RABiTS™ Substrates Research & Development

OAK RIDGE NATIONAL LABORATORY

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FY 2004 OETD Funding: $900K

Why do R&D of RABiTS™ Substrates?

Answer: To address "R&D Needs/Knowledge Gaps" identified in the DOE Roadmap (8/03).

Needs/Gaps addressed in this project include:

- To understand microstructural factors affecting J_c
- To develop rolling technology and tools to produce long, wide substrates
- To understand the interfaces between epitaxial layers
- To develop non-Ni substrates
- To study grain boundaries
- To develop methods to characterize physical properties

Objective and Approach

Objective: To **explore fundamental issues** of the RABiTS process and to **advance the technology** to enable commercial fabrication of YBCO/RABiTS

Approach: To focus on the two main steps of the RABiTS process – **fabrication of textured metal** and **deposition of buffer layers** and to address issues identified as important by our industrial partners and the broader technical community

Specific Objectives/Milestones

1. Develop robust buffers on ORNL Ni-3at%W substrates in reel-to-reel configurations.

2. Utilize the ORNL rolling mill with clean room facility to develop substrates. Support industrial partners with rolling activities. Develop with outside vendors better starting coils.

3. Continue magnetization studies for a better understanding of AC loss contributions from the alloy substrates.

4. Fabricate long lengths of Cu-based substrates and develop fully-conductive buffer architectures.

5. Perform percolation calculations using experimentally achievable texture in RABiTS, both in self-field and applied field.

6. Resolve the in-plane and out-of-plane misorientations from the total misorientation angle and relate this to critical current density.

7. Develop further solution buffers and fabricate double-sided RABiTS.

Presentation Outline

- **FY 2004 Results**

  Reel-to-reel buffer layer development on Ni-3at%W substrates **(Fred)**

  Development of ORNL Rolling facility with clean room (Amit)
  AC losses from alloy substrates
  Development of Cu-based, conductive RABiTS
  Development of Ni-based, non-magnetic RABiTS
  Percolation calculations in applied fields
  Separation of in-plane and out-of plane misorientations
  Enhancement of intragranular-J_c

  Development of solution buffers (Parans)

- FY 2004 Performance and FY 2005 Plans (Parans)
- Research Integration

Objective 1: Reel-to-reel buffer layer development on Ni-3at%W substrates

Fact: Over 1km of Ni-3at%W substrate was **successfully fabricated** in FY03 with ~100% cube texture and sharp in-plane and out-of-plane texture.

Problem: ***Frequent delamination*** of standard buffers, Y_2O_3/YSZ/CeO_2, was observed for this powder metallurgy derived ORNL Ni-W substrate.

In contrast: American Superconductor Corp. has observed **NO delamination** on Ni-W substrates. However, their substrates are from coils derived with vacuum melting and undergo different subsequent processing.

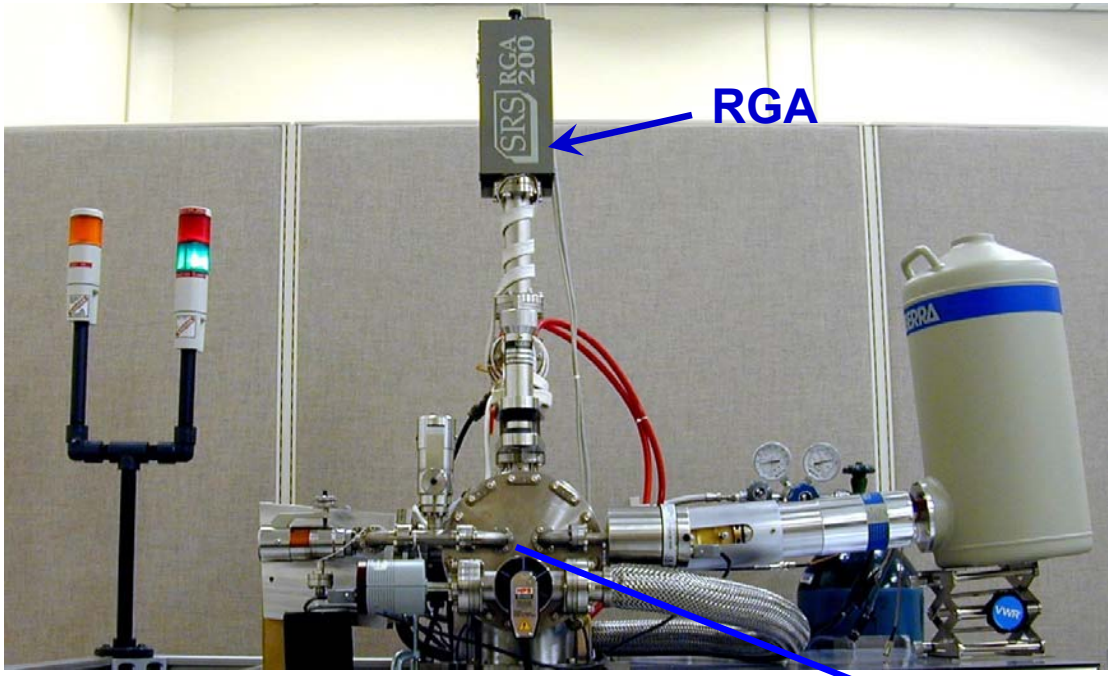
Question: Why do ORNL buffers delaminate while AMSC buffers don't?

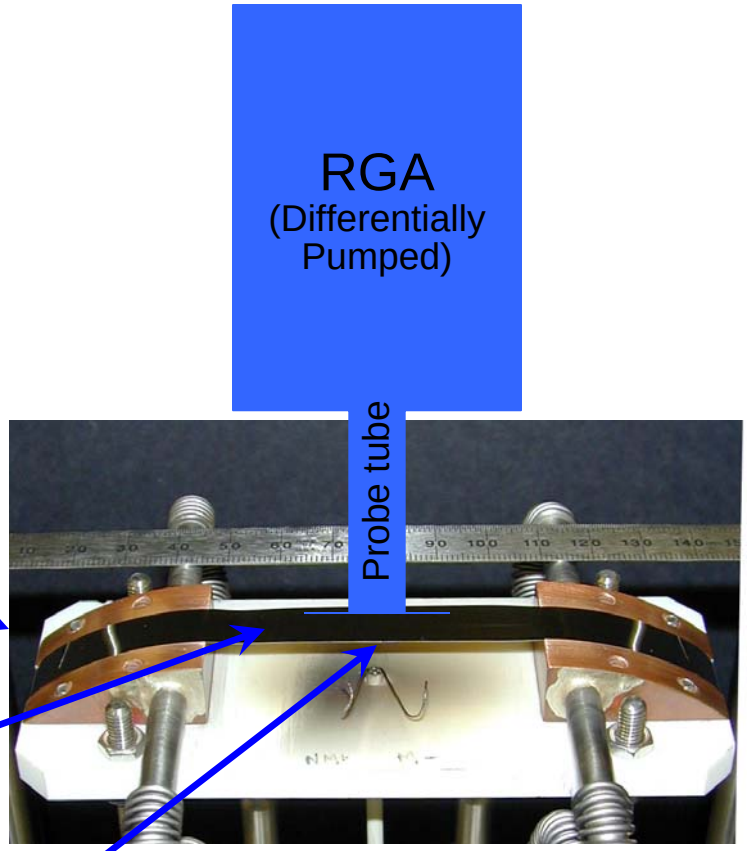
FY'04 Challenge: **Identify and eliminate the cause of delamination** of buffer layers on well-textured ORNL Ni-W substrate.

Numerous causes were explored in FY'04 including:

- buffer layer related (porosity, stoichiometry) ☹
- substrate related (carbon content, thermal history) ☺

Heat treatment of Ni/W substrates has been studied by thermal desorption spectroscopy (TDS)



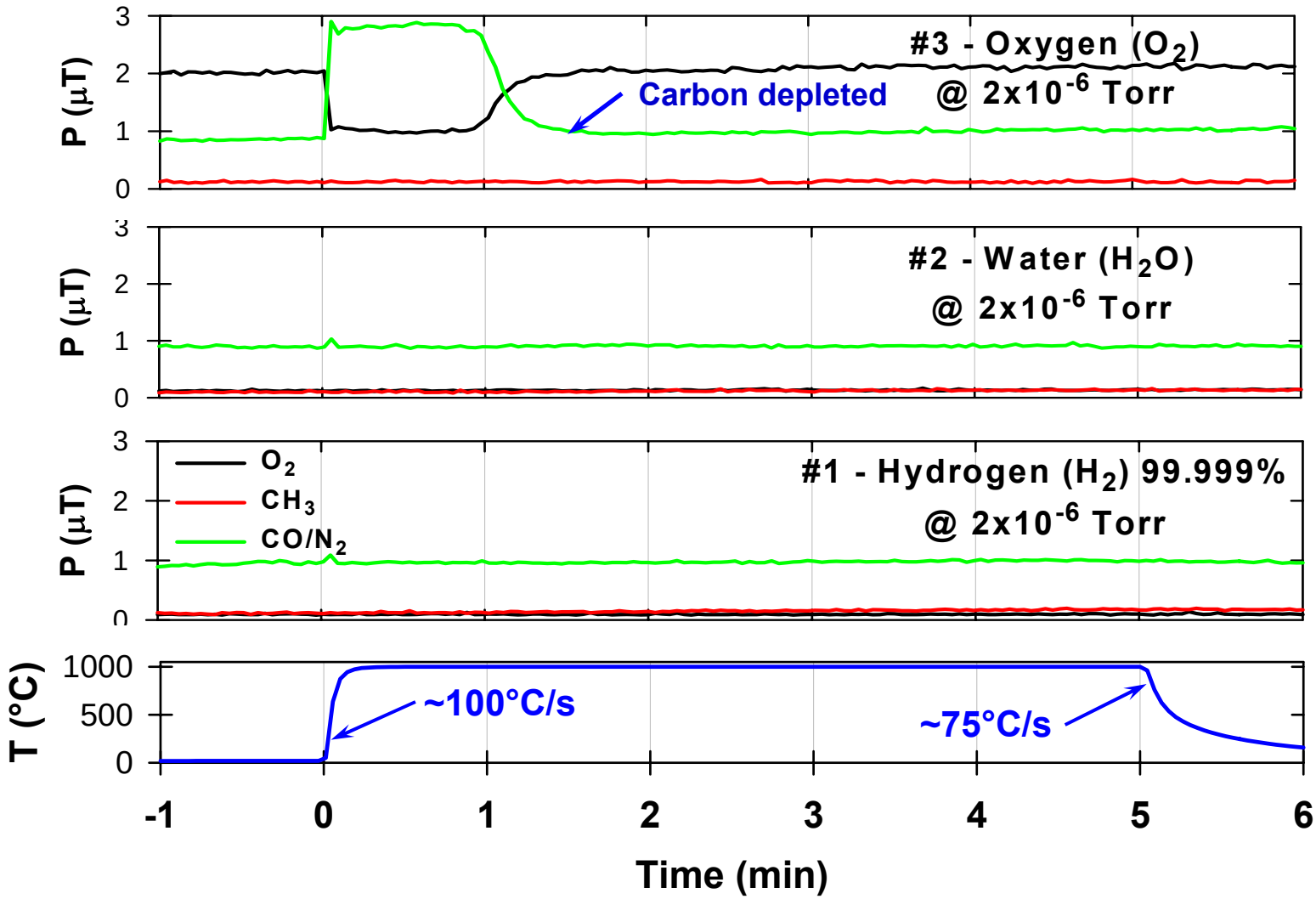


TDS System
Base pressure: ~5 x 10^{-8} Torr
Sample Heating: Resistive
Gases: H_2O, O_2, H_2

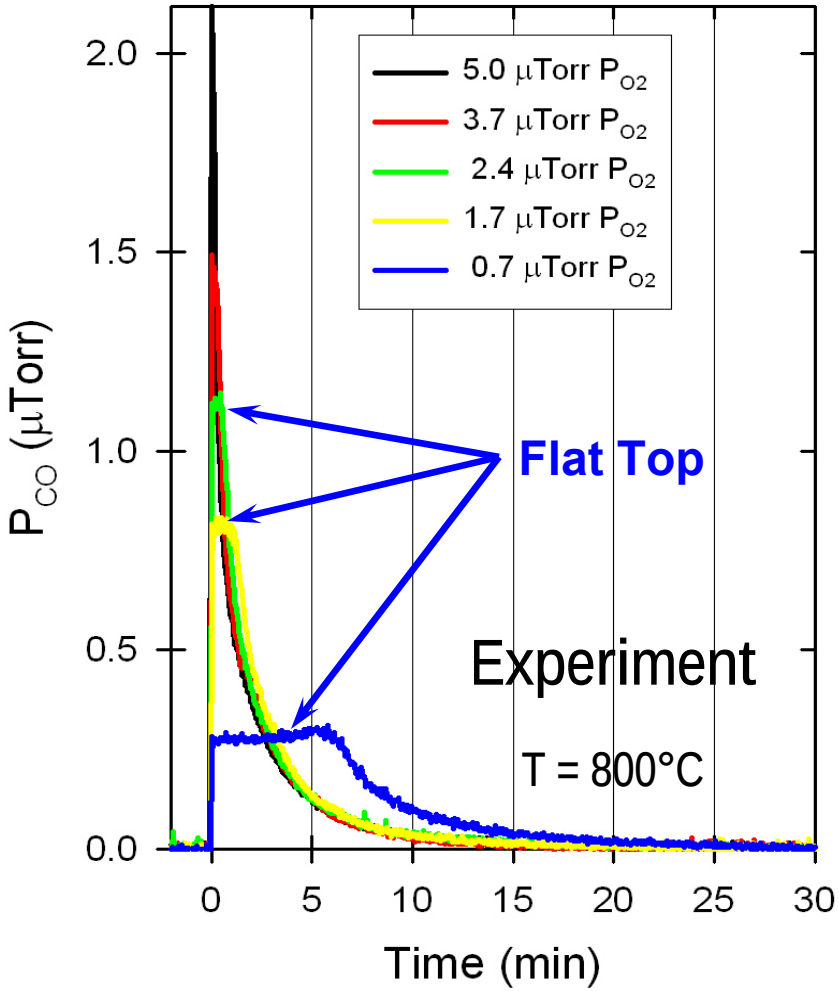
Ni/W Substrate

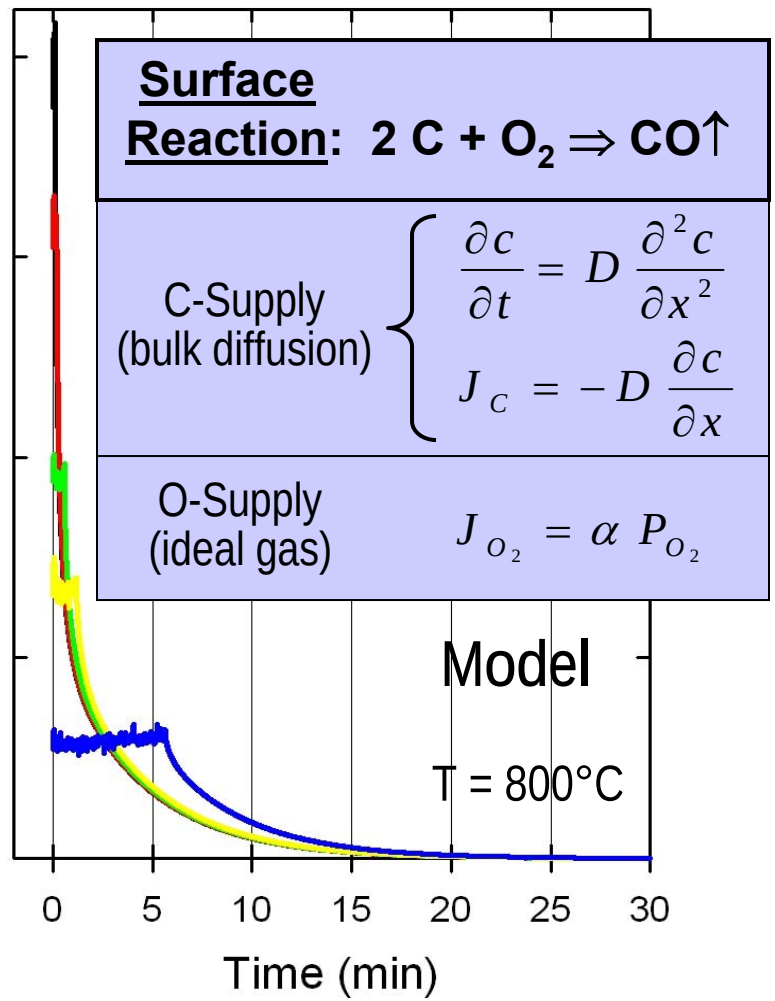
Thermocouple

CO desorption from Ni-3%W involves oxygen and a depletable source of carbon.

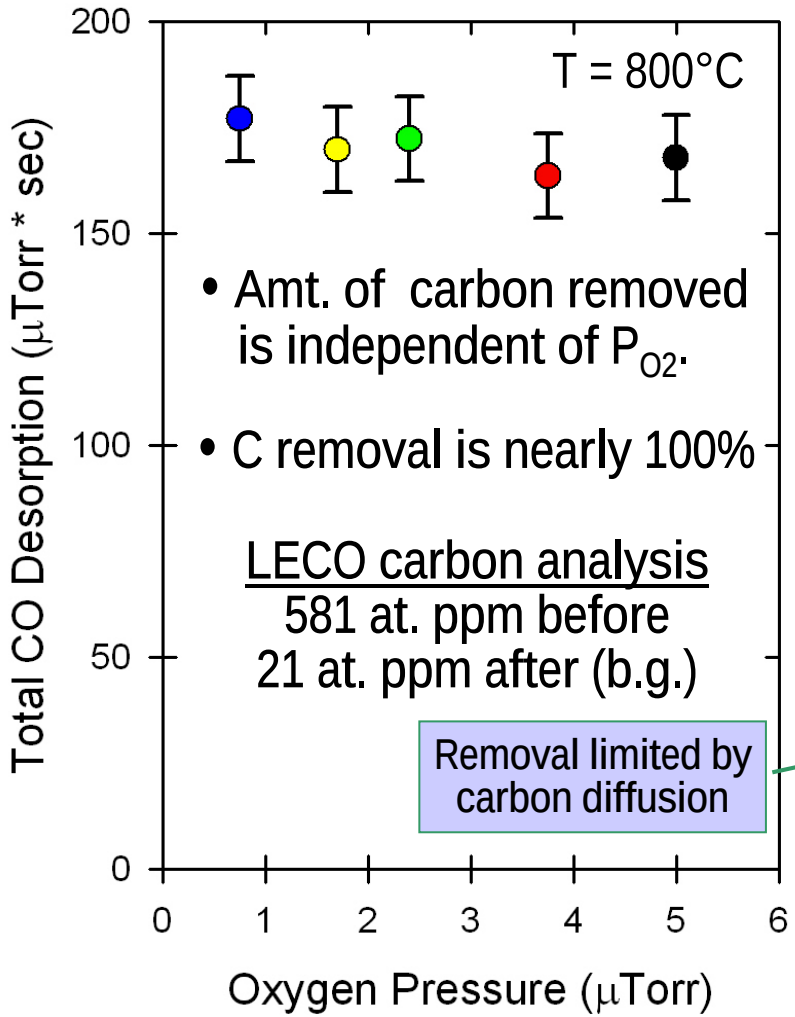


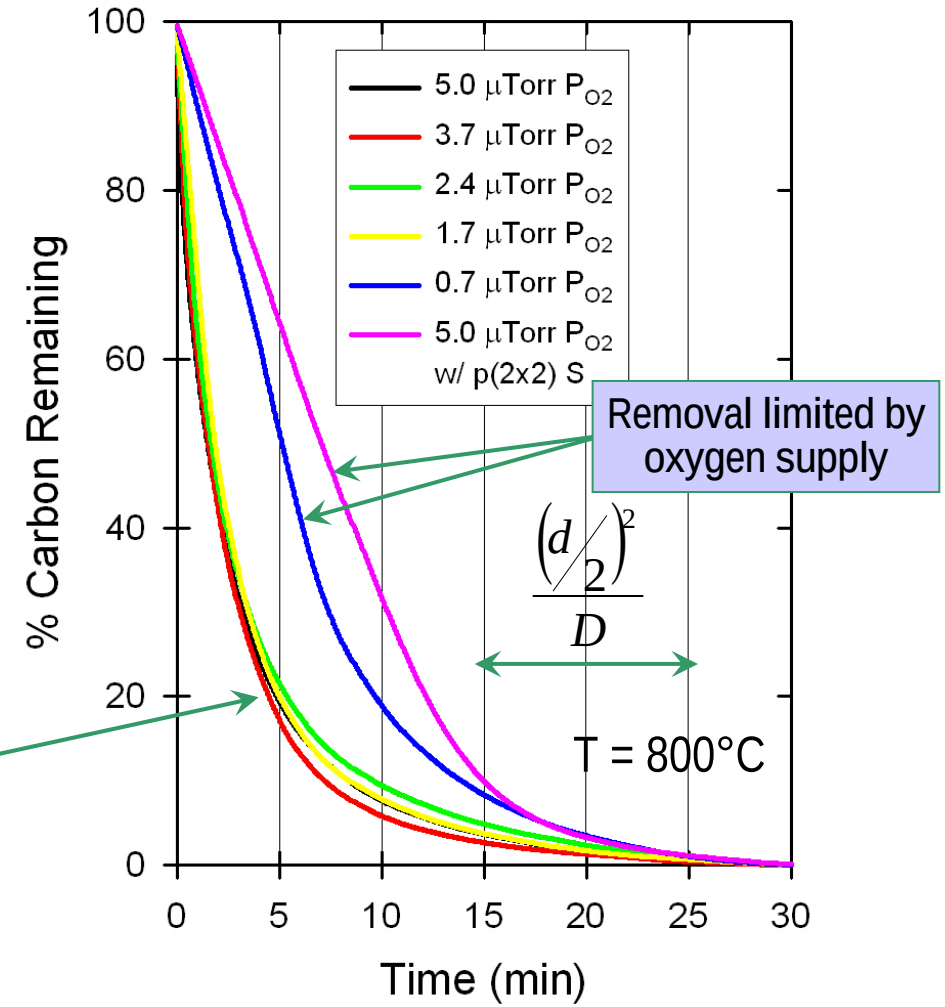
Good agreement of a 1-D diffusion model with the CO desorption data is obtained.



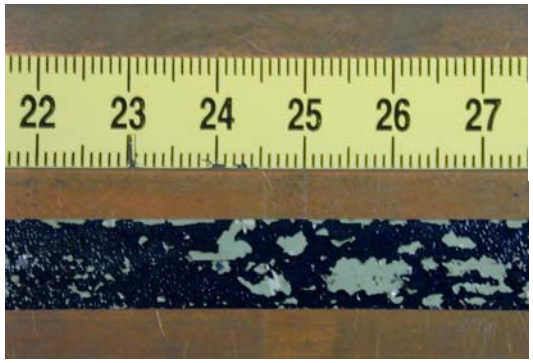


Carbon removal from Ni/W tape can be determined by integration of the CO desorption flux.





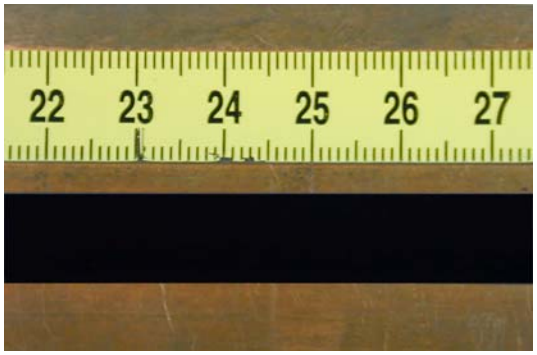
Carbon depletion on lengths of Ni-3%W gives high I_c/J_c and no buffer delamination.



No C-depletion

Severe delamination

$J_c = 0$



C-depleted

(850°C, 30 min, 5×10^{-6} Torr O_2)

No delamination

J_c = 1.2 MA/cm^2 – E-B precursor (ORNL)

J_c = 1.7 MA/cm^2 – MOD precursor (AMSC)

J_c = 1.2 MA/cm^2 – MOCVD *in situ* (MetOx)

- **Low levels of carbon (<600 at. ppm) can contribute to buffer delamination.**
- **Carbon removal is simple, rapid, and predictable.**

Problem solved !

Presentation Outline

- FY 2004 Results

  Reel-to-reel buffer layer development on Ni-3at%W substrates (Fred)

  Development of ORNL Rolling facility with clean room (Amit)
  AC losses from alloy substrates
  Development of Cu-based, conductive RABiTS
  Development of Ni-based, non-magnetic RABiTS
  Percolation calculations in applied fields
  Separation of in-plane and out-of plane misorientations
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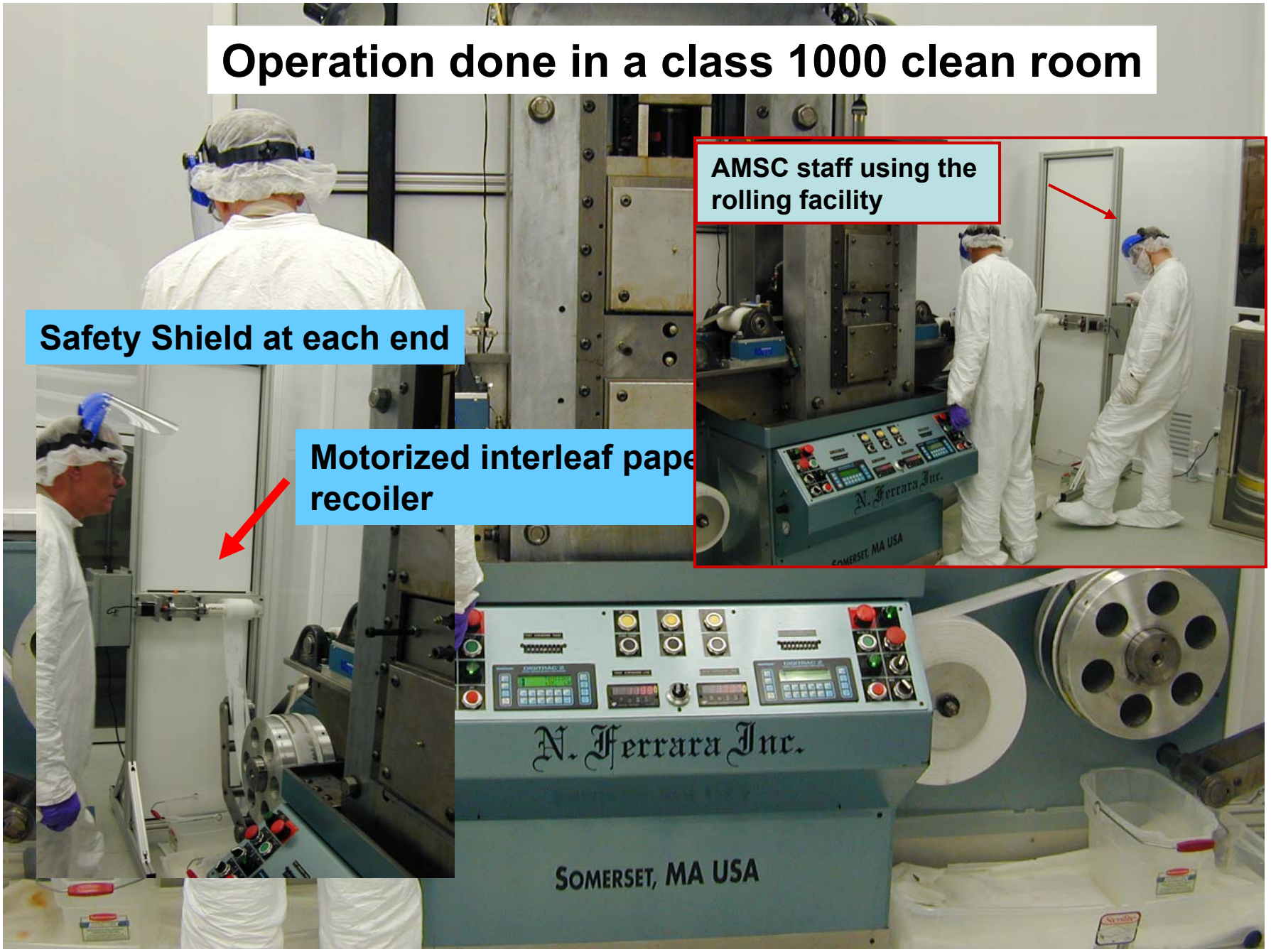
  Development of solution buffers (Parans)

- FY 2004 Performance and FY 2005 Plans (Parans)
- Research Integration

Objective 2: Development of Rolling Mill Facility at ORNL

- Water sprinkler system on roof (very expensive)
- Installed a pressure differential sensor
- particle count detector, telephone inside clean room

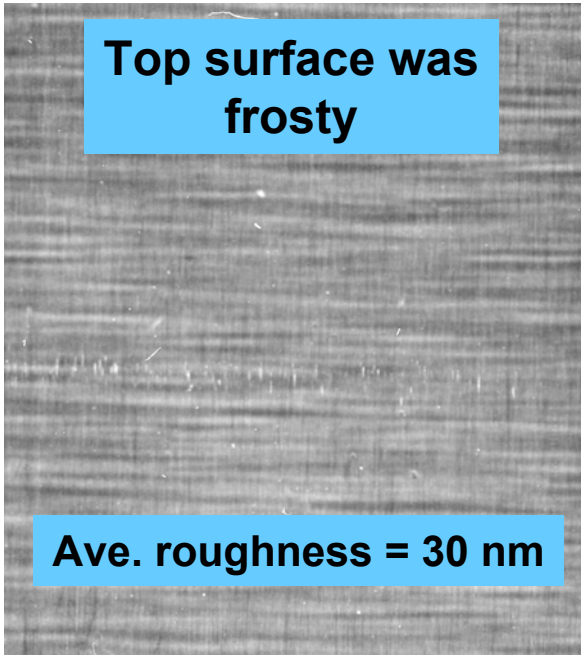
Operation done in a class 1000 clean room

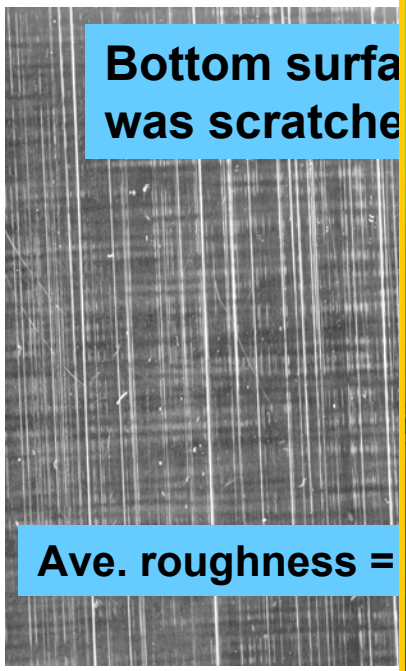


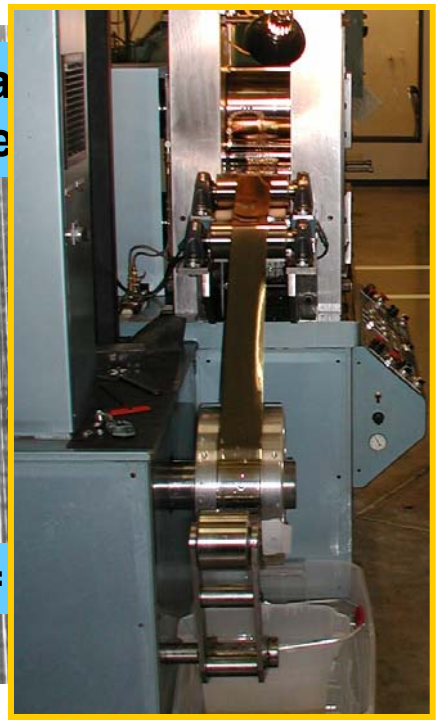
Goal was to fabricate wide area substrates for American Superconductor's scale-up efforts

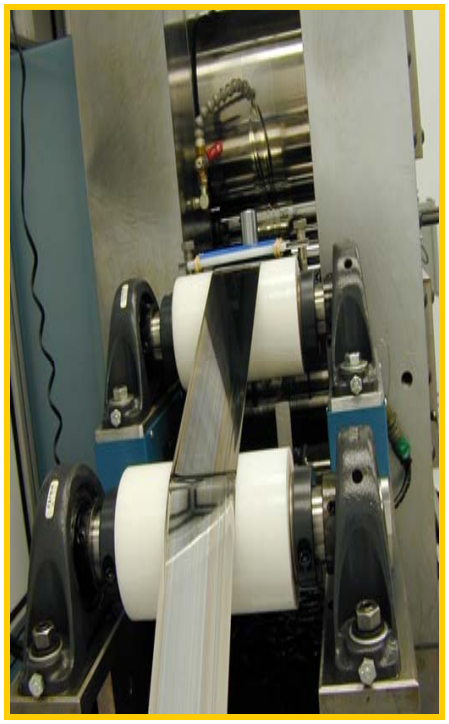
- AMSC interested in high rolling speeds for high throughput
- Significant problems were encountered initially

Fixing the bottom surface was easy

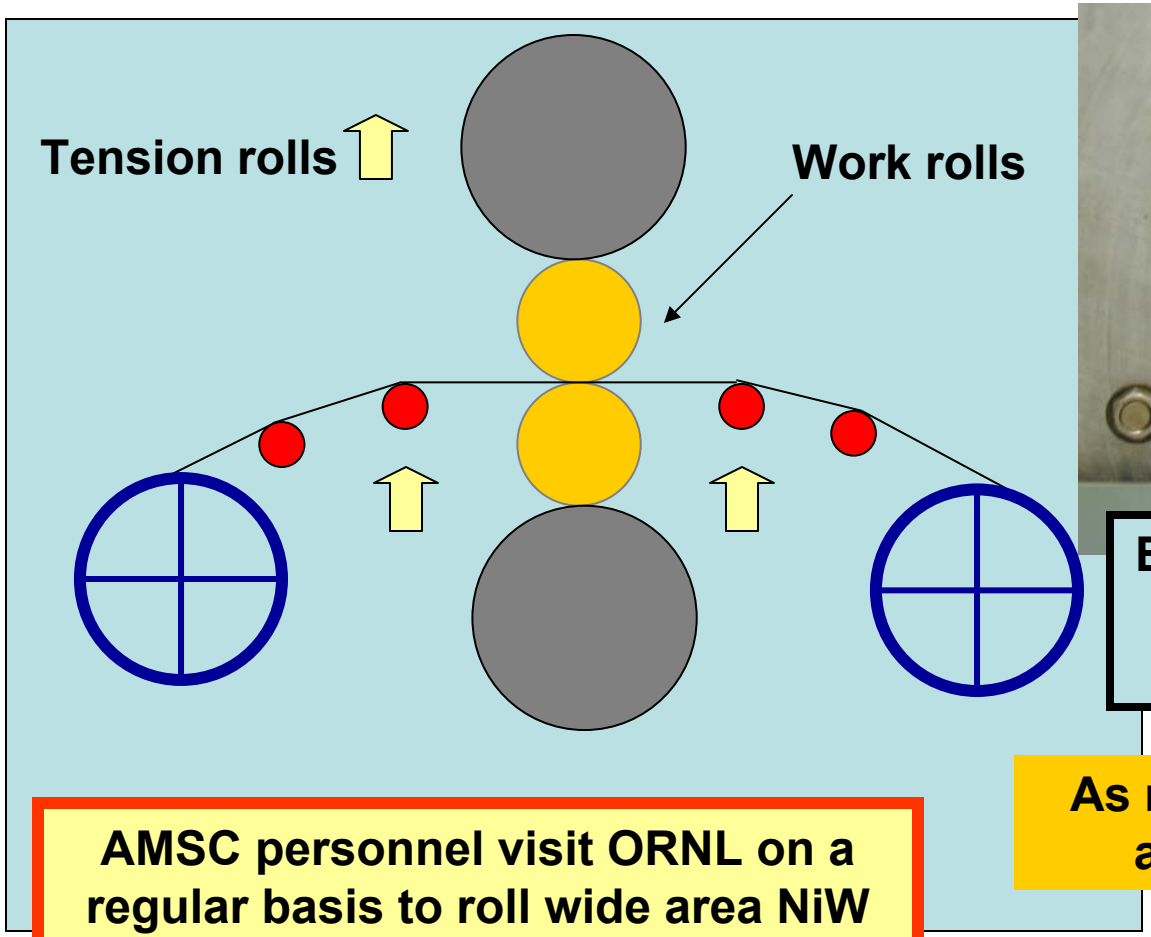


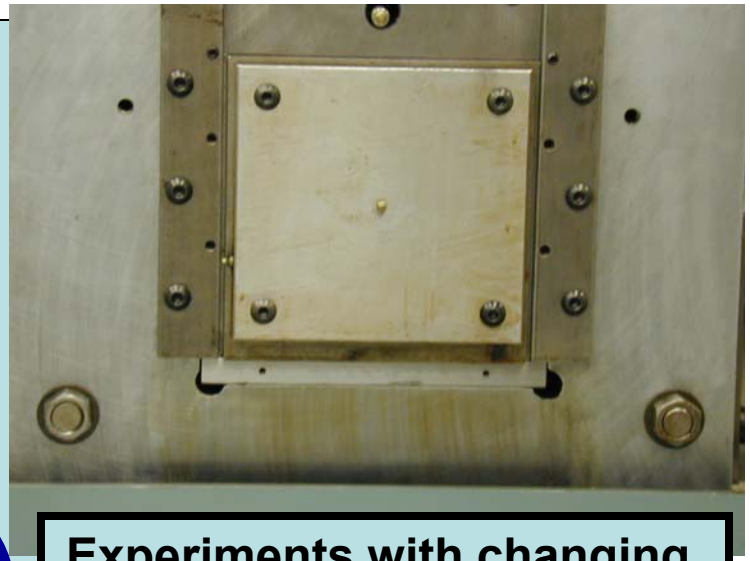






Modifications to the mill were made and lubricant viscosity was experimented with to obtain a smooth top surface





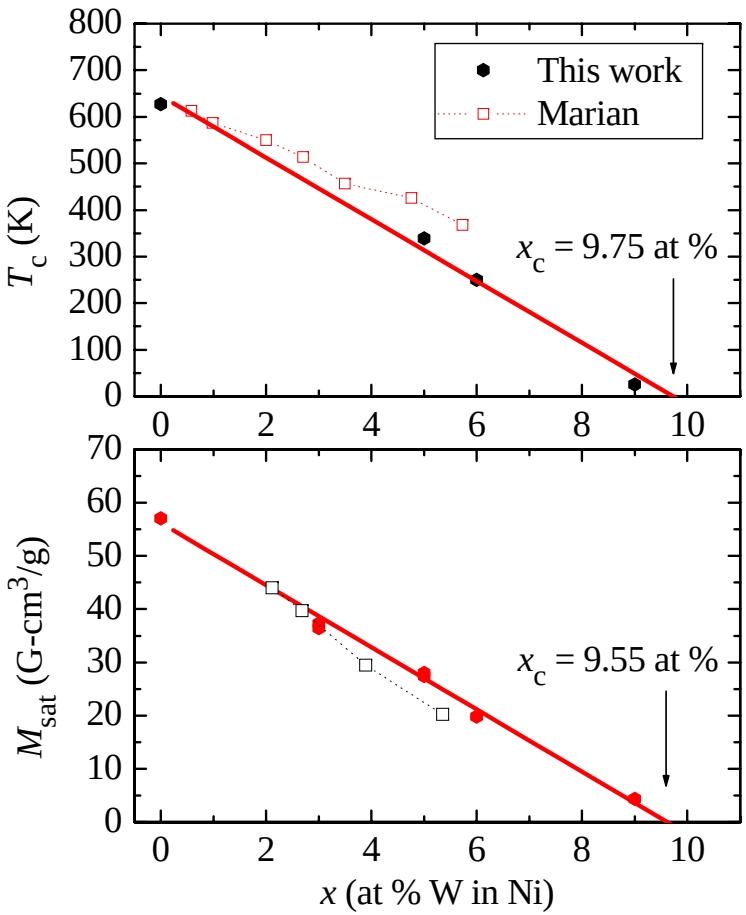
Experiments with changing lubricant viscosity were done

As rolled surfaces are smooth and require no polishing

AMSC personnel visit ORNL on a regular basis to roll wide area NiW substrates for scale-up efforts and this has been the primary activity of the mill this year.

Objective 3: Continue magnetization studies aimed at a better understanding of AC loss contribution from the alloy substrates

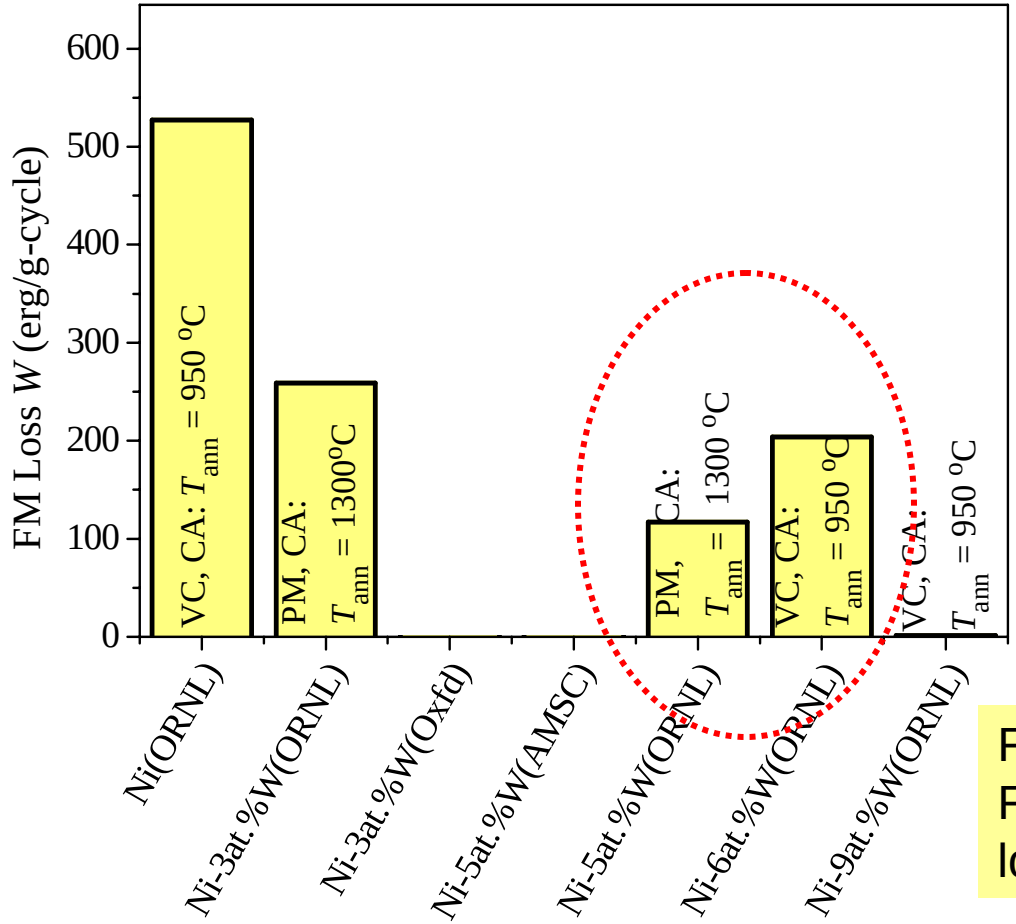
Focus this FY has been on textured Ni-W alloys



Ferromagnetic losses in low alloy content substrates are an *extrinsic* as opposed to an *intrinsic* property

Superconductor	Ferromagnet
Intrinsic properties	
T_c H_c	Curie temp., T_c Spontaneous magnetization
Extrinsic properties	
Vortex pinning Critical current density	Domain wall pinning Coercive field

ac losses in cube-textured Ni-W substrates



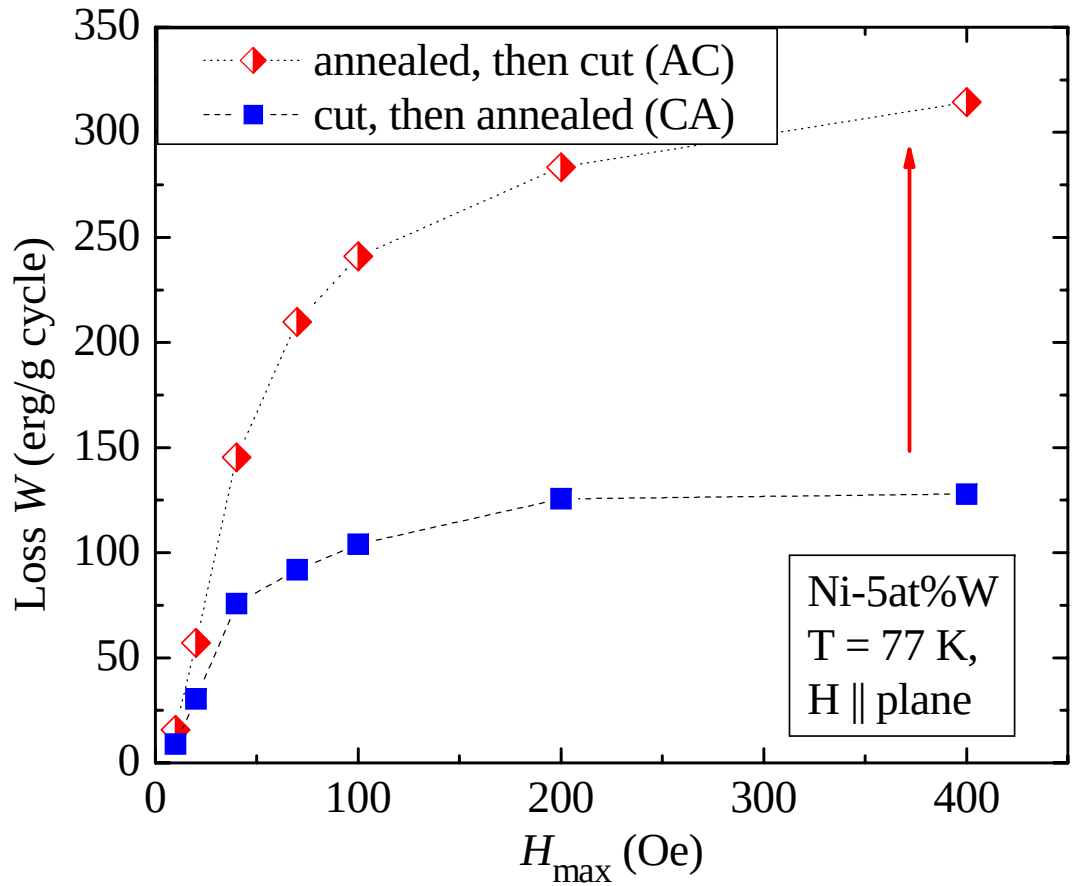
FM loss @ 77K
(H_{max} = 400 Oe)

Materials Preparation:
VC = vacuum cast
PM = Powder metallurgy
CA = Cut and anneal
AC = Anneal and cut

For I_o/I_c in the range of 0.6-0.8, the FM loss is about 4-10% of the total loss for bending strains of 0.4%

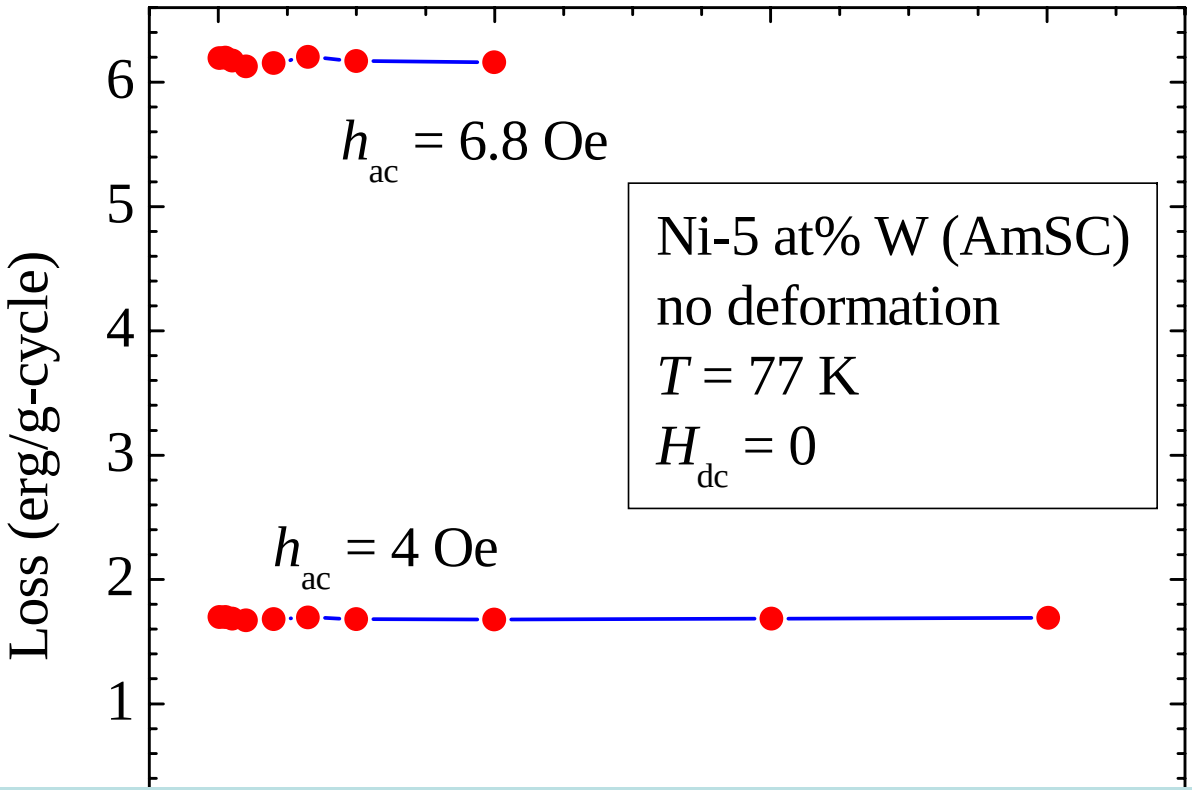
- loss tends to decrease as W-content *x* increases, and
- loss decreases for alloys annealed at higher temperatures (PM materials).
- **loss increases significantly with cutting/slitting; also bending deformation**

ac losses in cube-textured Ni-W substrates



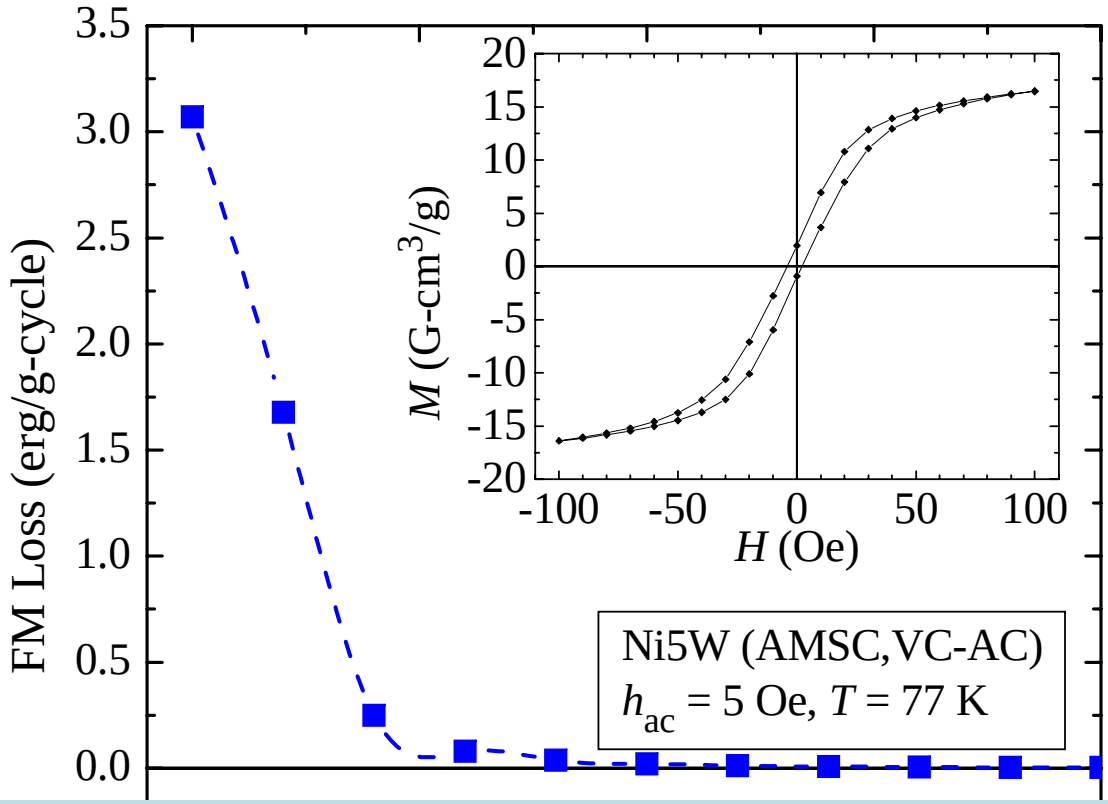
Use of a non-magnetic substrate is desired for applications in AC fields

ac FM losses are independent of ac frequency for 100's of Hz



This is important for specialized applications of coated conductors, such as airborne generators and devices, having operating frequencies well above the usual 50-60 Hz of the electric power grid

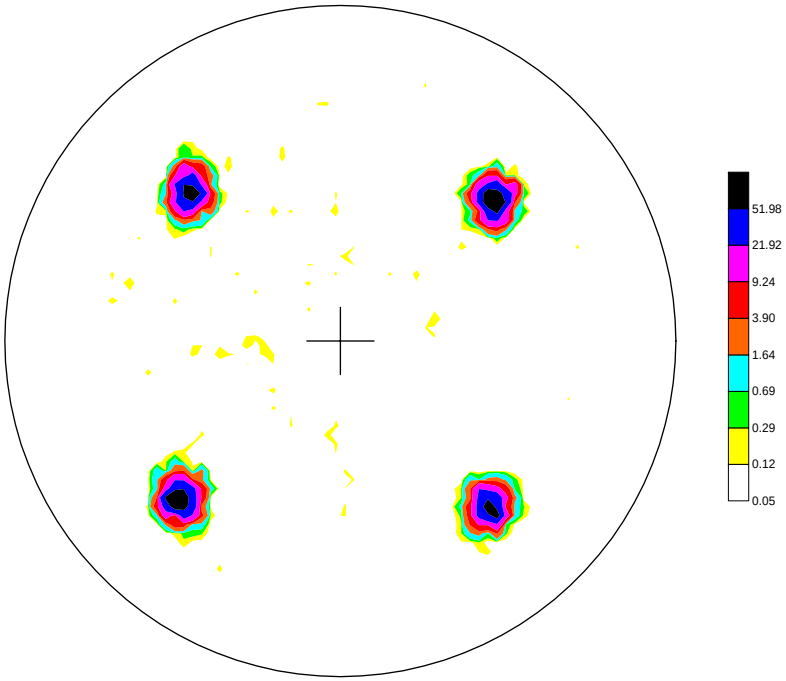
ac loss decreases significantly when dc bias field saturates the Ni-alloy substrate



This is important for certain applications where superpositioning of ac and dc fields can occur such as in the stator of a motor

Reel-to-reel rolling of vacuum cast derived, non-magnetic, Ni-13at%Cr coil has been accomplished in FY04

Ni-13at%Cr (111), log-scale pole figure ~100% cube



Texturing of non-magnetic NiW alloy is in development

FWHM $\Delta\phi$ = 6.0 (True Phi)
FWHM $\Delta\omega$ = 6.25, 4.5

BUFFER LAYER OPTIONS

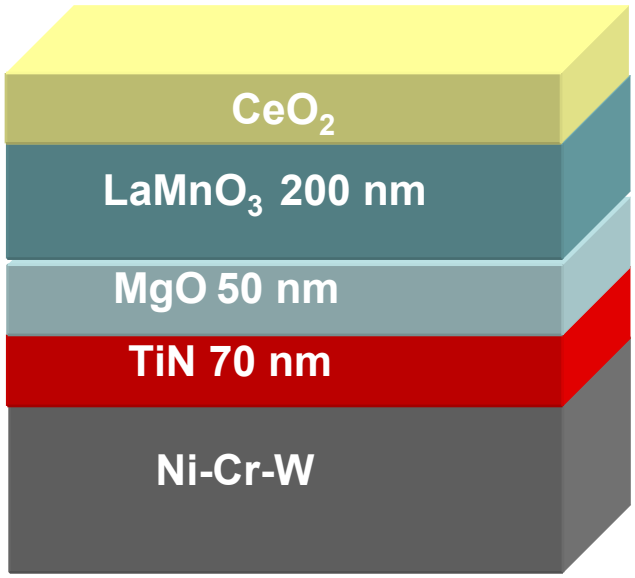
1) Ni-13%Cr/Pd/MgO/LMO
   J_c ~ 3 MA/cm^2 @ 77 K, sf

2) Ni-Cr-W/TiN/MgO/LMO/CeO_2
   J_c ~ 1.8 MA/cm^2 @ 77 K, sf
   Ex-situ 0.8 μm YBCO

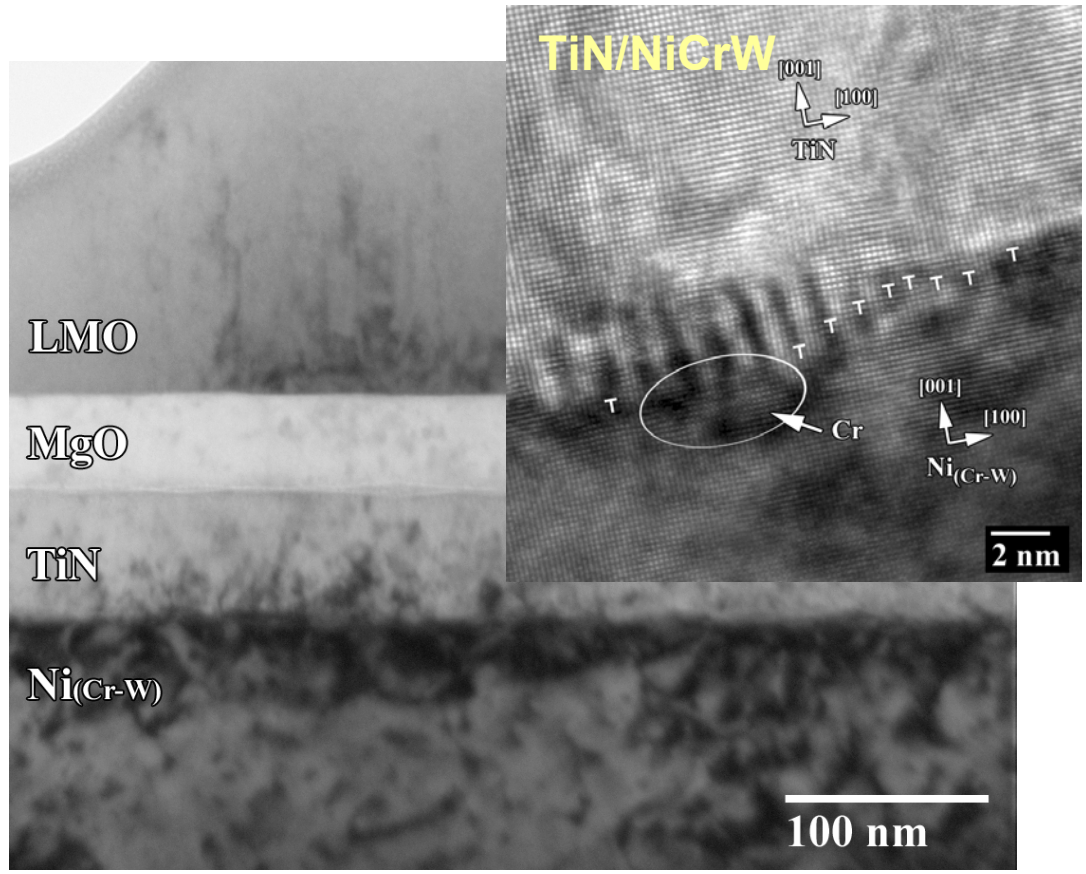
3) **Ni-13atCr/Ni-9at%W with Y_2O_3/YSZ/CeO_2**

Standard buffer stack

J_c of 1.8 MA/cm^2 was obtained for a 0.8 μm MOD YBCO on Ni-Cr-W/TiN/MgO/LMO/CeO_2



TiN, MgO, LMO grown by PLD



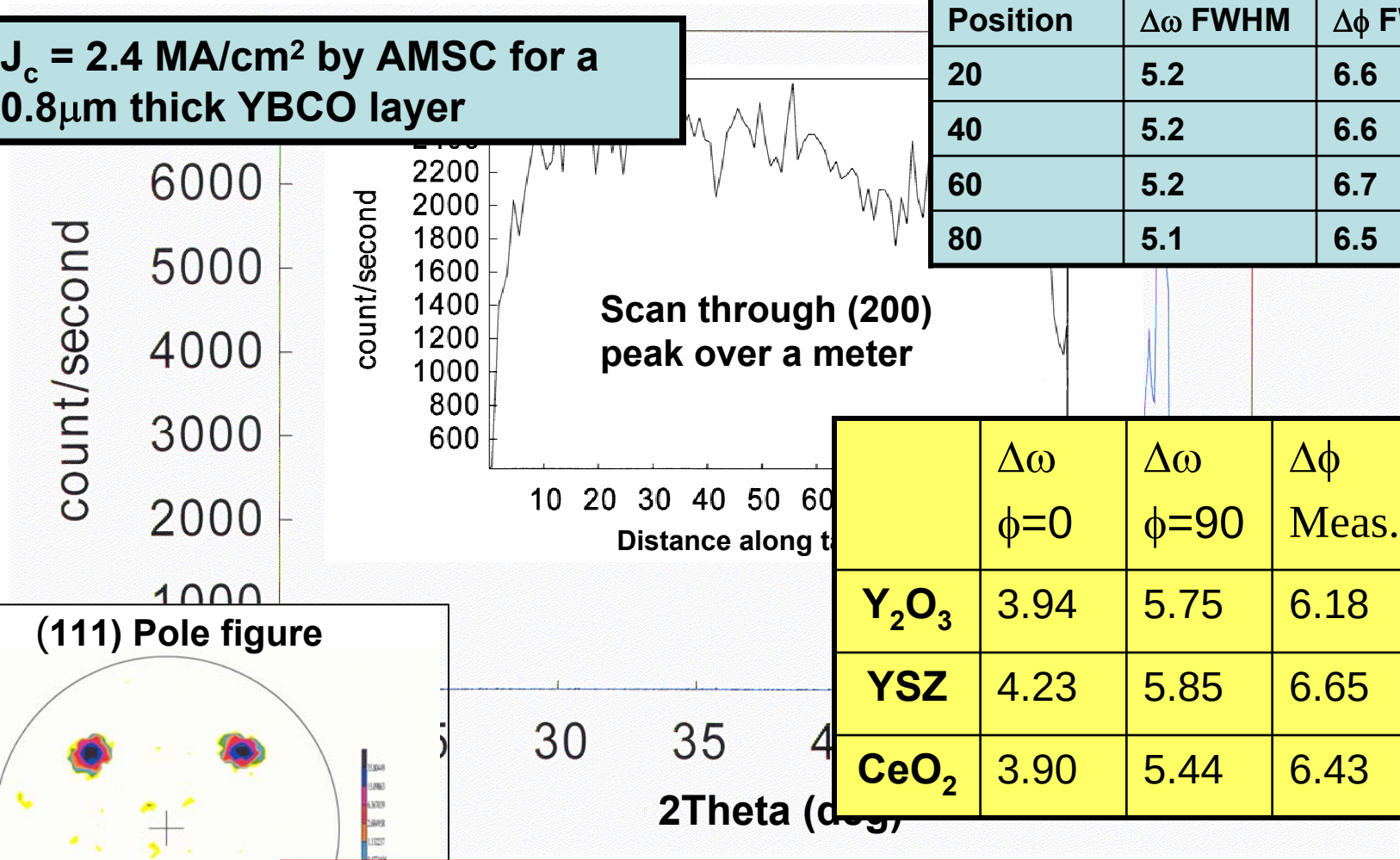
TiN/MgO/LMO/CeO_2 stack is an effective buffer layer architecture for the non-magnetic, Cr containing alloys

American Superconductor™

UT-BATTELLE

Reel-to-reel deposition of Ni-9at%W coatings on substrates followed by epitaxial growth of standard buffer layers

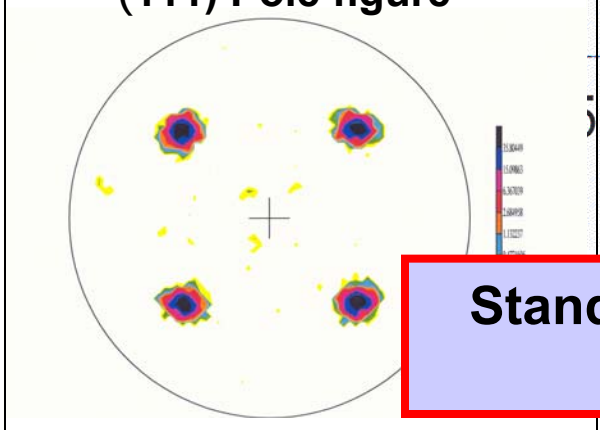
J_c = 2.4 MA/cm² by AMSC for a 0.8μm thick YBCO layer



Position	Δω FWHM	Δϕ FWHM
20	5.2	6.6
40	5.2	6.6
60	5.2	6.7
80	5.1	6.5

	Δω ϕ=0	Δω ϕ=90	Δϕ Meas.	Δϕ True
Y_2O_3	3.94	5.75	6.18	5.14
YSZ	4.23	5.85	6.65	5.61
CeO_2	3.90	5.44	6.43	5.51

(111) Pole figure

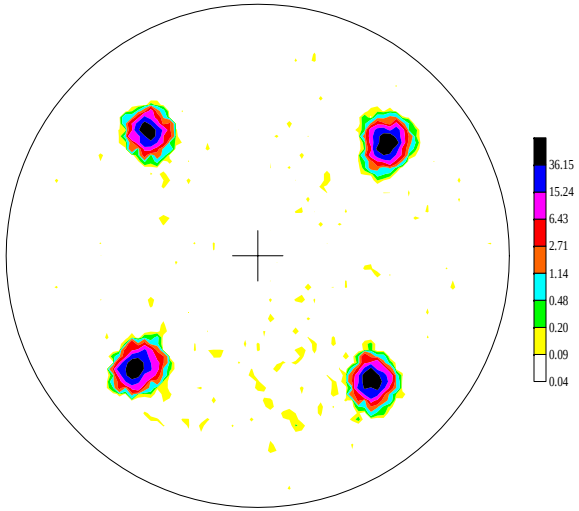


Standard oxide buffer stack will be compatible with a textured non-magnetic Ni-W substrate

Objective 4: Long lengths of sharply textured Cu substrates have been fabricated and all conductive architecture have been developed

1 km of 1 cm wide Cu substrate fabricated

Cu(111) log-scale pole figure
~100% cube



FWHM $\Delta\phi$ = 4.0 (True Phi)
FWHM $\Delta\omega$ = 6.9, 5.2

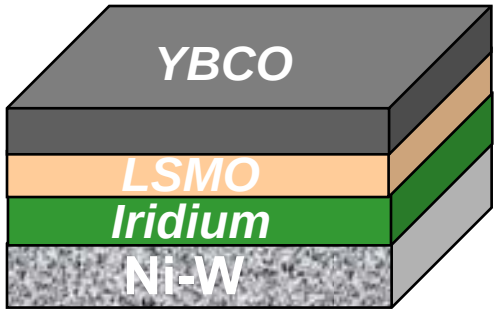
All Conducting buffer layer development

Conducting seed layer, preferably having a conductive native oxide is desirable

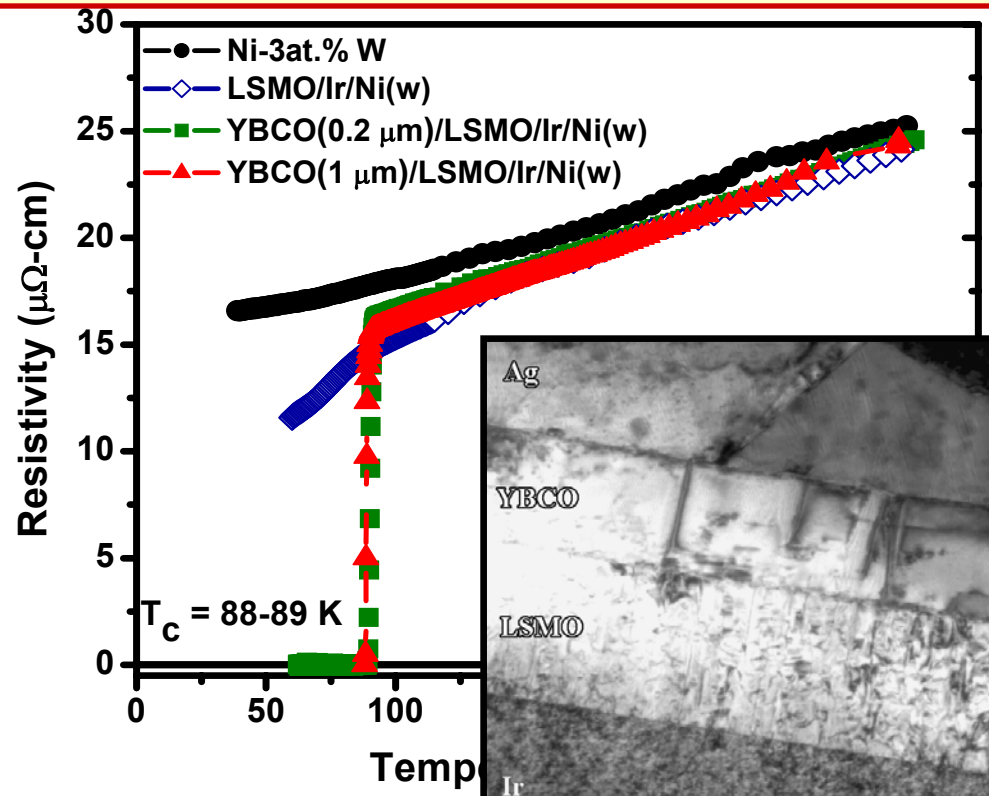
Iridium is a good choice

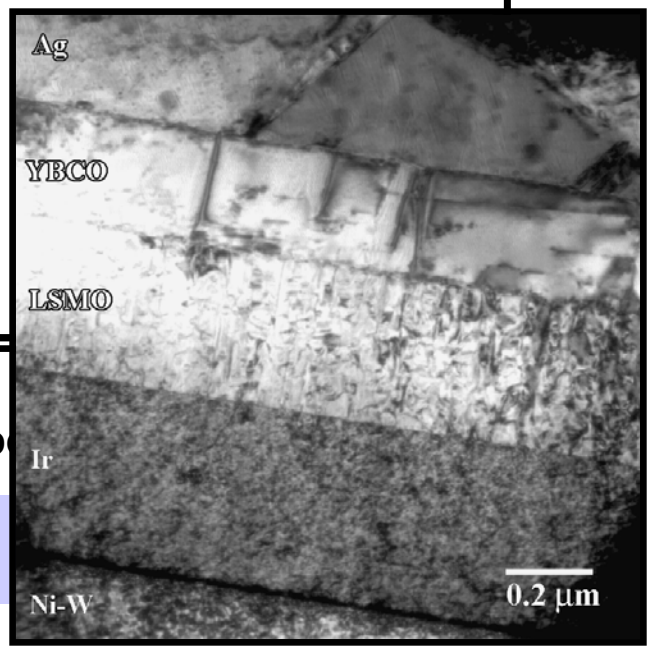
Material	Oxygen diff. (cm^2/sec) 800 °C
IrO_2 (< 50 μΩ cm)	6×10^{-15}
Ir (< 5 μΩ cm)	5×10^{-12}

CeO_2, Y_2O_3, YSZ ~ 10^{-8}-10^{-10}



$La_{0.7}Sr_{0.3}MnO_3$	5×10^{-15} cm^2/sec

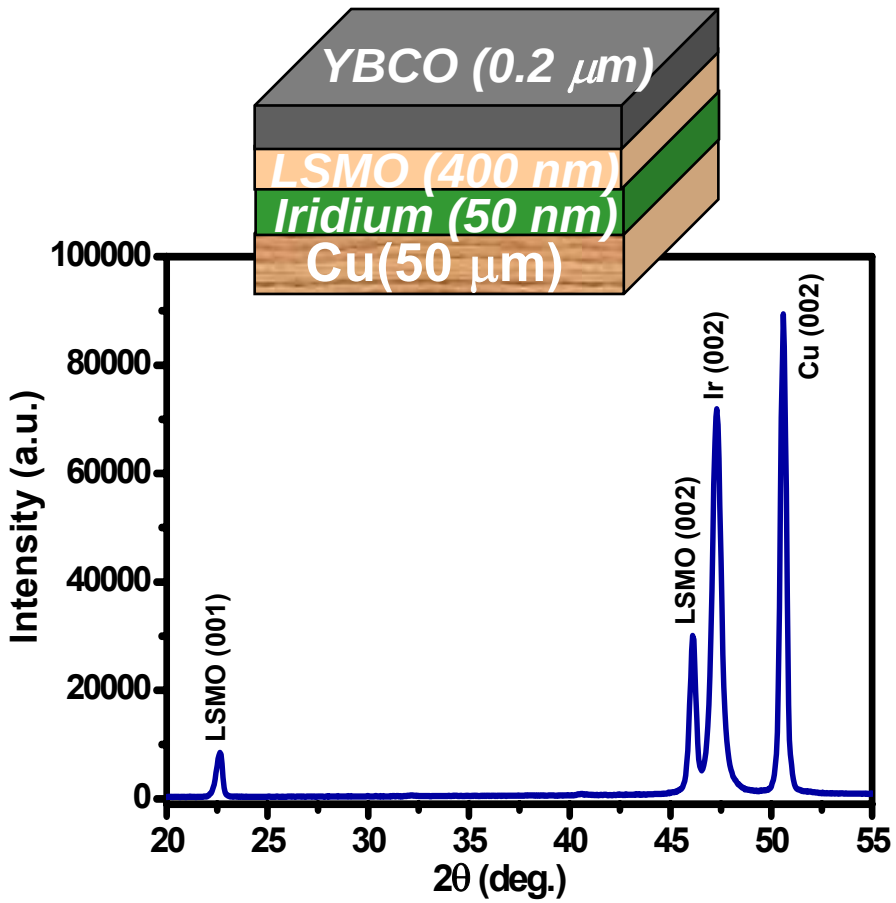




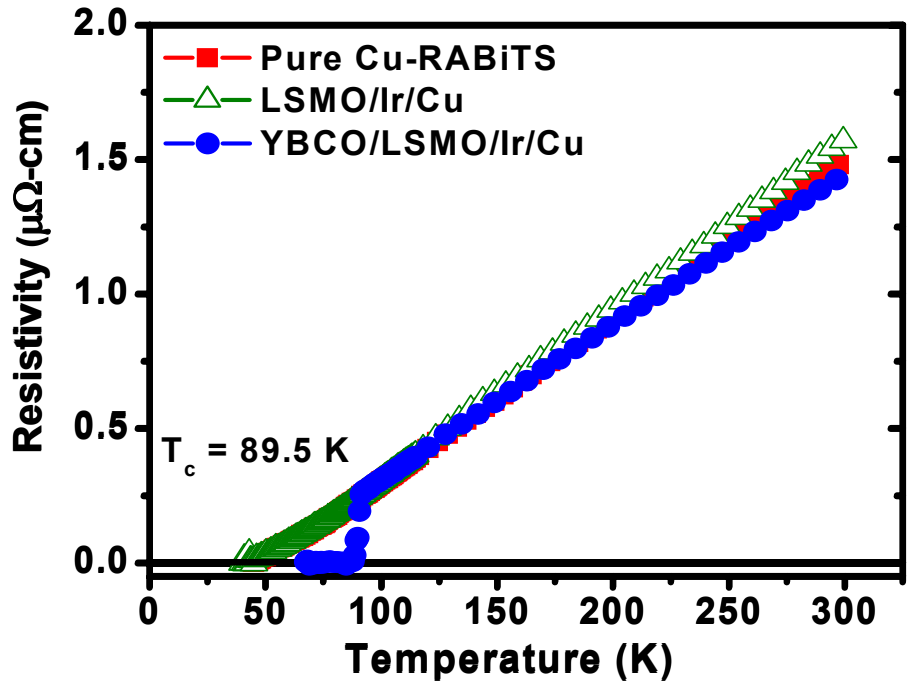
J_c (0.2 μm) = 2.2 MA/cm^2
J_c (1 μm) = 1.0 MA/cm^2

- Excellent electrical coupling among the individual layers
- TEM shows clean interface between NiW and Ir

PLD-YBCO(0.2 µm)/LSMO/Ir/Cu: A Fully Conductive Architecture is Obtained on Cu



J_c(77K, 0T) ~ 1×10^6 A/cm^2

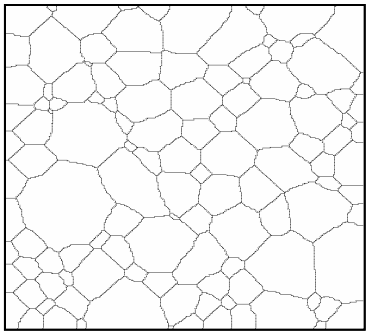


ρ_{net} - T shows good electrical coupling among the individual layers

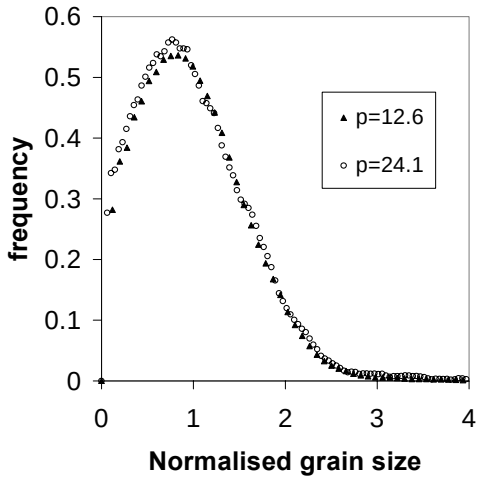
Objective 5: Perform percolation calculations using experimentally achievable texture in RABiTS, both in self-field and applied field

In FY 03 a new model for percolative current flow was proposed

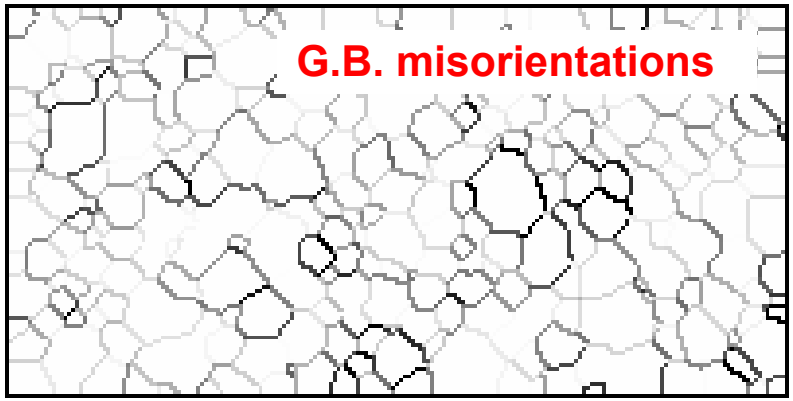
Simulation of grain structure



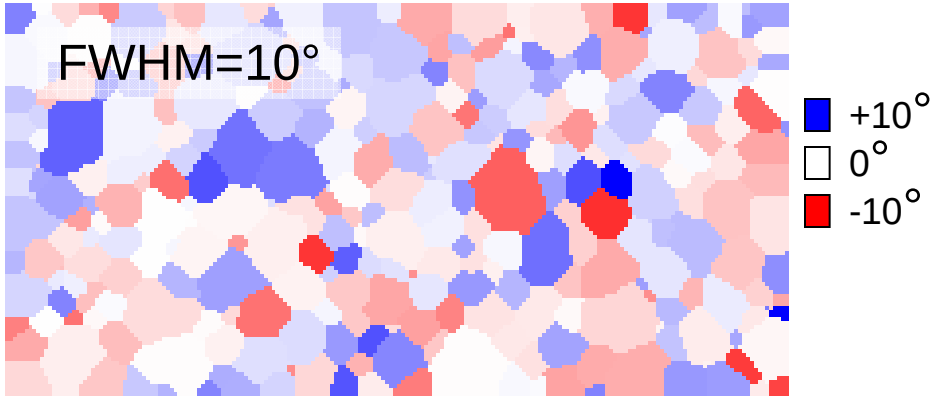
MCS = 1000



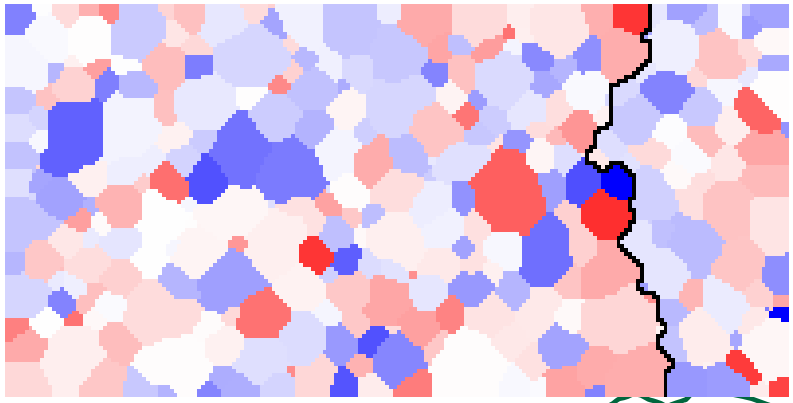
Calculate GB misorientations



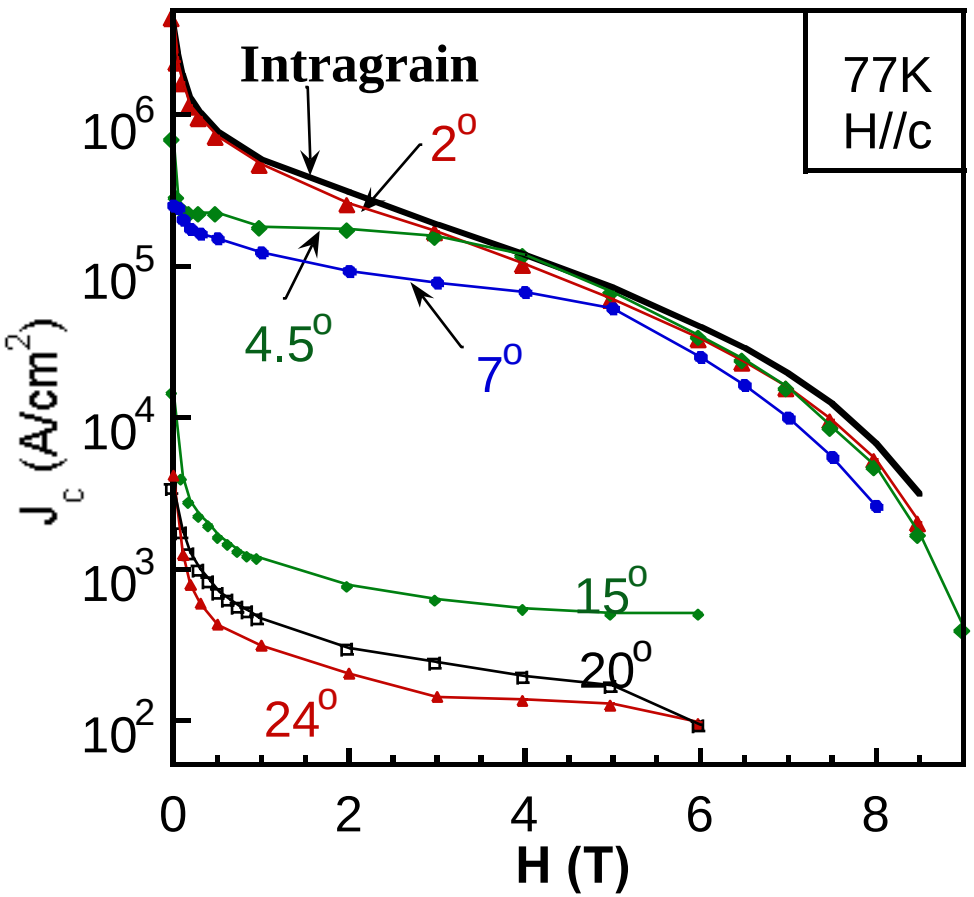
Assignment of orientations



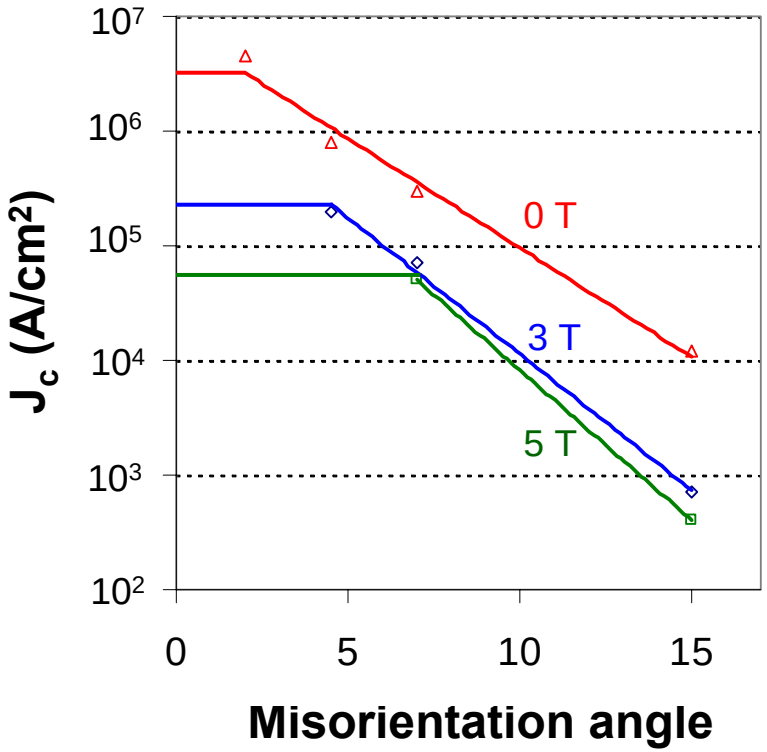
Calculate J_c based on J_c vs Θ



In FY04, current-flow modeling has been extended to calculation in applied fields

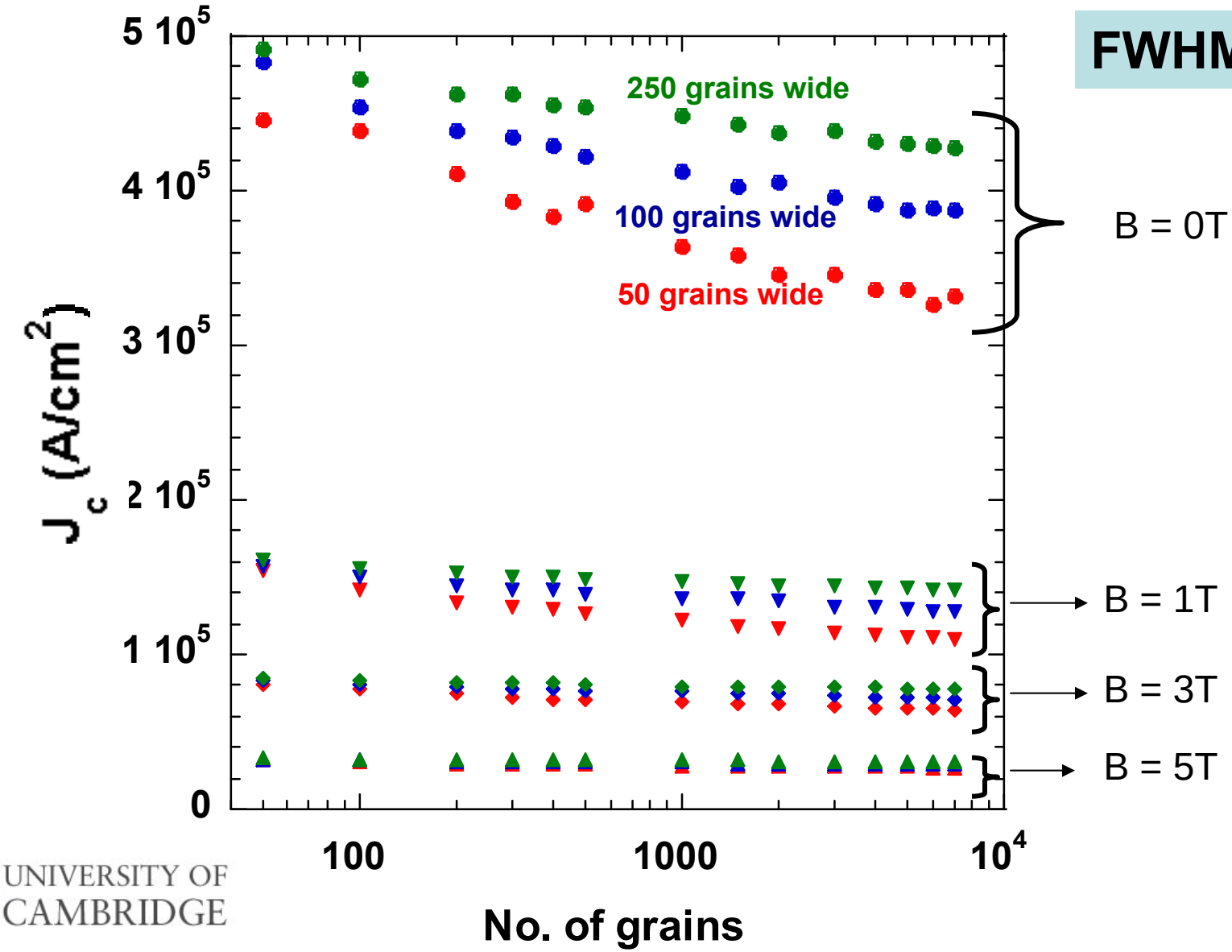


Verebelyi et al, APL 76 13 (2000)



In applied fields, grains can have lower J_c than low-angle GB's

Dependence of J_c on width in applied field is significantly reduced as expected



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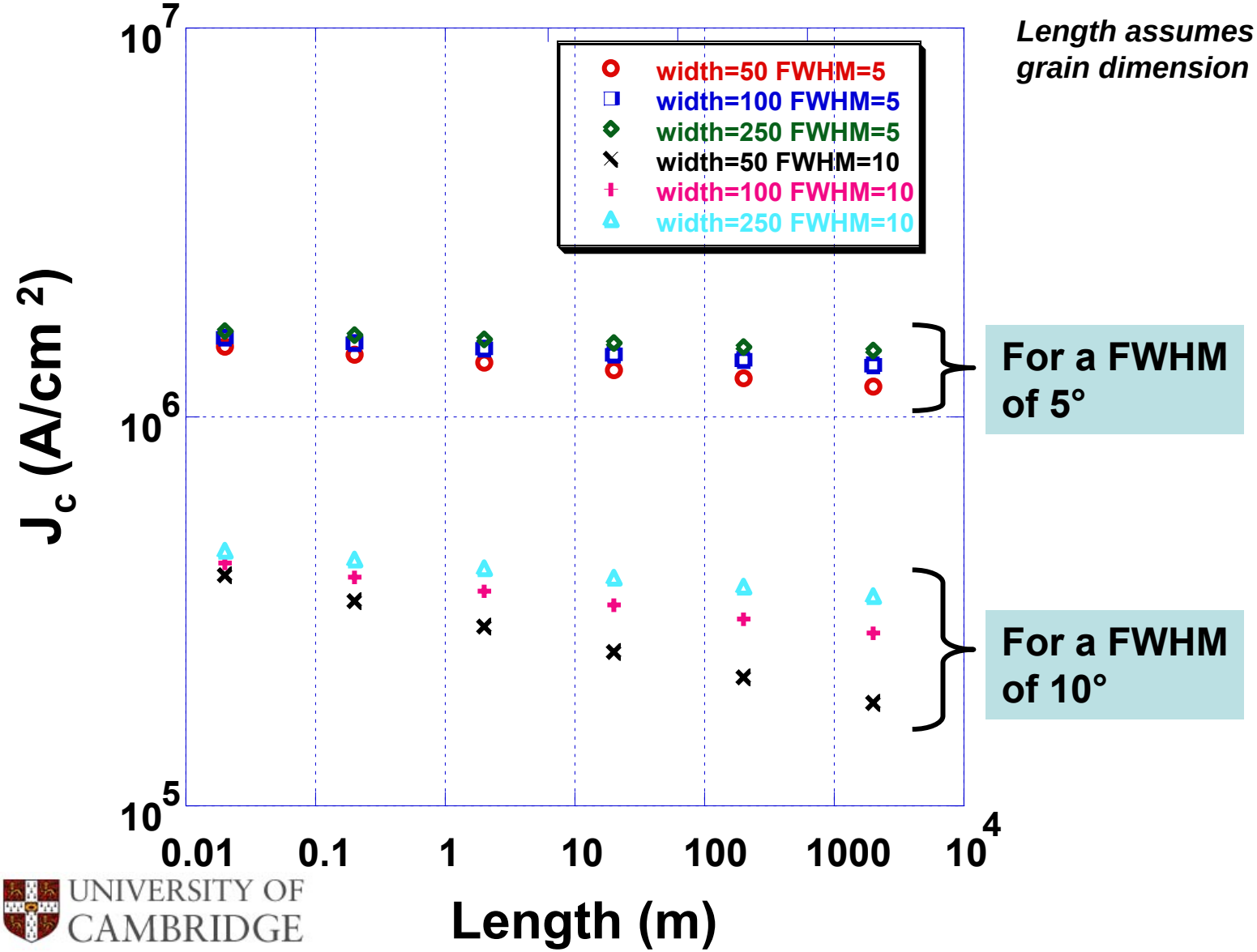
The presently achievable in-plane texture of ~5° FWHM supports 70-80% of single crystal J_c for YBCO/RABiTS

April, 2004

	YBCO on CeO_2/YSZ/Y_2O_3/NiW		YBCO/CeO_2/SC YSZ
	J_c = 3.3 MA/cm^2 I_c = 260 A	J_c = 3.4 MA/cm^2 I_c = 270 A	J_c = 4.3 MA/cm^2 I_c = 344 A FWHM of $\Delta\phi$ ~ 1-2°
YBCO	$\Delta\phi$ = 4.9° $\Delta\omega$ = 4.0°; 5.1°	$\Delta\phi$ = 4.8° $\Delta\omega$ = 4.0°; 5.2°	
Buffer	$\Delta\phi$ = 3.9° $\Delta\omega$ = 4.7°; 7.0°	$\Delta\phi$ = 4.0° $\Delta\omega$ = 4.77°; 7.3°	
NiW	$\Delta\phi$ = 4.3° $\Delta\omega$ = 5.29°; 8.37°	$\Delta\phi$ = 4.5° $\Delta\omega$ = 5.37°; 8.26°	

The grain boundary misorientation distribution is significantly different for $\Delta\phi$ of 5° vs 10° FWHM

Dependence of J_c on width is significantly reduced with sharper FWHM even in self-field



Length assumes that ave. linear grain dimension is 40μm

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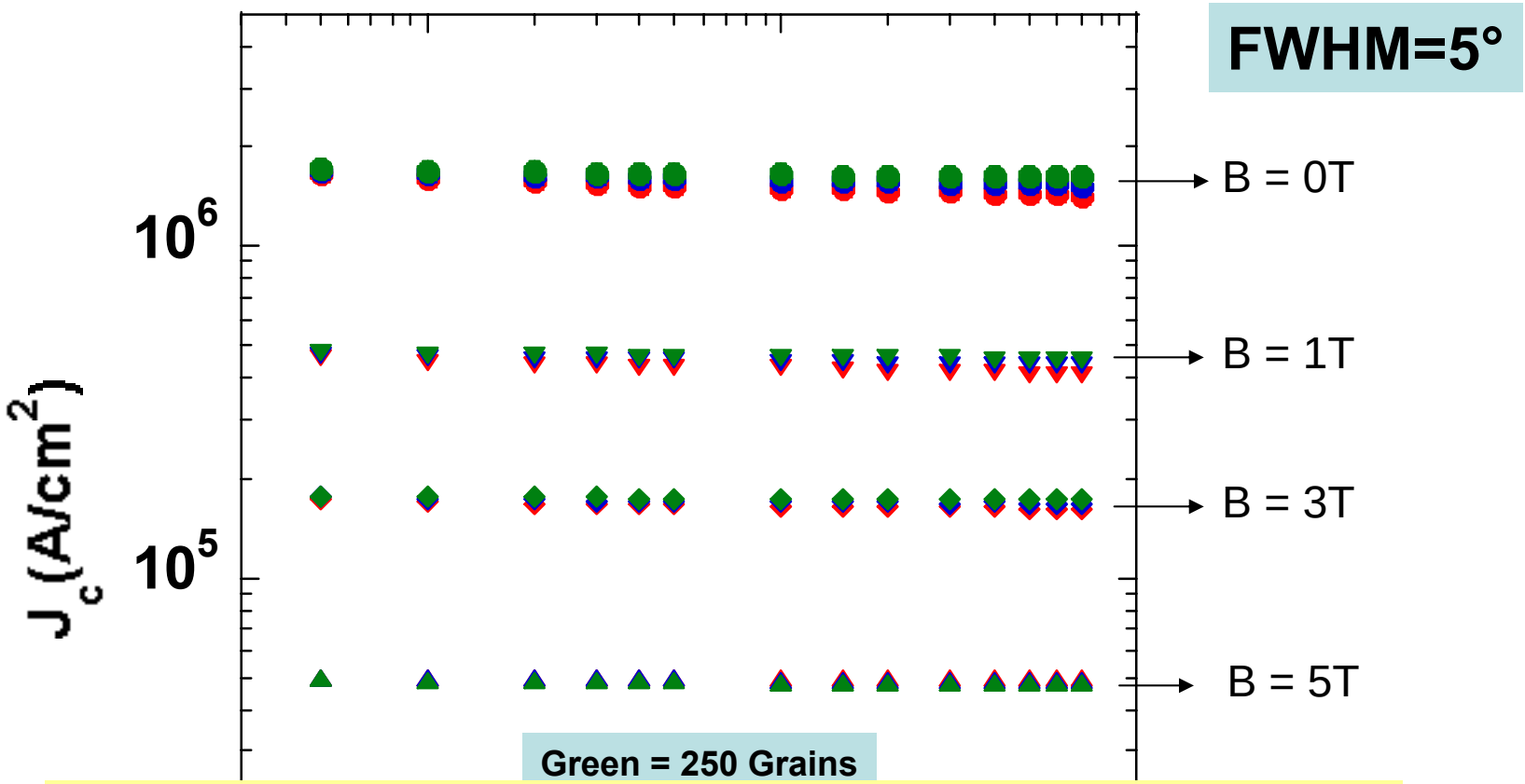
With sharper FWHM, in applied fields, the dependence of J_c on width is insignificant



This implies that J_c "pinch-off" in long RABiTS is NOT an issue and that subdivision of a RABiTS conductor into narrow filaments should be possible

No. of Grains

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Objective 6: Separation of in-plane and out-of-plane misorientations from total misorientation

Separation of in-plane and out-of-plane misorientation components from the total misorientation as measured for example by EBKP has been a goal for over 10 years

Has been difficult for two main reasons:

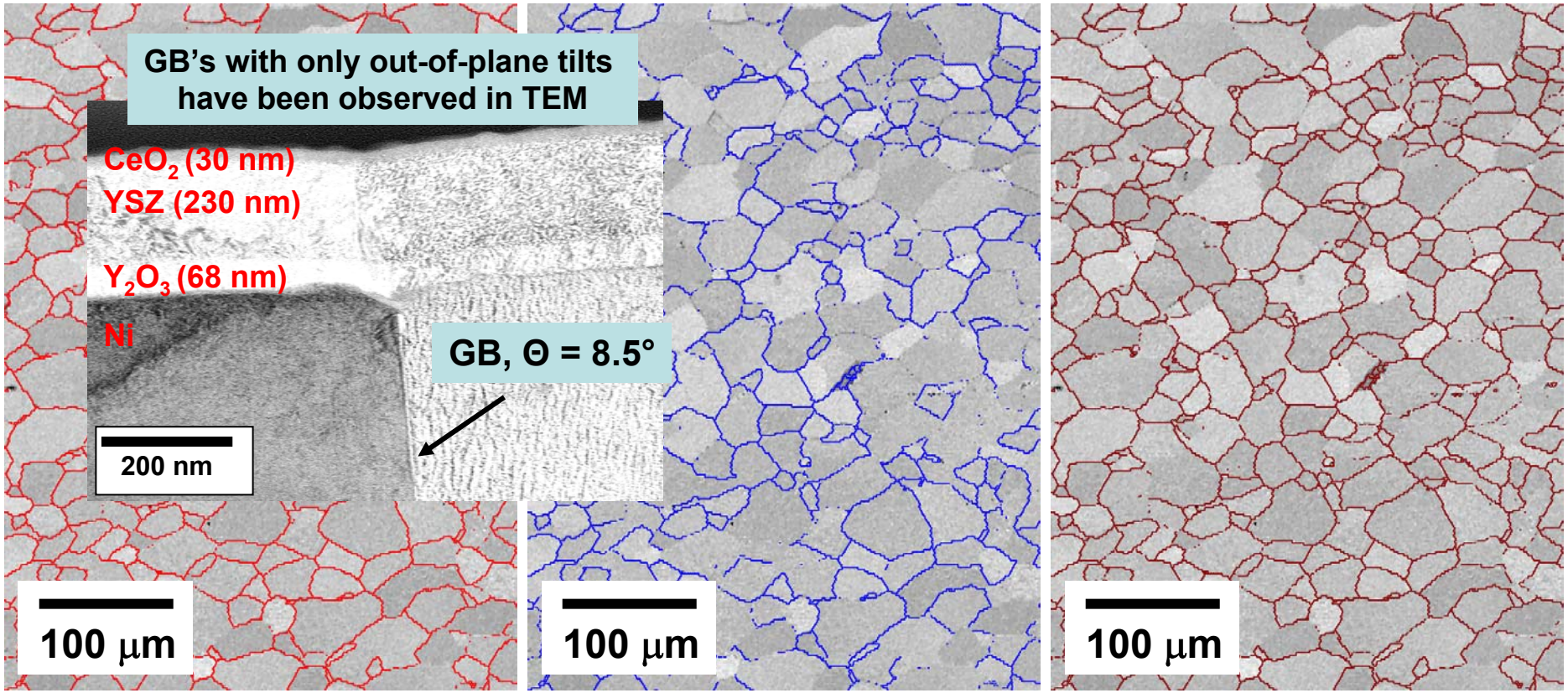
1) **Euler space which is normally used to represent orientations is highly non-linear thereby making any projections difficult**
2) **Calculation of misorientation results in loss of information pertaining to the specimen co-ordinate system again making projections impossible**

Separation of in-plane and out-of-plane misorientation components from the total misorientation was made possible in FY04 by manipulations in Rodrigues Space using a misorientation difference vector

Total grain boundary misorientation was separated into in-plane and out-of-plane contributions using manipulations in Rodrigues space

EBKP data from the CeO_2 layer and all GB's greater than 1° shown

Total misorientation | **In-plane** | **Out-of-plane**



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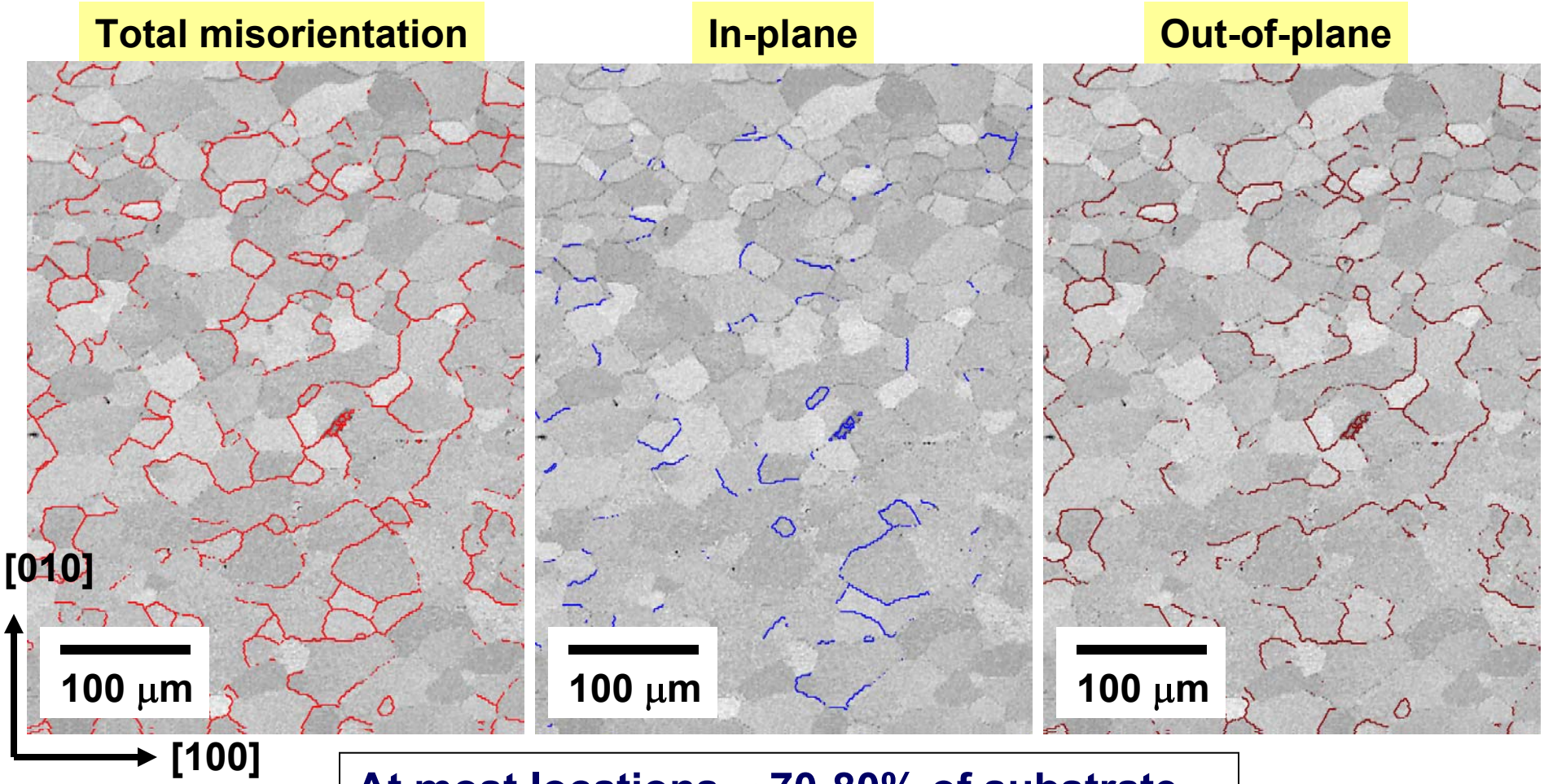
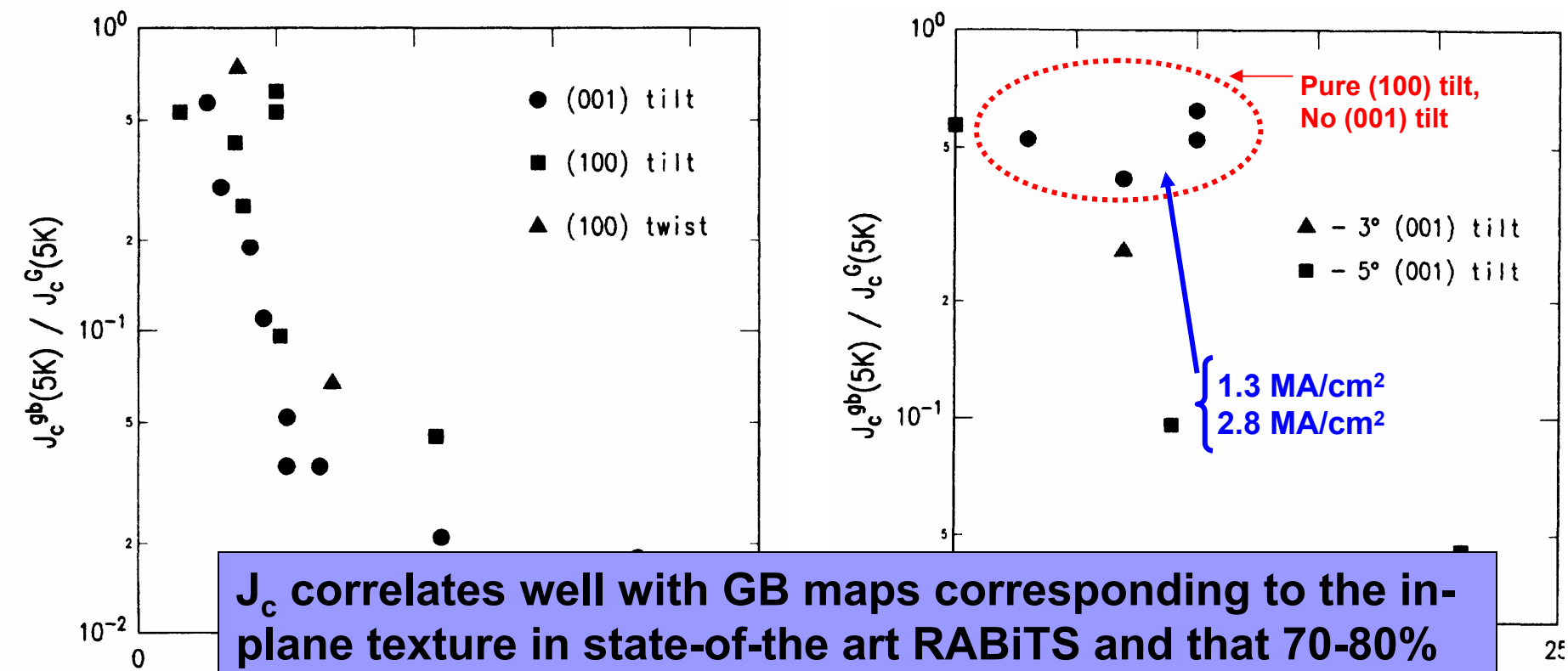
Grain boundary maps drawn with all GB's greater than 4° show that in-plane misorientation is determining J_c



At most locations ~ 70-80% of substrate is single crystal-like w.r.t. in-plane texture

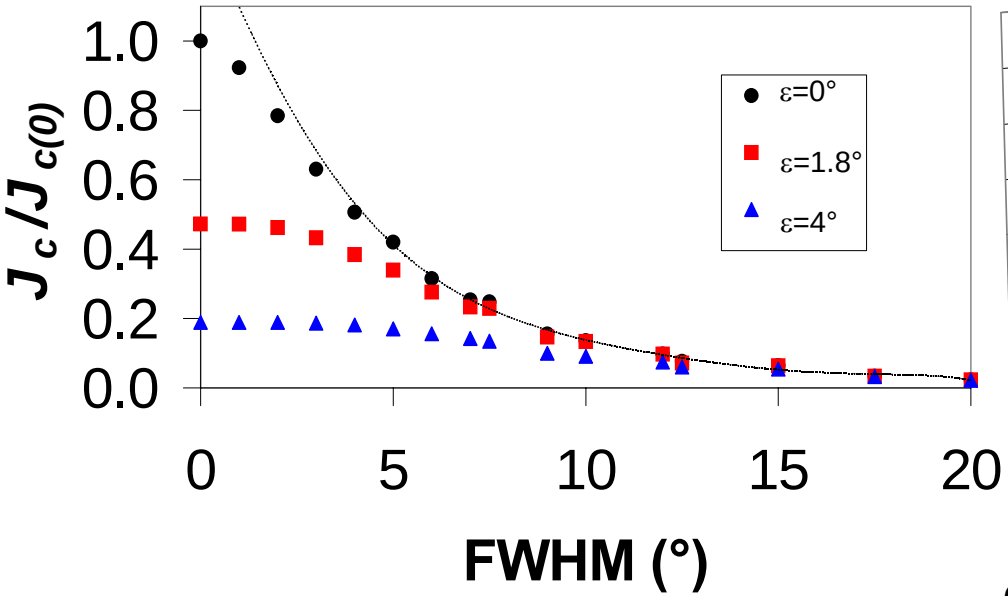
Observations are consistent with Dimos et al.'s work

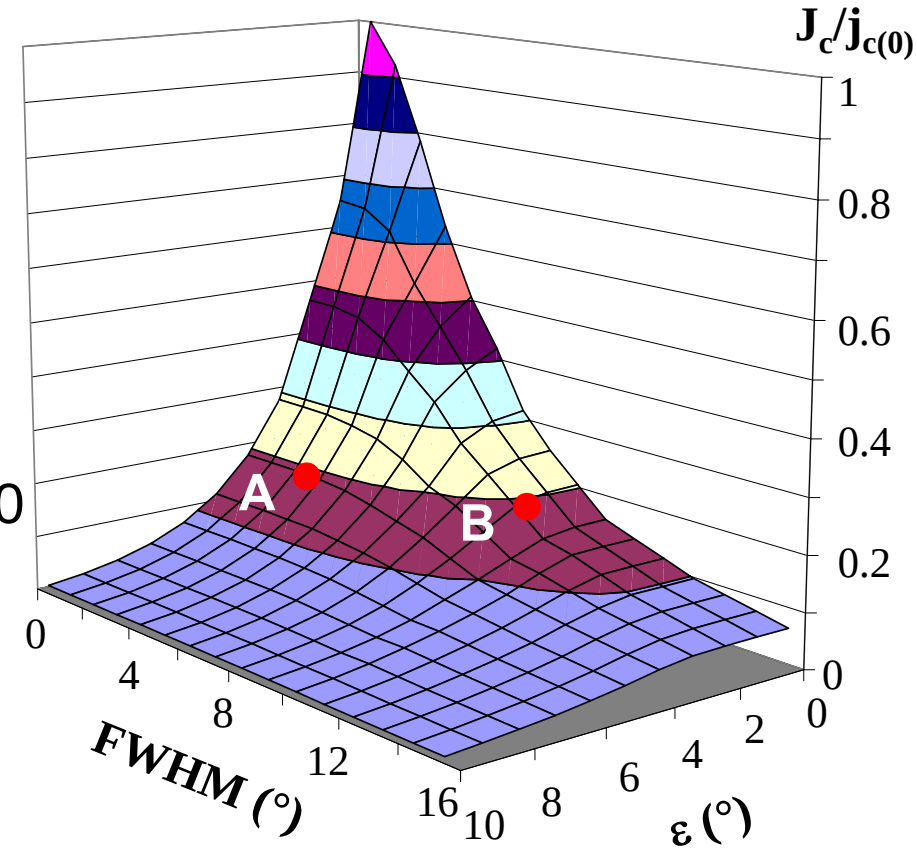
Ref: Dimos et al., Phys. Rev.B, 41, 4038 (1990)



J_c correlates well with GB maps corresponding to the in-plane texture in state-of-the art RABiTS and that 70-80% of single-crystal J_c is consistent with these GB maps

Consideration of the Intragranular J_c



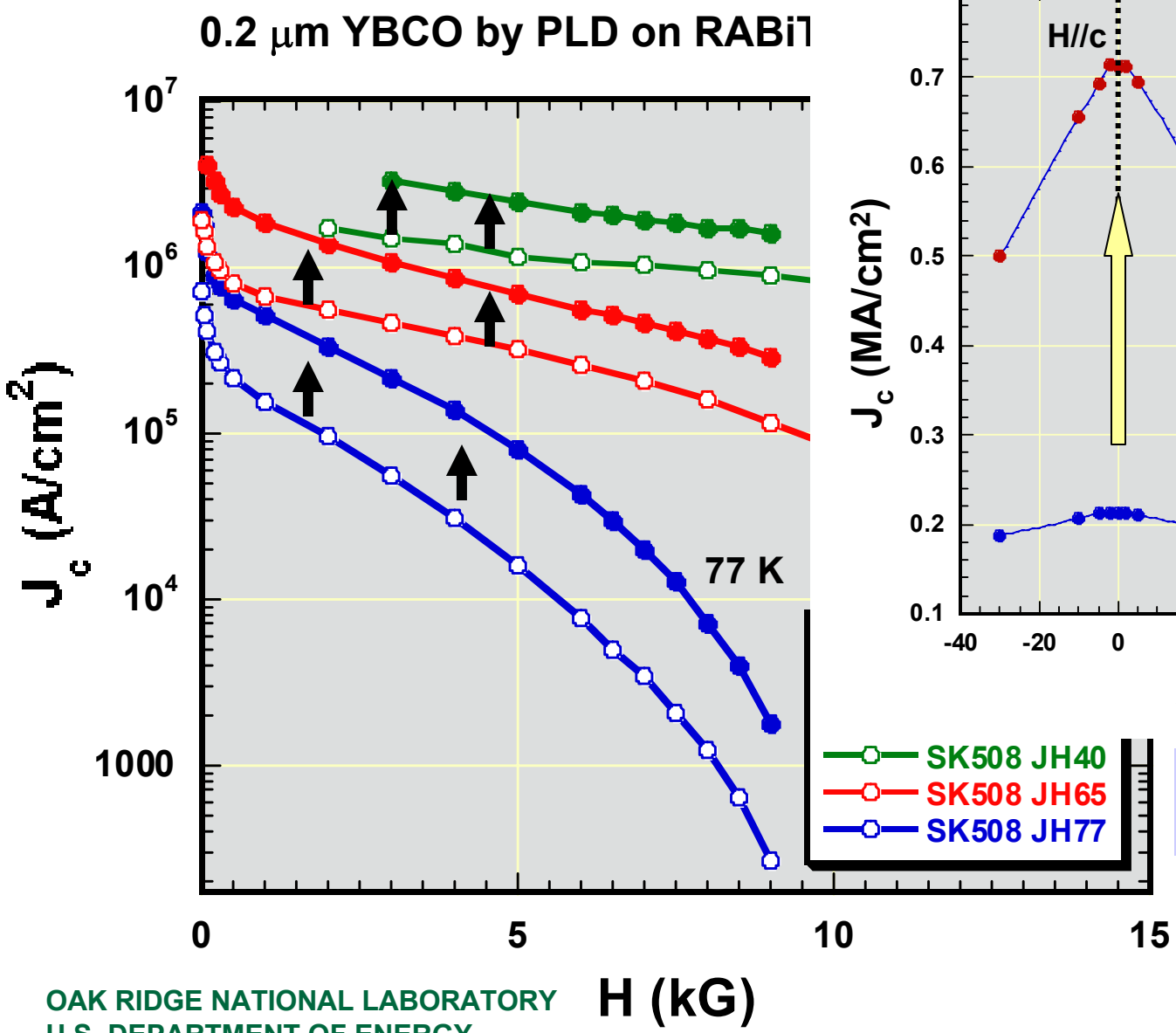


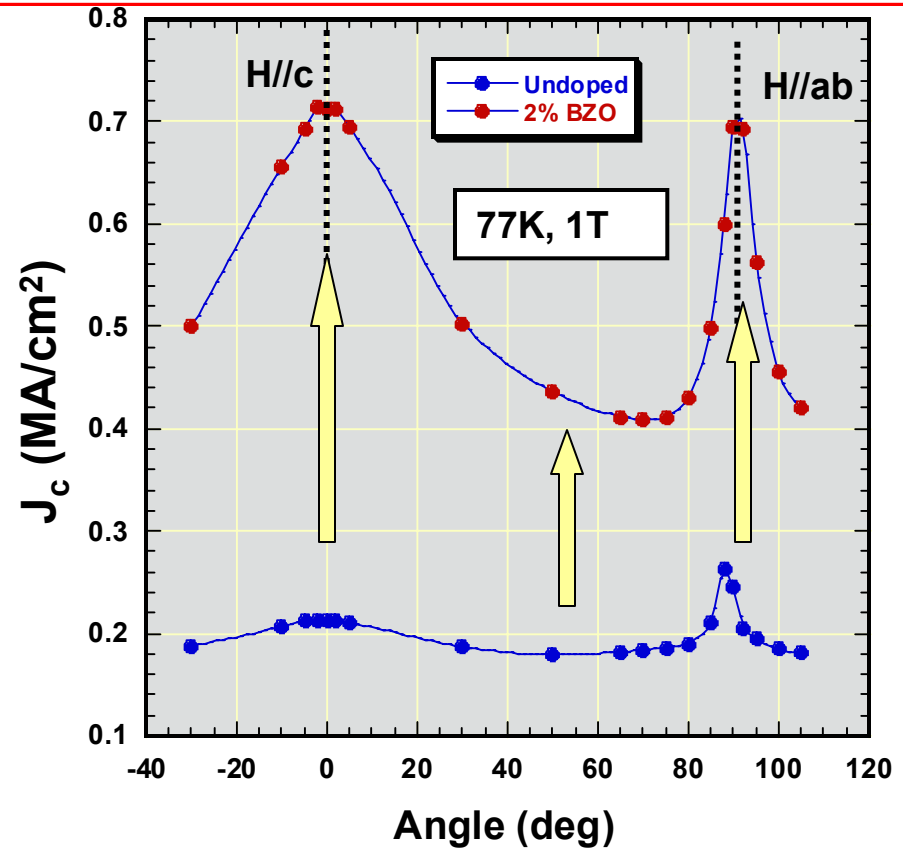
The best route to improve the overall J_c of a process depends upon where on the 3-D surface the tapes lie.

With the present level of texture in RABiTS, greater enhancements may be obtained by modification of intragranular J_c

Consider two points A and B with the same J_c:
- **A: FWHM = 2°; ε = 4°**
- **B: FWHM = 8°; ε = 2°**

*Intra*granular J_c can be significantly enhanced by incorporation of self-aligned nanodots in YBCO on RABiTS

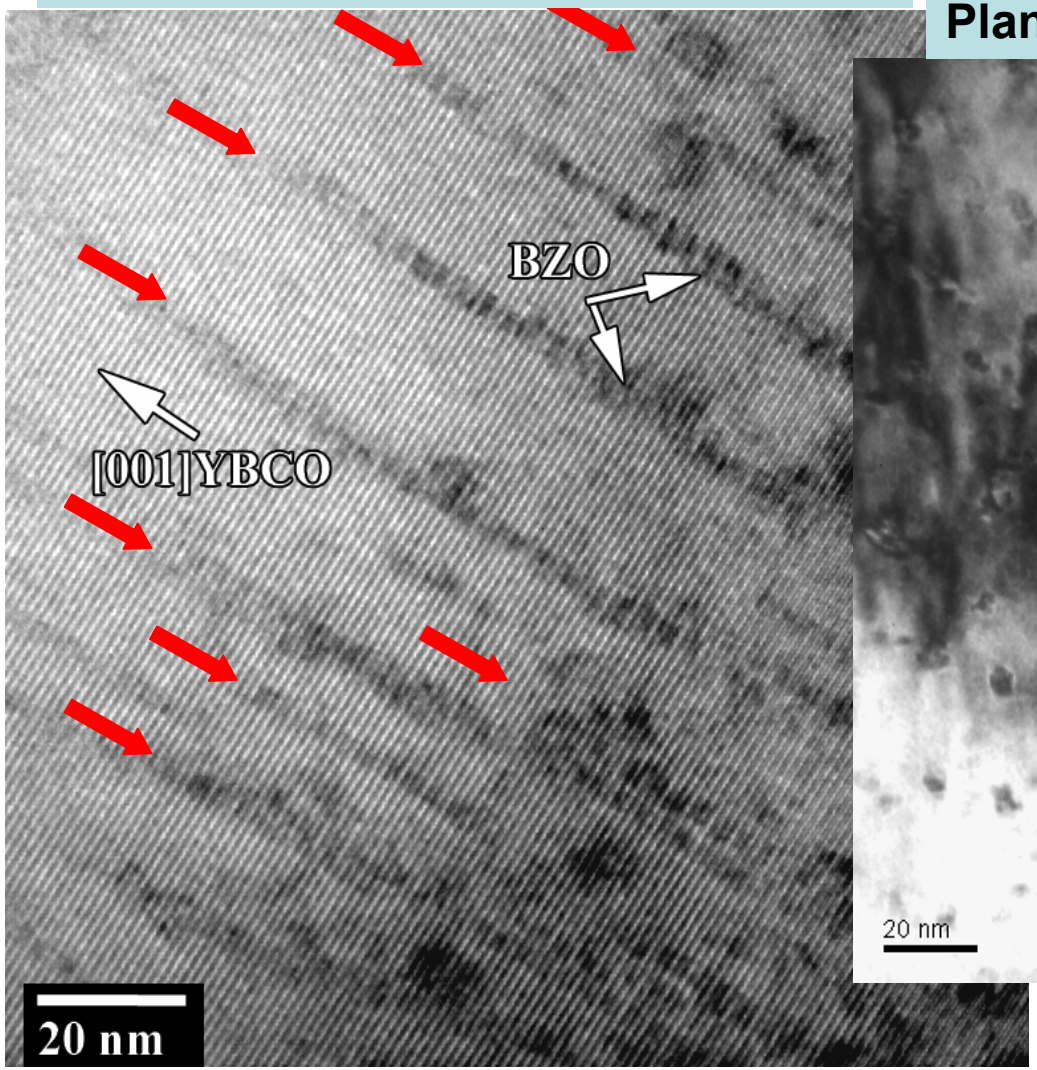




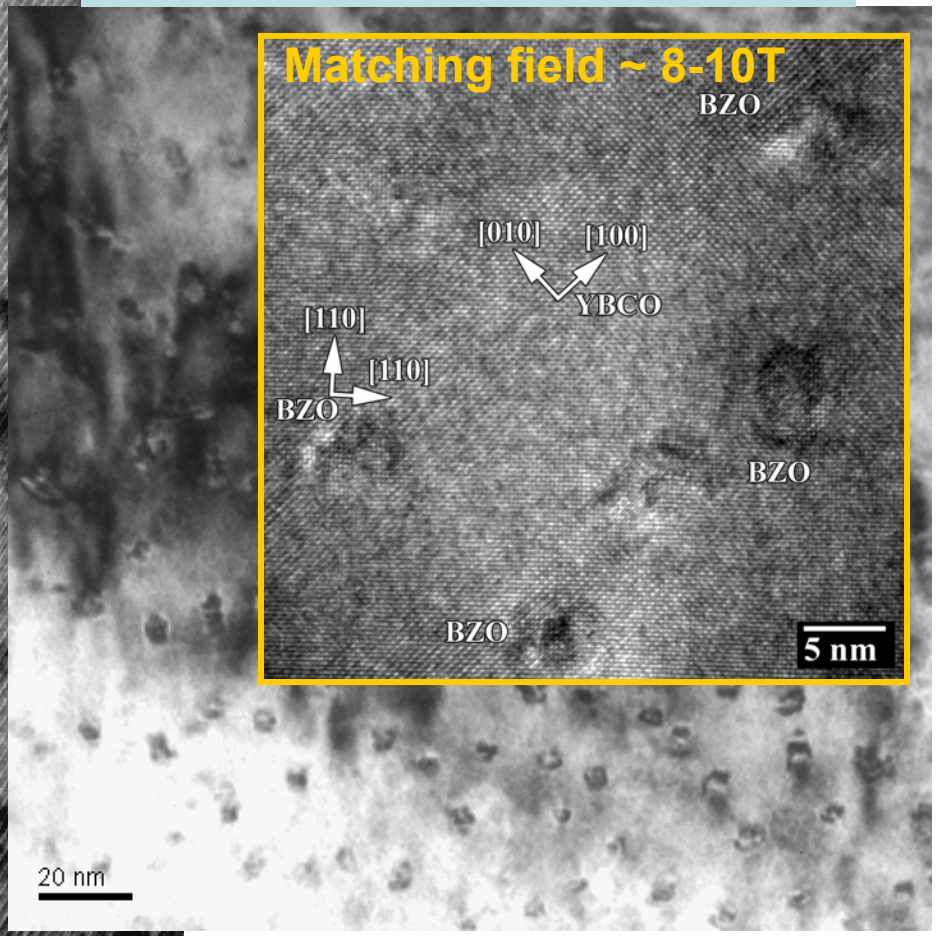
Significant enhancement in J_c is observed

TEM of self-aligned nanodots in YBCO on RABiTS

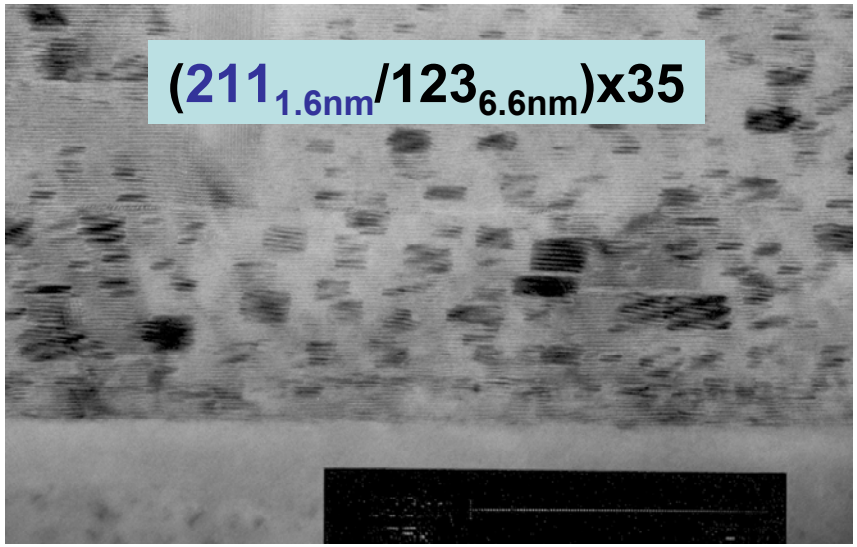
Cross-section TEM of YBCO/RABiTS



Plan view TEM of YBCO/RABiTS

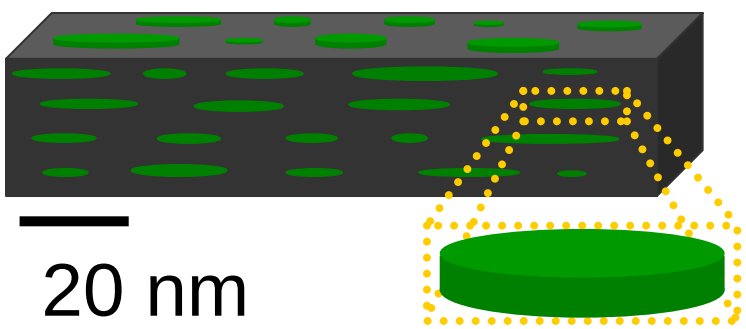


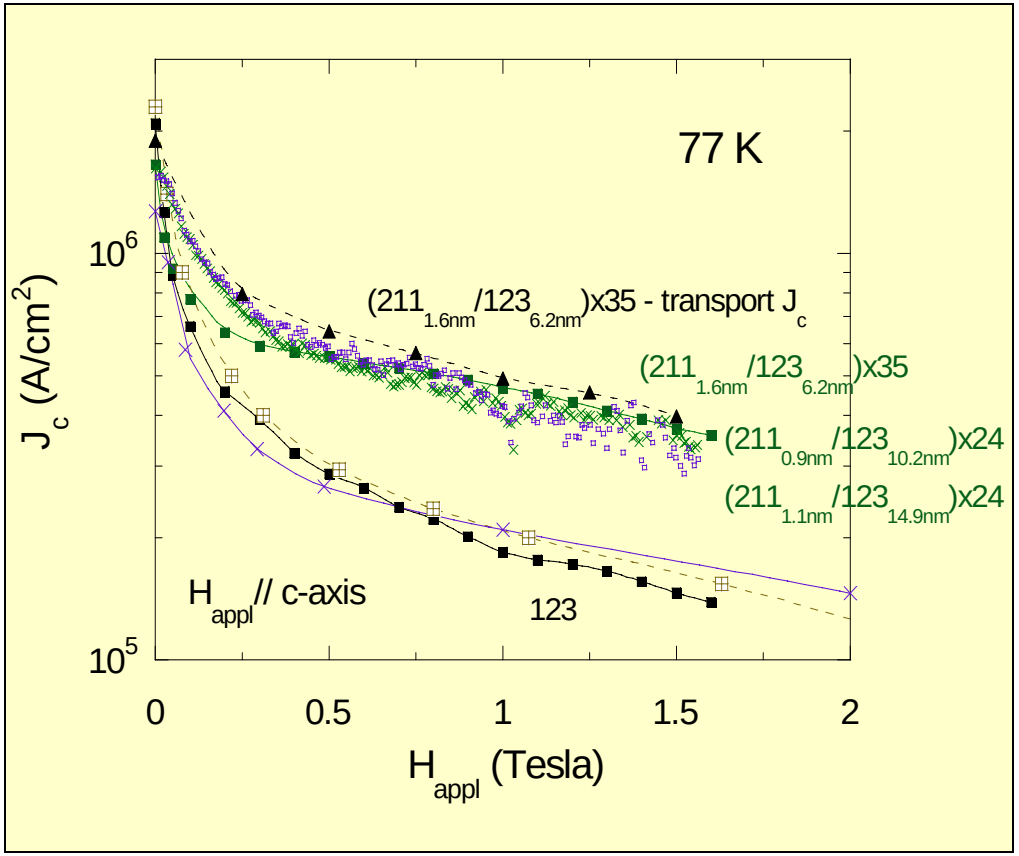
Pinning by 211 nano-particles in 211/123 multilayer films on RABiTS



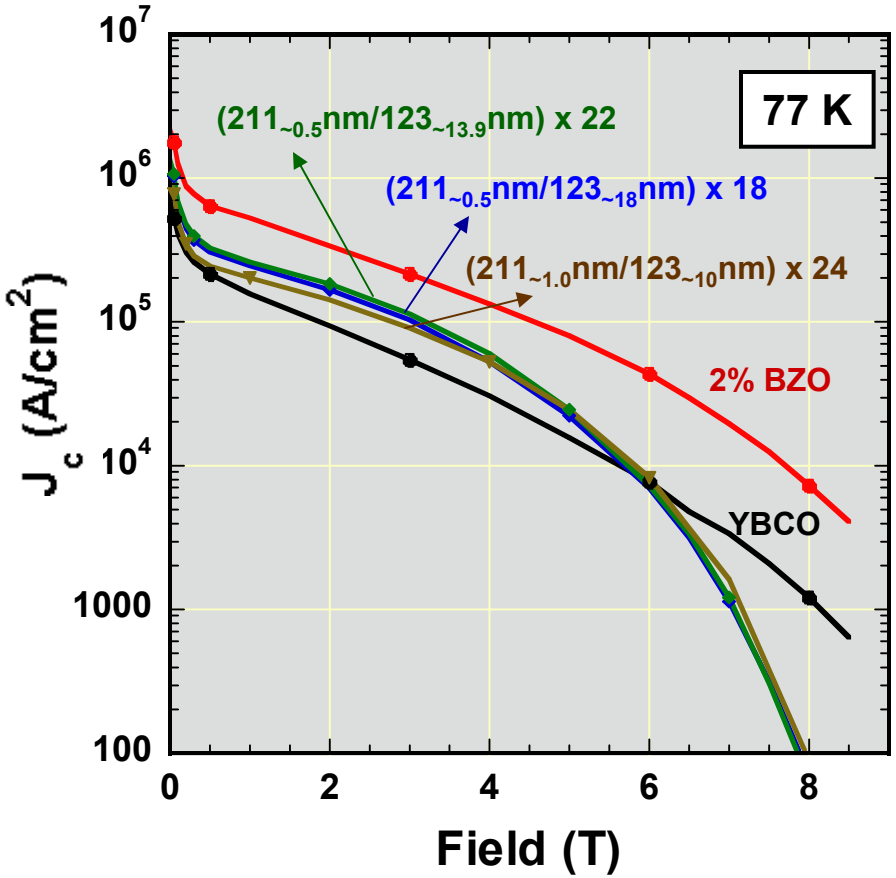
Particle Density ~ $3x10^{11}$ cm^{-2}

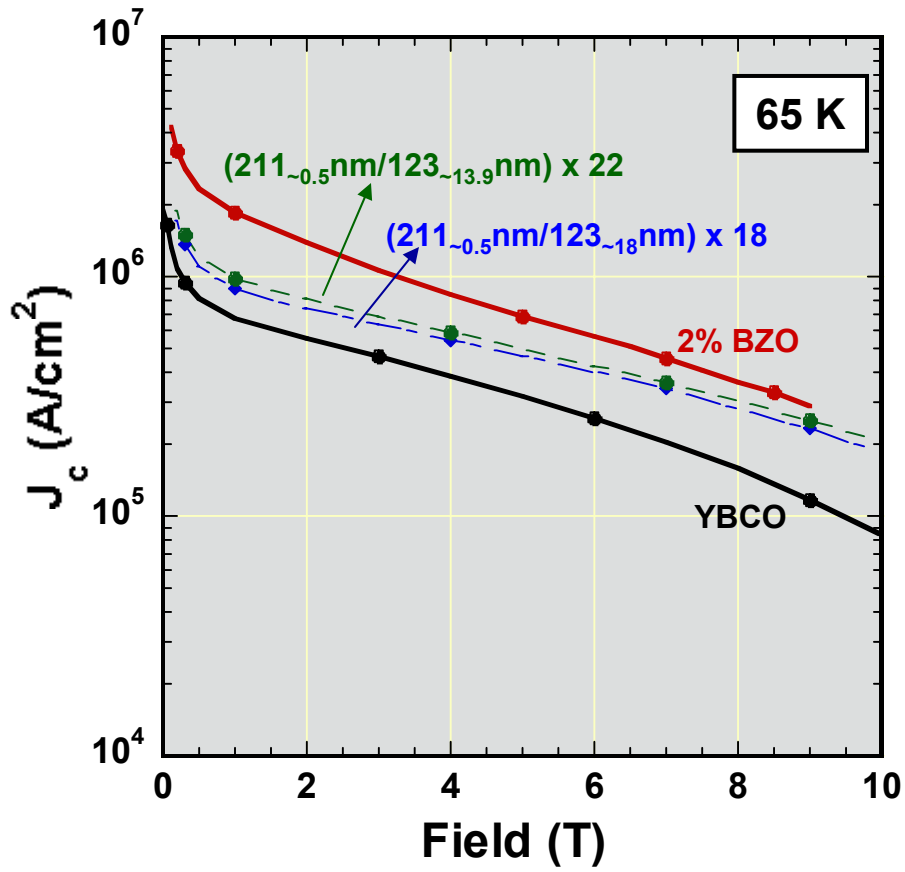
"Island growth of Y_2BaCuO_5 nanoparticles in $(211_{\sim 1.5nm}/123_{\sim 10\ nm})xN$ composite multilayer structures to enhance flux pinning of $YBa_2Cu_3O_{7-\delta}$ films", **T. Haugan, P. N. Barnes I. Maartense, C. B. Cobb, E. J. Lee, M. Sumption, J. Mater. Res. 18, 2618 (2003) - Nov. issue.**



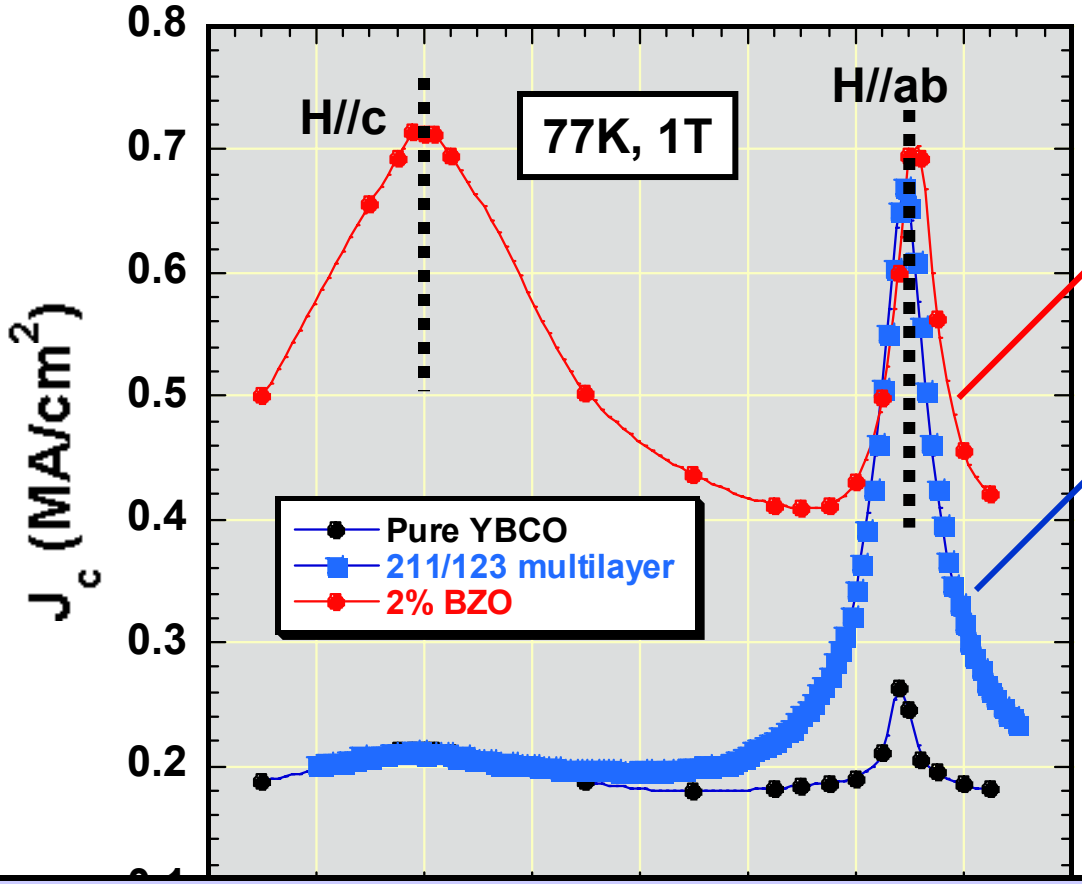


BZO nanodot/rod compared to pinning by 211 nano-particles for YBCO films on RABiTS





Angular dependence of J_c for 211/123 multilayer films on RABiTS



c-axis correlated pinning by extended defects + random pinning

random pinning by 211 particles

In summary, significant improvements in the intra-granular properties was shown possible for YBCO films on RABiTS

Presentation Outline

- FY 2004 Results

  Reel-to-reel buffer layer development on Ni-3at%W substrates (Fred)

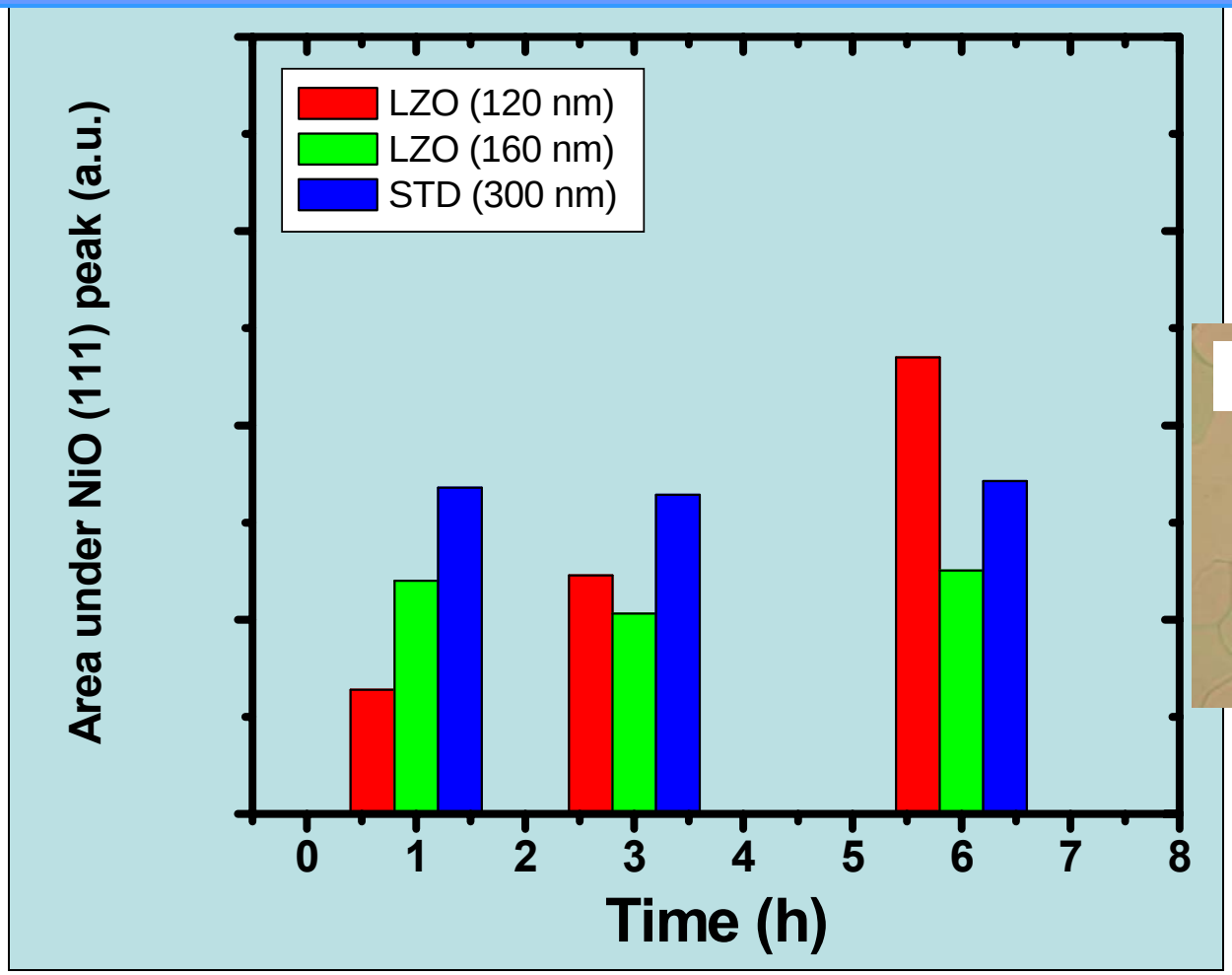
  Development of ORNL Rolling facility with clean room (Amit)
  AC losses from alloy substrates
  Development of Cu-based, conductive RABiTS
  Development of Ni-based, non-magnetic RABiTS
  Percolation calculations in applied fields
  Separation of in-plane and out-of plane misorientations
  Enhancement of intragranular-J_c

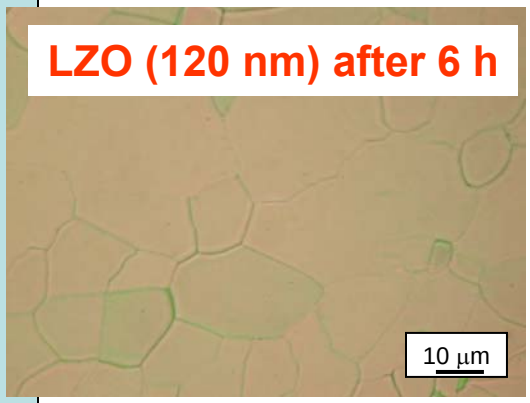
  Development of solution buffers (Parans)

- FY 2004 Performance and FY 2005 Plans (Parans)
- Research Integration

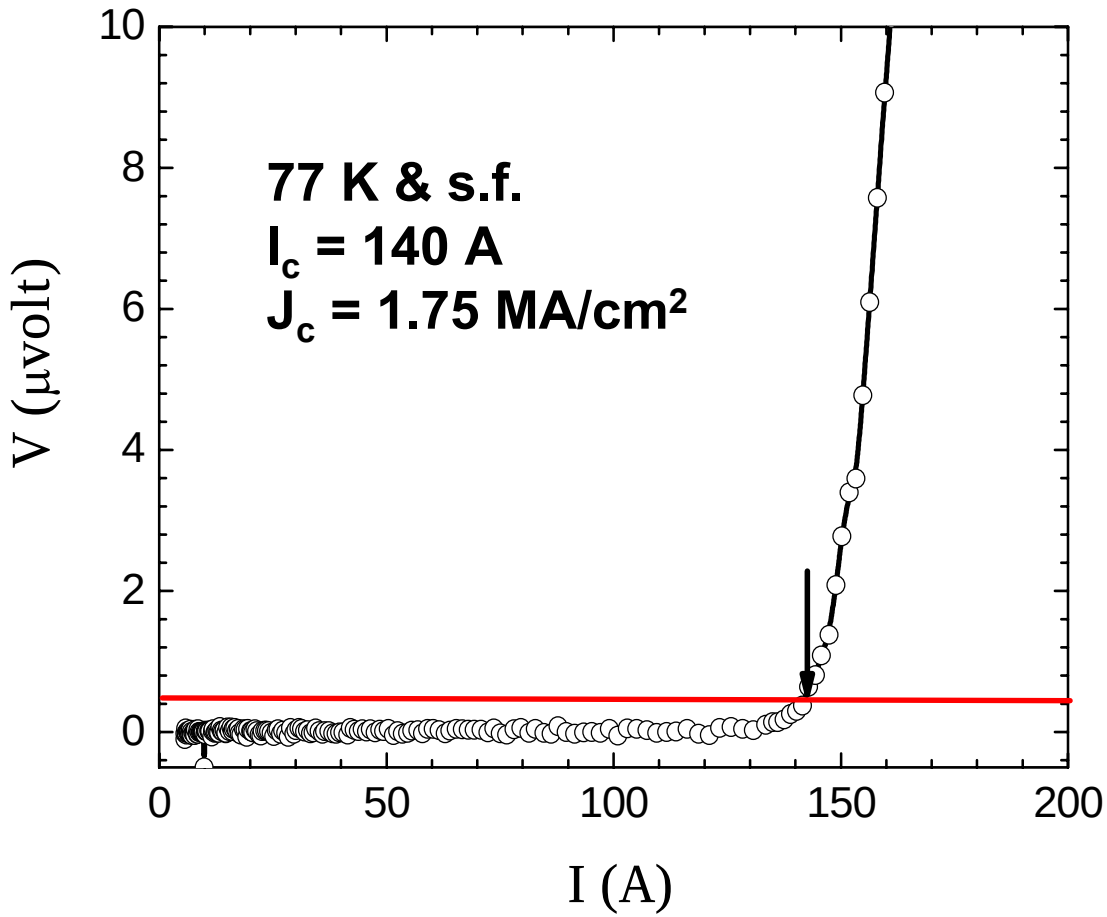
Objective 7: Development of low-cost, all-solution buffer layers

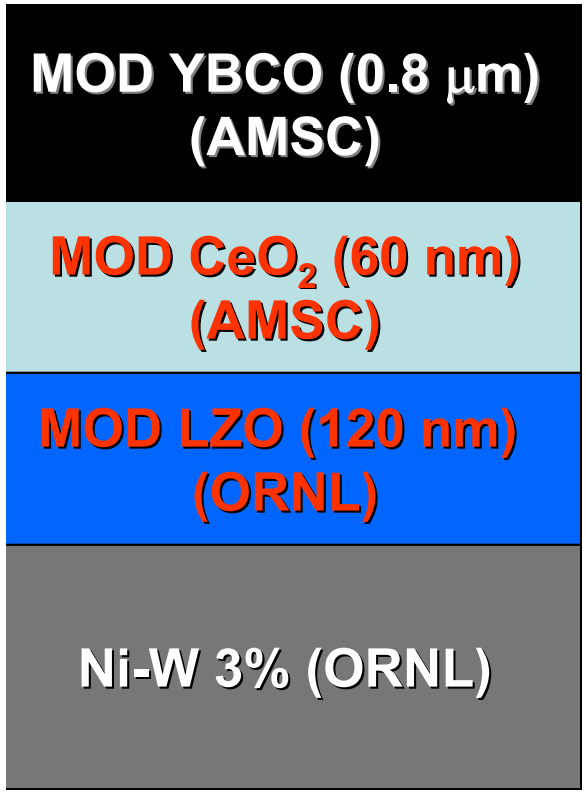
Upon annealing under standard conditions for ex-situ YBCO, NiO formation is comparable to RABiTS with vacuum deposited buffers





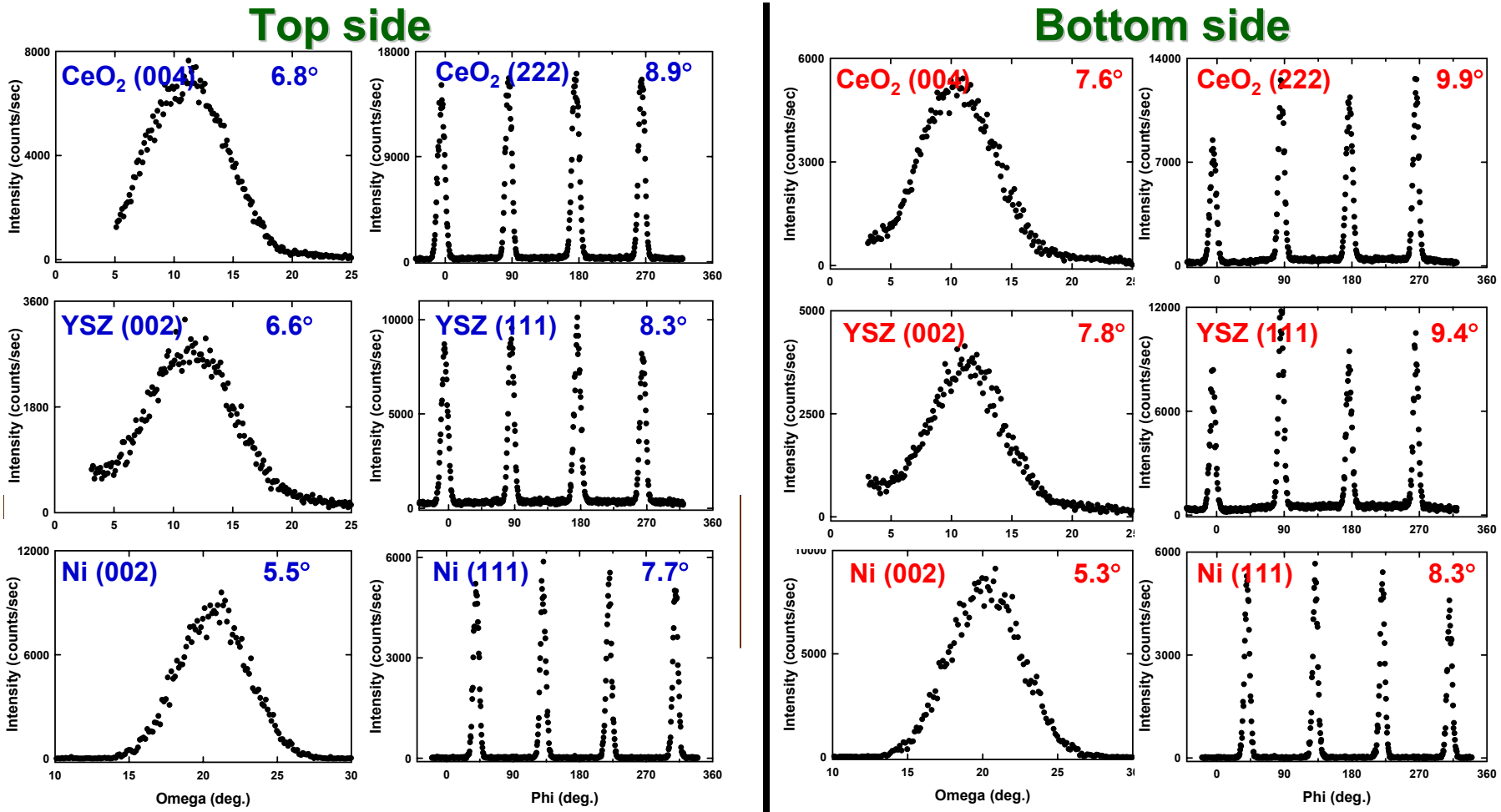
FY04 Results: First two-layer all-MOD buffer for a low-cost RABiTS process; 140 A/cm-width (77K,sf) performance demonstrated





Potential route towards fabrication of lower-cost YBCO coated conductors

Objective 7: Fabrication of double sided RABiTS with solution seeds



Due to reduced funding, we could not modify our equipment to sputter buffers through non-contact heating, improve the buffer microstructure, and hence YBCO with low J_cs were obtained

FY 2004 Plans and Performance

FY2004 Plans

- Develop reel-to-reel buffer layers on PM-derived NiW substrates

FY2004 Performance

- ✓ A major cause for delamination in PM derived NiW substrates was identified, understood and delamination has been eliminated
- ✓ Robust buffer layers on PM derived NiW substrates in reel-to-reel configurations were developed
- ✓ Buffer layer morphology was optimized with respect to columnar porosity in the YSZ and Y_2O_3 layers
- ✓ High critical currents were demonstrated using substrate processing

FY 2004 Plans and Performance

FY2004 Plans

- Develop rolling mill facility with clean room
- Support CRADA partners in the area of substrate fabrication
- Fabricate sharply textured substrates with smooth surfaces
- Work with outside vendors to obtain improved starting coils

FY2004 Performance

✓ Installation of rolling mill facility with a class 1000 clean room was completed and made the mill was made fully operational

✓ American Superconductor Corporation has used this facility on a routine basis for fabrication of wide substrates – materials from this facility are used for scale-up research on wide web processing

✓ Long lengths of sharply textured substrates have been fabricated

✋ Work with outside vendors for improving starting coils was done on a limited basis due to reduced funding

FY 2004 Plans and Performance

FY2004 Plans

- Perform magnetization studies aimed at a better understanding of ac loss contribution from alloy substrates

FY2004 Performance

- ✓ Performed a detailed study of ac losses from NiW substrates derived from vacuum casting and powder metallurgy routes
- ✓ Showed that ac losses are an *extrinsic* property of the substrates and depend on operations such cutting and/or slitting
- ✓ ac FM losses/cycle were found to be independent of ac frequency for 100's of Hz
- ✓ ac FM losses were found to decrease significantly when a dc bias field saturates the alloy substrate

FY 2004 Plans and Performance

FY2004 Plans

- Fabricate long lengths of Cu-based RABiTS with good texture and smooth surfaces
- Develop all-conductive buffer stack for Cu-based substrates
- Develop compatible buffer layer architectures for non-magnetic substrates

FY2004 Performance

- ✓ Kilometer long, 1 cm wide, Cu substrate was rolled at ORNL
- ✓ Sharp textures of ~4° in-plane true phi with ~ 100% cube texture was obtained
- ✓ A promising all conductive buffer stack of Ir/LSMO was identified
- ✓ Several options for buffer layers on Cr containing non-magnetic alloy substrates were identified – Pd/MgO/LMO or TiN/MgO/LMO
- ✓ A Ni-9at%W coating which has minimal contribution to ac FM losses was developed for both Cu and Ni-based substrates
- ✓ Epitaxy of standard buffers on Ni-9at%W surfaces was demonstrated

FY 2004 Plans and Performance

FY2004 Plans

- Perform percolation calculations in applied fields
- Perform percolation calculations using presently achievable texture in RABiTS

FY2004 Performance

✓ Percolation calculations in the presence of applied fields show a *diminished* dependence of J_c on width for long conductors

✓ Percolation calculations using the presently achievable texture of ~5° FWHM, show a *greatly reduced* dependence of J_c on width for long conductors

✓ Percolation calculations using the presently achievable texture of ~5° FWHM in the presence of applied fields, show a *negligible* dependence of J_c on width for long conductors

✓ Results point to feasibility of sub-dividing conductor into narrow filaments to reduce ac losses

FY 2004 Plans and Performance

FY2004 Plans

- Separate in-plane and out-of-plane misorientation components from the total misorientation at a grain boundary
- Relate misorientation to J_c

FY2004 Performance

✓ Separation of total misorientation into in-plane and out-of-plane components was made possible for the first time using manipulations in Rodrigues space

✓ In RABiTS substrates which can support a YBCO conductor with ~70-80% of the J_c of a single crystal, GB maps show that J_c correlates best with in-plane misorientation

✓ GB maps again point to feasibility of sub-dividing conductor into narrow filaments to reduce ac losses

FY 2004 Plans and Performance

FY2004 Plans

- Improve intragranular-J_c for YBCO films on RABiTS
- Demonstrate double-side, fully buffered RABiTS
- Further develop solution-based buffer layers

FY2004 Performance

✓ Significant enhancement of the intragranular-J_c was demonstrated for YBCO films on RABiTS

✓ Self-aligned nanodots along the c-direction of YBCO similar to discontinuous heavy ion-irradiation tracks were demonstrated for the first time. Significant enhancement in the in-field J_c and the angular dependence was achieved

✓ Double sided buffered RABiTS with good texture was fabricated

✓ An I_c of 140 A/cm corresponding to a J_c of 1.75 MA/cm^2 was demonstrated for 0.8 μm thick YBCO film by ALL-SOLUTION processing

FY2005 Plans

Metal/Alloy development:

- Work with outside vendors to obtain improved coils with reduced defects
- Research and develop long lengths of powder metallurgy derived Ni-(5-9.5)at%W substrates and transfer of technology to industry
- Study texture development of non-magnetic Ni-W substrates via vacuum casting derived coils
- Research and develop, strengthened and conductive Cu-based substrates with good texture

Texture and percolation:

- Develop methods aimed at separating the a-axis and c-axis tilt components from the total misorientation measured in EBKP for materials with lower symmetry such as YBCO
- Relate J_c to measured GB maps in laser-scribed samples and experimentally demonstrate filament sub-division to reduce hysteretic losses

FY2005 Plans

Buffer layer development:

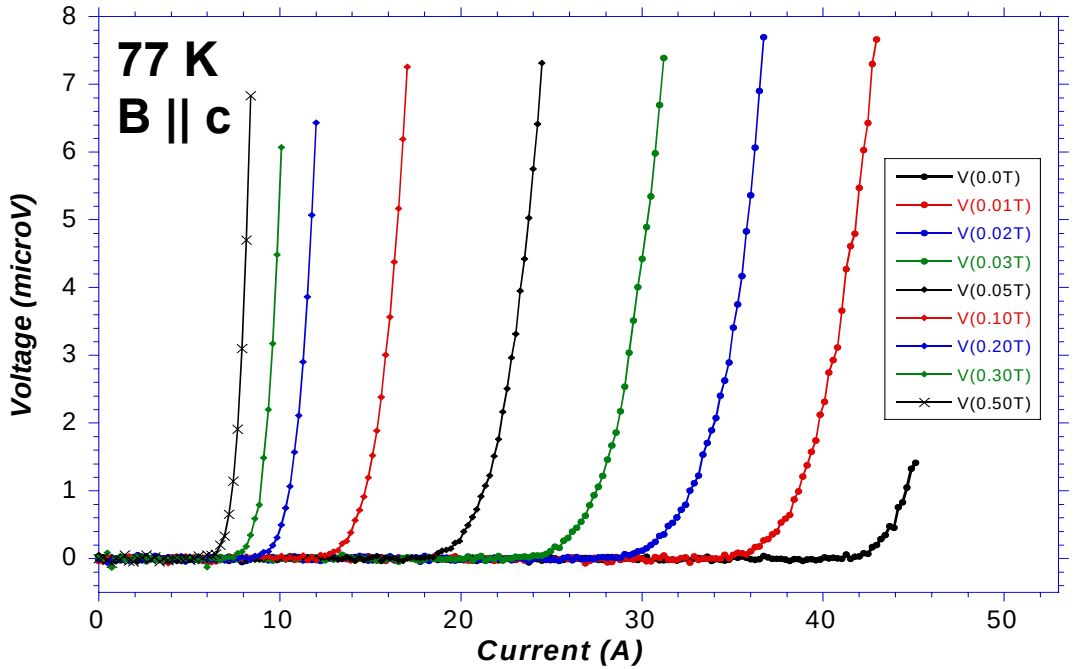
- Develop conditions for standard buffer layer deposition in reel-to-reel configurations for higher W containing Ni-based substrates
- Use thermal desorption spectroscopy to study evolution of gases from higher W containing Ni-based substrates for prevention of buffer delamination
- Develop improved buffer architectures which reduce oxygen diffusion to the metal/alloy substrate
- Further develop conductive architectures for Cu-based which can support a high-J_c, thick YBCO
- Further develop high rate processes for buffer layer depositions, such as solution or reactive sputtering

Research Integration: *Interactions with Companies*

- **American Superconductor Corporation (AMSC)**
  - Have a CRADA with AMSC and work on substrates is a significant component of the CRADA
  - A majority of wide area substrates for scale-up studies at AMSC were rolled in the ORNL rolling mill facility with clean room
- **MetOX**
  - Provided both textured alloy as well as buffered RABiTS substrates for growth of YBCO
- **Oxford Superconducting Technology (OST)**
  - Continue to collaborate on metal templates
- **Ametek Corporation** - Developing fabrication of starting coils
- **Hamilton Precision Metals** - Developing rolling & slitting process for coil
- **Flowserve Corporation - Development of vacuum cast starting materials**
- **Several other proprietary vendor companies**

Good J_c's have been obtained using MetOx R2R MOCVD YBCO on ORNL RABiTS

- **Houston-based small business company to produce YBCO coated conductors.**
- **Has proprietary <u>high-rate MOCVD</u> technology for buffers and YBCO growth.**
- **Collaboration status:**
  - Technical plan has been agreed upon, CRADA negotiation in process,
  - Initial evaluation of MetOx <u>R2R MOCVD YBCO</u> (non-optimized) on ORNL RABiTS yielded good YBCO texture: $\Delta\omega \sim 3°$; $\Delta\phi \sim 5.5\text{-}7.5°$



For YBCO < 1 μm:
I_c (max) = 73 A
J_c (max) =1.2 MA/cm^2

OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

MetOx

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Research Integration: *Interactions with universities*

Close collaboration with the following universities:

- University of Cambridge: Noel Rutter
- Washington State University: David Field
- University of Tennessee: Tolga Aytug, S. Sathyamurthy
- 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)

Acknowledge the support of DOE: LSTDP and RAMS programs

Research Integration: *Interactions with universities*

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

- University of Houston: Alex Ignatiev
- U. of Cincinnati: Donglu Shi
- University of Kansas: Judy Wu
- University of Missouri-Rolla: Jay Switzer
- North Carolina State University: J. Narayan
- California State University: Chuhee Kwon
- University of California at Santa Barbara: Fred Lange
- University of Wisconsin, Madison: Eric Hellstrom

Universities with arrows – close interaction as a collaborator on DOE University funded project

Research Integration: *Interactions with national laboratories*

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

- **NIST: N. Cheggour, J. Ekin, W. Wong**
- **SNL: P. Clem, M. Siegel**
- **NREL: R. Bhattacharya**
- **AFRL: T. Haugan, P. Barnes**

Developed $LaMnO_3$ buffers for IBAD-MgO from Research Park

- **LANL: V. Matias**

Communications:

- **Many publications**
- **Numerous presentations**
- **Several patents issued as well as filed**
- **Information also dispersed via regular CRADA teleconferences/meetings/annual reports**

Extras

Numerous potential causes for delamination have been explored throughout FY04

A. Porous/columnar grain morphologies

- Thicker Y_2O_3 and a higher rate YSZ deposition give rise to more porous/columnar film morphologies.

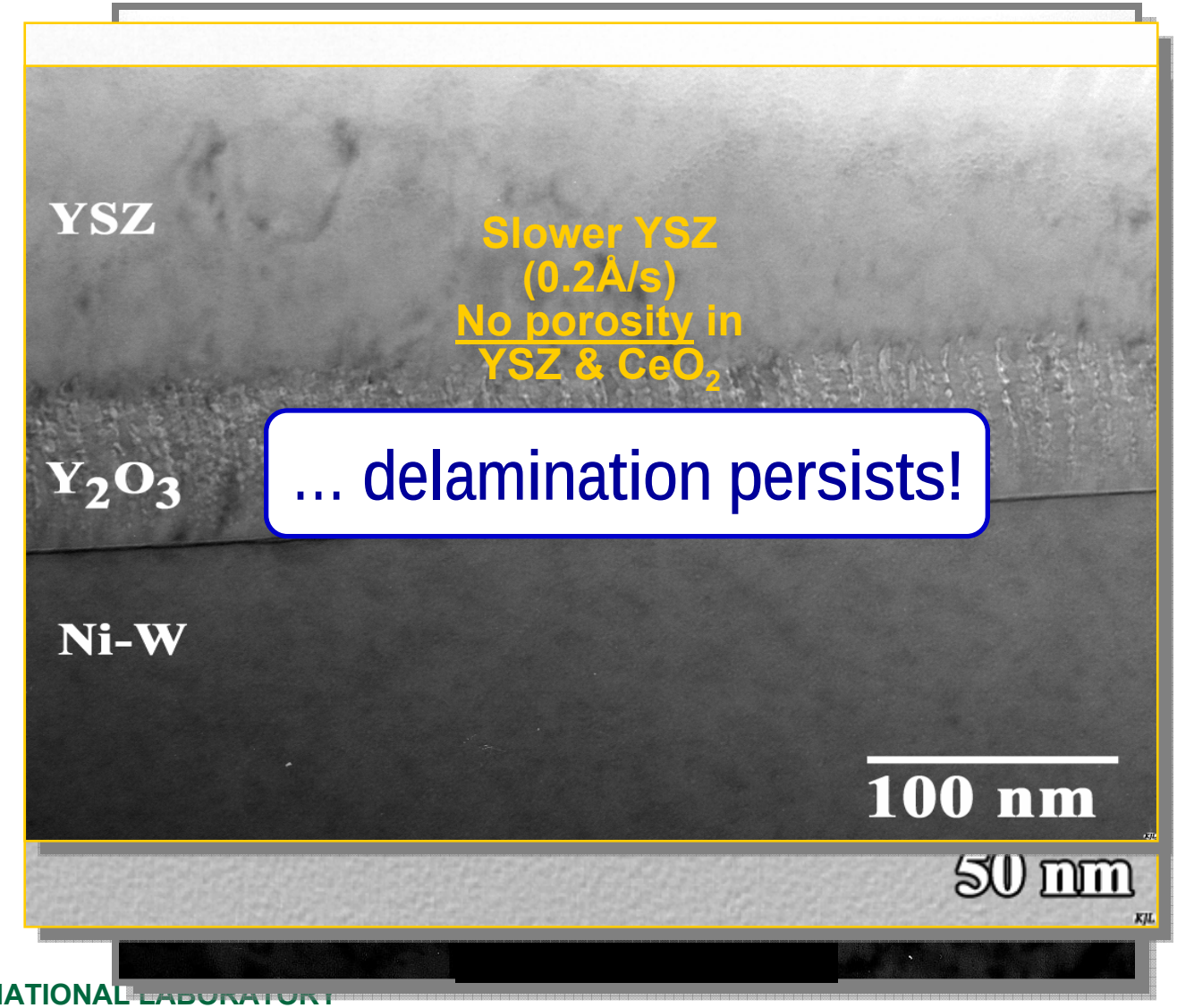
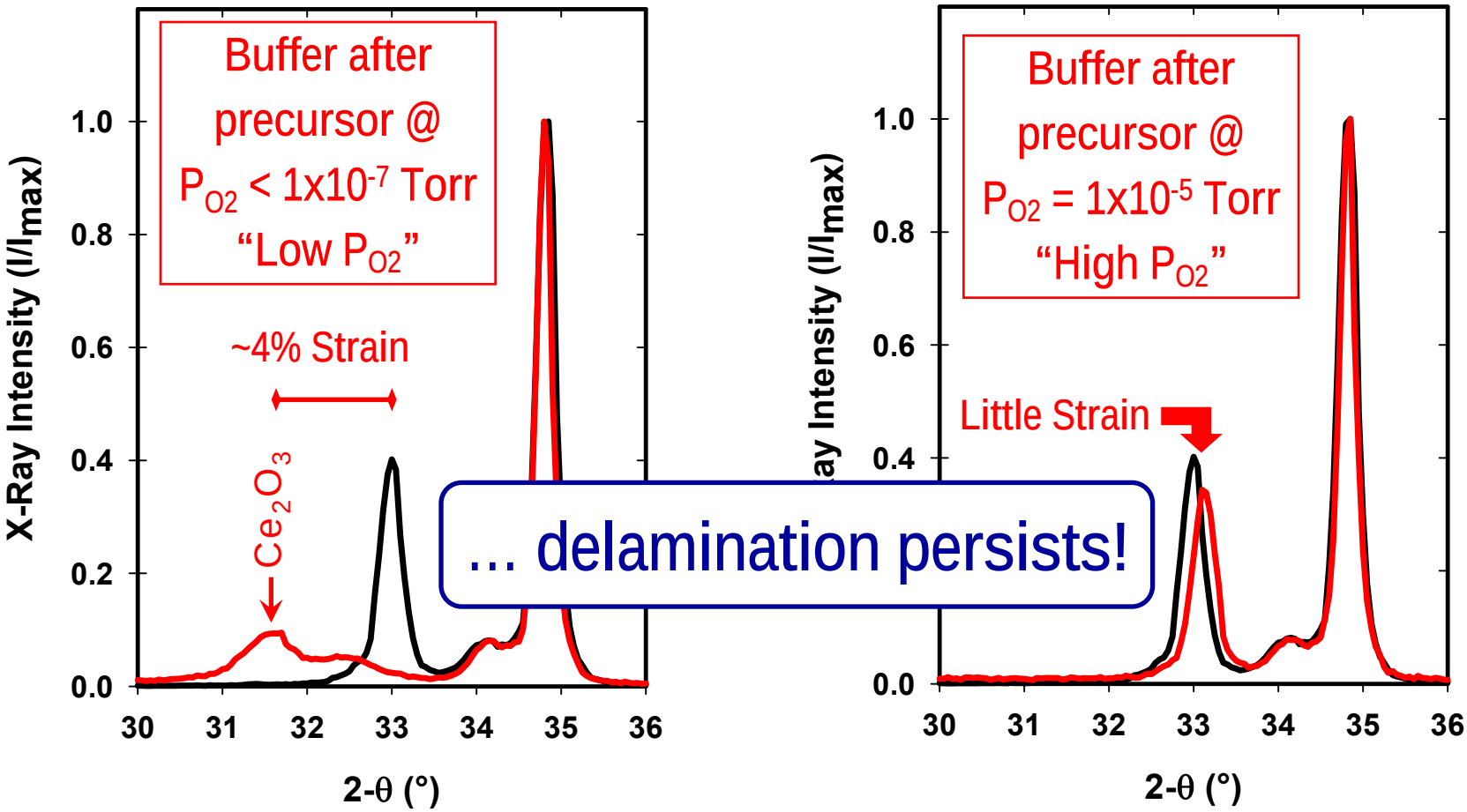
B. Oxygen non-stoichiometry of buffer layers

- CeO_2 cap layer can become oxygen deficient when the precursor is deposited in low P_{O2}.

C. Carbon oxidation at the metal/oxide interface

- CO desorption is observed for vacuum annealed Ni-3%W when heated in low P_{O2}.

A. Modified processing leads to improved buffer morphologies, but ...



B. Higher P_{O2} during precursor deposition preserves the CeO_2 stoichiometry, but…