Development of Biaxially Textured YBCO Coated Conductors in the United States

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by

Robert A. Hawsey

Director, Superconductivity Technology Center

Oak Ridge National Laboratory*

P.O. Box 2008, Oak Ridge, Tennessee USA 37831-6195

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Major U.S. Efforts Toward Coated Conductors

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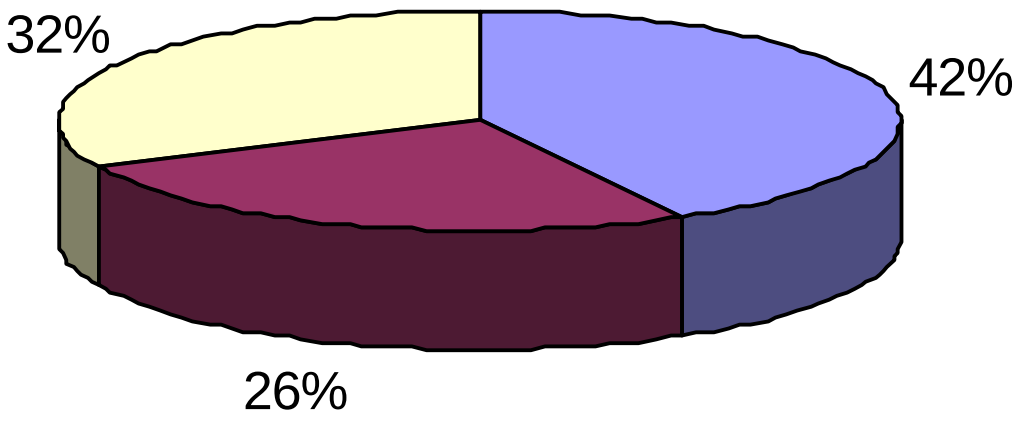
- **Los Alamos National Laboratory**
  - Paul Arendt, Steve Foltyn, Terry Holesinger et al.
- **Argonne National Laboratory**
  - Balu Balachandran
- **U.S. Industry: 3M Company, American Superconductor, MicroCoating Technologies, Oxford Superconducting Technology, EURUS Technologies, Intermagnetics General**
- **University Partners: Stanford University, University of Wisconsin, University of Houston**
- **Other Labs: Brookhaven, NREL, Sandia**

Outline

- Introduction
- National Laboratory Results
  - Film Growth Processes
  - Lengths
  - High Critical Currents
- Process Development and Industrial Partnerships
- Future Trend in the United States
- Conclusion

FY 2000 U.S. Department of Energy Funding Breakdown



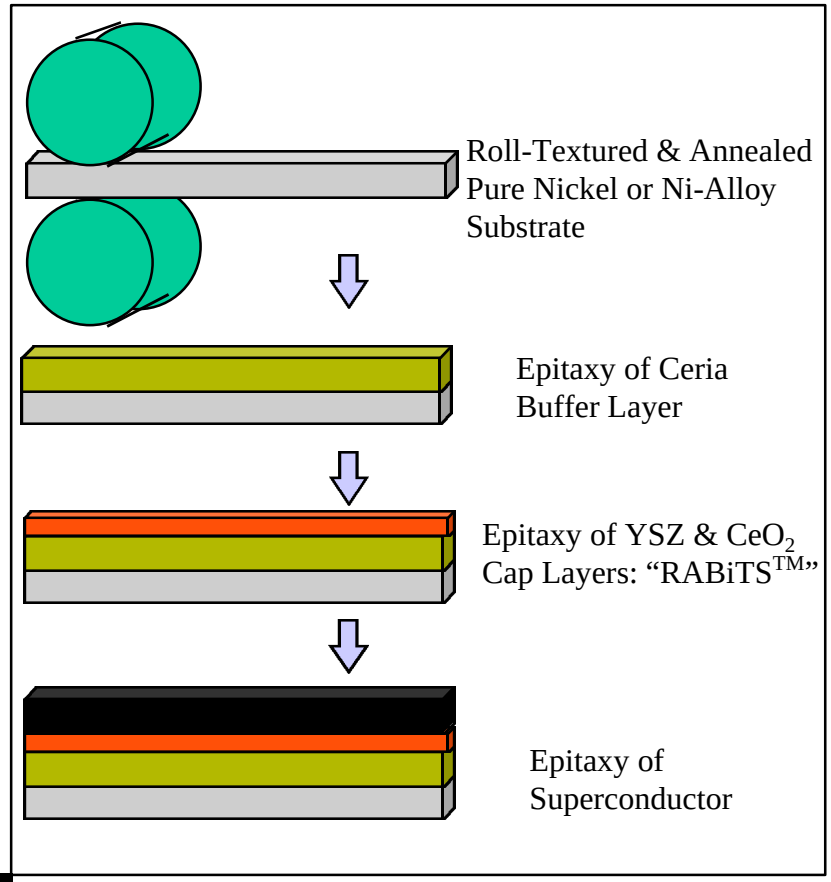
- Superconductivity Partnership Initiative
- Second Generation Wire Initiative
- Strategic Research (primarily CRADAs)

Total Funding: $32 Million*

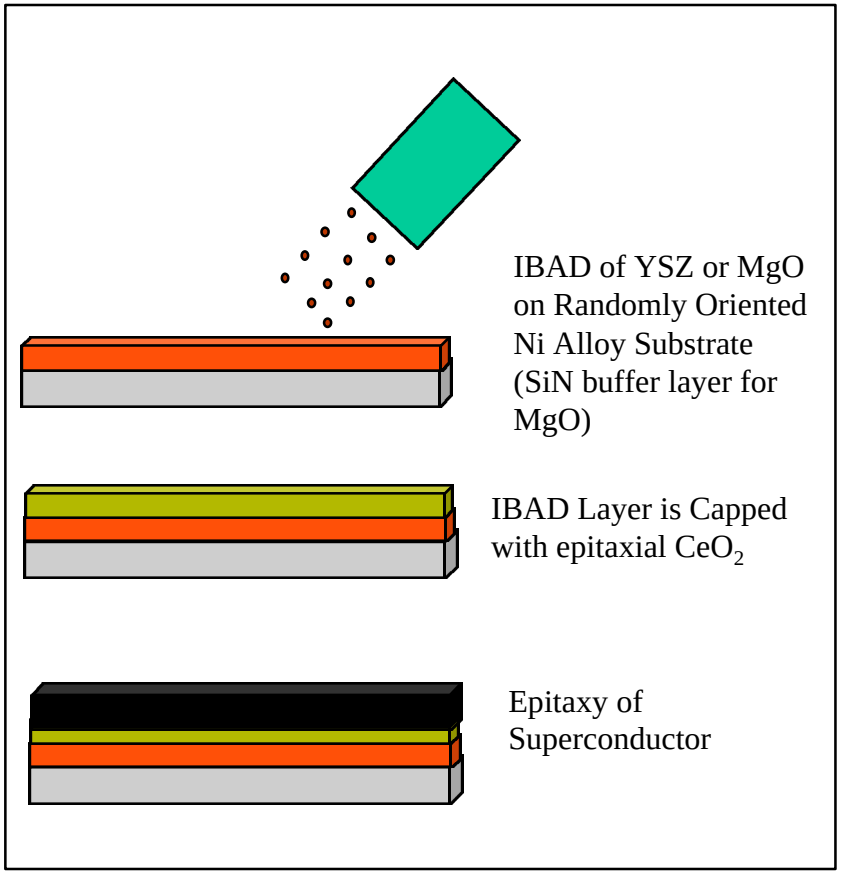
*All funding includes the work performed at U.S. national laboratories and universities/companies funded by DOE

Primary U.S. Routes to Coated Conductors

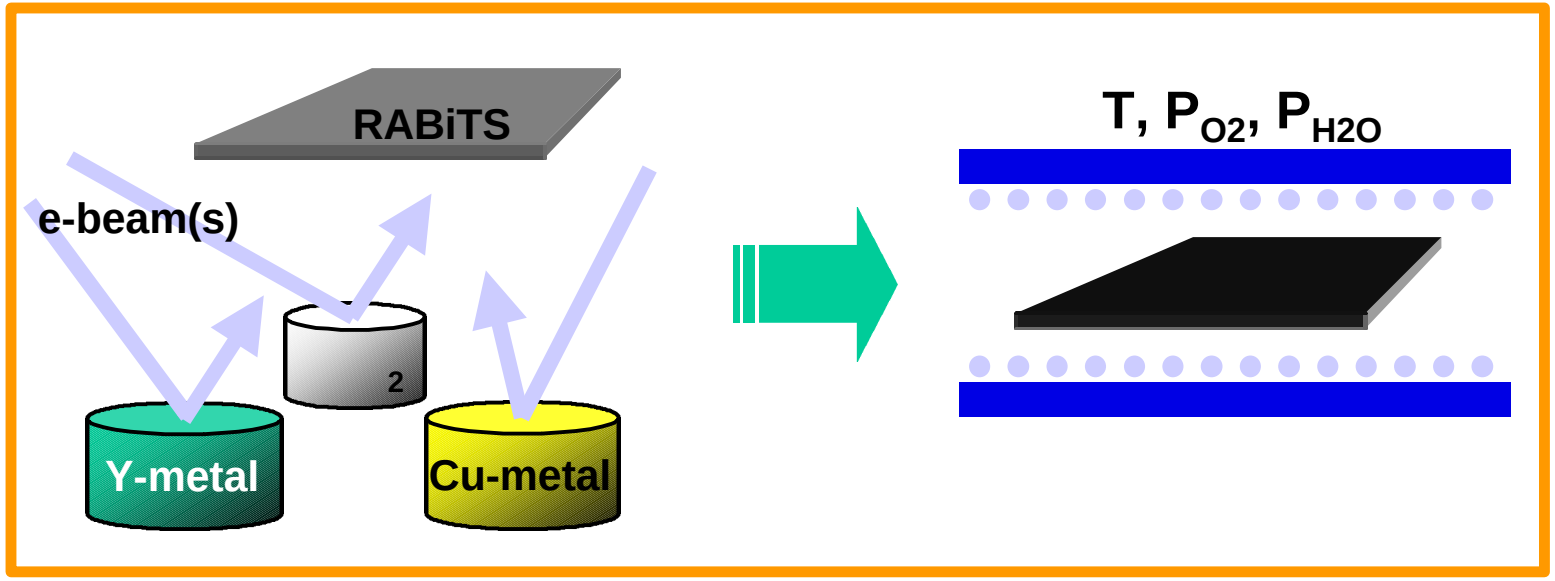
RABiTS (Rolling-Assisted Biaxially Textured Substrates)



IBAD-Ion Beam Assisted Deposition



Ex-situ Formation of YBCO by BaF_2 Precursor Offers Many Advantages



- **Advantages of ex-situ process:**
  - Deposition and formation steps are separated
  - Wider processing window - combination of temp, O_2 and H_2O partial pressures
  - "Adjustment" of precursor stoichiometry possible
  - Batch process. May also be deposited via solution.

The "Ex-Situ" (BaF_2) Method of Forming YBCO on IBAD and RABiTS Templates Has Proven Very Robust

(Standard RABiTS architecture produces consistently high-J_c results.)

CeO_2	0.03 μm
YSZ	1 → 0.25 μm
CeO_2	0.03 μm
Ni	125 → 50 μm

YBCO: 0.3 μm

typical **1.0 –1.7 MA/cm²**

best **2.3 MA/cm²**

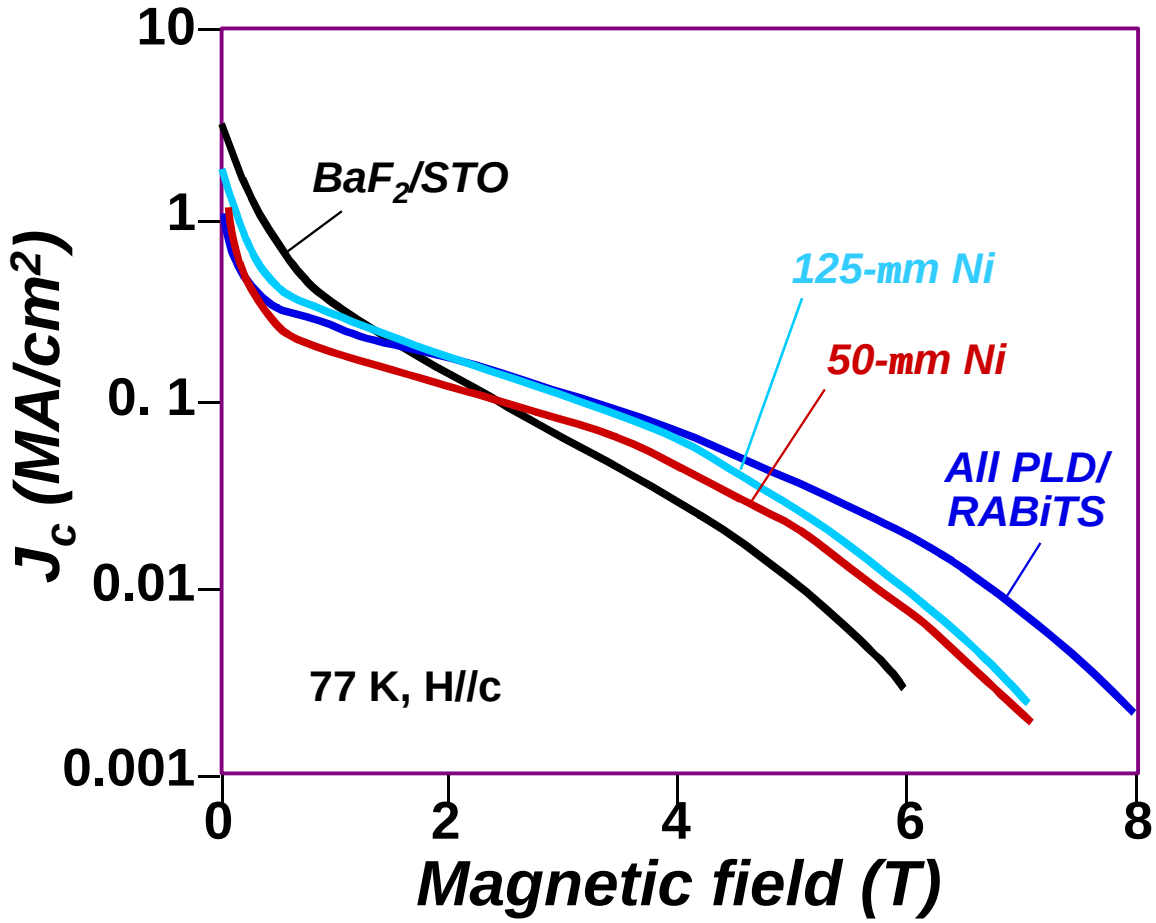
<---

- **thus far, CeO_2 is only compatible contact layer**

  must be of high crystallinity, and smooth and dense to enable reproducible YBCO quality

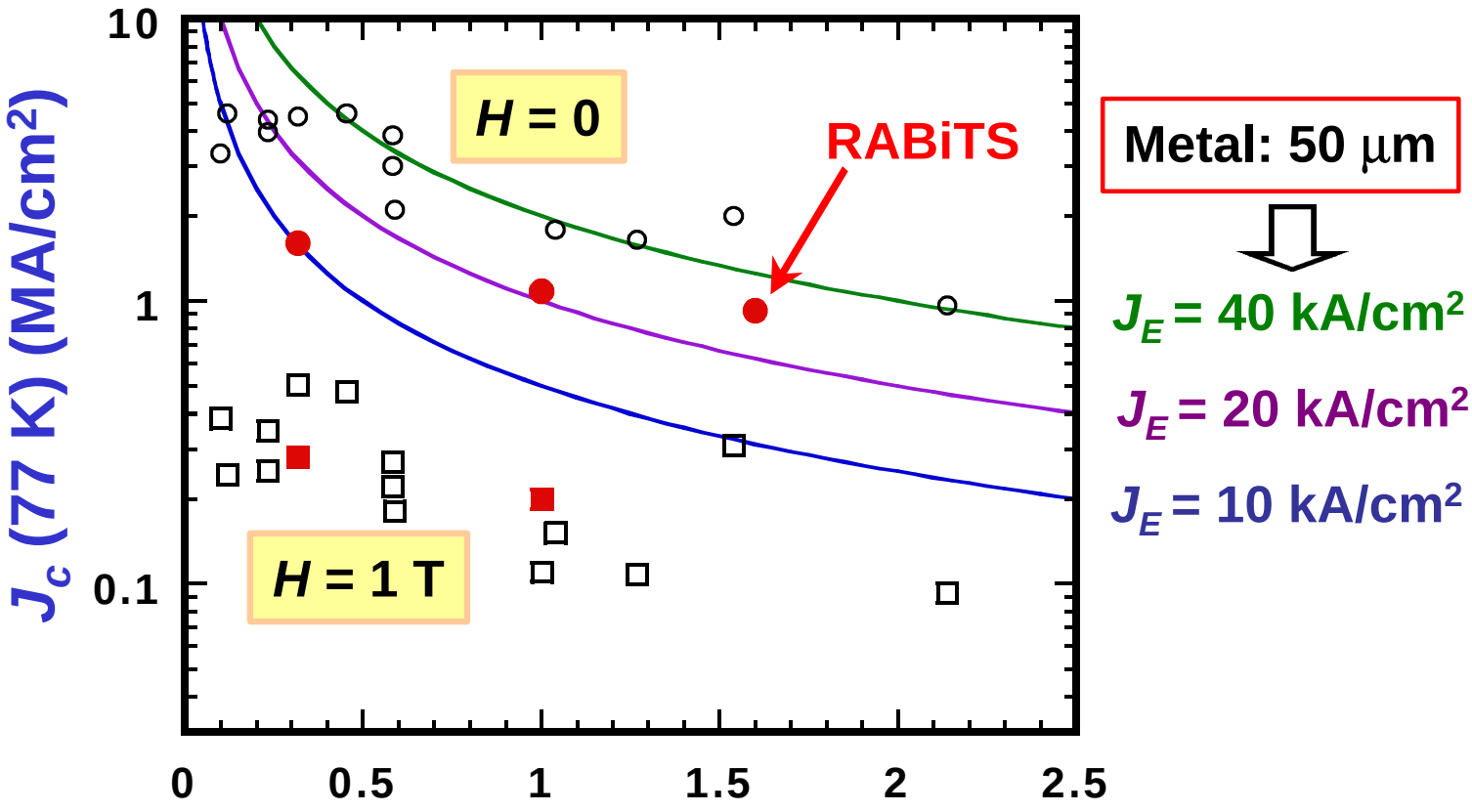
ornl

J_c of YBCO/RABiTS Processed by the BaF_2 Precursor Method is as Good as YBCO by PLD



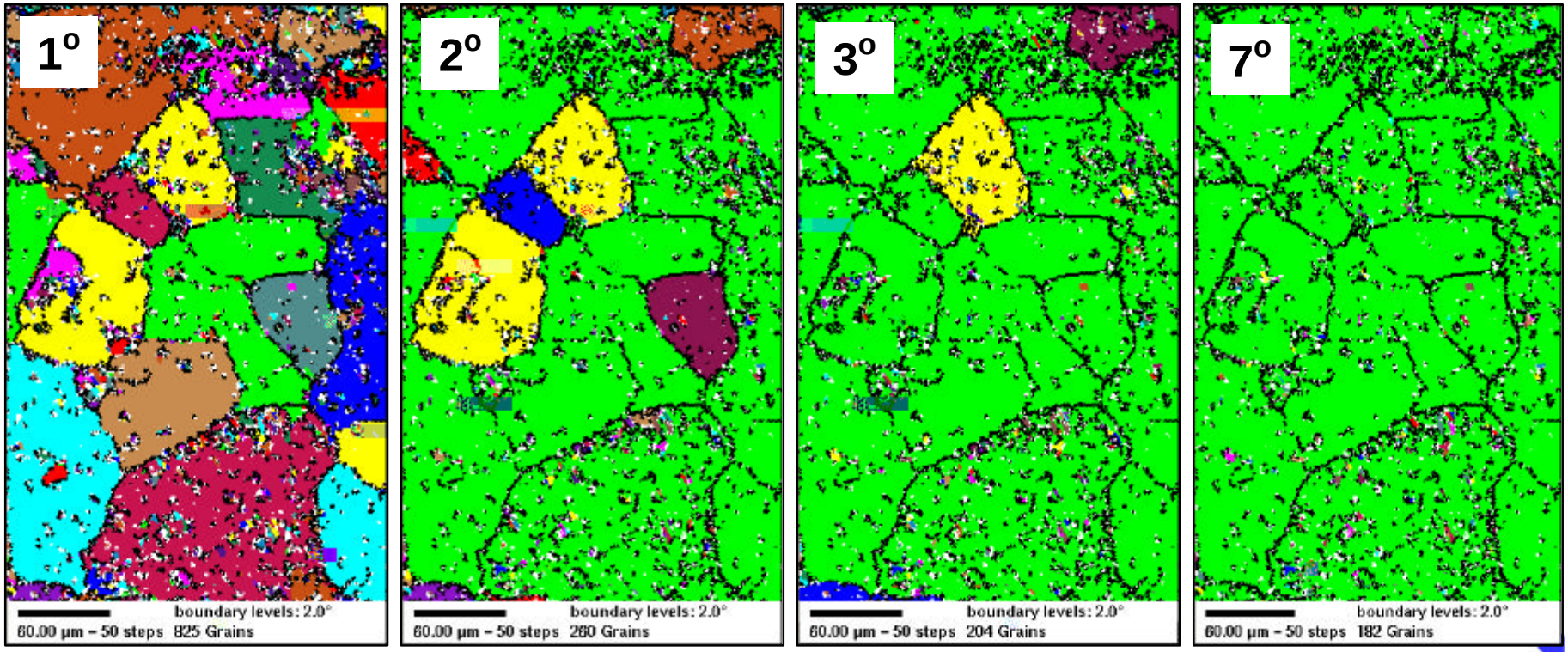
High J_E = 28 kA/cm^2 Has Been Obtained for 1.6-μm YBCO on 50-μm RABiTS (I_c=44 A, 3 mm)

- Strong behavior in magnetic field (H =1 T): J_c >100 kA/cm^2 at 77 K
- Target J_E = 40 kA/cm^2 expected for 2–2.5 μm YBCO coatings

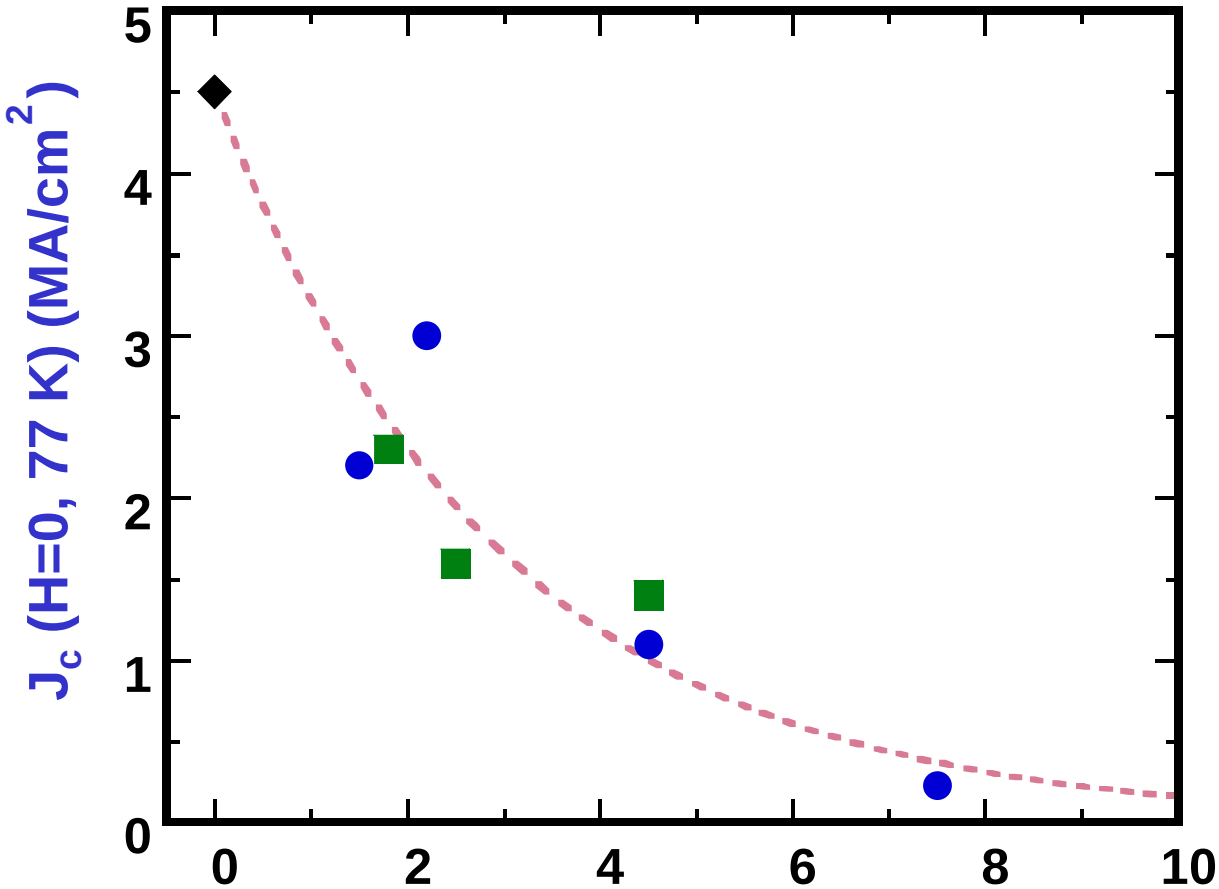


Grain Boundary Map of *Ex-situ* YBCO Film on RABITS (FWHM ≅ 10.8°; J_c=1.6 MA/cm^2)

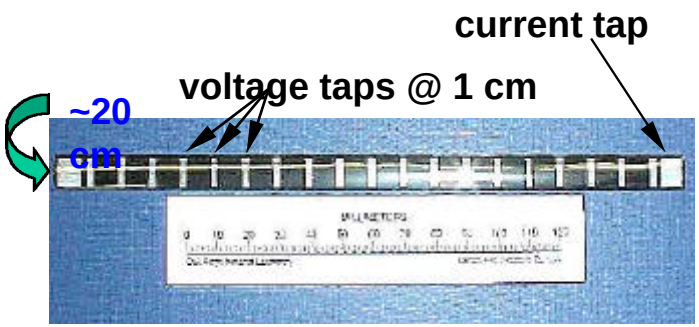
- **Local grain connectivity deviates from statistical distribution**
- ***Bias towards lower GB angles*** → **"J_c threshold" ≅ 2-3°**
- **Pervasive current transport is possible for $J < J_c$**

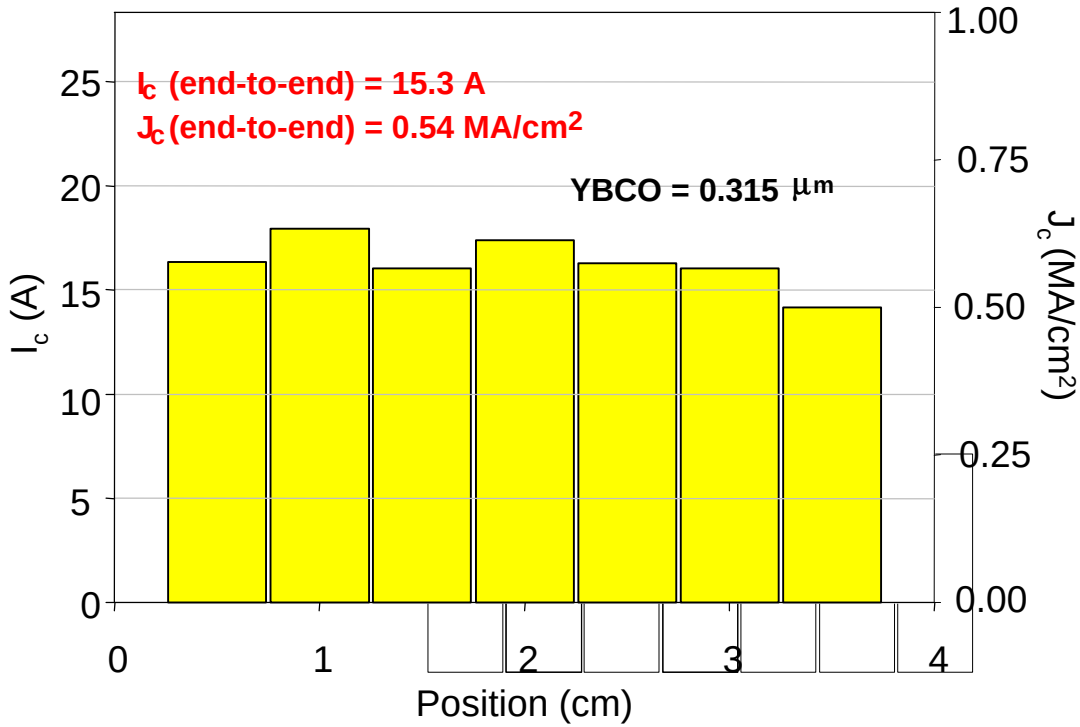


60 µm


J_c (H=0, 77 K) (MA/cm^2)
0
1
2
3
4
5
0
2
4
6
8
10

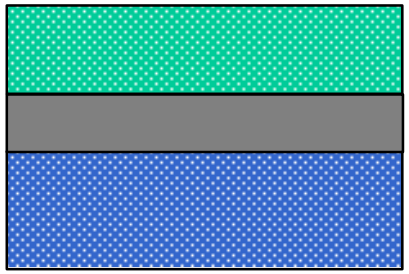
YBCO Conductor Deposited by All-Moving Vapor Deposition and BaF_2 Conversion is Black, Shiny, and Uniform





End-to-End J_c >500,000 A/cm^2 has been Obtained for All-Moving Vapor Deposited RABiTS Tape

Continuously Processed Conductor Geometries at Los Alamos

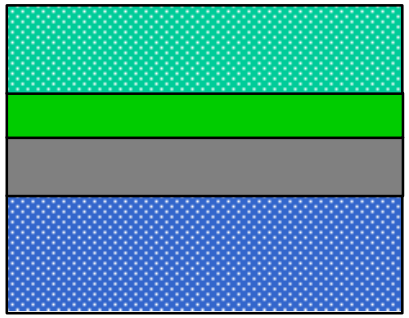


Y-123 1 - 3 µm

IBAD YSZ 0.5 µm

Substrate (Inconel 625)

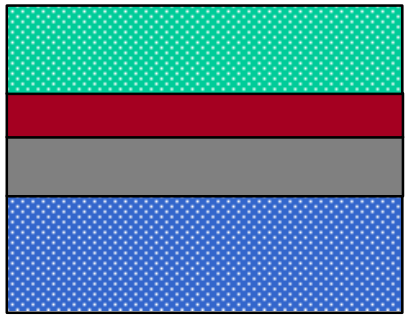
- Y-123 / IBAD YSZ
  J_c ~0.6 MA/cm^2
  I_c's ~ 100 A



Y-123 1 - 3 µm
Y_2O_3 - 30 nm
IBAD YSZ 0.5 µm

Substrate (Inconel 625)

- Y-123 / Y_2O_3 / IBAD YSZ
  J_c ~1 MA/cm^2
  I_c's ~ 120 A



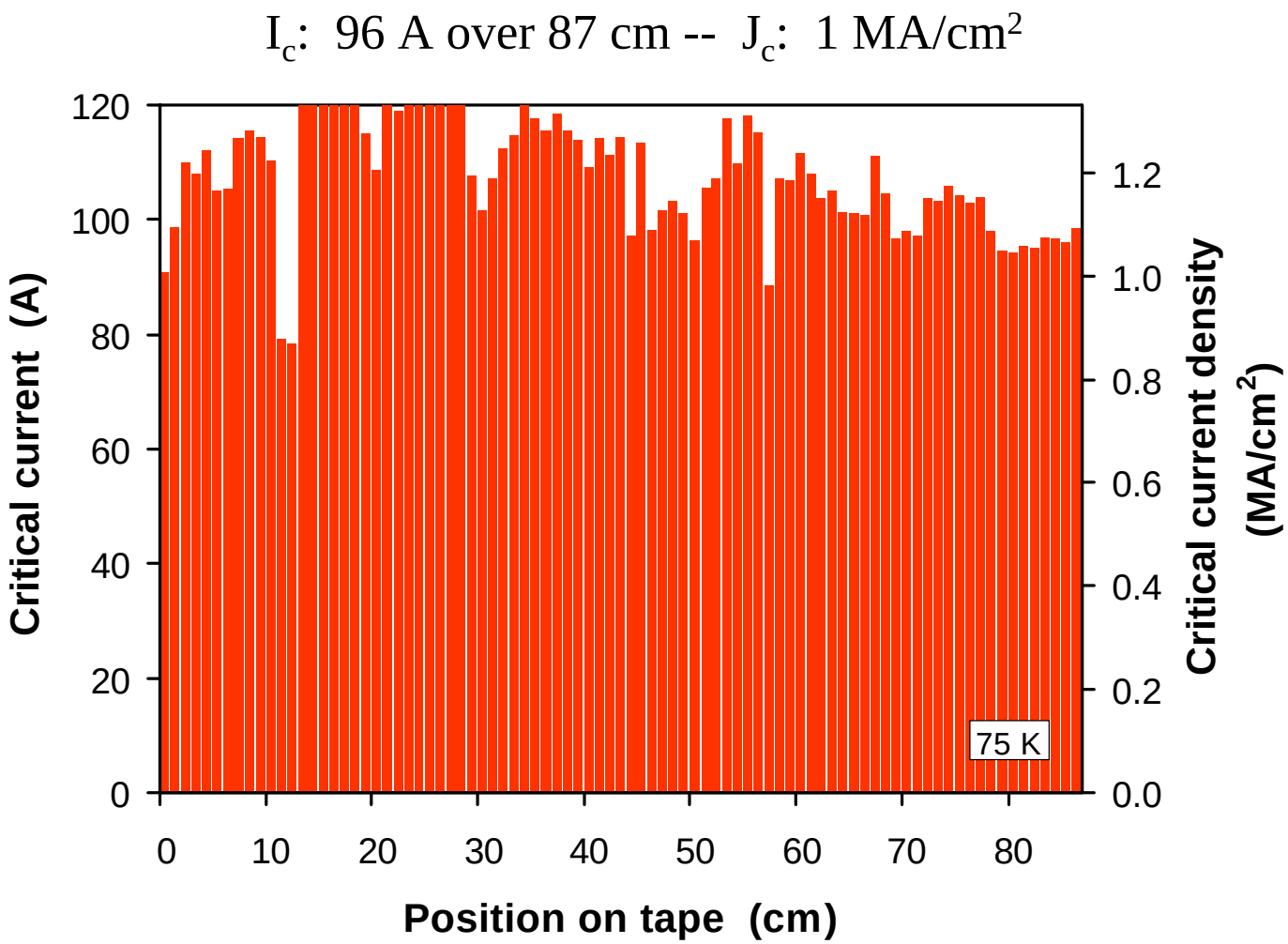
Y-123 1 - 3 µm
CeO_2 - 30 nm
IBAD YSZ 0.5 µm

Substrate (Inconel 625)

- Y-123 / CeO_2 / IBAD YSZ
  J_c ~1 MA/cm^2
  I_c's ~200 A

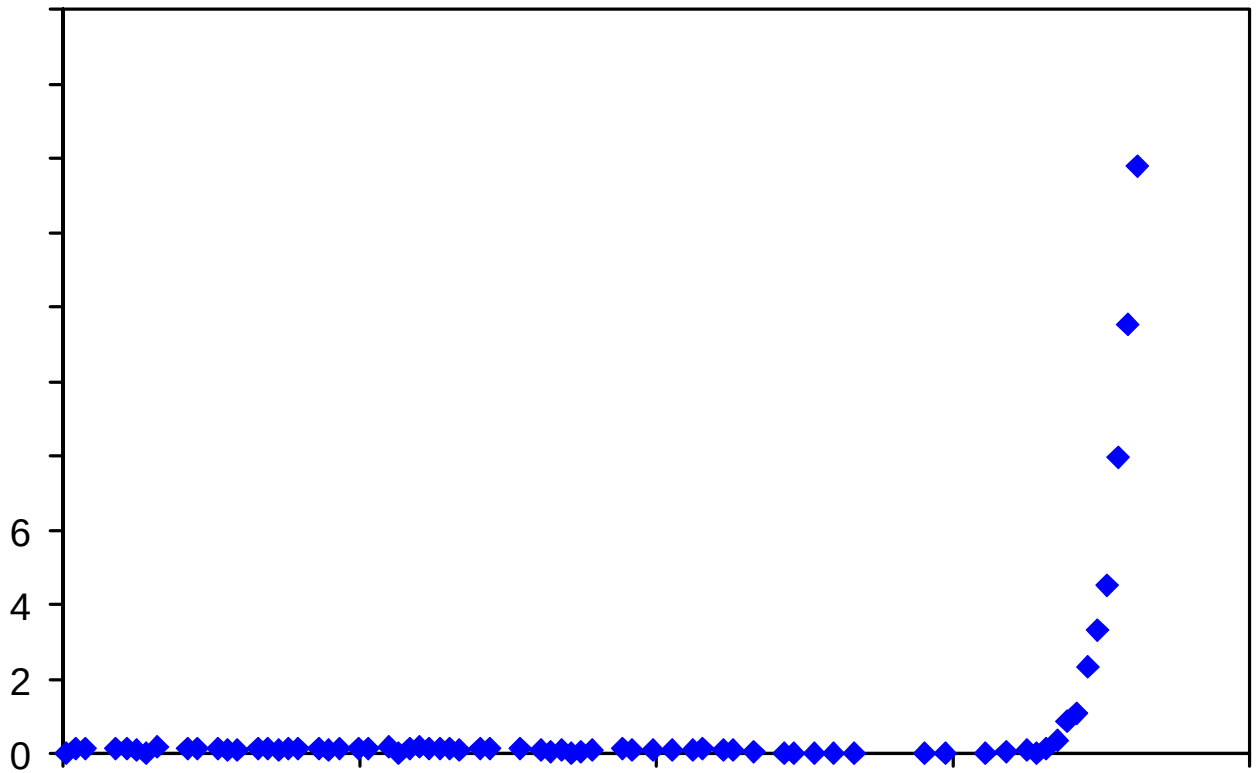
*****YSZ thickness is 0.5 µm**

The Most Uniform Tape Produced in the Past Year Had cm-by-cm Critical Current Variations of ±20%



Los Alamos

A Thinner Substrate was Used to Improve Engineering Current Density



Los Alamos

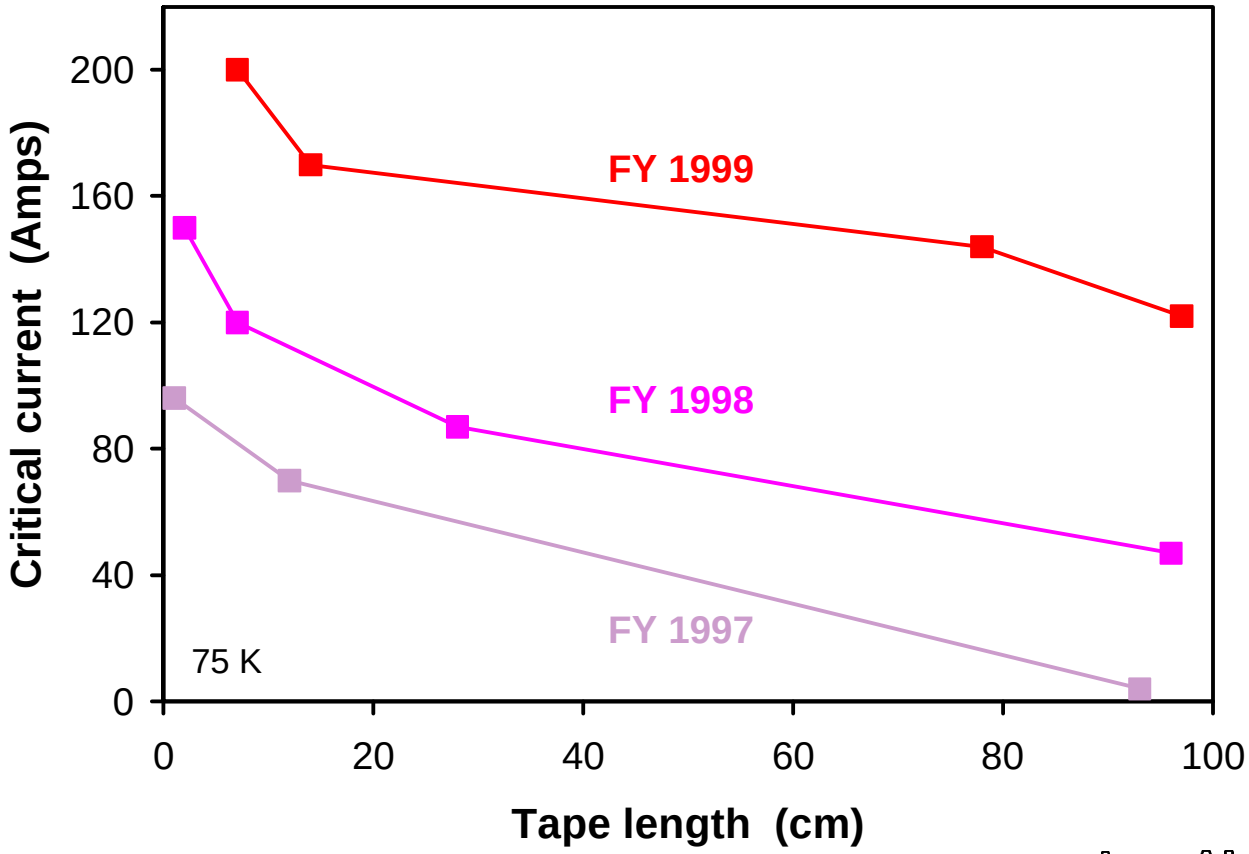
Los Alamos IBAD MgO Template Films: YBCO Texture/Performance Summary

(Short Samples)

Substrate	YBCO Φ FWHM	Jc(75 K,SF)	Thickness
YSZ	2.1°	3.1 MA/cm^2	0.46 μm
Hastelloy C-276	3.6°	3.9 MA/cm^2	0.22 μm
Hastelloy C-276	4.0°	0.86 MA/cm^2	1.0 μm
Hastelloy C-276	6.1°	0.73 MA/cm^2	1.3 μm

Los Alamos Has Made Consistent Progress in Coated Conductor Development

Results for continuously-processed, 1 cm-wide tape



Los Alamos

3M Company Cooperative Program

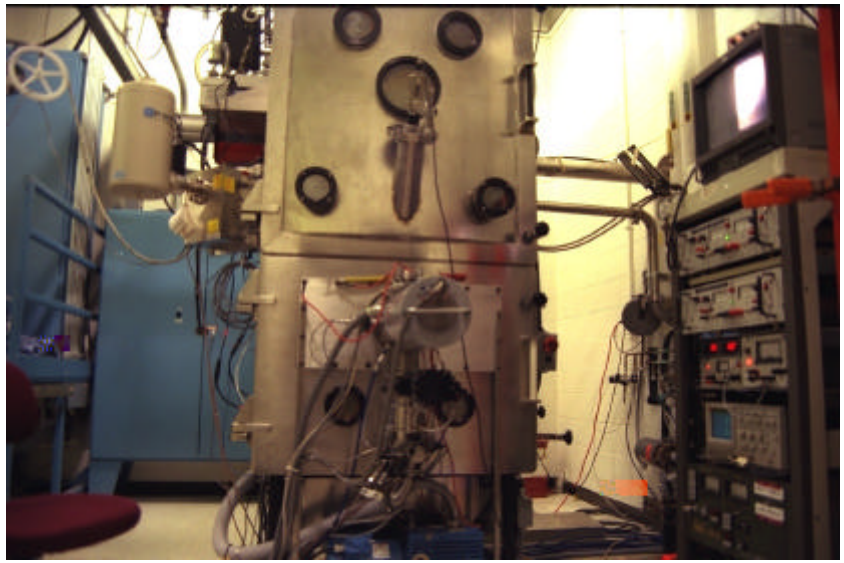
- **RABiTS™ Development => ORNL and 3M**
- **IBAD Development => LANL, DARPA VIP, and 3M**
- **E-Beam Development => 3M and VIP**
- **In-Situ Oxidation => Stanford University and 3M**
- **Ex-Situ (BaF_2) Method => ORNL and 3M**
- **Cable applications => Southwire and 3M**

3M is producing RABiTS

- **3M-Ni, Spool lengths (~300 m) compatible with RABiTS technology**
- **Reactive Sputter Deposition of Buffer Layers (high rate)**
  - **Dep. (001) CeO_2 onto 3M-Ni, 10-m long.**
  - **Stack completed at ORNL w/ (001) texture => J_c ~600 KA/cm^2, short samples**

3M E-Beam System

- **Evaporate 3 materials: Y, Ba or BaF_2, Cu**
- **30 KW, differentially pumped E-gun**
- **Tape transport system capacity = 3.8 cm x 100-m**

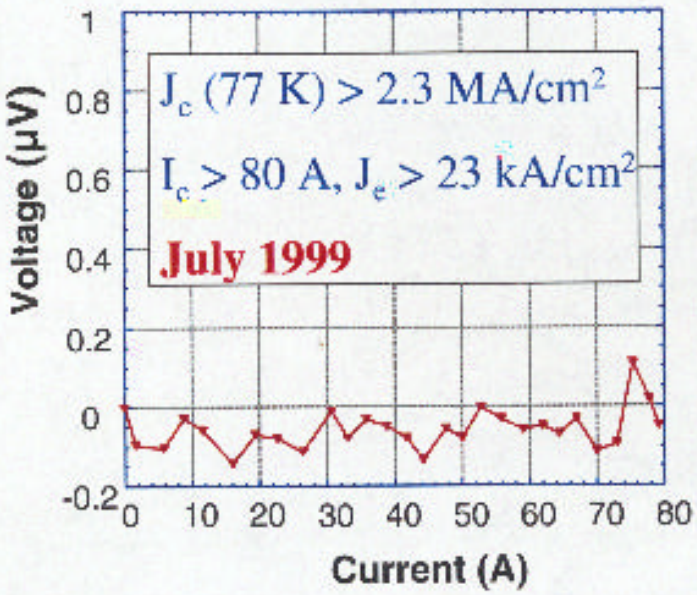


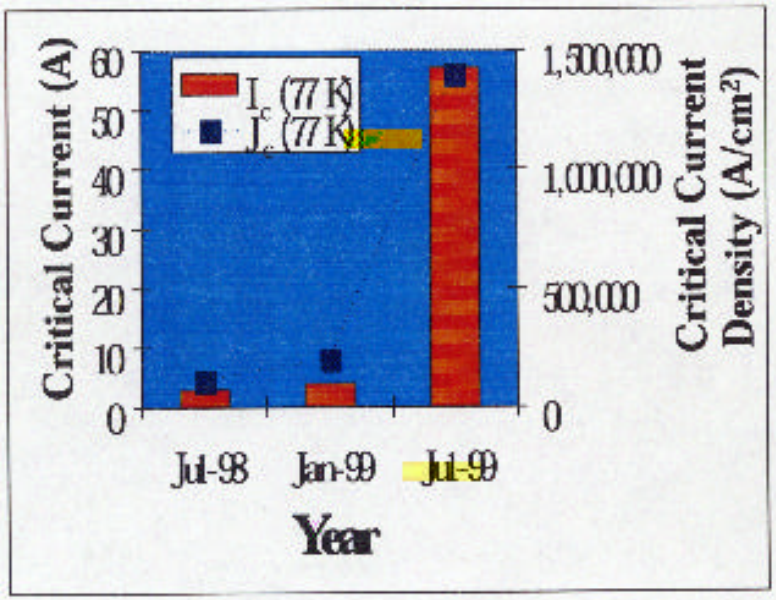
3M BaF_2 Precursor Films

LANL IBAD YSZ, 25-cm long

- **Converted and tested at ORNL, 4-each 10-cm. segments**
- **J_c varied, expectedly, with XRD texture**
- **J_c varied between 160 - 520 KA/cm^2**

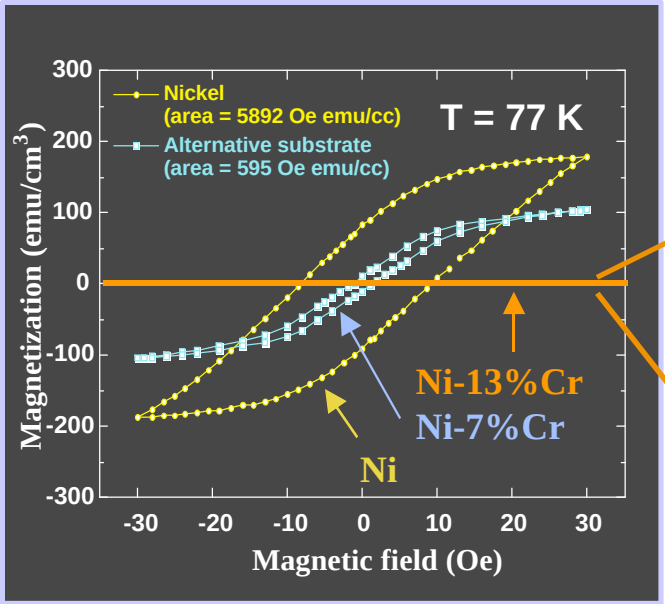
Progress in IBAD-MOCVD-based YBCO Conductor Development



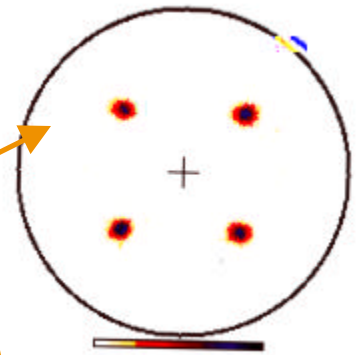


Obtained high critical current on IBAD substrates (including those provided by LANL)

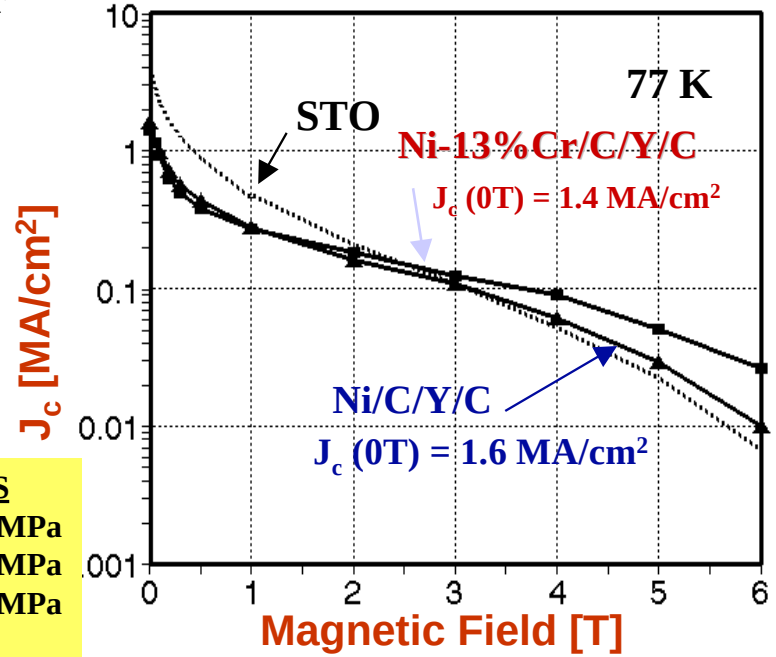
Non-Magnetic, Strengthened Substrate Development at ORNL



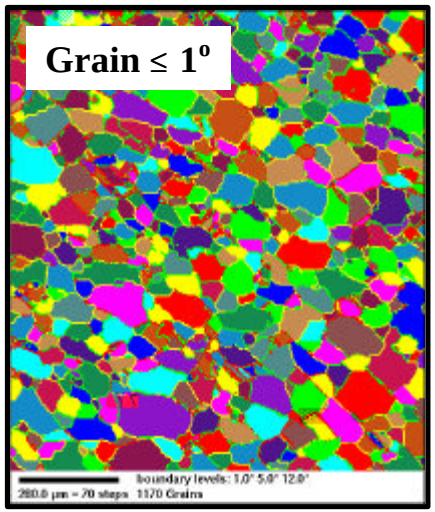
Log scale Ni-13%Cr (111) pole figure

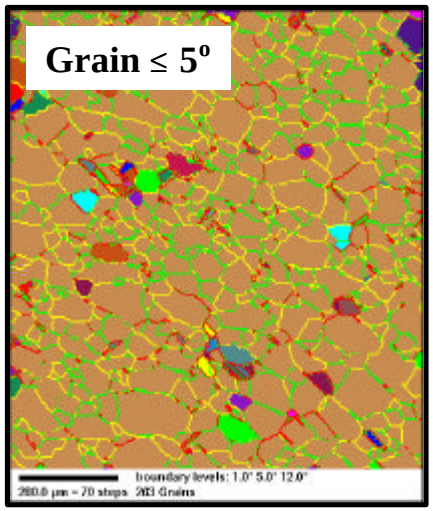


Substrate	YS (0.2%)	UTS
Ni	34 MPa	221 MPa
Ni-13%Cr	164 MPa	525 MPa
Ni-13%Cr -4%Al	228 MPa	657 MPa



Grain orientations in Ni-13%Cr Substrate

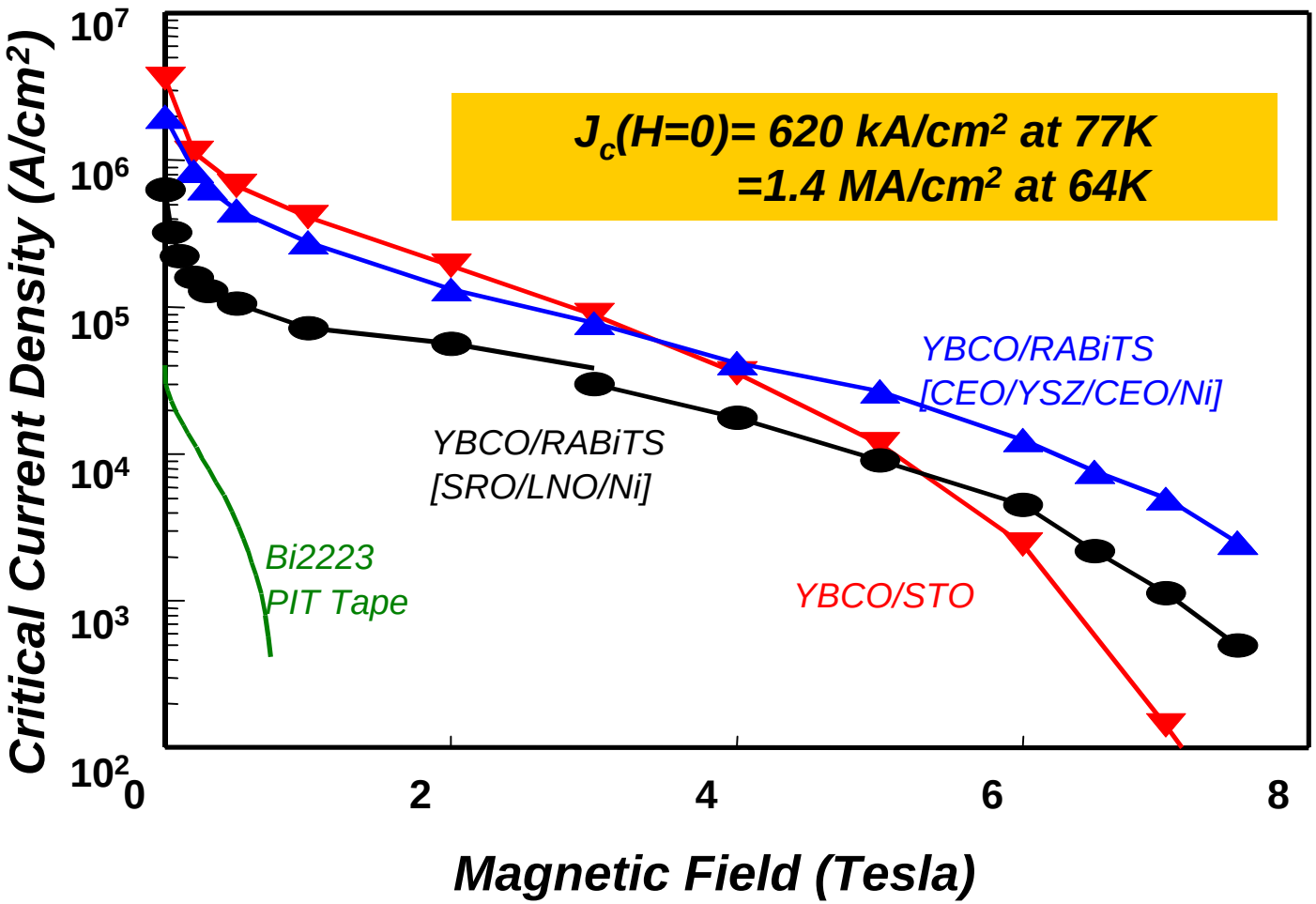




Summary

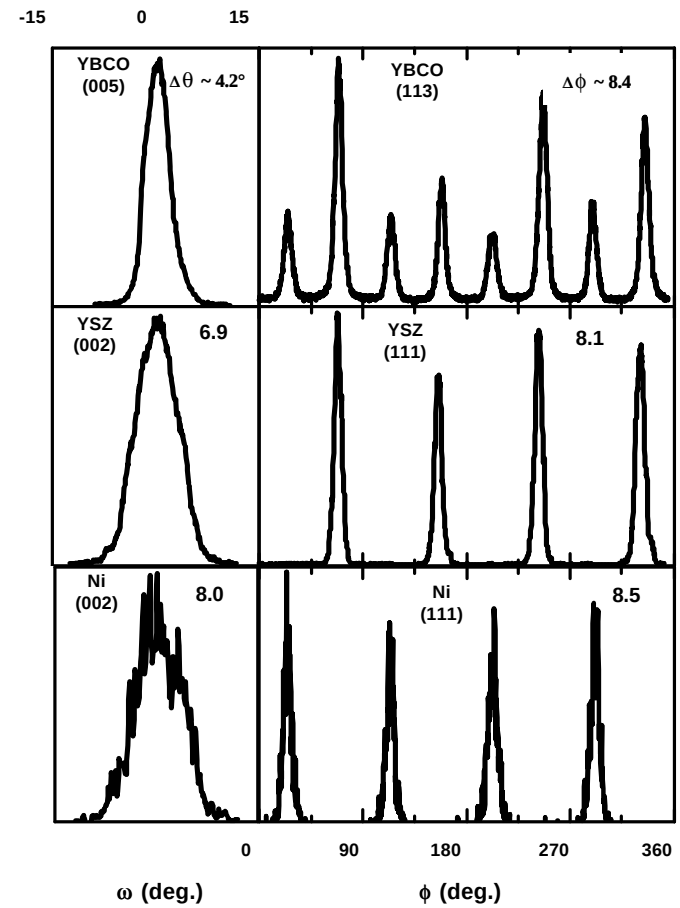
- J_c's over 1 MA/cm² on Ni-13%Cr.
- Other binary alloys - Ni-Cr, Ni-V, Ni-W, Ni-Cu, Ni-Mo and their ternary alloys with Al, Mg, etc. have also been investigated.

High-J_c was Obtained for YBCO (PLD) on $SrRuO_3$ (PLD) /$LaNiO_3$ (Sputtering)/Ni



High-J_c YBCO Has Been Made on YSZ/Ni

- Fully epitaxial YBCO/YSZ/Ni structure has been realized.
- J_c (77 K) > 0.5 MA/cm^2 for YBCO/YSZ/Ni structure
  - Some 45° rotated YBCO grains yield depressed J_c.
  - CeO_2 cap layer yields one in-plane variant.



U.S. Air Force Research Laboratory Coated Conductor Research

- **1.2-MA/cm^2 on Ni/CeO_2/YSZ/CeO_2/YBCO**
- **All layers deposited by PLD at AFRL**
- **Ni provided by EURUS Technologies, Inc.**

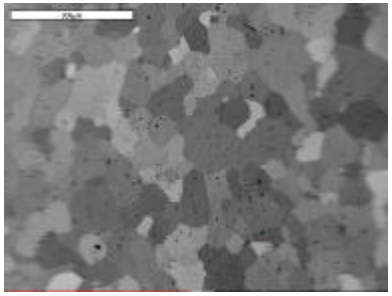
Private Companies to Scale Up YBCO Coated Conductors in U.S.

Company	YBCO Deposition Approach	Substrate
3M	Reactive co-evaporation (in-situ and ex-situ processes)	IBAD, RABiTS
Oxford Superconducting	PLD (research)	RABiTS
MicroCoating Tech.	CCVD (open atmosphere CVD), also sol-gel*	RABiTS
EURUS Technologies	sol-gel*, others	RABiTS
American Superconductor	sol-gel TFA*	RABiTS
Intermagnetics General	PLD, MOCVD	IBAD

******ex-situ* **YBCO formation using post-anneal**

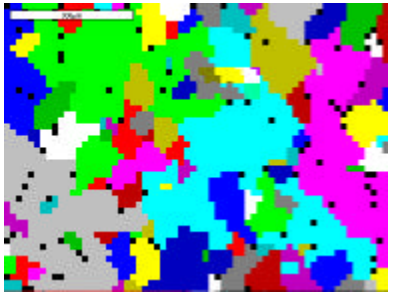
National laboratories will conduct continuous processing research at <10-m lengths in 2000

OST Pure Ni Substrate

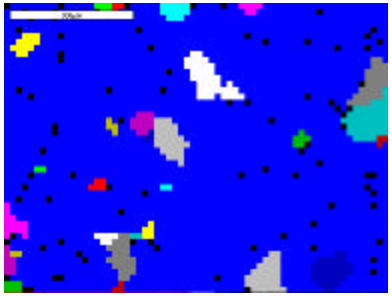


Electron image

Grains: 3º boundaries



Grains: 5º boundaries



Grains: 7º boundaries
(nearly full connectivity)

300 microns

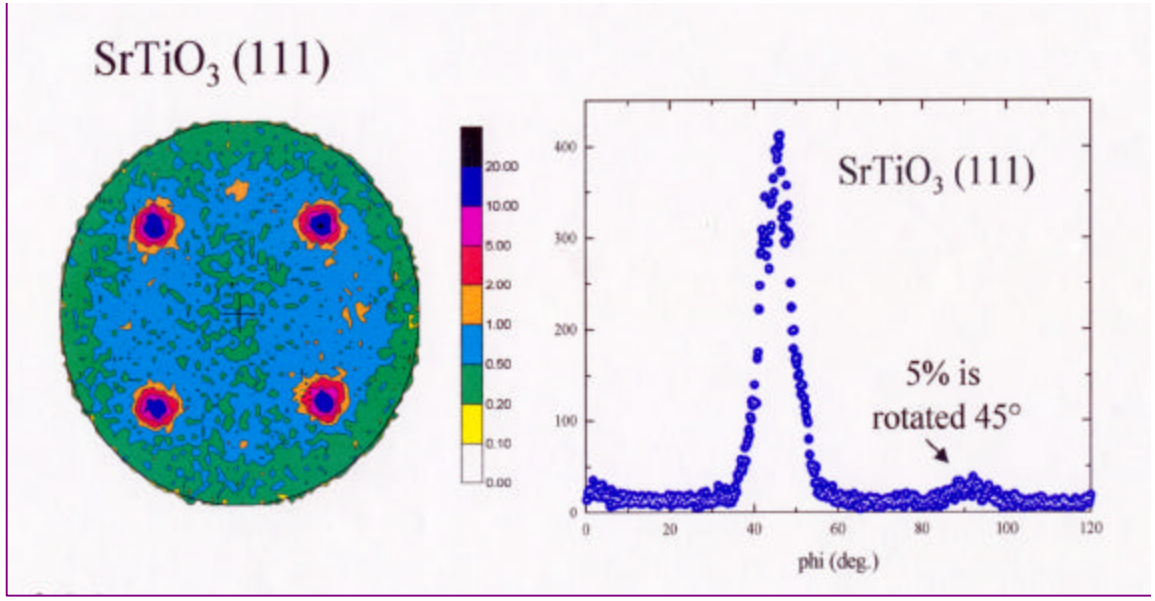
High J_c in BNL Coating on OST Substrate

- OST pure textured nickel (ORNL CRADA)
- Oxford Instruments PLD buffer layers
- BNL BaF_2 YBCO layer, 2-μm thick

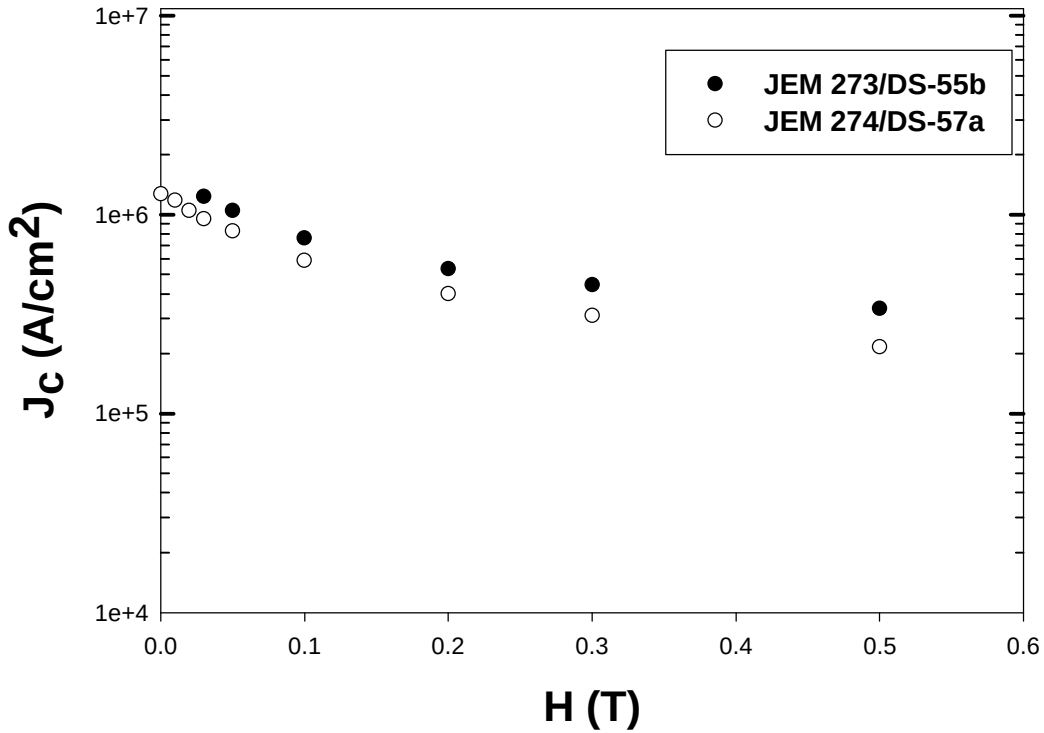
- J_c(77K, sf) = 0.86 MA/cm^2
- I_c(77K, sf) = 52 A
- J_c(77K, $1T_{perp}$.) = 0.17 MA/cm^2

OXFR

Near-Single Oriented CCVD $SrTiO_3$ Buffer on Textured-Ni Substrate

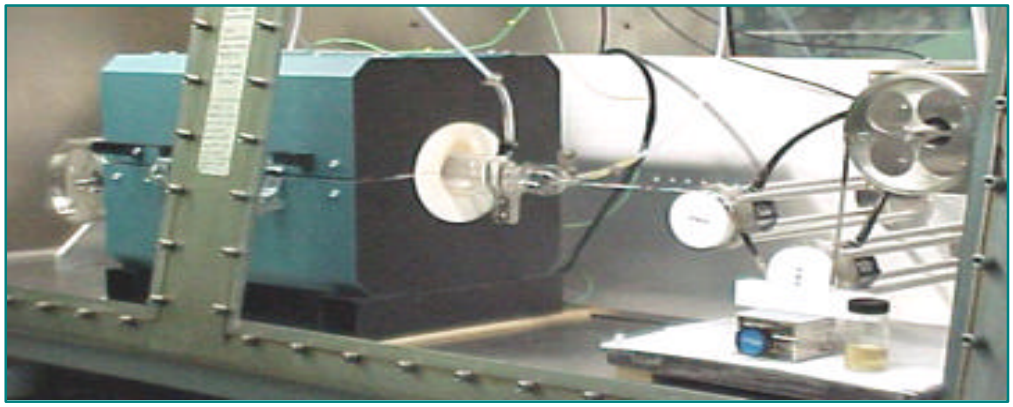


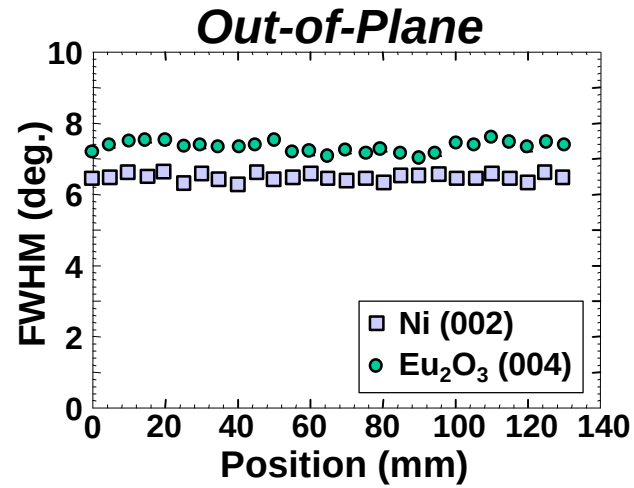
High J_c YBCO Film o CCVD-STO Buffered LAO Single Crystal Substrates Using PLD



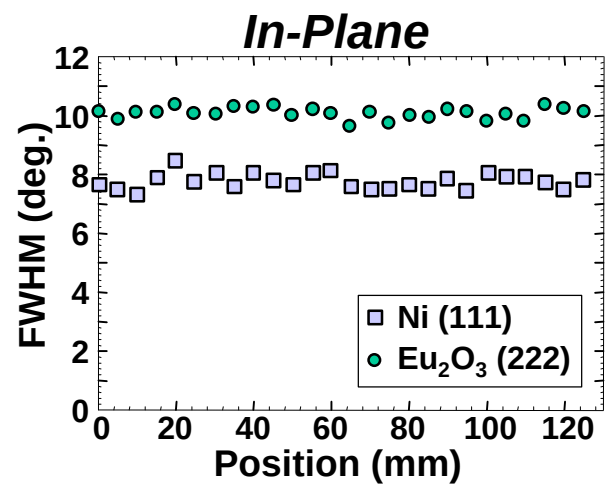
ORNL/MCT

Reel-to-Reel Continuous Dip-Coating Unit for Producing Long Lengths of Sol-Gel Buffered Ni Substrates at Laboratory Scale





Tape speed 3 m/h
Ar/H_2 4% flow
Double side coated
Almost 100% yield



$YBCO/CeO_2/YSZ/Eu_2O_3$(sol-gel)/Ni:

J_c(0T, 77K) = 1.1 MA/cm^2 .

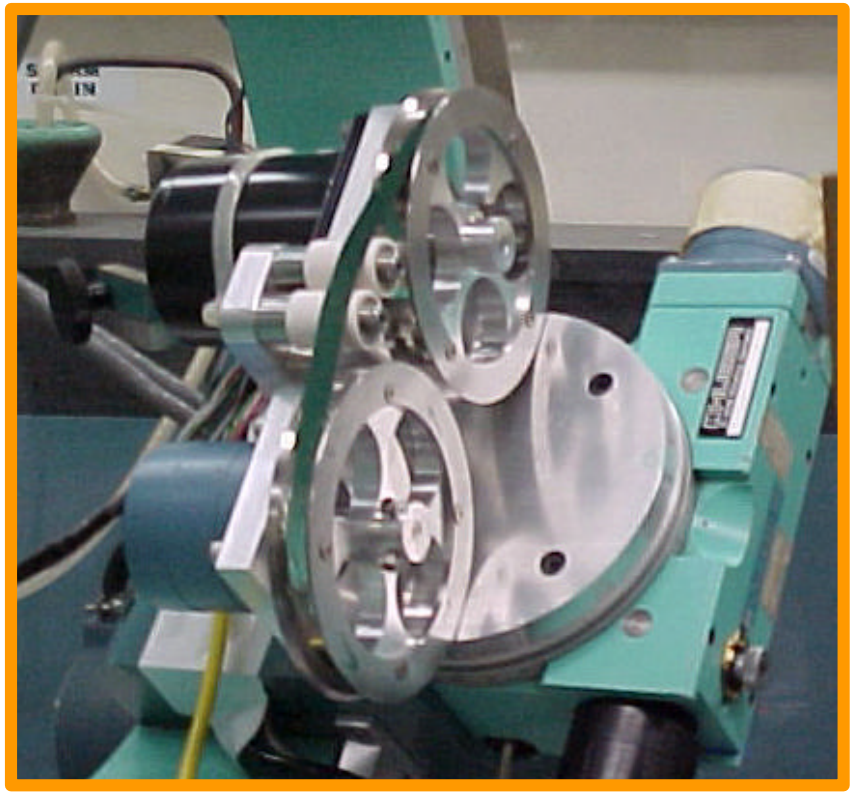
Completely *nonvacuum* process; 3-m lengths RABiTS

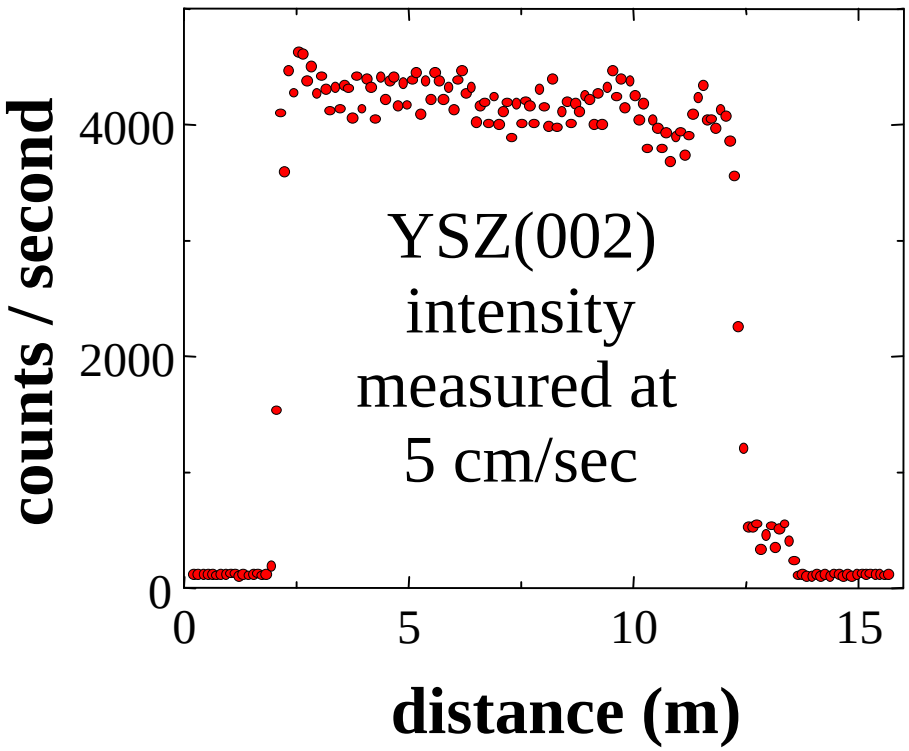
ASC/ORNL Collaborate on Low Cost Solution Processes for YBCO Conductors

- **Buffer Layer Development**
  - RE_2O_3 buffer layers deposited by a sol-gel process on meter length Ni substrates using a continuous slot die coating line
  - Gd_2O_3 texture/thickness is uniform over length and width of coating

- **YBCO Development on RABiTS™**
  - YBCO deposited by solution process using metal trifluoroacetate precursor
  - J_c > 800,000 A/cm^2 (77K, sf) achieved on 0.4-μm-thick YBCO film on ORNL RABiTS™ substrate (2-cm sample)
  - YBCO films show excellent texture and phase purity

Reel-to-reel continuous x-ray texture measurement is a prototype for on-line monitoring of deposited layers





Projected Timeline for Coated Conductor Scale-up in USA

Pre-commercial Scale-up Phase - US Industry	Year	Estimated Budget ($M) per year for each Phase		
	99 00 01 02 03 04 05 06 07 08	Commercial	Federal	Total
I Continuous Processing Feasibility & 1-m lengths		8.0	8.0	16.0
II 10-m piece lengths with lab-scale demonstration		12.0	12.0	24.0
III 100-m piece lengths and field tests using YBCO conductor in SPI		TBD	TBD	TBD
IV Pre-commercial production		TBD	0	TBD

US Government and industry research is expected to cost $16 million in 2000.

Conclusion

- **Consistent progress in increasing critical current of 1-m coated conductors in U.S. New materials and methods are being researched at the national laboratories.**
- **Industrially scalable *ex-situ* deposition of YBCO (by e-beam or wet chemical methods) on IBAD or RABiTS yields high J_c.**
- **Five processes for deposition of buffer layers and YBCO on nickel tapes are being developed.**
- **6 U.S. companies are researching scale-up of coated conductors to 10's of meters by 2001 and 100's of meters by 2002.**