STRATEGIC RESEARCH FOR COATED CONDUCTORS

OAK RIDGE NATIONAL LABORATORY

Chemical and Analytical Sciences Division

T. Aytug, D. B. Beach, M. Paranthaman, S. Sathyamurthy

Metals and Ceramics Division

S. Cook, A. Goyal, L. Heatherly, B. W. Kang, M. Kowalewski,
D. M. Kroeger, D. F. Lee, K. Leonard, F. A. List, P. M. Martin,
N. Rutter, E. D. Specht, R. K. Williams

Solid State Division

J. Budai, D. K. Christen, C. Cantoni, R. Feenstra, H. R. Kerchner, J. Thompson

- **FY 2001 EE/RE Funding: $1,900K:** 6 FTE Staff, 5.0 FTE Post-Doctoral Fellows
- **FY 2001 BES Funding: $350K**: 1.5 FTE Staff

Partnerships:

University Collaborators

- Universitat Augsburg: J. Mannhart, G. Hammerl
- University of Wisconsin: D. C. Larbalestier, S. E. Babcock, M. Feldman
- Stanford University: R. H. Hammond
- University of Florida: D. P. Norton

National Laboratory Collaborators

- National Institute of Standards & Technology:
  J. Ekin, N. Cheggour (Boulder); W. Wong-Ng (Gaithersburg)
- Sandia National Laboratory: M. Siegal, P. Clem
- Los Alamos National Laboratory: P. Arendt, S. Foltyn
- NHFML: Y. Hascicek

Industrial Licensees/Partners

- American Superconductor, 3M, Oxford, Microcoating Technologies, Neocera

GOAL: **To develop a basic understanding of strategic issues related to coated conductor development for high-temperature and high-field applications.**

APPROACH: **Address issues related to each of the three important steps of the RABiTS™ process - biaxially textured metal fabrication, buffer layer deposition and superconductor deposition.**

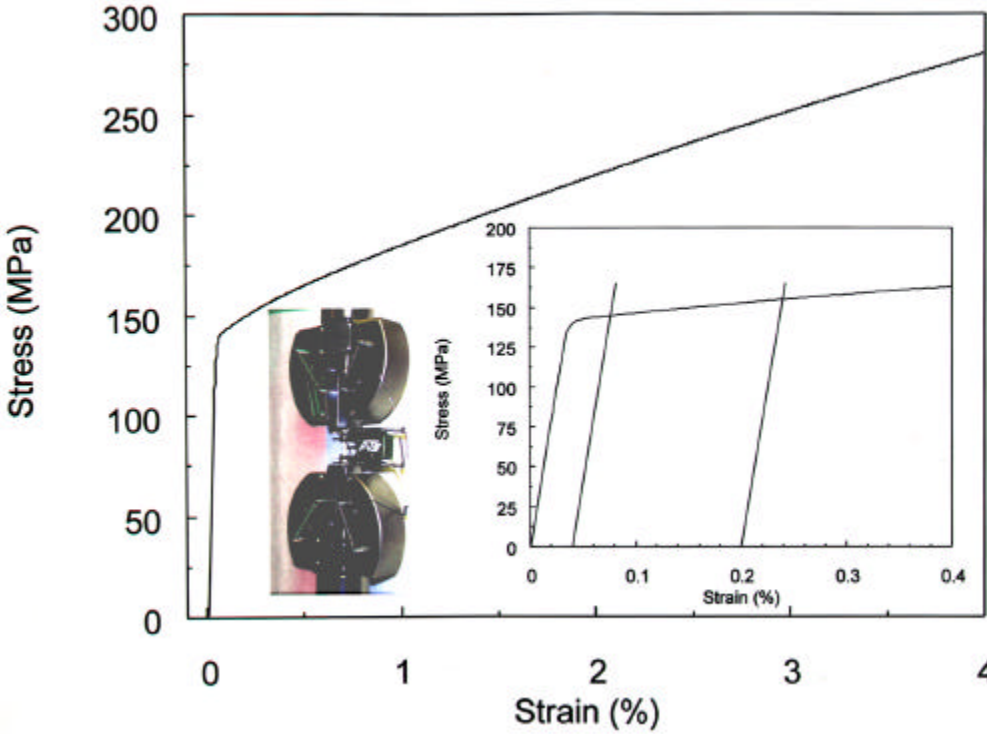
OUTLINE

- **FY 2001 Results:**
  - **Substrate issues and grain boundary effects on J_c (Amit Goyal)**
    - **Development of strengthened substrate with similar surface characteristics as Ni. Development of Ni-W alloys.**
    - **Progress in Ni-Cr alloys: texturing, GB's and buffer layer deposition**
    - **How full is the glass for enhancements in J_c?**
    - **Ca-doping of YBCO on RABiTS**
  - **Dip-coating of solution buffers (M. Paranthaman)**
  - **Processing for improved I_c in YBCO Coatings (R. Feenstra)**
  - **Stabilization of YBCO on metals (D. Christen)**
- **FY 2001 Performance and Plans for FY 2002**
- **Research Integration**

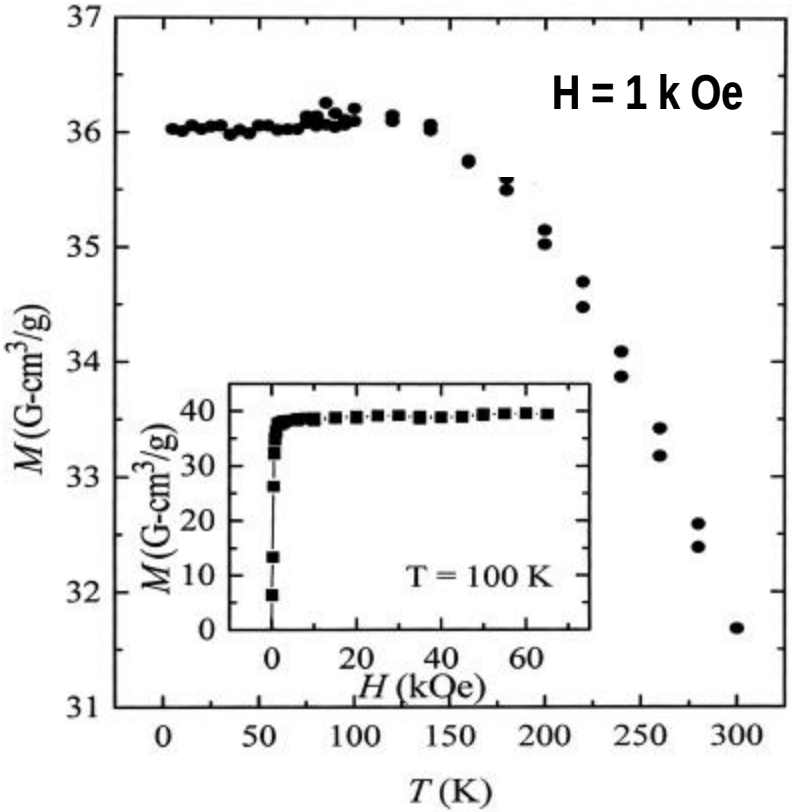
Strengthened Ni Substrate

Composition: Ni-3at%W-1.7at%Fe

Yield stress: ~ 150 MPa

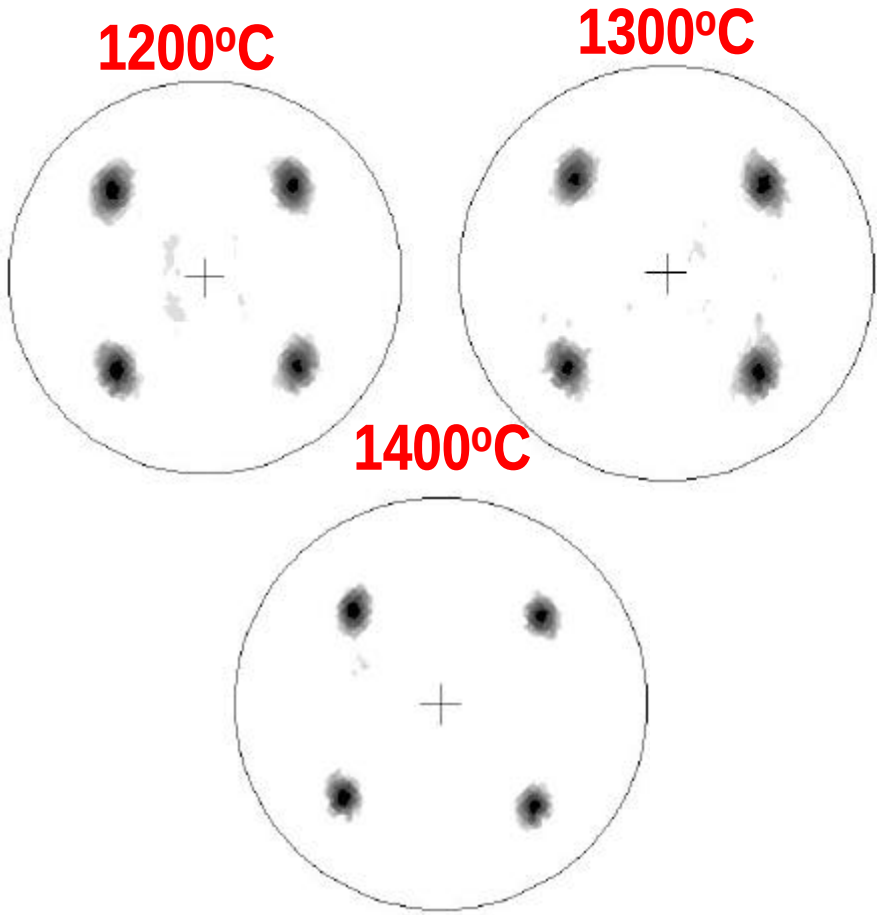


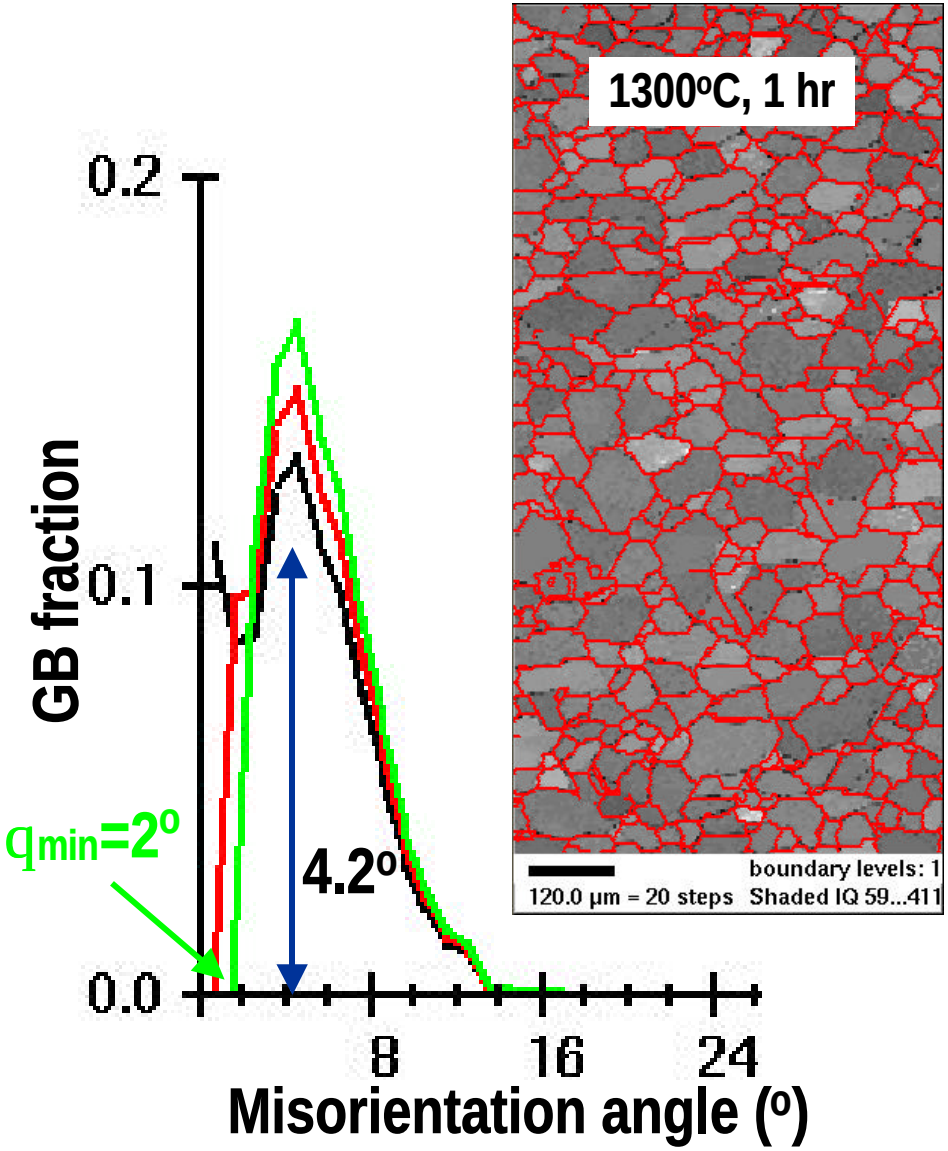
Substrate is ferromagnetic as expected…



High quality of cube texture has been obtained on Ni-3at%W-1.7at%Fe

Log-scale (111) pole figures



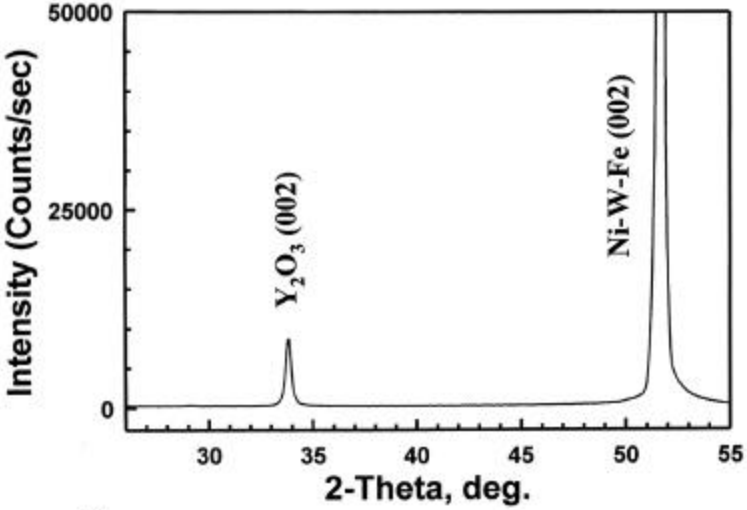


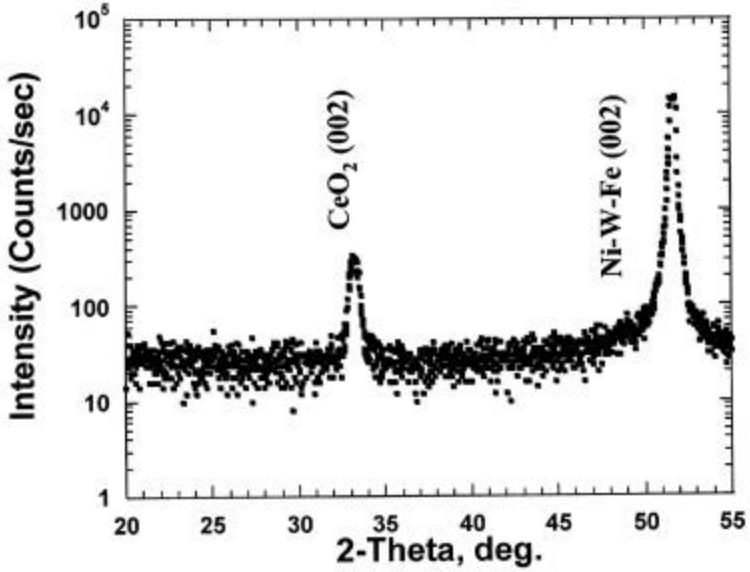
Buffer layer growth is similar to that on Ni

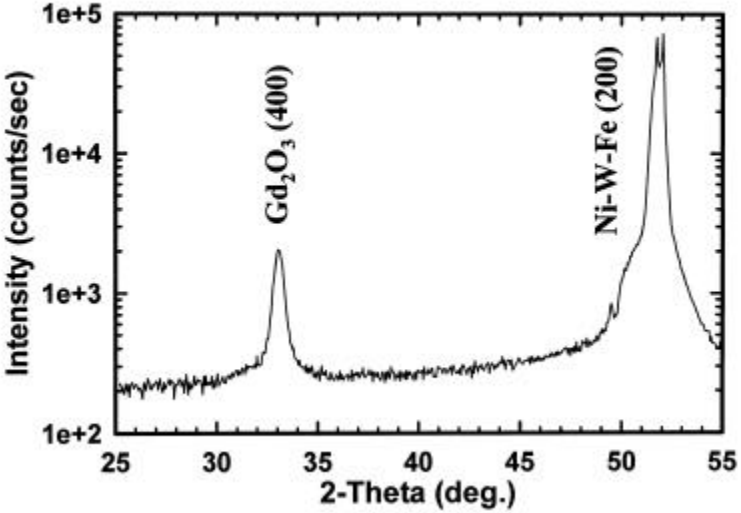
Using e-beam evaporation

-various oxides have been grown directly on Ni-3at%W-1.7at%Fe

Using sol-gel coating



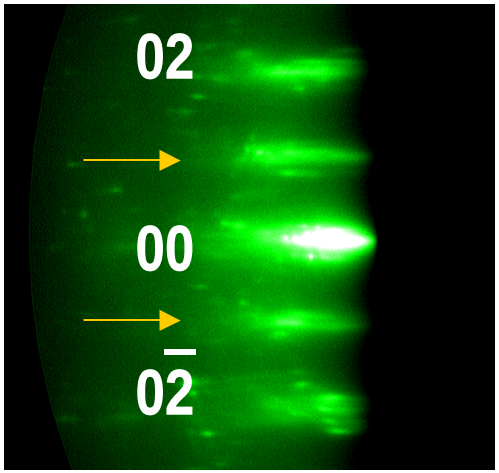


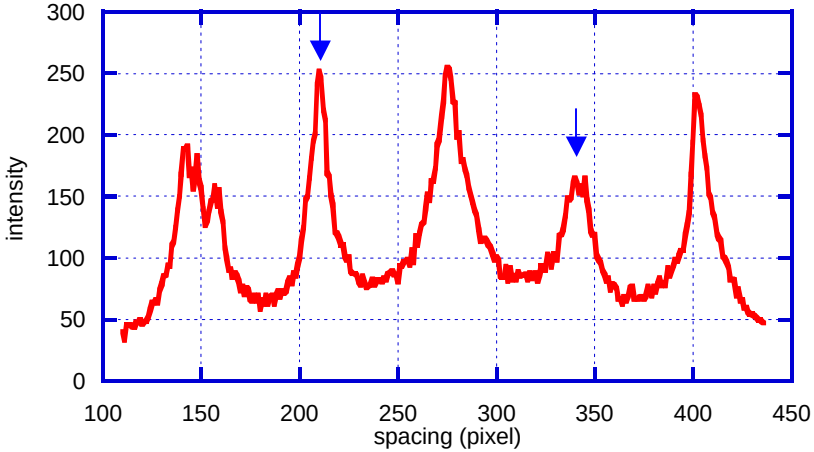


UT-BATTELLE

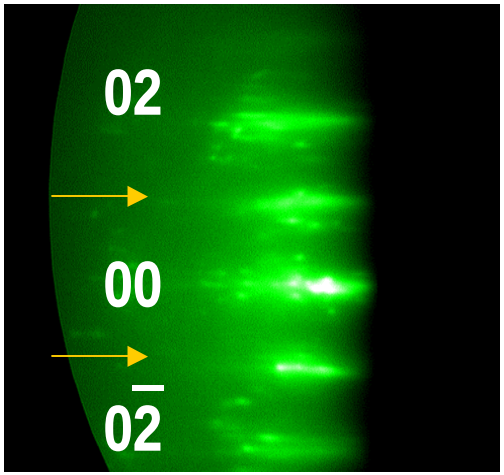
Sulfur superstructure controls epitaxy!

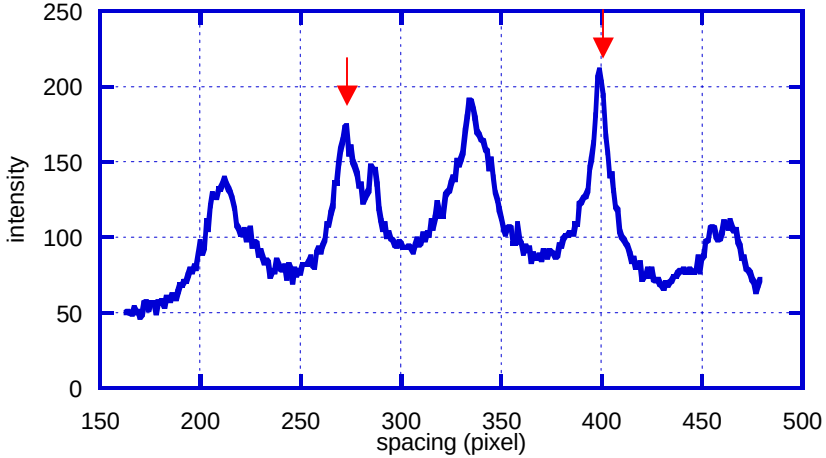
Ni-ORNL S30
1050 °C, 2 h



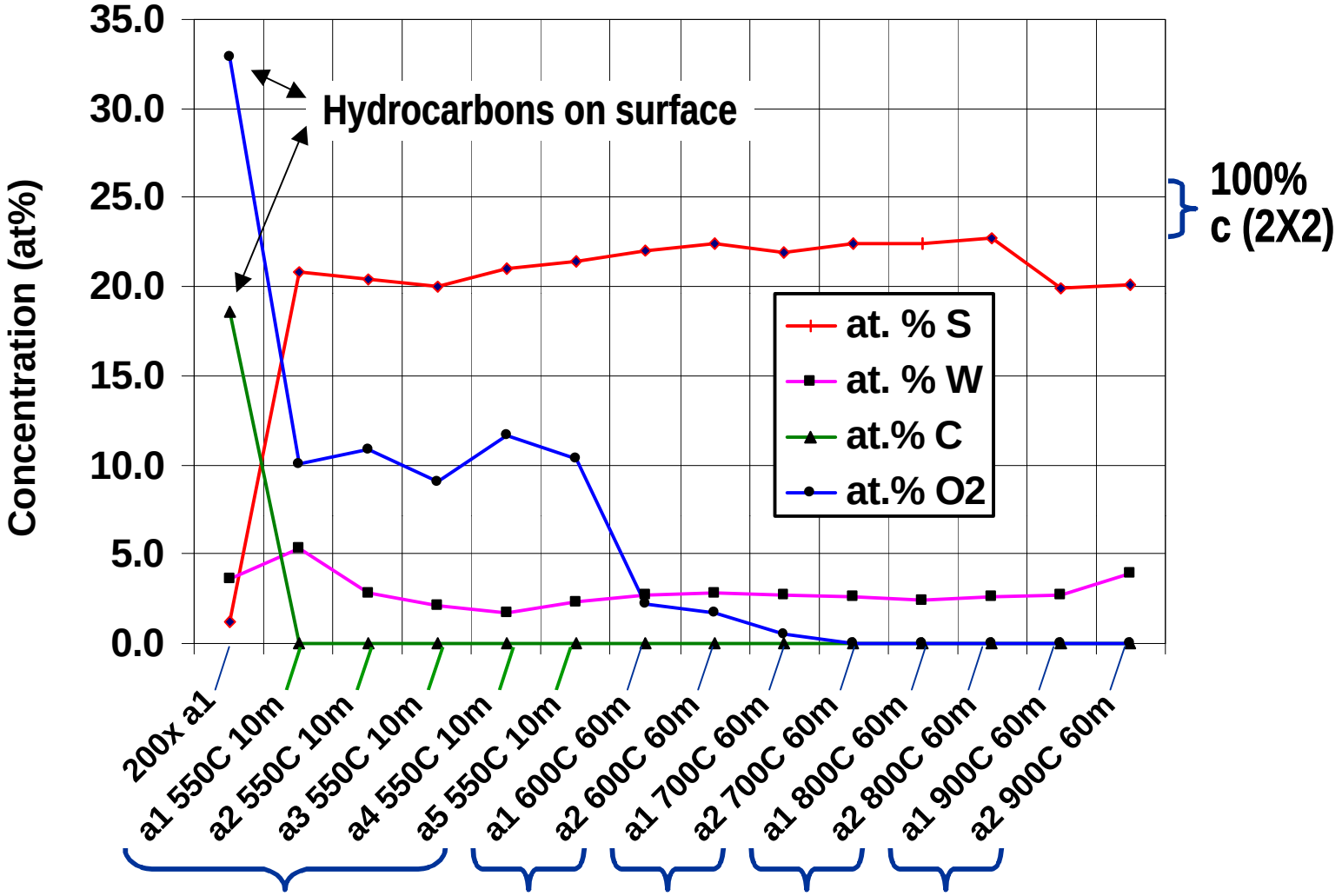


Ni-3%W-1.7%Fe
1100 °C, 2 h

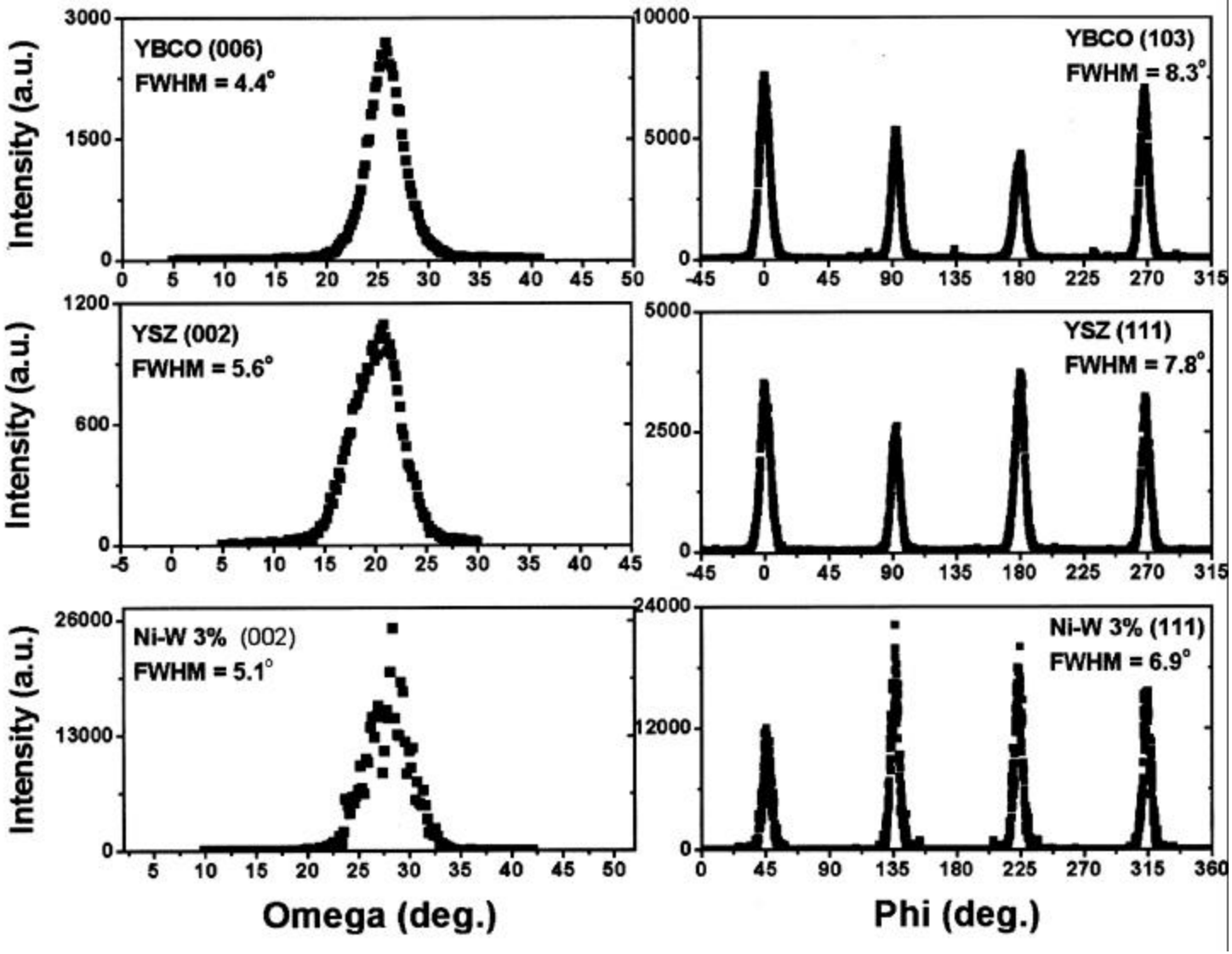




Auger analysis confirms high concentration of Sulfur at the surface



High-J_c YBCO with a J_c (77K, self-field) of 1.9MA/cm^2 has been deposited on Ni-W-Fe

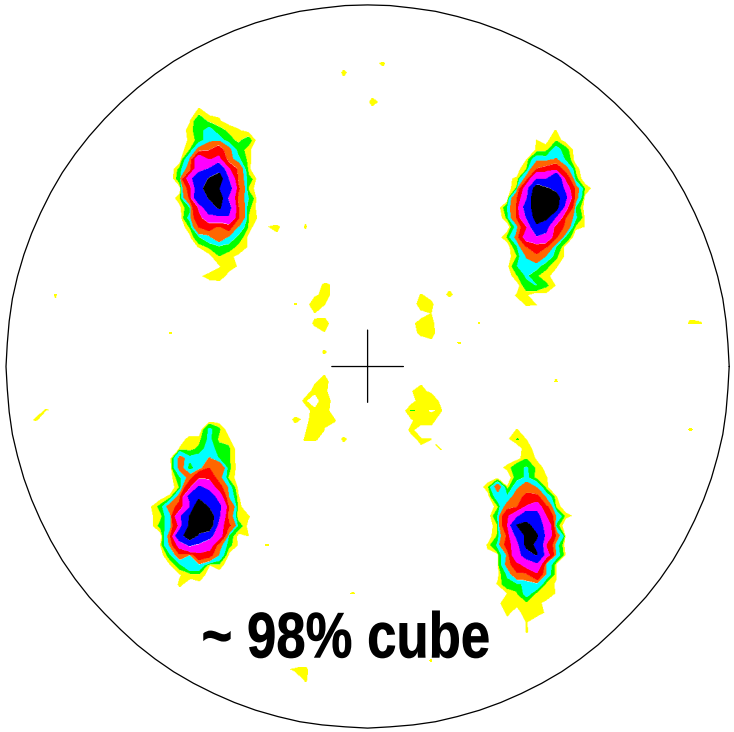


$Ni/Y_2O_3/YSZ/CeO_2/YBCO$

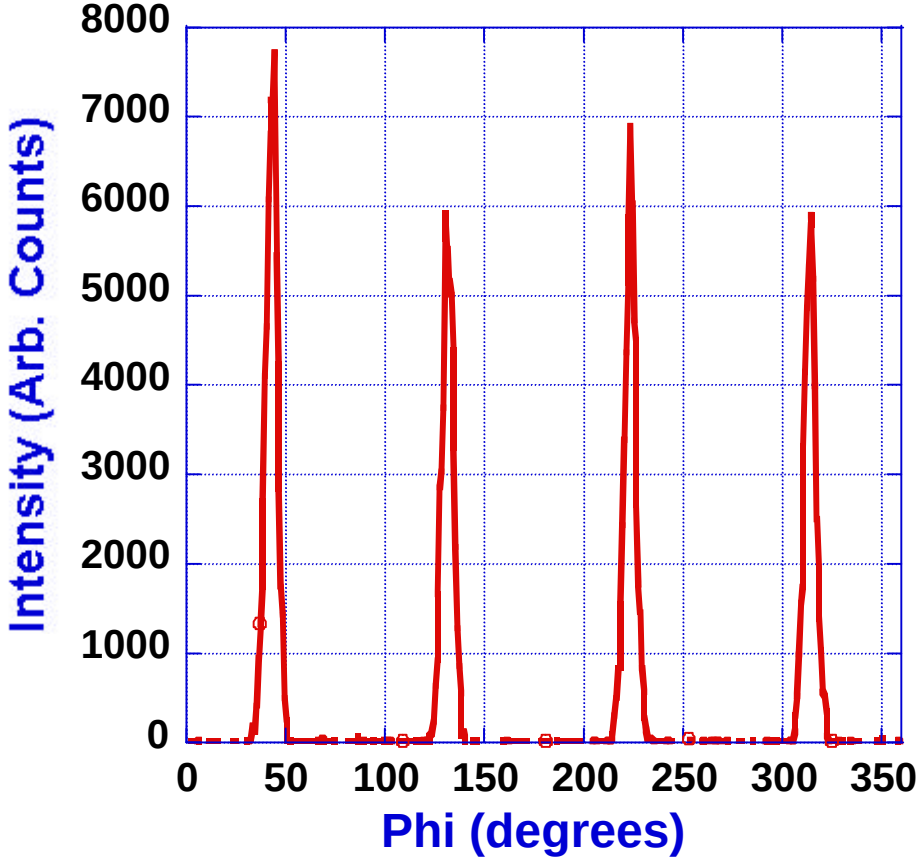
UT-BATTELLE

Ni-6at%W substrates also show good cube texture formation

Log-scale (111) Pole Figure



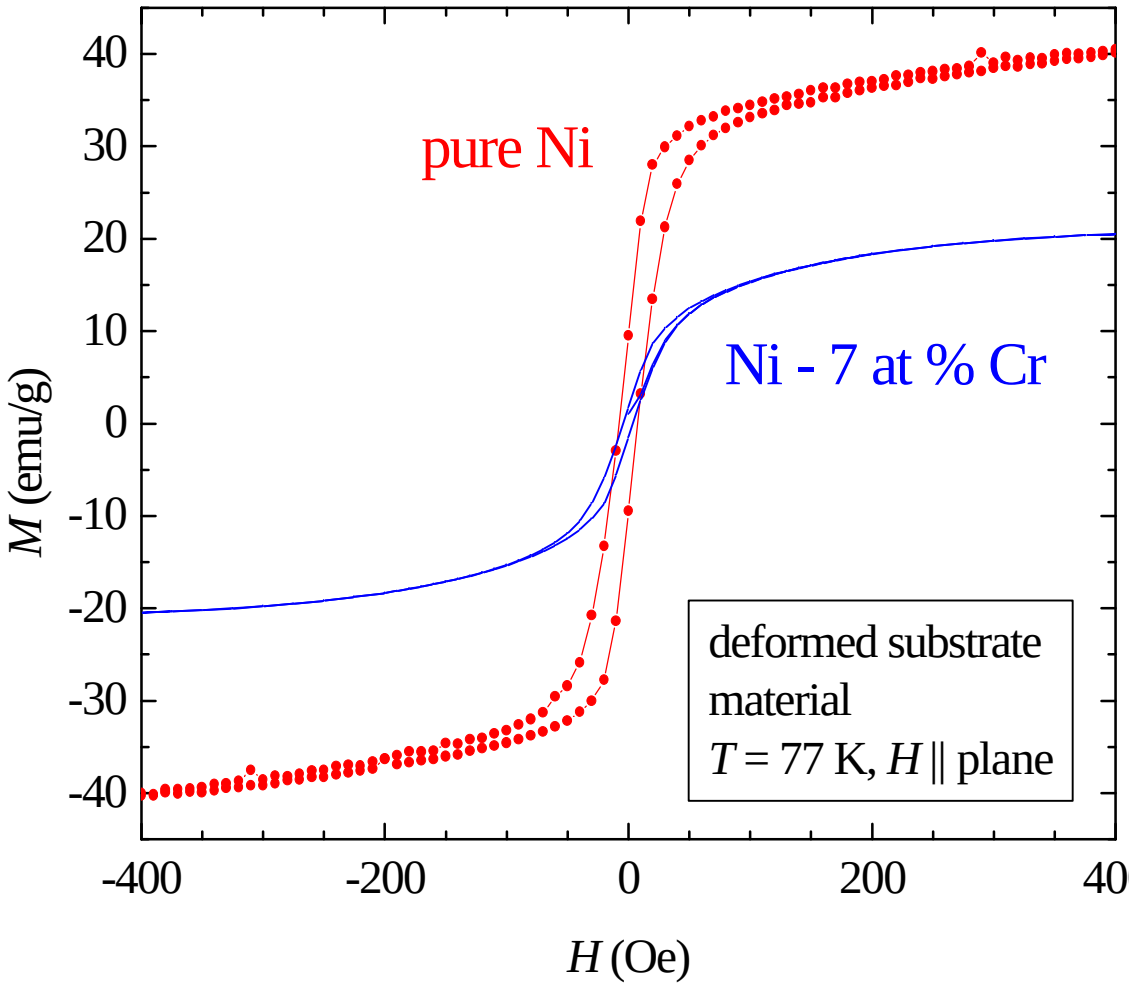
Df = 6.6º ; Dw = 5.3º , 10.4º



Yield Stress:
Ni-6W ~197MPa

- **Ni-9at%W ~ 93% Cube**

Magnitude of AC losses from alloy substrates compared to losses from the superconductor



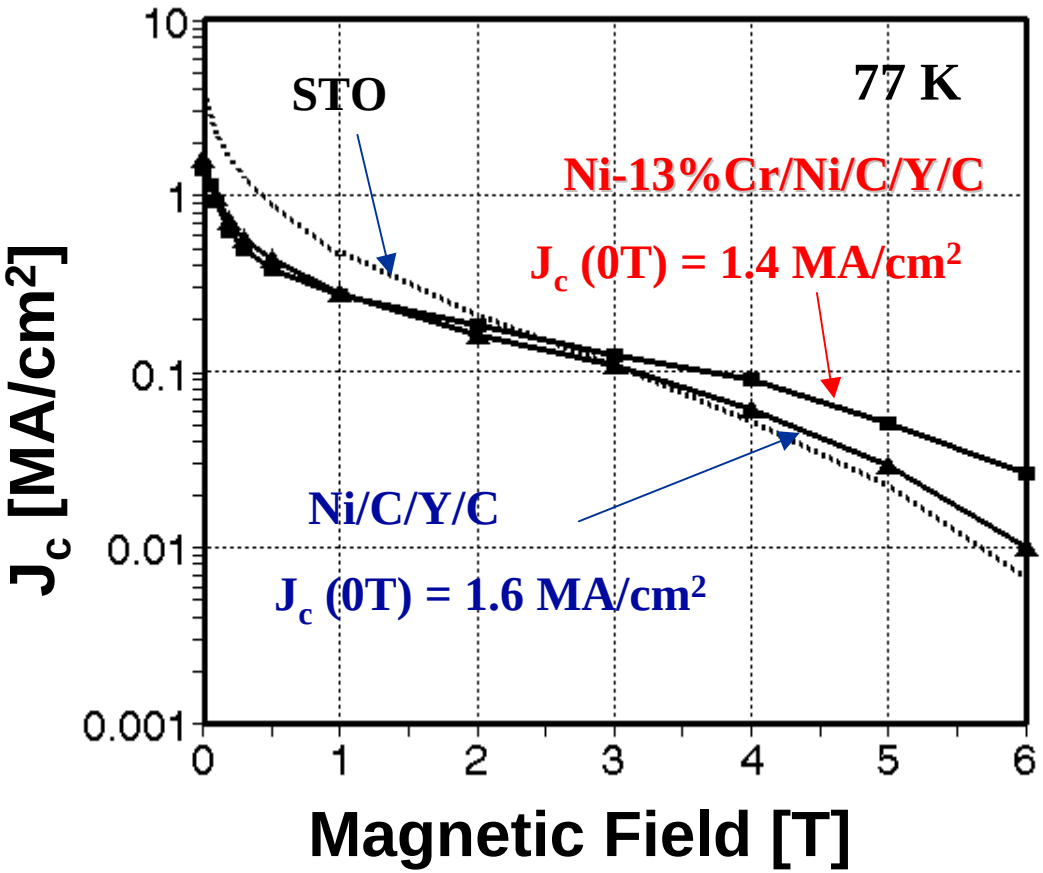
Ferromagnetic energy loss/cycle
-Ni: 1.8 mJ/cm^3
-Ni-7at%Cr: 0.17 mJ/cm^3

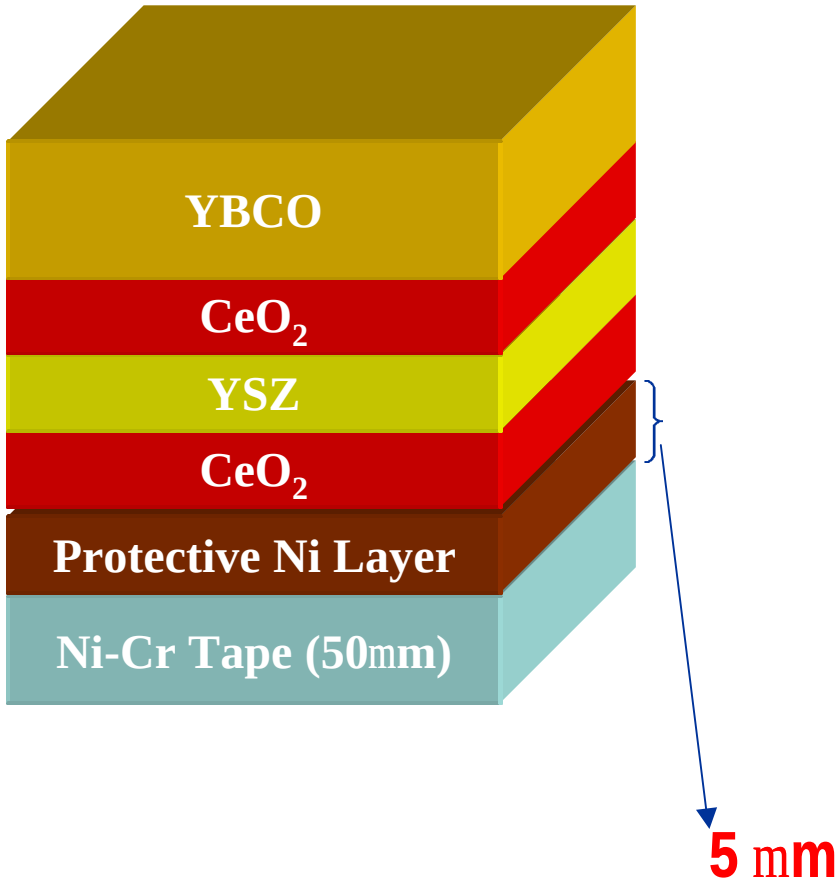
Hysteretic loss/cycle in YBCO for a conductor 8mm wide, 2.5 mm thick on a substrate 50 mm thick
-At 60Hz, assume peak ac current $I_o = I_c/2$ = 100A, SC loss is <u>0.27</u> W/kA-m at $I_o = I_c/2$

Ferromagnetic energy loss/cycle
- 0.4 cm^3 of alloy/metal per meter
-Ni: 0.43 W/kA-m
-Ni-7at%Cr: 0.043 W/kA-m

Low alloying content substrates may be adequate for many applications

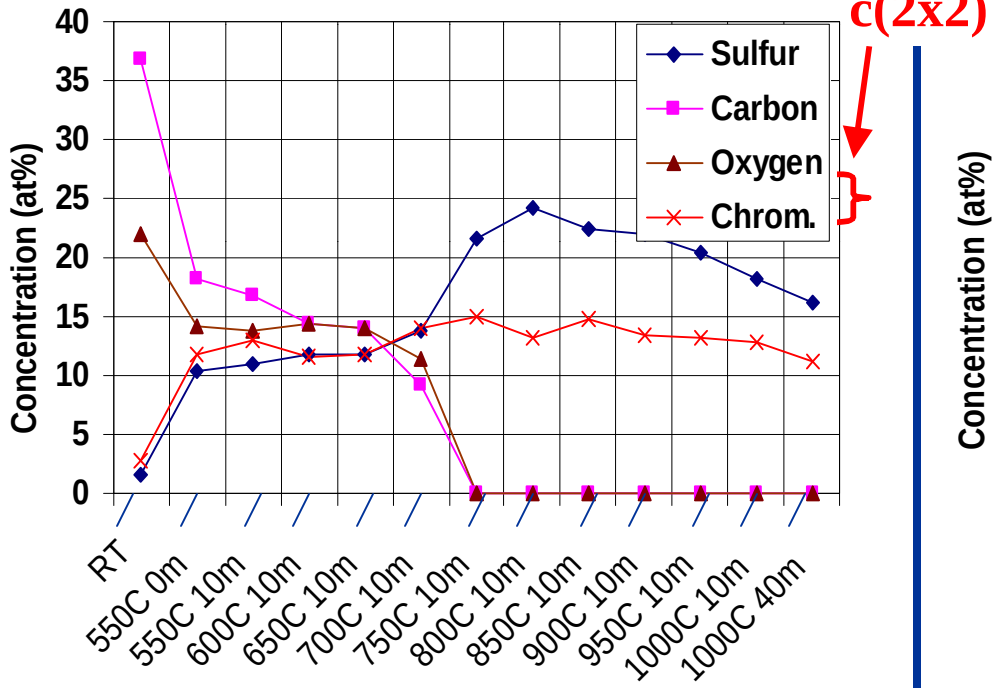
Excellent epitaxy and high-J_c was demonstrated for YBCO films on Ni-13at%Cr substrates last year



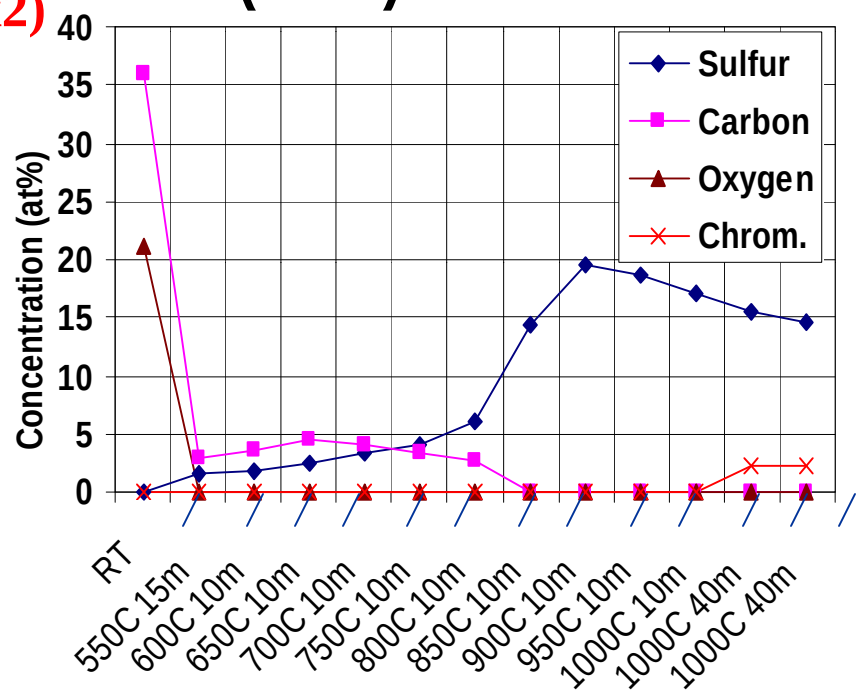


Surface superstructures also control epitaxy in Ni-13at%Cr substrates

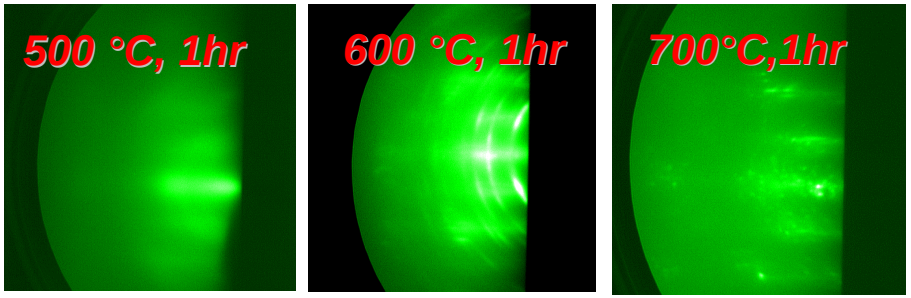
Ni-13at%Cr



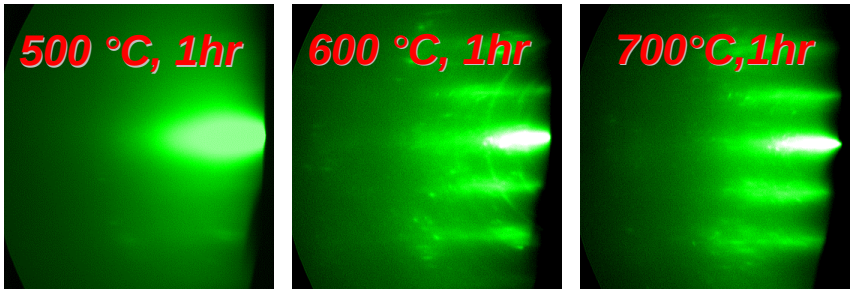
Ni (5 mm) / Ni-13at%Cr



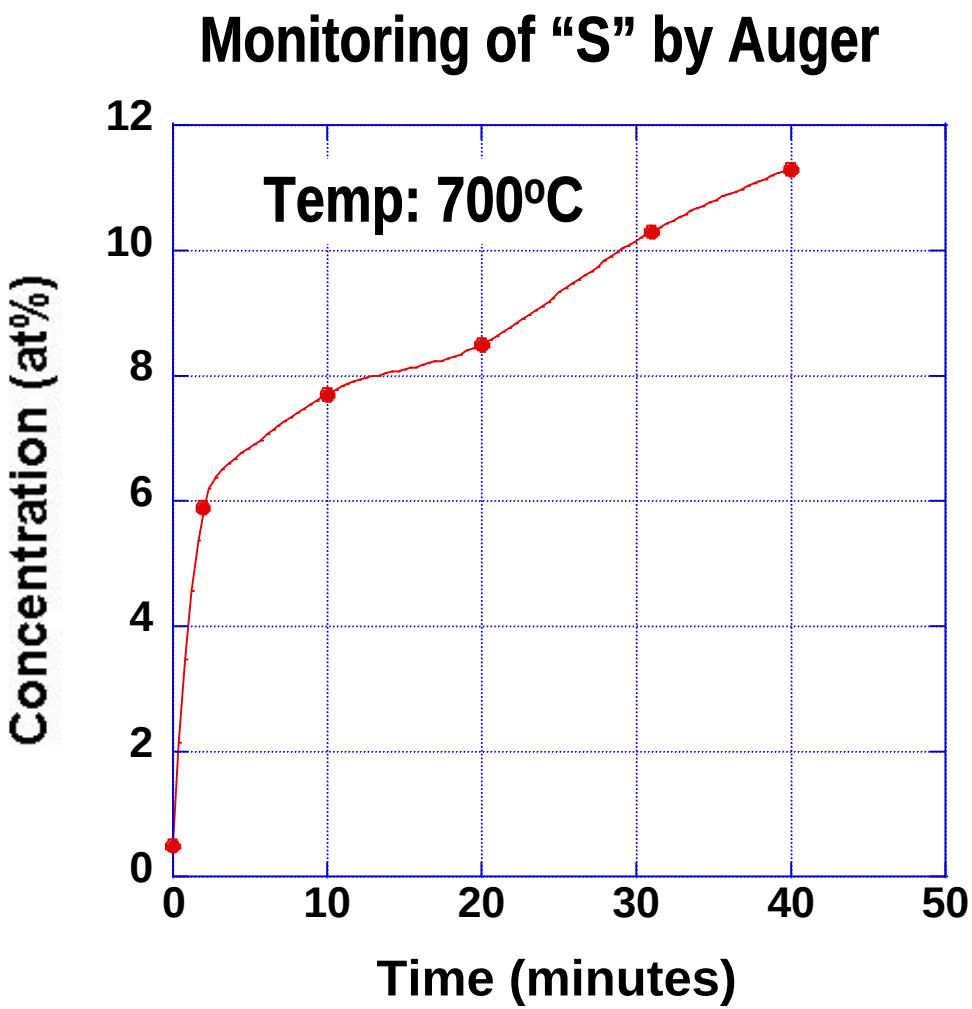
Rheed patterns from Ni-13at%Cr



Rheed patterns from Ni (5mm)/ Ni-13at%Cr

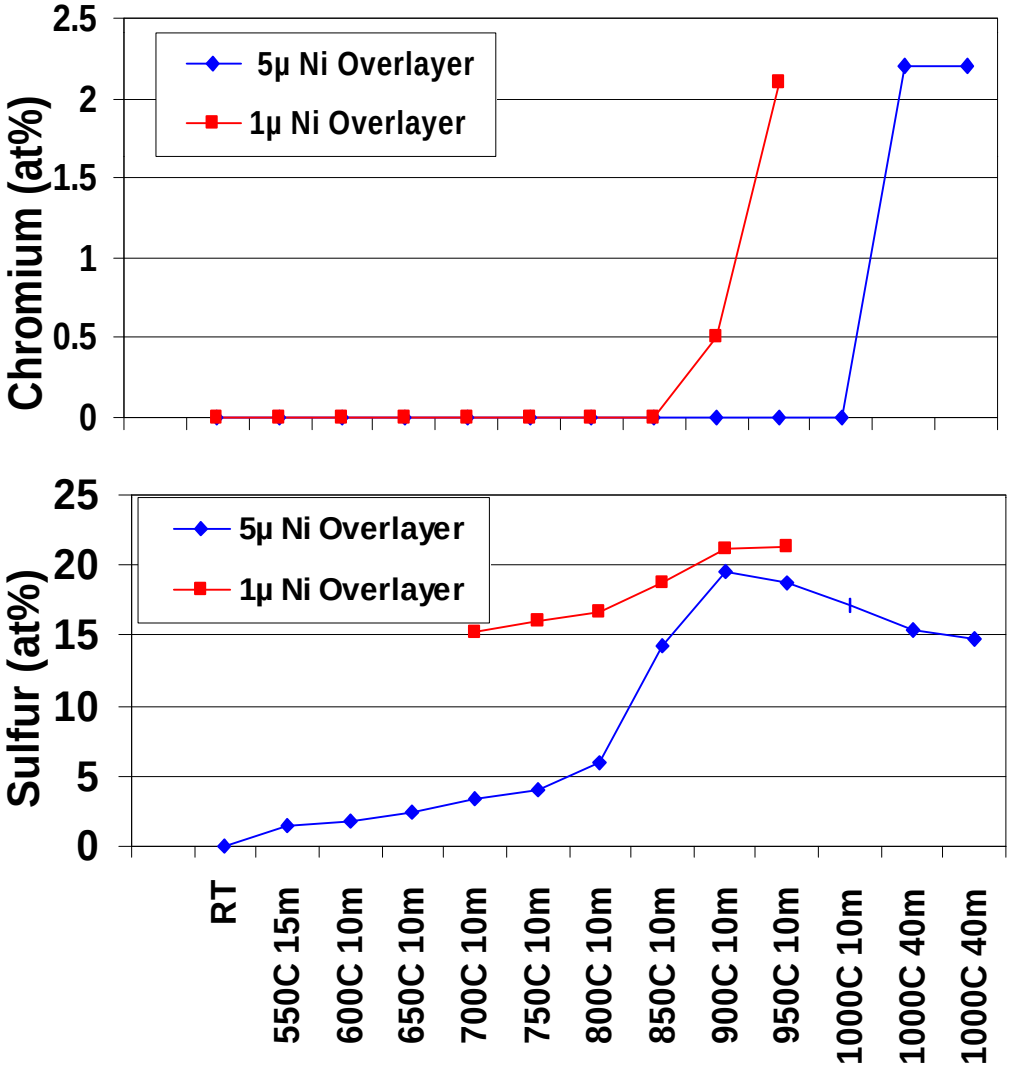


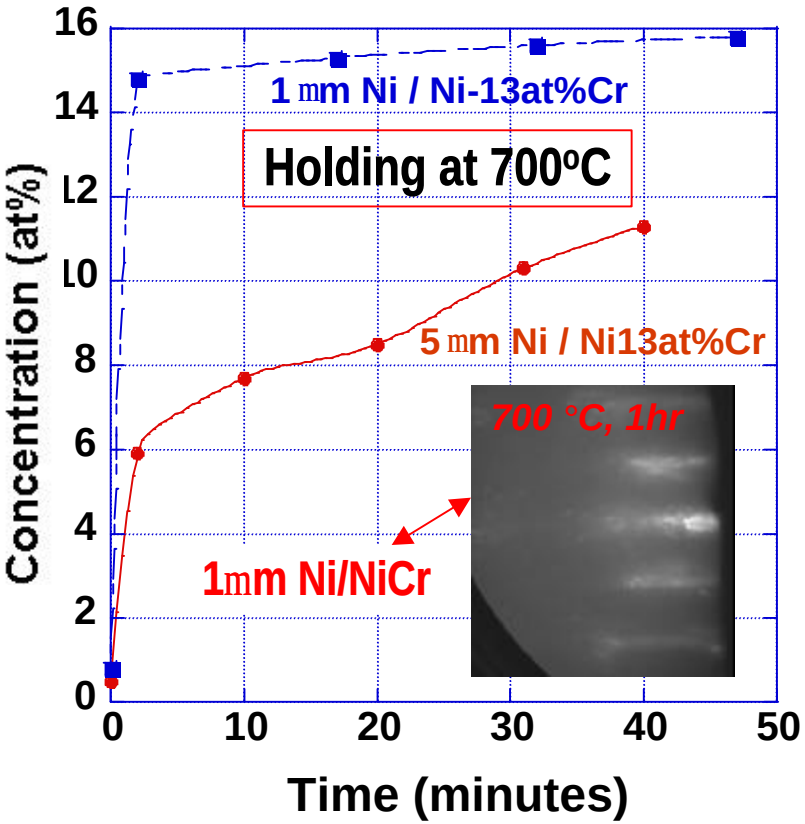
Typical seed layer deposition by e-beam evaporation of CeO_2 includes a hold at 700°C for 1hr



In-Situ Auger analysis indicates that there is enough time for sulfur to diffuse through the 5 mm thick Ni coating to form the sulphur superstructure

Can we decrease the thickness of Ni overlayer on Ni-13at%Cr ?

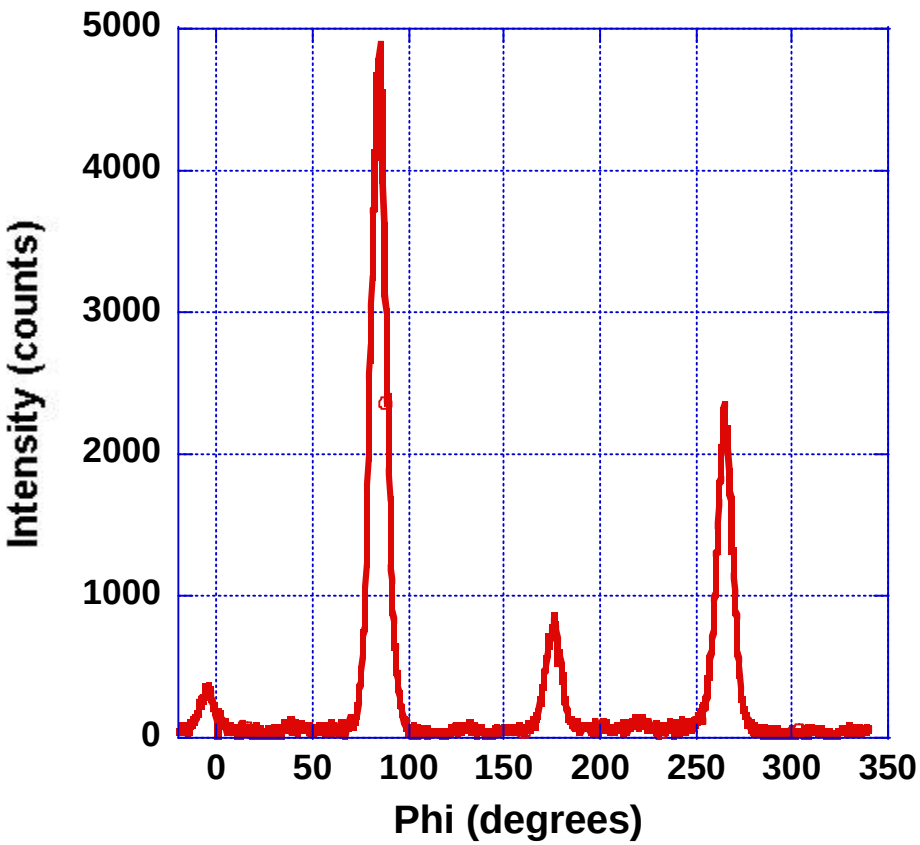




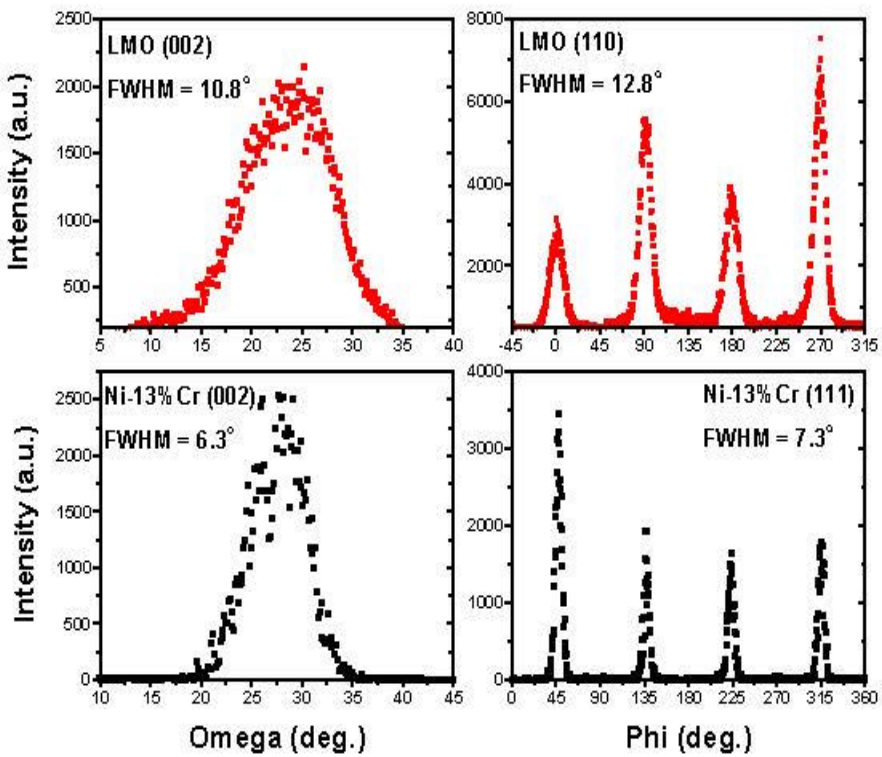
1 mm of Ni is more than sufficient to prevent Cr diffusion and results in the formation of the sulfur superstructure!

Epitaxial oxides have grown directly on Ni-13at%Cr substrates

YSZ (PLD) / Ni-13at%Cr

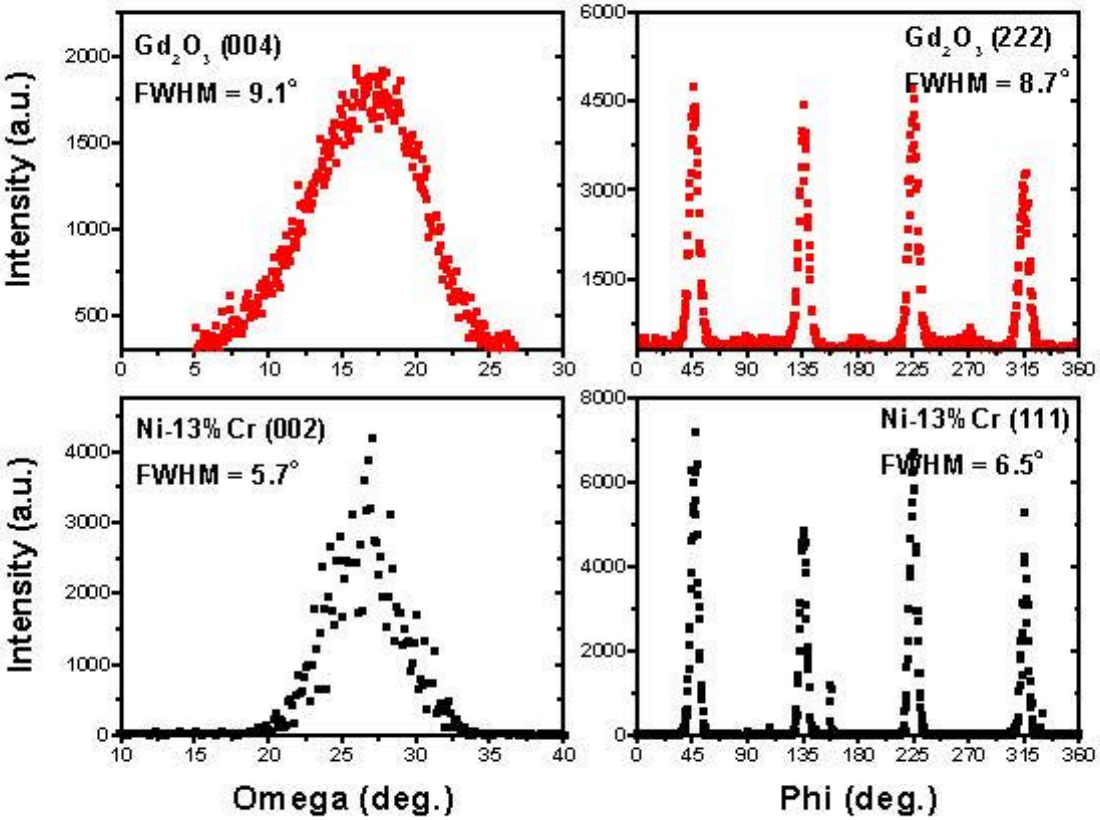


$LaMnO_3$ (Sputtering) / Ni-13at%Cr



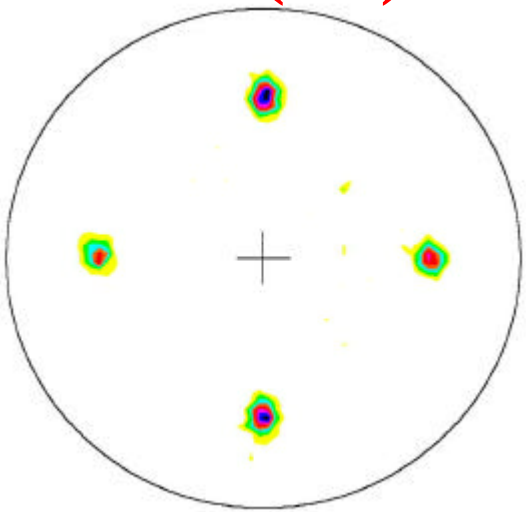
Epitaxial oxides by *sol-gel* deposition on Ni-13at%Cr substrates

Gd_2O_3 / Ni(5mm) / Ni-13at%Cr



$La_2Zr_2O_7$ / Ni-13at%Cr

LZO (222)

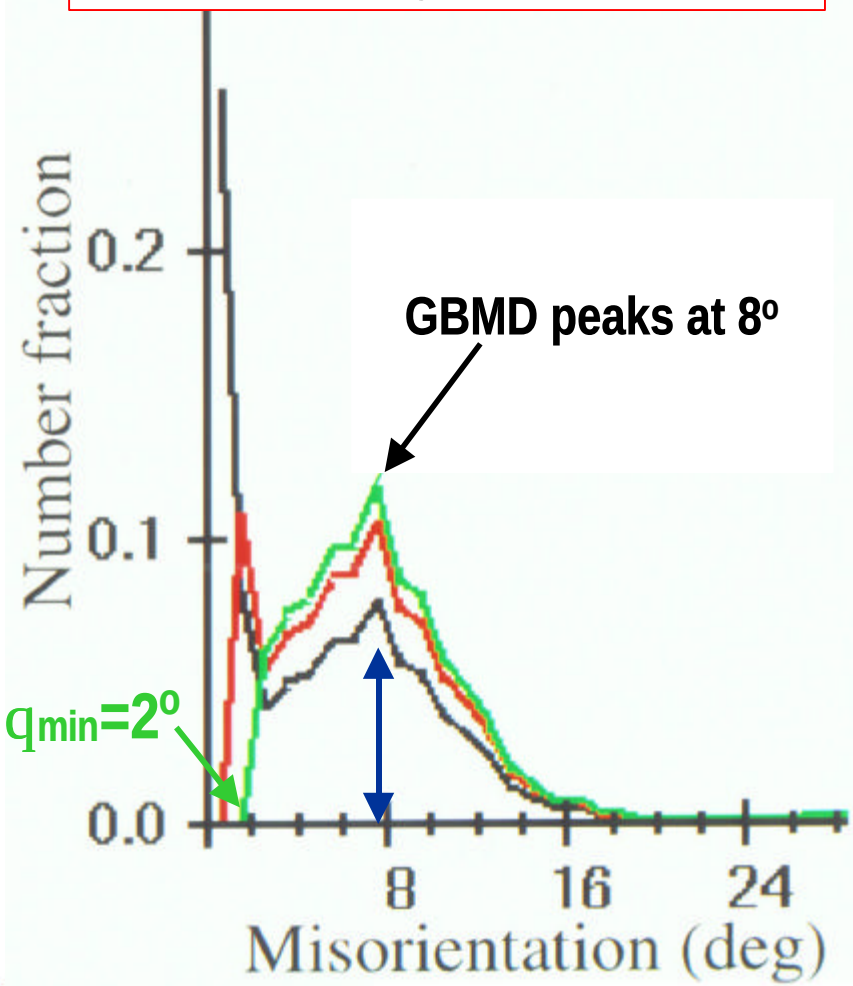


Summary: Alloy Substrates

- A significantly strengthened substrate of composition Ni-3at%W- 1.7at%Fe with similar surface characteristics as Ni was developed. High-J_c of 1.9 MA/cm^2 was obtained on this substrate.
- Significant progress was made in understanding superstructures associated with Ni-13at%Cr and the optimum Ni overlayer thickness
- Even low alloying additions to Ni, provide a significant reduction in AC losses
- Direct deposition of YSZ by PLD, $LMnO_3$ by rf-sputtering and $La_2Zr_2O_7$ by *sol-gel* deposition was demonstrated

How full is the glass for enhancements in J_c?

Grain boundaries in long length Ni produced using outside vendors



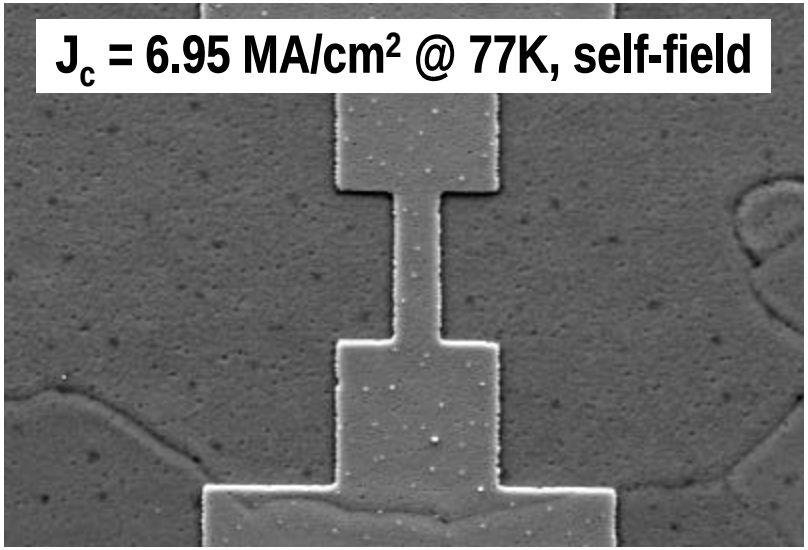
Issues:

- Intragranular J_c measurements on RABiTS
- Development of single crystal Ni tape
- Misorientations in YBCO compared to that in Ni
- What are we doing to get better long length Ni?

Intra-Grain J_c Measurements

Intragrain

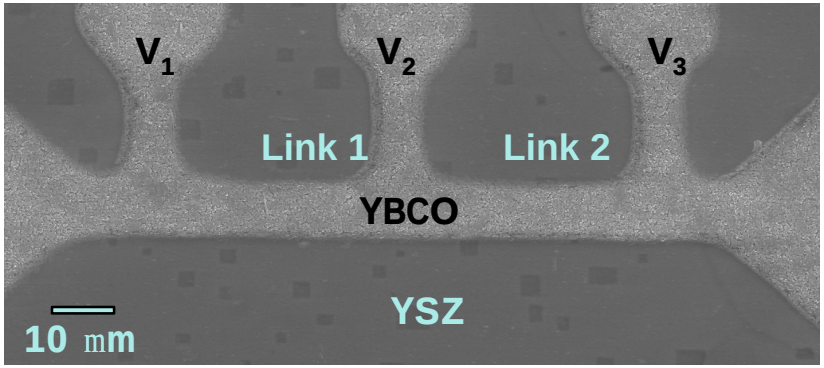
Collaboration with Mannhart and Hammerl at Universitat Augsberg



- Typical J_c for YBCO on this Ni = 1MA/cm^2
- Intragrain J_c = 3-7MA/cm^2 @ 77K, self-field

(YBCO by PLD)

Collaboration with Feldman and Larbalestier at U. of Wisconsin

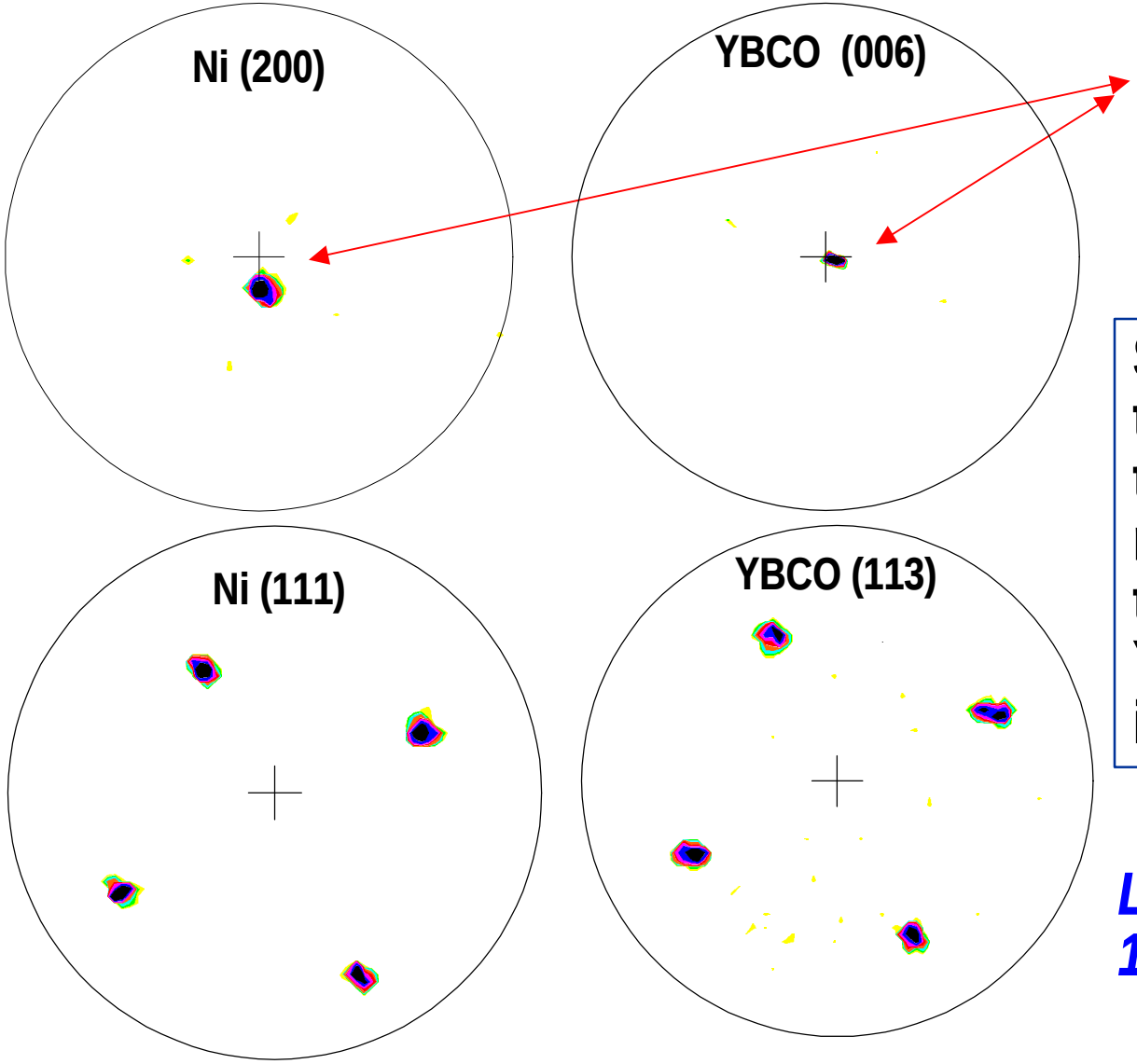


q/intra-grain	Link J_c(0 T) 10^6 A/cm^2
intra	5.1
2.8°	3.0
intra	>3.5
intra	3.8
intra	3.1
7.1°	0.7
5.5°	0.8
9.8°	0.4
2.9°	2.6

(YBCO by BaF_2)

Intragrain J_c:
3.0-5.1 MA/cm^2
Intergrain J_c:
0.4-3.0 MA/cm^2

Single crystal Ni Tape has been fabricated



YBCO c-axis moves 6° towards the normal of the Ni tape

Shifting of YBCO c-axis towards the normal of the tape is an important mechanism for reducing the angles in the YBCO relative to that in the RABiTS Ni tape

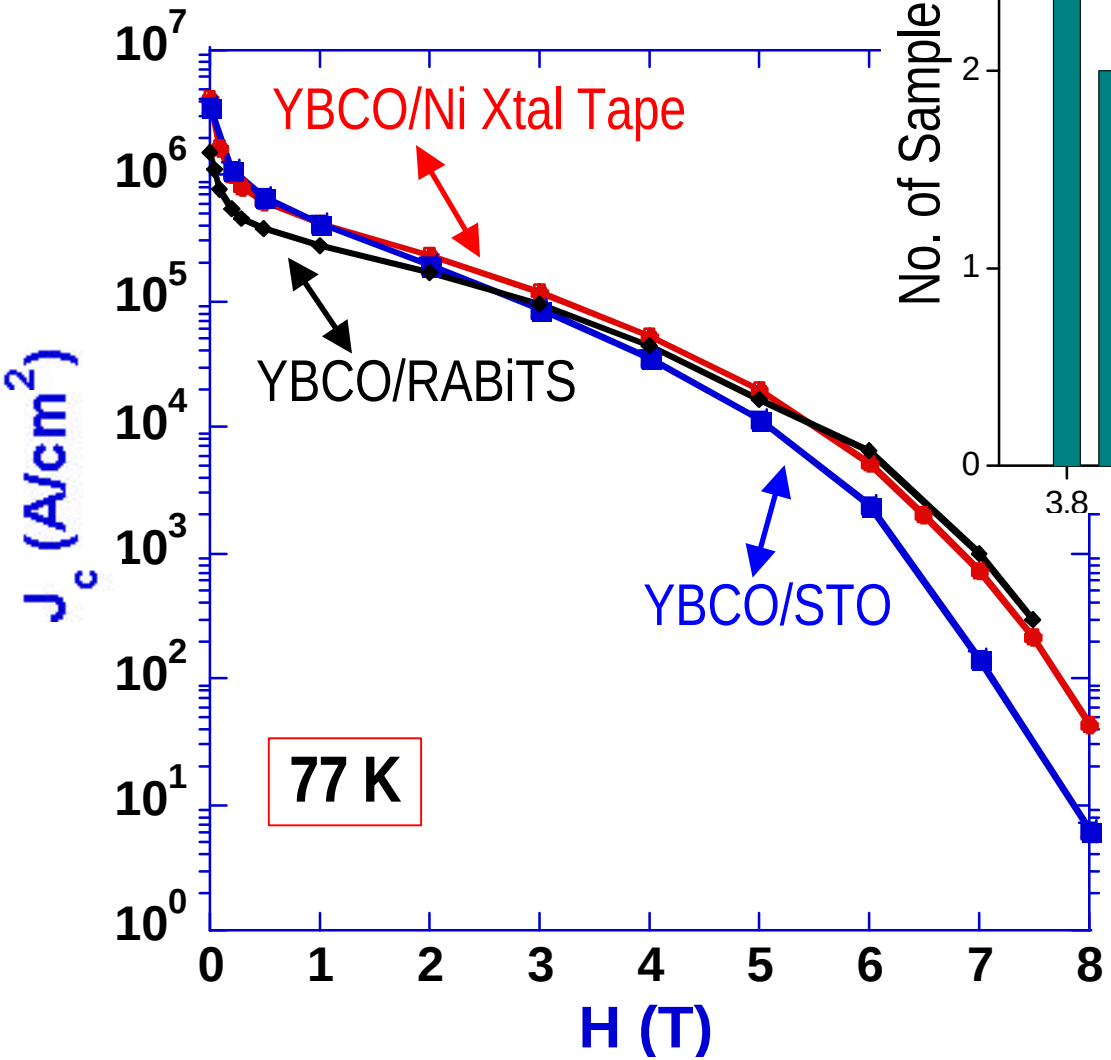
Likely able to make short, 1 m long tapes

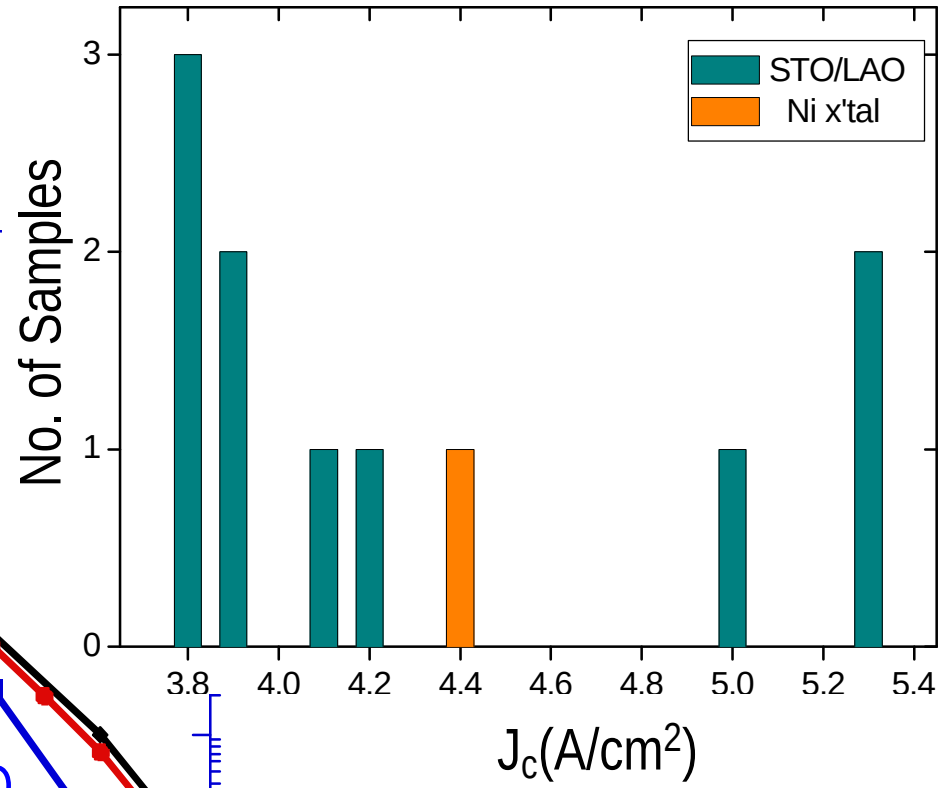
- tape is only slightly off-cube

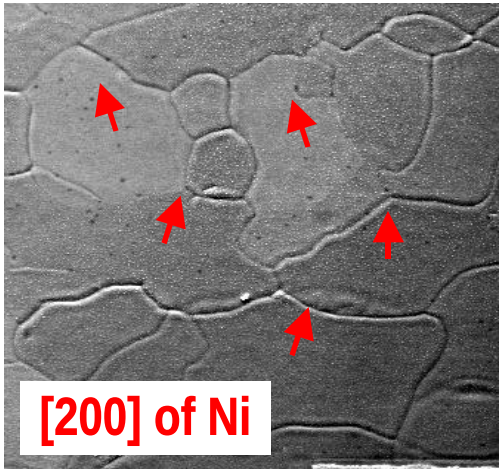
$Ni/CeO_2/YSZ/CeO_2/YBCO$

UT-BATTELLE

J_c of 4.4 MA/cm^2 obtained on 1in long, 0.5 cm wide single crystal Ni Tape

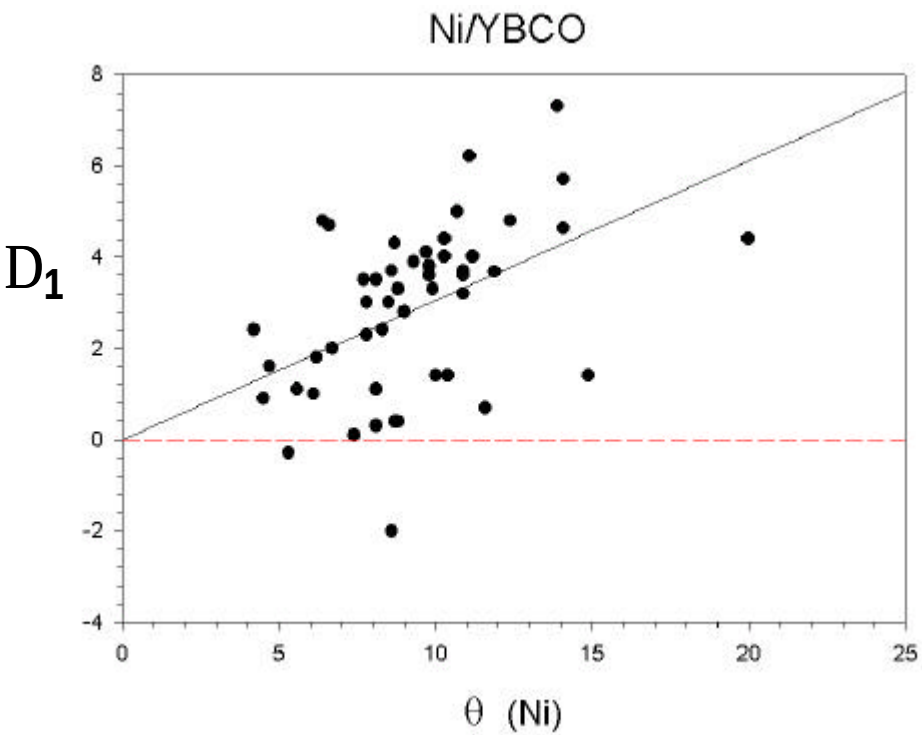


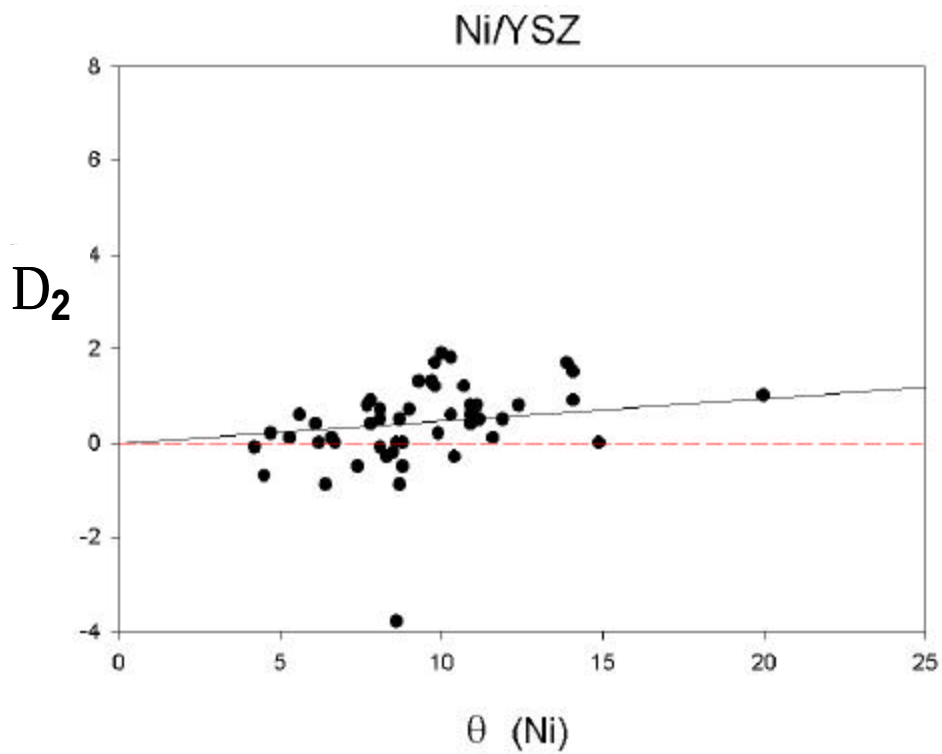




Improvement of GBMD in YBCO over that in Ni

Ni/CeO_2/YSZ/CeO_2/YBCO



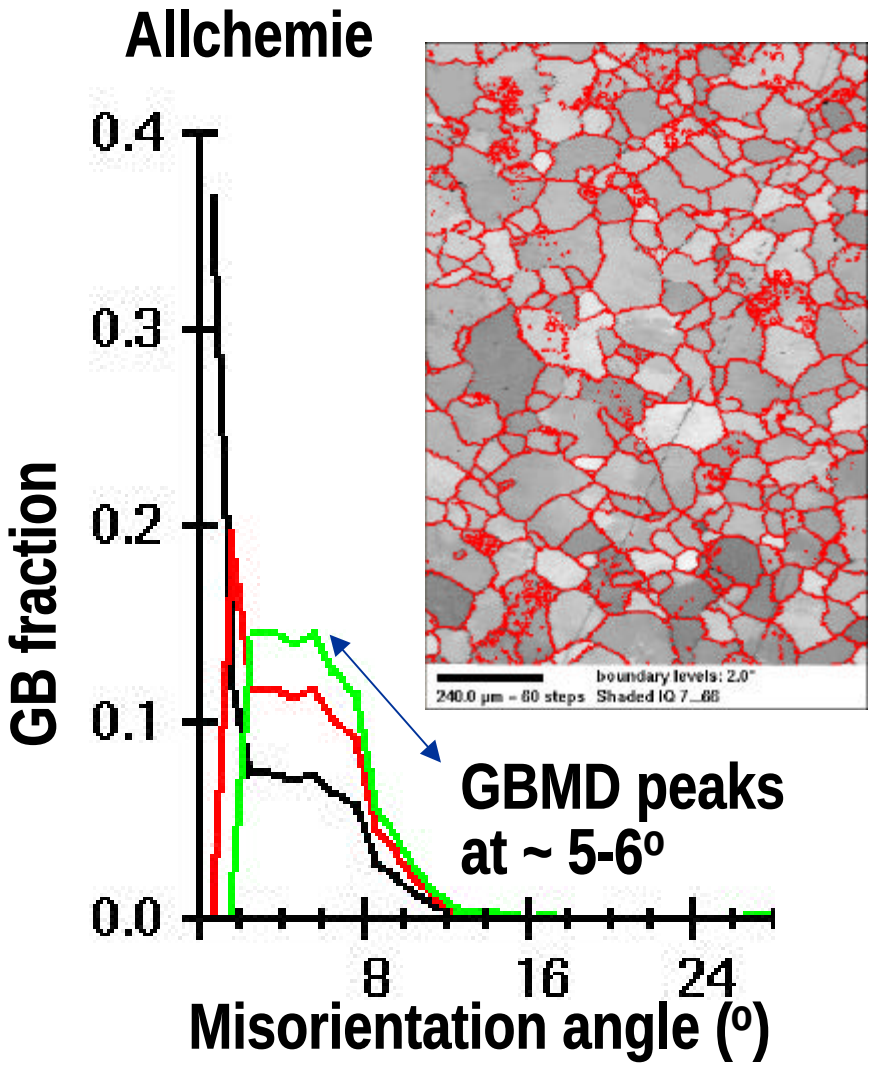


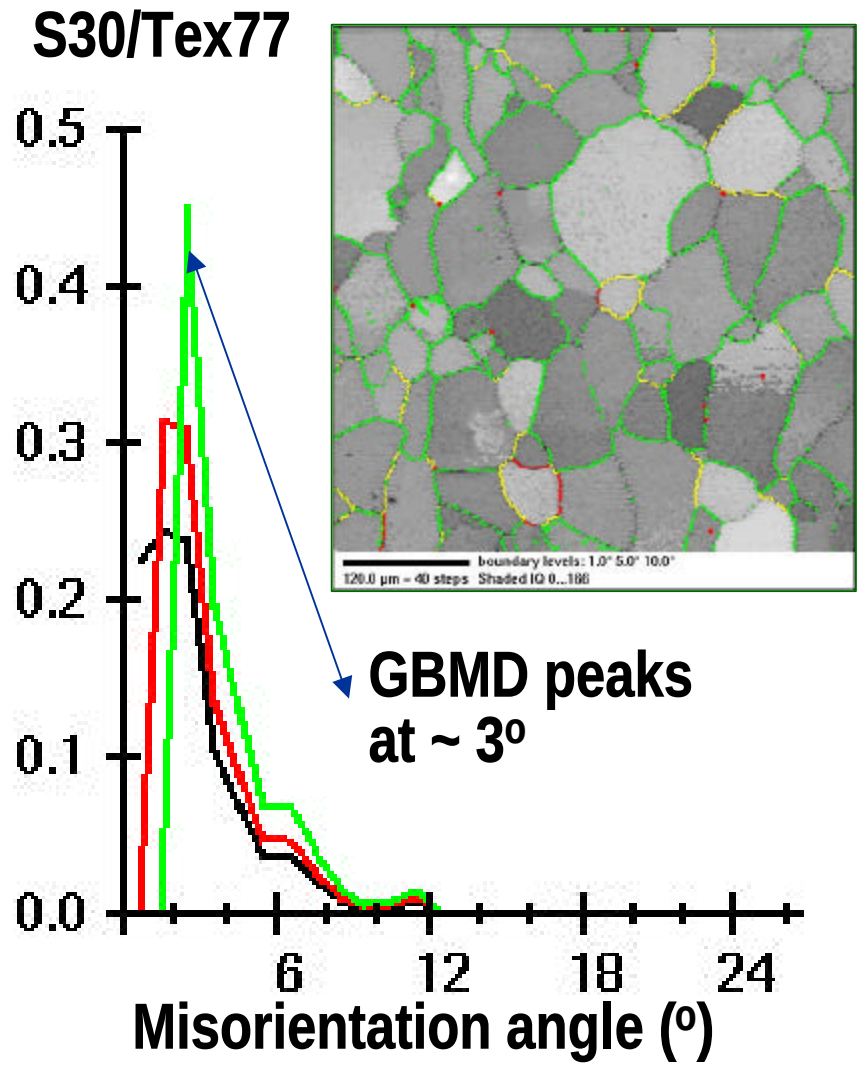
$D_1 = q\,(Ni) - q\,(YBCO)$

$D_2 = q\,(Ni) - q\,(YSZ)$

- Data gathered by Matt Feldman, Wisconsin

Better textured Ni has been made in-house at ORNL





Long Length Ni/Alloys

Need an adequate *supply* chain for starting materials and subsequent thermomechanical processing steps

Issues:

a) Starting material – powder metallurgy, vacuum melting

Powder metallurgy

Advantages
- Fine & homogeneous grain size
- Can obtain coils directly
- Thermomechanical processing steps minimized, so cheaper

Disadvantages
- Compositional control not easy
- Surface finish not very good

Vacuum melting

Advantages
- Good compositional control
- Can get very good surface finish

Disadvantages
- Difficult to control grain sizes
- Thermomechanical processing is complicated

b) Rolling – how to make a coil for rolling?

c) Annealing of long lengths, removal of oxide scale

d) Texture rolling – forward/backward tensions, deformation per pass, strain rate, lubricants, etc

Summary: Texture Issues

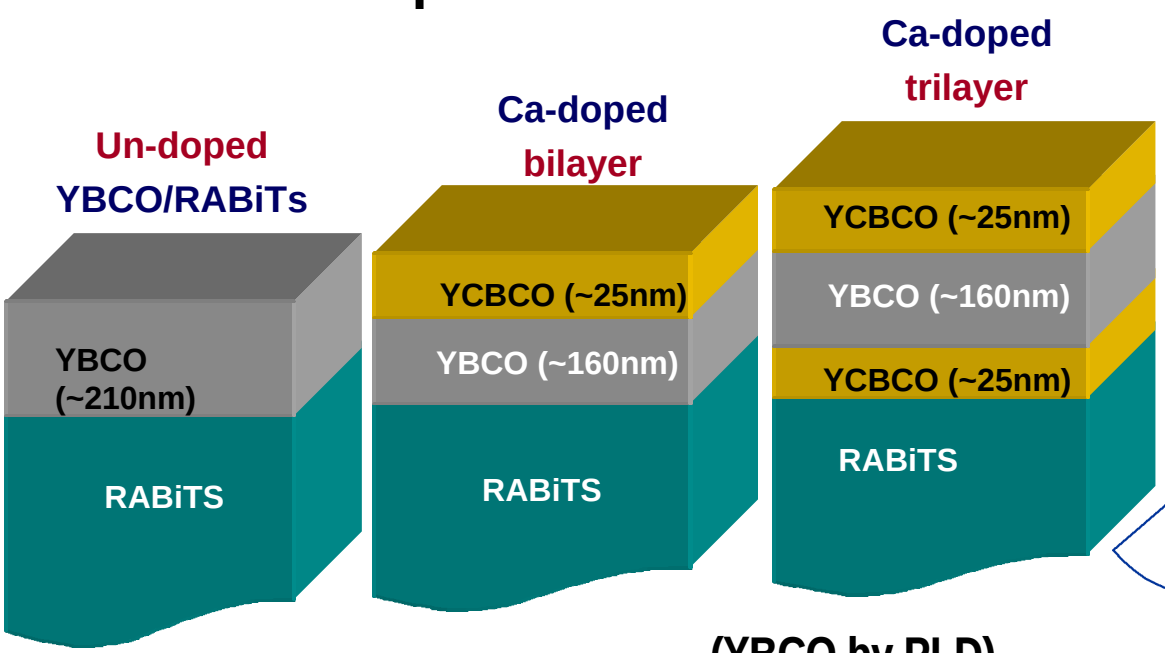
- There is significant room for improvement in long length Ni – at a J_c of 1 MA/cm^2 level, the glass is hardly full!
- Intragranular-J_c for YBCO/RABiTS ranges from 3-7 MA/cm^2.
- A single crystal Ni tape was fabricated, J_c of 4.4 MA/cm^2 was obtained.
- YBCO tends to shift its c-axis towards the sample normal during growth on metal tapes. GB misorientations in YBCO can be significantly improved over that in Ni (1-7°).
- Work in progress to obtain better textured substrates in long lengths.

Investigation of effects of Ca-doping of GB's for YBCO films on RABiTS

Motivation:

- Can J_c be enhanced in coated conductors via Ca-doping?
- Determine the effects of Ca-doping on low-angle GB's

Structure of experiment:



- Look at 30at%Ca, 20at%ca and 10at%Ca
- Vary the relative thickness of the Ca-doped layer and the Undoped layer (looked at three ratios)

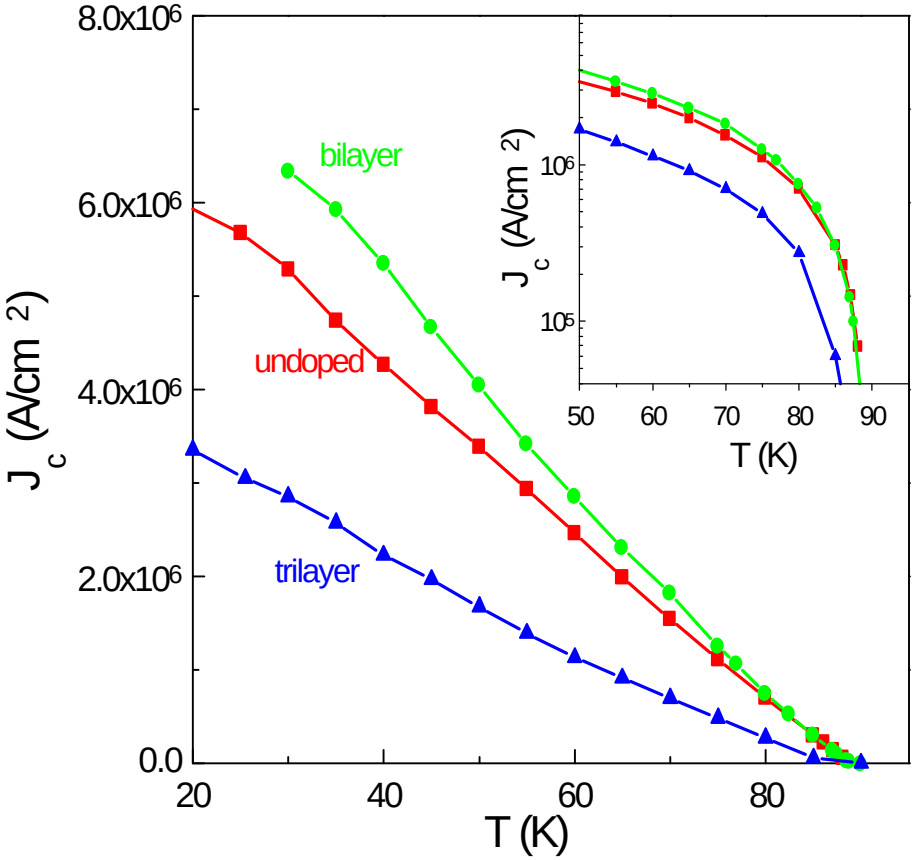
-(YBCO by PLD)

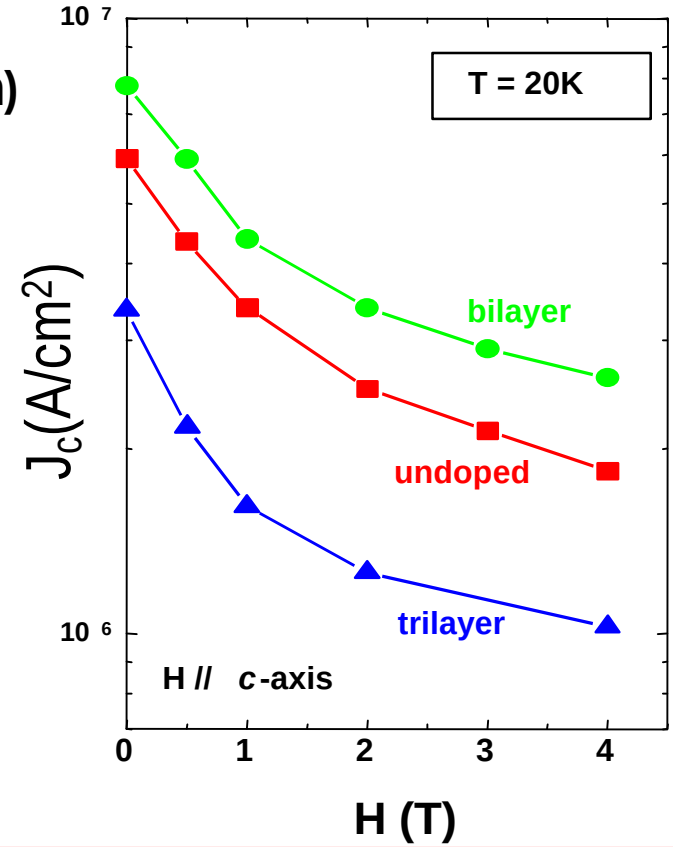
Substrate used: Comm. Ni
GBMD: Peaks at 8°

UT-BATTELLE

Transport properties of undoped films, bilayers and trilayers on RABiTS

Doped layer = $Y_{0.7}Ca_{0.3}$
Bilayer: Undoped (160 nm) / Doped (25 nm)
Trilayer: Doped (25 nm) / Undoped (160 nm) / Doped (25 nm)
T_c: Undoped – 90.7 K; Bilayer – 90.9 K; Trilayer – 89.6 K





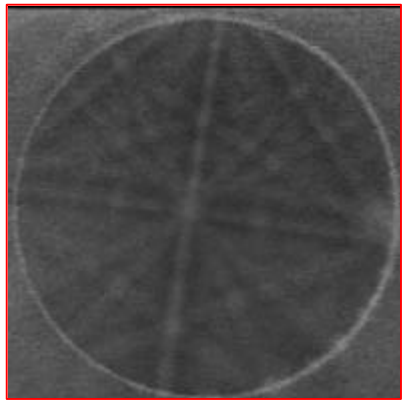
- **Bilayer: J_c enhanced 18% - 35% at low temp.**
- **Trilayer: J_c reduced at fields up to 60%**

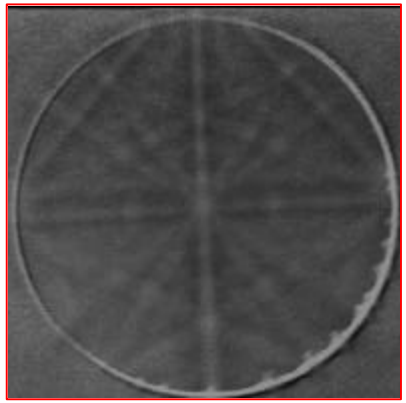
UT-BATTELLE

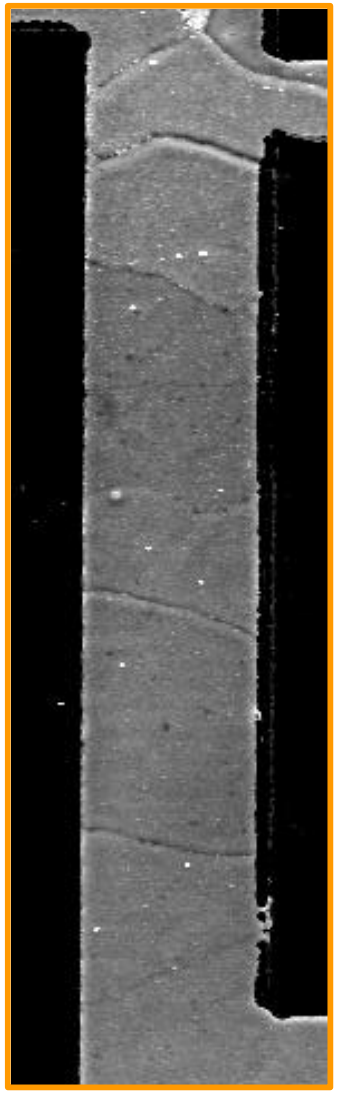
Local transport properties of monolayers and bilayers on RABiTS

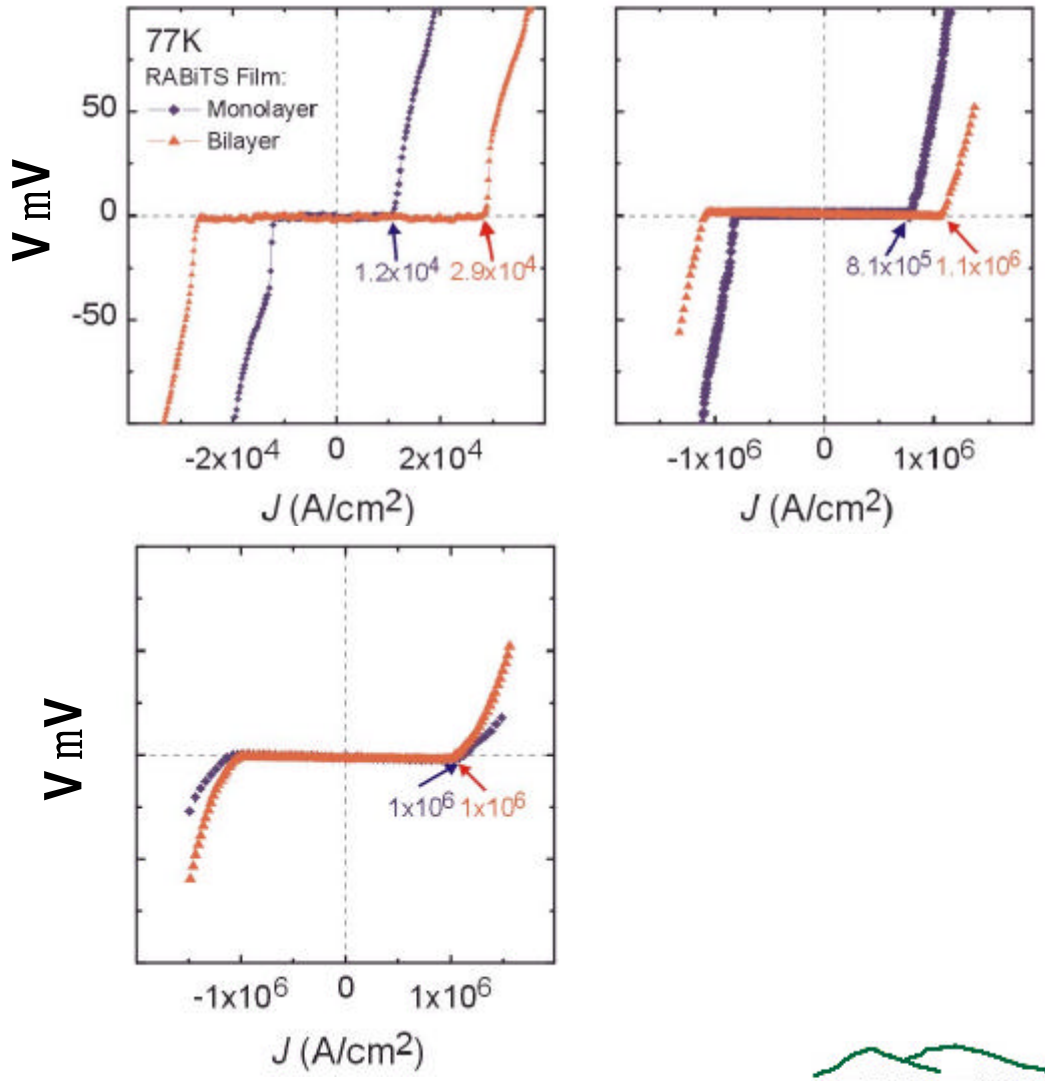
YBCO deposited by Mannhart and Hammerl, Universitat Augsburg

EBKP Patterns from either Side of GB









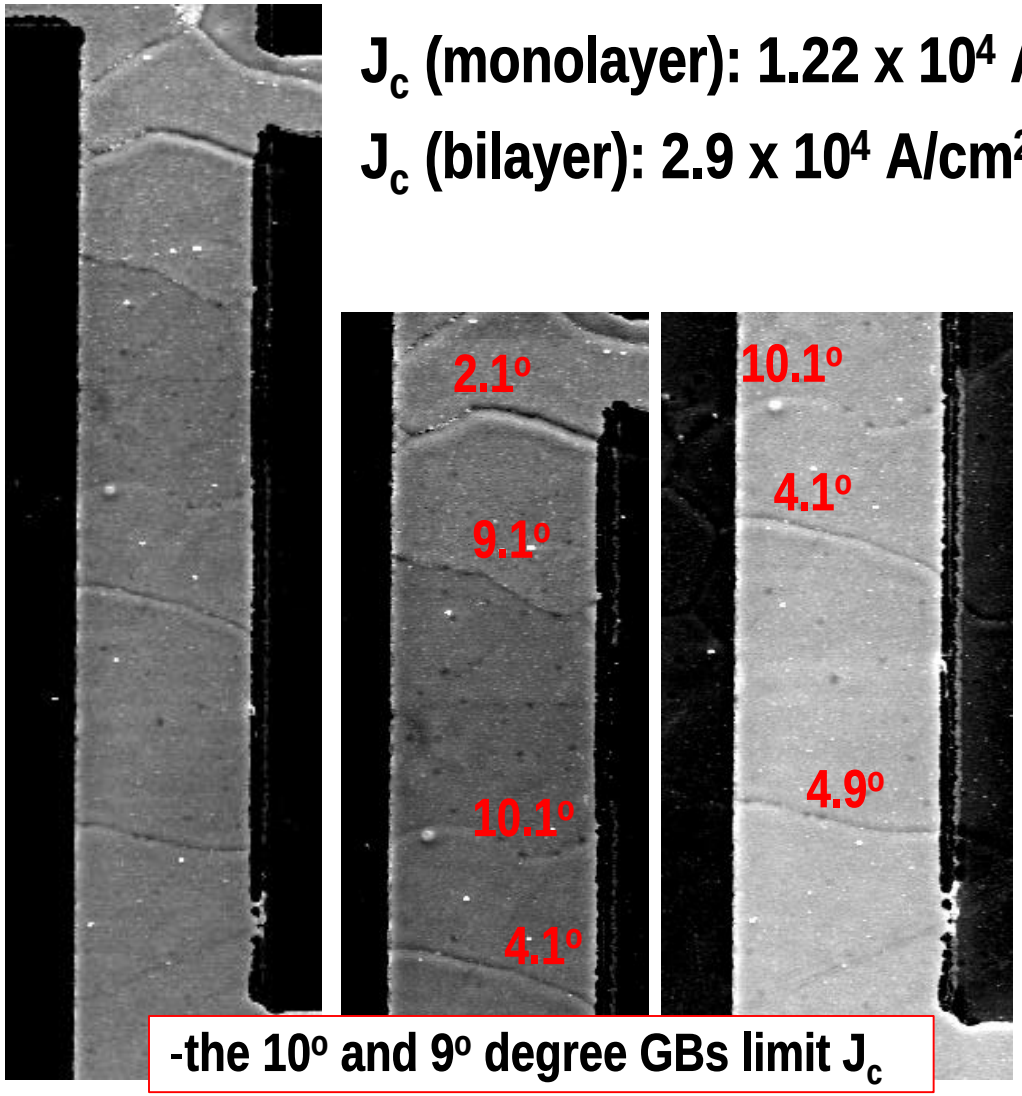
UT-BATTELLE

Microstructure of bridge with the biggest change in J_c

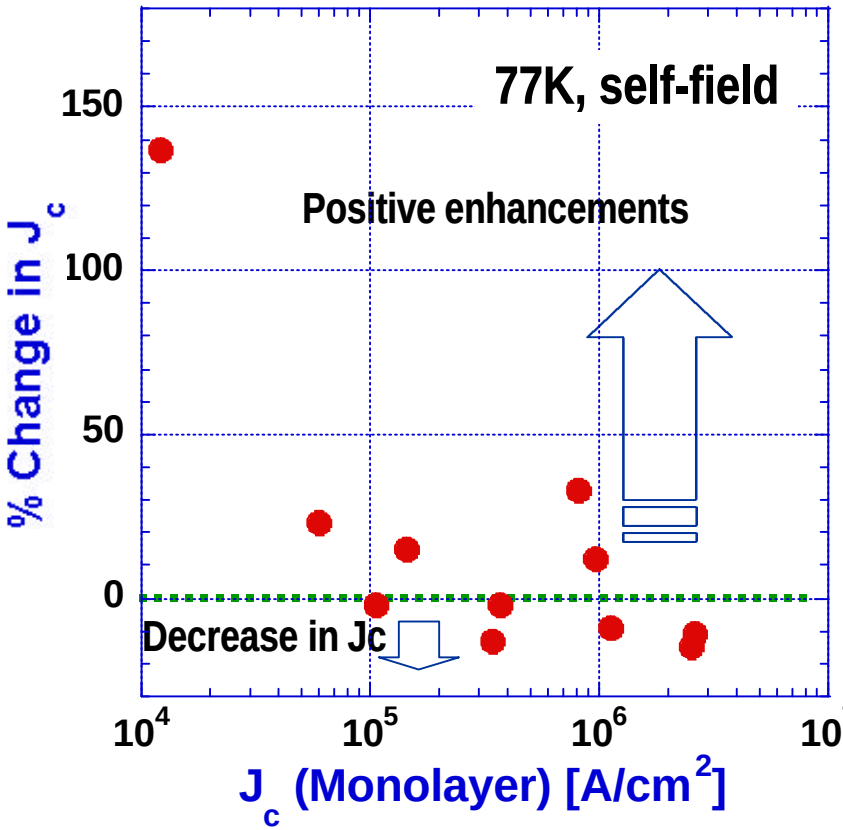
$J_{c,bi}/J_{c,mono}(\%) = +137\%$

J_c (monolayer): 1.22×10^4 A/cm^2

J_c (bilayer): 2.9×10^4 A/cm^2



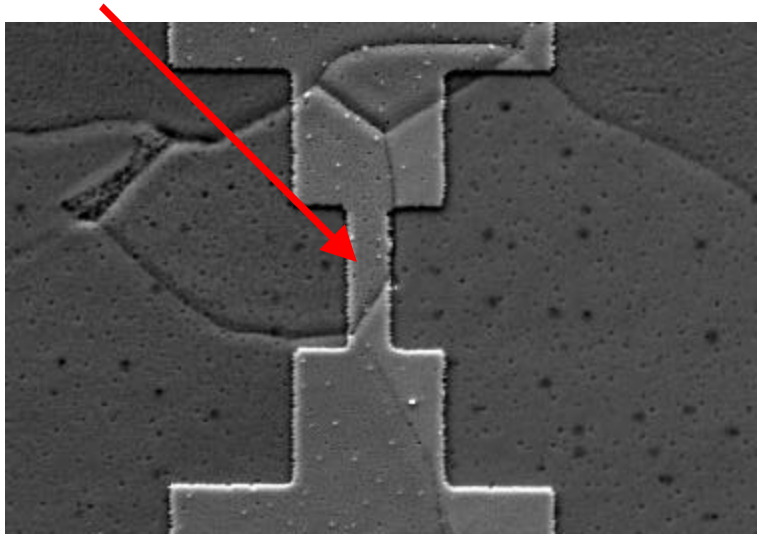
-the 10° and 9° degree GBs limit J_c



UT-BATTELLE

Summary: Ca-doping of GB's for YBCO on RABiTs

- For 30%Ca, 20%Ca, 10%Ca doped bilayers and trilayers on RABiTS, effects at 77K were not significant for standard samples
- For a 30%Ca doped bilayer, J_c enhancements of 18-35% were obtained at low temperatures, but for the trilayer J_c degraded
- Local transport measurements on bilayer samples with etched bridges show that % change in J_c at 77K varies over a wide range
- Work is in progress to look at individual GB's



UT-BATTELLE

OUTLINE

- **FY 2001 Results:**
  - **Substrate issues and grain boundary affects on J_c (Amit Goyal)**
  - **Dip-coating of solution buffers (M. Paranthaman)**
  - **Processing of high-I_c YBCO Coatings (R. Feenstra)**
  - **Stabilization of YBCO on metals (D. Christen)**

- **FY 2001 Performance and Plans for FY 2002**
- **Research Integration**

Dip-coating of solution buffers

Goal: All non-vacuum RABiTS and YBCO

FY 2001: Solution seed layers from a continuous process

- Critical first step

Approach:

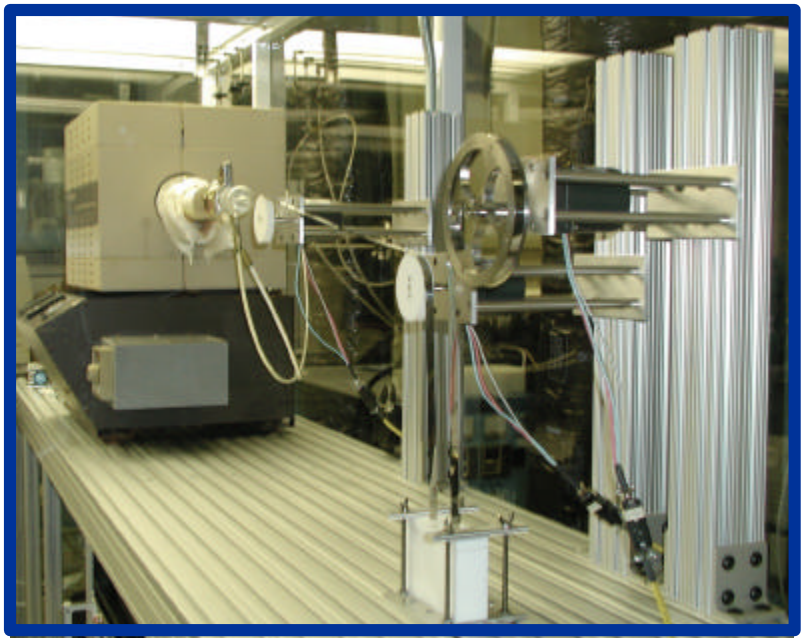
- Long length dip-coating of seed-layers on Ni and Ni alloys
  - Substrates used
    - ORNL Ni, and strengthened Ni-3% W-1.7% Fe
  - Buffers studied
    - Gd_2O_3 and $La_2Zr_2O_7$ (LZO)

      (potentially lower processing temperature with LZO)

Reel-to-reel Ni substrate cleaning and annealing

- Reel-to-reel substrate cleaner

- Meter lengths of Ni or Ni alloy substrates
- Sonicated in isopropanol
- Time: 1-m/hr



- High temp. furnace (1400 °C) with reel-to-reel capability was built (FY 2001)
- Ni, Ni-W, and Ni-13% Cr substrates were in-situ annealed in Ar/H_2 (4%)
- Temperature: 1100-1300° C
- Annealing speed: 30 cm/hr
- Dip-coating and post-annealing were done under continuous process conditions

IN FY2001: We Determined Process Conditions For Reproducible Solution Seed Layers

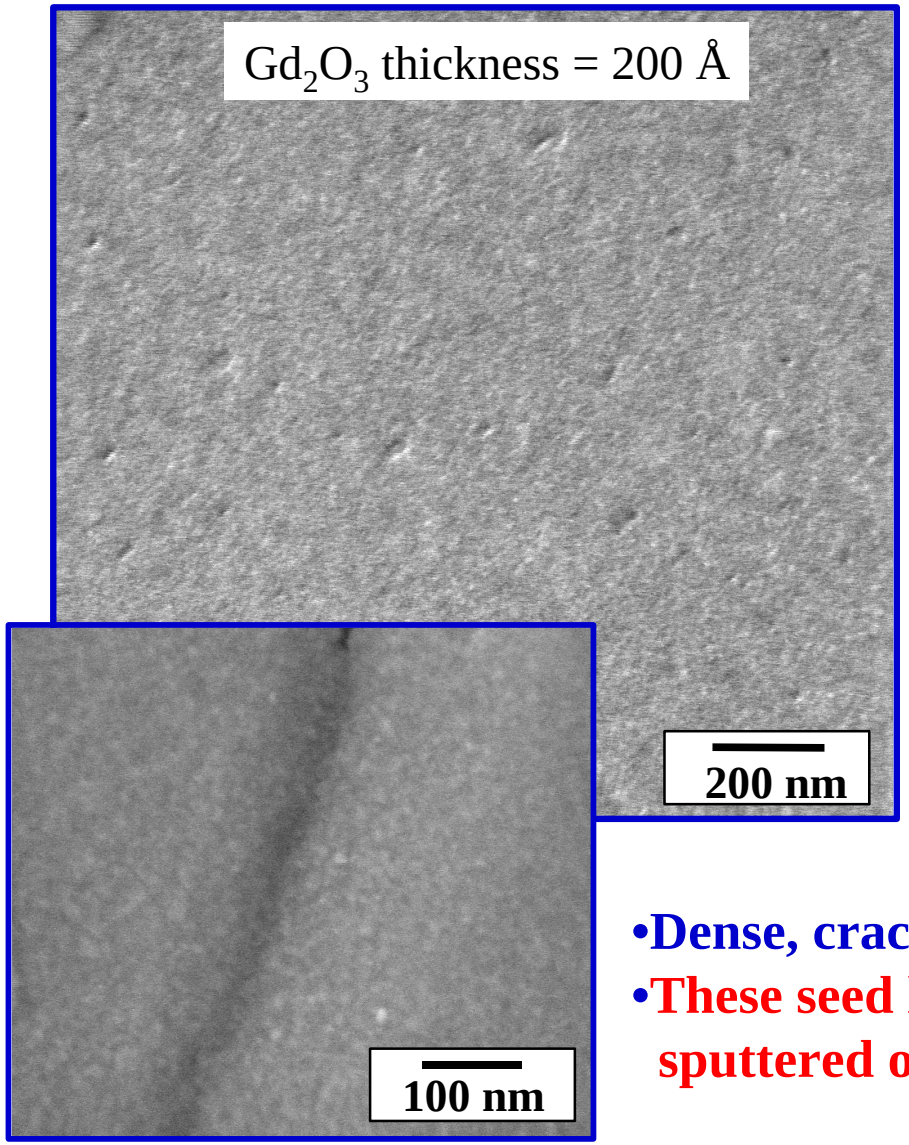
Table: Process conditions for dip-coated Gd_2O_3/Ni-W

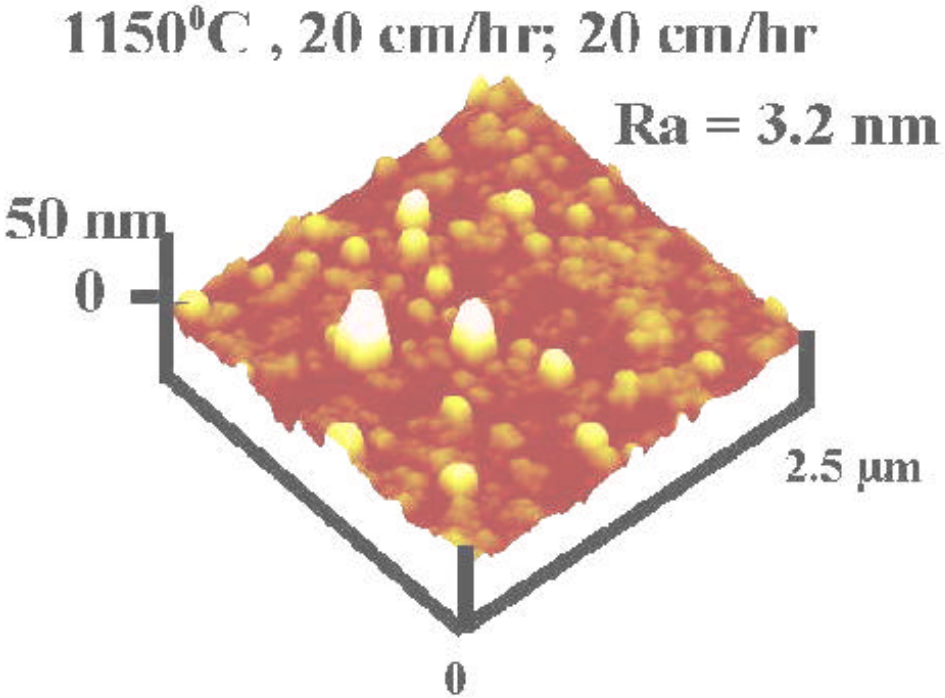
Temperature (°C)	*Coating Speed (cm/h)*	*Annealing Speed (cm/h)*	*Gd_2O_3 Thickness (Å)*	*# of carbon at. unit cell area*
1050	300	10	700	165
1100	300	10	700	149
1150	300	10	700	88
1150	20	5	200	35
1150	20	20	200	24
1150	20	30	200	40
1250 (decomposed)	20	stationary	200	4

- **Carbon content in Gd_2O_3 reduces by decreasing thickness & increasing temp**
- **Annealing speed does not significantly influence carbon amount in the samples**

Similarly, the optimum conditions for LZO seed layers are:
Coating speed: 3 m/hr; annealing speed: 30 cm/hr; solution conc. 0.5 M

Microstructure of Dip-coated Gd_2O_3 Layers on *Ni-3%W*

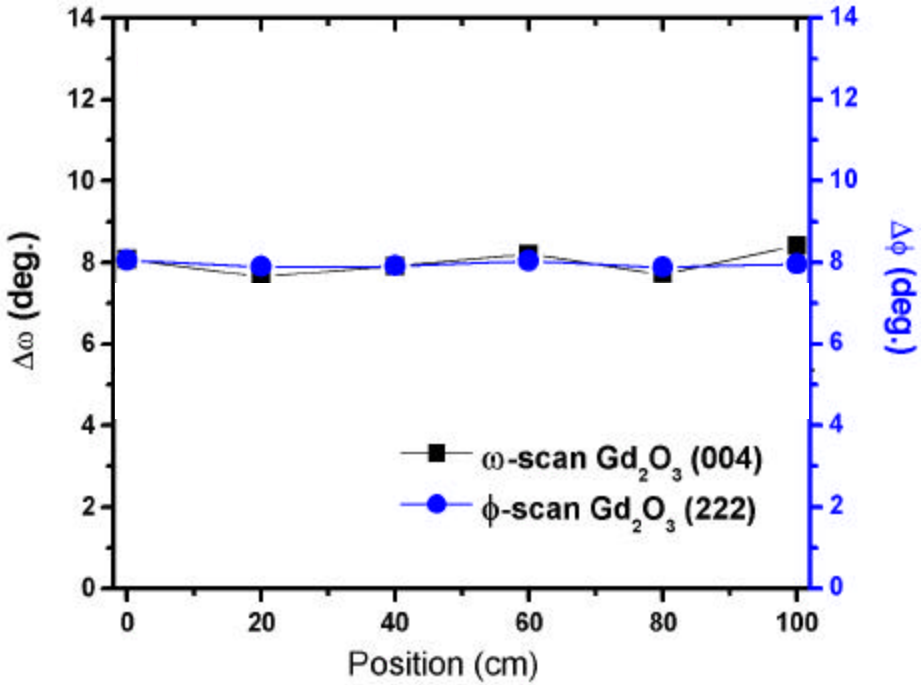




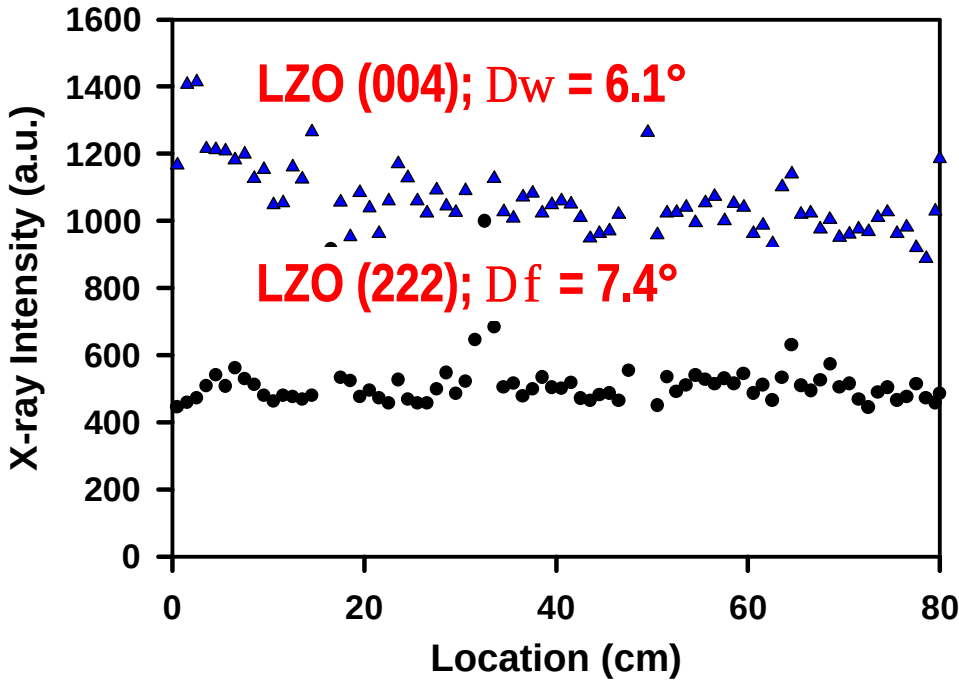
- **Dense, crack-free Gd_2O_3 seed layers were produced**
- **These seed layers support the epitaxial growth of sputtered over-layers**

Gd_2O_3 and LZO seed layers with uniform texture were fabricated on strengthened Ni-W substrates in 1-meter lengths

Gd_2O_3/Ni-3% W



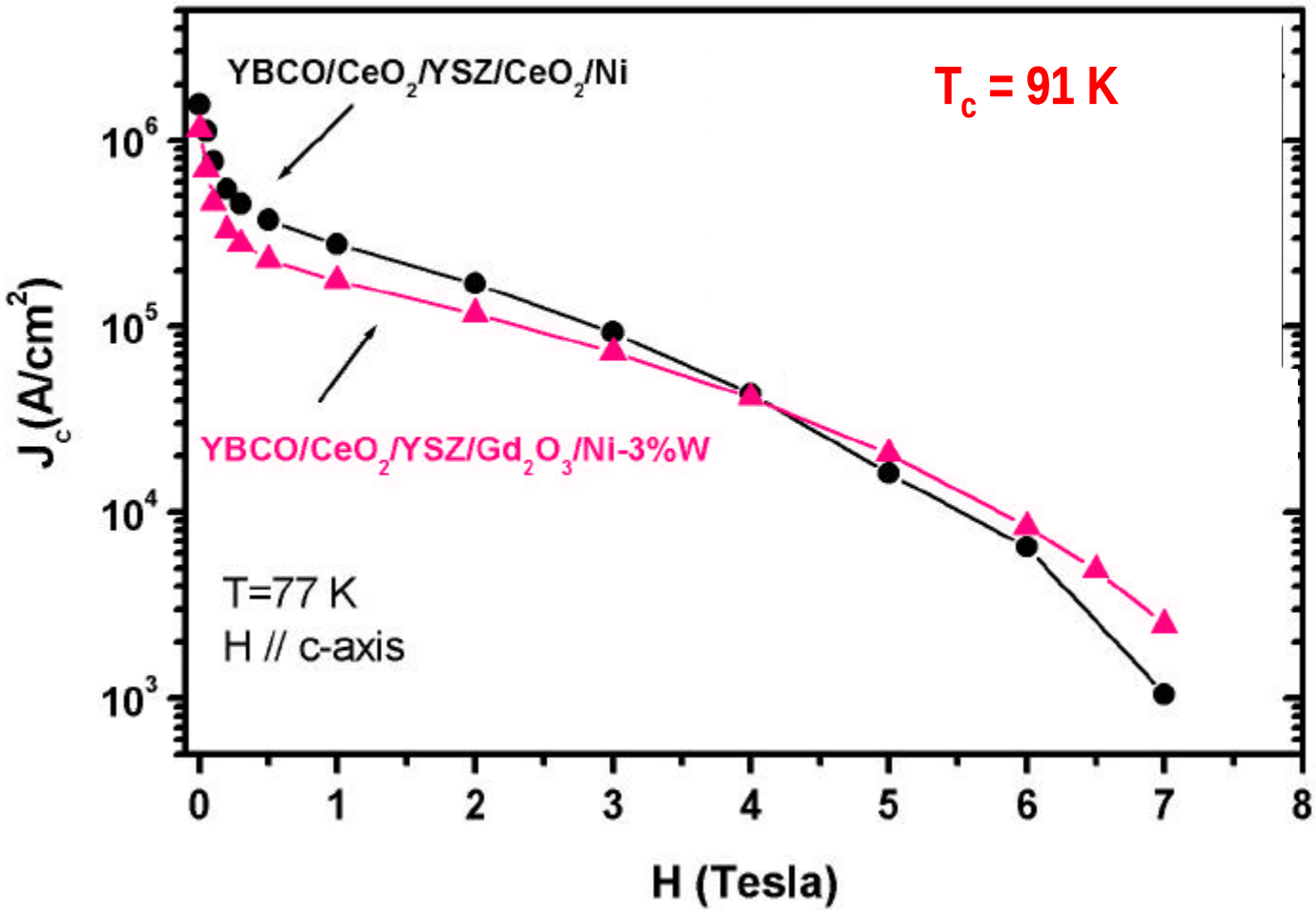
LZO/Ni-3% W



Ni (002) Dw = 5.3°; Gd_2O_3 (004) Dw = 8.0°
Ni (111) Df = 7.0°; Gd_2O_3 (222) Df = 8.0°

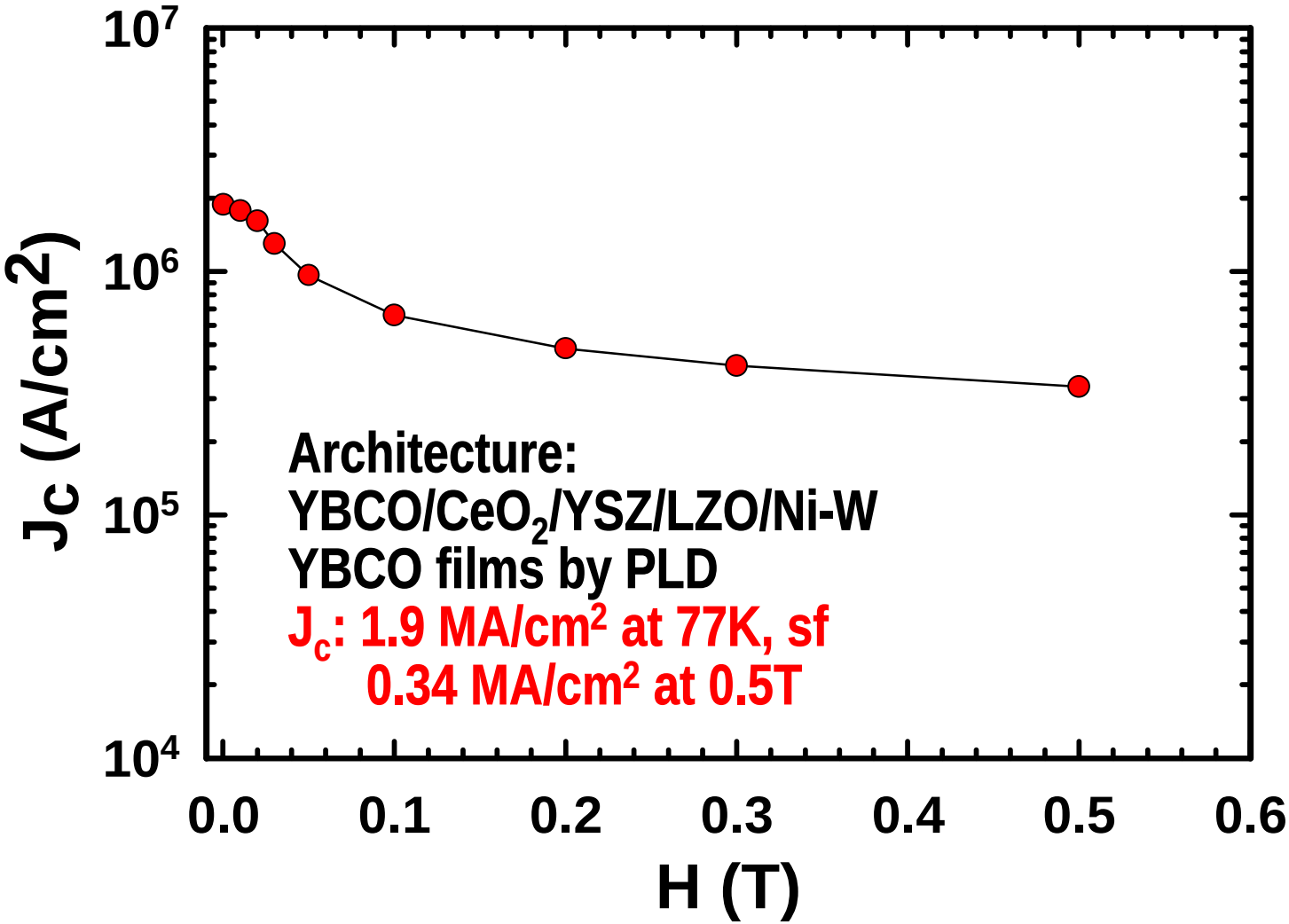
Ni (002) Dw = 5.3°; LZO (004) Dw = 6.1°
Ni (111) Df = 7.0°; LZO (222) Df = 7.4°

YBCO films with a J_c of over 1.2 MA/cm^2 were prepared on Gd_2O_3 seeds on Ni-3%W substrates using PLD



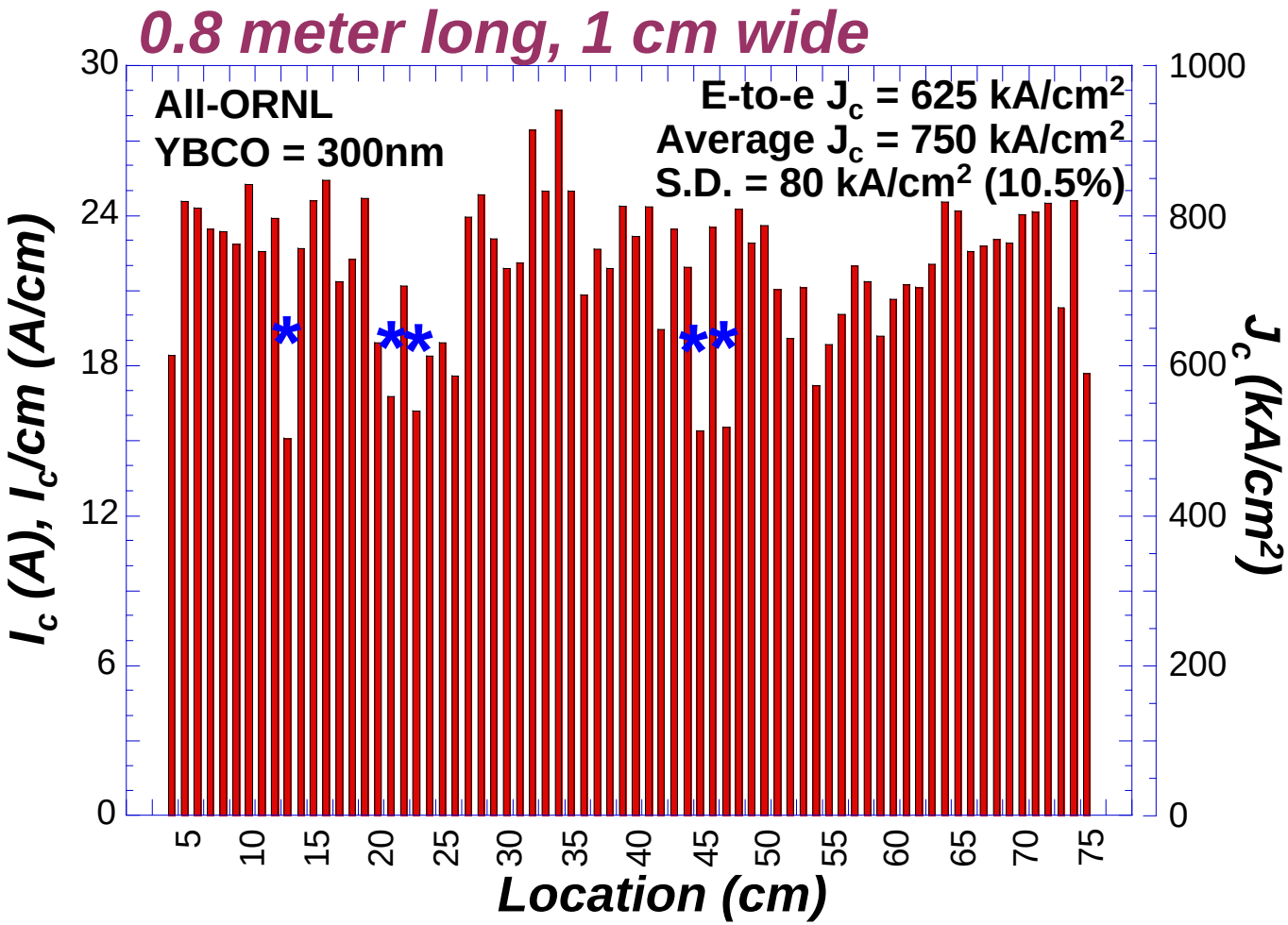
The performance of solution seed layers approach that of vacuum seed layers

LZO seeds on Ni-3%W substrates yielded very high current density YBCO films



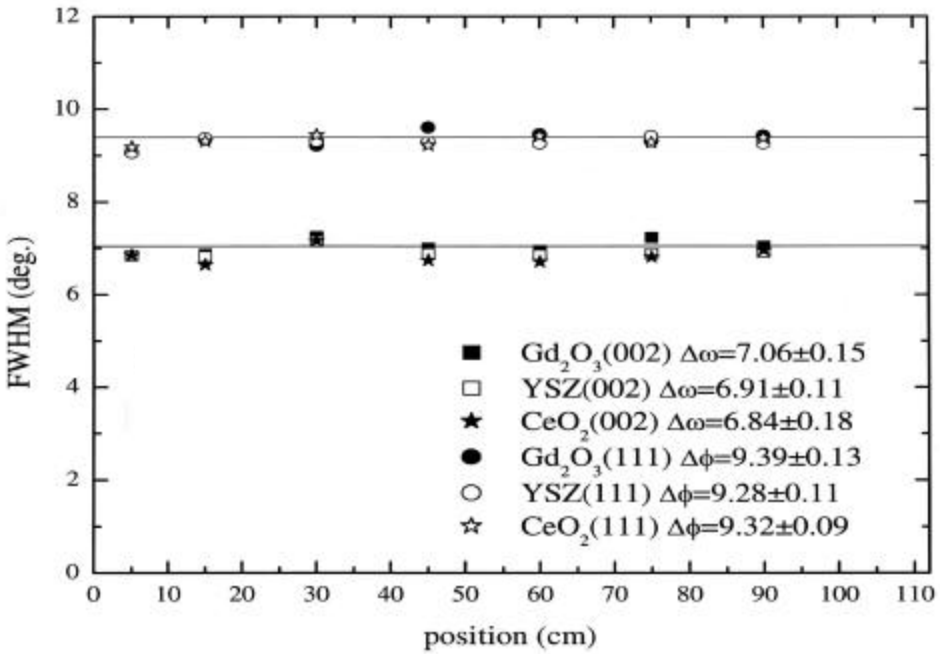
High J_c YBCO on Long Solution Seeds

- **0.8 meter on sol-gel Gd_2O_3 seed ORNL RABiTS with ORNL BaF_2 precursor (visible line features marked by *):**



Solution Deposited Buffer Layers Used in Reel-to-Reel Tape Fabrication (AMSC/ORNL)

- **Meter length RABiTS™ tapes prepared by combined sol gel and vacuum deposition processes**
  - **CeO_2/YSZ/Gd_2O_3/Ni:**
    - **Gd_2O_3 by reel-to-reel sol gel (AMSC)**
    - **YSZ and CeO_2 by by reel-to-reel magnetron sputtering (ORNL)**



J_c of 1.7 MA/cm^2 (77K, sf, short sample) demonstrated on CeO_2/YSZ/Gd_2O_3/Ni using TFA (AMSC)

Summary

- Successfully met our FY2001 milestone by demonstrating the growth of high quality solution seeds on alloy tapes
- 0.8-meter lengths of YBCO on buffered Ni tape with an end-to-end J_c of 625 KA/cm^2 were obtained using Gd_2O_3 seeds
- Both Gd_2O_3 and LZO seeds were reproducibly produced in meter lengths of strengthened Ni-W substrates
- On Ni-W substrates, YBCO films with a J_c of 1.2 MA/cm^2 on Gd_2O_3 seeds and 1.9 MA/cm^2 on LZO seeds (short samples) were produced
- Our technology has been successfully transferred to our industry partner – American Superconductor Corporation

OUTLINE

- **FY 2001 Results:**
  - **Substrate issues and grain boundary affects on J_c (Amit Goyal)**
  - **Dip-coating of solution buffers (M. Paranthaman)**
  - **Processing of high-I_c YBCO Coatings (R. Feenstra)**
  - **Stabilization of YBCO on metals (D. Christen)**

- **FY 2001 Performance and Plans for FY 2002**
- **Research Integration**

Processing of high-I_c YBCO coatings

BaF_2 process at the crossroads

candidacy of BaF_2 process for coated conductor applications was demonstrated in previous years

1998 compatible buffer layer architecture using CeO_2 cap layer
J_c = 1.6 MA/cm^2 (77 K) on RABiTS

1999 reproducibility optimized for 0.3 μm YBCO coatings
J_c = 2-3 MA/cm^2 (77 K) on RABiTS and IBAD-YSZ
correlations with substrate texture

2000 continuous reel-to-reel processing for long-tape production
high-I_c: 200 A/cm for 1 μm YBCO on IBAD-YSZ (short sample)

Outline of Results

Current research is focused on practical implementation of BaF_2 process for YBCO coated conductors

- Can I_c be improved to 500 A/cm by increasing YBCO thickness?
- Development of high-throughput process
  What are the limitations?
  Are processing conditions compatible with c-axis growth?

- reaction model for conversion process based on diffusion of H_2O and HF through the precursor layer
- new results regarding thermodynamics of BaF_2 conversion reaction
  - substrate induced limit to c-axis growth rate
- new initiatives to address complications of large-area processing
  - batch furnace with capacity of 6 m tape (1 cm width)

Enhancing I_c of *ex situ* YBCO coatings

- **evaporated precursors, single or multiple deposits**

  YBCO thickness: 1–5 μm

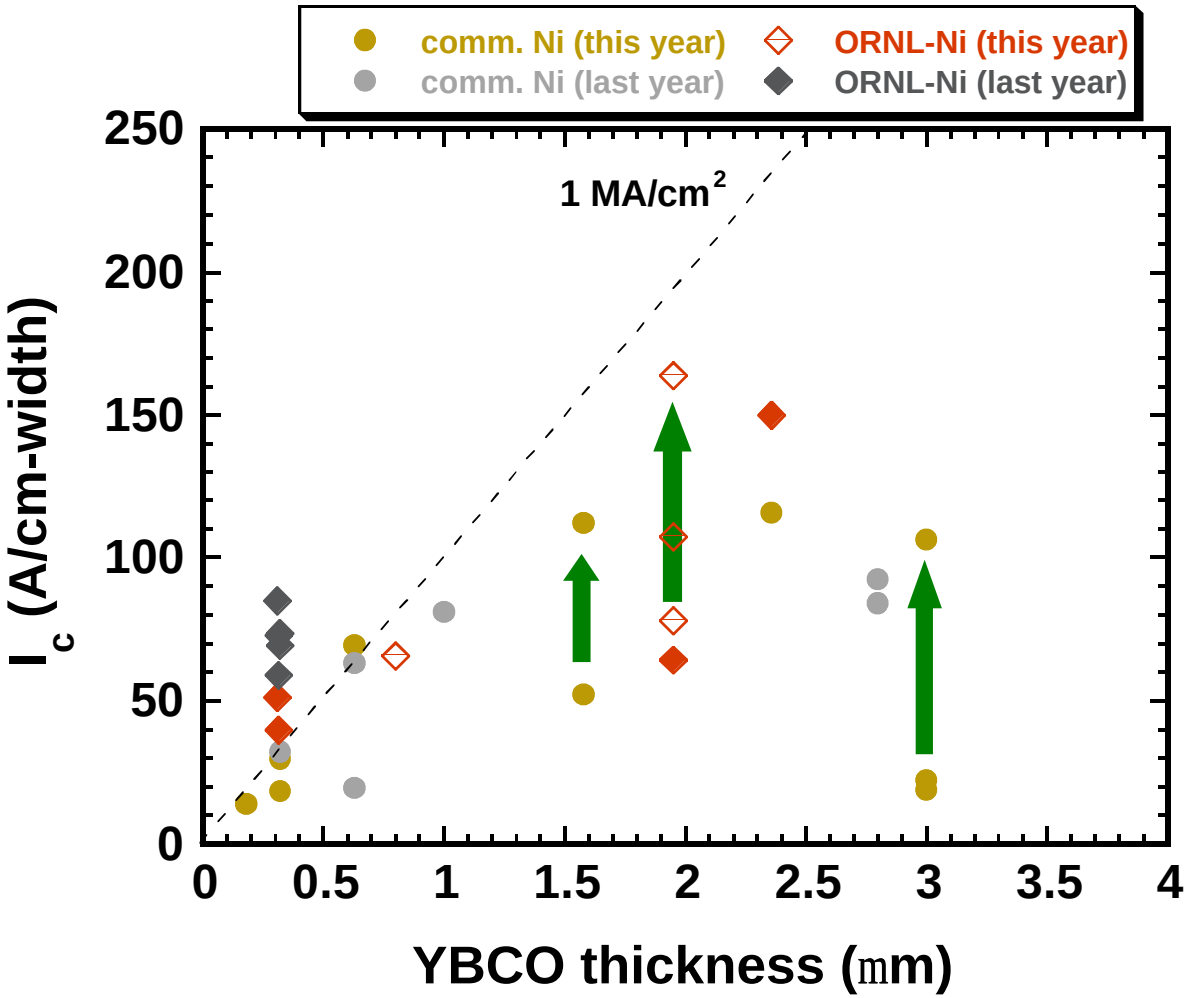
  - "unheated" during deposition
  - substrates: RABiTS roll-textured Ni ORNL (50 μm)
    commercial vendor (> 100 m)
    IBAD-YSZ LANL (100 μm inconel)

  I_c measured over full substrate width: 3-6 mm

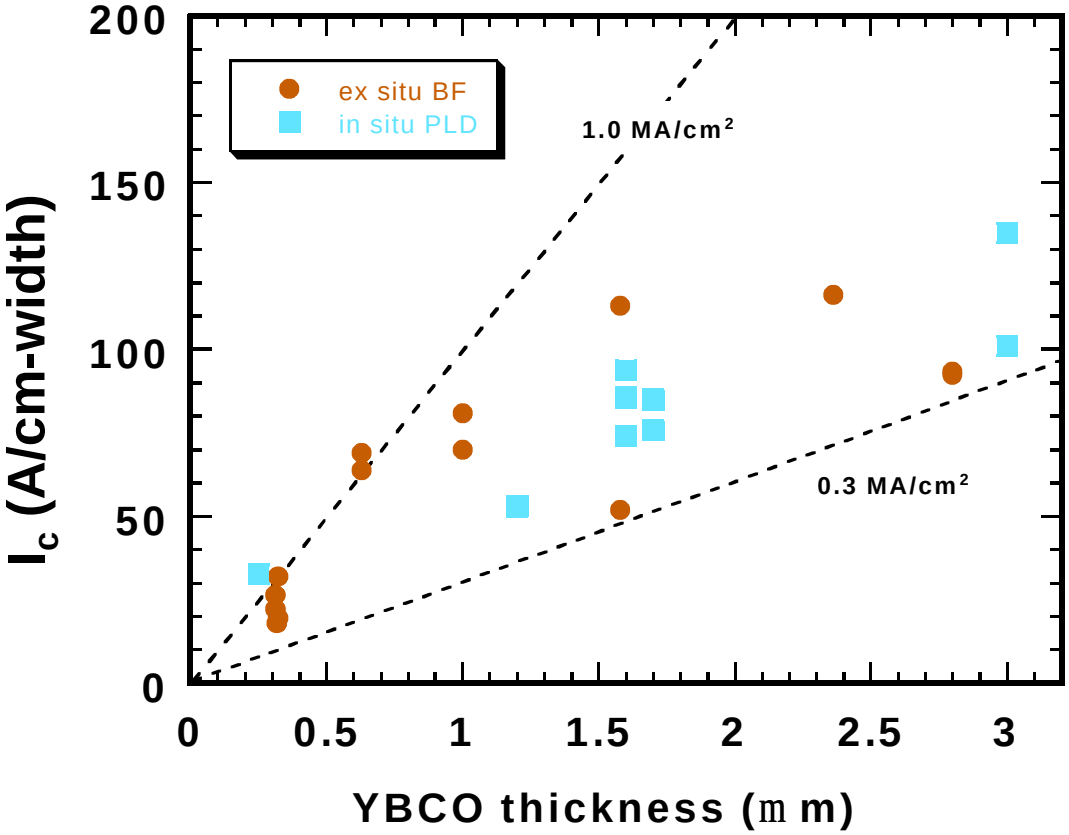
- **modified conversion process w/ low-H_2O nucleation step**
  - requires optimization for each thickness — incompletely carried out
  - present research still on "learning curve"

FY2001 milestone: demonstrate reproducible I_c(77K) > 150 A/cm-width

Improved processing has enabled increased critical currents in *ex situ* YBCO on RABiTS



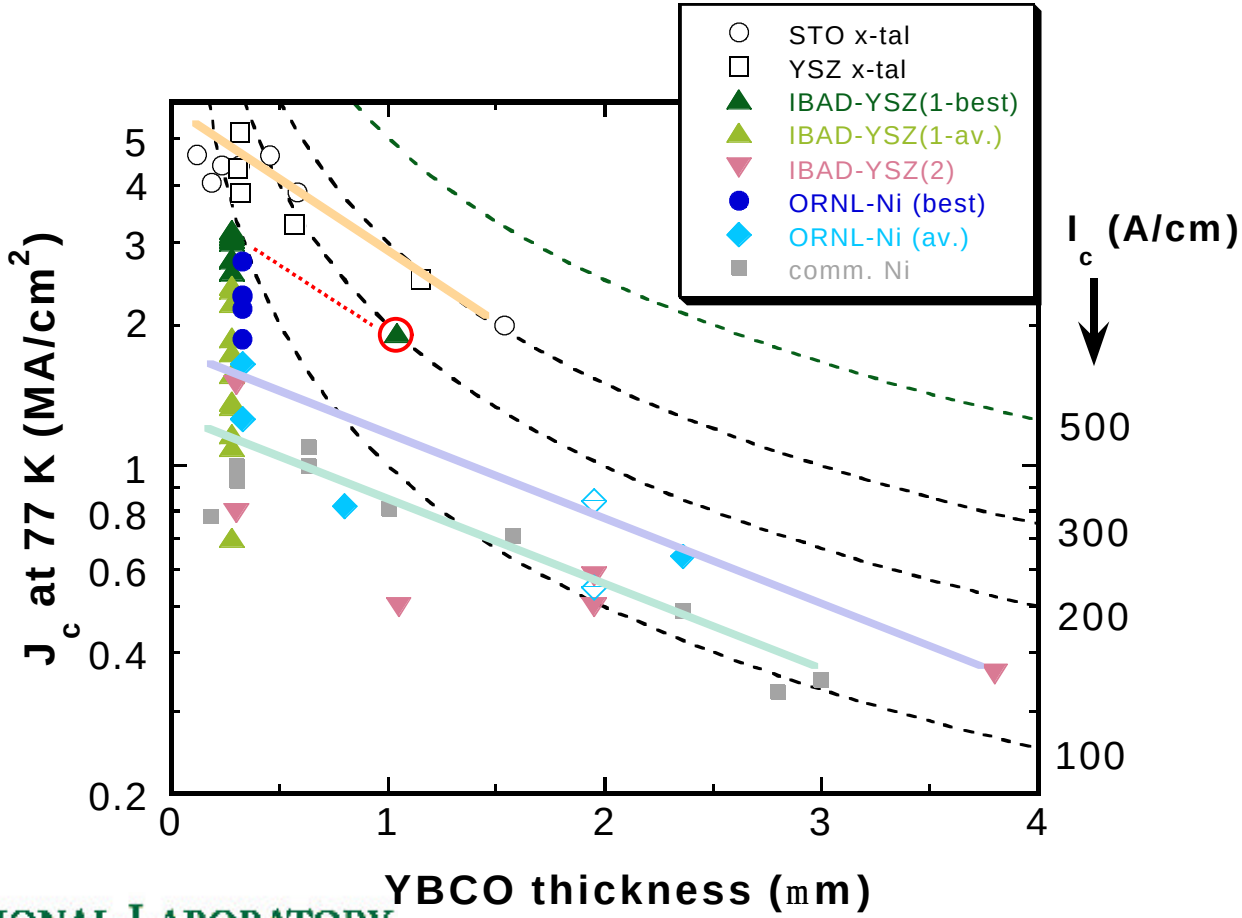
I_c of YBCO on "commercial" Ni increases with thickness: 30 A/cm (0.3 μm) ® >100 A/cm (3 μm)



- "commercial" Ni (> 100 m) produced by outside vendor using continuous process
- uniform substrate properties enable systematic study
- J_c is similar for *ex situ* BaF_2 and *in situ* PLD
- higher I_c expected from improved Ni texture

Rate of J_c decrease with YBCO thickness depends on substrate texture quality

- J_c of thin YBCO (0.3 μm) provides indicator of substrate texture
- diminishing returns of texture quality and added YBCO (increasing thickness)



The rate-limiting part of the BaF_2 process is the post-deposition *ex situ* anneal

Key characteristic (evaporated precursors and TFA)

- at the start of the anneal, the precursor contains BaF_2, Y_2O_3, and CuO
- YBCO forms through a chemical reaction of BaF_2 with H_2O

$$\mathbf{BaF_2 + H_2O \;®\; BaO + 2HF}$$

$$\mathbf{2\,BaO + ½\,Y_2O_3 + 3\,CuO \;®\; YBa_2Cu_3O_{6.5}}$$

$$DG = DG^o - RT\,ln\,(p_{H2O} / p^2_{HF})$$

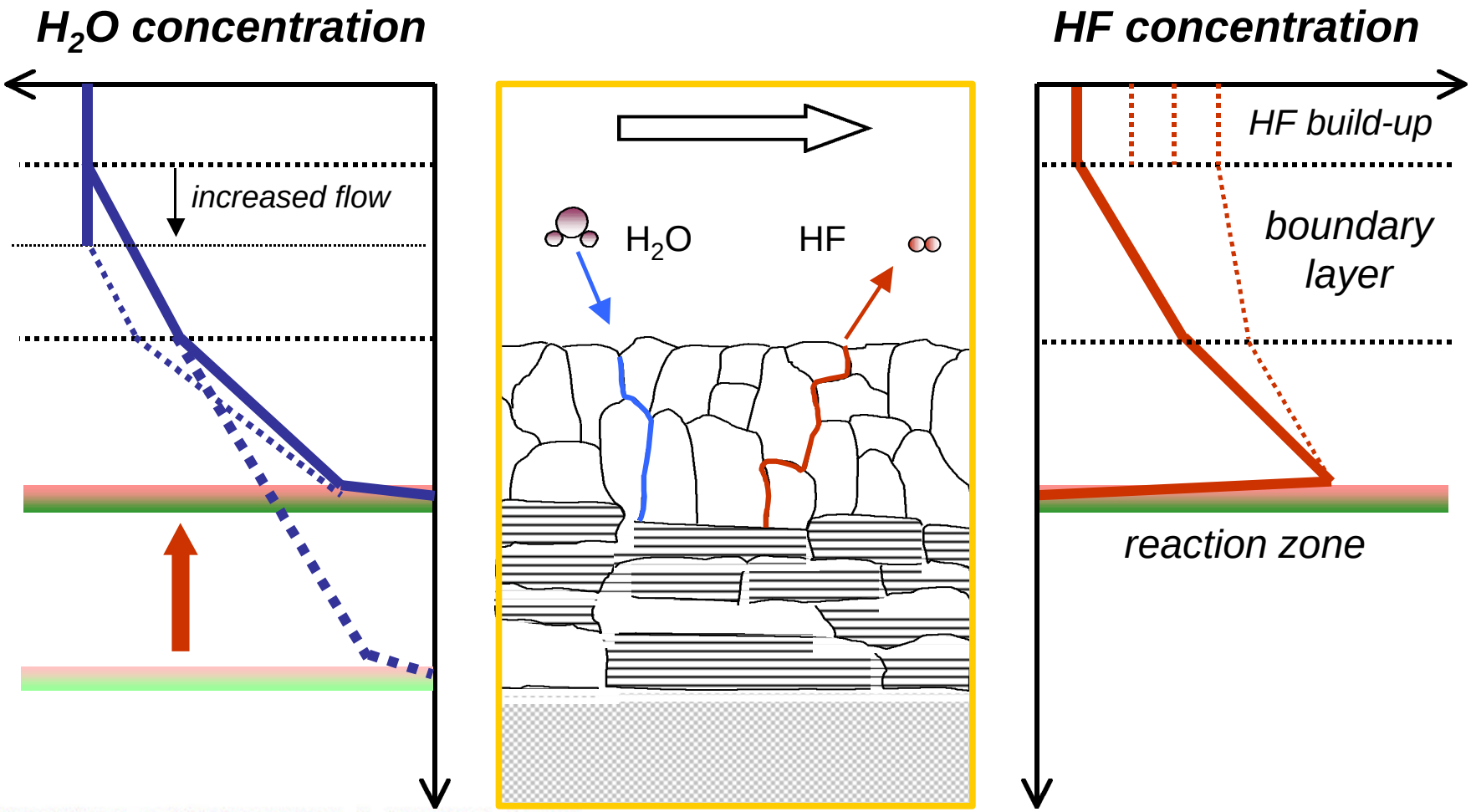
Chan et al.
APL 53, 1443 (1988)
JAP 77, 6376 (1995)

Reaction rate is controlled by H_2O supply and HF removal

- macroscopic (chemical engineering) view:
  H_2O and HF transport in/out reaction chamber ← *large-area processing*
- microscopic (materials science) view:
  p_{H2O} / p^2_{HF} controls: epitaxial growth ← *intrinsic growth rate*
  BaF_2 reactivity with substrate

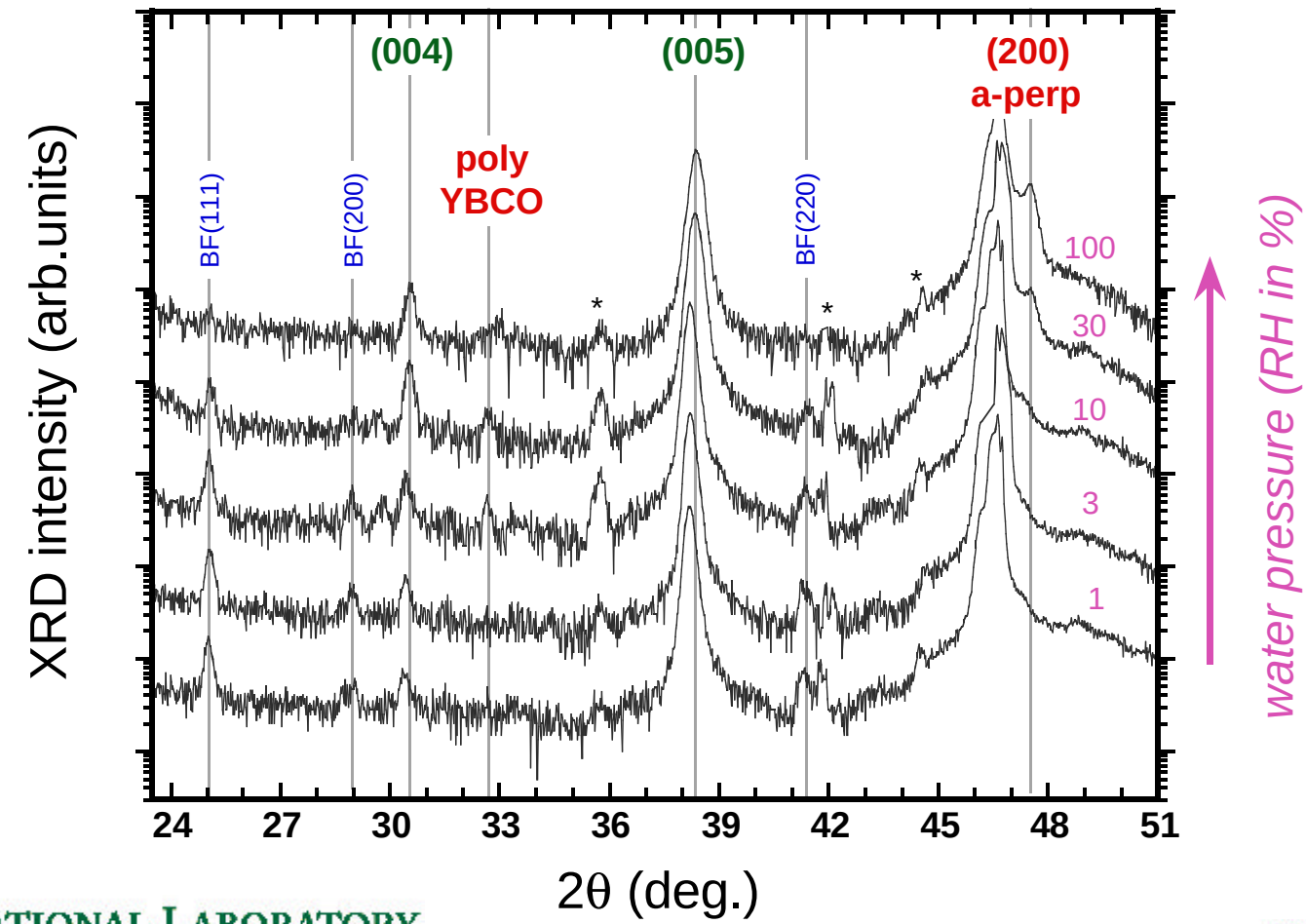
BaF_2 conversion reaction (rate) inside the precursor controlled by H_2O and HF in/out diffusion

Conversion rate µ H_2O and HF concentration gradients



Increasing p(H_2O) speeds up the BaF_2 conversion — however, causes non c-axis growth

0.6 μm YBCO, quenched after 0.3 h



(p_{H2O} / p^2_{HF}) controls BaF_2 conversion rate and reaction *type*

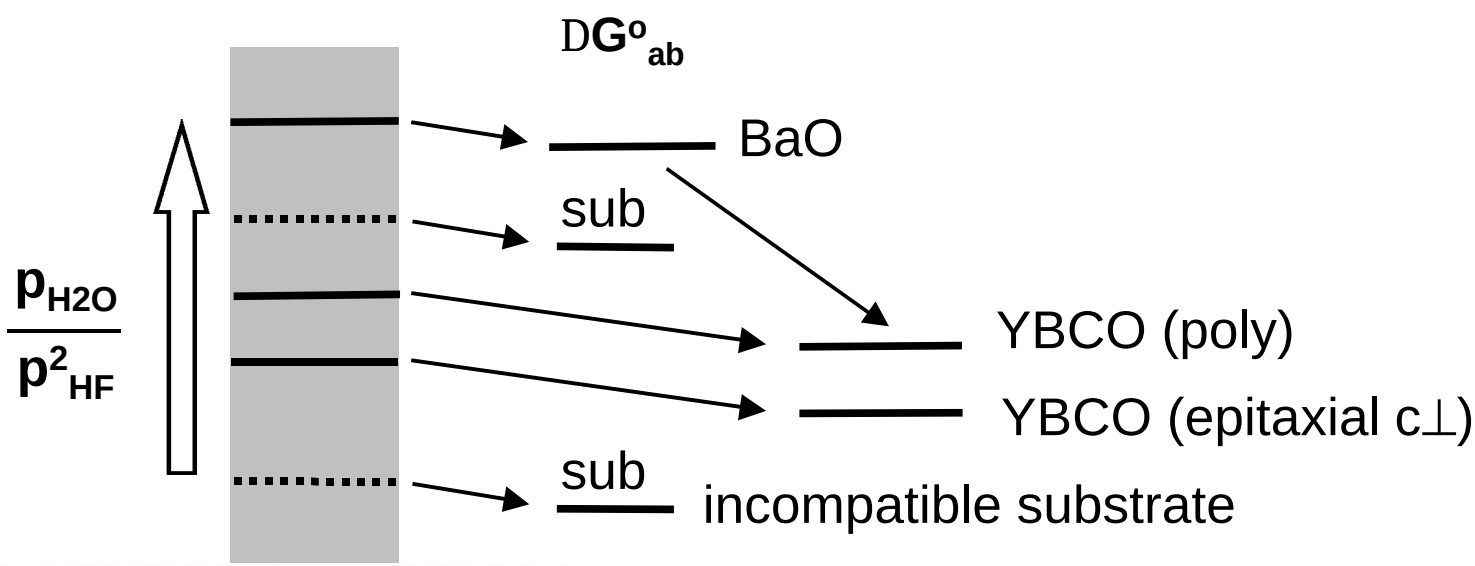
- reaction of BaF_2 with H_2O in presence of oxides $M(a)O_x$, $M(b)O_y$

$$\mathbf{BaF_2 + M(a)O_x + M(b)O_y + H_2O \;®\; Ba\text{-}M(a)M(b)O_z + 2HF}$$

e.g. $M(a)O_x = Y_2O_3$, $M(b)O_y = CuO \rightarrow YBa_2Cu_3O_{6.5}$

$$\mathbf{DG = DG^o_{ab} - RT\ ln\ (p_{H2O} / p^2_{HF})}$$

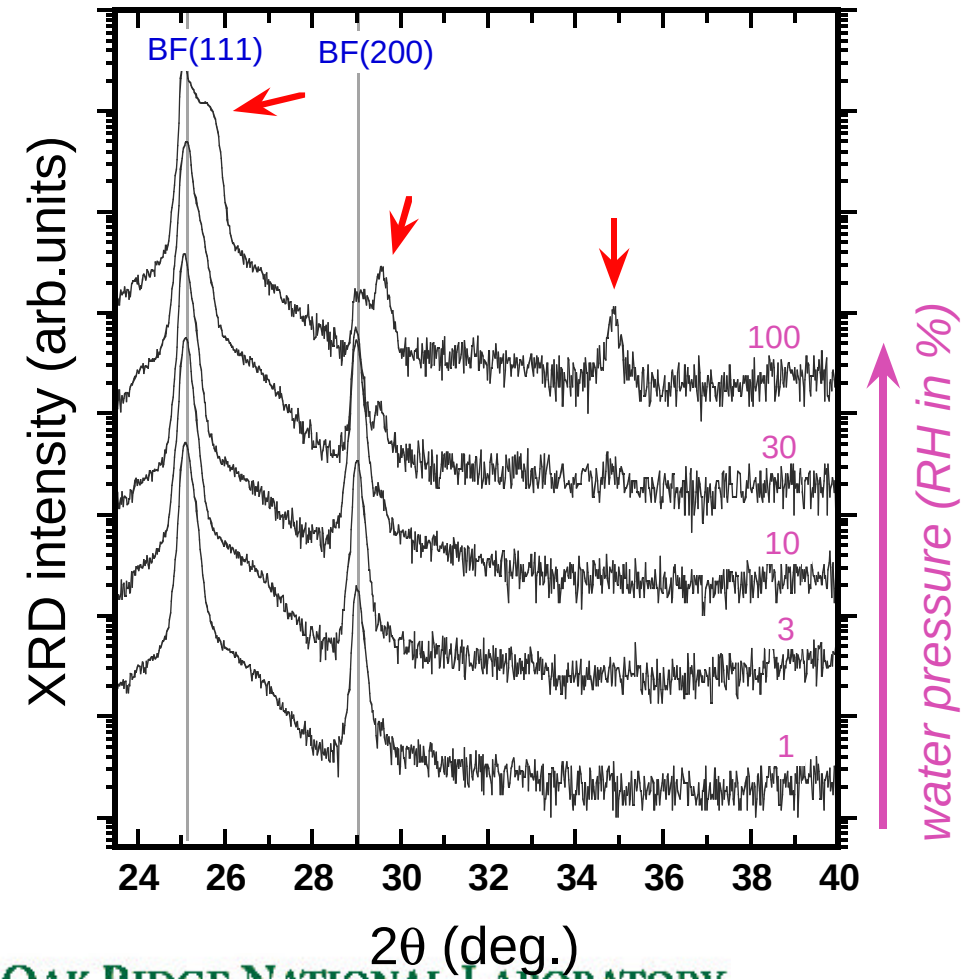
- reaction goes forward if $\Delta G < 0 \rightarrow RT \ln (p_{H2O} / p^2_{HF}) > \Delta G^o_{ab}$

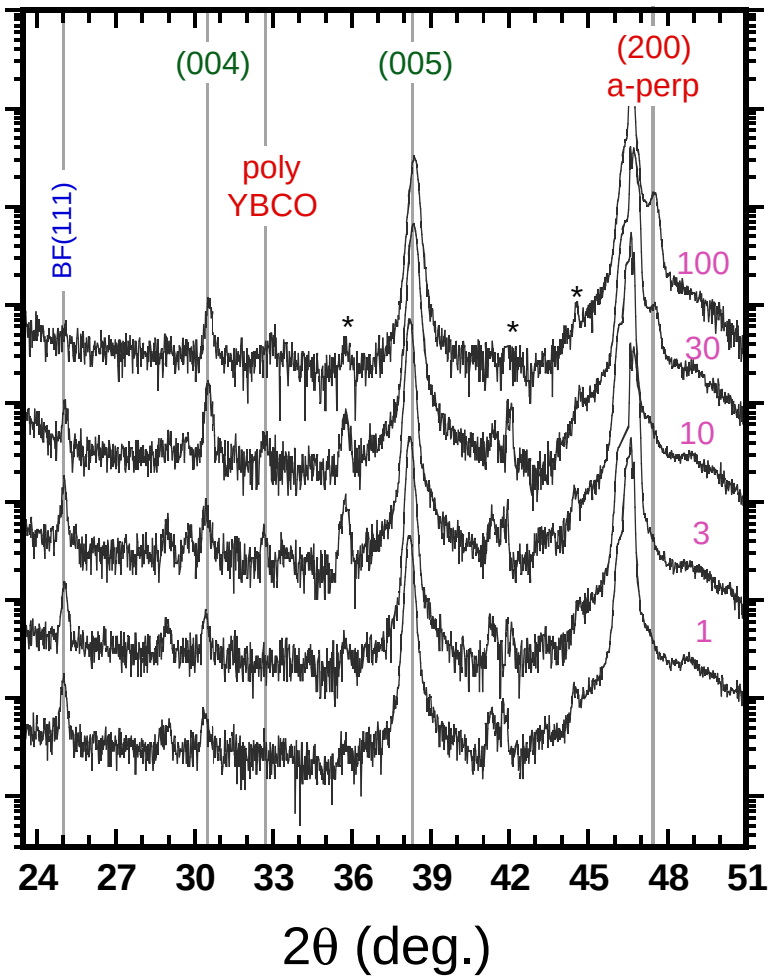


BaF_2 does not decompose in absence of Y_2O_3 + CuO — reacts with STO beyond $p(H_2O)$ threshold

BaF_2 / STO quenched after 0.3 h

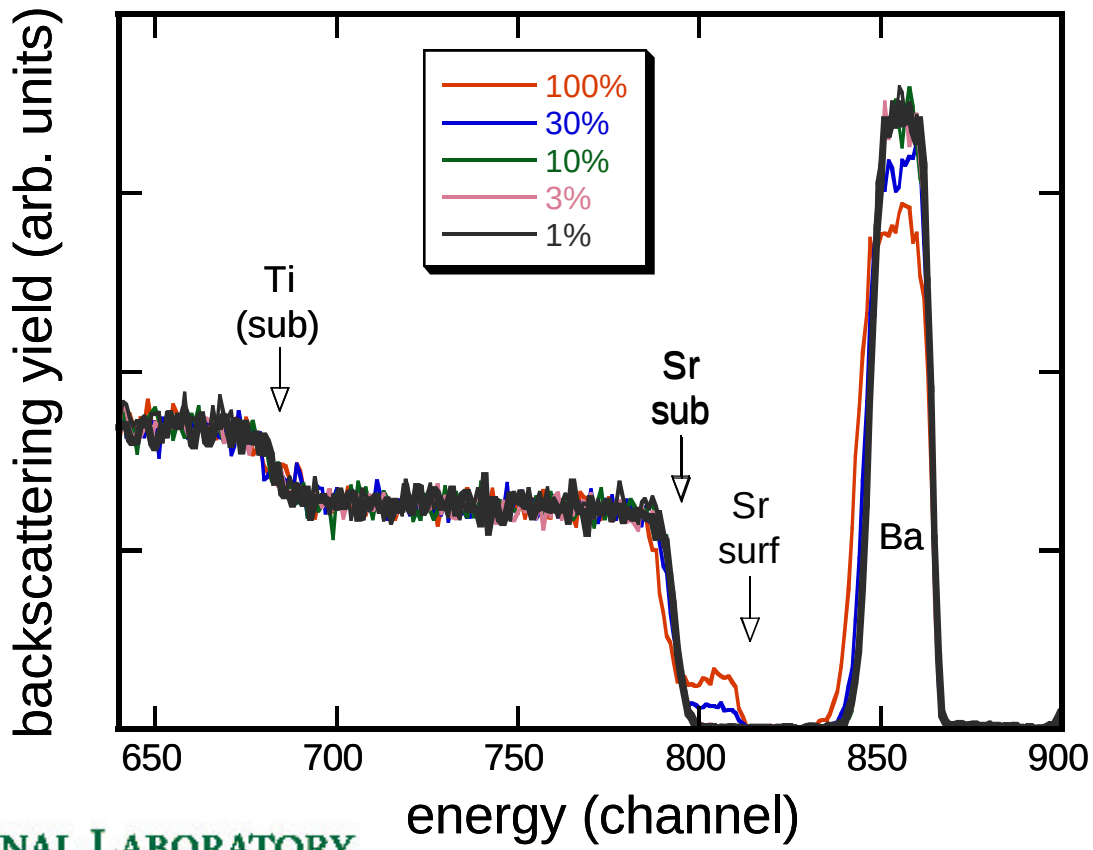
Non c-axis growth sets in at same $p(H_2O)$ threshold as BaF_2 – STO reaction





RBS shows intermixing of Sr and Ba at BaF_2 – STO interface beyond threshold $p(H_2O)$

- YBCO c-axis growth competes kinetically with BaF_2 – substrate reaction
- **substrate induced limit to maximum conversion rate: 1-3 Å / s**
- **new opportunities to explore higher rates**



High-throughput BaF_2 process will involve large-area conversion annealing

production rate PLD w/ industrial laser: **7–24 cm/min** (1 μm YBCO)

→ area to be processed at once for equivalent rate w/ BaF_2 process

PLD:	500 Å/s x 8 cm^2	(1 cm wide x 8 cm)
BaF_2 process:	1 Å/s x 4000 cm^2	(1 cm wide x 40 m)

- For large areas, HF build-up in the reactor may reduce conversion rate

$$G\ (\mathrm{mm/min}) \propto [p(H_2O)]^{1/2} \times F(\mathrm{L/min}) / A(\mathrm{cm}^2)$$

- **There is a need to overcome inefficiencies of flowing gases in removing HF**
- New research has been started at ORNL in FY2001 to explore reduced-pressure (vacuum) processing
  - 0.01-0.1 atm: effects of large $p(H_2O)/p^2(HF)$ on growth solvable reduced gas consumption rate
- A new batch furnace has been designed and installed to explore large-area processing

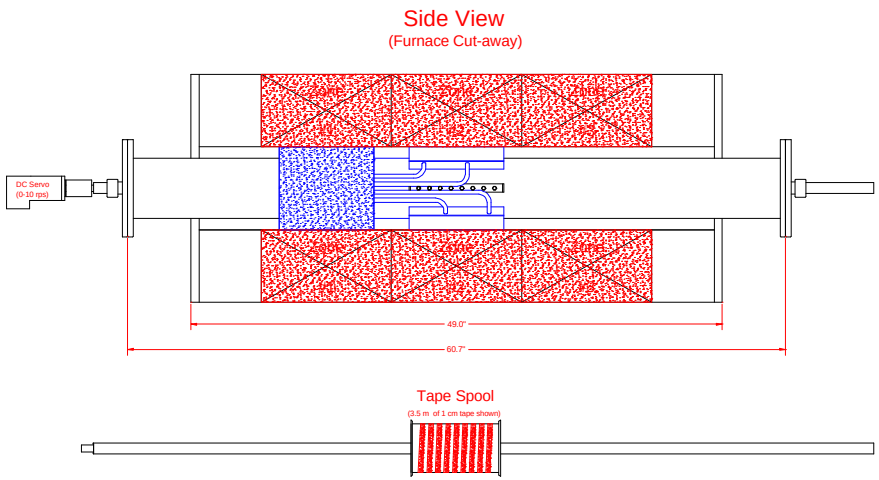
A batch furnace for simultaneous processing of long tape lengths has been constructed

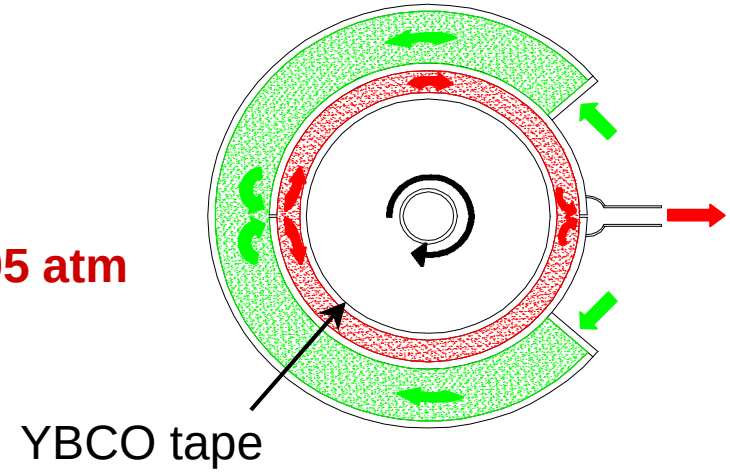
- **tape is wound on rotating spool**
  - d = 11.3 cm → 35.5 cm / turn
  - L = 20 cm → 18 turns (1 cm wide)
  - tape length → 6.4 m

- **gas handling**
  - homogeneous gas distribution
    - nozzle → spool width
    - rotation → perimeter
  - chamber volume: 0.78 L
  - flow rates (1 atm): 10-40 L/min
  - gas consumption (3hr): 2-8 m^3

capable of low-pressure operation 1– 0.05 atm

currently in testing phase





Summary and Plans

- **I_c of *ex situ* YBCO on RABiTS has been increased from 110 to 164 A/cm**
  - consistently high I_c > 100 A/cm is obtained for 2-2.5 μm thick YBCO
  - higher I_c is expected from improved Ni texture
  - **Plan for FY2002**: control study on single crystal Ni (w/ buffer layers)

- **Quench studies on thick and thin YBCO provide deeper understanding of the BaF_2 conversion process**
  - reaction between BaF_2 and substrate has been identified as possible cause of non c-axis growth, non-intrinsic(?) limit to YBCO growth rate
  - BaF_2 does not decompose in the absence of Y_2O_3 and CuO

YBCO growth rate = BaF_2 conversion rate

- **A batch furnace to address complications associated with large area processing has been constructed and installed**
  - optimize for efficient HF removal
  - parallel research is probing efficacy of reduced pressure (vacuum) processing

OUTLINE

- **FY 2001 Results:**
  - **Substrate issues and grain boundary affects on J_c (Amit Goyal)**
  - **Dip-coating of solution buffers (M. Paranthaman)**
  - **Processing of high-I_c YBCO Coatings (R. Feenstra)**
  - **Stabilization of YBCO on metals (D. Christen)**

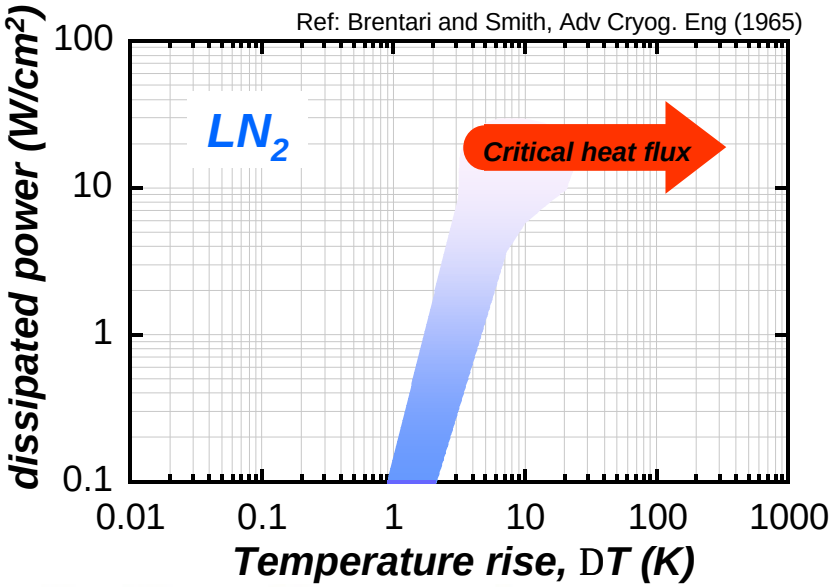
- **FY 2001 Performance and Plans for FY 2002**
- **Research Integration**

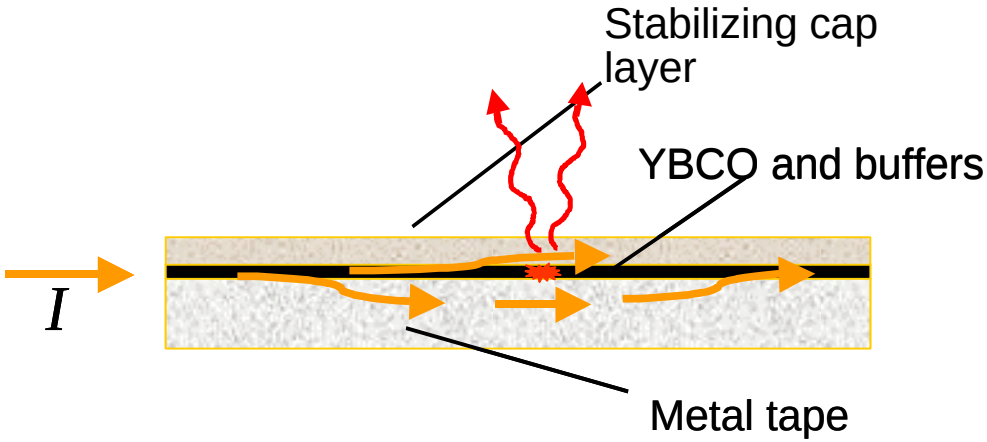
Issues of coated conductor thermal stability at liquid nitrogen temperatures

- ***For dissipative occurrence (e.g. overcurrent, microcrack, thermal transient), an isolated HTS layer is at risk***

  e.g., $W = (J_c)^2 \times r_n \approx (10^6\ A/cm^2)^2 \times 50$ mW-cm $\approx$ 50 MW/cm³!

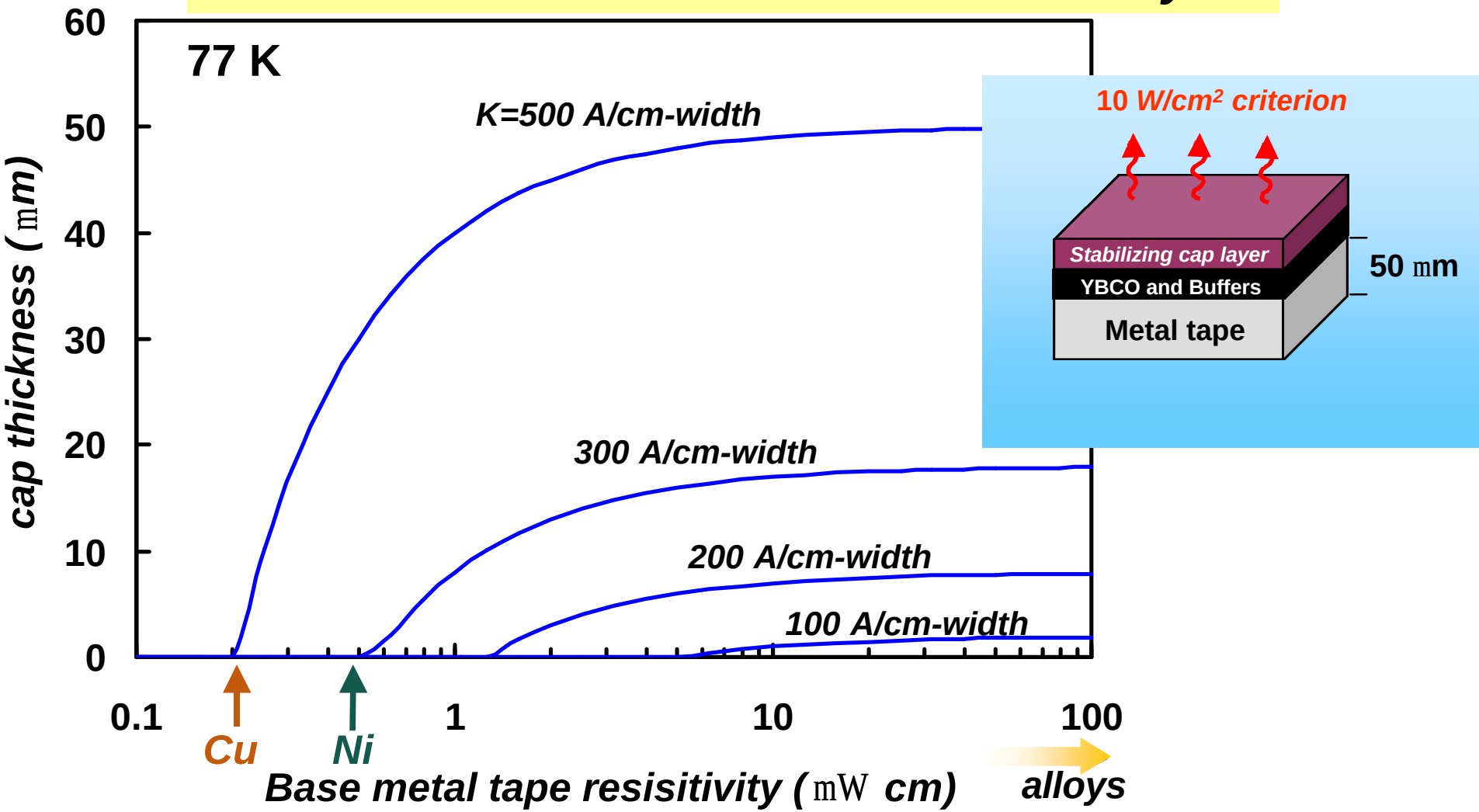
- ***For envisioned operating parameters, current must be shunted away from superconductor by a highly conductive cap layer and/or base metal***
- ***Model simulations have been studied, and prototype systems tested for operation in LN_2 and by conductive cooling***





Simulation: ideal current sharing into a cap layer and underlying metal tape

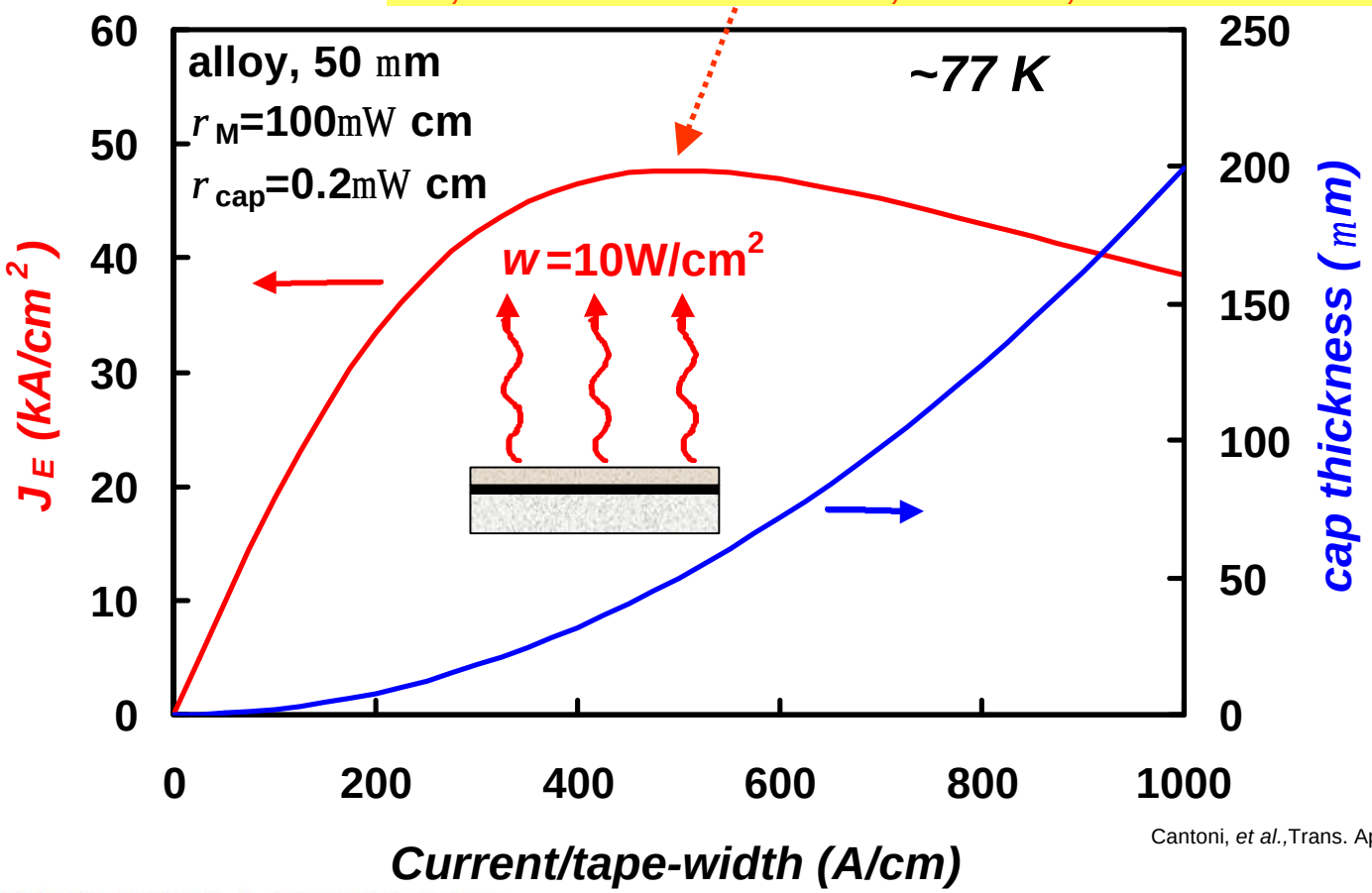
Potential benefits of conductive buffer layers



Alloy tapes/insulating buffers: stability criterion requires conductive cap layer

- *Required cap layer is very thick at large currents*
- *J_E acquires a maximum value » 48kA/cm^2, near K=500A/cm, and d_{cap}» 50 μm*

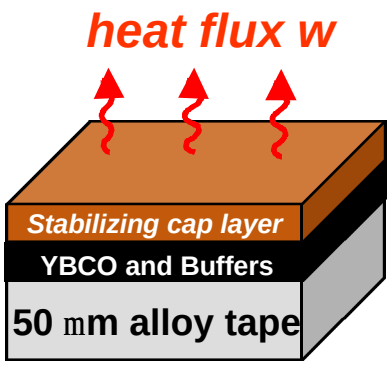
$$J_{E,max} = J_c \{(r_s - r_c)/ r_s + 2[J_c^2 r_c^2 r_{m,c}^{-1} (d_m /w)]^{1/2} \}^{-1};$$
$$d_{s,max} = [(w\, d_m)/(J_c^2 r_{m,c})]^{1/2};\ r_{m,c} = r_m r_c/(r_m - r_c)$$

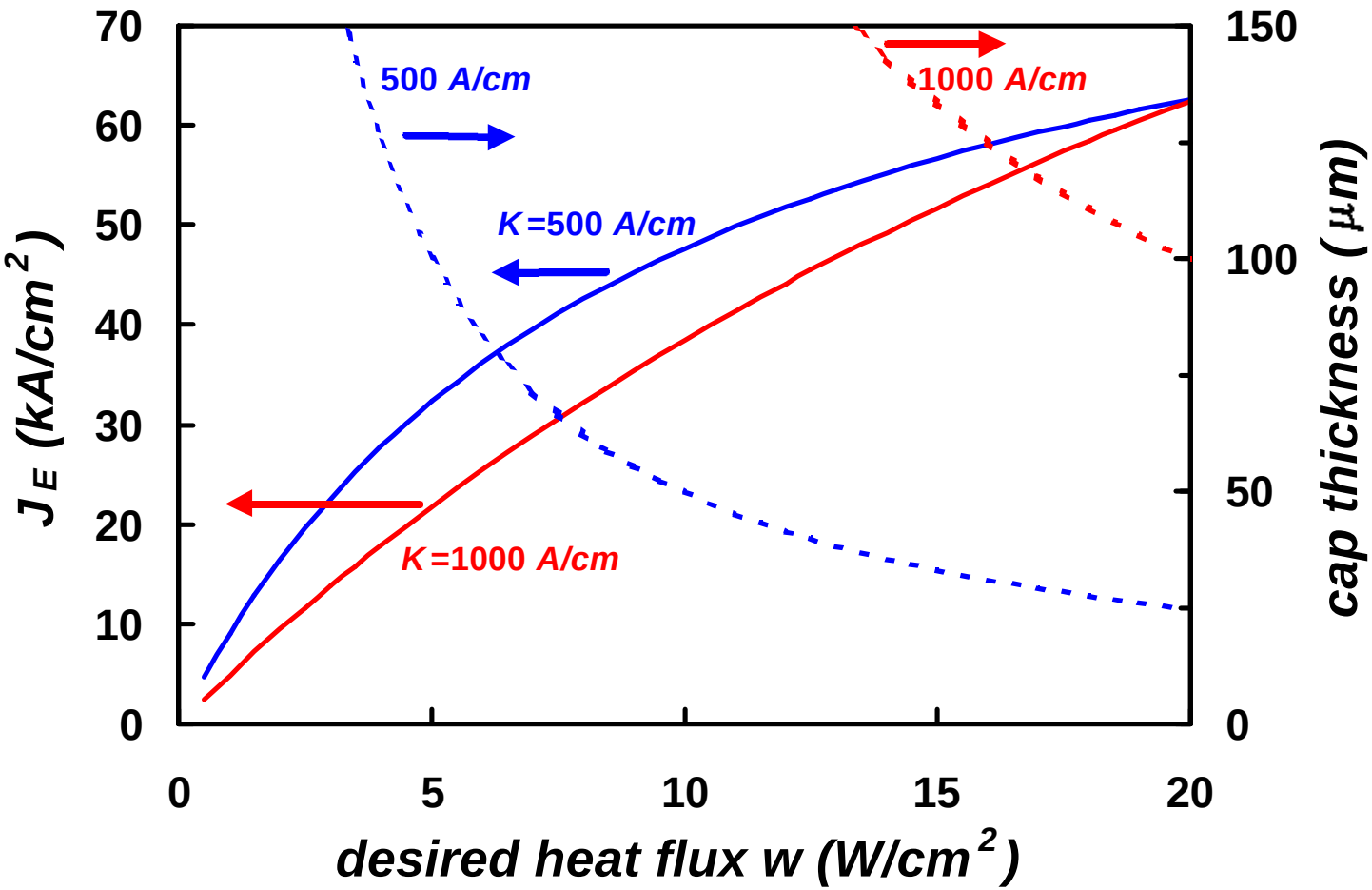


Cantoni, *et al.*,Trans. Appl. Supercond. (2001)

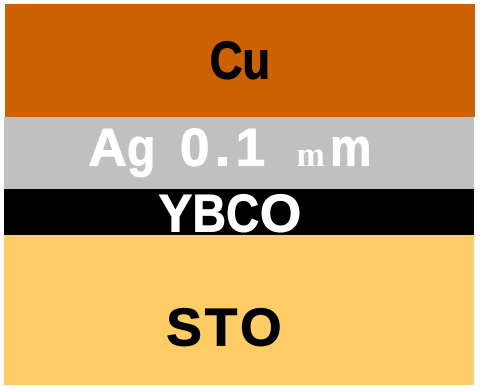
Dependence of maximum J_E and cap thickness on heat-flux stability criterion

- *Large current levels may yield lower J_E due to large required cap thickness*
- *Production of large-K tape allows design for in-field application at lower K*



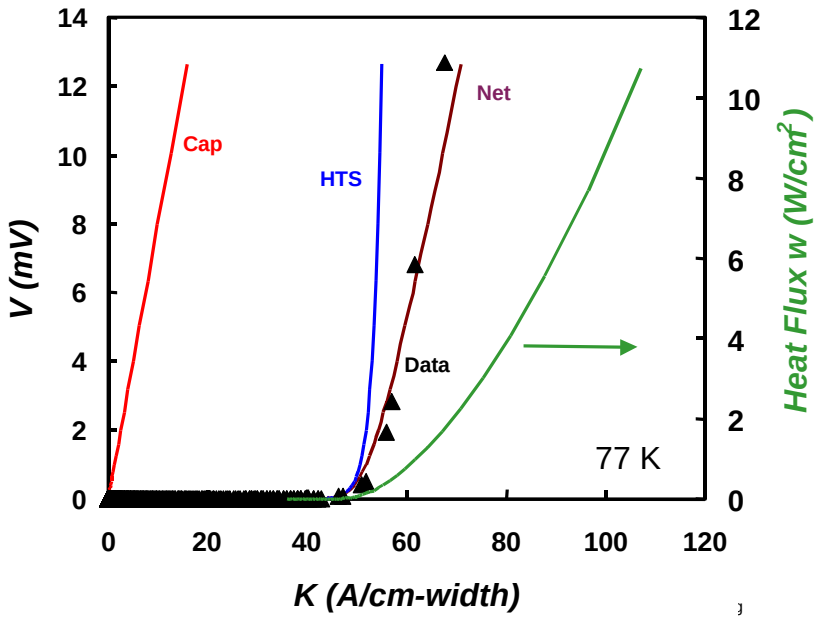


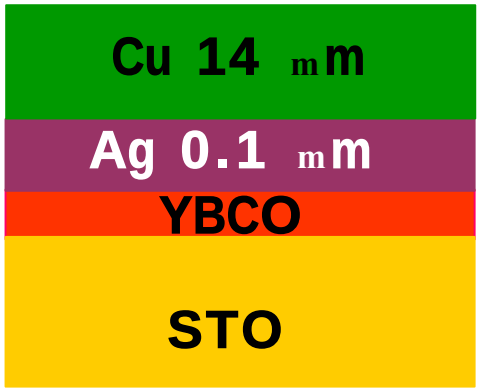
Fabrication and control studies of Ag/Cu cap layers on YBCO short-sample coatings



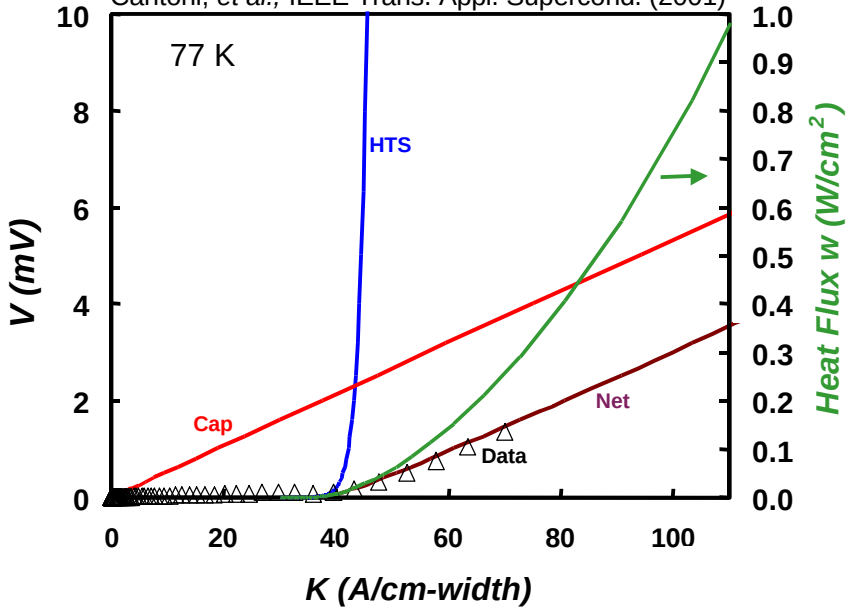
- ***YBCO films deposited by PLD on insulating, single crystal $SrTiO_3$***
  J_c » 3 MA/cm^2; thickness ~ 130 nm
- ***in situ deposition of thin Ag layer (typically 0.1mm) at <100°C, followed by 500°C anneal***
- ***ex situ deposition of Cu overlayer by dc magnetron sputtering***
  Interfacial areal resistances ~ 10^{-8} W cm^2

Measured voltage-current relations of YBCO coating with stabilizing cap layer (in LN_2)

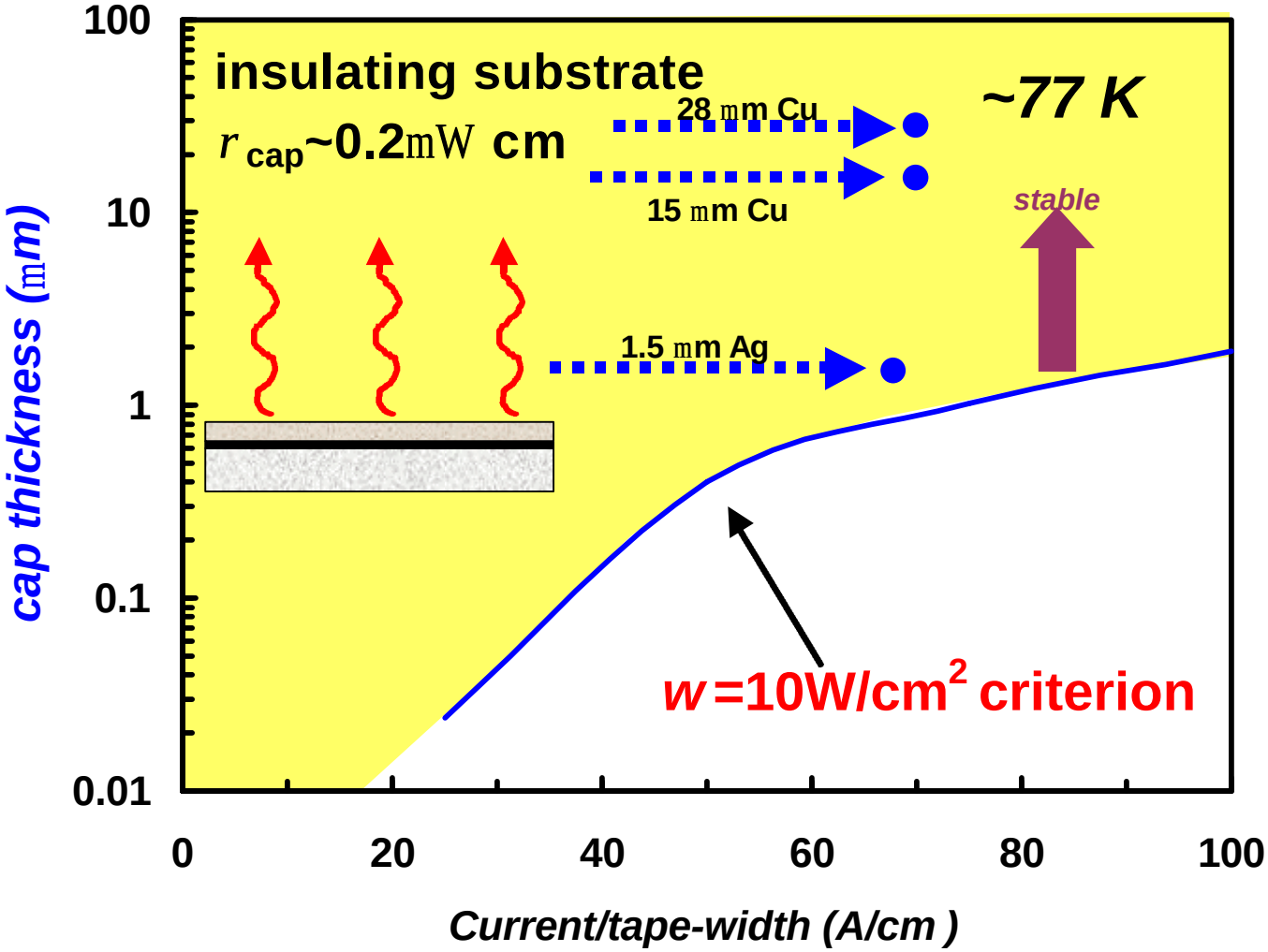




Cantoni, *et al.*, IEEE Trans. Appl. Supercond. (2001)

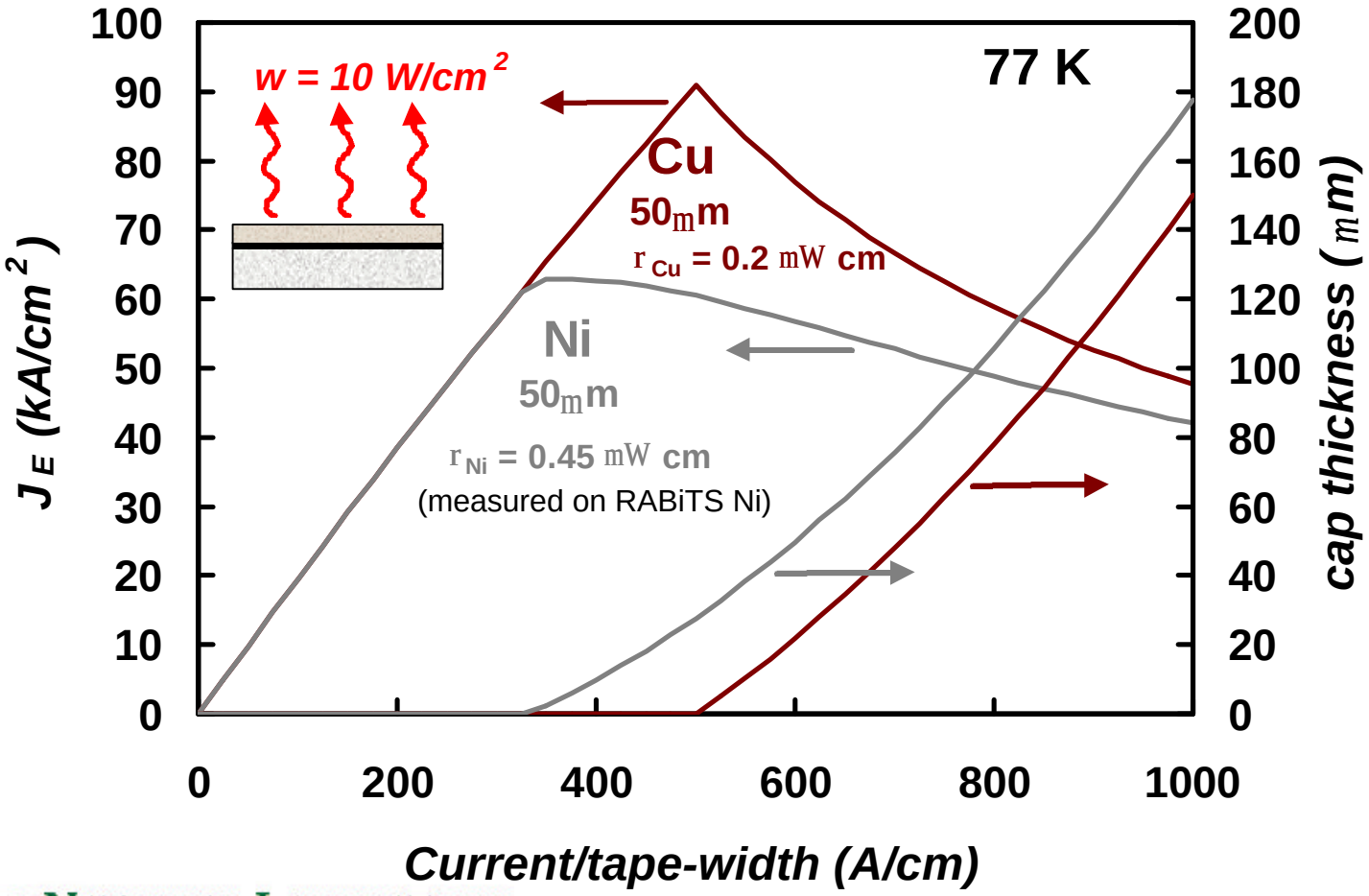


Observed stability consistent with heat-flux criterion



What if?: high conductivity base-metal tapes/ conductive buffer layers?

- *For Cu tape, no cap layer needed up to K~500 A/cm*
- *J_E up to ~90 kA/cm^2 (>60 kA /cm^2 for pure Ni)*



Development of conductive buffer layers: Work in progress

Aytug, *et al.*, APL (2000); JMR (2001); APL (2001)

	r @ 77 K (mW-cm)	a_o (Å)	Ni texture		YBCO texture		YBCO	
			Dw	Df	Dw	Df	T_c (K)	J_c(MA/cm^2)
$LaNiO_3$	300	3.86	6°–7°	7°	N.A.	N.A.	75	N.A.
$SrRuO_3$/ $LaNiO_3$	100	3.93	6°–7°	9.5^o	4°–5°	9.3^o	91	1.3
$La_{0.7}Sr_{0.3}MnO_3$	1000	3.86	7°	9.1^o	6°-7°	9.1^o	88	0.5
$LaMnO_3$	5000	3.9	9°-10°	9.8^o	10°	10°	90.5	0.5

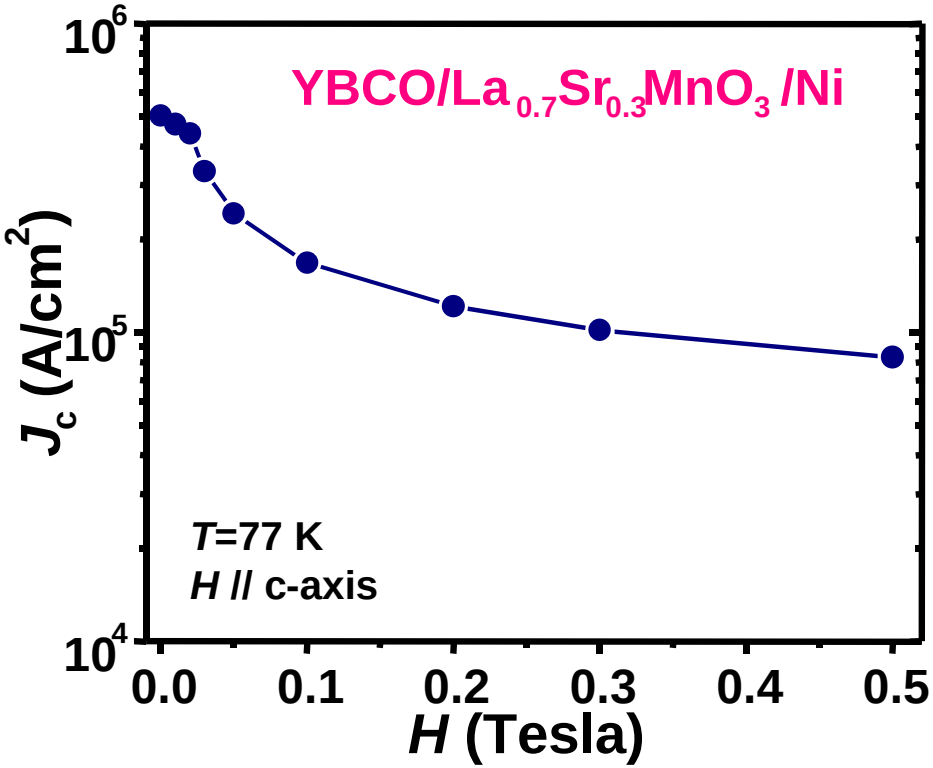
Example: electrical transport properties of conductive *YBCO/ $La_{0.7}Sr_{0.3}MnO_3$ /Ni* multilayer structure

A single, conductive buffer layer

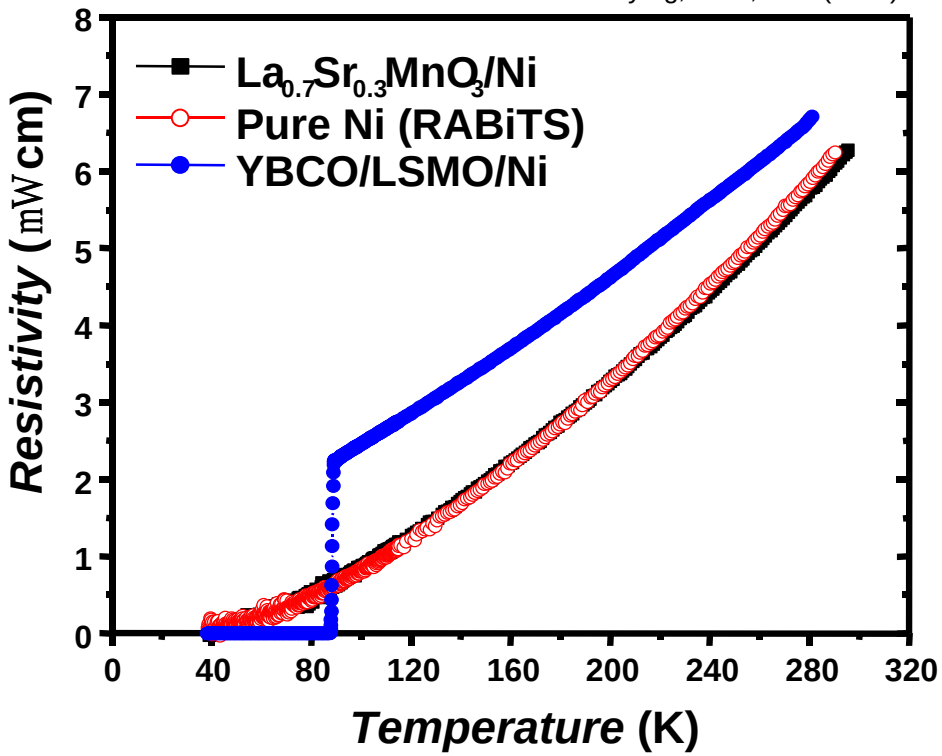
- T_c= 89 K
- $J_c(H=0)$ = 5x10^5 A/cm^2 @ 77 K

- Good electrical coupling with Ni.

↘ Overall low net resistivity (» 2-3 mW-cm), *but* four-terminal res. indicates some contact barrier.

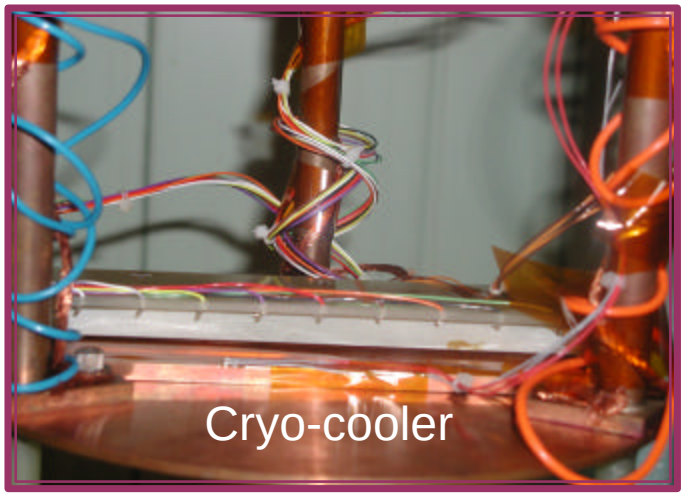


Aytug, *et al*., APL (2001)



Quench and stability properties of YBCO tape

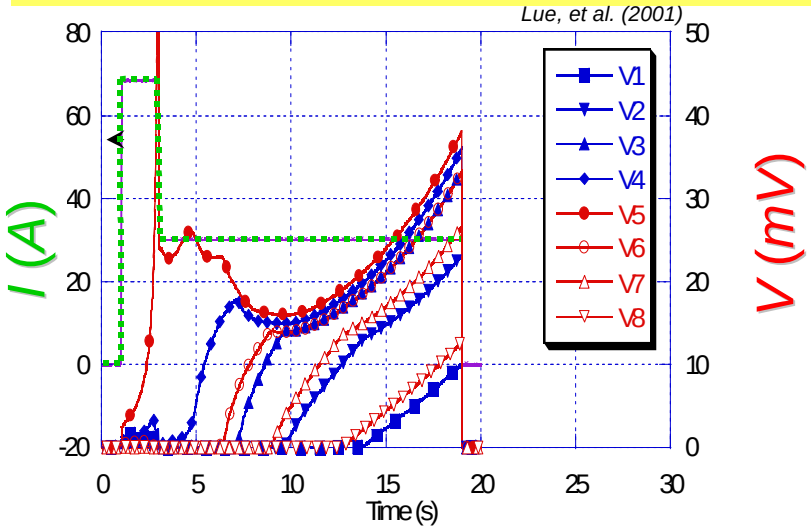
- **Ag-capped, 20-cm long RABiTS YBCO tape with 8, 2-cm long measurement zones**
- **Over-current pulse applied for 2 sec to produce normal zone in weakest zone**
- **Step back to steady-state operation current**
- **Time normal-zone propagation from observed V(t) of each voltage zone**



Conclusions:

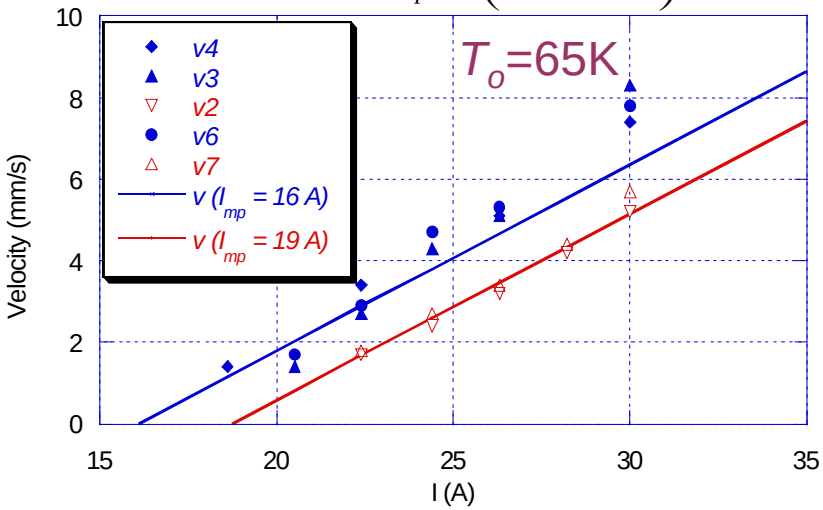
✪ Large stability margin of 100 J/cm³

☆ Slow normal-zone propagation of 1 – 8 mm/s



Good agreement with 1-D modified adiabatic theory (*Dresner, 1995*):

$$u = \frac{(I - I_{mp})}{A \cdot C_p} \cdot \left(\frac{kr}{(T_c - T_0)} \right)^{1/2}$$



Summary and Conclusions

- ***Limitations imposed by conductor stability were investigated***
  - *Operation in liquid nitrogen*
  - *Operation under near-adiabatic, conductive cooling*

- ***Control and prototype samples were fabricated and measured***
  - *high-conductivity cap layers of Ag and Cu applied*
  - *conductive buffer layers developed*
  - *Normal zone propagation in tape lengths were analyzed*

- ***Models and measurements underscore constraints on the achievable J_E and practical stabilizer thickness***
  - *under stability constraints, J_E is limited to modest values*
  - *measured over-current voltages consistent with models*
  - *tapes exhibit large stability margin, but slow normal zone propagation is a potential problem*

FY2001 Performance and FY2002 Plans

FY2001 Plans

- **Increase I_c/width to >150 A/cm for *ex-situ* processed YBCO coatings**

- **Develop solution-based buffer layer deposition on m-lengths of alloy tapes**

FY2001 Performance

High values obtained and process control refined

- ***Quench studies of nucleation and growth for thick films***
- ***Approach to large area processing for overall production rates***

Solution-based buffer layers

- ***Meter lengths of highly textured RABiTS w/solution seeds on strengthened Ni-W-Fe substrates were produced***
- ***J_c=1.9 MA/cm^2 on LZO solution seed layers (short samples)***
- ***High J_c YBCO over lengths on PVD-capped solution buffer on Ni tapes***
- ***Epitaxial LZO directly on Ni-Cr tape***

FY2001 Plans (cont'd)

- **Collaborate with LANL to develop *ex situ* YBCO on IBAD-MgO substrates**

- **Continue studies of thermo-mechanical processing for improved texture in metals**

FY2001 Performance

Work in progress to find suitable cap buffer layer

- ***LANL IBAD MgO just now available***

✓ **Highly-textured, strengthened Ni tape developed**

- ***Yield strength three times that of Ni***
- ***No changes required in seed buffer layer growth***
- ***High J_c values to 1.9 MA/cm^2***

New Task(s) Added in FY 2001

FY2001 Plans (cont'd)

- **Evaluate potential impact of Ca-doped grain boundaries on the performance of YBCO/RABiTS™**
- **Use single crystal nickel tapes to assess the affects of RABiTS intra-grains on J_c of both PLD and YBCO *ex situ* coatings**
- **Evaluate the constraints of thermal stability on the operating character-istics of coated conductors**

FY2001 Performance

✓ **In-house and collaboration with U. Augsburg for synthesis**

Observed possible benefits:

- ***low-temperatures for low-angle GB's***
- ***in LN_2 for high-angle GB's***

✓ **J_c values comparable those of YBCO on single crystal oxide substrates**

- ***no adverse effects from Ni or buffer surfaces***
- ***no chemical contamination***
- ***similar findings by U. Wisc and U. Augsburg within RABiTS grains***

✓ **Modeling and measurements**

- ***Limits on J_E and design imposed by stability requirements***
- ***Slow normal-zone propagation/large stability margins observed***

FY2002 Plans

- *Study the role of thermomechanical processing parameters and initial microstructure on grain boundary mis-orientations in alloy tapes*
- *Optimize epitaxial buffer layers on alloy metal substrates*
- *Determine efficacy of vacuum and batch furnace processing of ex situ YBCO coatings*
- *ORNL staff to use LANL continuous coater to deposit 1-m YBCO on RABiTS*

Research Integration

- **Four CRADA teams working with ORNL staff on diverse approaches to coated conductors**
  3M Company; American Superconductor Corp.; MicroCoating Technologies/Oxford Superconducting Technology

- ***New cooperative agreement initiated with Neocera Corporation (Beltsville, MD) on pulsed electron beam deposition of HTS on RABiTS™***

- **Collaborations with universities and other labs**
  U. Wisconsin; U. Kansas; Boston College; U. Augsburg; Stanford U.; U. Florida; ANL; LANL; NIST-G and NIST-B

- ***Information/expertise transfer:***
  - ***Over 50 publications and presentations, 5 U.S. patents issued***
  - ***WEB posting of Annual Report and presentations from this meeting***
  - ***Personnel exchange with AMSC, MCT, Boston College, Stanford U.***