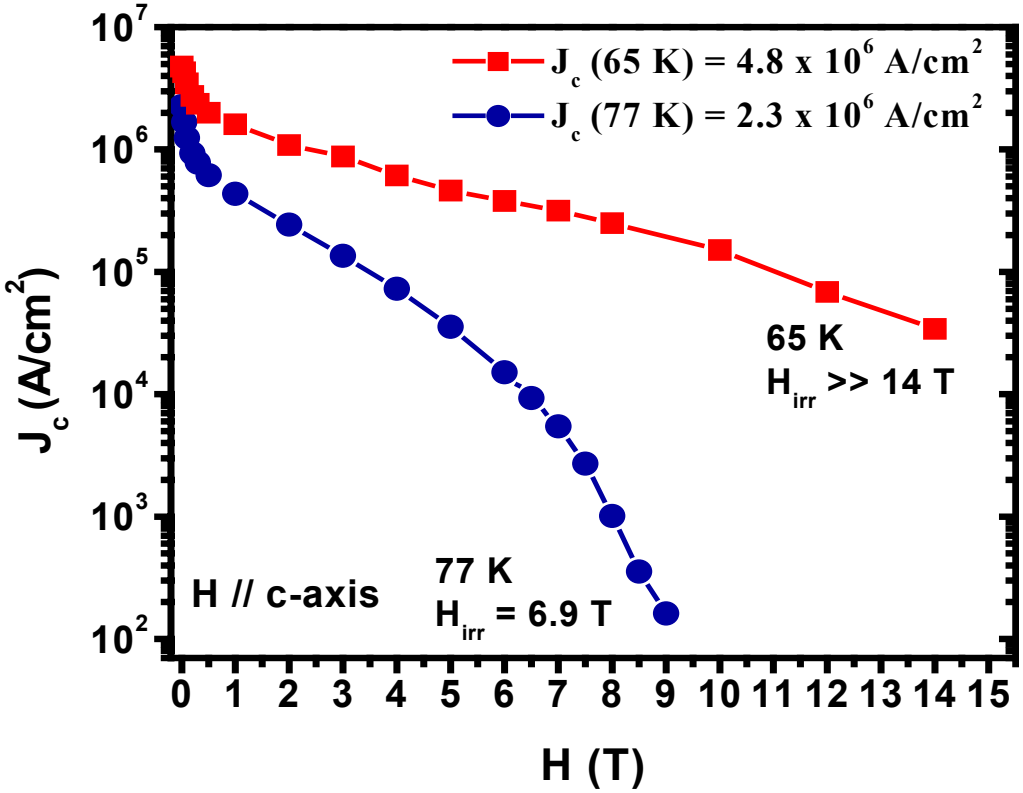


Critical issues:
1. nickel/copper interdiffusion
2. Losses from the Ni overlayer

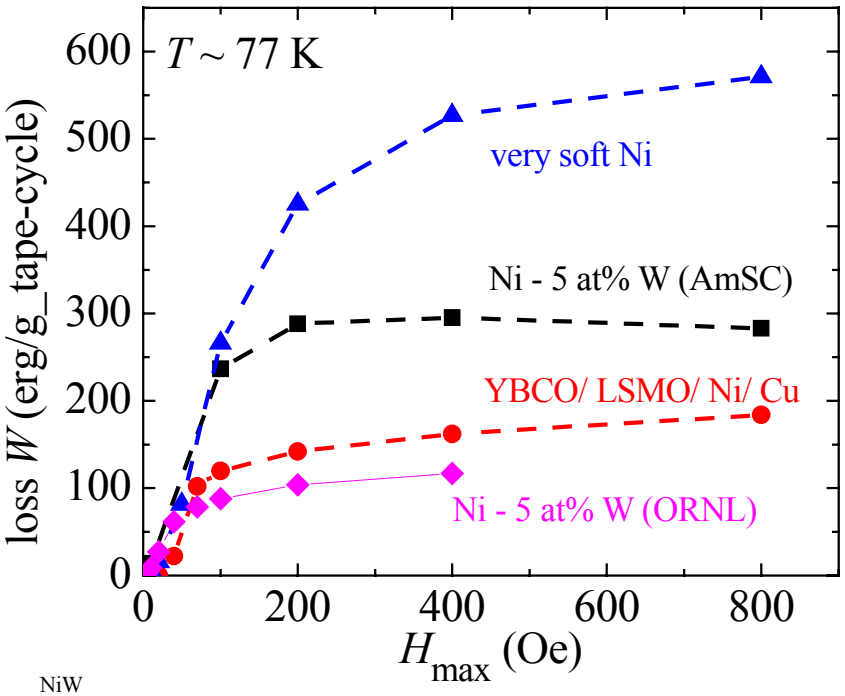


NiO formation after YBCO

High-J_c was obtained for *YBCO/LSMO/Ni/Cu* Structure



However, Ni overlayers are quite lossy



NiW

Cu-based RABiTS: Issues to be resolved

- Need for stronger Cu substrates with low resistivity
- Thick YBCO (1-3 μm) needs to be demonstrated
- Ni overlayer needs to be alloyed or minimized

Development of an improved percolation model for current flow in coated conductors

Comparison of new model to previous models

	Specht	Rutter	Holzapfel	Nakamura	New Model
Conductor scale	Large	Large	Small	Large	**Large**
Grain shape	Hexagonal	Hexagonal	Real	Square	**Realistic**
Misorientation extent	Bimodal (0 or 1)	3-D Continuous	3-D Continuous	1-D Continuous	**3-D Continuous**
Misorientation basis	Random	Bulk X-Ray data	Real EBSP	Gaussian (X-Ray-like)	**Bulk X-Ray data**
Jc assignment	Bimodal (0 or 1)	Dimos	Dimos	Dimos	**Dimos**
Algorithm	Exact	Inexact (good to few%)	Exact	Inexact	**Exact**
Granular dissipation	No	No	No	No	**Yes**

Specht, Goyal & Kroeger **Scaling of percolative current flow to long lengths in biaxially textured conductors.** *Supercond. Sci. Technol. 13 (2000) 592-597*

Rutter, Glowacki and Evetts **Percolation modelling for highly aligned polycrystalline superconducting tapes.** *Supercond. Sci. & Technol., 2000. 13: p. L25-L30*

Rutter, *Chapter 7, PhD Thesis, University of Cambridge 2001.*

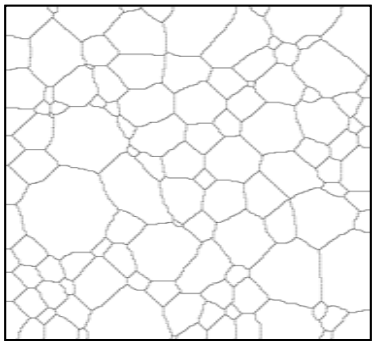
Holzapfel, Fernandez, Schindler, de Boer, Reger, Eickemeyer, Berberich & Prusseit **Grain Boundary Networks in Y123 Coated Conductors : Formation, Properties and Simulation.** *IEEE. Trans. Appl. Supercond. 11 1 (2001)*

Nakamura, Izumi & Shiohara **Percolation analysis of the effect of tape length on the critical current density of 123 coated conductors.** Phys. C 371 (2002) 275-284

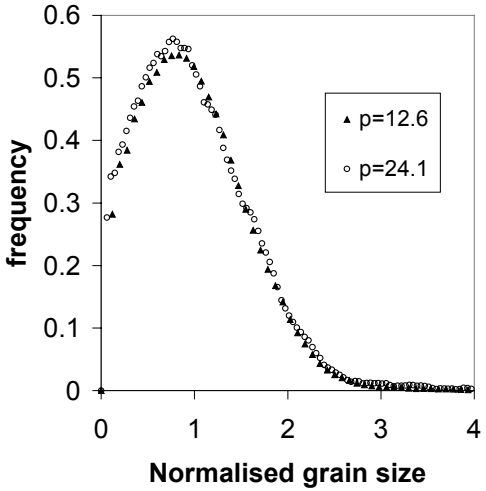
Rutter & Goyal **Modeling Current Flow in Granular Superconductors** *Advances in Superconductivity Volume 57, 2003*

Simulation of grain structure and misorientation of grain boundaries

A. **Simulation of a realistic grain structure is done using the Monte Carlo Potts method**

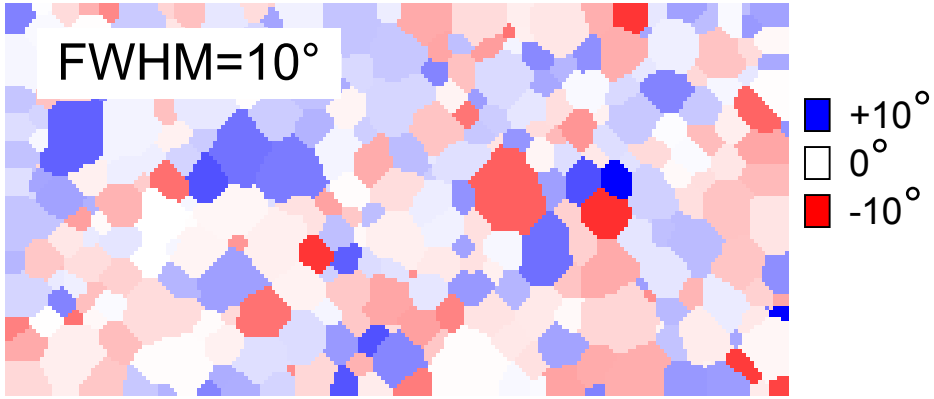


MCS = 1000



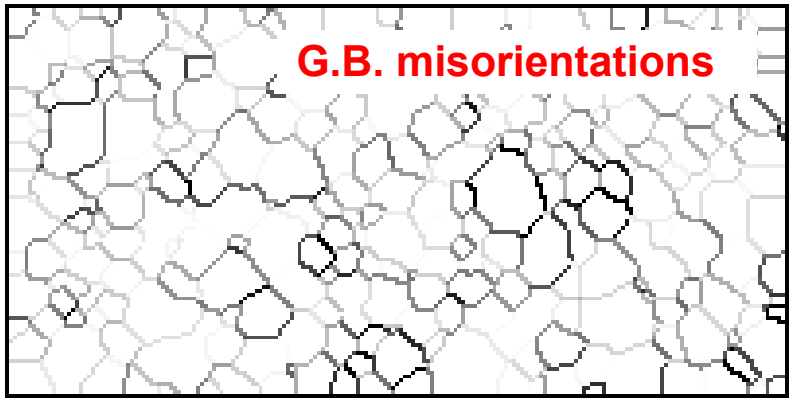
B.

Individual grains are assigned an orientation based on the global texture determined by the X-ray FWHM which is well simulated by a gaussian, assuming no correlations between neighbors



C.

The misorientation angles of grain boundaries are calculated and a grain boundary map generated

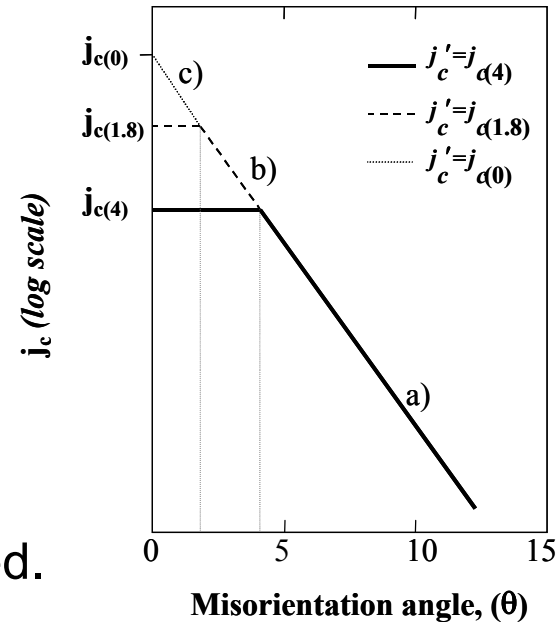


Calculation of the critical current

- Each boundary is then assigned a critical current, based on the misorientation angle (θ); α=2.4°, β=1.8°

  In general : $J_c(\theta)=j_c(0)\exp -((\theta-\beta)/\alpha)$ for $\theta > \beta$

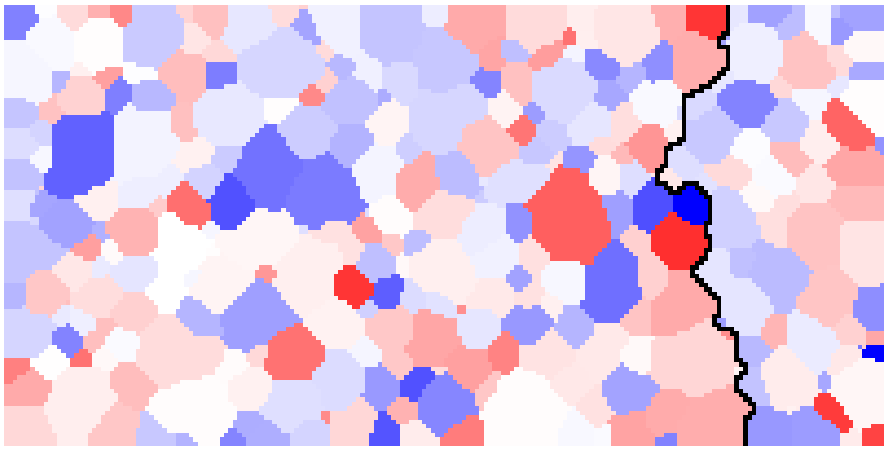
  $J_c(\theta)=j_c(0)$ for $\theta < \beta$



- The maximum flow through the grain boundary network (I_c) is equal to the value of the minimum cut across it.

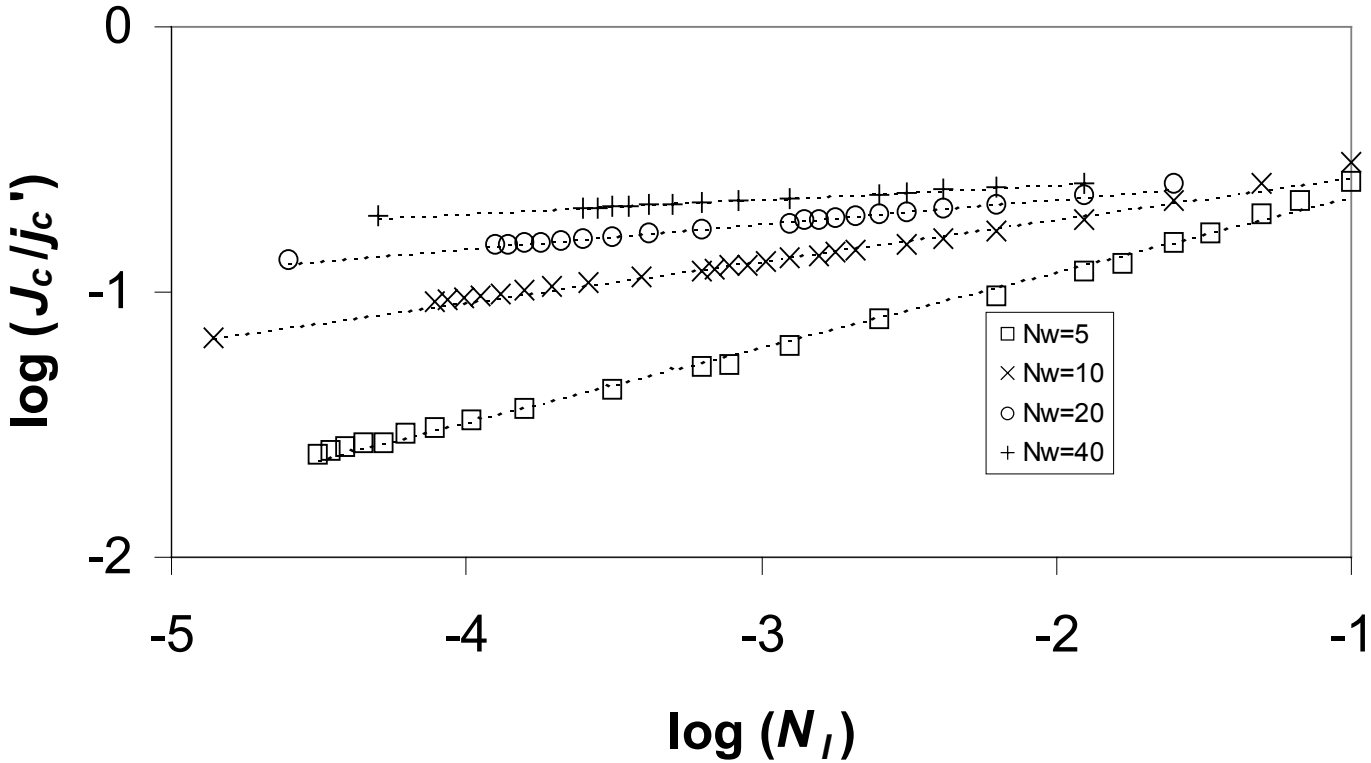
- A "limiting path" is found. Physically, this corresponds to the primary flux flow channel where dissipation is initiated.

- The total critical current of the sample is calculated by summing the individual critical currents of the pixel edges comprising the limiting path.



Effect of conductor dimensions

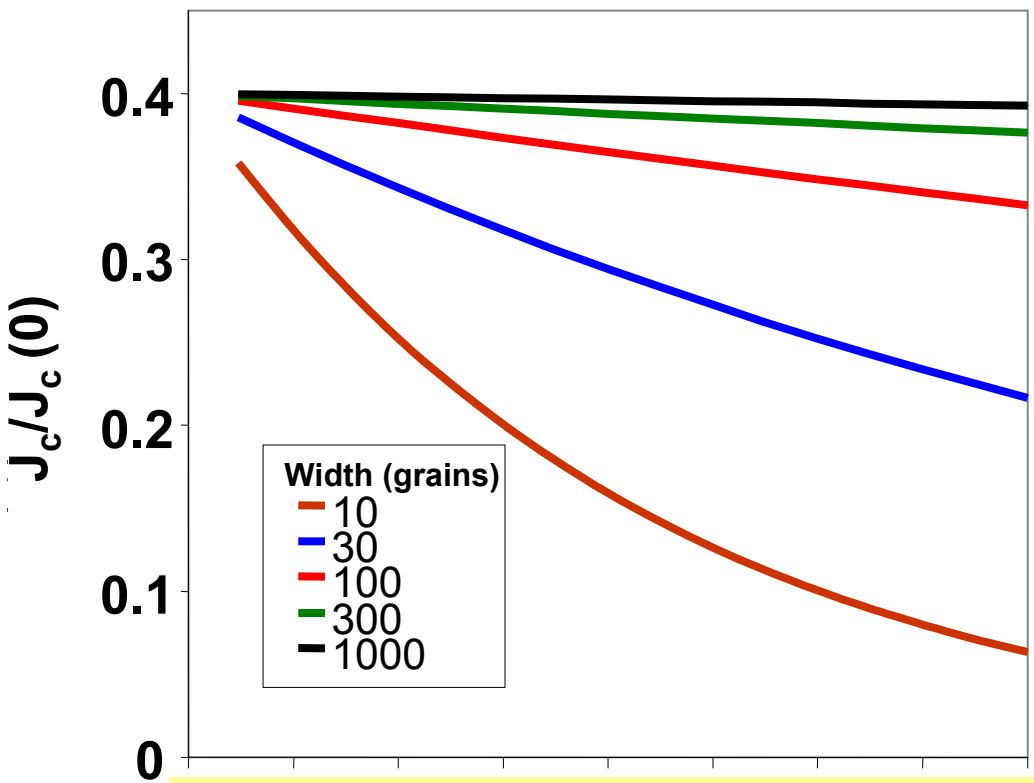
The graph shows how for a given number of grains across the width, log (J_c) varies linearly with log (N_l) and the slope increases as the width decreases.



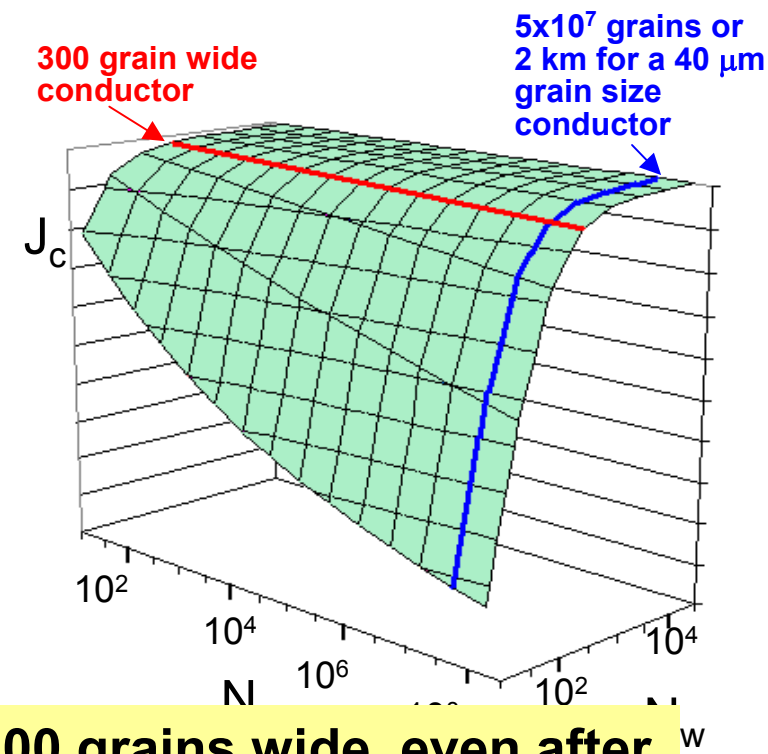
A reasonable approximation of this relationship is

$$J_c \propto (1/N_l)^{1/N_w}$$

Effect of conductor dimensions

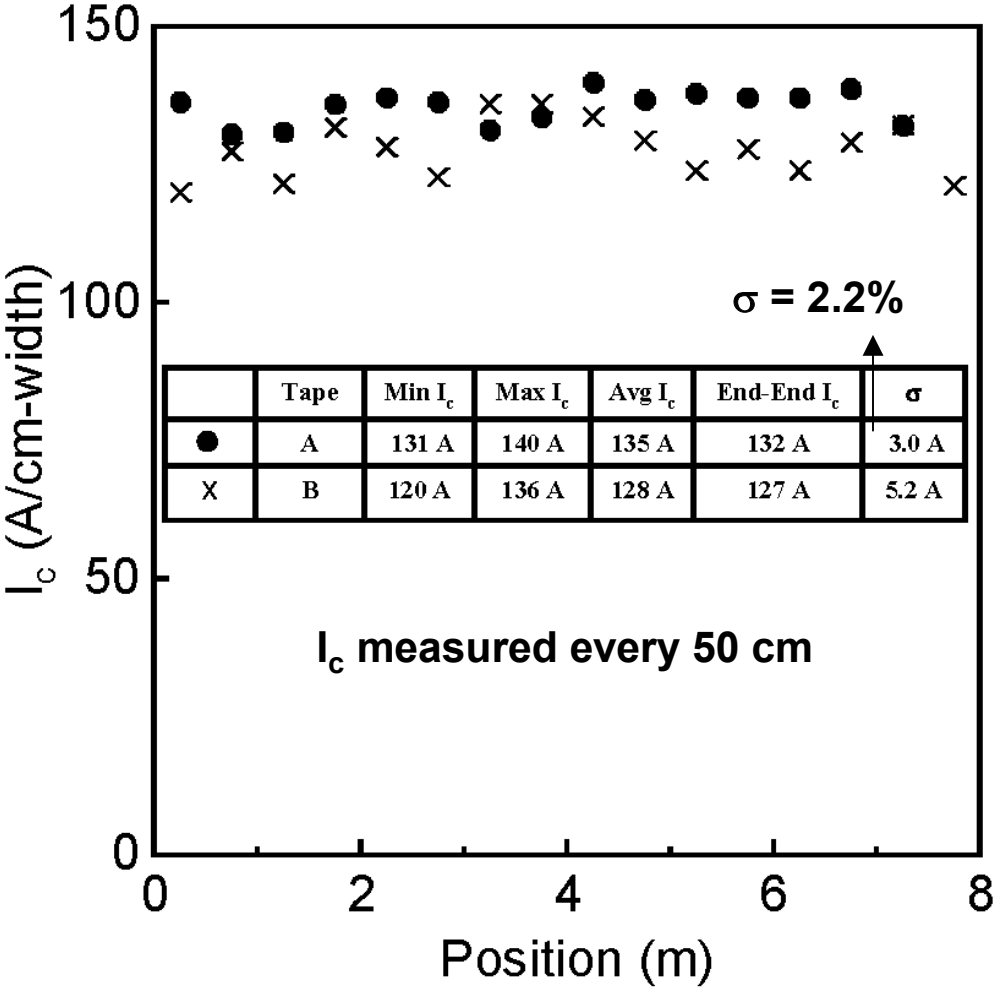


Scaleup to long lengths



As long as the conductor is at least 100 grains wide, even after considering a realistic grain size distribution, the improved percolation model shows that J_c is not significantly reduced and that a percolative pinch-off is not expected

I_c homogeneity in long length, reel-to-reel fabricated YBCO Tapes



	Tape	Min I_c	Max I_c	Avg I_c	End-End I_c	σ
●	A	131 A	140 A	135 A	132 A	3.0 A
X	B	120 A	136 A	128 A	127 A	5.2 A

- Since I-V curves are non-linear for HTS films, a small region anywhere between the voltage taps can be dominant source of voltage
- This results in a situation where the variation of I_c on any length of wire will increase with measurements at shorter voltage taps

1 m section of Wire A was measured every 1 cm at ORNL

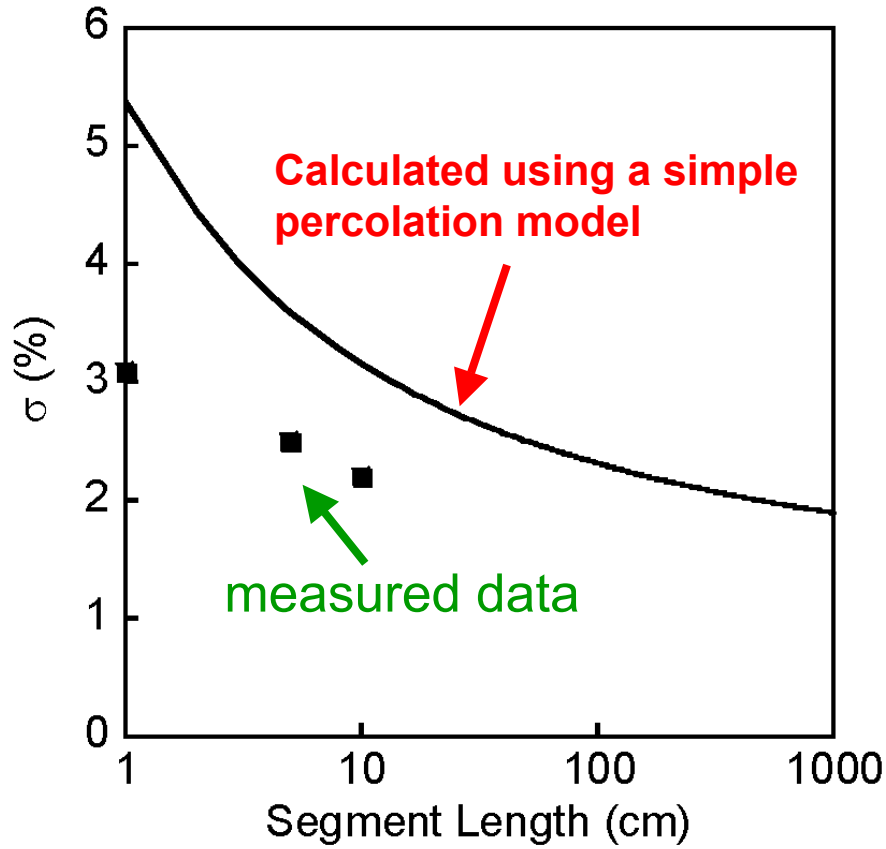
Wire A	1 cm	5 cm	10 cm
Minimum I_c (A)	130	135	135
Maximum I_c (A)	155	148	146
Average I_c (A)	144	143	143
Std. Deviation (A)	4.4	3.6	3.1
Std. Deviation (%)	3.1	2.5	2.2

Can observed variations of I_c in AMSC's YBCO/RABiTS tapes be explained by the inherent statistics of percolation?

Scaling of σ to long lengths

- Experimentally σ = 4.4A for 1 cm segments, with a mean I_c of 144A
- The statistical variation in I_c for longer tapes is simulated by choosing I_c for each 1 cm segment from a Guassian distribution with σ = 4.4 A with the overall I_c for the longer tape being its worst segment assuming an infinitely sharp I-V curve
- The procedure is repeated 10^6 times to find σ for the longer tape

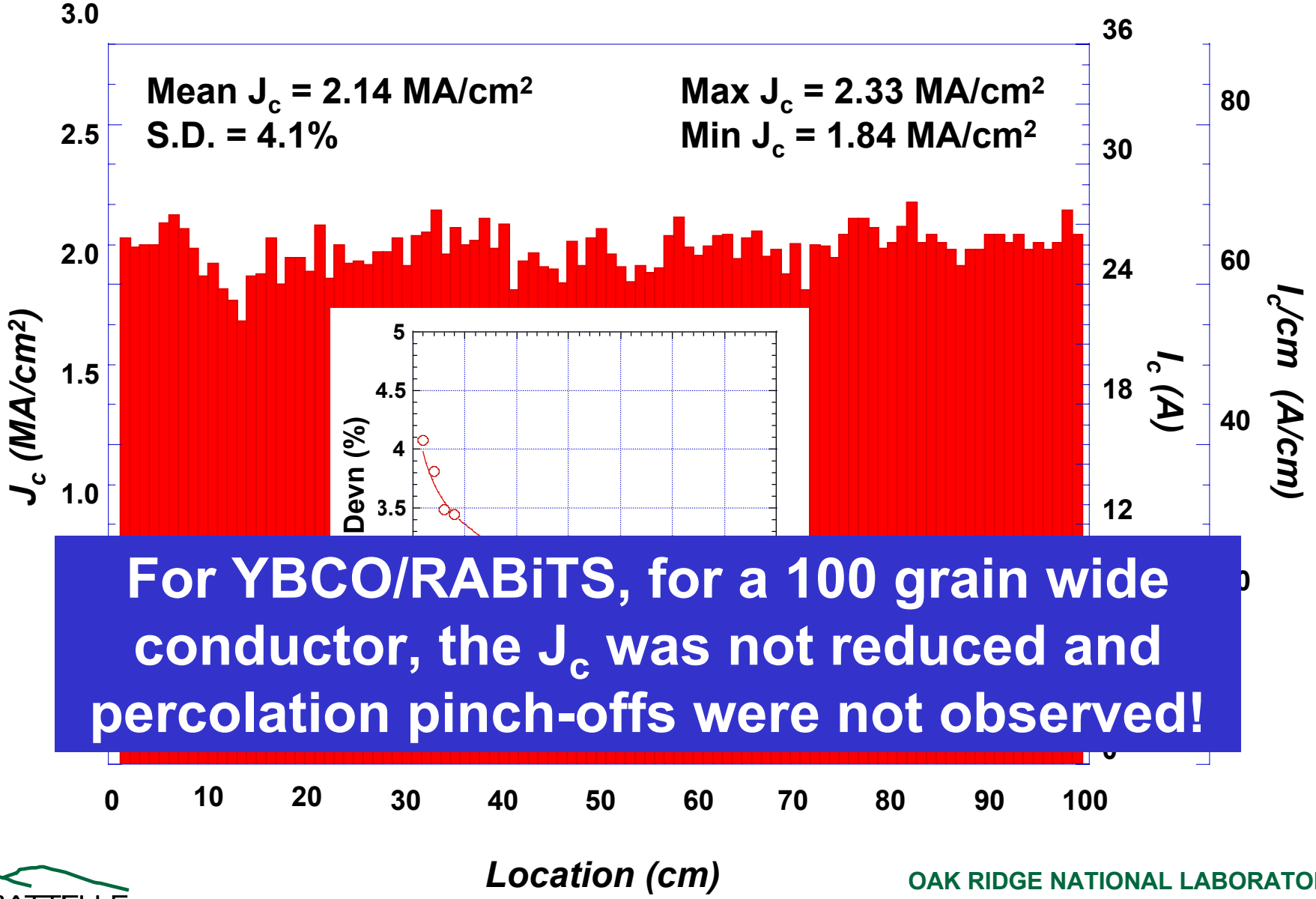
This suggests that the variations in I_c could be explained by the inherent statistics of percolation



Present processing methodology could be extended to long lengths without significant loss of overall I_c

American Superconductor

Actual measurements on a 4 mm wide, 1 meter long, 0.3 μm thick, YBCO/RABiTS



For YBCO/RABiTS, for a 100 grain wide conductor, the J_c was not reduced and percolation pinch-offs were not observed!

FY 2003 Performance

FY2003 Plans

- Develop/improve methodology for characterization of texture in RABiTS type substrates
- Correlate texture and critical current - are present J_c levels primarily limited by degree of texture attained in the substrate?

FY2003 Performance

- ✓ Developed the concept of true phi and illustrated its importance and relevance
- ✓ Determined that the true in-plane texture is 3-5°, and the out-of-plane texture is in the range of 4-8°
- ✓ Demonstrated that the above texture is sufficient to support high J_c and I_c YBCO
- ✓ Illustrated that for RABiTS with these textures J_c continues to increase with improvements in processing
- ✓ Emphasized the importance of determining the effects of small a-axis tilts in RABiTS type substrates

UT-BATTELLE

FY 2003 Performance

FY2003 Plans

- Fabricate long and wide metal/alloy substrates as well substrates with improved physical properties
- Fabricate a more robust buffer layer stack on Ni-3at%W substrates
- Fabricate simpler buffer layer stacks using higher rate deposition processes

FY2003 Performance

- ✓ Fabricated powder metallurgy based Ni-3at%W substrates, 1.2 Km long with excellent homogeneity of texture along the length and width of a 10cm wide substrate
- ✓ Fabricated textured, PM-based Ni-5at%W substrates with a yield strength of 195 MPa and significantly reduced AC losses
- ✓ Demonstrated that formation of a self-limiting $NiWO_4$ layer at the interface of the metal substrate and the seed layer results in better substrate and that uncontrolled oxidation of NiO is prevented
- ✓ Demonstrated that 2 layers in the standard stack can potentially be replaced with a solution LZO layer

FY 2003 Performance Cont'd.

FY2003 Plans (cont'd)

- Develop Cu-based RABiTS with respect to texture development and deposition of epitaxial buffer layers and YBCO
- Develop suitable buffer layer architectures for Cu-based substrates

FY2003 Performance

- ✓ Fabricated highly textured Cu substrates with a true in-plane texture of 4° FWHM and an out-of-plane texture of 4-6° & ~ 100% cube
- ✓ Demonstrated that TiN/MgO/$LaMnO_3$ is a suitable buffer stack for Cu-based substrates – a J_c of 3.5 MA/cm^2 on single crystal Cu and a J_c of 1MA/cm^2 on a 7° bicrystal was obtained
- ✓ Demonstrated a J_c ~ 0.7MA/cm^2 on RABiTS Cu
- ✓ Demonstrated a conductive buffer stack of Ni/LMO on Cu with a J_c of 2.3 MA/cm^2 at 77K, self-field

FY 2003 Performance Cont'd.

FY2003 Plans (cont'd)

- Develop a superior percolation model which takes into account the grain size distribution in the substrate
- Experimental verification of the developed percolation model on continuously fabricated, meter long substrates

FY2003 Performance

- ✓ A significantly improved percolation model which includes a realistic grain distribution was developed
- ✓ It was found from the model that percolative pinch-offs in a RABiTS type conductor would not occur in scale up to long lengths as long as the conductor was at least 100 grains wide
- ✓ Showed that the observed variation of J_c in AMSC 1 cm wide, 10 m tape can be explained by the inherent statistics of percolation
- ✓ Fabricated a 100 grain wide, 1 m long conductor with a J_c over 2 MA/cm^2 and a low standard deviation

FY2004 Plans

Metal/Alloy development:

- Work with outside vendors to obtain improved coils with reduced defects
- Utilize rolling mill with clean room facility to develop a better understanding of experimental parameters affecting texture development in Ni-based alloys
- Research and develop long lengths of powder metallurgy derived Ni-5at%W substrates and transfer of technology to industry
- Fabrication of strengthened Cu-based substrates

Texture and percolation:

- Develop methods aimed at separating the a-axis and c-axis tilt components from the total misorientation measured in EBKP
- Develop an understanding of the affect of small a-axis tilts on J_c

FY2004 Plans

Buffer layer development:

- Further research conditions to obtain a self-limiting oxide layer on Ni-3at%W and Ni-5at%W substrates
- Determine required thicknesses of the various oxide layers in the buffer stack to sustain the processing conditions for thick YBCO by ex-situ processing
- Develop improved buffer architectures which reduce oxygen diffusion to the metal/alloy substrate
- Further develop suitable architectures for Cu-based substrates which can support a high-J_c, thick YBCO
- Develop high rate processes for buffer layer depositions

FY2004 Plans

Utilize an additional attribute of the RABiTS substrate – same texture on both sides of the substrate

- **Develop processing conditions for fabricating double side coated substrates**

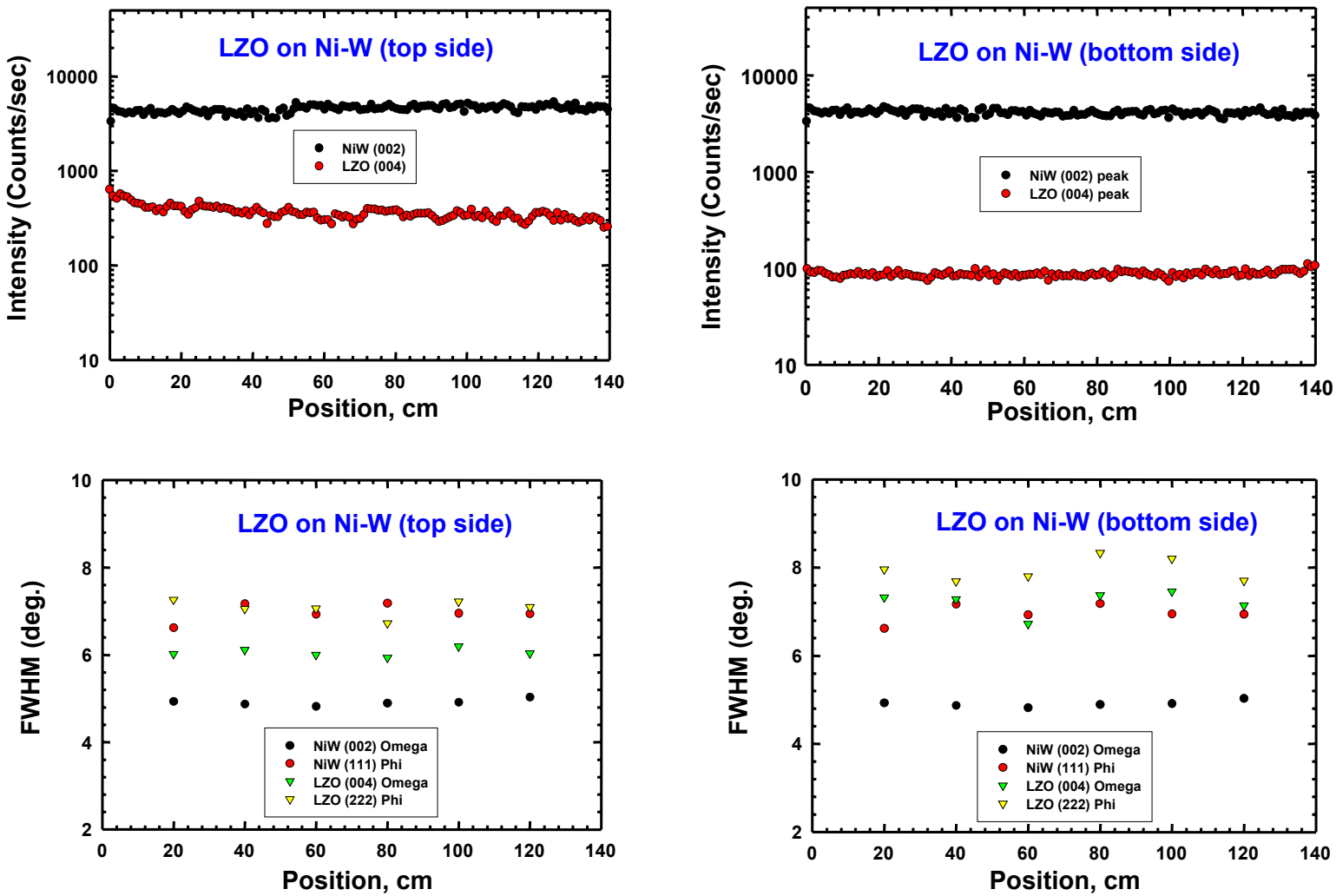
Advantages of double sided coating:

- Higher I_c and J_E
- For the same required I_c, thinner films are required because of the exponential drop of J_c with thickness
- Better mechanical stability
- Reduced overall processing times for ex-situ films
- Lower AC losses?

Disadvantages of double sided coating:

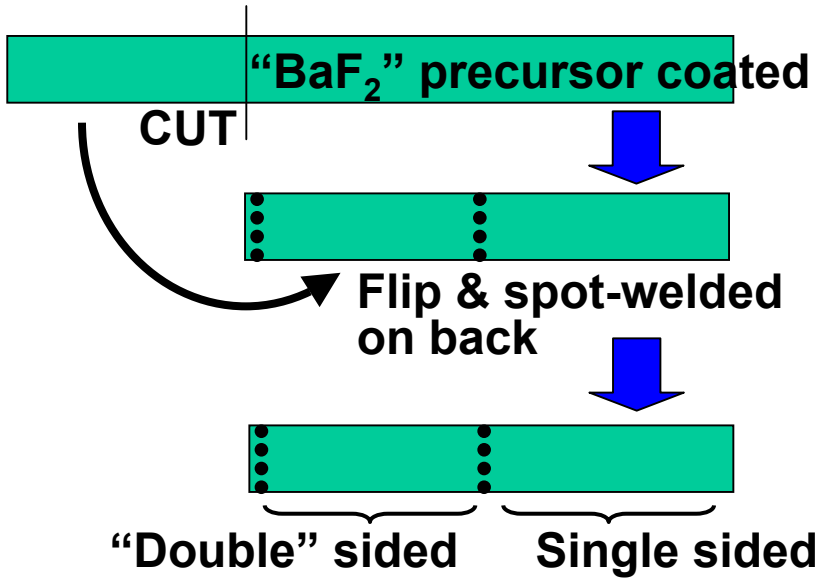
- More difficult processing
- Issues related to translating substrate on guides

Over 1.4 meter long, double-sided, reel-to-reel dip-coated LZO seeds on textured Ni-W substrates were produced



Can YBCO be converted easily using the ex-situ BaF_2 process if tape is coated on both sides?

Simple test using reel-to-reel atmospheric furnace → HF buildup, most unfavorable conditions among our systems:



0.9μm YBCO

	I_c (A)
Single sided	124
Double (top)	117
Double (bottom)	121

Processed with conversion time corresponding to that for single sided tape

Research into merits and problems of a double sided conductor is warranted

Research Integration: *Interactions with Companies*

- American Superconductor Corporation (AMSC)
  - Have a CRADA with AMSC
  - Work on substrates is a significant component of the CRADA
- MicroCoating Technologies (MCT)
  - Have a CRADA with MCT
  - Provided alloy substrates for growth of buffer layers and buffered substrates for growth of YBCO
- Oxford Superconducting Technology (OST)
  - Have a CRADA with Oxford
  - Work on substrates is the only task of the CRADA
- Neocera - Provided substrates for growth of YBCO
- Superpower - Provided substrates for growth of YBCO
- MetoX - Provided substrates for growth of YBCO
- Ametek Corporation - Developing fabrication of starting coils
- Hamilton Precision Metals - Developing rolling process for coil

Research Integration: *Interactions with universities*

Have provided substrates and/or YBCO/RABiTS to the following:

- University of Tennessee: J. R. Thompson / H. Weinstock (AFOSR)
- University of Houston: K. Salama / H. Weinstock (AFOSR)
- University of Florida: D. P. Norton / H. Weinstock (AFOSR)
- University of Houston: Alex Ignatiev
- University of Cincinnati: Donglu Shi
- University of Kansas: Judy Wu
- Embry-Riddle Aeronautical University: John Mathis
- University of Missouri-Rolla: Jay Switzer
- University of Augsburg: J. Mannhart
- SUNY Buffalo: David Shaw
- North Carolina State University: J. Narayan
- California State University: Chuhee Kwon

Research Integration

Interactions with national laboratories:

Have provided substrates and/or YBCO/RABiTS to the following:

- **NIST: N. Cheggour, J. Ekin, W. Wong**
- **ANL: V. Maroni**
- **LANL: T. Holesinger**
- **SNL: P. Clem, M. Siegel**
- **NREL: R. Bhattacharya**
- **WPAFB: P. Barnes, T. Haugan, R. Nekkanti**

Communications:

- **Many publications**
- **Numerous presentations**
- **Several patents**
- **Information also dispersed via CRADA teleconferences/meetings**