ORNL-AMSC Strategic Research

American Superconductor Corporation

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FY 2005 Funding: $800 K - DOE-OE
$250 K -Funds-in from AMSC
Matching funds at AMSC

CRADA Objectives

Provide advanced measurements and characterizations to assist AMSC's development of a commercial 2G HTS wire based on the MOD/RABiTS™ technology

Carry out R&D required for achieving the cost/performance necessary for commercial HTS applications

FY 2005 CRADA Goals

- Pilot line production of high quality (4 cm wide by 100 m long) alloy substrates using the ORNL rolling mill facility with clean room
  - ✓ Over 2.5 km of 4 cm wide NiW substrate produced with ORNL assistance
- Improvement of RABiTS template manufacturing process reliability through fundamental characterization of the buffer layer properties
  - ✓ Quality of 1 cm RABiTS template successfully extended to 4 cm wide process
- Reduction of the substrate/buffer manufacturing cost through improved understanding of the interactions of buffer deposition rates and intrinsic properties
  - ✓ High rate reactive sputtering of buffer layers successfully developed for 4 cm wide process

FY 2005 CRADA Goals

- Determine key flux-pinning mechanism in long-length, MOD YBCO, 4 cm wide YBCO wires
  - ✓ Stacking faults in the YBCO layer were shown to result in the strong peak in J_c vs angle for H//ab
- Improve the in-field J_c in all fields by incorporation of nanoparticles in long-length, MOD YBCO, 4 cm wide wires
  - ✓ Quality of 1 cm RABiTS template successfully extended to 4 cm wide process
- Analysis of the uniformity and reproducibility of long length, 4 cm wide RABiTS templates produced in a high-rate reel-to-reel manufacturing process
  - ✓ Quality of 1 cm RABiTS template successfully extended to 4 cm wide process
- Development of new, low-cost template architectures that are applicable to Ni-5at%W as well as non-magnetic Ni-9at%W and NiCrW substrates
  - ✓ All solution buffers demonstrated with performance > 180 A/cm-w

AMSC-ORNL CRADA Presentation

- **FY 2005 Results**

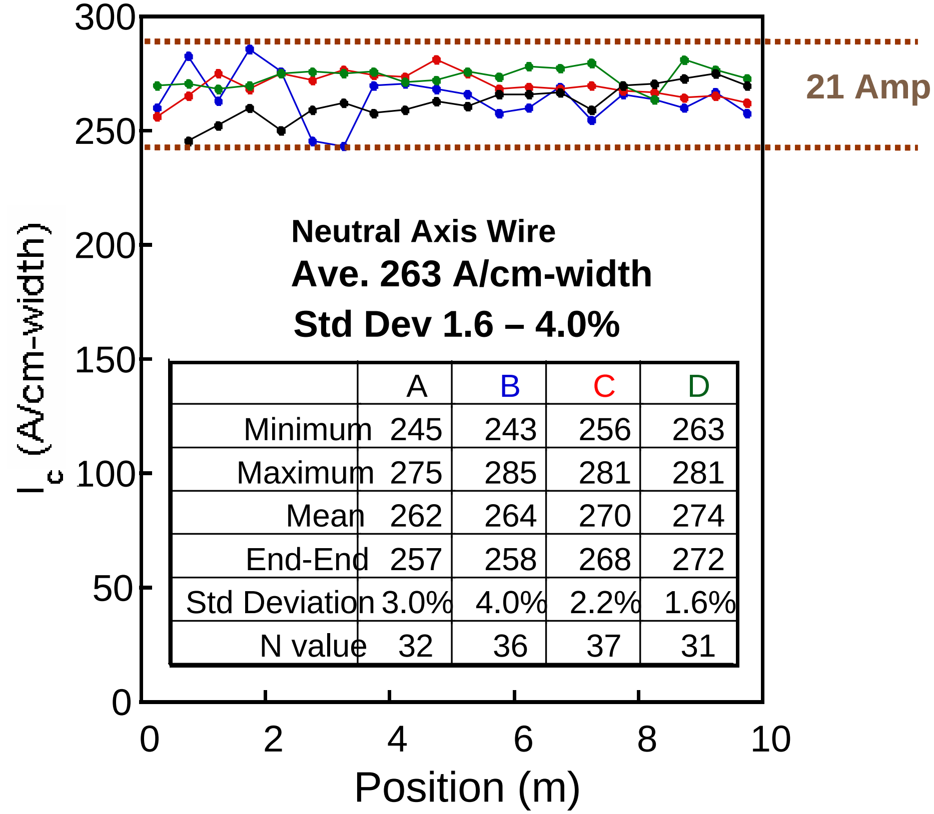
2G Development (YBCO/RABiTS) at AMSC **(Marty)**
2G wire manufacturing at AMSC
2G wire characteristics

Alloy substrate fabrication (4 cm wide) **(Amit)**
Buffer layer development for 4 cm wide process
Flux-pinning optimization in MOD YBCO
Striated conductor development
2G coil fabrication

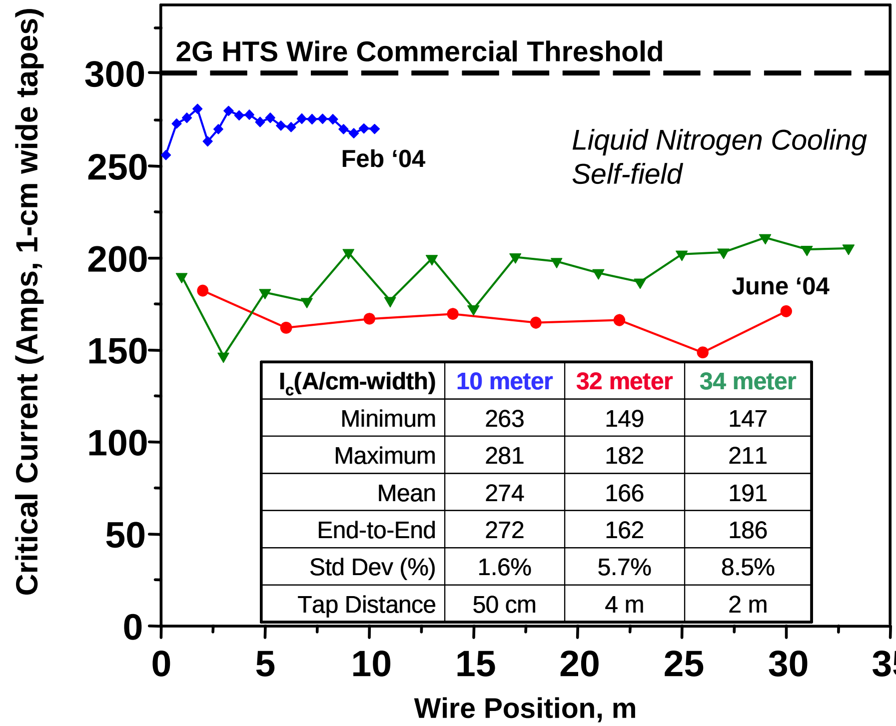
Development of low-cost, solution buffer layers **(Parans)**

- **FY 2005 Performance and FY 2006 Plans** **(Parans)**
- **Research Integration**

July 2004 Status:
1 cm Wide Strip Process Capability



	A	B	C	D
Minimum	245	243	256	263
Maximum	275	285	281	281
Mean	262	264	270	274
End-End	257	258	268	272
Std Deviation	3.0%	4.0%	2.2%	1.6%
N value	32	36	37	31



I_c(A/cm-width)	10 meter	32 meter	34 meter
Minimum	263	149	147
Maximum	281	182	211
Mean	274	166	191
End-to-End	272	162	186
Std Dev (%)	1.6%	5.7%	8.5%
Tap Distance	50 cm	4 m	2 m

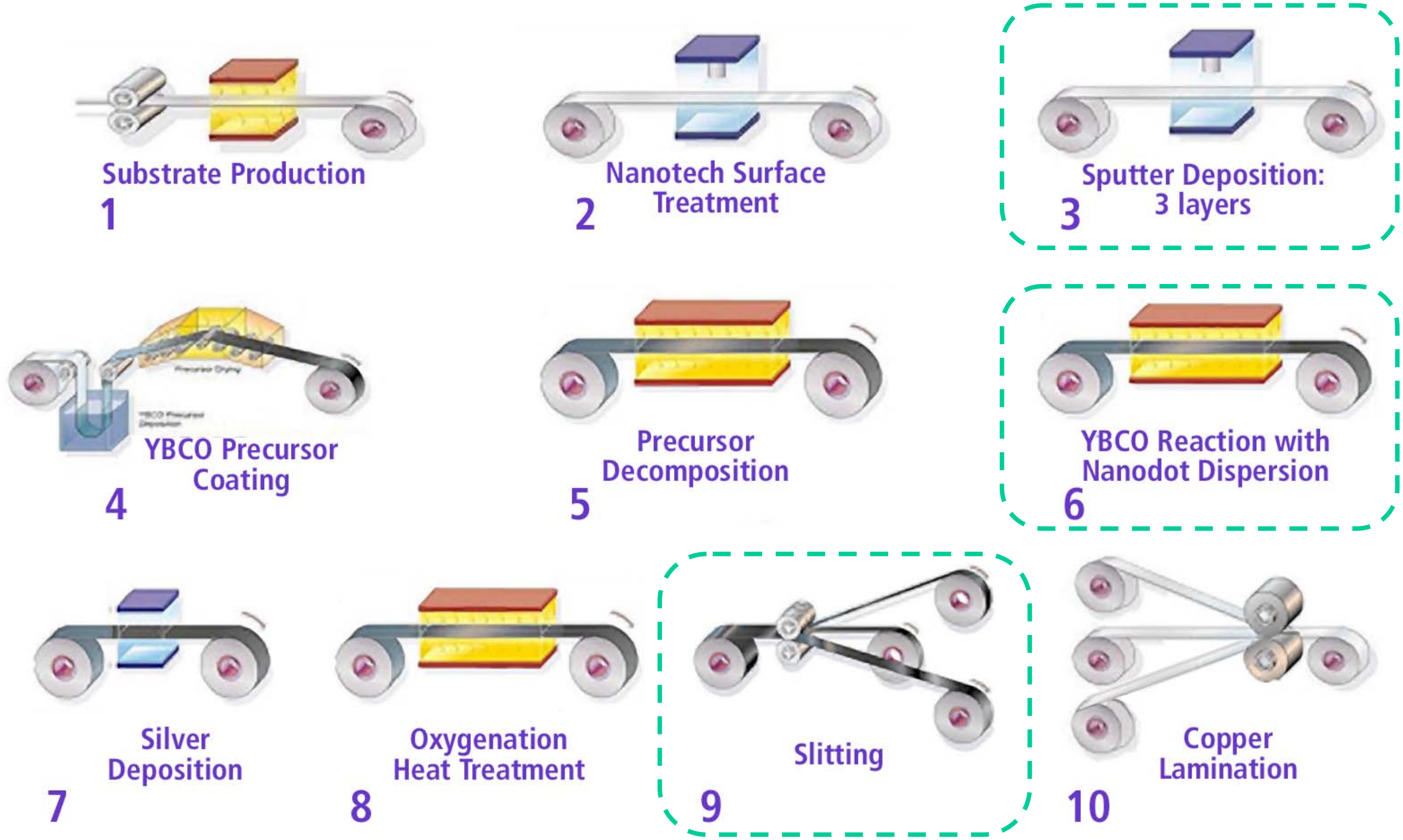
Performance, uniformity and reproducibility established scale-up readiness

2005 AMSC Focus

- **2G Scale-Up**
  - Transition to 4 cm wide process
    - New 4 cm capable "Pilot Scale" or upgraded R&D equipment
    - High-rate reactive sputtering process for buffer deposition
    - Processes optimized to match 2004 Baseline metrics
  - Length scale-up (~80 meter)
- **Supporting R&D**
  - Ic enhancements
  - Pinning improvements
  - Low-cost process exploration/development
    - Solution buffers
    - Inkjet printing
  - Substrate improvement (strength and thickness)
  - Wire Architecture enhancements

ORNL team provided critical R&D and characterizations for implementing 4 cm process

☑ 2005 *Goal: Complete and Qualify 4 cm x 100 m Process Capability*



Key production scale equipment developed for 4 cm wide process

4 cm RABiTS Manufacturing Process Capability Qualified

- RABiTS technology successfully developed for 4 cm x 100 meter NiW substrates at ORNL rolling facility
- ORNL facility used to supplement AMSC substrate production

- New rolling mill installed in AMSC's Devens plant with 4 cm x 1 km design capability will be qualified for 100 m production in 2005

4 cm x 100 m substrates produced routinely at AMSC and ORNL rolling facilities

4 cm Production-Scale Reactive Sputtering Process Capability Qualified

Reactive Sputtering

- Single method developed for all three buffer layers
- High deposition rate
- Industrial, large-area deposition process
- Performance qualified against benchmarks established for 1 cm process
  - Texture
  - Diffusion
  - Morphology
  - Critical Current

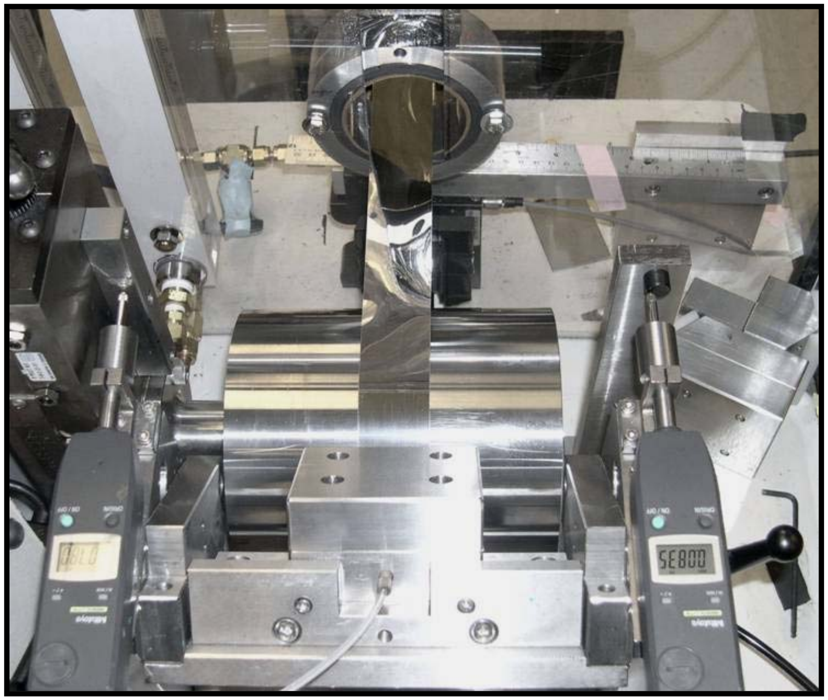
Dual-Layer Reactive Sputtering System

ORNL provided key metrics insuring successful transition to high-rate reactive sputtering

4 cm MOD-YBCO Process Capability Qualified

- Slot-die coating line and decomposition oven upgraded and qualified for 4 cm x 100 m process

Slot-Die Coater



Slot-Die Web Coating

- Industrial coating technology
- Fast line speeds (>600 m/hr)
- Adaptable to wide, continuous (km) tapes
- Produces uniform, reproducible coating
- Materials usage is ~ 100%

Coating technology adapted by ORNL to support solution buffer development

4 cm Production-Scale YBCO Reaction Process Capability Qualified

_ex_-situ MOD-based precursor is converted to epitaxial YBCO

$$2\ BaF_2 + 2H_2O + 0.5Y_2O_3 + 3CuO \rightarrow YBa2Cu3O7\text{-}x + 4HF_{(g)}$$

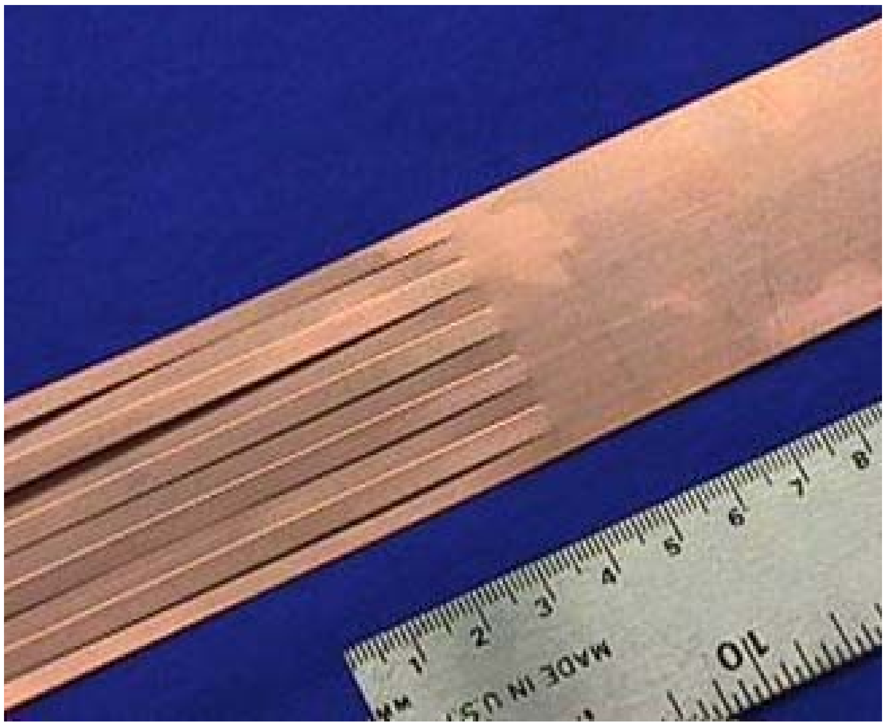
- 3-D CFD modeling used to engineer uniform 4 cm reaction zone
- High rate 20 Å/s process (2X rate of 1 cm furnace)

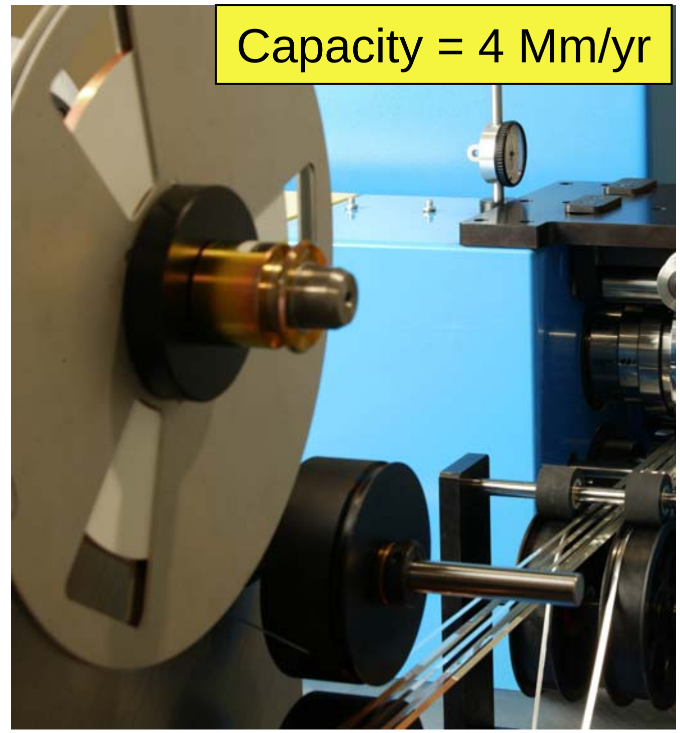
Texture analysis and Ic measurements key to insuring uniformity of 4 cm reaction process

4 cm Slitting Process Capability Qualified

2G semi-finished insert wires (4.1 mm wide) produced

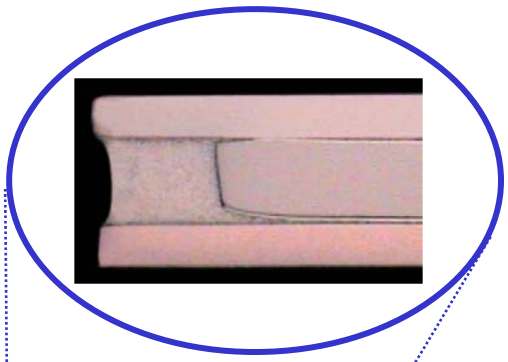
- Eight wires from each 4 cm strip
- Lengths up to 85 m



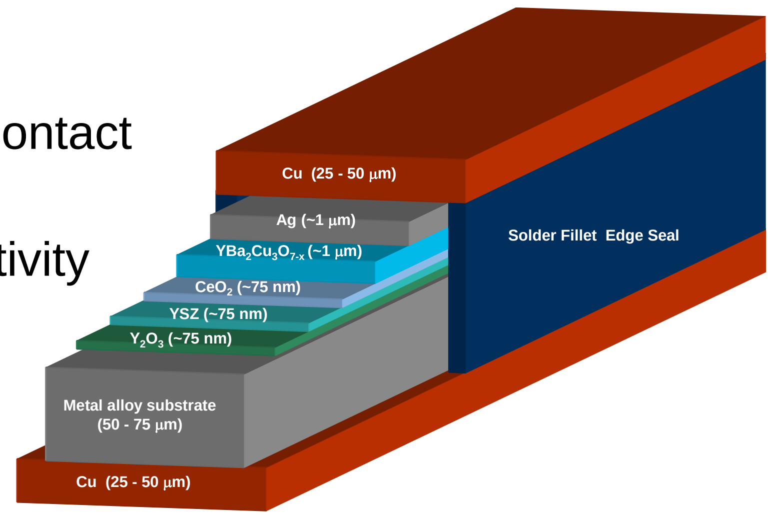


Fast, industrial slitting process enables cost-effective wire manufacturing

3 Ply Wire Architecture Developed to Meet Customer Needs



- Enhanced mechanical properties
- Electrical (solderable) contact to both sides
- Tailored stabilizer resistivity (Cu, SS, etc)
- Customizable width
- Hermetic

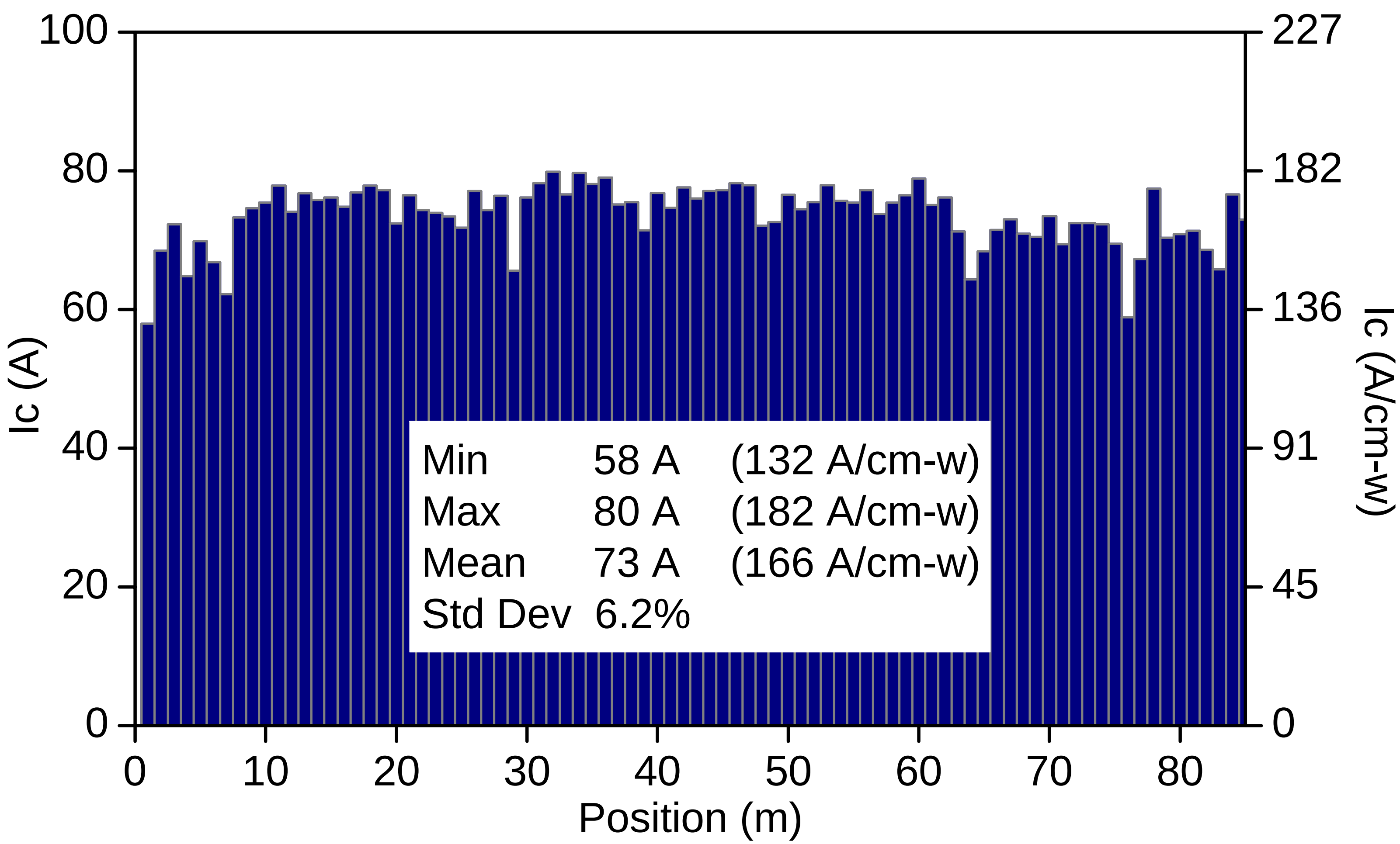


4.3 mm laminate
4.1 mm insert
4.3 mm laminate

Solder fillets

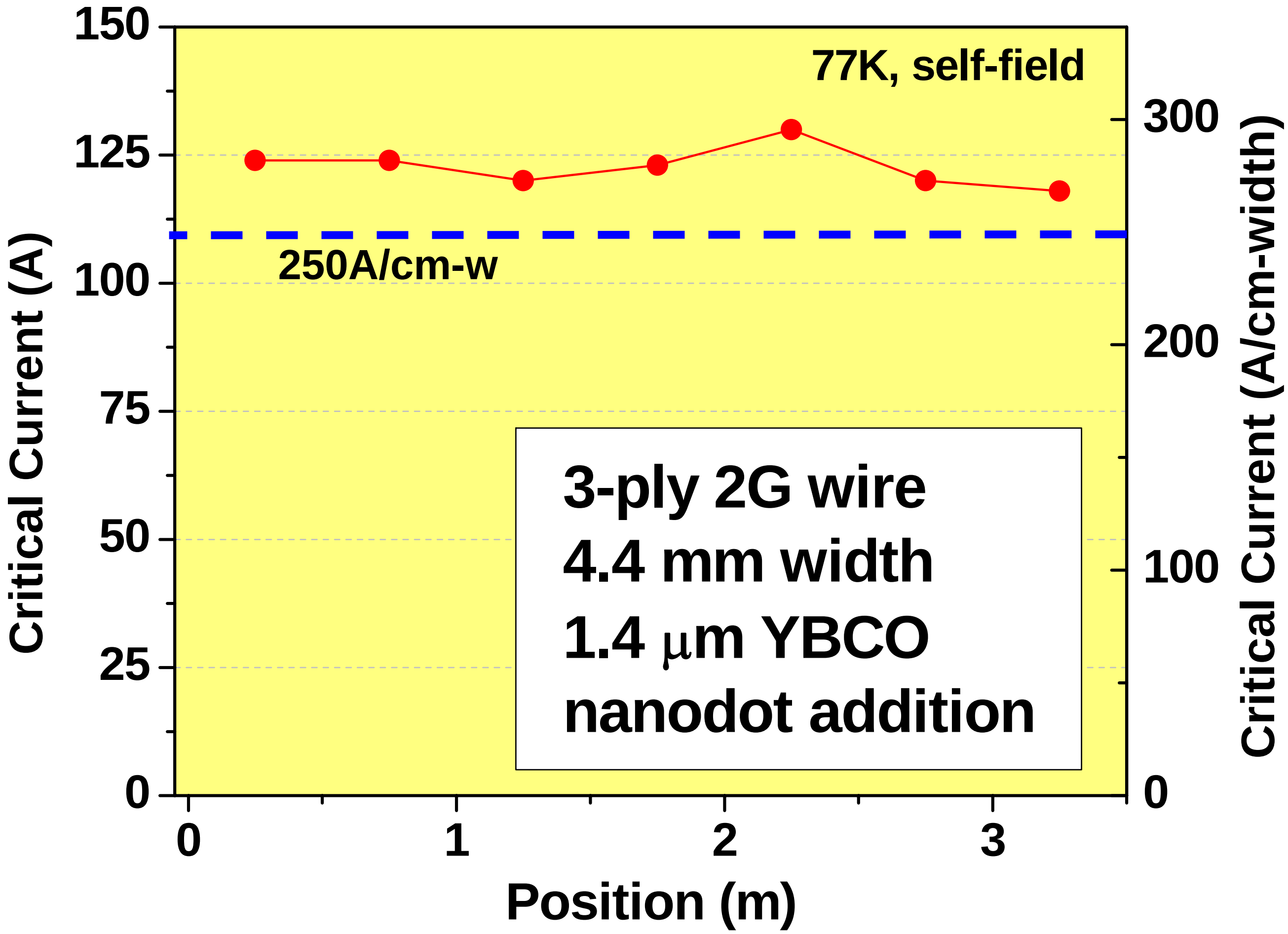
3 Ply wire meets specifications for commercial wire applications

85 m of 4.4 mm 3-Ply Wire – July 2005



Collaborative efforts key to successful scale-up of 4 cm technology to 85 m length

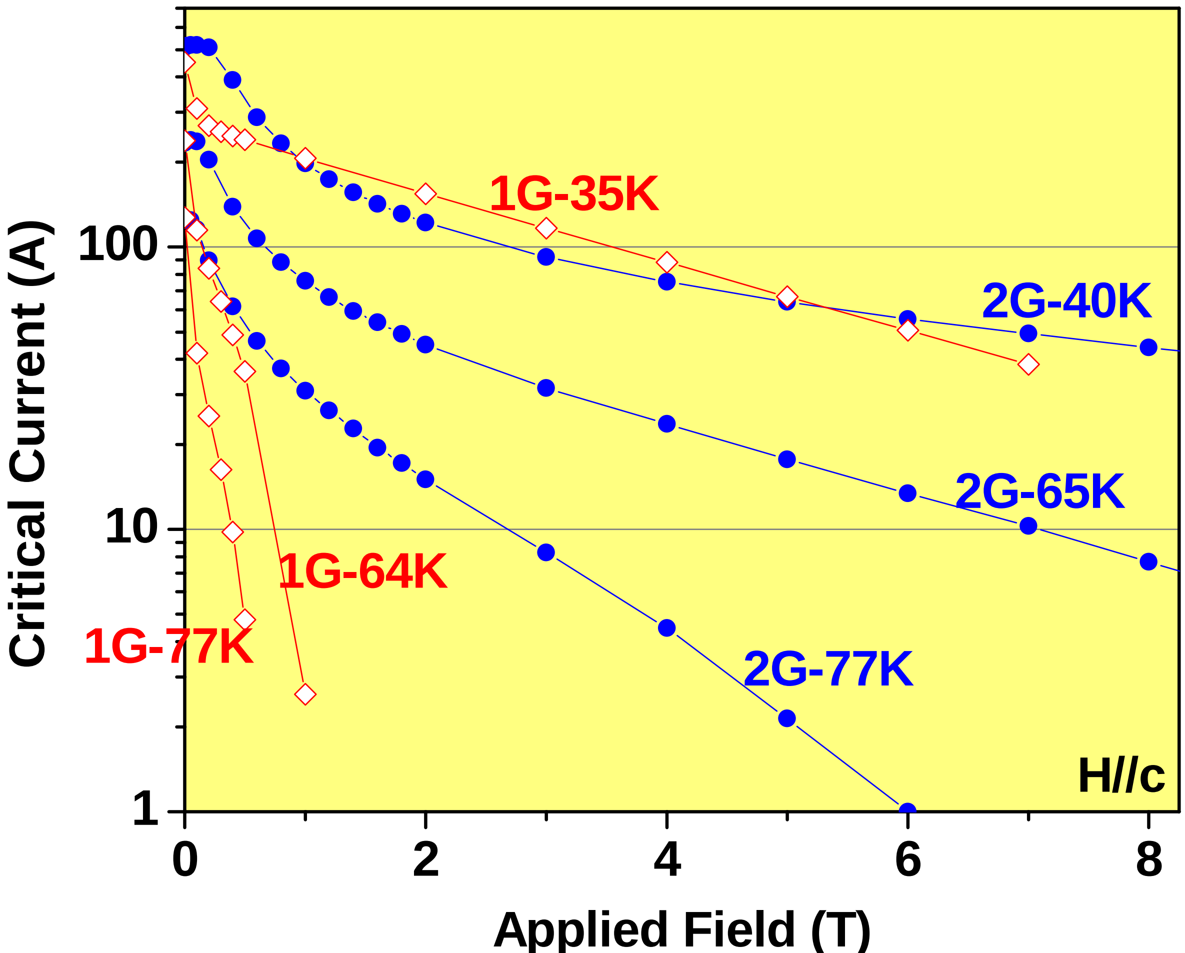
2G Wire Performance Exceeds 250A/cm-w



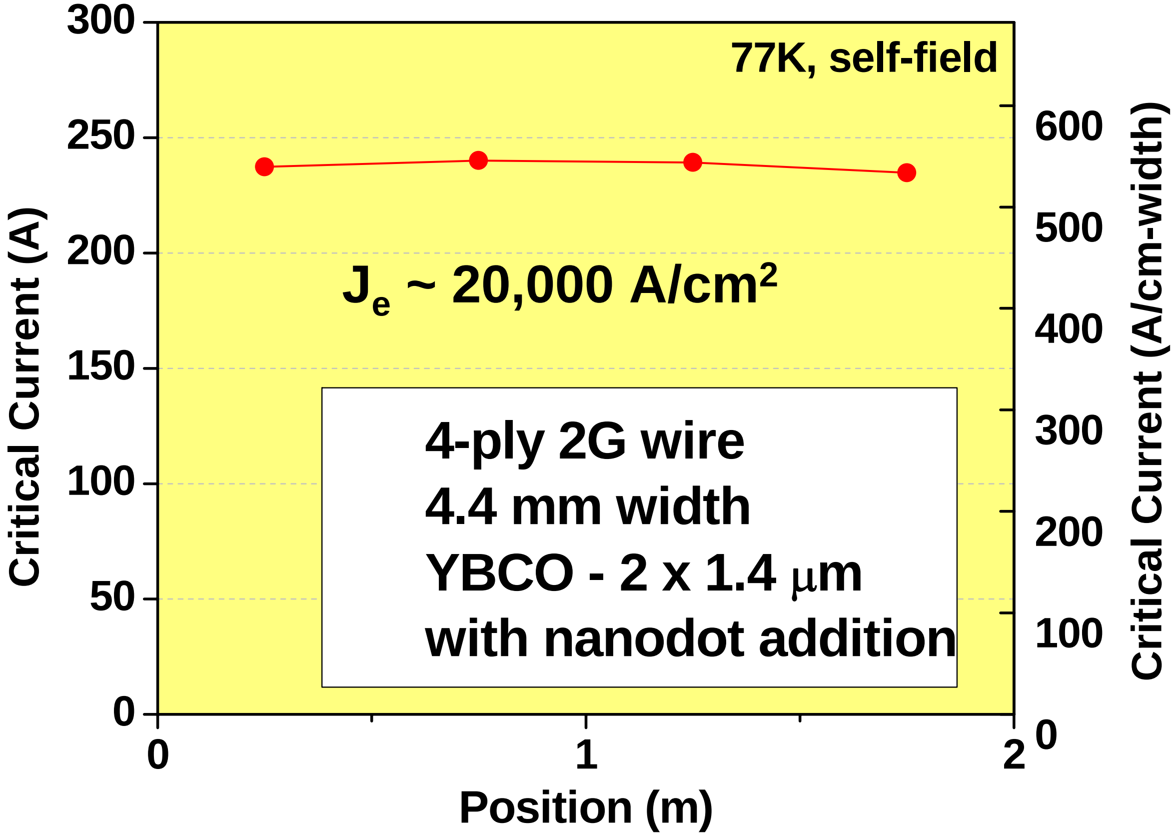
ORNL provided key characterization for nanoparticle addition and process optimization

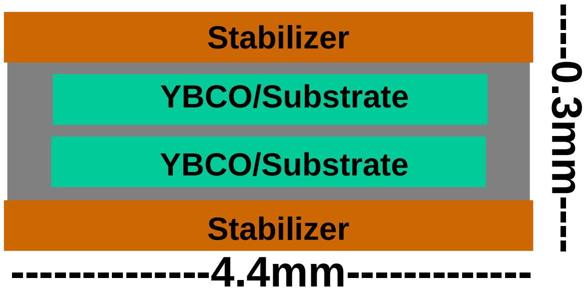
2G Wire is Form-Fit-Function for 1G Wire

1G Wire: 125A, 4.4 mm width → **2G Wire: 125A, 4.4 mm width**



4-Ply Architecture Promises Higher Ic's



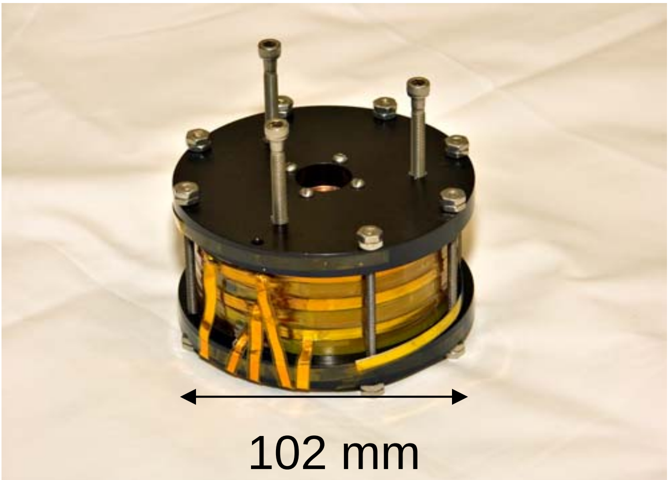


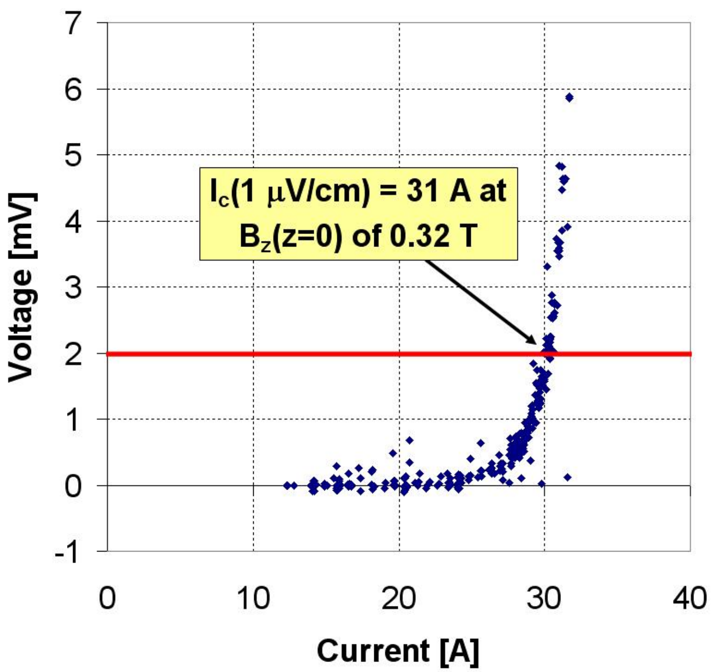
MOD/RABiTS process provides path to ultra high Ic wire

Successful Design, Fabrication, and Testing a of 2G YBCO Magnet

Magnet specifications

- Conductor type
  - 3-ply copper stabilized YBCO, 4.4 mm wide
- Geometry
  - ID 35 mm
  - OD 102 mm
  - Height 35 mm
  - No. of pancakes 6
  - No. of turns 582





	77 K	30 K (calc.)
Central field B_z(z=0)	0.32 T	1 T
Critical Current	31 A	100 A

AMSC-ORNL CRADA Presentation

- **FY 2005 Results**

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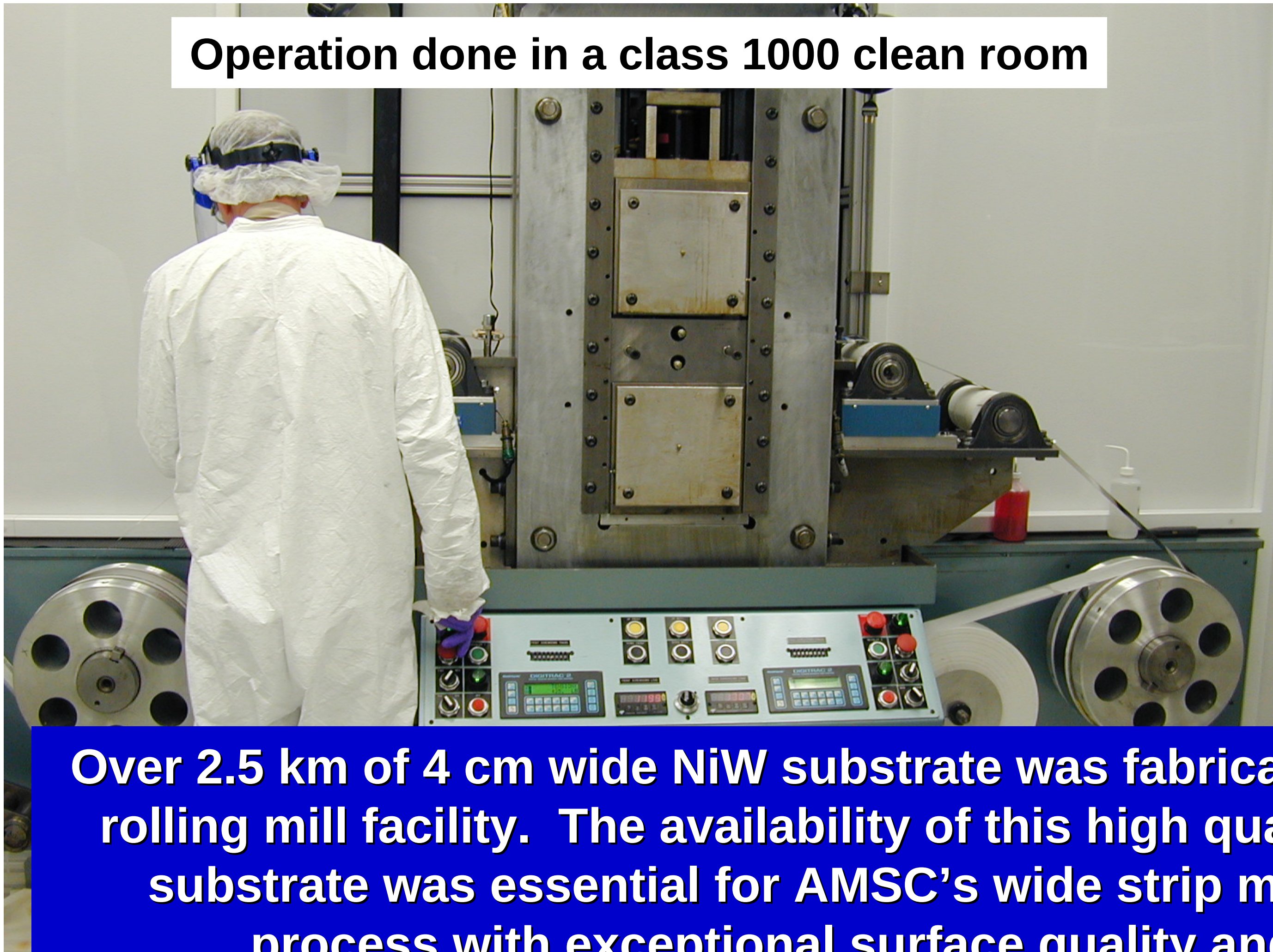
  2G wire characteristics

  Alloy substrate fabrication (4 cm wide) (Amit)
  Buffer layer development for 4 cm wide process
  Flux-pinning optimization in MOD YBCO
  Striated conductor development
  2G coil fabrication

  Development of low-cost, solution buffer layers (Parans)

- **FY 2005 Performance and FY 2006 Plans (Parans)**
- **Research Integration**

Goal: Pilot line production of high quality, 4 cm wide alloy substrates using the ORNL rolling mill facility

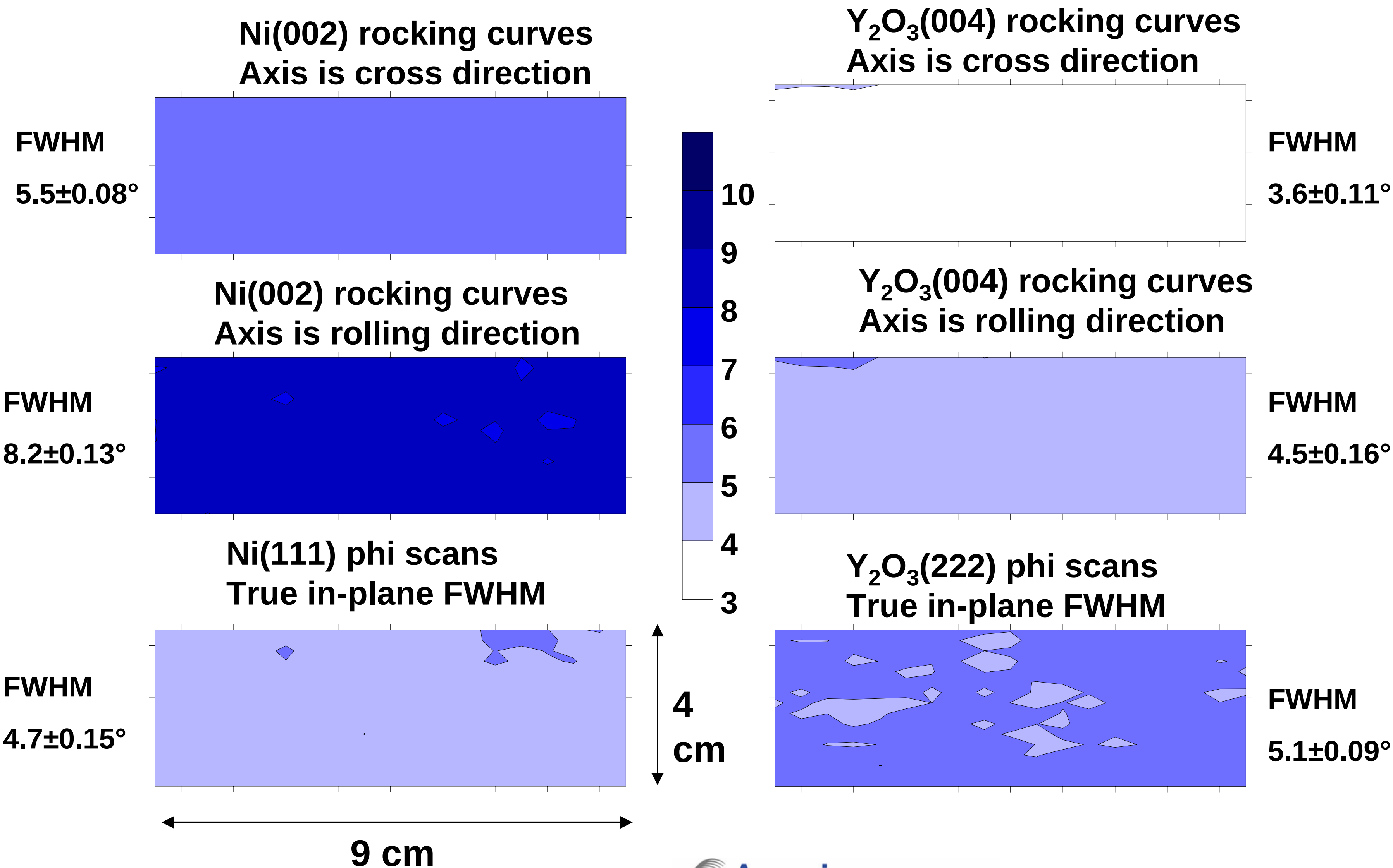


Operation done in a class 1000 clean room

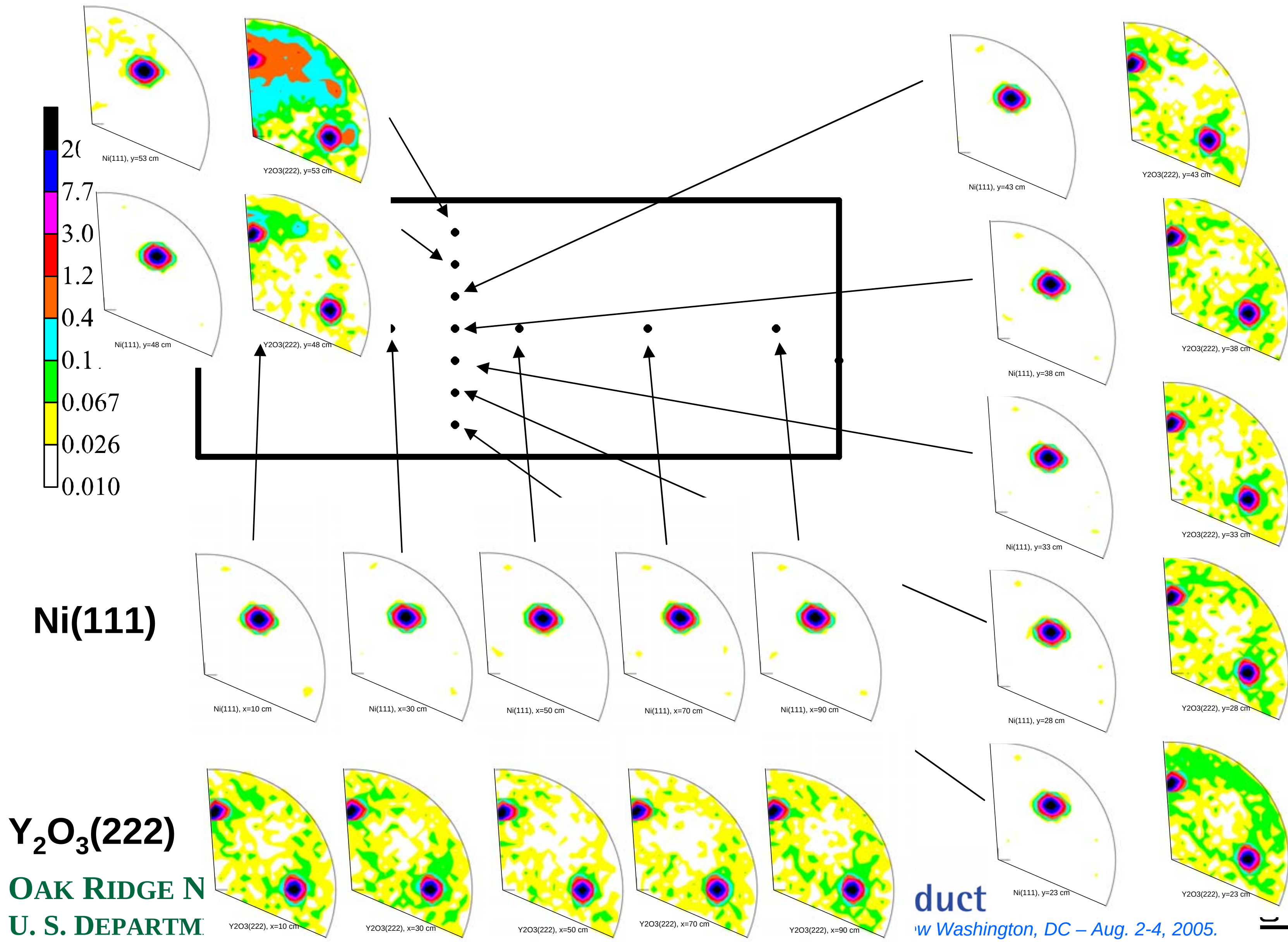
AMSC personnel visited ORNL on a regular basis for rolling of wide NiW substrates for scale-up efforts.

Over 2.5 km of 4 cm wide NiW substrate was fabricated in the ORNL rolling mill facility. The availability of this high quality, 4-cm wide substrate was essential for AMSC's wide strip manufacturing process with exceptional surface quality and texture

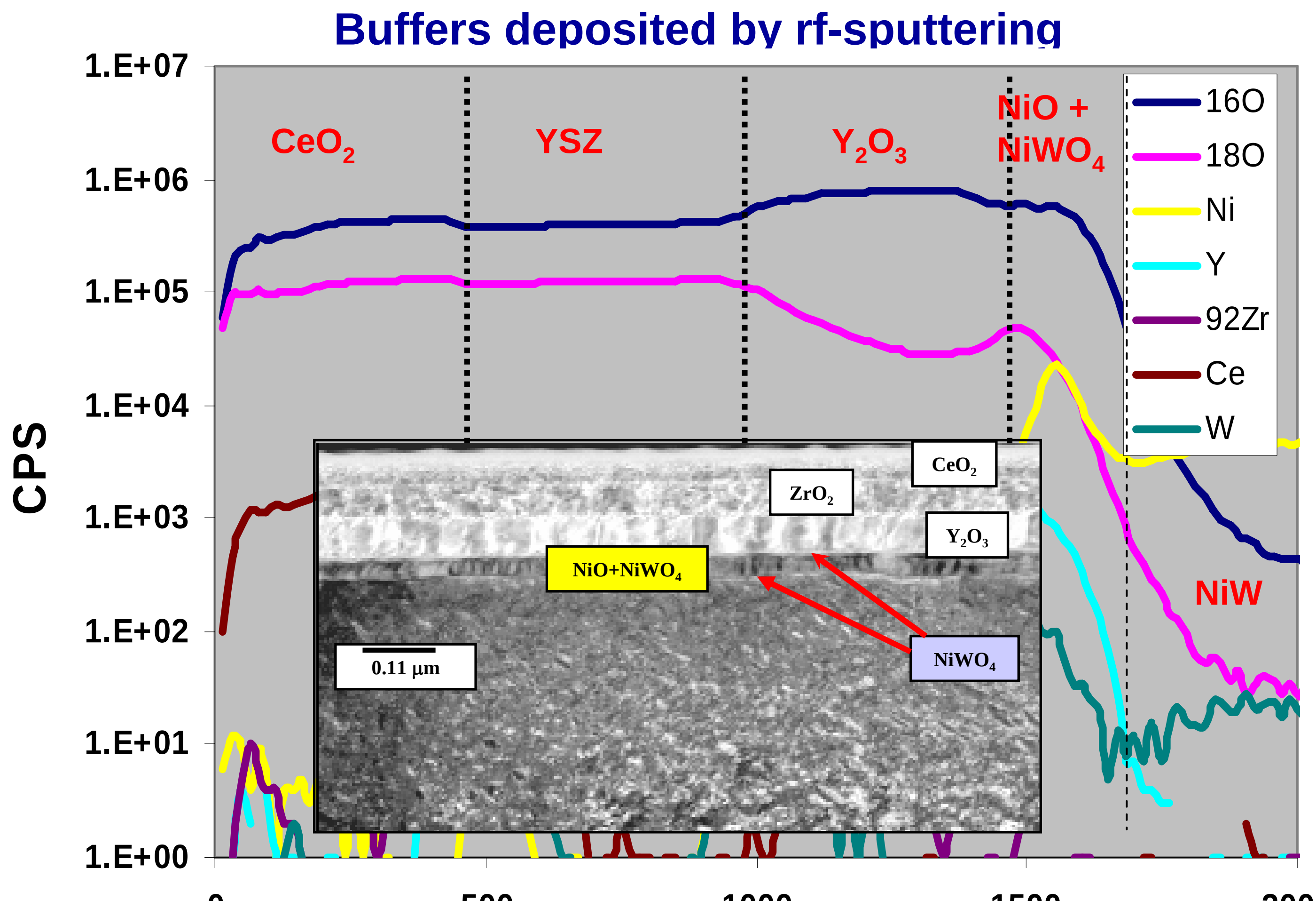
Uniform Texture Achieved in 4 cm wide Y_2O_3 Seed Layer on NiW Substrate



Detailed Pole Figure Analysis Shows that Reel-to-Reel Produced AMSC's 4 cm wide, Y_2O_3 Seed Layer has a Uniform Texture



FY04: **Understanding of the roles of various buffer layers allowed reduction of the total buffer thickness to Y_2O_3 (75nm) / YSZ (75nm) / CeO_2 (75nm)**

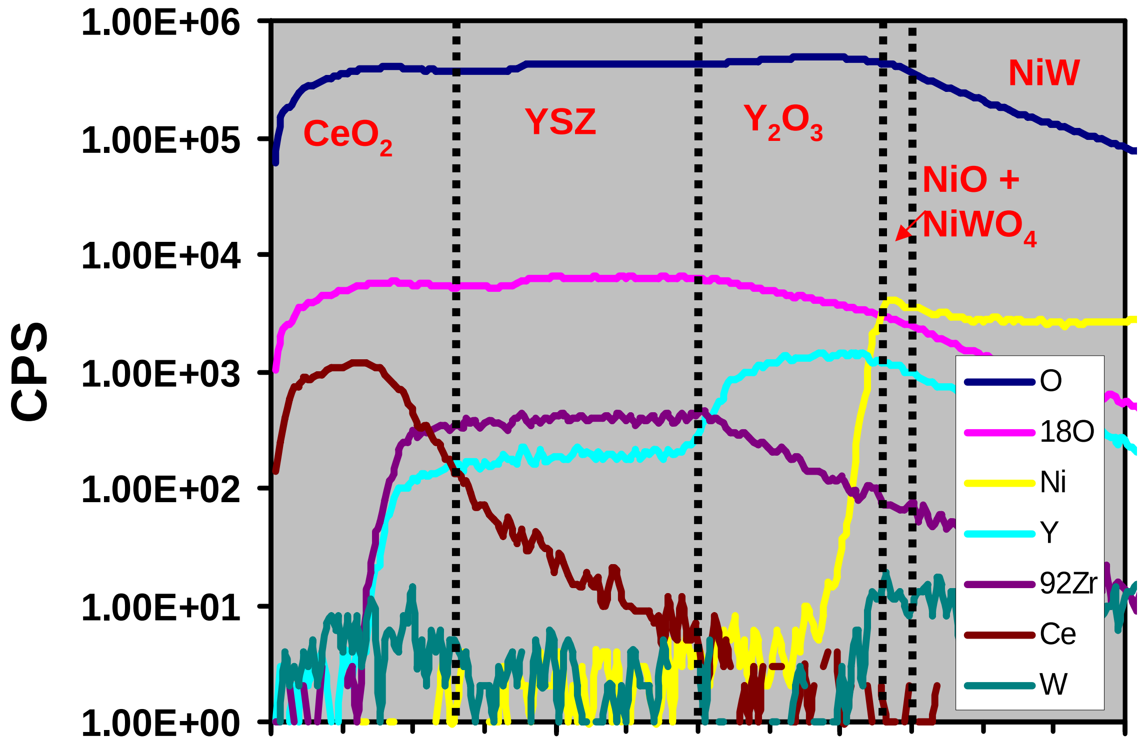


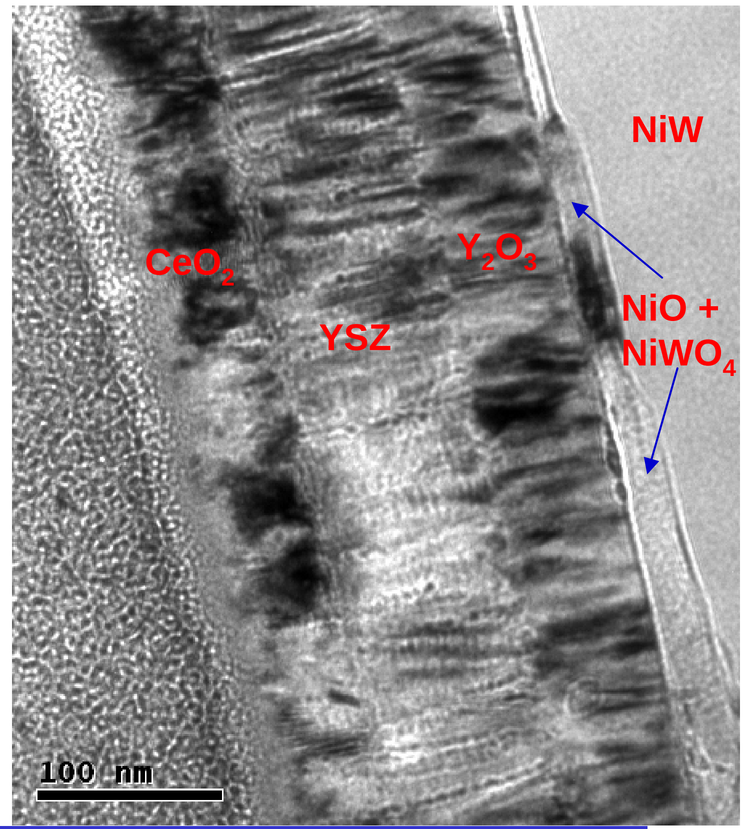
Methodology developed can be used to qualify buffer stack without the need to deposit and test YBCO layers

FY05 Goal: Improvement of reactive sputtering manufacturing process through fundamental characterization of the buffer layer properties

Approach: A combination of X-ray, TEM and SIMS was used to study buffer layer characteristics and guide optimization of deposition parameters

Simulated anneal in O^{18}

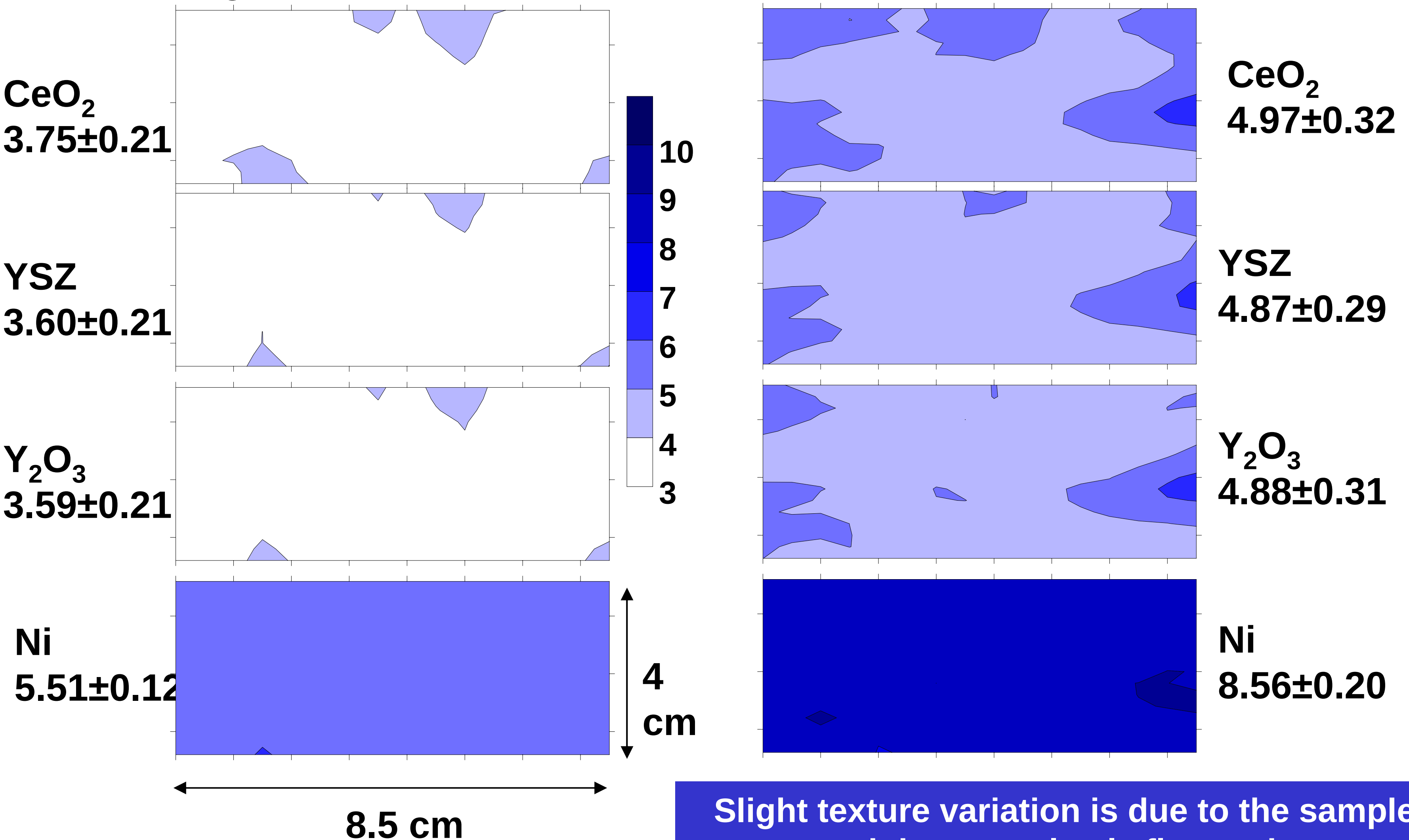




Reactive sputtering is now used in the manufacturing process to fabricate long lengths of 4cm wide, fully-buffered RABiTS

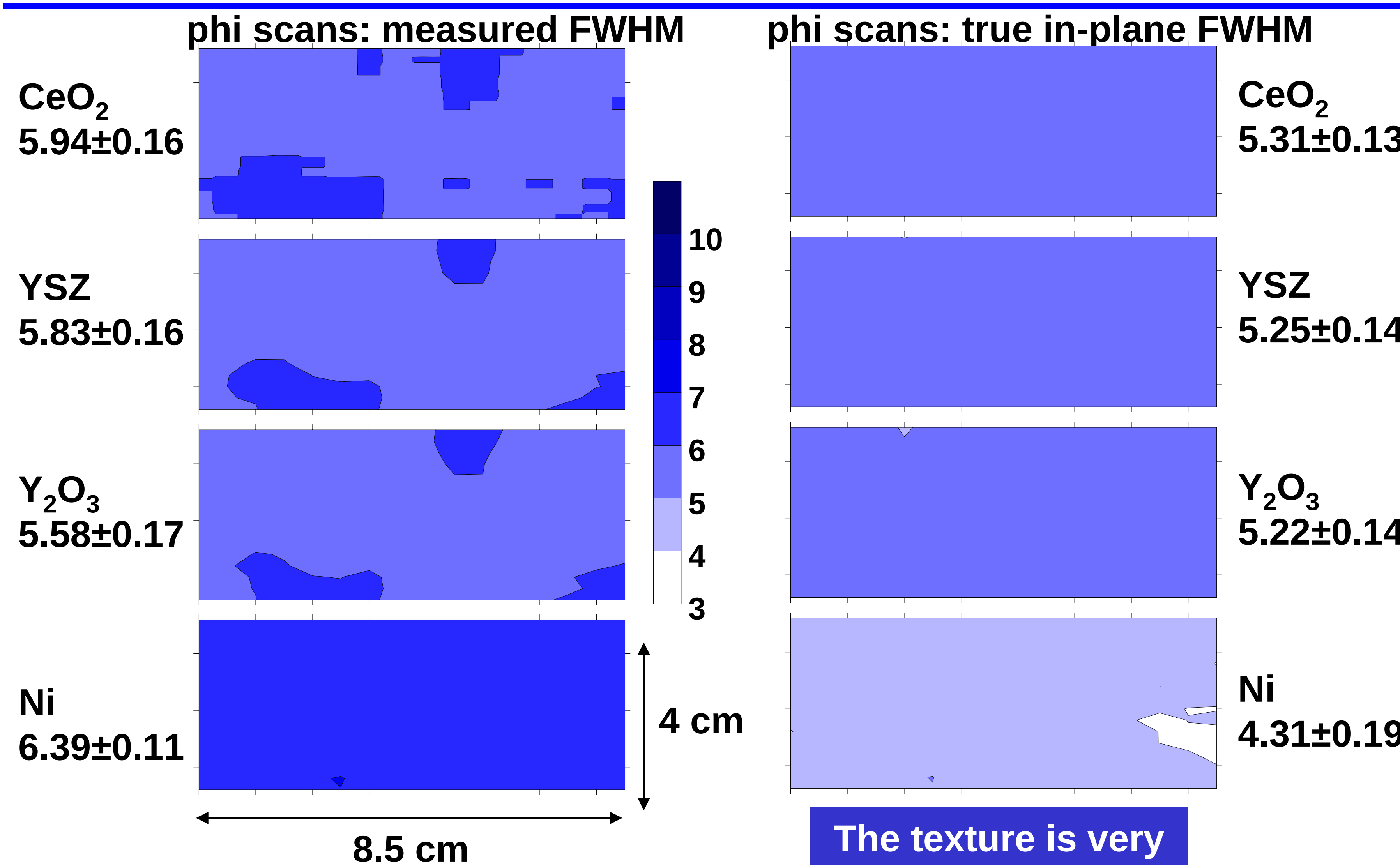
Good texture is also obtained for the full buffer stack ($CeO_2/YSZ/Y_2O_3/NiW$) made in long lengths in a reel-to-reel process

Rocking curve FWHM, axis is TD | **Rocking curve FWHM, axis is RD**



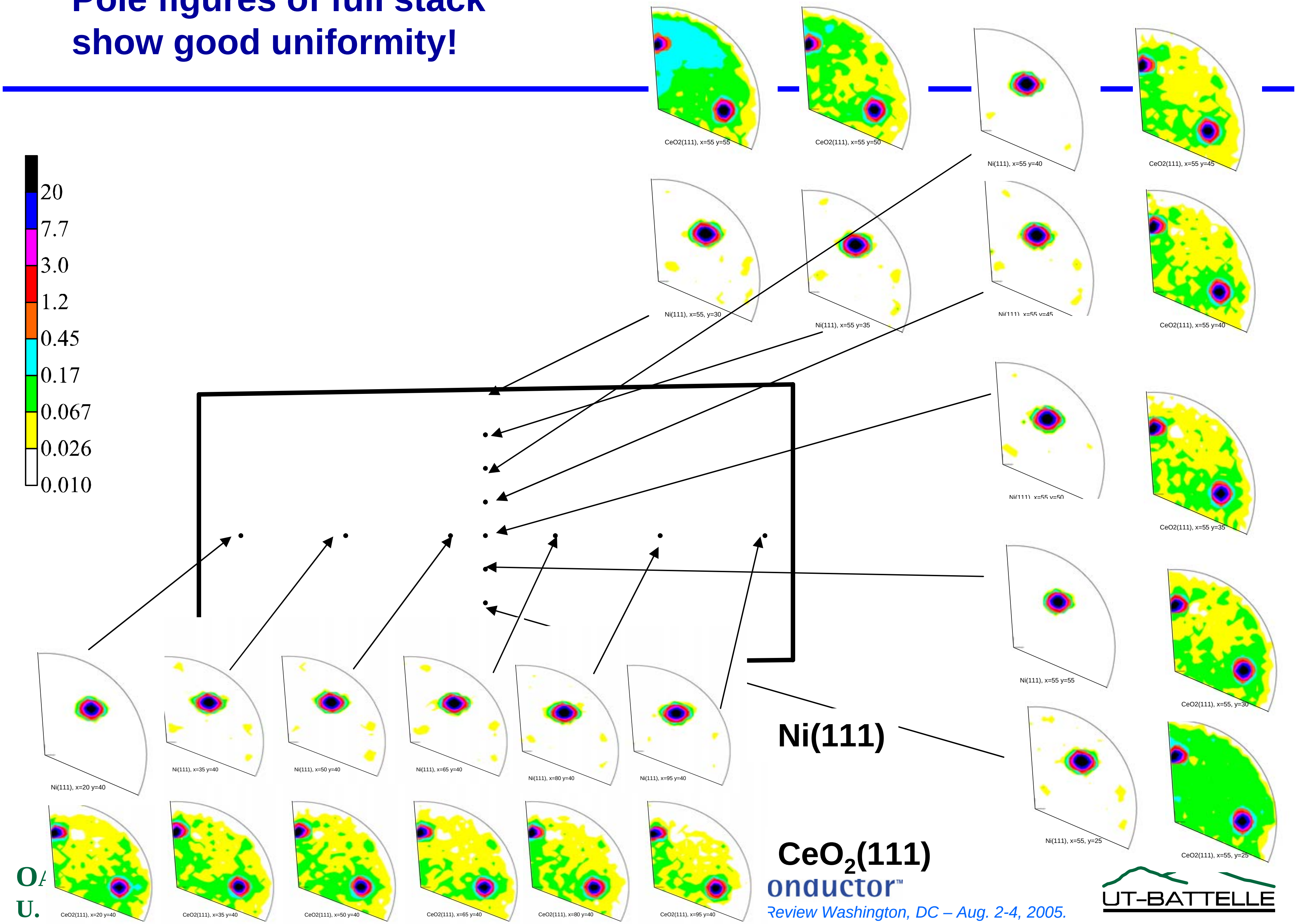
Slight texture variation is due to the sample not remaining completely flat on the stage

Good in-plane texture is also obtained for the full buffer stack ($CeO_2/YSZ/Y_2O_3$/NiW) made in long lengths in a reel-to-reel process



The texture is very homogeneous!

Pole figures of full stack show good uniformity!

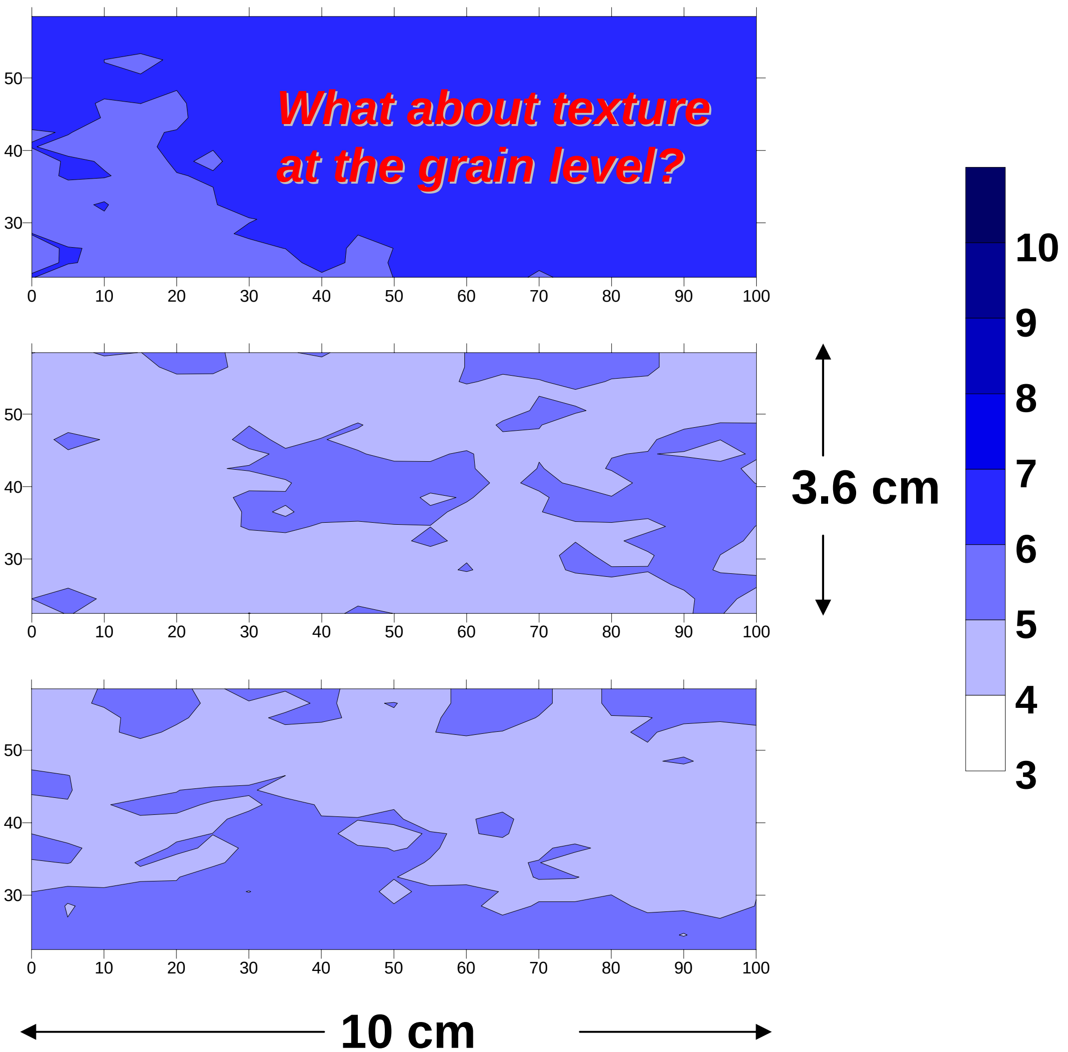


Good and homogeneous texture is also obtained for the MOD YBCO layer deposited on the full buffer stack in long lengths in a reel-to-reel process

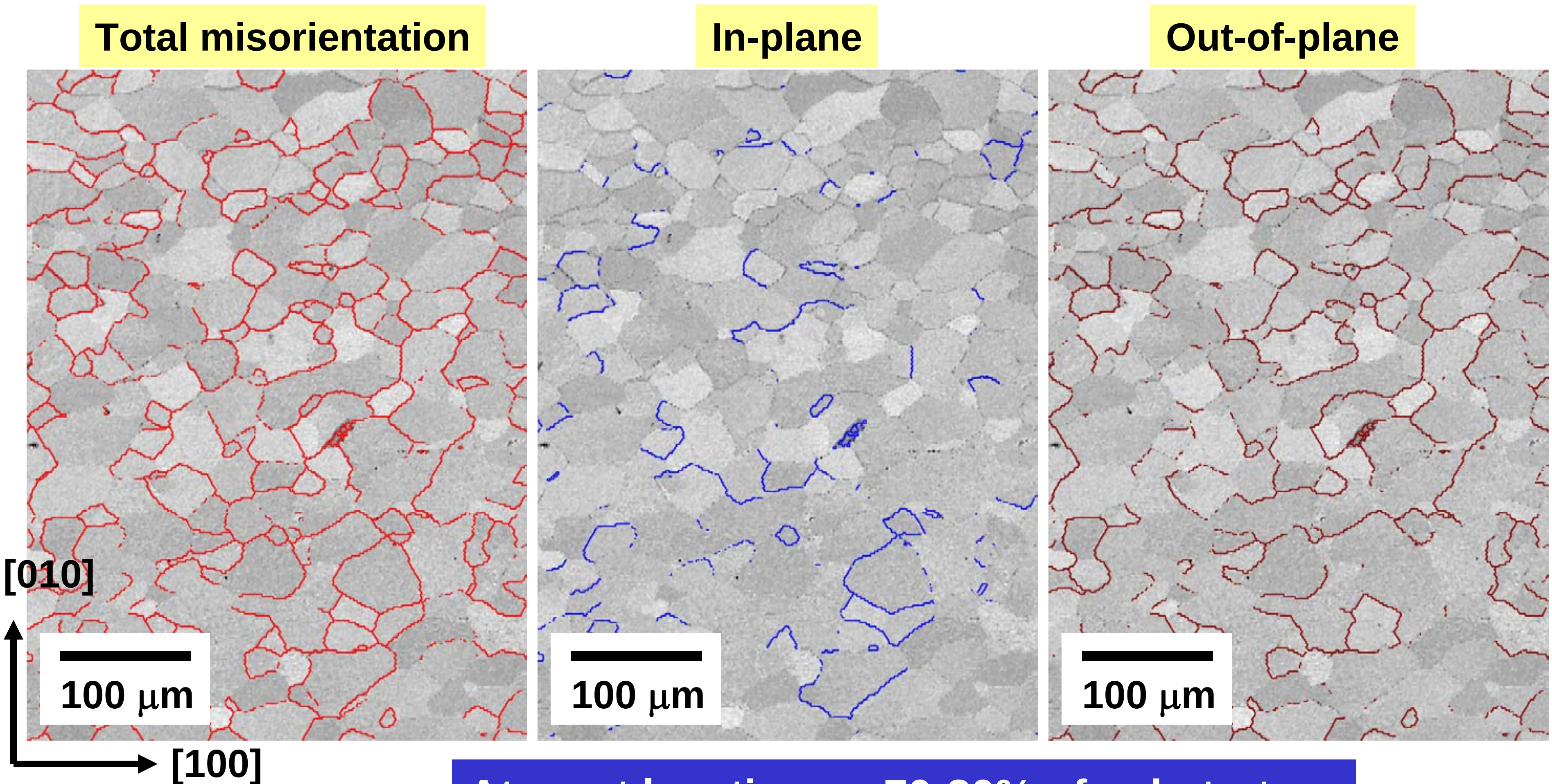
YBCO(006)
Rocking curve
Axis is RD
6.41±0.13°FWHM

YBCO(006)
Rocking curve
Axis is TD
4.95±0.07°FWHM

YBCO(113)
Phi scan
True in-plane
4.98±0.14°FWHM



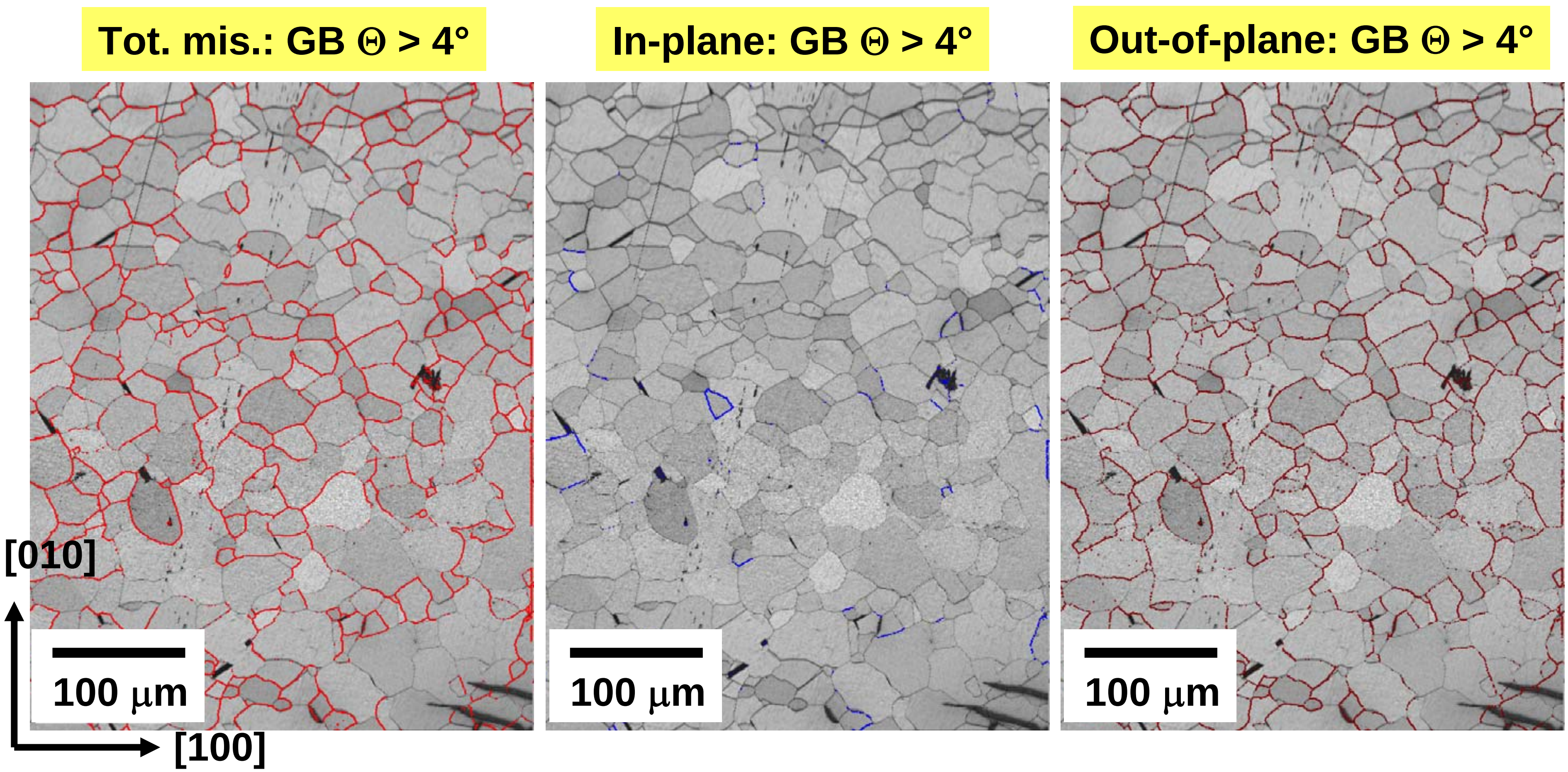
FY 04: Grain boundary maps drawn with all GB's greater than 4° show that in-plane misorientation is determining J_c



From CeO_2 cap

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

FY 05: GB maps of 4cm-wide buffer show that at most locations ~70-80% of the substrate is single-crystal-like w.r.t. in plane misorientation

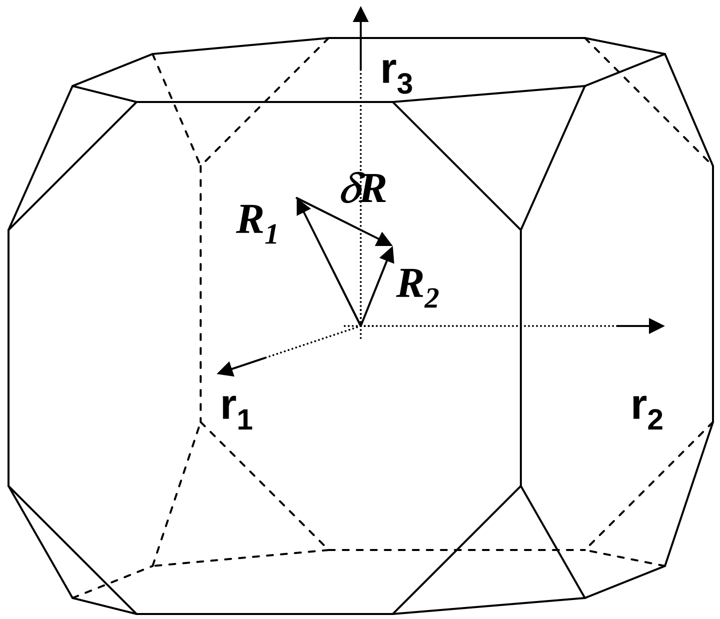


Results similar to what was observed last year for RABiTS produced using the non-pilot scale manufacturing

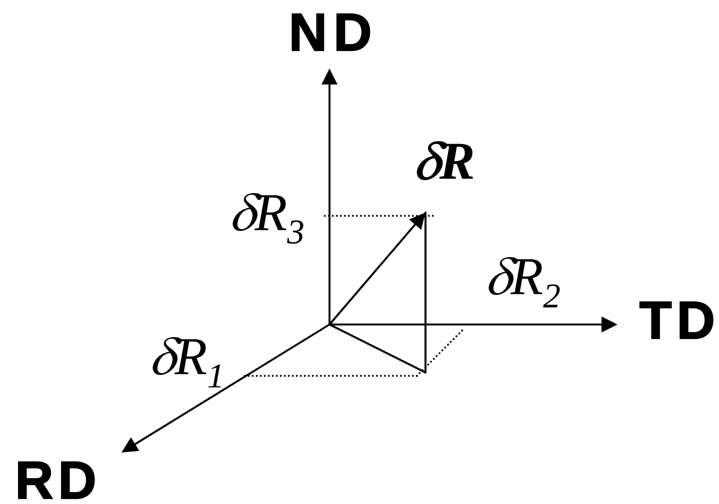
We have also developed the methodology to separate in-plane and out-of-plane misorientations from EBKD measurements in YBCO

For cubic materials, this was made possible in FY04 by manipulations in Rodrigues Space using a misorientation difference vector δR

Asymmetric region of Rodrigues space for cubic materials



Projection of the Rodrigues difference vector give the in- and out-of-plane misorientations



While this is much more complicated for materials with lower symmetry, we accomplished our goal this FY!

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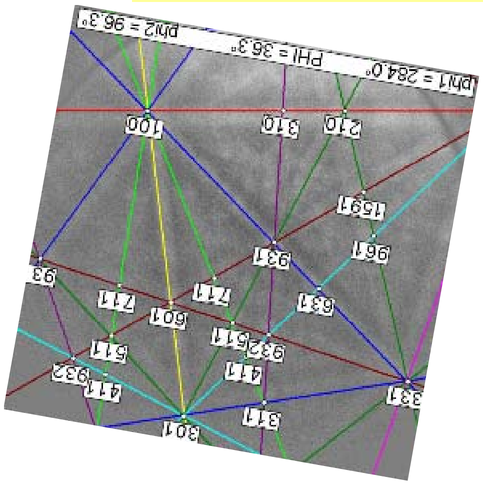
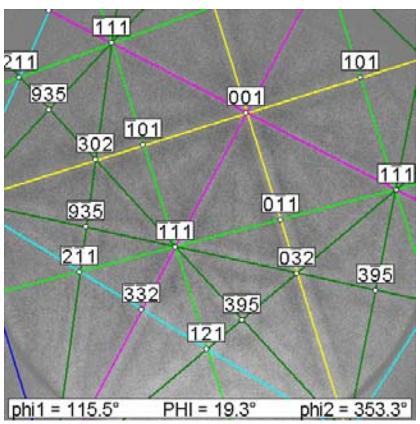
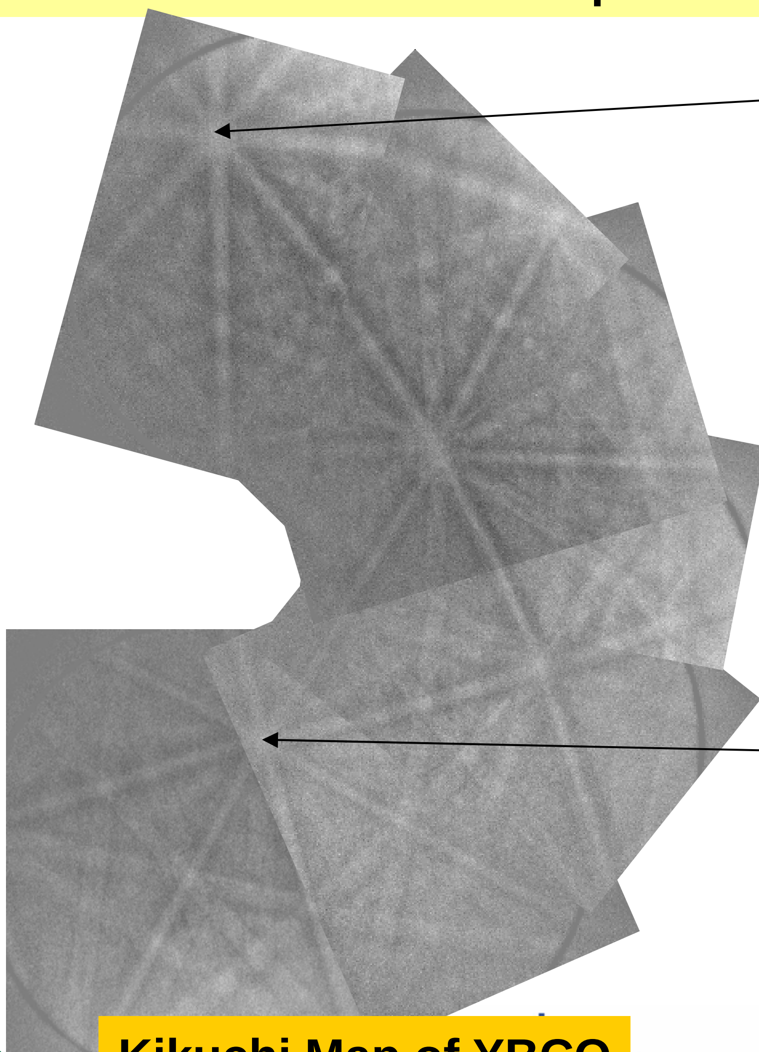
Automated indexing of YBCO with the correct crystal symmetry reflectors gives erroneous results

This is because it is not possible to distinguish between a a-axis and a c-axis orientation based on interplanar angles alone!







Kikuchi Map of YBCO

Indexing the YBCO pattern as a cubic pattern has been suggested before, but is crystallographically incorrect!

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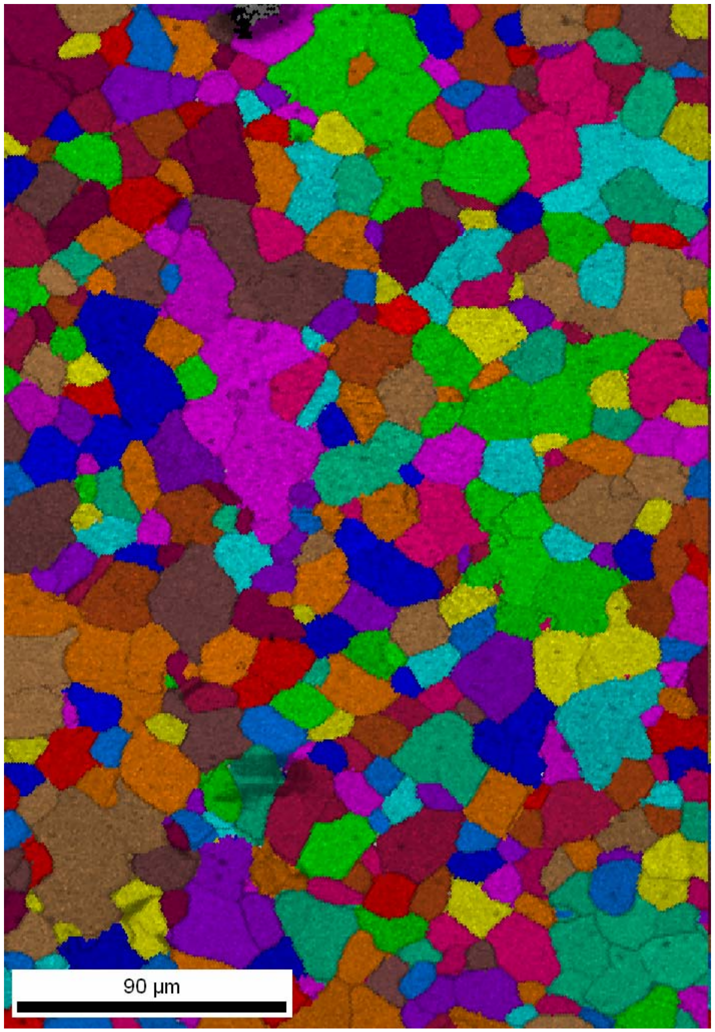
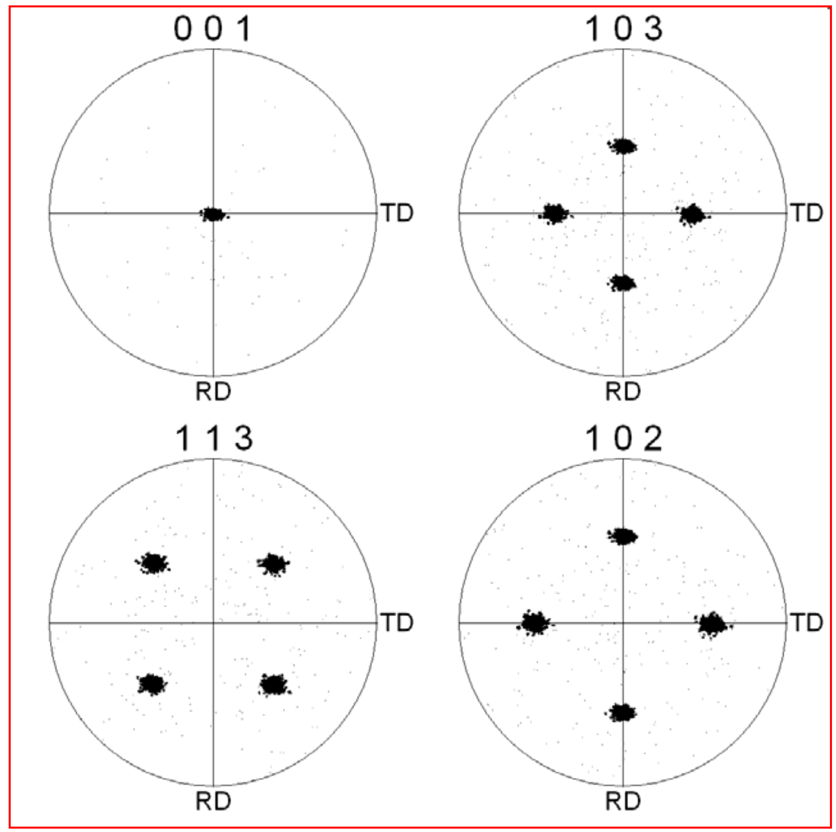
New methodology was developed for accurate indexing of electron backscatter Kikuchi diffraction patterns from YBCO

- Use of band widths as well as interplanar angles for indexing
- Choice of right reflectors for indexing
- New procedure to determine if indexing in an automated run is accurate (since the usual parameter "confidence index" cannot be used since c-axis and a-axis solutions get the same number of votes)
- New procedure to correct for incorrect indexing since the usual methodology based on confidence index does not work

Orientations in a 0.12 μm YBCO film with a J_c over 4 MA/cm^2. No grain boundary meandering is observed for such thin films



Pole figures for YBCO

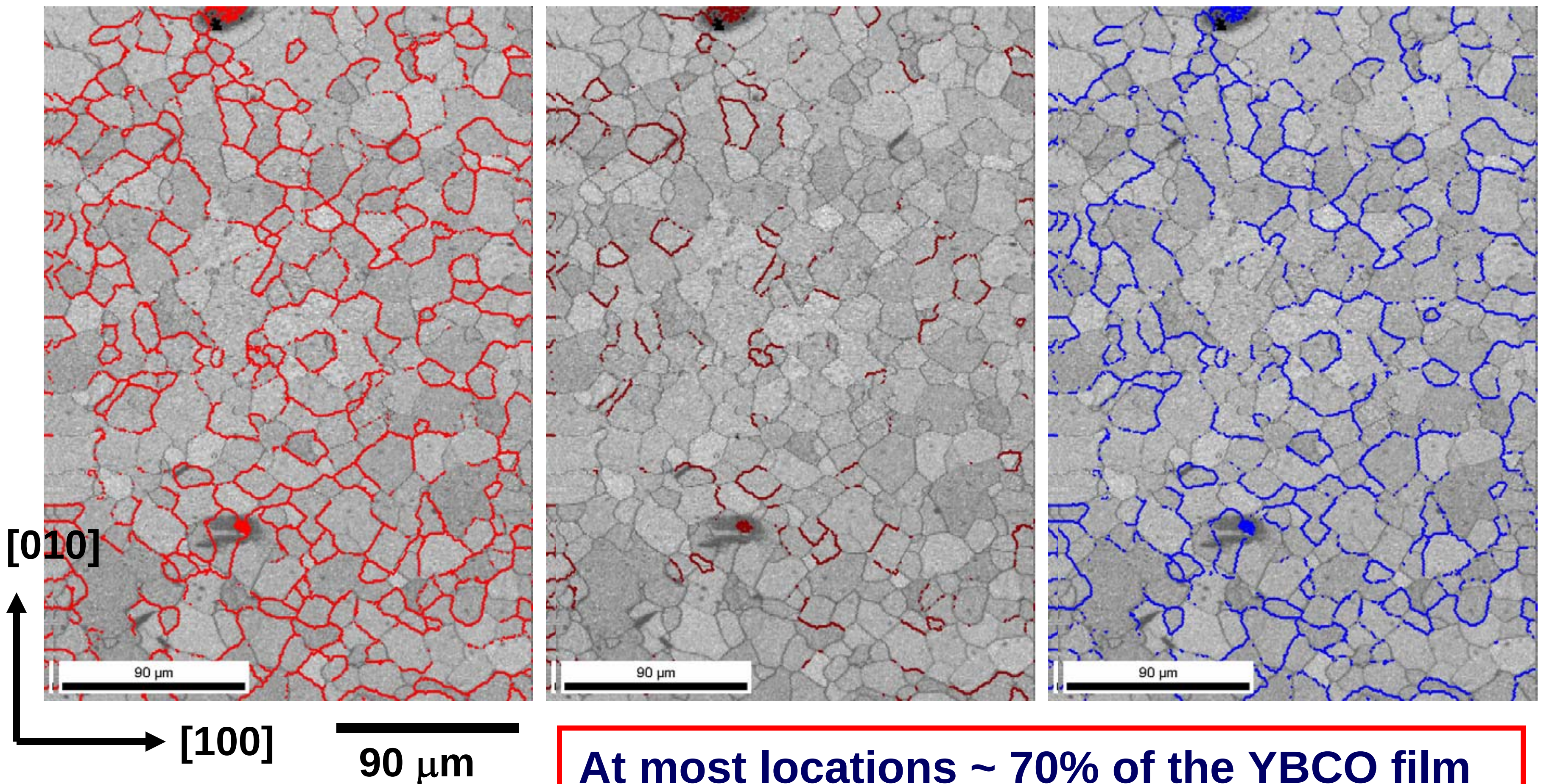


GB maps in a 0.12 μm YBCO film with a J_c over 4 MA/cm^2. All GB's greater than 4° are shown

Total misorientation

In-plane

Out-of-plane



At most locations ~ 70% of the YBCO film has no grain boundaries with respect to in-plane misorientations at the 4° criterion.

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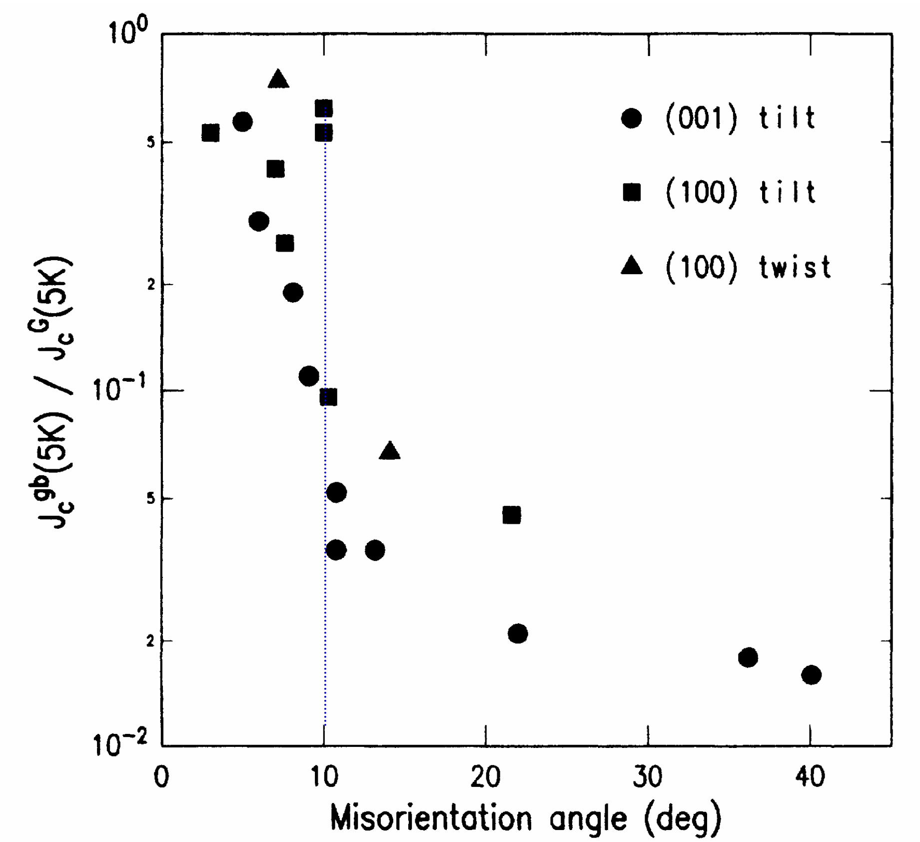
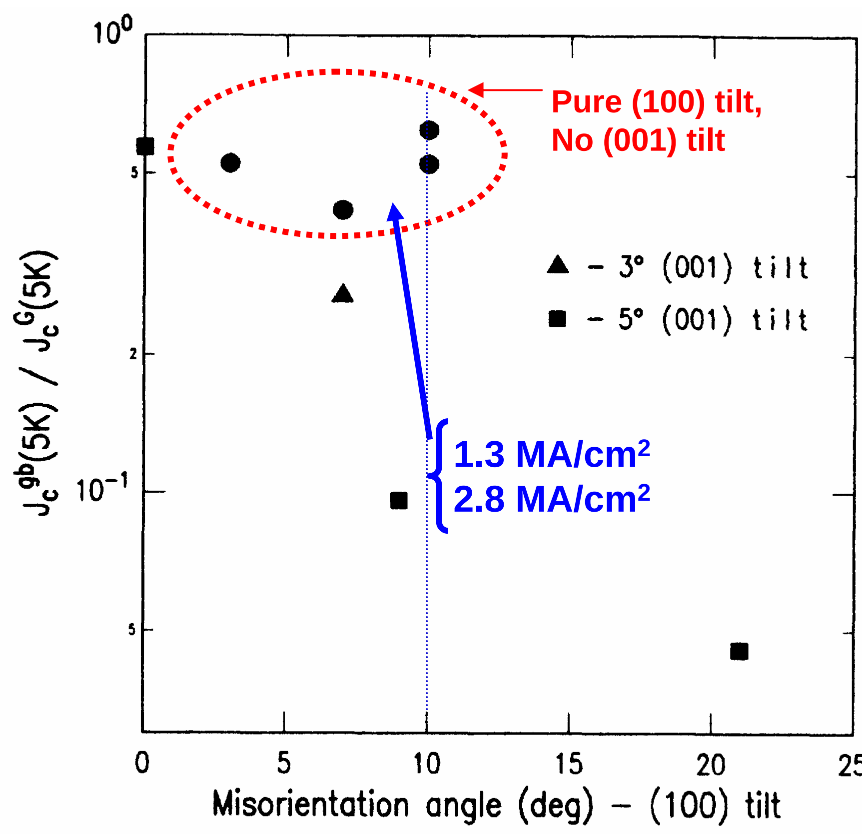
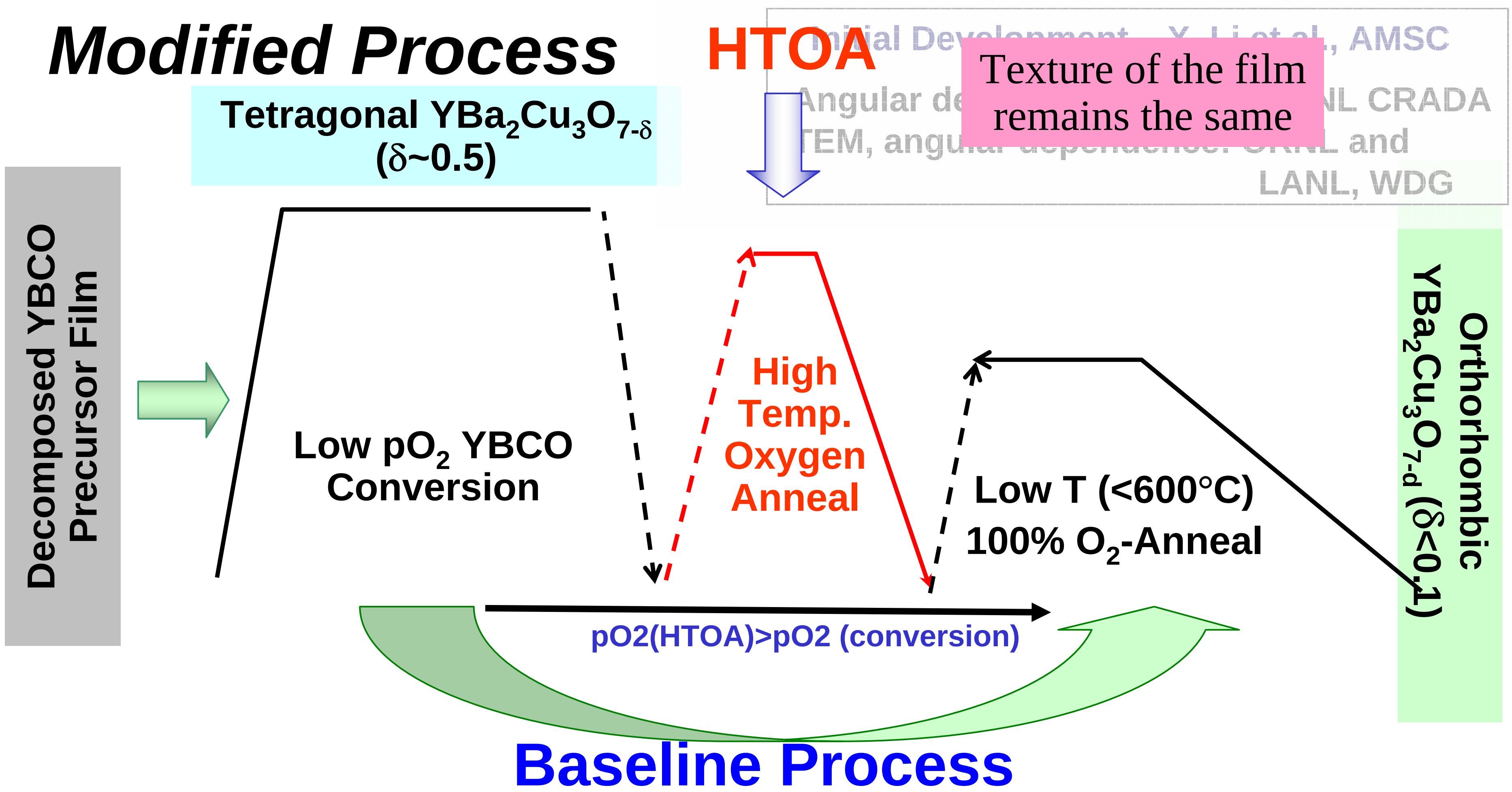
Observations are consistent with Dimos et al.'s work

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



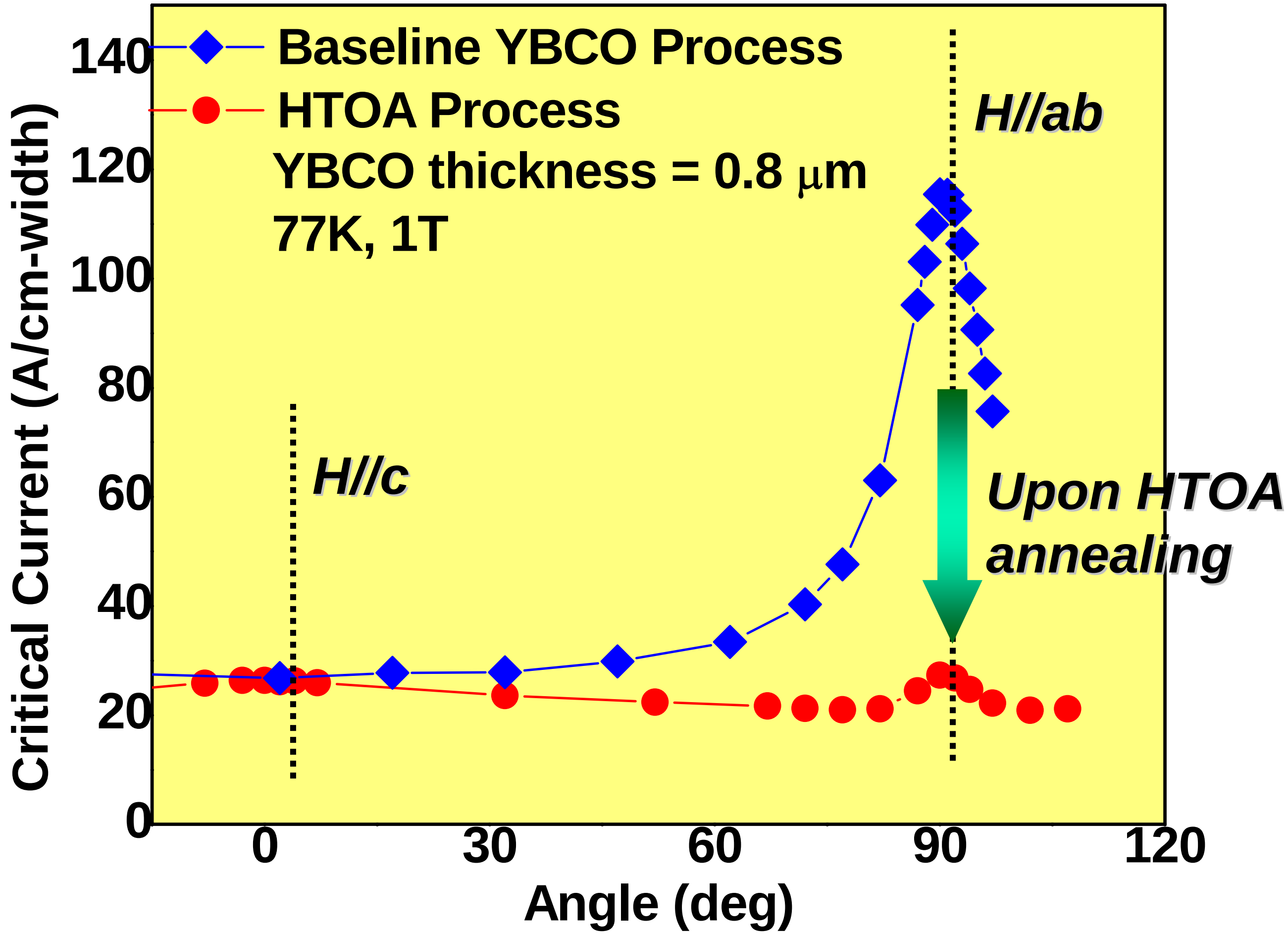


Properties of MOD YBCO Affected by High Temperature Oxygen Anneal (HTOA)

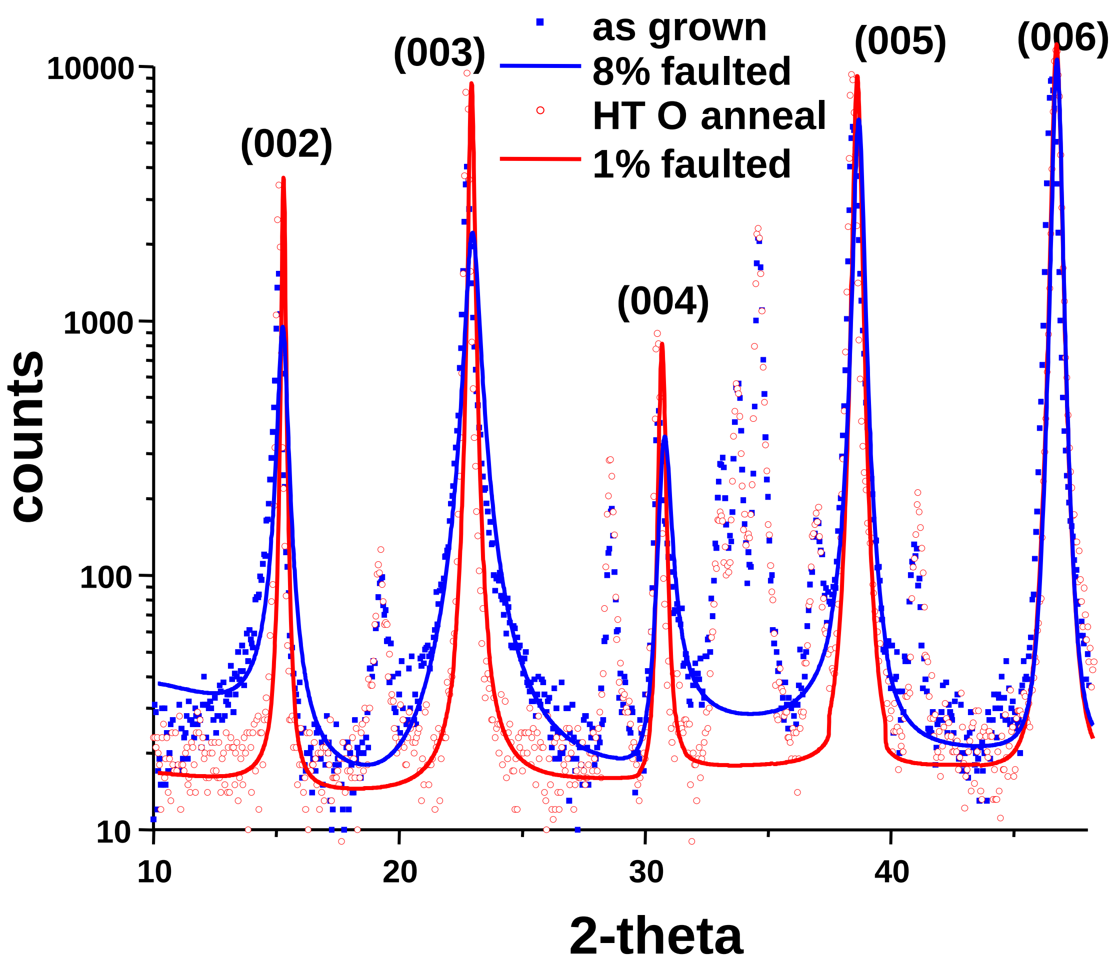


Fundamental science exploring mechanisms & microstructure of pinning in MOD-YBCO

I_c Peak with H//ab decreases substantially upon annealing!



High Temperature Oxygen Anneal (HTOA) Results in Sharpening of X-ray Peaks

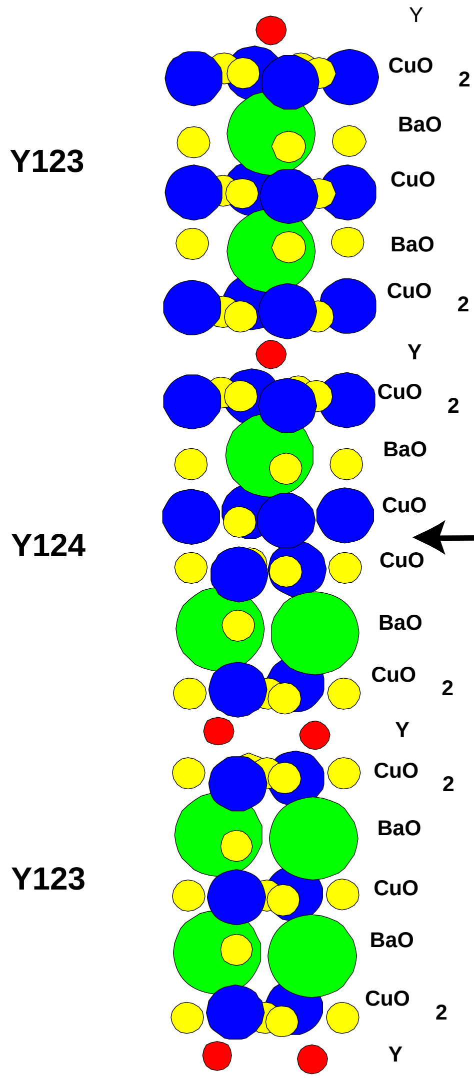


Key points:

- ➢ **Before HTOA, peak broadening is asymmetric - compare (003) with (004)**
- ➢ **No peak broadening for (006) peak**

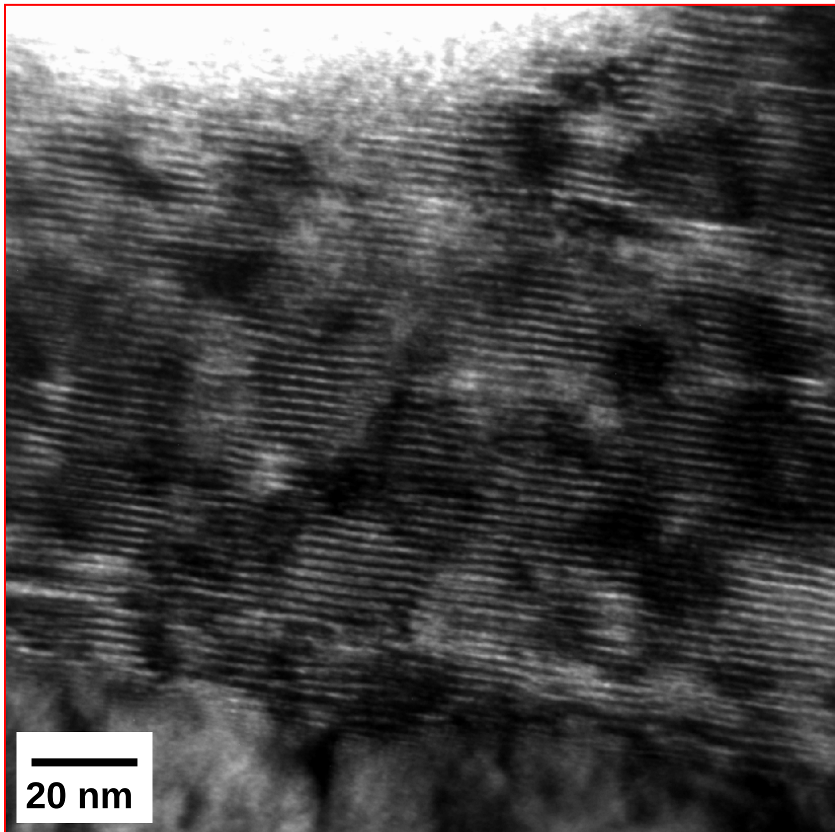
Modeled using the Hendricks-Teller model

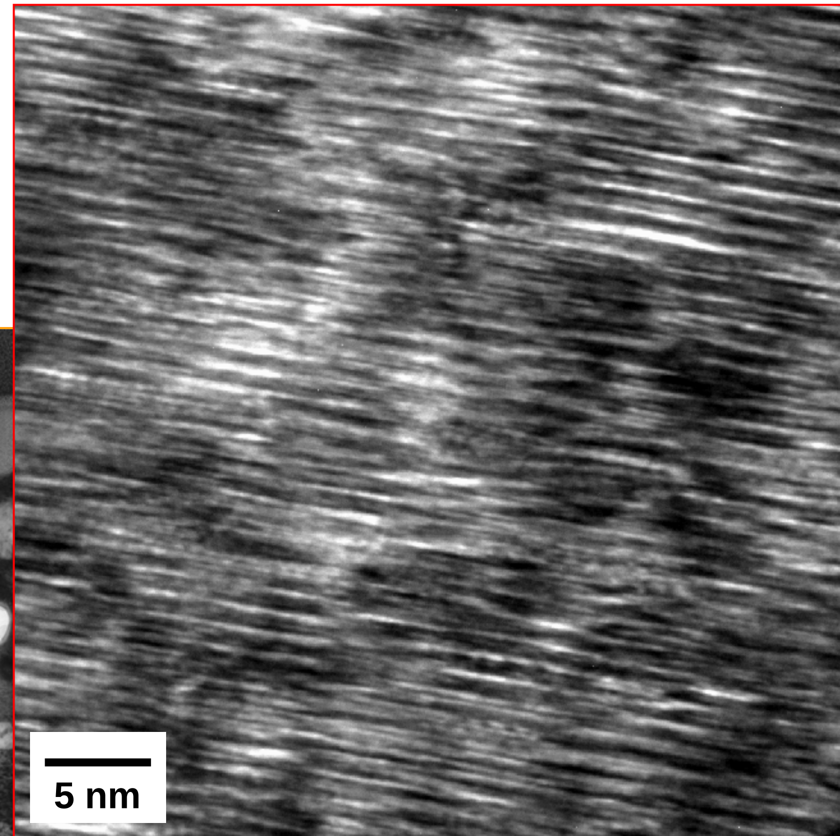
Hendricks-Teller Model Describes x-ray Diffraction from Y123 with Stacking Faults

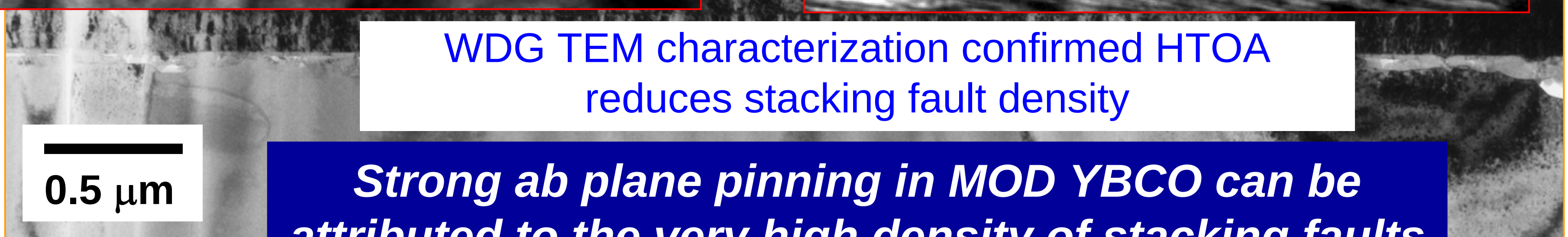


- **A stacking fault is an extra CuO plane forming a Y124 block in a Y123 lattice. Y247 lattice is an ordered stack of Y123/Y124 blocks.**
- **The broadened peaks for material with strong H//*ab* pinning is in the opposite limit: a completely random mixture of Y123 and Y124 cells, with 8% Y124, or a fault every 15 nm.**
- **Stacking faults produce a characteristically asymmetric peak broadening**
- **Stacking faults have negligible effect on the (006) reflection because 1/6 of a Y123 cell is equal in length to 1/7 of a Y124 cell to within 0.1%.**

Microstructure-Property-Processing Relationship: Pinning in Baseline MOD YBCO in 4 cm Process







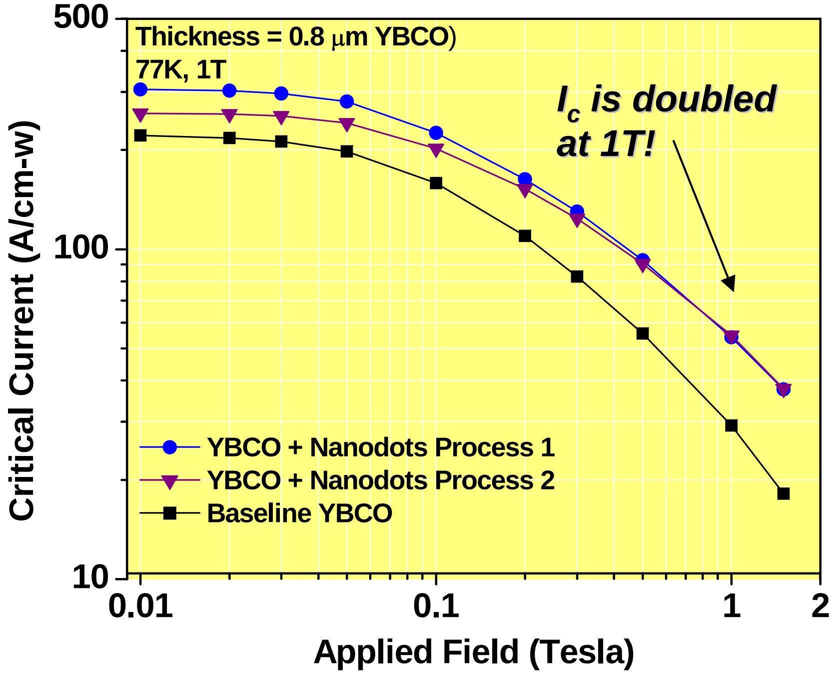
WDG TEM characterization confirmed HTOA reduces stacking fault density

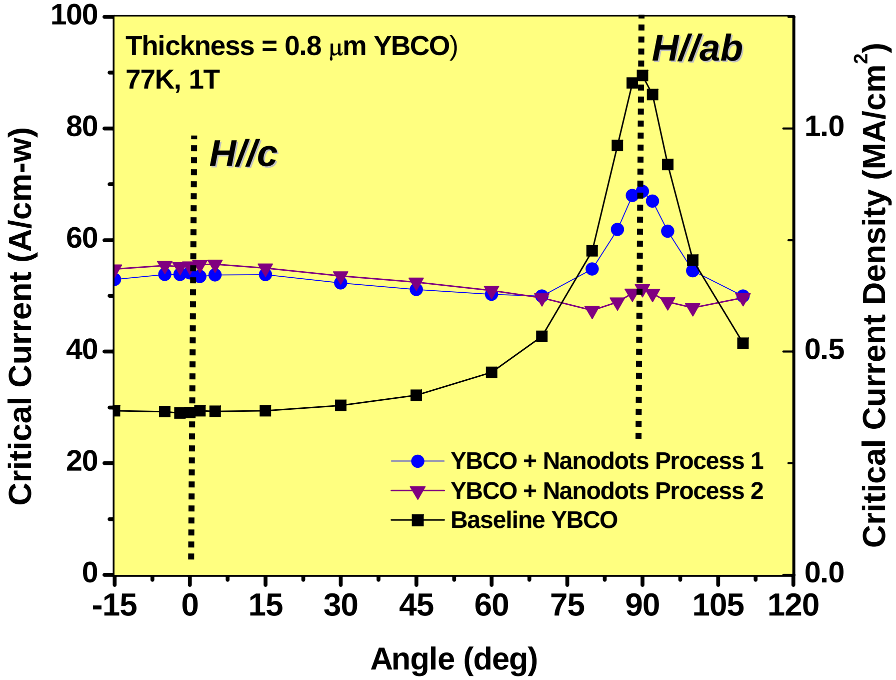
Strong ab plane pinning in MOD YBCO can be attributed to the very high density of stacking faults

Goal: *Optimize Processing of Nanodot -YBCO in 4 cm Reaction Furnace*

Many different RE_2O_3 additions have been examined, complementing WDG work

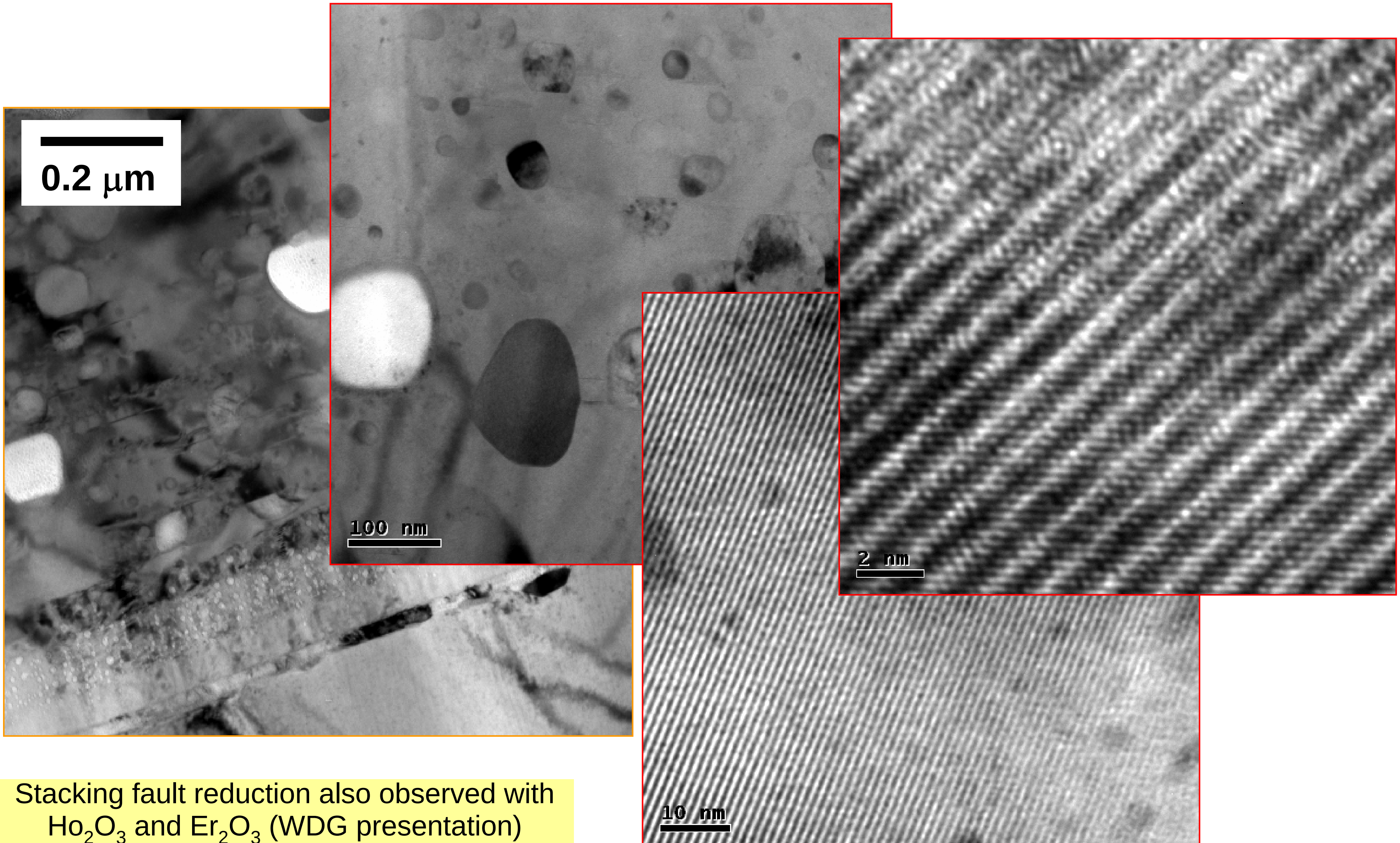
Illustrative example: RE_2O_3 based nanoparticles in YBCO with the same overall composition but different processing conditions





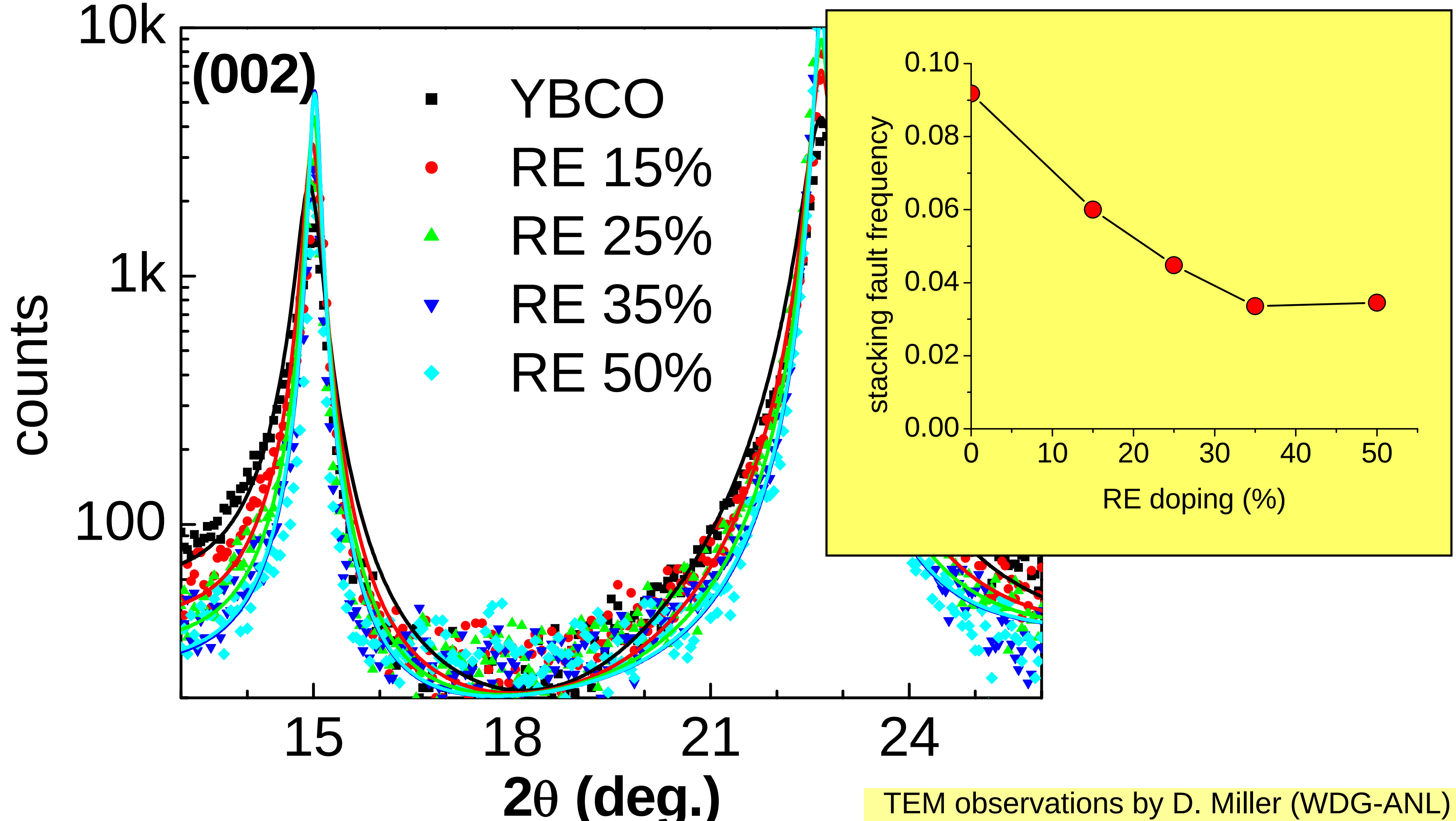
Sample property feedback guided process optimization of 4 cm wide nanodot doped YBCO

RE_2O_3 Addition Reduces Stacking Fault Density Resulting in Reduced ab-plane Pinning in 4 cm Process



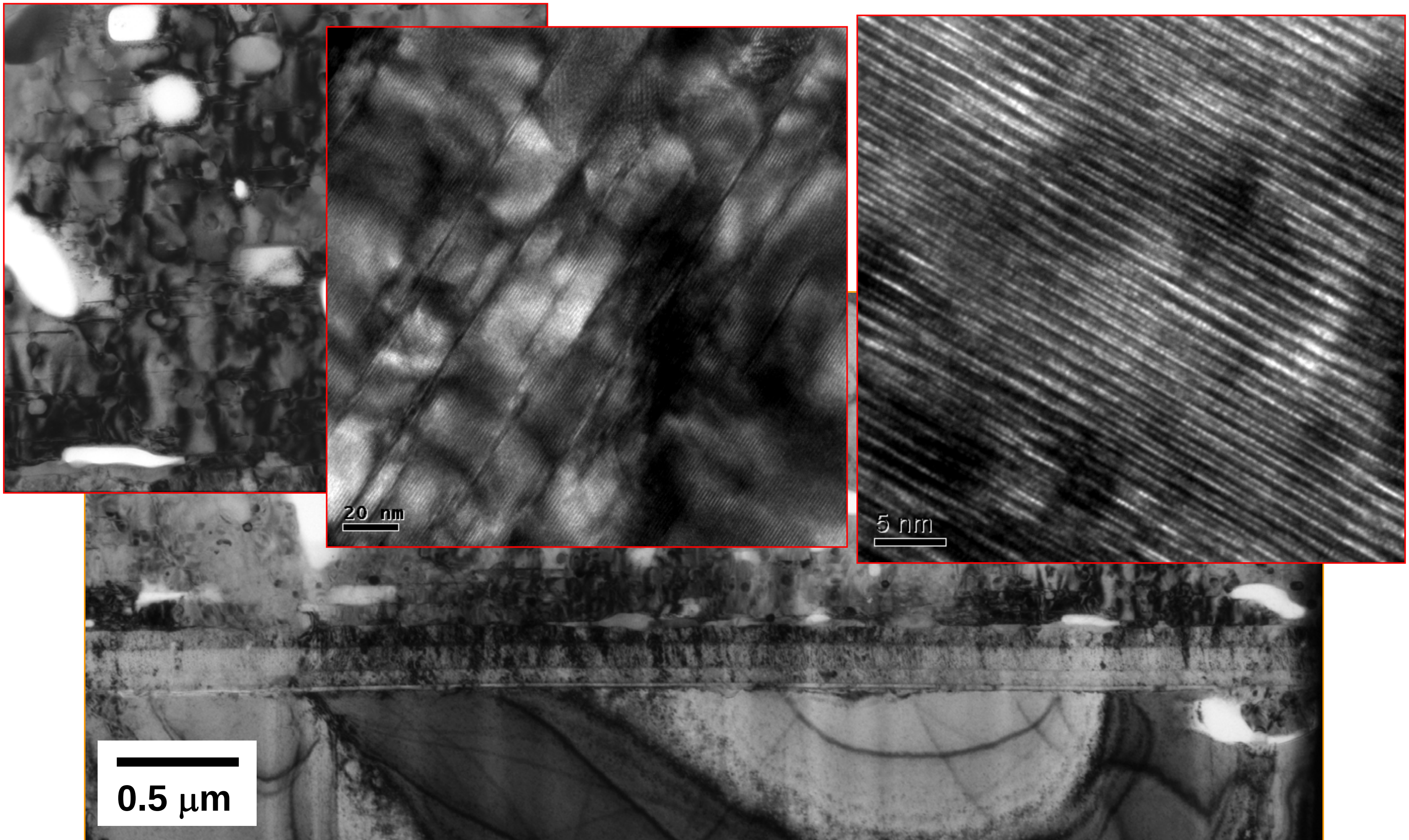
Stacking fault reduction also observed with Ho_2O_3 and Er_2O_3 (WDG presentation)

X-ray Analysis Shows the Stacking Fault Density Decreases with RE_2O_3 Nanoparticle Concentration

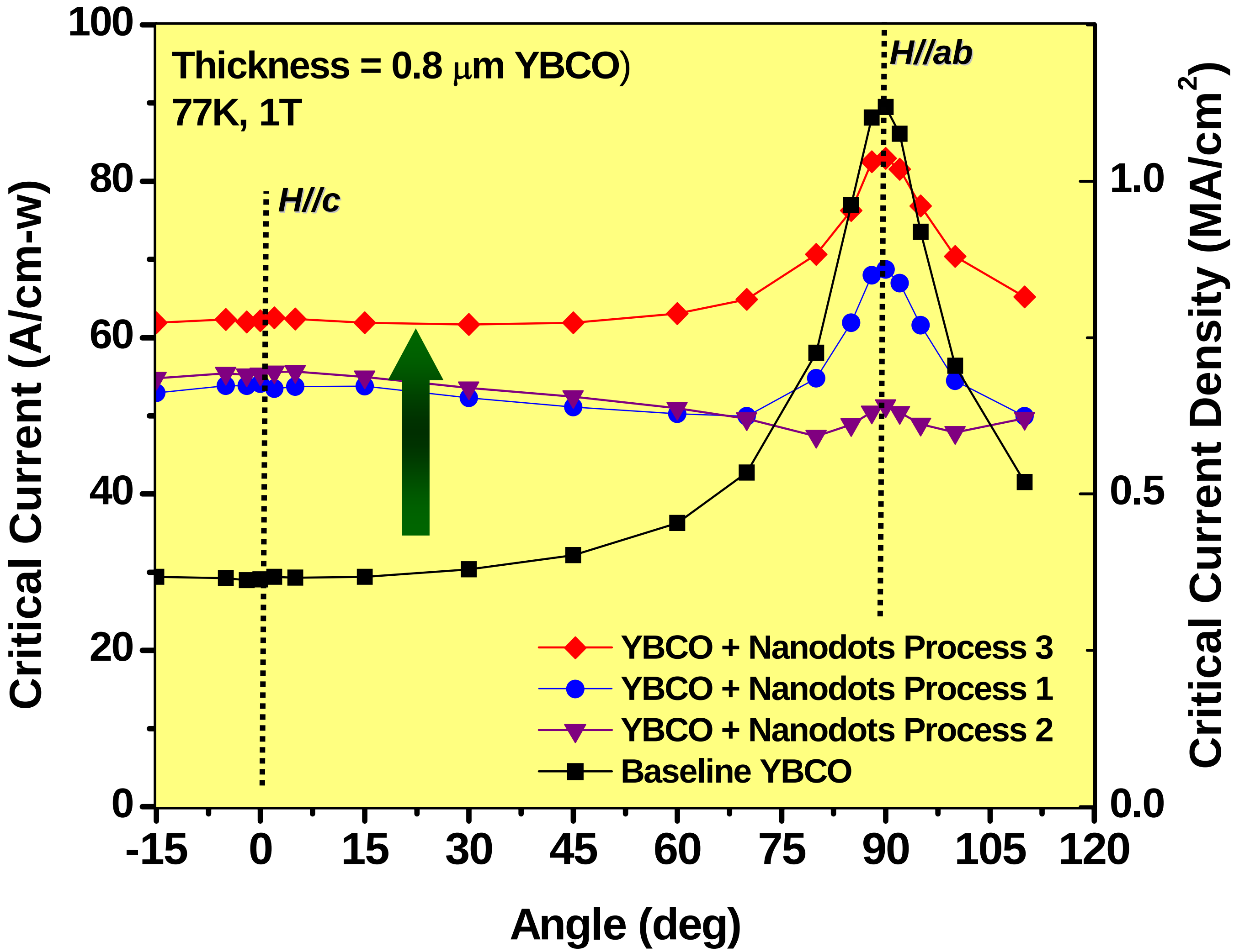


TEM observations by D. Miller (WDG-ANL) on Er_2O_3 doped samples confirm x-ray data

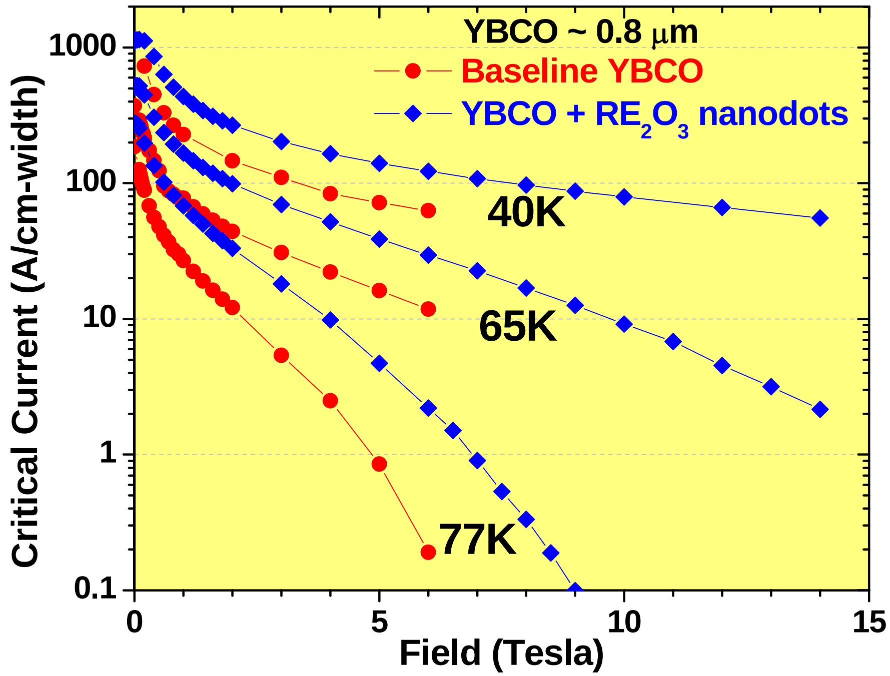
Control of YBCO Nucleation/Growth Allows Incorporation of RE_2O_3 Nanoparticles with Minimal Reduction in Stacking Fault Density

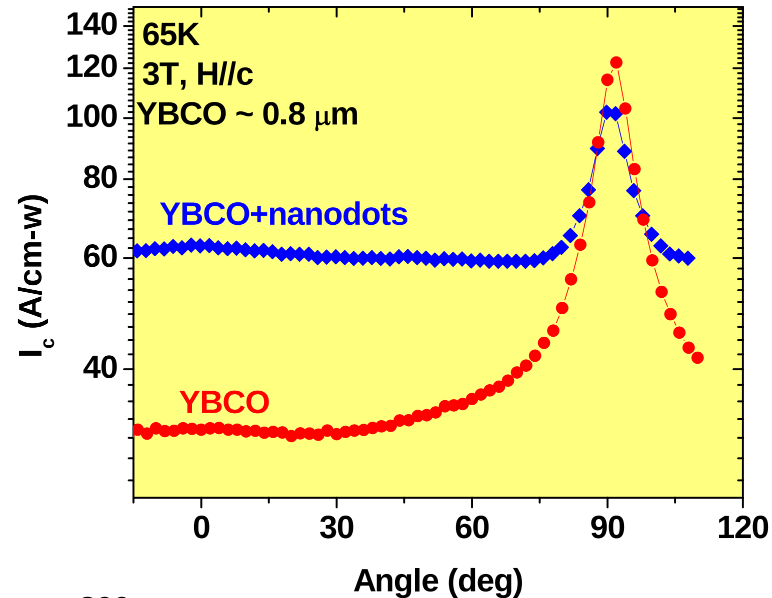


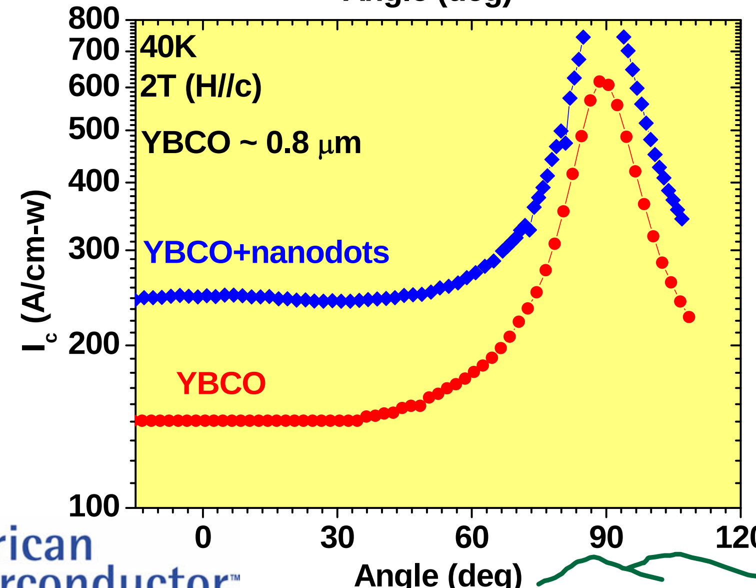
Optimized Sample Shows Good Pinning with H//ab and H//c



High-field and Low-temperature Transport Data on YBCO Samples from 4 cm Process

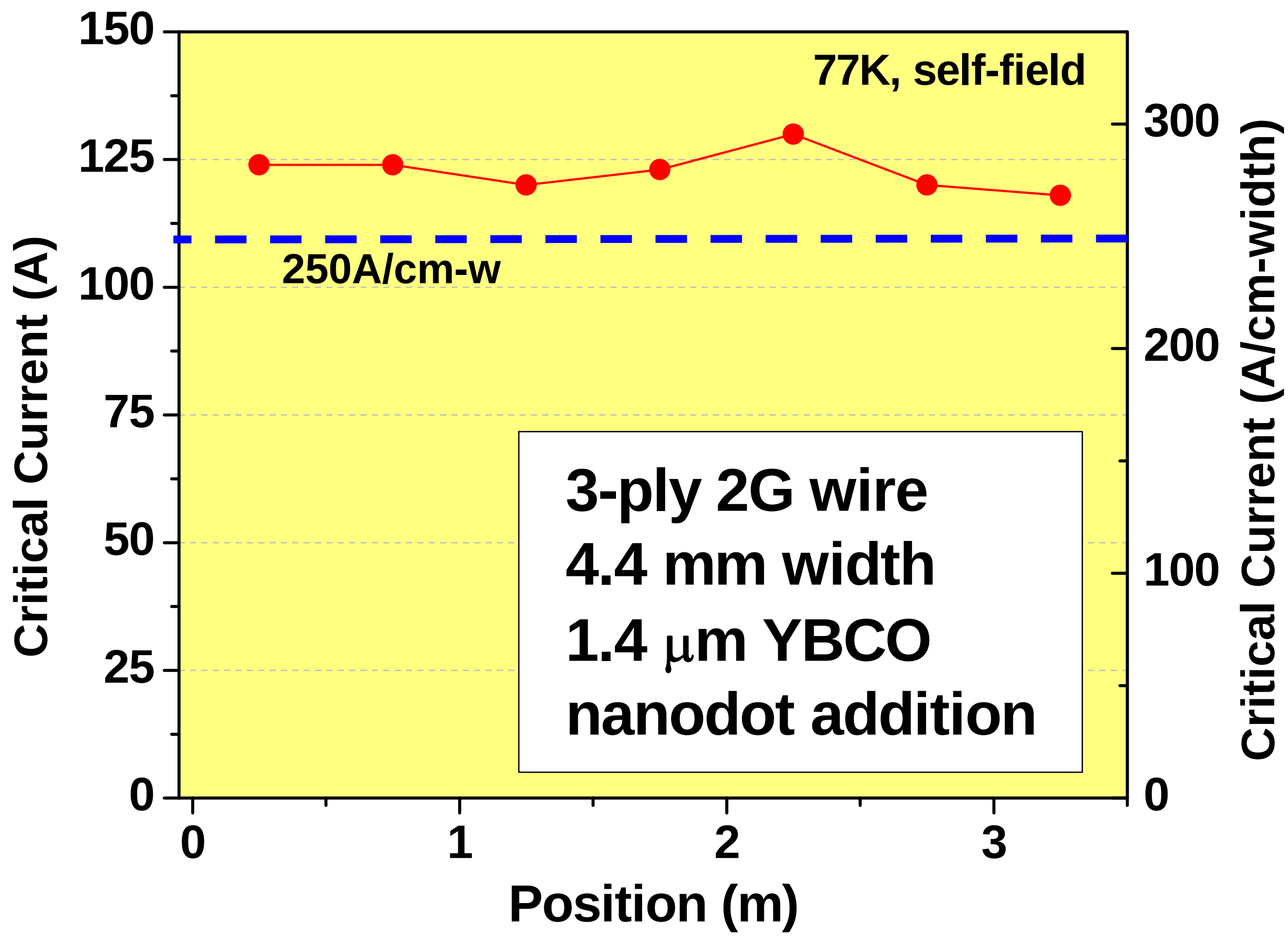






Nanodot doping improves I_c performance at all temperatures and field orientations

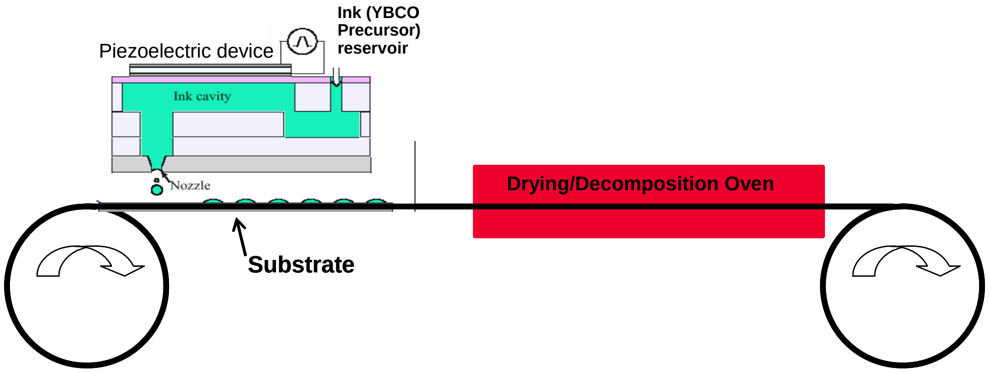
4 cm Reaction Optimization Contributed to First 4.4 mm Wide 2G Wire with Ic > 100 A

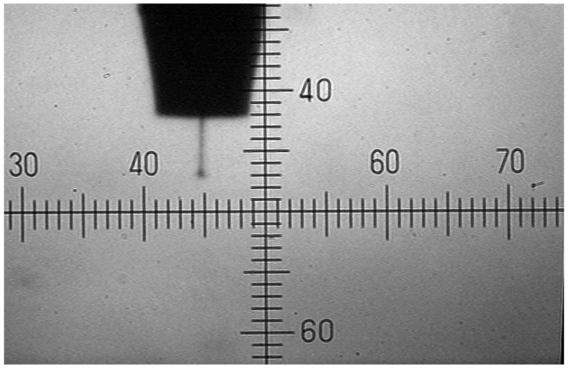


Summary: Flux-Pinning

- **Process modifications, including nanodots, in AMSC 4-cm-wide YBCO give significant improvement of J_c(H)**
- **J_c of greater than 0.7 MA/cm^2 at 77K, 1T was obtained for all angles in a 0.8 μm YBCO film processed as 4-cm strip**
- **The peak in the angular dependence at 77K, 1T for H // ab correlates with the stacking fault density as determined by simulated by X-ray broadening and TEM**
- **Enhanced pinning with H//c was correlated to the incorporation of rare earth nanoparticles into MOD YBCO films**
- **Under optimized processing conditions the J_c can be more than doubled at all angles at 77K, 1T over the standard baseline sample**

AMSC-ORNL STTR: Direct Printing of YBCO Filaments



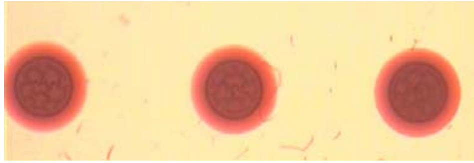


Direct (Ink Jet) Printing

- YBCO precursor is printed in defined pattern along length/width of substrate
- Pattern resolution determined by: droplet size, nozzle distance/arrangement, droplet placement (x-y movement), ink properties
- Complex wire architectures easily printed
- Widely used in commercial manufacturing (flat panel displays, transistor circuits, etc)

As printed

65 μm diameter

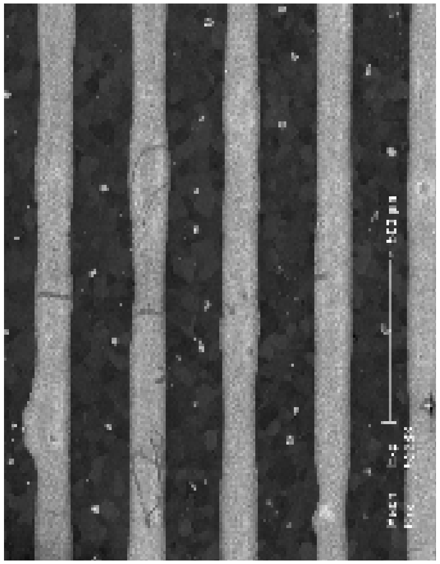


Decomposed

DARPA

Ink Jet printing is the low-cost technique for striated filaments required for ac applications

Direct Printing of YBCO Filaments with MOD Process

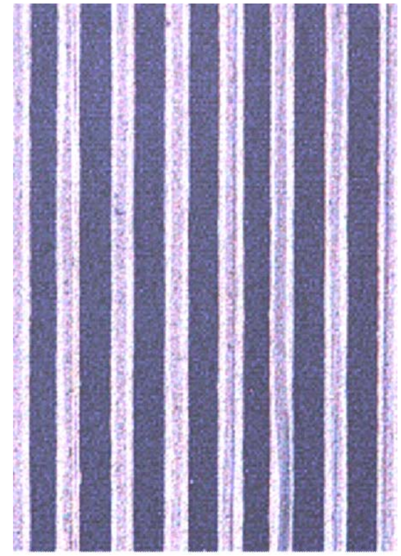


500 μm

Inkjet printing
(AMSC - YBCO)

500 μm

Laser ablation
(AFRL – YBCO)



500 μm

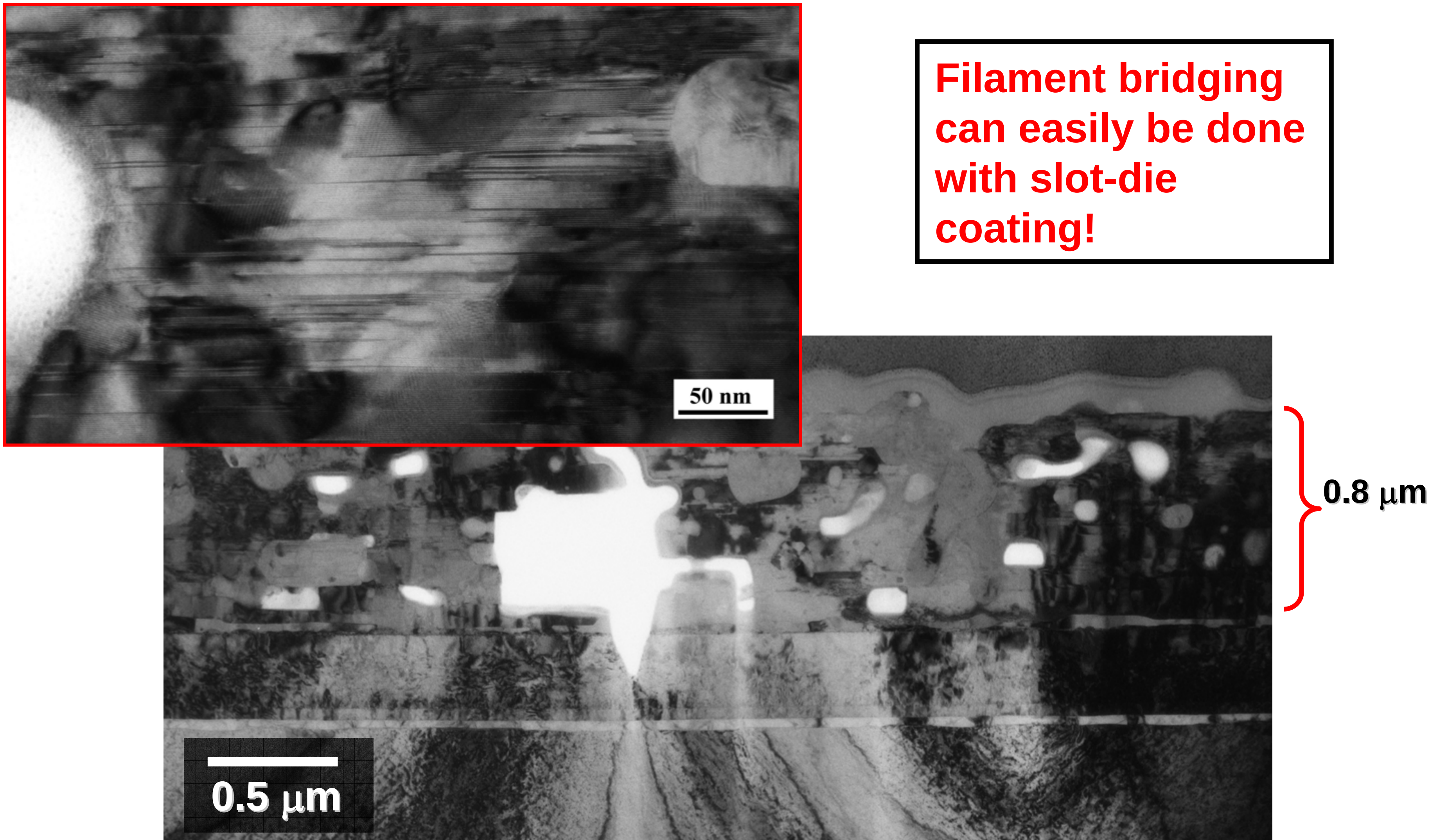
Photolithography/etching
(SuperPower)#

I_c = 200 A/cm-w Demonstrated for 3 x 2mm filaments

\# V. Selvamanickam, DOE 2005 Wire Development Workshop, St. Petersburg, FL, January 19-20, 2005

MOD approach is only process that can be used for direct printing of YBCO filaments

Printed Filaments are Homogeneous and Complex Patterns can be Directly Printed



Filament bridging can easily be done with slot-die coating!

AMSC-ORNL CRADA Presentation

- **FY 2005 Results**

  2G Development (YBCO/RABiTS) at AMSC (Marty)
  2G wire manufacturing at AMSC
  2G wire characteristics

  Alloy substrate fabrication (4 cm wide) (Amit)
  Buffer layer development for 4 cm wide process
  Flux-pinning optimization in MOD YBCO
  Striated conductor development
  2G coil fabrication

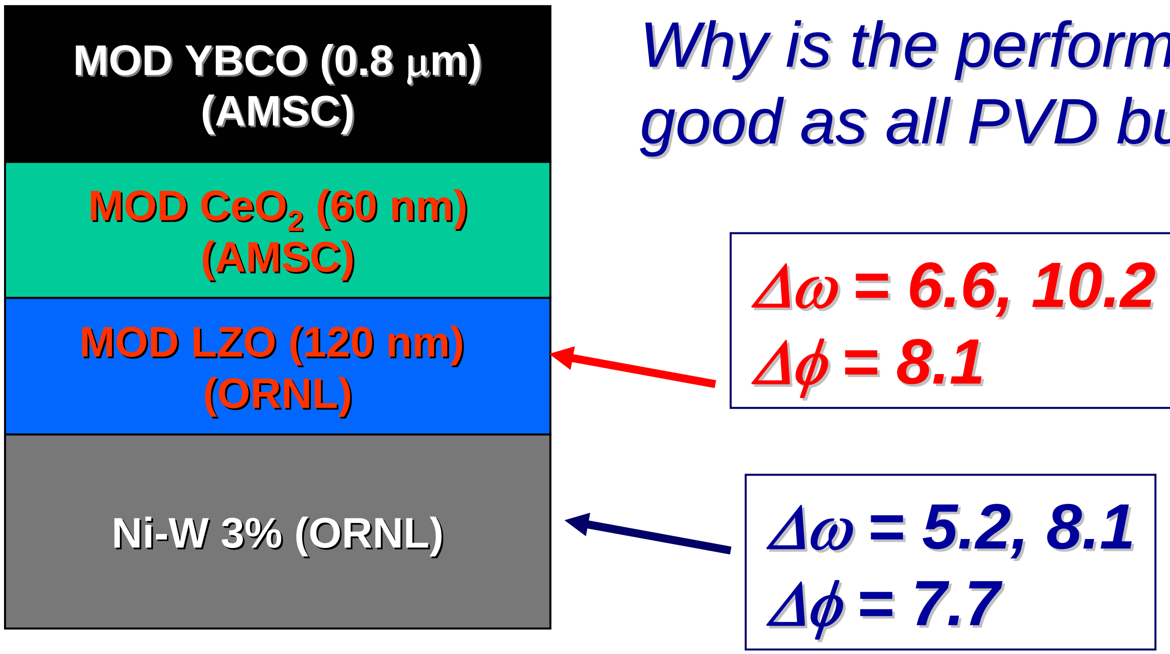
  Development of low-cost, solution buffer layers (Parans)

- **FY 2005 Performance and FY 2006 Plans (Parans)**
- **Research Integration**

MOD Buffer/YBCO Layer Development

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

Why is the performance not as good as all PVD buffers?

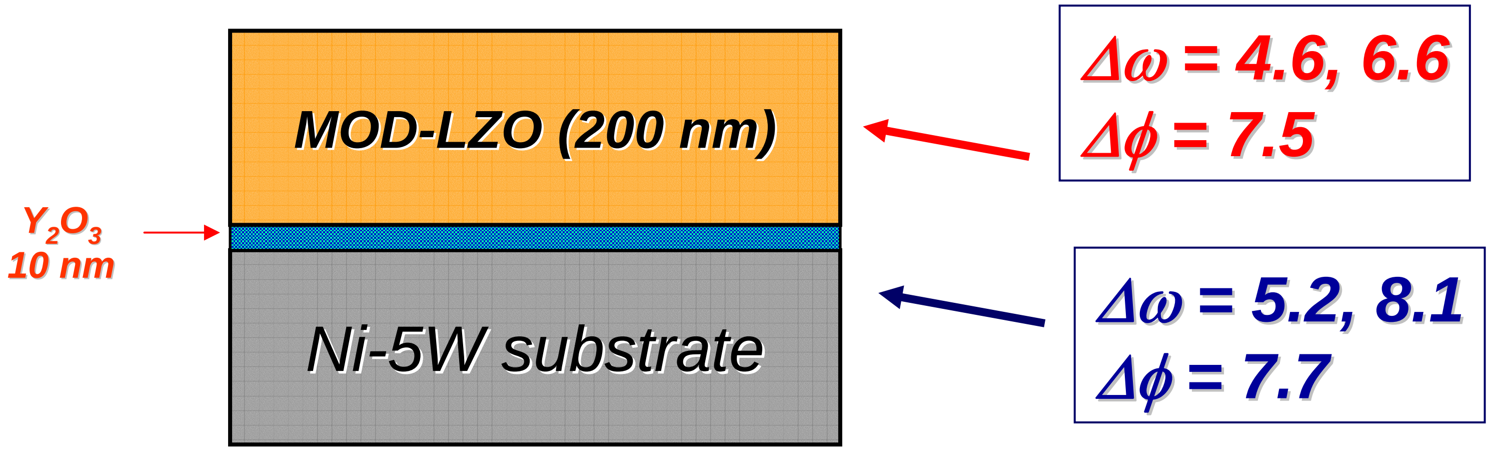


Lattice mismatch of LZO with Ni: 7.9%

Potential cost savings for large scale commercial manufacturing

Texture of LZO can be significantly improved

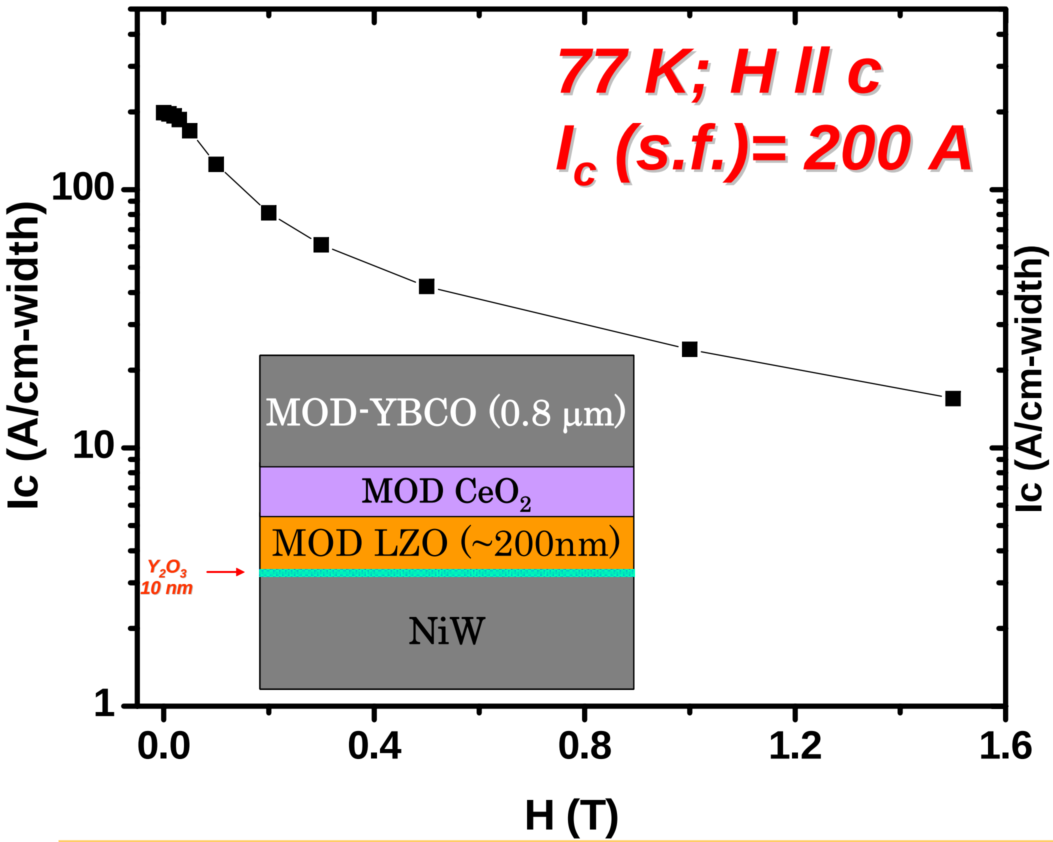
Insertion of a thin layer of Y_2O_3 changes the texture of LZO

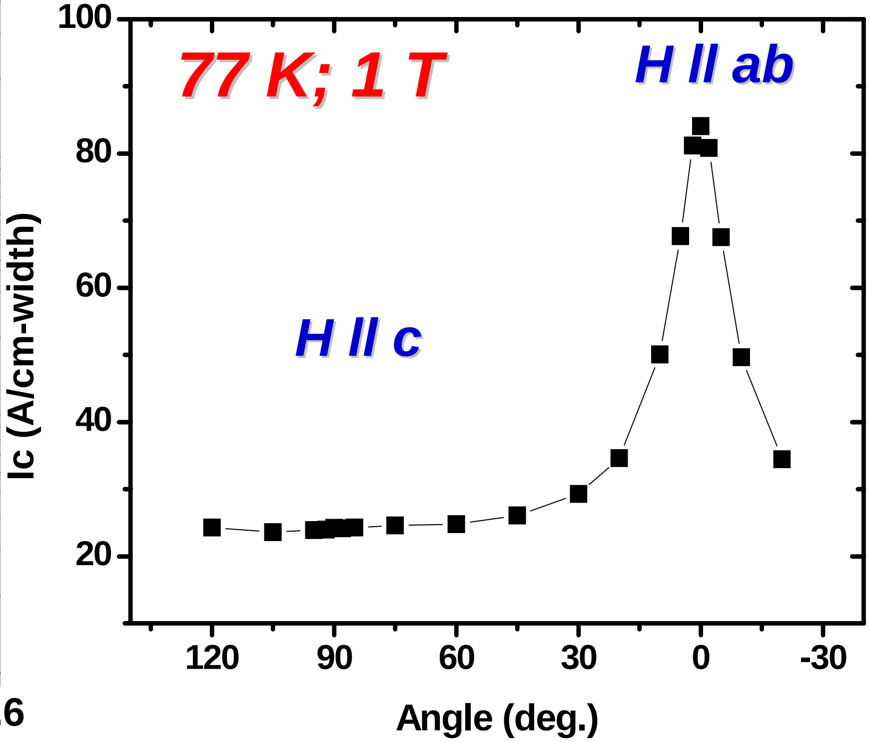


Lattice mismatch of LZO with Ni reduced by inserting Y_2O_3

Potential cost savings for large scale commercial manufacturing

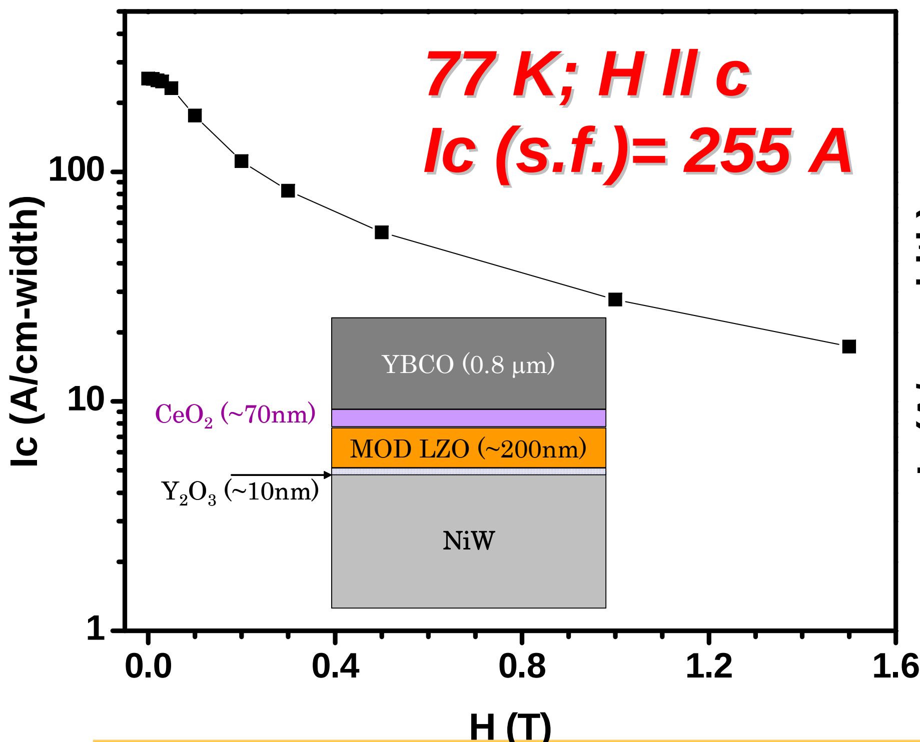
Performance of MOD LZO/CeO_2/YBCO stack improved to 200 A/cm

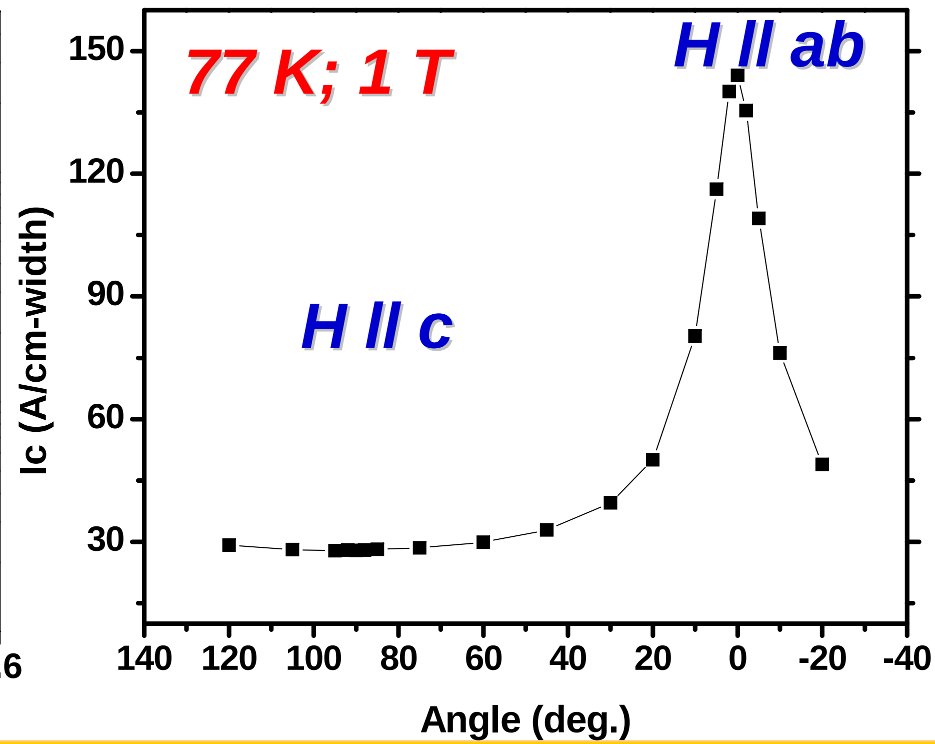




Is the performance of the stack being limited by MOD LZO or MOD CeO_2 compared to all PVD buffer stack with a performance of 250 A/cm width?

Replacing the MOD CeO_2 with rf sputtered CeO_2 cap layer results in 255 A/cm



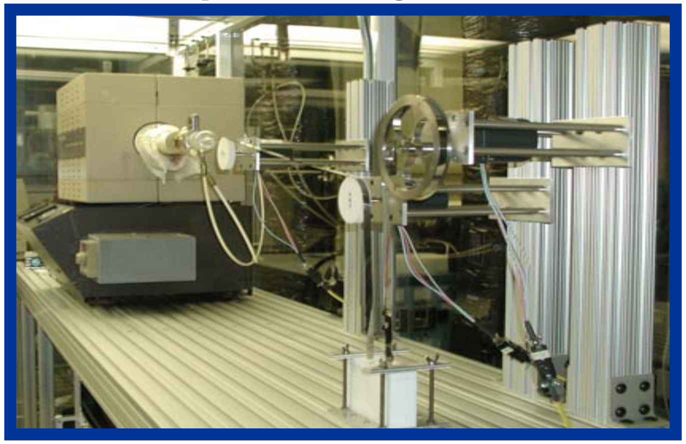


X-ray characterization indicated that there was no difference in the texture, however increased reaction of MOD CeO_2 resulting in higher $BaCeO_3$ was observed

We are also exploring a solution route for replacing the thin Y_2O_3 seed layer

MOD Buffer Scale-up Goal: To produce 100-150 nm Layer in a Single Coat

Dip-coating unit



Slot-die coater

- **One-pass coating process required for commercial applications**
  - **Essential to reduce equipment and labor cost for commercial manufacturing**
- **Developed experimental conditions to coat > 100 nm LZO layers/pass**
  - **Coating speed: > 120 m/hr**
- **Developed process conditions to produce textured LZO layers**
- **Evaluation of slot-die coated buffers is in progress**

Slot-die Coating technology transferred from AMSC to accelerate solution based buffer development

FY 2005 Plans and Performance

FY2005 Plans

- Pilot line production of high quality (4 cm wide by 100 m long) alloy substrates using the ORNL rolling mill facility with clean room

FY2005 Performance

✓ Produced over 2.5 km of 4 cm wide substrates with exceptional surface quality and texture

✓ ORNL's rolling facility was the primary facility used by AMSC for scale-up research towards wide substrates

FY 2005 Plans and Performance

FY2005 Plans (cont'd)

- **Improvement of RABiTS template manufacturing process reliability through fundamental characterization of the buffer layer properties**
- **Analysis of the uniformity and reproducibility of long length, 4 cm wide RABiTS templates produced in a high-rate, reel-to-reel manufacturing process**

FY2005 Performance

✓ **Quality of 1 cm RABiTS template successfully extended to 4 cm wide process**

✓ **Highly uniform texture obtained in reel-to-reel fabrication of long lengths of 4 cm wide buffers**

FY 2005 Plans and Performance

FY2005 Plans (cont'd)

- **Reduction of the substrate/ buffer manufacturing cost through improved understanding of the interactions of buffer deposition rates and intrinsic properties**

FY2005 Performance

✓ **Reel-to-reel, single pass, high rate reactive sputtering was for all three buffer layers: Y_2O_3, YSZ and CeO_2 for the 4 cm wide substrates**

✓ **Buffer production capacity extended to: 1.6 million meters/year**

FY 2005 Plans and Performance

FY2005 Plans (cont'd)

- **Determine key flux-pinning mechanism in long length, MOD YBCO, 4cm wide wires**
- **Improve the in-field J_c in all fields by incorporation of nanoparticles in long-length, MOD YBCO, 4 cm wide wires**

FY2005 Performance

✓ **Stacking faults in the YBCO layer were shown to result in the strong peak in J_c vs angle for H//ab**

✓ **Incorporation of nanoparticles to achieve significant improvement in the in-field J_c successfully demonstrated in 4 cm wide wires**

✓ **Highest performance doped YBCO via the MOD route was demonstrated**

FY 2005 Plans and Performance

FY2005 Plans (cont'd)

- **Development of new, low-cost template architectures that are applicable to Ni-5at%W as well as non-magnetic Ni-9at%W and NiCrW substrates**

FY2005 Performance

✓ **Demonstrated the direct printing of YBCO filaments with MOD process, Ic = 200 A/cm-w demonstrated**

✓ **Proof-of-principle demonstration of MOD-LZO barriers as replacement for PVD-YSZ; I_c of 249 A/cm or a J_c of 3.1 MA/cm^2 was demonstrated on MOD-LZO**

✓ **I_c of 188 A/cm or a J_c of 2.35 MA/cm^2 was demonstrated on improved MOD CeO_2/LZO buffers**

FY 2006 Plans

- ORNL assistance to AMSC in manufacturing alloy substrates (4 cm wide by 100 m long) using the ORNL rolling mill facility with clean room
- Improvement of RABiTS template and YBCO manufacturing process reliability through characterization of the individual layer properties
- Development of improved buffer architectures focused on improved performance and/or reduced manufacturing cost
- Evaluation and optimization of YBCO processing on 4 cm RABiTS templates
  - Self field Ic improvement in 0.8 – 2.0 µm YBCO layers
  - Optimized pinning via nanopartilce addition
- Demonstration of solution deposited buffer layers over 10 meter length with performance comparable to AMSC's standard $CeO_2/YSZ/Y_2O_3$ buffer architecture
- Development of a reel-to-reel direct printing technology for striated YBCO films
- Characterization and testing of 2G wires and wire products
  - 1T (at 77K) coil (contingent on funding availability)

Research Integration

- **Regular weekly conference calls**
- **Frequent sample exchanges**
- **CRADA meetings**
- **Personnel exchange – use of ORNL rolling mill facilities for all the scale-up activities by AMSC staffs (once a month)**
- **Joint development of substrate/buffers, joint materials evaluation and testing**
- **Interacted with LANL through AMSC on YBCO evaluation studies**
- **Several joint publications and joint presentations**
- **Joint patent applications filed**