ORNL-AMSC CRADA: Development of Reel-to-Reel Processing of YBCO Coated Conductors

American Superconductor Corporation

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PATENT LICENSE AGREEMENT WITH AMERICAN SUPERCONDUCTOR CORPORATION

ORNL and AMSC signed the CRADA On May 30, 2000

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CRADA Objective

- **To support and assist AMSC in development of a low-cost commercial YBCO composite conductor based on the RABiTS technology**
- **Conductor Requirements**
  - **Production Cost: <$10/kAm (Broad Market Penetration)**
  - **Form – Fit – Function replacement for BSCCO**

AMSC-ORNL CRADA Goals/Outline

- **FY 2002 Results**

  Transfer RABiTS technology from ORNL to AMSC (Parans)

  YBCO performance on meter length RABiTS tapes (Marty)
  Overview of coated conductor development at AMSC

  Substrate and YBCO characterization (Amit)
  Non-magnetic substrate development

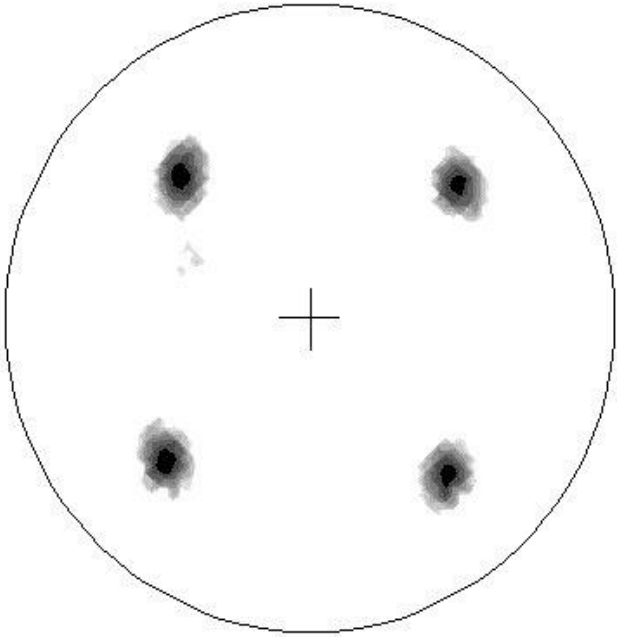
- **FY 2002 Performance and FY 2003 Plans**
- **Research Integration**

Rolling of metals and alloys (Ni, NiW,NiCr)

Grain Boundary Misorientation Distribution

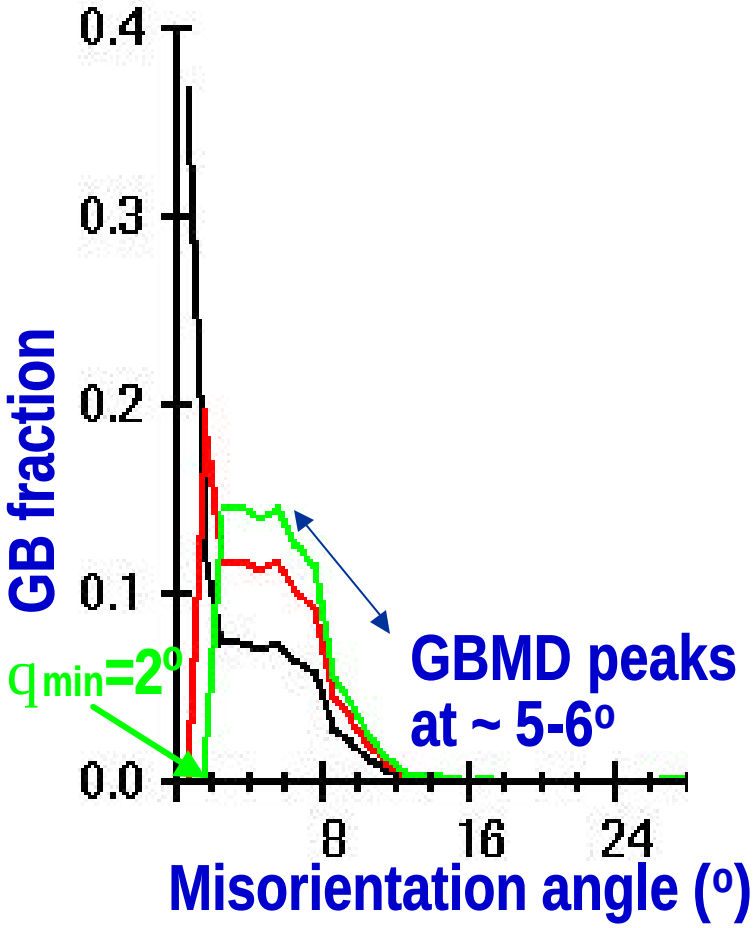
Composition: Ni-3at%W

1300°C @ 1hr



% Cube: ~100%

Allchemie Ni



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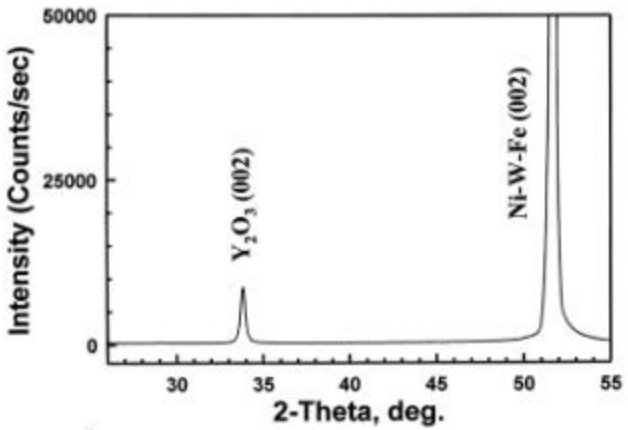
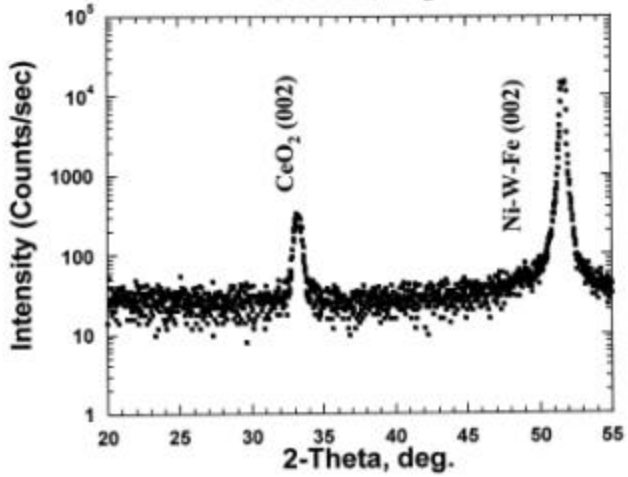
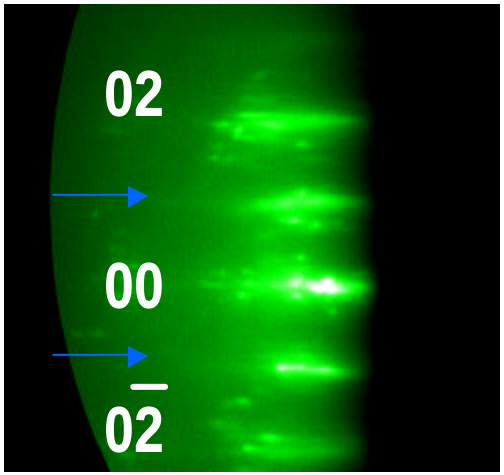
Buffer layer growth on Ni-3at%W substrates

-various oxides have been grown directly on Ni-3at%W





Sulfur superstructure controls epitaxy!



Auger spectroscopy shows that ~24 at% sulfur is present on the surface, corresponding to a near complete c(2x2) superstructure

Best J_c on Ni-W: 2 MA/cm^2

Key learning implemented at AMSC

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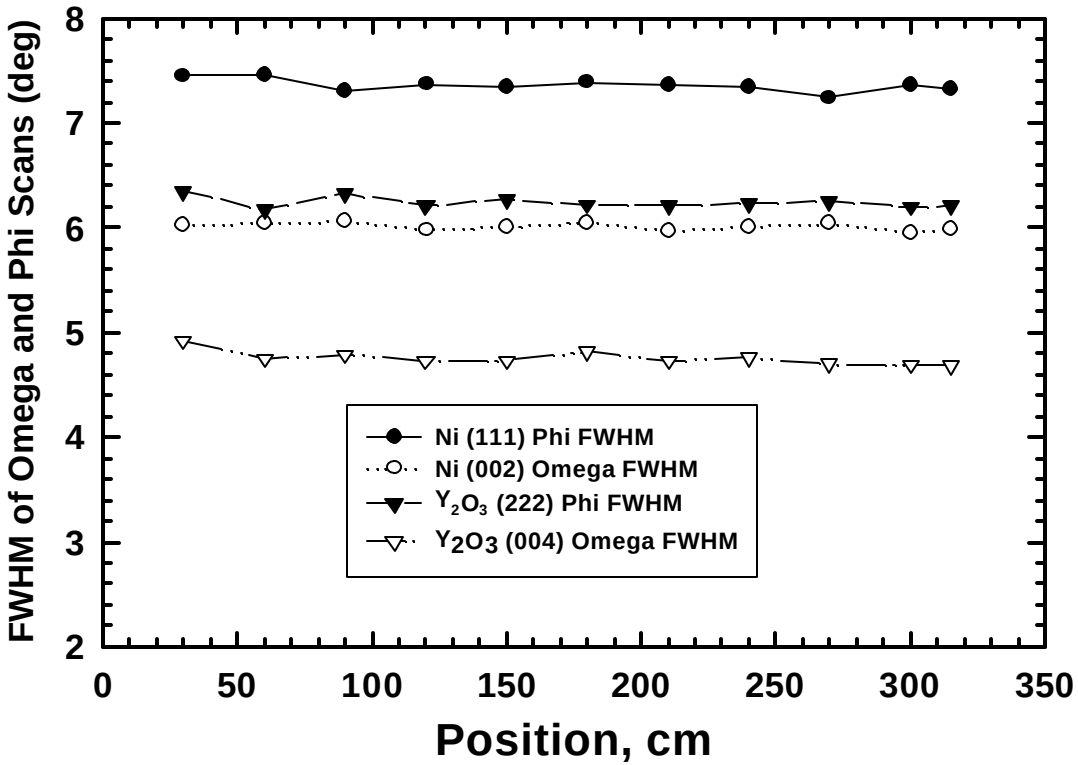
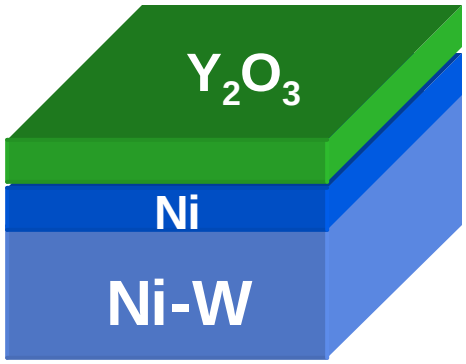
Y_2O_3 Deposition Transferred to Reel-to-Reel Process at AMSC



Textured Y_2O_3 seed layers in length at AMSC



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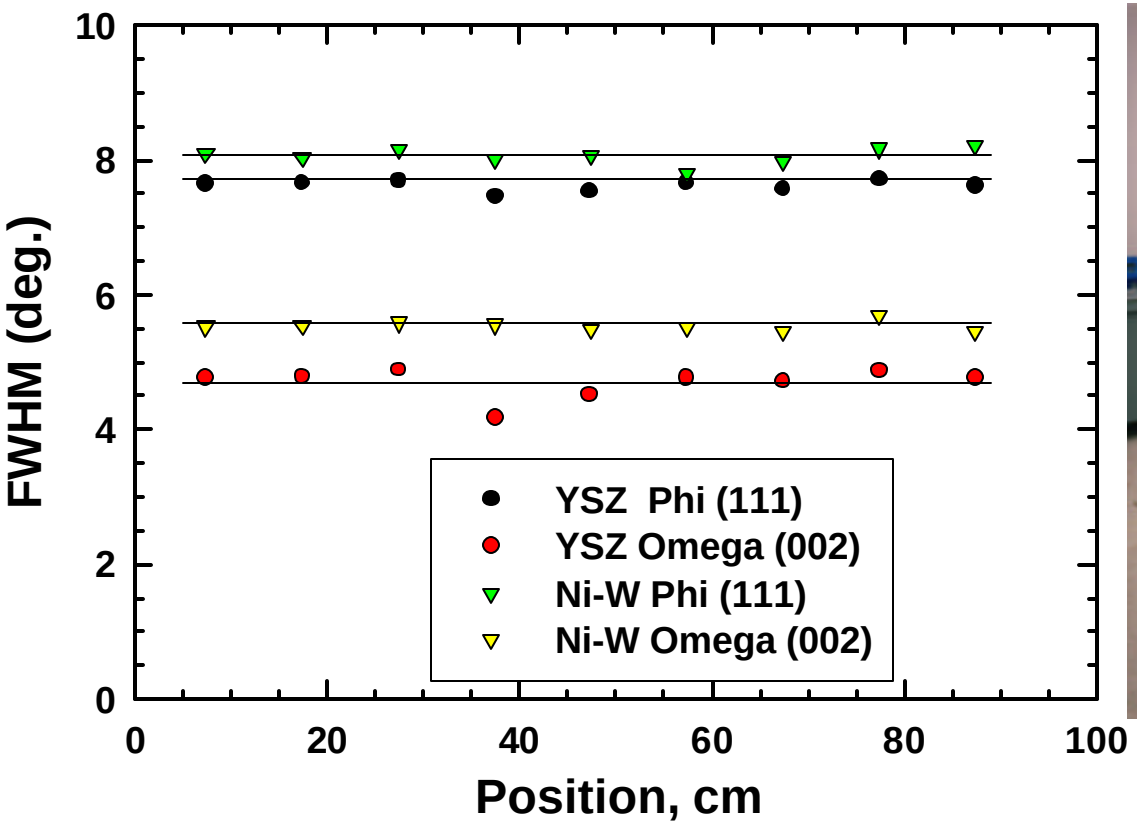
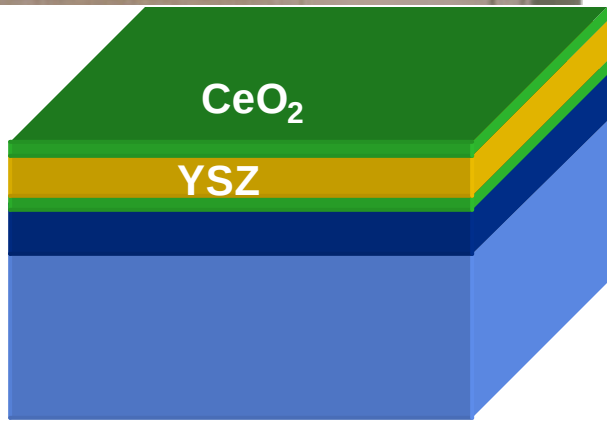
Rf-deposition of YSZ/CeO_2 Layers at AMSC





YSZ and CeO_2 layers with uniform texture were deposited on RE_2O_3 seeds

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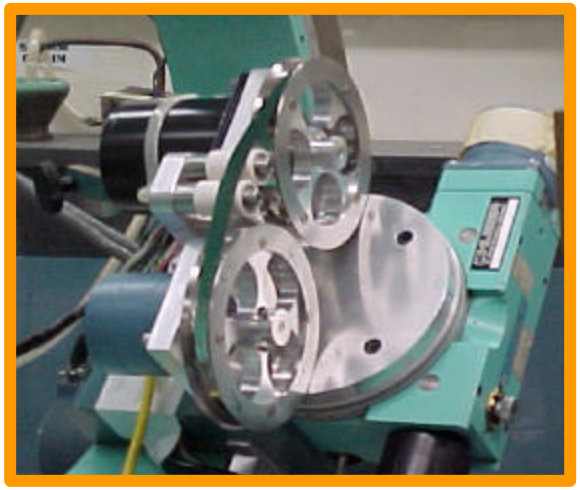
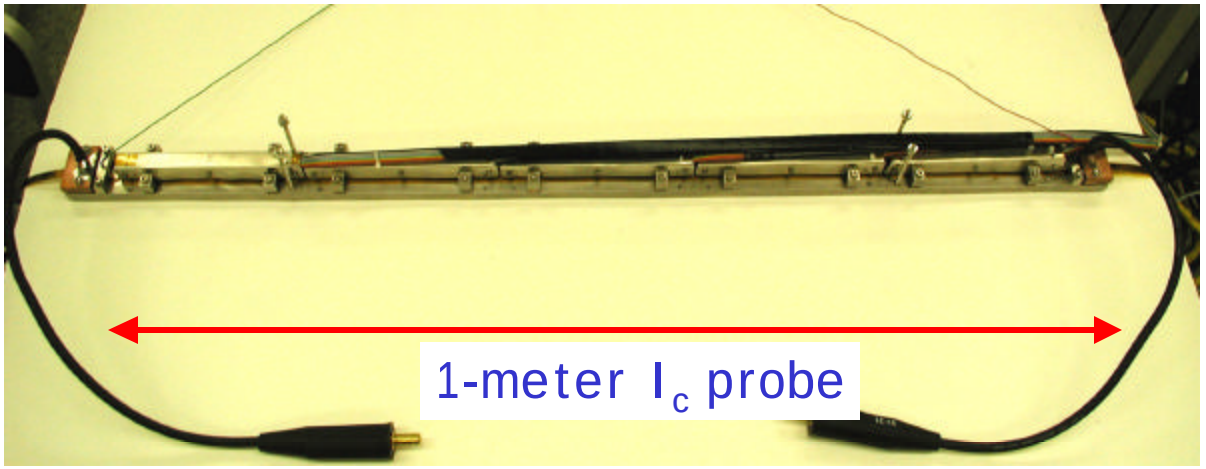
Evaluation and Characterization of AMSC Tapes at ORNL

- ORNL used reel-to-reel XRD to confirm the texture of AMSC tapes
- ORNL measured the Ic of AMSC meter length wires at 1 cm tap distance
- AMSC uses ORNL's Accelerated Coated Conductor Laboratory's facility





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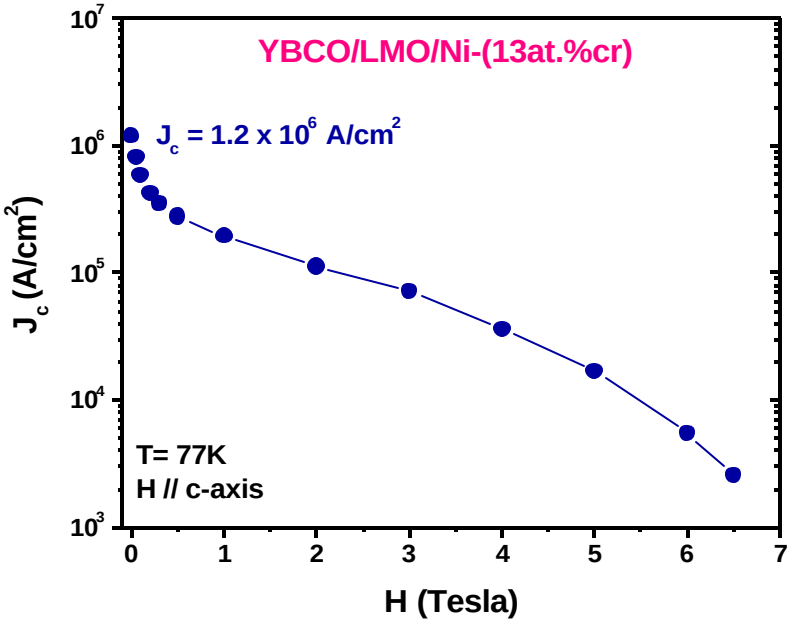
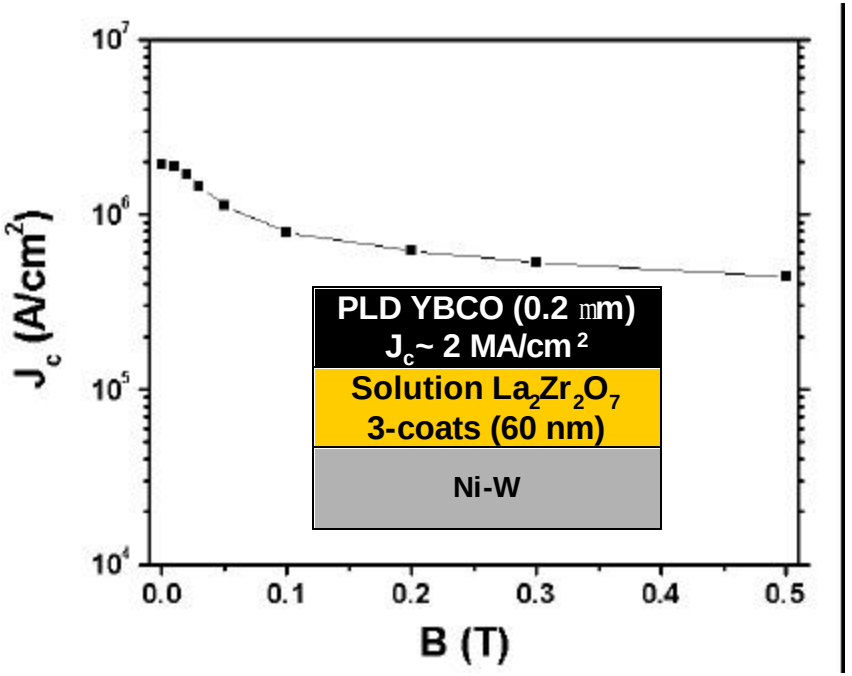
AMSC is collaborating with ORNL's base program activities

- **ORNL deposited >1 μm thick BaF_2 precursors on high quality AMSC RABiTS and sent back to AMSC for processing (Ic > 100 A/cm in short lengths)**

- **ORNL/AMSC is collaborating to develop alternative low cost buffer deposition technologies (Example: $LaMnO_3$, $La_2Zr_2O_7$ buffers)**





M. Paranthaman (Strategic Buffer Talk)

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AMSC-ORNL CRADA Goals/Outline

- **FY 2002 Results**

  Transfer RABiTS technology from ORNL to AMSC (Parans)

  YBCO performance on meter length RABiTS tapes (Marty)
  Overview of coated conductor development at AMSC

  Substrate and YBCO characterization (Amit)
  Non-magnetic substrates alloy characterization

- **FY 2002 Performance and FY 2003 Plans**
- **Research Integration**

AMSC/ORNL Collaborative Development of Long Length Coated Conductor Composite Technology

- **AMSC Combining ORNL RABiTS™ Technology with TFA-based Metal-Organic-Deposition for YBCO Composite Conductor Fabrication**
- **Key Program Goals**
  - **Achieve high performance RABiTS™/MOD wire by all continuous processing**
  - **Develop low-cost manufacturing process required for achieving conductor price of $10/kAm**

Program Focus is Developing a Commercial Composite Conductor with Price/Performance Superior to BSCCO MFC

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AMSC/ORNL YBCO Coated Conductor Composite Status Last Year

- **Basic technology for RABiTS™ substrate/buffer fabrication established at AMSC based on tech transfer from ORNL**
  - **Textured Ni substrates**
  - **Insight into role of sulfurization of metal surface**
  - **RE_2O_3/YSZ/CeO_2 buffer stack**

- **Quality of YBCO from MOD process matched that of PVD process for short samples**
  - **4.5 MA/cm^2 for 0.4 μm film on CeO_2/YSZ_{sc} (77K, sf)**
  - **2.2 MA/cm^2 for 1.1 μm film on CeO_2/YSZ_{sc} (77K, sf)**
  - **1.9 MA/cm^2 for 0.37 μm film on CeO_2/YSZ/CeO_2/Ni (77K, sf)**

- **YBCO films demonstrated on RABiTS™ substrates by continuous reel-to-reel process**
  - **15 A over 30 cm length (0.35 MA/cm^2)**
  - **42 A over 8 cm length (1 MA/cm^2)**

Development of Baseline Process Focus of Past Year

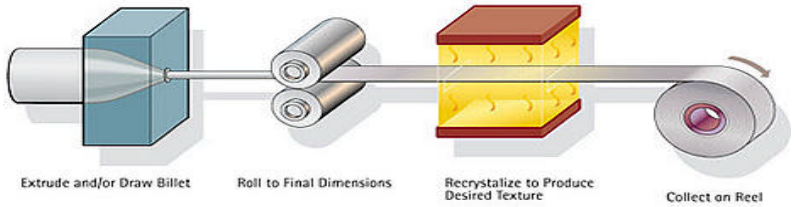
- **Development and Characterization of a Reproducible Reel-to-Reel Technology for**
  - **Alloy Substrate Deformation and Texture Anneal**
  - **Buffer Deposition**
  - **YBCO Deposition**

- **Extension of MOD Process to High Critical Current Films**
  - **Increased Critical Current**
  - **Long length uniformity**

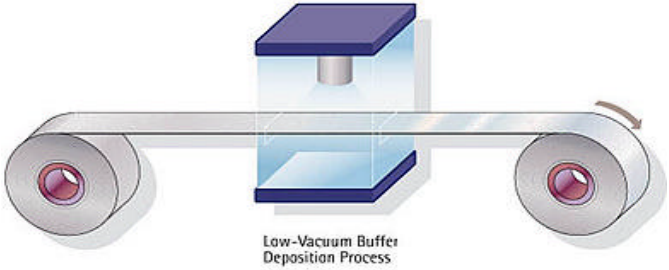
Stable, Reproducible Baseline Process Essential for Successful Development and Assessment of RABiTS™ Technology

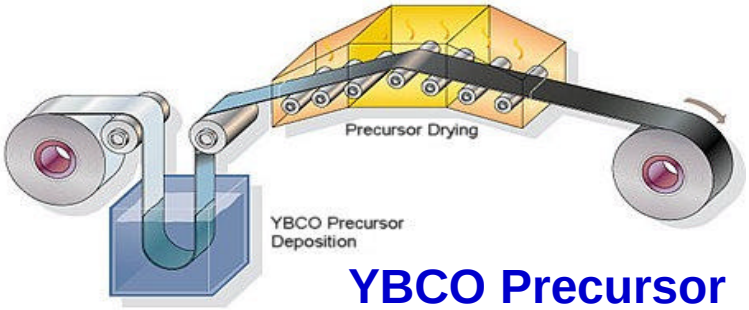
Coated Conductor Fabrication Process at AMSC

Substrate Production

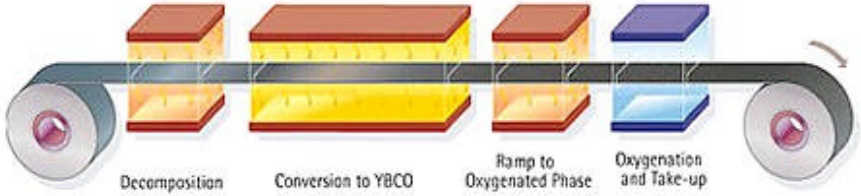


Buffer Deposition





YBCO Precursor Coating



YBCO Formation

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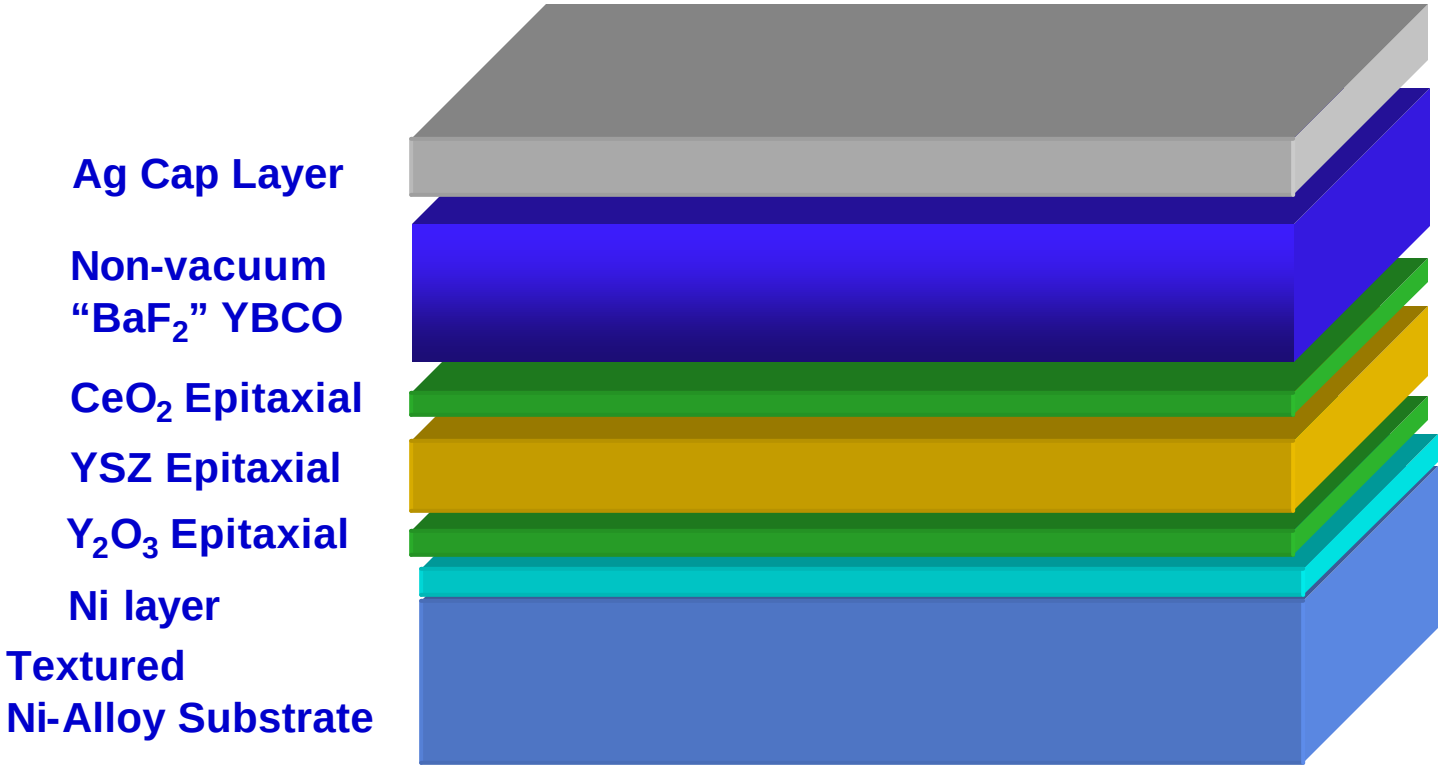
Present RABiTS™/MOD Architecture

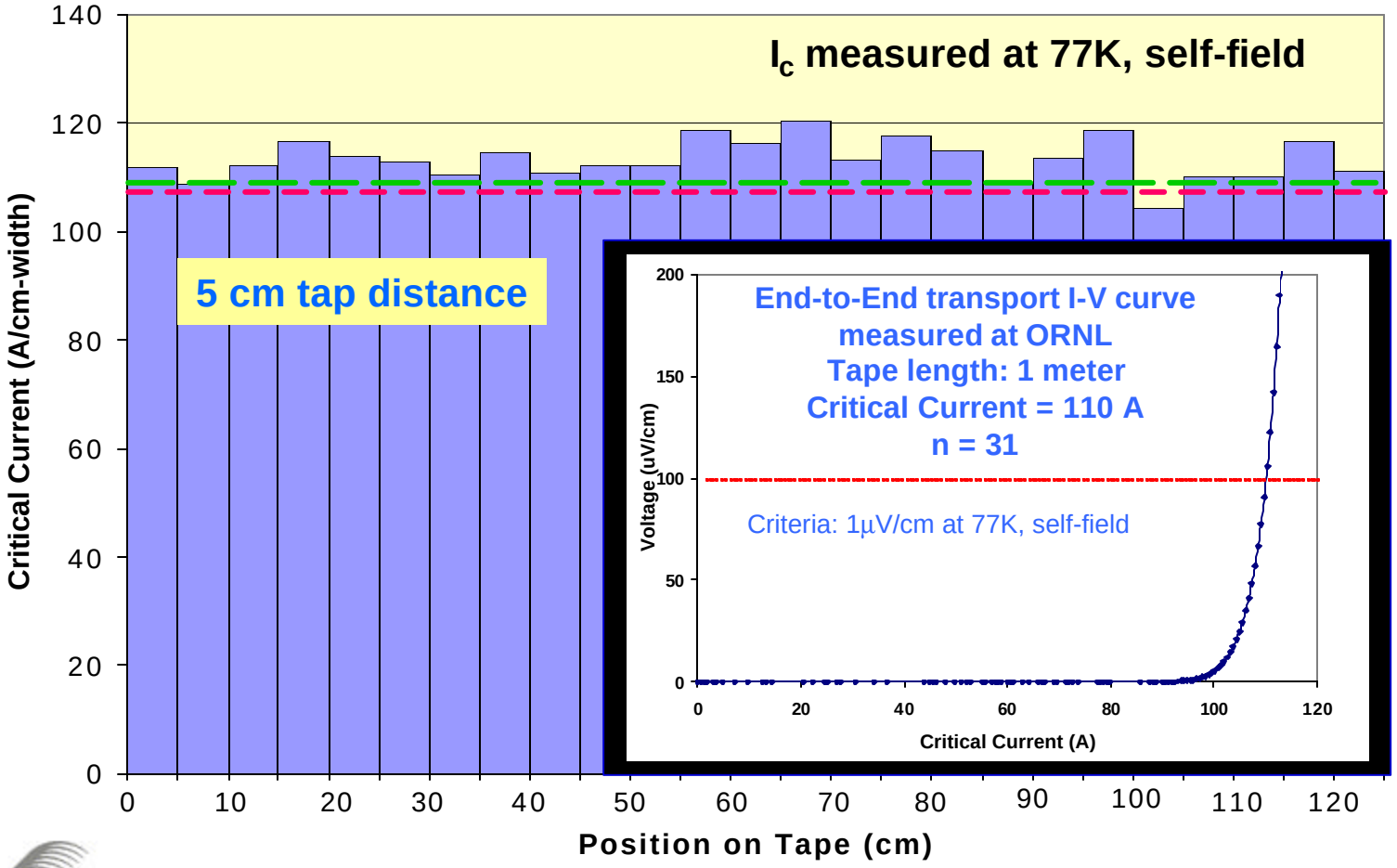


Reproducible Architecture and Quality Essential for YBCO Conductor Development and Improvement

YBCO Deposited on Meter Length RABiTS™ by Reel-to-Reel MOD Process

- MOD precursor deposited using conventional web coating line
- Precursor films decomposed in continuous reel-to-reel process to a "BaF_2" type precursor
- "BaF_2" precursor film converted to YBCO in reel-to-reel furnace at 700 – 800°C
- Short length performance predicts long length performance

High Critical Current and Exceptional Uniformity Obtained on Meter Length AMSC RABiTS™/MOD Conductors by Reel-to-Reel Process



Average Ic:
113 ±3.7 A

End-to-End Ic:
112 A

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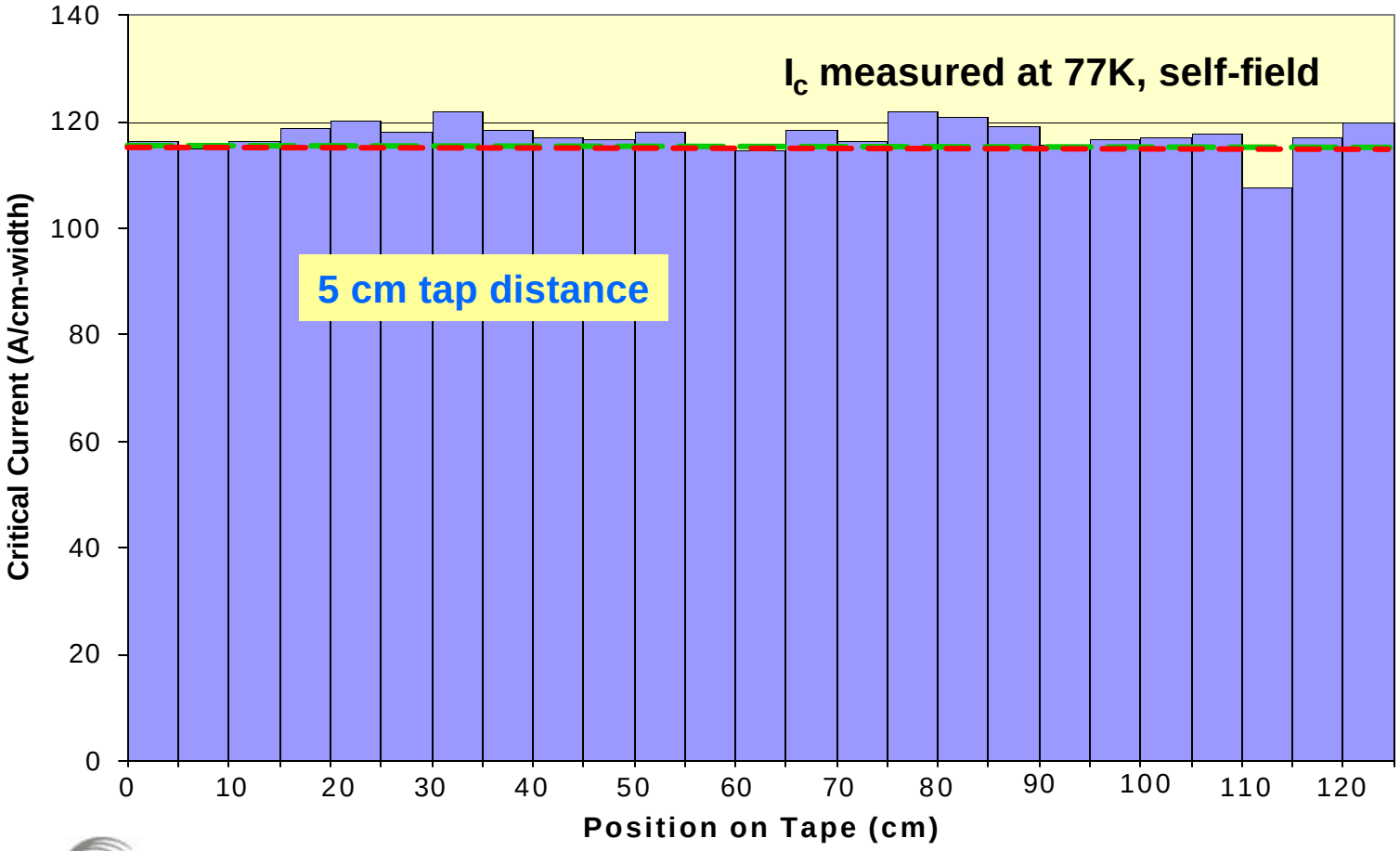
Comparable Performance Obtained with AMSC YBCO on ORNL Ni-3at%W Substrate with AMSC Buffer Layers



Average Ic: 118 ±2.9 A

End-to-End Ic: 118 A

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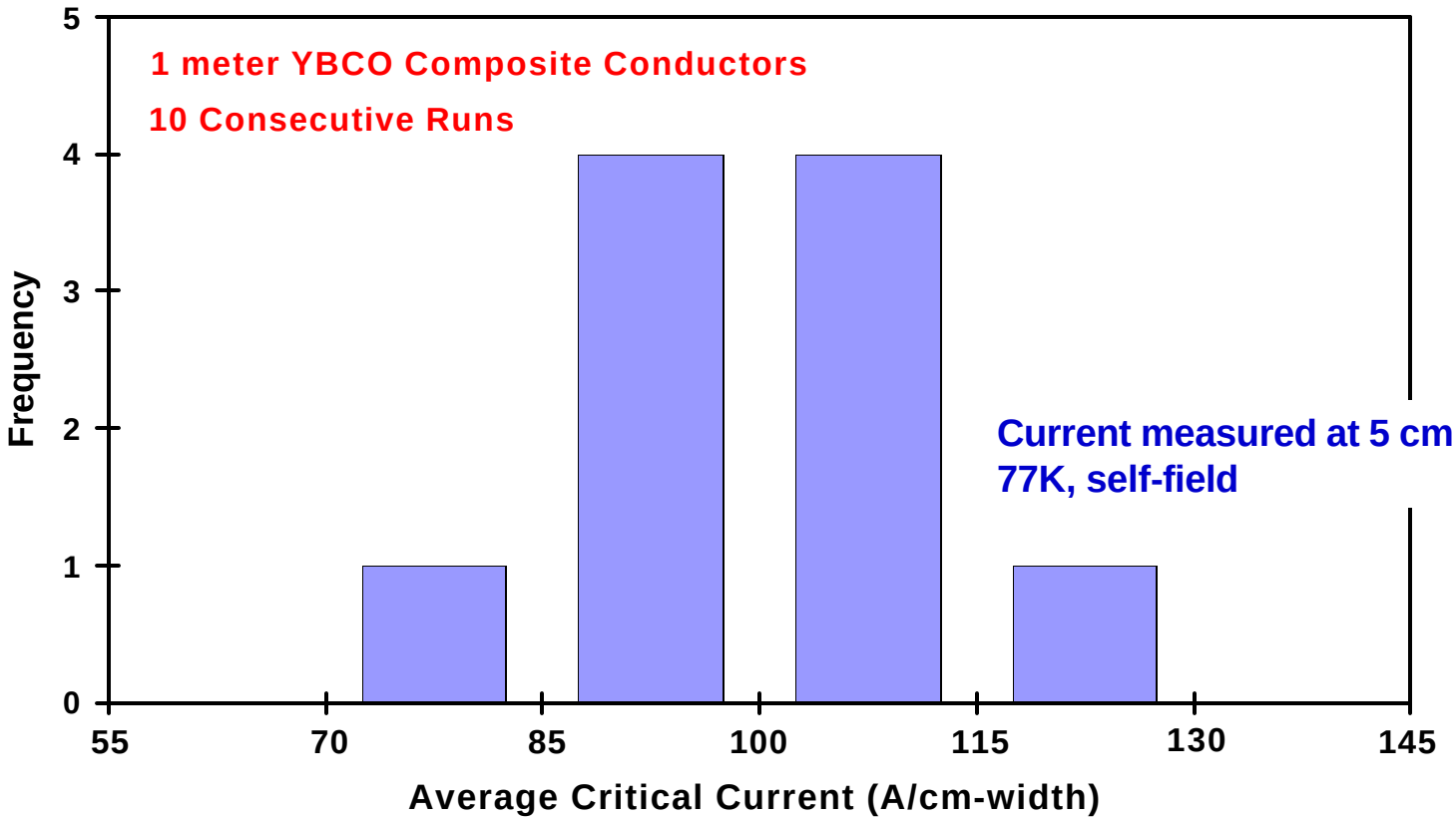
Reel-to-Reel RABiTS™ Process is Robust and Reproducible



100 A Conductors Routinely Produced by Reel-to-Reel Process

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AMSC/ORNL Achieve Outstanding Performance in Reel-to-Reel-Processed RABiTS™/MOD Coated Conductor

- **Performance**
  - Up to 118 A (77K, self-field) over 1 meter in 1 cm-wide tape
- **Uniformity**
  - 3% standard deviation in critical current Ic, measured on 5 cm scale
- **Reproducibility**
  - Average performance of 10 consecutive meter-length runs is 100 A

Implications of Uniformity and Reproducibility

- **Excellent prospects of scaling of RABiTS™/MOD process to long length without loss of performance due to statistical fluctuations**
- **Previous speculation about statistical fluctuations in moderate grain size (average 25 micron) template are unjustified**
- **An excellent basis for further process optimization: real process improvements are not masked**

Low Cost RABiTS™/MOD Conductor is Attractive for Near-term Pilot Scale-up

Meter Length AMSC/ORNL RABiTS™ Substrates Tested with e-beam BaF_2 Process

- Ni-3at%W substrate prepared at ORNL
- Buffer layers (Y_2O_3/YSZ/CeO_2) deposited at AMSC over 3 meter length
  - MOD qualification: 1.5 MA/cm^2 (0.4 μm YBCO, 1 cm length, 77K, self-field)
- YBCO deposition by e-beam BaF_2 at ORNL
  - Reel-to-reel e-beam deposition of BaF_2 precursor
  - Reel-to-reel reaction of "BaF_2 precursor"
- High End-to-End Critical Currents over 1.2 meter length (77K, sf)

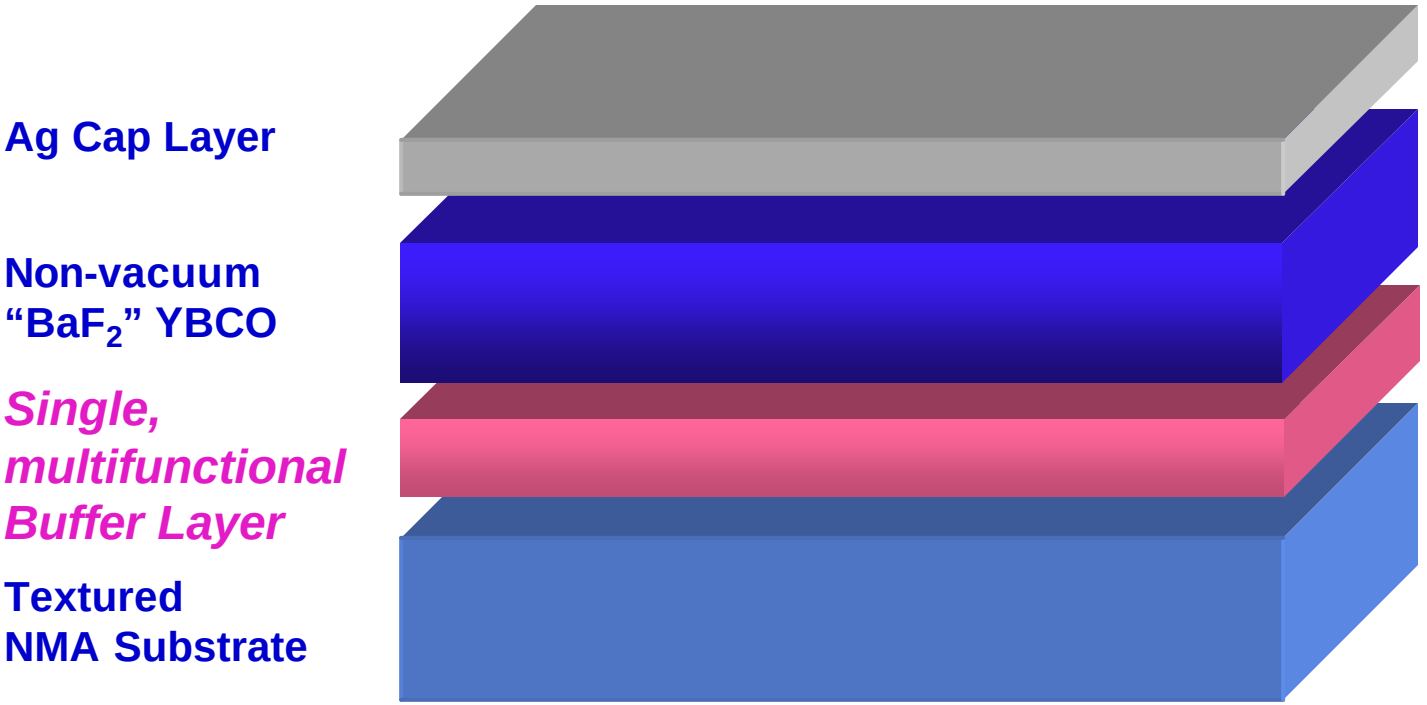
D. Lee will present results in detail tomorrow

Confirms Quality of AMSC Buffer RABiTS™ Technology

Fundamental Understanding is Key

- **Substrate**
  - Sharper texture and improved surface smoothness
  - Oxidation resistance
- **Buffer**
  - Simplified geometries (thinner, fewer layers)
  - Deposition parameters and rates (dense, low cost)
  - Texture and surface morphology
  - Oxygen and metal diffusion (thinner, low cost)
  - Substrate superstructure
  - YBCO compatibility
- **HTS**
  - Critical current limiting mechanisms (Jc, thickness, texture)
  - Flux Pinning
- **Product**
  - Electrical and thermal stability
  - Mechanical integrity
  - Ac loss

Vision of Future Low-Cost Commercial Coated Conductor Architecture



ORNL has been the major collaborator in successful development of RABiTS™/MOD technology

AMSC-ORNL CRADA Goals/Outline

- **FY 2002 Results**

  Transfer RABiTS technology from ORNL to AMSC (Parans)

  YBCO performance on meter length RABiTS tapes (Marty)
  Overview of coated conductor development at AMSC

  Substrate and YBCO characterization (Amit)
  Non-magnetic substrates alloy characterization

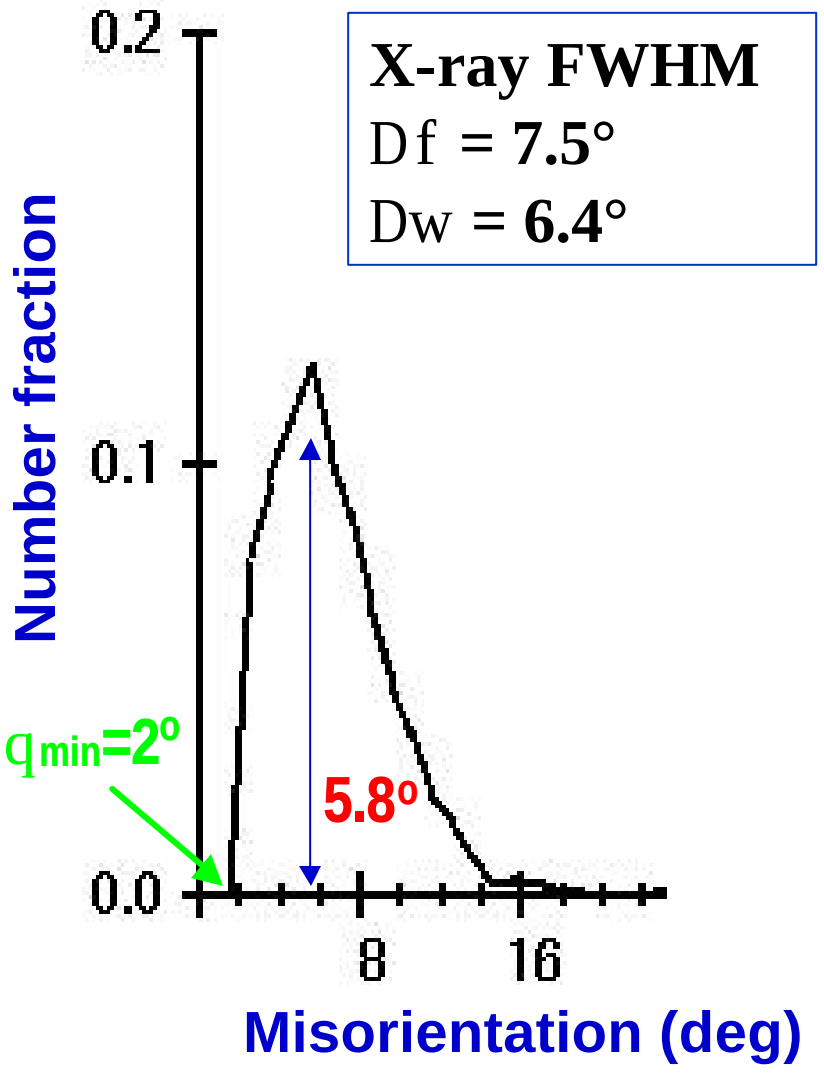
- **FY 2002 Performance and FY 2003 Plans**
- **Research Integration**

Outline

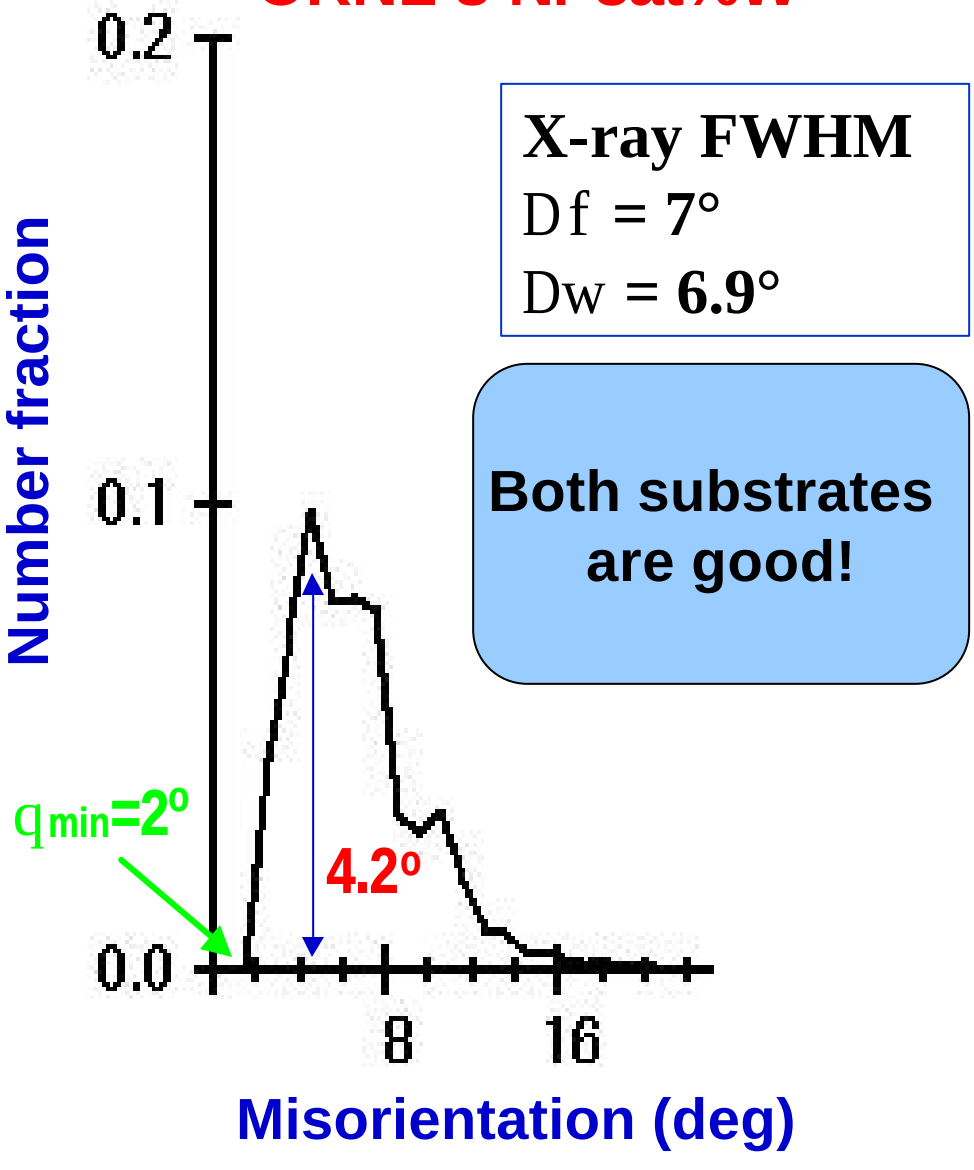
- Characterization of Ni-5at%W (AMSC) and Ni-3at%W substrates from ORNL: Texture and GBMD's
- Reel-to-reel X-ray characterization of high-I_c tape and comparison of calculated and measured J_c
- Magnetic measurements to infer AC losses on Ni-5at%W
- Joint, proprietary co-development of Ni-W-Cr substrates and high-I_c in meter long samples

GBMD's of Ni-W Substrates

AMSC's Ni-5at%W



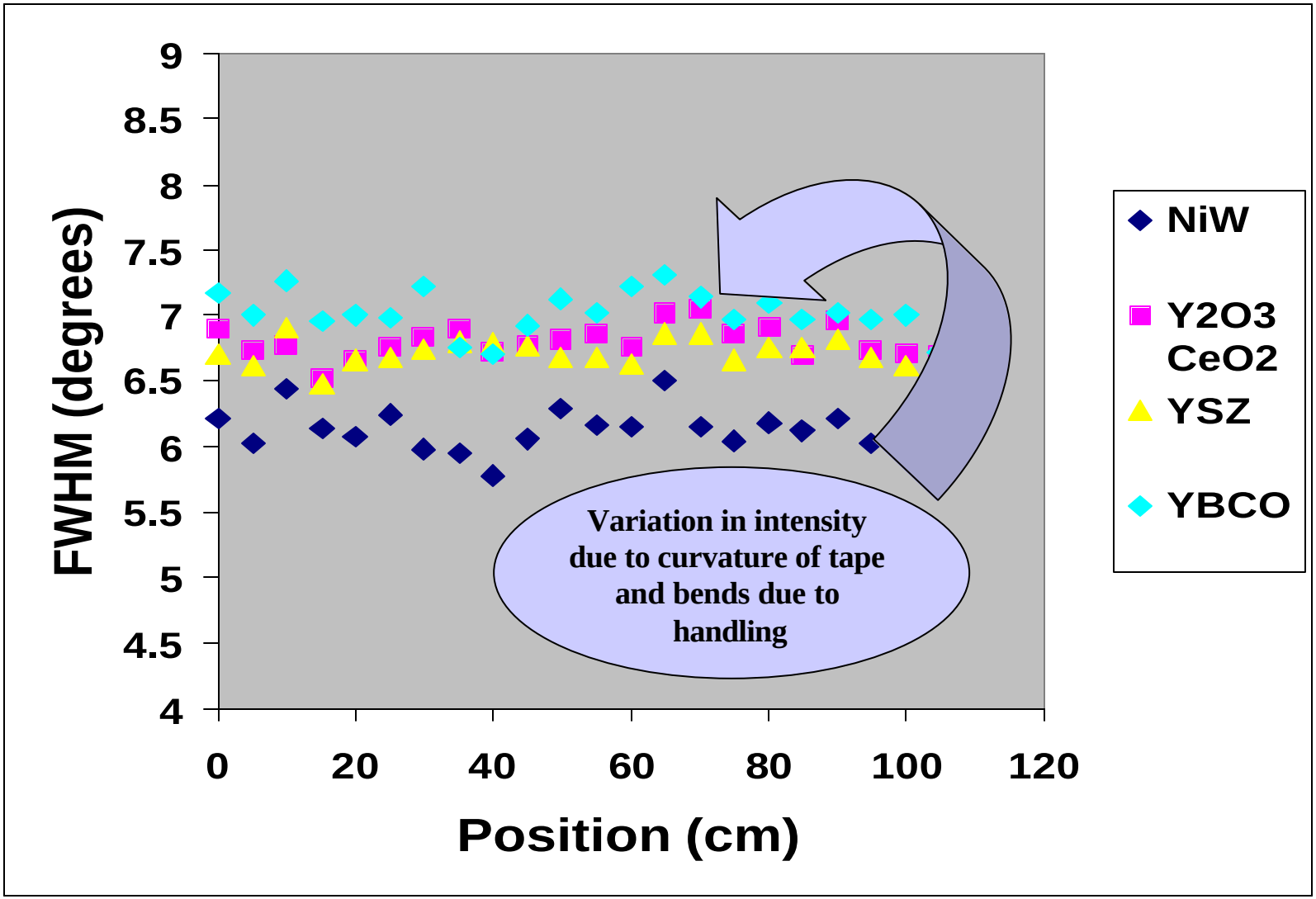
ORNL's Ni-3at%W



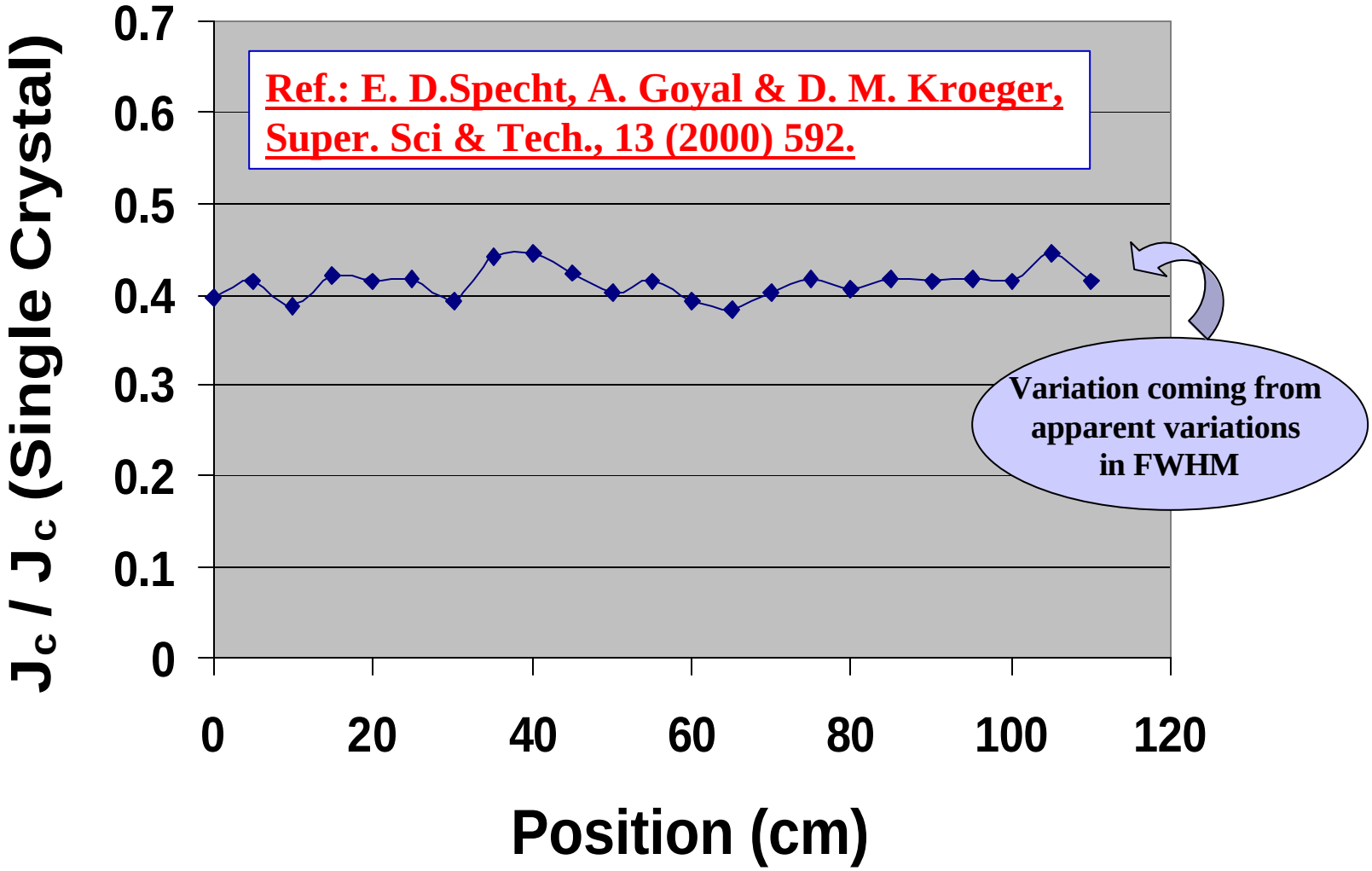
Despite the differences in composition, texture and GBMD's, the I_c results imply there is a wide process window with respect to these measured properties.

Source	Minimum I_c(A/cm)	Maximum I_c(A/cm)	Average I_c(A/cm)	End-End I_c(A/cm)	s (A/cm)
ORNL	108	122	118	118	2.9
AMSC	104	120	113	112	3.7

True Phi-scans for the AMSC YBCO & buffers on ORNL Ni-3at%W



Calculated J_c from the observed texture for AMSC YBCO on ORNL Ni-3at%W



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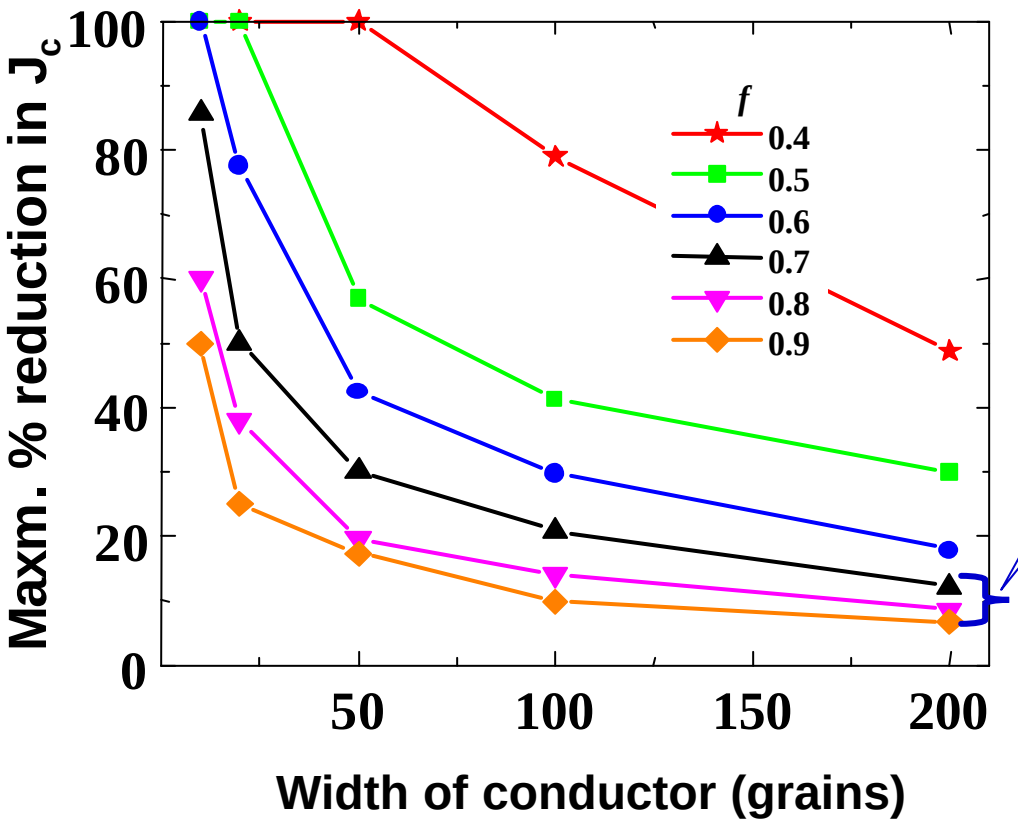
Reduction in J_c in going from a short sample to a kilometer is only 10-15%



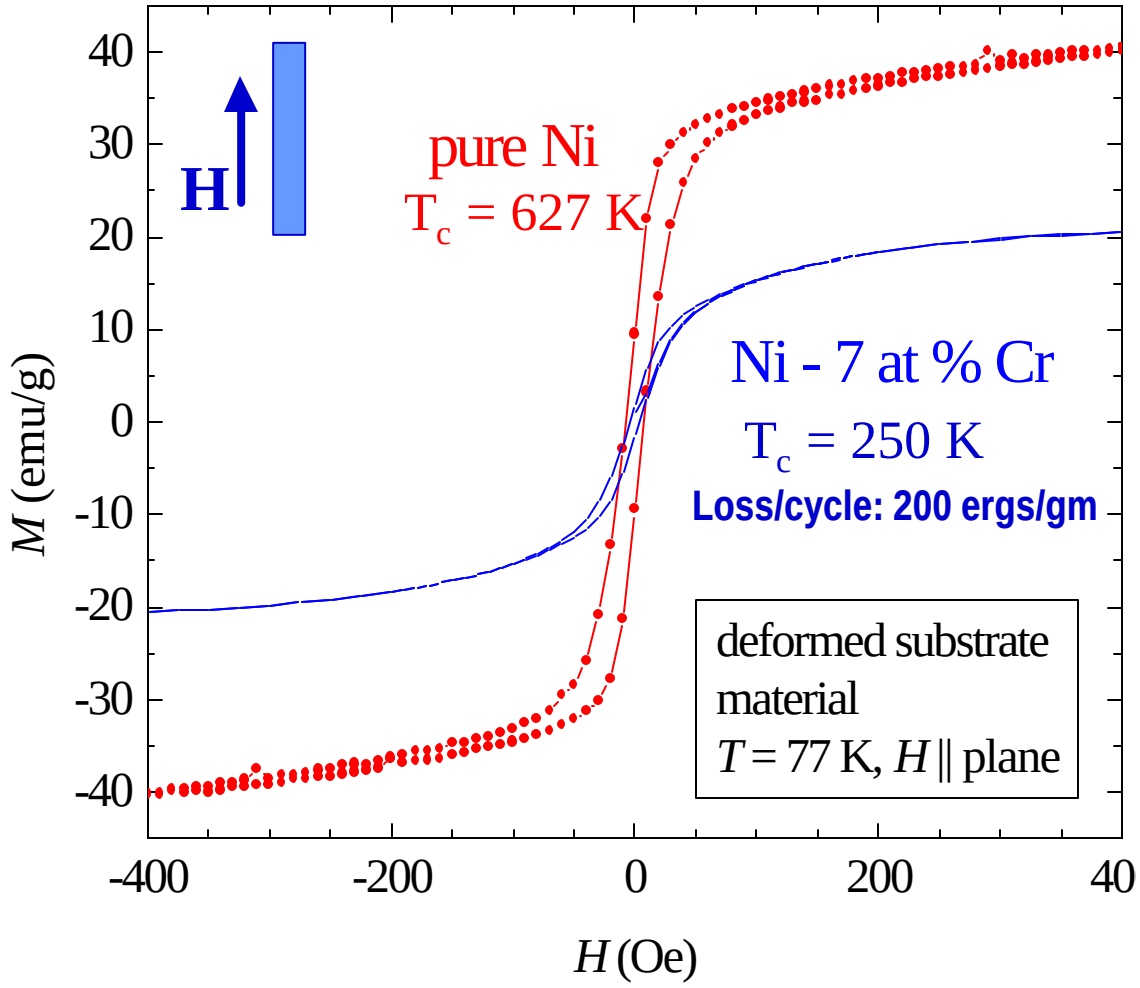
With FWHM of 6-7°, f is 0.7-0.8

A similar conclusion has also been reached by:

Y. Nakamura, T. Izumi and Y. Shiohara in Physica C, 371 (2002) 275.

Ref.: E. D.Specht, A. Goyal & D. M. Kroeger, Super. Sci & Tech., 13 (2000) 592.

AC losses in low Cr content Ni-Cr alloys are significantly reduced compared to Ni and to the loss in YBCO

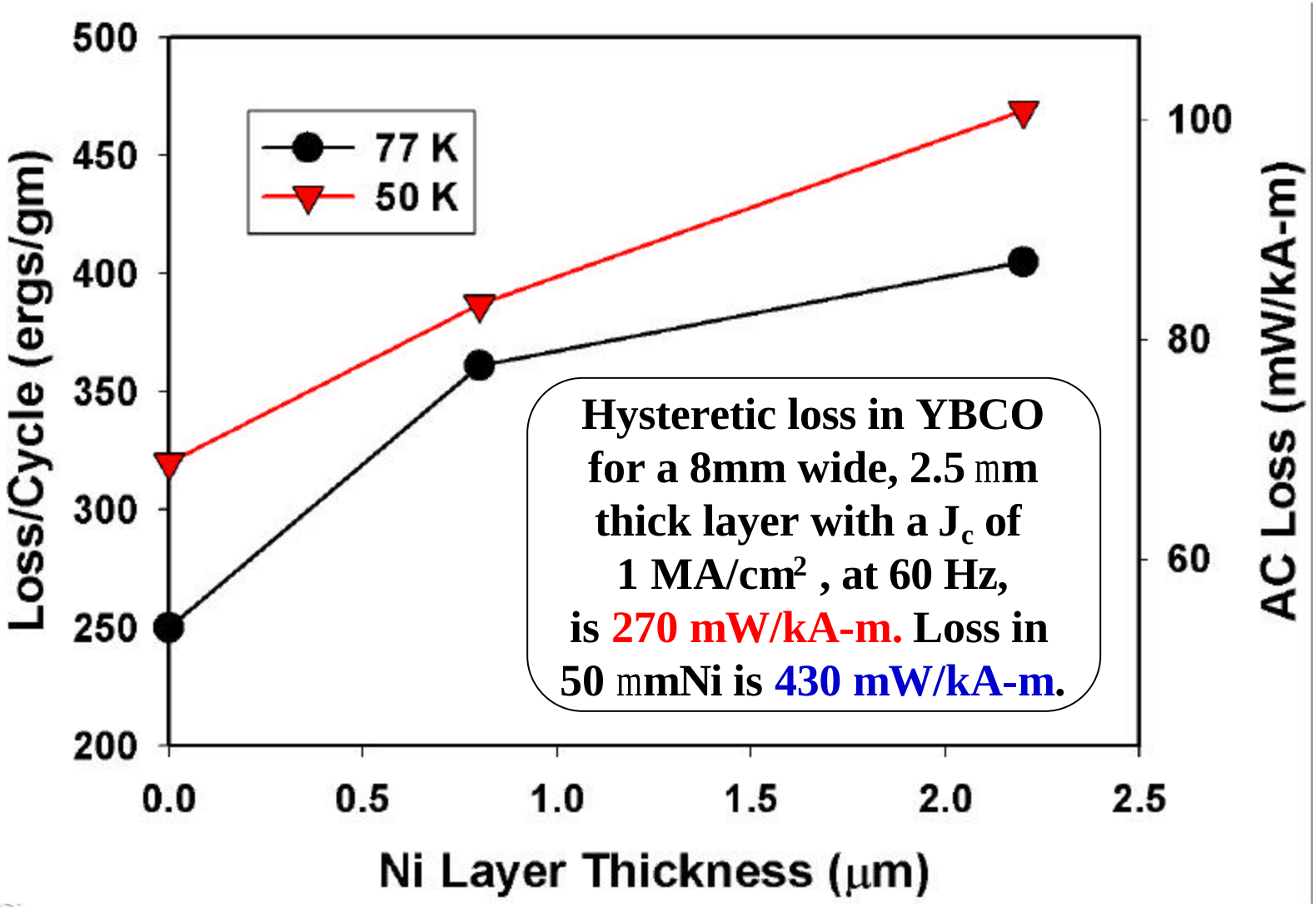


Hysteretic loss/cycle in YBCO for a 1 MA/cm² conductor 8mm wide, 2.5 mm thick on a 50 mm substrate. At 60Hz, assume peak ac current $I_o = I_c/2$ = 100A, SC loss is 270 mW/kA-m at $I_o = I_c/2$

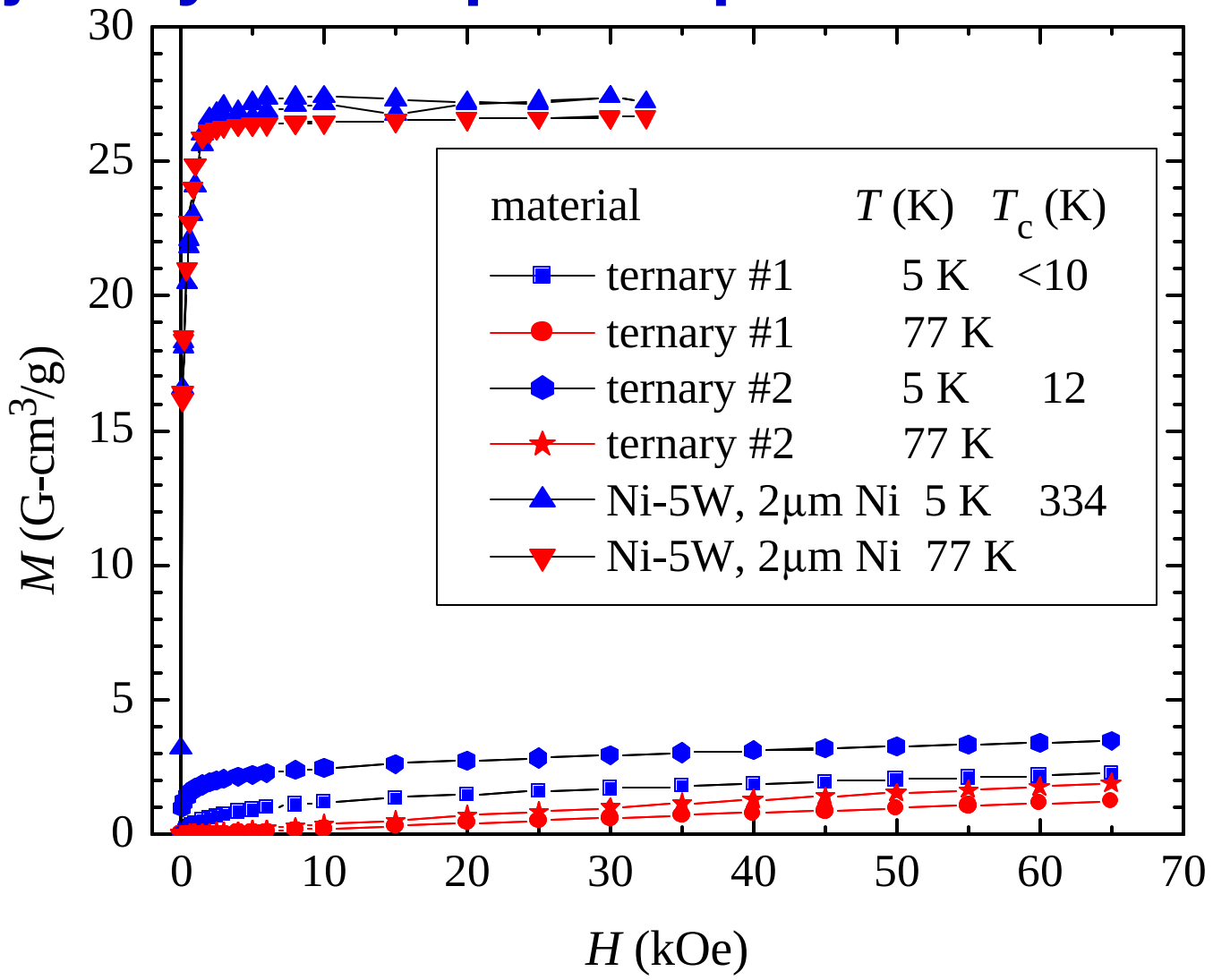
Ferromagnetic energy loss/cycle at 60 Hz for 0.4 cm³ of alloy/meter
-Ni: 430 mW/kA-m
-Ni-7at%Cr: 43 mW/kA-m

Low alloying content substrates may be adequate for many applications

Loss/cycle increases with Ni layer thickness on Ni-5at%W substrates, but is still small compared to the loss from YBCO



Non-magnetic Ni-W-Cr ternary alloys have been jointly developed as part of the CRADA



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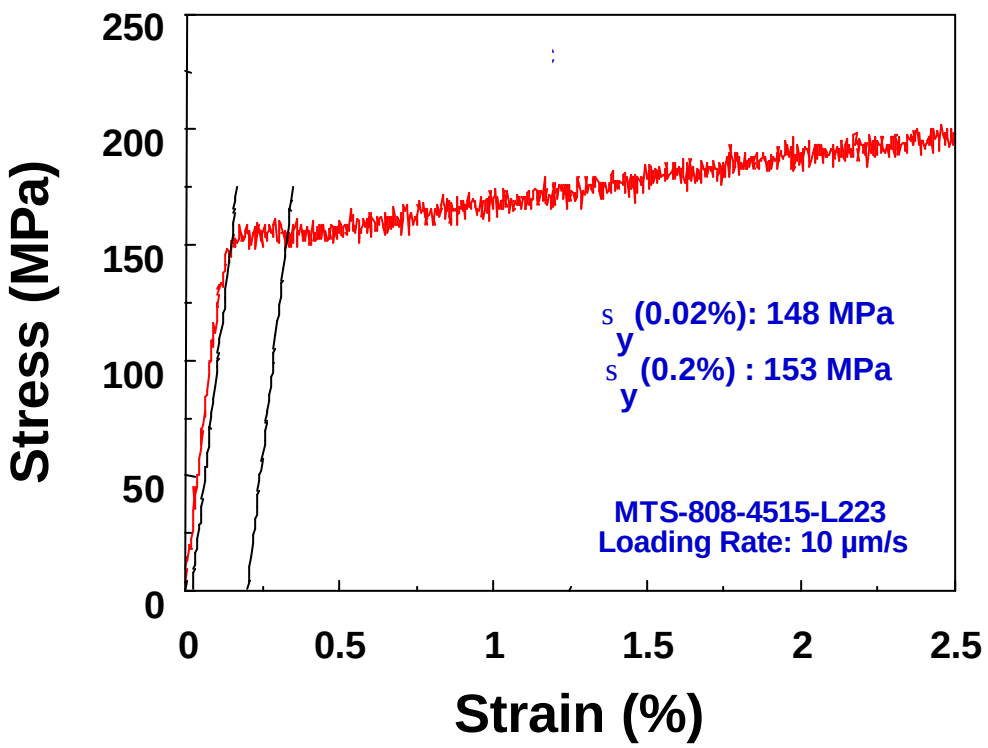
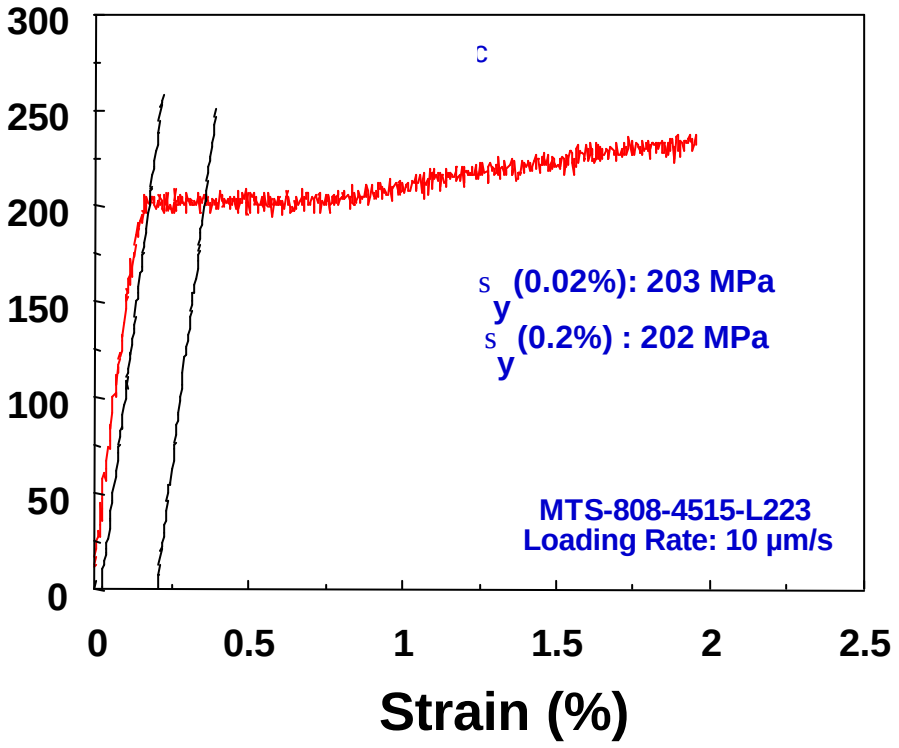
The ternary alloys have high yield strengths





Ni YS(0.2%) = 34 MPa

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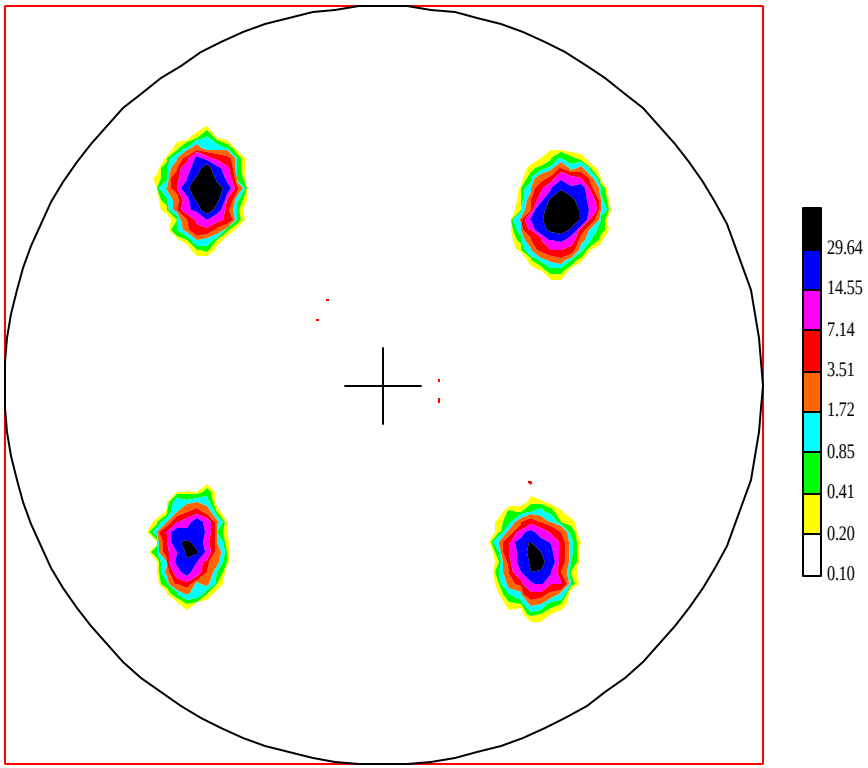
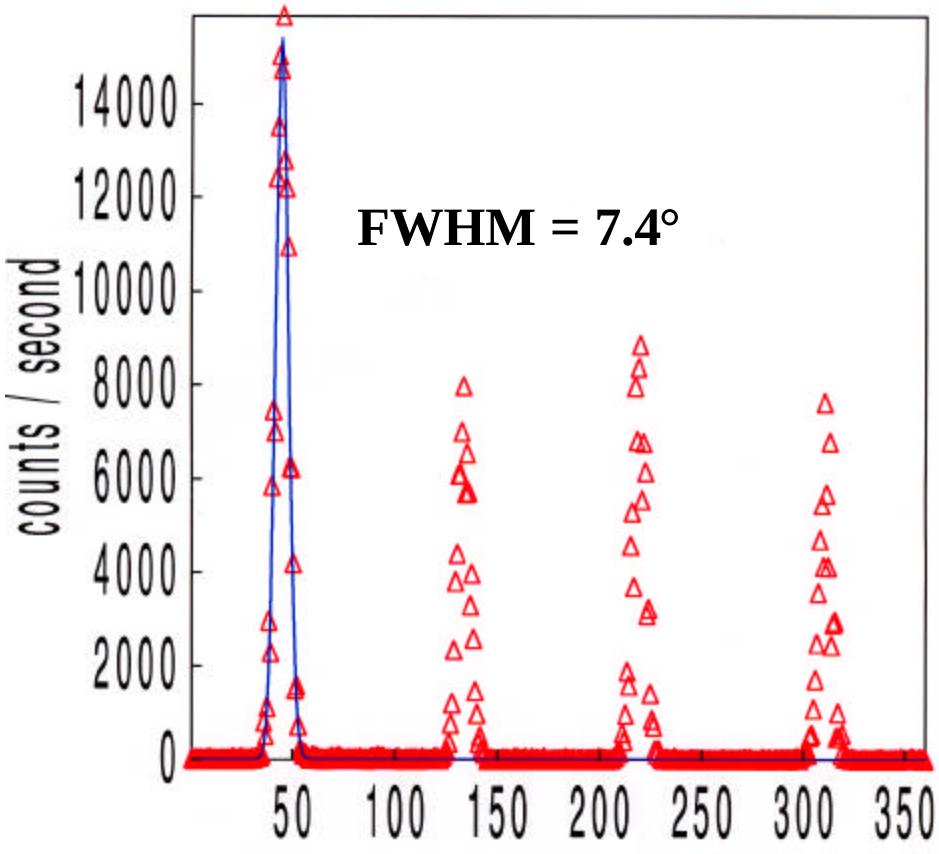
The alloys have been well-textured!

(111) Pole Figure



% Cube ~ 100%



Out-of-plane texture:
FWHM = 5.6° (f=90°);8.6° (f=90°)

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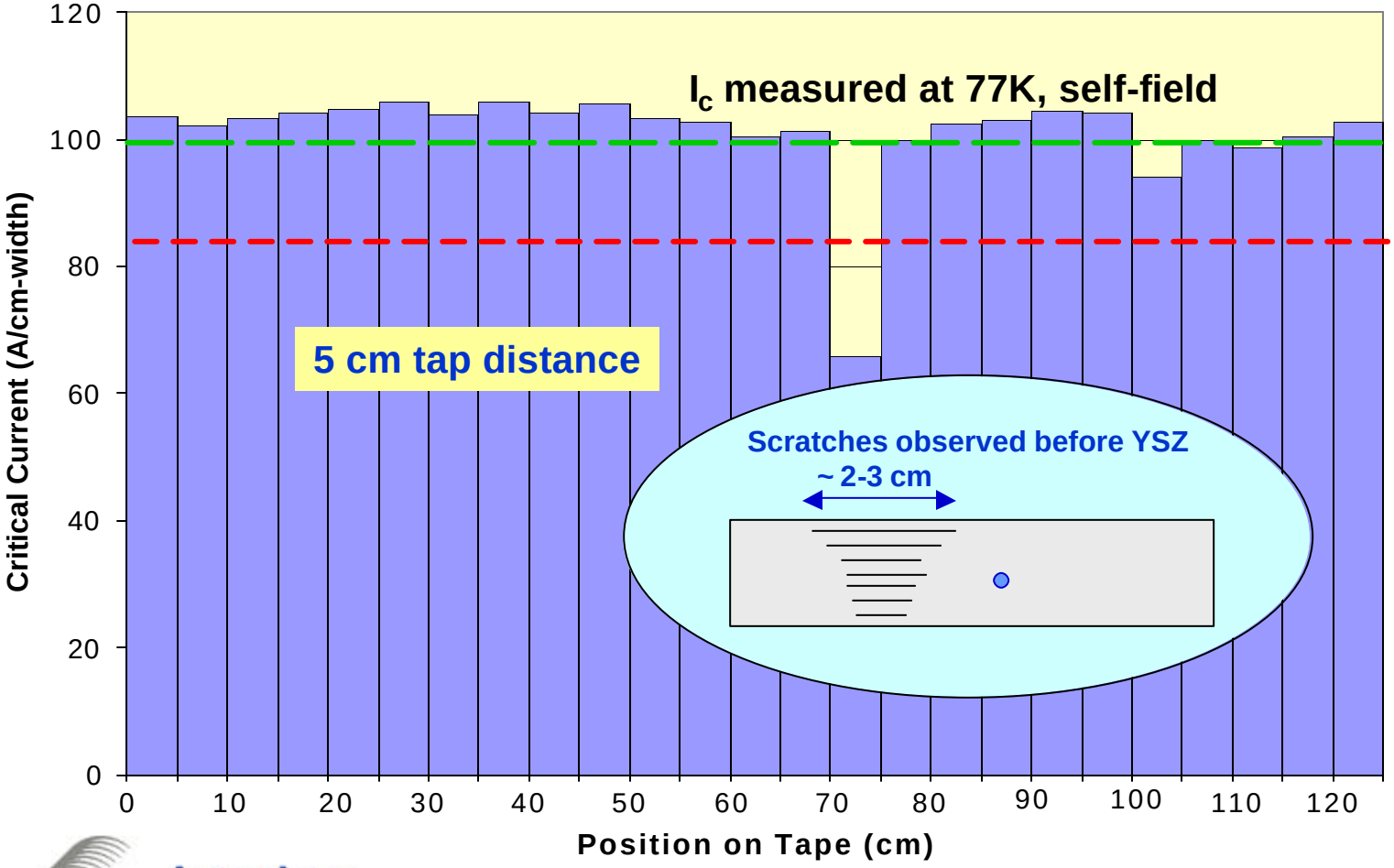
High Critical Current also Obtained with MOD Process on Proprietary non-Magnetic Ni-W-Cr Substrate Jointly Developed by AMSC and ORNL



Average Ic:
101.1 ±7.8 A

End-to-End
Ic: 85.0 A

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Summary

- **Significant transfer of technology from ORNL to AMSC, as well as further developments at AMSC, have produced meter long, conductors with end-to-end critical currents of 118 A/cm-width on NiW substrates.**
- **Excellent performance, uniformity and reproducibility of RABiTS/MOD conductors demonstrate feasibility of low-cost, long length, composite conductors**
- **Joint development between AMSC and ORNL has resulted in the fabrication of strong, non-magnetic (at 77K) Ni-W-Cr alloy RABiTS™ substrates which support critical currents of 100 A/cm-width.**

FY 2002 Plans and Performance

☑ **Development of materials and processes for preparing continuous lengths of deformation textured, alloy substrates.**

- **ORNL and AMSC fabricated Ni and NiW tapes with excellent texture:**
- **% Cube: ~ 100%**
- **In-plane texture = 6-7°**
- **Out-of-plane texture = 4-5°**

FY 2002 Plans and Performance

☑ Development of materials and processes for the continuous deposition of oxide buffer layers on deformation textured Ni substrates.

- **ORNL developed and characterized sulfur superstructure on RABiTS™ alloy substrates to enhance epitaxial texture of RE_2O_3 buffer layers.**
- **ORNL successfully transferred sulfurization knowledge to AMSC.**
- **AMSC fabricated tapes with highly epitaxial oxide layers (Y_2O_3/YSZ/CeO_2) in reel-to-reel process.**

FY 2002 Plans and Performance

☑ Demonstration of texture homogeneity in the metal/alloy substrate, the epitaxial oxide buffer layers and the YBCO layer.

- ORNL characterized NiW alloy substrates with sharp texture (6-7°) that is uniform over length.
- ORNL characterized epitaxial buffer layers (Y_2O_3/YSZ.CeO_2) with uniform texture over length on alloy substrates
- ORNL characterized YBCO films, on buffered alloy substrates, with uniform texture and critical current over length

FY 2002 Plans and Performance (Cont.)

☑ **Demonstration of I_c > 100A/cm width over > 1-meter length of conductor with a Ni-based alloy substrate by reel-to-reel processing at all steps**

- **AMSC demonstrated reproducible fabrication of high-I_c, meter long tapes with I_c > 100 A/cm width over 1-meter lengths, on substrates prepared at both AMSC and ORNL.**
- **ORNL demonstrated high J_c YBCO on alloy tapes buffered at AMSC on ORNL substrate**

FY 2002 Plans and Performance

☑ To fabricate Ni-Cr-W alloy substrates which are mechanically strong, non-magnetic and have good texture. Demonstrate high I_c in meter long tapes.

- Ni-W-Cr substrates jointly developed and fabricated ONRL/AMSC with near 100% cube texture
- ORNL characterized mechanical and magnetic properties of Ni-W-Cr substrates.
- AMSC deposited epitaxial oxide buffer layers over meter length Ni-W-Cr substrates via reel-to-reel process.
- AMSC achieved high critical current on meter length conductors using an MOD process for YBCO deposition.

FY 2003 Plans

- Jointly develop improved alloy substrates in long lengths. Improved substrate characteristics include: sharper texture, higher strength, lower magnetism, and/or surfaces enhancing growth of epitaxial buffer layers.

- Develop methodology to characterize the relation of “texture” and “grain boundaries” and develop an improved metric correlating texture of substrates to YBCO critical current density.

- Joint development of alternate buffer architectures and deposition techniques enabling a simplified structure with reduced fabrication costs.

FY 2003 Plans (continued)

- Develop methodologies to evaluate and characterize the quality of oxide buffer layers via microstructural techniques such as TEM, SIMS, EBSP, SEM, Auger Spectroscopy.

- Evaluate YBCO composite conductors as a form-fit-function substitute for BSCCO multi-filamentary conductors.

Research/Technology Integration

- Very close and active collaboration between AMSC and ORNL
- A *model* DOE CRADA – both transfer of technology from the base program at ORNL, as well as joint developmental activities
- One joint invention disclosure submitted
- Several publications, many co-authored invited talks

RABiTS™/MOD Process Enables Commercial YBCO Composite Conductor Technology

High Performance

Extraordinary Uniformity

Outstanding Reproducibility

All Using a Low Cost Process

DOE/Industry CRADA Success

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