U.S. Department of Energy

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1998 Wire Development Workshop Proceedings

January 29-30, 1998
St. Petersburg Bayfront Hilton
St. Petersburg, Florida

U.S. Department of Energy • Office of Energy Efficiency and Renewable Energy
Office of Utility Technologies • Office of Geothermal Technologies
Washington, DC 20585

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TABLE OF CONTENTS

SUPERCONDUCTIVITY PROGRAM FOR ELECTRIC SYSTEMS
WIRE DEVELOPMENT WORKSHOP - AGENDA

JANUARY 29-30, 1998
ST. PETERSBURG BAYFRONT HILTON

Thursday, January 29

7:00 Workshop Registration opens
7:30 Continental Breakfast
8:10 Introduction - Jim Daley, DOE

8:25 Welcome - John Simpson, Director, Systems Planning, Florida Power Corporation

8:30 Plenary: High Energy Physics Challenges for HTS Wire
Dave Sutter and Bruce Strauss, DOE

9:00 SESSION ONE - First Generation Wire Development: Status and Issues
Session Chair: Balu Balachandran, Argonne National Laboratory

Venkat Selvamanickam, Intermagnetics General ..... "Status of Bi-2223 Conductor Development at IGC"
Ken Marken, Oxford Superconducting Technology ..... "Progress in BSCCO-2212 for Magnetic Field Applications"
Mike Tomsic & Lyn Adams, EURUS Technologies ..... "Progress on High-Strength and Lower AC Loss BSCCO High-Temperature Superconductors"
Bart Riley, American Superconductor ..... "Composite Superconductors at ASC"
Paul Chu, University of Houston ..... "A New Bi-2212 Tape at Low Cost"

10:00 BREAK

10:30 SESSION TWO - First Generation Wire in Pre-Commercial Prototypes
Session Chair: Chris Rey, DuPont Superconductivity

Uday Sinha, Southwire Company ..... "Southwire HTS Cable Update"
Sam Mehta, Waukesha Electric Systems ..... "Conductor Needs for HTS Transformers"
Mike Walker, Intermagnetics General ..... "HTS Magnet Development Issues"
Boris Shoykhet, Rockwell Automation ..... "HTS Motor Development Update"
Eddie Leung, Lockheed Martin ..... "HTS Conductor Requirements for FCLs"
Mujib Rahman, Pirelli ..... "HTS BSCCO Tape for DOE/EPRI Project and Future Requirements"
Bob Schwall, American Superconductor ..... "HTS Applications at ASC"

12:30 LUNCH

1:30 SESSION THREE - Second Generation Wire Development: Private Sector Progress and Issues
Session Chair: Don Kroeger, Oak Ridge National Laboratory

John Hack, Midwest Superconductivity ..... "Coated Conductor Development at MSI"
Venkat Selvamanickam, Intermagnetics General ..... "Progress in YBCO Conductor Development at IGC"
Les Fritzemeier, American Superconductor ..... "Requirements for Commercialization of YBCO Thick Film Conductors"
Shara Shoup, MicroCoating Technologies ..... "Low-Cost, Open Atmosphere Combustion Chemical Vapor Deposition of Superconductor Related Materials on Single Crystal Substrates"
Jonathan Storer, 3M ..... "Update from 3M/LANL/ORNL/Southwire"

2:45 BREAK

3:15 SESSION FOUR - Second Generation Wire Development: Federal Laboratories
Session Chair: Steve Foltyn, Los Alamos National Laboratory

Dick Blaugher, National Renewable Energy Laboratory ..... "Progress on Thallium Wire and Tape Development"
Paul Arendt, Los Alamos National Laboratory ..... "Progress at Los Alamos on Scale-Up of YBCO Coated Conductors"
Ron Feenstra, Oak Ridge National Laboratory ..... "The BaF_2 Method: A Scalable Process for YBCO Coated Conductors"
Mas Suenaga, Brookhaven National Laboratory ..... "The Kinetics of YBCO Thick Film Formation by a Post-Annealing Process"
Balu Balachandran, Argonne National Laboratory ..... "International Perspective on Second-Generation Conductors"

6:30 GROUP DINNER ACTIVITY
Tour of Titanic Exhibit, Florida International Museum. Dinner at the Columbia Restaurant.

Friday, January 30

7:30 Continental Breakfast

8:00 SESSION SIX - Fundamental Research Issues for HTS Wire Development
Session Chair: Marty Maley, Los Alamos National Laboratory

Jack Ekin, National Institute of Standards and Technology ..... "Electromechanical Properties of LTS and HTS"
Ken Gray, Argonne National Laboratory ..... "Fundamental Grain Boundary Studies Aimed at HTS Wire Applications"
Steve Foltyn, Los Alamos National Laboratory ..... "The Role of Fundamental Research in Improving Performance of Coated Conductors"
David Larbalestier, University of Wisconsin ..... "Grain Boundary and Other Limits to J_c in BSCCO and YBCO"
Dave Christen, Oak Ridge National Laboratory ..... "Substrate Effects on Film Growth, Grain Boundaries, and Flux Pinning in Coated Conductors"

9:30 BREAK

10:00 Breakout groups meet

I. BSCCO Wire
II. BSCCO Applications
III. Coated Conductors and Fundamental Issues

12:00 LUNCH

1:00 Breakout groups resume

2:15 Workshop summary and closing remarks

3:00 Workshop Adjourns

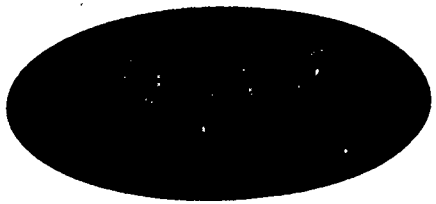
High Energy Physics Challenges For HTS Wires

Presentation
to
The Winter Wire Workshop
U. S. Department of Energy
St. Petersburg, Florida

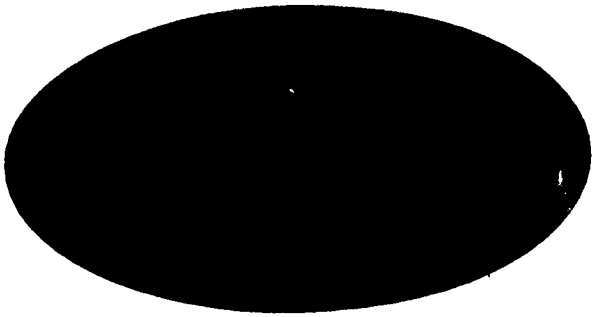
David F. Sutter
Bruce P. Strauss
January 30, 1998

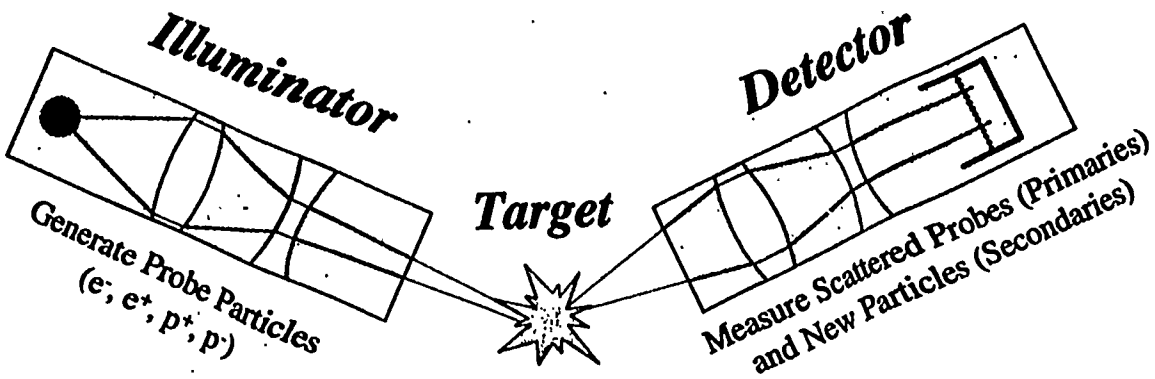
The Task of High Energy Physics: Probe Nature at the Most Basic Level

(Where you can't feel, see, hear, or smell it!)



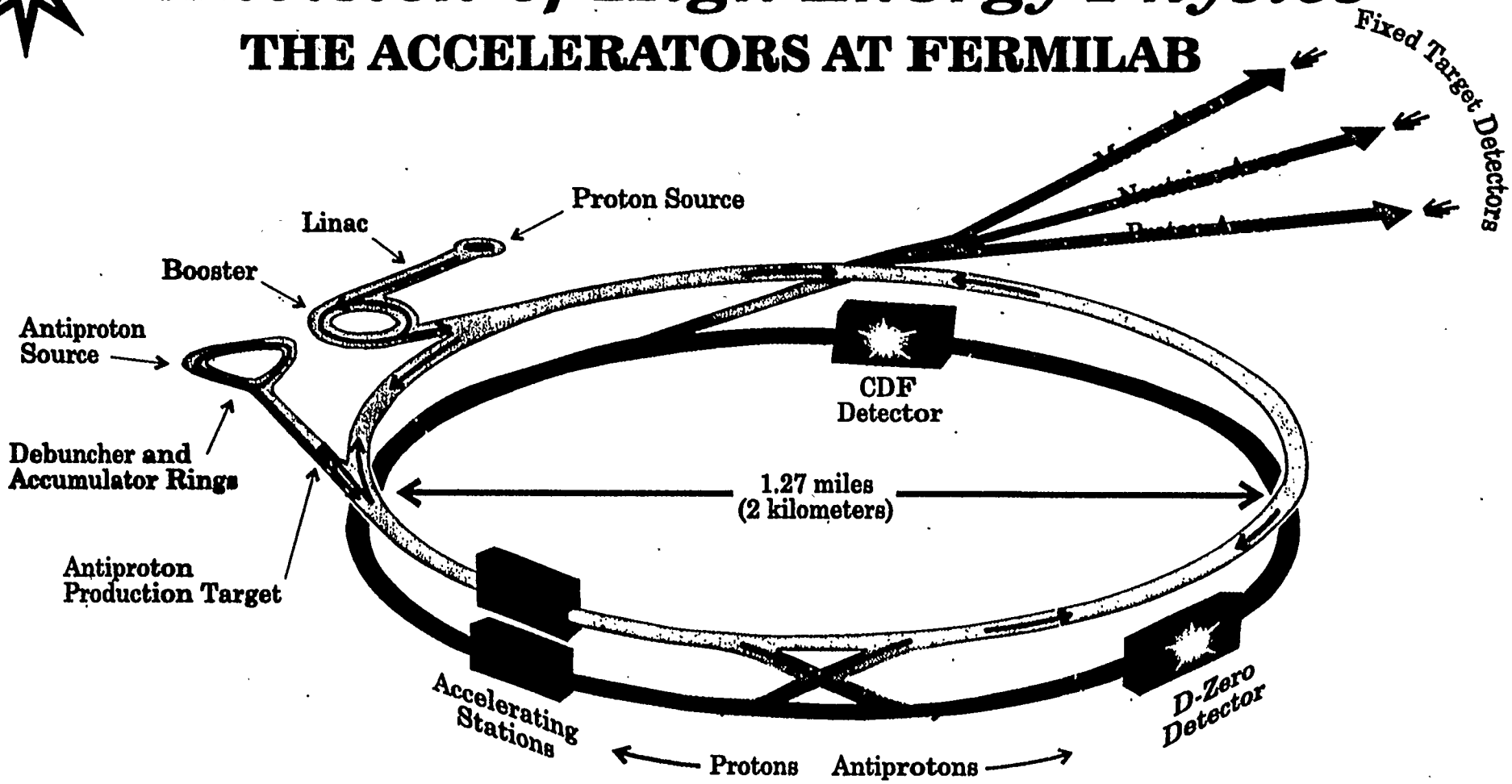
By illuminating the structure of matter and energy and observing the results





Division of High Energy Physics

THE ACCELERATORS AT FERMILAB



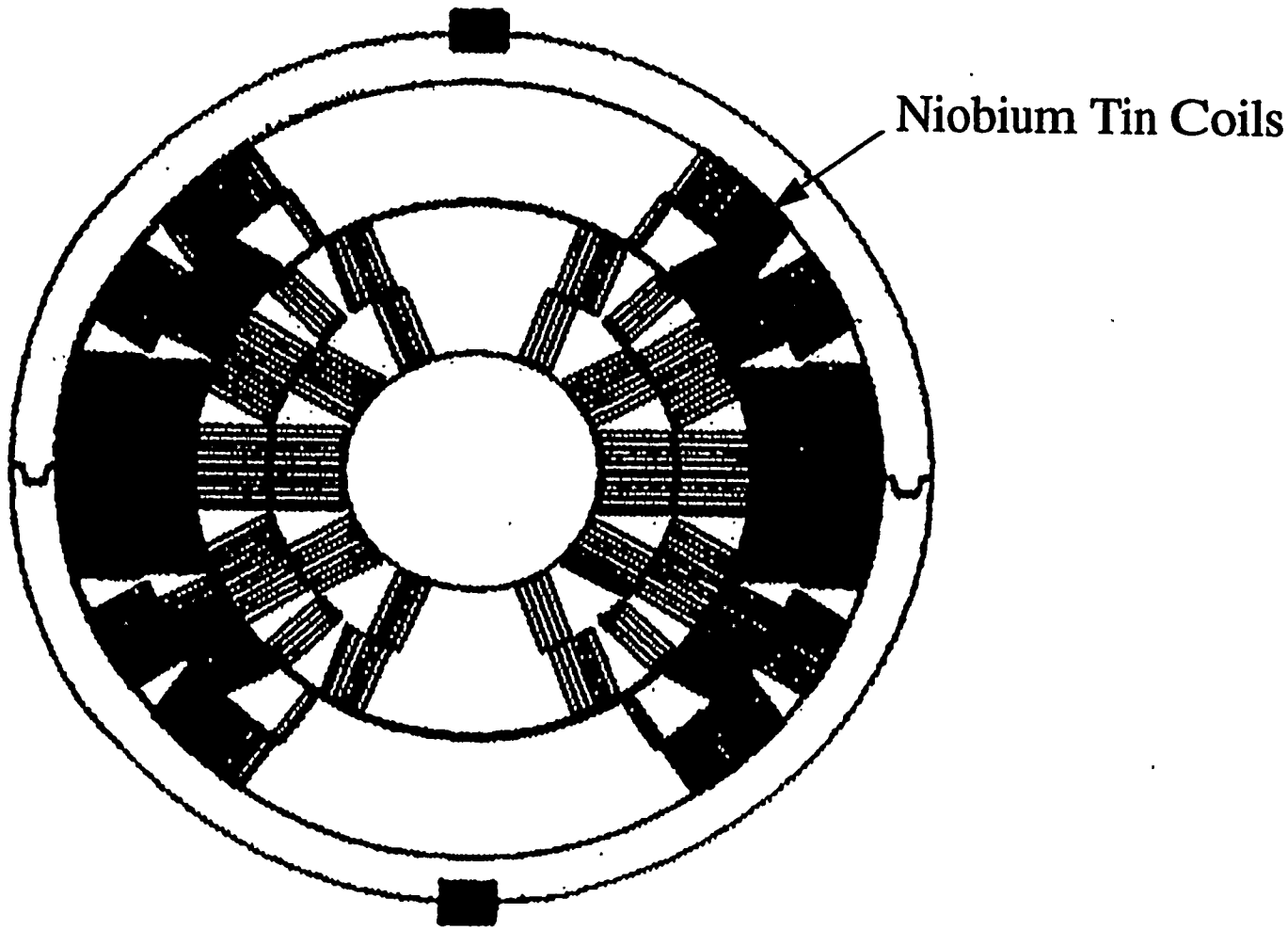
A series of four accelerators, culminating in the four-mile-around Tevatron, boosts protons to almost the speed of light. Antiprotons are created and stored in the antiproton source before being injected into the Tevatron in the opposite direction from the protons. Superconducting magnets guide the particles around the Tevatron. Each time a bunch of particles passes through an accelerating station, radio-frequency waves increase the energy of the particles, until the bunches make nearly fifty thousand round trips each second. When the protons and antiprotons collide, sophisticated electronic devices (detectors) track, identify, and record the new particles that are made from the energy of the collision. Protons and antiprotons continue to circulate and collide until there are not enough particles left for efficient operation, and the process begins again.

Enabling Technologies -- The Sandbox of the R&D

Technology	*Use*	*Intellectual Source/Developer*	*Principal Application*
• **Magnet**	Beam Transverse Control Beam Analysis (momentum)	Nat'l Labs, Universities & Industry	Protons & Muons ($\mu\mu$, Jupiter)
• **Acceleration**	Energy Transfer Longitudinal Beam Control	Nat'l Labs & Universities	Electron (NLC/ILC)
• **Vacuum**	Beam Friendly Environment	Industry	All
• **Infrastructure**	Utilities (Cooling, Electrical, Mechanical, Safety)	Industry (mostly)	All
• **Particle Sources & Conditioning**	Hi Brightness beams	Nat'l Labs & Universities	All
• **Controls & Instrumentation**	Measure Beam Performance & Modify It	Controls--Industry Instrumentation--Nat'l Labs & Some Universities	All
• **Accelerator Physics** (A Unifying Theme)	Beam Optics Machine Design New Concepts	National Labs & Universities	All

Superconducting Magnet - Cosine θ Structure

World record field = 13.2 Tesla



5

High Energy Physics

How we did it--

- First Device Planned Within Three Months of HFSC and many projects after that.
  - Major Bubble Chambers at ANL, BNL, Fermilab
  - Tevatron Project at Fermilab
  - SPS at CERN
  - HERA at DESY
  - SSC
  - RHIC
  - LHC at CERN
  - Major Detectors at all Facilities

High Energy Physics

- The Workhorse of Dipole Magnets has been the cosine θ family.
- What we learned
  - Stability
  - Force Containment
  - Cryogenics
  - Conductor - 90% of all superconductor sold before 1983 was to HEP.

High Energy Physics

- Stability

  - CRYOGENIC STABILIZATION- Developed in Industry

    Led directly to the construction of the 8 foot, 10 foot, and 12 foot Bubble Chambers at Brookhaven, Argonne, and Fermilab.

High Energy Physics

- Stability

  - ENTHALPY STABILIZATION
    Brookhaven Summer Study of 1968

    - Make filaments small enough so that change in magnetic field exclusion will not dump enough energy to raise T above T_c.

    - Twist wire to decouple the filaments.

  We could now talk seriously about ramping magnets for an accelerator.

High Energy Physics

- Conductor
  - Prior to the advent of the MRI commercial market HEP accounted for over 90% of conductor sales.
  - Technology Transfer.

High Energy Physics

- Cryogenics
  - HEP Laboratories are major operators of Cryogenic Systems
  - Cryogenics represents < 10% of System Costs.

High Energy Physics

- Force Containment
  - The cos θ winding is a Roman Arch
    - Buildup of stress on the midpland due to Lorentz Forces

$$\sigma_0 = B^2/2\mu_0$$

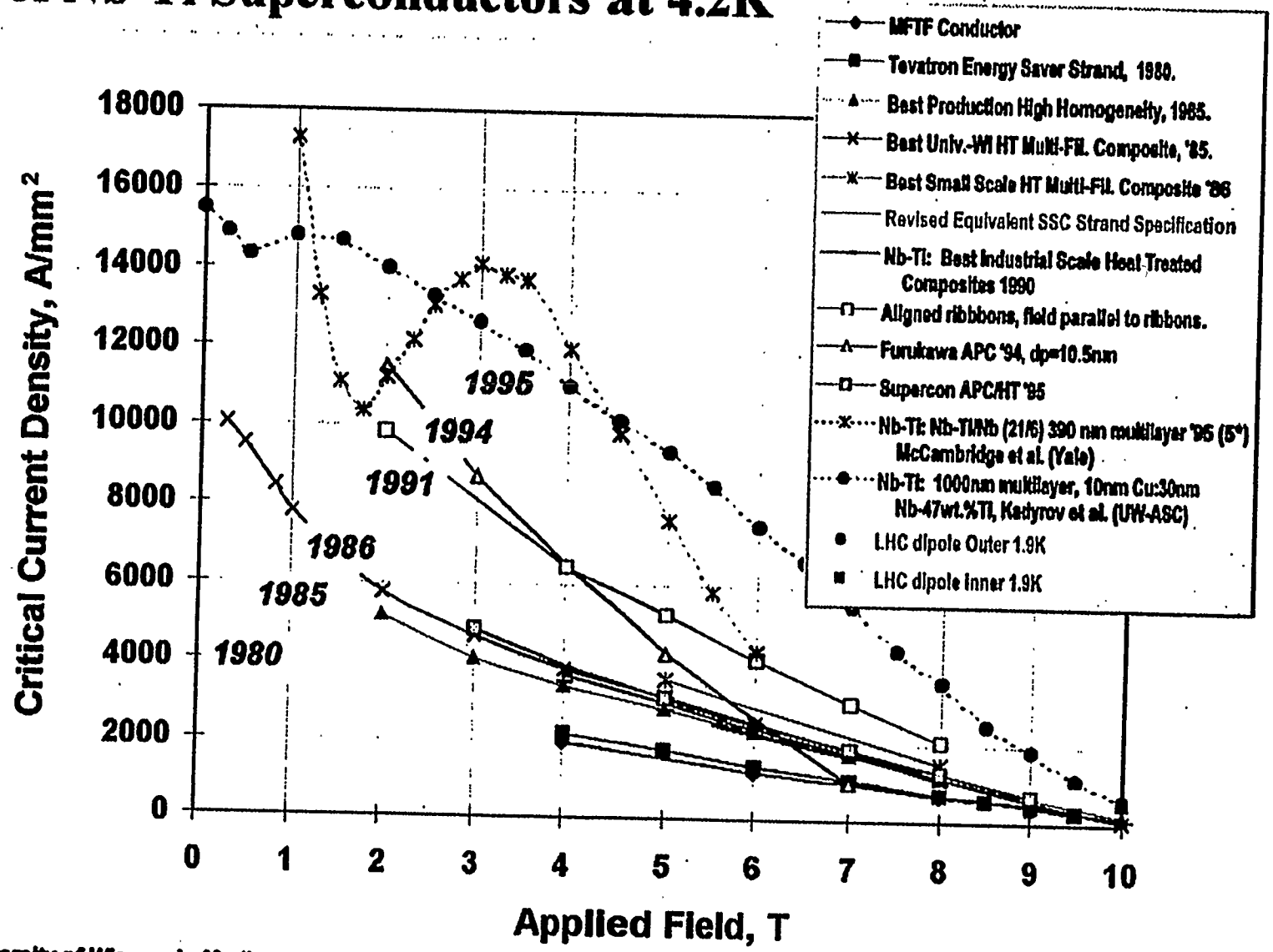
High Energy Physics

- Technology Transfer - Wire

  - Industrialization
    - High Volume Lots
    - Rutherford Cable

  - Wire Workshop
    - Hi Ho Alloy
    - Thermo-mechanical Processing

Advances in the Critical Current Density of Nb-Ti Superconductors at 4.2K

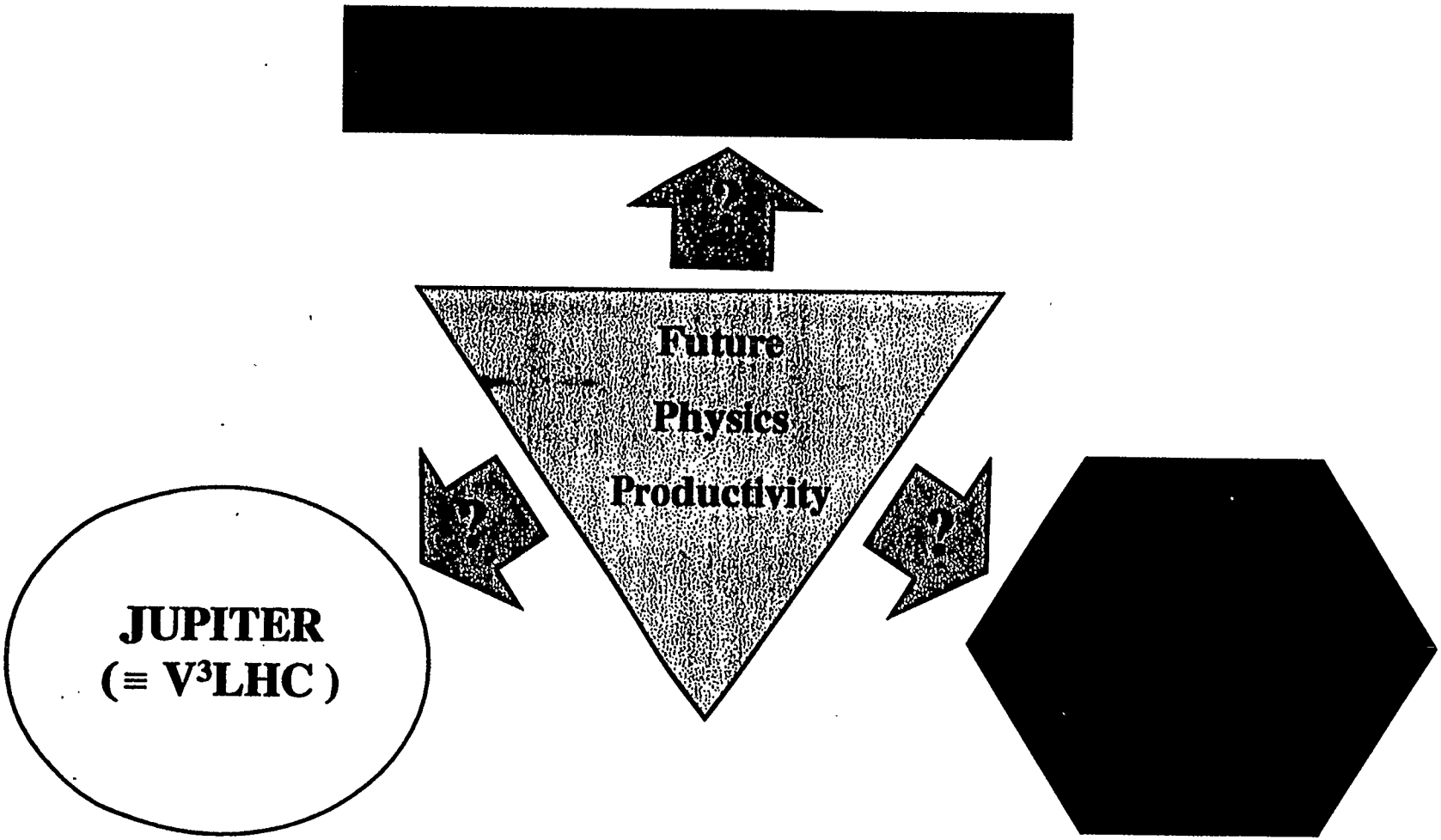


University of Wisconsin-Madison
Applied Superconductivity Center

High Energy Physics

- Technology Transfer - Magnets
  - A Mixed Bag

The Snowmass `96 Legacy



Possible future lepton colliders

Is there a lepton collider if we need high energy? Maybe.

- **Muon Collider**
  Muons are like heavy electrons -- 200 times heavier
  hence, muon collider can be circular but:
  muons decay (lifetime ~ 2 μs when at rest)

How inconvenient! Better be quick!

It's not known whether muon colliders will work, but if they do:

- they are expandable in energy up to about 2 x 2 TeV.
- some preliminary steps are useful in themselves

Enabling Technologies needed: Superconducting Magnets, Sources & Cooling

17

Future Accelerators -- Plans & Dreams

Possible future proton colliders

The Very Large Hadron Collider (VLHC) -- Jupiter

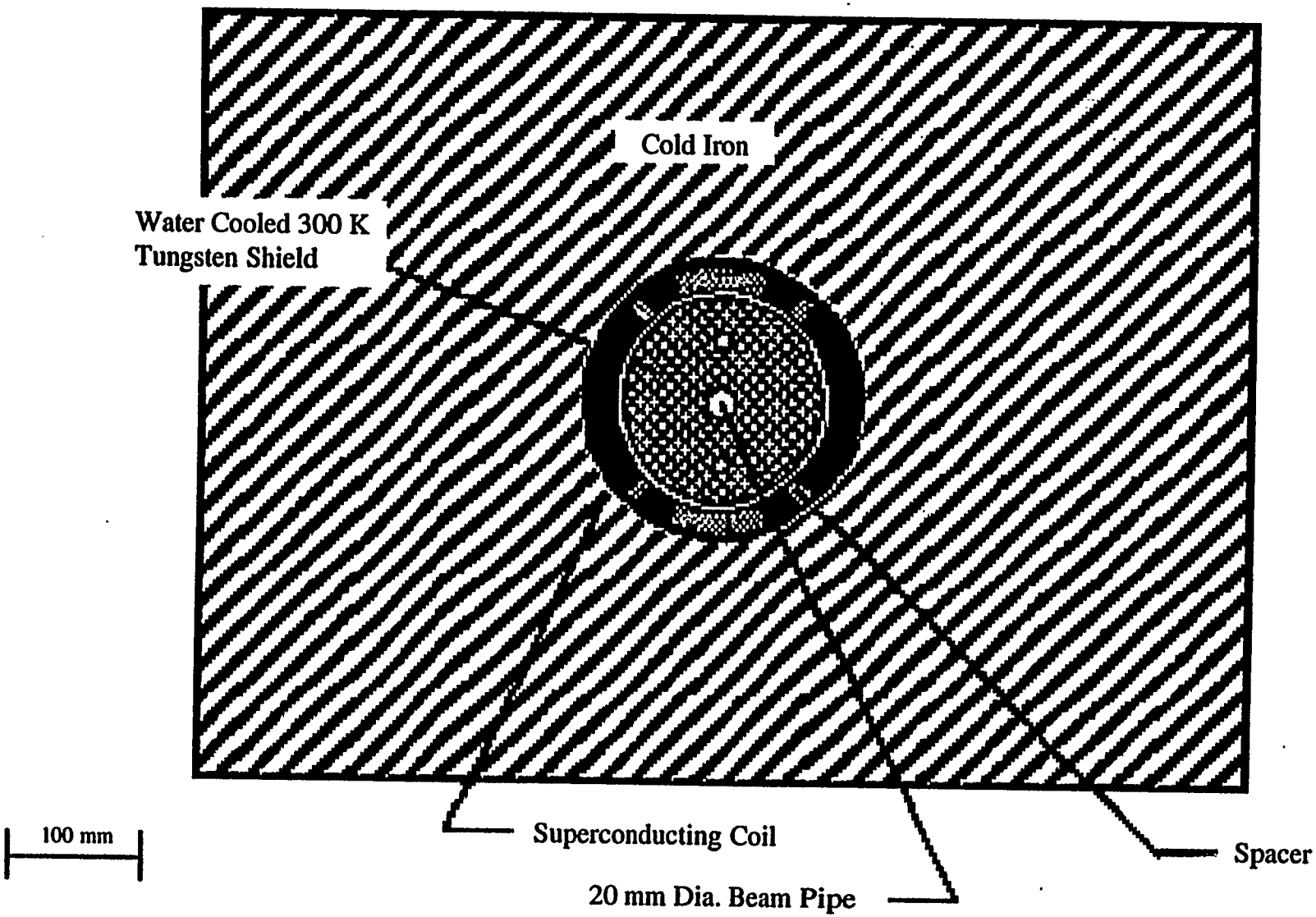
A 50 TeV x 50 TeV to 100 x 100 TeV proton-proton collider

Two possibilities--high field & low field

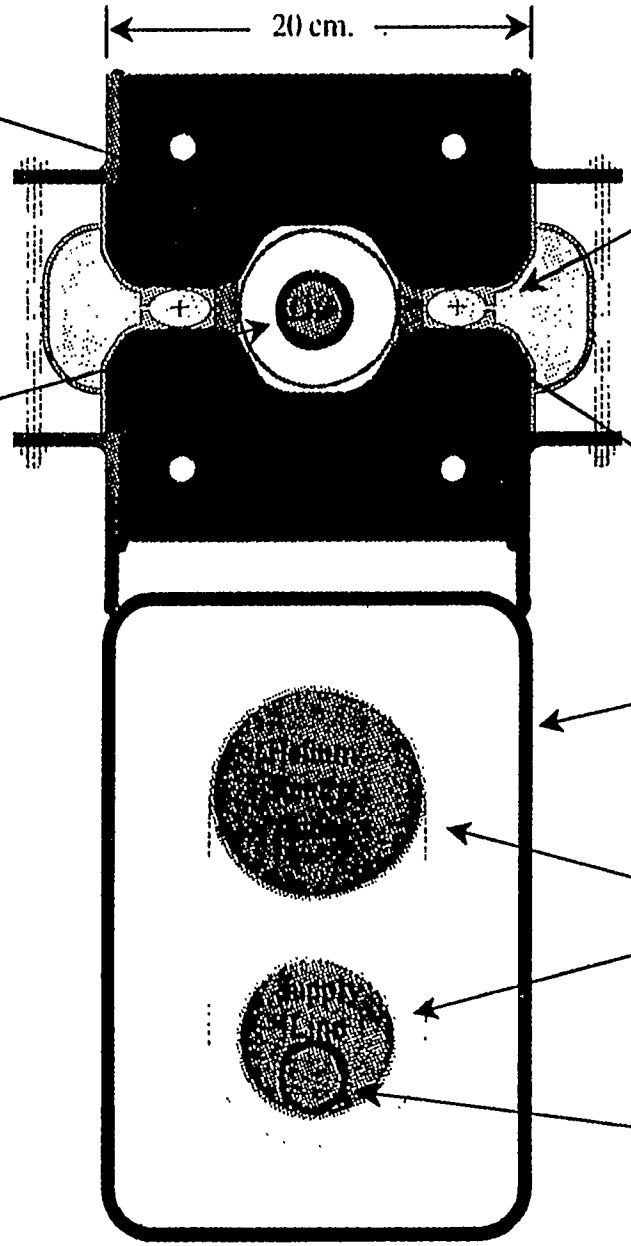
Distinguished by magnetic field strength, and hence, the amount of synchrotron radiation, and physical size.

- Synchrotron radiation is bad: it puts power into the cryogenics.
- Synchrotron radiation is good: it makes the beam emittance (size) smaller.

Generic μ–μ Collider Magnet



Transmission Line Magnet

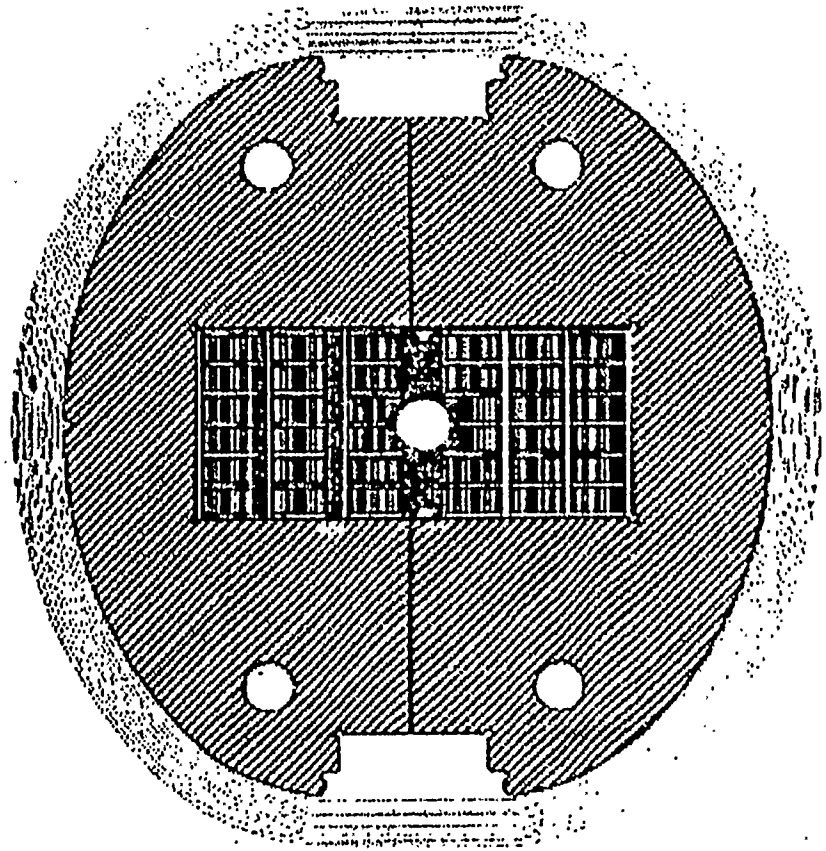


KEY FEATURES:

Simple Cryogenic System
Small Superconductor Usage
Small Cold Mass
Low Heat Leak
Continuous in Long Lengths
No Quads or Spool Pieces
Warm Bore Vacuum System
Standard Construction Methods

A Magnet with Rectangular Endoskeletal Structure

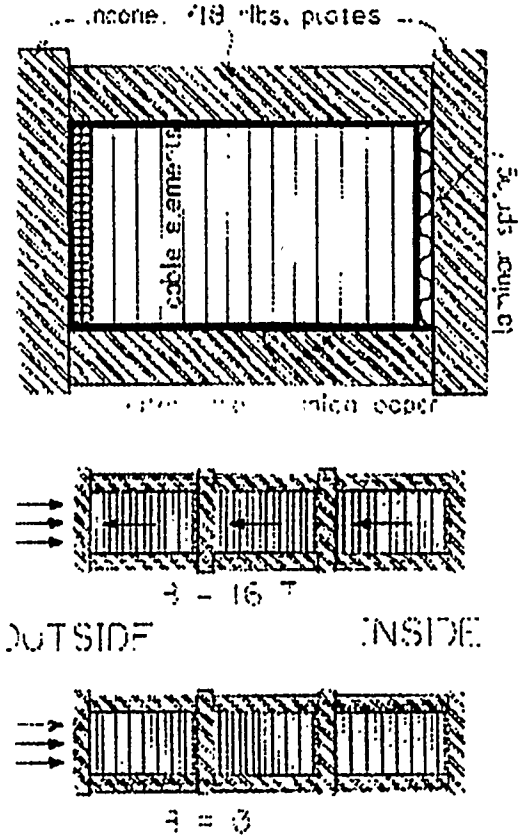
Texas A&M (McIntyre)



Block-coil NbTi single dipole, using same elements as Nb_3Sn dual dipole.

Stress management involves 3 ingredients:

the coil	(stiff, fragile)
support matrix	(very stiff, very tough)
spring	(very soft, elastic)



21

High Energy Physics

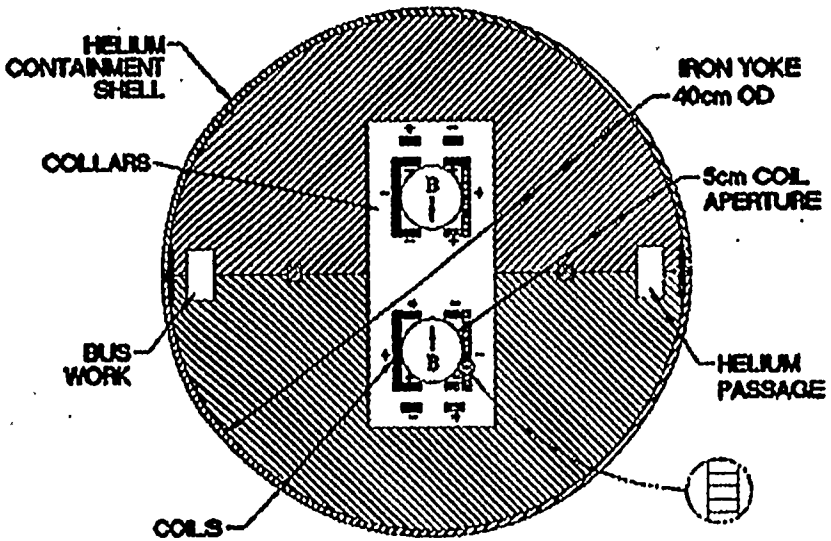
Texas A&M Block Coil Dipole - Properties

	Inner Coil	Middle Coil	Outer Coil	
Peak Field	16.2	13.2	10.0	Tesla
J in Nb_3Sn	528	1248	2098	A/mm^2
filament ϕ	20	18	18	μm
strand ϕ	1.26	0.77	0.62	mm
no. strands	20	32	40	
Cu/SC ratio	0.44	1.04	1.75	
turns/bore	54	90	108	
cable width	12.67	12.67	12.67	mm
cable thick.	2.62	1.71	1.43	mm

Superconducting Magnet - Rectangular Geometry (LBNL)

HIGH FIELD (10T-15T) TWIN APERTURE SUPERCONDUCTING DIPOLE

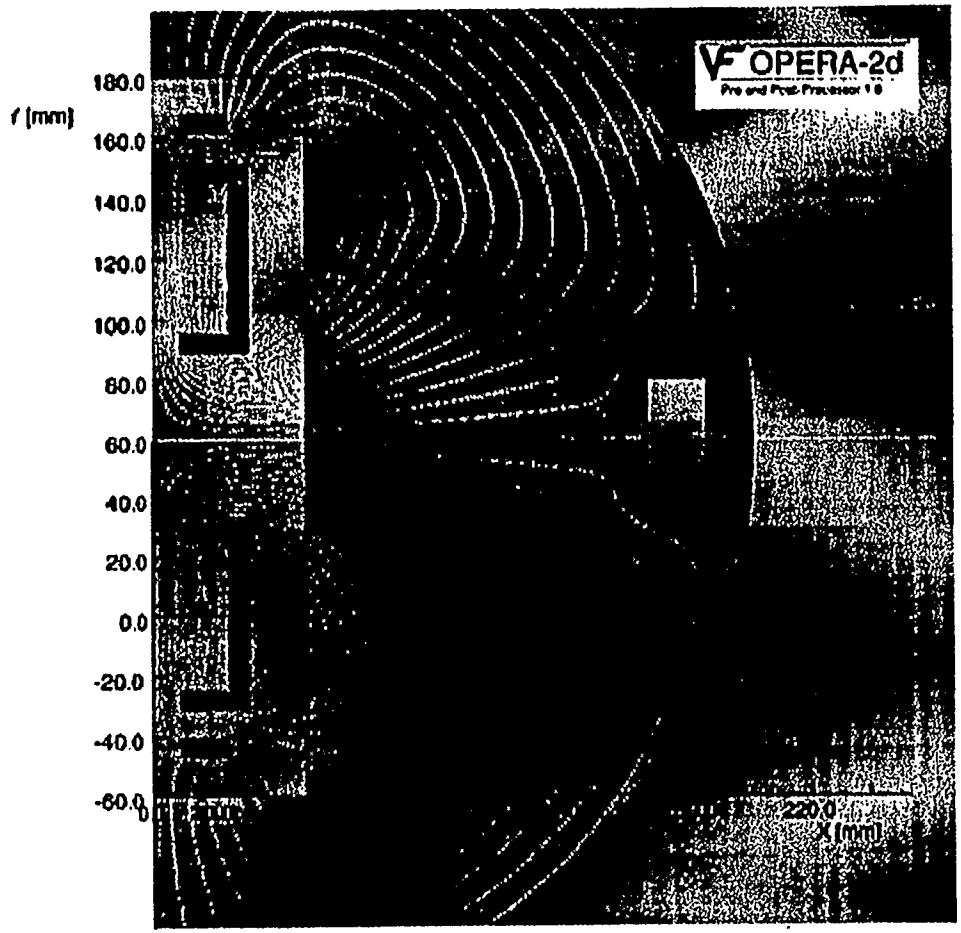
COMMON COIL DESIGN



COLD MASS CROSS-SECTION

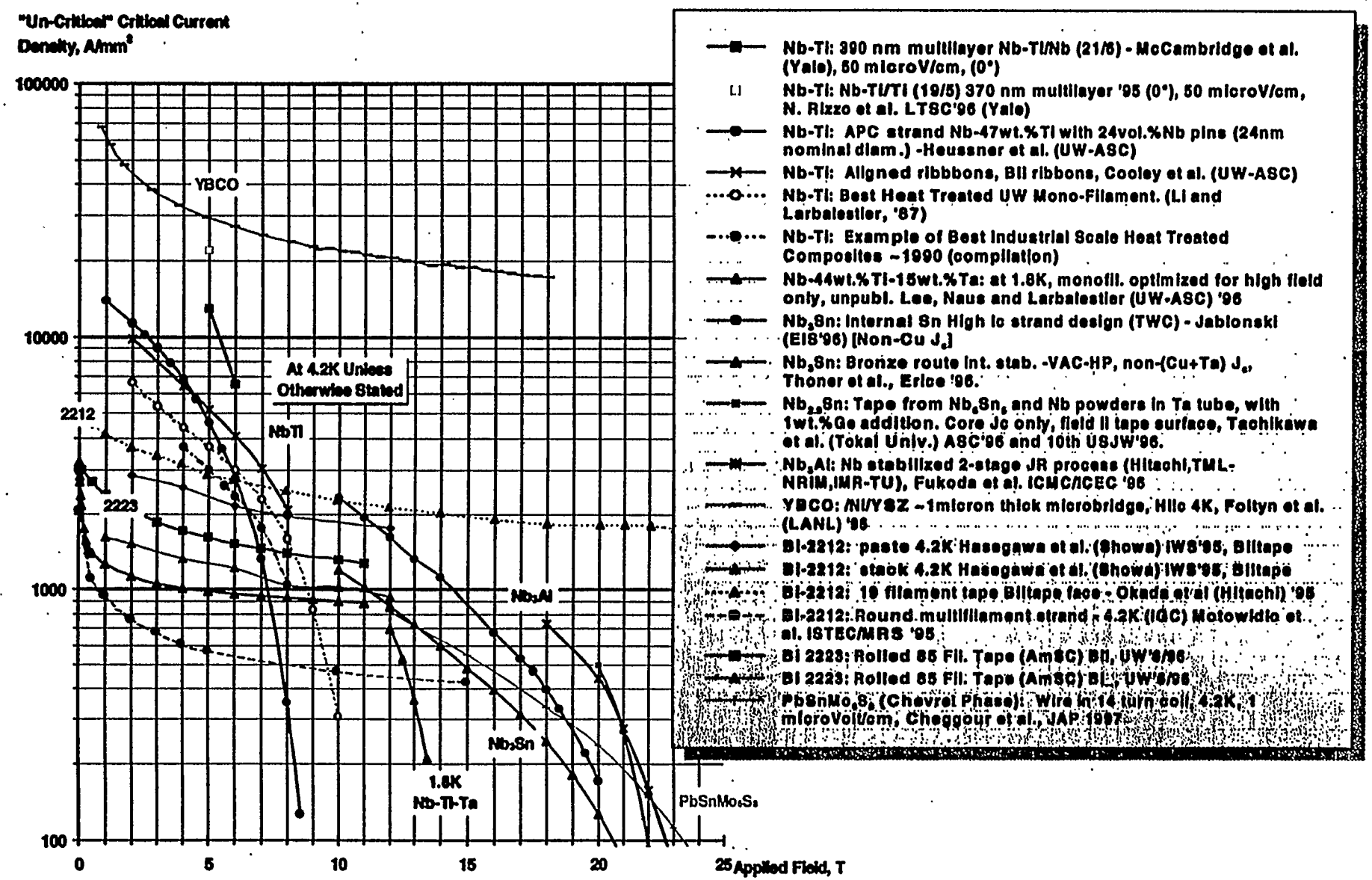
SCALE 1/4

Field Map



23

Advancing Critical Currents in Superconductors



November 3rd 1997 - Compiled by Peter J. Lee - BestinClass.ppt, JCProg40.xls

High Energy Physics

- Operating at high temperatures is not the enabling technology.
  - Less than 5% of costs of an accelerator are in cryogenics.
  - High ΔT is an operating advantage
- High H_{C2} is the great advantage.

High Energy Physics

- What are the desirable properties of a superconductor for high energy physics applications?

  - High Transport Current - Jc $\geq$ 1200 Amm^{-2}
  - High Engineering Current Density - $J_e \simeq 250$ Amm^{-2} ($H \geq$ 12 Tesla, T > 4.2 K)
  - Low anisotrophy
  - Controllable ac properties - small filaments
  - Manageable mechanical properties
  - Long lengths

    LENGTH, LENGTH, LENGTH↑

  - Manageable fabrication - Inclucing insulation system
  - Affordable

    COST, COST, COST↓

High Energy Physics

• HTS LEADS

- At Fermilab, replacing the conventional leads could save 25% of the heat load.
  - Substitute 30 to 50 pairs over the next five years.

- Fermilab has taken delivery of two pairs of test leads
  - ASC
  - IGC

- Negotiating with third vendor
  - Eurus

- In evaluation!!

- Goal is to use saved refrigeration to attain lower temperature, higher magnetic, field and thus higher energy. No safety risk to be taken.

INTERMAGNETICS GENERAL CORPORATION

High Temperature Superconductors

Status of BSCCO Conductor Manufacturing & Development at Intermagnetics

V. Selvamanickam

Intermagnetics General Corporation
Latham, NY 12110

DOE Wire Workshop, St. Petersburg, FL, January 29-30, 1998

Contributors

- **IGC** (P. Haldar, M.S. Walker, D.W. Hazelton, J. Hoehn)
- **Argonne National Lab** (U. Balachandran)
- **Oak Ridge National Lab** (R. Hawsey)

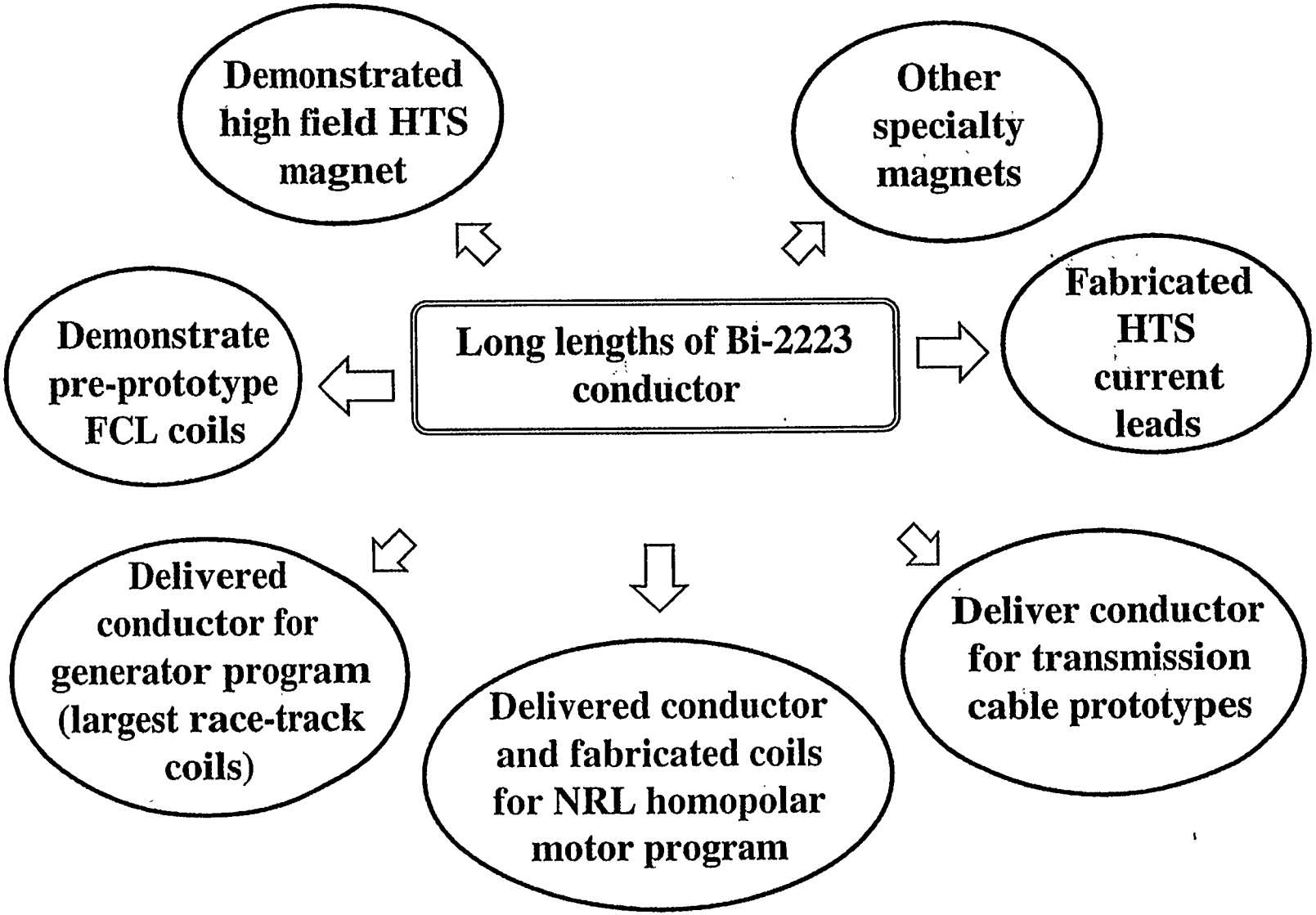
HTS Conductor Manufacturing and Development at IGC

- PIT Bi-2223
  100 km/year Production
  Development for cost-reduction & performance improvement
  Primary use in Fault Current Limiter, Current Leads, & Cables

- Surface-Coated Bi-2212
  50 km/year Production
  Primary use in 1 MVA Transformer

- Surface-coated YBCO
  Independent Development of all aspects of Conductor Fabrication
  Projected use in all potential applications of HTS

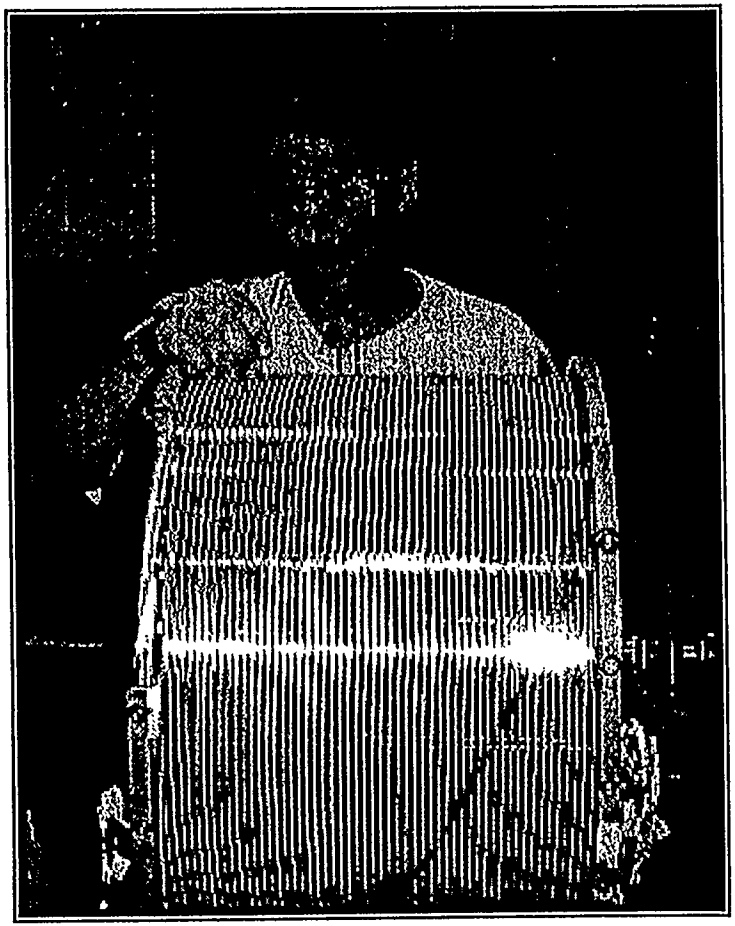
APPLICATIONS

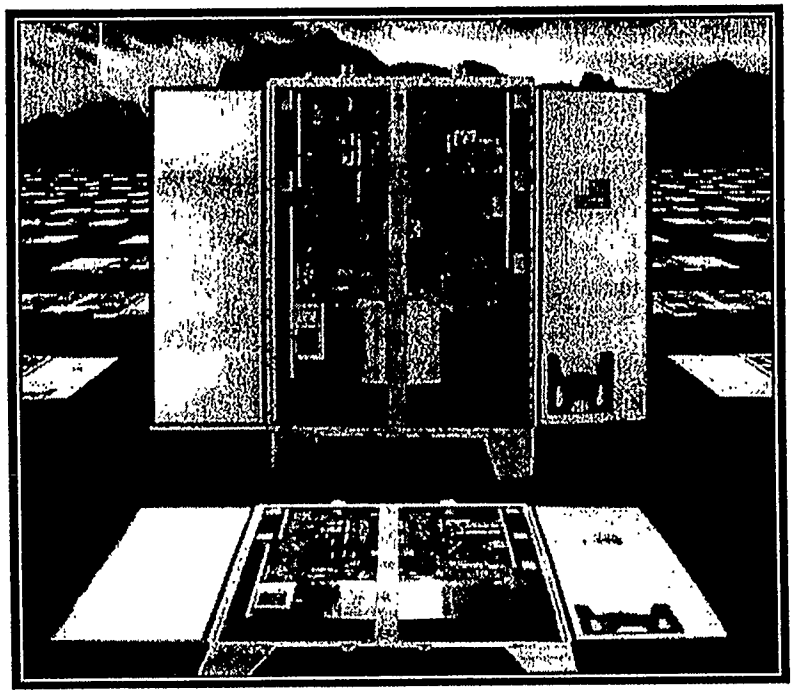


INTERMAGNETICS GENERAL CORPORATION

High Temperature Superconductors

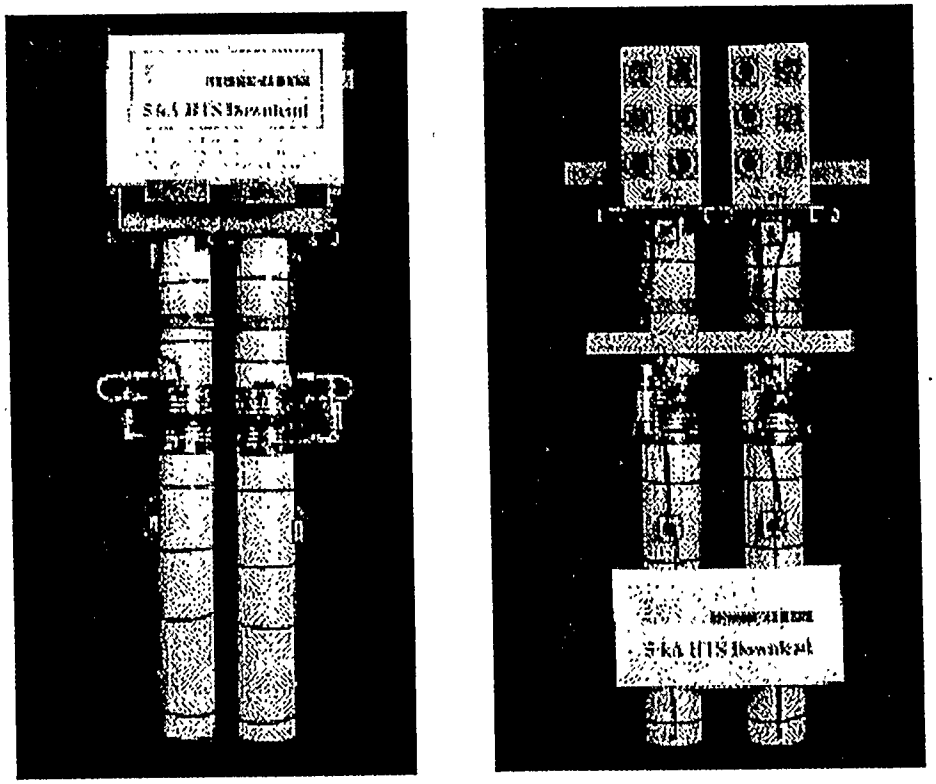
Fault Current Limiter





- Lockheed Martin, Intermagnetics, Southern California Edison, LANL
- 3 phase alpha unit 17 kV, 2 kA prototype
- 50 km Bi-2223 Conductor

HTS Current Leads



5 KA HTS Downleads

- Bi-2223/Alloyed Ag based HTS Leads
- 100 to 13 kA Leads available
- Mechanically Rugged
- Parallel Path Stablization
- Conduction or Vapor Cooling

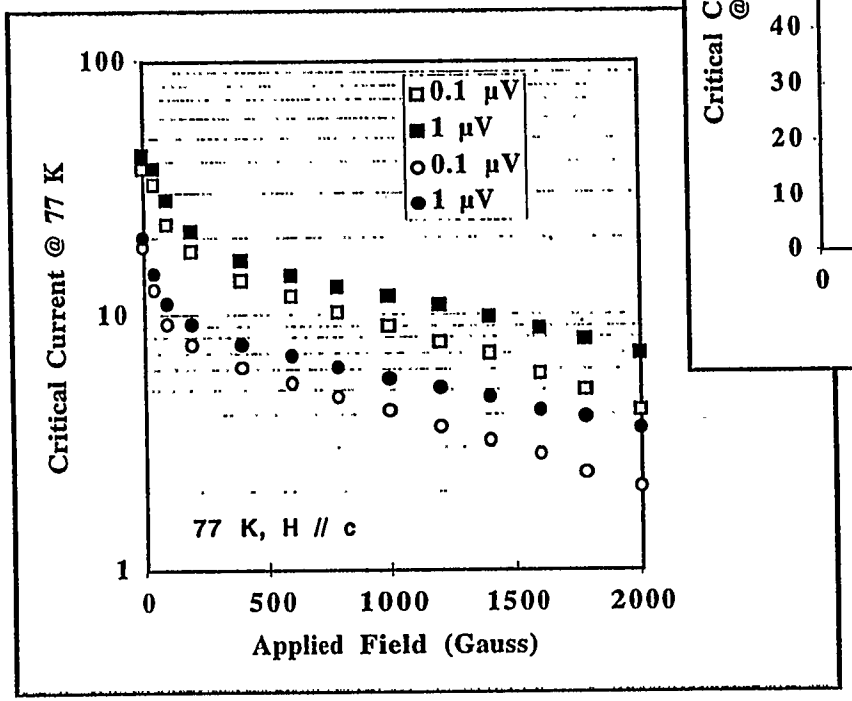
Bi-2223 Conductor at IGC
37 filament tape: (rolled & HT)

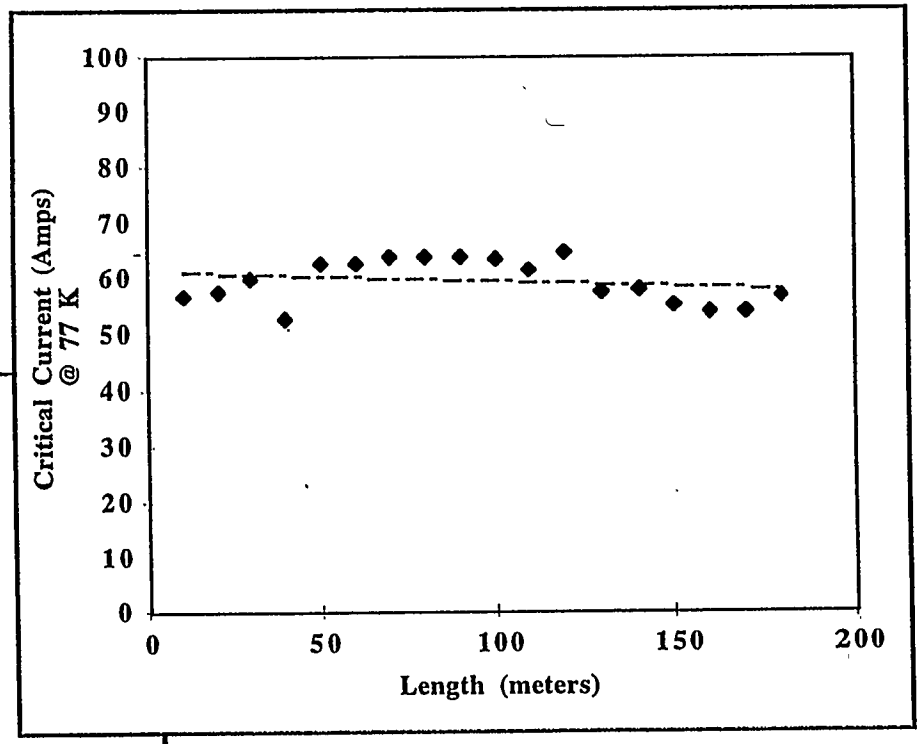
Conductor length (m)	Ic (A)	Effective Je (A/cm^2)	SC Jc A/cm^2
0.04	60	6,400	25,000
164	54	6,000	24,000
1260	18	3,500	12,000

INTERMAGNETICS GENERAL CORPORATION

High Temperature Superconductors

Field dependence of high quality conductor



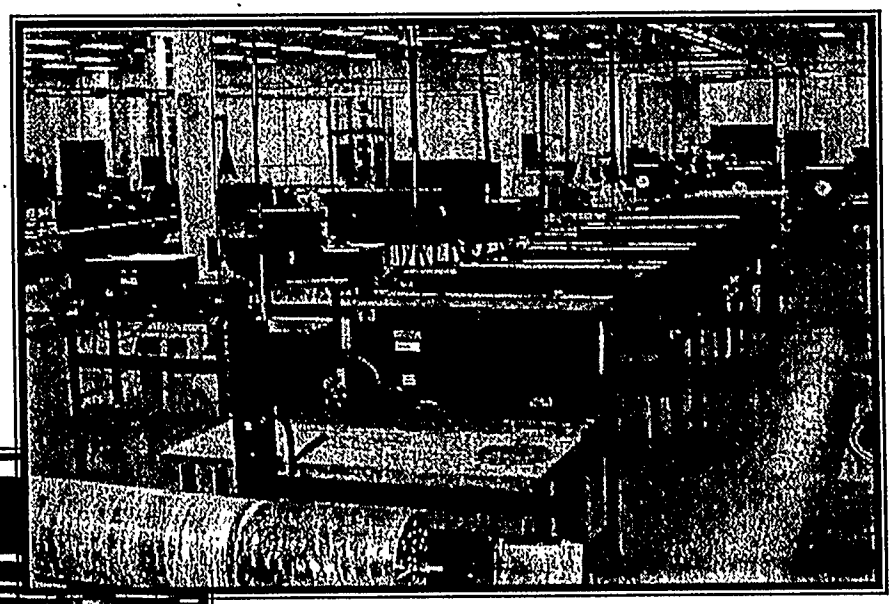


Uniform long length properties!

HTS Wire/Tape Requirements

Fault Current Limiters:	**50 km per system (17 kV)**
Transformers:	**40 km per system (30 MVA)**
Transmission Cables:	**20 km per 100 m (2 KA)**
Generators/Motors:	**72 km per system (20 MVA)**
Lab Magnets & Systems:	**10 km per magnet (>5 Tesla)**

Intermagnetics Capability



- **Current planned HTS capacity: 100 to 120 km per year**

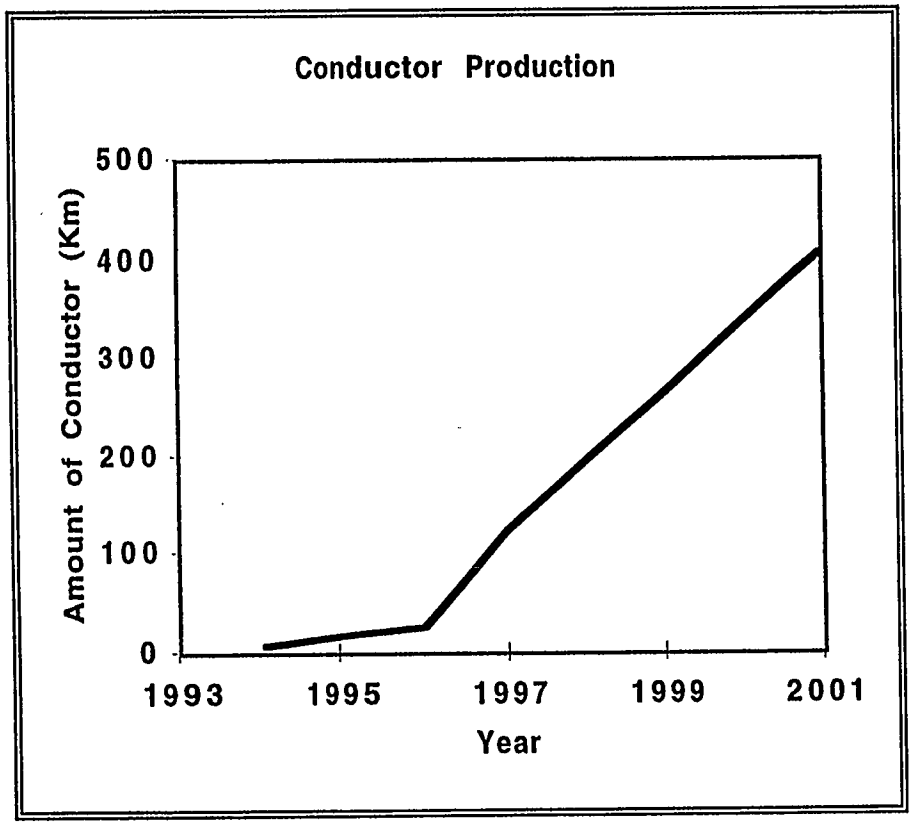
- **Dedicated HTS facility in New York**
- **Approx. 20,000 sq. ft. of space**

INTERMAGNETICS GENERAL CORPORATION

High Temperature Superconductors

One of three sophisticated rolling mills for HTS tape

Estimated growth in demand and production capability at Intermagnetics



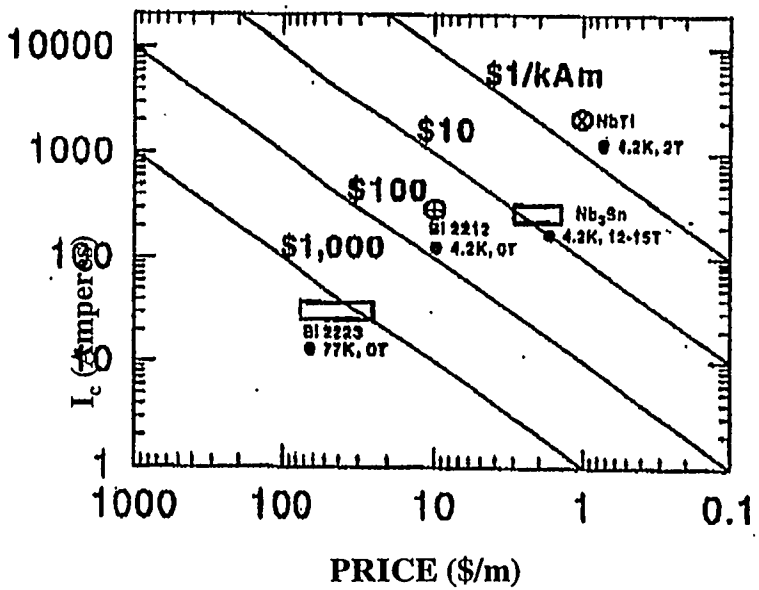
PIT Bi-2223 Cost

- Typical Today's Conductor :
  Critical Current = 30 A (100 to 200 m lengths)
  Conductor Cost = $ 30/m ----> **$ 1000/kA-m**

- Realistic Expected Improvement (next 5 years) :
  Conductor Cost = $ 10/m (Materials Cost = $ 4/m)
  Critical Current = 100 A (100 to 200 m lengths)

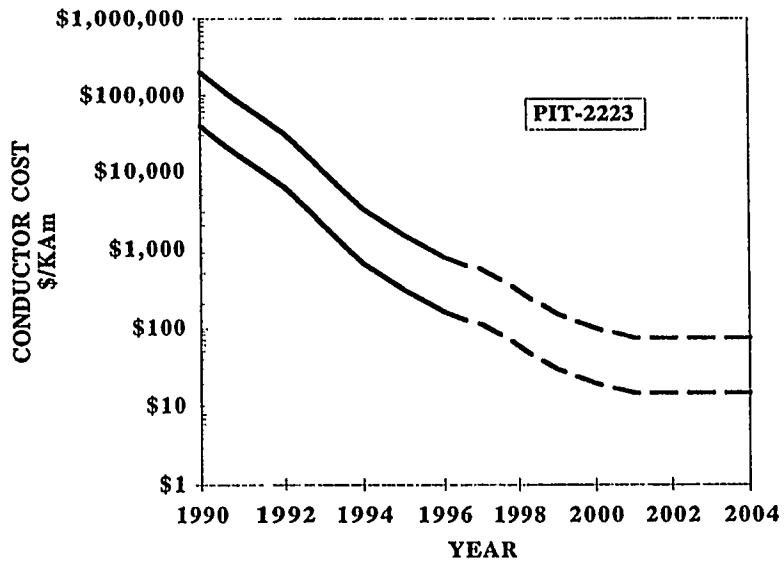
Realistic Target Cost -----> $ 100/kA-m (not $ 10/kA-m)

Cost reduction: key to success!



Comparative performance indexed prices for commercially important superconducting materials

Actual and anticipated reductions over ten years



PIT Bi-2223 Conductor Development

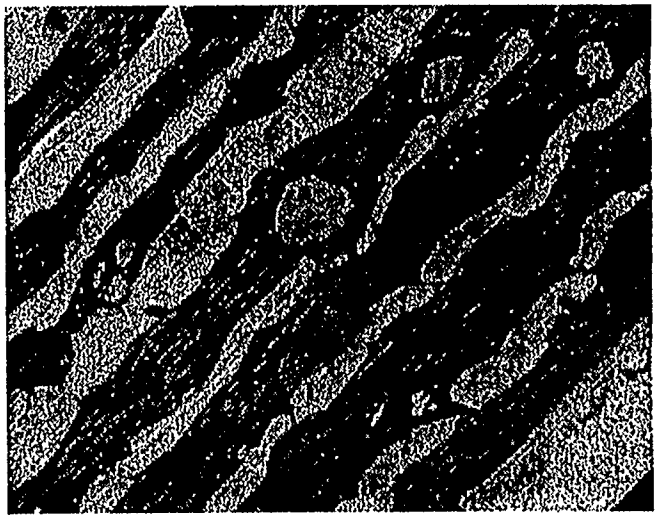
Objective :

Evaluate cost-effective approaches that will also improve performance

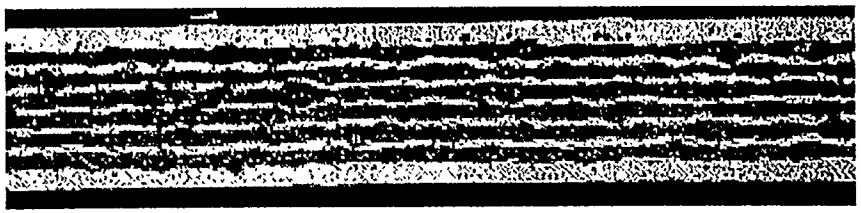
- Chemically-derived Powder (fine, uniform particle size)
- Consolidated Powder (near-net shape precursor)
- High volume fraction of HTS (40% HTS : 60% Ag)
- Improved Mechanical Processing & Heat treatments

PIT Bi-2223 Conductor Development

Solid State Powder

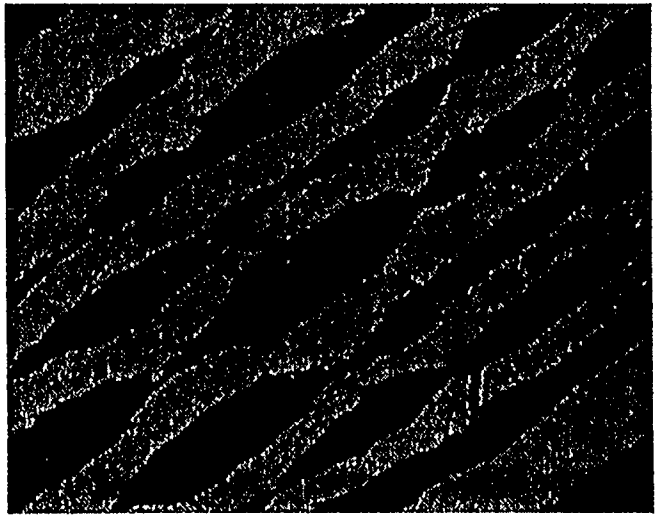


Large Secondary Phases

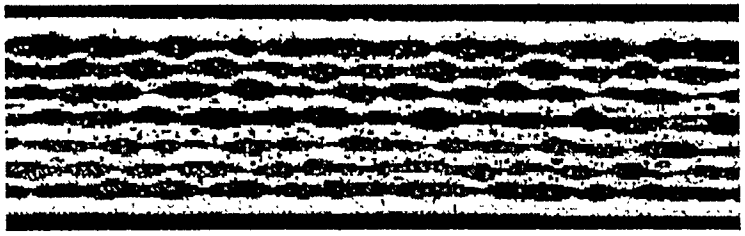


Optimized Mechanical Process

Chemically-derived Powder



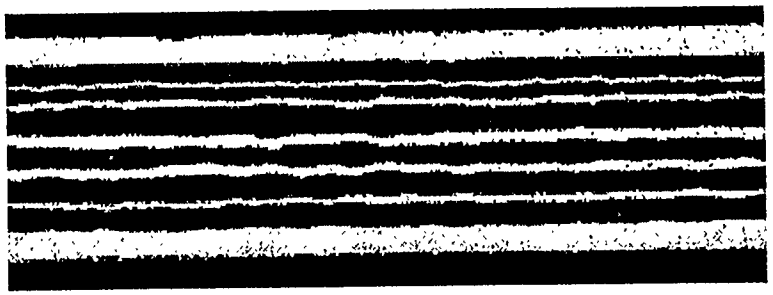
Uniform particle size



Unoptimized Mechanical Process

PIT Bi-2223 Conductor Development

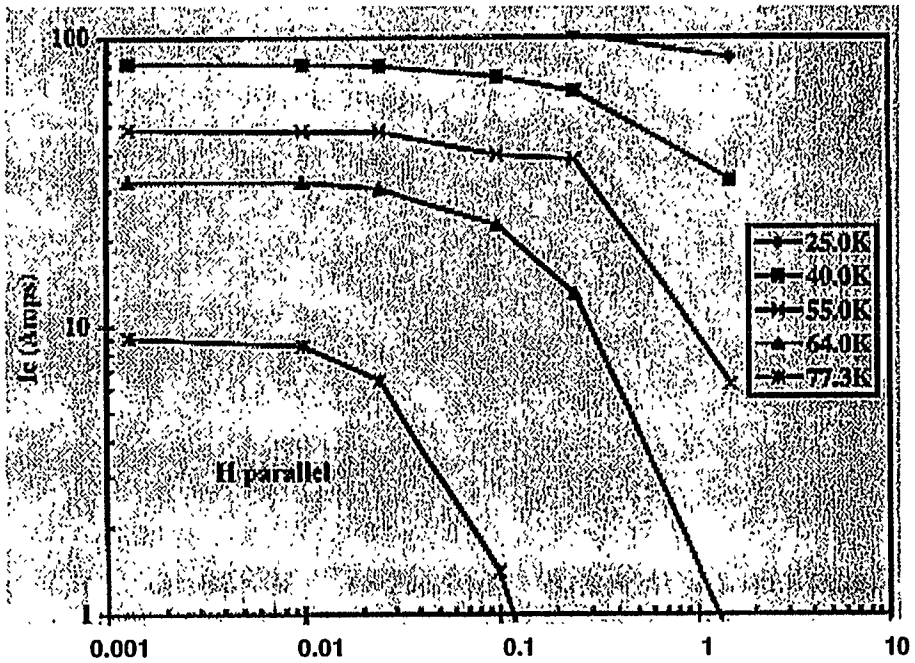
Consolidated Precursor Rod
Standard Mechanical Processing
Ic = 20 A over 0.5 m lengths

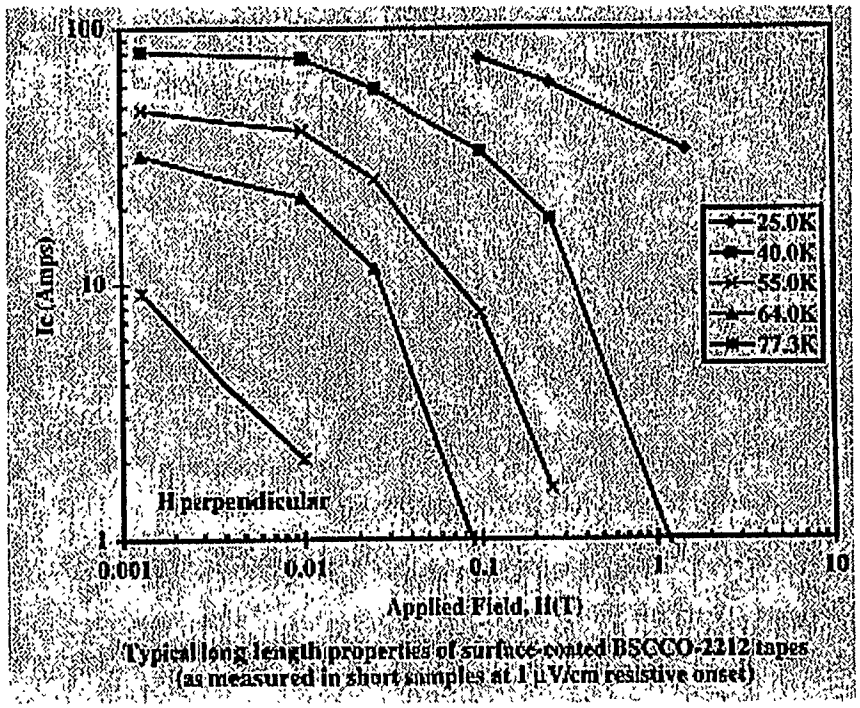


Consolidated Precursor Rod
Improved Mechanical Processing
Ic = 36 A over 0.5 m lengths

INTERMAGNETICS GENERAL CORPORATION

High Temperature Superconductors



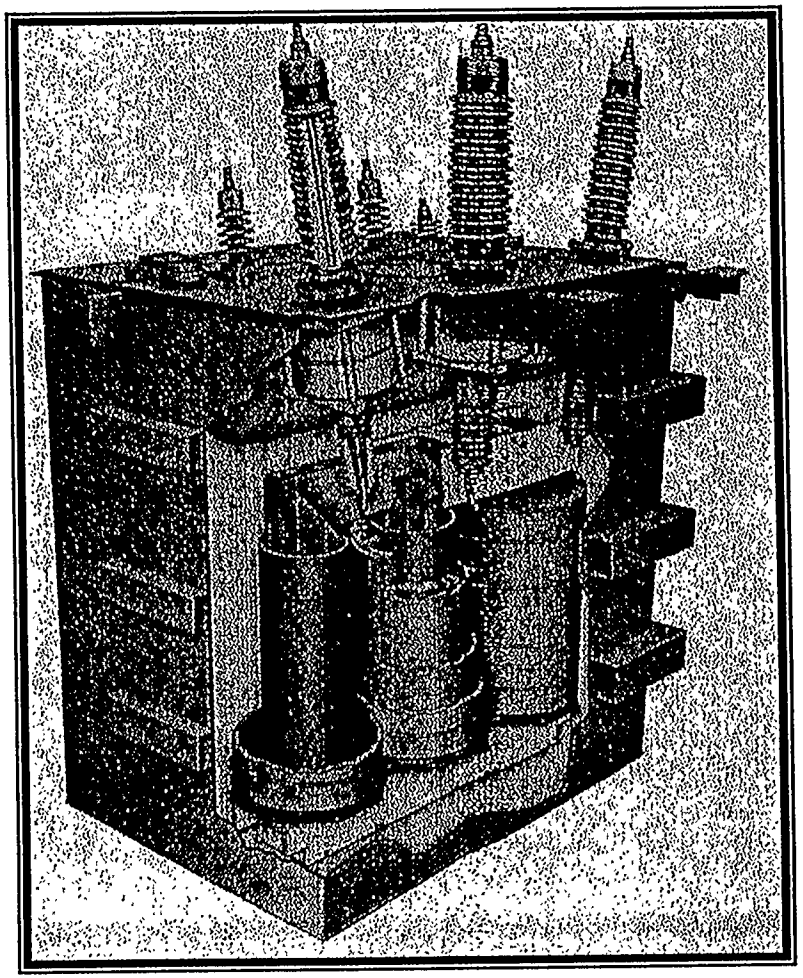


Intermagnetics General Corporation
450 Old Niskayuna Road
Latham, New York 02110-0461
Phone No.: (518) 782-1122
Fax No.: (518) 783-2615

Bi-2212 surface coated conductor critical current data

HTS Transformer

- Waukesha, Intermagnetics, Rochester Gas & Electric, ORNL
- Demonstrate prototype 5 MVA transformer
- Reduced size, weight, no hazardous material, 2x rating
- Bi-2212 Conductor 40 km / 30 MVA unit



INTERMAGNETICS GENERAL CORPORATION

BSCCO-2212

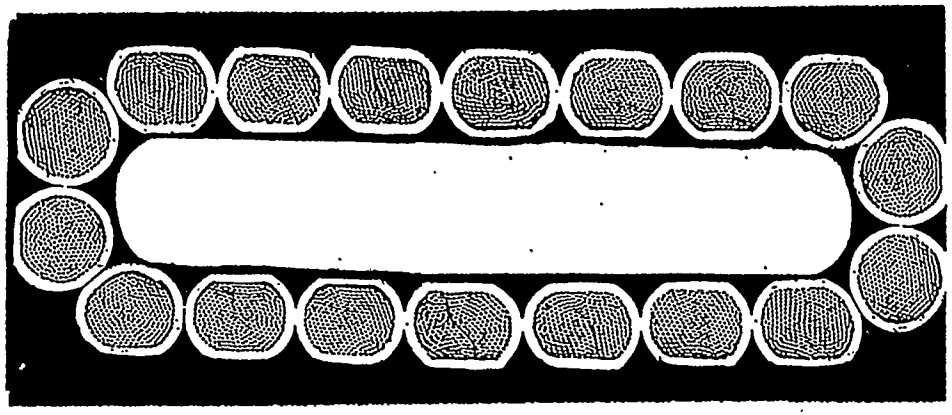
Low-Cost, Surface-Coated, React-Before-Wind Tape

(further developed with support from NASA, NIH, NRL)

Now being produced at up to 13 amps in long lengths
Priced at $6 to $10 per meter

Cables of PIT Multifilament Wires

(Being developed by Motowidlo with support of and in collaboration with Scanlan at LBL, results to be reported in greater detail at the High Energy Physics workshop in March)



.tfl

Ongoing Efforts

- Routine Manufacturing of Bi-2223 & Bi-2212 Conductor for Fault-Current Limiter, Cables, Transformer, and Current Leads.

- Improve Yield and Reduce Cost in Manufacturing Operations.

- Continue Development in Mechanical Processing & Heat Treament of Bi-2223 Tapes with New Chemically-derived Precursors for Enhanced Performance.

PROGRESS IN BSCCO-2212 CONDUCTORS FOR MAGNETIC FIELD APPLICATIONS

K. R. Marken, W. Dai, J. Parrell, and S. Hong

OXFORD
Superconducting Technology

Carteret, New Jersey
USA

Presented at
U.S. Department of Energy's
Wire Development Workshop
January 29-30, 1998
St. Petersburg, Florida

48

ADVANTAGES OF BSCCO-2212/Ag

- Can be melt processed with Ag, allowing:
  - ⇒ excellent grain alignment
  - ⇒ short heat treatments compared to 2223
  - ⇒ a wide variety of conductor configurations
  - ⇒ processing with or without deformation

- High J_c at high fields has been demonstrated
  - ⇒ 10^5 A/cm^2 range at fields above 20 T
  - ⇒ Record setting fields generated with 2212 insert coils

CHALLENGES OF MELT PROCESSING

- Leaking of melt through or around sheath
- Chemical interactions between melt and insulation or other components
- Bubbling of sheath
- Density change after melt/recrystallization

PROCESS CONTROL ISSUES

- Elimination of bubbles requires:
  - ⇒reduction of carbon
    - * carefully controlled powder calcination
    - * minimize exposure to ambient atmosphere
  - ⇒minimization of residual gas in the powder and restack billets
    - * control of packing environment
    - * billet heat treatment
  - ⇒control of melt heat treatment

- Elimination of 2212 leakage through sheath:
  - ⇒minimize sheath defects
  - ⇒reduce sheath grain size using alloys
  - ⇒control of melt heat treatment

- Control of 2212 melting behavior is quite important and difficult, affected by:
  - ⇒stoichiometry
  - ⇒carbon content
  - ⇒furnace atmosphere

19-FILAMENT CONDUCTOR

Tape Parameters

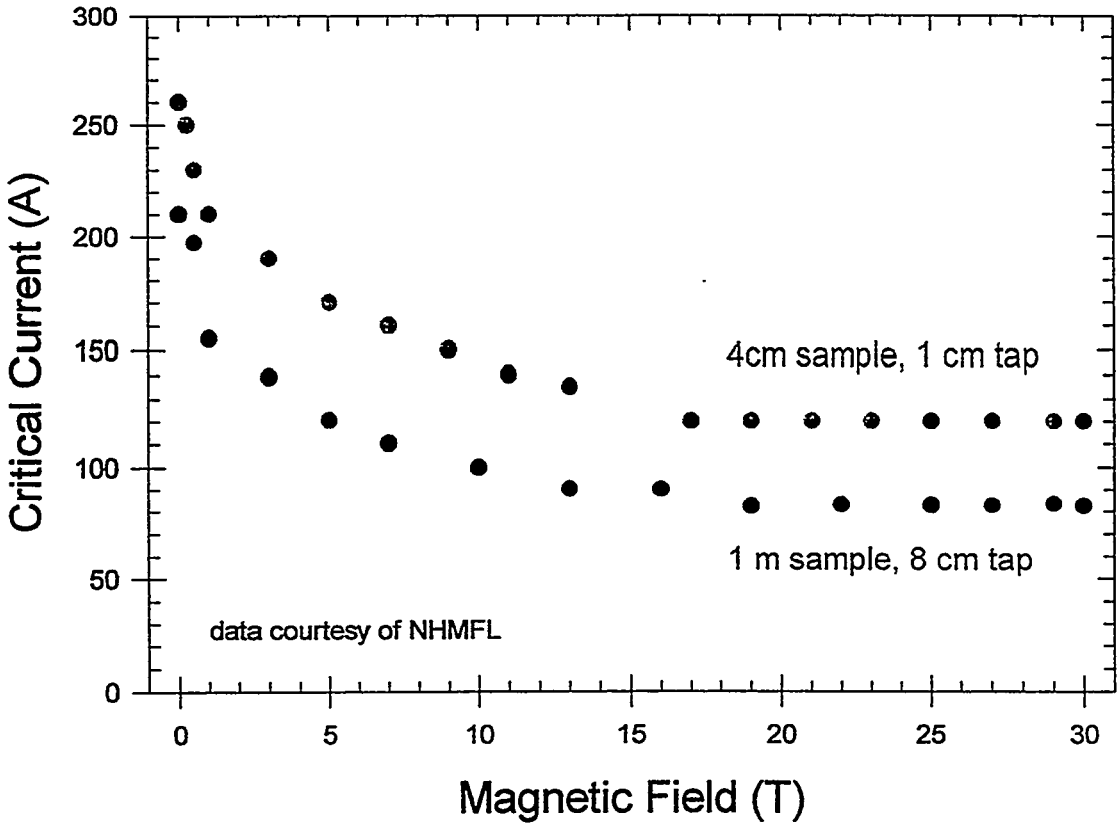
- Typical dimensions are 3 mm x 0.2 mm.
- Billets yield 300 m tape length at this size.
- Metal/ceramic ratio is nominally 3/1.
- Filament thickness is in the 15 - 30 μm range.
- Either all silver matrix, or silver core sheath with alloy bundle sheath.

OXFORD

19 filament 2212 tape at final size of 3 x 0.2 mm

OXFORD

OST 19 Filament 2212 at 4.2K



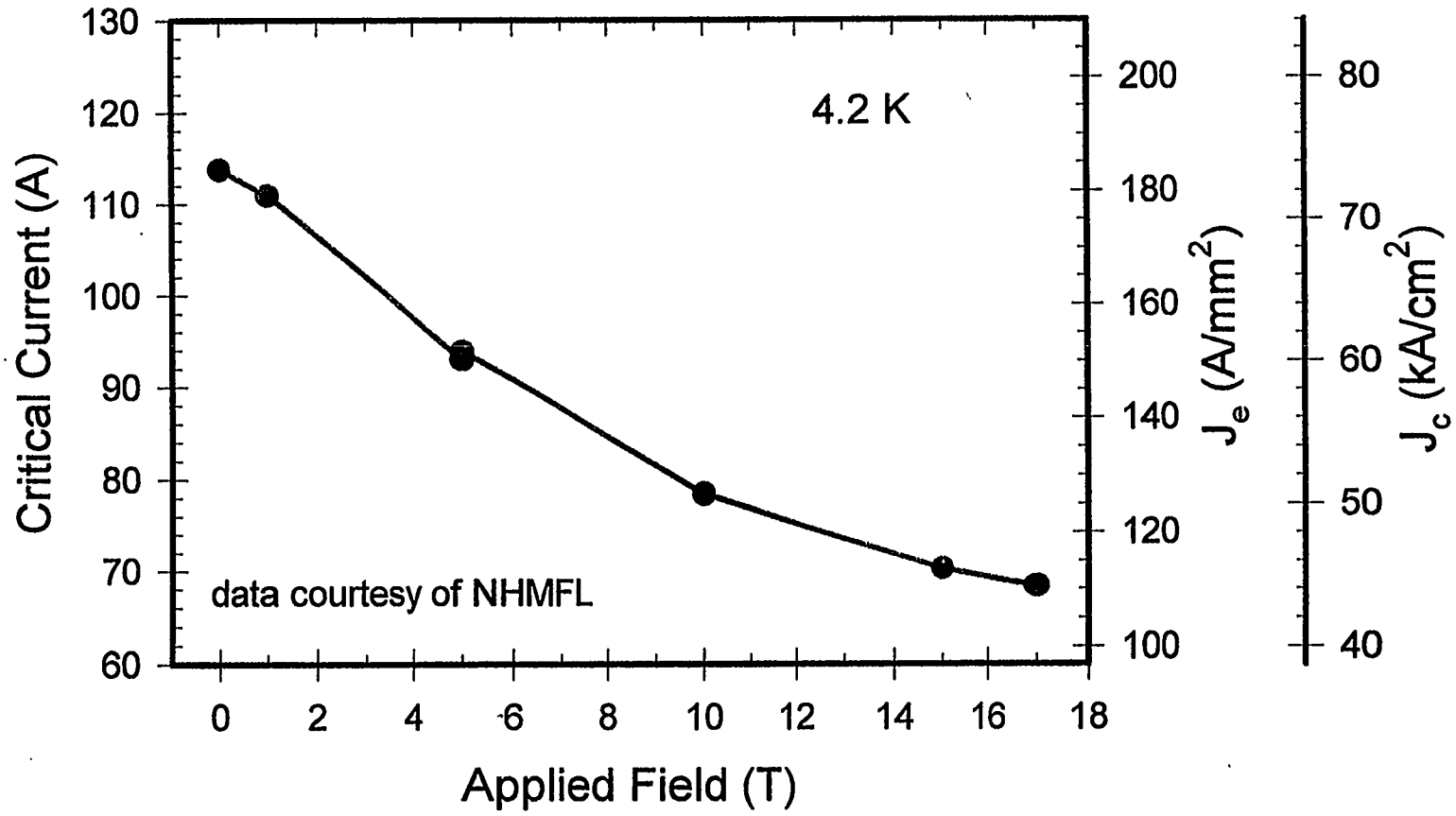
NHMFL 1T CLASS INSERT COIL

- Results presented by Weijers, et al., ICMC Portland, 1997.
- Coil stack contains 75 m OST 19 filament 2212 tape.
- J_e(4.2K, 18.2T central field) = 110 A/mm^2 across entire 75 m.
- At 4.2K coil generated:

  2.1 T self field
  1.2 T in 17T background

OXFORD

NHMFL Pancake coil stack with 75 m OST 19 filament tape



19-FILAMENT CONDUCTOR

Tape Performance

- 100 meter heat treated lengths with no bubbles

- Reproducible short sample:
  $J_c(4.2K, 0T) = 200\ kA/cm^2$
- 1 meter length as 19mm diam. helix:
  $J_c(4.2K, 0T) = 160\ kA/cm^2$
  $J_c(4.2K, 30T) = 75\ kA/cm^2$
- 5 m double pancake coil:
  $J_c(4.2K, 0T) = 125\ kA/cm^2$
  $J_c(4.2K, 17T) = 60\ kA/cm^2$
- 50 meter length as 100 mm diam. helix:
  $J_c(4.2K, 0T) = 102\ kA/cm^2$
- 75 meter length as 100 mm diam. helix:
  $J_c(4.2K, 0T) = 60\ kA/cm^2$
- 75 meter length as 46mm OD x 16mm ID stack of double pancakes:
  $J_c(4.2K, 0T) = 79\ kA/cm^2$
  $J_c(4.2K, 17T) = 44\ kA/cm^2$

ROUND WIRE

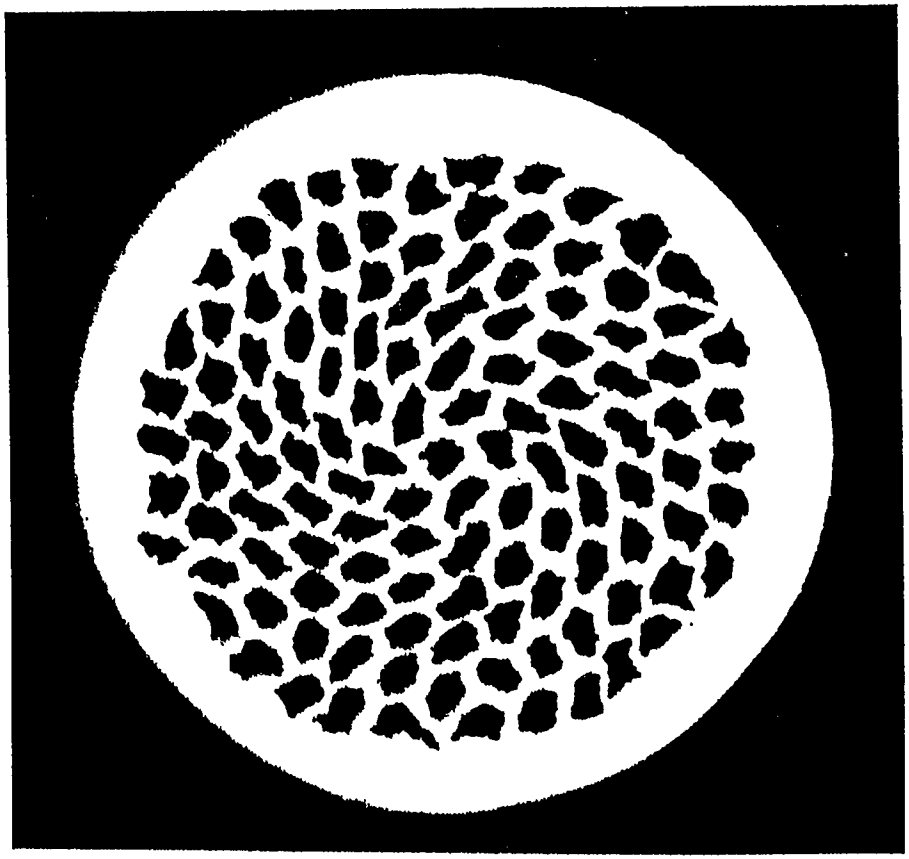
Wire Parameters:

- 0.8 mm diameter
- 121 filaments
- 40 μm nominal filament diameter
- Ag/SC ratio made in 2 ratios: 2.2 and 3
- Filament sheath is pure Ag
- Outer sheath is alloy

Wire Performance:

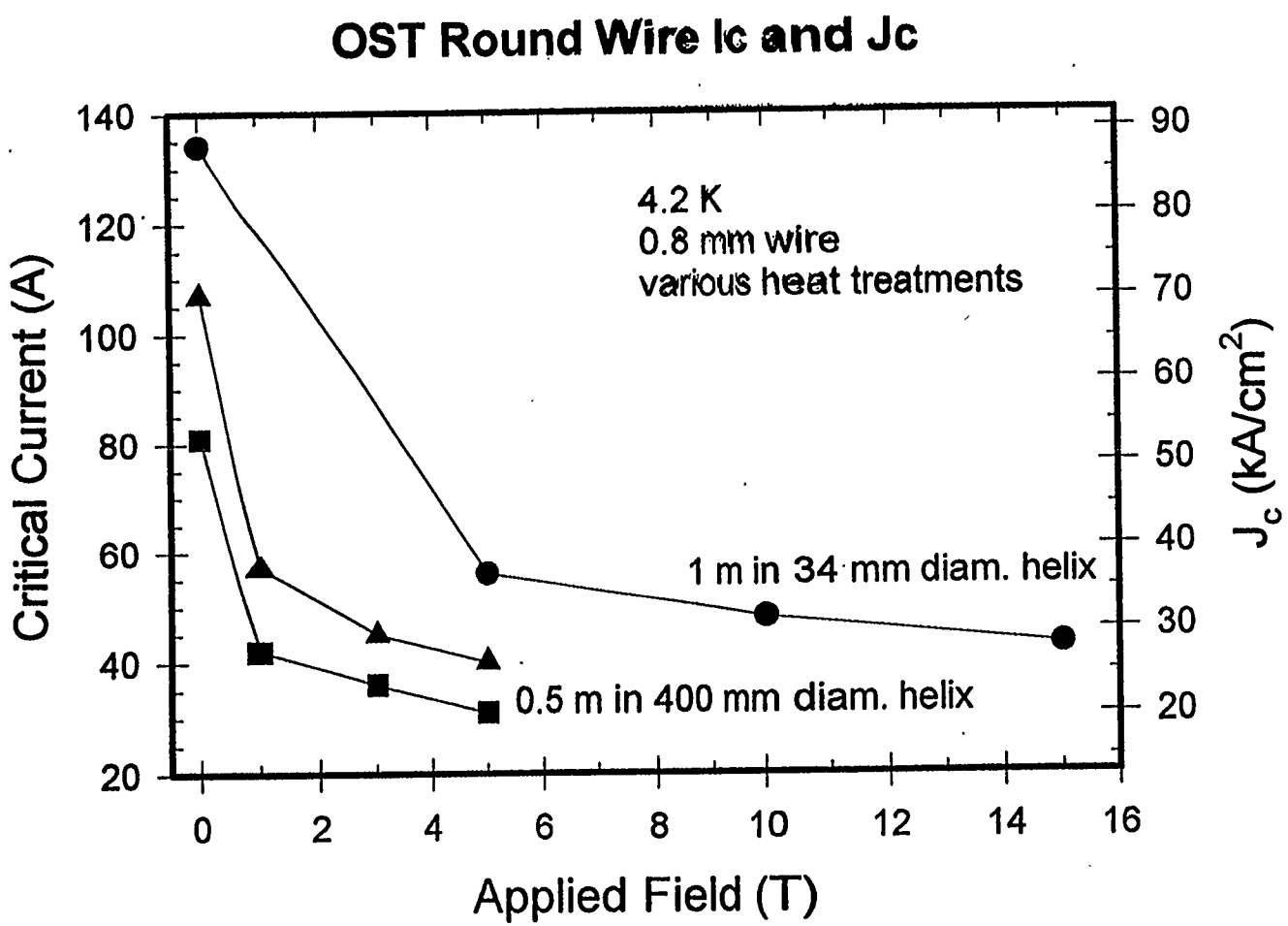
- Highest I_c(4.2K, 0T) = 141 A
  J_c(4.2K, 0T) = 93 kA/cm^2
- Highest I_c(4.2K, 15T) = 43 A
  J_c(4.2K, 15T) = 28 kA/cm^2
- 250 m piecelengths

OXFORD



121 filament 2212 wire at final size of 0.8 mm

OXFORD


OST Round Wire Ic and Jc
4.2 K
0.8 mm wire
various heat treatments
1 m in 34 mm diam. helix
0.5 m in 400 mm diam. helix
Critical Current (A)
J_c (kA/cm^2)
Applied Field (T)
140
120
100
80
60
40
20
90
80
70
60
50
40
30
20
0
2
4
6
8
10
12
14
16

DIP COATED CONDUCTOR

- Short sample $J_c(4.2K) > 200\ kA/cm^2$ is reproducible

- 4 m lengths in single pancakes have achieved:
  ⇒$J_c(4.2K) > 100\ kA/cm^2$
  ⇒0.85 T self-field at 450 A with 50 mm OD
  ⇒0.25 T in 17T applied field with 50 mm OD

- 100 m lengths in stacked pancake magnets:
  ⇒$J_c(4.2K) > 40\ kA/cm^2$
  ⇒Generated fields > 1T

DIP COATED CURRENT LEADS

- Multilayer stacks of dip-coated Ag alloy
- Can achieve metal:ceramic ratios less than 1:1
- High current density compared with bulk 2212
- Compact with high current up to ~60K
- Usable up to 77K

SUMMARY

- 2212 composites have been fabricated in lengths greater than 300 meters using both powder-in-tube and dip-coated methods.

- Melt related defects such as bubbles and melt leakage have been reduced through improved process control.

- J_c(4.2K, self-field) has been increased to more than 60 kA/cm^2 in 50 to 100 m lengths of tape conductor.

- J_c(4.2K, 30T) = 77 kA/cm^2 has been obtained in 19 filament tape samples.

- NHMFL insert coil added 1T in 17T applied field using 75 m of OST 19 filament tape.

- J_c in round wires shows promise for field applications.

Development of Strengthened Bundled High Temperature Superconductors

Presented By:

Lyn Adams, President - EURUS Technologies, Inc.

Michael Tomsic, President - Plastronic, Inc., subsidiary of EURUS

Contributors Include:

J.W. Lue, J.A. Demko, M.S. Lubell - ORNL

A. Sarkar - Univ. of Dayton

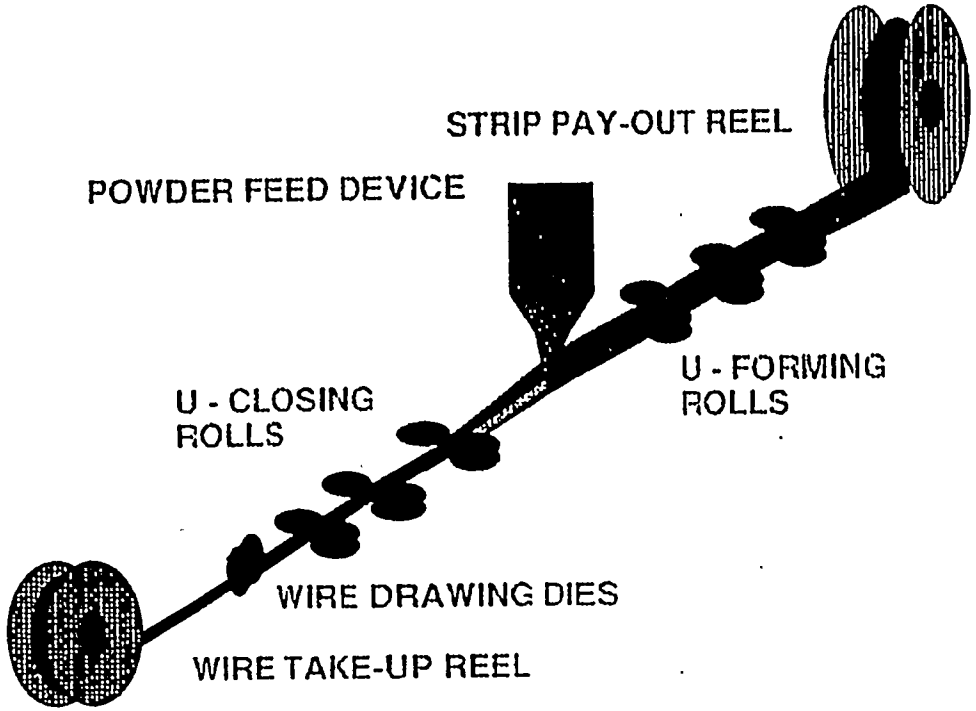
EURUS

Introduction

- Stronger, higher current carrying conductors are needed for large scale HTS applications
- Power Plus™ is manufactured by Continuous Tube Forming & Filling (CTFF) to make Bi-2223/Ag tapes
- Apply the CTFF technique to make strengthened HTS bundles

EURUS

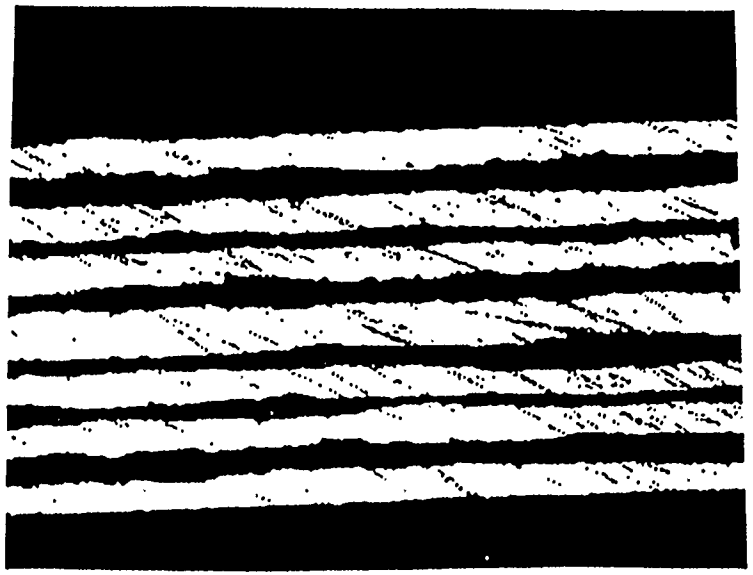
Continuous Tube Forming & Filling Process



EURUS

Cross Sections of Bi:2223/Ag Tape Showing Uniform Transverse & Longitudinal Filaments

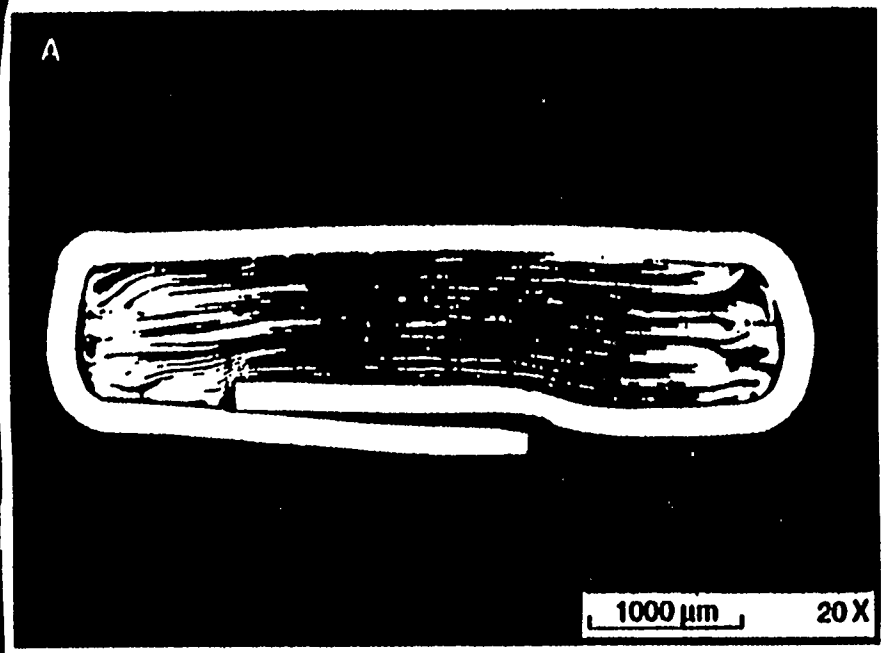
Transverse

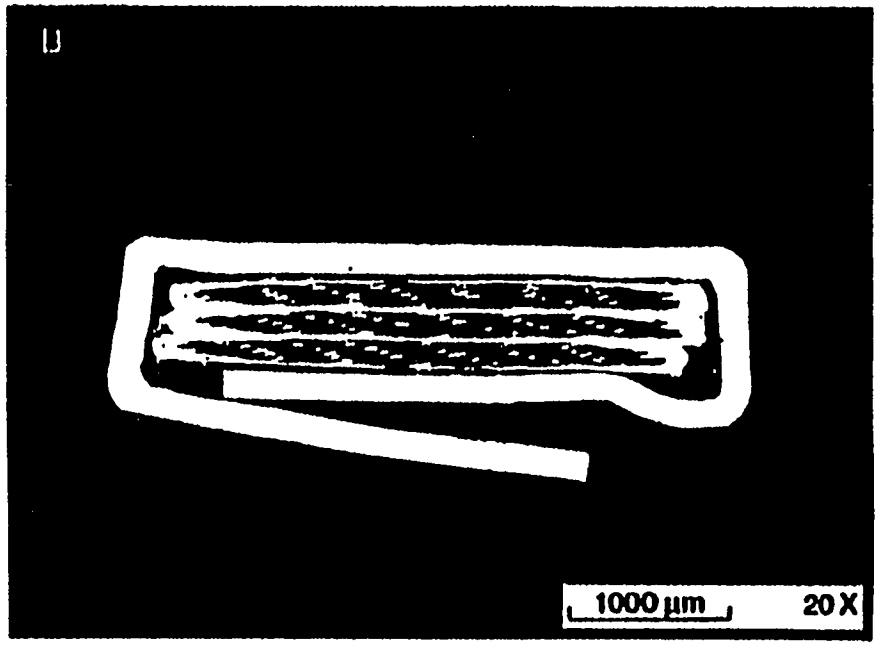


Longitudinal

EURUS

Bundle Superconductors Encapsulated in Non-Silver Sheath





EURUS

Encapsulated Bundle Superconductor

- HTS tapes are bundled, encapsulated with a metallic sheath, and resintered
- Strengthening is achieved by the sheath and its choice of material
- Current carrying capacity is increased by bundling
- No degradation of superconductor was seen when applied to finished HTS tapes

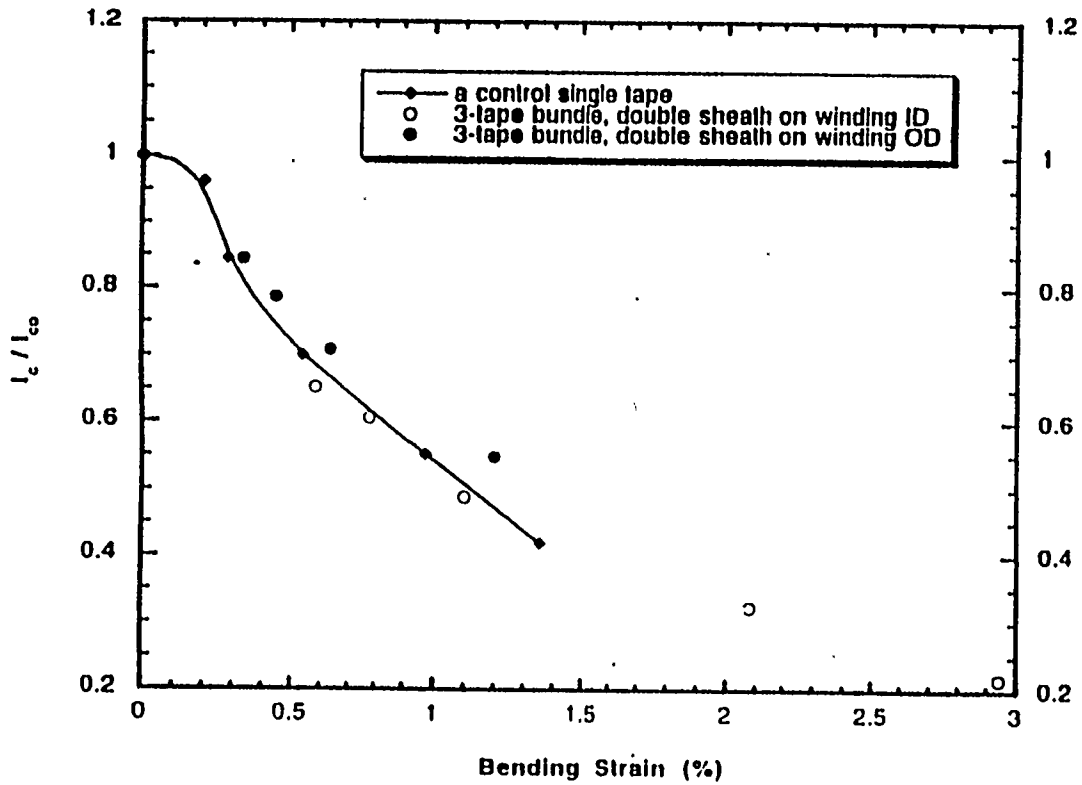
EURUS

Mechanical Properties of Tapes & Encapsulated Bundle Conductor

Sample	UTS (Mpa/ksi)	YS (Mpa/ksi)	Elongation (%)
CTFF- tapes	60 / 8.8	55 / 8.0	3.5
T- tapes	45 / 6.5	42 / 6.1	1.0
3-tape bundle	153 / 22.2	64 / 9.3	40
6-tape bundle	134 / 19.5	63 / 9.1	30

EURUS

Comparison of I_c Reduction of the Bundle Conductor to a Single Tape



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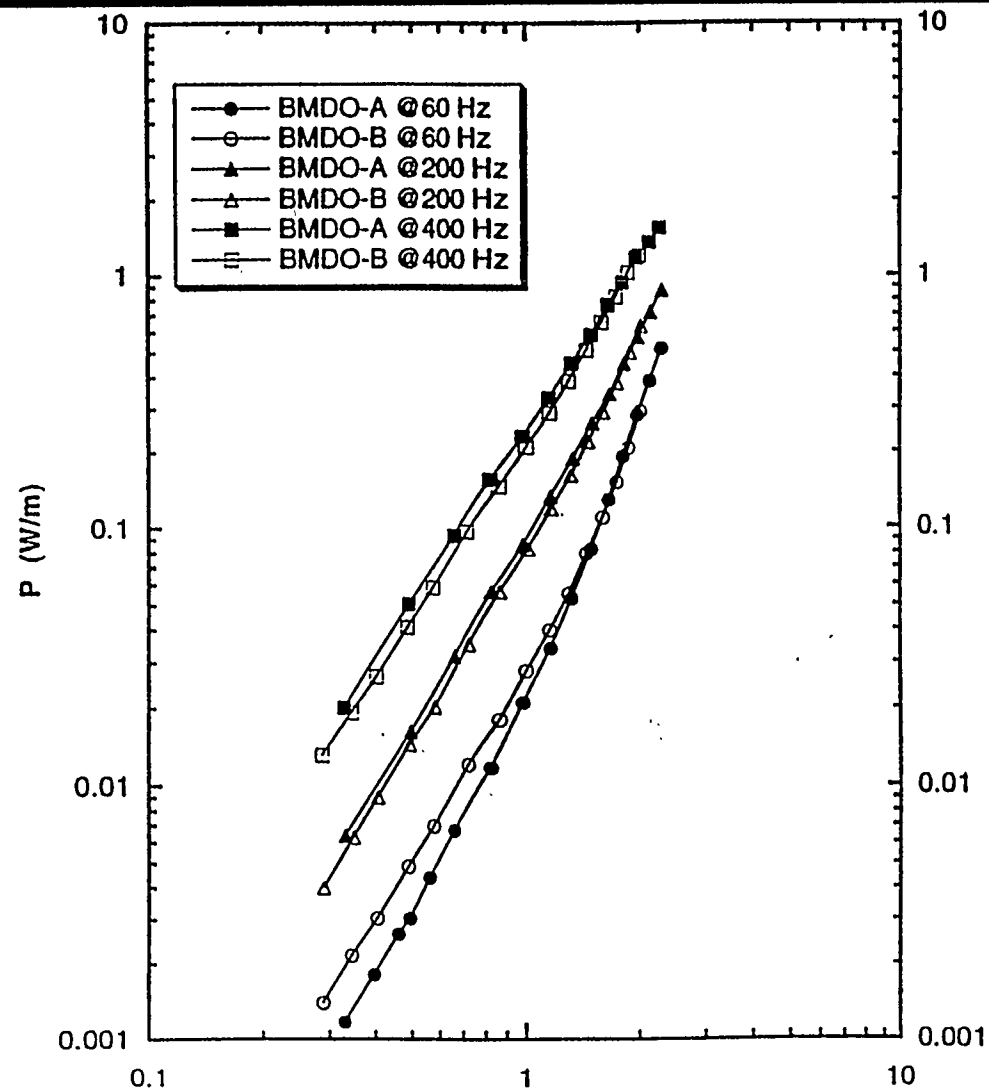
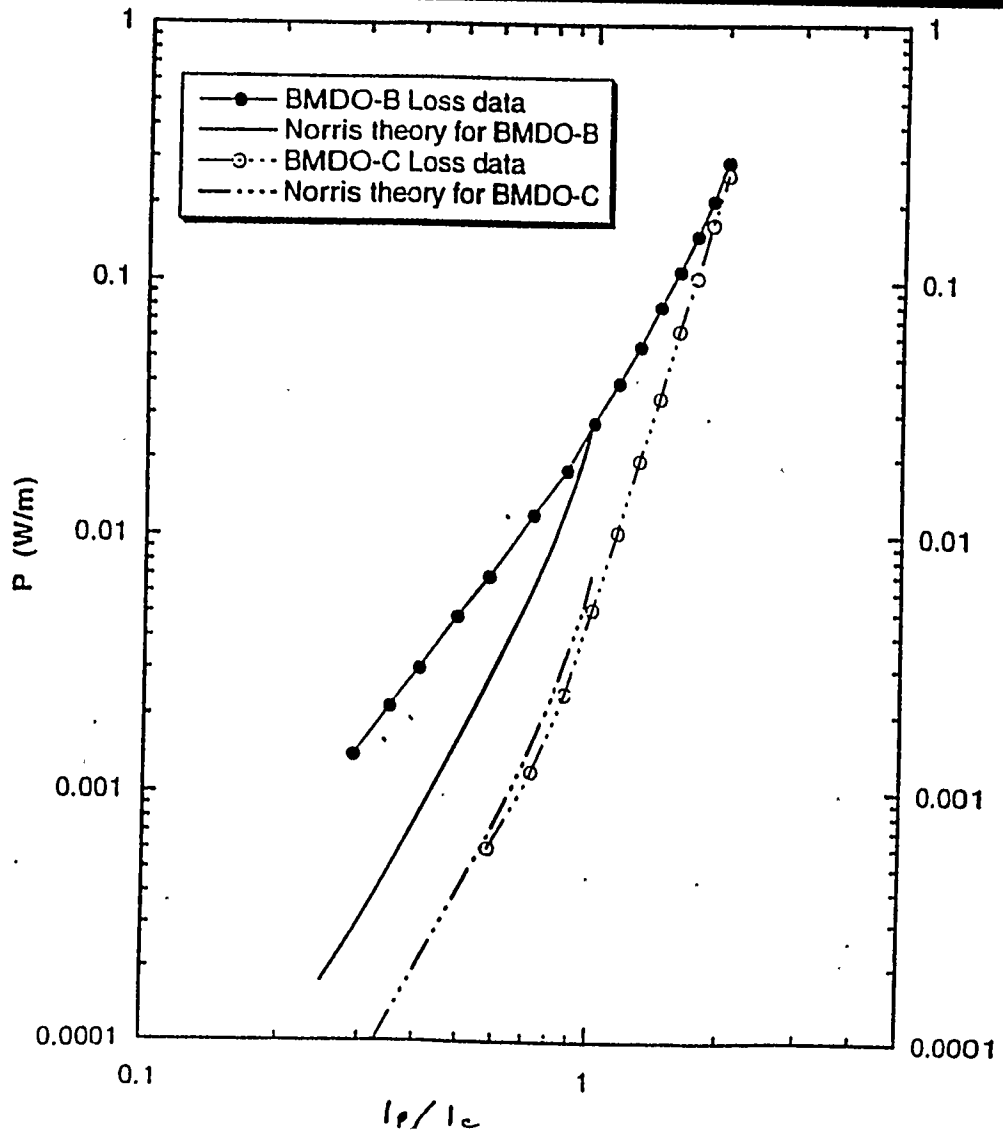
Comparison of BMDO-A with BMDO-B



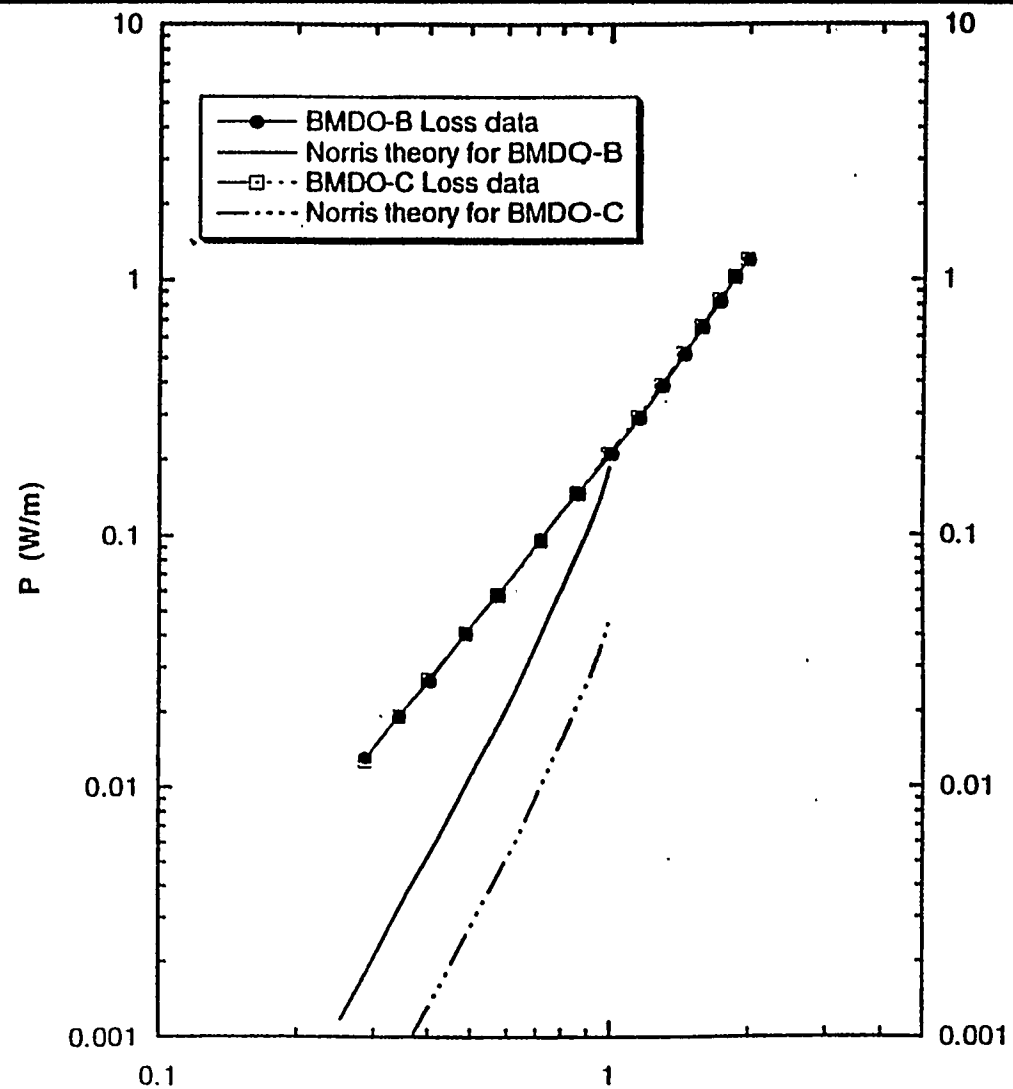
EURUS

Comparison of BMDO-B&C AC Loss @60 Hz



EURUS

Comparison of BMDO-B&C AC Loss @400 Hz



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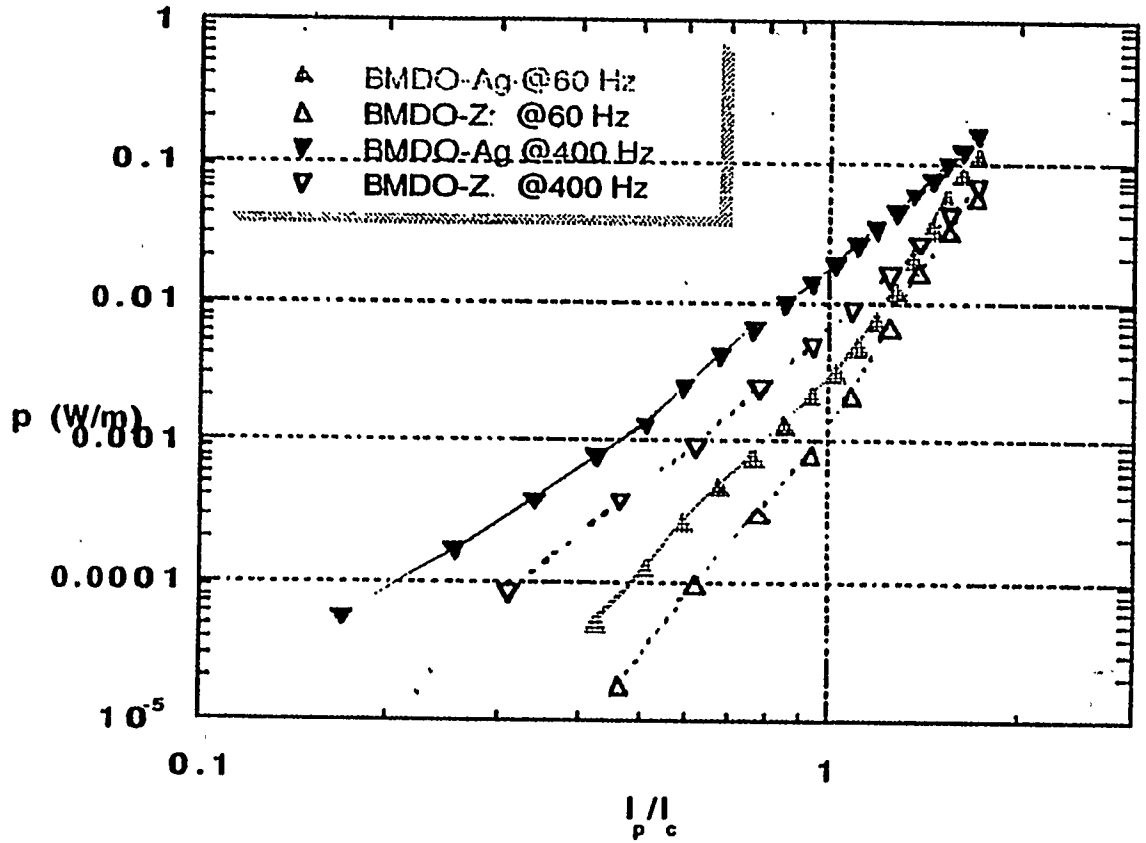
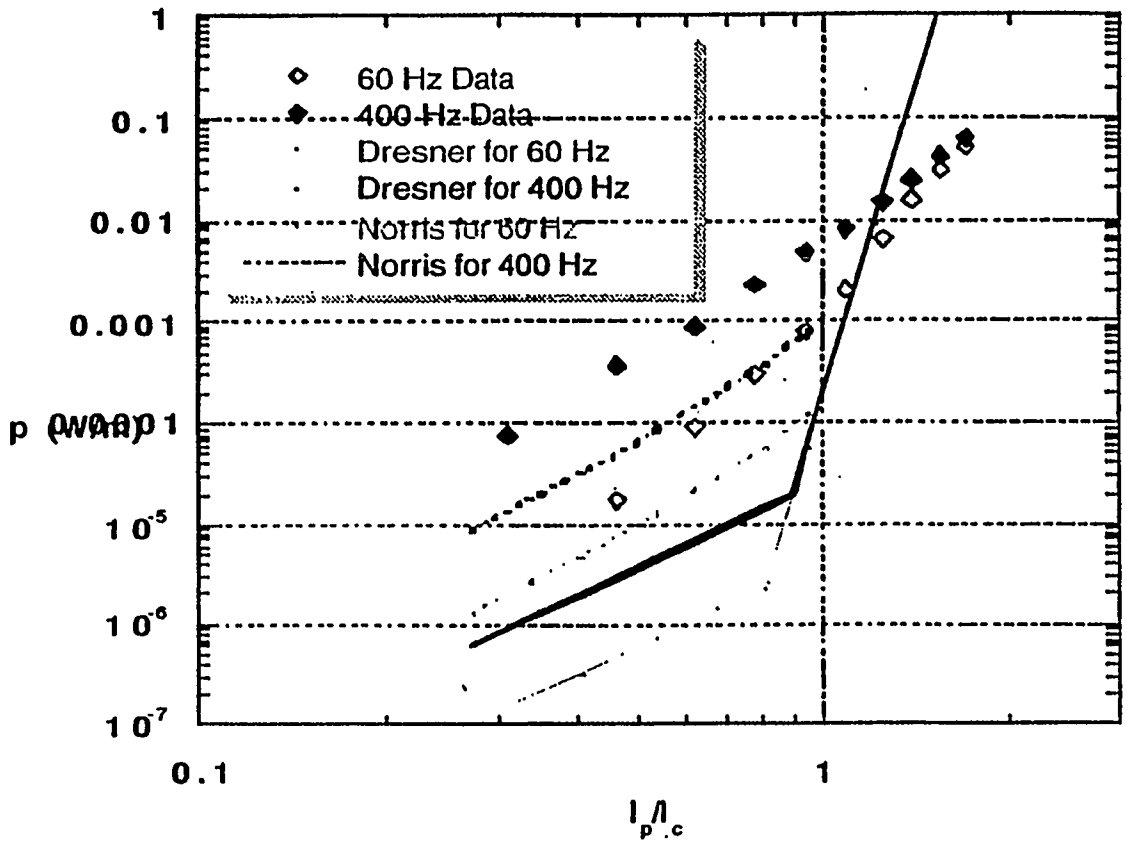
AC Loss Comparison of Standard & Coated-Filament Tapes



EURUS

Comparison of BMDO-Z AC Loss with the Theories



EURUS

Conclusion

- Strengthened and higher current HTS conductor is achieved by encapsulating a bundle with a sheath
- This process can be applied to finished HTS tapes and more than retains their superconductivity
- Mechanical strength of the finished conductor is dependent on the sheath; bending degradation is due mostly to the part under tension
- The robust and high current conductor will be very useful for large scale applications

EURUS

Composite Superconductors at American Superconductor Corporation

Acknowledgments:

Wire Development Group (WDG): LANL, ORNL, ANL, UW, NIST-G, ASC

DOE (BES, EERE, & HEP) and NSF SBIR Programs

The DOE SPI Program

NRL & ONR

Pirelli Cavi, spa

Rockwell Automation

ABB

The Community

American Superconductor CORPORATION

Outline

I. Short Lengths

II. Long Lengths

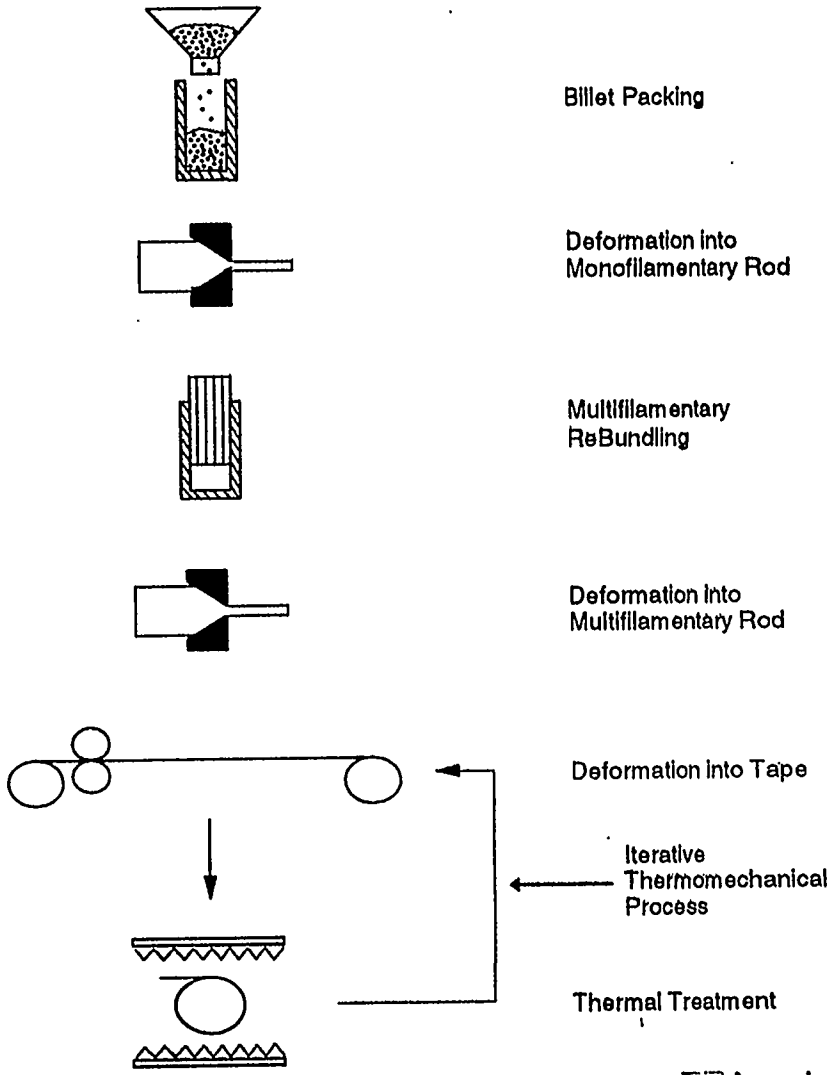
III. The Future

American Superconductor CORPORATION

Wire Technology

Bi-2223 Powder in Tube:

- Bi-2223 has Large Operational Temperature-Field Range
- PIT has *Demonstrated* Long Length Low Defect Performance
- PIT has Broad Product Architecture Flexibility
- PIT has Large Manufacturing Infrastructure Base



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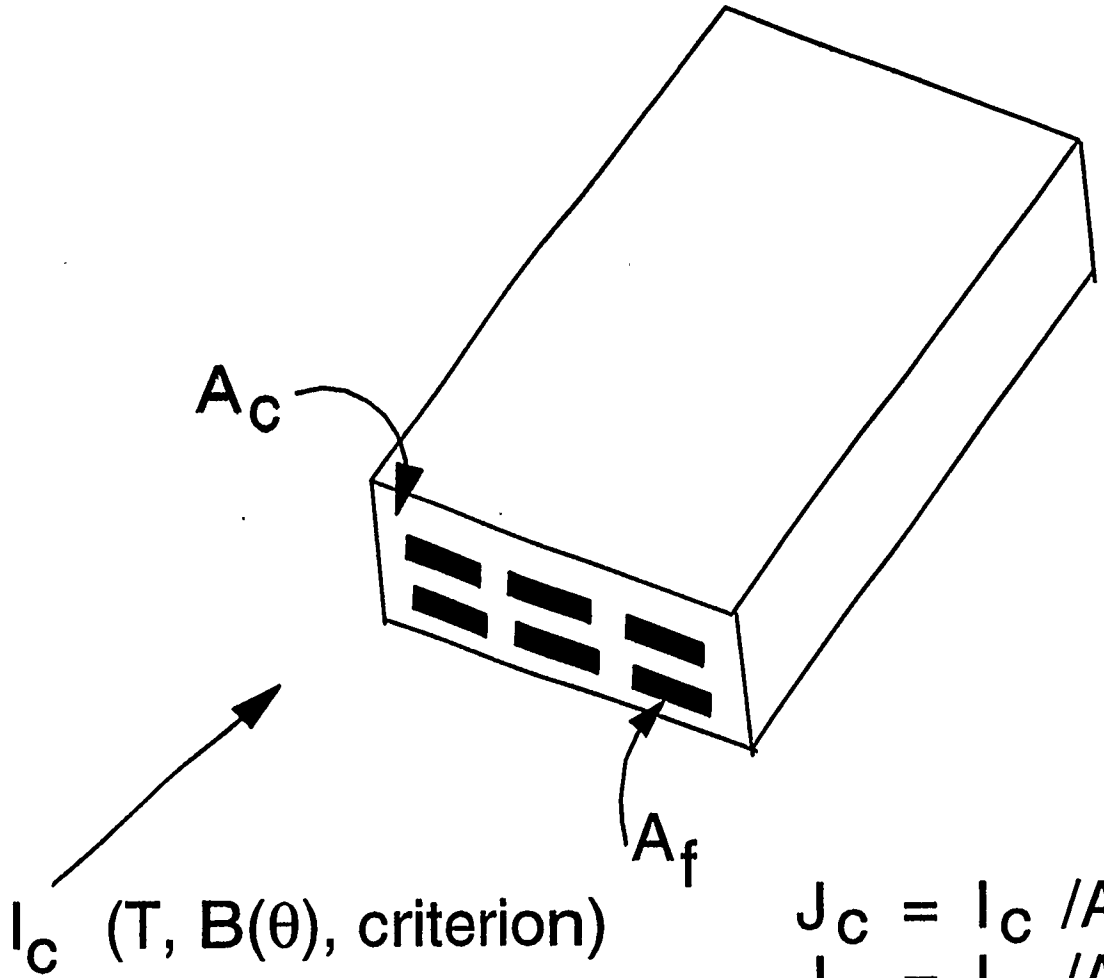
Measures of Performance



$J_c = I_c / A_f$

$J_e = I_c / A_c$

fill factor = A_f / A_c

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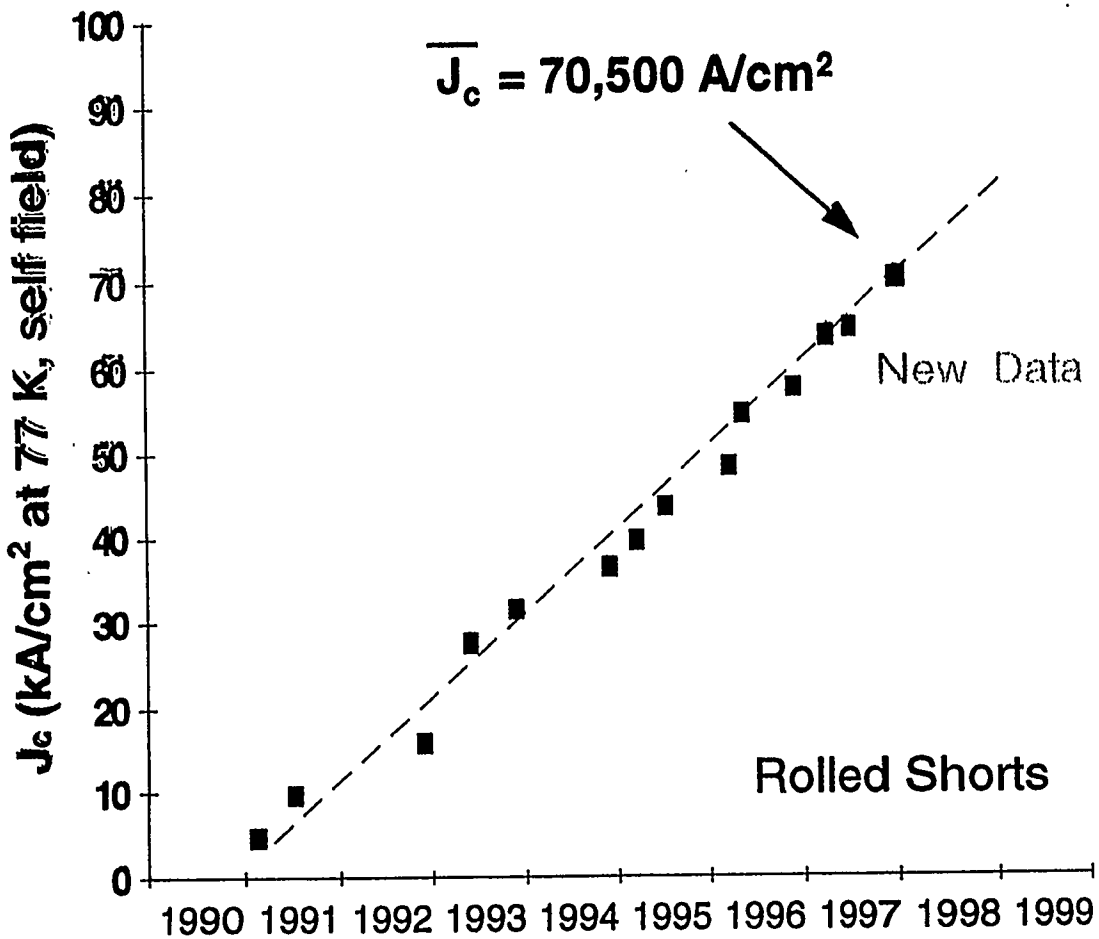
Multifilamentary Bi-2223 Wire Progress at ASC



- Inexorable Jc progress has continued.
- No sign of change in trend.

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Long Length Performance

- Results of Manufacturing Campaigns initiated in late '95 for Generation I wire and early '97 for Generation II wire.
- Campaigns consist of about 50 wire runs.
- Piece lengths greater than 100 m.
- Long length measurements at 77K, self field, 1 μV/cm.

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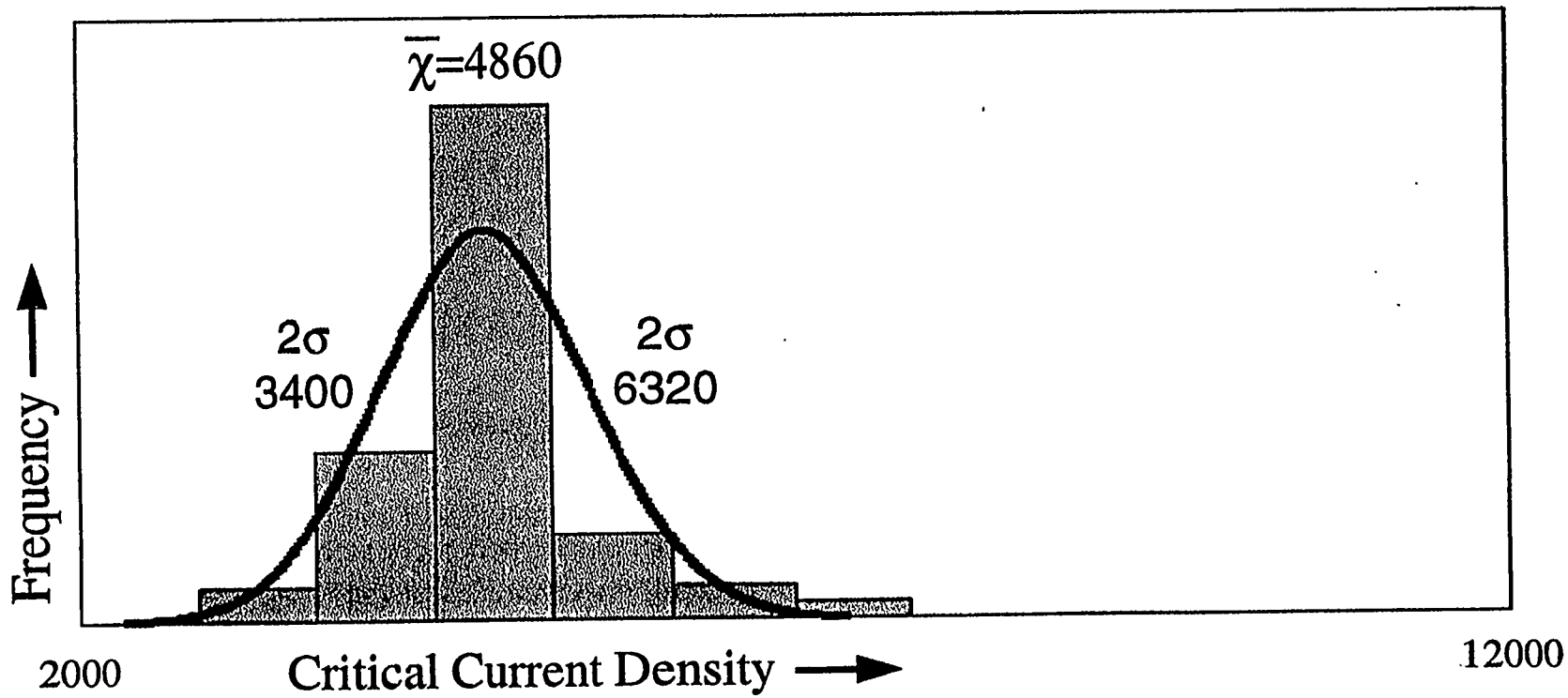
Generation I...

'95



Gaussian Distribution

$\sigma = 15\%$

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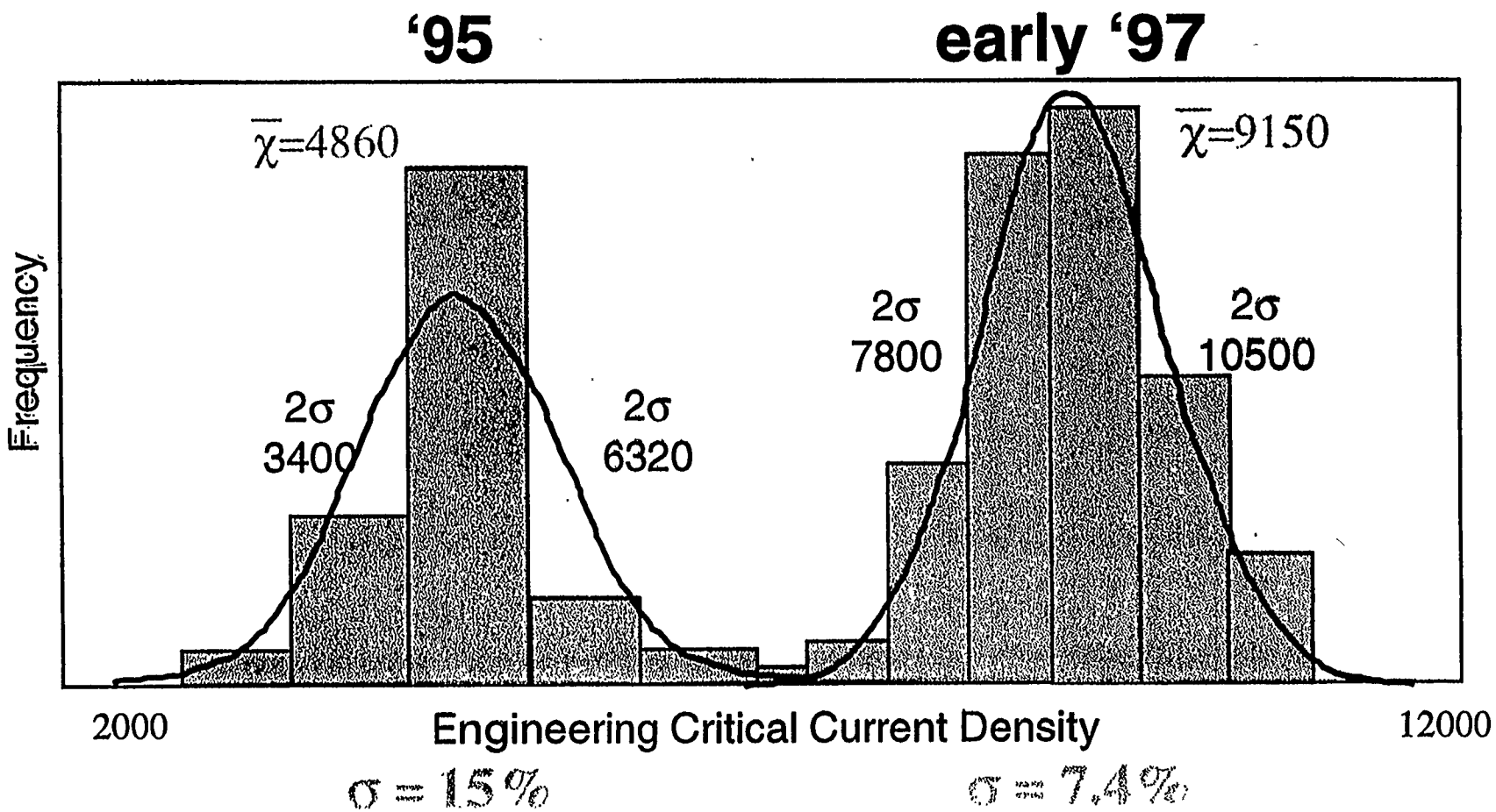
... and Generation II



Process mean increased by 88%, but process minimum ($\bar{\chi}$–2σ) increased by *130%*

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The Future

"The best way to predict the future is to create it."

A Prescient Person

American Superconductor CORPORATION

US Department of Energy
Conductor Performance Requirements

Application	Operating Jc[a] (A/cm^2)	Field (T)	Temp (K)	Ic (A)	Wire Length(M)	Strain (%)	Bend radius(m)	Cost ($/kAm)
Fault-current limiter	10^4-10^5	1 - 6	20-77	10^3-10^4	1,000	0.2	0.1	10 - 100
Large motor (1000 Hp)	10^5	4 - 5	20-77	500	1,000	0.2-0.3	0.05	10
Motor (125Hp)	1.5×10^4	1	27	75-80	~300		0.01	10-100
Generator (100 MVA)	5×10^4	4 - 5	20 - 50	500-1,000	500-1,000	0.2	0.1	10
SMES (1 MWh)	10^5	5 - 10	20-77	10^4	1,000	0.2	1	
Transmission cable	10^4-10^5	<0.2	65-77	25 - 30 [b]	100	0.4	2[c]	10-100
Transformer	~10^4	0.1 - 0.5	77		1,000	0.2	1	10

(a) Current density for individual high-temperature superconducting filaments

(b) Current for individual wire. Distribution cables, with multiple layers of tape, require transport current near 10kA.

(c) Cable requirement

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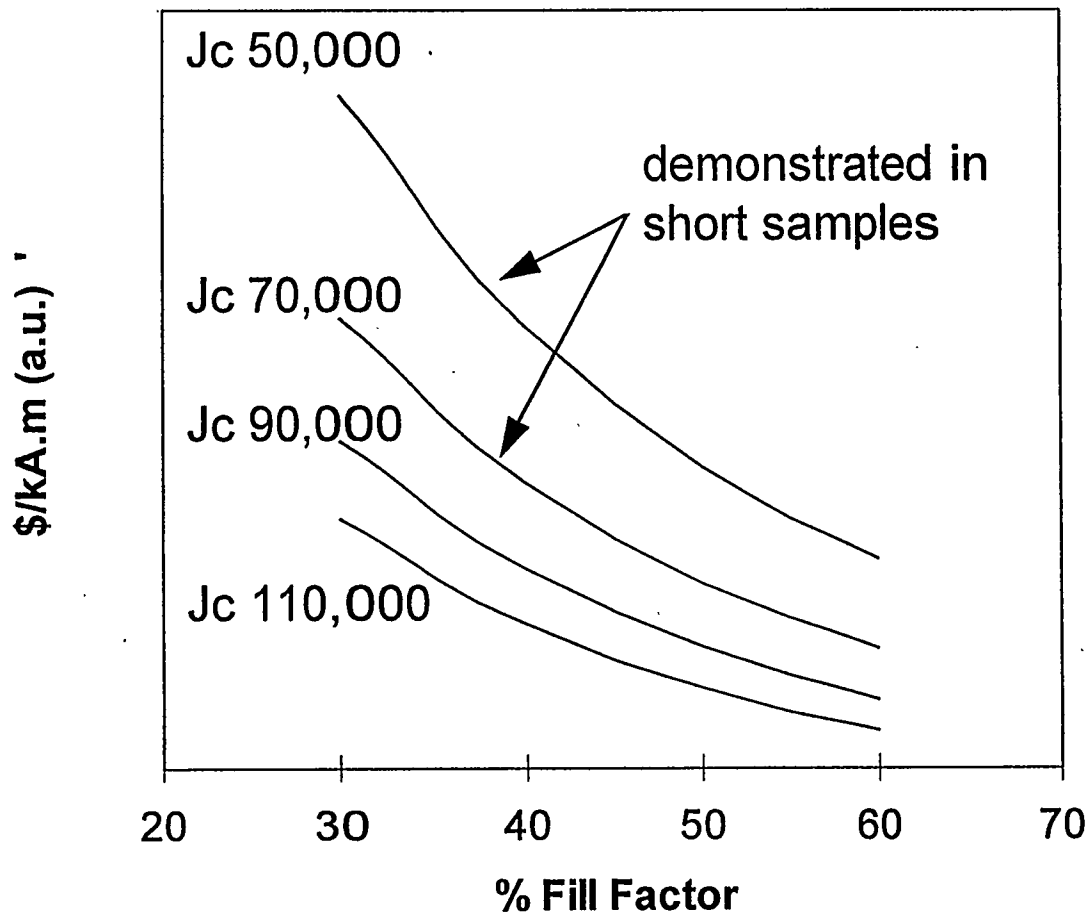
Pathways To Commercial Performance

For a fixed fabrication cost per meter:



- Increased fill factor has double benefit: improved Je and reduced Ag fraction
- Increase fill factor
- Improve Jc
- Replace Ag with inexpensive material

Cost Targets for Commercial Applications are Attainable

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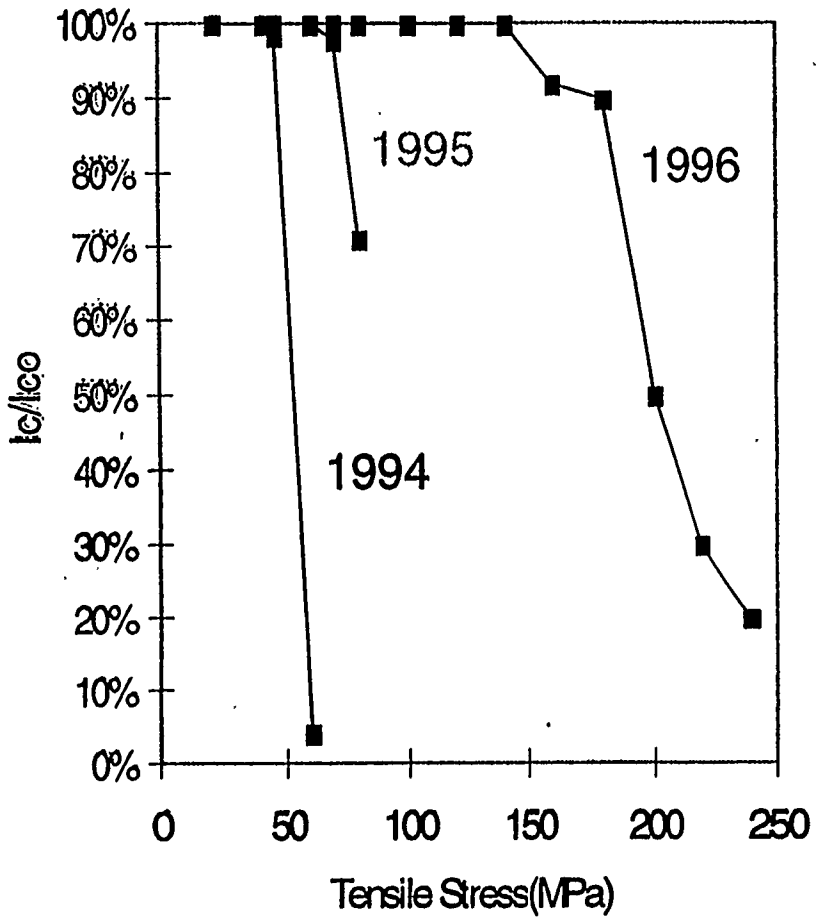
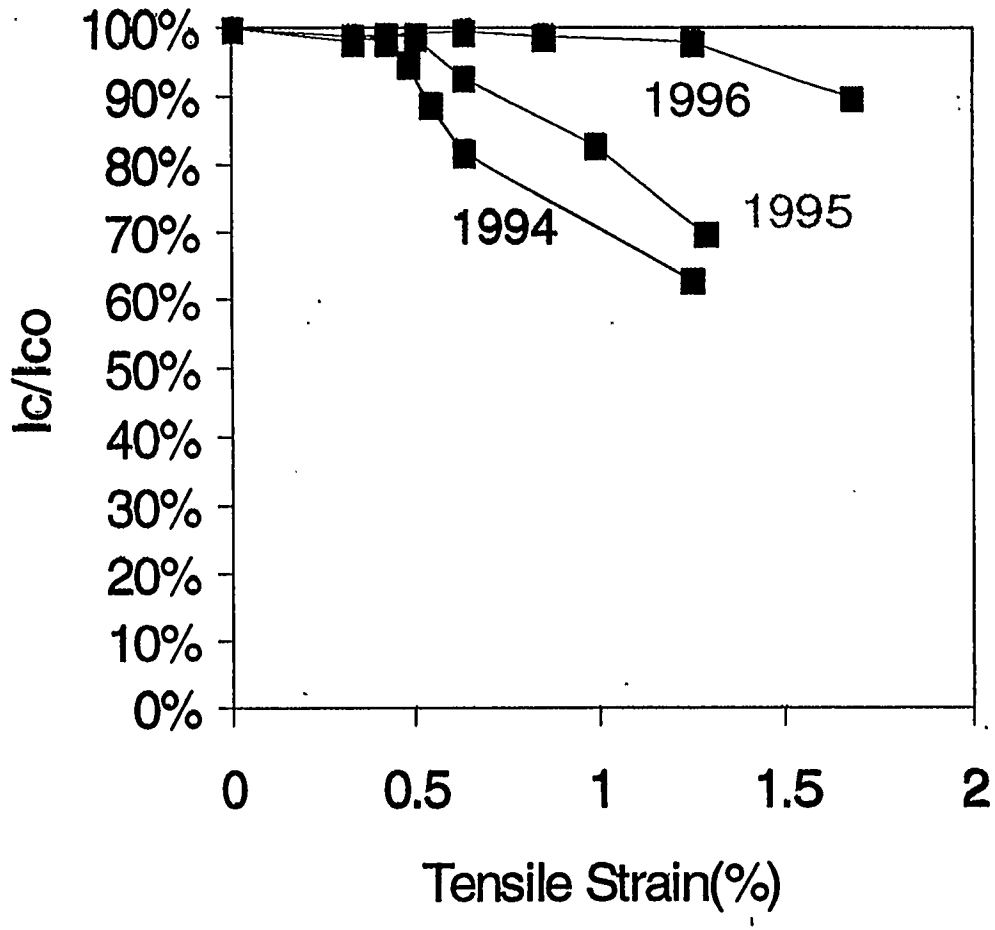
Mechanical Performance

Power Transmission Cable Wire





Improvements result from sheath engineering.

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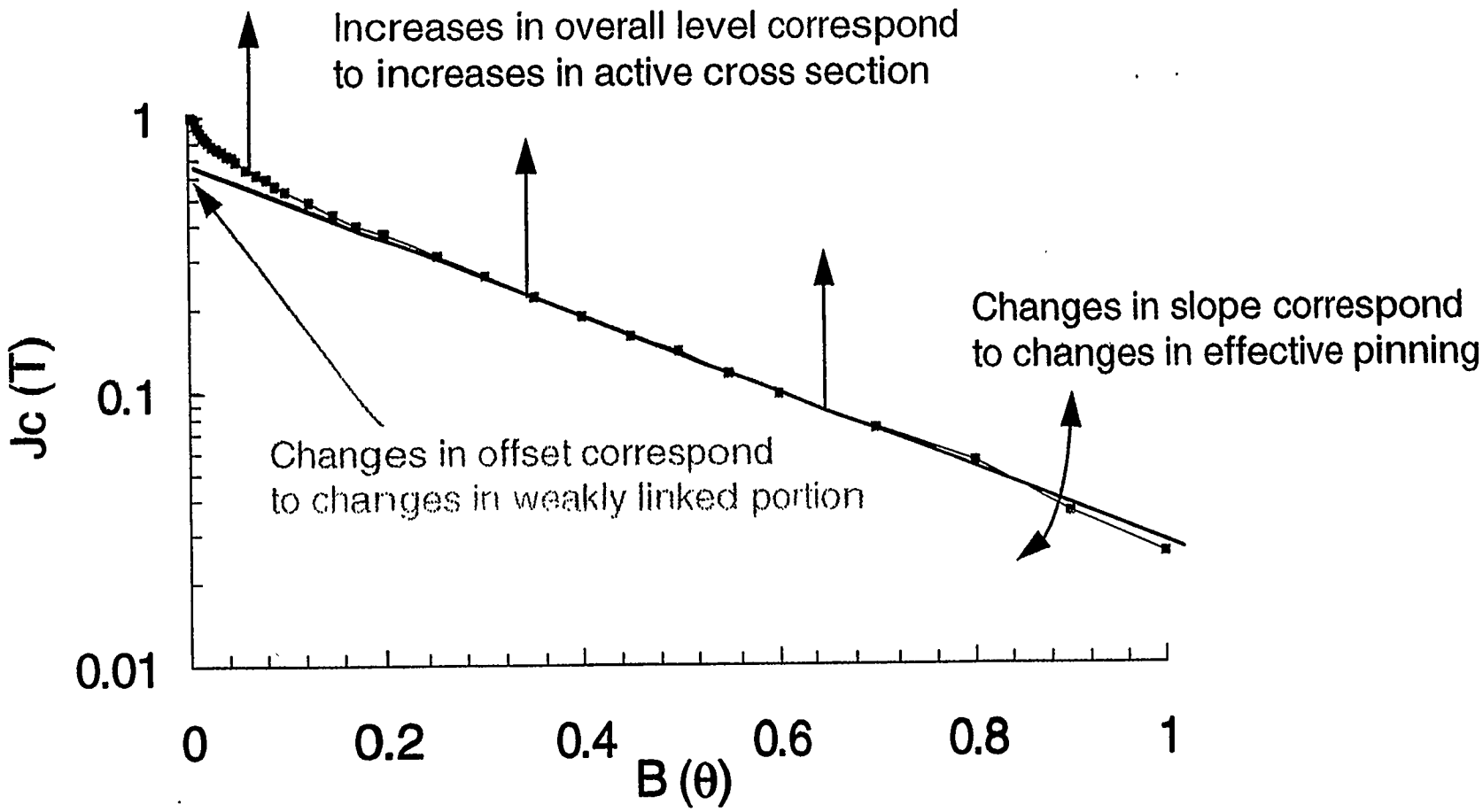
Transport Jc (T, B, θ)



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Where We Need Help

Technical:

- High fill factor processing
- Weak Link mitigation
- Connectivity enhancements
- Flux-pinning enhancements
- Ag replacement

Non-Technical:

- Stable support for BSCCO R&D
- Continued prototype system demonstrations

American Superconductor CORPORATION

Summary

For robust Bi-2223 wire:

- Long length HTS wire with Je performance greater than 10,000 A/cm2 (77, sf) is available *now*.
- $\overline{J}c$ improvements continue with new results of 70,500 A/cm2 (77, sf).
- Results of parametric analysis indicate clear pathways to DOE targets.

We can get there if we apply the effort!

American Superconductor CORPORATION

A LOW COST Bi-2212 TAPE

presented at

DoE Wire Development Workshop:
Superconductivity Program for Electric Systems

January 29-30, 1998
St. Petersburg, Florida

by

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Texas Center for Superconductivity
University of Houston

Collaborators:
R. L. Meng
C. Garcia
Y. Q. Wang
D. Pham
W. N. Kang
I. Rusakova

OUTLINE

- OBJECTIVE
- RATIONALE
- RESULTS
- CONCLUSION

OBJECTIVE

General: **To Develop a Low Cost HTSg Tape**

Specific: **To Develop a Low Cost Bi-2212 Tape**

RATIONALE

- Presently the Work Horse of HTSg Conductors is BSCCO Tape
- High Cost of HTSg Conductors — ~ $200/(kA-m) for BSCCO Conductor *vs* $10/(kA-m) Proposed by Industry (according to 1996 DoE report and 1997 NATO ASI at Loen)
- Cost Reduction — Material and Processing
  - Materials, *e.g.* $18/kA-m for Ag (based on J_c = 40 kA/cm^2, J_c/J_e = 4, @ $5.2/oz. for Ag)
  - Processing, *e.g.* annealing time ~ 7-70 hr
- Previous Experience on HBCCO — Inexpensive Ni-Substrate at $0.5/lb for Ni *vs* $5.2/oz for Ag) and simple processing *e.g.* annealing time 2 hr *vs* 7-70 hr)
- Decided to start with Bi-2212 on Ni
  - Bi-2212 performs well at low temperatures
  - Bi-2212 forms easily
  - well-established Bi-2212 on Ag processing
  - excellent experience with Hg-1223/Ni tapes

- **OPEN PROCESSES FOR Bi-2212 ON Ag**
  - Doctor Blade Casting
  - Dip-Coating
  - Electrophoretic Deposition
  - Organics Burnout → Partial Melting → Crystallization → Annealing (Bi-2201 → Bi-2212 conversion) → Cooling
  - Expensive Substrate
  - Not Taking Advantage of Thermomechanical Deformation Effect
- **CLOSED PROCESS FOR Bi-2212 IN Ag-TUBE**
  - PIT
  - O_2-Diffusion Limited
  - Taking Advantage of Thermomechanical Deformation Effect

OUR APPROACH

- THE TWO STEP SPRAY/PRESS PROCESS FOR Hg-1223 ON Ni

  - Ni-Substrate
    - flexible
    - low cost
    - low solubility (< 1%)
    - small T_c-suppression
    - necessity of buffer layer [Cr/(AgPd)] to reduce reaction and to improve adhesion

  - Two Step (Open) Process
    - simple
    - flexibility in process
    - taking full advantage of thermomechanical effect whose importance has been demonstrated in the PIT (closed) method for BSCCO tapes
    - $J_c \sim 7 \times 10^4$ A/cm^2 at 77 K

- **Bi-2212/Ni BY THE TWO STEP SPRAY/ PRESS PROCESS**

  - **Bi-2212/Ni Interaction**
    low solubility up to ~ 4%
    (in agreement with Natsume *et al.*)
    T_c suppression up to ~ 10 %
    (in agreement with Maeda *et al.*)
    slight H_i enhancement
    (Fuwa *et al.*)

  - **BSCCO Is More Malleable Than HBCCO**

  - **Solvent and Dispersant**
    alcohol

  - **Bi-2212 Adhesion to Ni**
    need of a buffer layer

  - **Processing Temperatures**
    compatible

- Our Process

  Bi_2O_3, SrO, CaO and CuO Powder Mixture

  Bi-2212 Powder

  Mix with Alcohol

  Spray to Ni/Cr/(AgPd)

  Press

  Preheat

  Cooling

  Press

  Partial Melt

  Crystallization

  Annealing

  Cooling

RESULTS

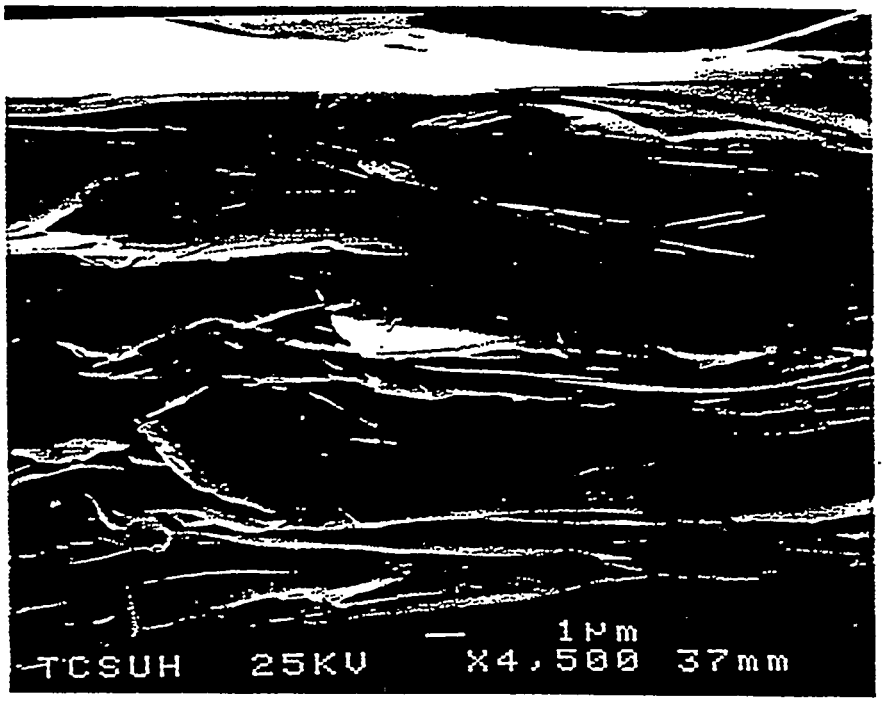
- J_c (4.2 K) ~ 5×10^5 A/cm^2 at 0 T
  ~ 3×10^5 A/cm^2 at 9 T
  (ours)

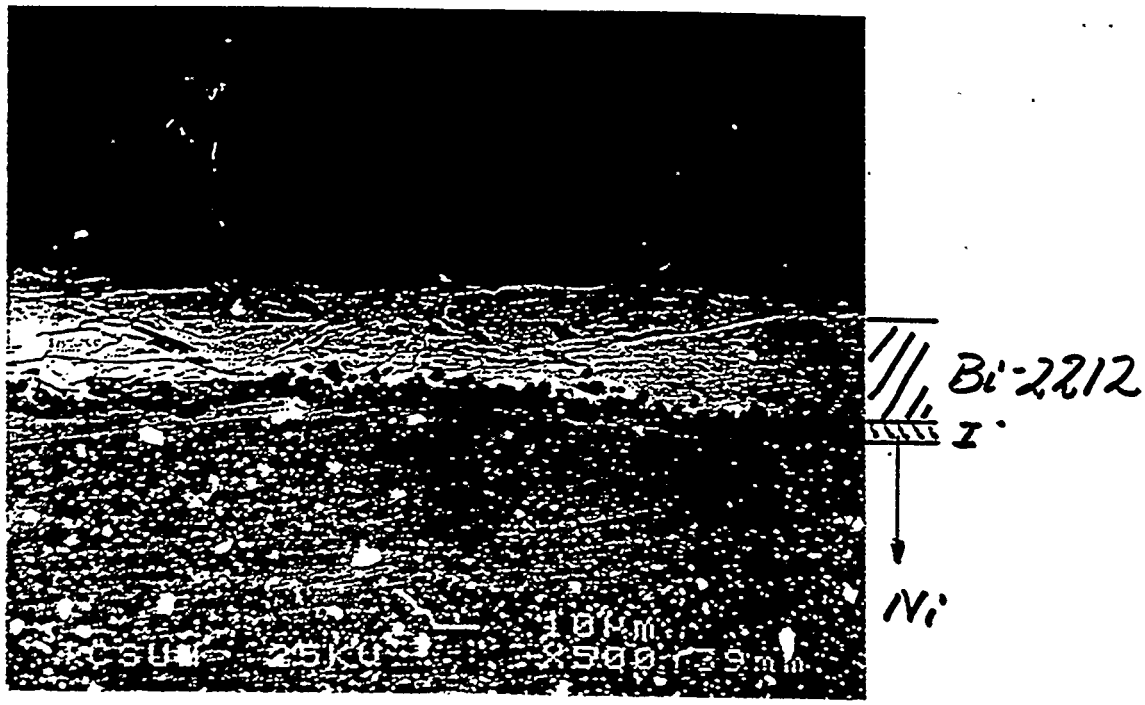
vs

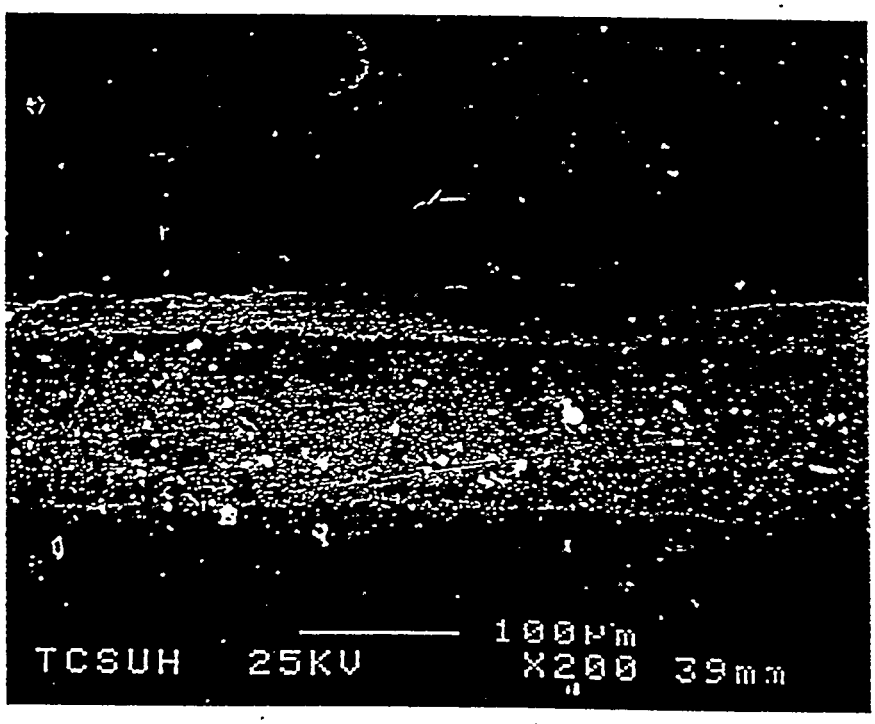
3.1×10^5 A/cm^2 at 0 T
1.3×10^5 A/cm^2 at 15 T
(Huang *et al.*, 1994)

- T_c ~ 70-80 K
- An Insulating Interlayer Between Bi-2212/Ni (good for FCLs)
- Excellent Grain Alignment
- Inexpensive Ni-Substrate
- Short Annealing Time

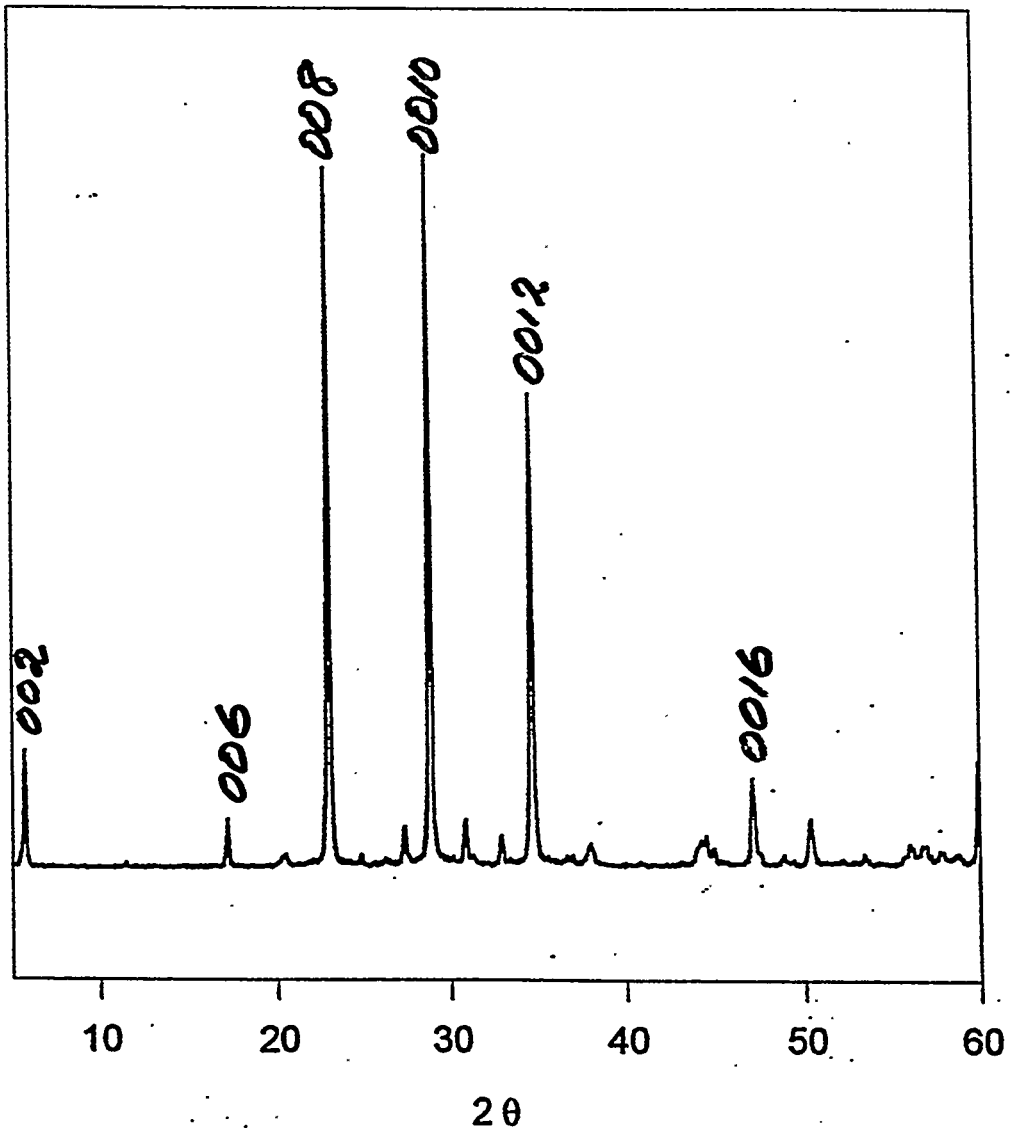
Incidental Total




Bi-2212
I
Ni
10μm
25KV
X500

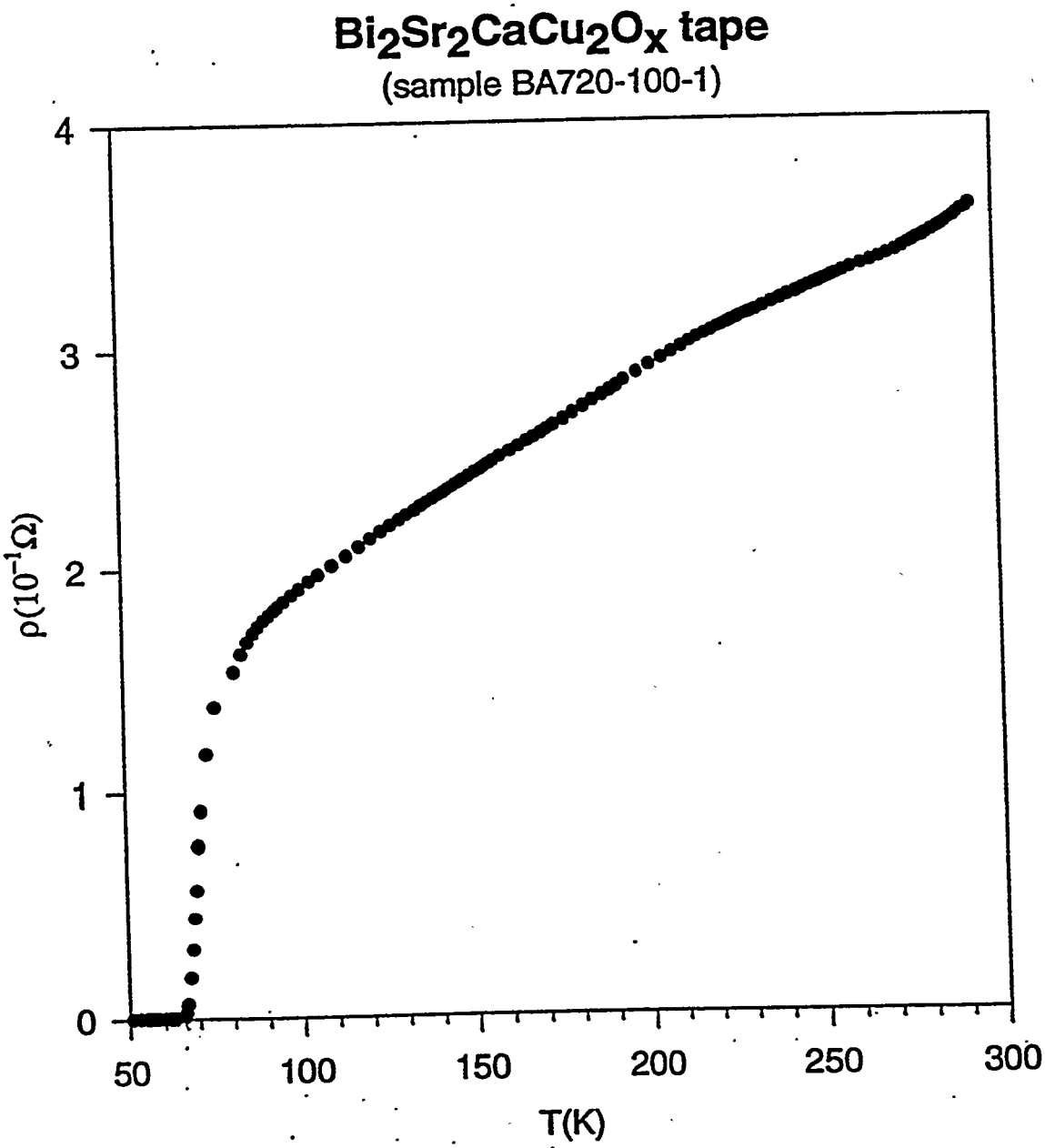

100μm
TCSUH 25KV X200 39mm

Incidental Total



Bi-2212/Ni Tape

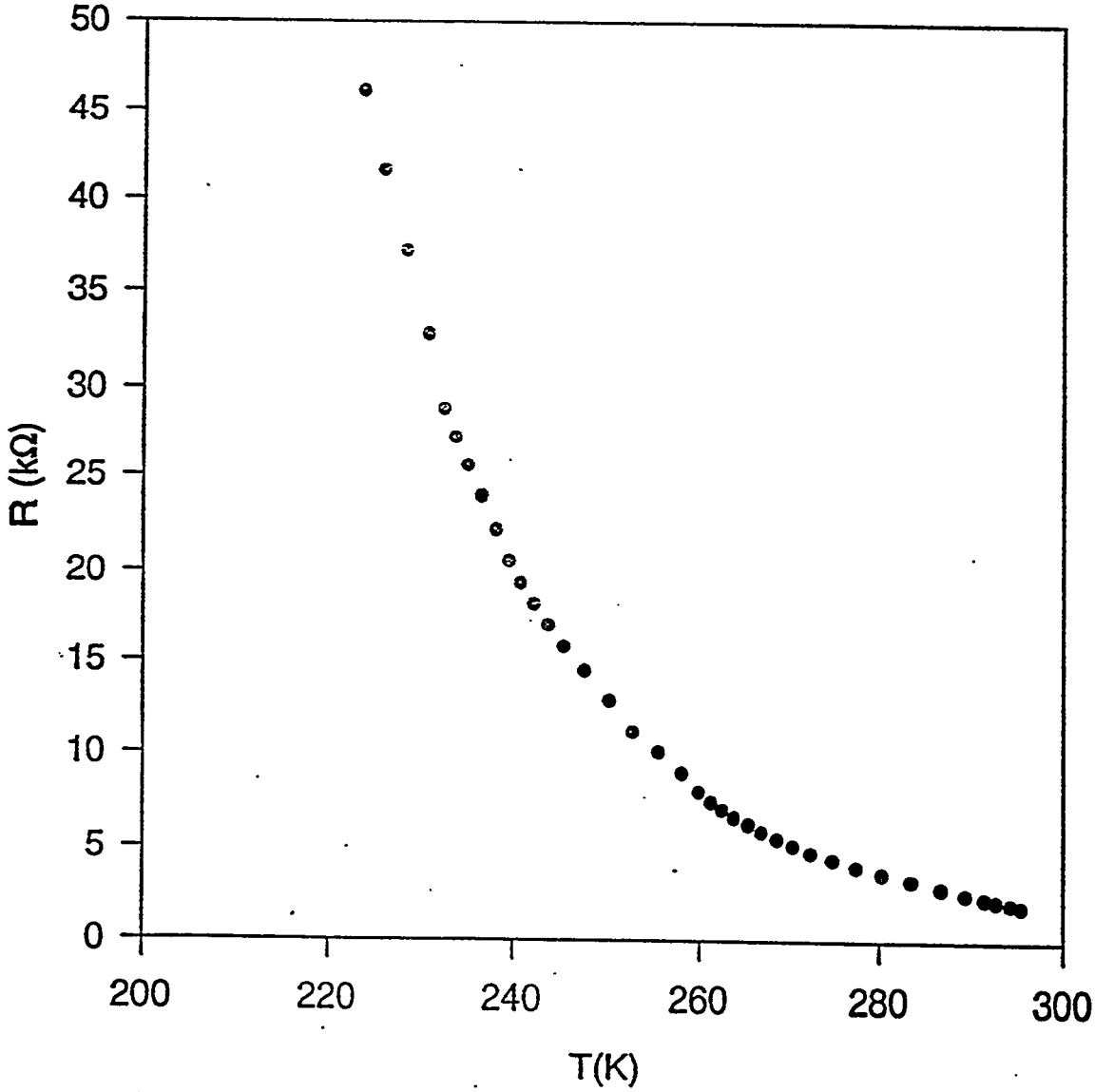
(excellent c-orientation)



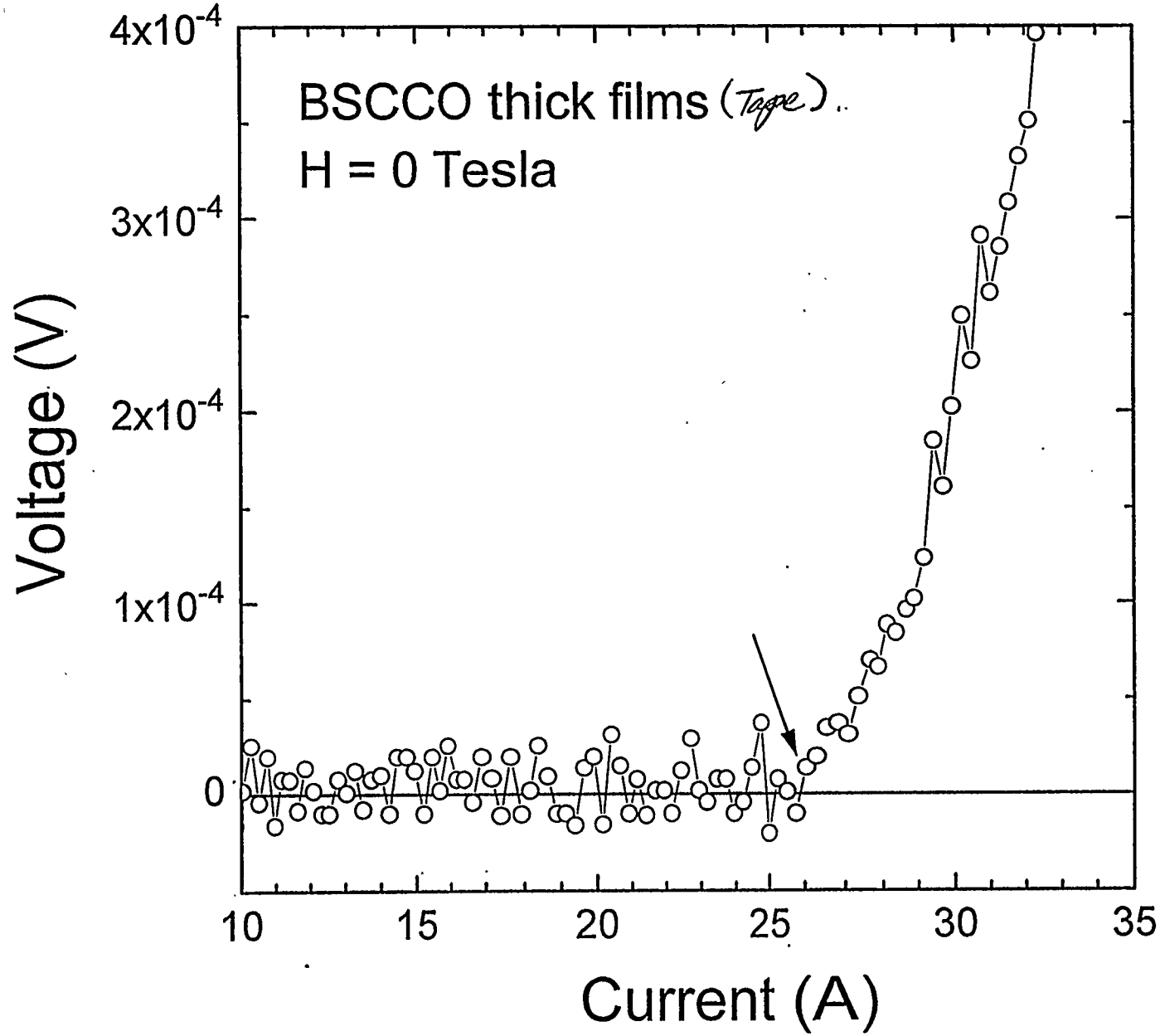
$T_c \sim 70K$

Not yet optimized!

Resistance between Ni Substrate and 2212 Tape

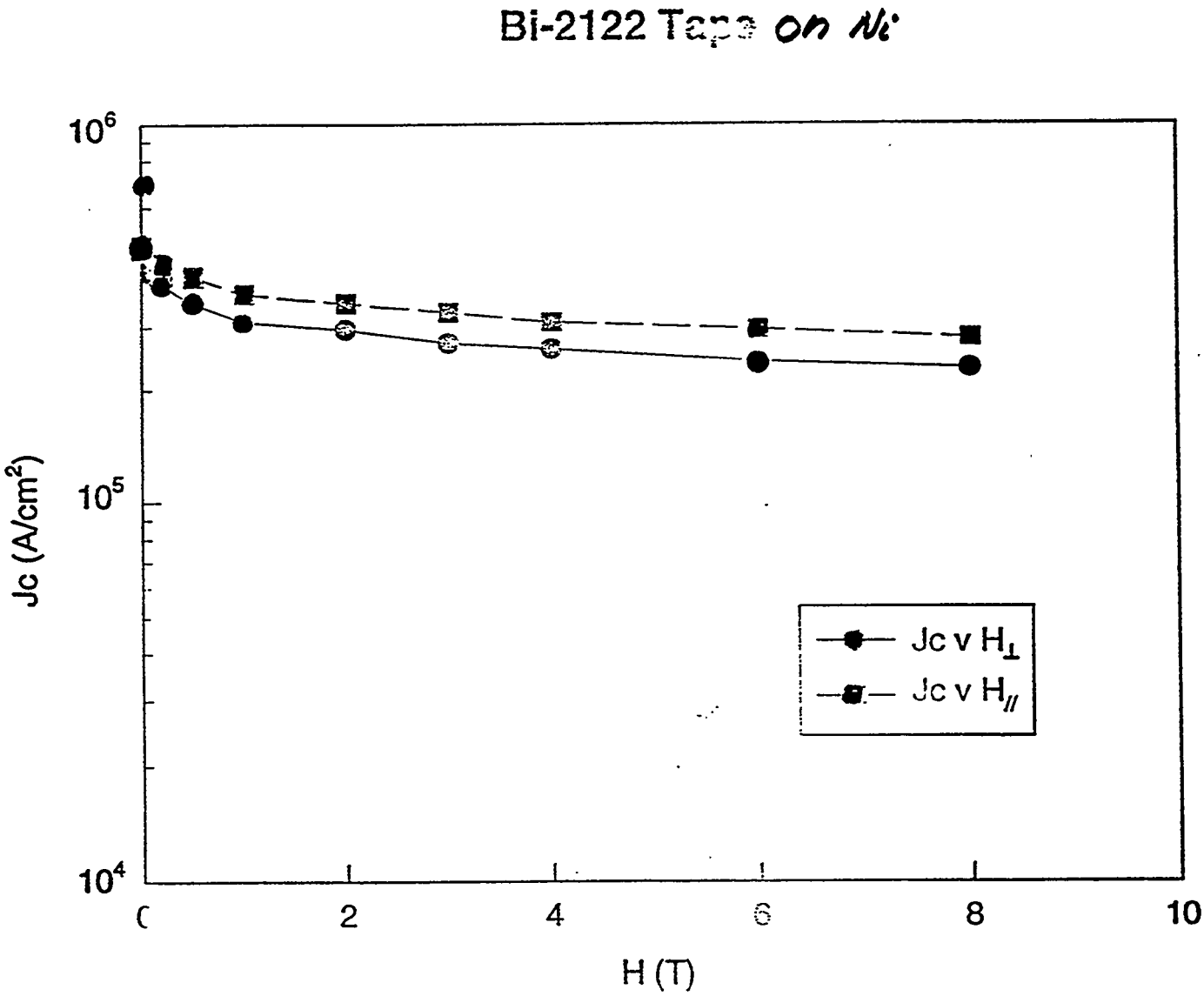


(15 μm x 0.3 mm)
x 0.5 cm



107

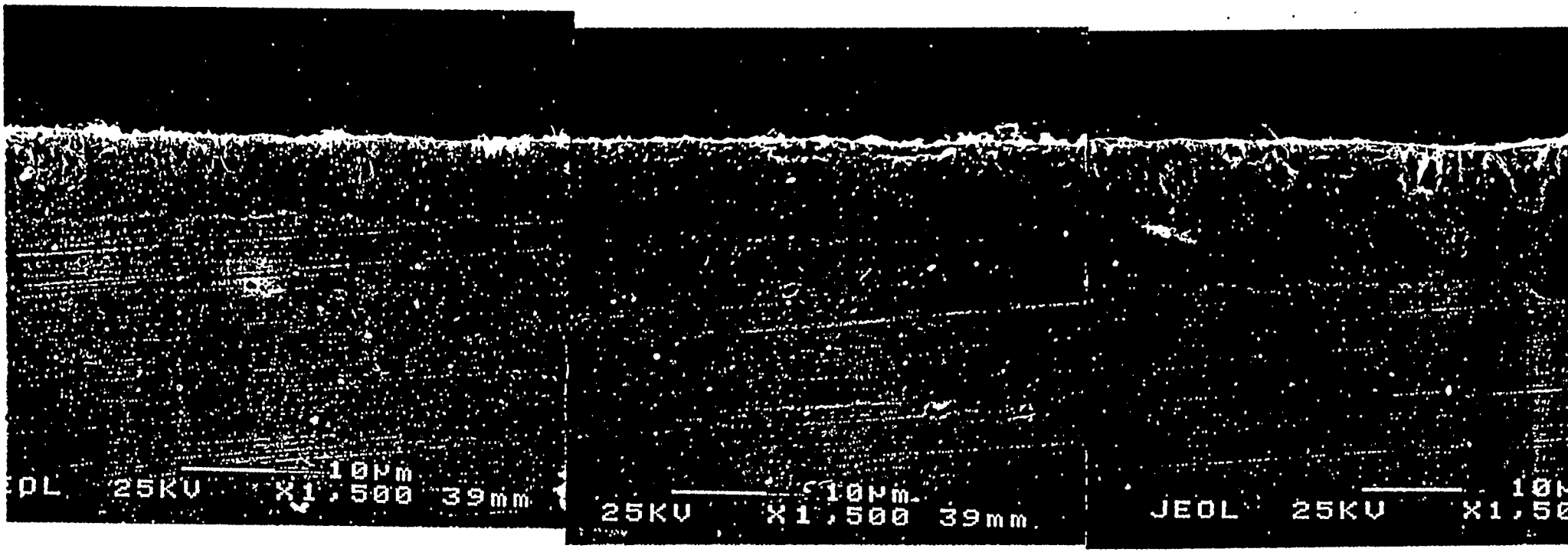
Incidental Total



Substrate # 5 Ag #/100.

FURTHER IMPROVEMENT

- Optimization of Processing Parameters
- Insulating Interlayer Control
- Ni-Surface Layer Control
- Selection of Improved Substrate Materials (including RABiTS and IBAD substrates)
- Demagnetization of the Substrate Materials While Retaining Other Desirable Properties (*e.g.* through alloying)
- Adaptation of EFD to Our Process
- Possibility of Bi-2223/Ni Tapes


10μm
25KV X1,500 39mm
10μm
25KV X1,500 39mm
JEOL 25KV

CONCLUSION

- Bi-2212 Tapes with Superior J_c Have Been Fabricated on Ni-Substrates Whose Cost Is Only ~ 0.6% That of Ag Used in the Existing HTSg Conductors, by a Process Which Is Simpler and Requires Less Processing Time (2 hr *vs* 7-70 hr during the annealing stage)

- Adaptation of Our Process to Bi-2223 Tapes, Which Perform Better Than Bi-2212 Tapes at Higher Temperatures May Be a Possibility

- Optimization in Terms of Substrate Materials and Control of the Insulating Interlayer May Be Possible

Southwire's HTS Cable Update

Uday Sinha and RL Hughey

✦Acknowlegements:

–Southwire: Jerry Tolbert, Ron Martin, Nick Ware, Darrell Jeter, Kim Nuckles, and others

–ORNL: Bob Hawsey, Winston Lue, Jonathan Demko, Bill Schwenterley, John Stovall, Randy James, and others

General Outline

- ✦Overall Cable Project
- ✦15 - Ft Cable
- ✦SW Time Table
- ✦Cable Components Progress
- ✦Dielectric Development
- ✦15 - Ft Cable Test Program
- ✦SW 5 - Yr's Tape Needs

SW HTS Cable Project

- 30-m, 3-phase, 12.5 kV, 1250 A
  - 3 phase in separate cryostats
    - overhead and HTS phase comb.
    - coated cond. on one phase
    - phase with improved PIT tapes

SW HTS Cable Project

- 3 year project (1997-1999)
- Testing in year 2000
- Power: Two Mfg Plants and SMD
- Real World Cable
  - Varying loads
  - Lightning & Env. Problems
- Load eqiv. to City of Carrollton

115

5-M (15 Ft) Cable

- ✦Machine stranded
- ✦12.5 kV, 1250 A, as 100 Ft cable
- ✦Single Phase, Cryo. design
- ✦Diel., Ther. Ins., Termination's
- ✦Complete Cable
- ✦To be tested at ORNL
- ✦Ready by end of Feb. 1998

Phase-1: 1996 Developments

Cab. #	Tapes #	Angle & Dir.	Des. Ic (A)	Nom. Ic (A)	Meas. Ic (A)	Ic/Tp wound	% Ret.
1	73	15 (+-+-)	500	847	670	9.2	78.1
2	67	15 (+-+-)	500	844	560	8.4	66.4
3	200	15 (+-+-10)	2000	3400	1630	8.2	47.9

Phase - 1 : 1997 Developments

Cable #	Tapes #	Angle & Dir.	Des. Ic (A)	Nom. Ic (A)	Meas. Ic (A)	Ic/tape wound	% Ret.
4	112	15 (+-+-)	1250	2033	975	8.7	48
5	96	30 (+-+-)	1250	2237	**957/460**	**19.0/9.6**	**84.9/49**
6*	51	30 (+-)	500	765	365	6.1	47.7
7	108	30 (+-+-)	1250	1875	1520	14	81.1
8	104	28 (+-+-)	1250	2380	1250	15.4	67.4
9	100	28 (++--)	1250	1420	1267	12.7	89.2

Southwire's Time Table

- 1997 Plans
  - Design, Install, and Test Stranding Machine
  - Design (construct ?) 15-ft cable
- 1998-1999 Build Cable Comp.
- 1999 Install Cable
- 2000 Test Cable

Cable Components Progress

- ✦Stranding Machine
- ✦10,000 Class Clean Rm Installed
  - –HTS Tape/Dielectric Tape stranders installed
  - –Under Test
- ✦HTS Tapes ordered
- ✦Delivery: 2/3 weeks
- ✦Former: Flexible - in stock

Diel. Mat. Development

- ✦SW Cryoflex- a prop. material
- ✦BD Voltage and PD tests at ORNL
- ✦Model Diel. Cable
  - –Tests at ORNL
  - –Equip. from BNL
  - –being furbished for tests

122

15 Ft Cable Test Program

- Testing to be done at ORNL
- Termination's Installed
- Cryog. delivered by mid Feb.
- SW HTS Cable by mid Feb. 1998
- Cable ready for tests by early March

5-M Cable Test Plans

- ✦Elec. Ind., Cap., and Loss Angle
- ✦7 days at rated cap. (8/12 hrs)
- ✦Pulse current 2.5/5 X
- ✦Cable Partial Discharge
- ✦Term. Partial Discharge
- ✦AC volt. test 2.5 X
- ✦Impulse Test: to 110 kV

Phase II: Lessons Learned

- ✓ Cryo Diel. Matls./Requirements
- ✓ HTS Matl. Machine Applied
- ✓ Cable Des.-Cryo flows-AC Loss
- ✓ Thermal Insulation System
- ✓ Cryogenics System
- ☆ Term. - Liq. Nit --Ambient (?)
- ✓ Cable & Sys. - Cost/Relia. Bas

SW 5 yr's HTS Tape Needs

- Desired: Ic min. 30 Amps
  - YS 0.2% Strain > 100 MPa (alloy Ag)
- 1997: 5,000 m (2-5 m cables)
- 1998: 10,000 m (1-30.5 m)
- 1999: 20,000 m (2-30.5 m)
- 2000: 10,000 m (1-30.5 m test)
- 2001: 36,500 m (1-phase of 100 m)
- Total expected = 81,500 m in 5 years

Summary

- ✦SW HTS Program on Schedule
- ✦15 Ft cable will be const., inst. and tested by mid 1998
- ✦SW 100 Ft cable const. and install. plans allows flexibilities
  - –coated conductor
  - –or newer PIT tapes
- ✦

Conductor Needs for HTS Transformers

presented by

Sam P. Mehta

of the

Waukesha/Intermagnetics /RG&E /ORNL team

for the

DOE Wire Development Workshop

St. Petersburg, Florida, January 29-30, 1998

Schedule to Commercial

- We intend introducing the first commercial 30- MVA transformers in four years

HTS TRANSFORMER COMMERCIALIZATION PLAN

Phase	Objectives	Schedule						
		96	97	98	99	00	01	02
I	Determine Commercial Feasibility & 1-MVA Demo							
II	Alpha Prototype (5-10 MVA to Power Waukesha Transformer Plant)							
III	Beta Prototype and Start Commercial Sales							

WAUESHA/IGC/RG&E/ORNL

Comment on Schedule

- This schedule is consistent with the "window of opportunity" for the introduction of HTS power apparatus described by Darrell Piatt of Southern Company before this group last year
- That is, either utilities use $ earmarked for refurbishing the system for HTS or they will have to raise new $ to replace relatively new equipment later (much more difficult).

2nd Comment on Schedule

- It calls for completion of a single-phase 1-MVA Demonstration transformer (Phase I, about now) in preparation for
- the (Phase II) construction in two years of a three-phase, 5/10-MVA HTS transformer to power Waukesha's main transformer manufacturing plant and
- the (Phase III) construction of 30-MVA Beta prototypes in the following two years

132

Phase I Status

- 30-MVA transformer conceptual designs have been produced and HTS are projected to have strong advantages over conventional transformers at 30-MVA (and higher) ratings at competitive cost
- As of this meeting the core and coil assembly of our 1-MVA demonstration transformer is nearly ready for insertion into the transformer tank, completing construction.

Comment on C&C VG-1

- This is part of the Waukesha HTS transformer team (in front of the C&C assembly)
- (Note Waukesha president John Wagner at left and retired president and chairman Nick Aversa, now very active in this project, at the right)
- IGC and ORNL have comparably sized contingents: two engineers from RG&E have been active in the project.

Comment - 1 on VG-2 of C&C Assembly

- The shiny cylinder at the left is the 80K radiation shield
  - » surrounds the coils of low-cost, surface-coated BSCCO-2212 conductor
  - » which will operate cryocooled at 20K-35K
- The right core leg is the return path for the magnetic field (In a three-Phase transformer there would be three legs, all with LV and HV coil sets)

Comment-2 on VG-2 of C&C Assembly

- Above the top yoke of the core (which weighs about 10 tons) is a liquid nitrogen tank into which the cold ends of transformer terminals (bushings) will be inserted.
- The LN2 intercepts heat leaks down the transformer leads. For commercial units, the LN2 tank will provide thermal ballast and an emergency cooling reserve for the cryocooled system in case of extended power outages.

Comment-3 on VG-2 of C&C Assembly

- Note that the cross section of the coils and the core are approximately the same in size and configuration as will be used for 30-MVA commercial transformer and Beta prototype and 5/10-MVA Alpha prototype
- This minimizes complications in scaling to higher ratings: more and improved conductor and the incorporation of high voltage insulation.

Comment-3 on VG-2 of C&C Assembly

- Note that the cross section of the coils and the core are approximately the same in size and configuration as will be used for 30-MVA commercial transformer and Beta prototype and 5/10-MVA Alpha prototype
- This minimizes complications in scaling to higher ratings: more and improved conductor and the incorporation of high voltage insulation.

Comment on VG of the Tank

- The tank is very similar to a conventional transformer tank, consisting of 5/8" steel in an all-welded construction. It provides a vacuum thermal insulation of all interior components
- Commercial units will operate in static vacuum. The vacuum pumping apparatus at bottom left will be removed. (MRI magnet systems made by IGC operate for >10 years, sealed under static vacuum.)

Comment 2 on Tank

- Except for an increase in width (to accommodate the third phase) and the addition of an enclosure to house cryocoolers (in front, rather than at the side) this tank is essentially the size anticipated for the 30 MVA.
- Because it has no oil, has light windings, and will not need large heat exchangers, the HTS Xformer will be half the footprint area and half the weight of its conventional counterpart.

Phase I Completion

- Cooldown of the 1-MVA transformer should be underway within the next two weeks
- Tests over the next two months will include:
  - » **Cryo-system operation checkout**
  - » **Operation to rated current at low V**
  - » **Operation to rated V, no I**
  - » **Operation to full 1-MVA power levels (rated V and I)**
  - » **Simulated fault current to many times rated current.**

HTS Conductor Needs

- We have chosen a cryocooled HTS transformer approach for many reasons
- One of these is to increase the Ic (at lower T) and therefore reduce the quantity (and thus the total cost) of all candidate HTS conductors
- This is especially important if we wish to to have affordable conductor to begin to introduce a cost competitive product within the next four years. (see next VG)

Target Conductor Costs and Properties for 200 Ampere Tape in the Year 2002

Transformer Type	Cryocooled			(for reference) LN2 Cooled	
Operating T (T_{op})	25K	35K	35K	68K	68K
HTS Conductor Composition	BSCCO-2212	BSCCO-2223	YBCO-123	BSCCO-2223	YBCO-123
Jc(T_{op} +5K, B_{perp} = 0.1 Tesla)	2.0×10^5 A/cm2	1.2×10^5 A/cm2	2.6×10^6 A/cm2	3.0×10^4 A/cm2	1.0×10^6 A/cm2
Cross Section	4mm x .05mm	3.5mm x 0.1mm	4mm x .05mm	3.5mm x 0.1mm	4mm x .05mm
Target($/m)/(area, width)	($10/m)/(mm2)	($10/m)/(mm2)	($7/m)/(cm)	($10/m)/(mm2)	($7/m)/(cm)
Target($/m)	$2.00/m	$3.50/m	$2.80/m	$3.50/m	$2.80/m
$/kA-m	$10/kA-m	$17.50/kA-m	$14/kA-m	$70/kA-m	$36.40/kA-m
Length	42 km	40 km	40 km	160 km	104 km
Conductor Cost per Xformer	**$84,000**	**$140,000**	**$112,000**	**$560,000** (unacceptable)	**$290,000**

Waukesha/Intermagnetics/RG&E/ORNL

Comment on VG of Conductor Costs

- Remember that the HTS transformer must compete with conventional transformers (at about $300K for 30-MVA)
- With target conductor properties and costs shown, cryocooled HTS transformers begin to be cost competitive
  - » BSCCO Jc's better than achieved to date
  - » 1/3 to 1/10 current BSCCO costs per meter

Comment 3 on VG of Conductor Costs

- Cryocooling achieves the needed reduction in conductor quantity, but it places emphasis on low ac loss conductor and coil designs (to be addressed by Mike Walker in his presentation to follow)

INTERMAGNETICS GENERAL CORPORATION

HTS "Magnet" Development Issues

by

M. S. Walker and D. W. Hazelton

of

Intermagnetics General Corporation

for the

DOE Wire Development Workshop

St. Petersburg, Florida

January 29-30, 1998

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145

Scope

- Interpret "Magnet" development to include all types of HTS windings

HTS Applications Considered

- HTS Leads
- Power Applications
  - » Transformers
  - » Fault current Limiters
  - » Transmission Lines
  - » SMES
  - » Generators
- Industrial Applicat'ns
  - » Motors
  - » Magnetic Separation
  - » MRI
- Research Facilities
  - » Particle Accelerators
  - » High Field NMR

	Power Applications									
	Transm Cables		Transformers		Fault Limiters		SMES		Generators	
	(ac)	(dc)	(Cryocooled)	(LN2)	(Bridge)	(Rho.-L)	(Micro)	(etc)	(Synchr)	(Homop)
T of Operation										
B of Operation										
Candidate HTS										
"Magnet" Develop-										
ment Issues										
Conductor Cost										
Ic										
Cost/m										
ac Losses										
Coil Design										
Conductor Design										
Refrigeration										
Refrigeration Cost										
Heat Transfer										
Thermal Issues										
Overcurrent Ridethru										
Stability										
Recovery										
Quench Propagation										
Winding Current Density										
Conductor Jc										
Insulations										
Packing Factor										
Mechanical Integrity										
J X B										
Shear										
Pancake/Layer Wind										
Handling/Wind Strength										
Winding Shape/Size										
Saddle Coils										
Small diameter										
Wind & React, R & W										

	Industrial Applications				Large Research Facilities			
	Motors		Magnetic	MRI	High Energy Physics			NMR
	(Synchr)	(Homop)	Separation		(Dipoles)	(Leads)	(Cables)	(Insert)
T of Operation								
B of Operation								
Candidate HTS								
"Magnet" Develop-								
ment Issues								
Conductor Cost								
Ic								
Cost/m								
ac Losses								
Coil Design								
Conductor Design								
Refrigeration								
Refrigeration Cost								
Heat Transfer								
Thermal Issues								
Overcurrent Ridethru								
Stability								
Recovery								
Quench Propagation								
Winding Current Density								
Conductor Jc								
Insulations								
Packing Factor								
Mechanical Integrity								
J X B								
Shear								
Pancake/Layer Wind								
Handling/Wind Strength								
Winding Shape/Size								
Saddle Coils								
Small diameter								
Wind & React, R & W								

Objective

- To touch on a few magnet development issues which affect HTS conductor needs over the next five years
- Try to show some of the applications affected by these issues in the approximate chronological order in which HTS wire will be needed for them commercially

Issues: HTS Conductor Cost

- Nearly all applications require improved Ic at reduced $/m (altogether, lower $/kA-m)
- This still after $/k-Am needs have been reduced for many applications by cryocooling below LN2 temperature, in a trade-off with the increased costs of lower T refrigeration
- But cryocoolers now operate at 4K; LTS is more competitive for low loss applications
- HTS leads are helping HTS, LTS especially

152

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HTS Leads: First HTS Commercial Success?

- Status - HTS leads ready for high energy applications
- Over the next five years leads like the 5,000 amp pair developed for Fermilab (shown next) may require:
  - » > 100 km
  - » of untwisted multifilament Bi-2223
  - » with low K silver alloy matrix

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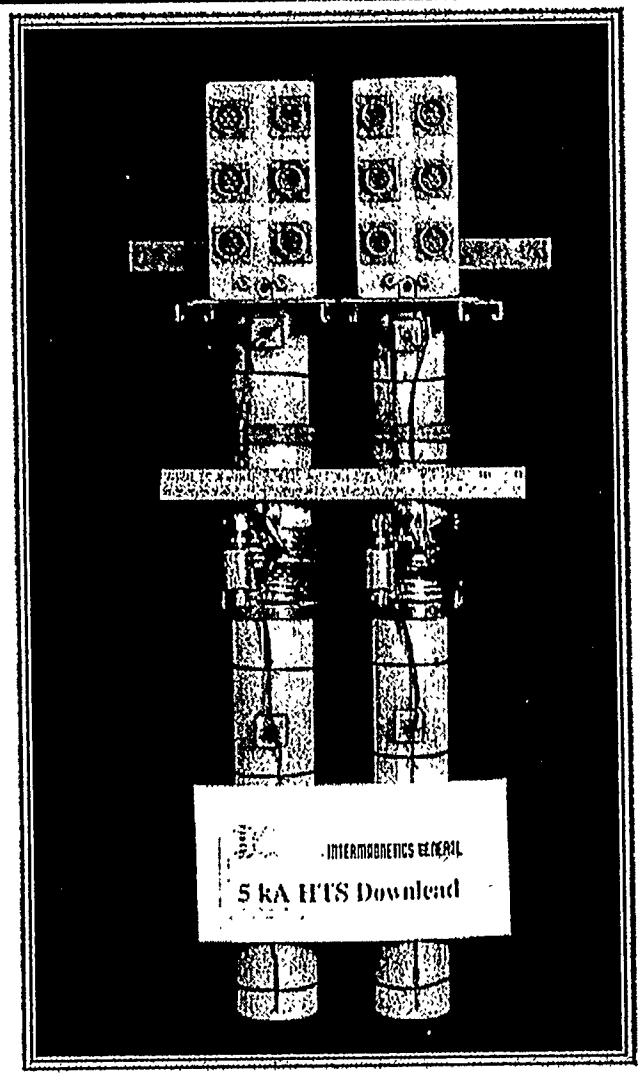
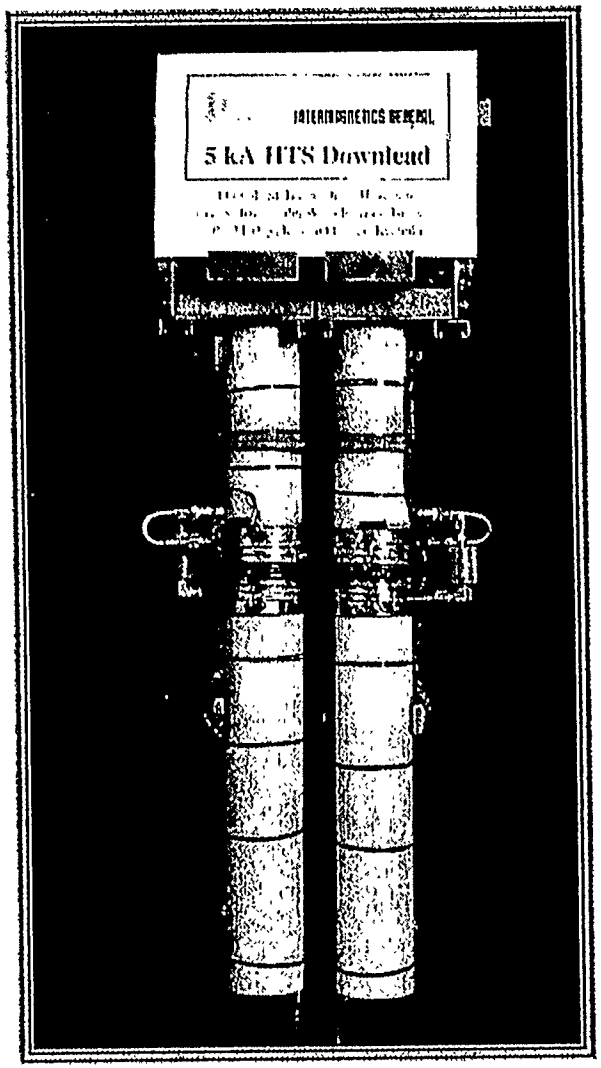
Fermi Lead Program





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INTERMAGNETICS GENERAL CORPORATION

Application: LM-FCL (DOE SPI)
Issue: Low Loss Coil Design

- Status
  - » The 17kV, 2000A prototype FCL coil is presently being wound of untwisted MF Bi-2223 conductor (in follow-on of the pre-prototype coil completed last year, shown next)
- Conductor Need: (50 km / 17 kV unit)
  - » The prototype uses a new low loss coil design. It does not require transposed multifilament superconductor.

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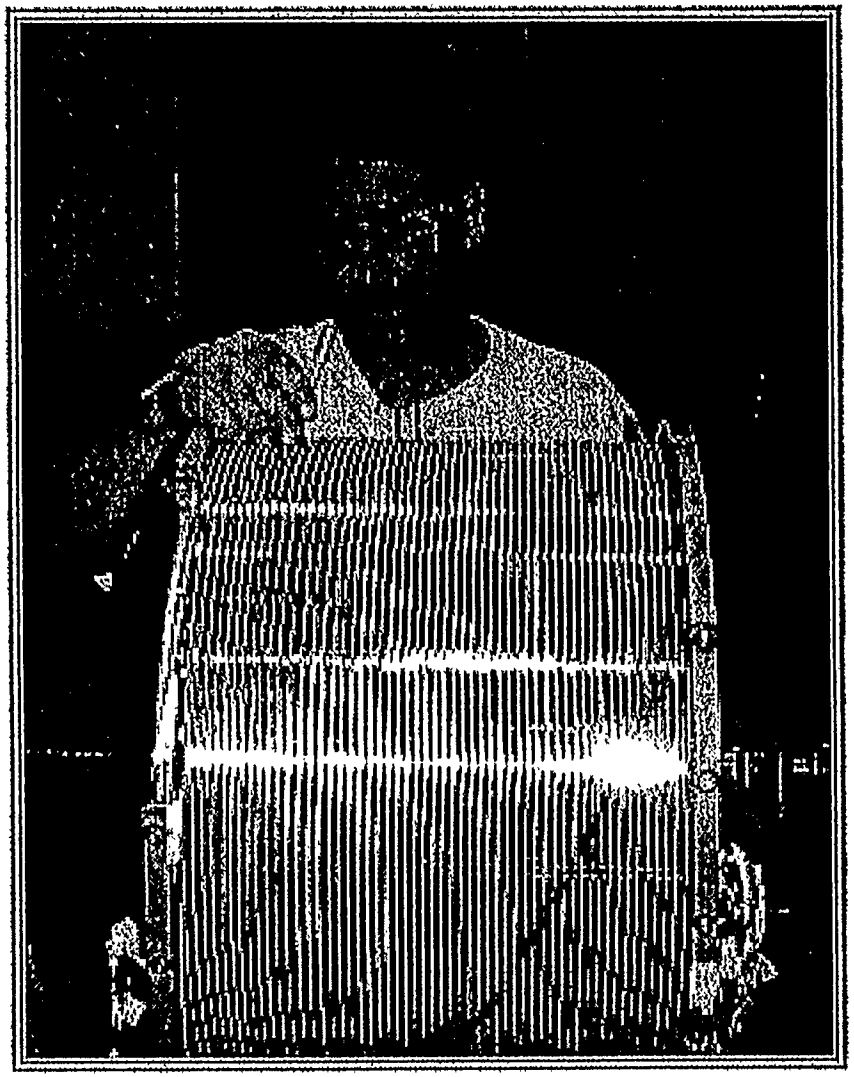
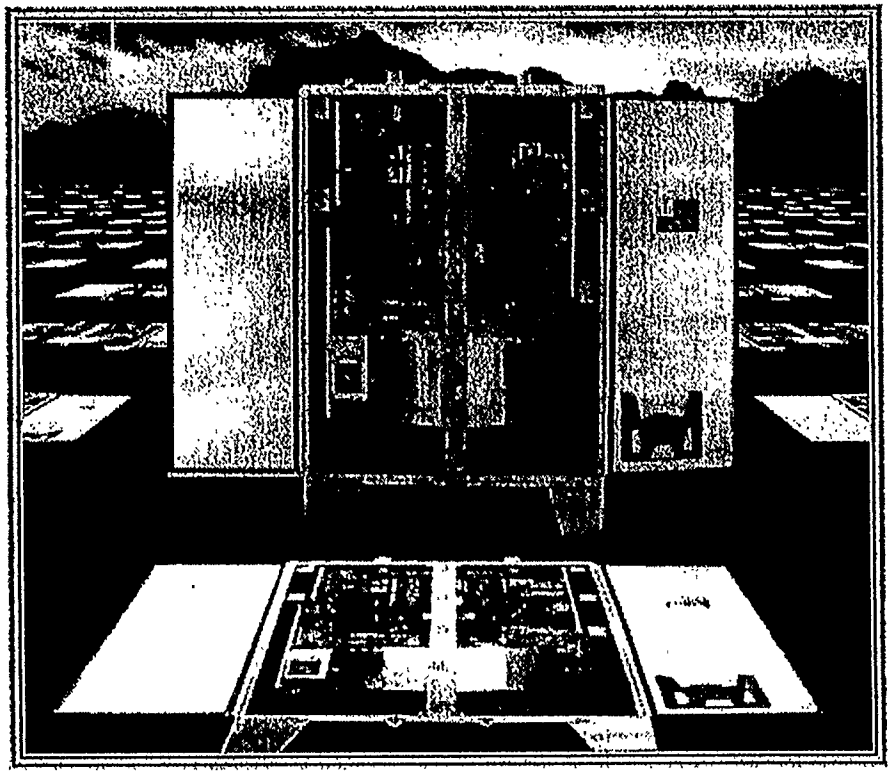
INTERMAGNETICS GENERAL CORPORATION





- DOE SPI - Lockheed Martin, Intermagnetics, Southern California Edison, LANL
- Demonstrate 3 phase alpha unit 17 kV, 2 kA prototype

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155

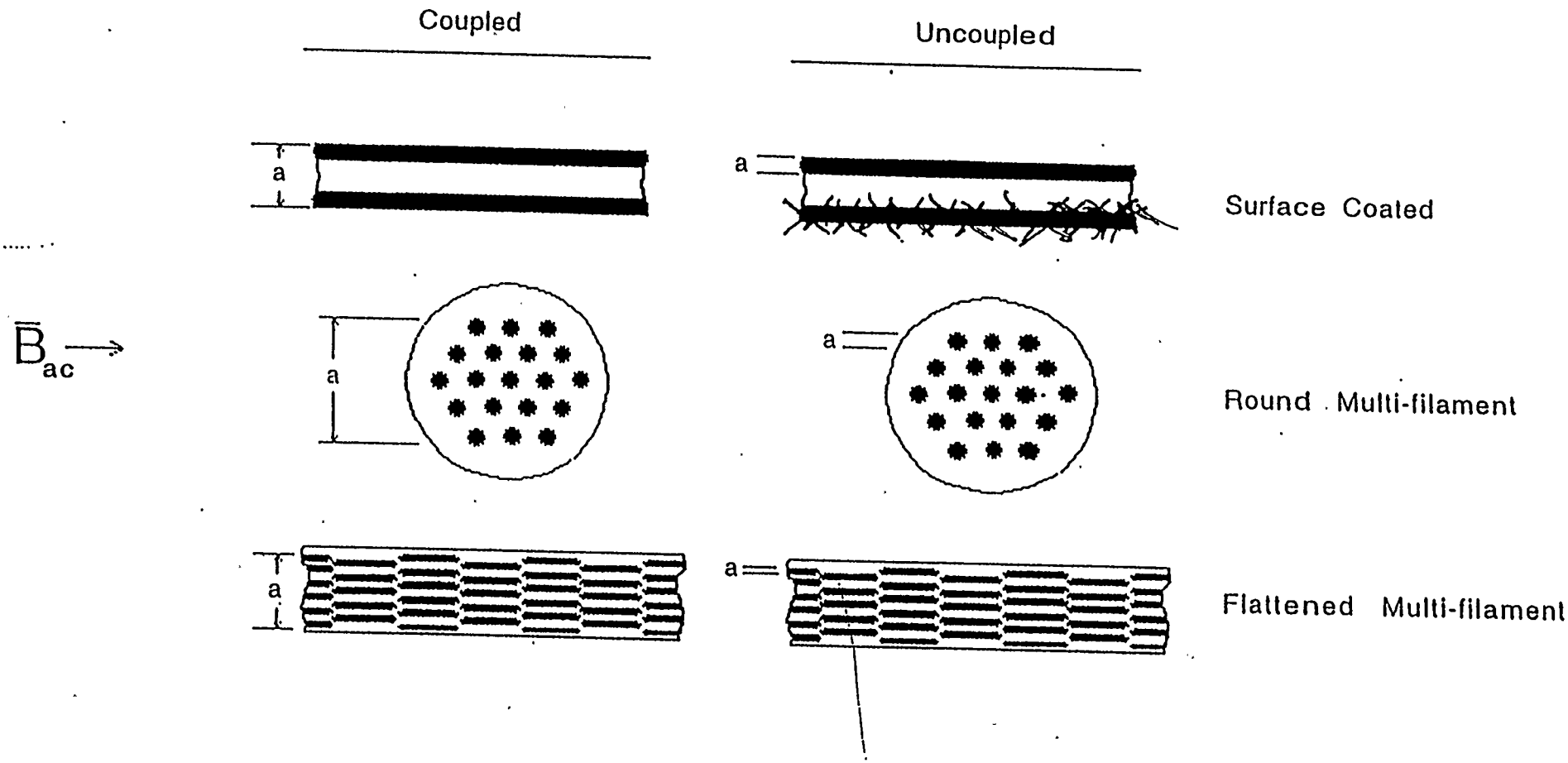
INTERMAGNETICS GENERAL CORPORATION

Application: Waukesha Transformer (DOE/ORNL)
Issue: Low loss Conductor Design

- Status
  - » 30-MVA transformer coils are being designed to minimize ac losses (low cost Bi-2212, 1-MVA coils shown next)
- Conductor Need (40 km / 30 MVA unit)
  - » Even so, meeting target refrigeration costs will require thin high Jc HTS coatings or transposed fine filaments (as described last year)
  - » 240 km of Bi-2212 or Bi-2223 will be needed in 2003 at $3.50/m, > km/yr and <$/m thereafter

$$\frac{P_{Loss}(B_{//})}{kA\text{-}m} \propto (f) \times (B_{ac}) \times (a), \qquad \text{(No dependence on } J_c\text{)}$$

60Hz [redacted] 0.1T



Suppose $40,000 For Cooler @ T_{op} , 30 MVA (One Type of Design), B_{ac}= 0.1 T: *Then*

T_{op}	20K	40K	60K	80K
Refrigeration Available	36 ~~18W~~	100 ~~50W~~	180 ~~90W~~	260 ~~130W~~
Allowed Transposed Oxide Width Perp B (microns)	2	6	10	14

Waukesha/IGC/RG&E/ORNL

INTERMAGNETICS GENERAL CORPORATION

Application: Southwire Transmission Line
Issue: Tape Strength for cabling

- Status
  - » Strong Bi-2223 tapes being developed at IGC
  - » Improved short cables being constructed at Southwire PH
- Conductor Need
  - » 81.5 km within the next five years

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INTERMAGNETICS GENERAL CORPORATION

App'n: Insert Magnets for High Field NMR (NIH)
Issue: High $J_{winding}$, High Composite Strength in 20T, 4K

- Status
  - » 50mm I.D. X 160mm O.D. X 200 Long, Bi-2212 surface coated conductor coil being wound to produce 2.5T? (smaller predecessor shown next)
  - » Practical bore size with 2.5T
- Conductor Need (3 km/unit)
  - »

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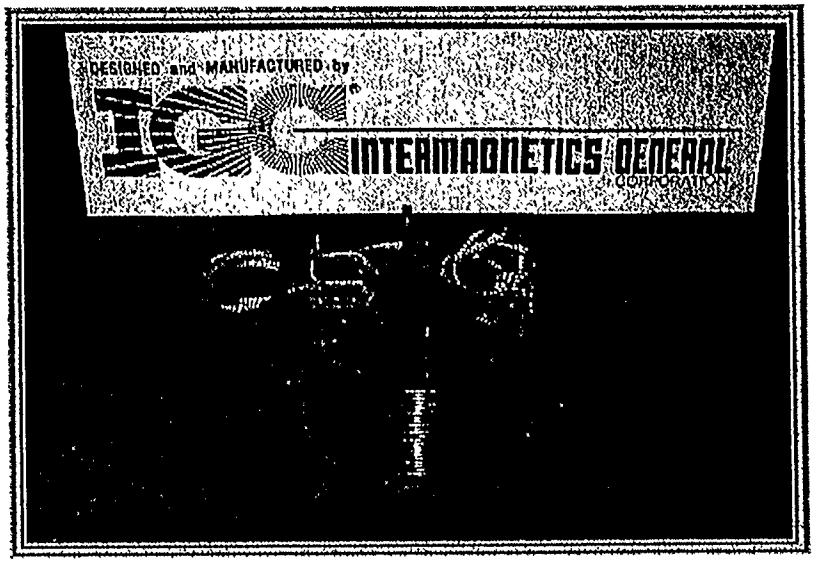
HTS High Field Insert Coils

- BSCCO-2212 surface coated conductor based coils
- Simple React/Wind construction
- Layer wound coils
- Large bore size (>50 mm)
- Prototype coil
  - 50.8mm clear bore
  - >800m of conductor (3x270m)
  - B_o = 1.2T @ 242K, 0T Background
  - B_o = 1.08T @ 4.2K, 5.5T Background
- Demonstration Coil (in process)
  - 4 nested coils to handle stress considerations
  - Target > 2.5T B_o in 20T background, 4.2K



INTERMAGNETICS GENERAL CORPORATION

Application: HEP Accelerator Dipoles (DOE) Issue: >15T, 4K or Saddle Winding Needed

- Status
  - » for >15T, 4.2K: Motowidlo's Bi-2212 PIT React-After-Wind Rutherford Cables being developed under support from Scanlan at LBL (as shown next).
  - » for 3T, 25K - 35K Saddle Dipole: with Cornell, preliminary dipole design studies underway
- Conductor Needs
  - » Within five years, magnet development quantities of conductor will be needed

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INTERMAGNETICS GENERAL CORPORATION

BSCCO-2212

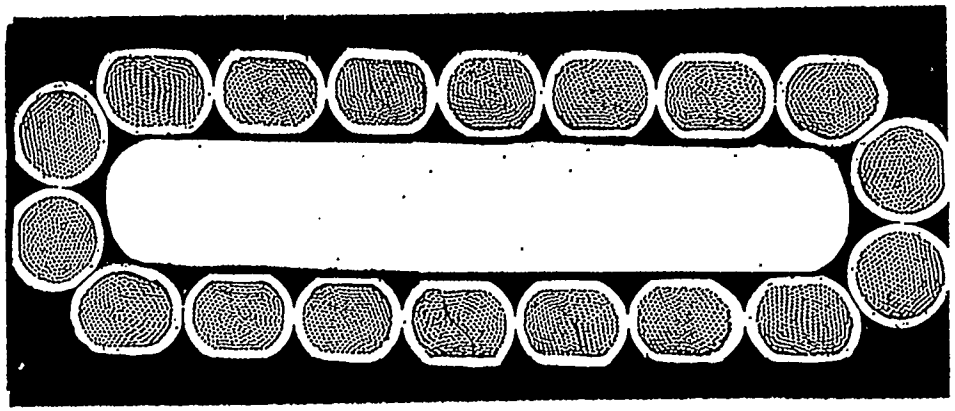
Low-Cost, Surface-Coated, React-Before-Wind Tape

(further developed with support from NASA, NIH, NRL)

Now being produced at up to 13 amps in long lengths
Priced at $6 to $10 per meter

Cables of PIT Multifilament Wires

(Being developed by Motowidlo with support of and in collaboration with Scanlan at LBL, results to be reported in greater detail at the High Energy Physics workshop in March)



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163

High Temperature Superconducting Motor Development Update

DoE Wire Development Workshop

St. Petersburg, FL

January 29 & 30, 1998

Presented by

Boris Shoykhet, Ph.D.

Reliance Electric

Rockwell Automation

Cleveland, Ohio

Overview

- SPI Motor Program Overview
- 1,000 hp HTS Motor Development Status
  - Wire / Coil Development
  - Refrigeration Systems
  - Motor Component Status
  - Milestones
- 5,000 hp HTS Motor Development
- HTS Wire Requirements for Commercial Motor

Advantages of High Temperature Superconducting Motors

- How are HTS materials used?
  - Lossless DC HTS coils produce higher motor air gap magnetic field
  - Higher magnetic field results in smaller motor size
  - Smaller motor size results in lower losses
- Best Suited Motor Topology
  - "Air-core" synchronous motor with rotating HTS field winding
- Projected Applications
  - Large motors (greater than 1000 hp) for pump and fan drives for utility and industrial markets. Motors will be powered by an adjustable speed drive.
- Expected Benefits
  - Compared to conventional high efficiency motors ...
    - HTS motors will be approximately half the volume
    - HTS motor will have half the losses
  - Lower life cycle costs

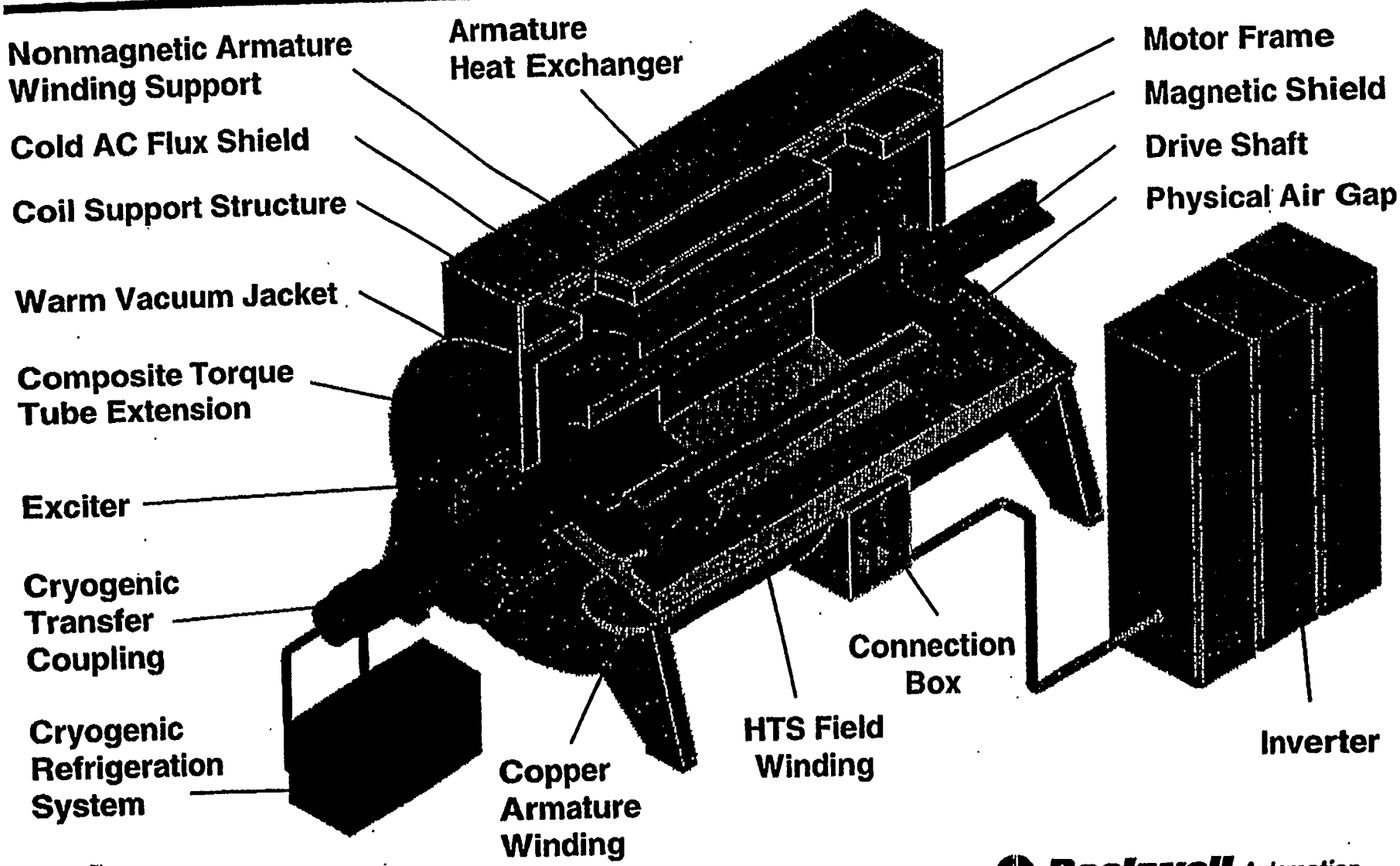
DoE SPI HTS Motor Project
Phase 2 - Team Members

- Rockwell Automation / Reliance Electric
  - *Project Leader - motor design, construction and test*
- American Superconductor Corporation
  - *HTS wire and coils, and cryocooler development*
- Sandia National Laboratory
  - *Flow instability analysis, material outgassing analysis, thermal contact resistance analysis, and general collaboration*
- Air Products & Chemicals, Inc.
  - *Provide industrial user perspective and potential field test site*
- Centerior Energy Corporation
  - *Provide utility user perspective and potential field test site*
- Electric Power Research Institute
  - *Project advisor*
- Kato Engineering
  - *Motor stator components and exciter*

DoE SPI HTS Motor Project
Phase 2 - Major Tasks

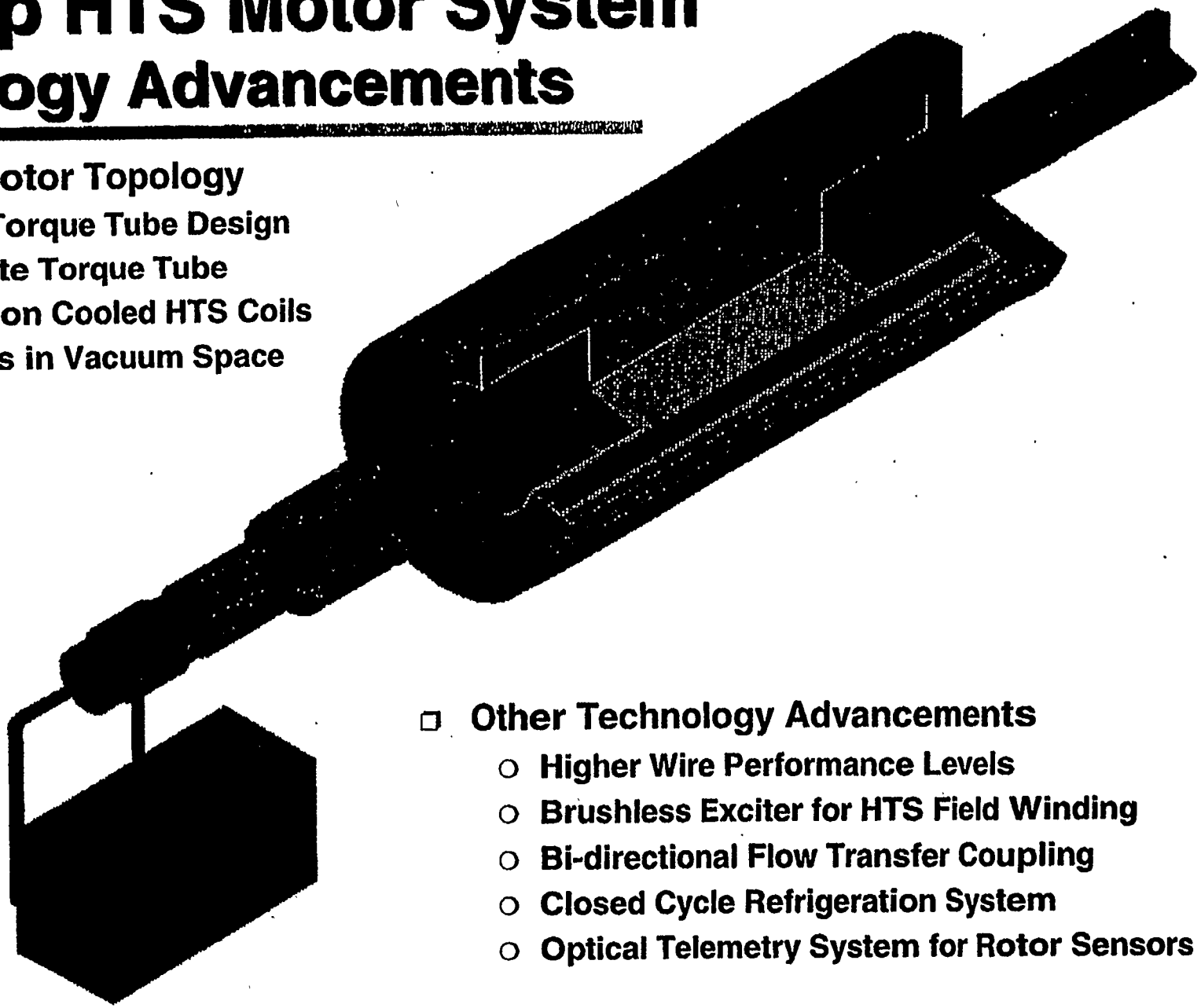
- Refrigeration Systems Development
- HTS Wire & Coil Development
- Motor Demonstrations
  - Design, build & demonstrate synchronous motor w/HTS coils operating in 25 to 40 K temperature range
  - Motor Topology: Air-core AC synchronous with HTS field winding operating at 1800 rpm with integrated cooling system
  - Maximize motor efficiency with available HTS wire performance level
    - **1,000 hp HTS Motor System**
      - Demonstrate motor comparable in size and efficiency to a conventional motor
      - Field test the motor at an industrial site
    - **5,000 hp HTS Motor System**
      - Demonstrate motor with half the volume and half the losses compared to a conventional motor
      - Install and test at potential utility customer site

1,000 hp HTS Motor Salient Features



1,000 hp HTS Motor System
Technology Advancements

- Advanced Rotor Topology
  - Internal Torque Tube Design
  - Composite Torque Tube
  - Conduction Cooled HTS Coils
  - HTS Coils in Vacuum Space



- Other Technology Advancements
  - Higher Wire Performance Levels
  - Brushless Exciter for HTS Field Winding
  - Bi-directional Flow Transfer Coupling
  - Closed Cycle Refrigeration System
  - Optical Telemetry System for Rotor Sensors

1,000 hp HTS Motor System
Basic Specifications

Motor Operating Parameters

Rated Output Power	1,000 hp
Rated Shaft Speed	1,800 rpm
Rated Output Torque	2,920 ft lb
No. of Poles	4
Armature Voltage	4,160 V
Armature Line Current	104 Amps
Power Factor	1.0
Predicted Efficiency	97.9%

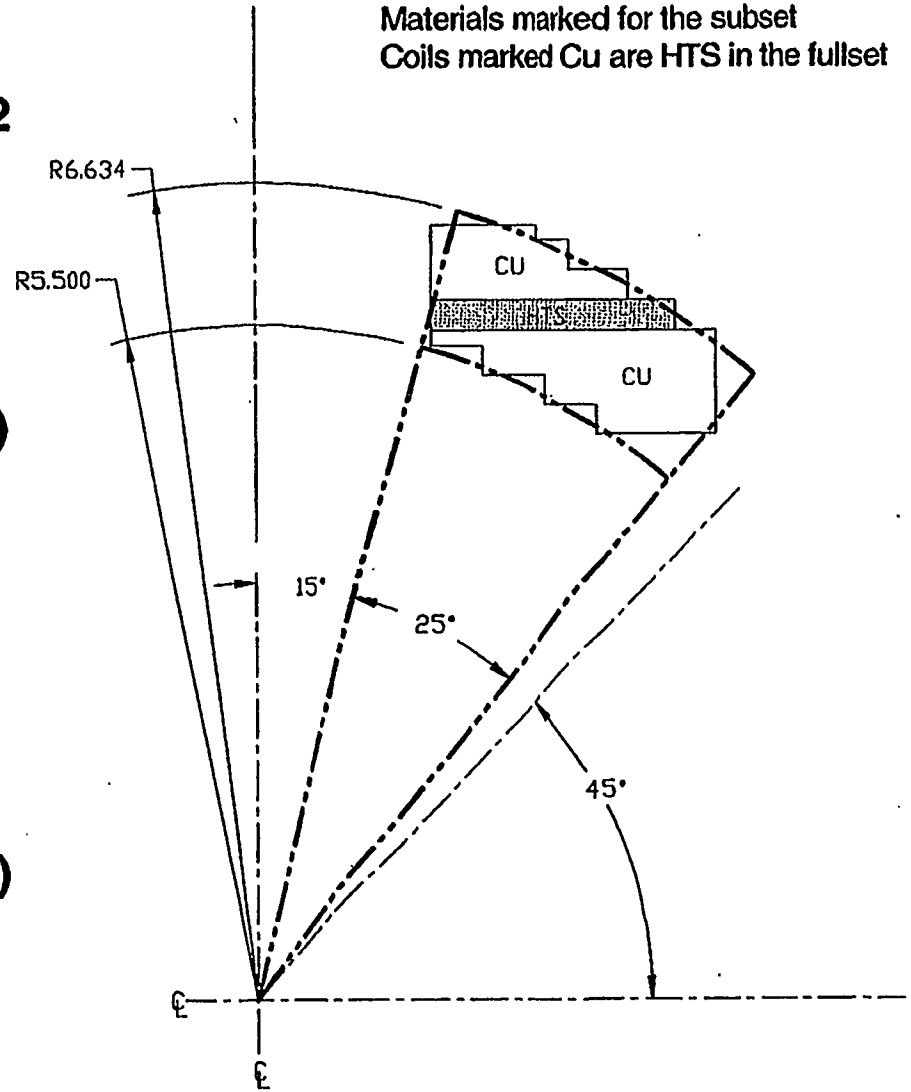
Motor Dimensions

Rotor OD	15.8 in
Armature OD	27 in
Armature Length	48 in

1,000 hp HTS Motor System
HTS Wire / Coil Requirements

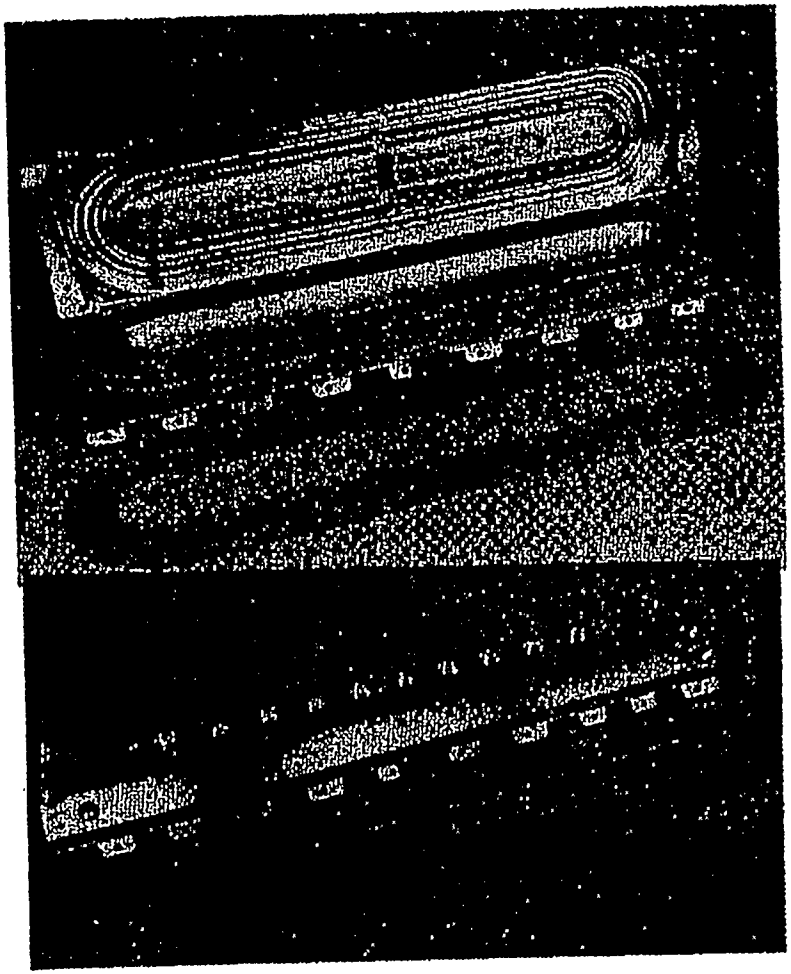
- **Full Set Requirements**
  - Current Density, Je — 14,500 A/cm2
  - Max Field Mag Flux — 1.5 T
  - Temperature — 33 K
  - Full coil turns — 1,290
  - Current (33 K) — 133.3 A (two in hand)
  - Amp-turns / pole — 172,000
  - Required Ic (77 K,self) — 52 A / wire
- **Subset Requirements**
  - Subset coil turns — 246
  - Subset Current (33 K) — >133.3 A (two in hand)
  - Required Ic (77 K,self) — >40 A / wire

Materials marked for the subset
Coils marked Cu are HTS in the fullset

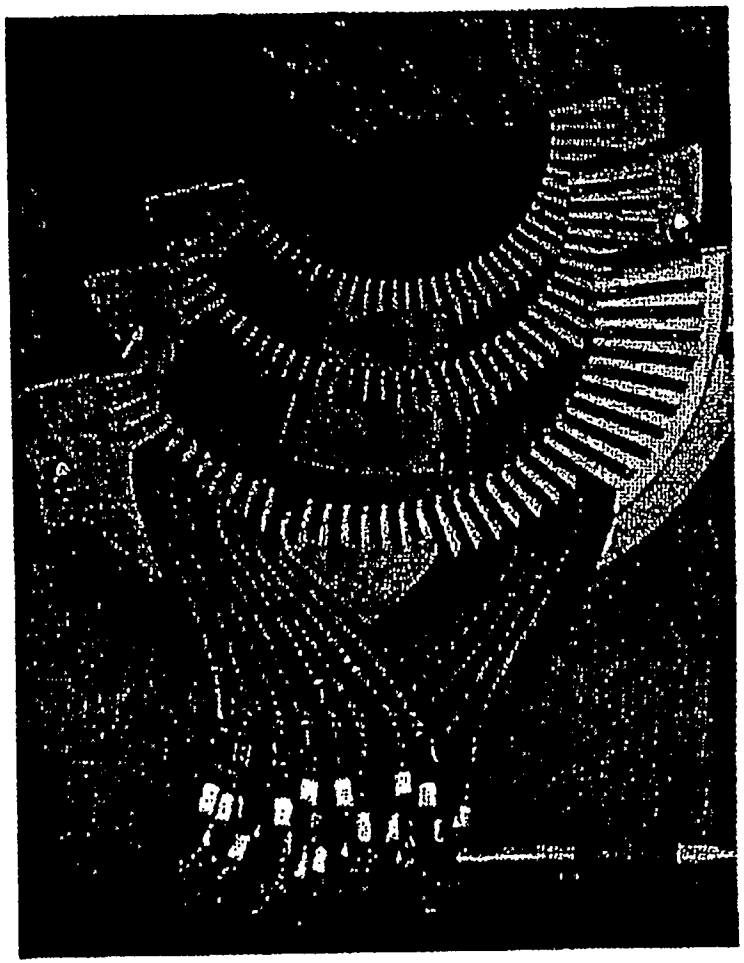


1,000 hp HTS Motor System Component Status

- Pole assembly in progress



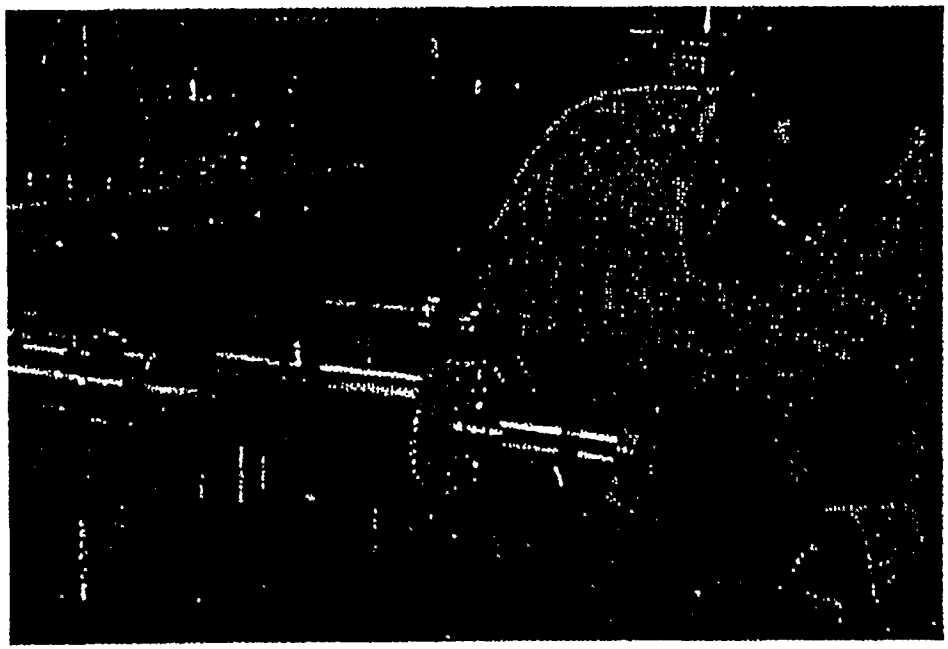
- Stator mock-up built



1,000 hp HTS Motor System Component Status (cont'd)

- Composite torque tube testing in progress

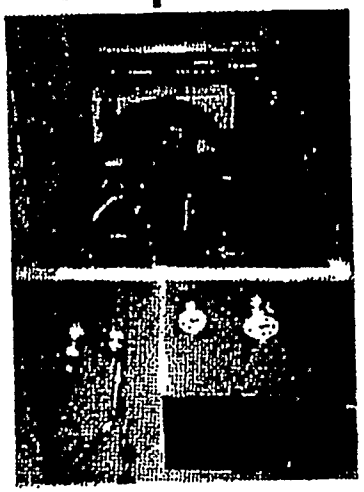
- Transfer coupling being set-up for initial testing



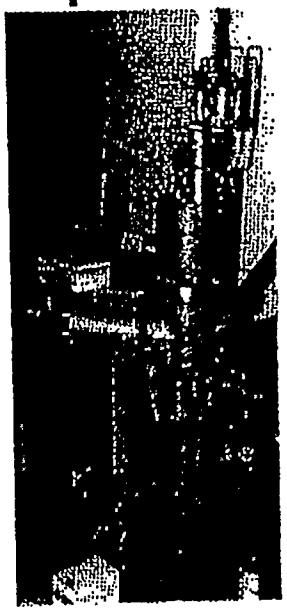
1,000 hp HTS Motor System
Baseline Refrigeration Cycle

- 60 watt provided at <30 K
- 4.5 gm sec Helium circulated at 6 atm
- <7 hp compressor power

compressor

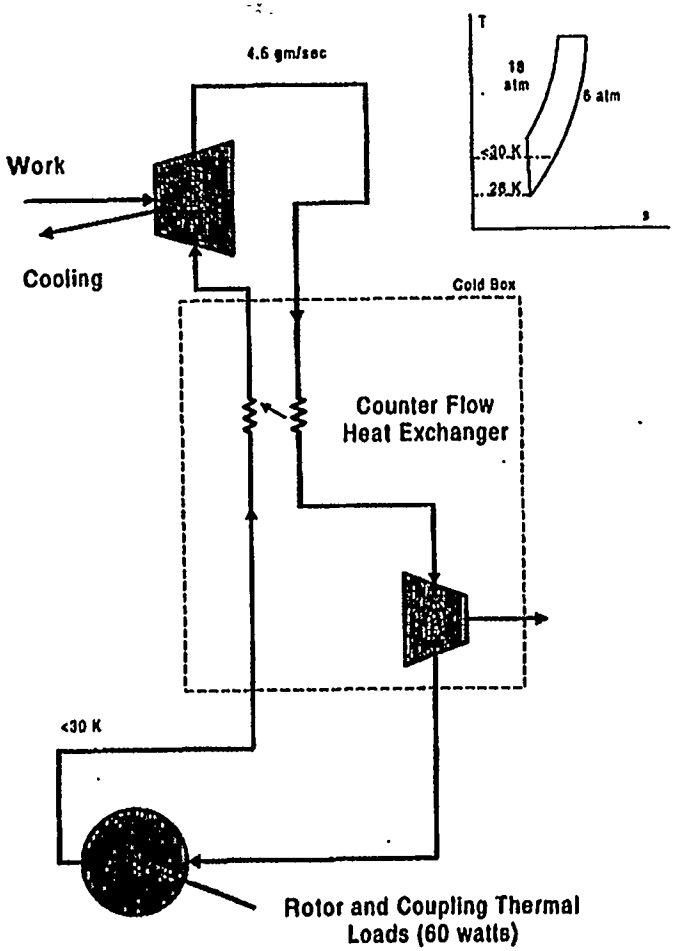


expander



coldbox

cycle



175

1,000 hp HTS Motor System Milestones

- Final rotor design review completed
- Rotor detail drawings completed
- Drawings out for quotes--some rotor components fabricated for preliminary testing
- Subset coil testing to occur in the 3rd quarter '98
- Fullset coil testing to occur in the 4th quarter '98
- 1,000 hp motor tests to occur in early '99

5,000 HP HTS Motor System

- HTS Wire Development
  - Jc performance of 70,500 A/cm^2 (77 K, self field) has been achieved for multifilamentary wire in short lengths in a scalable process
  - This world record is in excess of performance needs for the 1,000 HP motor and at high fill factor approaches the needs of the 5,000 HP motor

- Preliminary Electrical Design
  - HTS wire performance review underway
  - Preliminary motor configuration layouts generated

HTS Wire Performance Requirements for Electric Motors

- Commercial 5,000 hp HTS Motor

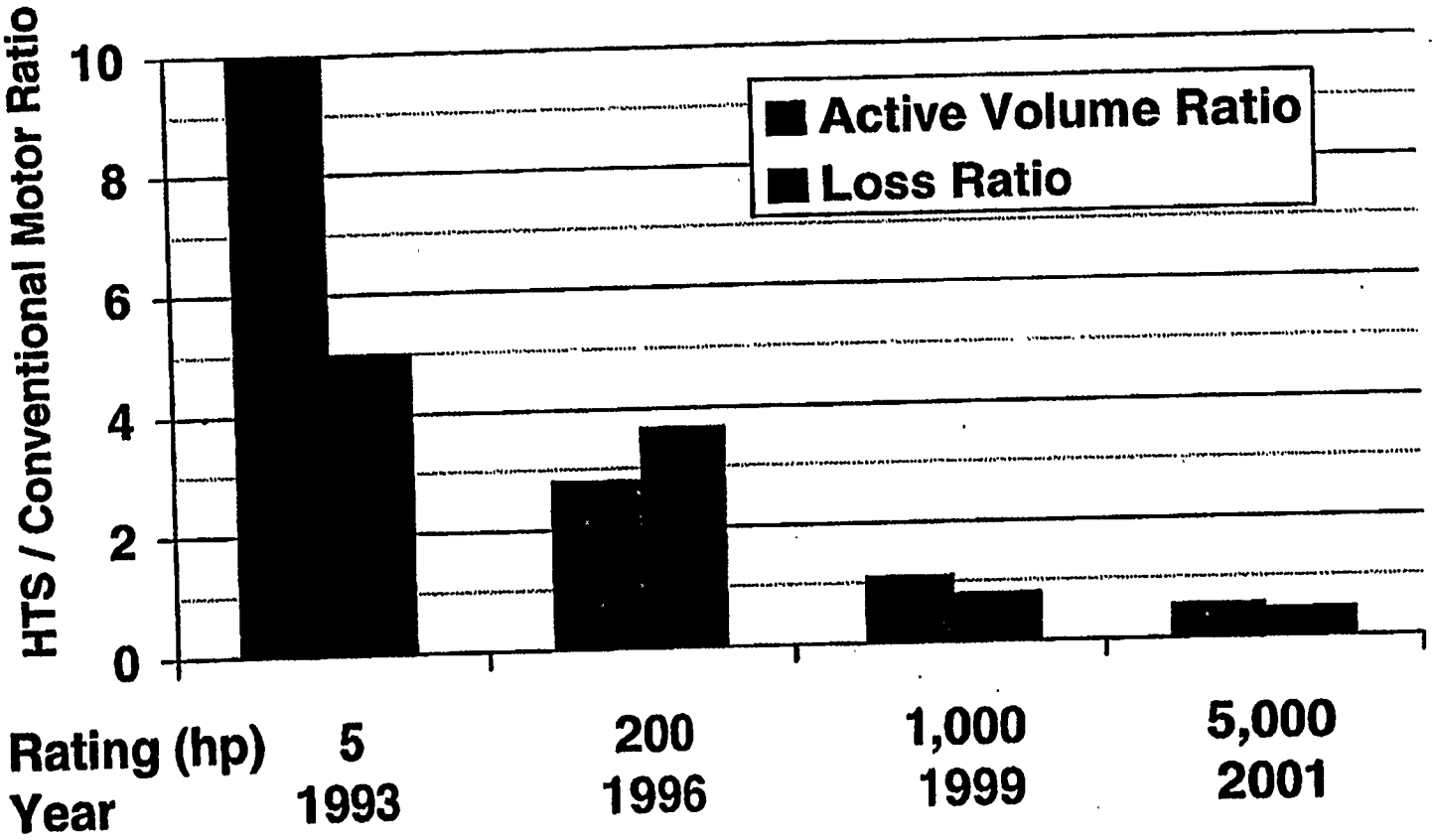
HTS Wire Performance Targets

Field (T)	$Temp_{on}$ (K)	J_e (kA/cm^2)	Strain (%)	Bend Radius (cm)	Cost ($/kA-m)
~ 4	> 25	25 - 30	0.2 - 0.3	5	10

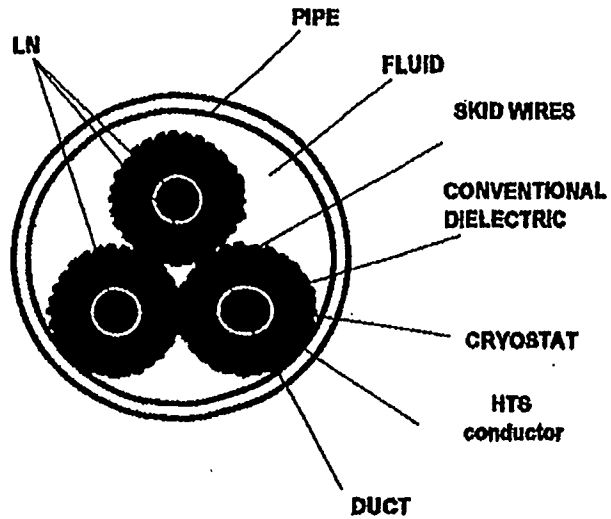
Approximate Motor Design Targets

Field MMF (MA-turns)	Winding Space Volume (cm^3)
1.7	23,000

HTS Motor Demonstration Trends



PIRELLI - ASC - EPRI - DOE HTS PROJECT



Warm Dielectric Design
115 kV, 2000 ac, 400 MVA

[redacted]

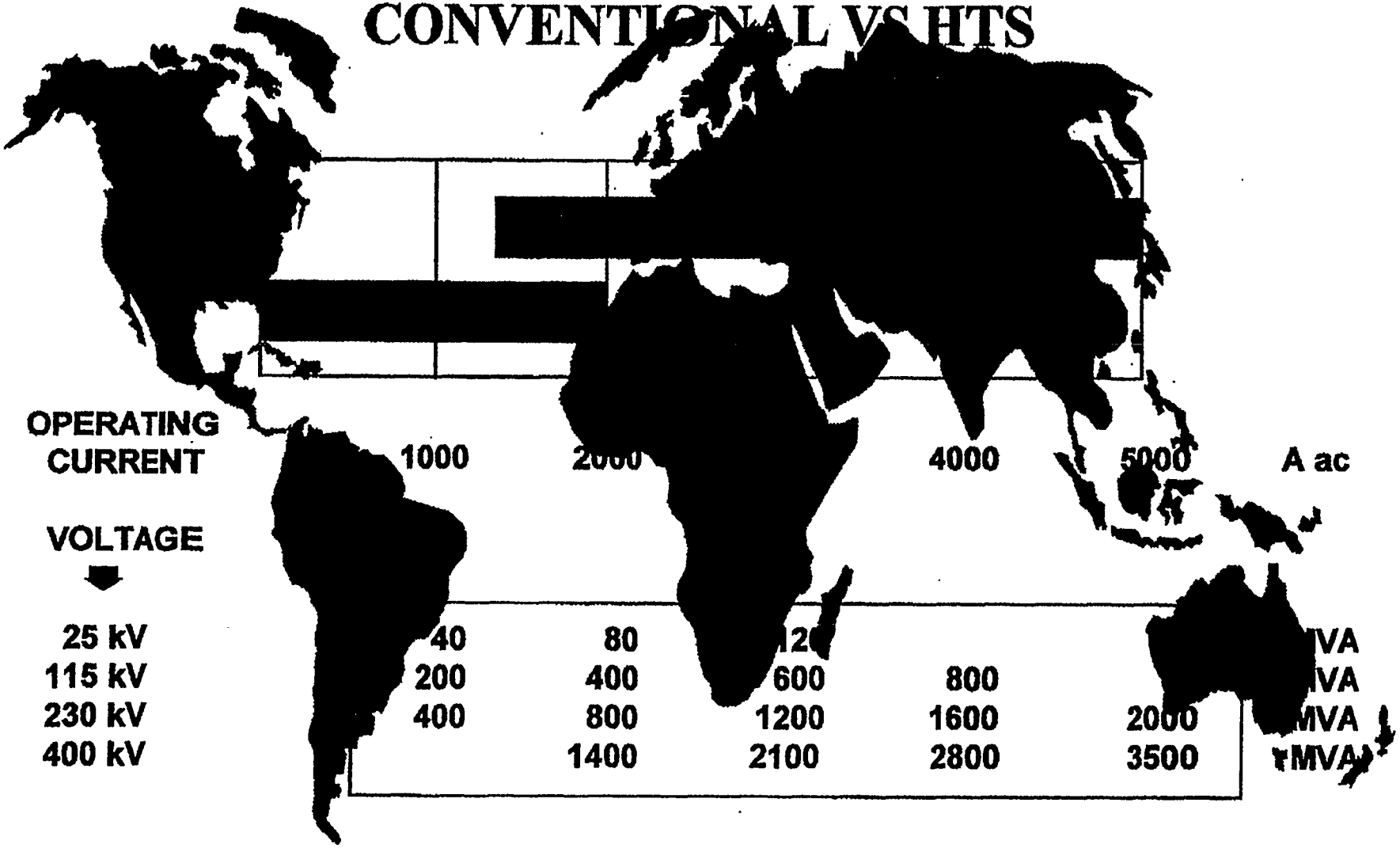
PIRELLI

REPORTED BY MANUFACTURERS IN 1997

PIRELLI

181

CURRENT CARRYING CAPACITY OF CONVENTIONAL VS HTS



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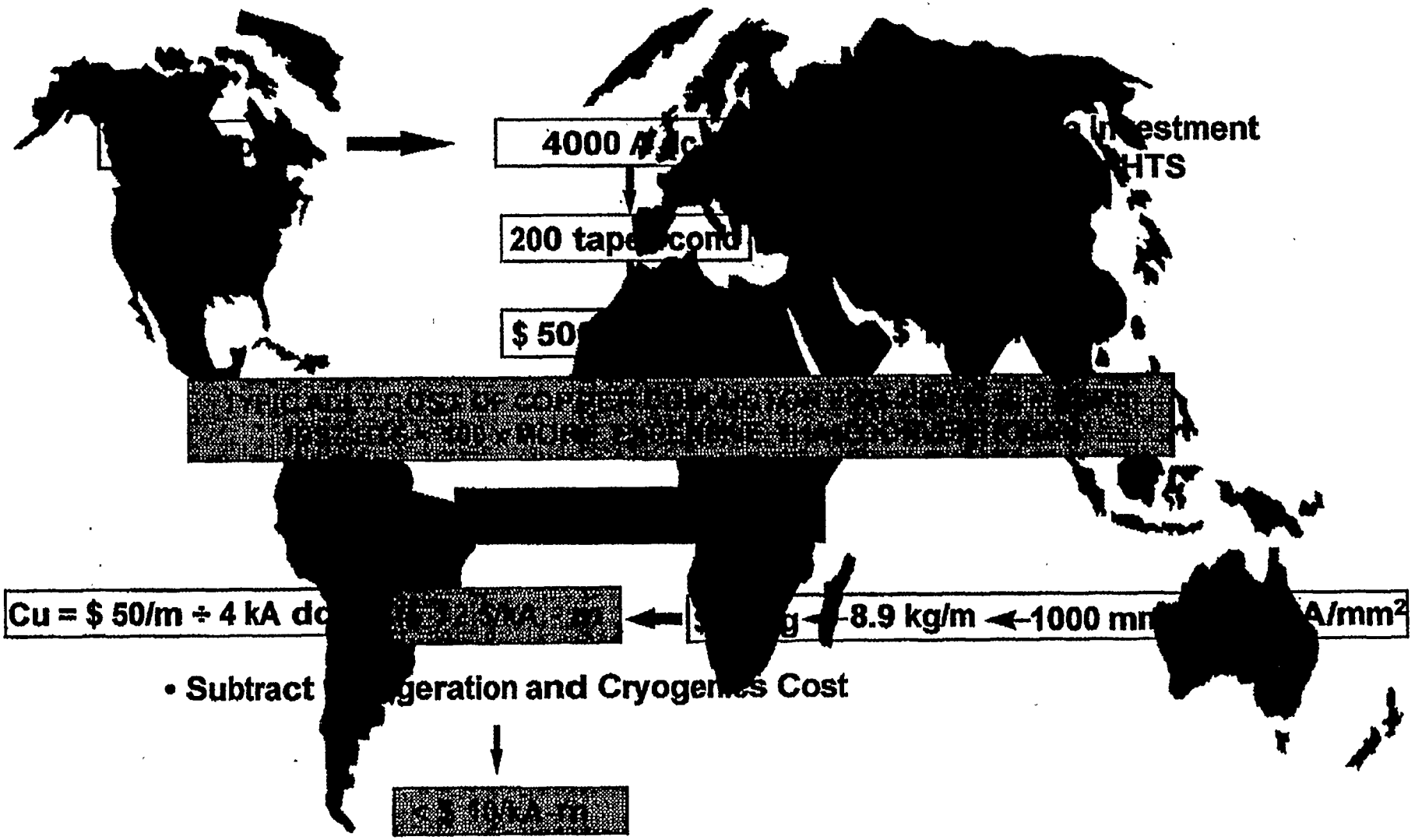
COST OF HTS VS CONVENTIONAL



PIRELLI

HTS WIRE REQUIREMENT

- Ic = 200 - 3
- Cost < $10
- Length = 1
- Consista y and

HOW D ERE ?

INNOVATIO	DEVELOP	ENGINEERING
• MATERIAL • MAT. REPLAC • FONDM. TECH GY	• SCALE-U LOGY • PERF. VER TI N • COST TAR	• COST ACHI NT • CONSISTA • INDUSTRIA

PIRELLI

HTS Device Development at American Superconductor

Bob Schwall

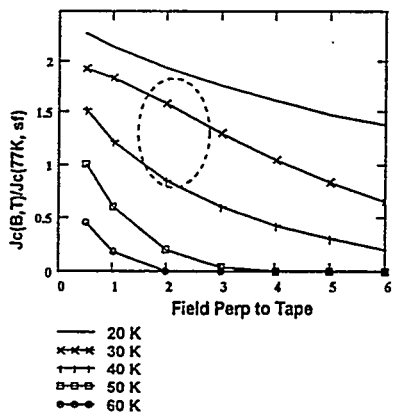
DOE Wire Workshop

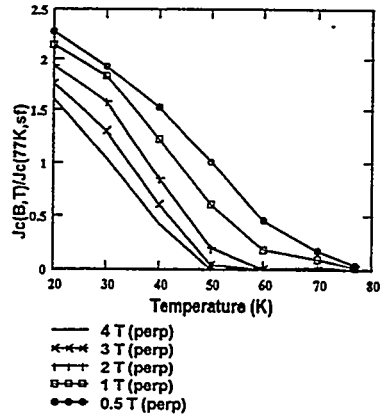
St. Petersburg FL 1/29/98

What's BSCCO 2223 good for?

- ASC's current conductor technology provides:
  - Je (77K, sf) >10,000 A/cm^2
  - Mechanical robustness
  - Long piece lengths
- This supports significant magnet demonstrations.
  - SPI 1000 HP motor
  - NRL/NSWC Homopolar Motor
  - NRL High Field Magnet

Operating conditions influence conductor choice

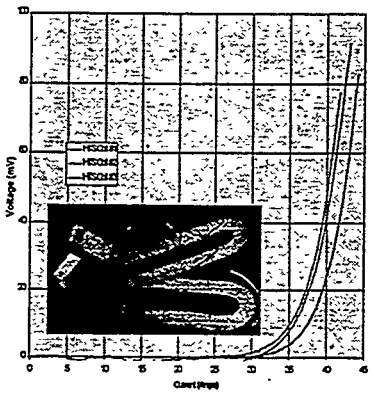




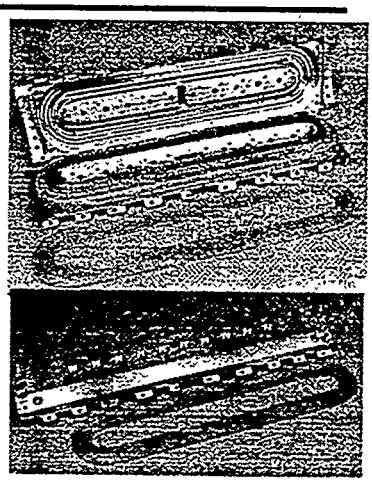
AMERICAN SUPERCONDUCTOR CORPORATION

SPI Motor Program

- Subsets subcoils tested



- Pole assembly in progress



AMERICAN SUPERCONDUCTOR CORPORATION

NRL/NSWC Program

- The Navy and DARPA have supported HTS development for ship propulsion for several years at NRL and NSWC.
- This has included:
  - BSCCO conductor development
  - Coil technology improvement
  - Demonstration motor program

HTS Homopolar Motor

- NSWC procured motor coils from two vendors to a form-fit-function specification
- ASC provided Bi 2223 coils; another vendor provided a mixture of Bi 2223 and Bi 2212 coils.
- The motor was initially tested at lower performance with coils from both vendors
- A Navy program decision to operate the motor at liquid Neon and liquid Nitrogen temperatures necessitated the use of only Bi 2223 coils.
- The highest performance motor demonstrations used only ASC coils

Homopolar Motor Test Results

- Motor was run at NSWC in in liquid cryogens (LN_2, LNe and LHe)
- Results:
  - 77K 104 HP
  - 28K 230 HP
  - 4.2K 320 HP
- Next step in program is to run motor on a cryocooler.

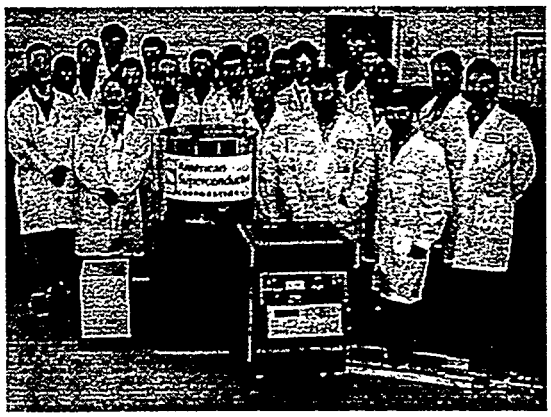
NRL High Field Magnet

- As part of the Navy HTS coil development program ASC is building a high field conduction-cooled magnet system for installation at NRL

Central Field	>6 Tesla
Warm Bore	51 mm
Homogeneity	1% in 51mm DSV
Ramp Rate	>2 Tesla/min
Operating Temperature	~20 K
Refrigerator input power	~6 kW

System Components

- Magnet
- Cryostat
- Cryocoolers
- Magnet Protection System
- Field Probes
- Power Supply
- Computer
- Control software



Cryoplate Cooling

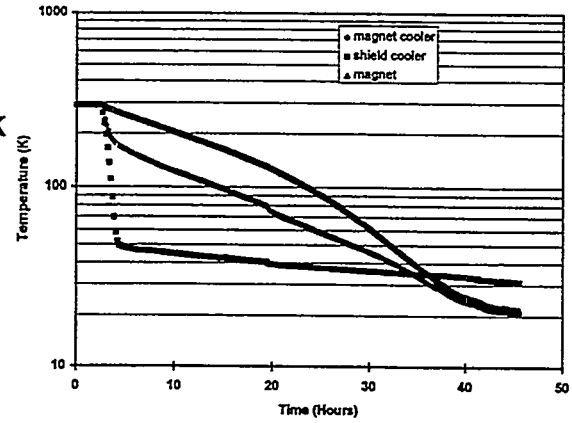
- DC and slow ramp HTS magnets may be conduction cooled from the OD or the ends
- AC coils (e.g. SMES) and fast ramp magnets require extended thermal buswork
- ASC Cryoplate utilizes a laminated cooling plate on individual pancake coils and ensures minimum thermal impedance
- This technology was shipped on the LANL magnetic separation magnet (M. Daugherty 1995 DOE Peer Review) and other ASC systems

NRL System Status

- Initial System Cooldown was 1/23 to 1/25/98
- First current was 1Q XXXII
- First field run was 1/26/98

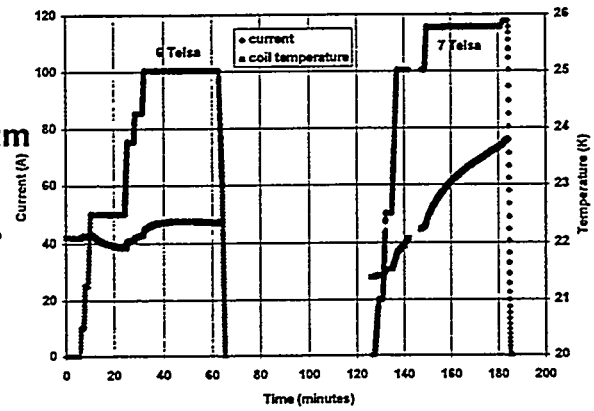
System Cooldown

- Magnet cooled to 22K in 45 hrs.
- Radiation shield stabilized at 55 K



First Field Run

- Magnet was held at 6 Tesla for 30 min and reached thermal equilibrium
- Magnet was held at 7 Tesla for 30 minutes.



Summary

- ASC Bi 2223 conductor is regularly produced with Je (77,sf) > 10,000 A/cm^2
- This material is being incorporated in the SPI 1000 HP motor subsets
- Similar material produced record Homopolar motor performance in a direct head to head competition.
- First tests of a HTS high field magnet have produced 7 T at 23 K in a conduction cooled system.

DEVELOPMENT OF COATED CONDUCTORS ON RABiTS

J. E. Hack
Midwest Superconductivity, Inc.

A. Goyal
Oak Ridge National Laboratory

D. Moon
Westinghouse Science and Technology Center

1998 DOE Wire Technology Workshop
St. Petersburg, Florida
January 29 -30, 1998

192

COLLABORATORS AND FUNDING

- Midwest Superconductiviy, Inc.

  Ying Xin — D. Lenshek
  K. Penner — M. Dai
  M. Reiser — H. Muller

- Oak Ridge National Laboratory

  B. Hawsey — D. Norton
  D. Kroeger — D. Christen
  Elliot Specht — P. Paranthaman
  F. List — a host of others

- Westinghouse

  D. Moon — M. Burke

- Brookhaven National Laboratory

  M. Suenaga

- Plastronic

  M. Tomsic

- American Thin Film Services

  L. Homstad

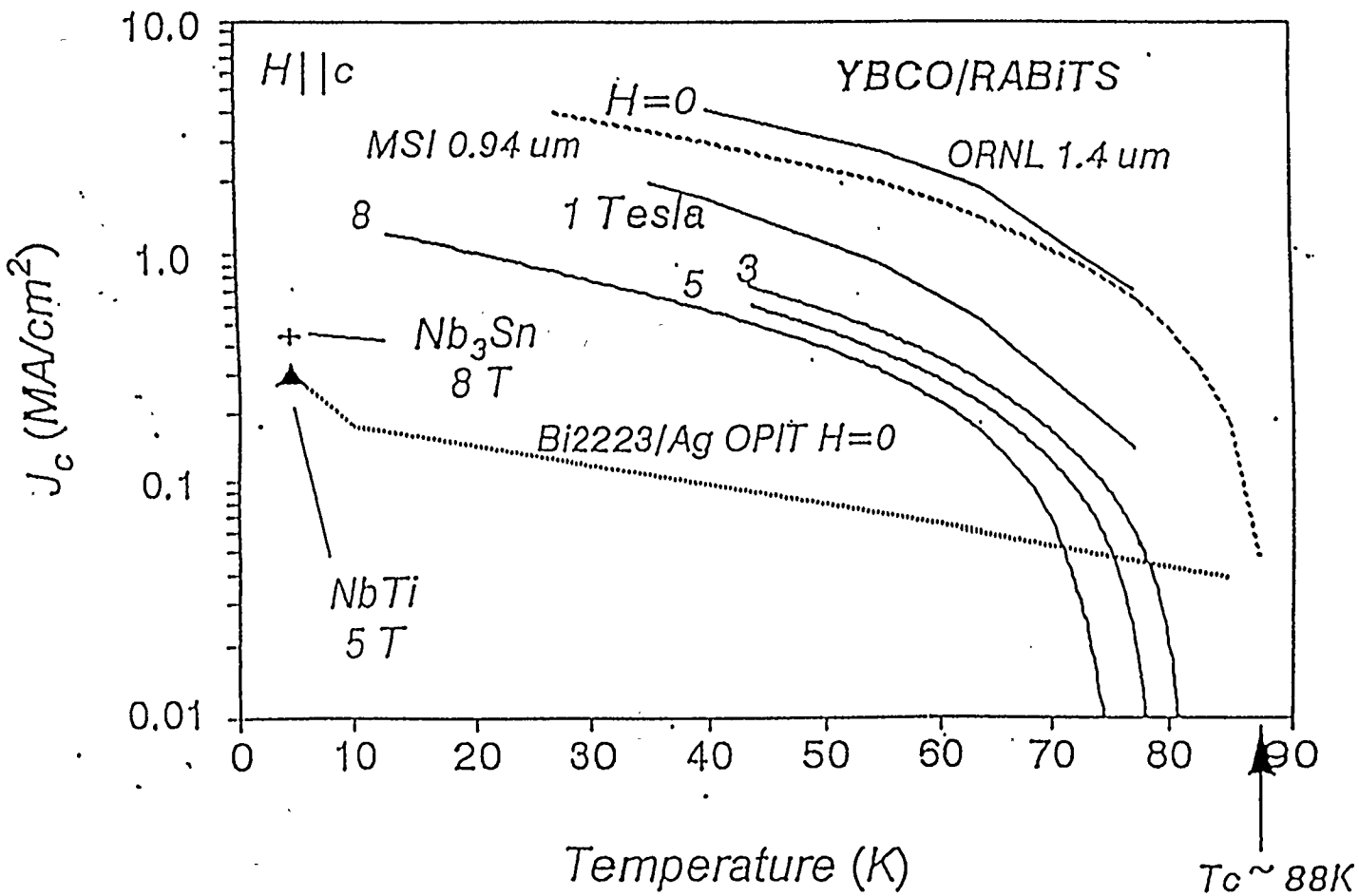
- DoE SBIR on High Current Capacity Tape for Accelerator Magnet Applications

OUTLINE

- SHORT LENGTH RABiTS
- ROLLING OF Ni
- BUFFER LAYER WORK
- MOCVD PRECURSOR DEVELOPMENT
- ONE METER TAPE DEMONSTRATIONS
- PRODUCTION PROTOTYPE REACTOR
- ECONOMICS

Temperature Dependence $J_c(T)$

- *YBCO / RABiTS show large enhancements as the temperature is decreased*
  - Good in-field properties
    - at ~ 64K comparable to NbTi at 4.2K
    - at ~ 45K comparable to Nb_3Sn at 4.2K



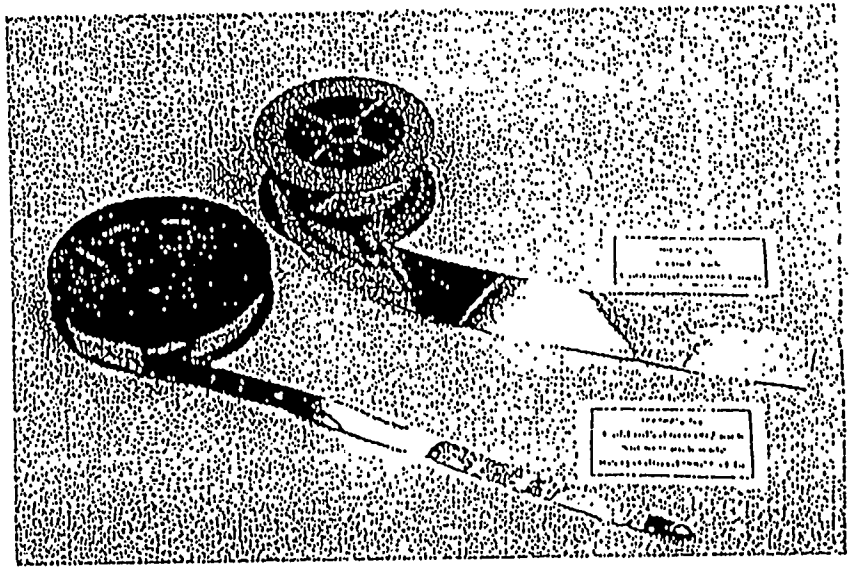
SET AGGRESSIVE GOALS

- DEMONSTRATE A ONE METER TAPE CONSISTING OF AN HTS FILM ON BUFFERED RABiTS BY SEPTEMBER 30

- DEMONSTRATE 10 - 30 METER TAPE BY END OF 1997 8

Westinghouse STC

- Develop Industrial Process for Long Length Production of Nickel Substrate
- Improve Texture Quality, Reproducibility and Reduce Thickness
- 100 Ft. Length of 0.0015" Tape has been Rolled and Recrystallized



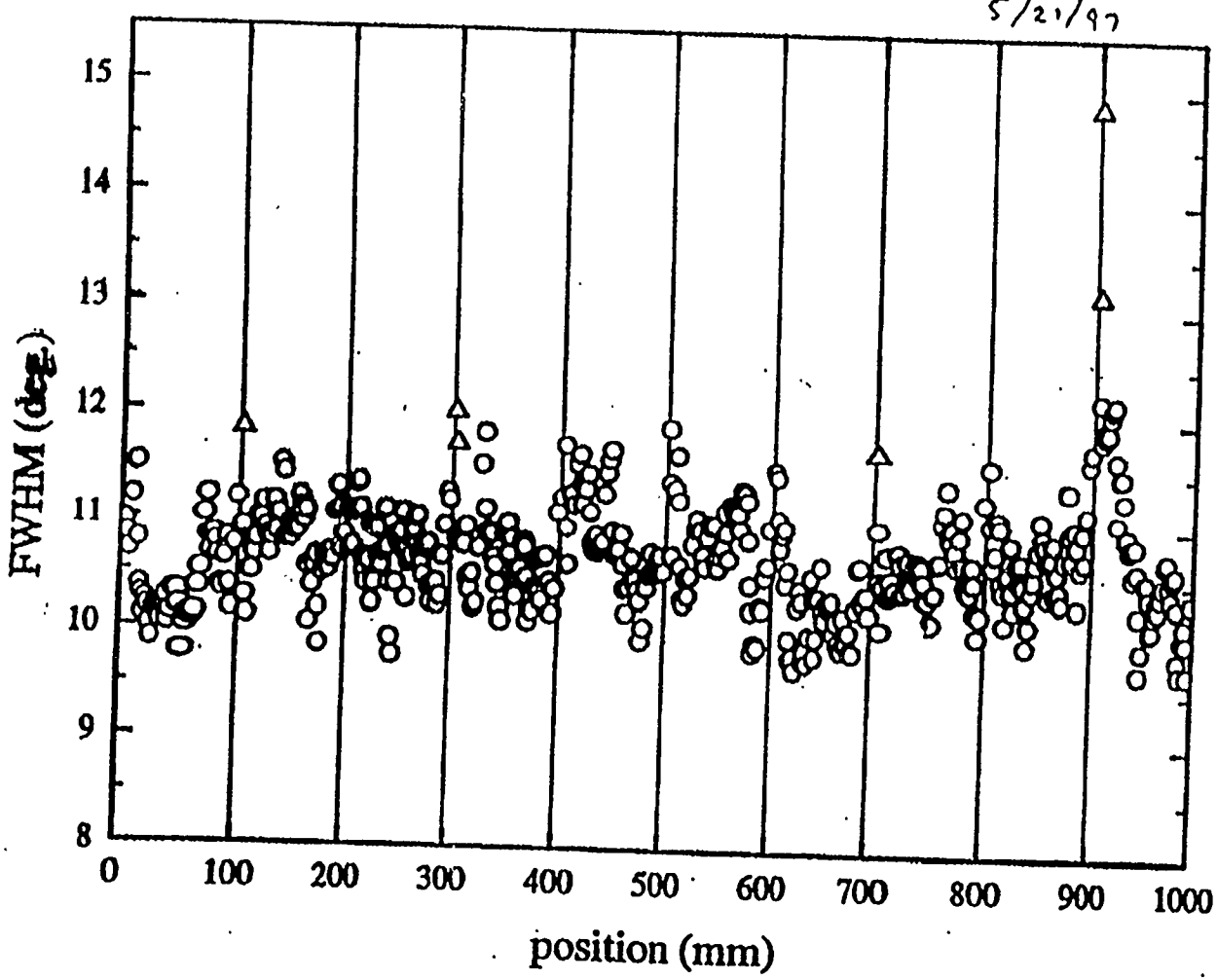
MSI

198

In-plane alignment of 1 m of Westinghouse 30 m strip

Excluding edge points (triangles), FWHM=10.65±0.46°

Elias Spocha
5/21/97



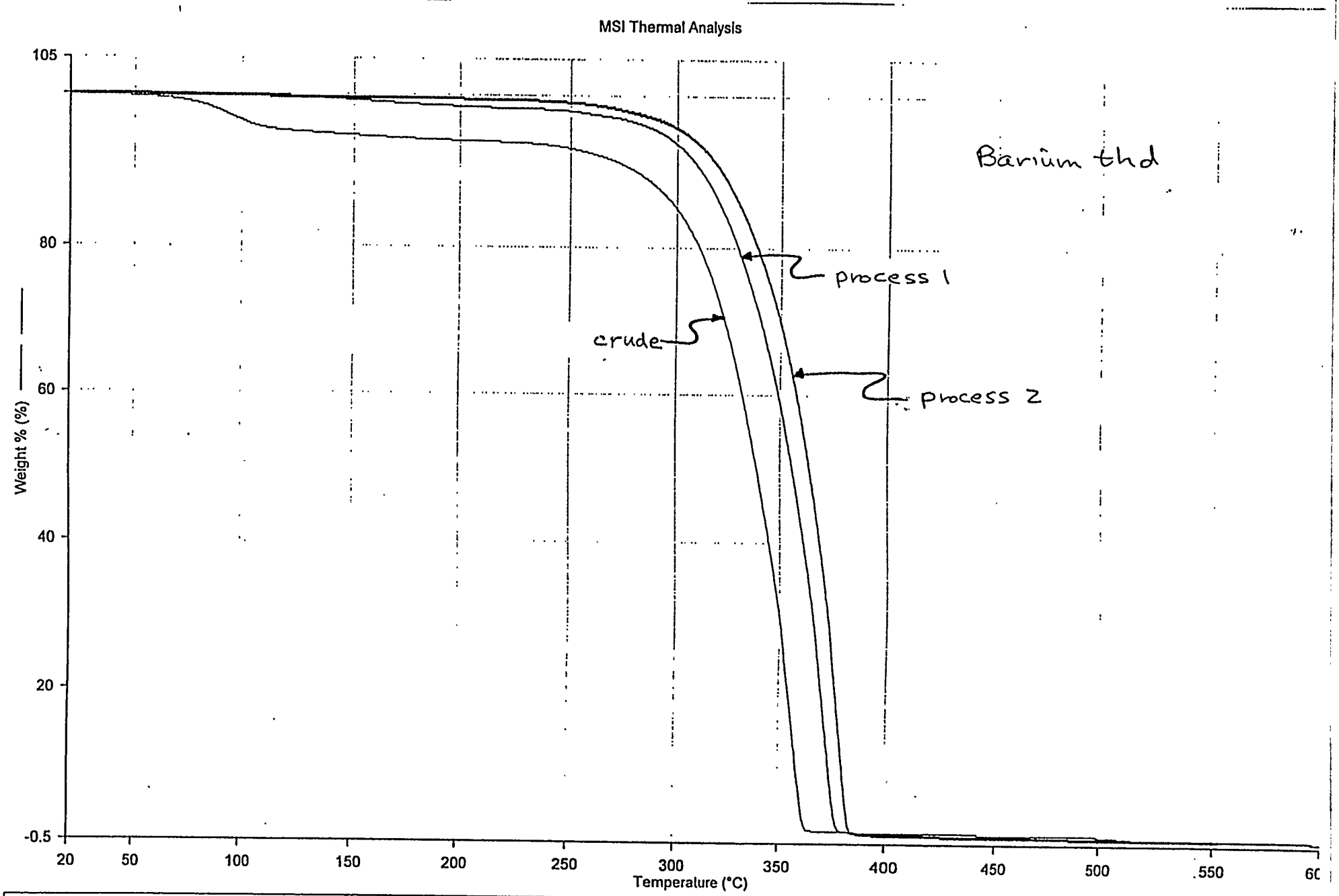
SUMMARY OF PRELIMINARY RESULTS ON Ni AND BUFFER LAYERS

- HANDLING OF 0.002" NICKEL TAPE AT 800C IS NOT A PROBLEM IN THE ATFS SYSTEM

- TEXTURE OF Ni OVER LONG LENGTHS LOOKS VERY CONSISTENT

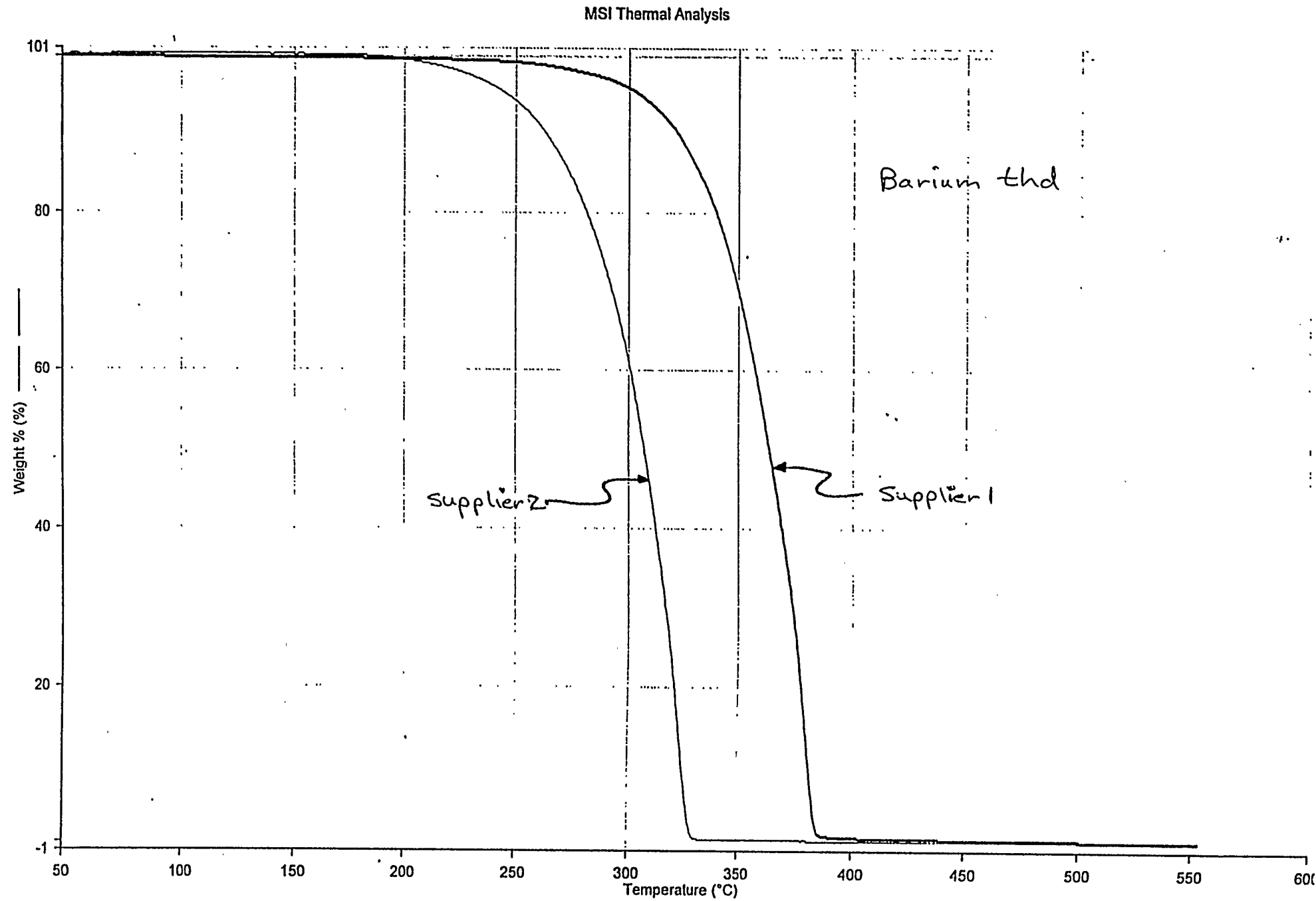
- NICKEL OXIDE LAYER HAS BEEN ELIMINATED BUT PROBLEMS WITH EPITAXY OF BUFFER LAYERS PERSIST

- AN INDEPENDENT EFFORT TO DEPOSIT BUFFFERS BY MOCVD HAS BEEN INITIATED AT MSI AND MOCVD WAS USED FOR THE ONE METER TRIALS



1) Heat from 15.00°C to 600.00°C at 15.00°C/min

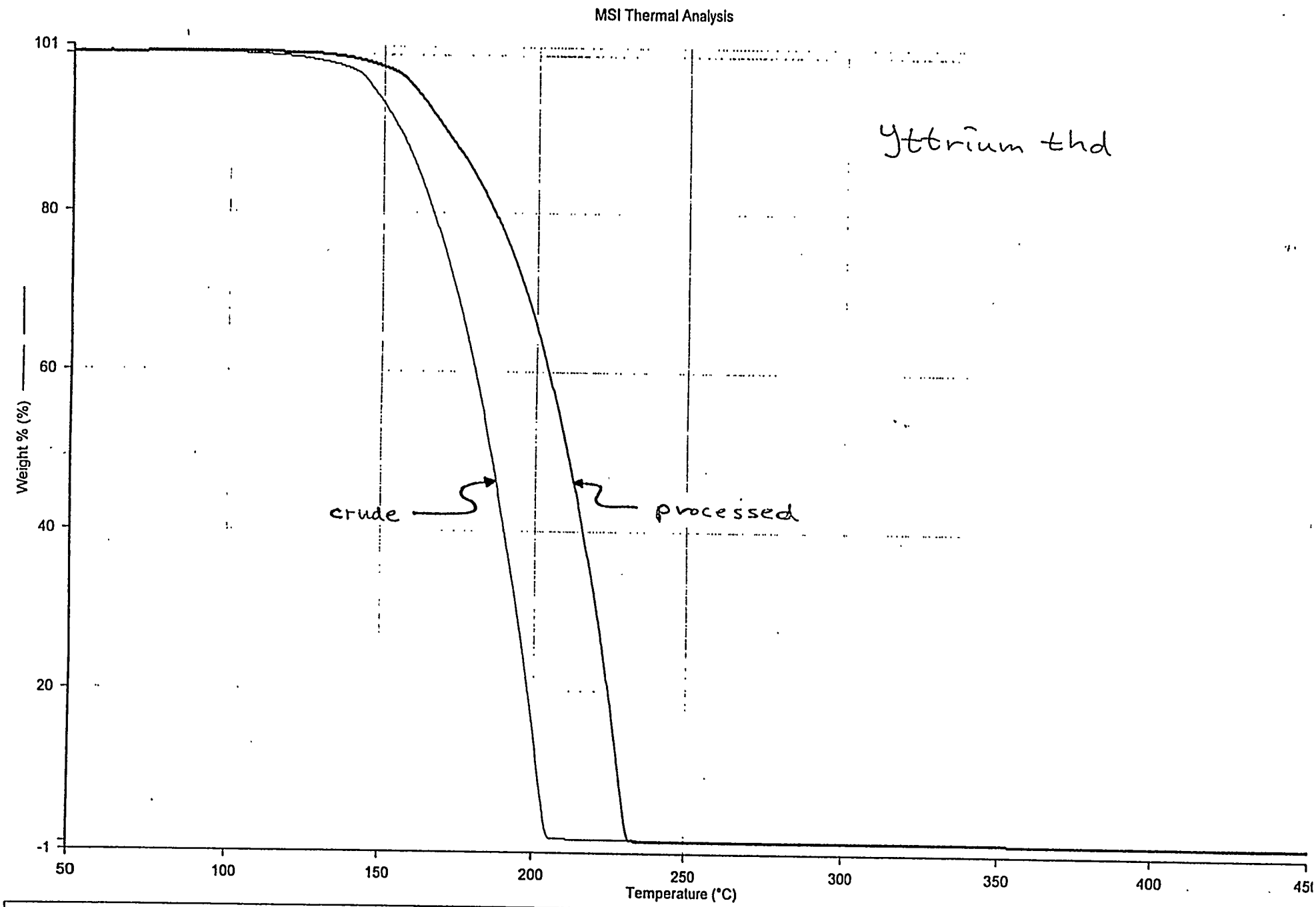
8/26/97 7:38:46 AM



1) Heat from 15.00°C to 600.00°C at 15.00°C/min

8/26/97 7:39 24 AM

201



1) Heat from 30.00°C to 500.00°C at 15.00°C/min

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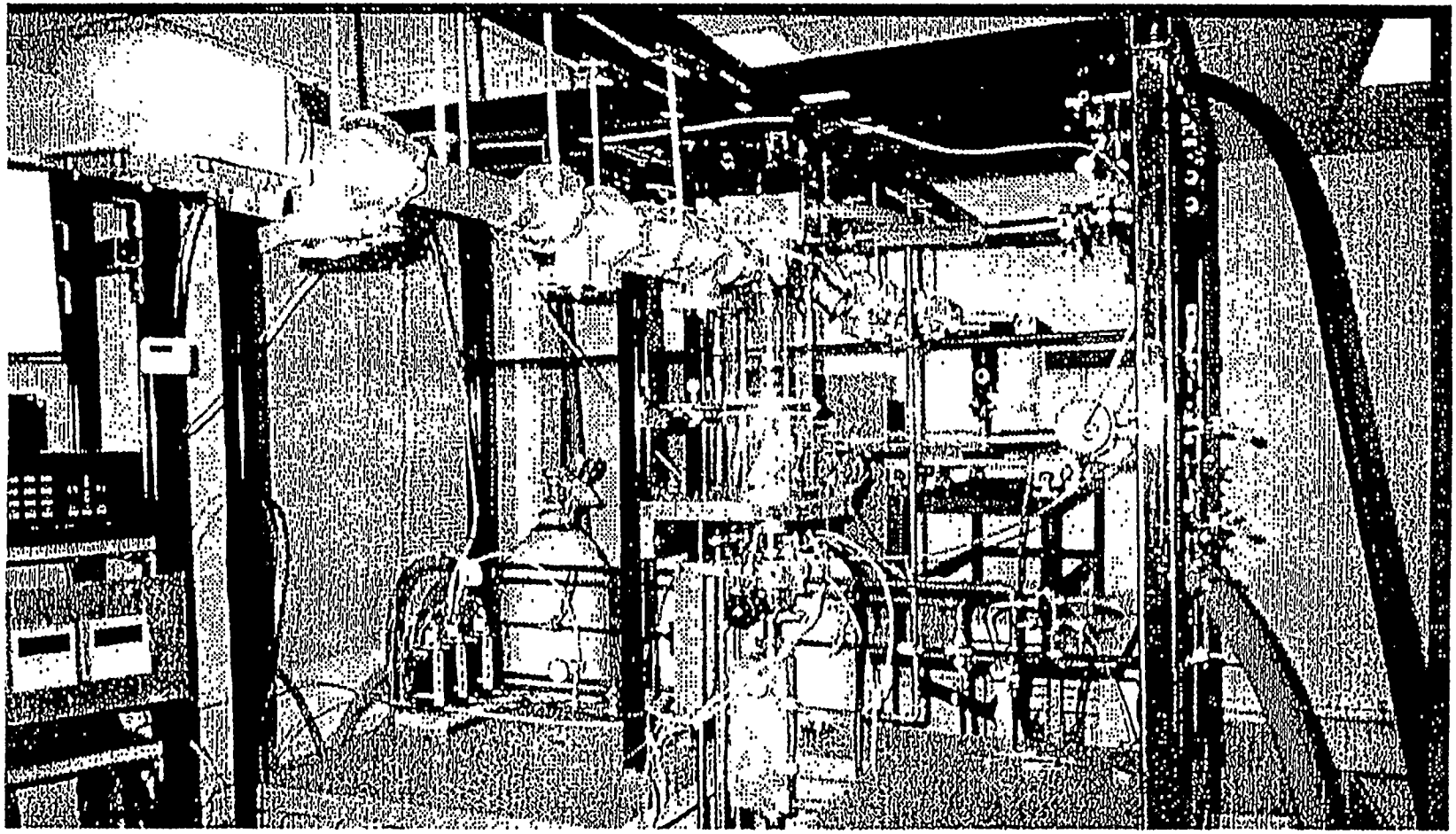
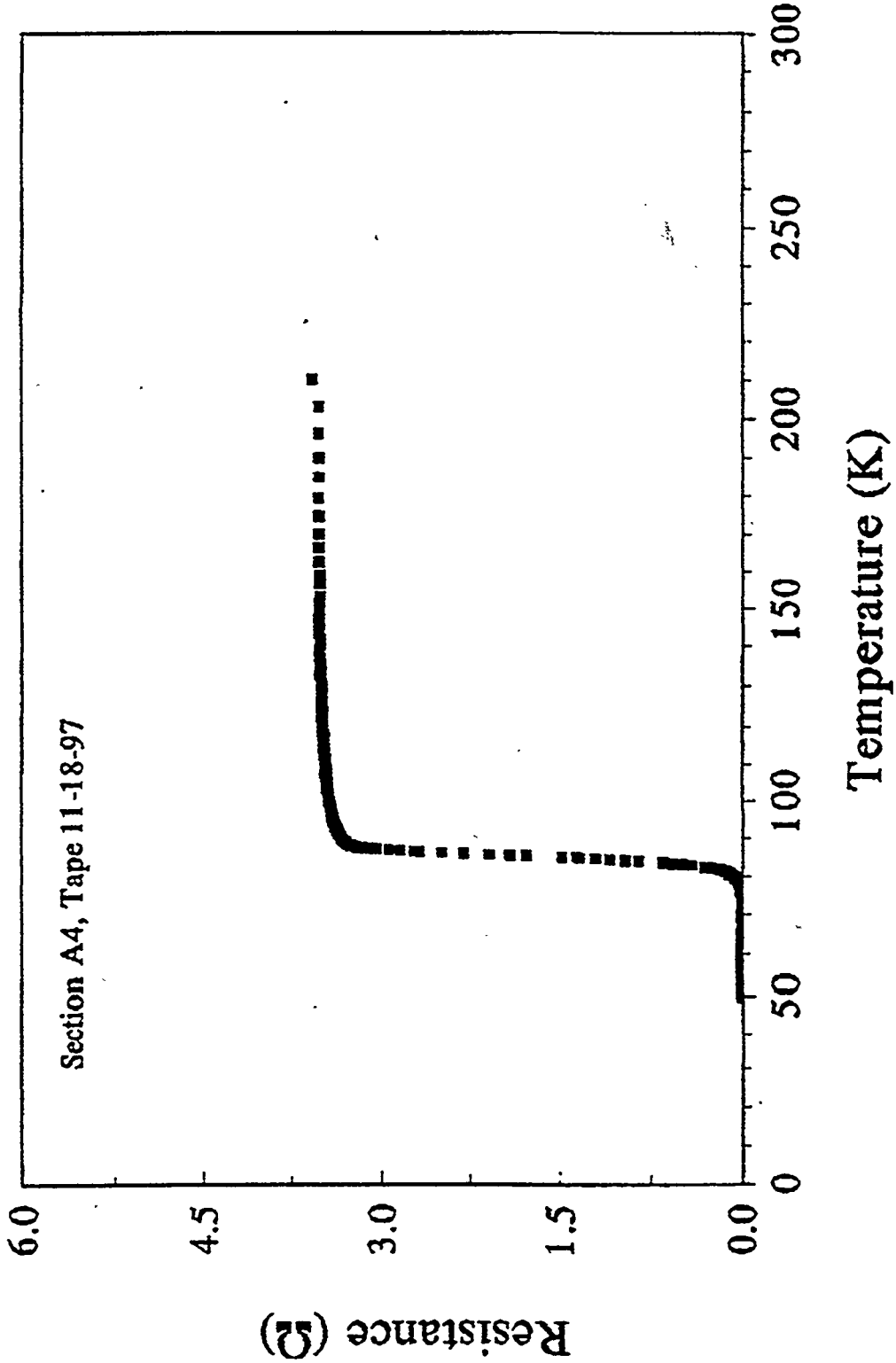
MOCVD Development Reactor for One Meter YBCO Tape Demonstration

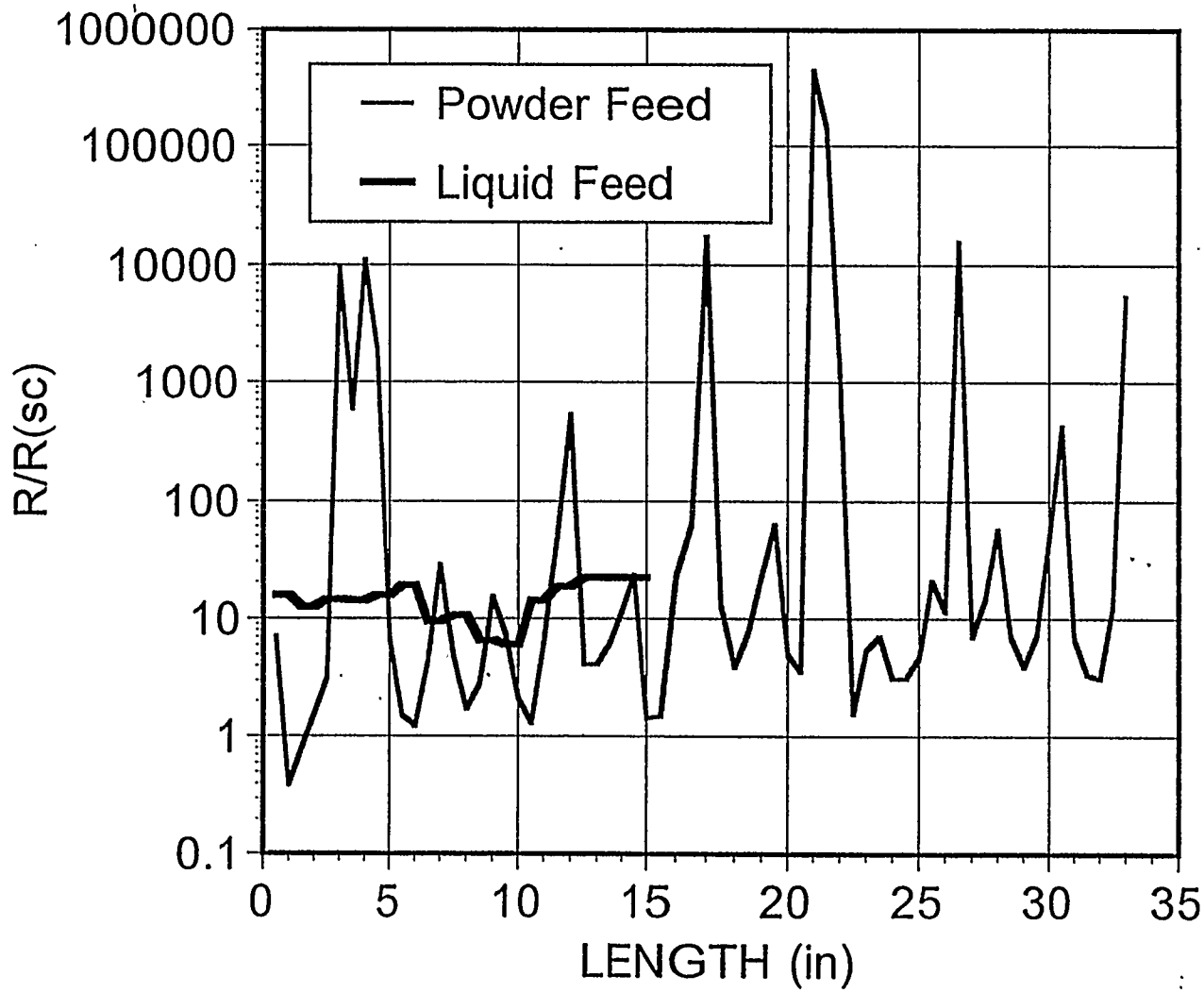


MSI

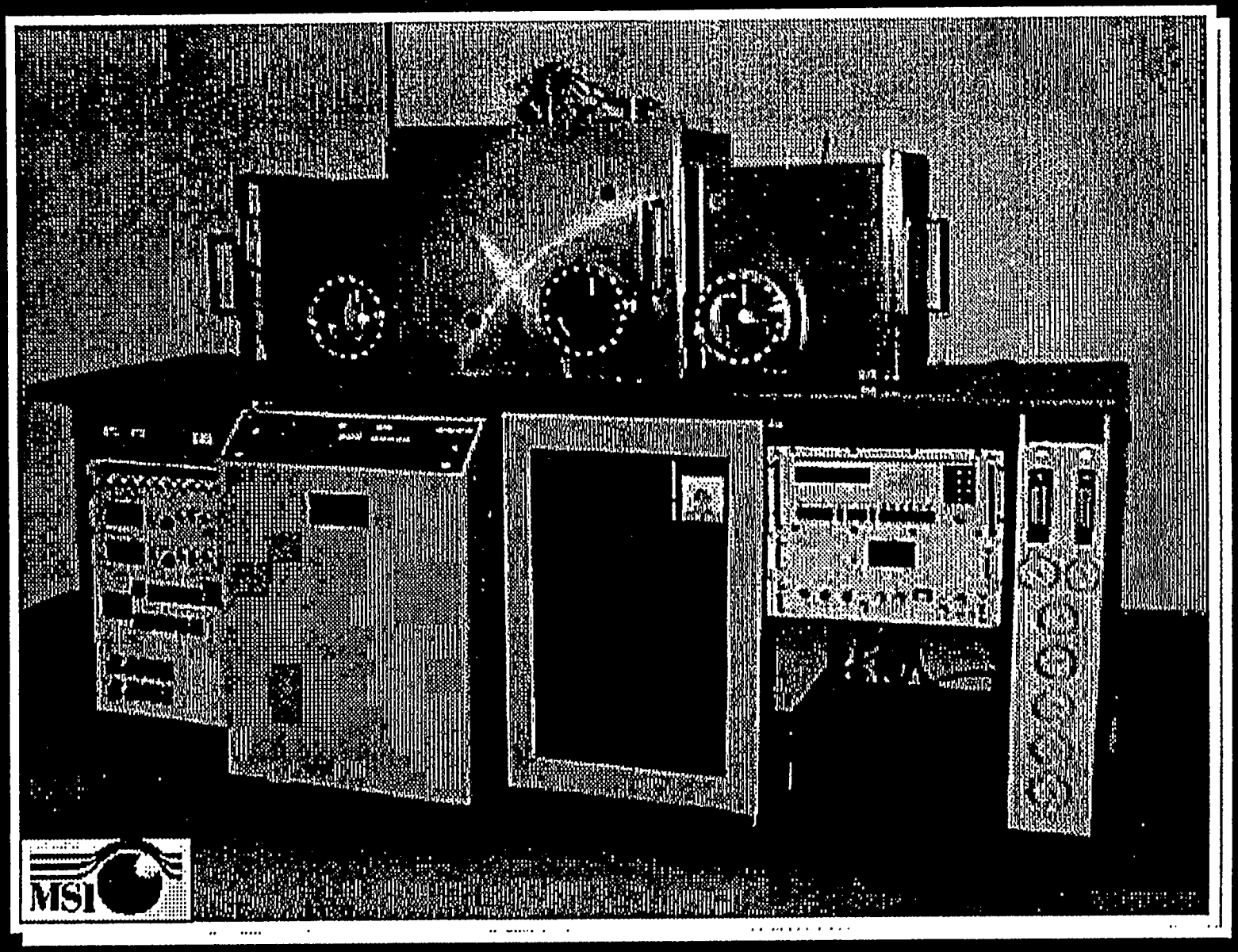
203

NOW!
NISTI


Section A4, Tape 11-18-97
Resistance (Ω)
6.0
4.5
3.0
1.5
0.0
0
50
100
150
200
250
300
Temperature (K)



RESISTANCE VS POSITION FOR FIRST TWO CONTINUOUS DEPOSITIONS USING DIFFERENT PRECURSOR FEED METHODS


MSI

PRELIMINARY ECONOMIC ANALYSIS

Precursor -

- Initial costs were approximately $30/g
- After negotiation of spec's, modest quantities are below $10/g
- Even modest production quantities can drive this down to $1-2/g
- Price of precursor is less than $0.50/m at pilot production levels

Nickel Tape -

- 99.998 - $850/lb
- 99.99 - $390/lb
- 99.5 - $20/lb (Ni270)
- No discernable difference in texture between grades
- Fully fabricated cost is less than $0.20/g
- Costs of Ni and precursor are both less than $0.50/m in pilot production quantities

Add labor, indirect costs and profit - $100/kAm at 77K and $10/kAm at 4K in pilot production are achievable goals

OTHER ACCOMPLISHMENTS

- LIQUID PRECURSOR FEED SYSTEM HAS BEEN USED TO PRODUCE GOOD QUALITY SUPERCONDUCTING FILMS ON LANTHANUM ALUMINATE SUBSTRATES

- SUBSTRATE HEATER AND LIQUID PRECURSOR FEED SYSTEM FOR PRODUCTION PROTOTYPE REACTOR WILL BE DELIVERED IN FEBRUARY

- A PATENT FOR A METHOD FOR IMPROVING TEXTURE IN Ni TAPE IS IN THE APPLICATION PROCESS AND CONFIRMING DATA SHOULD BE AVAILABLE BY THE PEER REVIEW THIS SUMMER

FUTURE WORK

- **SET NEW AGGRESSIVE GOALS**

  Demonstrate a One Meter Tape With a J_C > 100,000 A/cm^2 By End Of First Quarter Of 1998

  Demonstrate 10 - 30 Meter Tape By End Of Second Quarter Of 1998

- **BIGGEST CHALLENGE**

  Ni Rolling And YBCO Deposition Are Moving Along But Long Lengths Of Buffered Substrate Must Be Developed For Progress To Continue

Progress in YBCO Conductor Development at Intermagnetics

V. Selvamanickam

Intermagnetics General Corporation
Latham, NY 12110

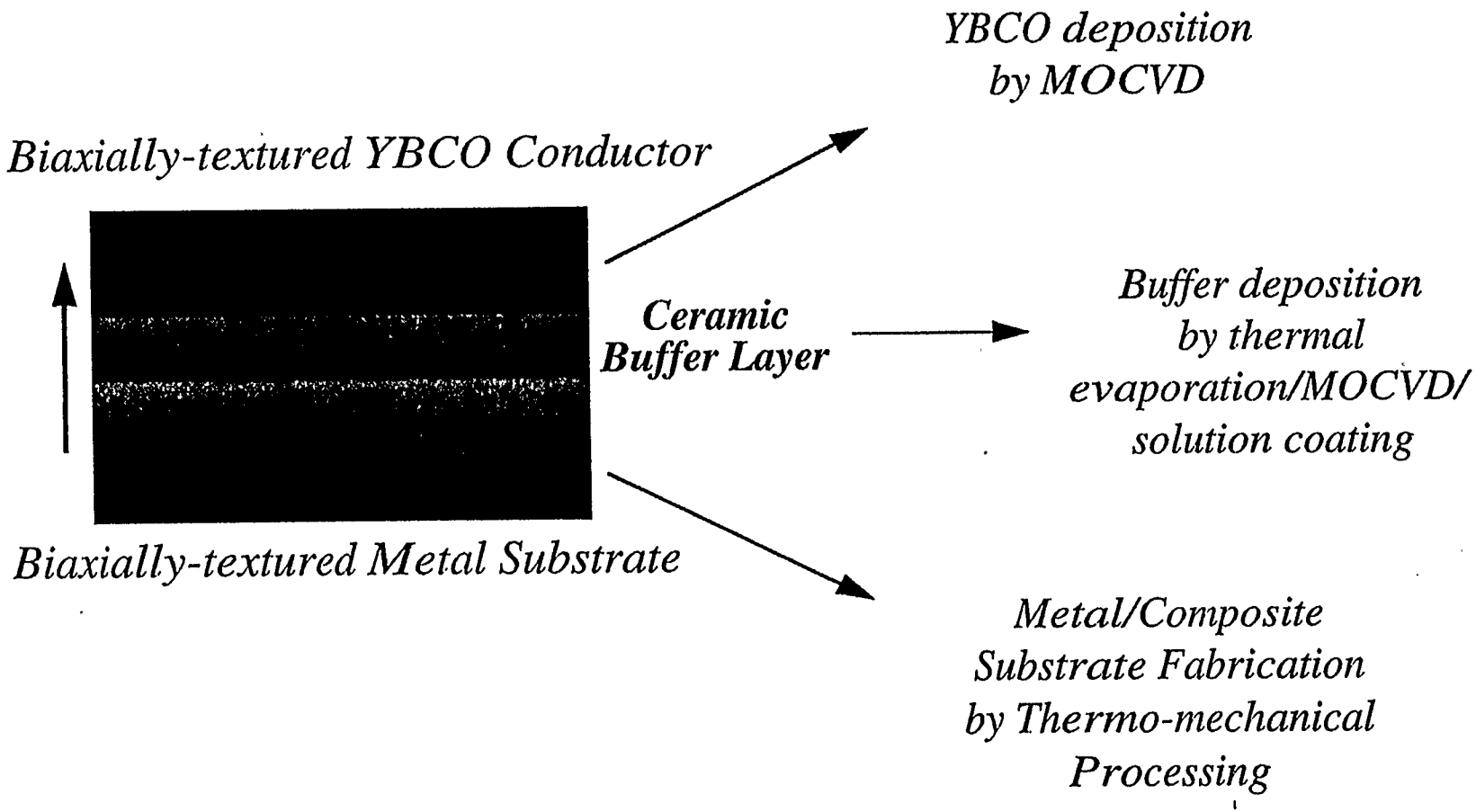
DOE Wire Workshop, St. Petersburg, FL, January 29-30, 1998

211

Contributors & Collaborators

- **IGC** (J. D'Frank, G. Galinski, C. Trautwein, P. Haldar)
- **Argonne National Lab** (U. Balachandran, M. Lanagan)
- **University of Pittsburgh** (N. Eror and M. Lelovic)
- **Wright Patterson AFB & UES Inc.** (C. Oberly, R. Nekkanti)

Development of Next Generation HTS conductor



YBCO Conductor Development at IGC

IGC has established an independent YBCO Conductor Development Program and has set up facilities for all aspects of YBCO Conductor fabrication

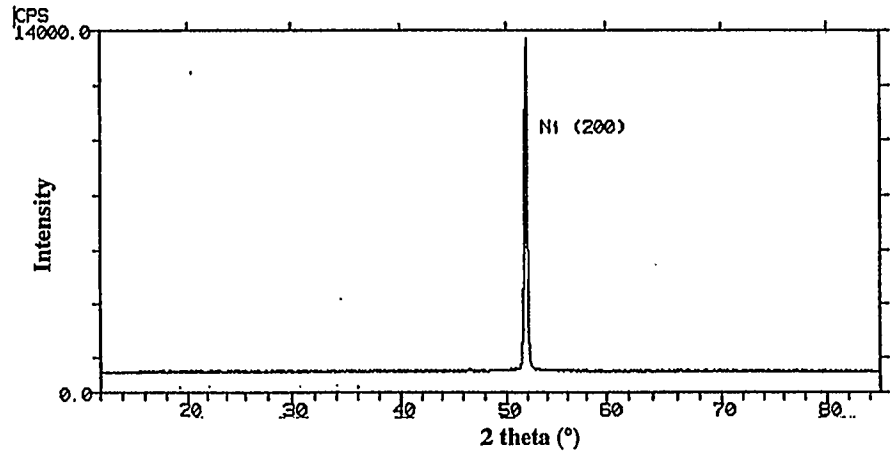
- **Textured Metal Substrate Fabrication**
  - Metal working techniques
- **Thin Film Buffer Layer Deposition**
  - Thermal Evaporation, Metal Organic Chemical Vapor Deposition (MOCVD)
- **YBCO Thin Film Deposition**
  - MOCVD

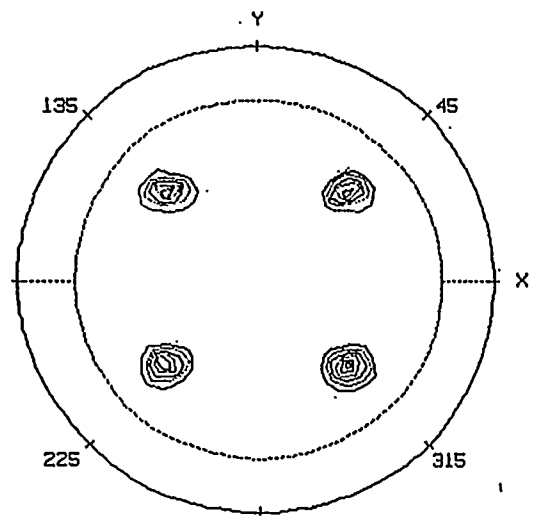
Biaxial Texturing of Metal Substrates

- Process involves heavy reductions in cross sectional area (> 90%) followed by recrystallization.
- The recrystallized metal develops a cube texture i.e. (100) along the deformation plane and [100] along the deformation direction.
- Ni, Cu and few other f.c.c. metals can be textured by this technique.

Cube-textured Metal Substrates for YBCO Conductor

- Biaxially-textured Ni and Ni composite substrates are routinely fabricated at IGC in lengths of several meters.
- The texture of the substrates is good enough to achieve Jc of 1 MA/cm^2 at 77 K



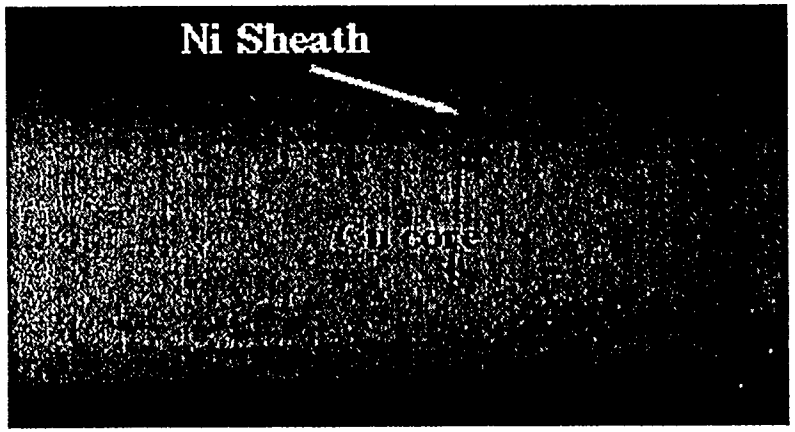


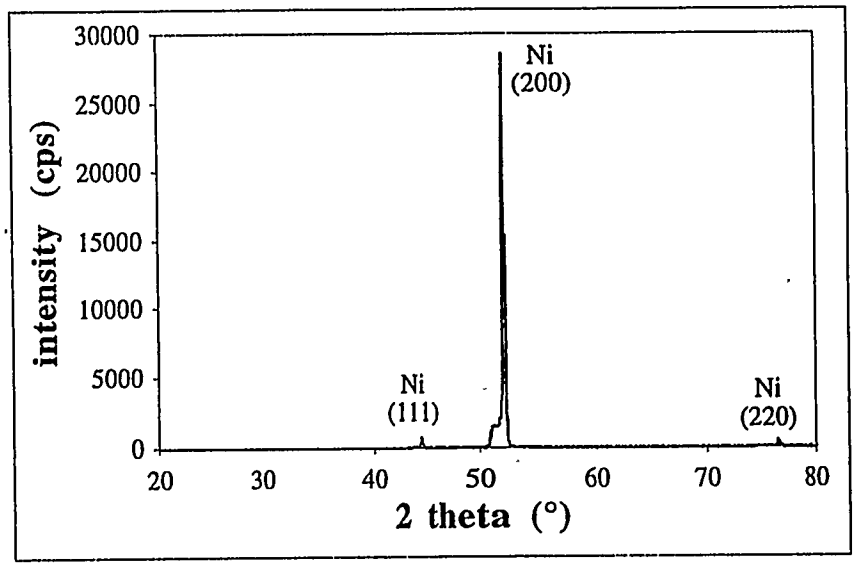
In Plane texture FWHM = 6°

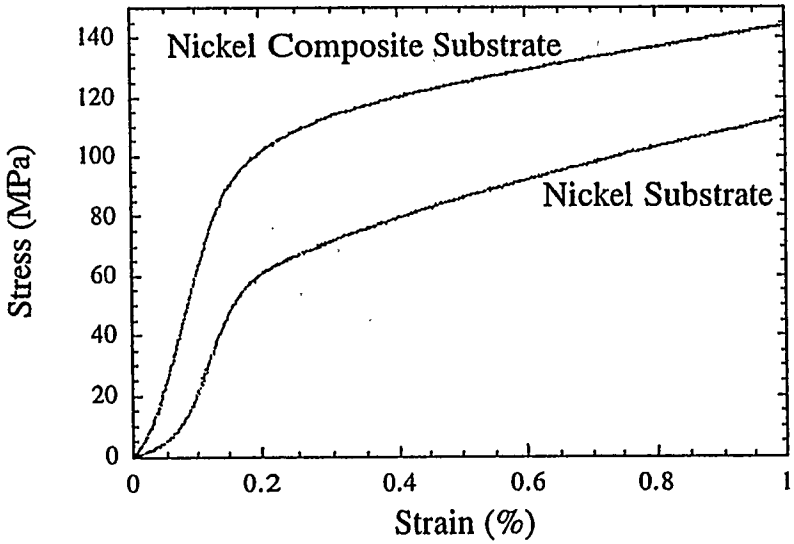
Cube-textured Nickel substrate

Improved Textured Metal Substrates

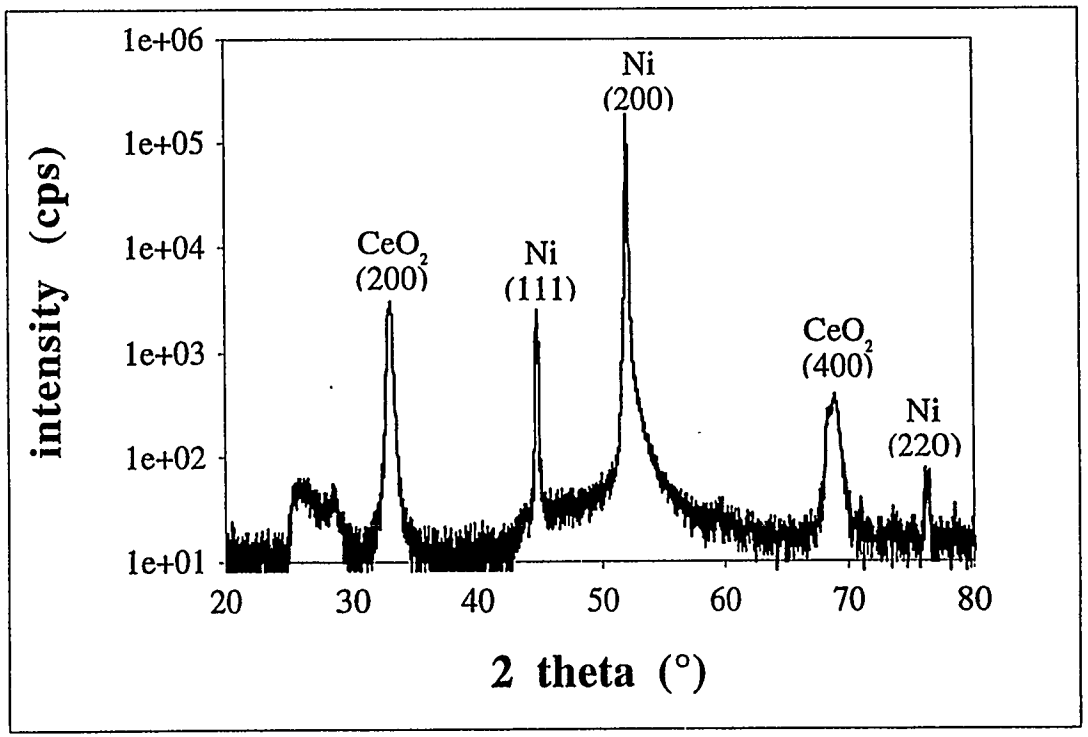
Composite, Biaxially-textured Metal Substrates have been fabricated with Improved Mechanical Properties

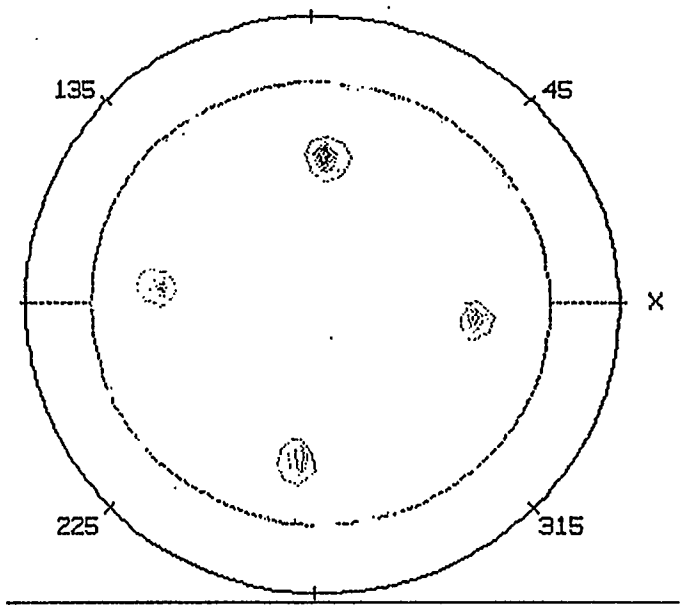






CeO_2 Buffer Deposition on textured Ni Substrate by Thermal Evaporation

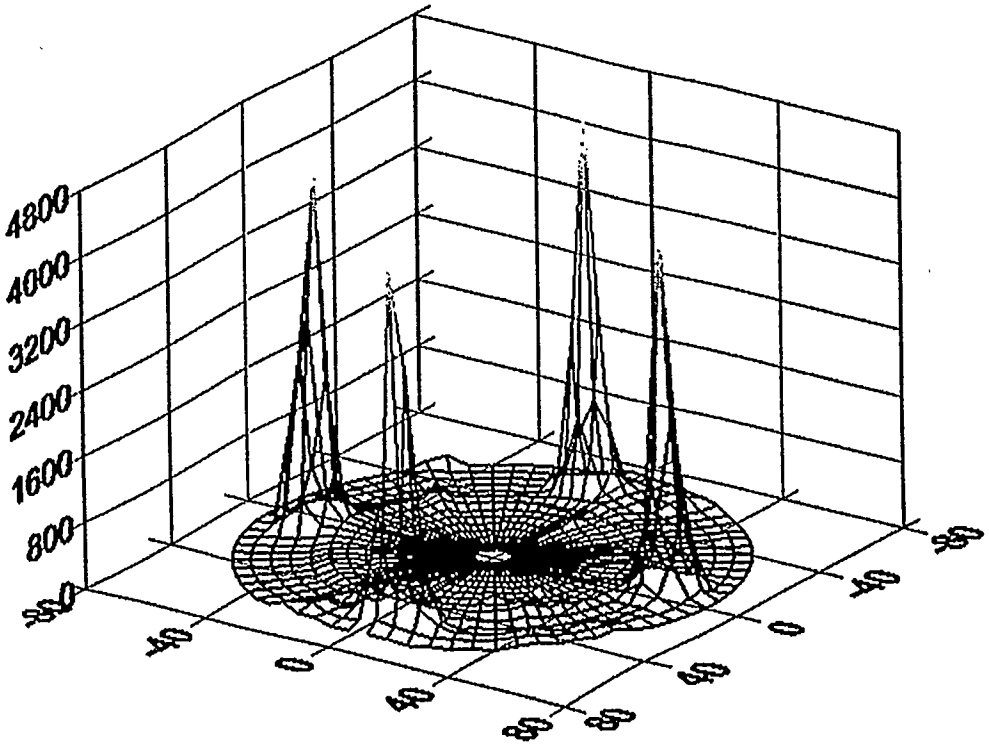


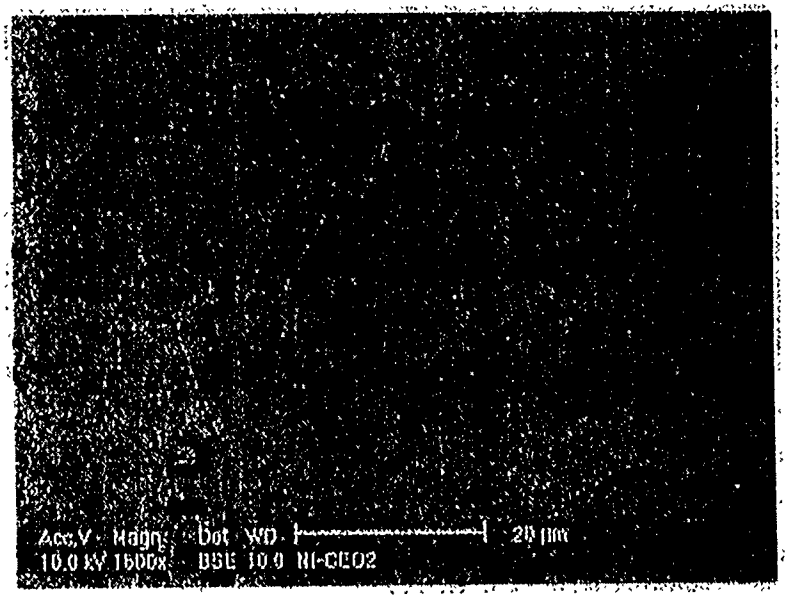


FWHM = 8°

Biaxially-textured CeO_2 buffer layer successfully deposited on cube-textured Ni substrate by thermal evaporation

Buffer Layer Deposition on Cube-textured Ni Substrates





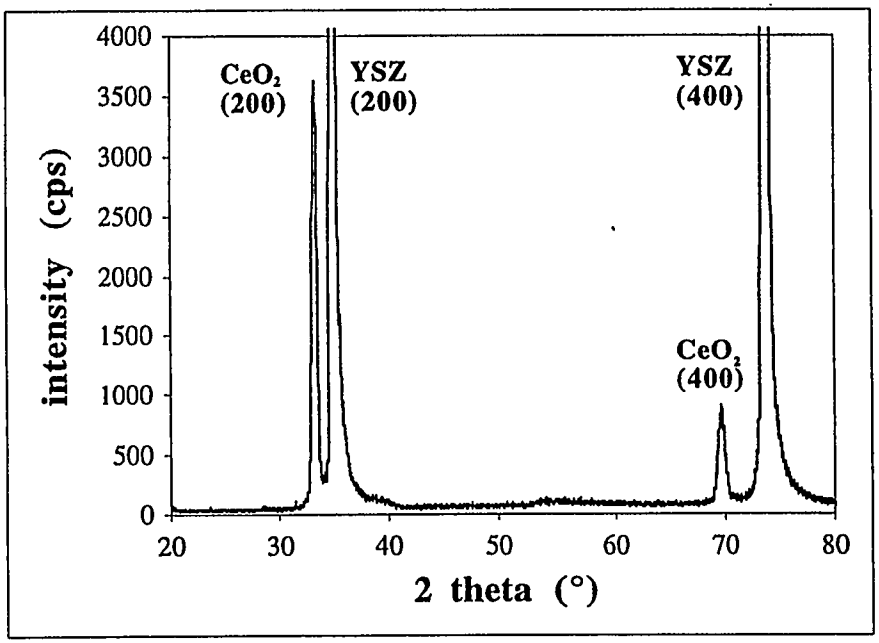
Biaxially-textured, dense, crack-free, 500 - 5000 A°thick CeO_2 buffer films deposited on cube-textured Ni substrates by thermal evaporation

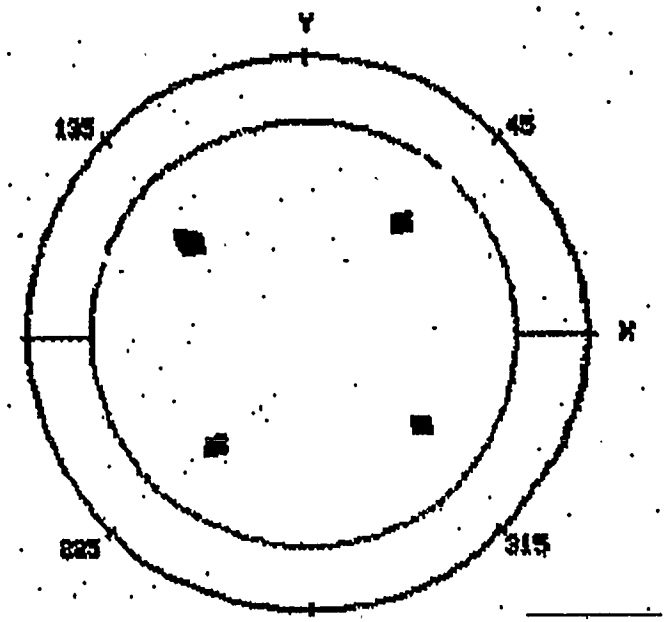
Solution Deposition of Buffer Layers

Metal Organic Deposition (MOD) :

Solution Coating of Metal Organic Precursors followed by Crystallization

Economical, High Rate Deposition Process





CeO_2 (111)

Highly biaxially-textured CeO_2 deposited by MOD on single crystal YSZ substrates

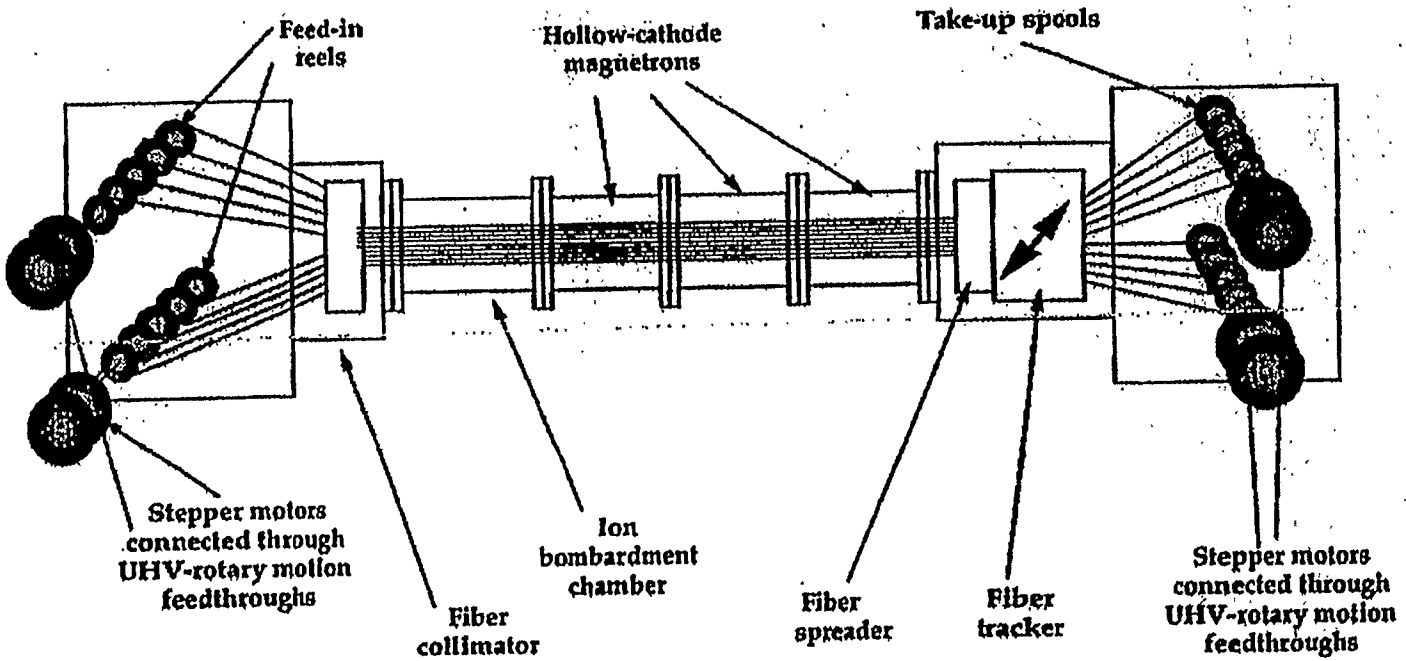
Buffer Deposition by R.F. Sputtering

Phase I DOE SBIR with UES Inc.

IGC : Provide Textured Metal Substrates to UES

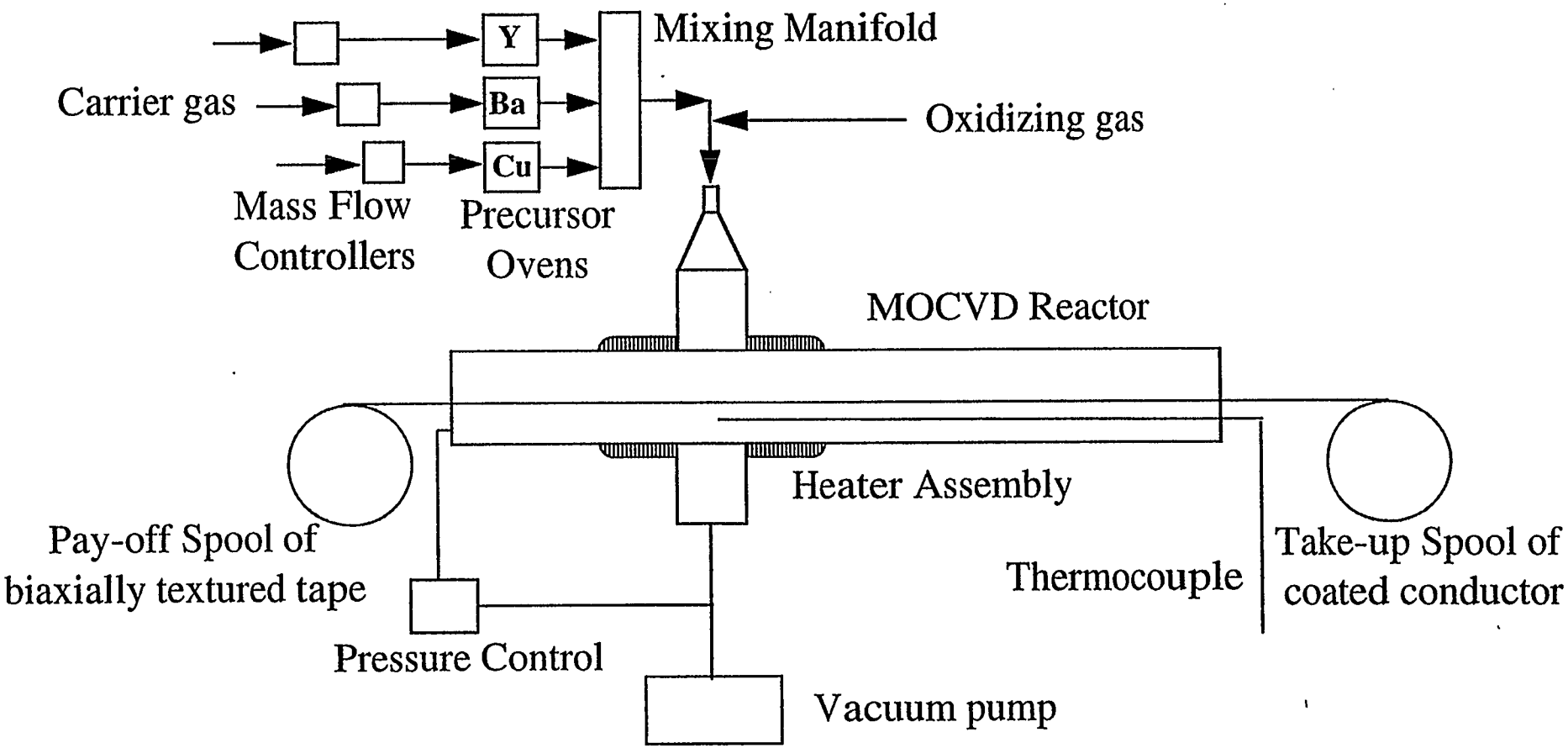
UES : Deposit Buffer Layers by R.F. Sputtering

IGC : Deposit YBCO by MOCVD

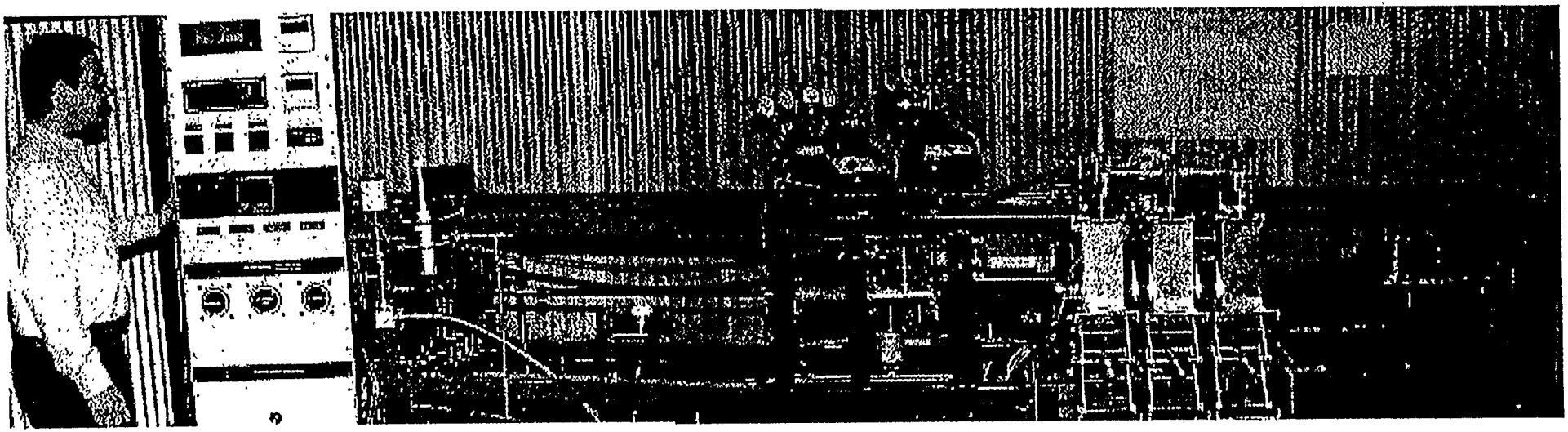


Continuous Hollow Cathode Magnetron Sputtering Facility at UES

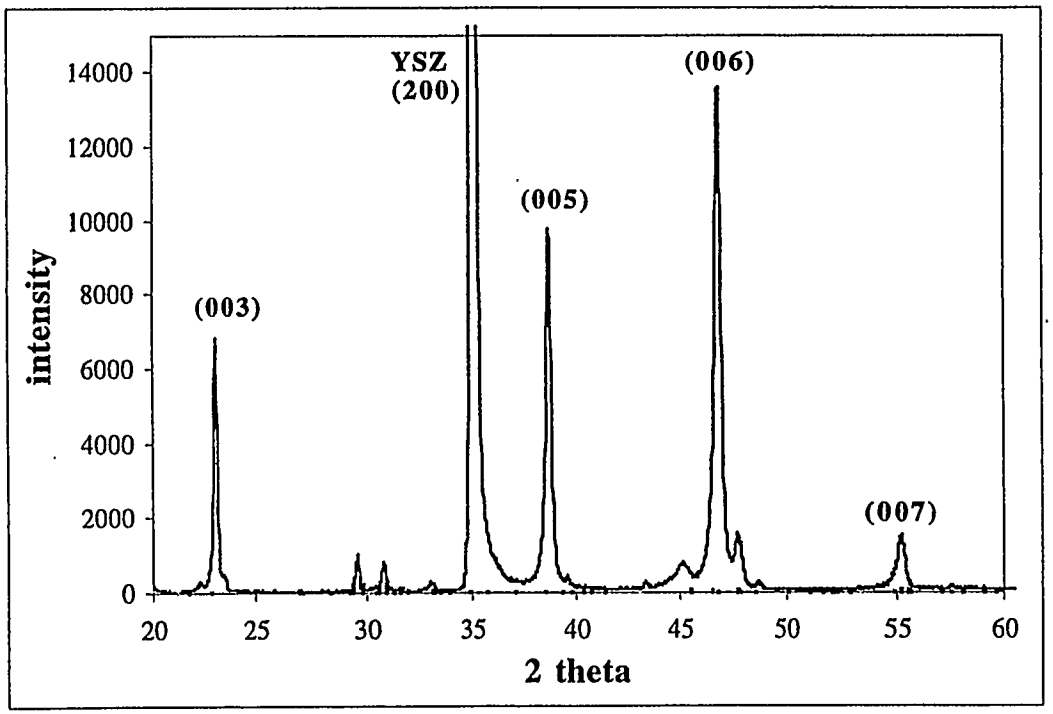
MOCVD Facility at IGC for YBCO Conductor Fabrication

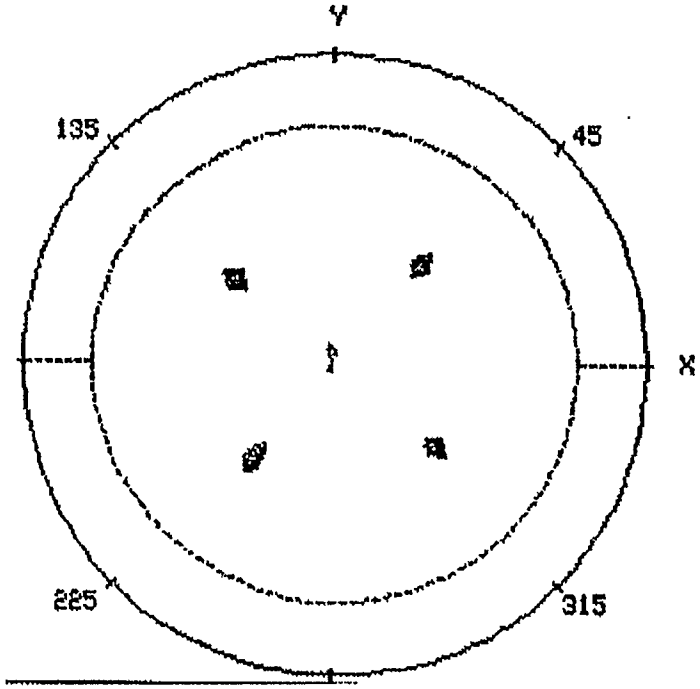


MOCVD Facility at IGC



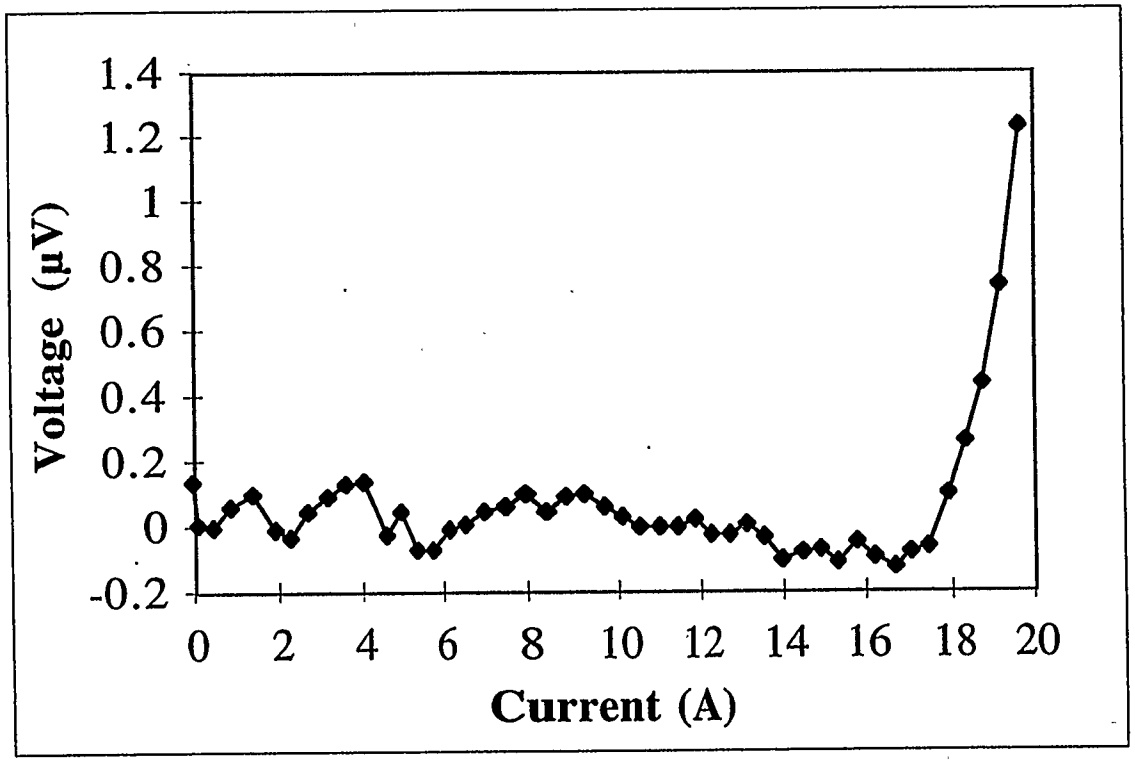
YBCO Deposition by MOCVD





Biaxially-textured YBCO successfully deposited by MOCVD on single crystal YSZ substrates

YBCO Deposition by MOCVD



Critical current of 18 A achieved in YBCO deposited by MOCVD on single crystal YSZ substrate

INTERMAGNETICS GENERAL CORPORATION

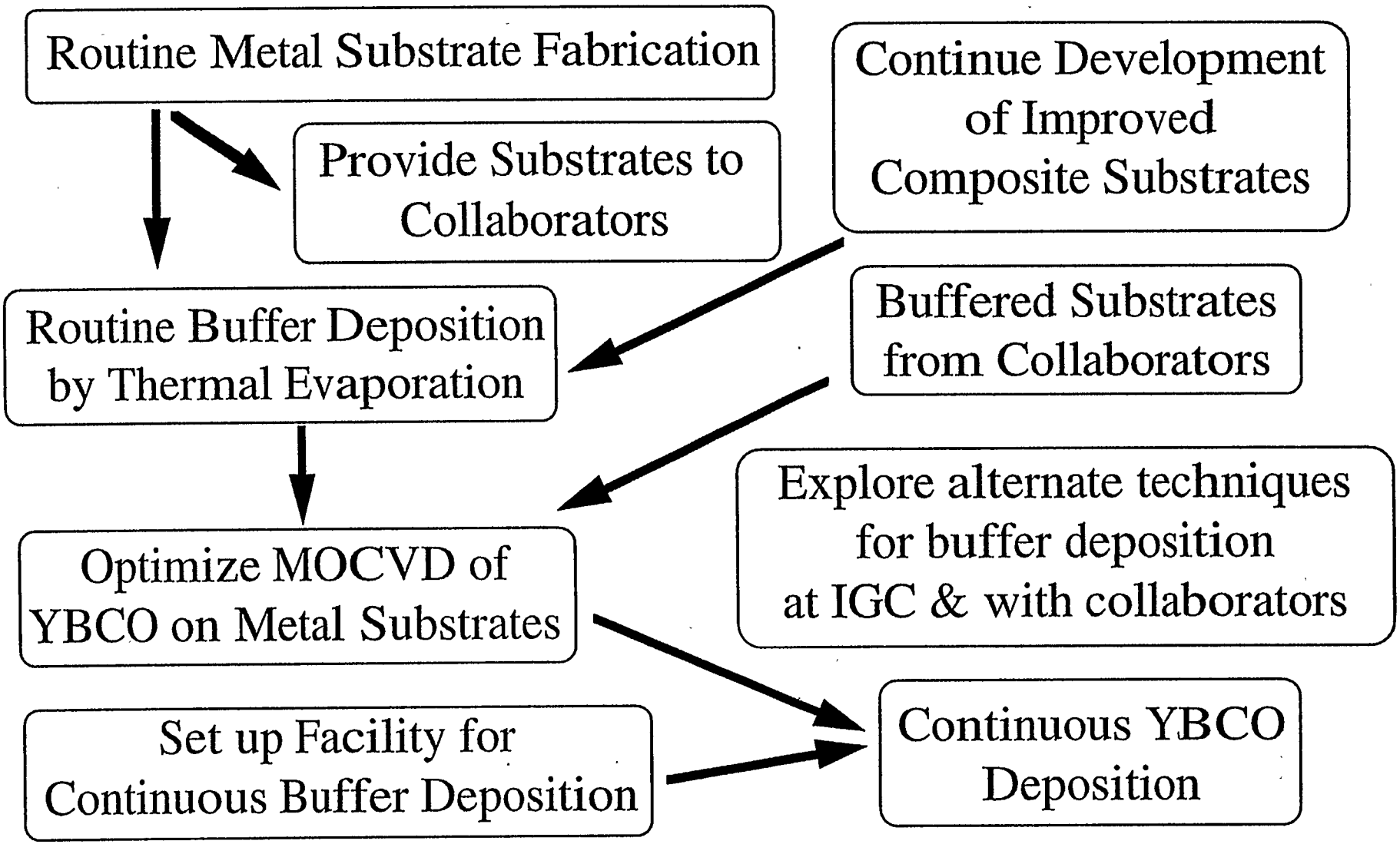
High Temperature Superconductors

Cost Comparison of PIT Bi-2223 & YBCO Conductor

(Projected 3 to 5 years)

	PIT BSCCO	MOCVD YBCO
Production rate (km/yr)	100	100
Labor cost ($/m)	5.0	2.0
Precursor cost ($/m)	1.5	1.8
Metal cost ($/m)	2.5	0.2
Total cost ($/m)	9.0	4.0
Critical current at 77 K (A)	50	200
Conductor cost ($/kA-m)	**180**	**20**

Ongoing & Future Efforts



MicroCoating Technologies

3901 Green Industrial Way
Chamblee, GA 30341
(770) 457-8400

Low Cost, Open Atmosphere Combustion Chemical Vapor Deposition of Superconductor Related Materials on Single Crystals

Shara Shoup
Andrew Hunt
Subu Shanmugham

E-mail: mct@ccvd.com
http://www.mindspring.com/~mct

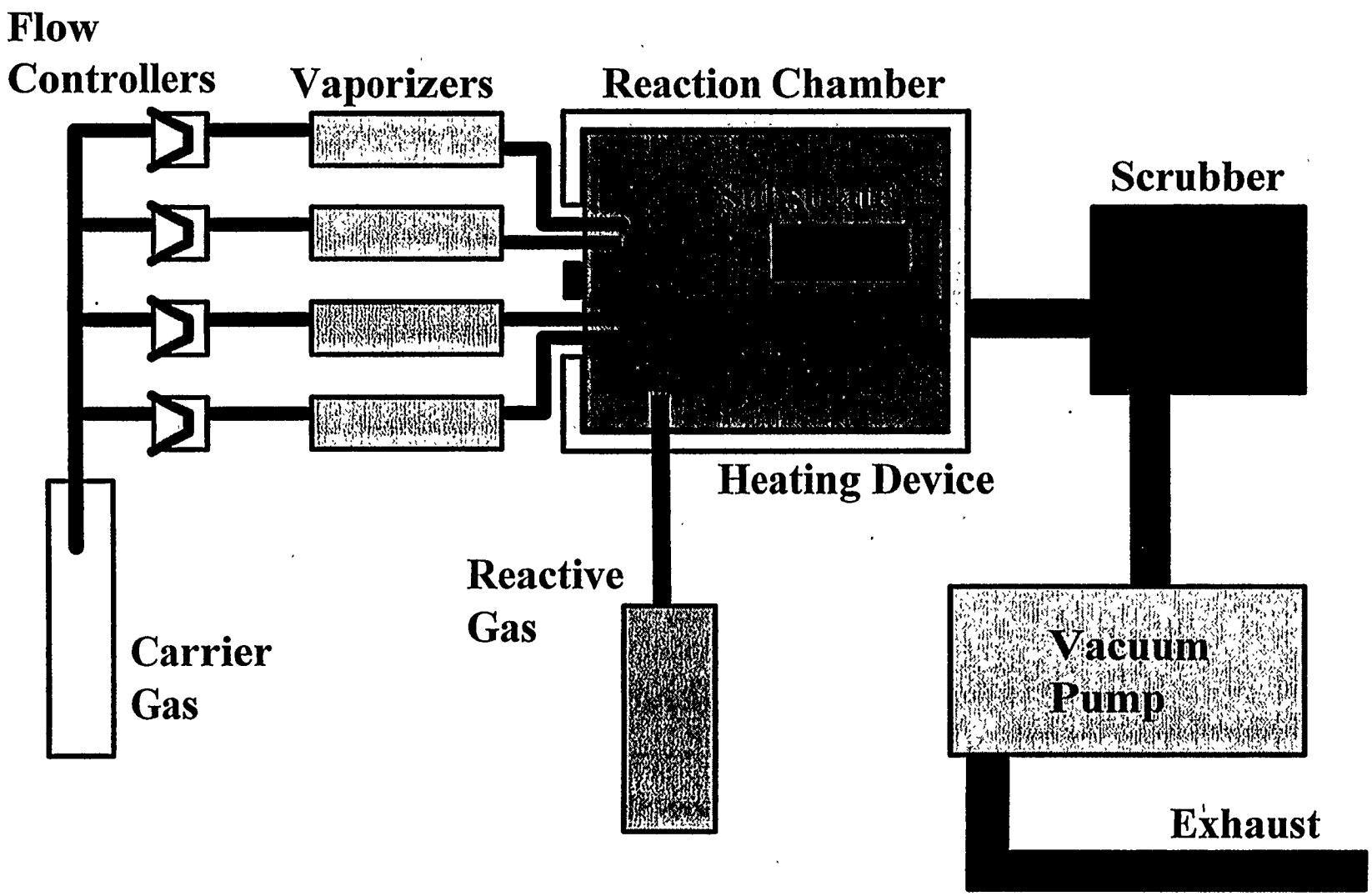
Presentation Overview

- Brief Introduction to the CCVD Technique.
- Cost Projections.
- YBCO Project.
- Buffer Layers Project.
- Conclusions.

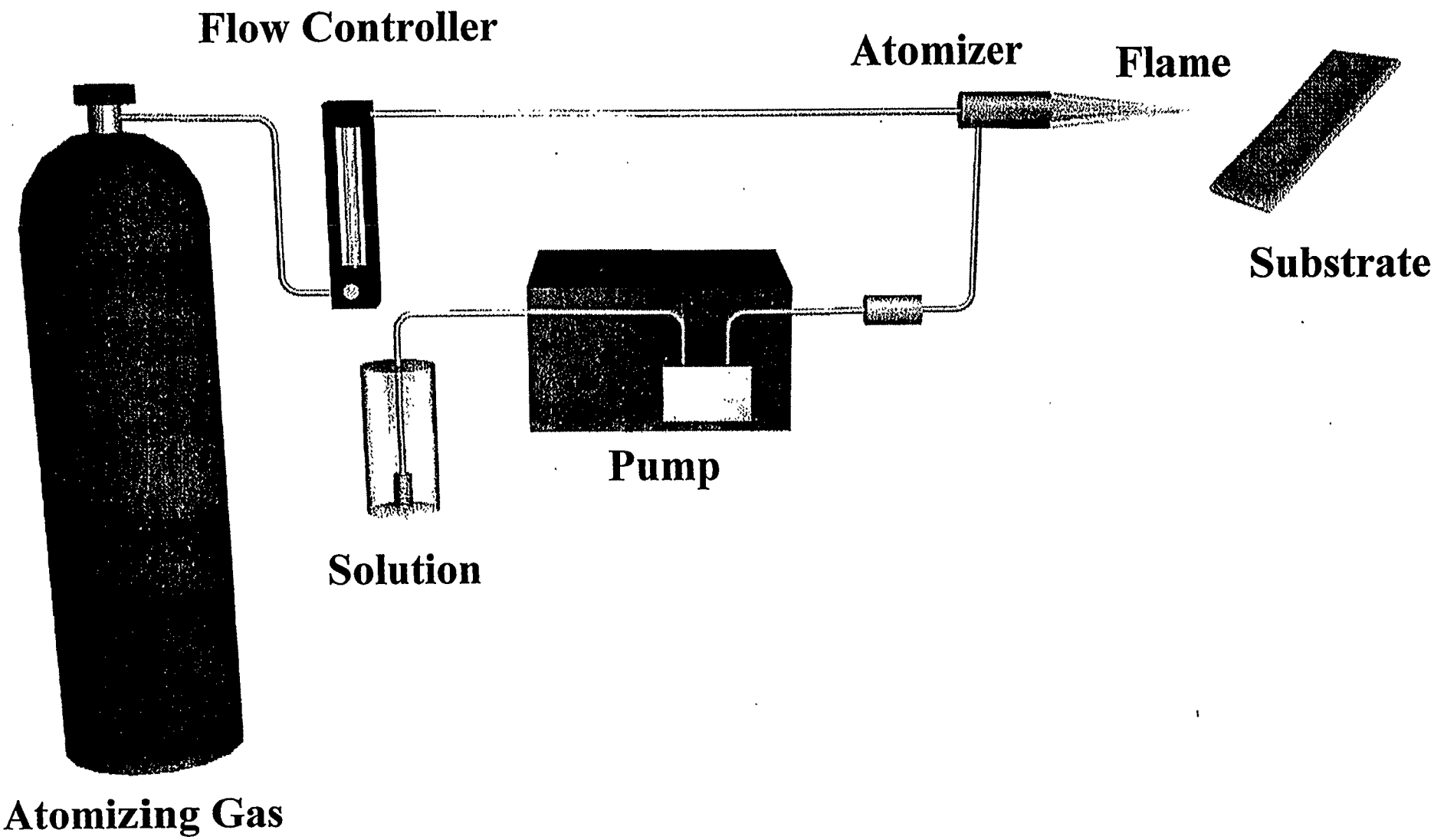
CCVD Technical Top Ten List

- Deposits very thin films, <10 nm, to thick films > 5 μm.
- Controls density/porosity.
- Enables high compositional control and multi-layering.
- Deposits onto complex/large substrates - Not line of sight.
- Allows substrate temperatures less than 100°C.
- Offers *in situ* capability.
- Forms epitaxial and preferred growth films
- Avoids use of high vapor pressure precursors.
- Enables up to 1 μm/min dense oxide coatings.
- Facilitates quick development cycles.

Traditional CVD System



CCVD System


Flow Controller
Atomizer
Flame
Substrate
Pump
Solution
Atomizing Gas

Deposition Summary

Materials Deposited

Metals	Ceramics	Other
Ag, Au, Cu, Ir, Mo, Ni, Pt and Rh	Al_2O_3, Doped-Al_2O_3, Al_2O_3/MgO, $3A_{12}O_3/2SiO_2$, $BaCeO_3$, $BaTiO_3$, BST, $Ce_8Zr_{12}O_2$, Cr_2O_3, $[La_{0.95}Ca_{0.05}]CrO_3$, Cu_xO, DLC, Fe_2O_3, In_2O_3, ITO, LSC, LSM, MgO, MnO-Pt, MnO_2, MoO_3, Nb_2O_5, NiO, NSM, $PbTiO_3$, PdO, PLZT, PMN, PMT, PNZT, PZT, RbO_x, RhO_x, RuO_2, SiO_2, Silica Glasses, Doped-SnO_2, $SrLaAlO_4$, $SrTiO_3$, Ta_2O_3, TiO_2, V_2O_3, $YBa_2Cu_3O_x$, YIG, YSZ, YSZ-Al_2O_3, YSZ-Ni and ZrO_2, fully and partially stabilized ZrO_2 (dopants: Y, Ce, Al)	$BaCO_3$, $LaPO_4$ and $PbSO_4$

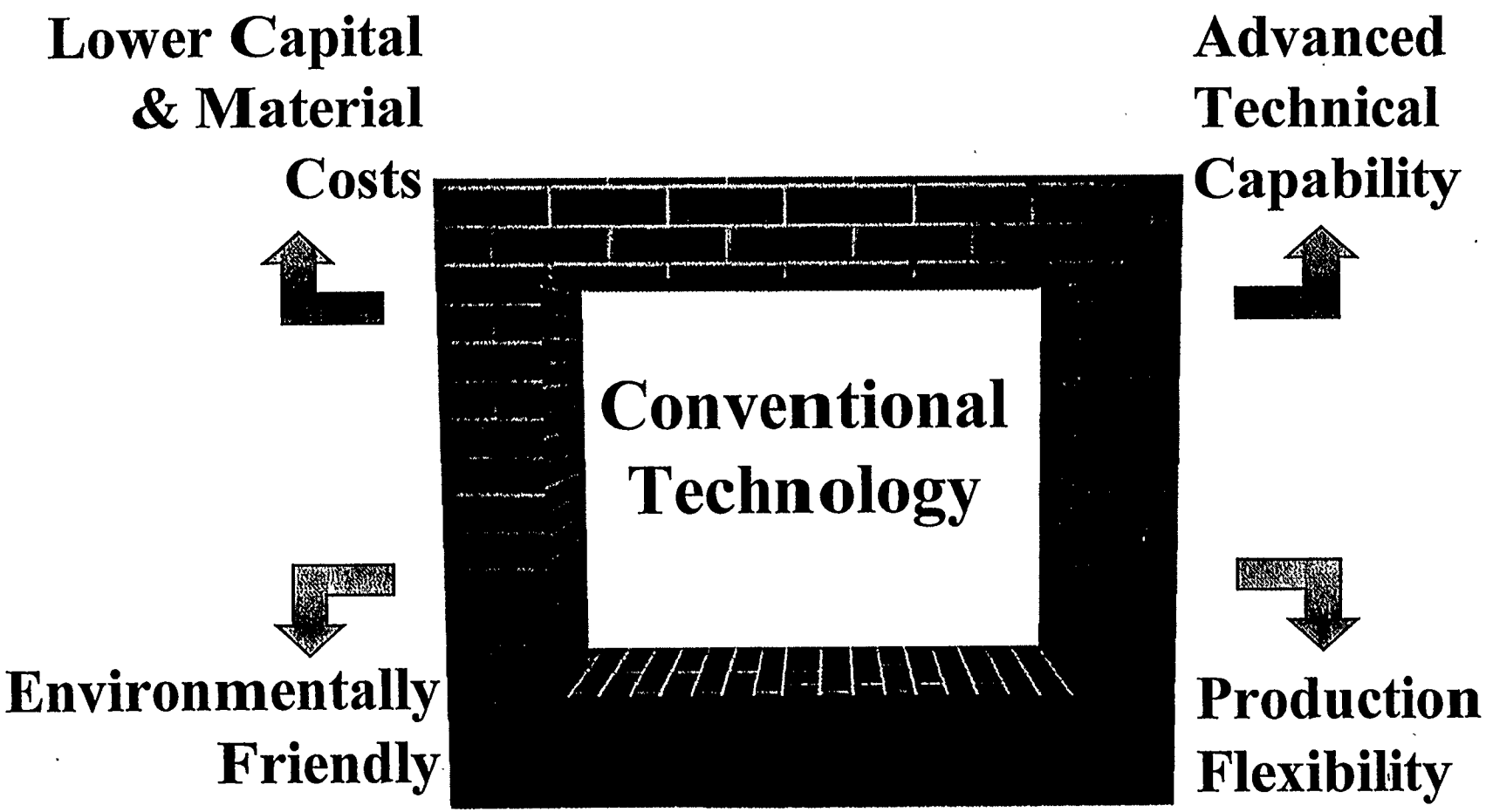
Substrates Used

Al, Brass, Ag, Cu, Pt, Ni, Stainless and C-Steel, Al_2O_3, Fiber Tows, Glass, Graphite, $LaAlO_3$, MgO, Nafion™, NiCr, Optical Fibers, Polycarbonate, Silica, Si, Si-Ti/Pt Wafers, SiC, Si_3N_4, Super Alloys, Teflon™, Ti, TiAl Alloy and YSZ

Possible Applications

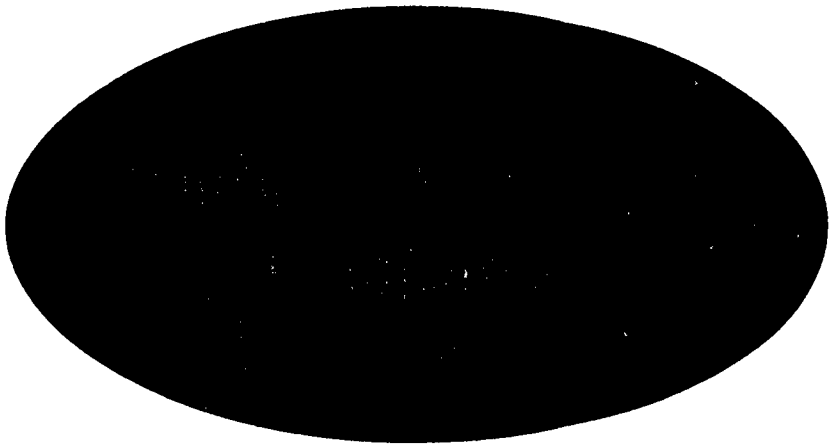
Architectural finishes, capacitors, catalytic, corrosion resistance, electronics, engines, ferroelectric, FGM, fuel cells, integrated circuits, optical, piezoelectric, replacement for nickel plating, superconducting, thermal barrier, thermal control material, wear resistance

Outside the Bounds of Conventional Technology

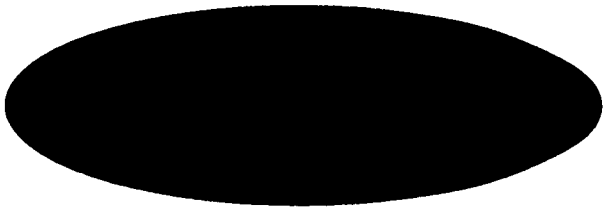


Capital Cost Savings

Traditional thin film technology equipment cost significantly more than CCVD equipment



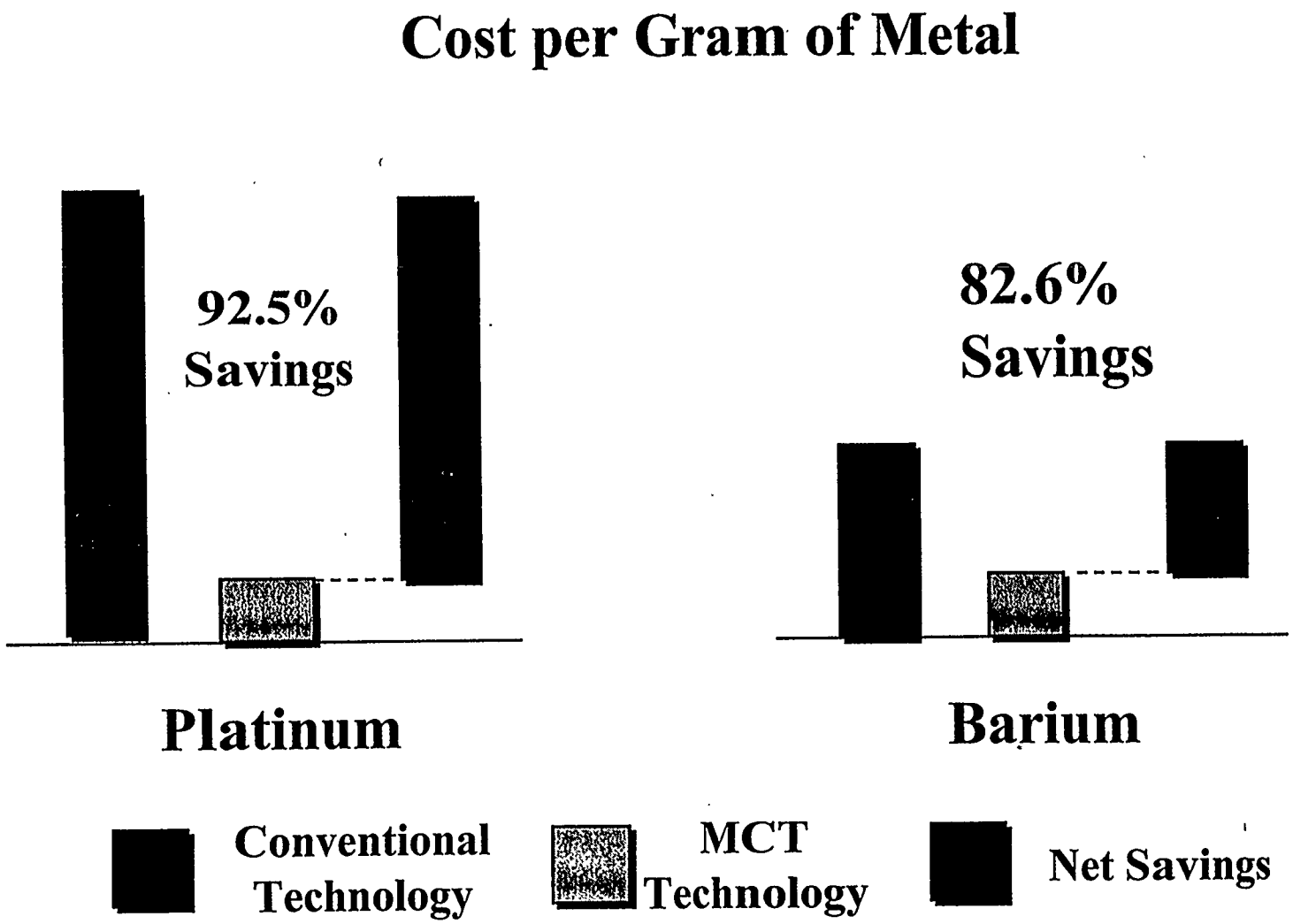
$500,000 - $20,000,000



$100,000 - $1,000,000

235

Chemical Cost Savings



Commercial Viability of CCVD for HTSC Applications

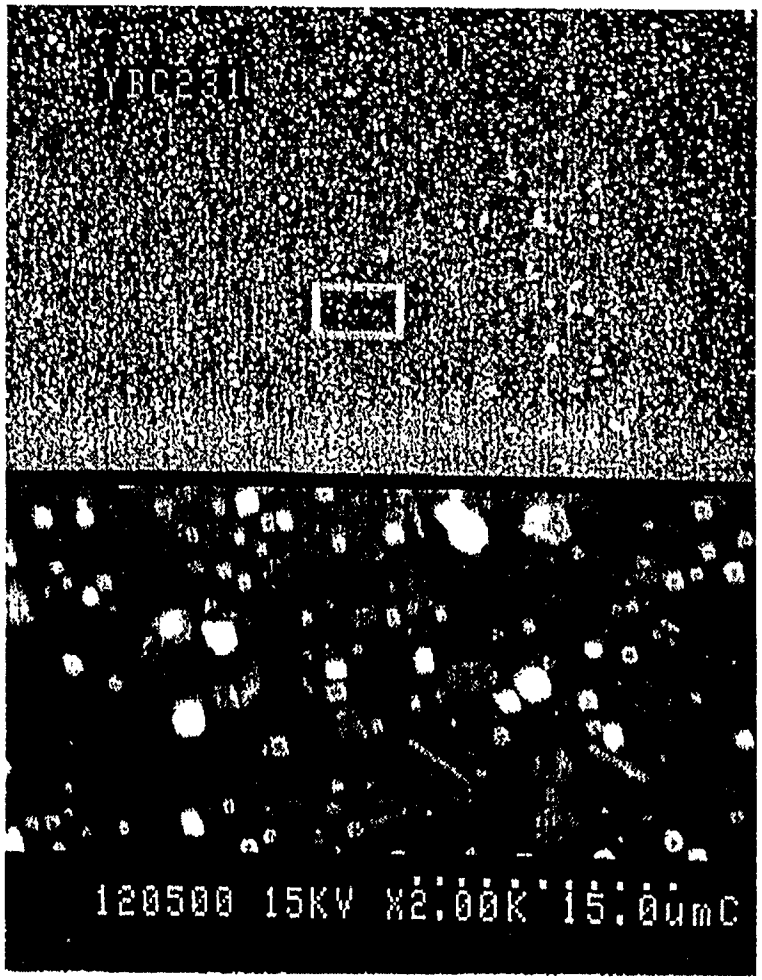
- Cost analysis was performed for production-scale YBCO and buffer layer coatings.
- Analysis included all direct costs (labor, chemicals, etc.), overheads, depreciation, maintenance, and cost of capital.
- Based on targets set at the DOE Superconductor Workshop '97, CCVD will be economically viable for nearly all applications.

Goal for the DOE SBIR Phase I YBCO Project

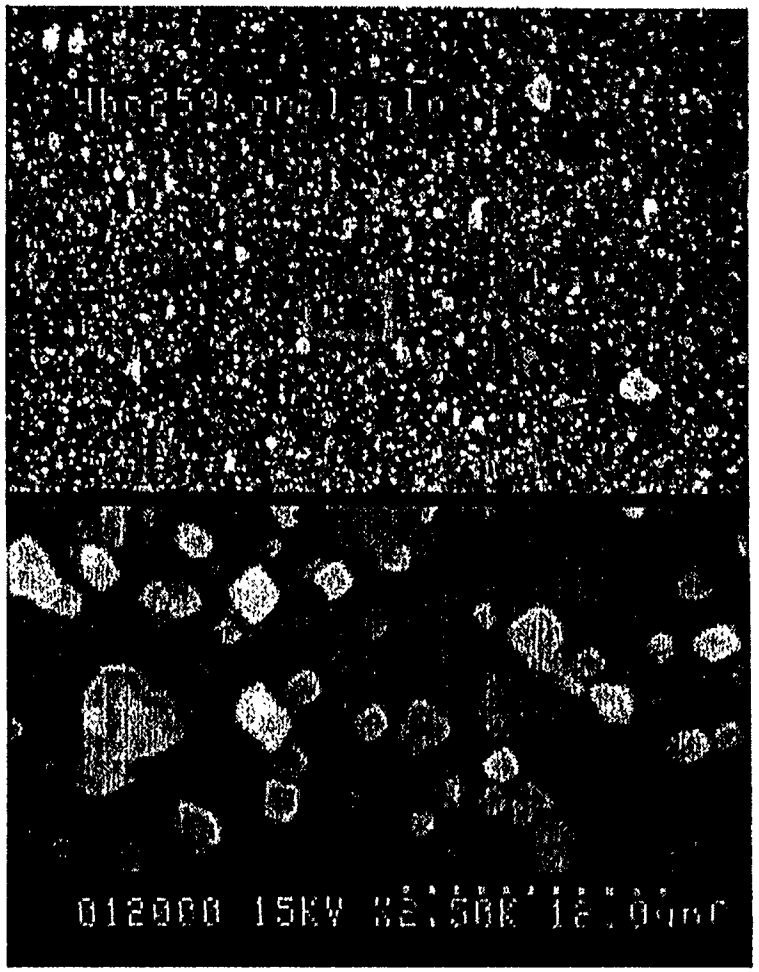
"For the six month Phase I effort, we propose to utilize the CCVD technique:

- To deposit inexpensively high quality undoped or doped CCVD YBCO epitaxial coatings on single crystal substrates (such as $LaAlO_3$) and RABiTS with a predeposited CeO_2/YSZ buffer layer."

Dense CCVD YBCO Coatings Were Deposited on MgO and $LaAlO_3$ Substrates

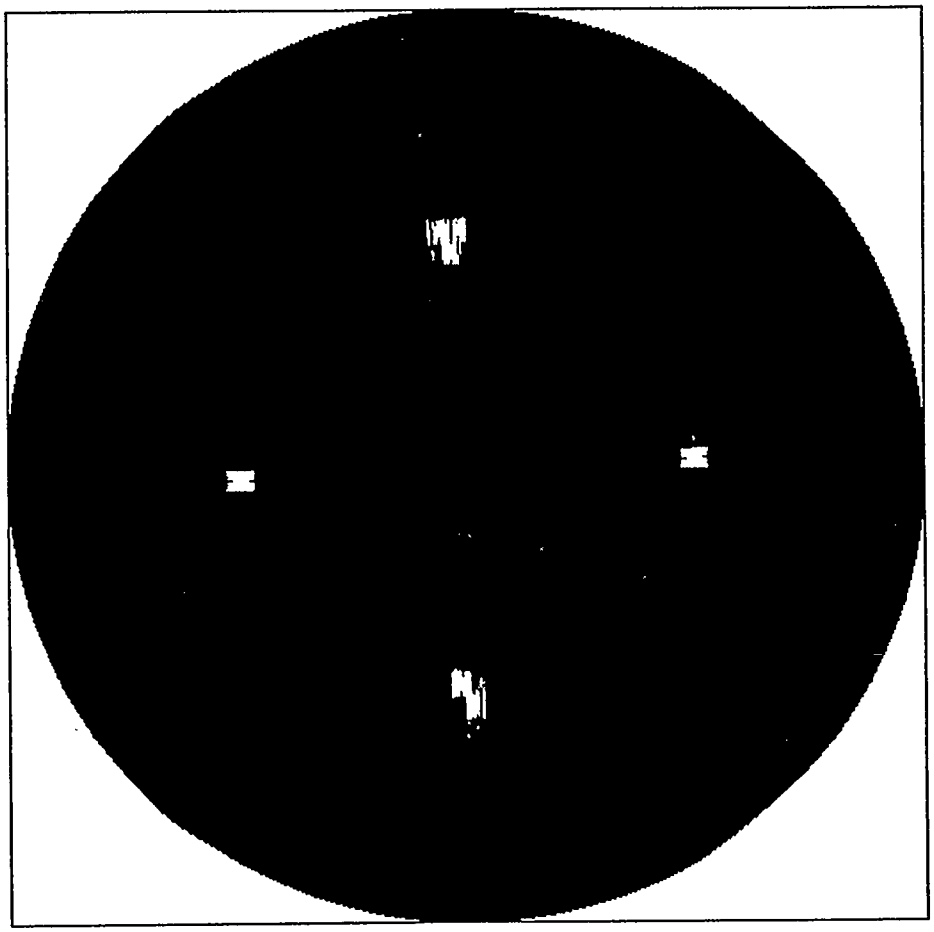


YBCO on MgO



YBCO on $LaAlO_3$

YBCO Pole Figure of a [103] Reflection on a (100) $LaAlO_3$ Substrate Shows Single In-Plane Epitaxial Orientation

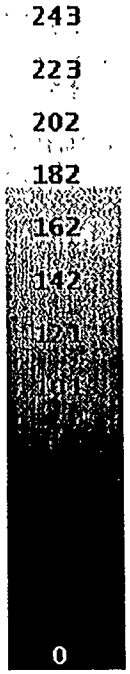


Pole Figure at 2theta: 32.

d:\subu\pybc232.dat
12/09/97 16:48:52
Created 12/08/97
Mag,Quad 1 0
Phi .0000
Width 5.000
Counts 261420
Time (s) 615.00
Distance 5.800
Size 512

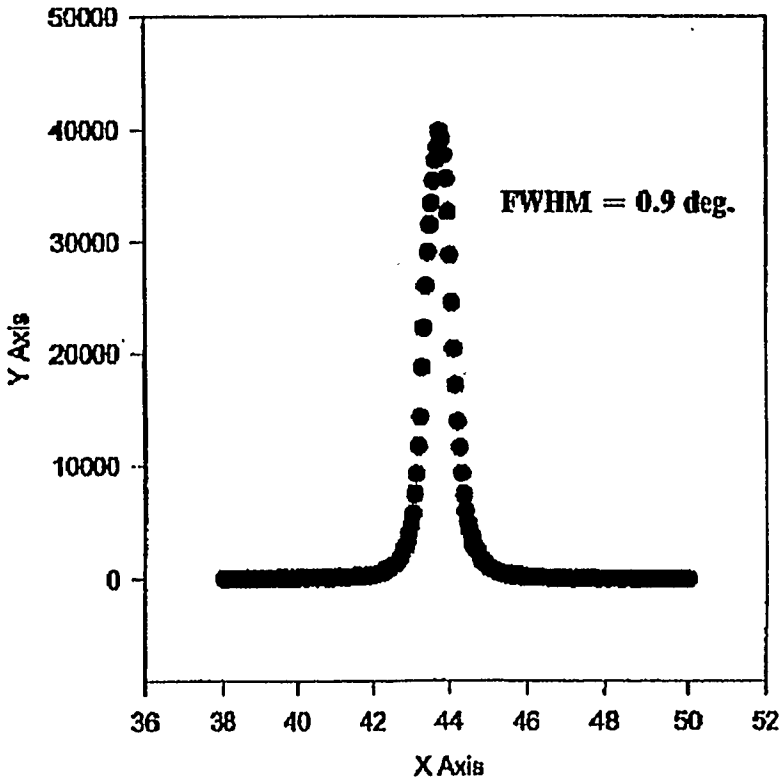
Seconds: 602

2Theta 45.000
Omega 12.000
Phi .000
Chi 54.740
Shutter CLOSED
Distance 5.800
FloodFld HL091097
Spatial HL091097
1024x1024 Cu Bias

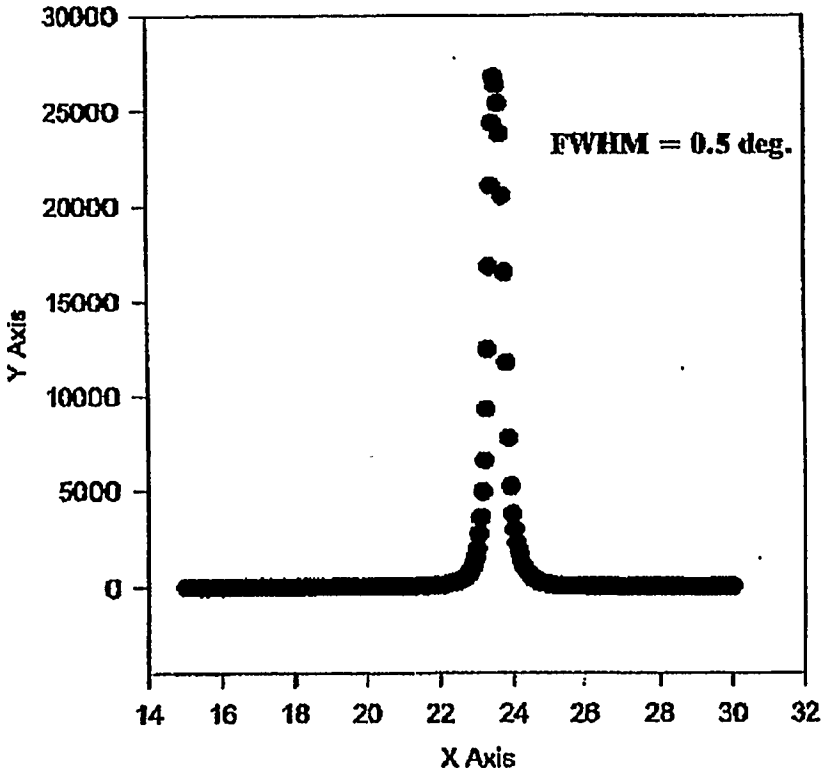


As-Deposited CCVD YBCO Coating

The In-Plane and Out-of-Plane Orientation of the CCVD Applied YBCO Coating is One of the Best Results of Any Vapor-Based Technique

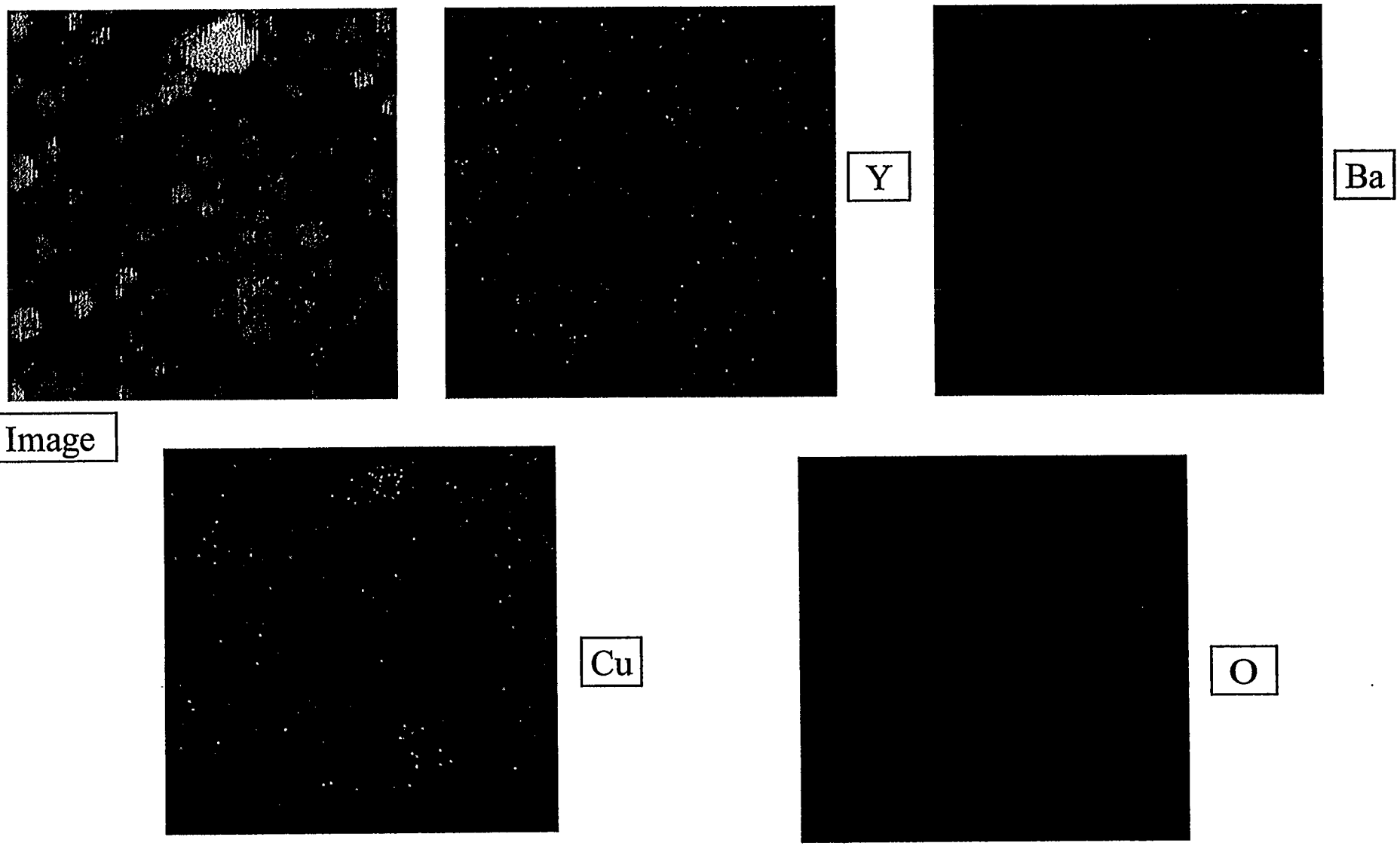


(103) phi scan: In-Plane



(006) Omega scan: Out-of-Plane

X-ray Mapping Study Indicates That the YBCO Coatings Were Relatively Uniform



Goals for the DOE SBIR Phase I Buffer Layer Project

"For this 6 month Phase I effort, we propose to utilize the CCVD technique to:

(1) develop a low cost coating procedure for biaxial textured buffer layers on single crystal substrates, such as $LaAlO_3$ and YSZ;

(2) develop and demonstrate a low cost coating procedure to obtain epitaxial ceria and YSZ deposits on a textured Ni substrate; and

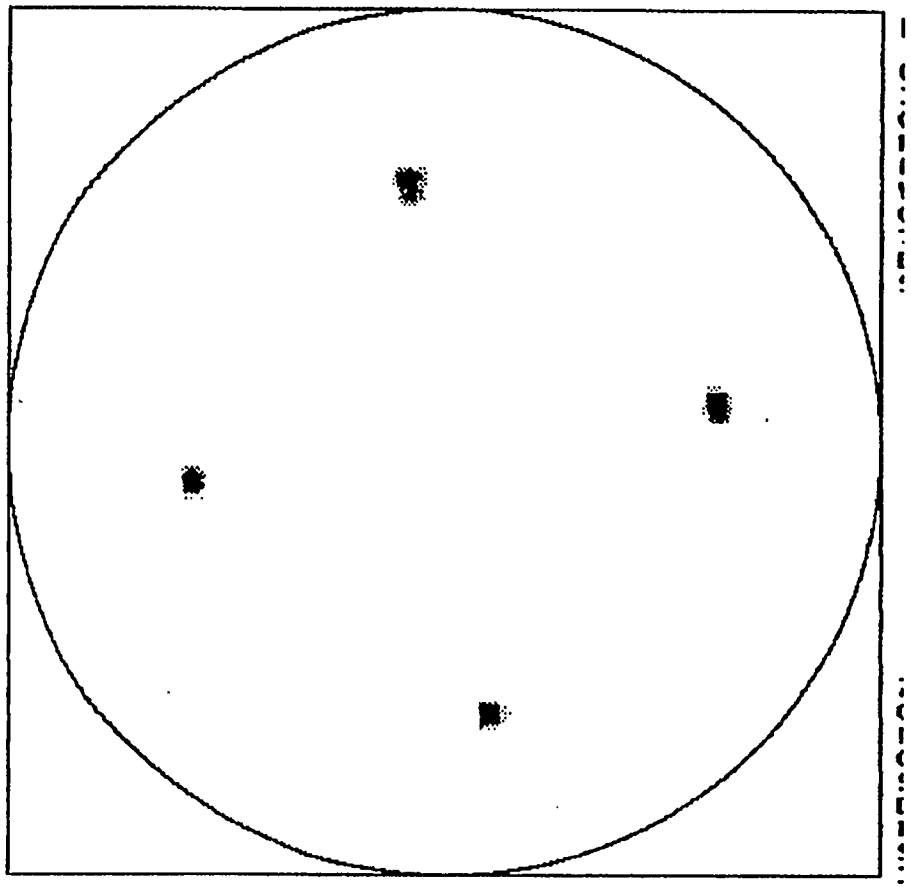
(3) conduct microstructural and texture analysis on the coated RABiTS."

CCVD Buffer Layers are Highly Aligned on Single Crystals

	In-Plane (FWHM):	Out-of-Plane (FWHM):
	(220)	(200)
CeO_2 on $LaAlO_3$	$2.45^o \pm 0.05$	$1.688^o \pm 0.006$
YSZ on $CeO_2/LaAlO_3$	$3.37^o \pm 0.01$	$2.37^o \pm 0.01$
	(110)	(200)
$SrTiO_3$ on MgO	$2.020^o \pm 0.004$	$1.67^o \pm 0.01$

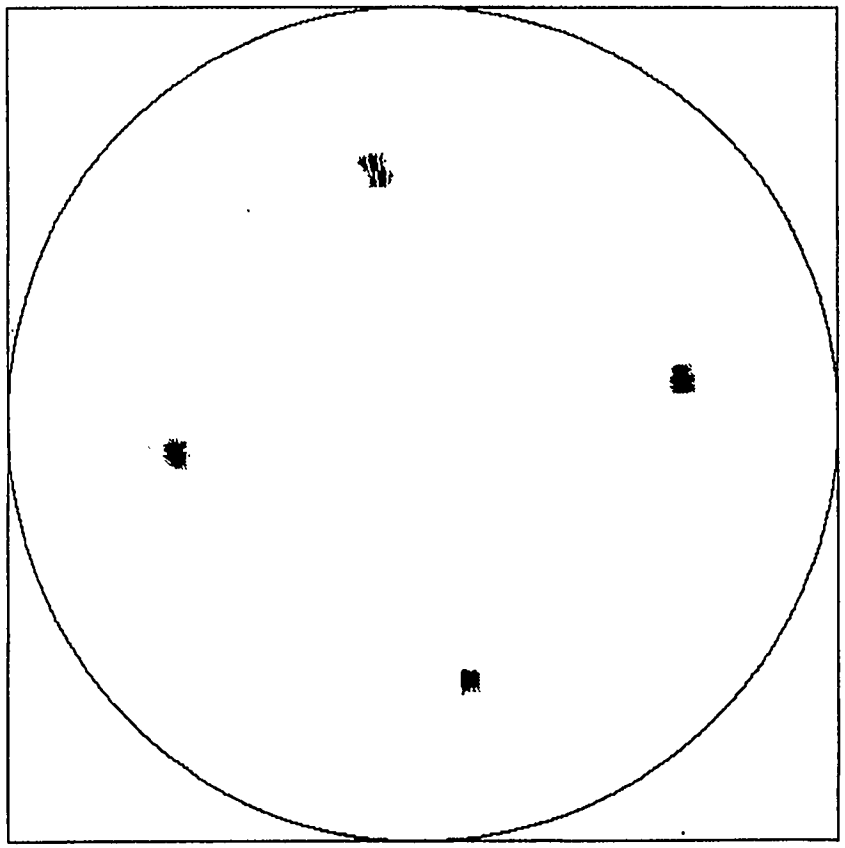
Analysis Compliments of ORNL, M. Paranthaman

(111) Pole Figure of CeO_2 on (100) $LaAlO_3$ Shows 1 Epitaxial Relationship

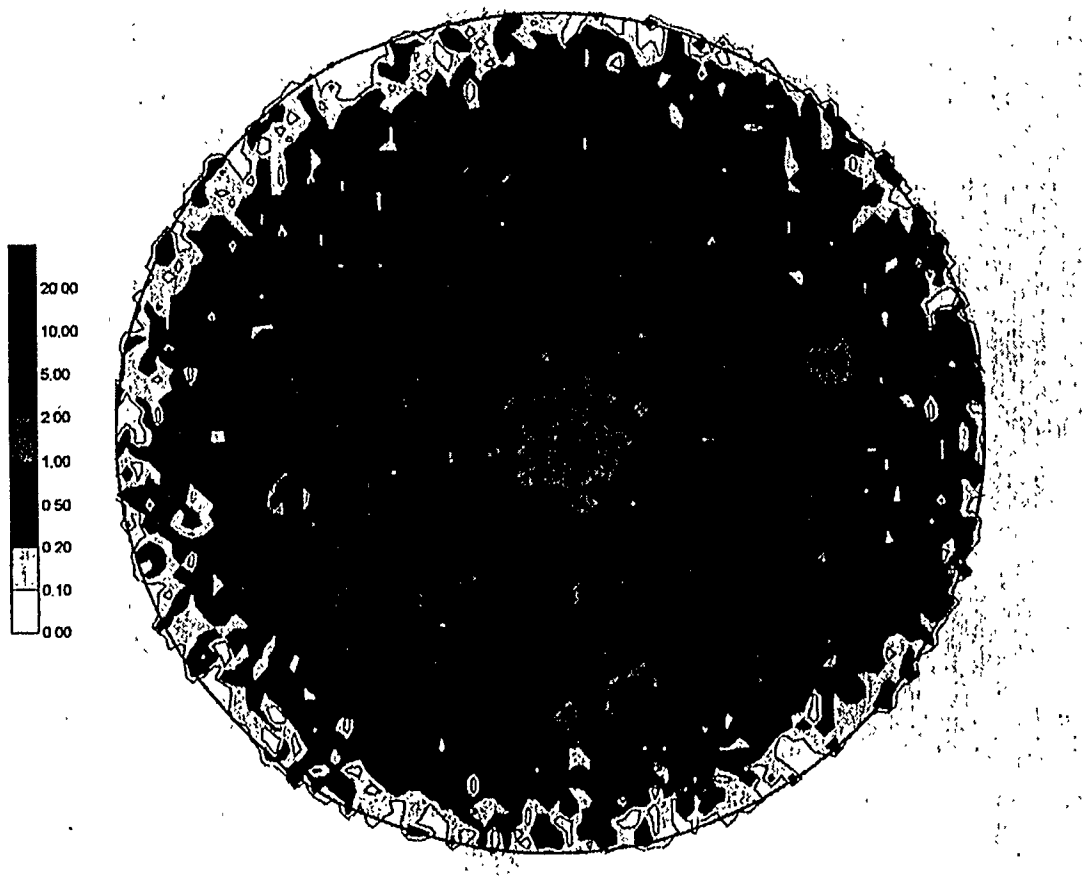


245

(111) Pole Figure of YSZ on CeO_2(CCVD)/$LaAlO_3$ Shows 1 Epitaxial Relationship



(111) Pole Figure of $SrTiO_3$ on (100) MgO Shows 1 Epitaxial Relationship

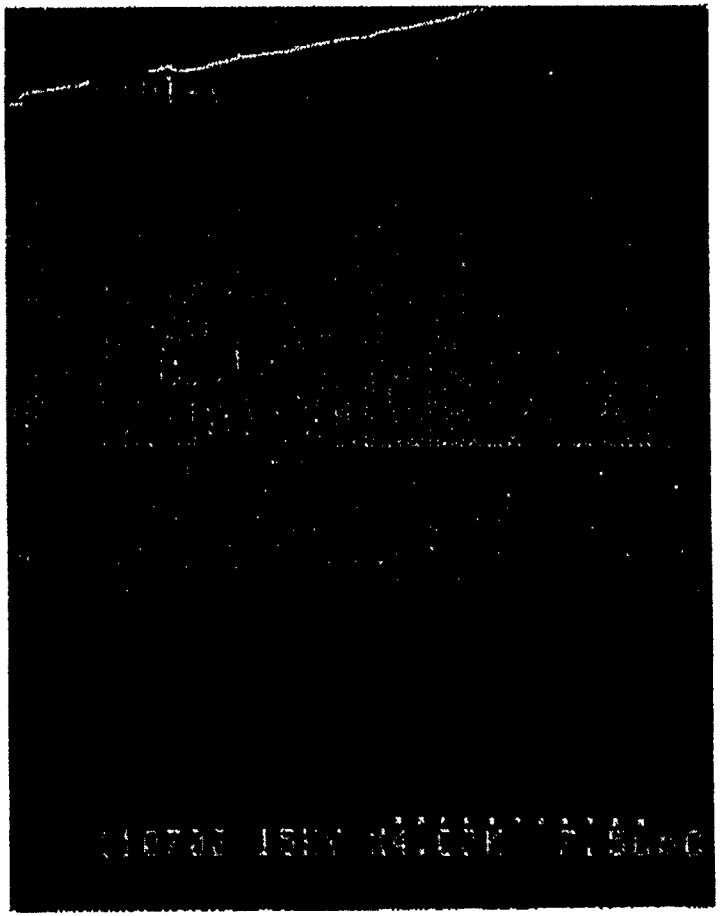


Compliments of ORNL, M. Paranthama

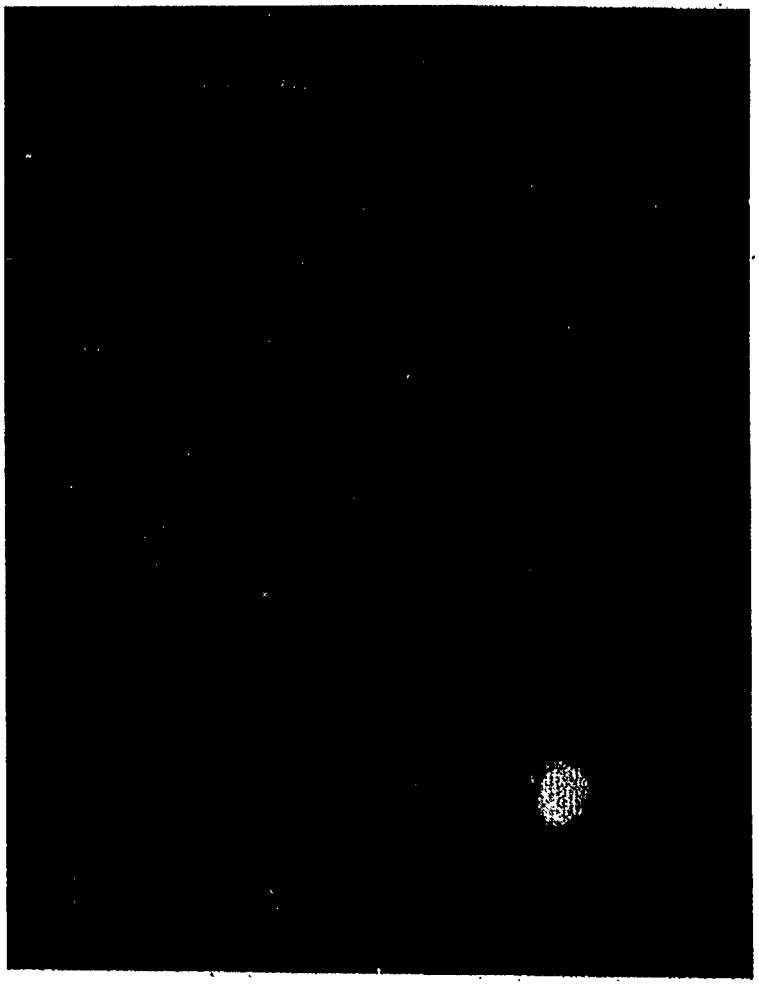
247

Smooth, Dense, and Continuous Buffer Layer Films Can Be Deposited By CCVD

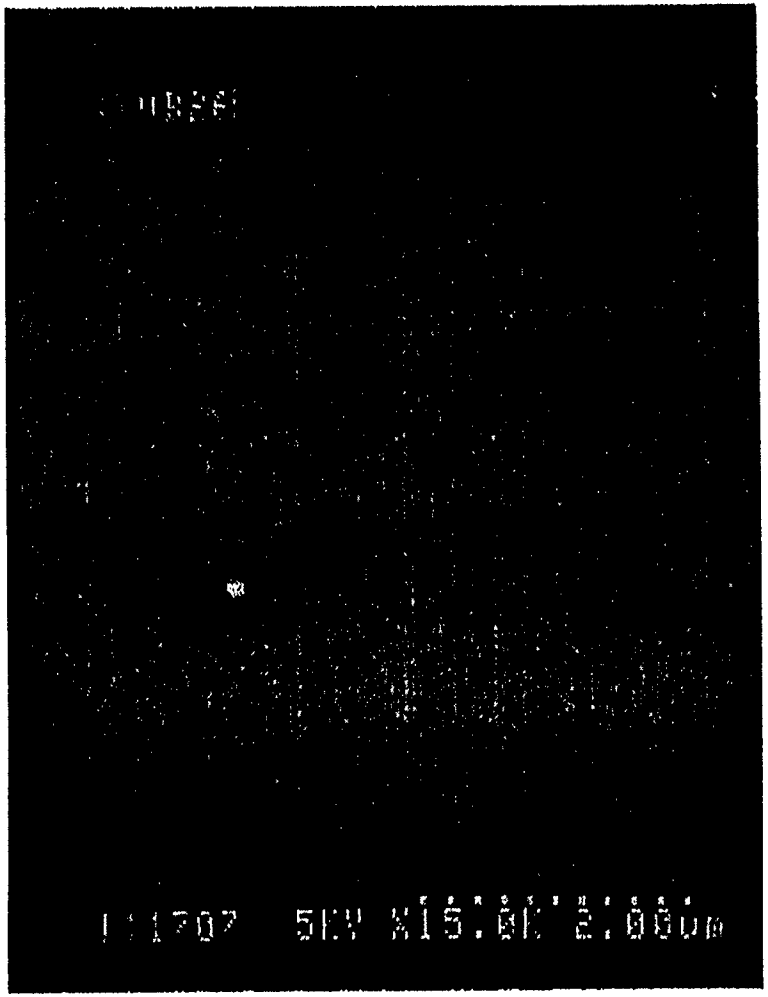
CeO_2 on MgO



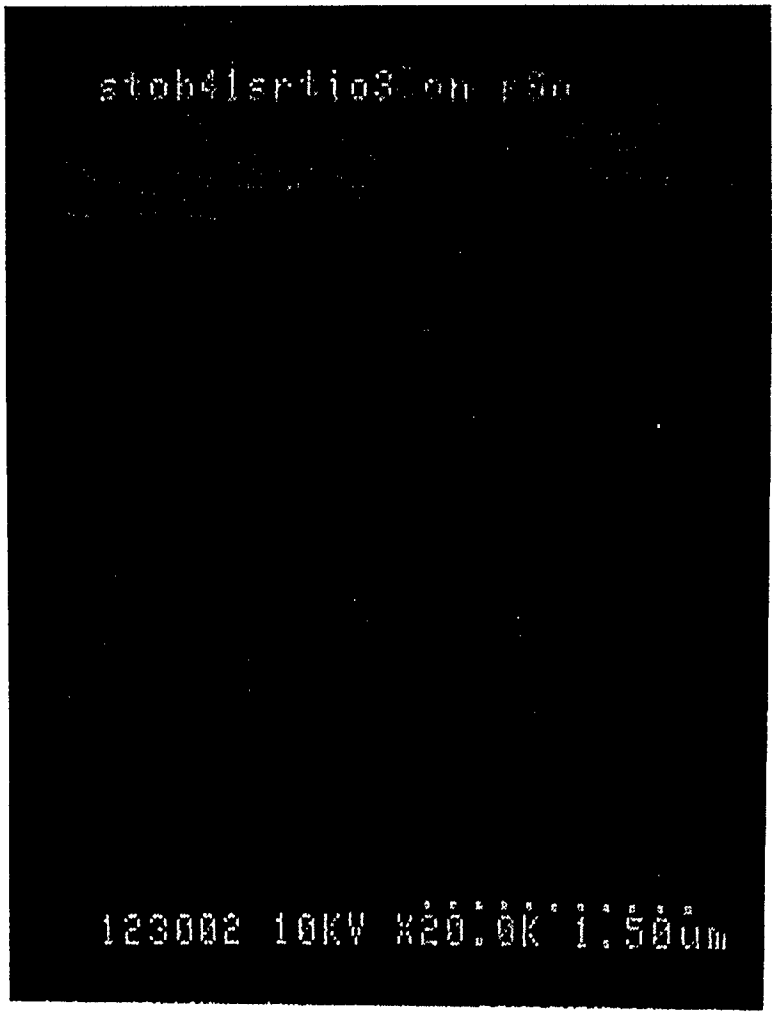
YSZ on MgO



$SrTiO_3$ on MgO



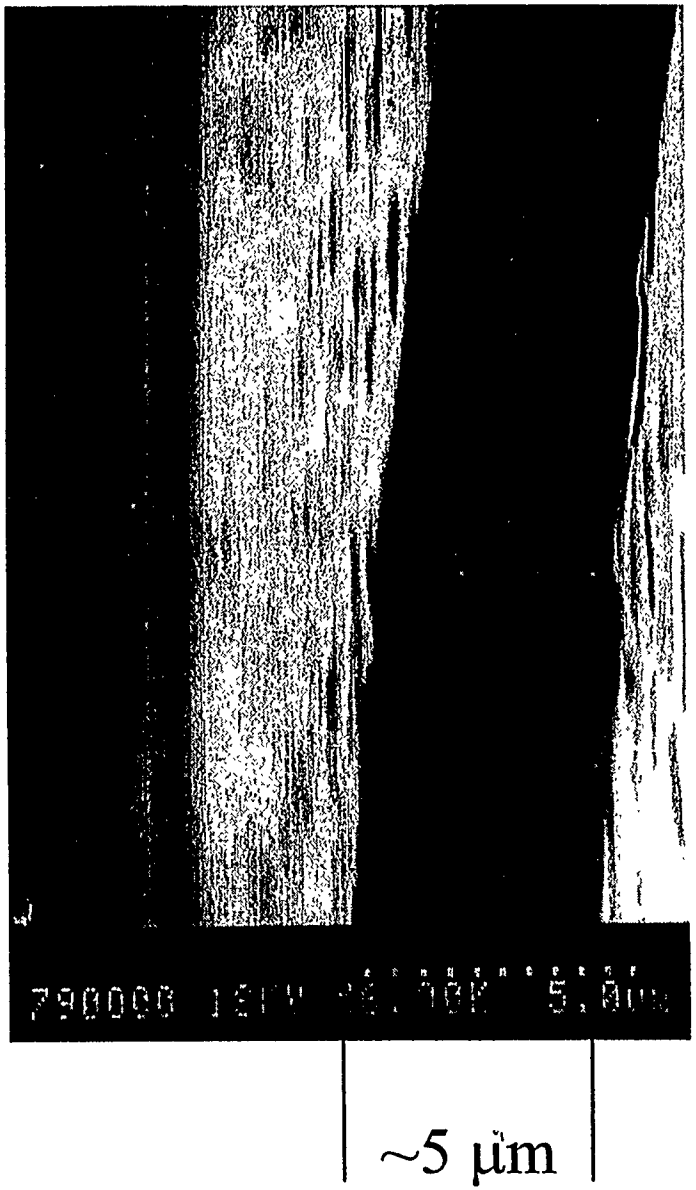
SEM Cross section of $SrTiO_3$ on MgO



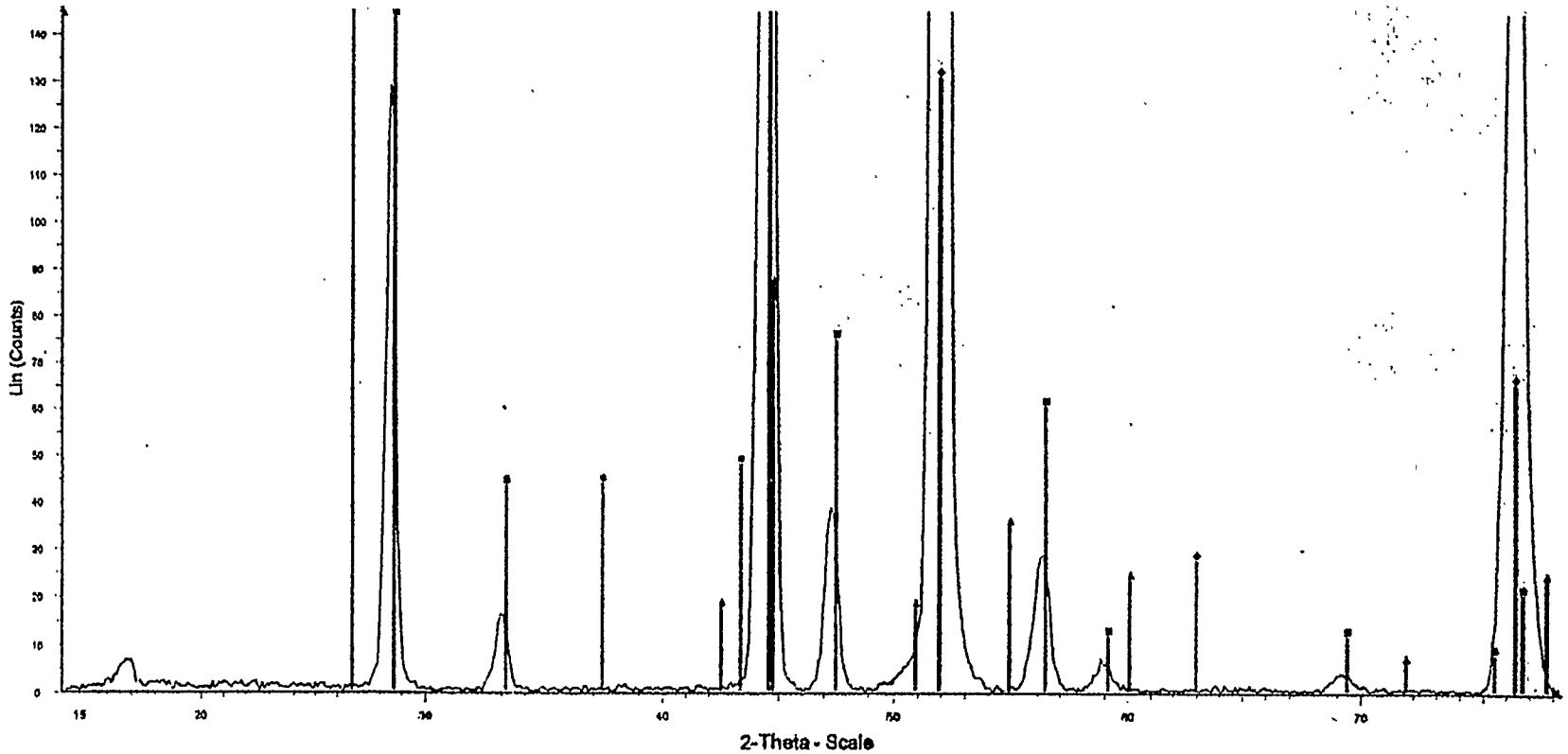
~380 nm

249

Extraordinarily High Deposition Rate of <u>100 nm/minute</u> Demonstrated for Epitaxial YSZ on Sapphire.



Preferentially Oriented CeO_2 Can Be Deposited on Ni Without NiO Forming!



CeO2 on Ni, 2%H2 - File: ni23.raw - Type: 2Th alone - Start: 14.300 ° - End: 78.600 ° - Step: 0.100 ° - Step time: 602.7 s - Temp.: Room - Time Started: 0 s - 2-Theta: 14.3
Operations: Background 0.031,0.010 | Import
34-0394 (*) - Cerianite-(Ce), syn - CeO2 - Y: 6.25 % - d x by: 1.000 - WL: 1.54056
04-0850 (*) - Nickel, syn - Ni - Y: 13.54 % - d x by: 1.000 - WL: 1.54056
04-0835 (I) - Bunsenite, syn - NiO - Y: 2.08 % - d x by: 1.000 - WL: 1.54056
25-0284 (D) - Graphite, syn - C - Y: 25.00 % - d x by: 1.000 - WL: 1.54056

Conclusions

- Epitaxial and dense YBCO, CeO_2, YSZ, and $SrTiO_3$ coatings were deposited on MgO and $LaAlO_3$ substrates.
- T_c and J_c values of the YBCO are being measured.
- Further experiments with YBCO include deposition onto RABiTS.
- CeO_2 was deposited on textured Ni without NiO forming.
- Further experiments include depositing epitaxial CeO_2, YSZ, and $SrTiO_3$ on textured Ni.
- Cost analysis shows commercial viability.

Update from 3M/LANL/ORNL/Southwire

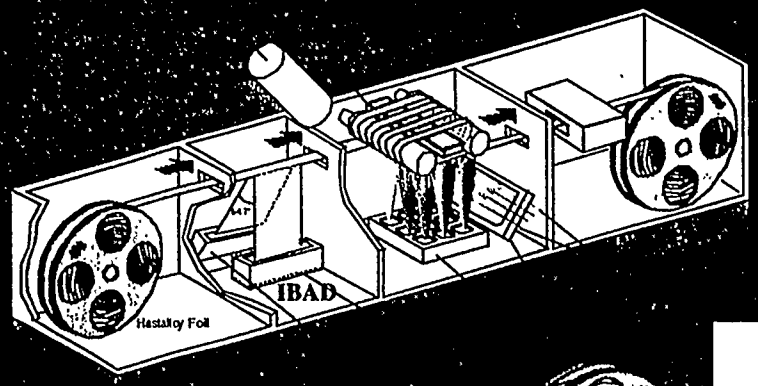
Jonathan Storer and Arnie W. Funkenbusch

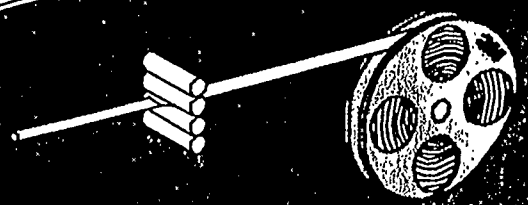
Wire Development Workshop
January 29-30, 1998

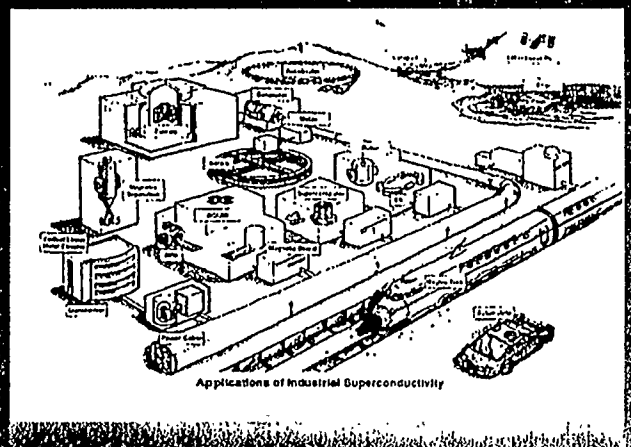
253


Los Alamos
Southwire

3M is Teamed with ORNL, LANL, and Southwire to Develop HTSC Film Conductors with Material Science Focus





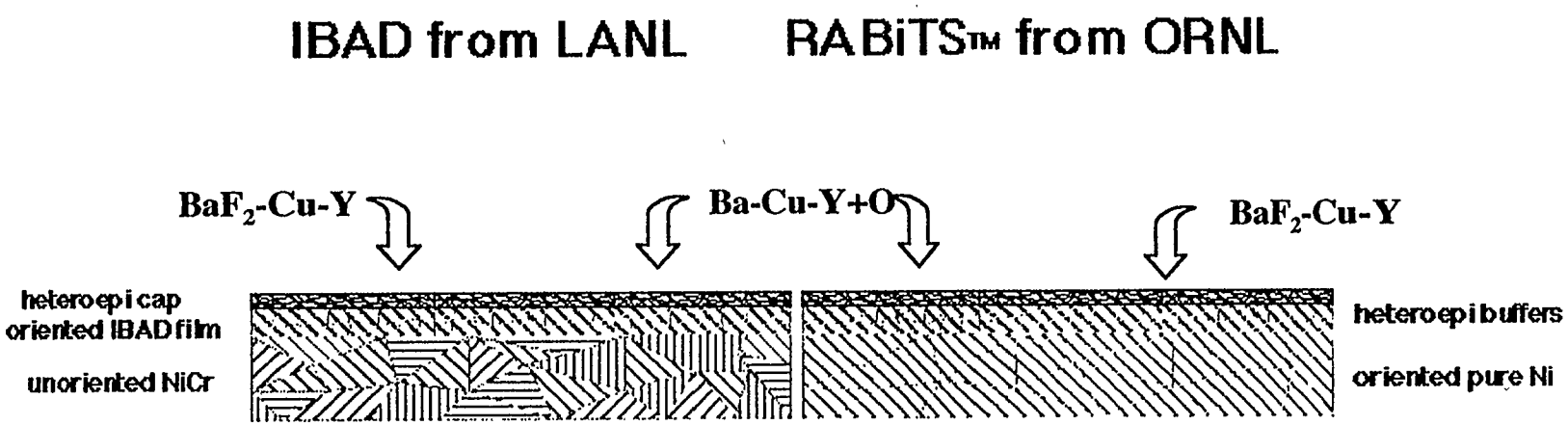


Los Alamos

Many applications

Southwire ornl 3M Los Alamos

3M is Examining Several Concepts



The Team is Examining Several Options

	RABiTS™	IBAD
BaF_2	Nickel properties Substrate thickness Buffer changes from PLD? Defluorination during evap BaF_2 sensing Transient liquid phase?	IBAD layer thickness IBAD layer composition Cap layer? Foil properties; smoothness Availibility of foil
In-situ oxidation	Atomic oxygen generation Atomic oxygen sensing Strip heating Ba evaporation Copper sensing	Atomic oxygen generation Atomic oxygen sensing Strip heating Ba evaporation Copper sensing In-line process?

Atomic absorption sensors for Y and Ba have been developed.

Copper sensor to be demonstrated 3rd Q '98.

Stanford know-how with laboratory scale YBCO evaporation is guiding 3M's feasibilty demonstration effort.

The CRADA team has been working for 9 months.

The key problem is still YBCO film deposition.

Proven process
Cost effective
High Jc
Scaleable

3M has constructed a vacuum coater with a roll-to-roll capability. This machine will elucidate obstacles to feasibility demonstration and methods for overcoming them.

Summary

Good results with BaF_2 approach show that it merits further study.

Roll-to-roll coater on line.

Atomic absorption sensor showing promise.

Progress on Thallium Wire & Tape Development

National Renewable Energy Laboratory

Oak Ridge National Laboratory

Sandia National Laboratory

State University of New York at Buffalo

University of Colorado

263

Joint Activities

Oak Ridge National Laboratory:

NREL is working closely with ORNL on the development of suitable buffers for the bi-axial texturing of Tl-oxide superconductors on ORNL's RABiT substrates.

Sandia National Laboratory:

SNL and NREL are collaborating on the thallination of Tl-1223 & Tl-1212 films.

Tech. transfer of SNL's 'hybrid' two-zone to NREL. (Hybrid work at SNL carried out under OER.)

SUNY (Buffalo):

SUNY, ORNL, and NREL are evaluating the advantages of Tl-containing precursors and using the crucible thallination method.

University of Colorado:

Characterization and study of new Tl-1223 compounds with NREL.

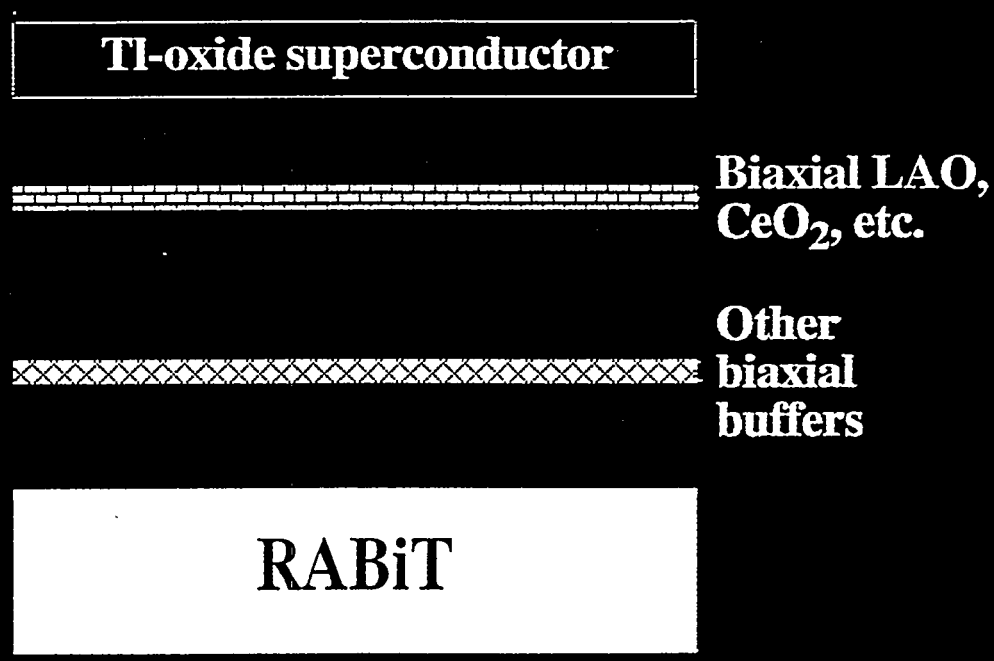
NREL

Thallium Oxide Tape Development

- Rationale for Tl-oxide tapes
  - Better field performance than BSCCO at high temperatures
  - Higher T_c than YBCO
  - Promising H_{irr} in doped material
  - Colony microstructure
    - Grains grow somewhat aligned even without a biaxial substrate
- LAO is premier substrate for Tl-oxide material
  - Remains epitaxial to thickness > 10 μm
  - Enhances proper phase development
- LAO is also excellent for other HTS materials

Buffer Layer Methodology

- Transfer Tl-oxide superconductors to biaxial tape substrates, *i.e.*, RABiTS
- Buffer layer structure should be as simple as possible
- Use single crystal substrates for prototyping buffer structure



Buffer Growths on RABiTS

Configuration	Result
LAO/STO/CeO_2/Ni	Biaxial Texture
LAO/LNO/CeO_2/Ni	?
LNO/CeO_2/Ni	?
CeO_2/YSZ/ CeO_2/Ni	Biaxial Texture

LAO/STO/CeO_2/Ni RABiTS is Successful!

LAO/LNO/CeO_2/Ni RABiTS looks promising on single crystals

LAO/STO/CeO_2/(100) YSZ Film

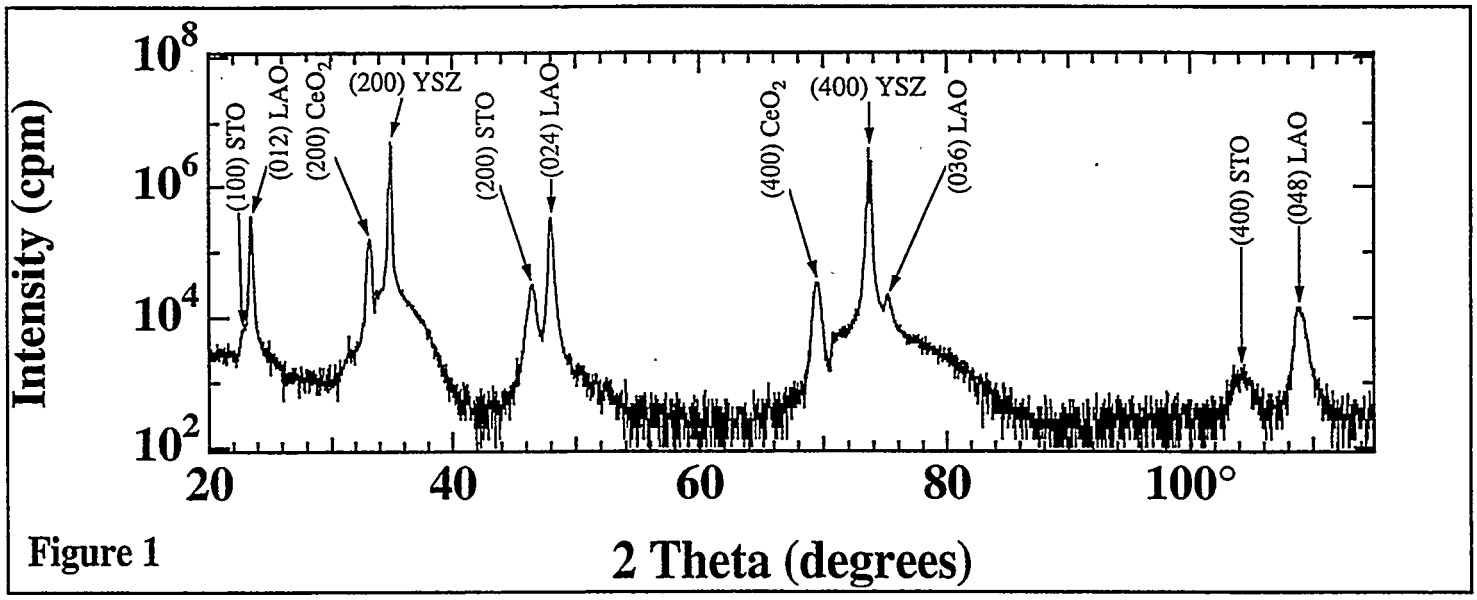


Figure 1

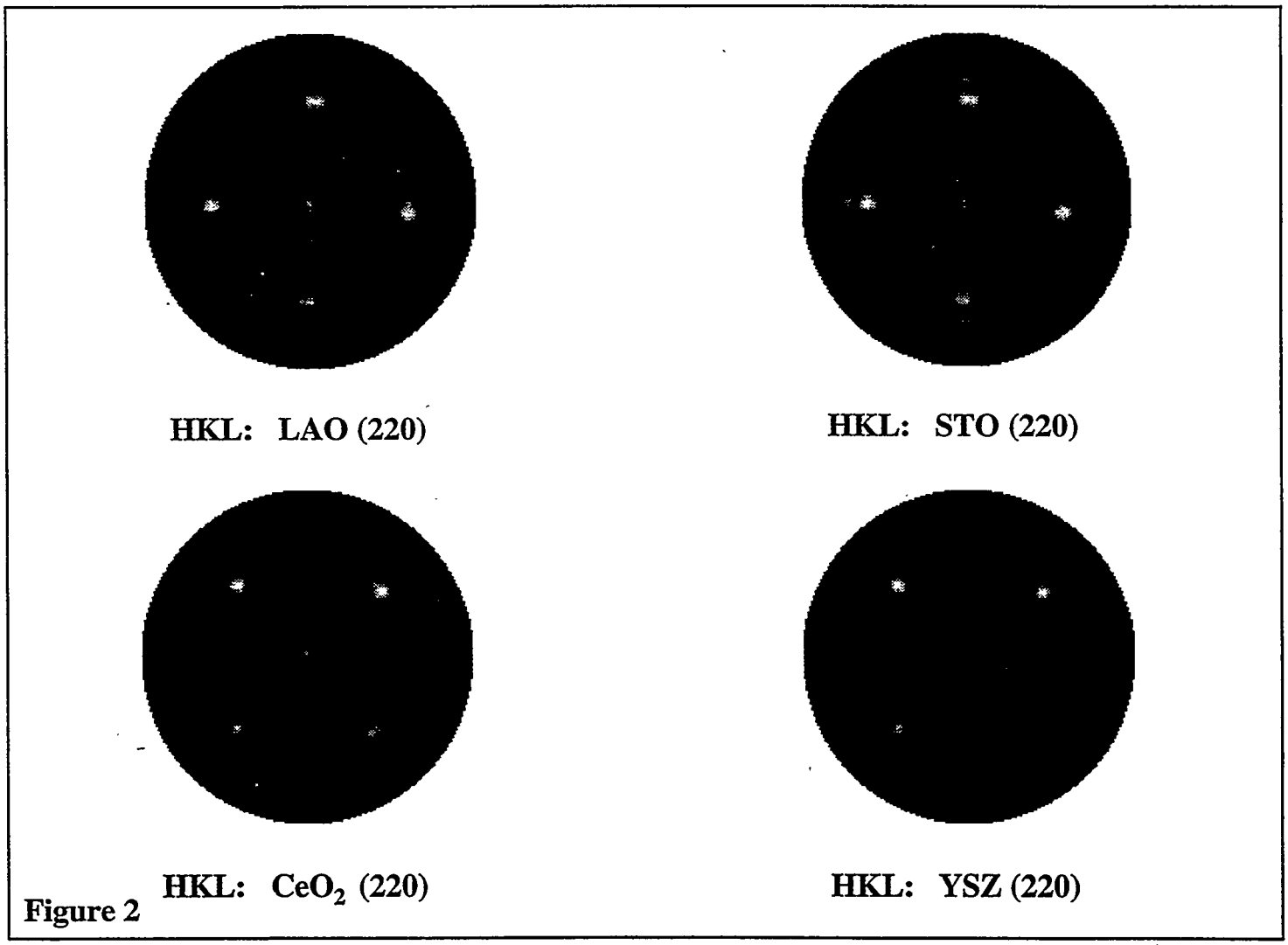


Figure 2

NREL

LAO/STO/CeO_2 /Ni RABiTS Film

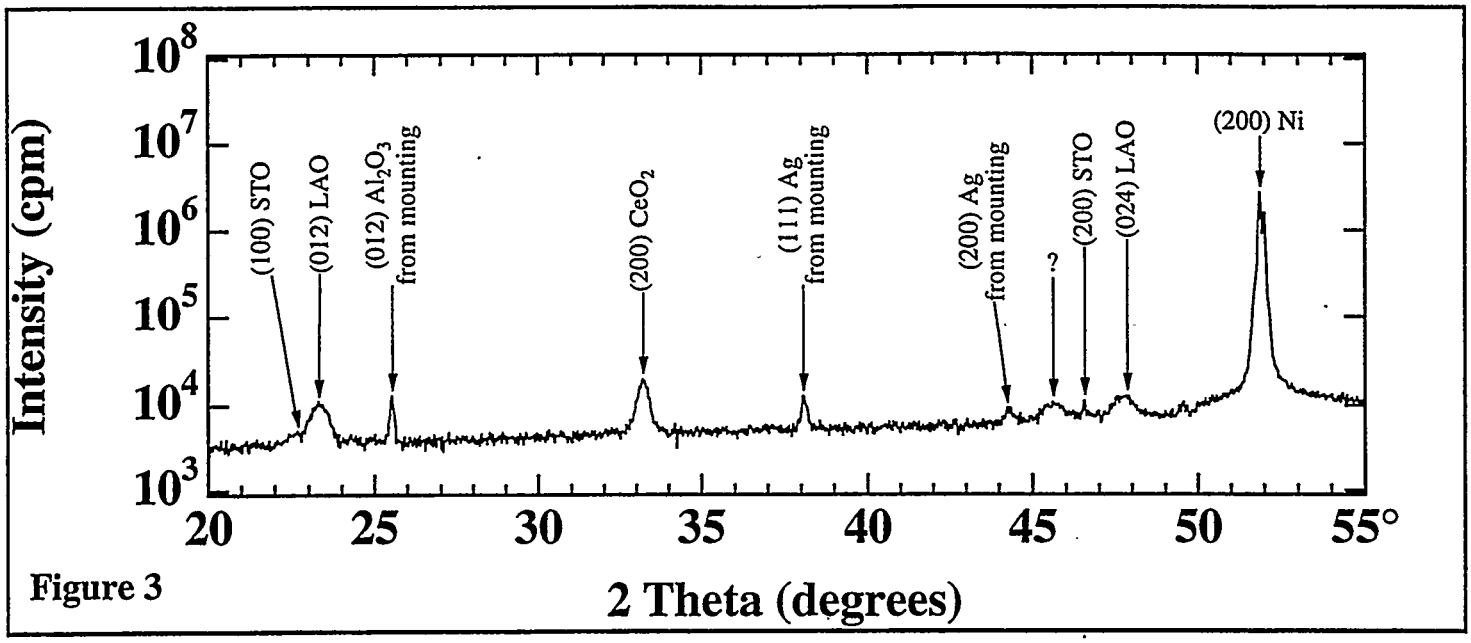
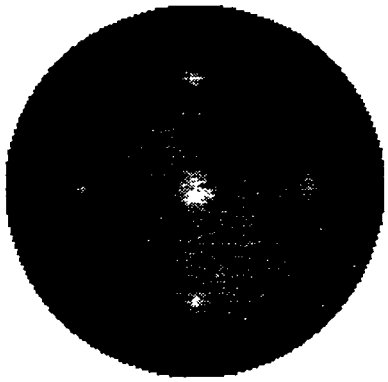
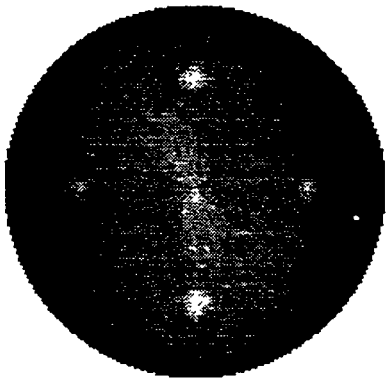


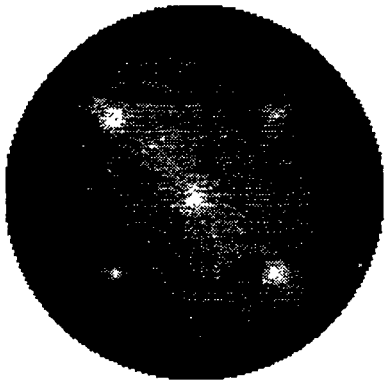
Figure 3



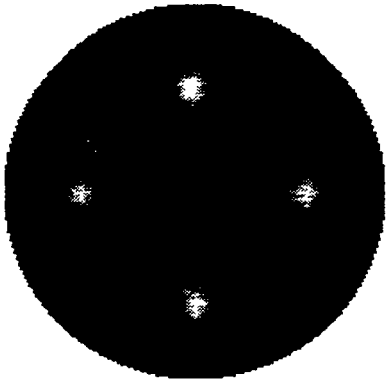
HKL: LAO (110)



HKL: STO (110)



HKL: CeO_2 (220)

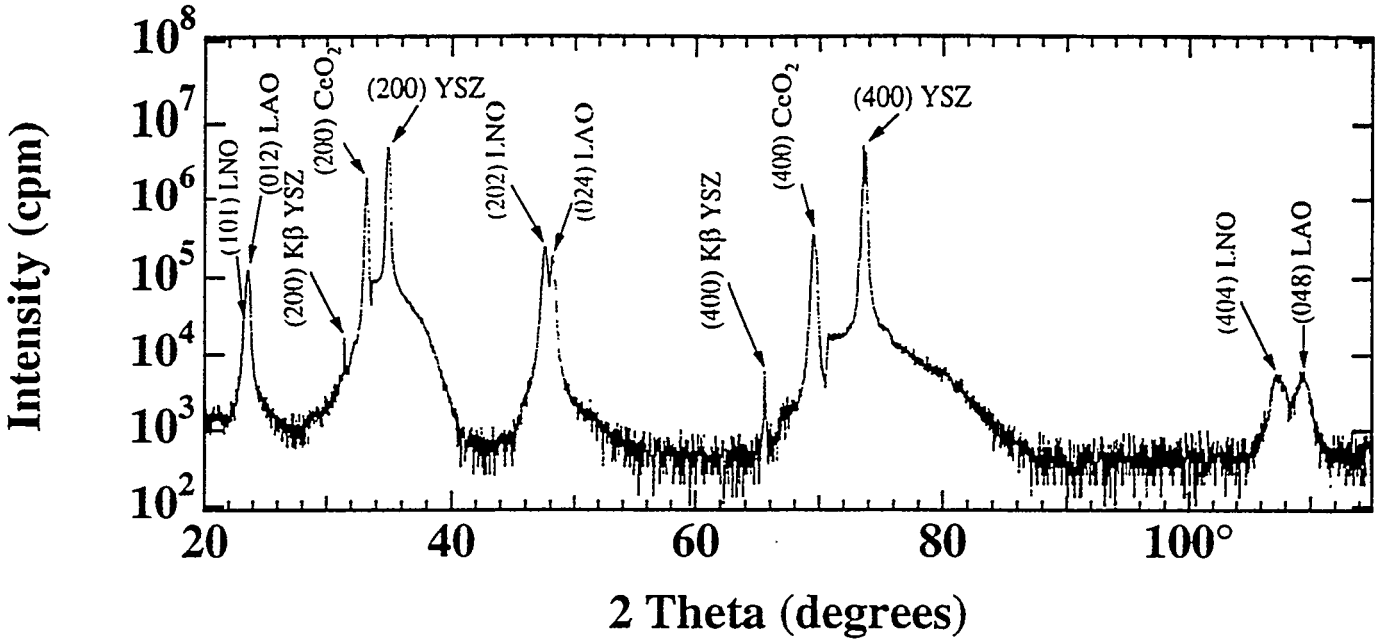


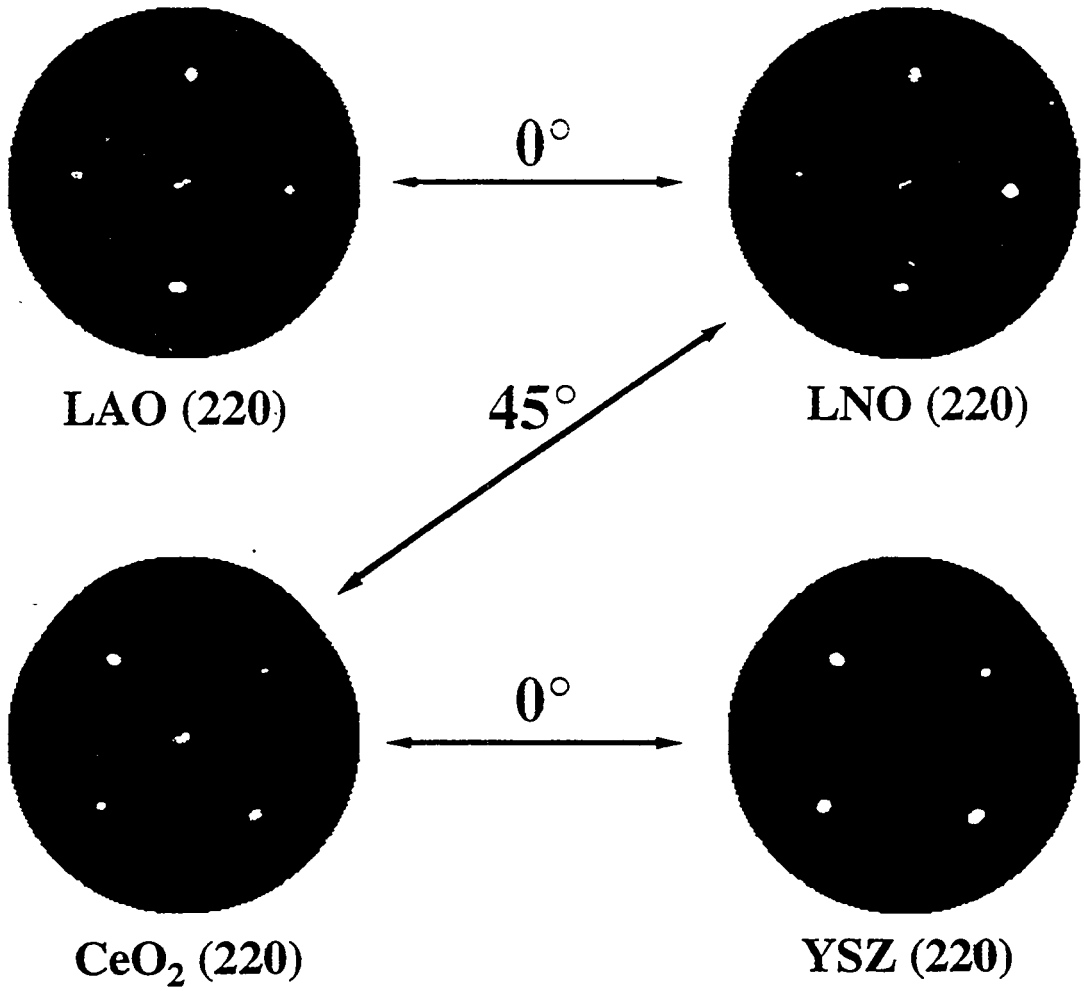
HKL: Ni (220)

Figure 4

NREL

XRD Data for LAO/$LaNiO_3$ (LNO)/CeO_2 /YSZ Film

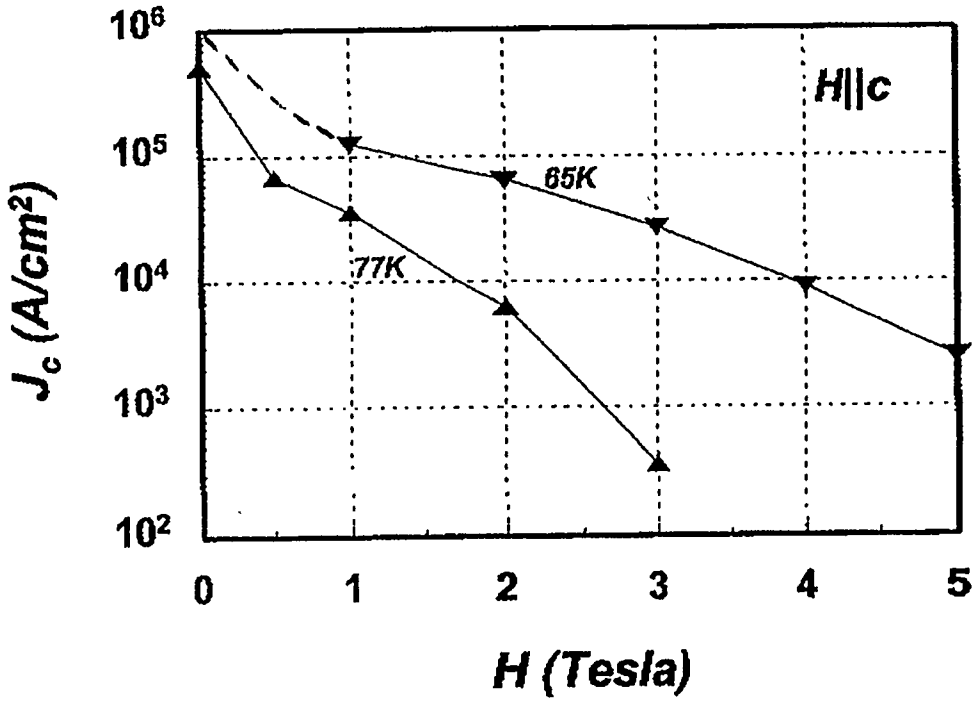


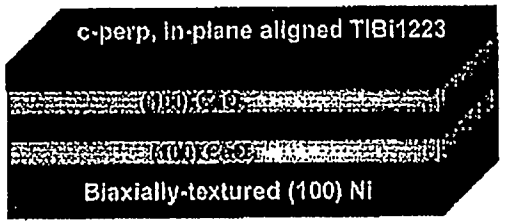


NREL

Superconducting Transport of TlBi1223/RABiTS in the Liquid Nitrogen Temperature Range

- RABiTS: Rolled-textured Ni; buffer layers by e-beam deposition, ~125 μm thick
- TlBi1223 coating by PLD precursor deposition and post-annealing, ~1.5 μm thick

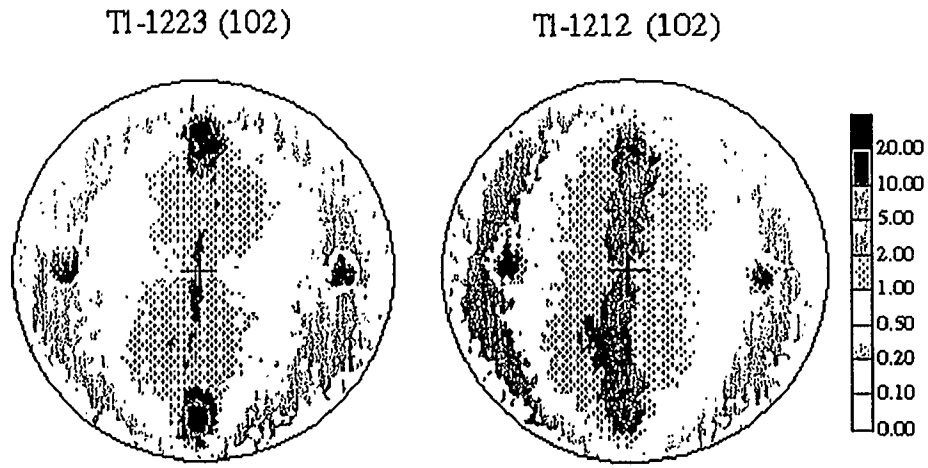




ornl

R1126B Tl,Bi-1223/CeO_2/YSZ/CeO_2/Ni

epitaxial 1223 dominant phase, with some 1212



ORNL

- Omega scans
  (out-of-plane)
  (FWHM values in deg.)
  - Ni (200) 7.8
  - Tl-1212 (005) 9.7
  - Tl-1223 (007) 9.0

- Phi scans
  (in-plane)
  (FWHM values in deg.)
  - Ni (111) 12.0
  - YSZ (111) 7.9
  - Tl-1212 (102) 8.9
  - Tl-1223 (102) 7.2

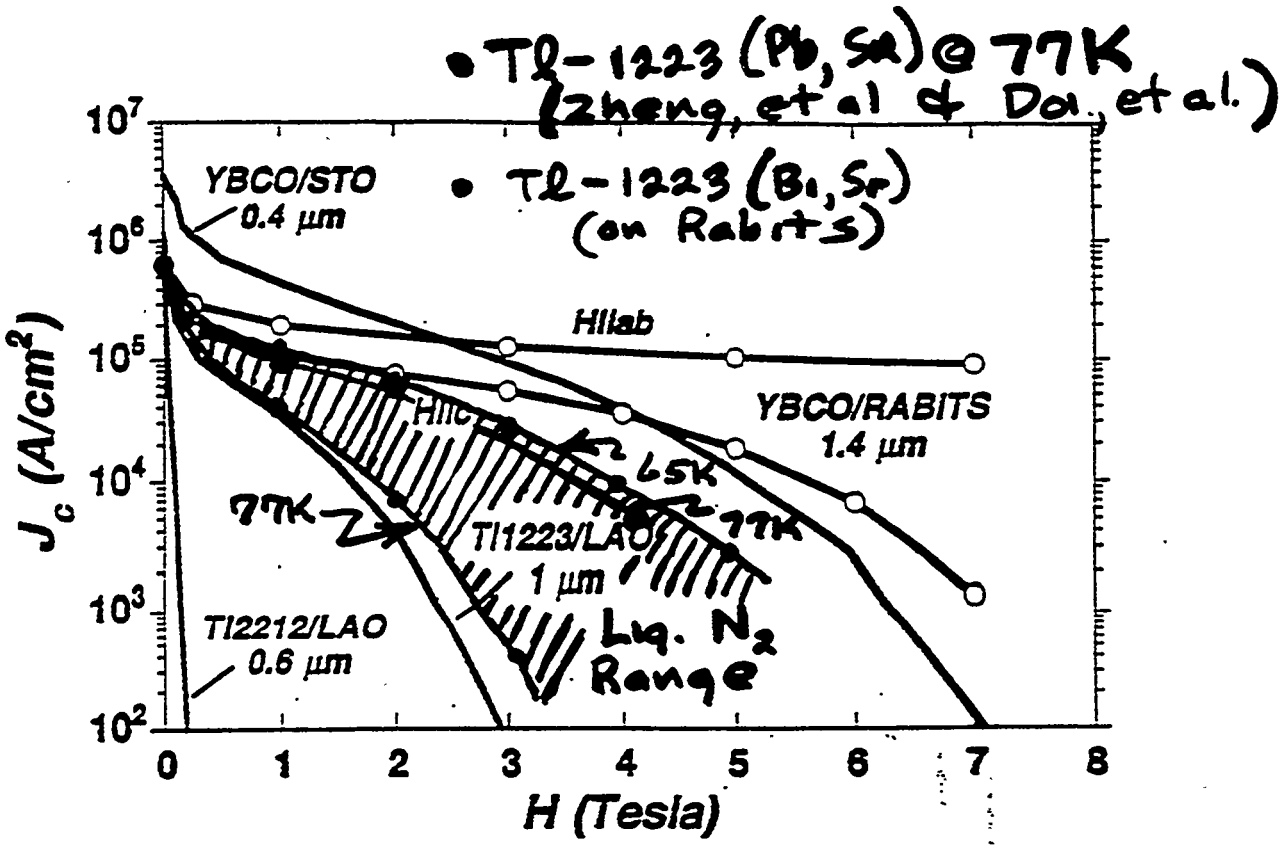


Fig. 1. The magnetic field dependent J_c of a YBCO/RABiTS, compared to other HTS epitaxial thin films that have been deposited on single crystal oxide substrates. Most data are shown for $H||c$, the applications-limiting orientation. The characteristics with $H||ab$ are typical of the strong intrinsic pinning observed for all HTS materials.

Application	Commercial HTS Wire Requirements								
	J_c (A/cm^2) 77 K, self-field	Cost/tape ($/kA-m)	Field (T)	$Temp_{op}$ (K)	I_c/tape (A) 77 K, self-field	AC loss (mW/A-m)	Bend Radius (m)	Strain (%)	Wire Length (m)
Fault Current Limiter	**10^3-10^4**	**30->10[a]**	0.3-3	40->65	100	0.4	0.15-0.05	0.2-0.4	200-1000
Motor	**10^4**	**10**	4	>25	300	NA[b]	0.05	0.2-0.3	1000
Generator (100 MVA)	**10^3**	**10**	4-5	20->65	100-200	NA[b]	0.1	<0.2	500-1000
Cable	**10^3-10^4**	**10-100**	<0.2	>65	>30[c]	0.15	0.01	>0.4	100-1000
Transformer	**10^3-10^4**	**20->5**	0.15	20-65	**200**	**0.25**	0.1-0.2	0.1	250-3000
High Field Magnet	**10^3-10^5**	5->1	>20	4.2->65	300-500	NA	0.01	**0.5**	500-1000
Magnetic Separator	100	10	**2-3**	77	500	NA	0.5	0.2	1000

a- Arrow represents cost decrease necessary from pre-commercial to final cost necessary to enable commercial devices.
b- For current field coil design.
c- Current for individual wires; full cable assembly will carry 3-5 kA.

Table developed at 1997 DOE Wire Development Workshop and represents consensus of industrial participants.
Bolded figures represent highest priorities for each application according to panel participants.
Table based on initial data collected by R. Blaugher, NREL.

Progress at Los Alamos on scale up of YBCO coated conductors

P. Arendt, J. Groves, R. DePaula, J. Roper, R. Springer - IBAD template films

S. Foltyn, P. Dowden - PLD YBCO

M. Maley, J. Willis, Y. Coulter, - Jc, Ic characterization

E. Peterson, J. Bingert - Film crystal structure/texture characterization

B. Hammond, C. Wang* - IBAD MgO template films

Industrial collaborators: J. Storer - 3M, L. Fritzmeyer - ASC

* Stanford University

Processing steps for tape fabrication

Substrate preparation

IBAD deposit template film

PLD deposit buffer layer and YBCO

Sputter deposit Ag cap layer and anneal

Measure Ic, Jc, etc.

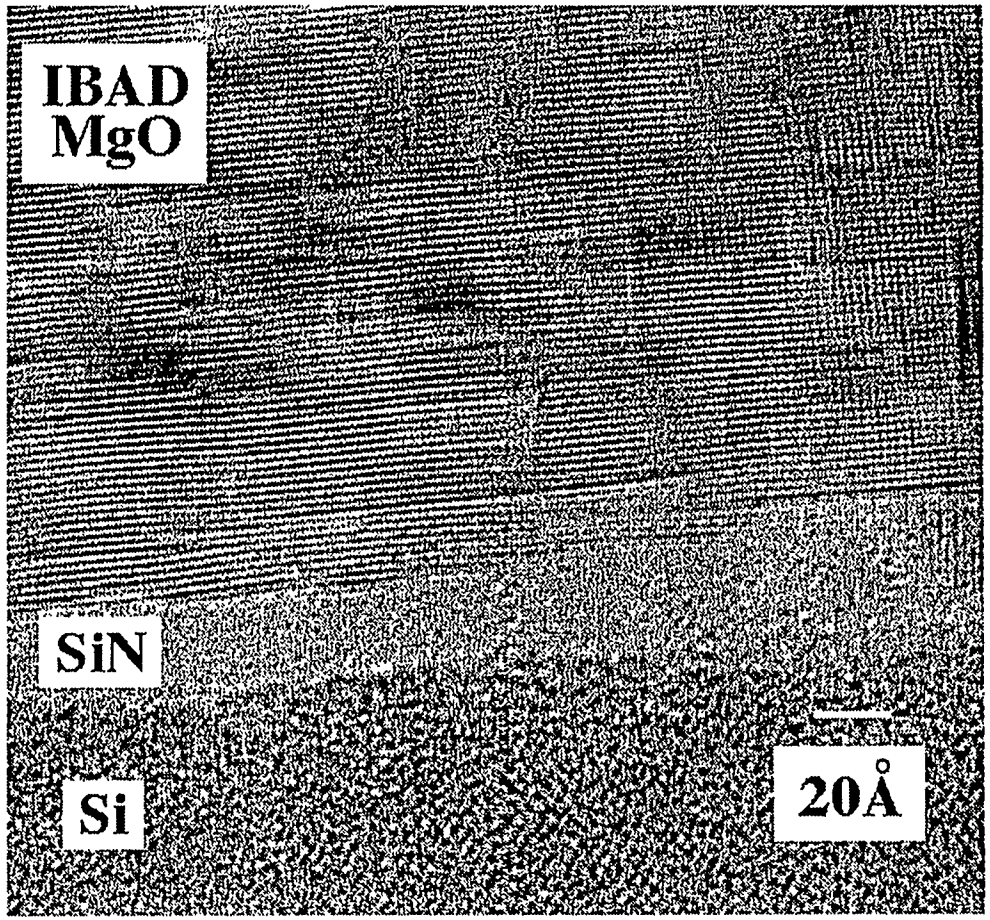
Options for biaxial template film formation

IBAD YSZ - thickness 0.5 to 1 μm, slow (7+ groups)

ISD YSZ or MgO- thickness 0.5 to 1 μm, slow (3 groups)

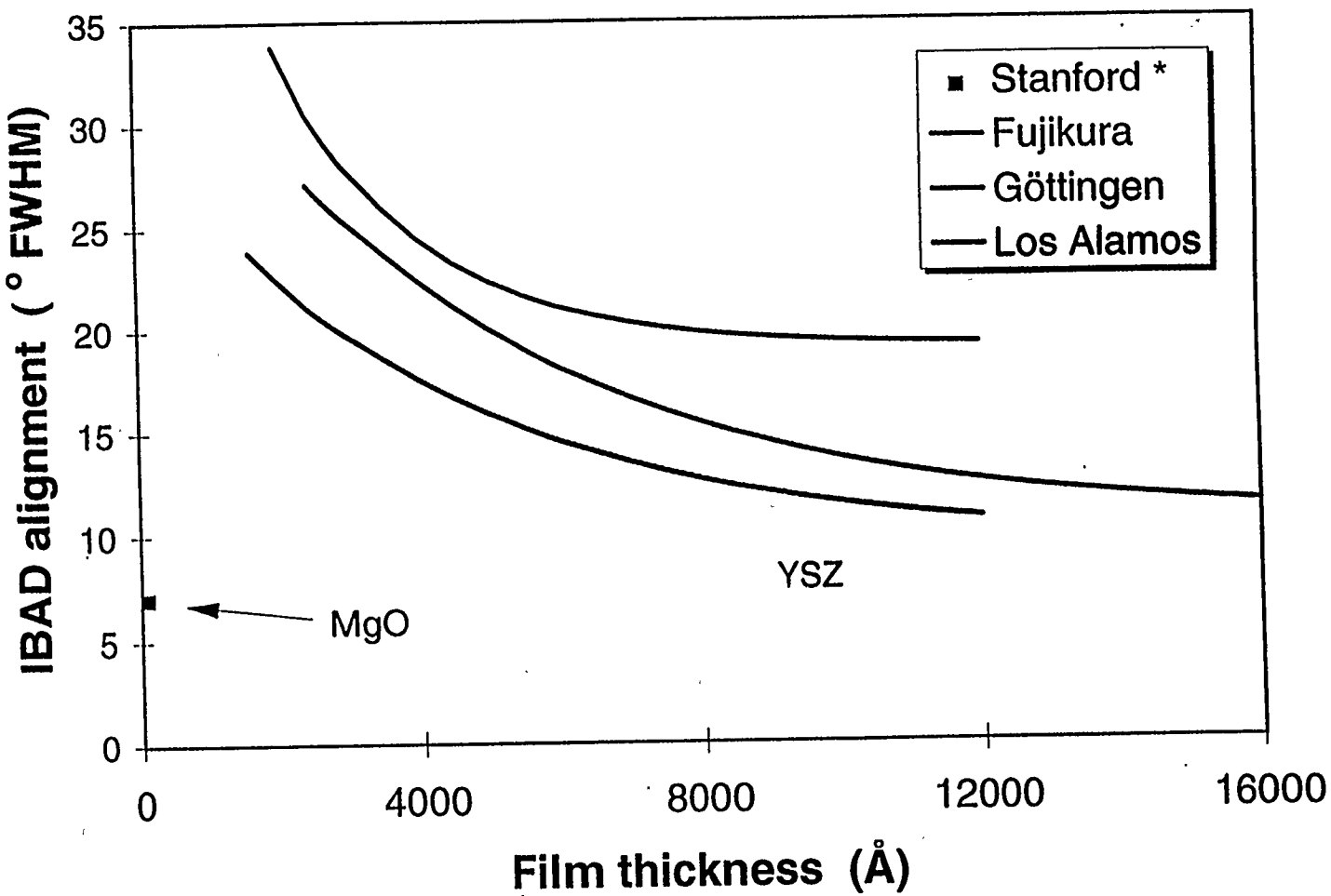
IBAD MgO - thickness 10 nm, fast (1 group)

TEM cross section of IBAD $MgO/Si_3N_4/Si$ film



Appl. Phys. Lett. **71** 2955 (1997)
Courtesy C. Wang (Stanford University)

Comparison of YSZ and MgO texture development during Ion Beam-Assisted Deposition

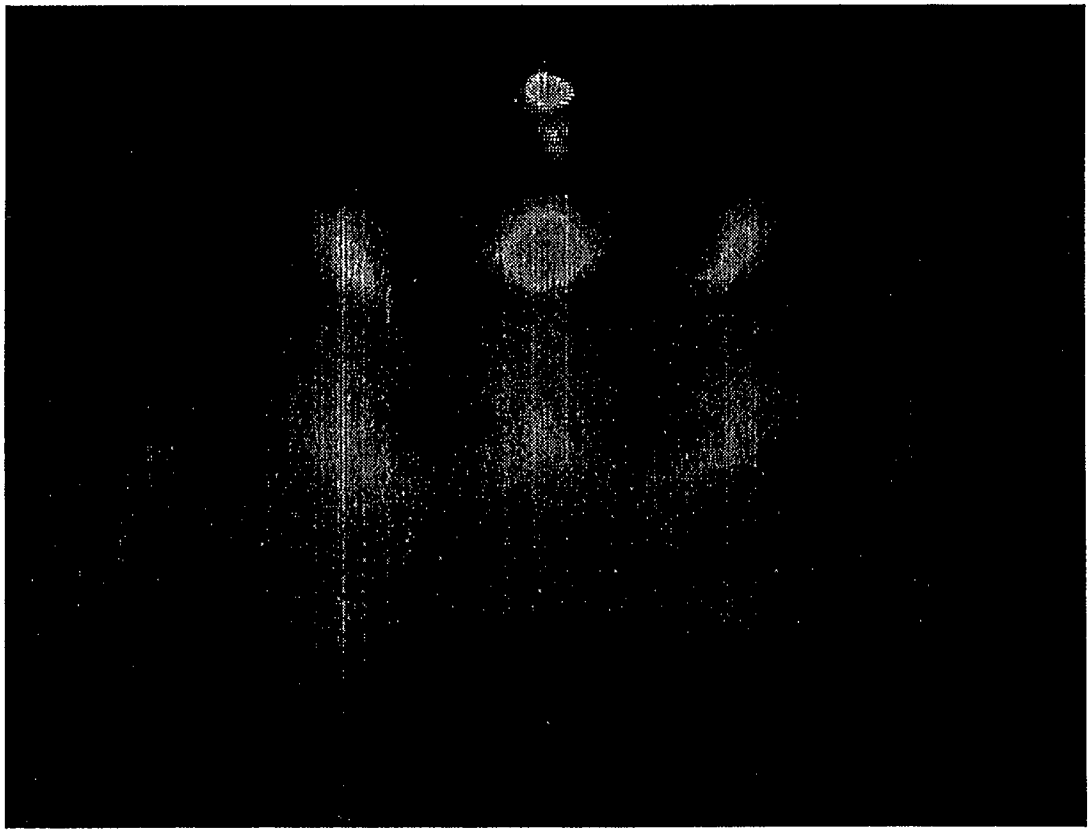


* Appl. Phys. Lett. **71**, 2955 (1997)

Los Alamos

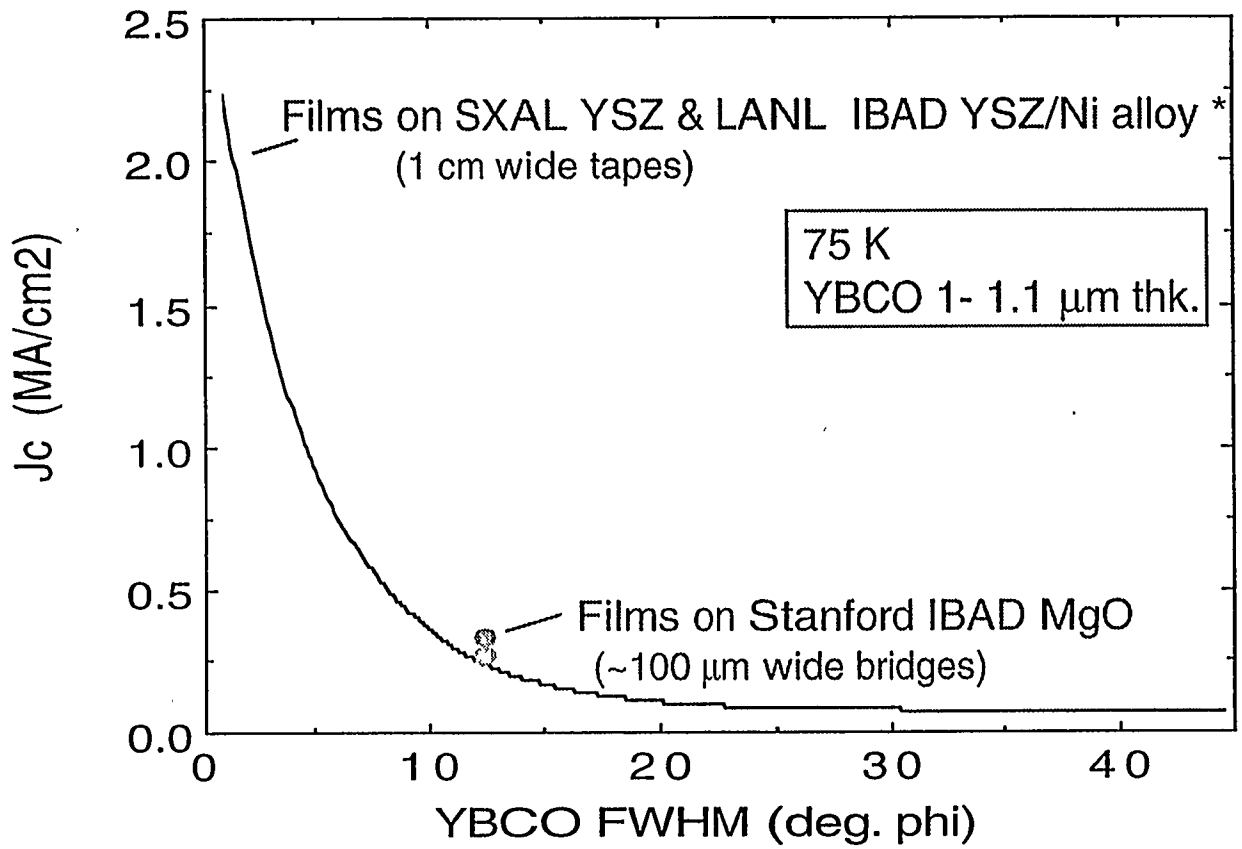
279

RHEED pattern of IBAD $MgO/Si_3N_4/H242$ film ~ 10 nm thick



Courtesy C. Wang (Stanford University)

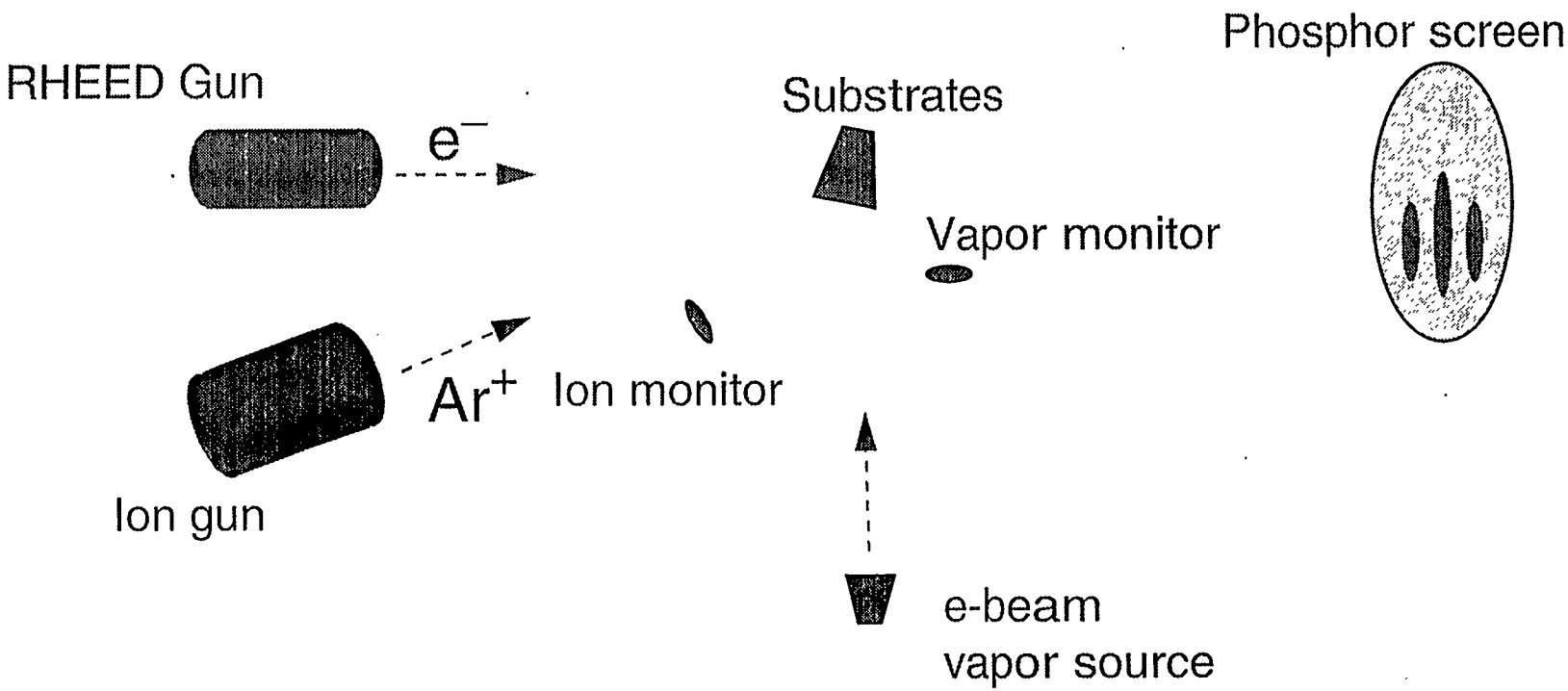
Jc vs YBCO texture



* Appl Phys Lett **67** 2397 (1995)

Los Alamos

Schematic of IBAD/RHEED film deposition system



Los Alamos

Ni alloy substrates

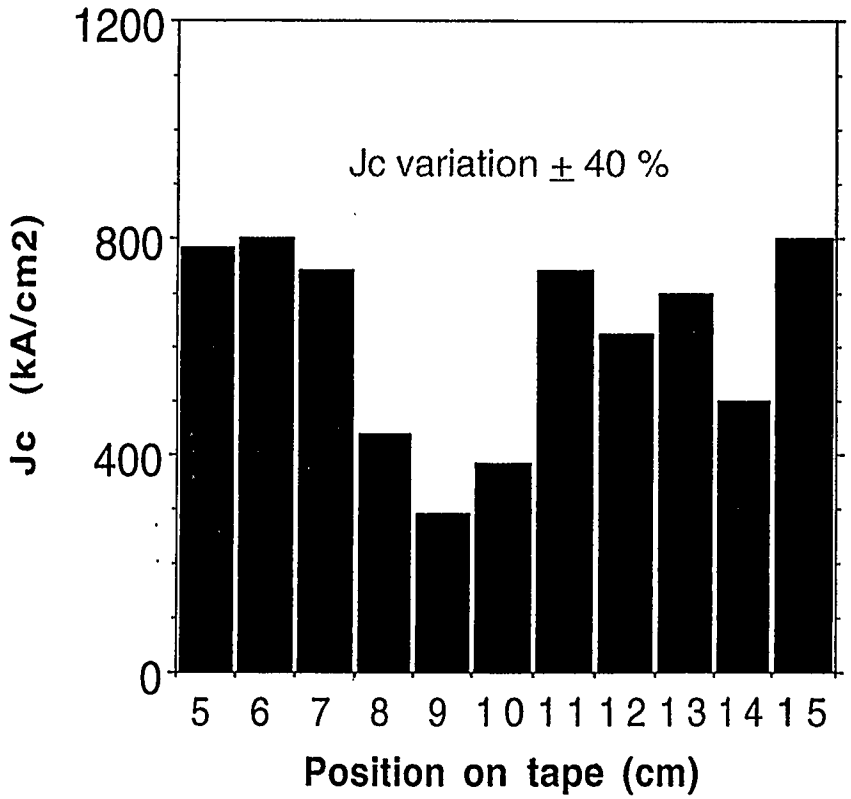
Cross section dimensions:	50 or 100 μm x 1 cm	
Preparation:	Polish 100 μm, no polish for 50 μm, Soap & water clean Vacuum bake	
Ra (100 μm scans):	as rolled	polished
50 μm tape	20±5 nm	NA
100 μm tape	50±10 nm	3 nm

Los Alamos

YBCO uniformity and fabrication speed of tapes improved

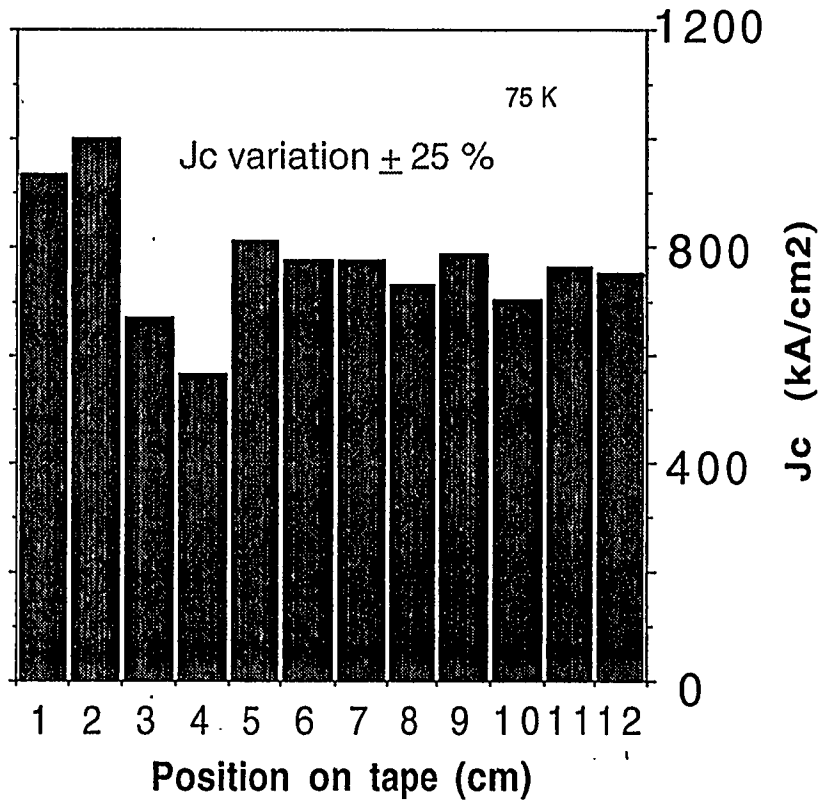
WW 1997 $\bar{I}c$=70 A

12^0 IBAD texture
YBCO thick$\bar{k}$=1.7μ



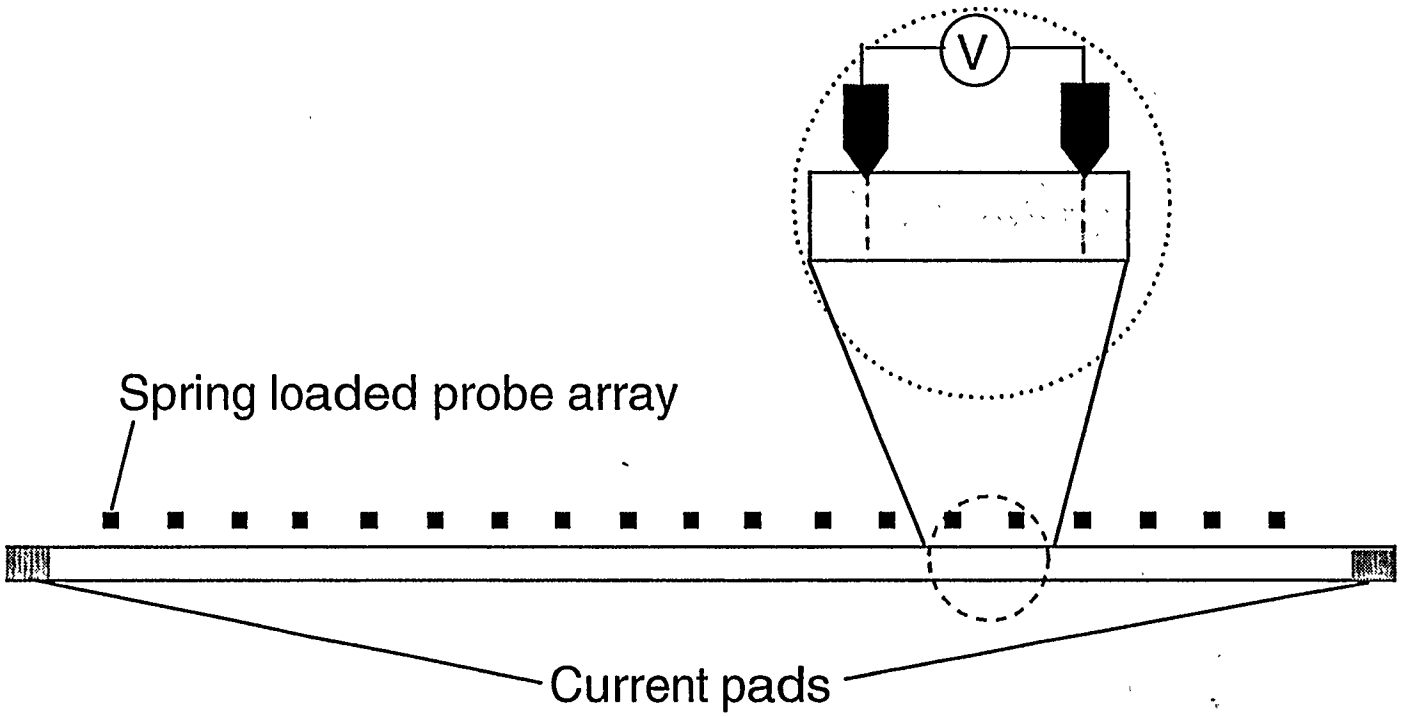
WW 1998 $\bar{I}c$=60 A

18^0 IBAD texture
YBCO thick$\bar{k}$=0.9μ



Los Alamos

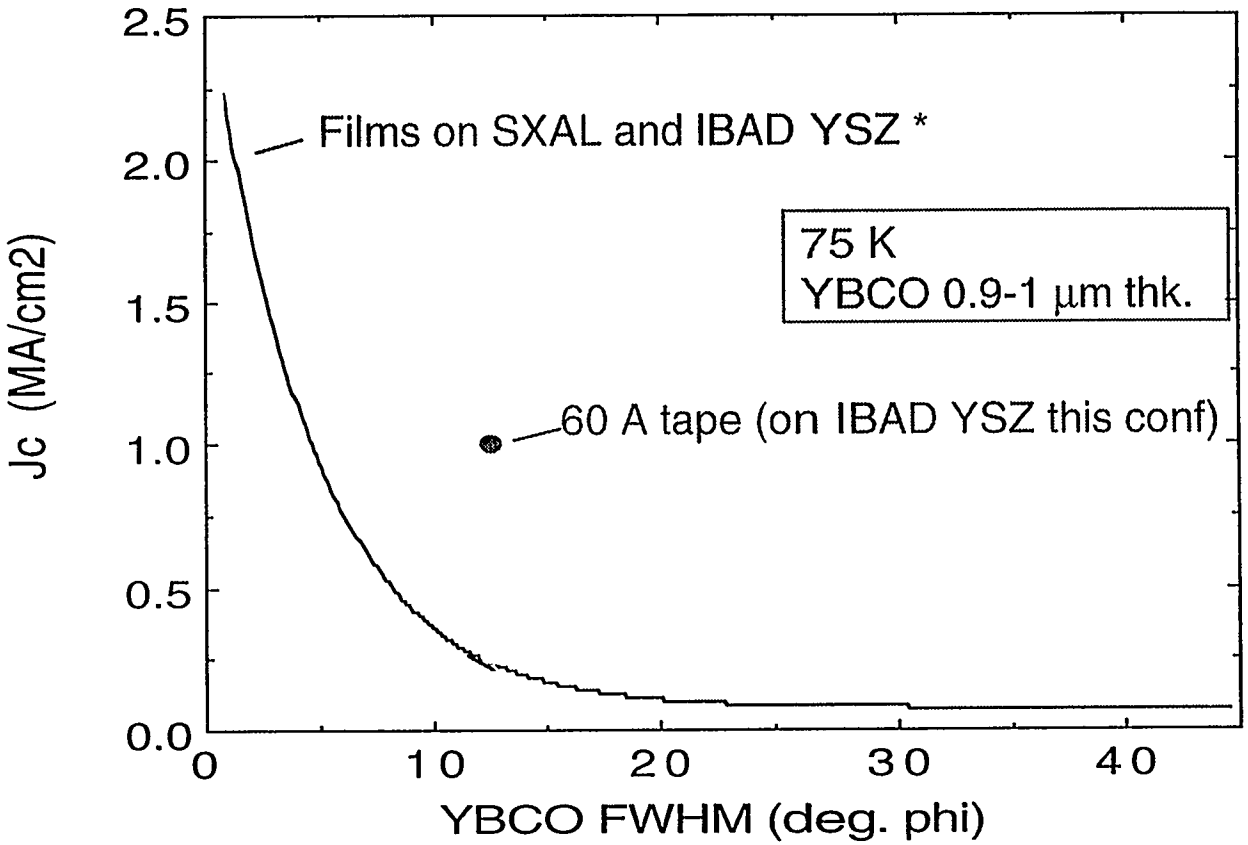
Solderless contact probe array allows rapid measurement of Ic(position)



285

Los Alamos

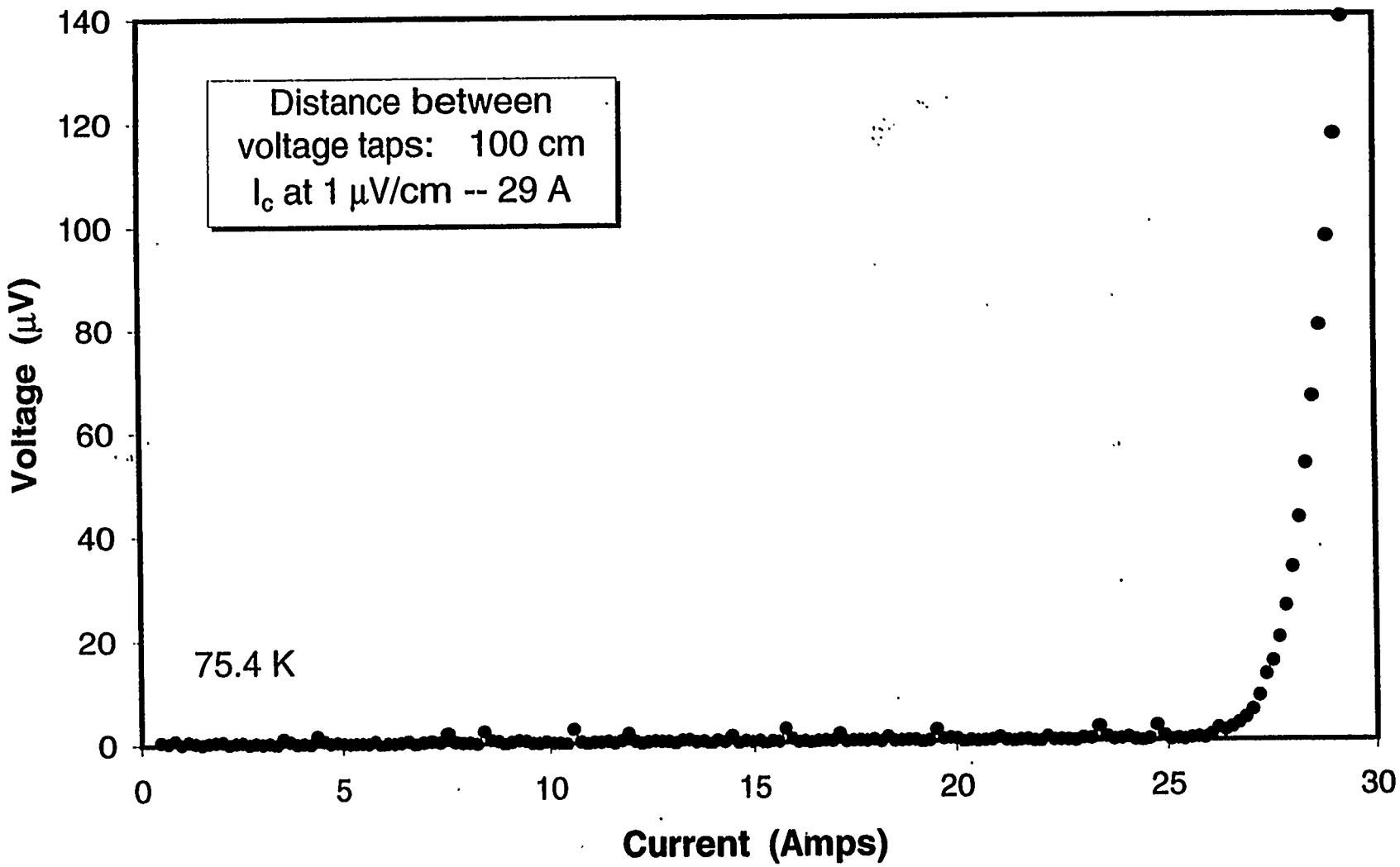
Improvement of Jc vs YBCO texture



* Appl Phys Lett **67** 2397 (1995)

Los Alamos

Current - voltage curve for 1 meter YBCO/IBAD coated conductor



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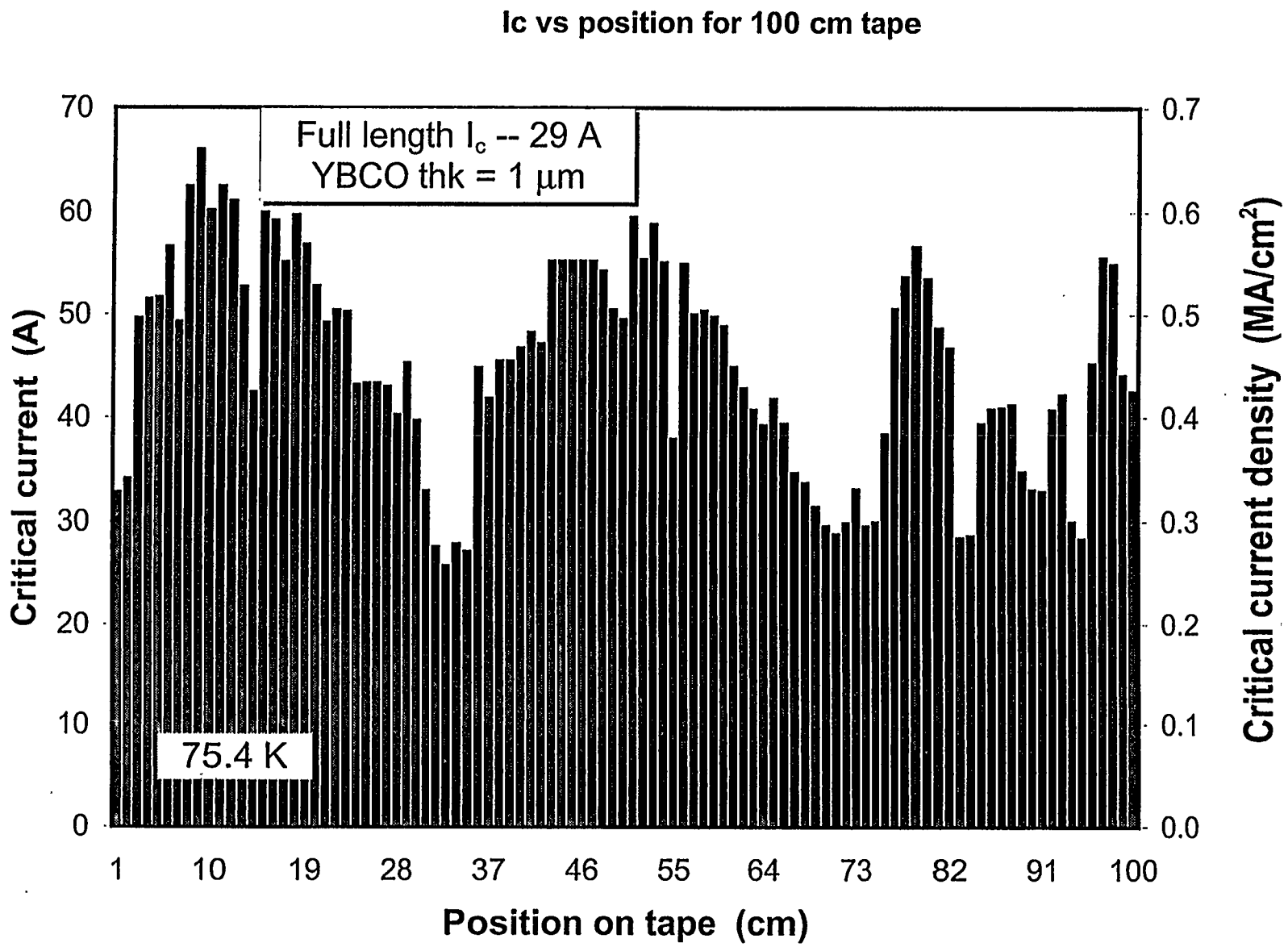

Note: substrate as rolled

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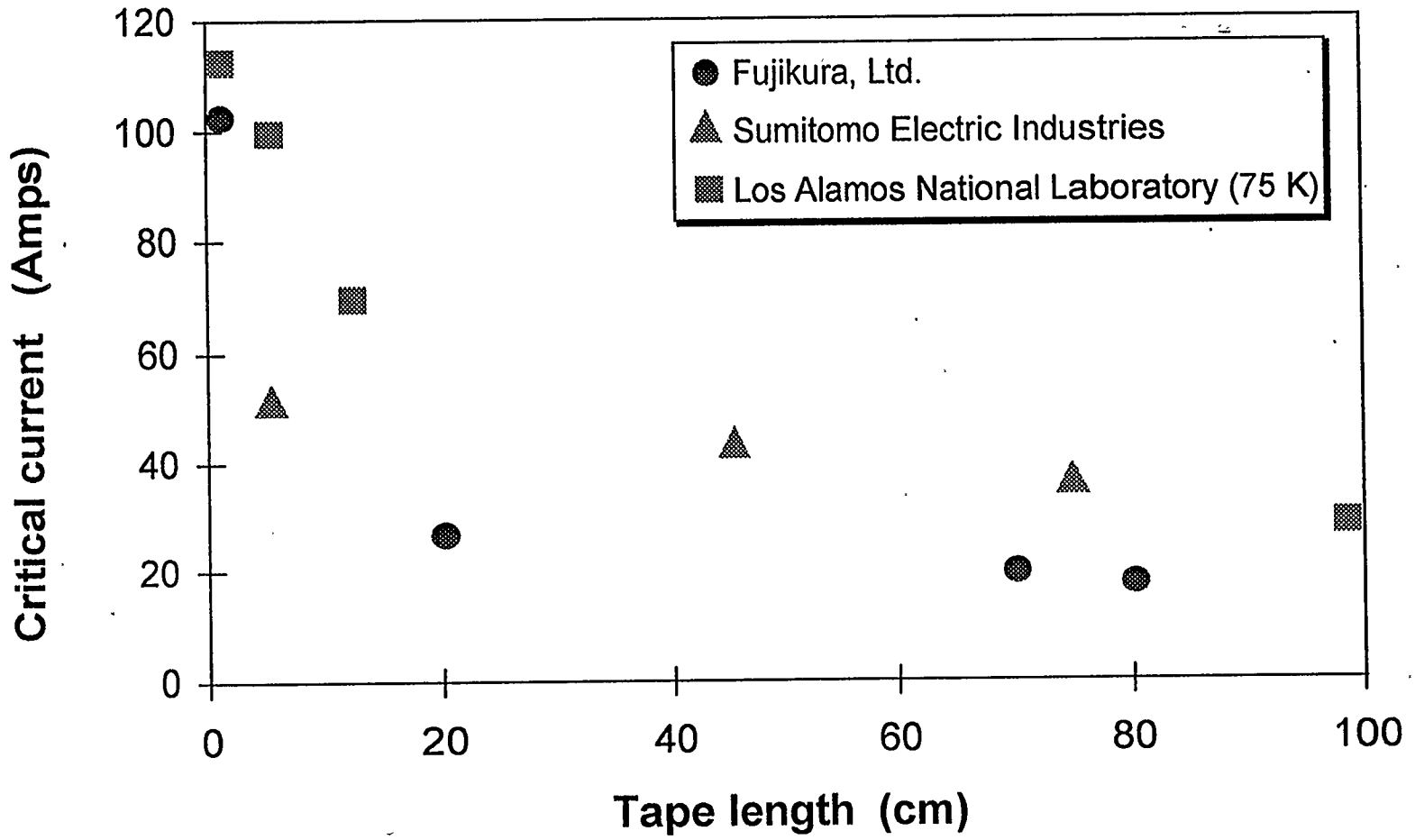
Critical current for 1 cm wide coated conductors at liquid nitrogen temperature



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287

Summary of year's progress

IBAD YSZ: Produced 1.1 m templates

IBAD MgO: ~100X speed improvement and demonstrated YBCO Jc merits intensified efforts

YBCO films: Ic > 100A - 5 cm tape, Je > 20,000 A/cm^2 (as rolled subs.)

Ic = 60 A - 12 cm tape (YSZ & YBCO thickness' halved, uniformity impr. to $\pm$25%)

Ic = 29 A - 100 cm tape (as rolled subs.)

The "BaF_2 method": A scalable process for YBCO coated conductors

DOE Wire Workshop
St. Petersburg, FL
Jan. 29-30, 1998

R. Feenstra, D. K. Christen, M. Paranthaman

Oak Ridge National Laboratory

Ex situ processed high-J_c YBCO films on RABiTS

CeO_2 / YSZ / CeO_2 / Ni
$J_c \geq 100$ kA/cm^2 at 77 K

Enhanced critical thickness for c-axis growth

thickness dependence 1-5 μm ($SrTiO_3$)
deposition rates up to 10 nm/s *(coll. BNL and SU)*

➢ ***ORNL research sponsored through ER-LTR and EE-RE CRADA with 3M / Southwire / LANL***

ORNL

A. Goyal
D. F. Lee
F. A. List
E. D. Specht
D. M. Kroeger
D. P. Norton
C. Park
D. T. Verebelyi
J. D. Budai
C. E. Vallet

Stanford Univ.

R. H. Hammond
M. Bukshpun

BNL

M. Suenaga
S. F. Solvjov

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BaF_2 method *(cont.^{d})*

➢ DECOUPLING OF COMPLEX PROCESSING STEPS:

1. *material accumulation on substrate (deposition)*
2. *chemical reactions leading to formation of YBCO crystal structure*
   stoichiometry (Y, Ba, Cu, and O), temperature

☺ **relaxed control requirements during film deposition:**

- *facilitate long-duration process (long tape lengths)*
- *high rates*

☹ **extra processing step: high-T anneal**

- *reactivity with substrate enhanced*
  previously: lattice-matched perovskites ($SrTiO_3$, $LaAlO_3$, $KTaO_3$, . .)
  needed: "simple" buffer layer oxides (Y-ZrO_2, CeO_2, MgO, . .)
- *reduced control over microstructure (epitaxy)*
  "shake and bake" ↔ layer-by-layer growth
  critical thickness for c-axis growth

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Artificial substrate: RABiTS

Rolled Ni with biaxially aligned buffer layer

Standard architecture

CeO_2	reactive e-beam evaporation	625 °C, $Ar+H_2$ (H_2O)
YSZ	rf magnetron sputtering	780 °C, $Ar+H_2$
CeO_2	reactive e-beam evaporation	625 °C, $Ar+H_2$ (H_2O)
Ni	rolled, recryst. anneal	> 400 °C, vacuum, $Ar+H_2$

- *derived from previously established architecture:* YSZ / CeO_2 / Ni
  CeO_2 cap layer eliminates YBCO(F) – YSZ reaction

- ***evap./sputtered buffer layer:*** thick YSZ ~1 μm
  thin CeO_2 20-40 nm

- ***all PLD buffer layer:*** thick CeO_2 bottom layer 350 nm
  intermediate YSZ 150 nm
  thin CeO_2 cap layer 15 nm

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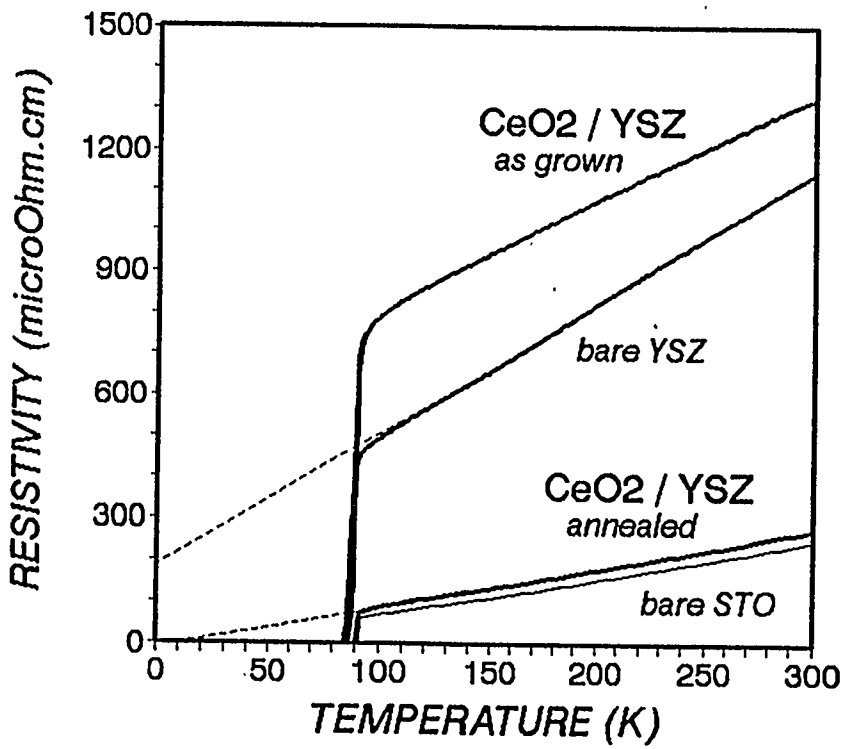
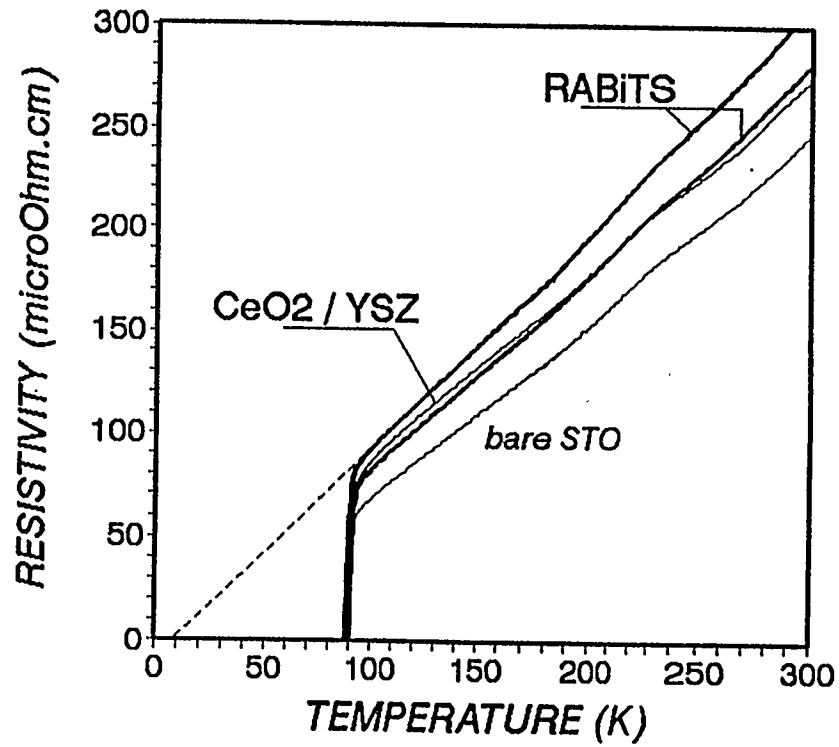
High-J_c films on RABiTS with BaF_2 method

★ *development of compatible cap layer (crystal substrates)*

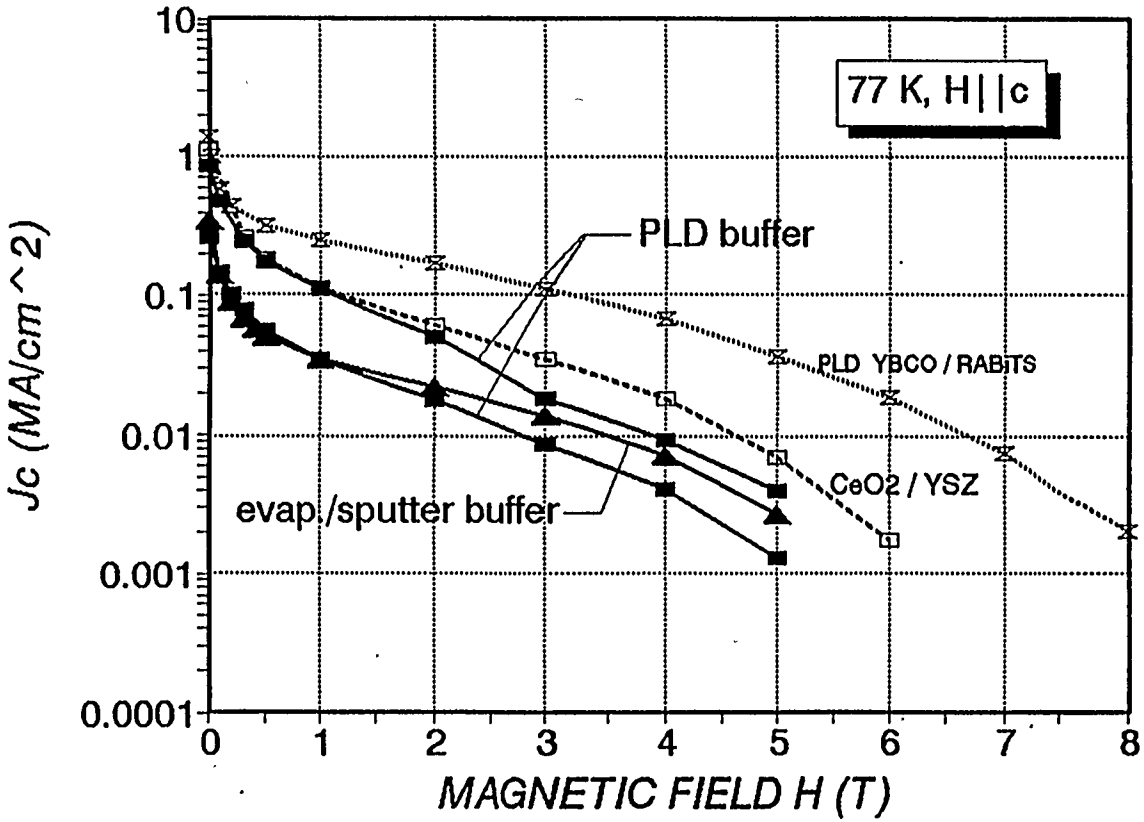
★ ***evap./sputtered*** *and* ***all-PLD*** *buffer layers on Ni (RABiTS)*





High-J_c films on RABiTS with BaF_2 method

- ★ ***evap./sputtered*** *and* ***all-PLD*** *buffer layers on Ni (RABiTS)*
- ★ *H field dependence indicates strongly linked YBCO*
- ★ *pinning depends on growth method, conditions*



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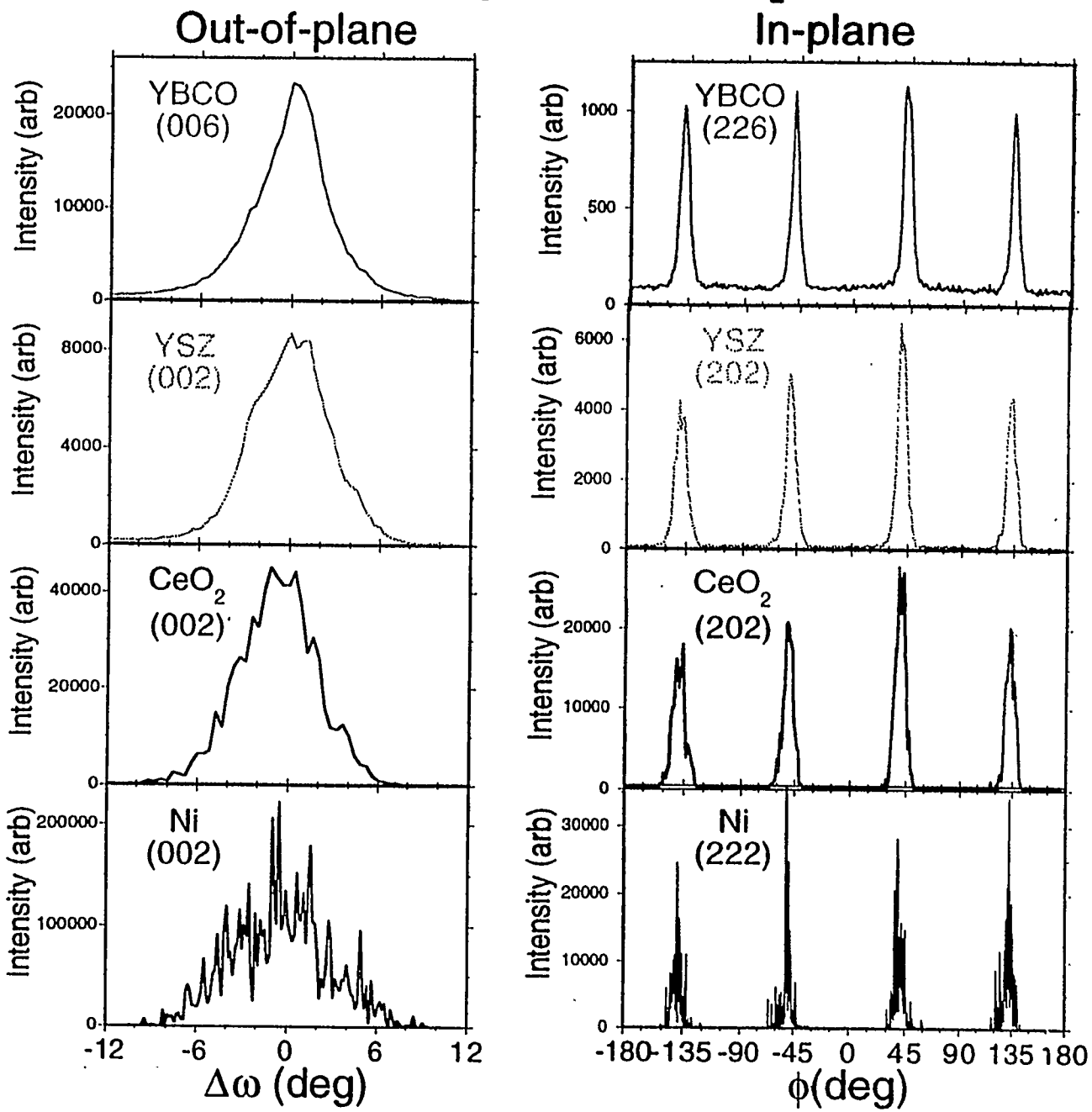
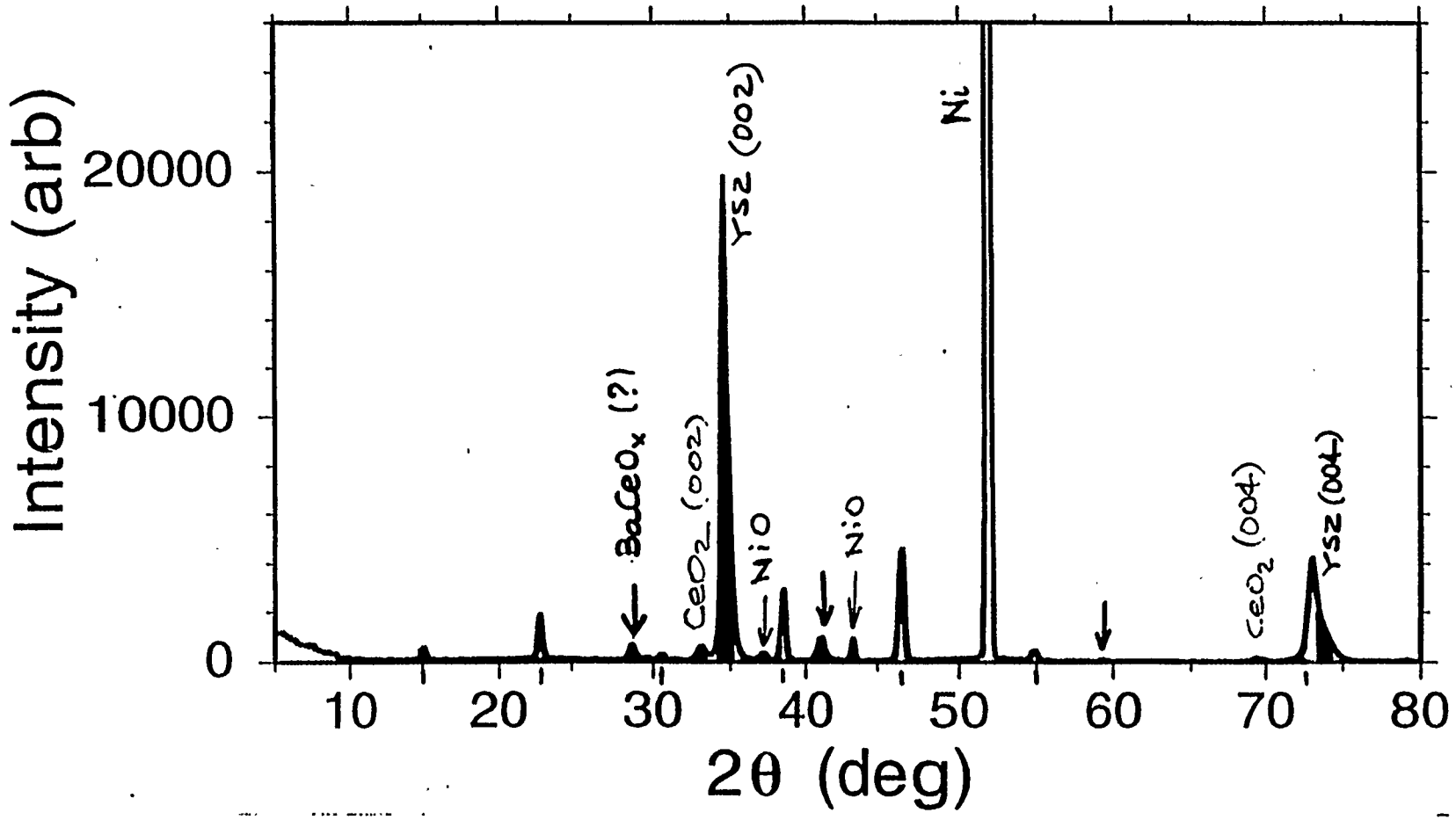
PLD Buffer: CeO_2 / YSZ / CeO_2 / Rolled Ni



Evap. - Sputter Buffer: CeO_2 / YSZ / CeO_2 / Rolled Ni

θ- 2θ scan



BaF_2 process for high-J_c YBCO films on metal substrate *(cont.[d])*

deposition precursor film:

- ✡ **strongly relaxed control requirements facilitate scale-up**
  - long deposition times (long cable lengths)
  - high rates
- ✡ application of non-vacuum techniques

➢ <u>post-deposition anneal</u>

- enhanced oxidation of precursor film
- dissociation of BaF_2
- nucleation and growth of YBCO epitaxial structure
- minimal thermal budget: stability of artificial substrate

here (demonstrated):

performed in tube furnace	gas flow, 1 atm total pressure
gas ambient	O_2 (< 500 ppm) + H_2O (<3%)
annealing (reaction) temperature	740 °C
duration	1 hr (film thickness 0.3 μm)

➢ <u>Oxidation anneal</u>:

optimization of carrier concentration in orthorhombic YBCO

- 500 °C / 1 atm O_2 / 0.5 hr / slow cooling

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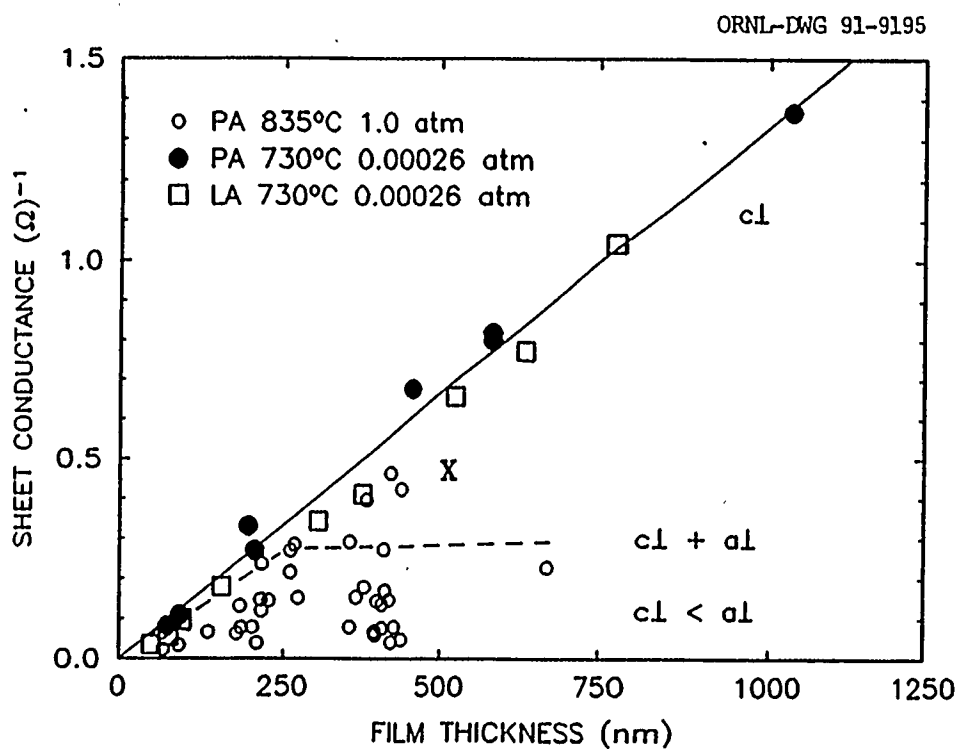
Critical thickness for c-axis growth

★ *transport properties controlled by anisotropy: c-axis epitaxy essential*

★ *ex situ processing ↔ layer-by-layer growth*

★ *early results indicate: c-axis growth enhanced at low $p(O_2)$*

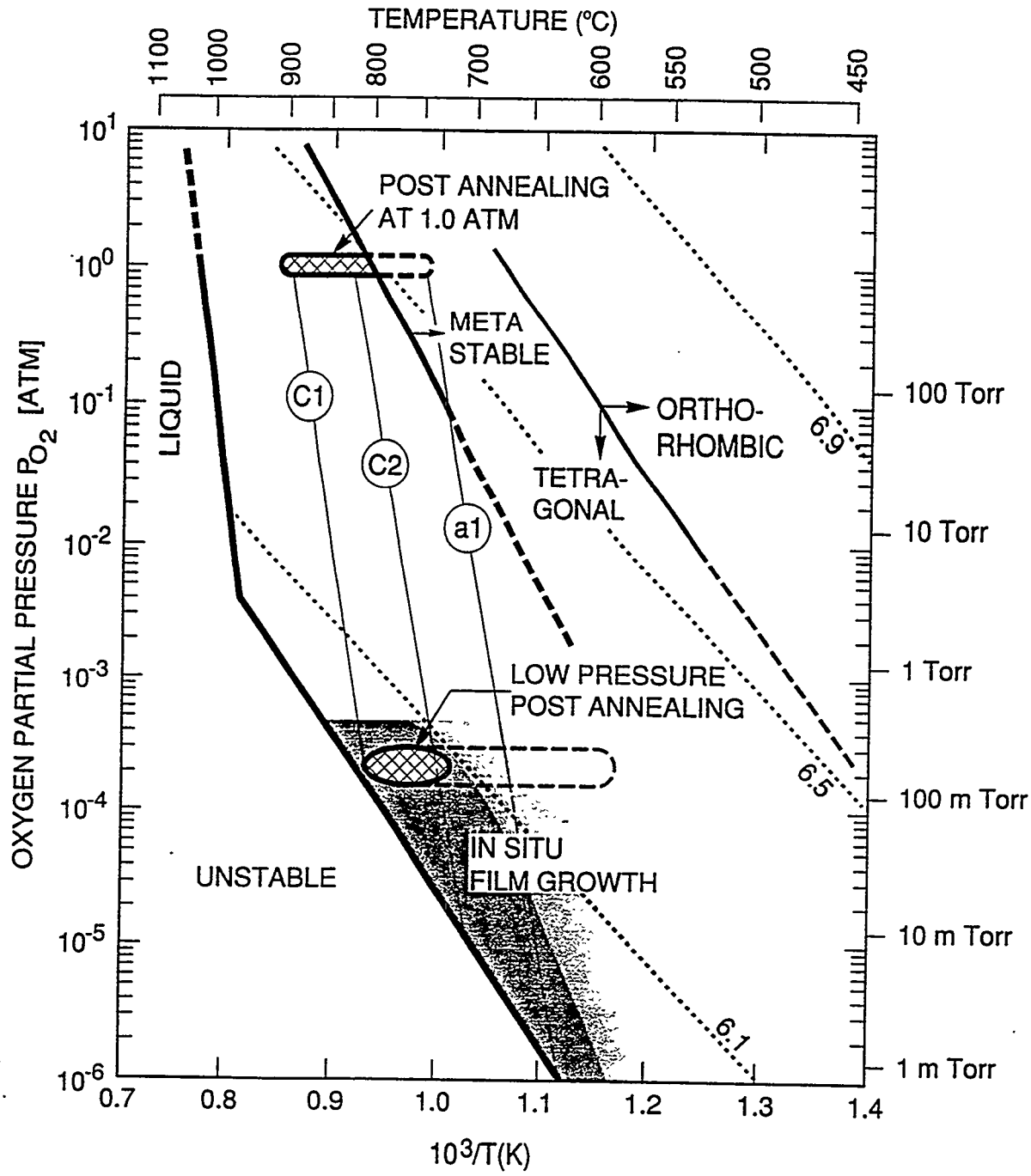


299

Processing diagram $YBa_2Cu_3O_x$ films

BaF_2 method

[Feenstra, Lindemer et al., *J. Appl. Phys.* **69**, 6569 (1991)]



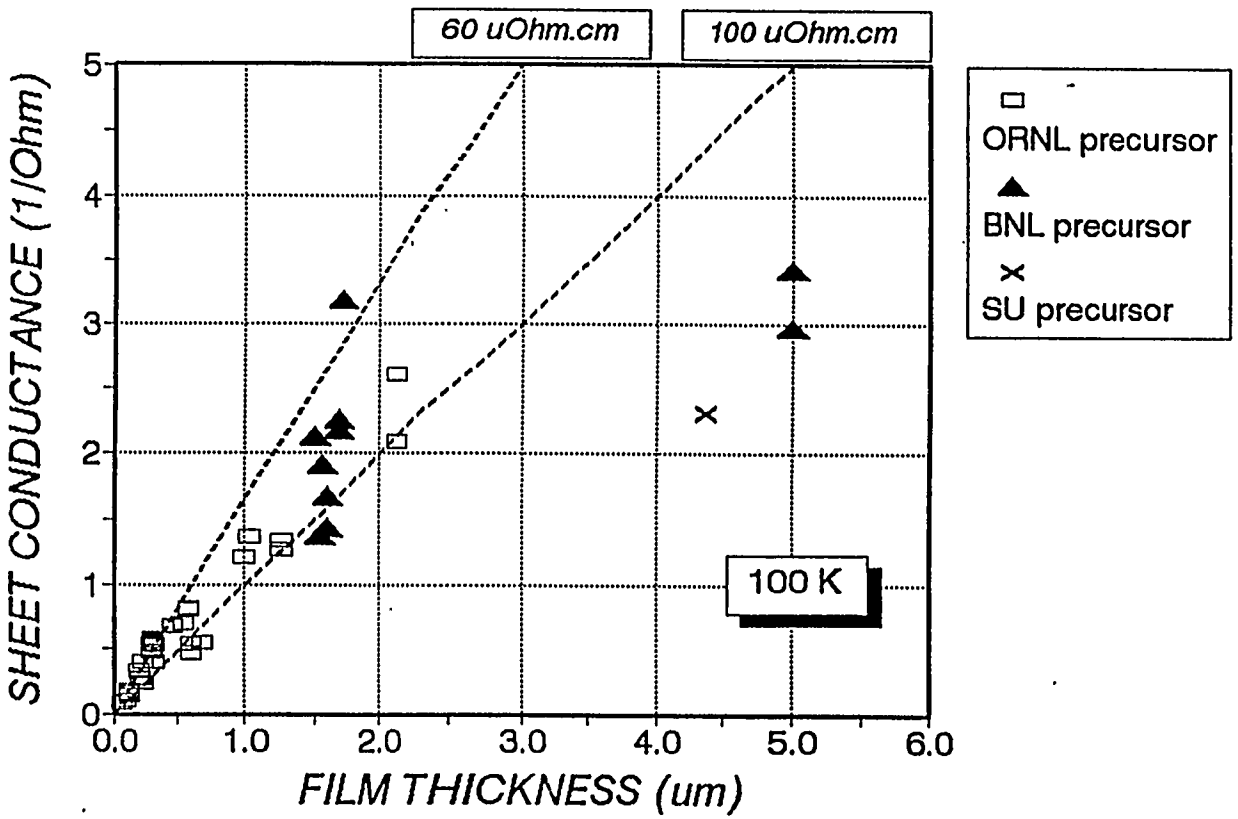
300

Critical thickness for c-axis growth: *beyond 1 μm*

★ *thick precursors films deposited at ORNL (multiple deposits), BNL, and SU.*

★ *chemical anneal at ORNL: 740-780 °C, low p(O_2), 1-16 hr*

★ *c-axis critical thickness expanded to (at least) 2 μm*



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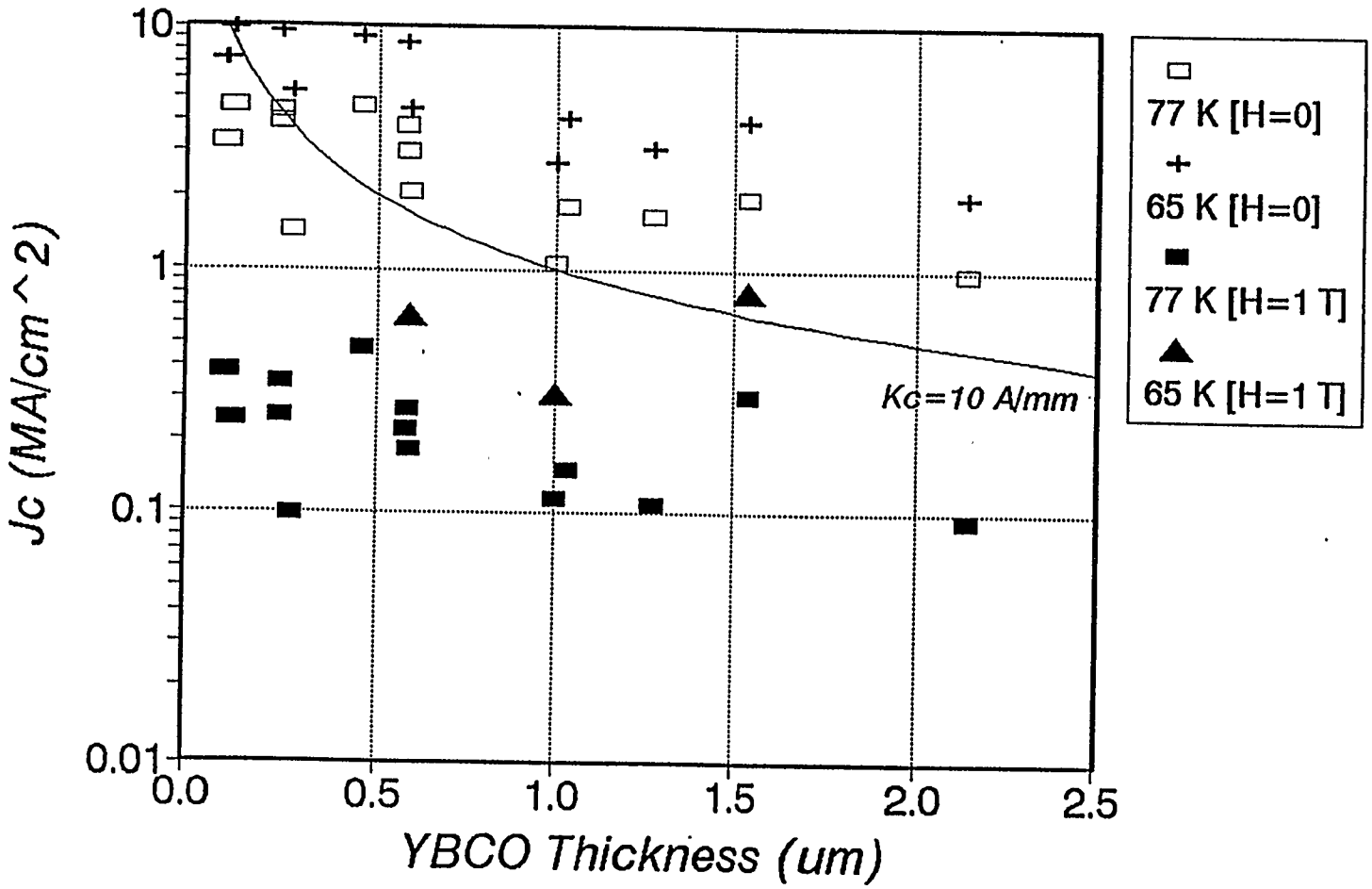
Critical thickness for c-axis growth: J_c

★ *zero applied magnetic field: $J_c > 1$ MA/cm^2 at 77 K*

★ *J_c in magnetic field remains nearly constant*



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Summary

Synthesis of high-J_c YBCO films on artificial substrates with the BaF_2 method has been demonstrated

Critical thickness for c-axis growth has been expanded to (at least) 2μm (crystal substrate)

Near-term goals

- demonstrate thick films on RABiTS
- demonstrate BaF_2 method on IBAD

  IBAD-YSZ: *same chemistry as RABiTS buffer layer*
  IBAD-MgO: *find compatible cap layer(s)*

➢ 2 new evaporation systems coming on-line at ORNL

in situ buffer layer – BaF_2 precursor film deposition

I. **scale-up**: reel-to-reel deposition on tapes (radiant heater)
II. **basic studies**: multi-component buffer layers
metal-oxide interface (RHEED)

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Summary *(cont.^{d})*

Critical issues

- enhance reproducibility: *improve quality buffer layer*
  - *structure, morphology*
  - *chemistry* (CeO_2 reacts with BaF_2 precursor)
- growth mechanism during post-deposition anneal
  - *motion of growth front*
  - *role of fluorine (liquid phase?)*
  - *enhance critical thickness*
- film deposition: develop long-term monitoring techniques
  - *multiple sources: composition control*
  - *homogeneity of YBCO conductor*
- ***establish practical windows for processing parameters***

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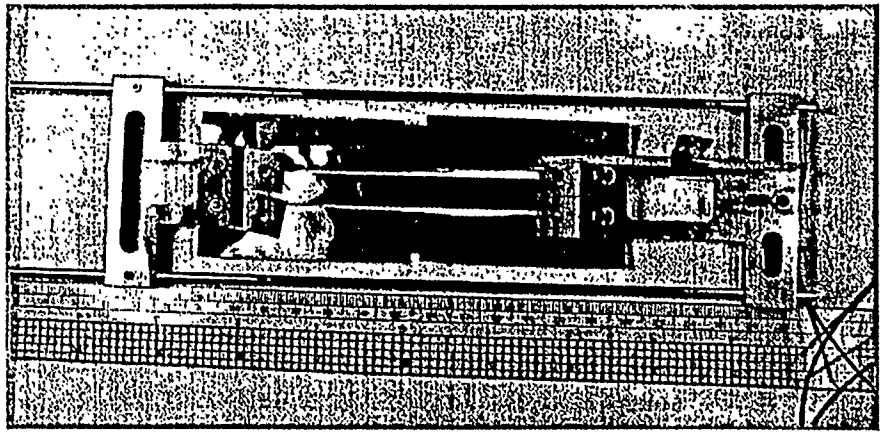
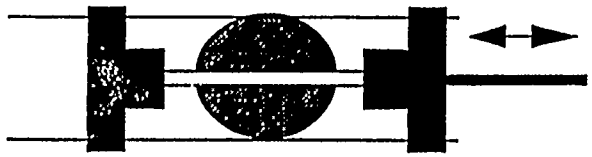
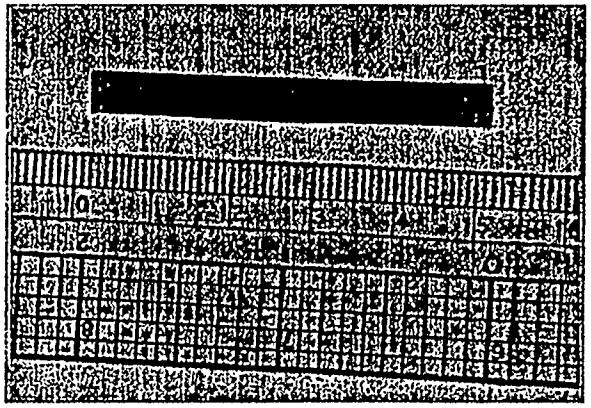
Synthesis of "Long-Length" Superconducting RABiTS™

A quartz lamp is used to radiantly heat rolled Ni tapes in a pulsed-laser deposition system



A linear translation sample holder can accommodate sample lengths up to 10 cm





Initial results for stationary 5 cm long samples have yielded $T_c \sim 87$ K, $J_c(77\text{ K}) \sim 270$ kA/cm^2

(contribution by Chan Park and David Norton)

305

YBCO Thick Films on $SrTiO_3$ by a BaF_2 Post Annealing Process

V. F. Solovyov, H. W. Wiesmann, Li-jun Wu,

R. Budhani, Y. Zhu, and M. Suenaga,

Brookhaven National Laboratory, Upton, NY 11973

and

R. Feenstra

Oak Ridge National Laboratory, Oak Ridge, TN 37831

Why ?

1) An electron beam deposition is an very high rate process (> 0.5 μm/min) and scaleable to an industrial process

2) The BaF_2 post annealing process does not require *in situ* formation of YBCO and is quite robust against composi-tional fluctuations.

3) What is not known is how thick a c-axis oriented film can be made.

Thus, **our initial objective** is

(1) to show whether it is possible to make films with > **5 μm** thick on $SrTiO_3$ substrates.

and other associated objectives are to investigate:

(2) $J_c(H)$ vs. thickness

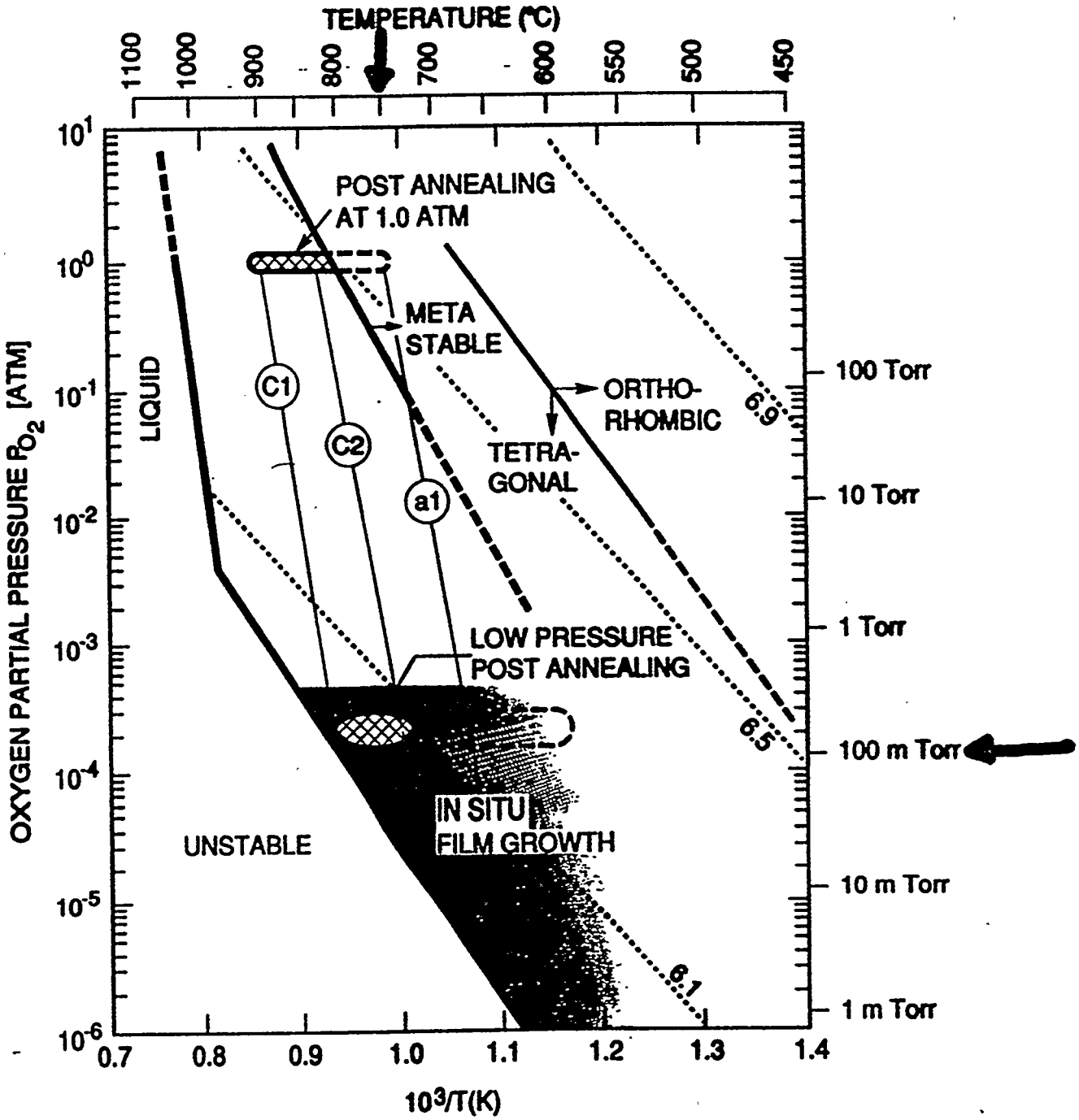
(3) Kinetics of the YBCO formation

(4) The growth rate and thickness limiting processes

Processing diagram $YBa_2Cu_3O_x$ films

BaF_2 method

[Feenstra, Lindemer et al., *J. Appl. Phys.* 69, 6569 (1991)]



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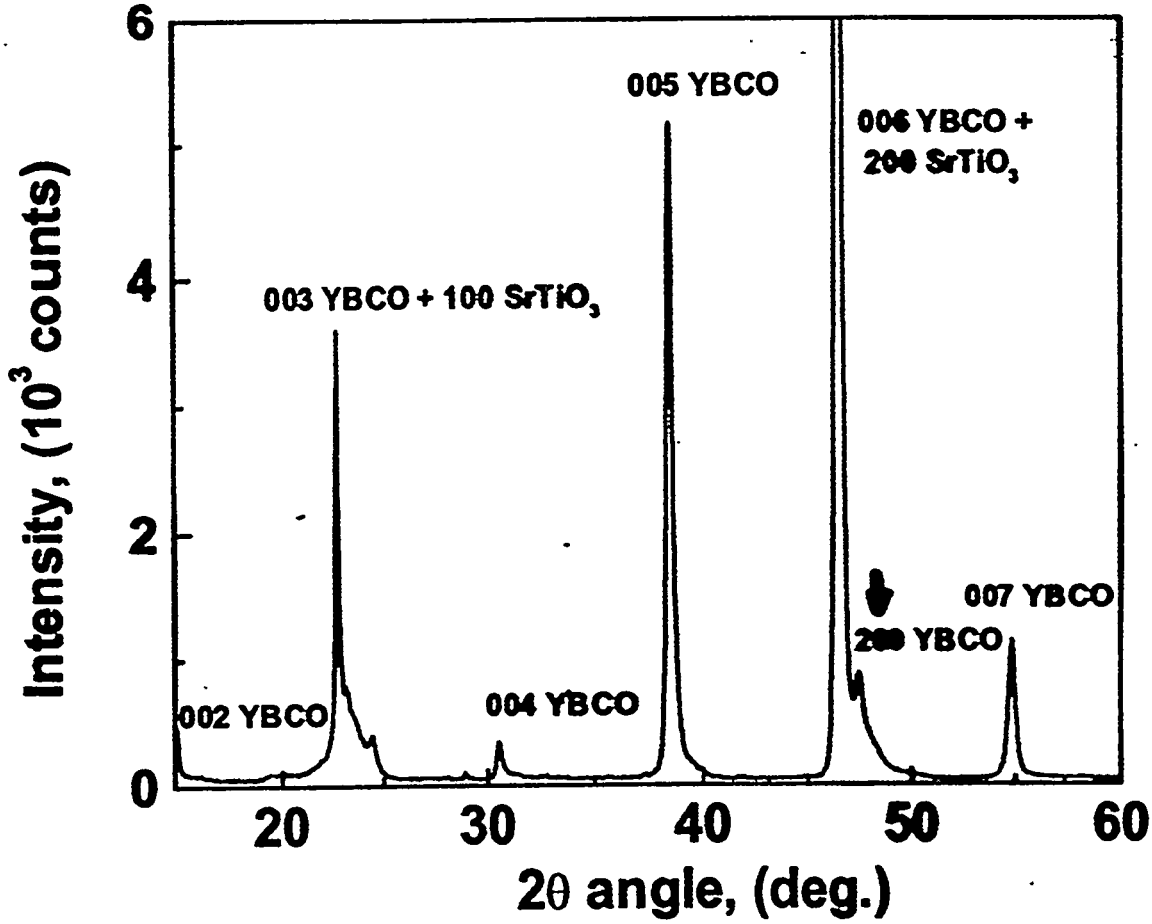
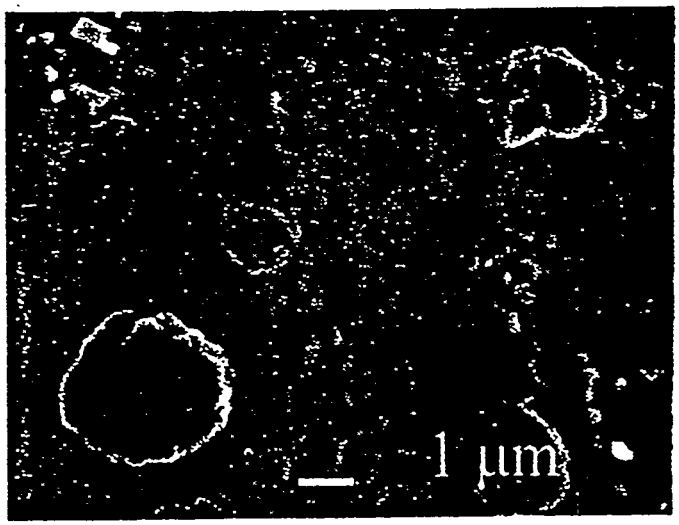
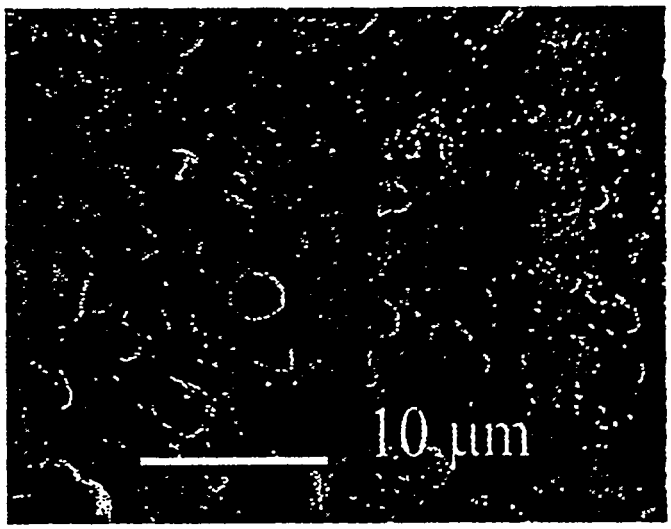
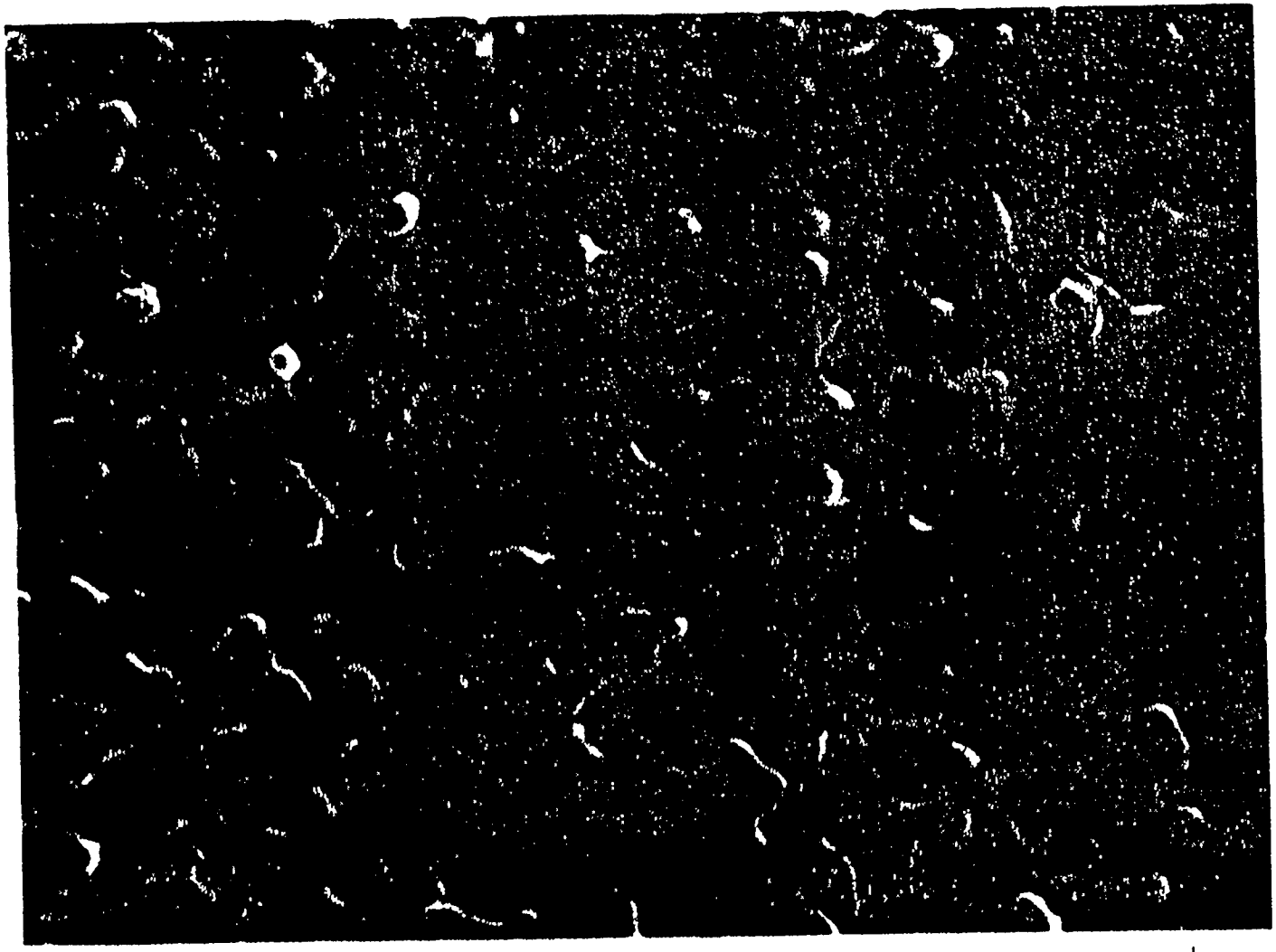
Brookhaven National Laboratory

Powder diffraction spectrum and SEM micrographs of 3 μm YBCO film crystallized under optimized conditions: 725° C 120 mTorr









1 μm

a 2.5 μm thick film

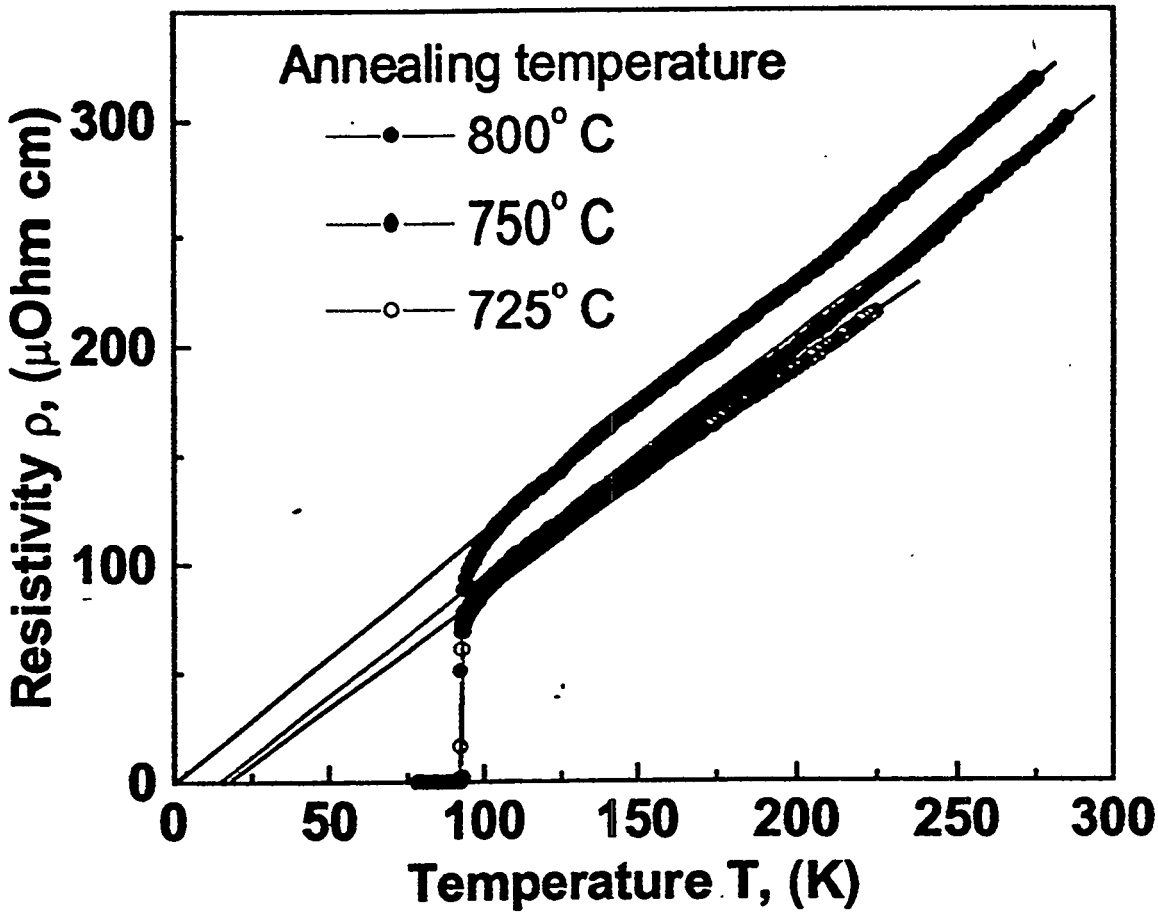
Brookhaven National Laboratory

Annealing temperature dependence of the critical current density

We prepared three 3 μm thick films, deposited at 100 A/s rate. The films were annealed at optimized conditions:

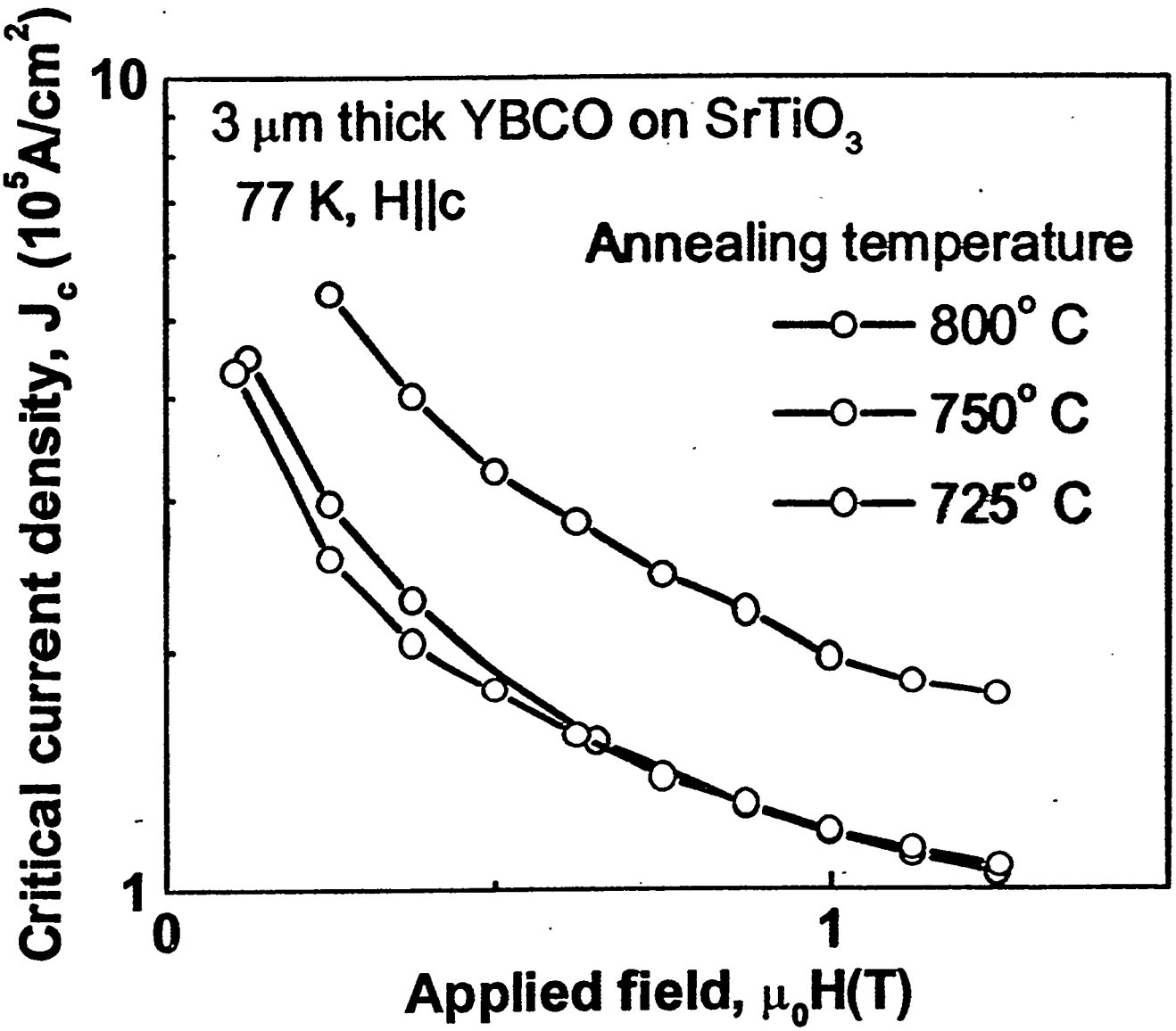
Annealing temperature C°	O_2 pressure mTorr	Annealing time hr
800	330	3
750	120	10
725	120	14

XRD show c-orientation and temperature dependence of the films resistivity evidence for weak-link free behavior of the films:

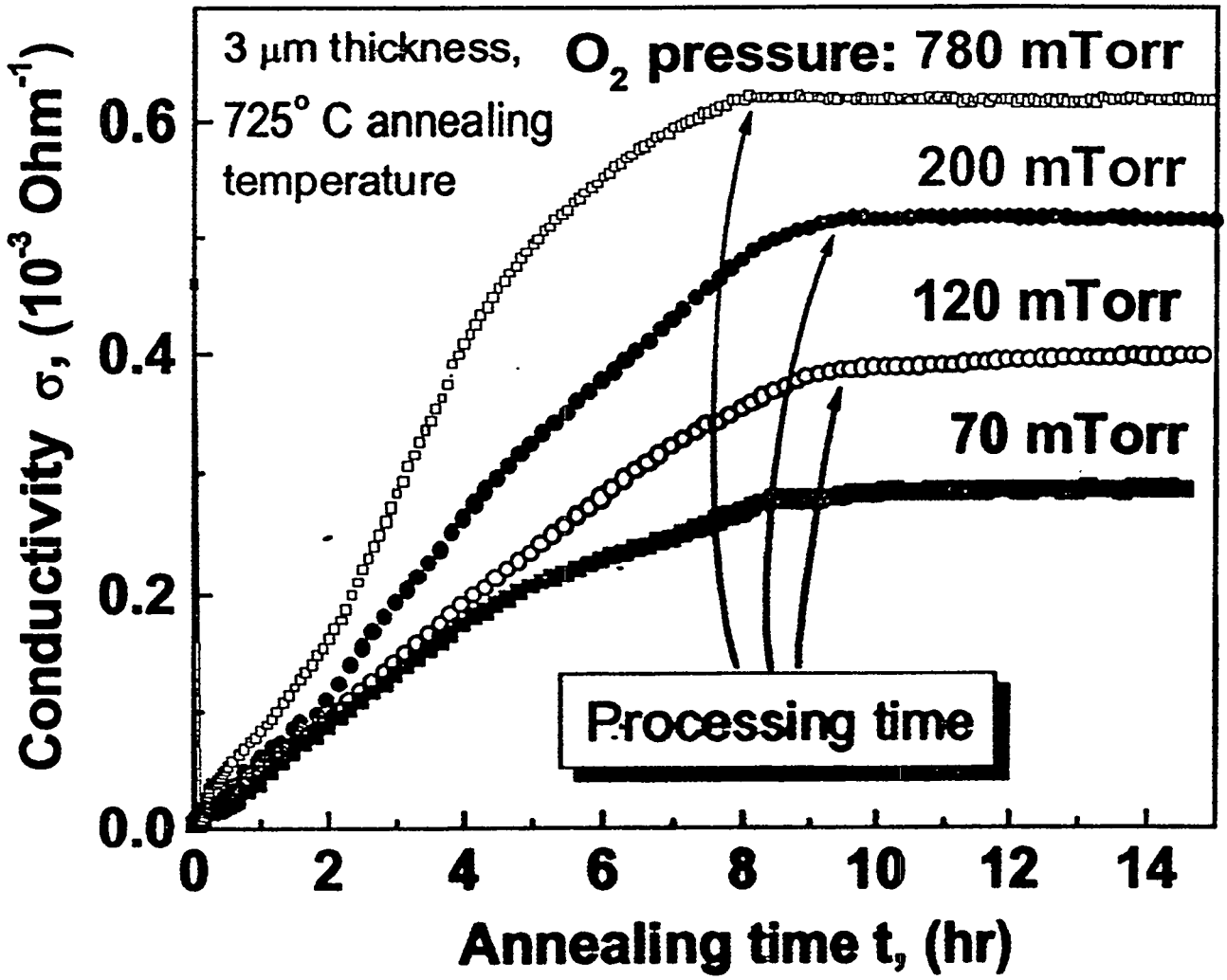


Measurements of the J_c by DC four probe method at 1 μV/cm electric field strength resulted in the following $J_c(H)$ and $J_c(\theta)$ dependences (here θ-angle between *C*-axis and applied field vector **H**):

Field dependences of the critical current density for 3 μm YBCO films processed at 800, 750, 725 C.

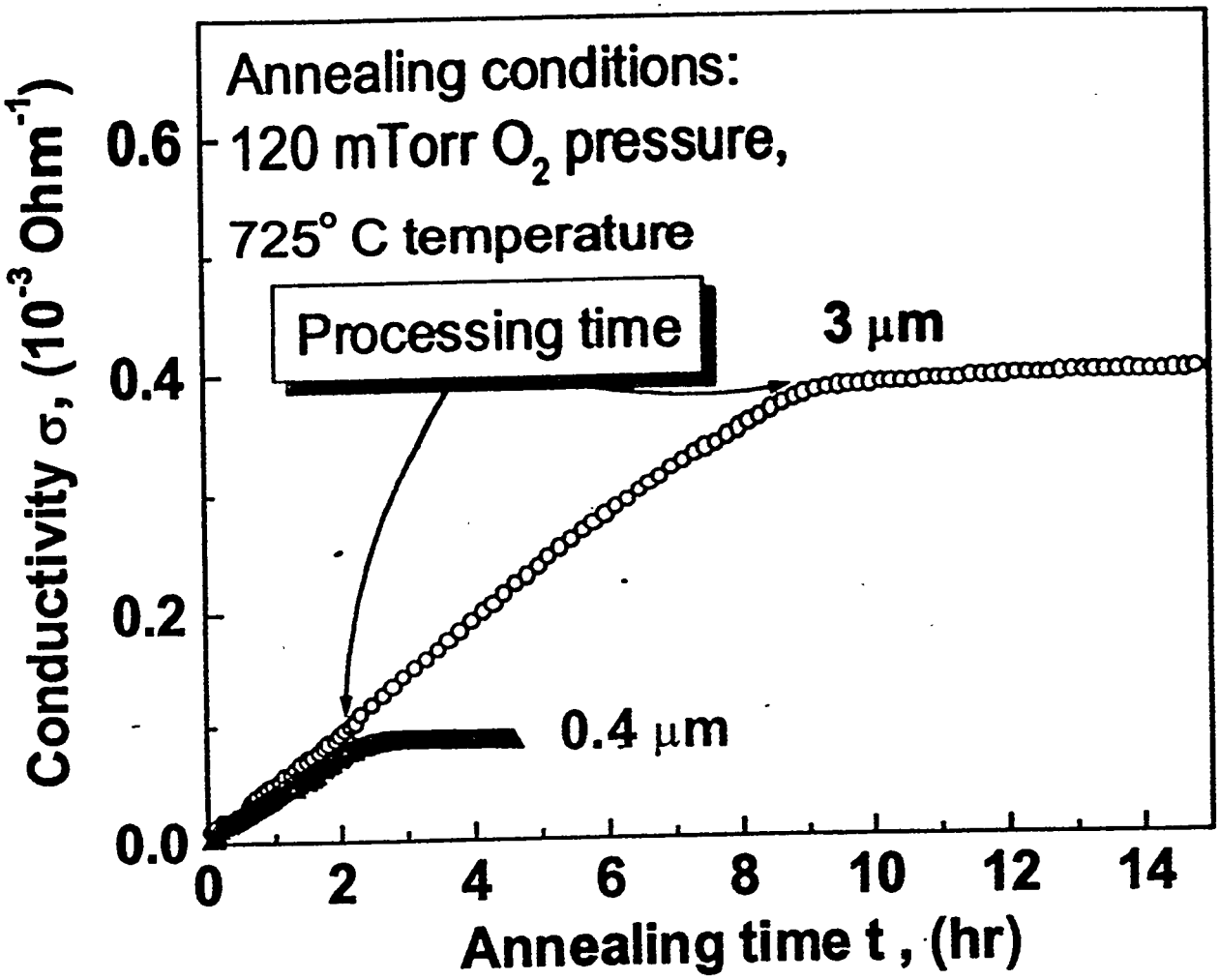


Variation of the *in-situ* film conductivity σ(t) curves as the oxygen partial pressure in the annealing atmosphere is changed from 70 to 780 mTorr at 725° C annealing temperature.



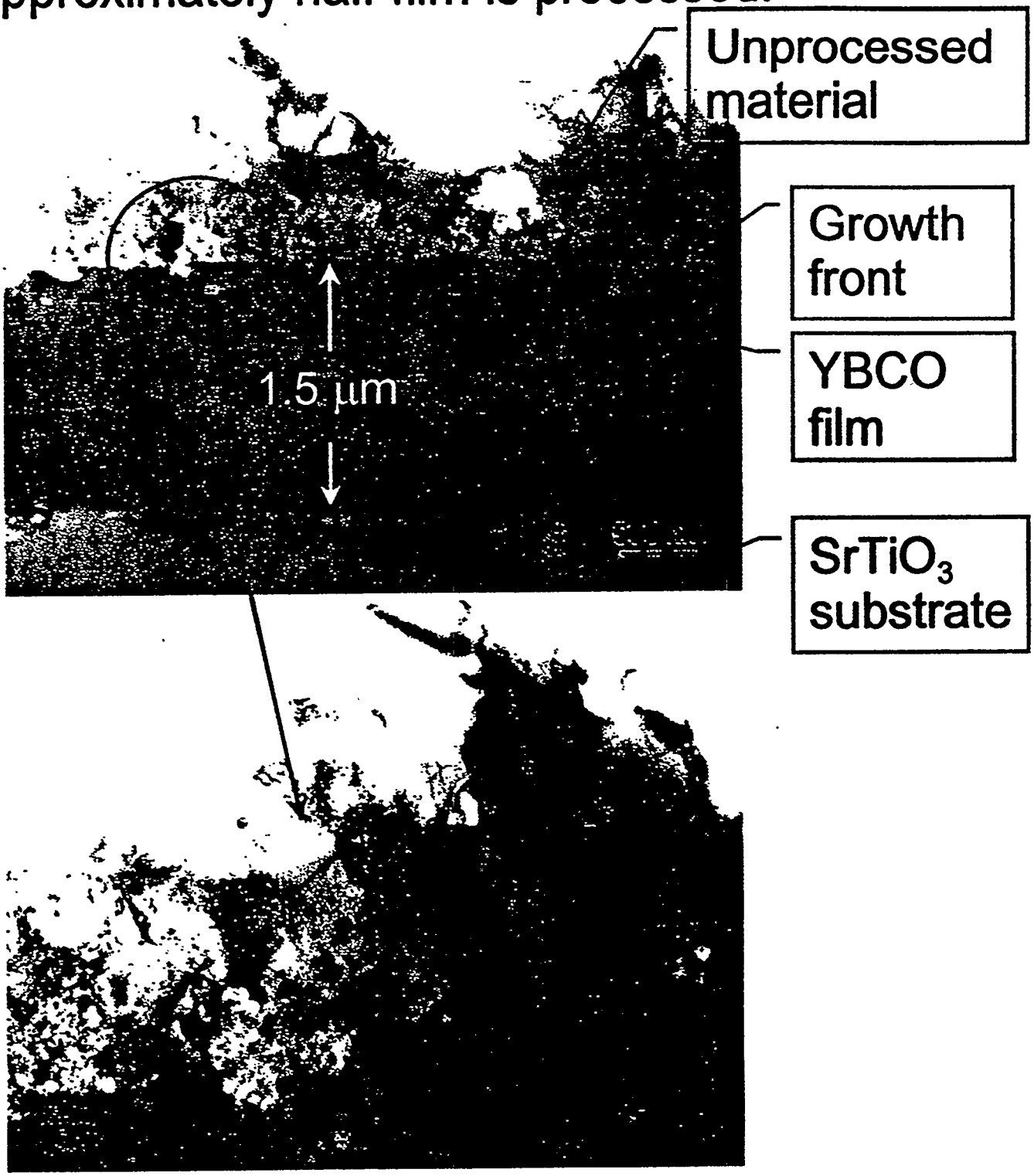
The results show that the processing time change 10% while the oxygen partial pressure is increased by an order of magnitude and growth habit of the film changed from purely C⊥substrate (120 mTorr)

to predominant C||substrate (780 mTorr). The film with optimum properties (120 mTorr) is characterized by linear change of the conductivity, which means uniform advance of flat growth front. The equivalent "growth rate" under these conditions is ≈1 Å/s. The following figure demonstrates **thickness variation of the σ(t) curve**. We observe some thickness dependence of the σ(t) slope, the fact indicates on influence of surface effects on the growth dynamics.

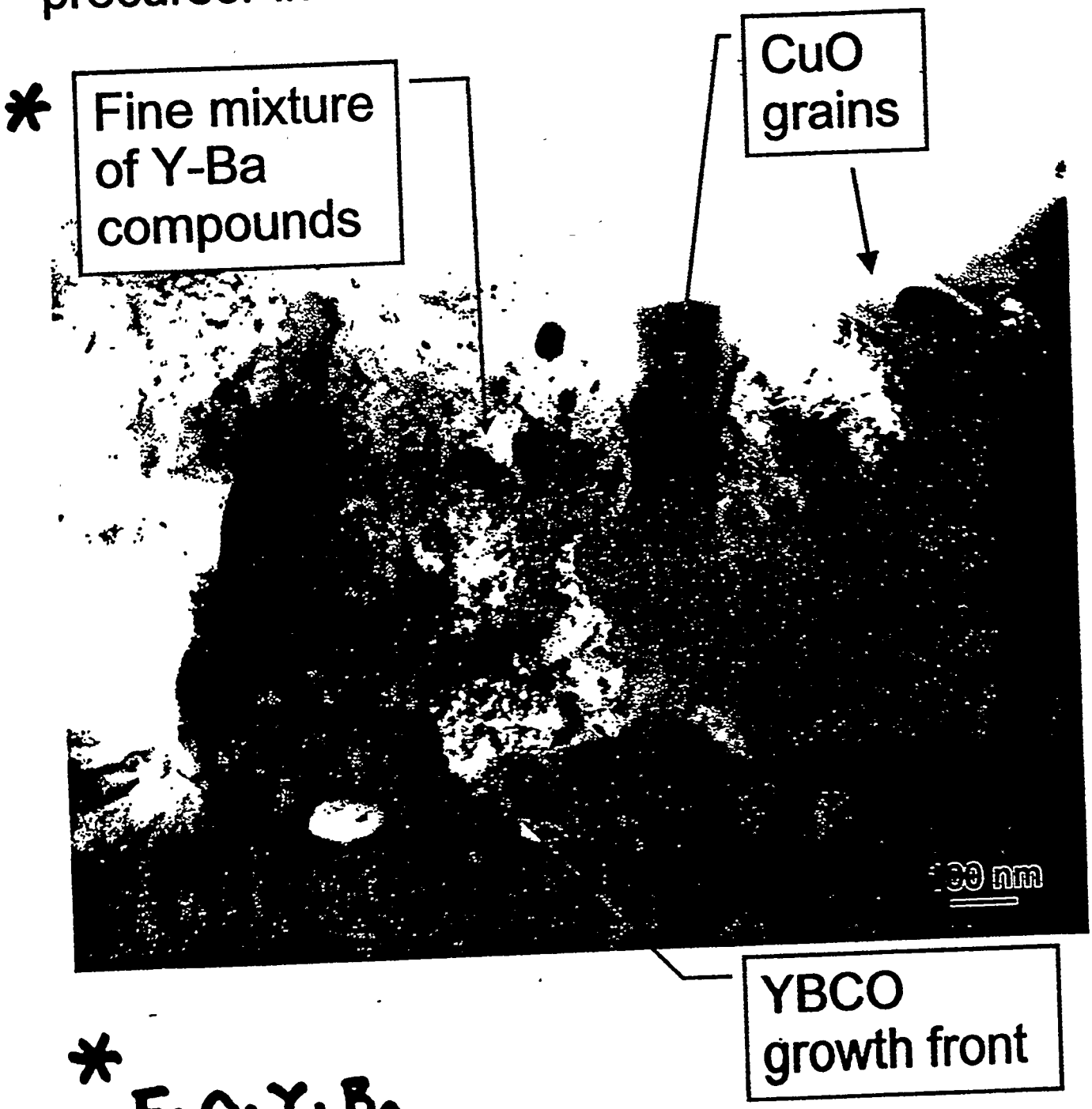


Brookhaven National Laboratory

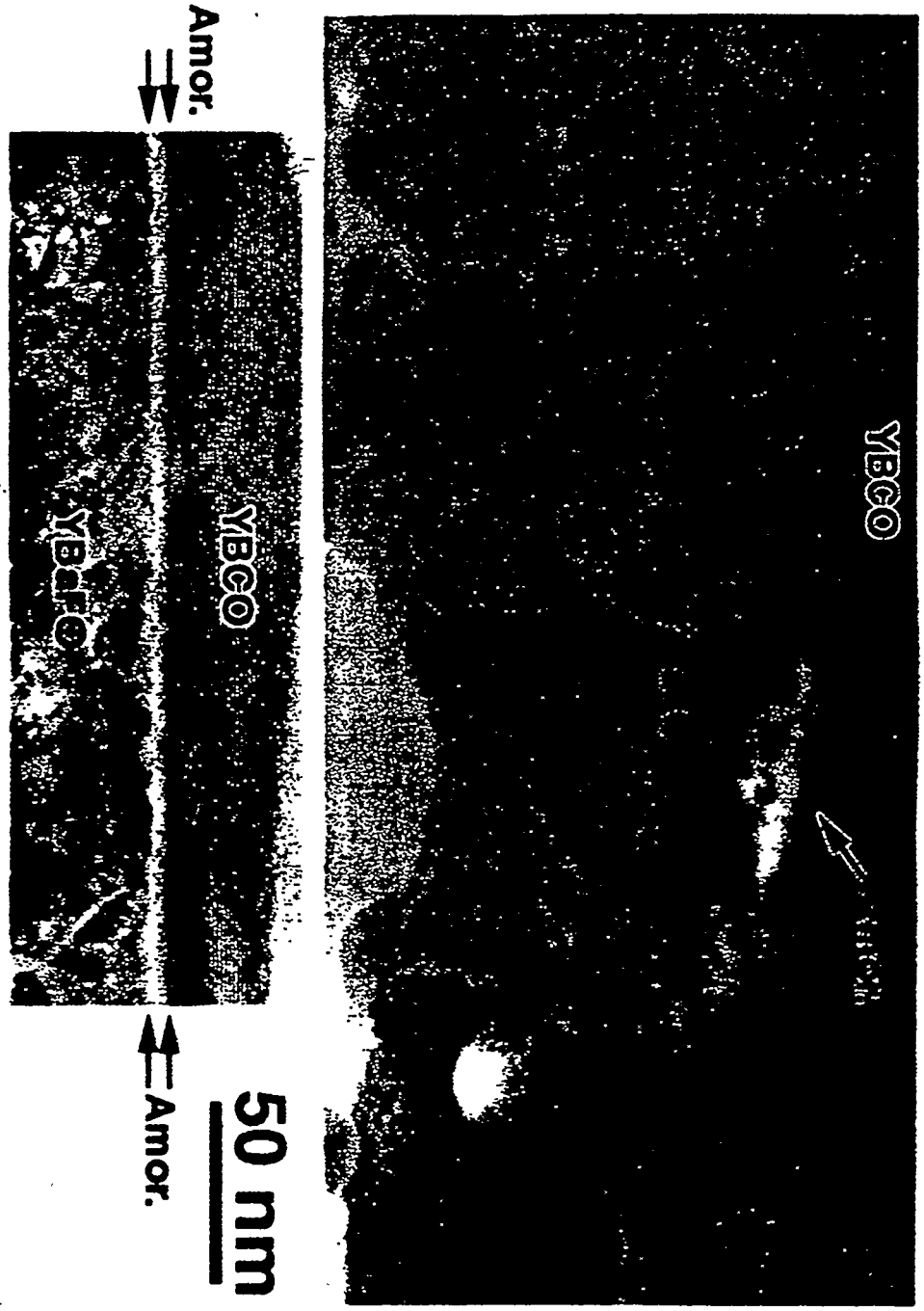
TEM micrographs showing YBCO film growth front. 3 μm film, annealing at 750° C for 5 hr, approximately half film is processed.



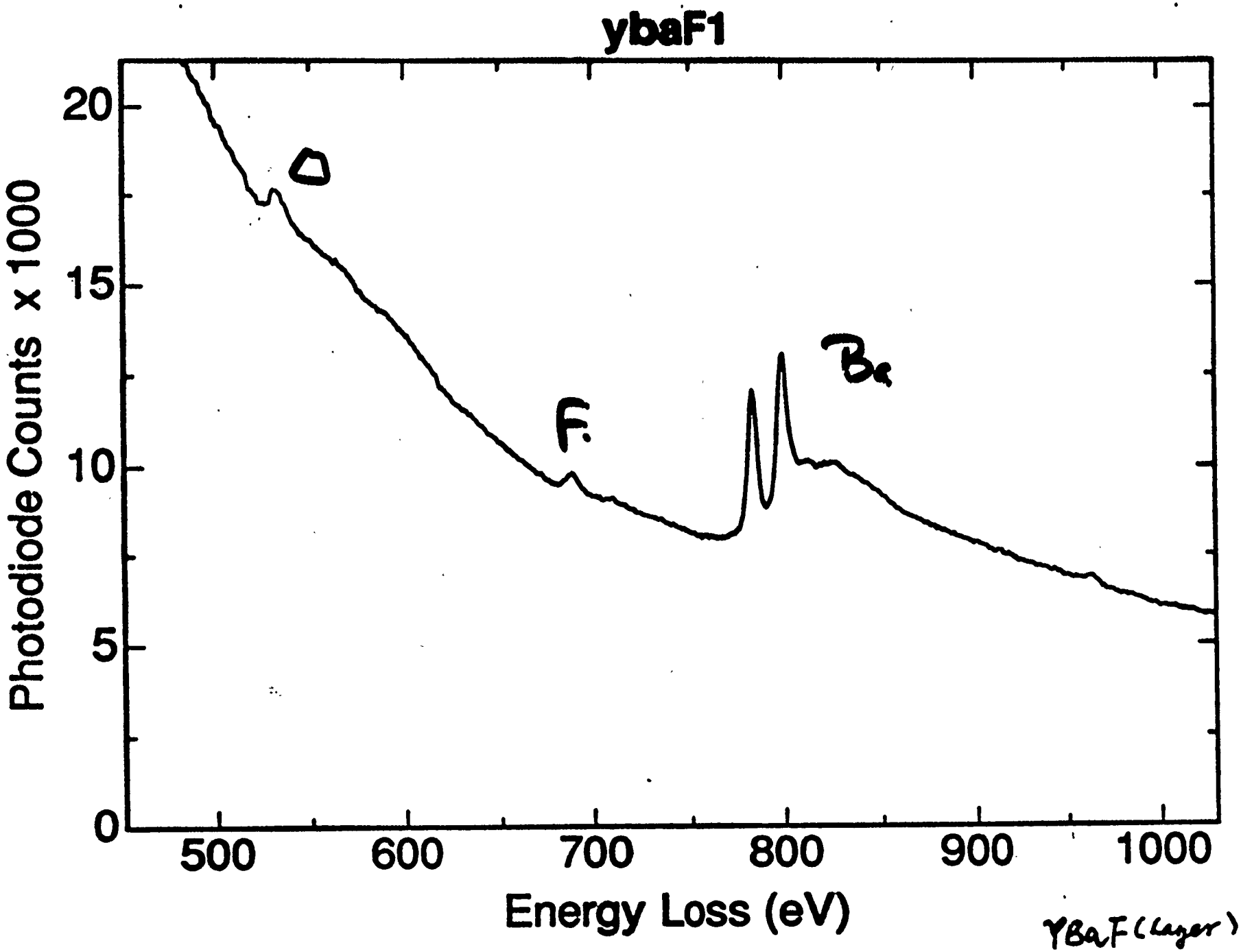
TEM micrograph showing details of the epitaxial growing YBCO - amorphous precursor interface.

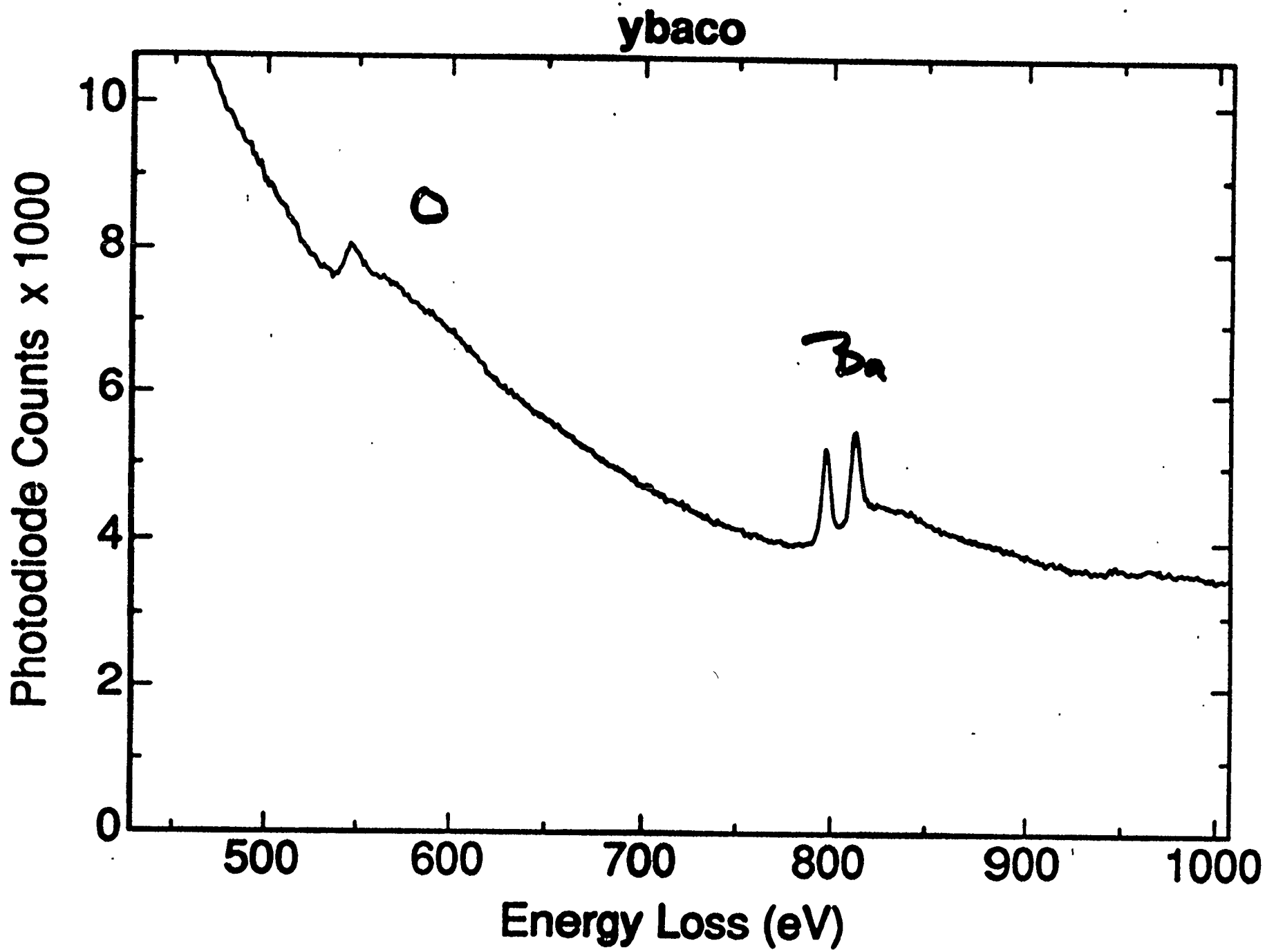


* F·O·Y·Ba
fcc; $a > a_{BaF_2}$


YBCO
YBCO
YBFCO
Amor.
Amor.
50 nm

Electron Energy Loss Spectroscopy (EELS)




ybaco
Photodiode Counts x 1000
0
2
4
6
8
10
500
600
700
800
900
1000
Energy Loss (eV)
O
Ba

320

What we know so far from the preliminary results:

1) the deposition rate > 0.6 μm/min

2) the evaporation of BaF_2 is by a thermal source.

3) we have shown that YBCO layers thickness can be greater than 3 μm, (and we will most likely be able to make ~ 5 μm thick layer.)

4) the growth of YBCO layers are from the substrate. No nucleation of YBCO at the top surface was noted.

What we do not know yet: **a lot ??**

Effects of .....on the growth rates, the maximum thickness, Jc, etc.

.....

(1) the gas flow rates

(2) the moisture contents in the gas

(3) the compositions

Kinetics of the growth

(1) when does the a-layer form ?

(2) what is the role of water ?

(3) what promotes the nucleation of the a-axis oriented grains in very thick films ?

Some of other issues are:

(1) Is it possible to make a double or a sequential coating ?

(2) What is the best buffer layer ?

(3) Require improvements in the instrumentation for deposition rate monitoring.

(4) Yields ?

INTERNATIONAL PERSPECTIVE ON 2nd GENERATION WIRE DEVELOPMENT*

U. (Balu) Balachandran

Argonne National Laboratory

Presented at the U.S. DOE Wire Development Workshop, St. Petersburg, FL, Jan. 29-30, 1998

* Work supported by the U.S. Dept. of Energy, Energy Efficiency and Renewable Energy.

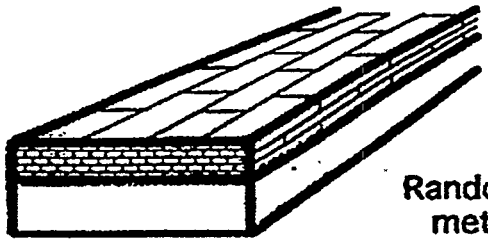
MAJOR PLAYERS INVOLVED IN THE COATED-CONDUCTOR RELATED R&D (non-USA)

Fujikura	IBAD for YSZ; PLD, MOCVD for YBCO
Sumitomo	PLD for YSZ and YBCO
ISTEC	LPE for HTS
NRIM	Bias sputtering for YSZ; laser ablation for YBCO
Univ. of Munich	IBAD for YSZ; thermal co-evaporation for YBCO
Univ. of Gottingen	
Siemens	
Showa Electric	Dip coating and continuous thermal treatment (Bi-2212)
Hitachi	Hot-rolling Ag; spray-pyrolysis for Tl-1223

Aligned Buffer Layer and/or Substrate for Next Generation Wires (Japan)

IBAD

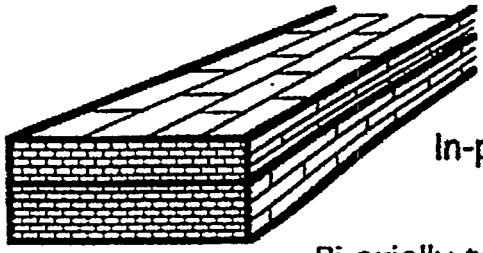
In-plane aligned oxide buffer layer



Ion Beem Assisted Vapor Phase Deposition

Randomly oriented metal substrate

RABiTS (CUTE)

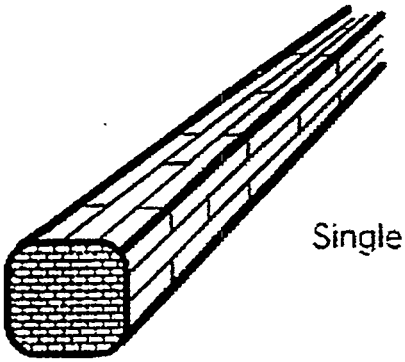


Oxide buffer layer

In-plane aligned metal substrate

Bi-axially textured metal substrate (by rolling & heat treatment)

Single Crystal Oxide Fiber



Single crystal oxide

Ref. ISTEC Report, Nov. 26, 1997

FUJIKURA

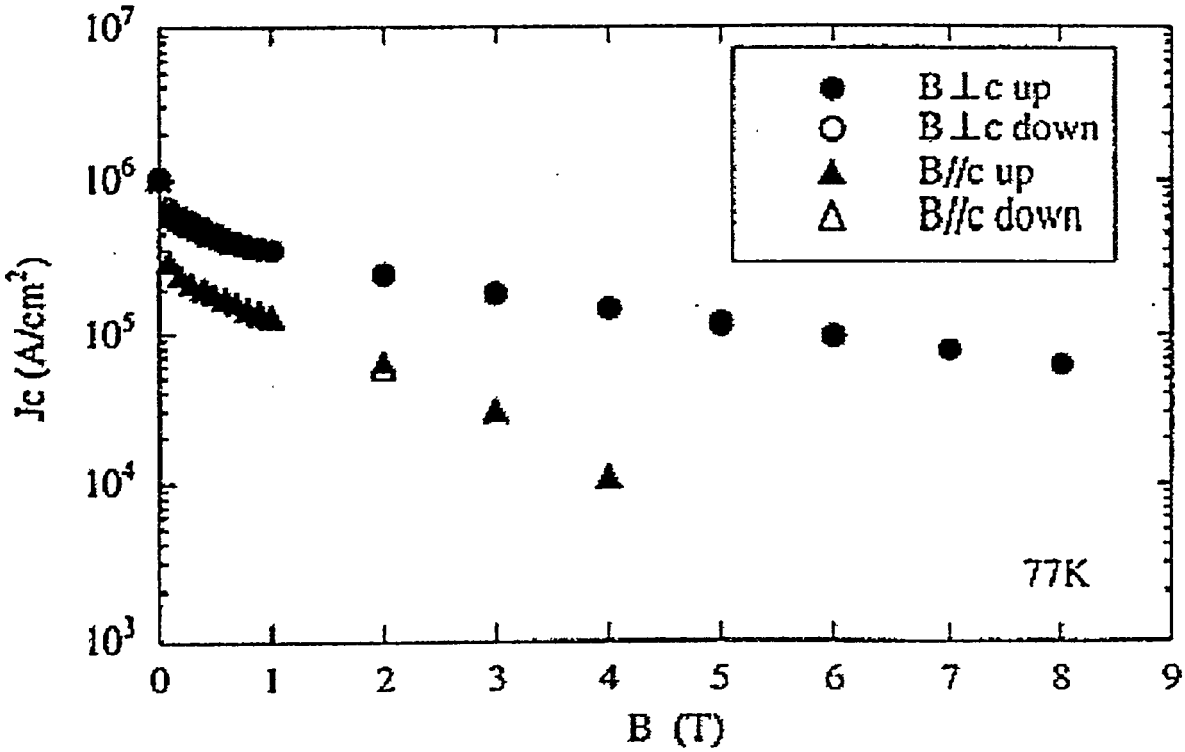
- IBAD for YSZ on Ni-alloy substrates and PLD; MOCVD for YBCO.
- Highest J_c (1-cm sample): 1.13×10^6 A/cm^2 at 77 K, 0 T; 1.1×10^5 A/cm^2 at 5 T ($B_{perp}c$).
- 1-m-long tape on Hastelloy substrate had been processed (IBAD/PLD).
  - I_c - 20 A, $J_c = 2.1 \times 10^5$ A/cm^2 (1 μm YBCO on 0.7 μm YSZ layer)
- YSZ deposition at 5 cm/h and YBCO at 1 m/h.

FUJIKURA (contd.)

- Continuous MOCVD reactor for YBCO film deposition.
- Hot-wall reactor with liquid delivery system is used.
- A 16-cm-long tape had a $J_c = 2 \times 10^5$ A/cm^2 ($I_c = 30$ A).
- Tape speed ≈30 cm/hr.

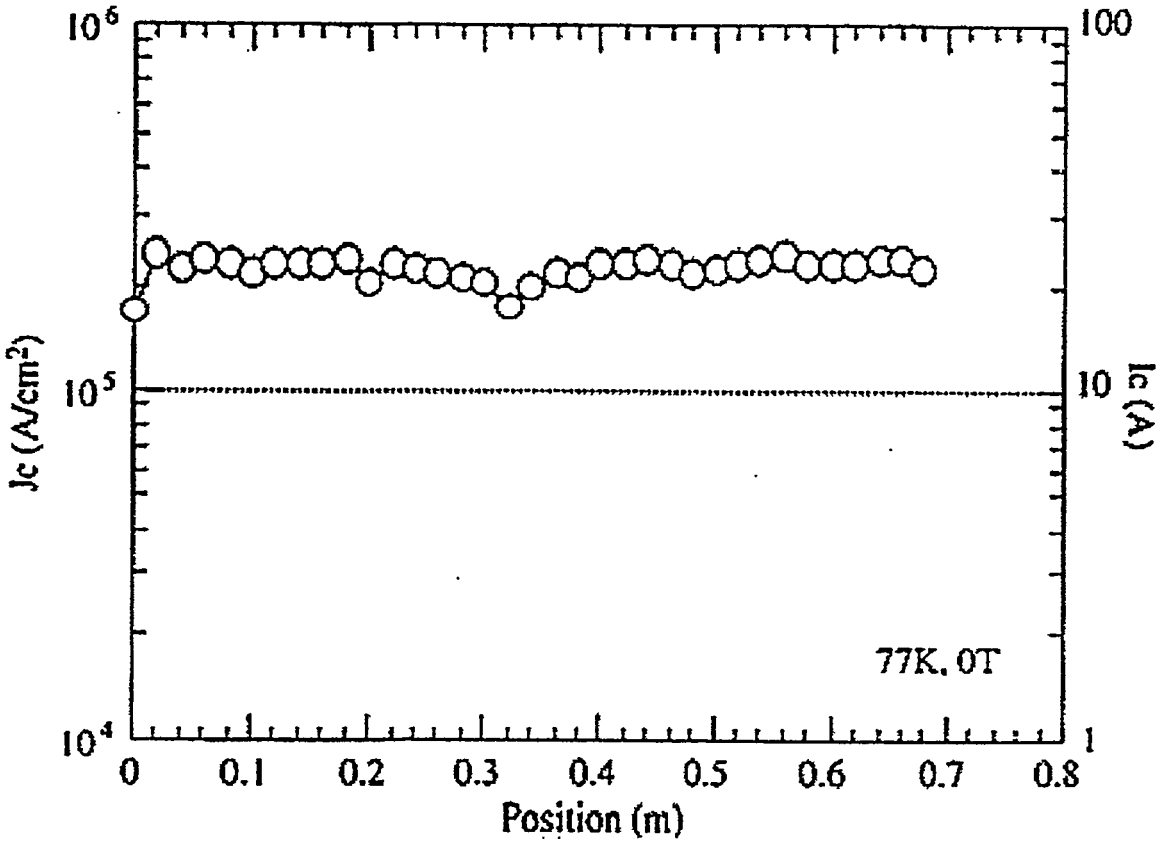
Ref: ISS '97, Oct. 1997.

Field Dependence of J_c at 77 K for high J_c Sample



Ref: M. Hosaka et al., 7/29/97 (Fujikura Ltd.)

Longitudinal J_c and I_c distribution in the 0.7 m YBCO tape (77 K, 0T)



Ref: M. Hosaka et al., 7/29/97 (Fujikura Ltd.)

SUMITOMO ELECTRIC INDUSTRIES

[Inclined Substrate Deposition-ISD]

- Substrate is Hastelloy tape (10 mm wide; ≈100 μm thick).
- Obtained in-plane textured YSZ by PLD (1-2 μm).
- YBCO has an in-plane FWHM = 12.8° (1-4 μm).
- Best $J_c = 4.3 \times 10^5$ A/cm^2 (77 K, 0T; $I_c = 42$ A on 3 μm YBCO).
- YSZ and YBCO deposition rate: 0.5 μm/min.
- $J_c = 3 \times 10^5$ A/cm^2 (10 cm); $J_e = 4000$ A/cm^2.
  $= 2 \times 10^5$ A/cm^2 (55 cm).
  $= 1.5 \times 10^5$ A/cm^2 (100 cm).
- Shielding type FCL fabricated using the YBCO tapes.

SUMITOMO

YBCO Deposition

- PLD of YBCO on $LaAl0_3$ crystal substrates.
- Double-sided deposition on 1-inch dia. substrate.
- $J_c = 10^6$ A/cm^2 on both sides at 77 K, 0 T.
- Single-side deposition on 3-inch dia. substrate ($J_c = 10^6$ A/cm^2).
- 3-inch film/0.4 micron thick formed within 20-minutes.

Ref: ISS '97, Oct. 1997.

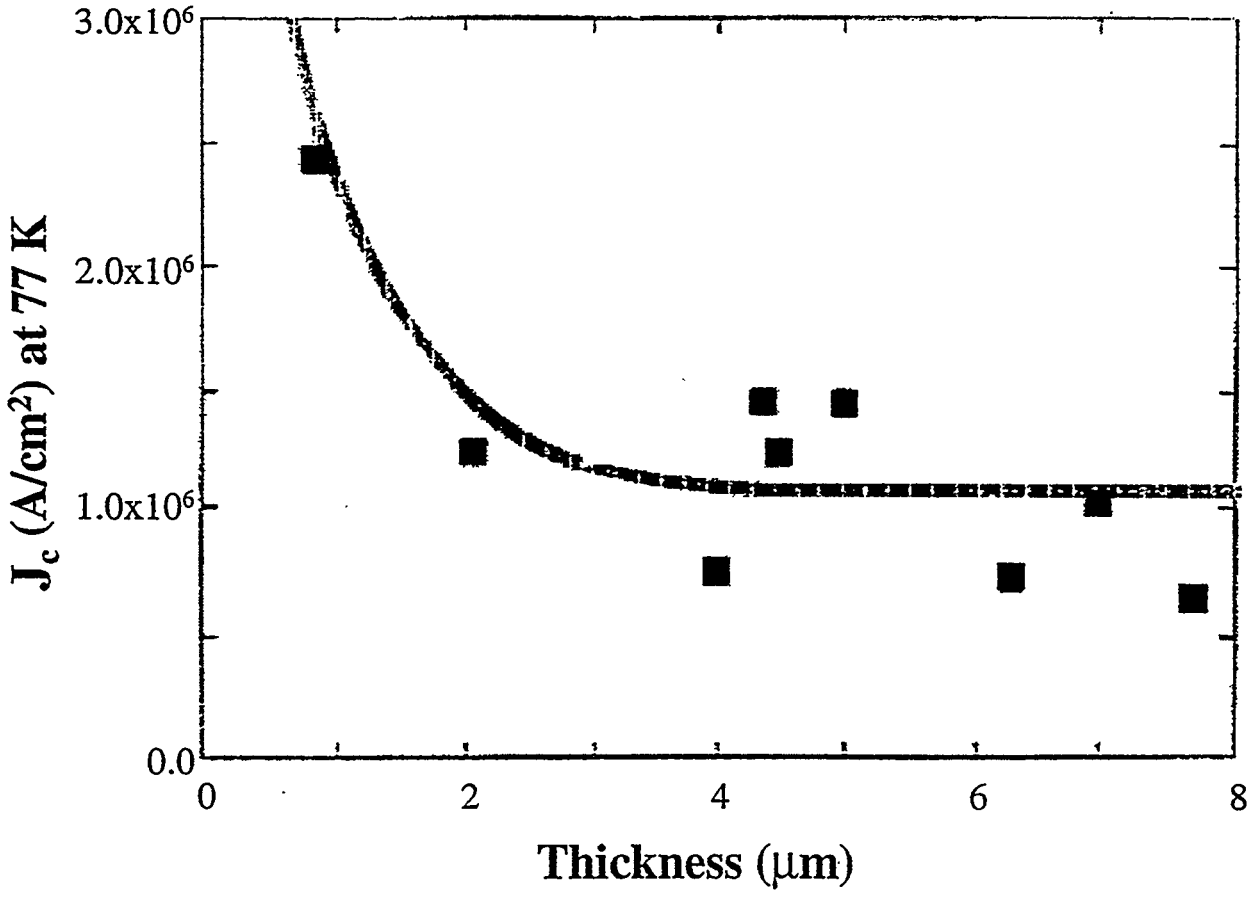
ISTEC

- Liquid phase epitaxy (LPE) of YBCO on MgO, $SrTiO_3$ fibers
- $J_c \approx 1 \times 10^6$ A/cm^2 for 10-μm-thick film on MgO fibers
- $J_c \approx 2.5 \times 10^6$ A/cm^2 for 1-μm-thick film on YSZ fibers

NRIM

- Textured YSZ is obtained by applying bias voltage to substrates
- rf sputtering system is used
- The substrates are tilted in a bias field (Ar ions impinge at ≈55°)
- $J_c \approx 3\text{-}5 \times 10^5$ A/cm^2

J_c (77 K) vs. Thickness of LPF grown YBCO film



Ref: ISTEC Report, Nov. 26, 1997.

SHOWA ELECTRIC

- Dip coating/continuous heat treatment of Bi-2212.
- $J_c \approx 1.3 \times 10^5$ A/cm^2 at 20 K, 0 T (100 m).
  $\approx > 10^5$ at 4.2 K, 21 T (100 m).

HITACHI

- Hot-rolled Ag to obtain cube texture (5 mm wide and 40 μm thick).
- Tl-free precursor deposited by spray pyrolysis at a rate of ≈1 m/hr.
- 50-m-long tape was continuously thallinated (0.5 m/hr).
- $J_c \approx 2 \times 10^4$ A/cm^2 at 77 K, 0 T (1-μm-thick film; 1-m-long)

GERMANY

- University of Munich (Kinder), University of Gottingen (Freyhart), and Siemens are working as a team.
- Kinder uses co-evaporation technique (≈650°C) to deposit uniform YBCO films on IBAD substrates (Freyhart) as large as 20 cm x 20 cm.
- $J_c = 0.7 - 2 \times 10^6$ A/cm^2 (on small regions of 20 cm x 20 cm film)
- $J_c \approx 7 \times 10^5$ A/cm^2 on a 10 cm x 10 cm IBAD substrate (small sample $J_c = 1.4 \times 10^6$ A/cm^2)
- Double-sided deposition was also reported
- $J_c \approx 2.5 \times 10^6$ A/cm^2 obtained in a two-sided, 5 cm $LaAlO_3$ wafer.
- Highest J_c of 4×10^6 A/cm^2 in a 400-nm-thick Nd-123 film.

SOME OF THE ISSUES

- Scale-up, cost, and in-situ monitoring.
- Possibilities for speeding IBAD/maximum possible throughput.
- Identify technical issues common to IBAD and RABiTs and those that are particular to each.
- Explore ways to speed the deposition of buffer and conductor layers.
- Explore the ways to thicken the YBCO film and to thin the substrate.
- Consider electrical and magnetic behavior of the substrate.
- Investigate whether Tl-1223 offers better performance than YBCO.

Ref: A. M. Wolsky, IEA report, March 24, 1997.

UNITED STATES DEPARTMENT OF COMMERCE

National Institute of Standards and Technology

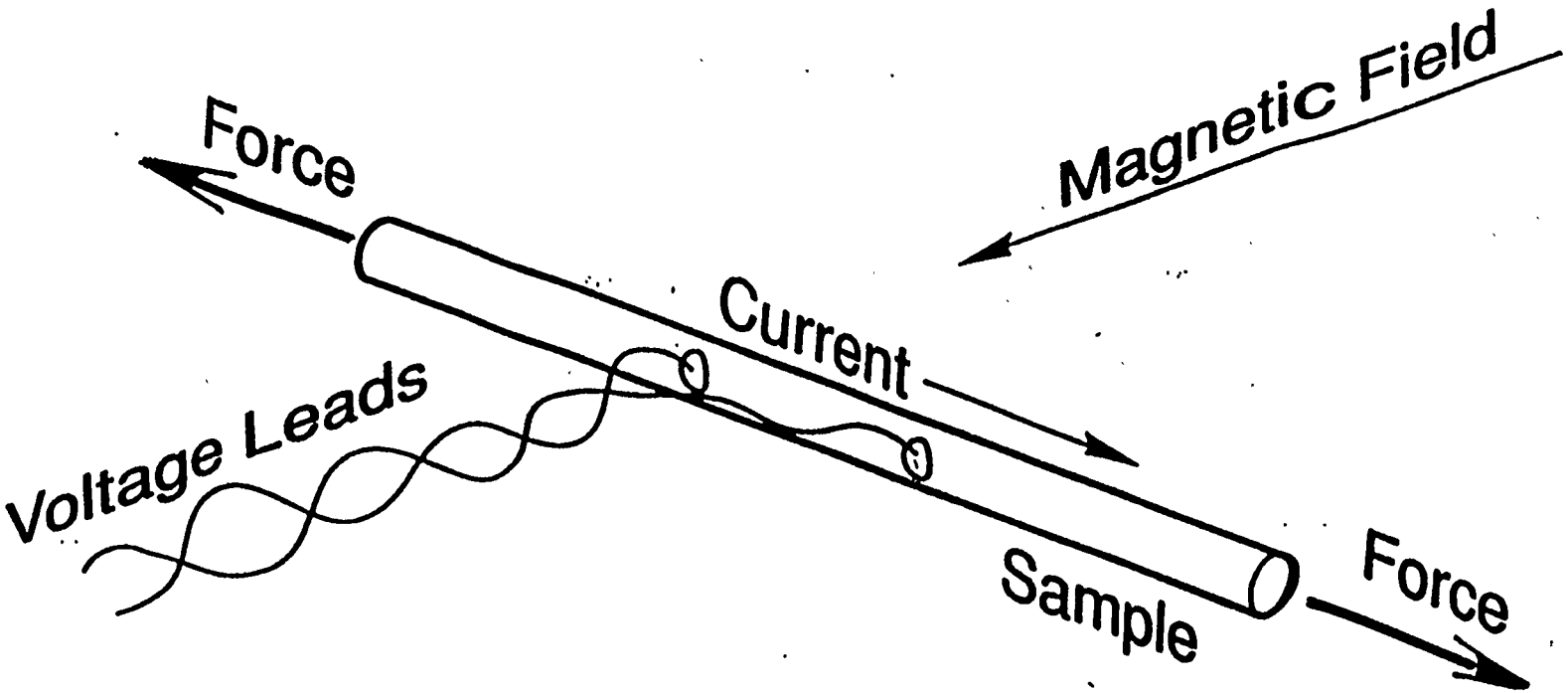
Electromechanical Properties of LTS and HTS

Jack Ekin, Steve Bray, Cam Clickner, & Yizi Xu

National Institute of Standards and Technology
Boulder, CO 80303

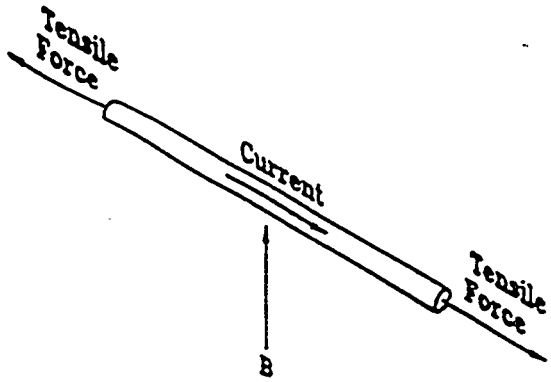
Talk Outline:

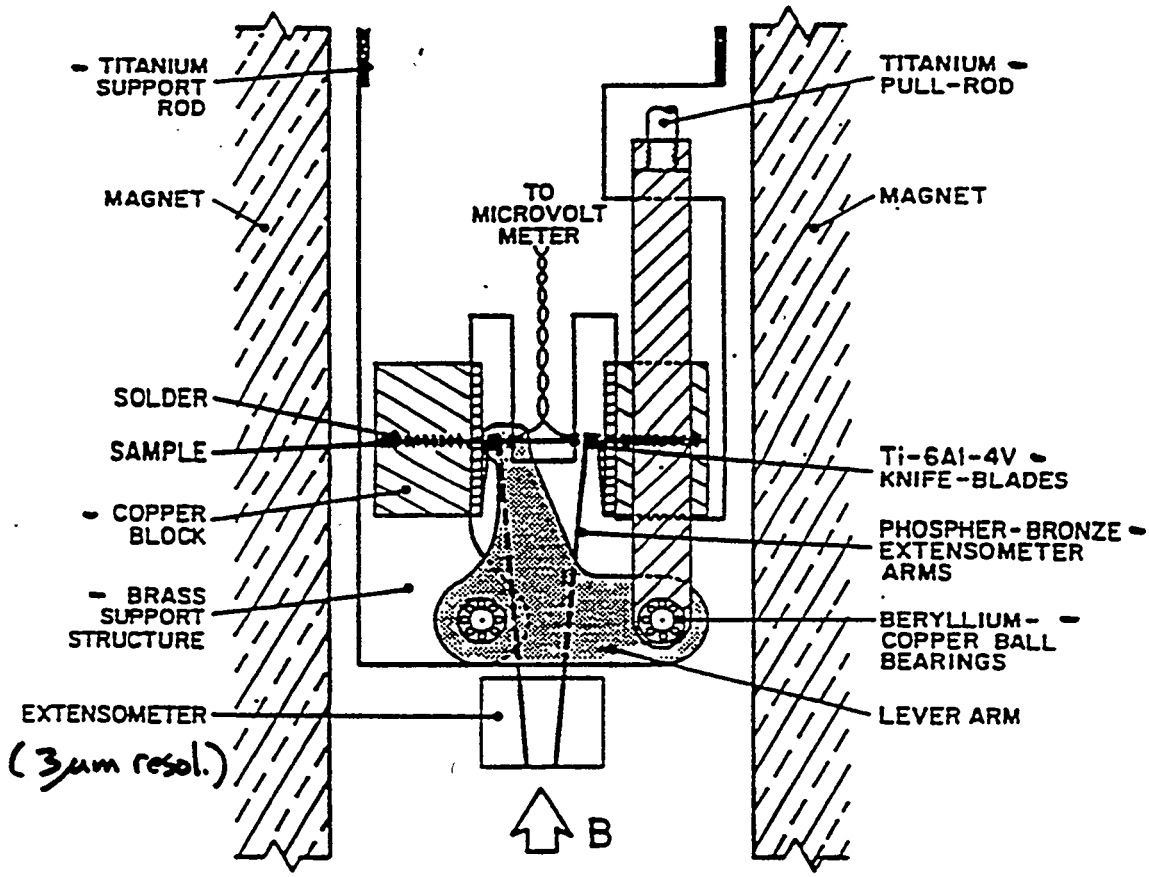
1. Axial strain effects
2. Transverse stress effects
3. Coil performance
4. Contacts

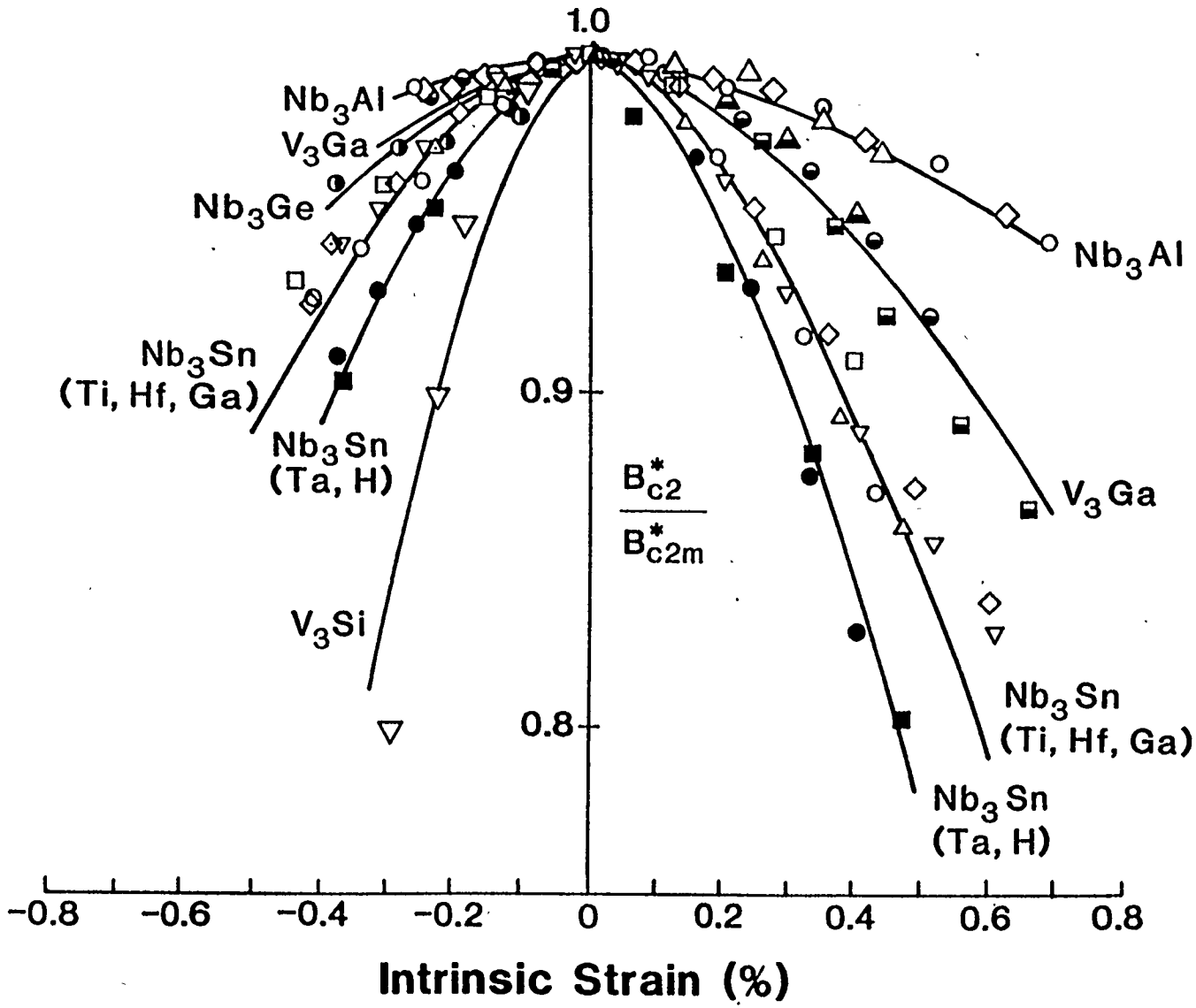


Axial Stress Test

$J_c - \epsilon_{\parallel}$ (Axial Strain Effect)

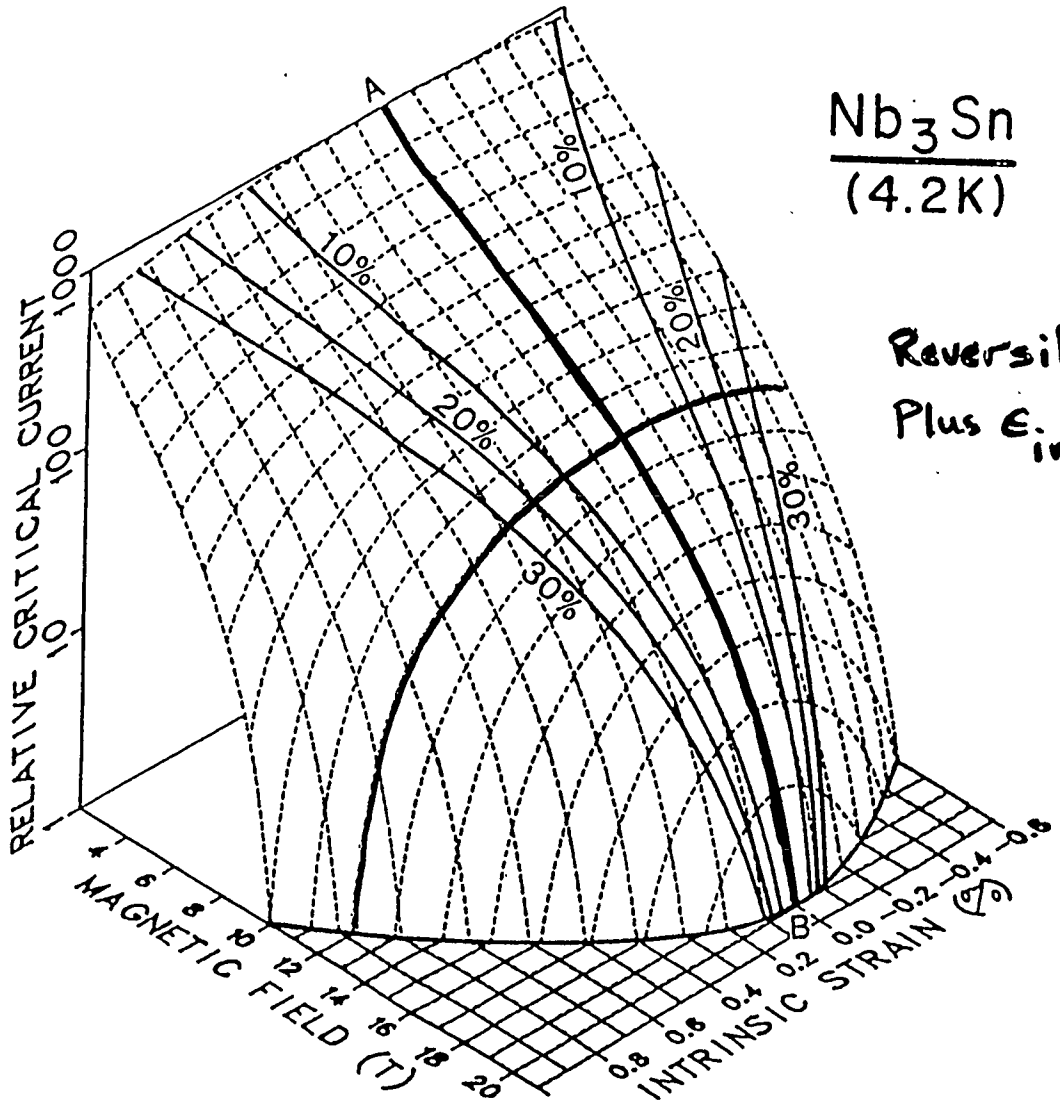






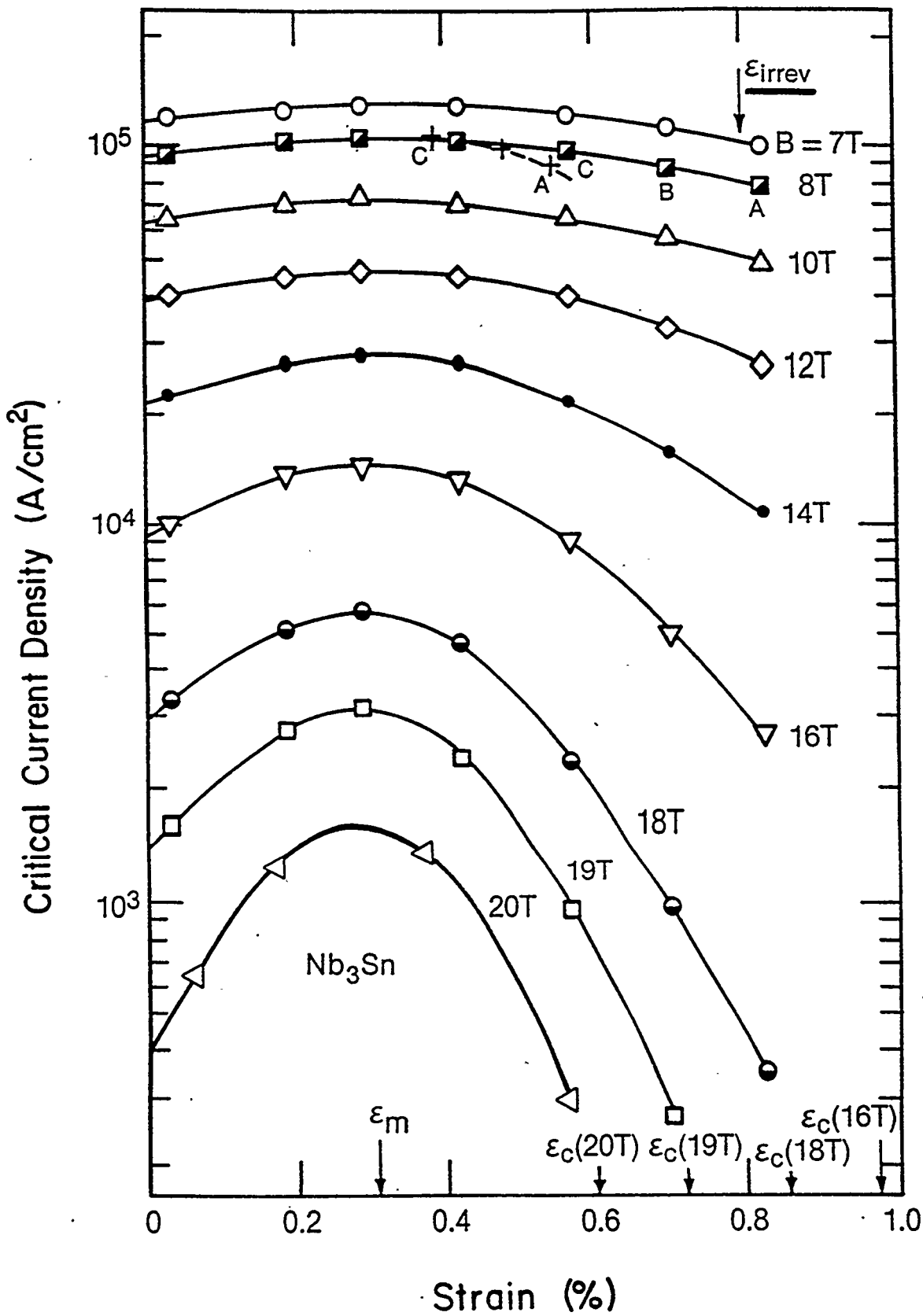
From J.W. Ekin, Adv. Cryo. Eng. 30 823 (1984)

CRITICAL J-H-ϵ SURFACE



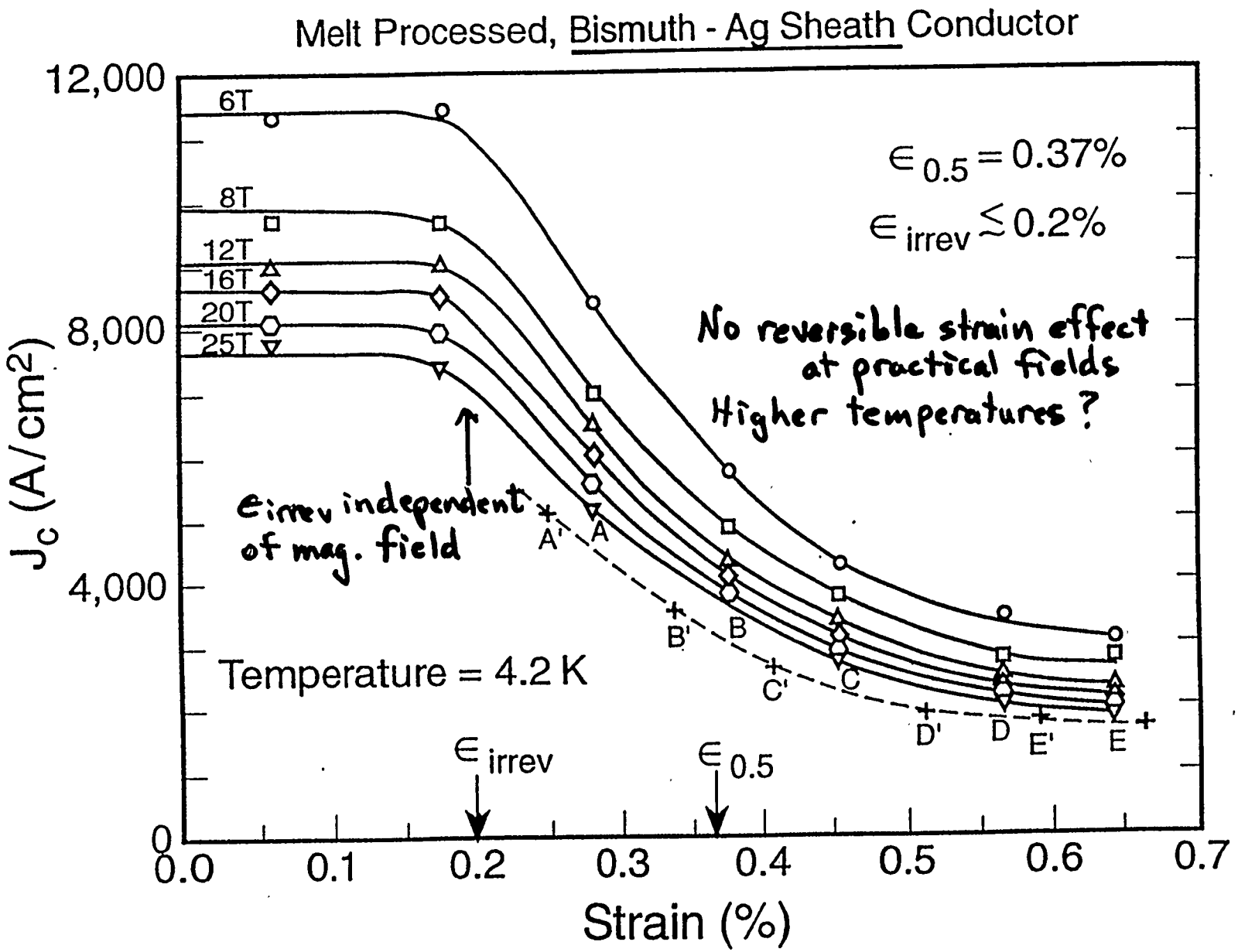
$\frac{Nb_3Sn}{(4.2K)}$

Reversible strain effect
Plus ϵ_{irrev} effect

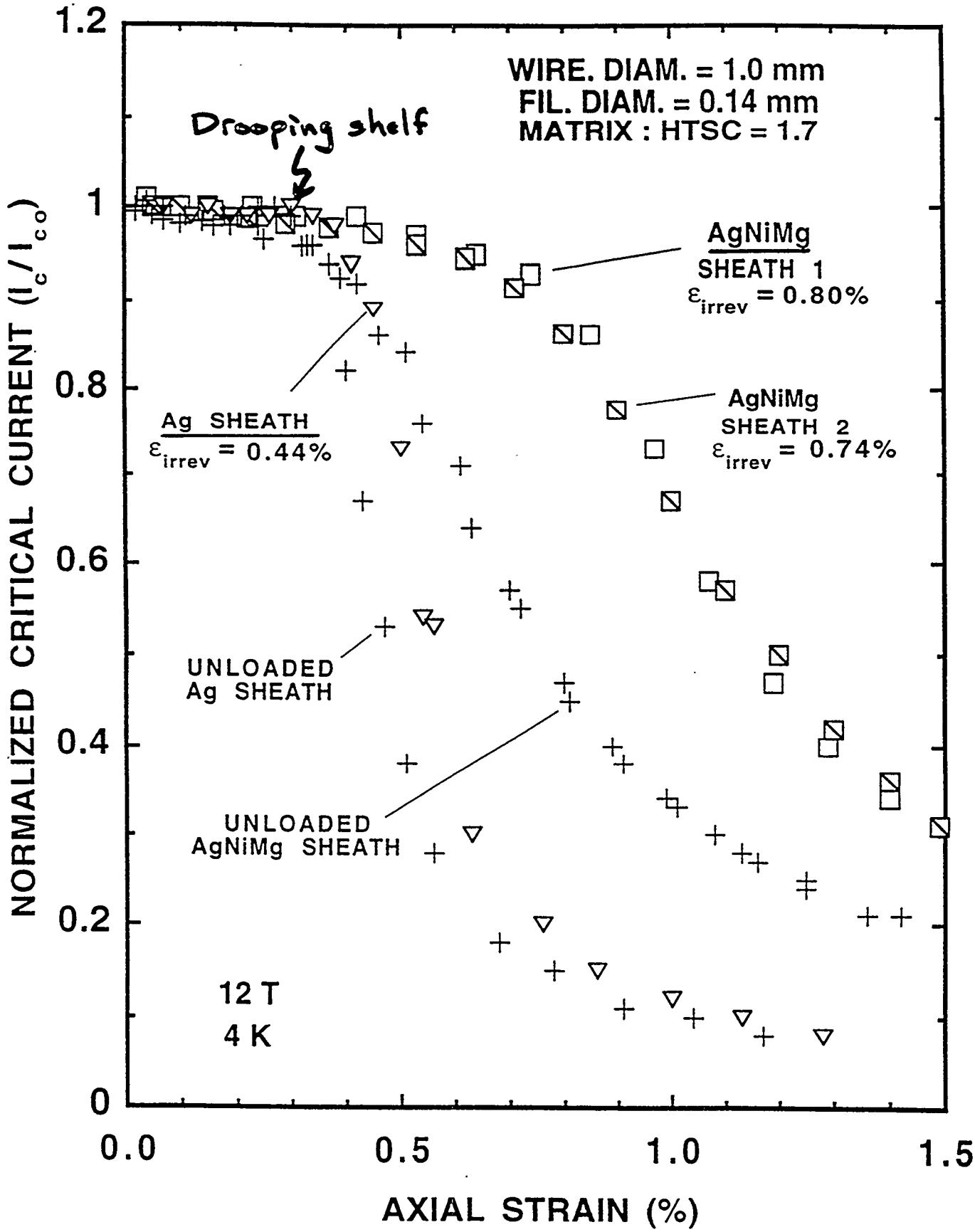

ε_{irrev}
B = 7T
8T
10T
12T
14T
16T
18T
19T
20T
A
B
C
A
C
Nb_3Sn
ε_m
$\varepsilon_c(20T)$
$\varepsilon_c(19T)$
$\varepsilon_c(18T)$
$\varepsilon_c(16T)$
10^5
10^4
10^3
0
0.2
0.4
0.6
0.8
1.0
Critical Current Density (A/cm^2)
Strain (%)

ε_{irrev} is strong function of filament diameter.

Nb_3Sn	Filament Diameter	ε_m	$\varepsilon_{o,irrev}$ (Intrinsic Irreversible Tensile strain limit)	Total ε_{irrev}
Tape	2-10 μm	0.4-0.6%	≤0.2%	
Monofilament (>5 μm reaction layer)	>100 μm	---	≤0.2%	
Tubular Filaments internal bronze	11-26 μm	0.2-0.4%	0.2-0.25%	
Tubular Filaments internal $NbSn_2$ powder	57 μm	0.06%	0.44%	
→ Bronze Process solid filaments	5-50 μm	0.2-0.4%	0.4-0.5%	→ ≳ 0.7%
Expanded Metal Process	2 μm	0.4%	0.6%	
Powder Process liquid Sn infiltrated	0.8 μm	0.13%	0.9%	
In-situ	0.4 μm	0.5-0.6%	0.9%	→ ≳ 1.4%
Cable	3.5 μm	0.24%	0.9%	

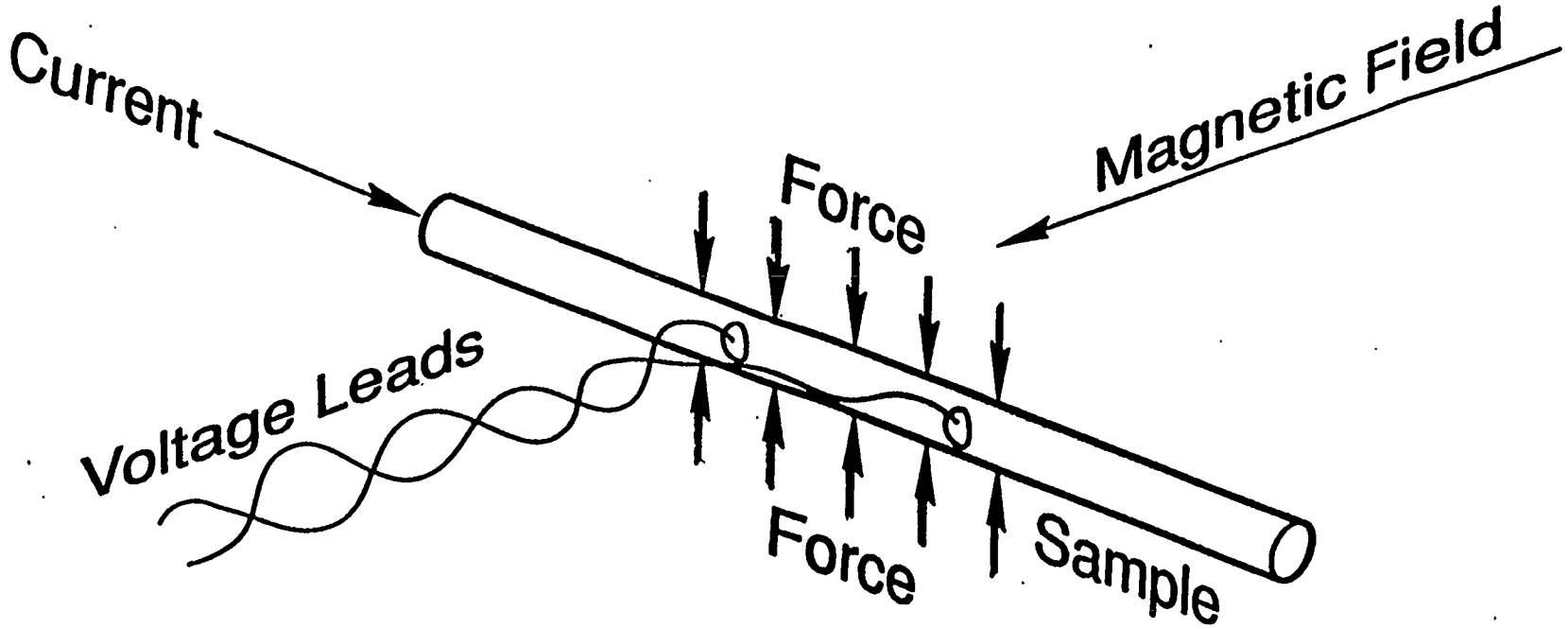


From: Ekin et al, Appl. Phys. Lett. 61, 858 (1992)


WIRE. DIAM. = 1.0 mm
FIL. DIAM. = 0.14 mm
MATRIX : HTSC = 1.7
Drooping shelf
AgNiMg
SHEATH 1
ε_{irrev} = 0.80%
AgNiMg
SHEATH 2
ε_{irrev} = 0.74%
Ag SHEATH
ε_{irrev} = 0.44%
UNLOADED
Ag SHEATH
UNLOADED
AgNiMg SHEATH
12 T
4 K
NORMALIZED CRITICAL CURRENT (I_c/I_{co})
AXIAL STRAIN (%)
0
0.2
0.4
0.6
0.8
1
1.2
0.0
0.5
1.0
1.5

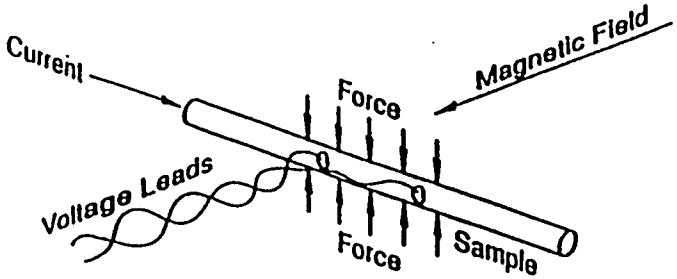
Strain Effects - IBAD YBCO

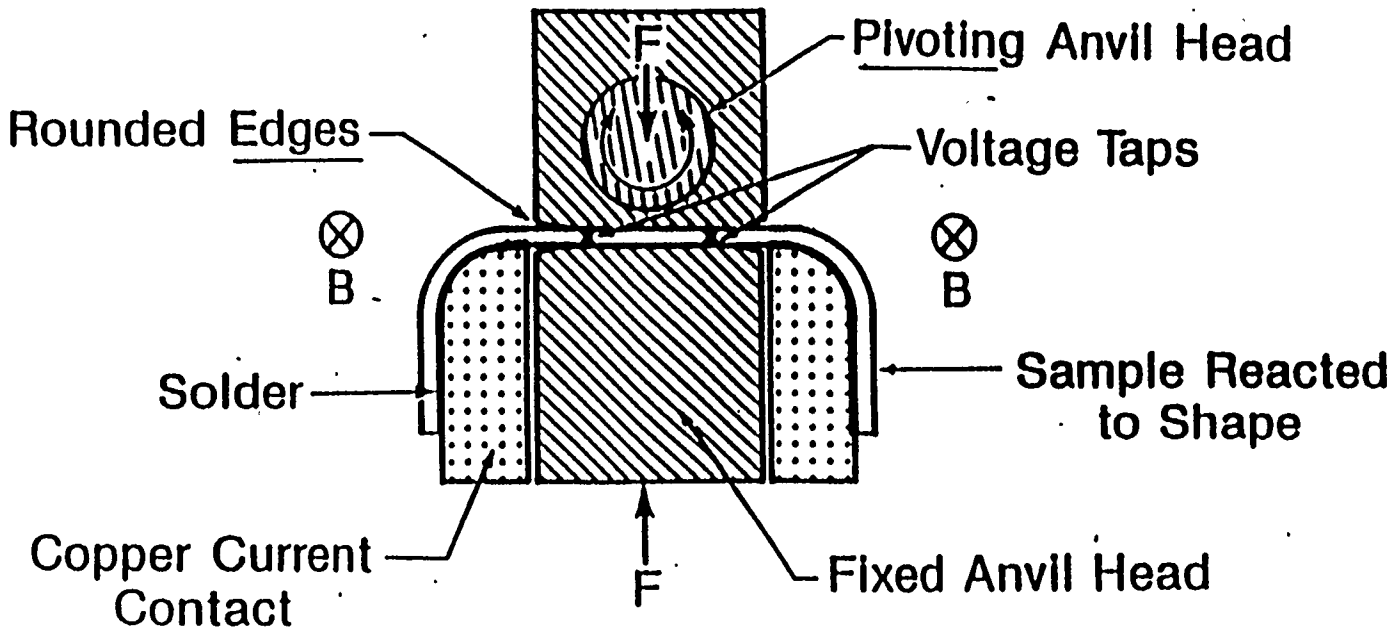
Tensile bending	0.5 %
Compressive bending	1 %



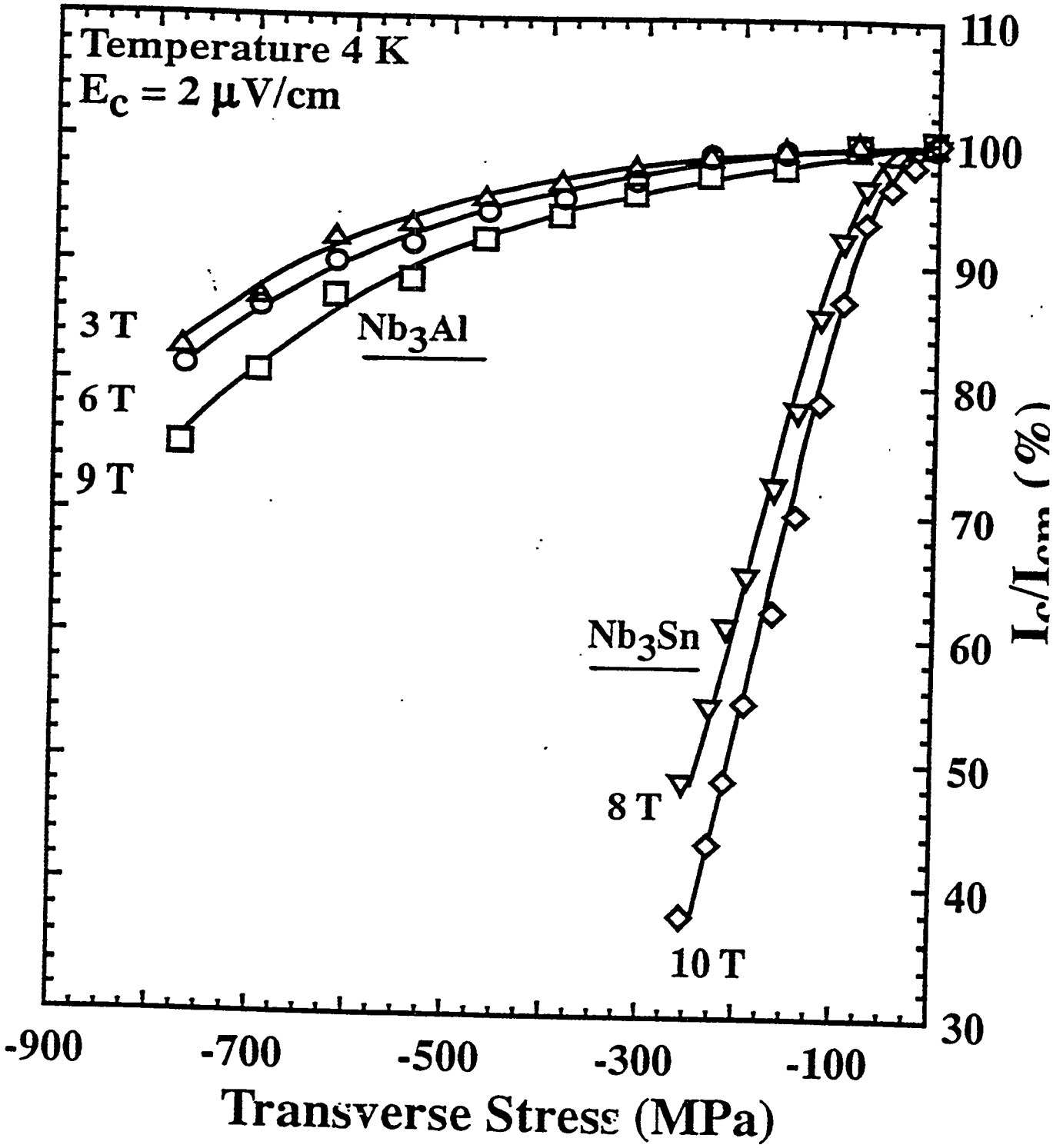
Transverse Stress Test

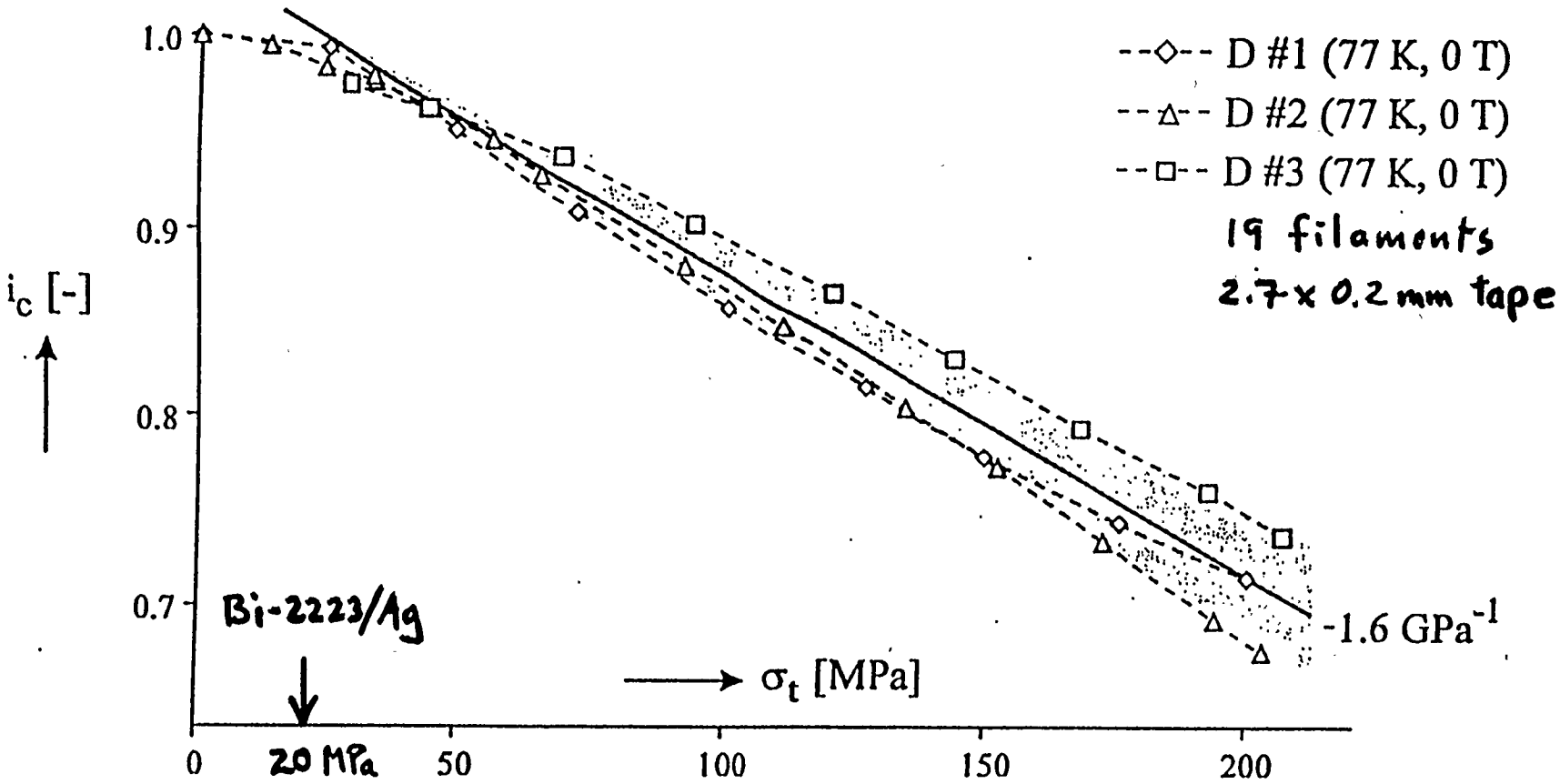
$J_c - \sigma_\perp$ (Transverse Stress Effect)





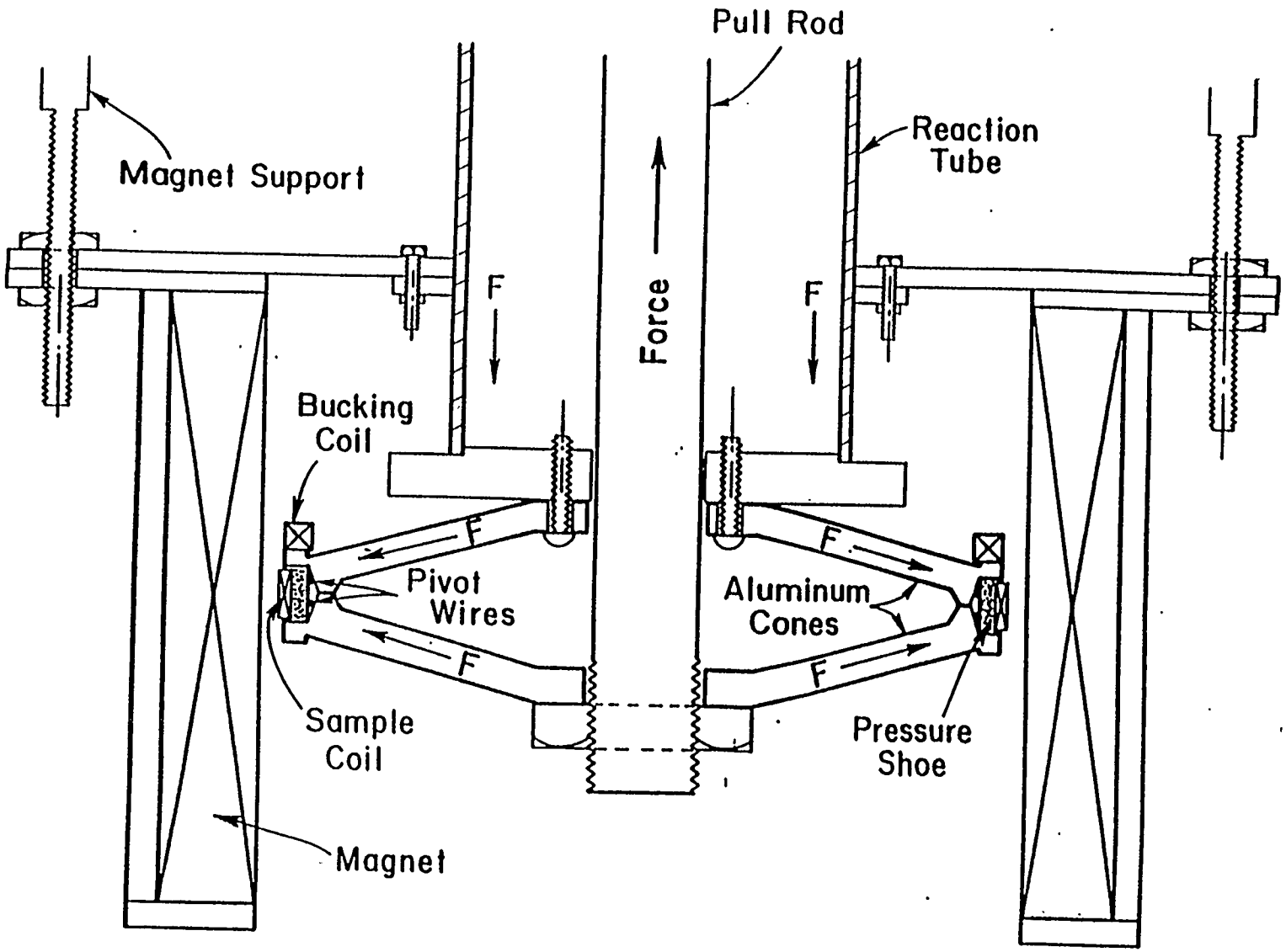
At 9T, transverse strain tolerance of Nb_3Al ≈ 5 times that of Nb_3Sn





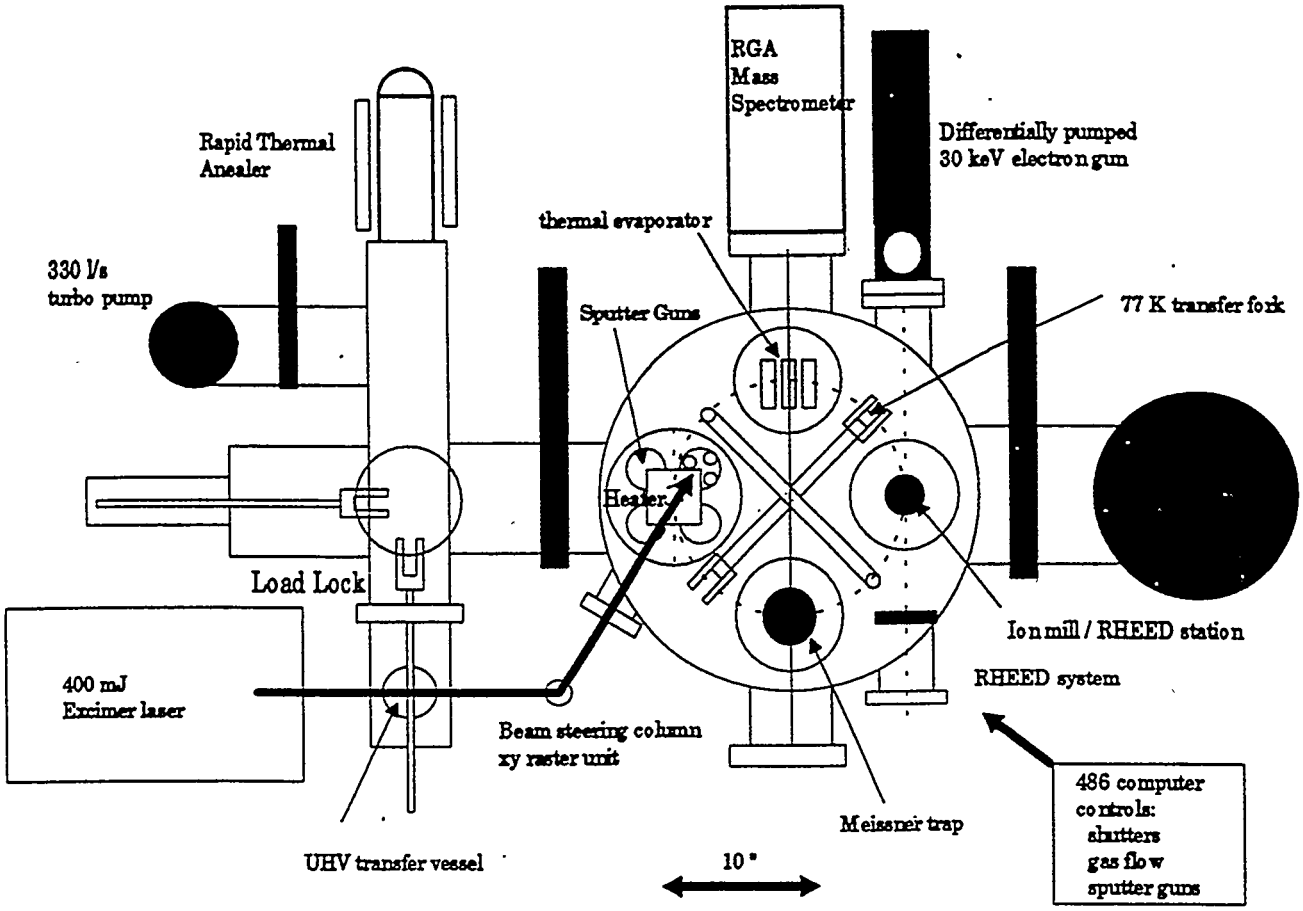
B. ten Haken et al., Adv. Cryo. Eng. 42, 651 (1996)

Composite Coil Testing



Laser Ablation:

Wavelength = 248 nm, Fluence = 2.0 J/cm^2
Substrate Temperature = 740 °C
Oxygen Pressure = 200 mT
Deposition Rate = 10 pulses/s, .03 nm/pulse



RHEED: 20 kV, Incident angle 1- 2°, Substrate temperature 20 °C

STM, AFM: Nanoscope II & Nanoscope III, in air

Summary

Axial strain (desired $\varepsilon_{irrev} > 0.4$ to 0.6%)

	Reversible	Irreversible ε onset
A15	yes	0.7 - 1.4 %
Chevrel	yes	–
B1	no	1 %
C-15	no	–
Bi	no (at practical B & T)	+0.2 %, −0 %
YBCO-coated	?	+0.5 %, −1.0 % ?

Transverse stress (desired $\sigma_{irrev} > 100$ MPa)

	Irreversible σ onset
Nb_3Sn	50 - 100 MPa
Nb_3Al	> 100 MPa
Bi-2223/Ag	~ 20 MPa

Coil Performance

Epoxy cracking can limit coil performance more than ε_{irrev} of conductor

Contacts (desired $\rho_c \simeq 10^{-6}$ to 10^{-8} $\Omega\cdot cm^2$)

Coated YBCO $\rho_c \sim 10^{-5}$ Ω-cm^2

Wire Workshop

St. Petersburg, Fla.

January 30, 1998

Fundamental Grain-Boundary Studies Aimed at HTS Wire Applications

Kenneth E. Gray, Argonne National Laboratory

Collaborators: Dean J. Miller, Michael B. Field, Xiao F. Zhang

This work partially supported by:

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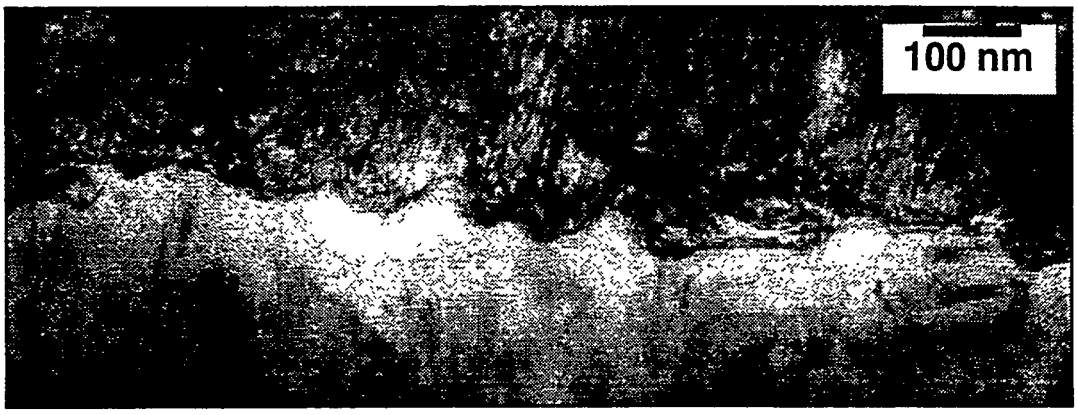
U.S. Department of Energy, Basic Energy Sciences-Materials Sciences

National Science Foundation, Office of Science and Technology Centers under contract DMR 91-20000.

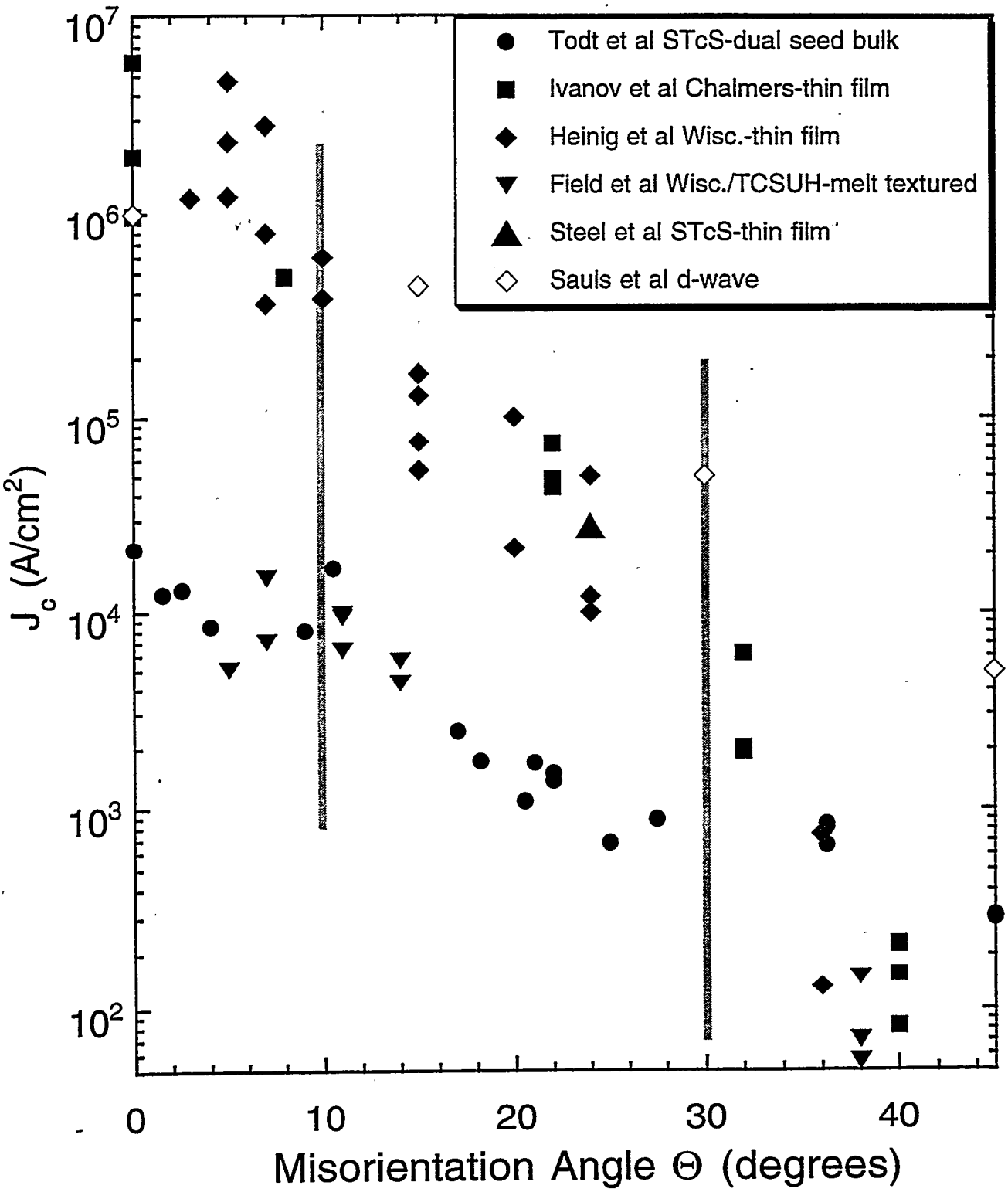
Grain boundary microstructures

Sputtered thin film - Northrup-Grumman

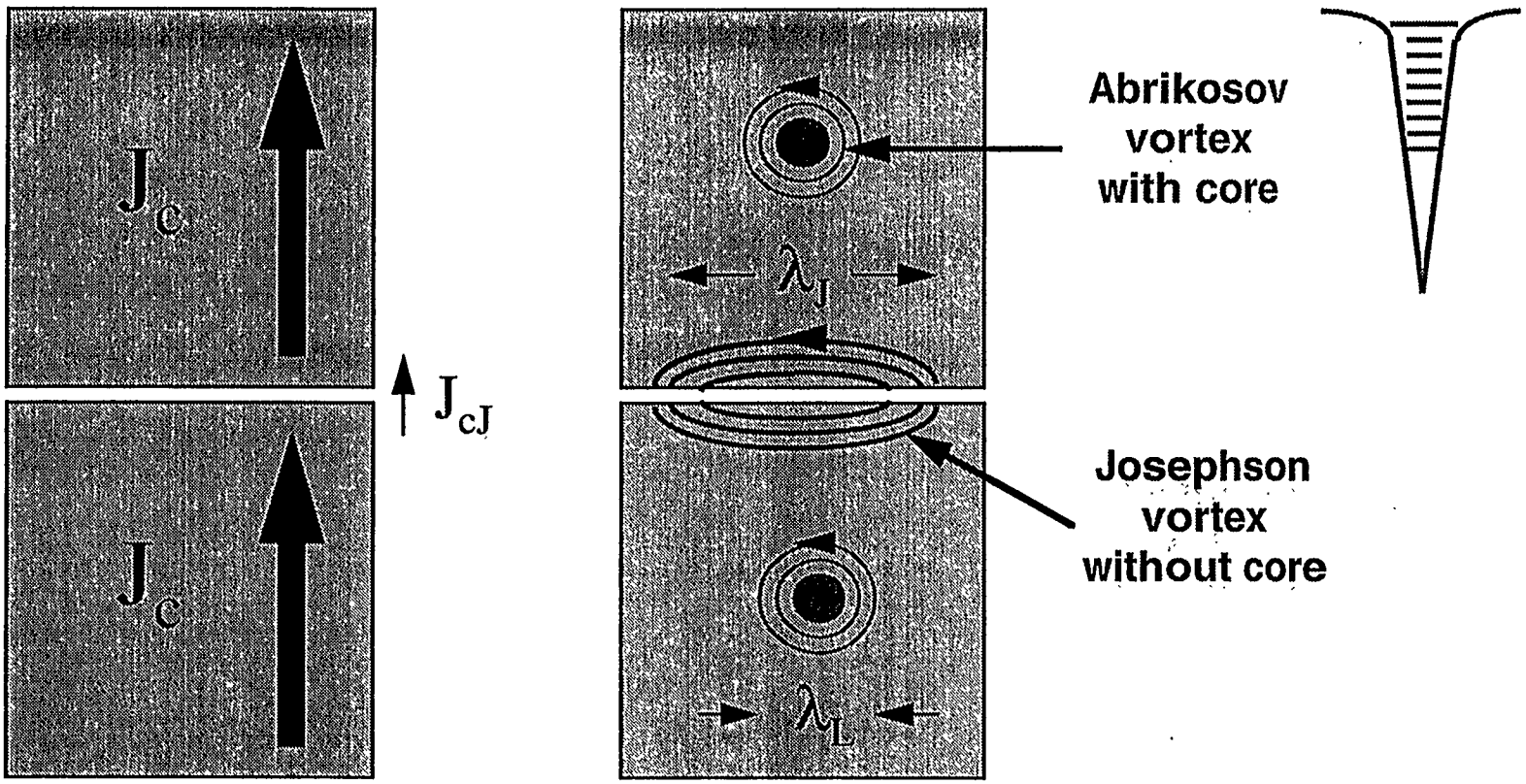


POMBEthin film - NU

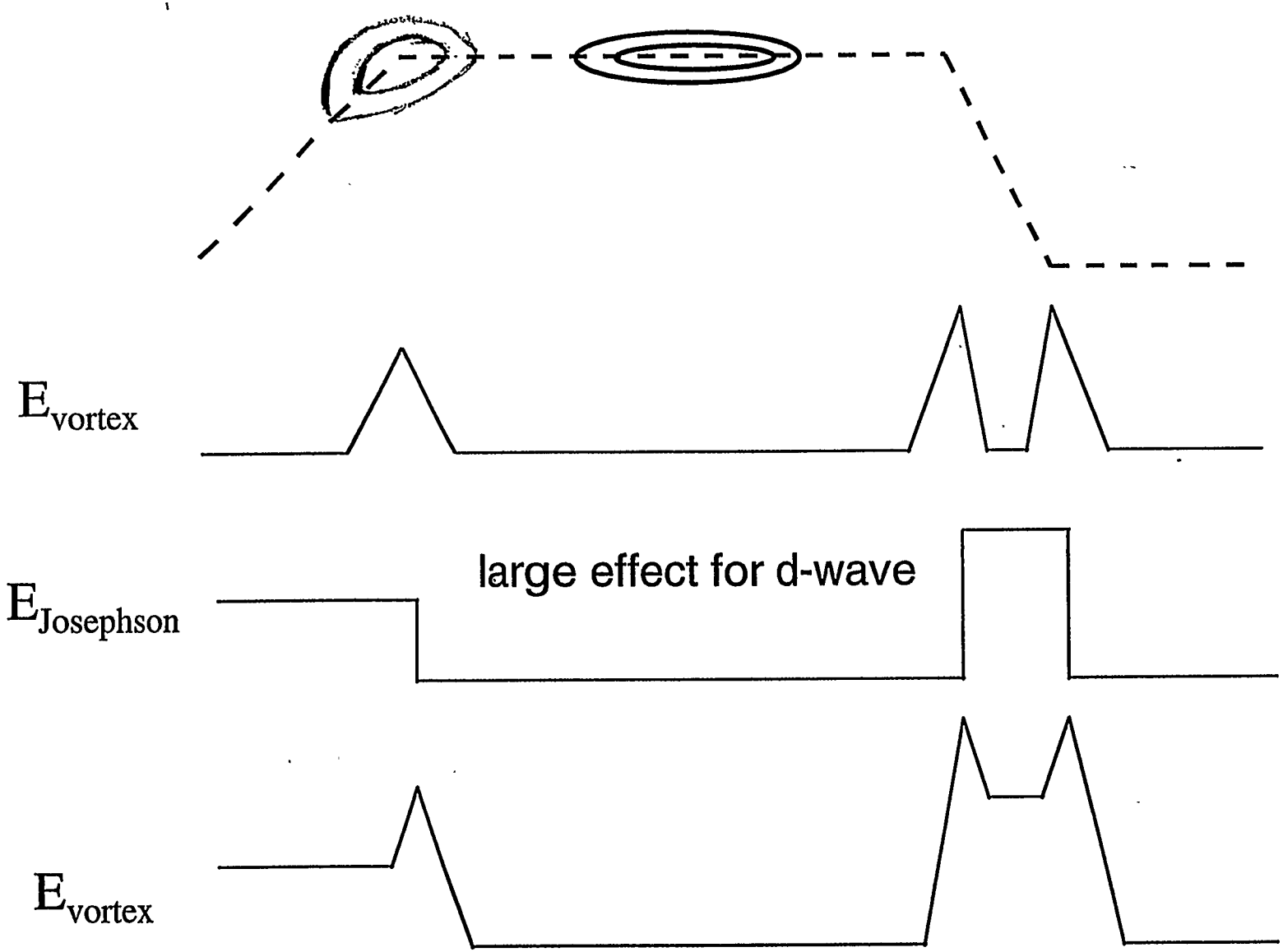
Bulk bicrystal - ANL


Todt et al STcS-dual seed bulk
Ivanov et al Chalmers-thin film
Heinig et al Wisc.-thin film
Field et al Wisc./TCSUH-melt textured
Steel et al STcS-thin film
Sauls et al d-wave
10^7
10^6
10^5
10^4
10^3
10^2
J_c (A/cm^2)
0
10
20
30
40
Misorientation Angle Θ (degrees)

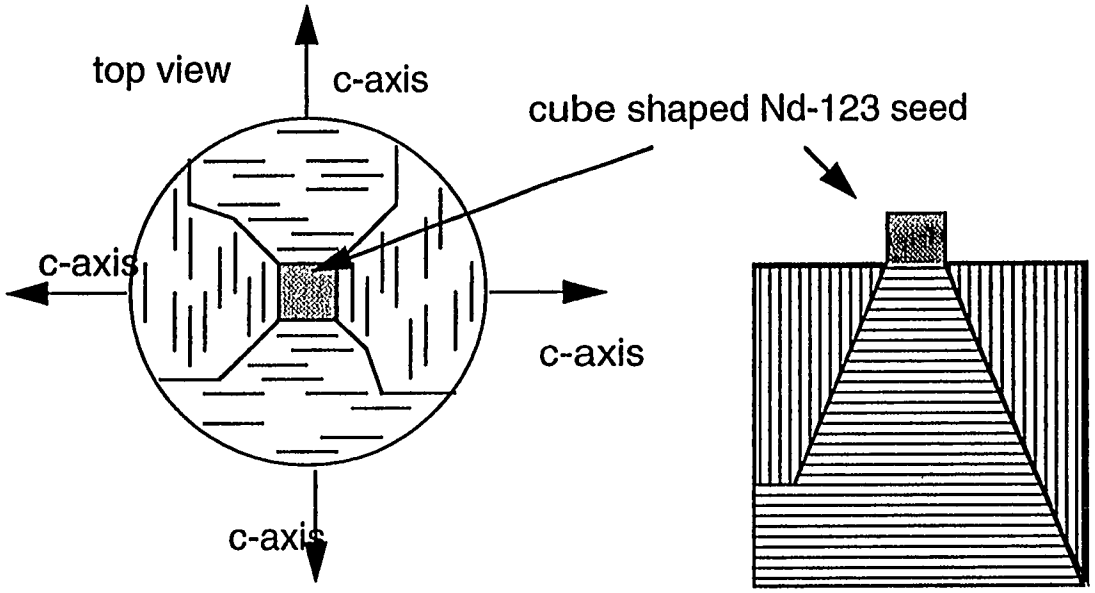
Josephson Junctions and Vortices



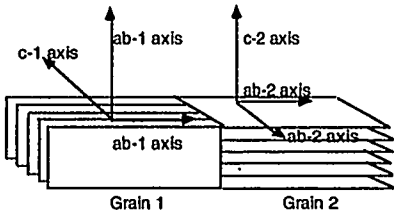
Effects of Meandering on Josephson Vortex Pinning

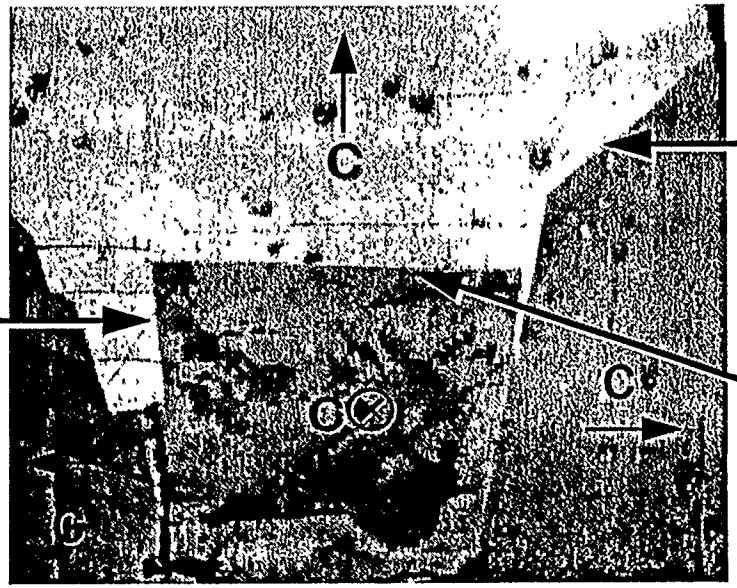


90° [100] grain boundaries

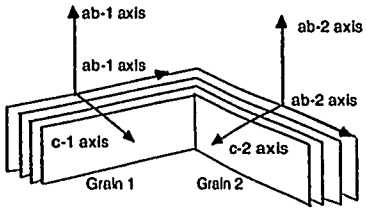


90° [100] twist GB

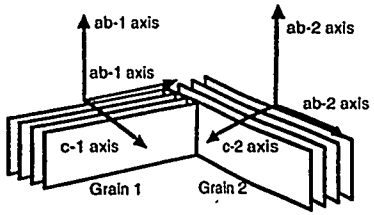




100μm

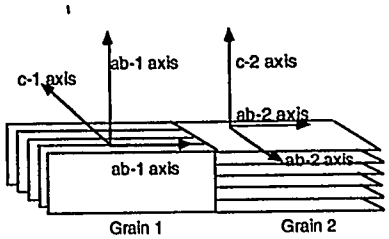


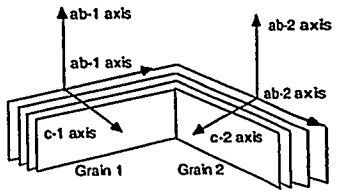
90° [100] symmetric tilt GB

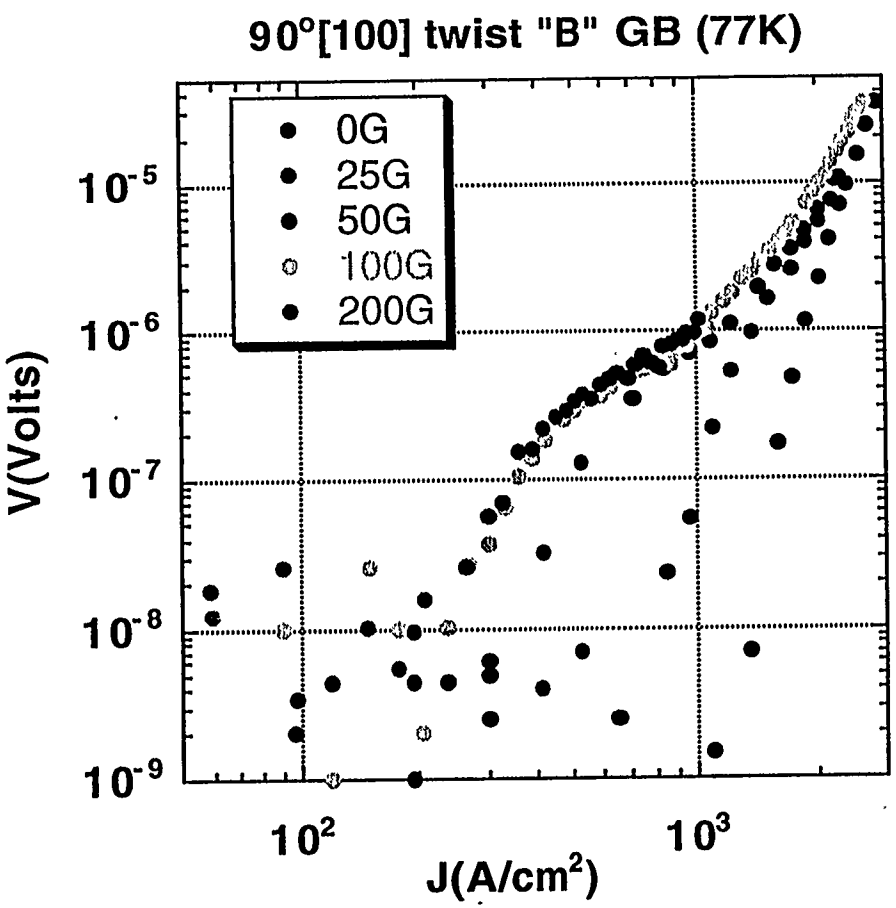


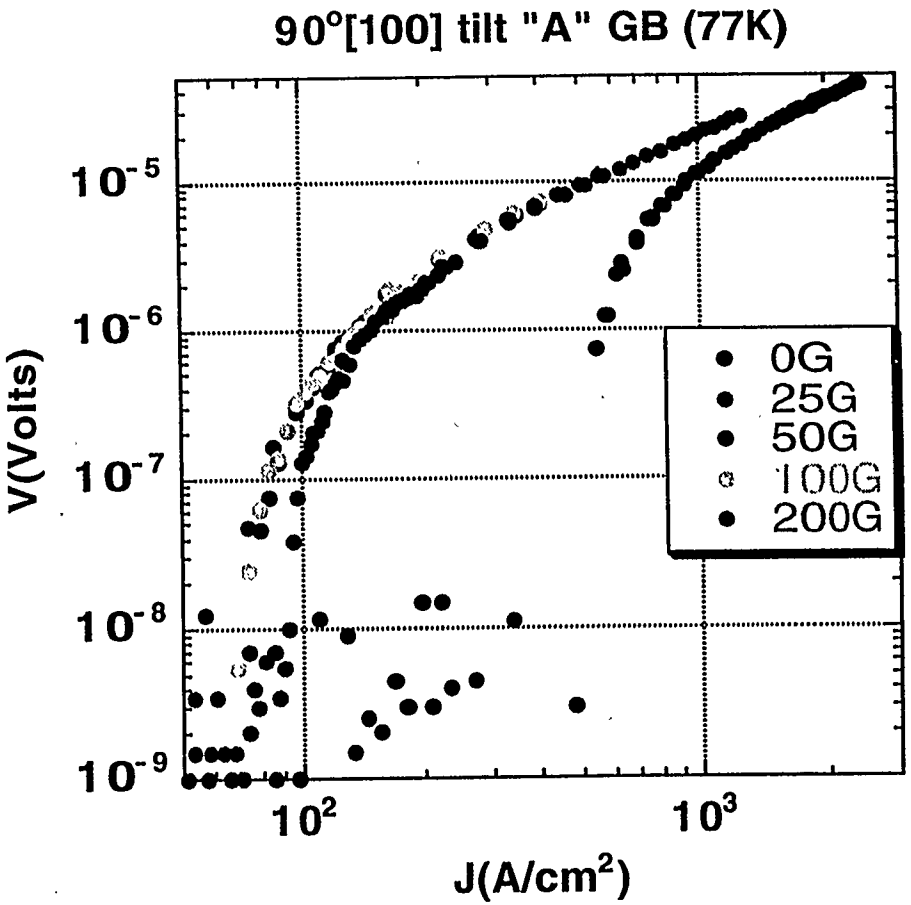
90° [100] basal plane faced GB

Results

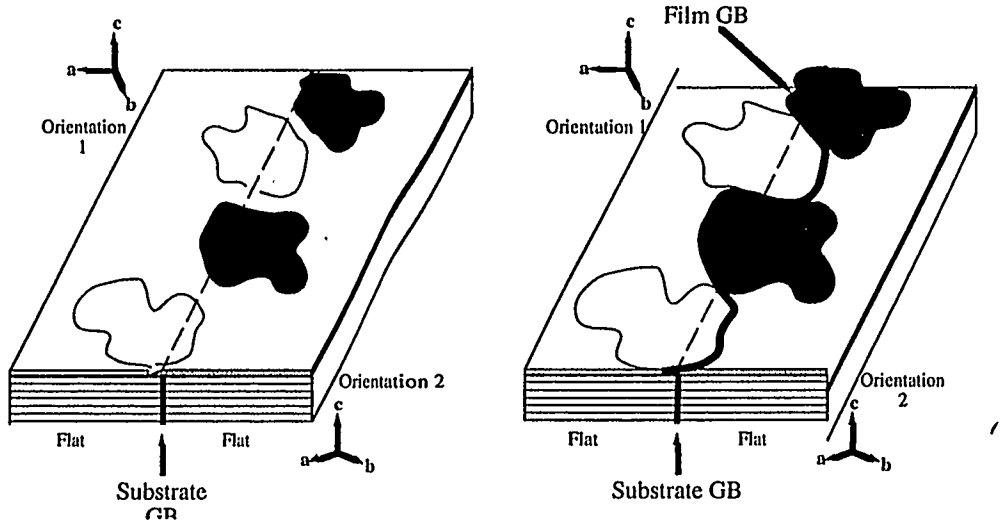

c-1 axis
ab-1 axis
c-2 axis
ab-2 axis
ab-2 axis
ab-1 axis
Grain 1
Grain 2


ab-1 axis
ab-1 axis
ab-2 axis
ab-2 axis
c-1 axis
c-2 axis
Grain 1
Grain 2


90°[100] twist "B" GB (77K)
0G
25G
50G
100G
200G
V(Volts)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{2}
10^{3}
J(A/cm^2)


90°[100] tilt "A" GB (77K)
0G
25G
50G
100G
200G
V(Volts)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{2}
10^{3}
J(A/cm^2)

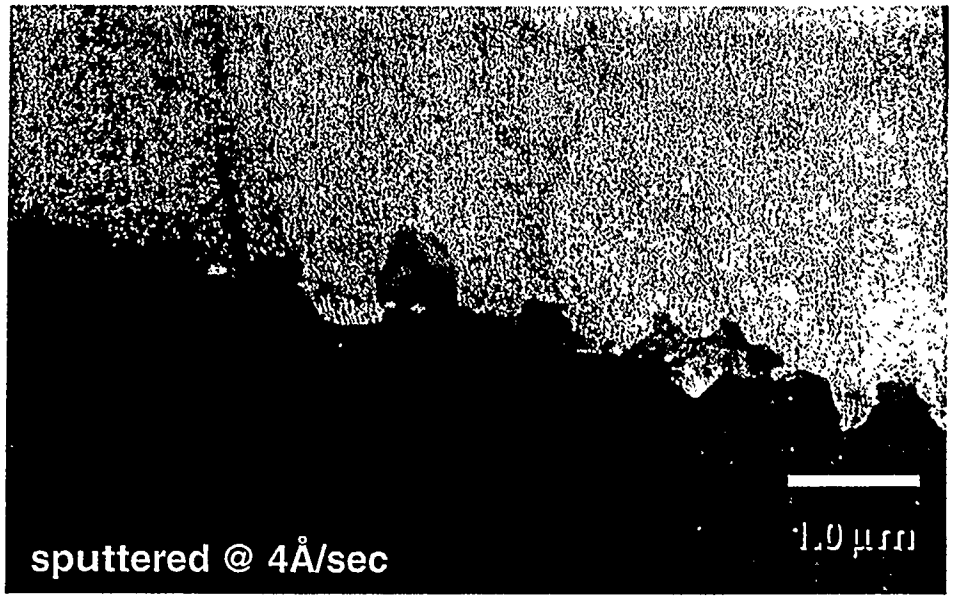
Growth mechanism leading to meandering GB configurations

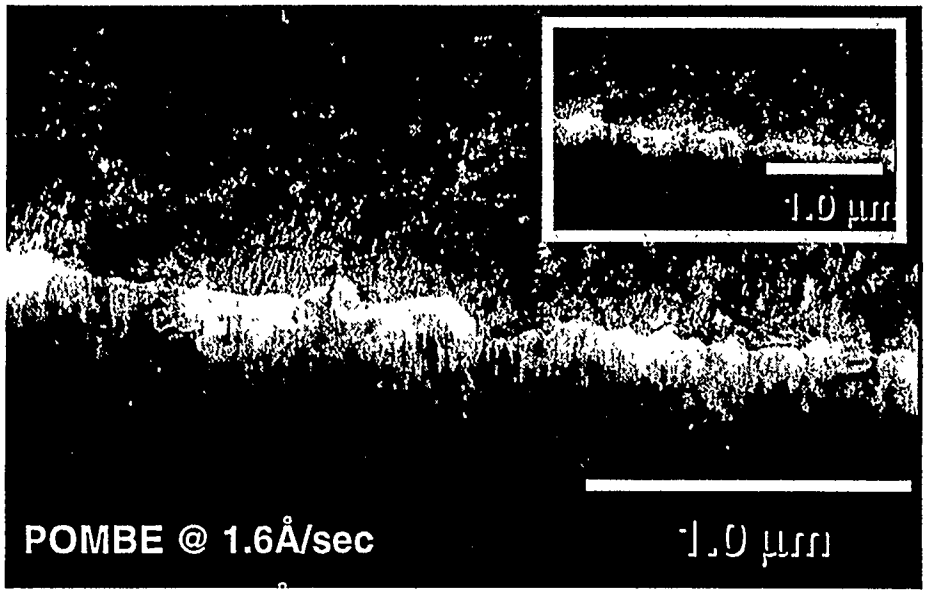


24° [001] GB

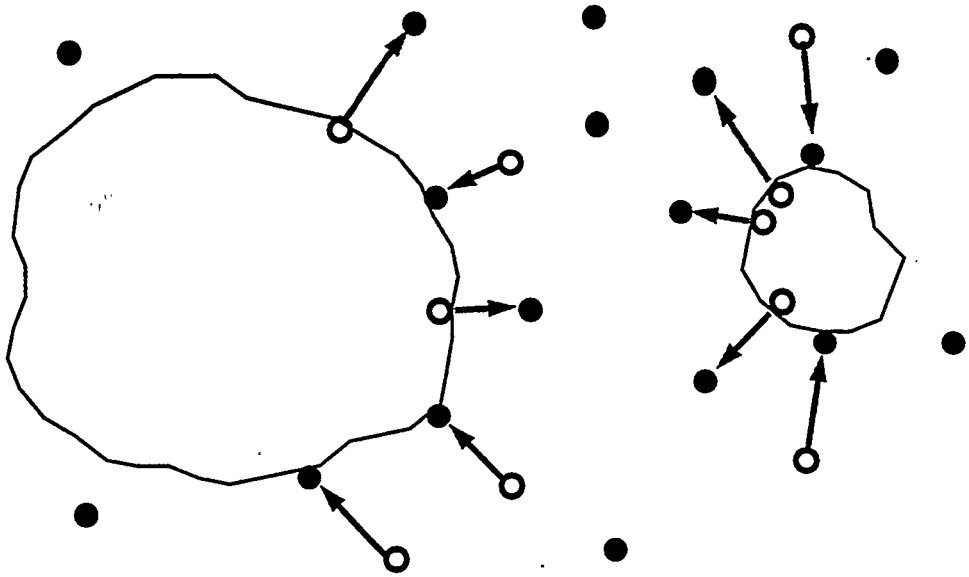
TEM

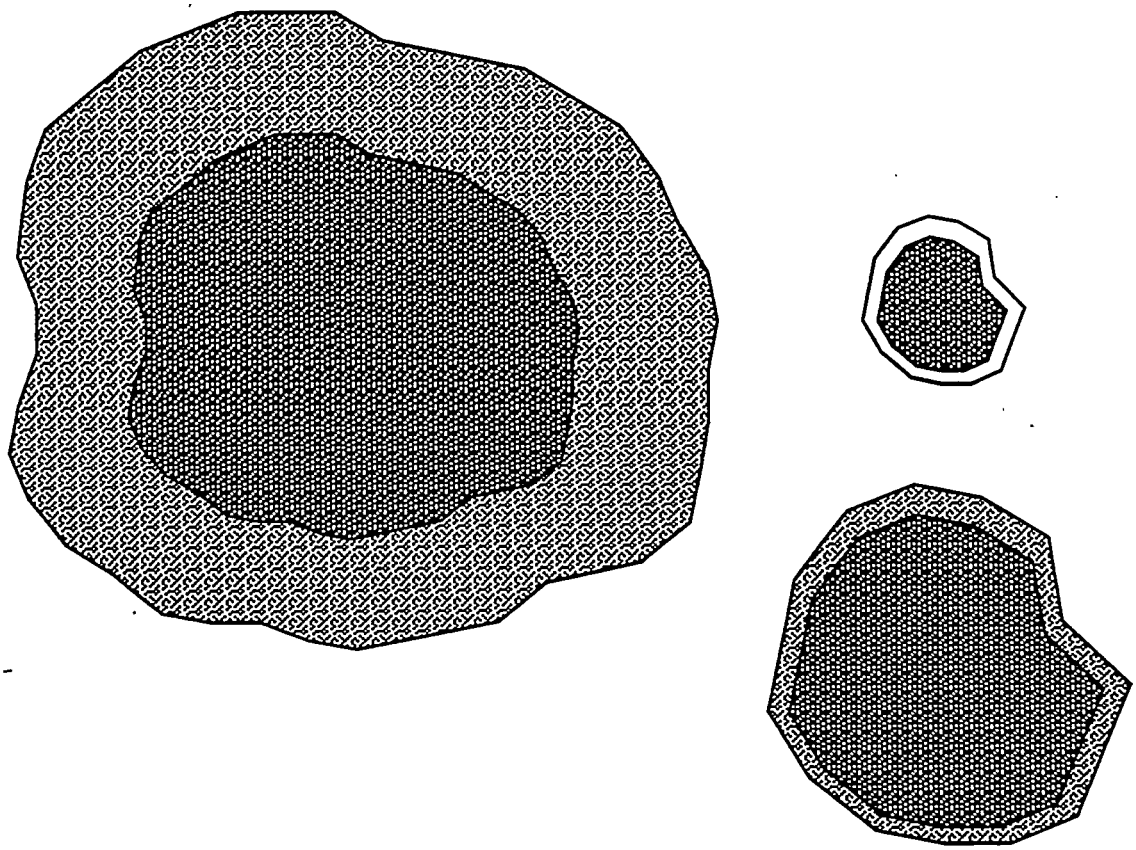
Effect of deposition rate on "meandering"



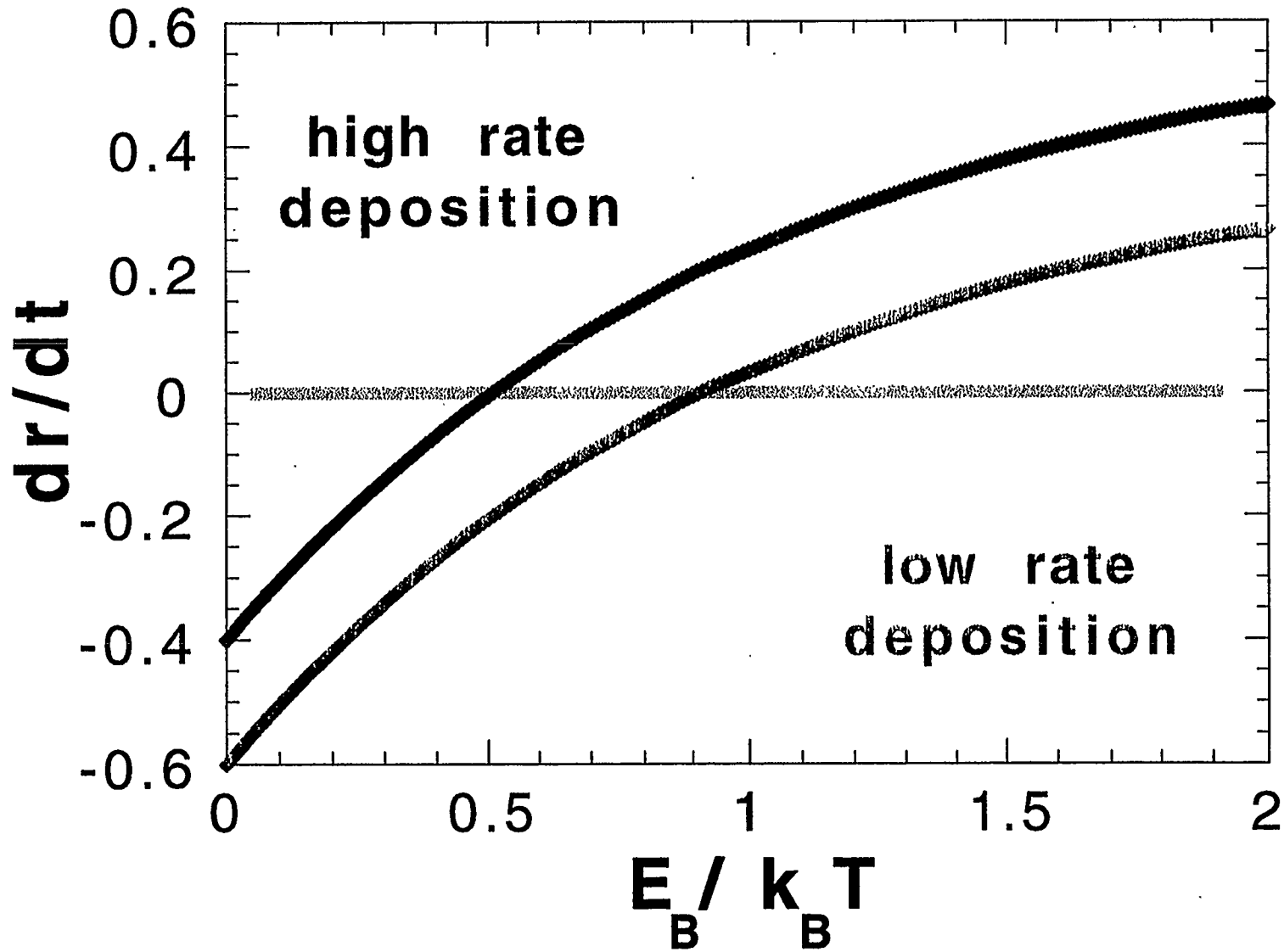


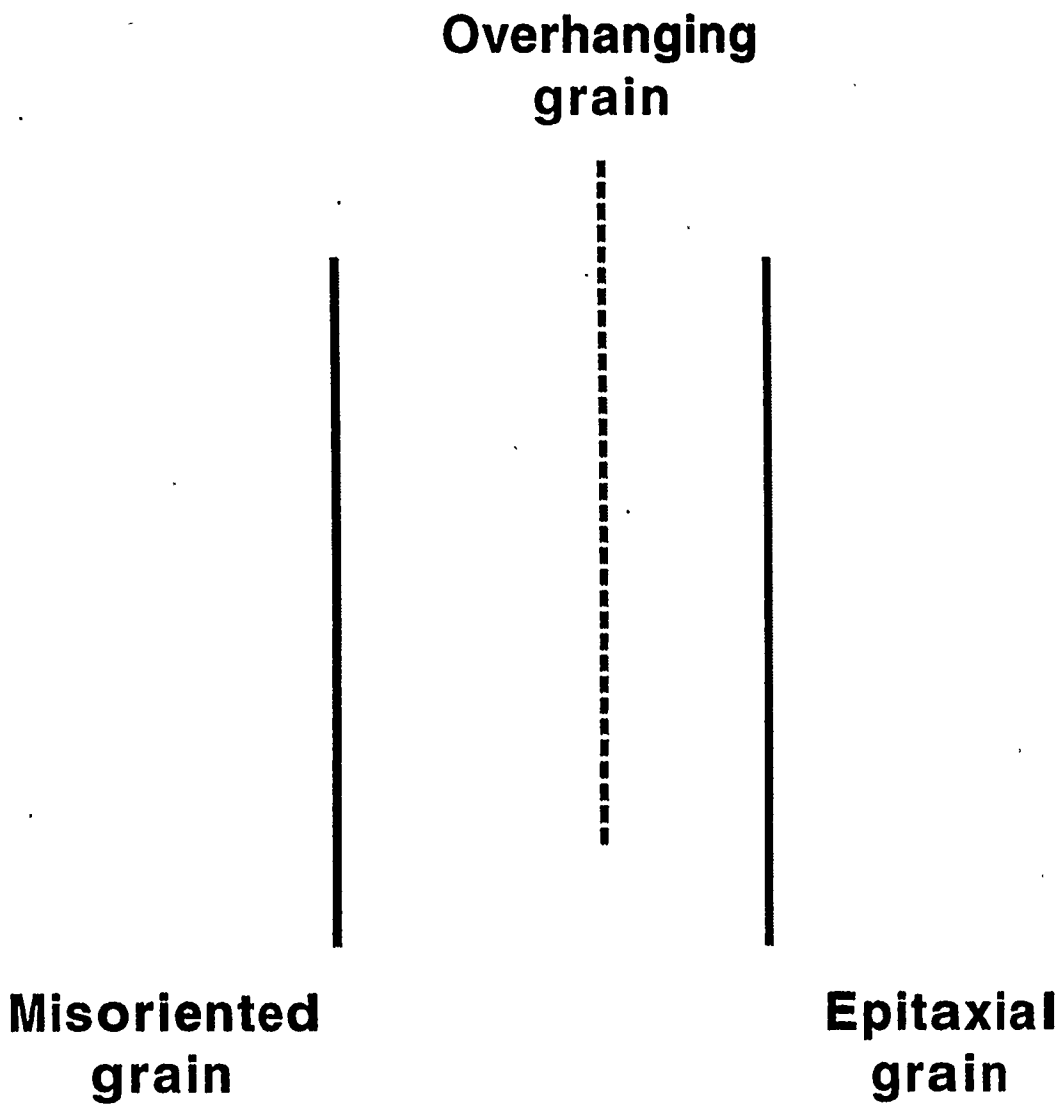
Dynamic Coarsening Model





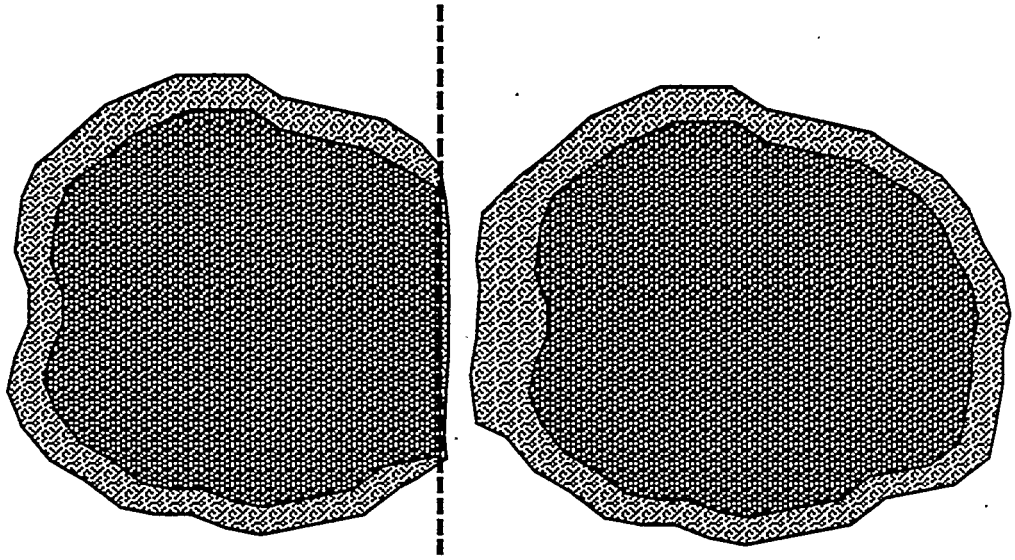
$$dr/dt = a\ R_{dep} - b\ \exp(-E_B / k_B T)$$



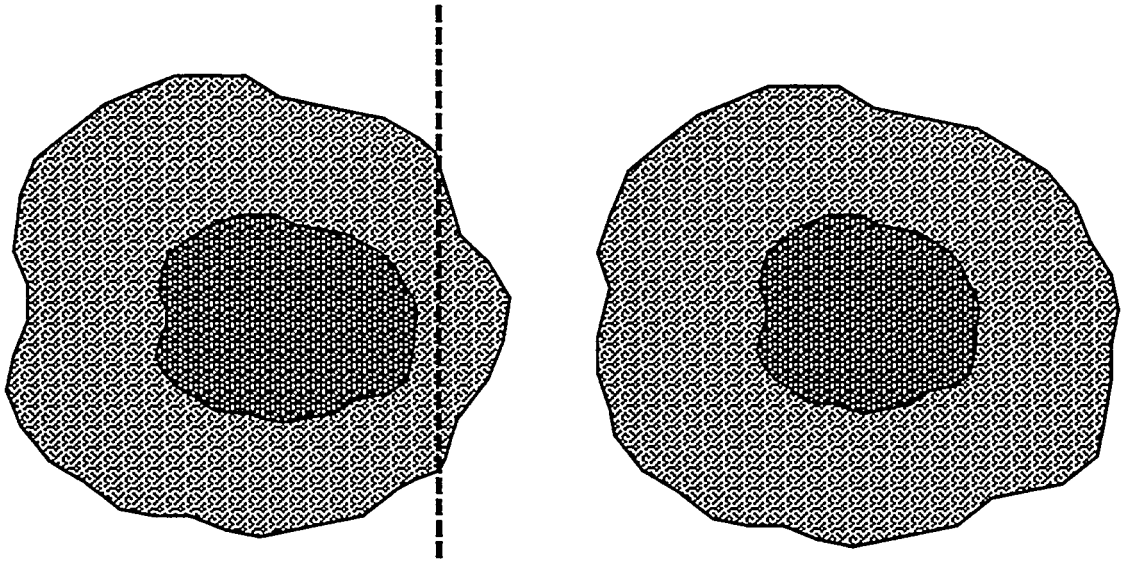

Overhanging grain
Misoriented grain
Epitaxial grain

Dynamic Coarsening Model at Substrate Grain Boundary

Low deposition rate:



High deposition rate:



Summary

- Thin-film and bulk [001] tilt, bicrystal grain boundaries (GBs) in YBCO

  strong dependence of J_c on misorientation angle, Θ

- But, J_c for bulk GBs are thirty-times-*lower* in magnitude

  yet they are microscopically more-perfect, i.e., flatter, minimally-faceted and free of impurity phases

- A plausible explanation is proposed here:

  pinning of Josephson vortices in these GB types

- Sources of pinning -- variation of E_{vortex} --*only* large along meandering GB

  affects current paths on each side of boundary and thus E_{vortex}

  d-wave symmetry means E_j, and thus E_{vortex}, depends on GB plane

  experimental verification for 90° twist and tilt GBs in YBCO

- Control of meandering--empirically: higher deposition rates→larger meander

  nucleation site density--unlikely to explain this

  dynamic growth model of grain coarsening

The role of fundamental research in improving the performance of coated conductors

S.R. Foltyn, P.N. Arendt, Q.X. Jia, X.F. Zhang, H.H. Kung, E.J. Peterson,
P.C. Dowden, J.M. Roper, J.R. Groves, J.Y. Coulter, M.P. Maley, D.E. Peterson

Superconductivity Technology Center
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

US Department of Energy
Wire Development Workshop
St. Petersburg , Florida
January 29-30, 1998

Coated Conductor Issues

Longer

- scale-up length of high I_c small samples
  $\Rightarrow$ *new result: 1 meter length with $I_c = 29\ A$*
- switch to continuous processing
- improve process control / uniformity

Faster

- address IBAD speed
  $\Rightarrow$ *new result: 370 kA/cm^2 on Stanford's IBAD MgO*
- investigate high deposition rate for YBCO
- increase J_c

Better

- increase I_c
- increase J_e
  $\Rightarrow$ *new result: 5 cm tape with $J_e = 20{,}000\ A/cm^2$*
- maintain or improve I_c in magnetic field

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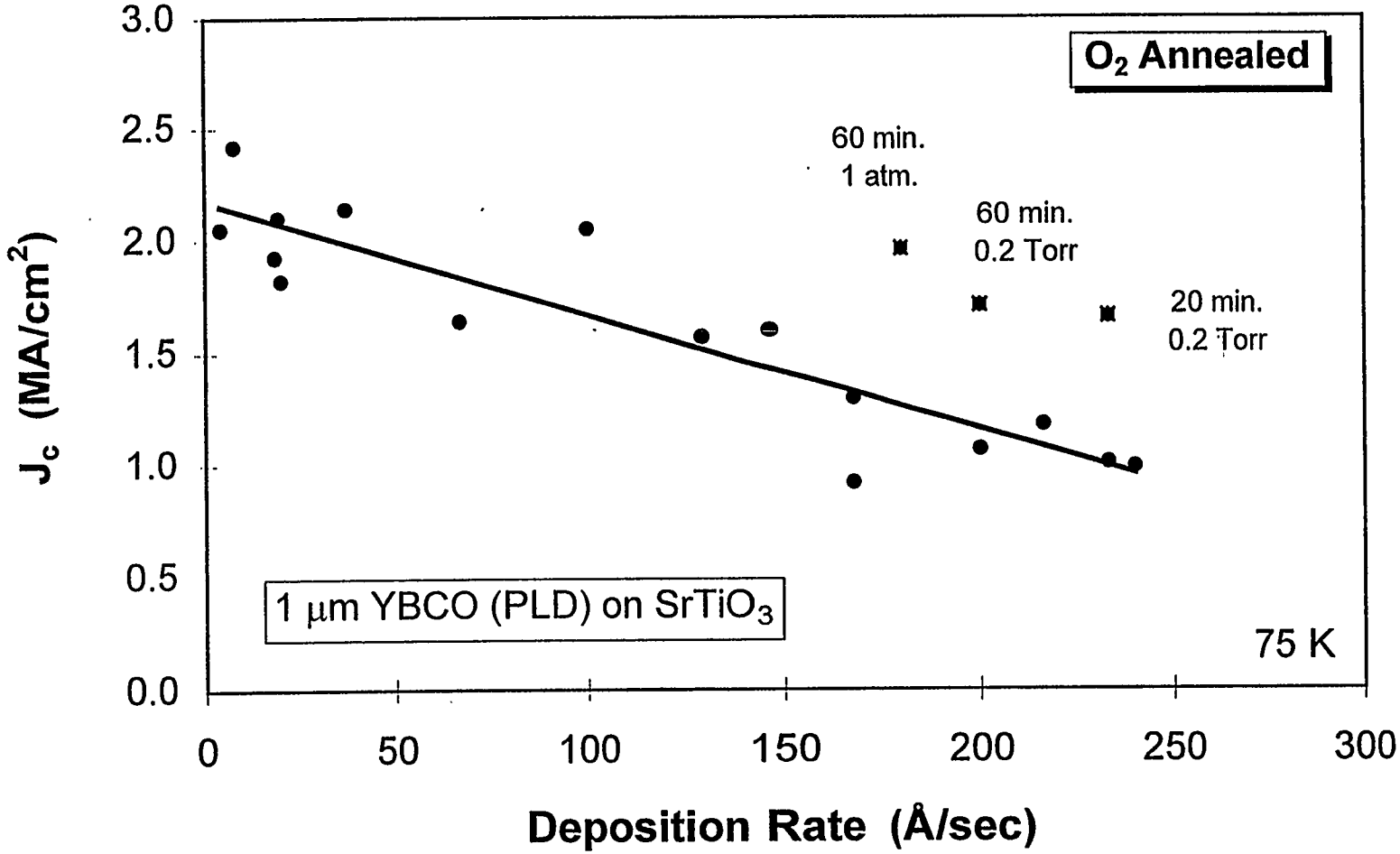
Reduction in critical current density at high deposition rate is partially restored by 790°C oxygen anneal



J. Mater. Res. **12**, 2941 (1997)

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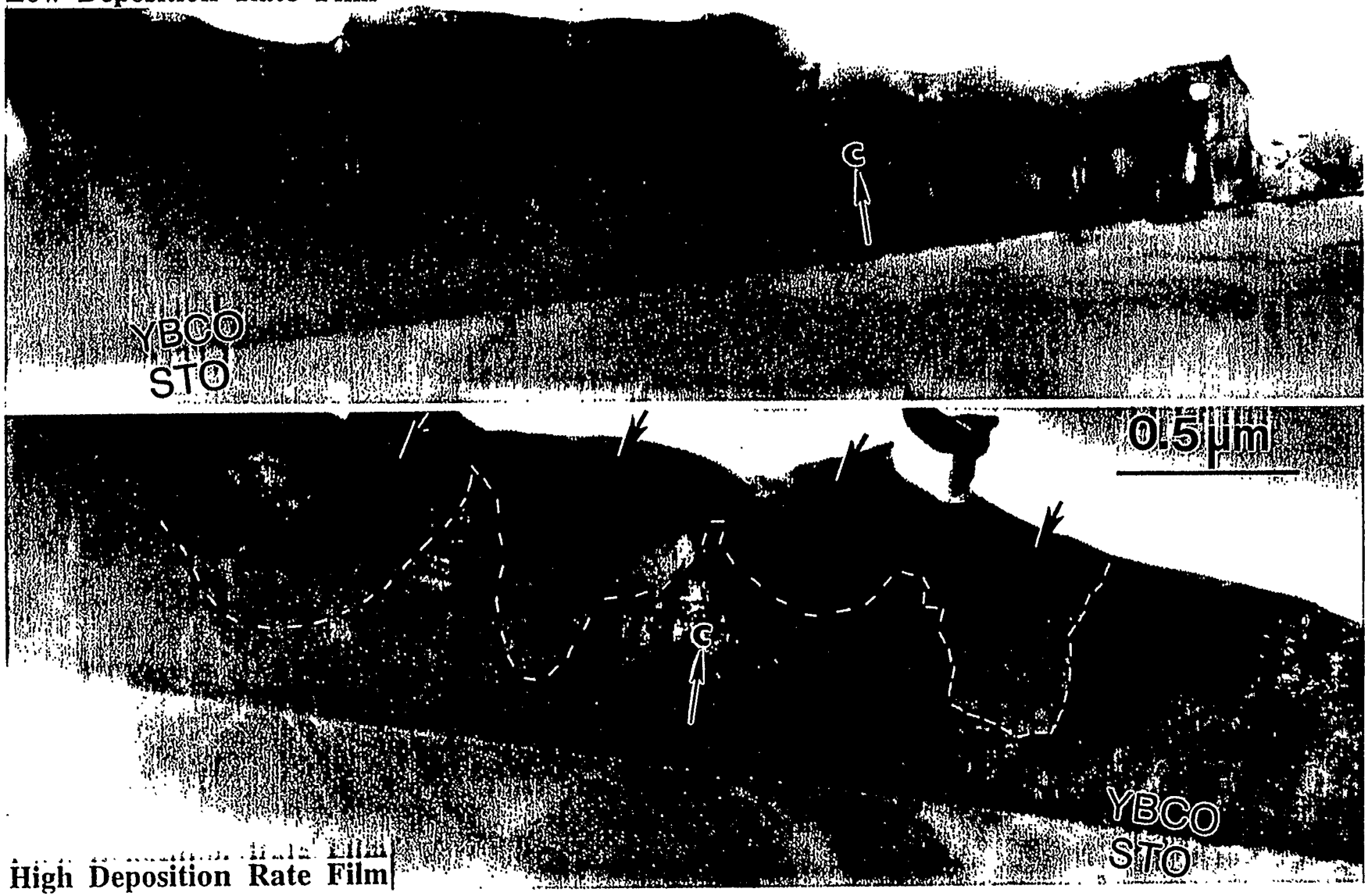
Results of RBS channeling analysis

- Single crystal substrate or very thin film $\rightarrow$ χ_{min} = 2-3%

<u>1 μm YBCO coatings on $SrTiO_3$</u>

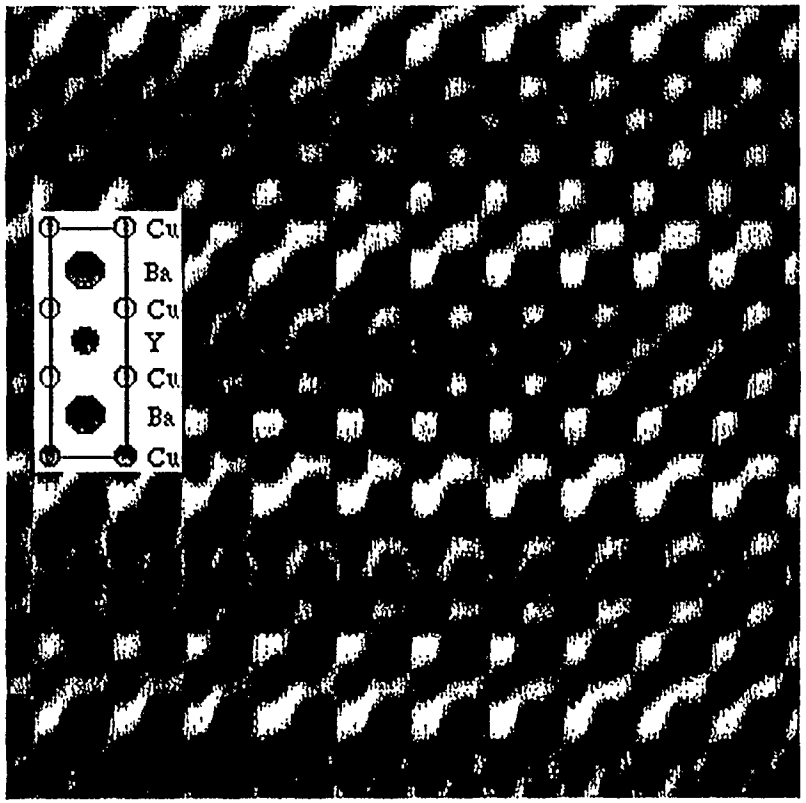
- Low deposition rate (5.9 Å/sec) $\rightarrow$ χ_{min} = 12%
- High deposition rate (200 Å/sec) $\rightarrow$ χ_{min} = 56%
- High deposition rate (174 Å/sec) with 825°C anneal $\rightarrow$ χ_{min} = 54%

Low Deposition Rate Film

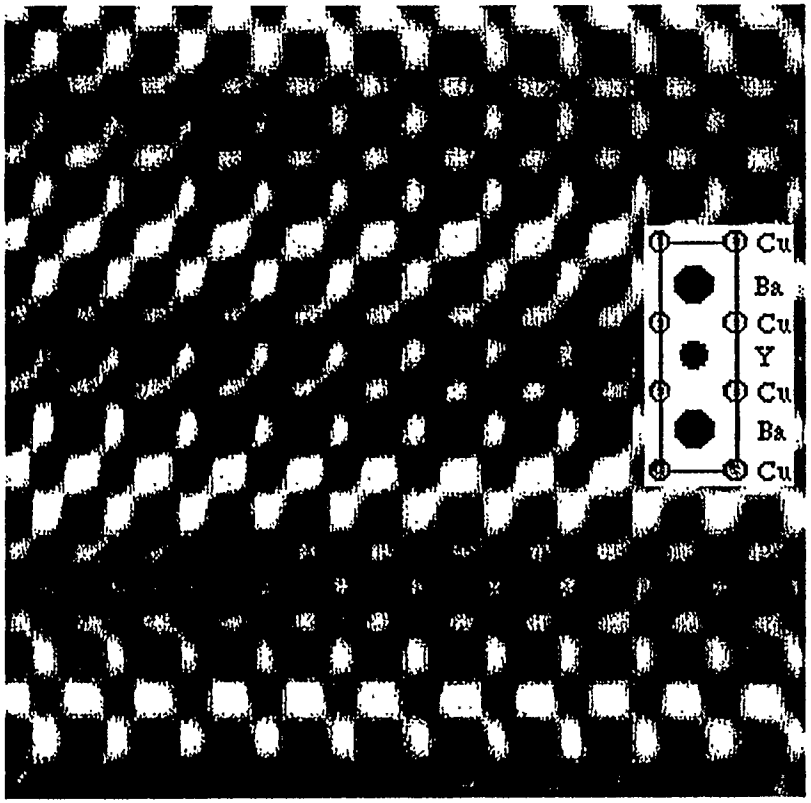


High Deposition Rate Film

High deposition rate



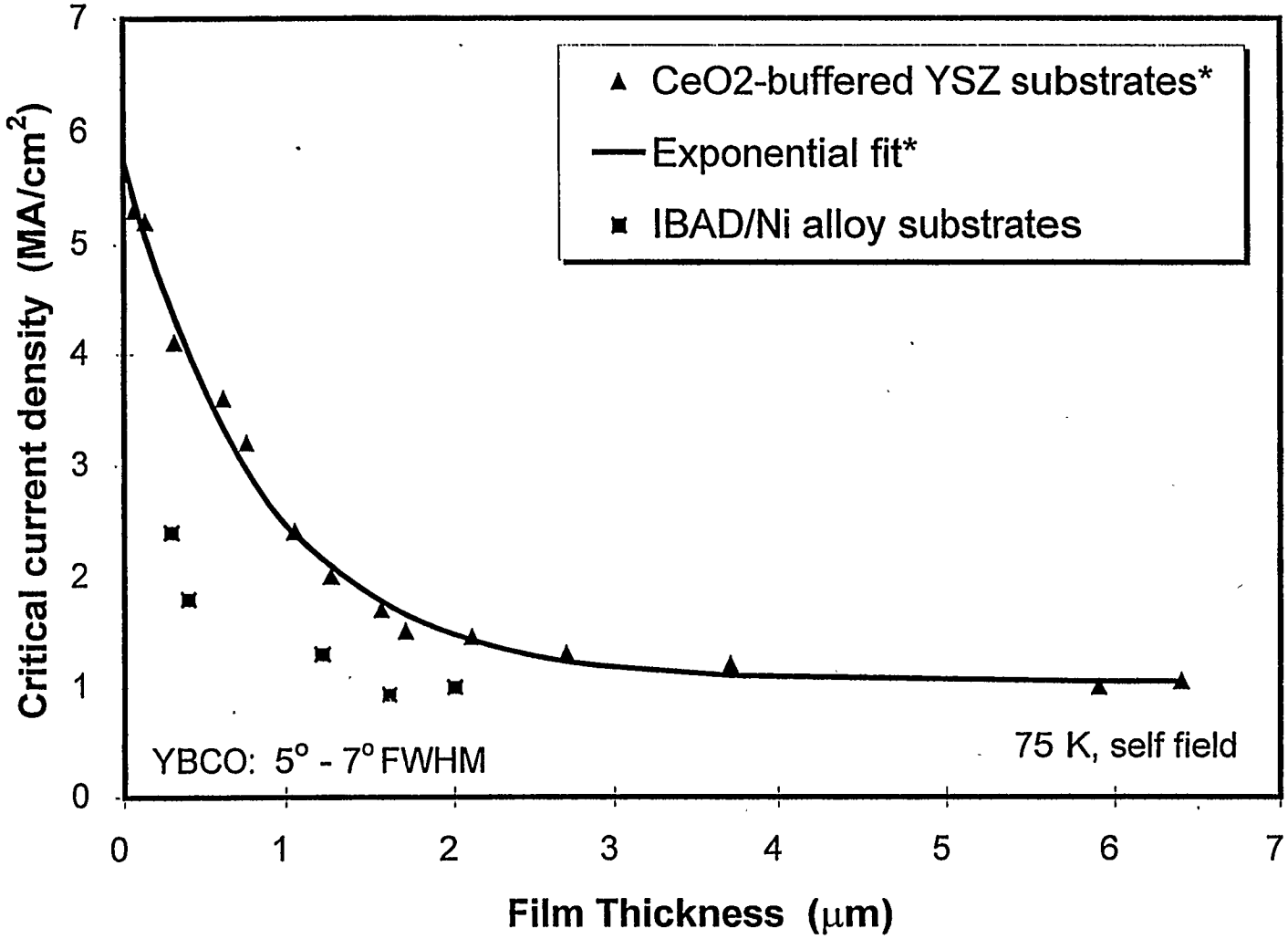
Low deposition rate



Obstacles to the fabrication of a 1 cm wide 1000 Amp coated conductor

- Empirical limit for J_c YBCO is 5-6 MA/cm^2 (77 K, self field)
- Even this limit cannot be attained for film thickness > 1 μm
- Weak-link characteristics of YBCO grain boundaries reduce J_c in practical conductors

YBCO critical current density decreases with increasing film thickness



* Appl. Phys. Lett. **63**, 1848 (1993)

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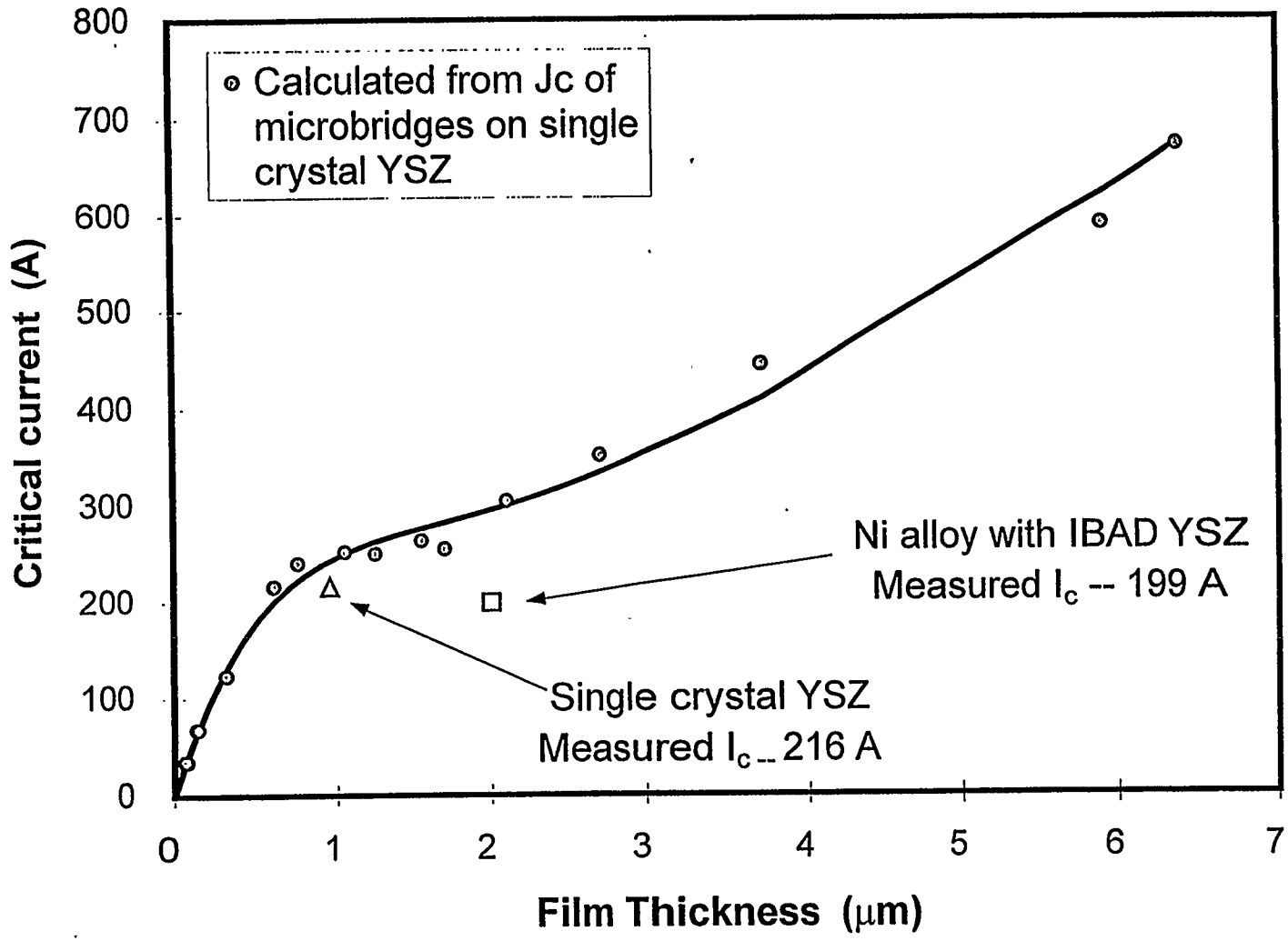
Critical current for 1 cm-wide conductors

YBCO with CeO_2 buffer layer



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Approaches to reducing YBCO texture requirements

- Improve J_c through high-angle grain boundaries.
- Investigate the limits for crystallinity of textured coatings or textured metal.
- Search for improved I_c through the network of grain boundaries relevant to a real coated conductor.*

*F. Yang, *et al.*, Physica C **244**, 299 (1995)

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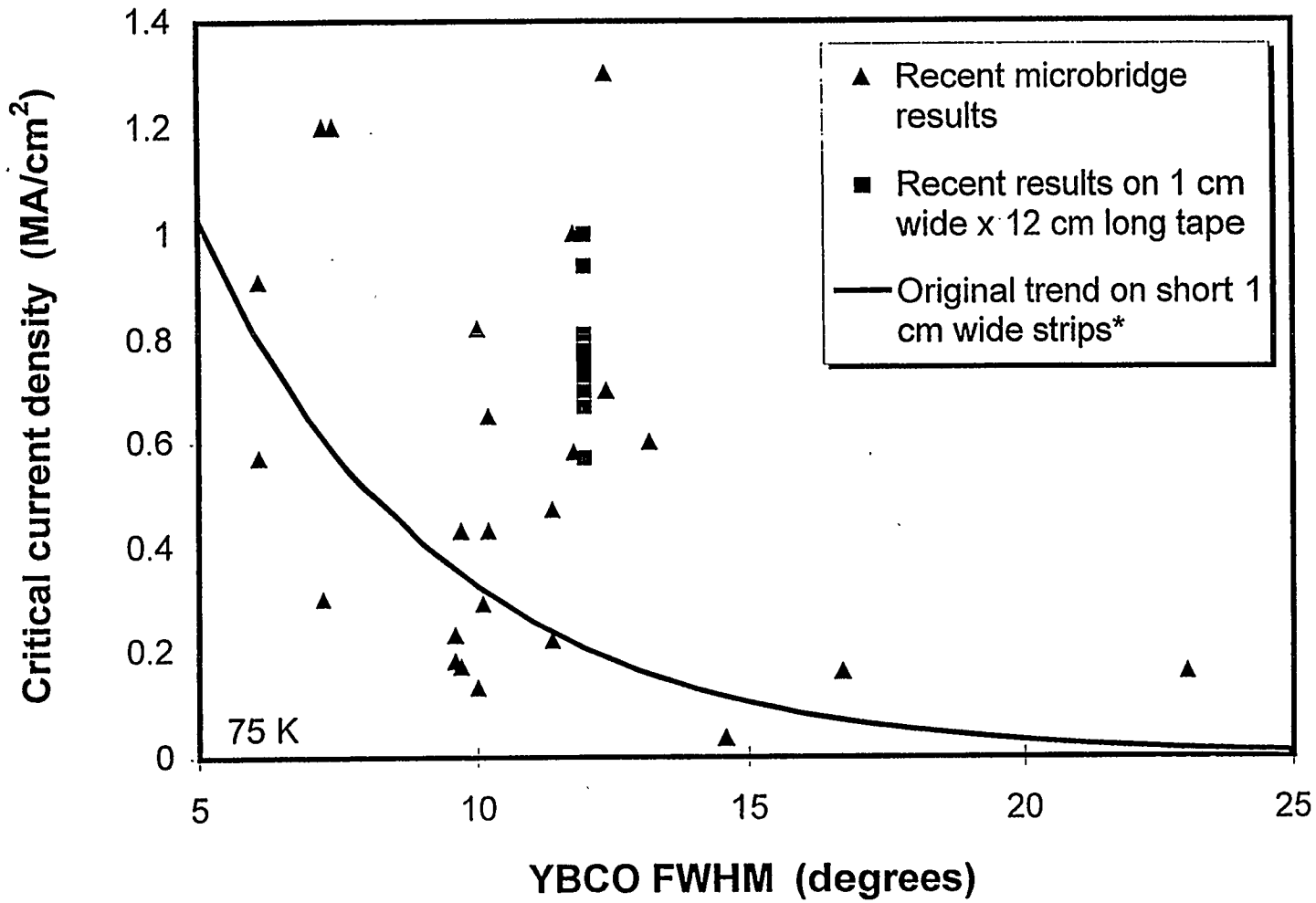
Relationship between J_c and texture for 1.0 μm thick YBCO films on IBAD / Ni alloy substrates



*Appl. Phys. Lett. **67**, 2397 (1995)

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Coating requirements for a 1000 A, 1 cm wide coated conductor

Assumptions

- J_c constant between 6.5 μm and 10 μm YBCO thickness
- Texture "penalty" is constant from 1 μm to 10 μm YBCO thickness
- YBCO texture: 5° ... or J_c comparable to that for 5° alignment
- Two-sided coating

Result

Above assumptions lead to a 10 μm thick YBCO film with $J_c = 0.5$ MA/cm^2, which will have an I_c of 500 A. Application to both sides of a flexible metal strip results in a 1000 A coated conductor.

Future work

- Continue study of the effect of high deposition rate on YBCO
- Work toward a 1000 A conductor by:
  - * researching limits to J_c of thick YBCO
  - * investigating the limits of IBAD texture enhancement
  - * exploring the relationship between J_c and texture
- Transition from YSZ IBAD to MgO IBAD

GRAIN BOUNDARY AND OTHER LIMITS TO JC IN YBCO AND BSCCO-2223

David Larbalestier

X. Y. Cai, A. Polyanskii, J. Anderson, Nina Heinig, George Daniels, Jodi Reeves, E. E. Hellstrom, S. E. Babcock (UW),
Q. Li, R. Parella, G. N. Riley Jr.. (American Superconductor Corp.)
Steve Foltyn, Paul Arendt (LANL)
, Jeff Parrell (now at OST), Steve Dorris (ANL)

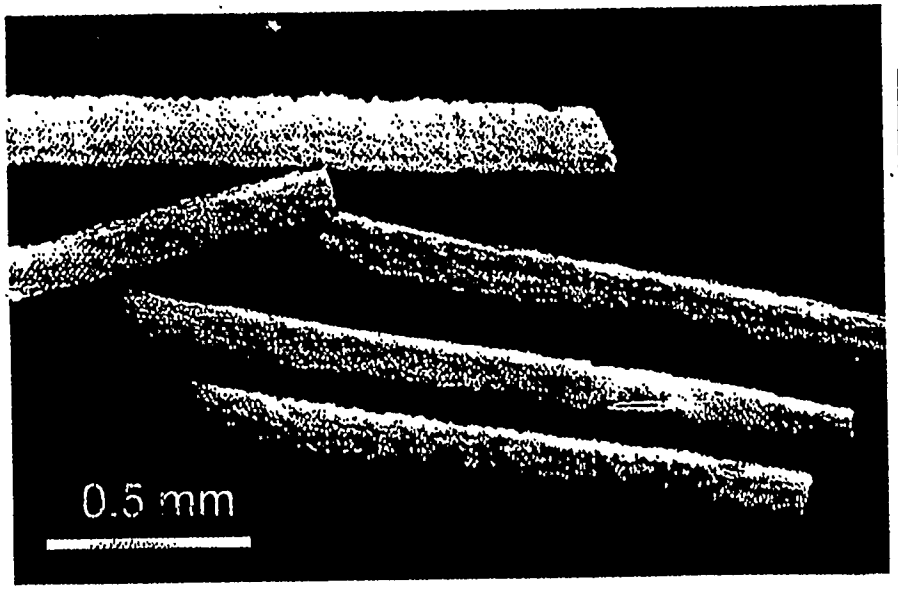
Work supported by NSF-MRSEC and by EPRI

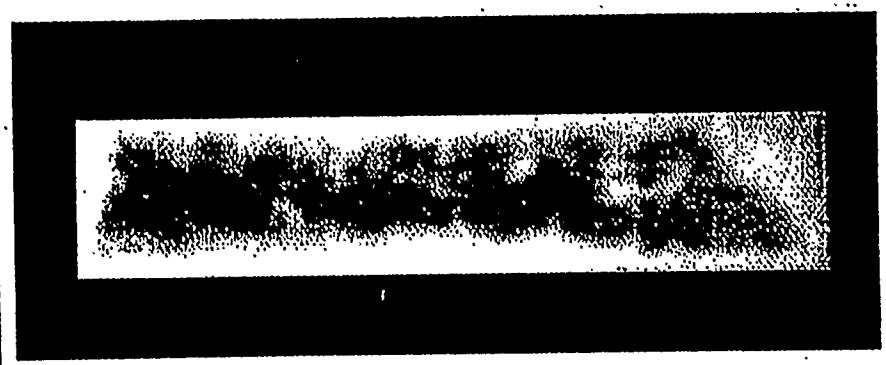
University of Wisconsin

Key Issues

- What limits the current?
  - Vortex pinning
  - Grain boundaries
  - Blocking second phase
  - Void spaces
  - Cracks
  - Substrate defects
- Study the percolation and its signature
  - controlling and understanding percolation

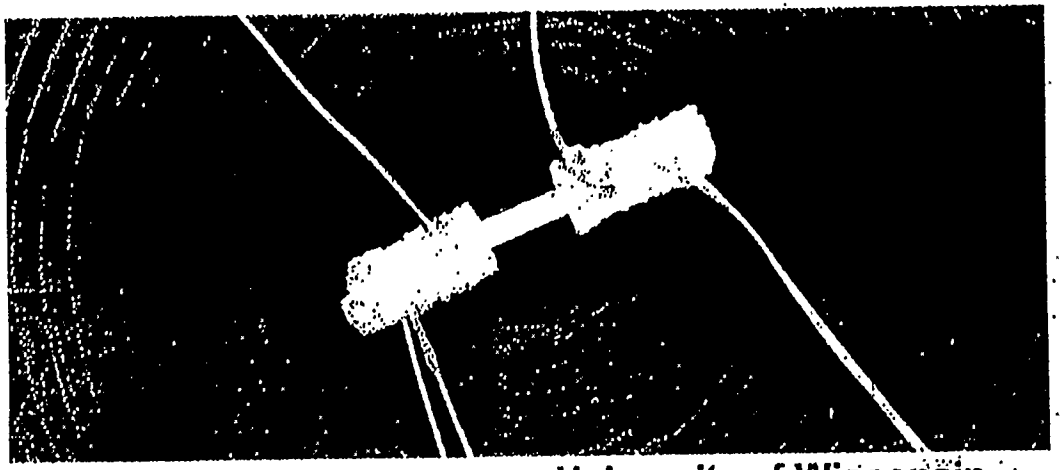
EXTRACTED HIGH-Jc FILAMENTS: 85 filament TAPE





Magneto-Optic Image of Individual Filament

TRANSPORT MEASUREMENT
symmetric current feed
1 micro-V/cm



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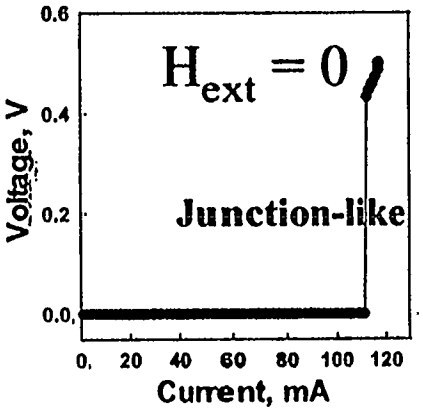
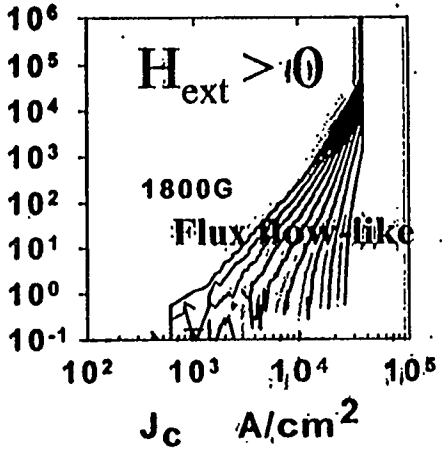
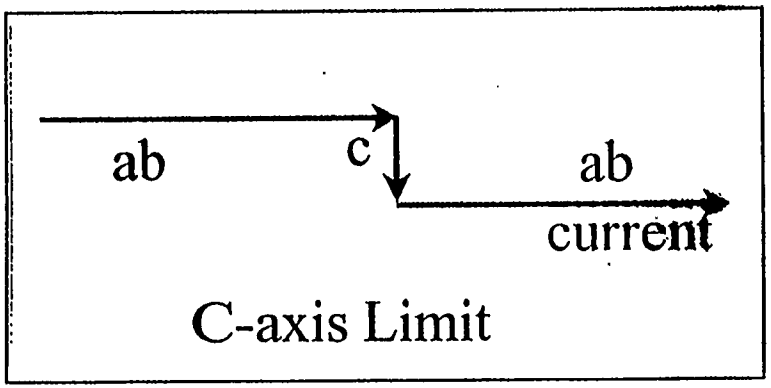
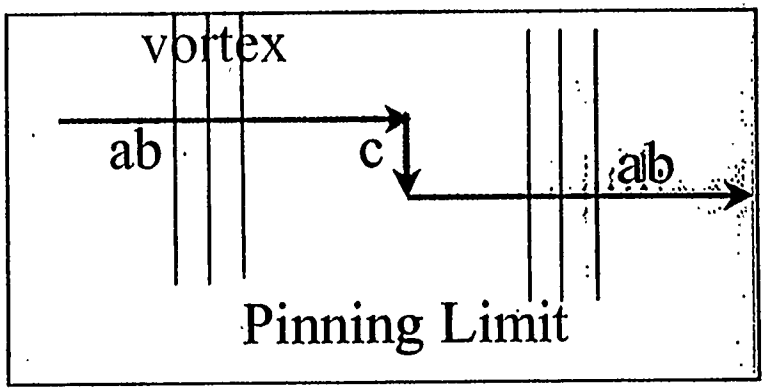
Single Filament Transport: Is Current Limited by Flux Flow in Grains or by C-Axis Links in the Polycrystalline Chain?



Etched, single filament
$\langle J_c \rangle > 50$ kA/cm^2

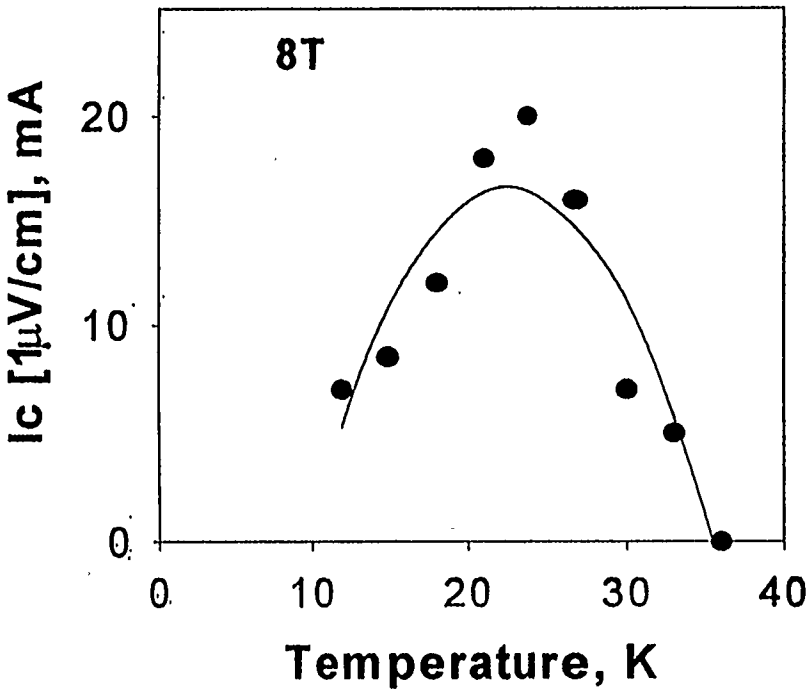


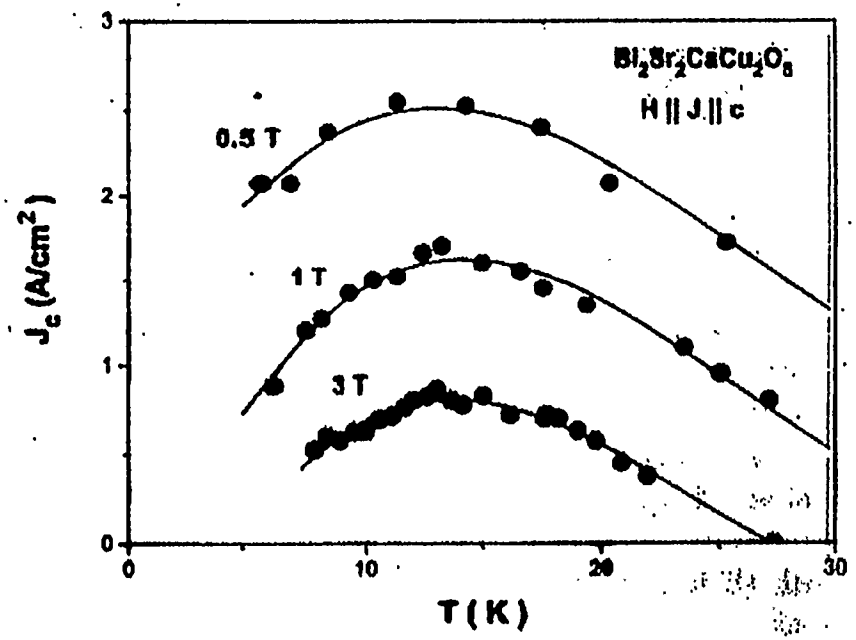




Cai, Larbalestier, Li, Riley (ASC)
University of Wisconsin

CHARACTERISTICS OF C-AXIS TRANSPORT III





Filament:
H // normal to broad face
I // broad face

2212 Single Crystal:
H // c-axis
I // c-axis
Rodriguez et.al PRL 71 (1993)

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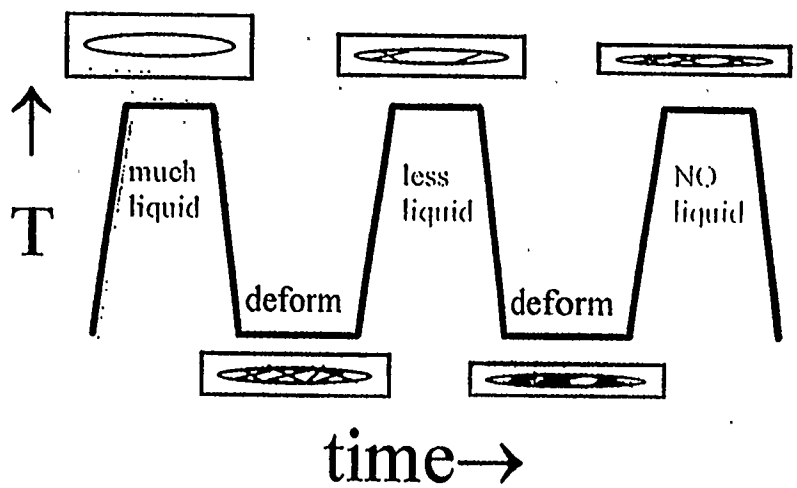
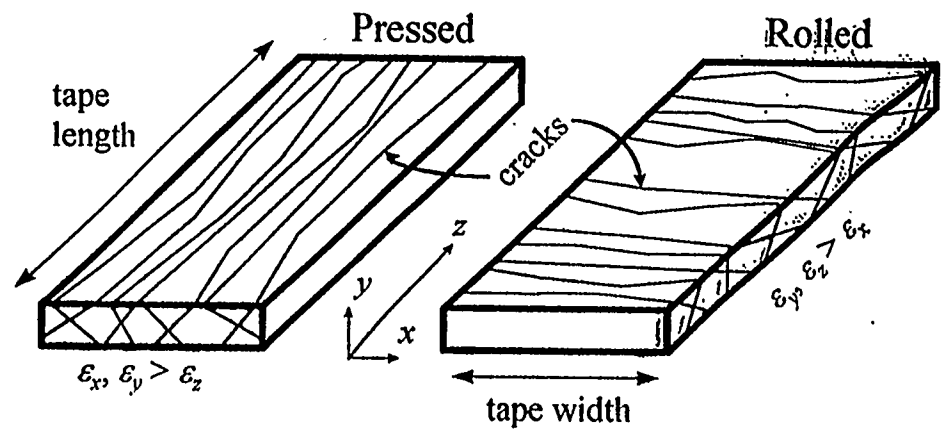
385

COLONY 1
COLONY 2
10 mm

Densification,deformation, alignment are intertwined





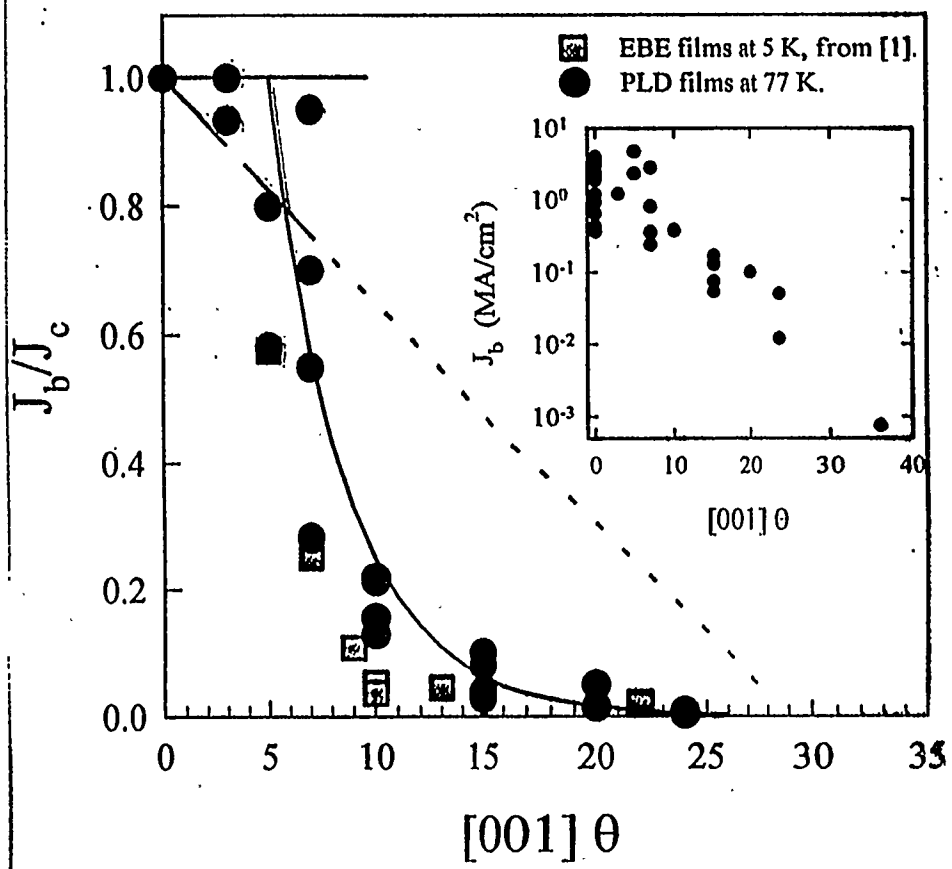
SUMMARY: Single filament experiment

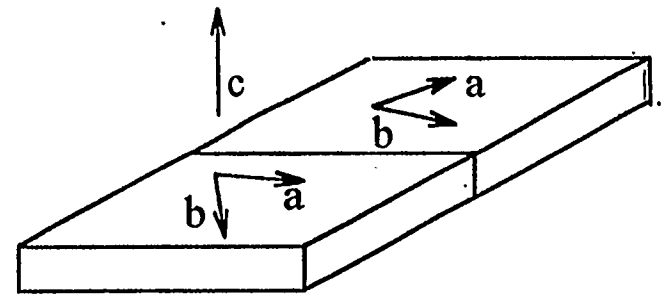
1. Multiple current limiting mechanisms on nanoscale and ~0.1 mm scale

2. At nanoscale, strong evidence of c-axis current paths and cross over from c-axis, junction control to flux flow with increasing field

3. Unhealed mechanical damage plays major role on macro scale

Granularity in $YBa_2Cu_3O_{7-x}$ is an obstacle to high current, high field applications.





- J_b/J_c decreases rapidly with θ.
- The green line indicates the prediction of the GBD overlap model.
- Understanding and minimizing the weak-coupling across low angle GBs can help in developing practical biaxially textured coated conductors.

*[1] D. Dimos et al. PRL, **61**, 219 (1988).*
*N. Heinig et al., APL, **69**, 577, (1996).*

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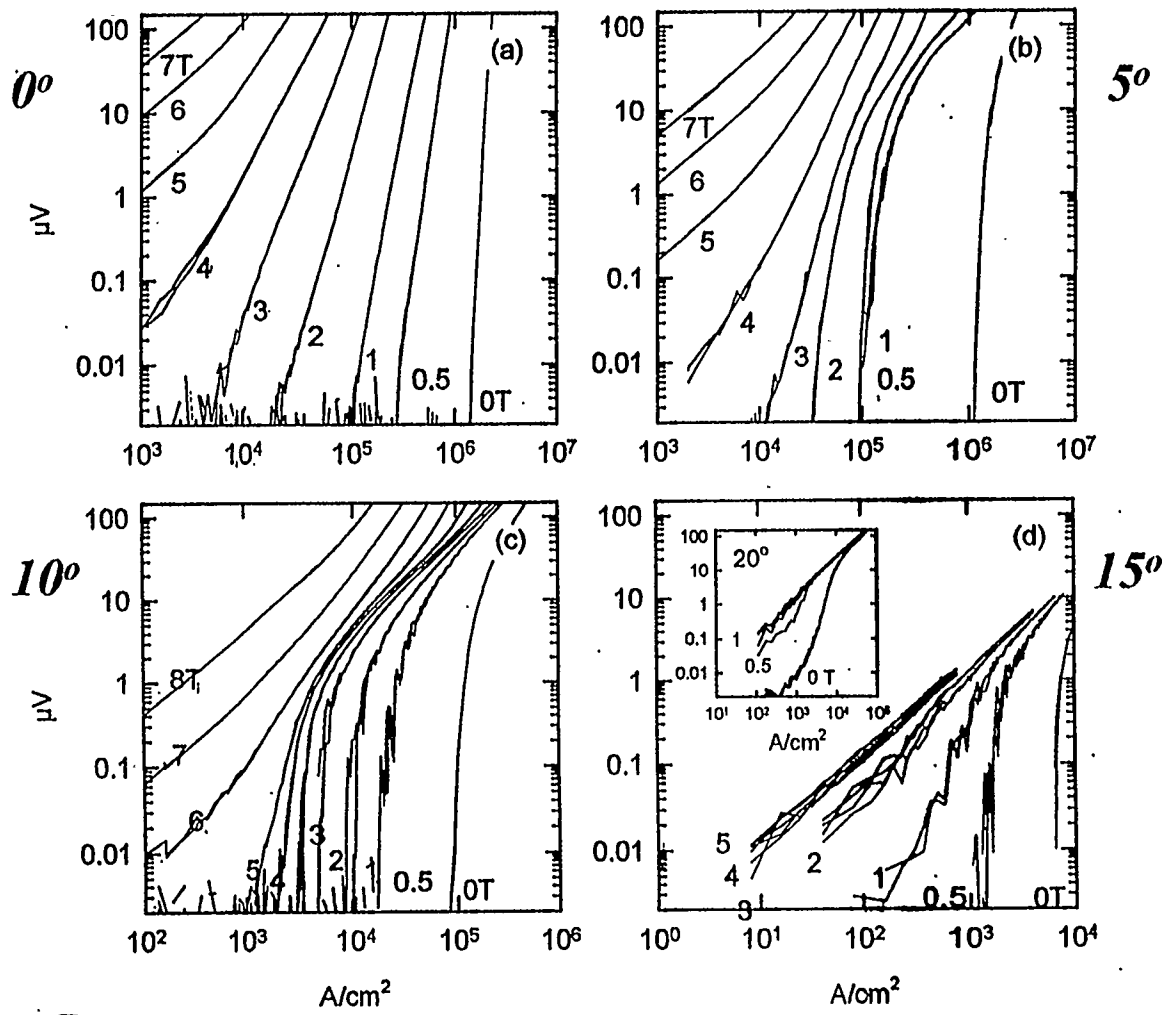
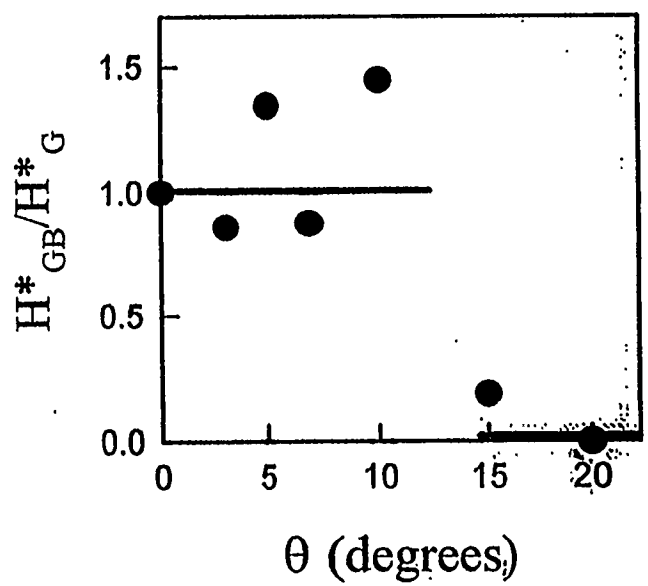
389

Extended V-I characteristics show progressive change with θ.

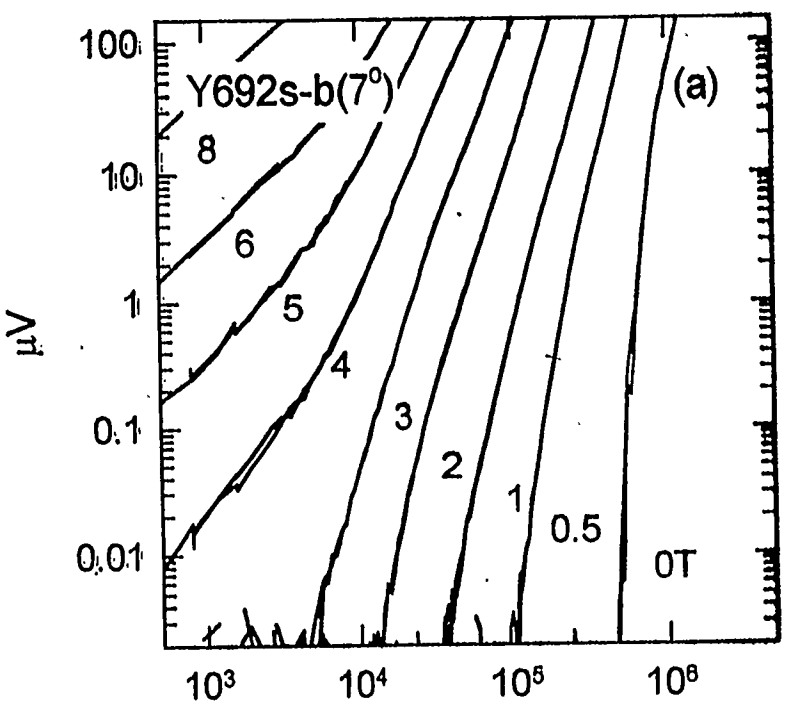


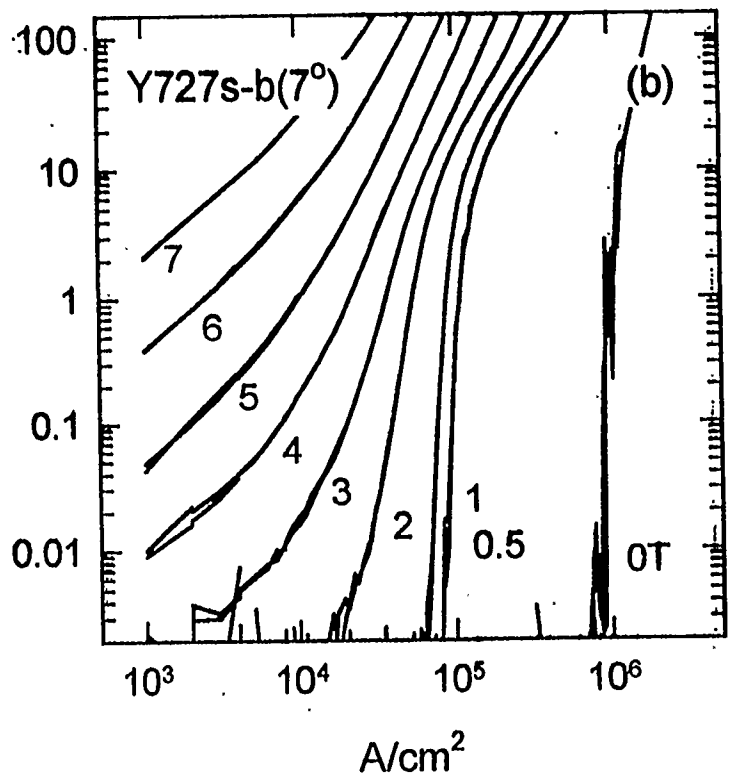
At both high and low voltage, log(V)-log(I) curves at 77 K show greater GB influence with larger θ.



Heinig et al., Appl. Phys. Lett., 69, 577, (1996).

Different 7° thin film bicrystals can have very different extended V-I characteristics.





In one bicrystal, there is little evidence of the GB in the V-I characteristic.

The other bicrystal shows evidence of weak coupling and flux flow along the GB at higher V.

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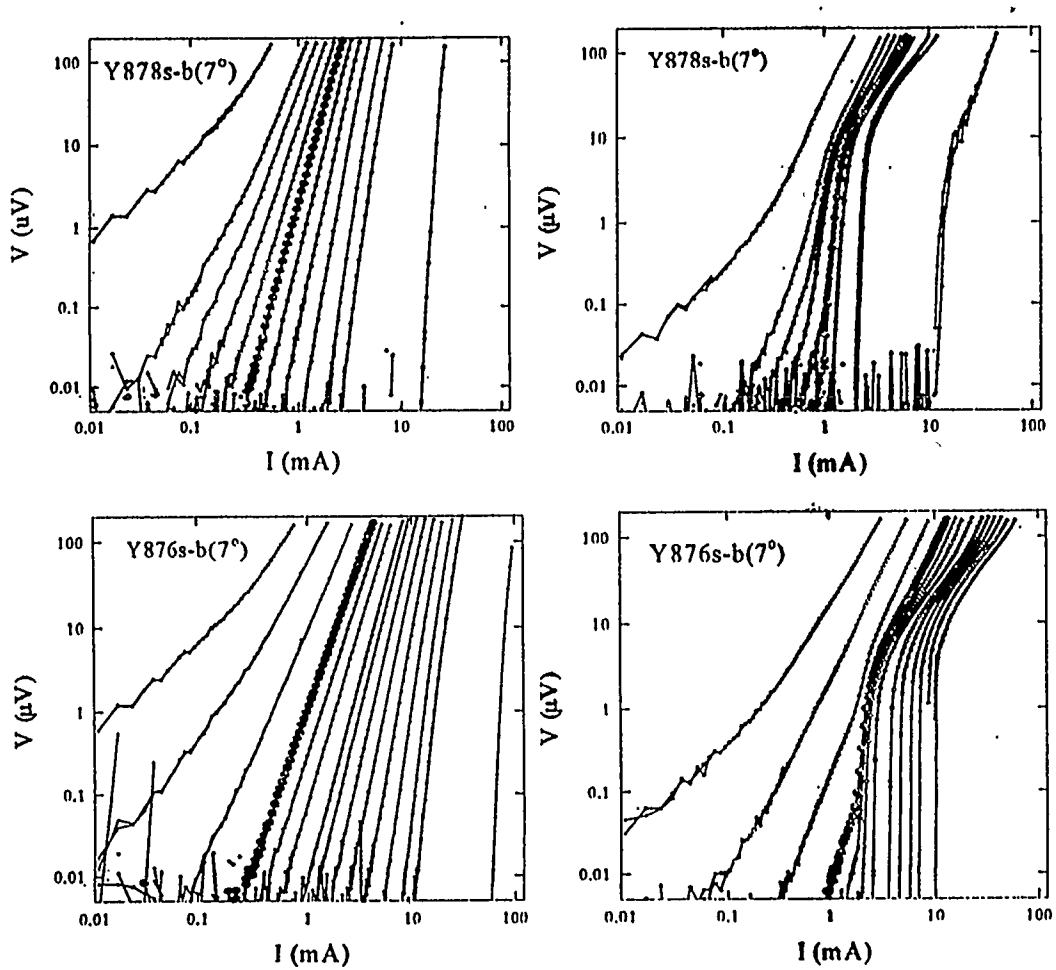
Thicker films have larger H* (77 K)



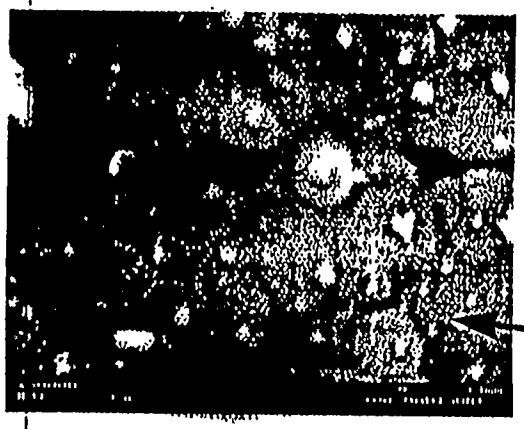
0.12 μm film had intragrain H* = 2.5 T.

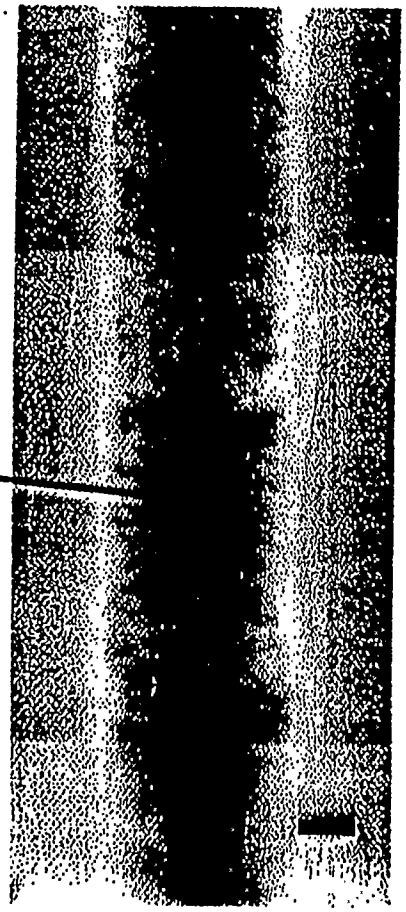
0.25 μm film had intergrain H* ~ 3.5 T.

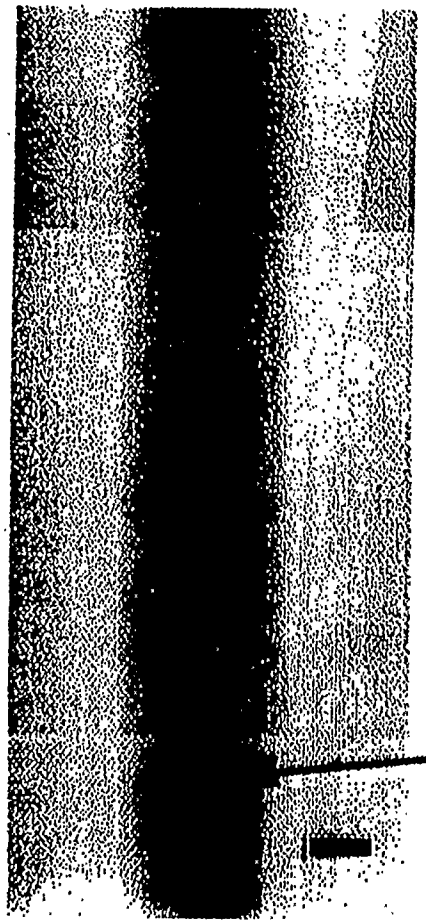
0.50 μm film had intragrain H* = 5 T.

IBAD PLD films have H* = 5.5 T and bulk-scale $YBa_2Cu_3O_{7-x}$ have intragrain H* = 7-8 T.

LANL IBAD $YBa_2Cu_3O_{7-x}$ thick films observed by magneto-optic imaging and SEM







Link A
J_c = 0.7 MA/cm²

Link B
J_c = 1.3 MA/cm²

J_c of nearby links can vary by a factor of 2.

MOI indicates more granularity in the low J_c link.

This suggests voids or misaligned grains as the cause of low J_c.

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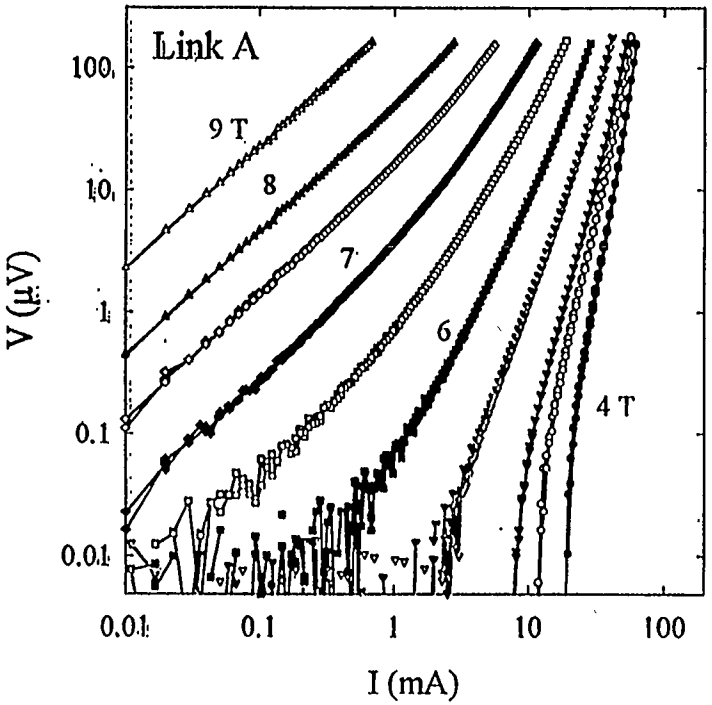
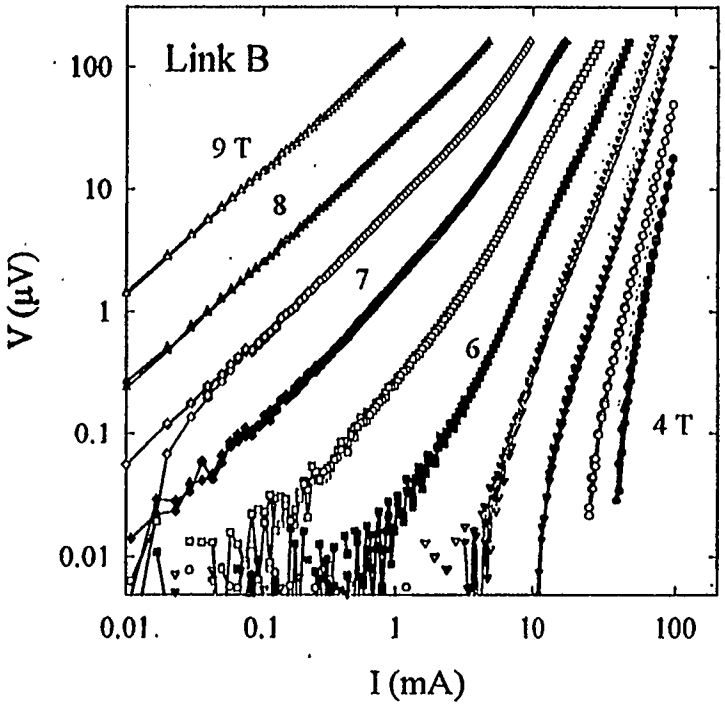
Extended V-I characteristics of the IBAD films show shape variations consistent with granularity.

"Granular" IBAD link



"Well-Connected" IBAD link



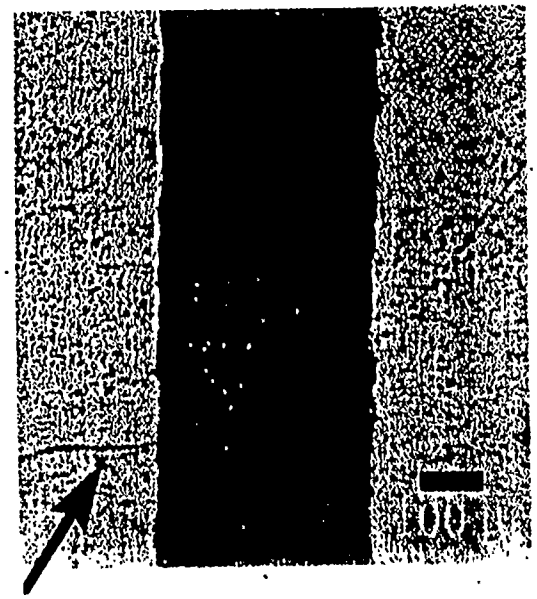
Both links have H* = 5.5 T @ 77 K.

Link A has (i) a high voltage change in curvature in the V-I curve.
(ii) more closely spaced V-I curves at lower magnetic fields.

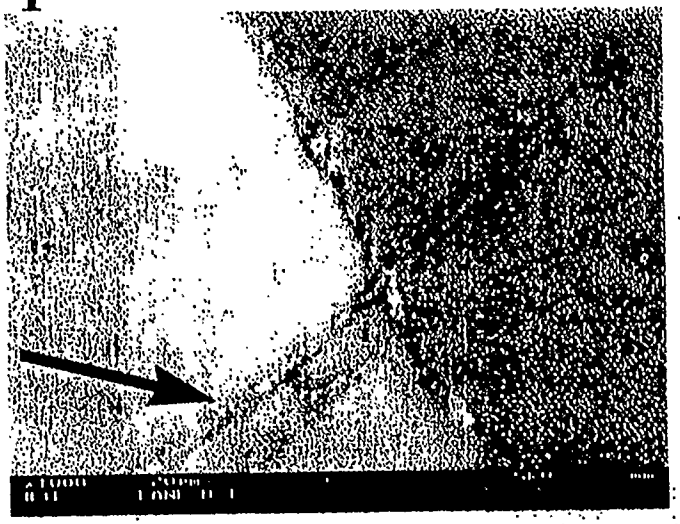
LAGB studies indicate these are signs of weak coupling.

MOI and SEM are used to characterize local defects in the IBAD sample.

MOI shows poor electromagnetic connectivity at the scratched region.



Light micrograph shows scratched substrate.



SEM shows scratch on substrate and film.

Higher magnification SEM shows second phase growing in scratched film.

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Summary and Conclusions

- Reproducible LAGB bicrystal films were grown by PLD:
  - Repeatable zero field properties indicate good control over T_{growth}.
  - H*(77K) depends on film thickness, t = 0.12 μm to 0.5 μm.
  - high voltage curvature in the extended V-I does not depend on thickness.

- Polycrystalline IBAD films from LANL were measured:
  - characterized by transport, MOI, and SEM.
  - variation in zero field J_c is caused by granularity; i.e. poorly connected or misaligned $YBa_2Cu_3O_{7-x}$ grains.
  - granularity in V-I characteristics can be understood by comparing to transport in the LAGB bicrystals.

Substrate effects on film growth, grain boundaries, and flux pinning in coated conductors

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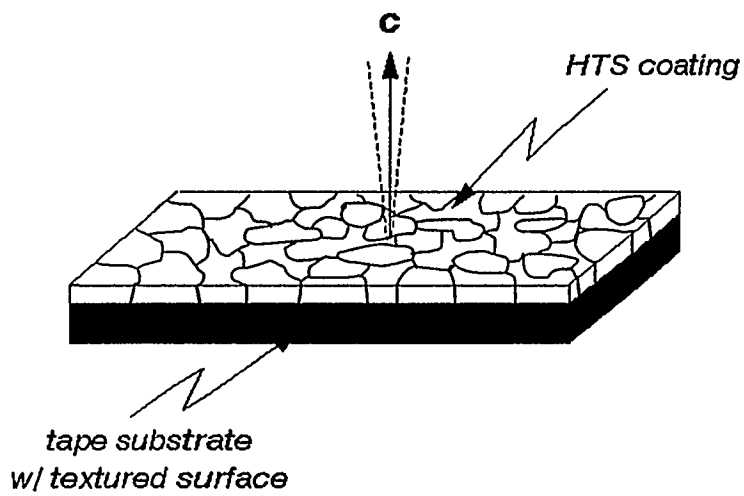
- R. Feenstra
- Q. He
- H. R. Kerchner
- D. P. Norton
- C. Park
- C. Prouteau
- B. C. Sales
- J. R. Thompson
- D. Verebelyi

ornl

Some General Features of Coated Conductors



Thin-Film like:

- Epitaxial growth from textured substrate surface
- c-axis oriented, with ~planar grain boundaries

  [*(001) tilt boundaries determine gb conduction*]

- Strong influence by substrate properties

  [*texture distribution, lattice match, chemical compatibility, surface defects, ...*]

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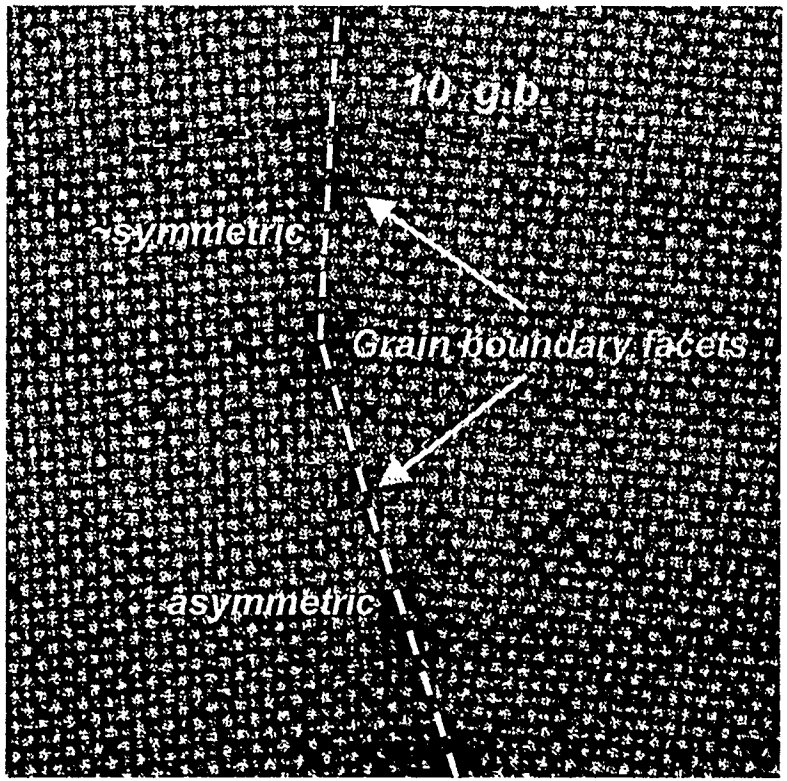
Factors Limiting Current Conduction

- **Transport properties of single (001) tilt boundaries**
  - ➢ *mechanisms? Special boundaries? Tailoring?*
- **Distribution of gb orientations**
  - ➢ *contiguous vs long-range?*
- **Microstructural defects: origin and control for flux pinning**
  - ➢ *composition (2nd phase precipitates, intergrowths, etc.)*
  - ➢ *growth method and conditions*
  - ➢ *substrate-surface induced growth defects*

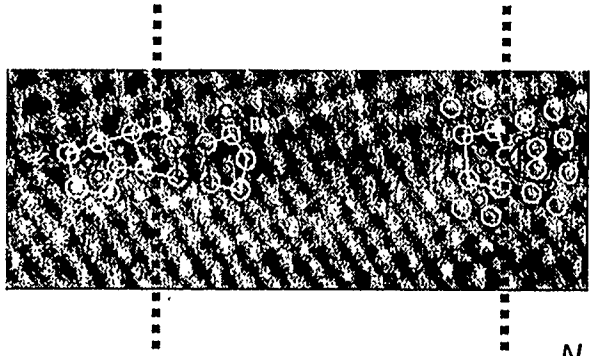
Micro-Electronic Properties of Grain Boundaries

- *G. B.'s in YBCO films have facets*
- *Hole carrier density varies with g.b. symmetry*

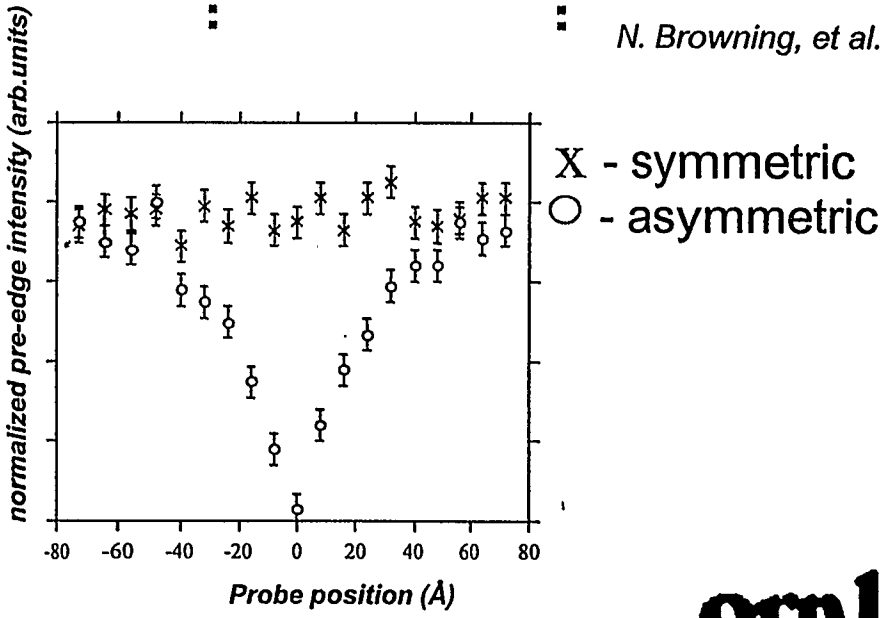
Are symmetric facets strongly linked?



M. Chisholm



N. Browning, et al.



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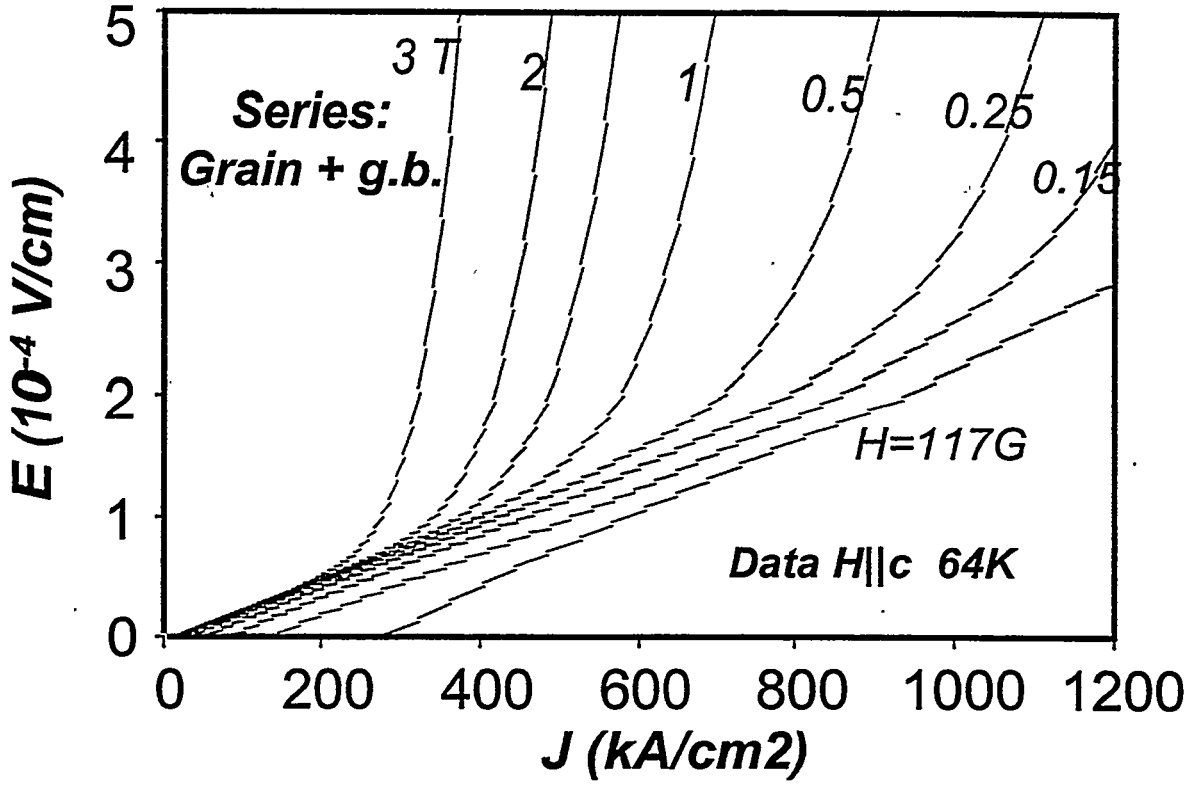
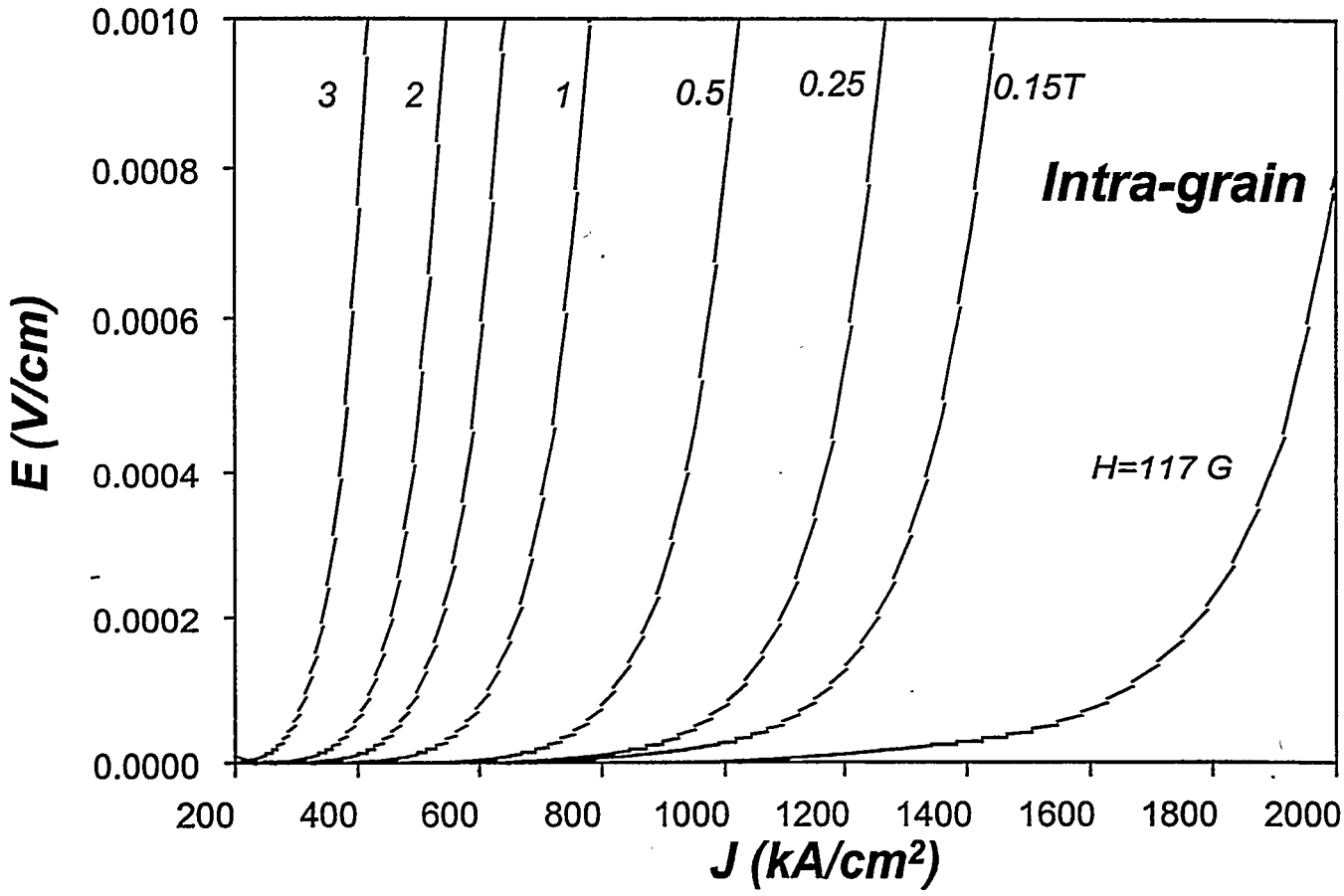
Field dependence of V(I) curves at 64K 24° Grain Boundary ($YBCO/SrTiO_3$)

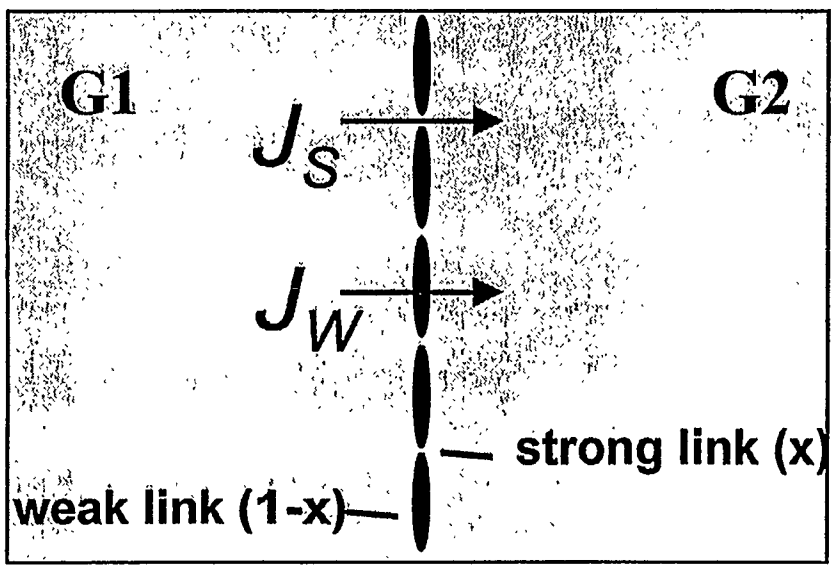


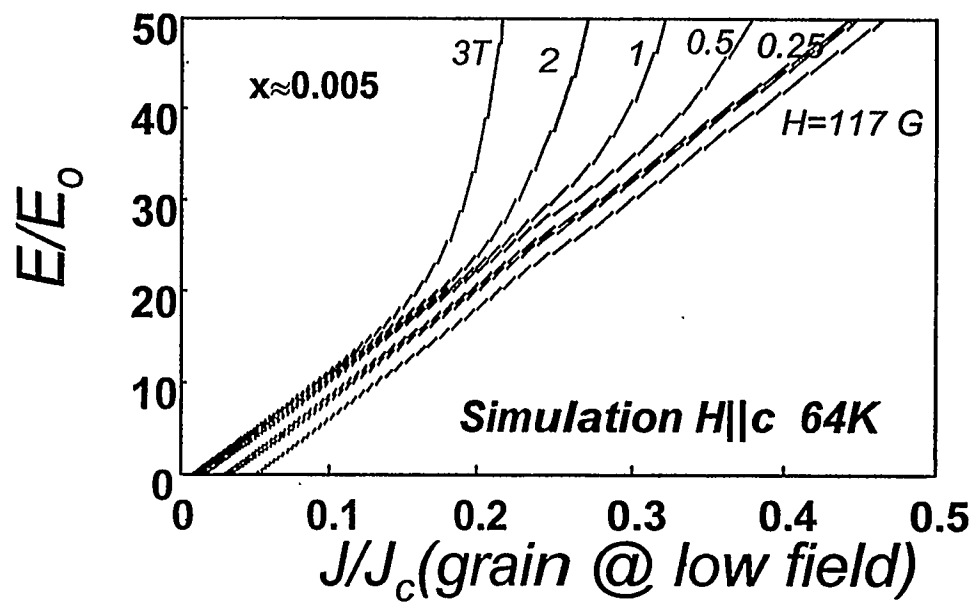


Measurements Indicate a Strong Component

A Model

- The grain boundary is composed of equally sized and spaced dislocation cores separated by a very small fraction of strong links (x).
- The weak links have a tunneling behavior and carry J_W, and resistance R_b
- The strong links?: Intra-grain like J_c; very strongly couple J-junctions; other?





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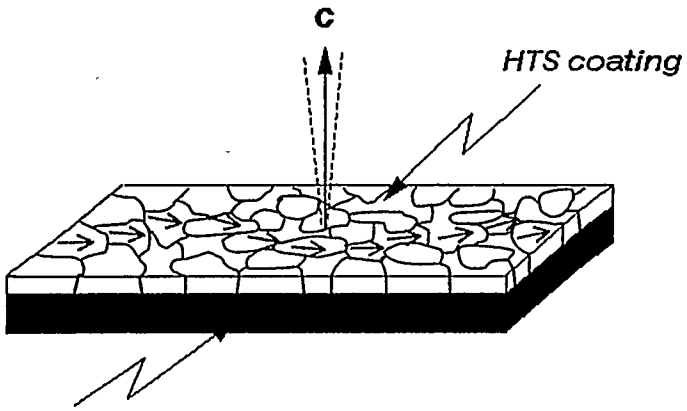
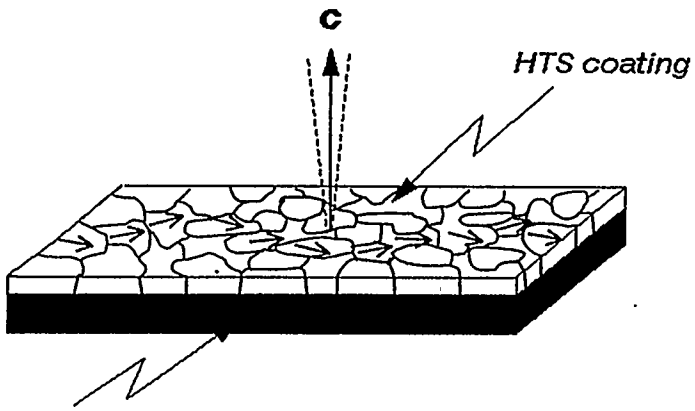
Distribution of Grain Boundary Orientations in Coated Conductors

- **Need grain-to-grain low-angle boundaries**
  - ➢ *long-range alignment may not be essential!*

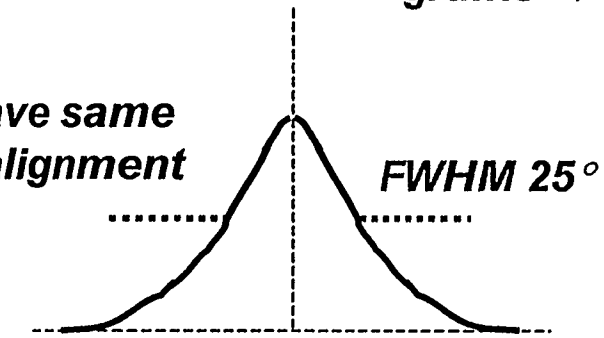


only low-angle, contiguous grains ⇒ high J_c



many high-angle, contiguous grains ⇒ low J_c

but, both have same long-range alignment

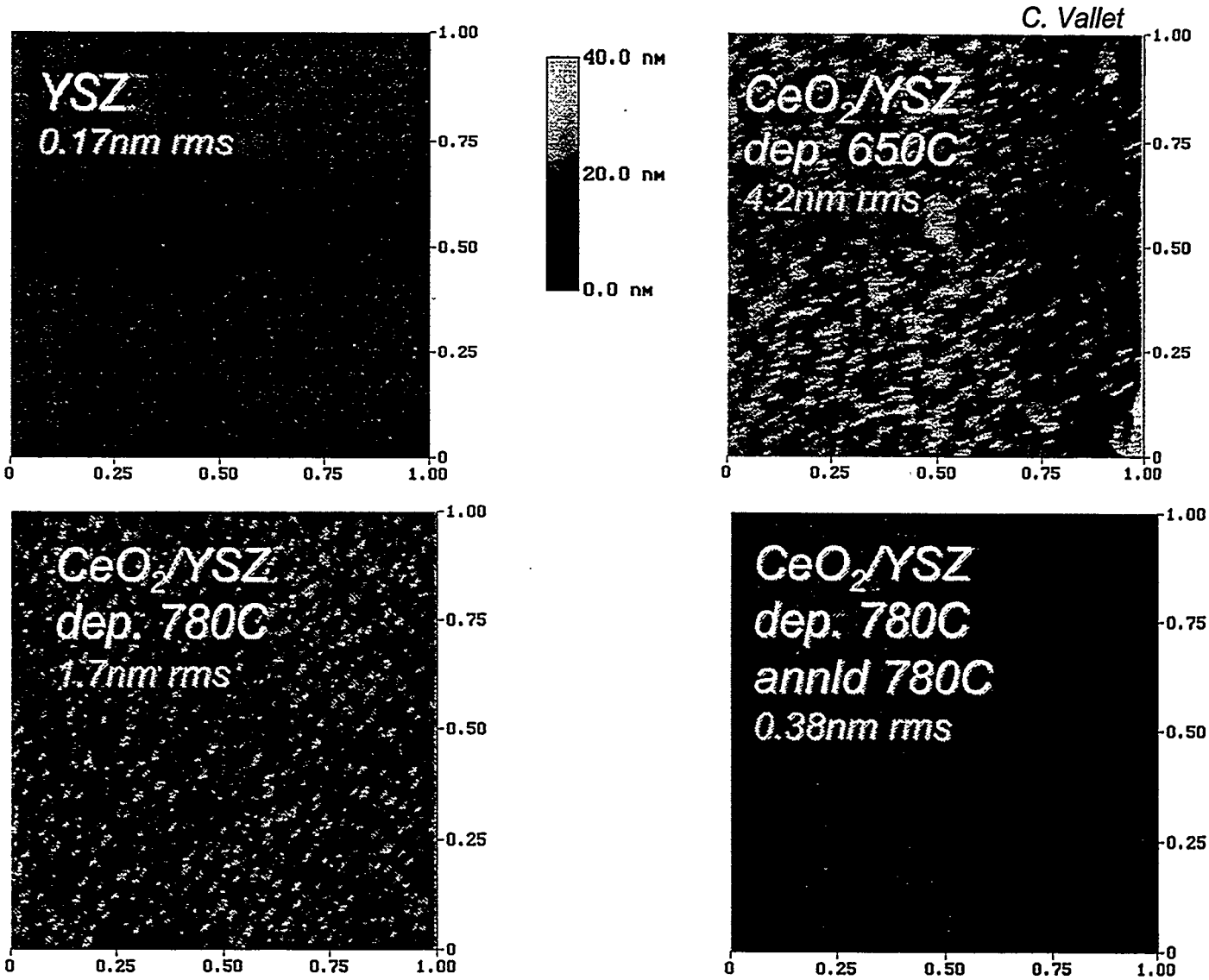


Morphology of CeO_2 Buffer Layers on YSZ

- CeO_2 layer (~20-40nm thick) by e-beam evaporation
- As-deposited and post-annealed in oxygen
- High-J_c films by BaF_2 process only on ann'ld subst.

Surface Roughness Depends on Preparation &Treatment

C. Vallet



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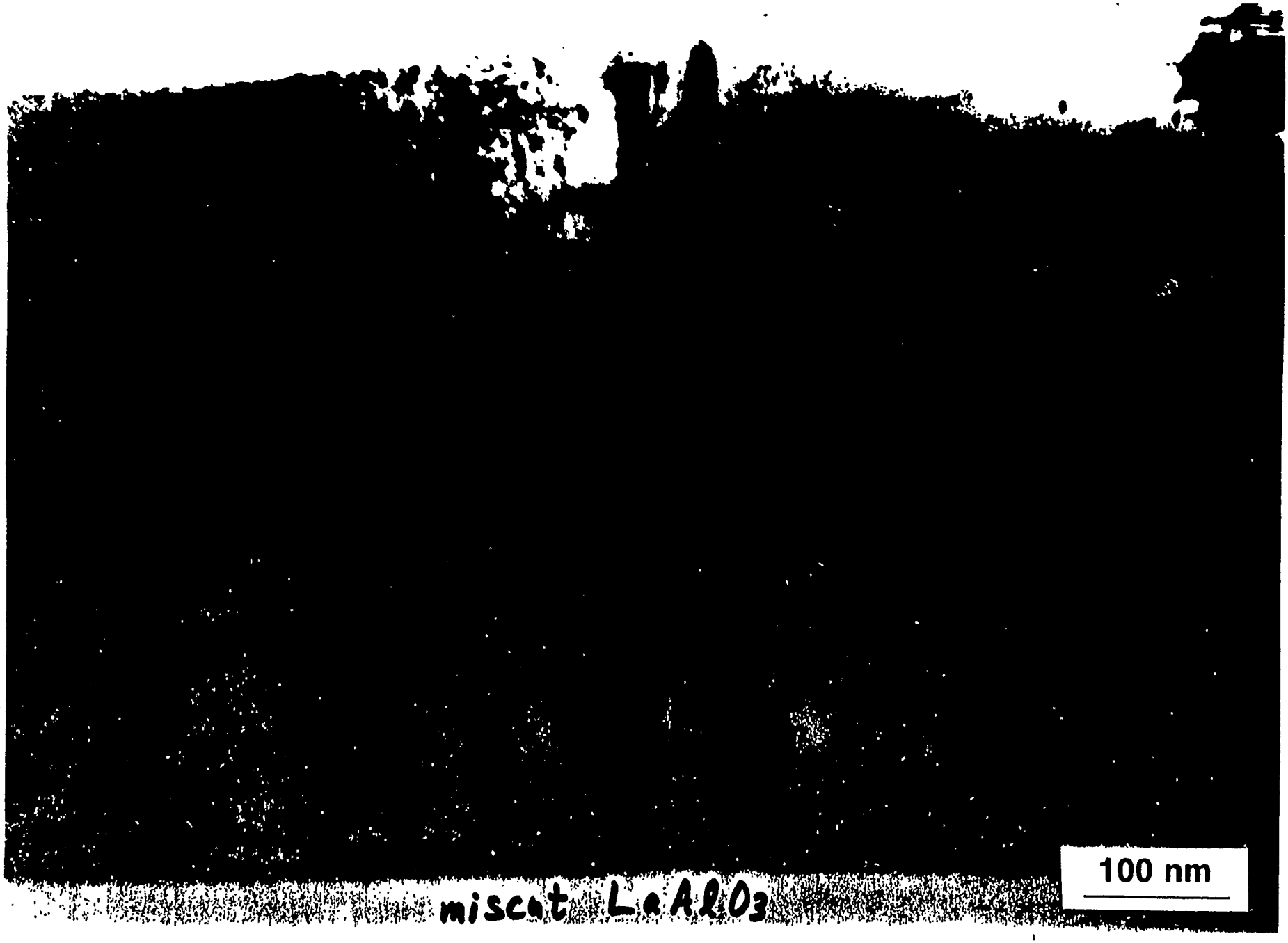

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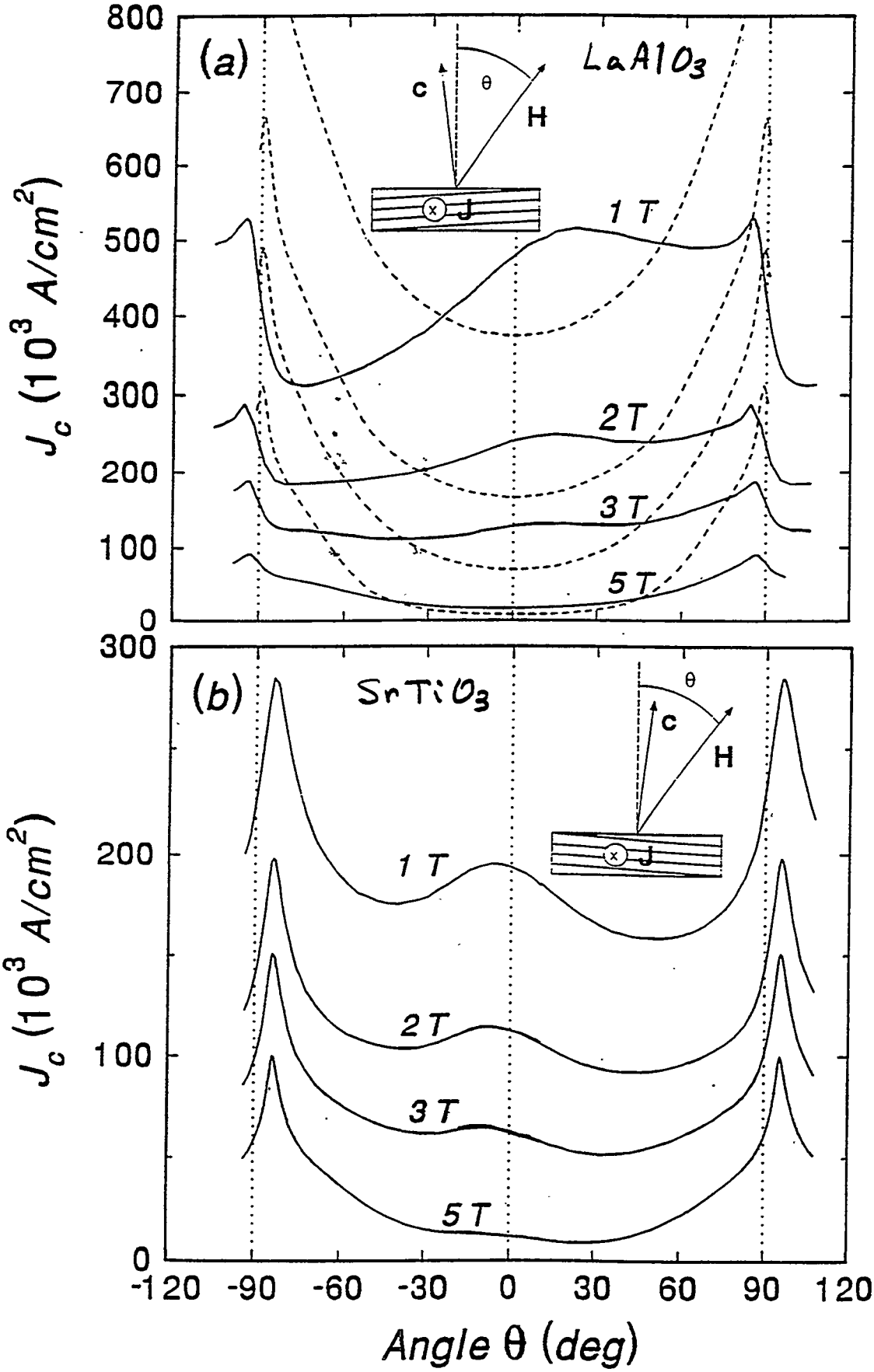
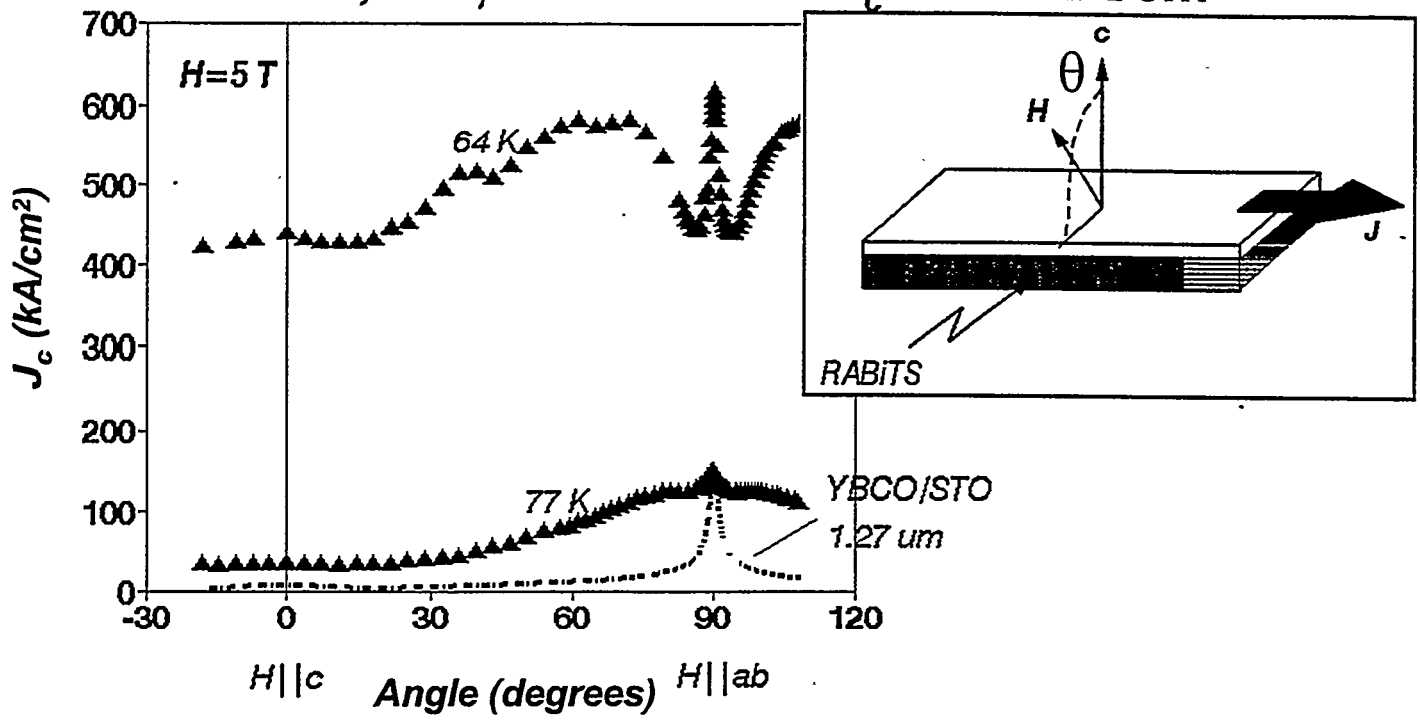
YBCO on miscut substrates



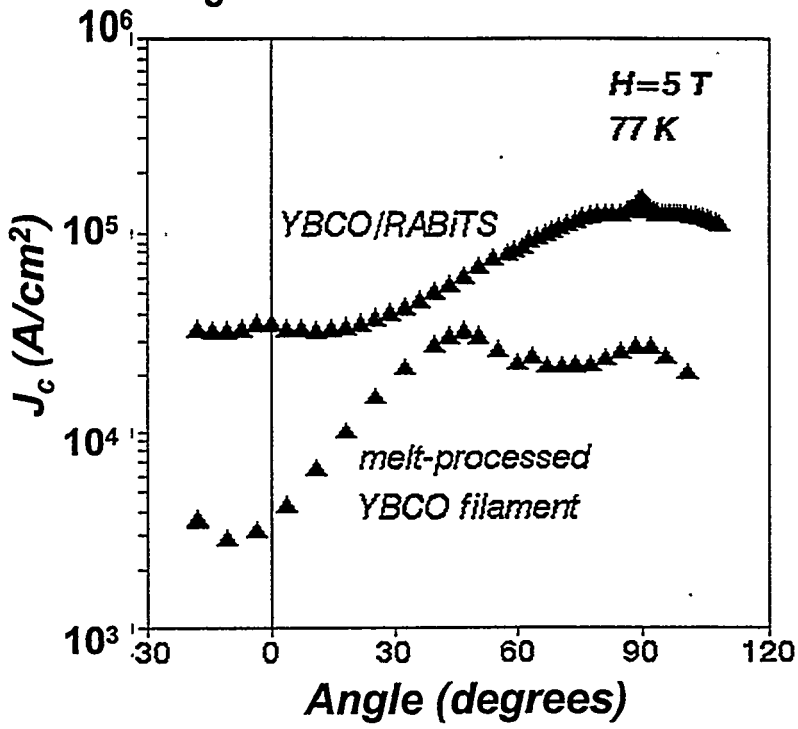
Strong Flux Pinning and Anomalous Angular Dependence of J_c

YBCO/RABiTS, 0.6 μm thick with J_c = 1.4 MA/cm^2

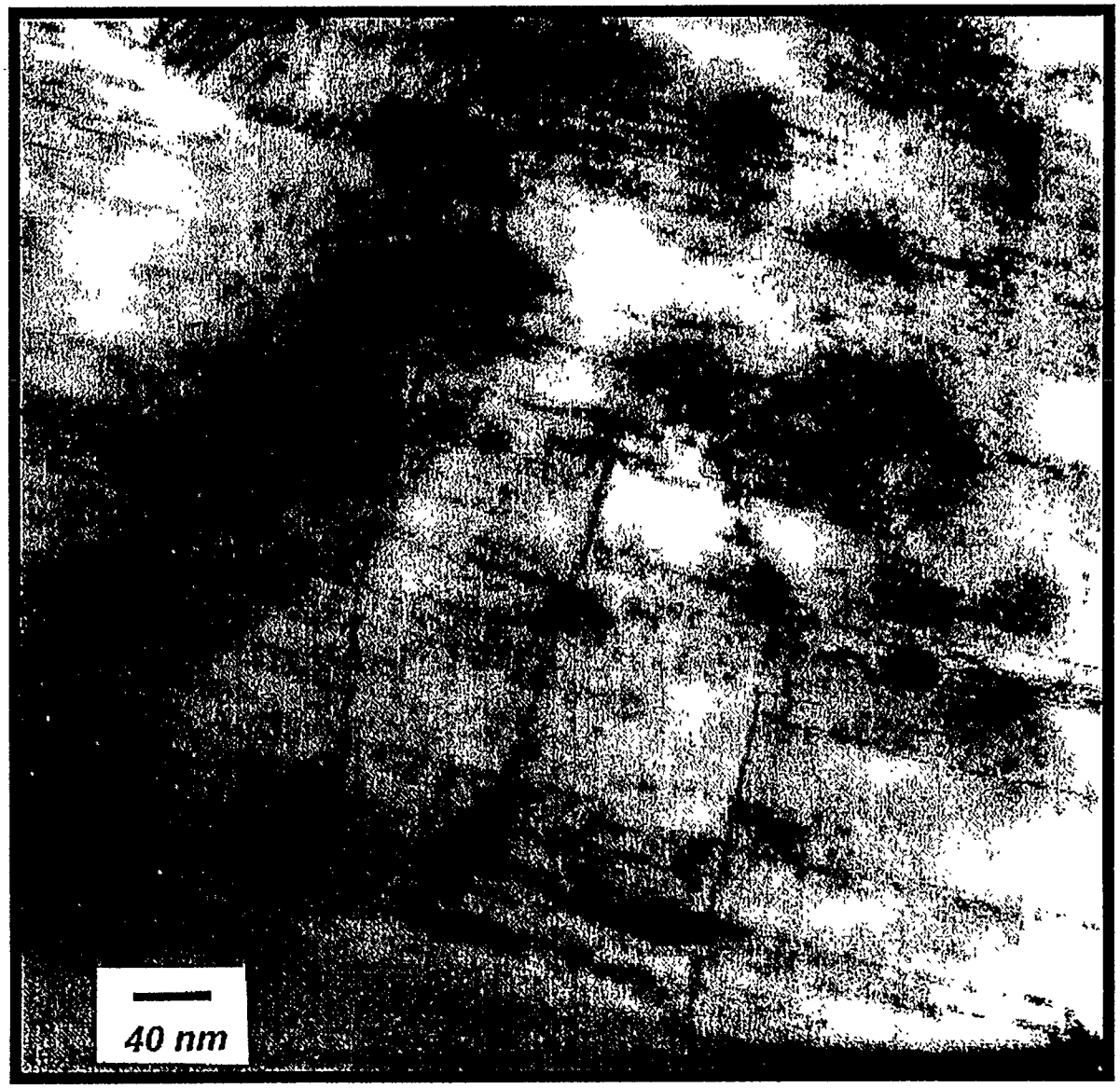


Analogous strong-pinning systems

- *Melt-processed/deformed bulk YBCO*
- *Heavy-ion irradiated YBCO films*
- *YBCO films grown on substrate with surface steps*



Presence of extended strain fields and many planar defects in YBCO/RABiTS



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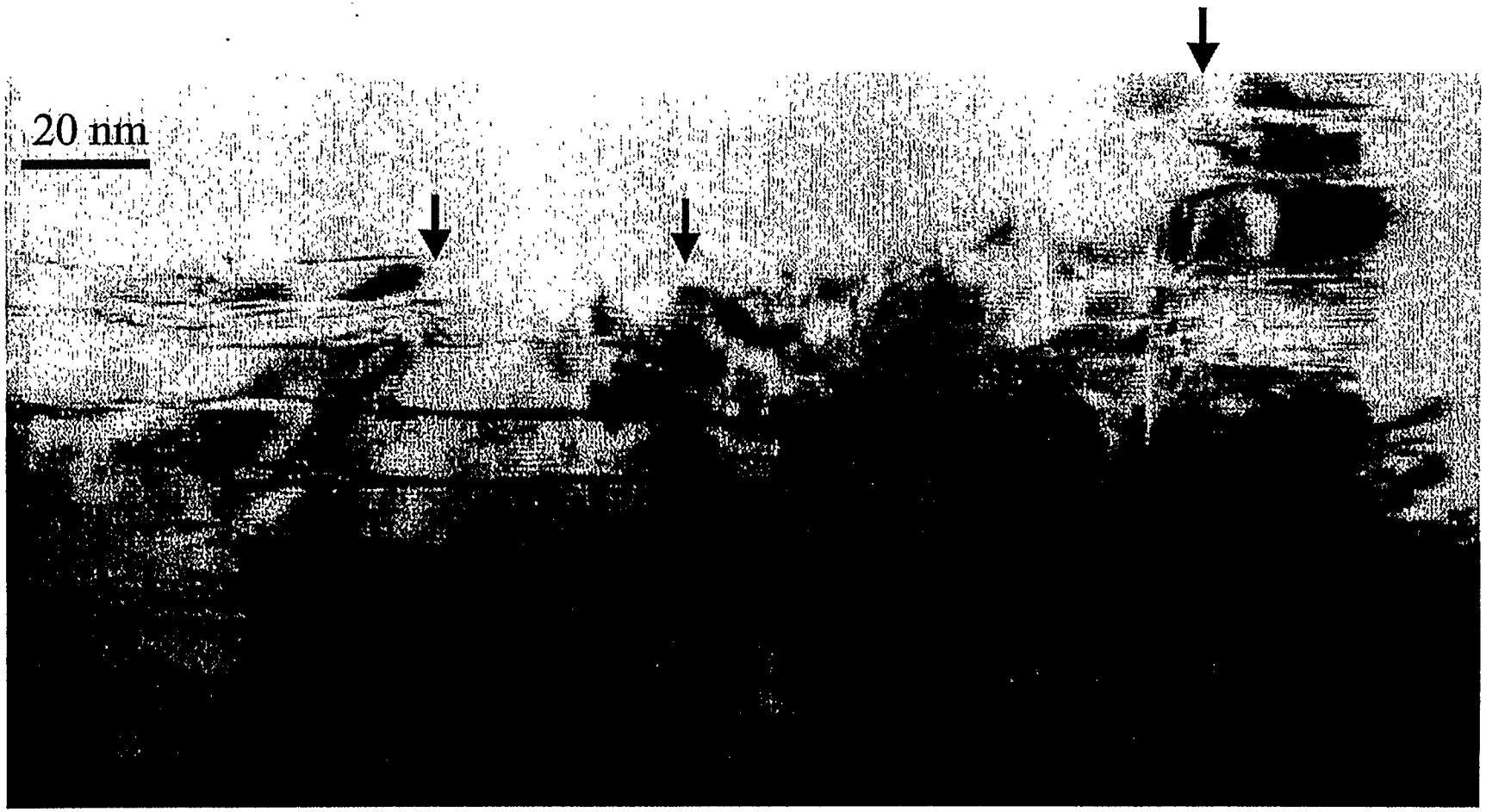
Presence of extended strain fields in YBCO



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SUMMARY: Fundamental Studies of Substrate Surface Effects

- **Mechanism and Control of Grain Boundary Conduction**
  - ➢ *Special grain boundaries? Improvements through carrier doping?*
- **Characterization and Control of Grain-Alignment Distributions**
  - ➢ *Texturing mechanism for grain-to-grain low-angle boundaries?*
- **Origin and Control of HTS Defects for Flux Pinning**
  - ➢ *compositional effects (2nd phase precipitates, intergrowths, etc.)*
  - ➢ *substrate-surface induced growth defects (stacking faults, strains)*

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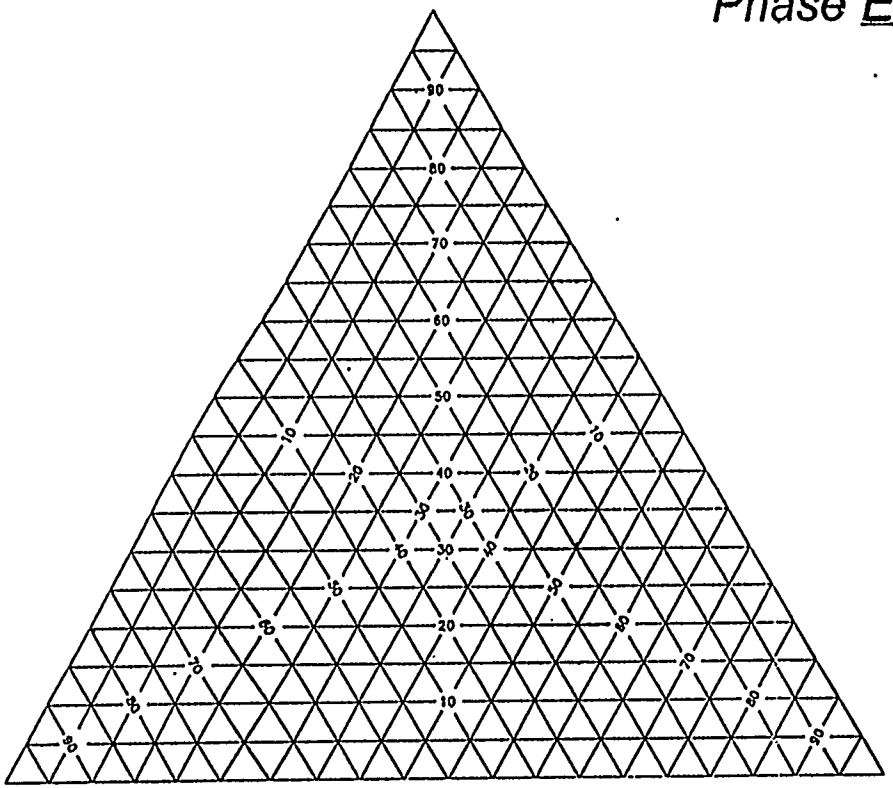
Phase Equilibria Studies of Electronic Ceramic Systems

T.A. Vanderah

National Institute of Standards and Technology
Gaithersburg, Maryland

Materials Science and Engineering Laboratory
Ceramics Division
Phase Equilibria Group



I. Dielectric oxides for wireless communications

II. High-temperature superconducting oxides

"Thermodynamics is like my wife – I've never understood her but I've gotten used to her."

Prof. Isaac Michaeli
1984, The Univ. of Conn.

"The primary objective of chemical thermodynamics is the establishment of a criterion for the determination of the feasibility or spontaneity of a given transformation."

"Thermodynamic methods provide mathematical relations necessary to estimate the maximum, i.e. equilibrium yields."

Klotz, 1964

"Thermodynamics may rule out a given reaction by indicating that such a transformation cannot proceed spontaneously under any set of available conditions. In such a case we have a definitive answer. On the other hand, if the analysis indicates that a reaction may proceed spontaneously, no statement can be made from thermodynamics alone that it will do so in any finite time."

Klotz, 1964

"Thermodynamics is the practice of the possible in principle. It tells you what <u>can</u> happen, not what <u>will</u> happen."

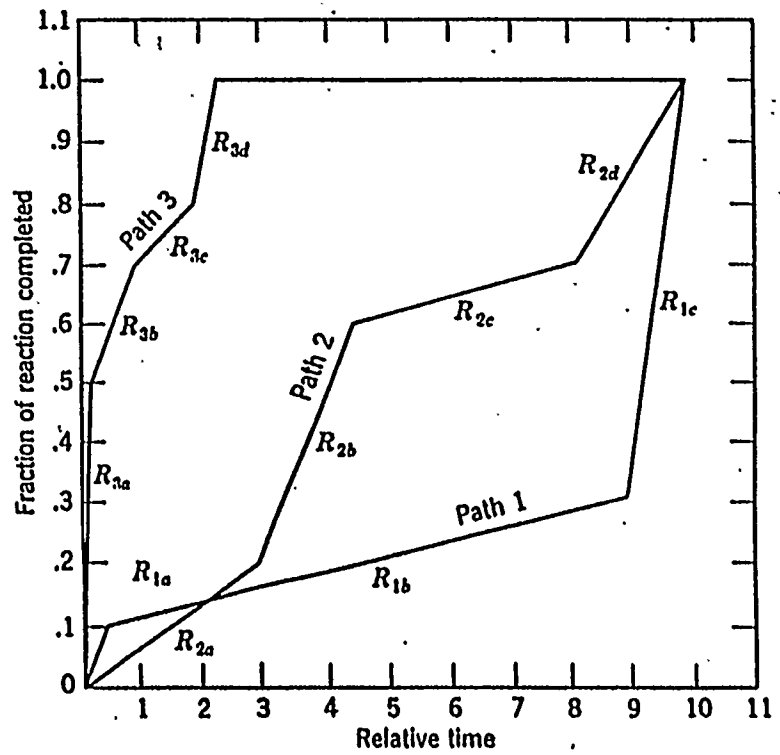
"You must have the thermodynamics first in order to get the kinetics right, because the thermodynamics tell you what valleys you can fall into."

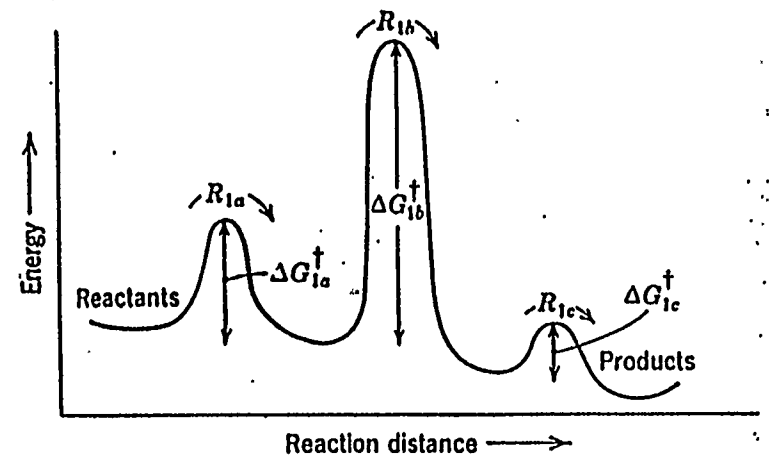
"Phase equilibria relations describe the valleys but tell you nothing about the surrounding mountains."

"Thermodynamics cannot predict the <u>time</u> required for a reaction nor the practical <u>extent</u> to which a reaction may proceed."

"There is no relation between the kinetics of a reaction and the thermodynamic energy changes accompanying the reaction."

Klotz, 1964





from Kingery, 2nd ed., p. 383

"Thermodynamics is a phenomenological science that describes the <u>macroscopic</u> properties of bulk systems. Thermodynamics tells you nothing about <u>microscopic</u> processes that control <u>rates</u> of reaction."

Some Important Kinetic Factors

- Nature of microscopic process
  (transport-rate vs. phase-boundary-reaction-rate limited)

- Interfacial surface areas (with associated free energies)
  - grain boundaries
  - twin boundaries
  - dislocations/defects/vacancies

- Diffusion mechanism

- Catalysts

Nonequilibrium

Unstable System:

- Duration unpredictable and may change suddenly to a lower energy state with no external change (e.g. nitroglycerin)

Metastable System:

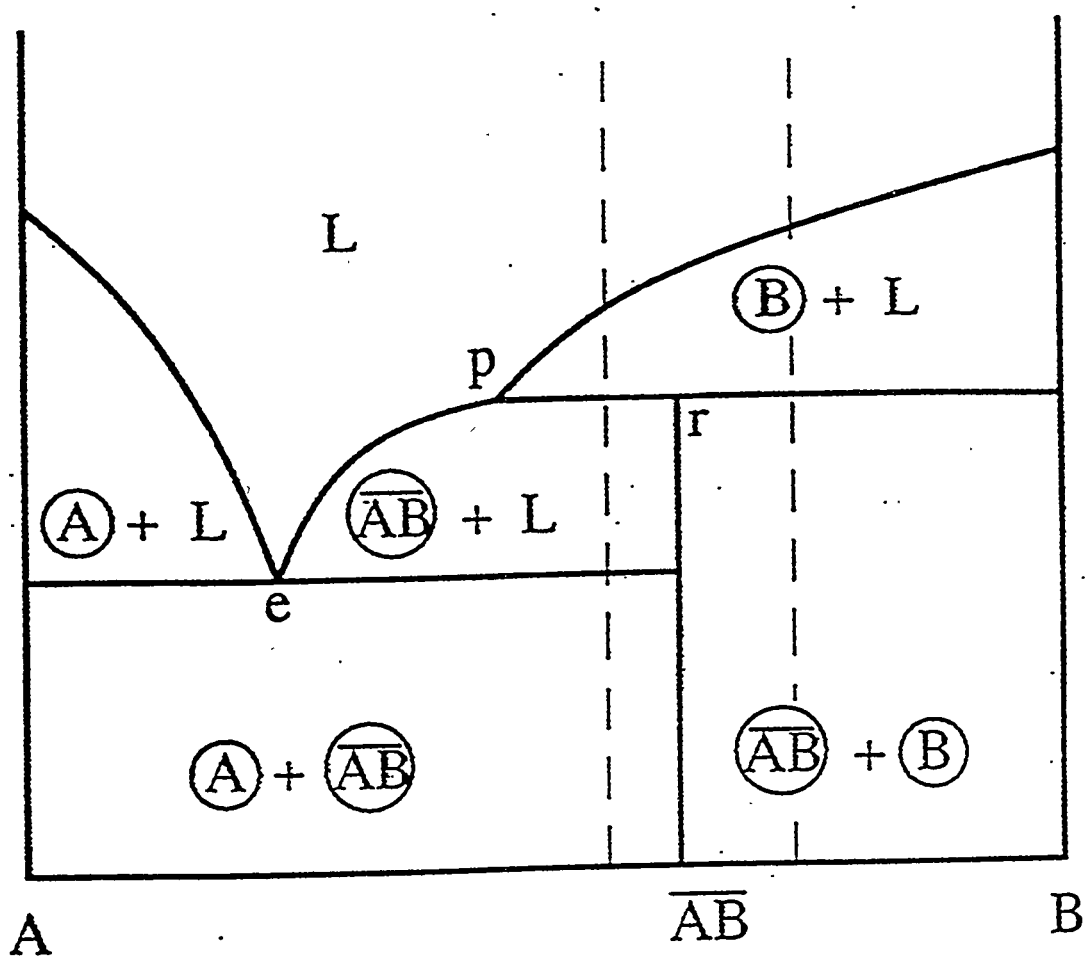
- Will persist indefinitely if external conditions are not changed
  (supercooled liquid water requires nucleation to crystallize equilibrium form)
- *Violates thermodynamic rules underpinning the study of phase equilibria*
- Attempts to include effects on phase relations can only be general and qualitative
- Details depend strongly on
  - state of subdivision of constituents
  - thermal history

Berard & Wilder

"Thermodynamics can rule out certain reactions under <u>any</u> conditions, thus saving a great deal of time and effort."

"Accurate phase equilibria data tell you where all processing is headed."

$\overline{AB}$ = Incongruently melting compound



- Recrystallization of pure phase $\overline{AB}$ from liquid of composition $\overline{AB}$ is kinetically difficult (all B crystals must be resorbed).
- Cooling in the primary phase of $\overline{AB}$ would speed up resorption owing to liquid - would get larger crystals of $\overline{AB}$ but also impurity A.

Berard & Wilder

(44) **Primary Phase:** The only crystalline phase which can exist in equilibrium with liquid of a given composition. The primary phase is the first crystalline phase to appear on cooling a composition from the liquid state; or conversely, it is the last crystalline phase to disappear on heating a composition to melting (see, also, Boundary Line (3) and Liquidus (35)).

(45) **Primary Phase Region:** The locus of all compositions in a phase diagram having a common primary phase.

(a.k.a. "Primary Crystallization Field")

Determination of (Outline of) Primary Phase Field

1. Identify <u>all compounds</u> in subsolidus equilibrium with the phase of interest

2. Identify all <u>*n*-phase compatibility regions</u> involving the phase of interest
   (*n* = number of components)

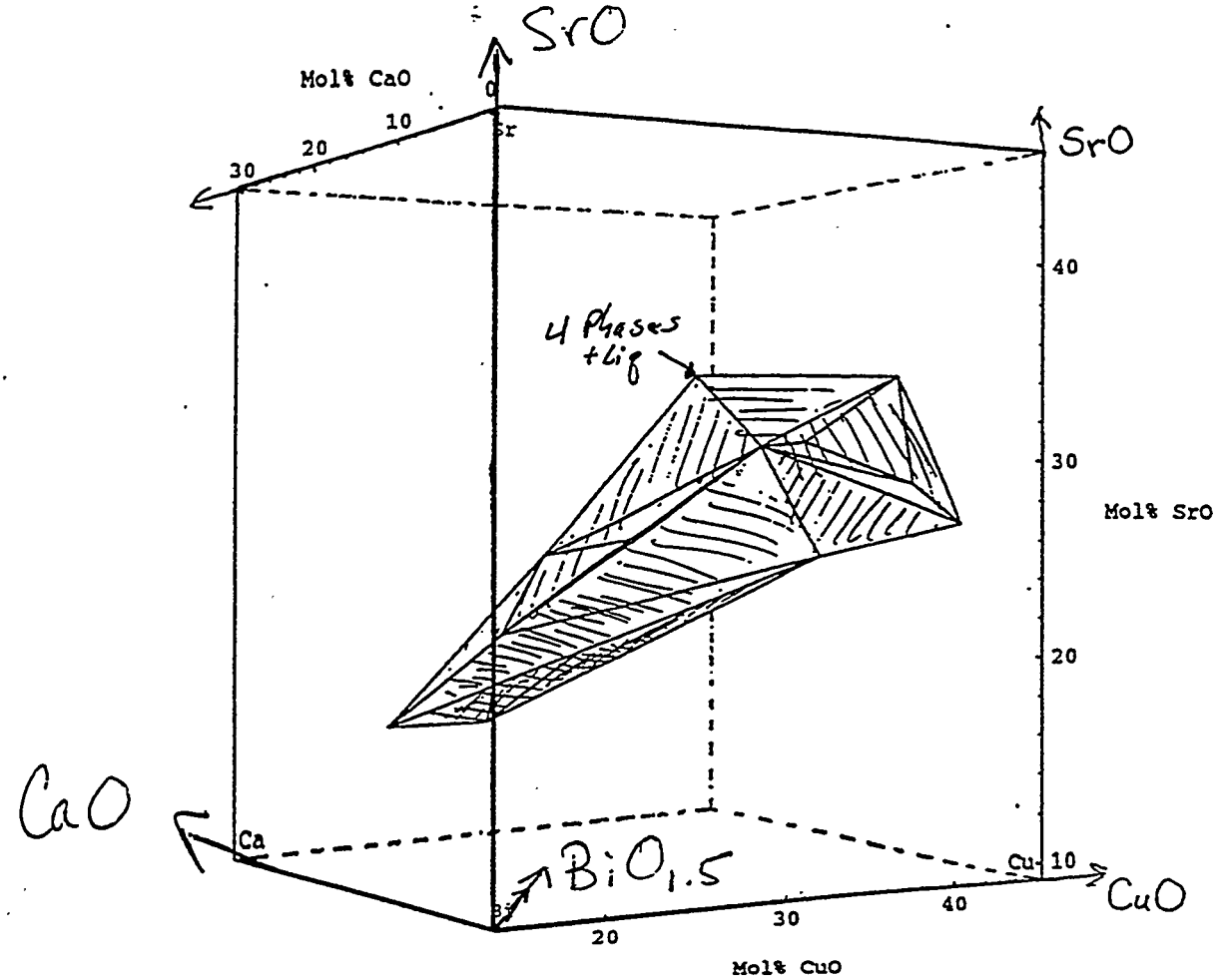
   e.g. *ternary systems* ⇒ triangles (3-phase regions)
   quaternary systems ⇒ 4-phase volumes

3. Determine <u>solidus temperature</u> (onset of melting) for each *n*-phase compatibility region

4. Determine which *n*-phase compatibility regions are <u>stable</u> up to the solidus

5. Sample and analyze <u>composition of the first liquid</u> formed upon heating each stable *n*-phase compatibility region to the solidus

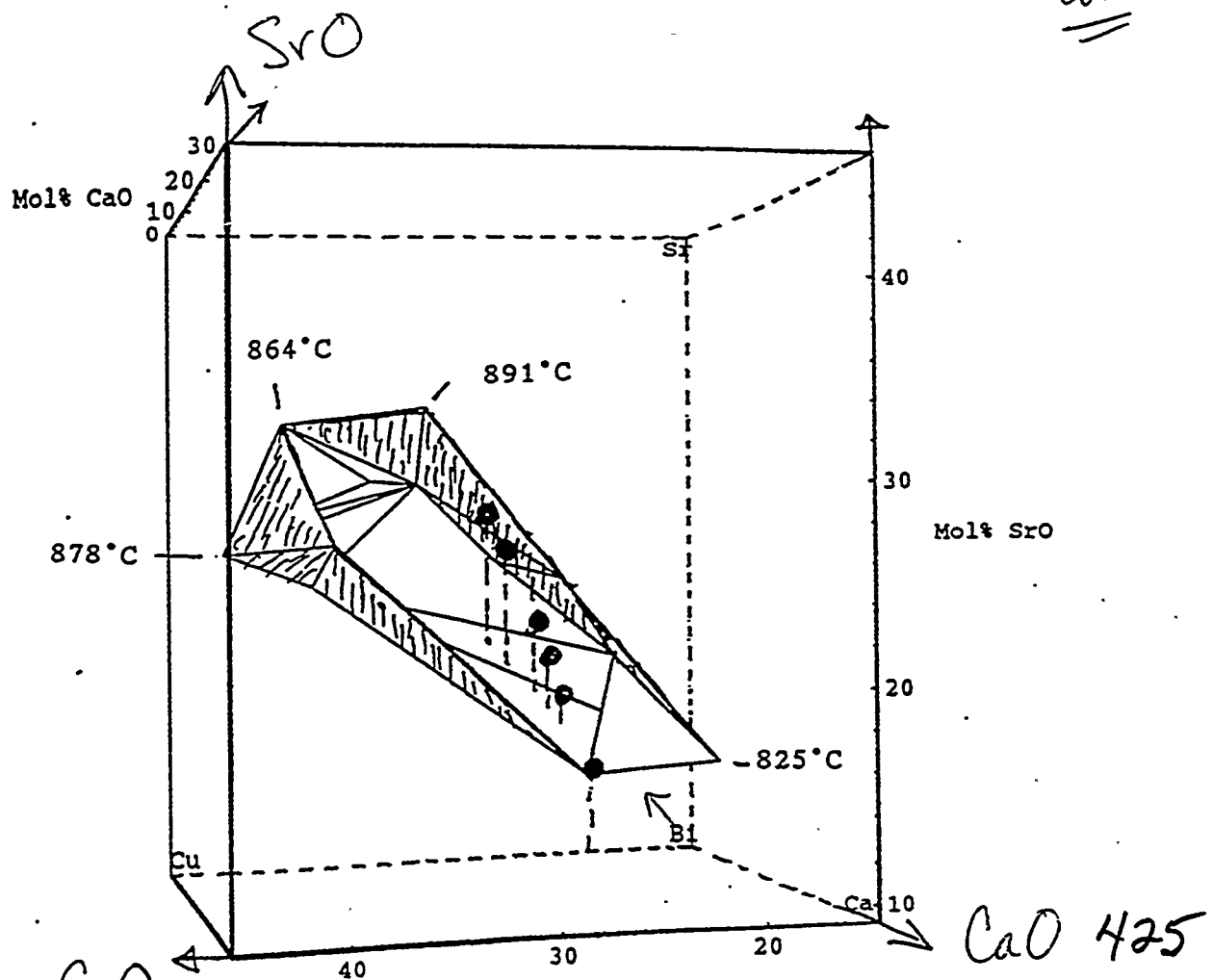
6. Compositions of the first liquids locate the <u>corners</u>, hence outline, of the primary phase field



From 22
4-phase
stable
assemblages

2212

air



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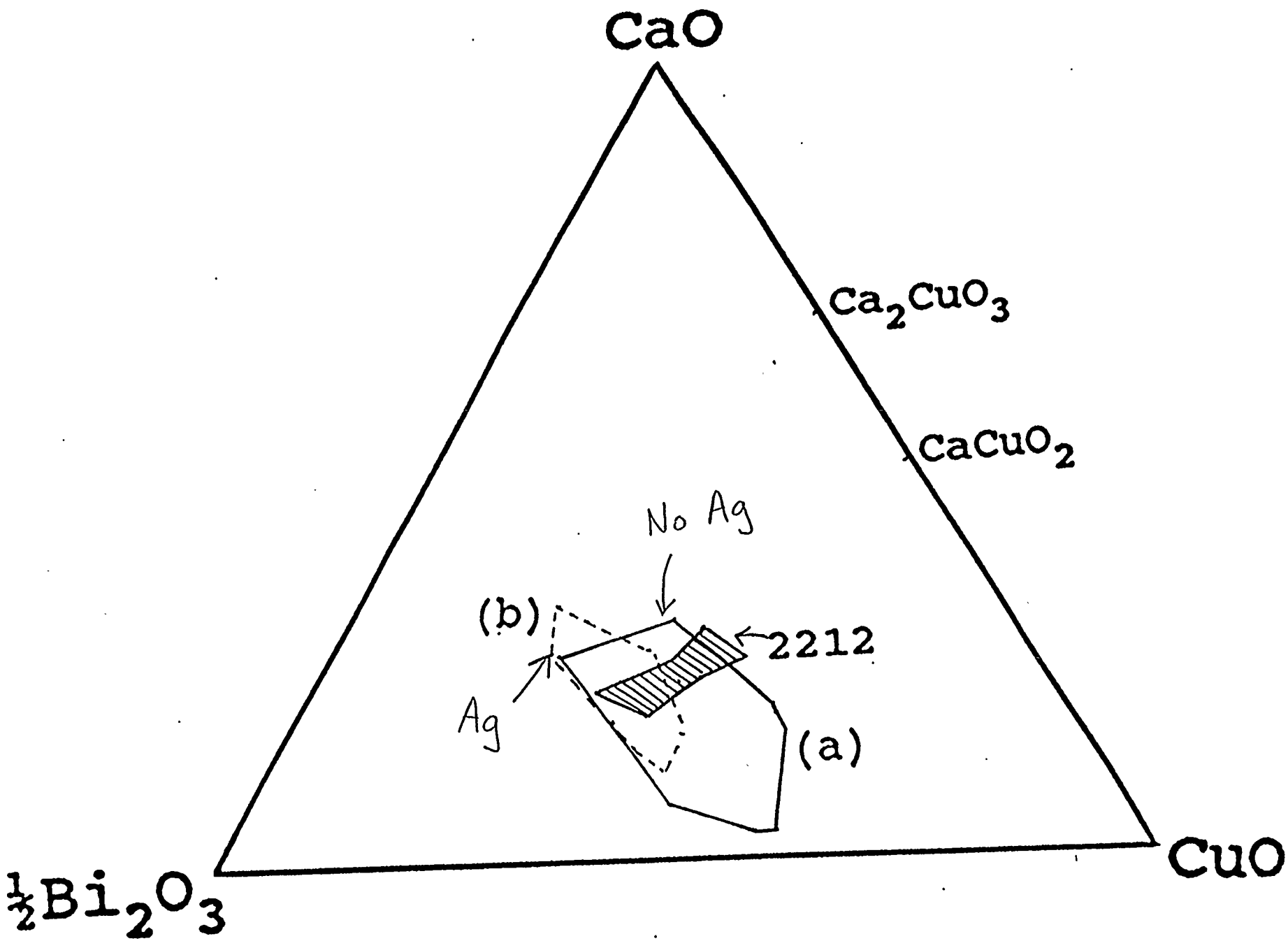

CaO
Ca_2CuO_3
$CaCuO_2$
No Ag
(b)
2212
Ag
(a)
CuO
$\frac{1}{2}Bi_2O_3$

Summary of Results on BiSCCO 2212

- At 830°C the 2212 is in equilibrium with 10 phases:

	CaO
	CuO
11 9x5	$Bi_{2.2+x}Sr_{1.8-x-y}Ca_yCu_{1\pm½x}O_z$
0 14 x 24	$(Sr,Ca)_{14}Cu_{24}O_{41}$
2201	$Bi_2Sr_2CuO_{\approx 6}$
4805	$Bi_4Sr_8Cu_5O_x$
2110*	$Bi_{14}Sr_{6-x}Ca_{6+x}O_{33}$
0x21	$(Ca,Sr)_2CuO_3$
2310*	$Bi_2(Sr,Ca)_4O_x$
0x11	$(Ca,Sr)CuO_2$

* extensive solid solutions

- At 830°C twenty-two four-phase compatibility regions were found around the 2212. The four-phase volumes are often very shallow due to extensive solid solution behavior.

- Minimum melting of 2212:

  ≈825°C (complete melt at 830°C)
  phase assemblage = 2212 +2110 + 11 9x5 + CuO
  melt composition =41.7:16.1:22.3:19.9
  ($BiO_{1.5}$:SrO:CaO:CuO)

- Initial melt compositions of samples centered in the four-phase compatibility regions were used to obtain a preliminary estimate of the primary crystallization field of 2212:

$BiO_{1.5}$	20→42 mol%
SrO	15→35 mol%
CaO	2→25 mol%
CuO	20→43 mol%

- The 2212 primary phase field lies on the alkaline-earth-poor side of the 2212 solid solution → *2212 melts incongruently to liquid plus alkaline-earth-rich phases.*

- The crystallization field for 2212 is relatively thin (a few mol%) compared to its lateral extension → *small changes in composition may have very large effects on phase assemblages/melting behavior.*

- Ag saturates in the melts at 6 to 8 mol%.

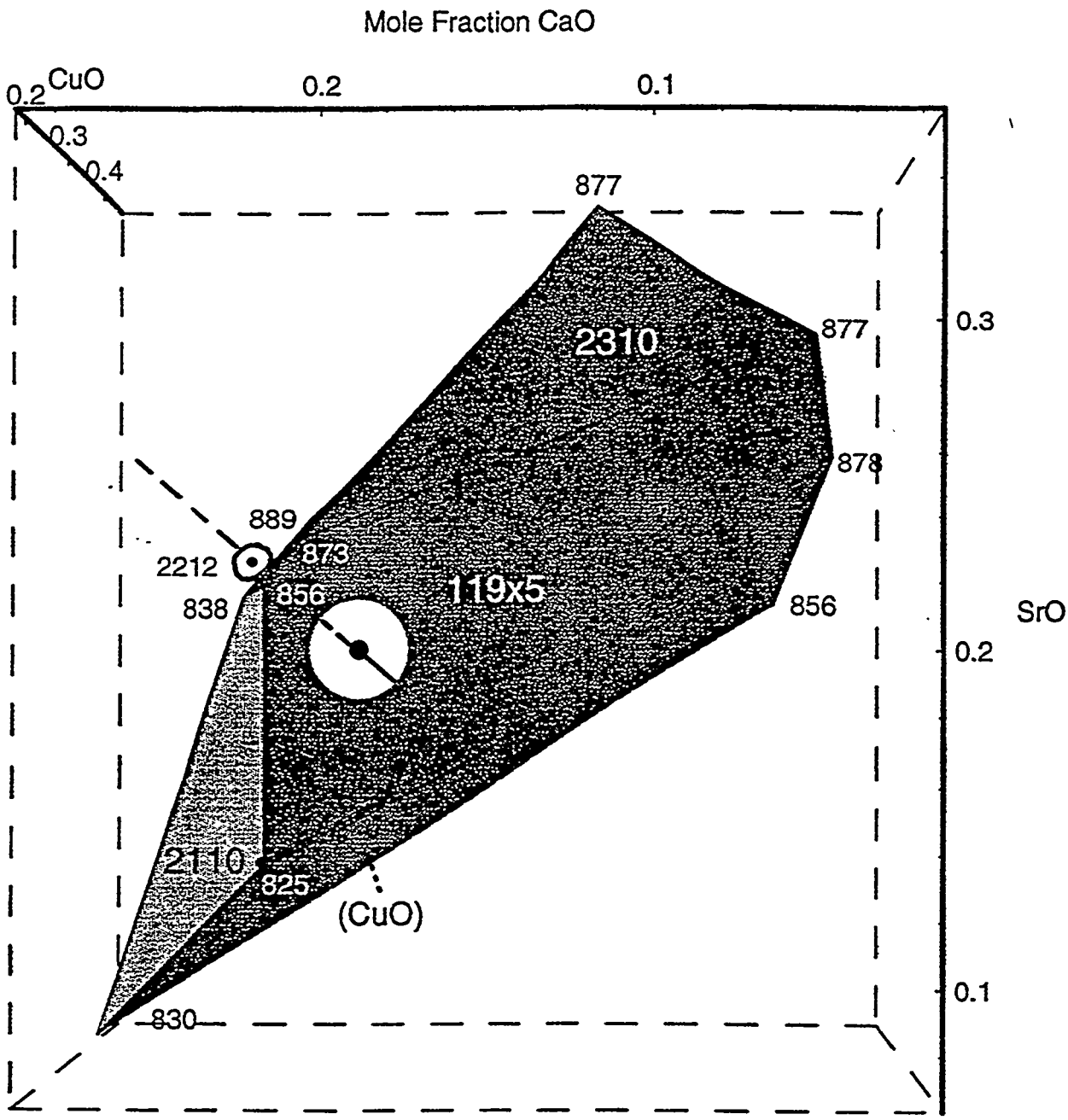
- The presence of silver lowers the melting temperatures 3 to 26°C and primarily shifts the crystallization field away from CuO. Ag lowers the viscosity and increases wetting capability of the melts.

- Cu enters silver, lowering its melting point.

(Phase Equilibrium Studies, NIST)

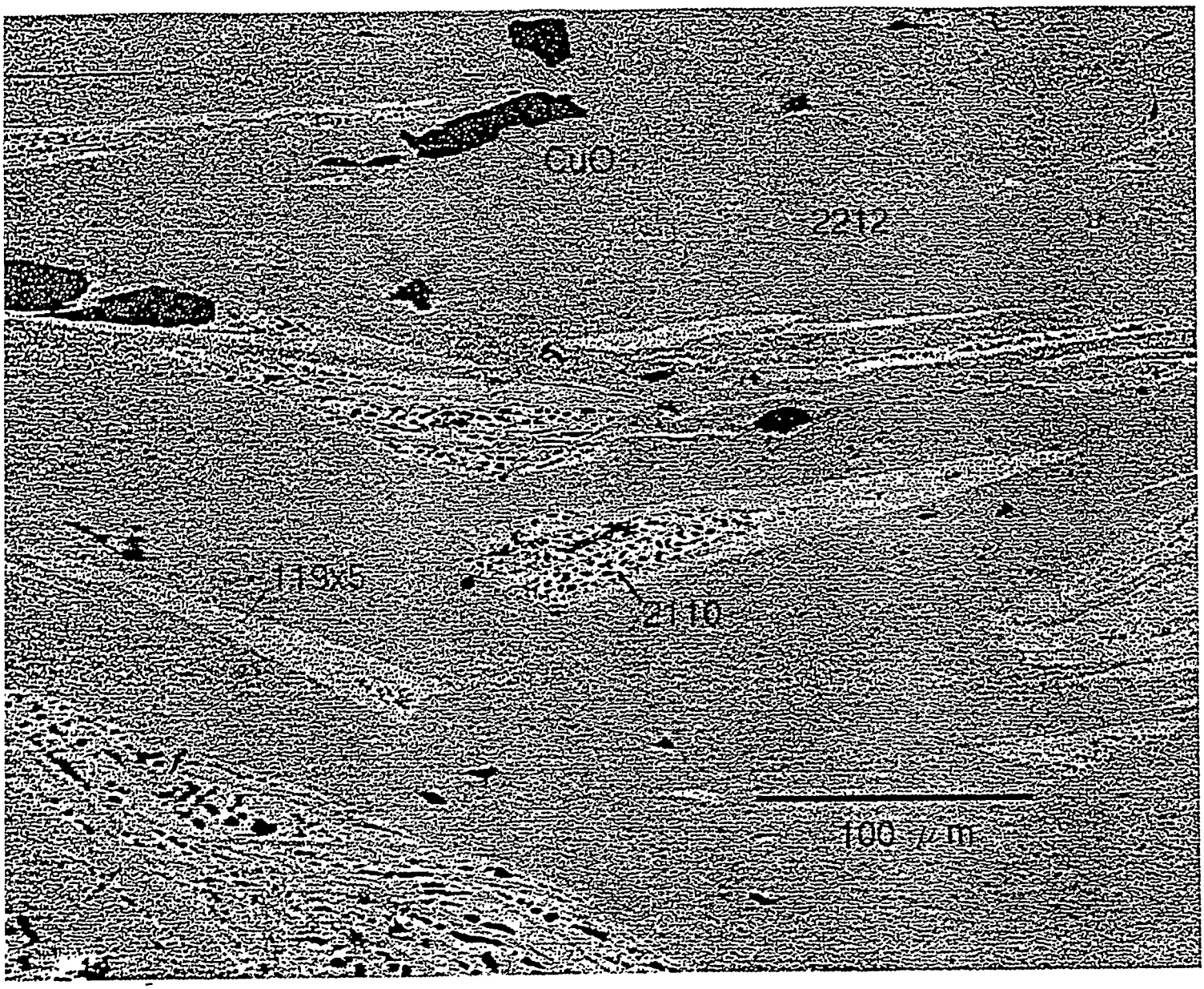
Recent Results

- Application of 2212 Primary Phase Volume Data to Melt Crystallization Paths
- Determination of Pb Content of Coexisting Pb-2223 Phases
- Development of Graphical Methods For Representing 5-Component Pb-2223 Phase Equilibria
- Measurement of Pb-2223 Subsolidus Phase Equilibria in 7.5% O_2
- Detailed Mapping of Pb-2223 + 2212 Liquidus
- General Model for Pb-2223 Primary Crystallization Volume in 7.5% O_2



BSCCO 2212 Crystallization Path, Composition I (in air)

BSCCO 2212 Slow Cooling Experiment, Composition I, Cooled at 0.2°C/min



BSCCO 2212 Crystallization Experiments

Sample	Composition (mole%)			
	$BiO_{1.5}$	SrO	CaO	CuO
I	26.9	24.7	17.6	30.8
II	28.7	21.4	20.8	29.1

BSCCO 2212 Slow Cooling Experiment, Composition II, Cooled at 0.2°C/min

Table 1. Symbols and compositions of phases in equilibrium with 2223

Symbol	Nominal Composition
2223	$(Bi_{1.8}Pb_{0.4})Sr_2Ca_{2.2}Cu_3O_x$
2212	$(Bi_{1.9}Pb_{0.1})Sr_{1.5}Ca_{1.5}Cu_2O_x$
014x24	$Sr_7Ca_7Cu_{24}O_{41}$
0x21	$(Ca_{1.9}Sr_{0.1})CuO_3$
3221	$Bi_{0.5}Pb_3Sr_2Ca_2CuO_x$
2310	$Bi_{27.8}Pb_{6.18}Sr_{49.5}Ca_{16.5}O_x$
119x5	$Bi_{1.8}Pb_{0.4}Sr_{1.6}Ca_{0.2}CuO_x$
0x11	$(Ca_{0.86}Sr_{0.14})CuO_2$
0x11´	$(Ca_{0.5}Sr_{0.5})CuO_2$
1x20	$(Ca_{1.9}Sr_{0.1})PbO_4$
CaO	$(Ca_{0.9}Sr_{0.1})O$
CuO	CuO

Subsolidus Equilibria of Pb-2223

- 11 phases (k) in equilibrium gives large number of potential 5-phase (m) combinations with 2223:

$$C = k! / (m!(k - m)!) = 330$$

- <u>Solution:</u> initially choose only combinations with 2212+2223

  - significantly reduces number of possible combinations ($C = 120$)

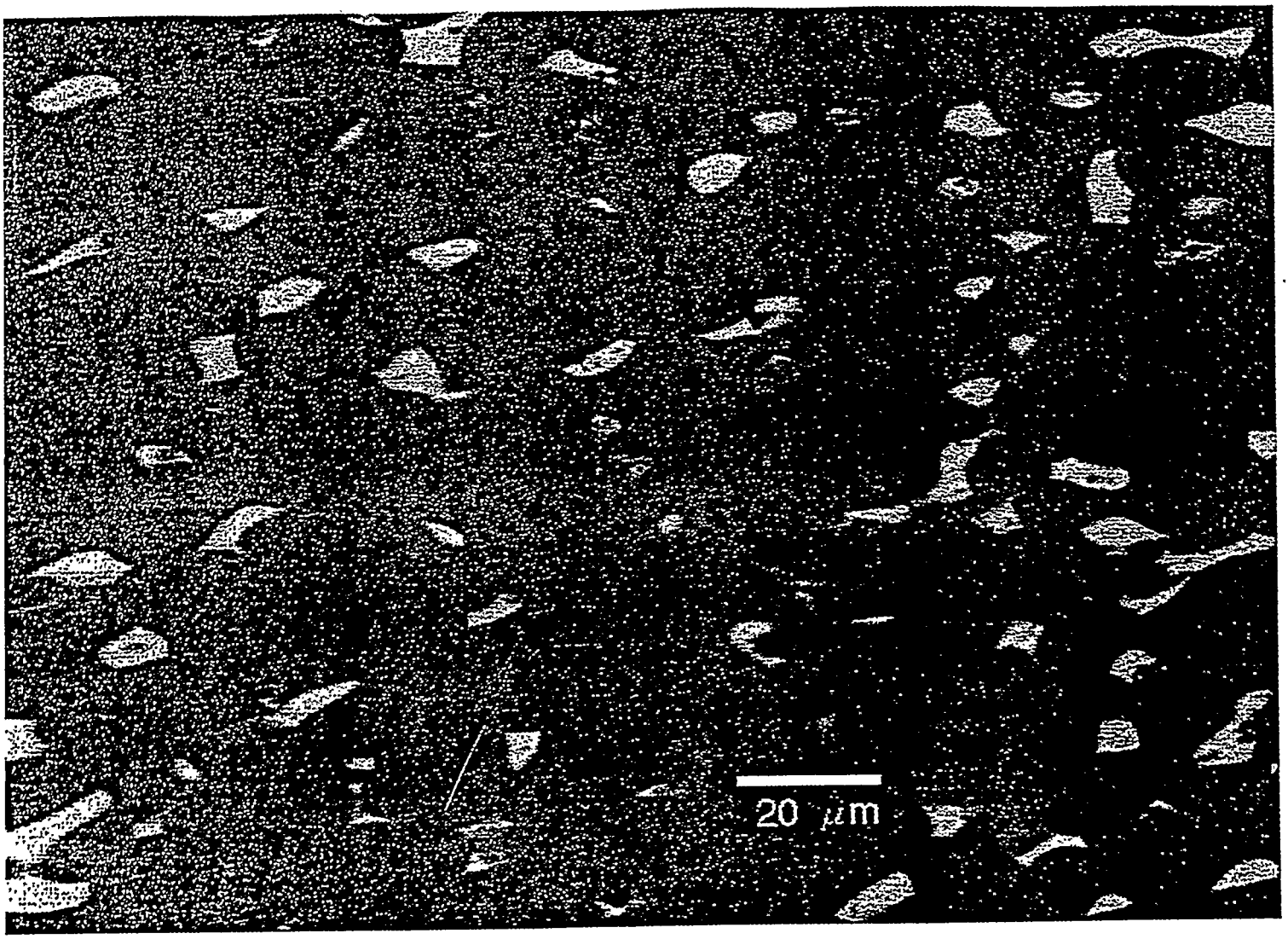
  - remaining possibilities rapidly narrowed as experimental data accumulate

  - repeat for other combinations with 2223

Complete Set of Pb-2223 Initial Melting Equilibria (7.5% O_2)

	Five-phase Equilibrium Assemblage	DTA T(°C)		Five-phase Equilibrium Assemblage	DTA T(°C)
1	2223-2212-1x20-119x5-2310	825	17	2223-1x20-CuO-0x21-014x24	828
2	2223-2212-1x20-2310-CaO	830	18	2223-1x20-CaO-0x11'-2310	820
3	2223-2212-0x21-1x20-CuO	837	19	2223-1x20-CaO-0x11'-3221	828
4	2223-2212-1x20-0x11-3221	838	20	2223-1x20-CuO-0x11'-01424	815
5	2223-2212-1x20-CuO-0x11	839	21	2223-1x20-2310-014x24-0x11'	830
6	2223-2212-0x21-014x24-CuO	840	22	2223-1x20-0x11'CuO-0x11	838
7	2223-2212-014x24-1x20-119x5	840	23	2223-1x20-0x11'-3221-0x11	815
8	2223-2212-2310-0x11-3221	840			
9	2223-2212-119x5-0x11-CuO	842	24	2223-0x11'-CaO-0x11-3221	822
10	2223-2212-014x24-119x5-CuO	845	25	2223-0x11'-CaO-2310-0x11	840
11	2223-2212-014x24-0x21-1x20	846	26	2223-0x11'-2310-0x11-119x5	848
12	2223-2212-3221-CaO-1x20	848	27	2223-0x11'-2310-119x5-014x24	817
13	2223-2212-0x11-2310-119x5	850	28	2223-0x11'-014x24-119x5-CuO	840
14	2223-2212-0x11-0x11'-CuO	850			
15	2223-2212-0x11-0x11'-2310	853	29	2223-2310-3221-CaO-0x11	835
16	2223-2212-3221-CaO-2310	865			

Partially Infiltrated MgO Wick



Projective Methods for Representing Multicomponent Phase Equilibria

A. Normalization Method

-creates overlap

B. Isopleth Method

-provides a section, but incomplete information on location of equilibria relative to the section

C. Thermodynamic Method

-project through phase of common equilibrium

-gives most accurate sense of equilibria

Model of Pb-2223 Primary Crystallization Field

Convex Polytope in $\Re^5$ (5-dimensional space)
-excellent fit to 29 invariant points!

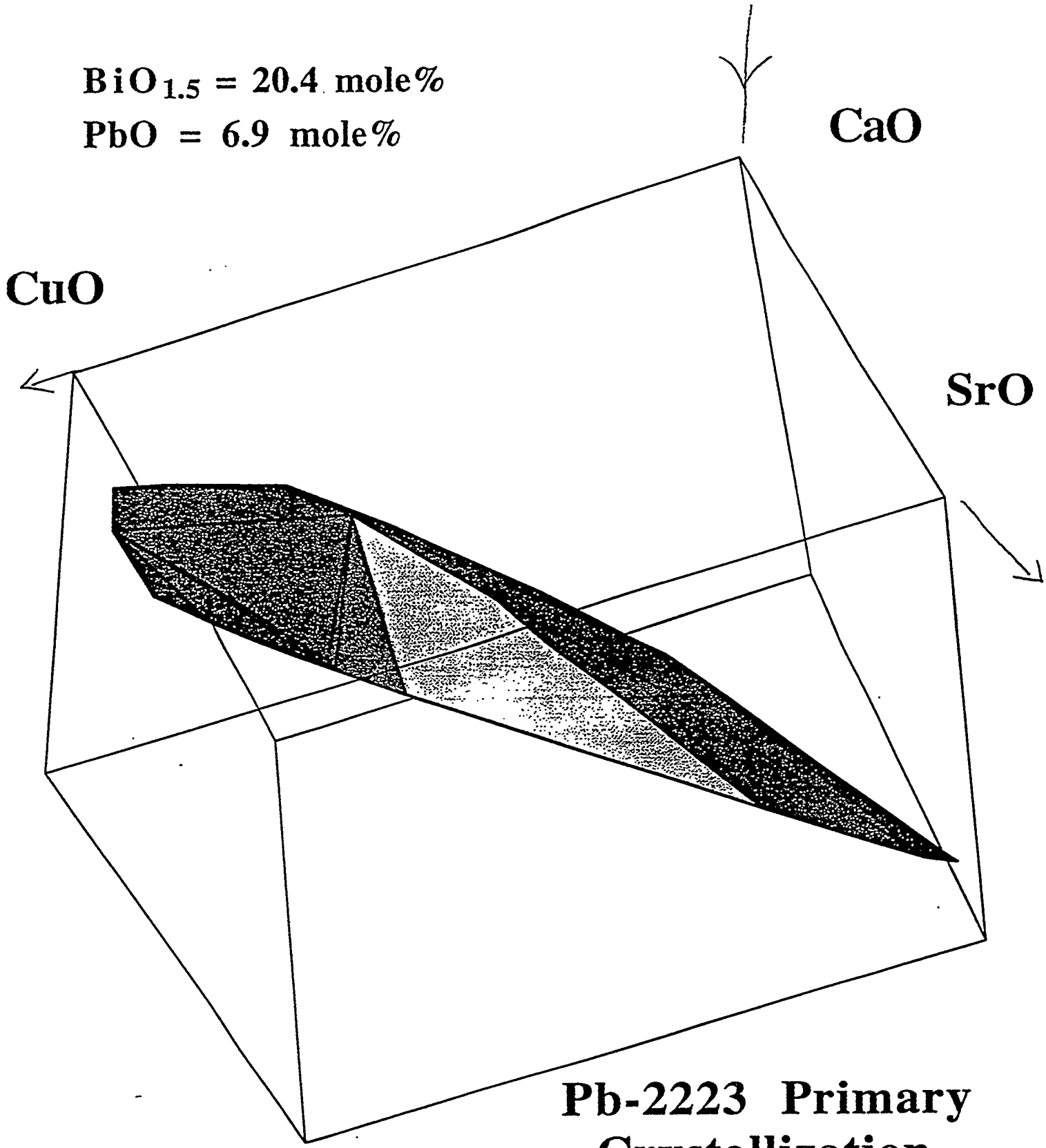
- 162 Faces
- Equation (coefficients will be E-mailed on request):

$$A\underline{x} + \underline{b} \leq 0$$

To determine if a trial point, ^$\underline{x}$^ , is within the Pb-2223 primary phase field:

A ^$\underline{x}$^ + $\underline{b}$ < 0, then ^$\underline{x}$^ is inside;

A ^$\underline{x}$^ + $\underline{b}$ > 0, then ^$\underline{x}$^ is outside

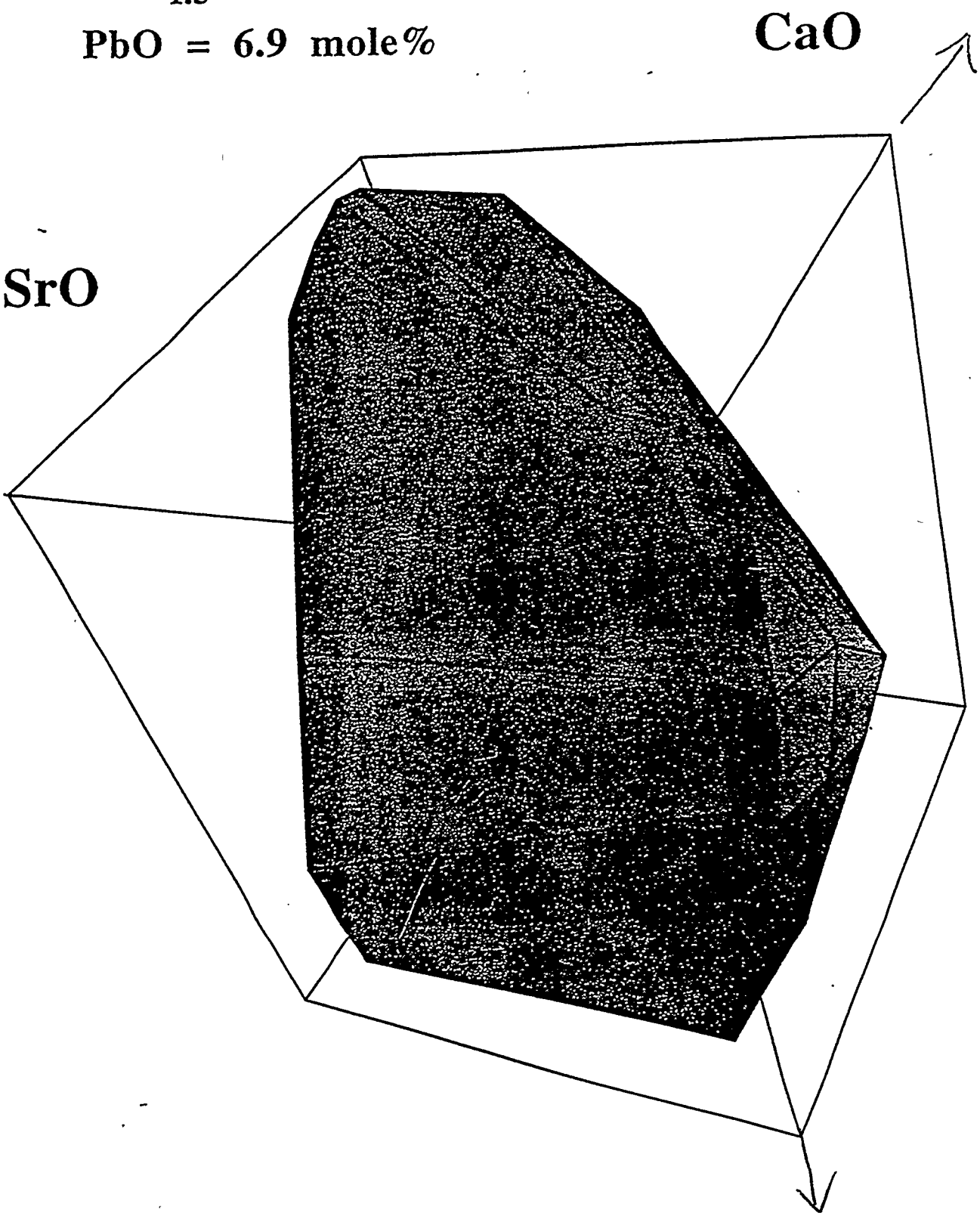


Pb-2223 Primary Crystallization Volume

4140

$BiO_{1.5}$ = 20.4 mole%

PbO = 6.9 mole%



Pb-2223 Primary Crystallization Volume

Current Project Status: Pb-BiSCCO 2223

- Add Ag to each phase participating in subsolidus equilibria.
  → Look for unidentified XRD lines and ss formation. (7.5% O_2)
- Add Ag as a sixth component to each 5-phase assemblage.
  → Check for stability (7.5% O_2).
- Then: DTA/melting/first-liquid-capture from each 6-phase assemblage. (7.5% O_2).
  → Measure new location of primary phase field.

Possible Future Directions

Selected BaO-R_2O_3-CuO systems:

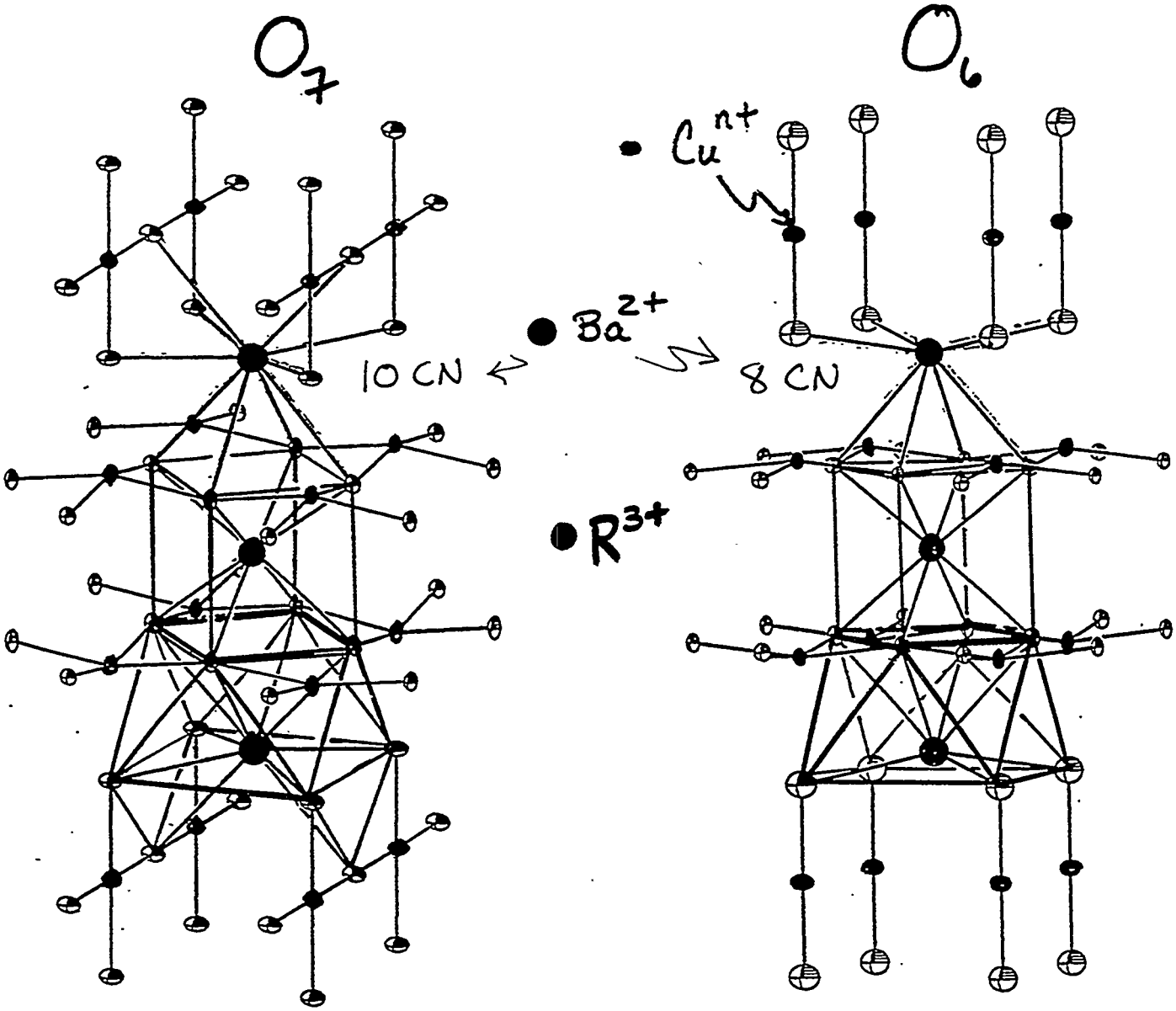
- Subsolidus ternary diagrams as $f(pO_2, T)$
- e.g. Nd, Sm, Eu, Yb
- 0.01, 0.10, air, 1.00 atm O_2

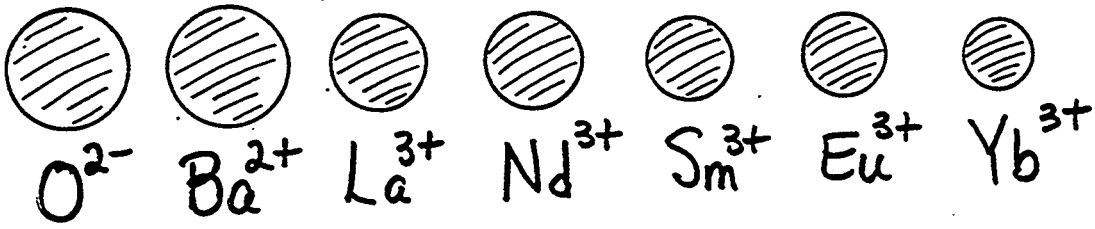
$\Rightarrow$ *Issues for coated conductors:*

$Ba^{2+} \leftrightarrow R^{3+}$ site exchange may be related to

- Texture development (a- and c-alignment)
- Formation of impurities (flux-pinning)
- Formation of non-superconducting domains (flux-pinning)

$Ba^{2+} \leftrightarrow R^{3+}$ site exchange very sensitive to size and pO_2





$\Longrightarrow$ $Ba^{2+} \leftrightarrow R^{3+}$ site exchange is sensitive to size and pO_2

HHH

Breakout Group Summary

BSCCO Wire

Session Chairmen: D.F. Lee (ORNL) and V.A. Maroni (ANL)

This breakout group organized its discussions around three central themes: (1) cost/performance of BSCCO composite conductor (in terms of $/kA-m), (2) product reliability and engineering viability, and (3) a near-term opportunity to forge a market in the electric utility transformer area. Oral presentations given on the first day of the workshop clearly emphasized that the current cost of silver-clad Bi-2223 wires was still around $1000/kA-m and that this cost needed to drop to less than $10/kA-m for most practical applications. Discussion on this topic within the breakout group embraced a range of attitudes and opinions. American Superconductor Corporation (ASC) representatives and others argued that the $1000/kA-m figure is (1) based on wire performance levels that are lower than the best values achievable today, (2) not representative of the influences a large commercial market would have on manufacturing costs, and (3) perhaps in conflict with some notions about how manufacturers should market high-T_c wire and where profit should be made in the manufacturing of high-T_c devices.

The breakout group generally concurred that lower conductor cost translates to two factors: higher critical current densities (i.e., amperes per unit area) and lower product cost per unit volume. The first of these factors involves reaching the highest attainable value of J_c, and the pursuit of this goal was given the highest priority because it represents the greatest opportunity for improvement. Progress on J_c will come from a thorough elucidation of phase formation processes and current-limiting mechanisms in BSCCO composite conductors. Cost per unit volume was dissected into several goal areas as follows:

-maximizing the fill factor by minimizing the amount of sheath material required per kA-m and by optimizing the filament architecture;

-implementing lower cost sheath materials without sacrificing performance;

-simplifying the composite conductor fabrication process by reducing the number and duration of labor intensive steps; and

-increasing/improving the yield of acceptable defect-free product.

In the course of this discussion, further recognition was made of the probability that the scale-up required to meet a heavier demand for HTS conductor would have a price-reducing effect in terms of cost/volume advantages associated with the product itself, and at least some of the materials that go into making it, such as the precursor powder.

The group recognized the compelling evidence presented in several workshop talks that certain persistent (seemingly inherent) classes of defects must be eliminated or better

controlled if maximization of J_c is to be achieved. This will require better characterization/quantification of known defect types, such as grain boundaries, nonsuperconducting second phases, cracks, and voids in terms of origin, size, shape, and influence on HTS performance properties. Continued studies of the many types of grain boundary interfaces and interconnects observed in BSCCO wires is recommended to fully elucidate the current flow mechanisms and associated limitations. This should be carried out with an eye toward developing methods for engineering the most desirable types of grain interconnects.

There was also recognition of the need for better understanding of the micromechanics of the composite conductor deformation process to improve superconducting phase texture, eliminate voids and filament non-uniformities, maintain filament continuity, and exploit aspects of the mechanics that facilitate reducing the fill factor. In addition, recent magneto-optic imaging results showed that the superconducting filaments are inhomogeneous, with dimensionality and characteristics strongly suggesting that these defects are cracks. Since these flaws constitute a substantial portion of the filament cross section, knowledge gained from micro-mechanical modeling of fracture processes could suggest alternative processing routes utilizing stress states and strain paths that mitigate crack initiation and create microstructures less susceptible to crack propagation. The elimination of these flaws would provide an immediate enhancement of J_c.

There was discussion of the relative merits and possibilities associated with increasing the self field J_c (call it $J_{c/s}$) and with trying to improve the in-field J_c (call it $J_{c/B}$) at temperatures above 20 K. The former appears to require the elimination of defects (as defined above) and the perfection of BSCCO texture development; the latter appears to require the incorporation of properly sized nanoscale inclusions/defects throughout the ceramic core of each filament (in the bulk ceramic instead of at grain boundaries or interfaces). Success in improving $J_{c/B}$ may be difficult to achieve, may add expense to the wire making process, and may concomitantly cause degradation of $J_{c/s}$. Nonetheless, there is much to be gained in the area of fabrication and operating cost reduction by raising the effective working temperature of BSCCO-based conductor, and this translates, more than anything else, into better flux pinning. At this time we know very little about flux pinning in BSCCO composites, beyond the fact that it is highly variable and there is no substantive evidence to suggest that it can not be done cost-effectively.

With regard to insuring the reliability and engineering viability of BSCCO-based conductor in long lengths, it may be time to establish specifications for the materials that go into the wire-making process, the product wire itself, and the product inspection/ verification methods. It is also important to note that a successful HTS industry based on BSCCO conductor is not necessarily predicated on 77 K operation even in the long run. BSCCO wire technology is an established small industry today at temperatures from 4.2 K to 40 K.

The opportunity that appears to exist in the utility transformer area concerns the fact that a large number of transformers will be reaching the end of their expected operating life in about four to five years. There is then an opportunity to replace some or all of these units

with high-T_c analogs. BSCCO-based composite conductor is the only demonstrated long-length HTS option that could possibly meet the operational requirements in the specified time scale. There were, however, some in the breakout group who felt that the existing research and development support base for BSCCO wire technology was not adequate to answer the transformer challenge, particularly in areas related to cost reduction. Penetration of the transformer market by high-T_c-based versions (i.e., BSCCO-based) would provide an excellent demonstration of a DOE development that produced an energy saving/environmentally friendly solution to a real utility need in the United States.

Breakout Group Summary

BSCCO Applications

Session Chairman: Chris Rey (DuPont)

Coming Events
The discussion was quite lively during the break out session. The session opened with a brief summary of near term HTS systems' tests and events. The discussion quickly turned towards further recognition of the needed dialog between the utility users and the superconducting community. It was felt that a "change in culture" was needed in the utility community if a transition from conventional technology to superconducting technology was ever going to occur. The utility customers need to be involved in order to get the perspectives and details necessary for HTS acceptance and commercialization.

Standards
The discussion then turned toward one of the standards for the superconducting community to adopt in order to facilitate utility acceptance of superconducting products. Standards such as: ASME, IEEE, ANSI, and OSHA were suggested as logical starting points of reference. It was also pointed out that where these standards do not apply on "first of a kind" equipment, it was up to the collective utility and superconductivity community to define and coordinate new standards. It was also recognized that each utility most likely would have different requirements and use different standards.

HTS Wire/Tape Cost
The discussion and most of the concern then turned towards the HTS wire/tape cost issue. It was felt that many of the engineering requirements for the introduction of HTS products could be met, but that it was HTS wire cost that would ultimately dictate the acceptance of HTS products. Issues as simple as the continued availability of silver and its price stability were discussed. There was considerable debate among users as to what is an appropriate initial capital cost for HTS systems. The question, "Does the initial capital cost for HTS systems have to be less expensive, or will users pay a premium price for higher performance?" was discussed. Many felt that in order for HTS products to even be considered, the initial capital cost must be less expensive than existing conventional technology. The rationale to this point dealt with established markets, where hundreds or thousands of conventional units were already in place. For these markets, some companies saw little financial incentive to establish a few new HTS units which had different OEM needs and requirements, but at the same time had equal or higher initial capital cost.
The opposing viewpoint believed that companies were more concerned with total ownership cost. Initial capital costs could be up to 15 % higher than conventional technology if the total ownership was substantially less. The HTS transformer was used as a primary example. The primary advantages of the HTS transformer were its over capacity capability, lower fire hazard, and lower environmental impact. Energy efficiency was cited as secondary advantage. It was recognized that the initial capital cost of the HTS transformer was higher, but its total ownership

cost could be lower.

Both viewpoints agreed, however, that without successful pilot-scale demonstrations of HTS systems' performance and reliability, utility acceptance of HTS technology was nearly impossible. Furthermore, only through continued financial support by the DOE would these successful demonstrations take place.

Bi-Oxide Conductor

The issue was raised concerning the continued financial support by DOE of first-generation Bi-oxide-based HTS conductor. All agreed that research and development of second-generation coated conductors should be vigorously pursued, however, it was felt that the continued support of Bi-oxide-based conductor should be re-emphasized. Some felt that the efforts were mutually beneficial and that the introduction of successful Bi-oxide-based HTS systems would promote a more widespread acceptance of coated conductor. As summarized by one statement, "It's the only material system we have that is technically viable at the present time."

Cryogenic Funding

The issue of providing new funding for improved cryogenics, out of existing funds for superconductivity, was hotly debated. The issue quickly divided itself into two schools of thought. Some felt that while providing new funding for improved cryogenics was an important issue, it could not be justified with the present size of the DOE HTS budget. They felt that the projected DOE funding for superconductivity was best spent supporting the existing HTS projects, and if additional funding became available later, then the issue could be reevaluated. Others felt that since cryogenics were an integral part of any HTS system, it was necessary to support further development of improved cryogenics. In particular, lower systems cost and higher reliability were the two primary issues that most people felt needed to be addressed. Proponents of this view felt that, until HTS materials have sufficient current densities to operate at liquid nitrogen temperatures, it will be necessary to rely on cryocooled systems.

Commercialization Workshop

Finally, some suggested that DOE sponsor a commercialization workshop. The purpose of the workshop would be to bring in companies not in the field of superconductivity, which could provide guidance, experience, and expertise in trying to bring new research products into the commercial market. Related fields such as biotechnology, telecommunications, and computer chip hardware were suggested as possible candidates.

Breakout Group Summary

Second Generation Conductors and Fundamental Issues for HTS Wire Development

Session Chairmen: Don Kroeger, Steve Foltyn, Marty Maley

Discussion in this group related primarily to YBCO coated conductors on flexible metal substrates, since another breakout group provided a forum for discussion of fundamental issues in BSCCO wire development. Coated conductor issues were discussed under the following three headings:

TEXTURED TEMPLATES

THE SUPERCONDUCTOR

SCALE-UP, MANUFACTURING, COST

TEXTURED TEMPLATES

Within the Department of Energy program, two approaches to fabricating flexible metal strips with textured surfaces on which the superconductor can be deposited epitaxially are being heavily pursued: IBAD, or ion-beam-assisted deposition of a textured oxide buffer layer on metal strip, and RABiTS, or rolling-assisted biaxially textured substrates, in which an oxide buffer layer is deposited epitaxially on a metal strip which has been textured by thermomechanical processing. Technical issues and challenges for these two approaches were discussed.

- ***IBAD***

- Deposition rate
  - -Development of adequately textured YSZ layer is relatively slow
  - -Thin MgO IBAD layers are highly textured and appear to be an attractive alternative
- Reproducibility and uniformity over length
- Effect of surface roughness of metal substrate
- Mechanisms for texture development have not been established
- Modeling studies are needed
  - -Is there an upper limit on texture?
  - -Dependence of Texture on thickness, rate
- Can other materials, e.g. perovskites, be textured?

- ***RABiTS***

- Developments of alternatives to nickel which are
  - -Stronger
  - -Non-magnetic
- ac losses in Ni
- Fundamental understanding is needed of cube texture development particularly with respect to
  - -Alloys
  - -Effects of impurities
  - -Composite structures
  - -Limits to degree of texture
- Development of new and better buffer layer architectures
- Development of chemical, i.e., non-vapor deposition processes for buffers
- Uniformity of texture over length, reproducibility

- ***OTHERS***

The group suggested that other methods of preparing a textured buffer layer should also be investigated, including:

- Deposition onto inclined substrates
- Combinations of inclined substrates with IBAD

The mechanism by which texture develops on inclined substrates has not been established.

THE SUPERCONDUCTOR

Issues raised concerning the superconductor related primarily to grain boundaries and weak-link behavior. A need for fundamental understanding of the causes of weak-link behavior was identified. It was noted that recent results demonstrate that the relationship between J_c and the FWHM of a phi scan is not unique. Therefore a need was seen for measures or indices of grain alignment in the superconductor, which correlate well with J_c. Grain orientation maps and grain boundary misorientation statistics which can be derived from electron backscatter diffraction are useful supplements to x-ray diffraction characterization.

Additional suggested activities and questions included:

- Correlation of gb microstructures with weak-link effects
- Study of grain size dependence of J_c
  - -Do small angle boundaries pin flux?
- More detailed studies of J_c vs. gb misorientation
  - -Need better data at low angles; define plateau
  - -Effects of gb type, gb plane

- Further study of deposition process parameters
  - -Temperature
  - -Rate
- Can the buffer layer induce flux pinning defects in the superconductor?
- Are there advantages to other superconducting compounds?
  - -High J_c Tl-1223 films have been made on RABiTS
  - -Hg-1223, RE-123?

SCALE-UP AND MANUFACTURING

Many comments under this topic related to cost, as determined by processing and the properties of the product. There was little discussion of the appropriateness or achievability of the $10/kA-m target price, but use of the kA-m pricing unit provides clear motivation for maximizing J_E.

Issues related to J_E included:

- Deposition rate
- J_c vs. thickness of superconductor
- Mechanical properties and strain resistance vs. thickness of superconductor
- Performance in field-J_c vs. H
- Mechanical properties, handling of thin (~ 25 μm) metal substrates
- Double-sided deposition?

Issues related to scale-up to long lengths included:

- Heating of continuous tapes for in-situ formation of YBCO
  - -Temperature uniformity over deposition area
  - -Width of temperature window
- Composition control-improved methods are needed for monitoring deposition rates in a continuous, long-length process
- Maintenance of texture over length in roll-textured metals and epitaxial and IBAD buffers
- Patterning of the superconductor layer to reduce ac losses
- Choice of deposition process for superconductor
  - -Vapor deposition, in-situ formation of YBCO
  - -Non-vapor, or "chemical" processes
  - -Vapor deposition of precursor - BaF_2, Y, Cu

Demonstration of technical feasibility by preparing at least moderate lengths of conductor with good properties is the most important task facing us. Scale-up of processes for preparation of long lengths, it was agreed, must be done through collaborations between the national laboratories and industry. Projects are presently in progress at national labs to prepare meter lengths of conductor by both IBAD and RABiTS approaches. Collaborative projects with industry directed toward preparation of longer lengths are also underway.

SUMMARY

of the

Wire Development Workshop

January 29-30, 1998

by Thomas P. Sheahen

The Superconductivity Program for Electric Systems of the Department of Energy held its annual Wire Development Workshop in St. Petersburg, Florida on January 29-30, 1998. These notes were taken rapidly during the consecutive presentations, and are not necessarily complete.

OPENING TALKS

Program Manager Dr. James G. Daley of DOE opened the workshop Thursday morning by noting that 130 people attended, as contrasted to about 80 in the past. Jim briefly recapped the goal of the program: it is still to produce wire with 100 times the current-capacity of copper or aluminum, and without the resistive losses. This wire will be used in electrical devices which must be very large, in order to offset the cost of refrigeration. Internationally, we are competing with Japan and Germany; in the field of *coated conductors*, we are about even now, but the United States is starting to move ahead. Last year, 150 km of HTS wire were delivered.

John Simpson spoke on behalf of Florida Power Corporation, our host at this year's meeting, and presented a "user perspective" to the attendees. Today, the electrical energy delivery service is a mature industry. Bulk power transmission is about 97% efficient; from generator to home is about 94% efficient. Transmission lines are always of great interest; currently, Florida Power is working on a 500 kV line.

Simpson gave an example of the complexities faced by utilities: At present, their power flows geographically in a "horseshoe" pattern, and they really need a connecting link to decrease the risk of blackouts. While a blackout would cost about $90 million, the cost of the connecting link would be $80 million. Moreover, many opponents of the project challenged it on various legal grounds. So they abandoned the link project, and instead introduced a fast *load-shedding* scheme.

In another category, utilities are trying to find alternatives to overhead lines. Underground cable is preferable to the public, but it has technical obstacles. Also, the interties between systems are not easily able to carry huge amounts of power. With all the wheeling of power that people will want to do in the years ahead, various kinds of new tielines will be needed, which are not cheap: putting up 450 miles of 500 kV line would cost $600 million. Basically, peninsular Florida needs to generate and use its own power; Pinellas County, for example, contains 1400 families per square mile. With the growth and population density being experienced, Florida Power needs a variety of cost-effective options to increase its transfer capabilities. Hopefully, superconductivity can help improve the performance of their transmission system; improved transformers are one likely application.

The first plenary talk was by Bruce Strauss and David Sutter from the High Energy Physics part of Energy Research within DOE. High Energy Physics may become a leading customer for HTS wire someday.

Dr. Strauss characterized their business as making extremely sophisticated "microscopes". Since the early 1960s, consecutive improvements at various accelerators have been made; their magnets now reach fields of 13.2 tesla. At one time, High Energy Physics was the main purchaser of superconducting wire. Cryogenic stabilization was a key to their success. A 1968 workshop at Brookhaven introduced the idea of "Enthalpy stabilization". We learned how to make tiny filaments, and to twist wires. In an accelerator today, cryogenics is less than 10% of the capital cost, but cryogenics comprises nearly all of the operating costs. Still, that cost is much smaller than it would have been using resistive wire.

At the very high magnetic fields in use today, force-containment is a big issue. A superconducting dipole magnet has a lot of stress on the mid-plane, due to Lorentz forces, which escalate as B^2. Holding magnets together has been a big learning process over the past 30 years.

NbTi wire has improved in J_c a lot in recent years; $J_c = 3500$ A/cm^2 is now the state of the art. Today, wire is ordered in "ton" lots. Magnet technology is *the* enabling technology for High Energy Physics.

What does the future hold? The *Large Hadron Collider* (LHC) at CERN in Switzerland is going to use 8-tesla magnets in an existing tunnel. Beyond that, there are three major items being discussed: a) the next linear collider; b) *Jupiter*, a proton-collider, also known as the VLHC, or *Very Large Hadron Collider*; c) a muon-muon collider. The trouble with muons is that they go away so fast: their lifetime is 10^{-6} sec in their reference frame, and only a few milliseconds in the laboratory frame. If B = 3T were used, it would require hundreds of miles of tunnels for such a "low field" approach. If B = 15 T were used, one would have to design the magnets to accommodate great forces. Texas A&M, as well as LBL, have various designs to minimize the stresses.

The attraction of HTS is that the upper critical field (H_{c2}) is so large; we can achieve fields around 15 T, while still having J_c above 1200 A/mm^2, and an engineering J_e around 250 A/mm^2. Still, the cost of the structure to hold it together will go up as B^2. The goal is to build magnets having B > 12 T, running above 4.2 K, with controllable AC properties, manageable mechanical properties, and manageable manufacturing methods. Strauss emphasized that High Energy Physics needs "length, length, length" for magnets that will be 1000 feet long. Finally, all this has to be affordable, at a cost near that of a 10-tesla magnet made of Nb_3Sn. HTS could be very helpful here.

Session One: First Generation Wire Development

Intermagnetics General Corp.: Venkat Selvamanickam described the progress made by IGC's cooperative agreement with Argonne and Oak Ridge. They are now producing powder-in-tube (PIT) Bi-2223 wire at the rate of 100 km/yr, in a new factory that has been running for 7 months. Their wire contains 37 filaments, and the pieces are typically 100 m long.

Cost reduction is the key to success. Cost has dropped several orders of magnitude in recent years. The cost now is about $30/meter, which equals $1000/kA-meter. IGC expects its manufacturing speed to increase rapidly in the next few years, and realistically expects to lower the production cost to $100/kA-m. They are also working to get the volume fraction of BSCCO up to 40% (60% silver), and are improving mechanical properties as well.

The key improvement now is that the properties are *uniform* over the full length. Their *chemically-derived powder* is much better than solid-state powder; it provides finer particles, and more uniform filaments. A new method known as *Consolidated Precursor Rod* looks favorable.

Bi-2212 is also being made by IGC, as a tape coating a substrate. The SPI program to build a HTS transformer (Waukesha Electric) is the main user of IGC's Bi-2212. This wire is now being produced at up to 13 amps in long lengths, at a price of $6 to $10 per meter.

IGC is also starting an effort to make surface-coated YBCO.

Oxford Superconducting Technology: Ken Marken reviewed their progress at making Bi-2212 conductors. Using melt processing, they have attained $J_c = 10^5$ A/cm^2 above 20 tesla. Oxford is attentive to several process-control issues: reduction of carbon, residual gas, control of the melting behavior; control of the heat-treatment step are crucial. They use a 19-filament conductor, typically 3 mm x 0.2 mm, and the filaments have diameters of 15 - 30 microns. The critical current levels off at 100 amps, and stays there up to over 30 tesla, at 4.2 K. The engineering critical current (J_e) is about 19 kA/cm^2 in this material. Testing was done at the NHMFL in Florida; the magnets are eight stacked pancakes. Oxford hopes to make a round-wire version of Bi-2212, containing 121 filaments (of about 40 μm diameter), in which the silver to HTS ratio is 2.2 to 3.0.

Oxford has also tried dip-coating of conductors. The current leads fabricated by dip-coating are better than those made of bulk Bi-2212.

EURUS Technologies: Mike Tomsik discussed their AC loss measurements. They have found a way to decouple the filaments, which reduces AC losses considerably (but the decoupling is not total). By putting a sheath around their conductor, they get greater strength.

American Superconductor: Bart Riley reviewed their work on Bi-2223 using the Powder-in-Tube (PIT) process. ASC is getting long lengths with low defects, across a large operational temperature-field range. In short lengths, Jc gets better all the time. Riley stated that their Jc is double what anybody else has, about 70,000 A/cm^2. Moreover, their trend-line over time is steady, so they are confident of still better Jc in the future.

For long lengths (pieces > 100 m), ASC measures current in self-field at 77 K. Typically, 85 amps are being carried. For this geometry, they obtain 5000 A/cm^2, with a standard deviation of $\sigma = 15\%$. Their generation-2 wire gets 9150 A/cm^2, with $\sigma = 7.4\%$. The low-end performance has improved by 130%, which is very encouraging for future improvements.

The cost-of-manufacturing this wire is in the range of $10 - $100 per kA-meter. As the fill-factor increases, the cost of silver decreases, and Je improves. Fill-factors of 40% have been demonstrated in short samples. Power-transmission cables need good mechanical properties, which requires high fill-factors.

Bart Riley also presented a list of "where we need help": On the technical side, it contained items such as higher fill-factor, replacement of silver, weak-link mitigation, flux-pinning enhancement, and connectivity enhancement. Riley is optimistic about the future, saying "we can get there if we apply the effort."

Texas Center for Superconductivity at the University of Houston: Professor Paul Chu described their recent efforts. First of all, TCSUH is trying to reduce the cost of Bi-2212 tape. At $5.20 per ounce for silver, the cost of the silver alone is $18/kA-m, which is already above the $10/kA-m target.

In another project, TCSUH has been able to deposit Hg-1223 on nickel, which is a lot cheaper. They use a 2-step spray/press process for this, and so far have gotten $J_c = 70{,}000$ A/cm^2 at 77 K. Subsequently, they tried making Bi-2212 on nickel by the same 2-step spray/press process. They do a lot of heat-treating tricks here, operating in a very narrow temperature range near 850 C, and are getting excellent grain alignment. Using Ag/Pd layers as well as Cr, they obtain a 5-micron thick layer of semiconducting material in between the Bi and the Ni. Unfortunately, some Cu, Bi and Ca diffuses into the Ni; and T_c is depressed to 70 K. However, at 4.2 K and 9 tesla, J_c is about 300,000 A/cm^2 in this Bi-2212.

Further improvements are needed in the areas of: optimization of process parameters, and control of nickel substrate surfaces. TCSUH plans to use IBAD and RABiTS to improve substrates.

They also want to de-magnetize the substrate to improve AC behavior. Finally, they hope to apply this to Bi-2223 eventually.

The questions-and-answers that followed this set of presentations dealt mainly with issues of reducing cost.

Session Two: Pre-Commercial Prototypes

Southwire Company: **Cable Project:** Uday Sinha described their 3-year project to make 30 meters of 3-phase HTS cable that will carry 1250 A at 12,500 V. The cable will be tested in the year 2000, running between two Southwire manufacturing plants. They have made several different varieties of Cable. In 1997, they designed, installed & tested the *stranding* machine, which is inside a clean room. In 1998, their timetable has slipped some, but they expect to get tape-conductors from IGC in a couple weeks. A 15-foot cable is to be tested in February 1998, with measurements of inductance, capacitance and loss-angle. It will be run continuously for 7 days. Sinha expects to learn a lot from these tests: thermal insulation, cryogenic dielectric materials requirements, etc.

Over the next 5 years, Southwire's tape needs are to make tape that will carry 30 amps, with a yield strain of 0.2%, able to withstand > 100 Mpa. By 1999 they will need 20 km length, and by 2001, 36.5 km; the cumulative length of all samples will be 81.5 km.

Waukesha Electric Systems: **Transformer Project:** Sam Mehta described their 5-year program to build a 30 MVA HTS transformer. There is a window of opportunity ahead soon, because so many transformers are aging and will need to be replaced; if people buy replacement transformers of a conventional type, Waukesha won't be able to sell them HTS transformers.

So far they have a 1 MVA prototype, which will be cooled down within the next two months. In 1999 and 2000, they hope to build a 10 MVA prototype. During phase 1, they have done a conceptual design of a 30 MVA transformer, which looks favorable compared to traditional 30 MVA units. Waukesha has chosen to use cryocooled BSCCO, for several reasons, notable that it is the most cost-effective system.

Intermagnetics General: **Magnet Development:** Mike Walker addressed the subject of wire cost. the cost ($/kA-m) figure that IGC gets by pushing beyond where they are now is still above $ 10/kA-m. For a big transformer such as Waukesha has in mind, the wire costs about $500,000. That cost has to drop below $300,000, in order to compete with other transformers. For a Fault Current Limiter, the cost-constraint is very severe.

Cost is also the major problem in IGC's magnet development project. It is equally possible to cryocool LTS (down to 4.2 K), and that sets a competitive price range. Moreover, the cost-targets are constantly declining, as competing technologies improve. The first commercial application may be in the accelerator at Fermilab, meeting the needs described by Bruce Strauss and Dave Sutter.

Rockwell Automation: **Motor Project:** Boris Shoykhet stated that their goals are to build a 1000 hp motor by 1999, and a 5000 hp motor by 2001. The test-stand has been built; testing will begin about a year from now. *Stator Windings* and *Pole Assemblies* are being fabricated. The refrigeration system will deliver about 60 watts of cooling. Wire comes from ASC; but they still need to have the wire cost only $ 10/kA-m.

Lockheed Martin: **Fault Current Limiter:** Eddie Leung reviewed their progress: In the summer of 1995, they tested a 3000 A FCL; its normal operating current was 85 A at a voltage of 2.4 kV. They are now building a bigger unit -- a huge device, which goes on a trailer. The coil is

about 1 meter in diameter, but they hope to reduce that in the future. This "phase-two" unit will be 15.5 kV, with a normal operating current of 1200 A; it is expected to withstand 2 one-second faults within 15 seconds.

The next unit after that will carry 2037 A under normal conditions, peaking at 9000 A rms. It will operate at 40 K, occupy about one cubic meter, store 20.7 kJ of energy, and sustain a maximum voltage across the coil of 15,500 V.

1997 saw Lockheed Martin file 4 new patent disclosures relating to the FCL: {Iron ring approach, hybrid coil approach, advanced heat-sink design, the no-biased power supply}.

The high cost of HTS wire has been a major concern. Leung contacted many suppliers, and got a range of price quotes from them, averaging $ 1222 /kA-m. This is two orders of magnitude too high. (Remember that NbTi costs $ 1/kA-m and Nb_3Sn costs $ 8/kA-m.) By running the FCL at 40 K, Leung feels they can get the $1222 figure down to $ 680/kA-m. Of course it would be cheaper still to run at 77 K, but YBCO coated-conductor is further away.

In conclusion, Eddie Leung stated that existing Bi-2223 tape conductor works, technically, but is too costly. Therefore, coated-conductor development is terribly important.

Pirelli: **Cable Project:** Mujib Rahman reviewed the improvements that have taken place since their first-generation tapes two years ago. At that time, I_c was 33 A, the length was 200 m, and the strain limit was 0.3%; also, AC losses were 9×10^{-5} W/m at 7 A rms at 55 Hz. Today's cable, which is the *warm dielectric* design, is definitely better: I_c is 20 to 80 A, length > 250 m, strain is 0.2 to 0.5%. The trouble is, the price is $ 1200/kA-m.

Where do we need to go? Rahman looks at it from the customer's point of view: ordinary cable (Cu, Al) runs in the 0 to 2000 A range, whereas HTS conductor will go up to 5000 A. There is no value in running HTS cable below 2000 A. A cable length over 1000 m is needed, with defect-free and consistent material. The critical current must be $I_c = 200 - 300$ A.

Still, cost is the most important issue. Copper costs $12.50/kA-m, and right now HTS is 100 times more expensive. Allowing for cryogenic costs, HTS must come in below $10/kA-m in order to be competitive. Rahman emphasized that industry needs to focus on the cost question.

American Superconductor: **Wire Production:** Bob Schwall began where Bart Riley left off earlier, reminding his audience that it is essential that there be stable support for R&D on BSCCO, and continued prototype-system development. ASC has attained Je > 10,000 A/cm^2 with mechanical robustness in long lengths. Their philosophy is that at 4 K, NbTi is the conductor of choice; below 15 K, Nb_3Sn; but above 20 K, HTS is needed. At 20 K, ASC comes pretty close to Bruce Strauss' criteria for the needs of the high-energy physics community.

ASC derives some of its support from the military. DARPA and the Navy have supported HTS work for minesweepers and for ship propulsion. A homopolar motor-generator was run back in the early 1980s using NbTi; lately the coils have been replaced with HTS coils supplied by ASC and others. In tests of the refurbished motor, it delivered

104 hp at 77 K
230 hp at 28 K
320 hp at 4.2 K.

These numbers are all close to the performance of the Rockwell Automation motor.

ASC is also working on a big new high-field magnet program. They have just completed testing a unit, and found that it takes 45 hours to cool it to 22 K, using *cryoplate* cooling. That magnet was then held for 30 minutes at 7 tesla.

Concluding, Schwall said that Bi-2223 conductor is good, applications are going well now, and ASC is optimistic about the future.

Session Three: Second-Generation Wire -- Private Sector

Midwest Superconductivity: John Hack described their coated-conductor work. Midwest has an SBIR from the High Energy Physics office of DOE to make high-J_c tapes, using MOCVD techniques, and RABiTS to prepare the substrate. So far, $J_c = 640{,}000$ A/cm^2 at 77 K. They are making progress, but the challenge is: how do you make long lengths of MOCVD wire? At present, their MOCVD reactor is set up to produce one-meter long YBCO tapes for demonstration. Midwest has not yet made a one-meter tape. They also are building a reel-to-reel system for depositing YBCO, and think that 50 m is the most they can do.

Midwest has set very aggressive goals. Westinghouse is scaling up the RABiTS process from Oak Ridge, and has accomplished a lot. The texture along the tape is good. Preliminary results include that the texture of the nickel is fine, and they can handle 2-mil thick nickel tape at 800 °C without trouble. The NiO layer has been eliminated.

Difficulties include the great variability in materials from lot to lot and vendor to vendor. Midwest has to clean up the barium content of the chemicals reaching them; this goes under the name of *In-house Qualification*. The chemicals are extremely sensitive to moisture and oxidation; for example, yttrium picks up moisture easily.

John Hack also reported on their economic analysis: the Ni tape and the precursor cost only about $0.50/m; when labor, indirect cost and profit are added, they wind up at $ 100/kA-m at 77 K, and $ 10/kA-m at 4.2 K. In the immediate future, Midwest will continue to work with its one-meter apparatus. They look forward to someday having long lengths of buffered substrate.

Intermagnetics General: Venkat Selvamanickam explained that they start with a RABiTS substrate, apply a buffer, and then coat with YBCO; all these components are made at IGC. They have made good, well-textured substrates, and supplied samples to many national laboratories. So far their buffer layers have been put down using thermal evaporation, but they are experimenting with rf sputtering to deposit buffer layers. When they calculate the economic numbers, they get an *eventual* cost of $ 180/kA-m.

American Superconductor: Les Fritzemeier said that ASC uses the CCVD method, always in one atmosphere air. They shoot the precursors at the substrate, without heating the substrate. This is outside the bounds of conventional CVD. The thickness of the films they have made ranges from < 10 nm up to > 5 microns.

ASC's cost analysis is optimistic; they believe they *can* reach the goal of $10/kA-m.

MicroCoating Technologies: Shara Shoup discussed how they apply very dense YBCO coatings to MgO and $LaAlO_3$ substrates. They are getting good epitaxy of the YBCO, and very uniform films. Using CCVD, they also get good results for buffer layers of CeO_2, YSZ, etc. They obtain the lowest FWHM values of anybody. The buffer layers are smooth, dense and continuous. They have even deposited at the very fast rate of 100 nm/min. They can grow CeO_2 on nickel. MicroCoating Technologies is very happy with their progress. Shoup also asserted that their cost analysis shows commercial feasibility.

3M: Jonathan Storer, substituting for Arne Funkenbush, described their collaborative effort with Stanford University (Prof. Bob Hammond). 3M hopes to apply something from their own technology base that can enhance the known IBAD and RABiTS products.

Their focus is on developing control methods to overcome the widely-varying vapor pressure of YBCO. Bob Hammond uses Stanford's electron-beam equipment to deposit the precursor material. YBCO film deposition is still a very tough problem.

Atomic-absorption remote sensors have been built for Y and Ba; a Cu sensor is still under development. They have constructed a vacuum coater, and are characterizing it now. They have gotten good results with BaF_2. 3M's roll-to-roll coater is working well, too.

In questions addressed to this group of speakers, Alan Wolsky of Argonne directed attention to the very severe penalty going from Jc to Je when the thick substrate is compared to the thin YBCO coating. This is recognized as a major limitation. Everyone is hopeful of getting the YBCO coating up to a few microns thickness, but there may be additional mechanical problems, such as the films lifting off the substrates. Also, the variability of Jc as a function of increasing film thickness was discussed; this too is an active area of research concern.

To a question from Udaya Rao of FETC about the possibility of texturing Ni/Cu substrates which are non-magnetic, Selvanamickam replied that IGC is working on this.

Session Four: Second Generation Wire -- Federal Laboratories

National Renewable Energy Lab: Dick Blaugher stated that work continues on thallium, in a collaboration with several national labs and universities, supported by Basic Energy Sciences of DOE. They are able to make good buffers (CeO_2, YSZ) on nickel using RABiTS techniques; Blaugher showed pole figures to verify this. Their electrodeposited films of Tl-1223 also show good texture. NREL is working toward getting Jc to hold up at higher magnetic fields. The advantage to Tl-1223 is that in the LN_2 range (64-77 K), it would meet the needs for transformers (<0.5 T) and transmission lines (< 0.02 T). Electrodeposition is relatively cheap, and therefore Tl-1223 is still in the running. NREL is also doing some work on (Pb, Bi) compounds.

Los Alamos: Paul Arendt described progress using the *Ion Beam Assisted Deposition* (IBAD) technique, especially in preparing YSZ and MgO buffers. They are building an IBAD/RHEED apparatus to make better films.

The variation of Jc with position along the tape has improved greatly in the last two years, but there is still room for improvement. They now have 1.1 m IBAD-YSZ templates, and IBAD-MgO production has improved one-hundred-fold in speed. Their YBCO films show Ic > 100 A in a 5 cm tape, which implies Jc > 20,000 A/cm^2.

Oak Ridge: Ron Feenstra discussed the BaF_2 method, which is a scaleable process for making YBCO coated conductors. This method differs somewhat from the usual methods. They first put buffers of CeO_2/YSZ/CeO_2 on a nickel substrate. The BaF_2 process (first introduced by AT&T Bell Labs in 1987) is a two-step process. There is a low-temperature *deposition* step followed by a high temperature *annealing* step. This way, two complex processing steps are decoupled. The idea is just to get the right stoichiometric mixture down onto the substrate, and then form YBCO crystals by chemical reactions. This relaxes the control requirement, at the expense of an extra processing step (the high-temperature anneal). The substrate is an important actor in the process.

Results have been favorable: photomicrographs show good crystal structure, and Jc vs. B looks good as well. Moreover, as the thickness increases, Jc remains nearly constant all the way out to 2 microns thickness of YBCO. They see a critical thickness for C-axis growth.

Oak Ridge is now constructing a second system, to look at other issues, such as:

a) enhancing reproducibility
b) studying growth mechanism
c) devising monitoring techniques for film deposition
d) establishing windows for processing parameters.

Brookhaven: Mas Suenaga presented their work on YBCO thick-film formation. Brookhaven is also using the BaF_2 process, in collaboration with Feenstra et al at ORNL. The advantage is in the possibility of industrial scale-up, because electron-beam deposition is a very high-rate process (> 0.5 microns/minute). The unknown factor is, how thick can the YBCO coating be made. Brookhaven set out to find this thickness limit. They found they can put down rather thick coatings, provided that the composition is controlled carefully. A 3-micron thick YBCO film on $SrTiO_3$ at 77 K shows Jc dwindling from 10^6 to 10^5 in the usual way. In the BaF_2 process, the fluorine doesn't leave the compound until the YBCO forms. There is a thin amorphous boundary between YBCO and YBFO.

Suenaga gave a list of what is known so far:

a) BNL has a deposition rate > 100 Angstroms/sec (0.6 microns/min.),
b) evaporation of BaF_2 is by a thermal mechanism,
c) we can make YBCO this way up to 3 μm, and hopefully up to 5 μm,
d) the growth of YBCO layers is only upward from the substrate.

What we don't know yet includes:

a) effect on the growth rate of various factors: {gas flow rate, moisture content in the gas, compositions}
b) kinetics of the growth: {when does the a-layer form, what is the role of water, what promotes nucleation of a-axis grains in thick films}

Argonne: Balu Balachandran summarized the international perspective on coated conductors:

In Japan, Fujikura is doing IBAD for YSZ, then PLD or MOCVD to add the YBCO; they get Jc = 1.1 x 10^6 A/cm^2 at 77 K in no field. Sumitomo uses *Inclined Substrate Deposition*. ISTEC obtains Jc = 10^6 for 10-micron thick YBCO; Jc is greater at thickness below 2 microns, but then levels off. NRIM is using laser ablation for YBCO. Hitachi is using hot-rolling of silver, with spray-pyrolysis of Tl-1223.

In Germany, U. Munich, U. Gottingen and Siemens are all working on IBAD.

For all competitors in the coated-conductor business, *speed = cost*. Uniformity gives good yield, which reduces cost. Monitoring and control also improves yield, reducing cost. Everyone worldwide has to work on all these areas.

In the question/answer session to these speakers, the thickness of attainable films was considered. If the surface temperature is well controlled during growth, then the in-situ process of growth is controlled, in which case very great thicknesses should be possible.

Session Six: Fundamental Research Issues for HTS Wire Development

National Institute of Standards and Technology: Terrel Vandevah discussed phase-equilibrium issues, which are being studied at NIST. She reminded listeners that thermodynamics is about *equilibrium*, and never tells you how fast a reaction will proceed. The kinetics determine the speed of reaction. Kinetics is for *microscopic* processes, and thermodynamics is for *macroscopic* processes.

In this business, it is necessary to deal with *incongruent* melting, which requires you to deal in kinetics. In a 5-component system, such as Pb-BSCCO, you're dealing with a 5-dimensional phase space. There are no shortcuts, and it may take a decade to analyze. There are very complex

mixtures precipitating out when BSCCO is cooled. The Pb-BSCCO primary crystallization volume is only a thin wafer in that 5-dimensional space.

Jack Ekin of NIST covered the electromechanical properties of superconductors. First of all, there is a limit to scalability, because the weight scales as X^3, while strength scales as X^2. This means that new problems crop up as things get bigger.

In magnets, hoop stress needs to be taken into account. If axial stress is applied to a Nb_3Sn wire, J_c and H_{c2} will change in a certain way. The main determinant of the importance of strain on J_c is the slope of the critical field curve. When the strain in Nb_3Sn exceeds 0.8%, filaments start to break, and then it is impossible to do reversible stress-strain measurements any more. If very small filaments are used (< 0.4 micron), the strain tolerance goes up to 1.4%.

In BSCCO, the irreversible strain limit is down around 0.2%. When the transverse stress exceeds 20 Mpa, Jc starts to deteriorate. It is not yet known if reducing filament diameter will help. The outlook for BSCCO in tension is very bleak.

In YBCO, it appears that tensile bending can withstand 0.5% strain, and 1% in compression.

Summarizing, Ekin stated that in the A15 compounds, there is reversibility, and they are generally better in stress-strain survival. But in YBCO and BSCCO, we do *not* see a reversible strain effect at fields of practical interest. We *wish* we could get the reversible strain effect to hold even out to 0.6%.

Argonne: Ken Gray discussed grain boundary issues. We know that conductance is bad at the grain boundaries. In coated conductors, at Argonne they can make *very* flat grain boundaries. However, the electrical properties seem to be better in grain boundaries that are *not* of such superb quality. Why?

At a grain boundary, there is essentially a Josephson junction, and thus there will be a *Josephson vortex* across the grain boundary. Because it is confined to the area of the grain boundary, it's an elongated vortex. At a conventional [old-fashioned, Abrikosov] vortex, pinning by defects deters vortex motion and helps to keep Jc high. In the Josephson vortex case, a much larger size needs to be pinned.

This implies that a *meandering* boundary may be preferable to a perfectly flat boundary. Consider a grain boundary in terms of the *Dynamic Coarsening Model*: the radius of a grain is related to the binding energy. An epitaxial grain has the highest binding energy; a misaligned grain is lower in binding energy. Good epitaxial films are normally made at high temperatures. A meandering boundary is made when high deposition rates and somewhat lower temperatures are used. It is possible to get almost an order of magnitude change in Jc here, depending on details.

Los Alamos: Steve Foltyn succinctly categorized the issues for improving performance of coated conductors. From a very long list, three major categories of issues emerge:

Longer: continuous processing, process control and uniformity.

Faster: IBAD speed, deposition rate for YBCO.

Better: Increase Ic and Jc, maintain or improve Ic in magnetic fields.

Foltyn discussed their high-deposition rate YBCO process, using PLD; the deposition rate is up from 2 to 240 Angstroms/sec. By annealing this rapidly-deposited material, they believe Jc can be made much higher. Unfortunately, high deposition rates sometimes give badly-misoriented crystals, but annealing such films can restore Jc again.

Los Alamos has a collaboration going with Oxford (England) to study how Raman Spectroscopy can identify cation disorder.

For improving Ic, the goal can be stated as "What will it take to get to a 1 cm wide tape that will carry 1,000 Amps?" The empirical limit on Jc seems to be around 5×10^6 A/cm^2 (at 77 K, in self-field). However, Jc is not that high in one-micron thick films -- 10^6 is more typical for thicker

films. Jc levels off for thicknesses of 3, 4, 7 μm. Also, the weak-link character of YBCO grain boundaries set a practical limit. Thus, for a 10 micron film, 1 cm wide, Ic = 500 A is optimistic but plausible. Such a coating applied to both sides of a substrate could carry 1,000 A.

University of Wisconsin: David Larbalestier considered various limits to Jc. In LTS, the current is usually limited by vortex-pinning. In HTS, there are many contributing factors, especially weak links. The process of *percolation* plays a crucial role here.

At Wisconsin, they have been looking at filamentary conductors provided by American Superconductor, and have done some magneto-optical imaging of individual filaments. They are also looking for ways to heal residual crack damage.

C-axis transport of current is a major target for study, because if C-axis performance can be improved, the overall Jc in the wire is greater.

As is well known, granularity of YBCO is an obstacle to high-current, high-field applications. The angle θ between grains is a major factor here; using IBAD, some defects in the substrate propagate through to the YBCO layer. They have compared a "granular IBAD" weak-link with a "well-connected IBAD" weak link, and found that, although the Jc values are quite different, both links have H* = 5.5 tesla at 77 K.

Oak Ridge: Dave Christen reviewed the effects of substrates on thin films. In general, for coated conductors, there is epitaxial growth from textured substrates; that growth is C-axis oriented, with planar grain boundaries. But there are strong influences on the YBCO from the substrate. For example, the transport properties of the {001} tilt-boundaries matter; as does the distribution of grain-boundary orientations, because individual grain boundaries have both symmetric and asymmetric faces. There seems to be a strong-coupling component between the symmetric faces. Most of the interface is weak-coupled, but a small fraction is strong-coupled. Oak Ridge has generated a simulated I-V curve using this model, and it fits the data reasonably well.

To attain high Jc, it is necessary to have low-angle grain boundaries from one grain to the next, so the current can meander along the path. If the grain-to-grain orientation is less than 5°, there is excellent percolation conduction.

In the question and answer part of this session, discussion dealt mostly with grain-boundary angle effects. Ken Gray of Argonne emphasized that it is first necessary to get rid of macroscopic defects (scratches, etc.) before any grain-boundary effects can be seen. David Larbalestier pointed out that when there are large-angle grain boundaries, there are much greater stresses and strains in the material.

Breakout Groups

The workshop then split into three breakout groups:
BSCCO wire,
BSCCO applications,
Coated Conductors and Fundamental Issues.

Each group was directed to synthesize the key results and issues in their area, add to the list of issues, prioritize them, and suggest new experiments. After lunch the attendees reconvened to hear the reports from each breakout group.

BSCCO Wire: Vic Moroni of Argonne summarized the deliberations of this group. He recalled that their report last year called for improvements in Jc, better performance in magnetic fields, and enhancing performance of long-length conductors.

This year, *cost* is the main concern with each of three categories of issues:

a) Increasing Jc is the leading priority; but note that if the fill-factor is increased, Je goes up without changing Jc. Also, removing cracks and second phases, and getting better grain alignment, will improve Jc.

b) Process simplification is needed. Reliability issues include quantifying, understanding and controlling processes. One key topic is the micromechanics of deformation, which bears on strain tolerance, etc. To pursue this, we need better *tools* for looking at microstructure.

c) Finally, the cost of the sheath material needs to come down.

Maroni made the point that BSCCO is the only *demonstrated* long-length HTS option available now. BSCCO is not "just" a 77 K superconductor, but is used over a very wide range. We can expect the operating temperature to move upward from 20 K gradually over time.

In the discussion period that followed, Jim Daley noted that the fraction of the program devoted to BSCCO has been declining slowly in the past few years. Jim stated that BSCCO is the only option available for the next 4+ years, so there will still be support for BSCCO.

BSCCO Applications: Dick Blaugher of NREL spoke on behalf of this break-out group. There are several important milestones coming up this year:

- A 1 MVA transformer will start cool-down next week (Waukesha Electric)
- A 50-m long transmission line, carrying 2000 A at 115 kV, will be tested at Pirelli.
- A 15 kV-class FCL will start testing in October 1998 at Southern Cal. Edison.
- A 1000 hp motor will begin testing at Rockwell Automation next year.

The group agreed that performance and cost requirements must be addressed. The cost of BSCCO conductor has to come down.

Certain key issues were identified:

a) Commercialization of the superconducting electric power devices will require a "change in the culture".

b) All customary standards (ANSI, IEEE, EPA, etc.) must be followed in order to achieve commercial success.

c) In areas where there are no standards, we must *define* some standards; but standards do add cost, so this must be done thoughtfully.

d) Because of utility deregulation, there is very little market for HTS technology. It will be difficult to sell *any* new technology to utilities.

e) Demonstration/prototyping is crucial for convincing utilities with respect to performance and reliability. It has to be done within a "utility framework". Therefore, some of the upcoming tests will be crucial.

f) Producers and users (i.e., utilities) need to maintain an open, two-way dialog.

g) Continued support for BSCCO conductor development is still needed. This is the only thing we have at this time with which to make coils.

h) Refrigeration and cryogenic support is a key component of successful commercialization. If this fails, everything fails.

In the discussion period, it was noted that the resources for refrigeration work must come out of the SPI program, but the wire groups don't want their money shifted away. Present day off-the-shelf cryogenic equipment is not necessarily optimum; no great research breakthroughs are needed here, just engineering development work. Jim Daley posed the question whether part of the

program should be devoted to cryogenic engineering and equipment development. He said that if people think so, it would be possible to ask for more money in FY2000 to pursue such efforts. The alternate viewpoint of some participants was that cryogenic considerations are secondary, because the cost of wire is so high that the program assets should be put there. It was agreed that the *total* system must be cost-optimized, which means both wire *and* cryogenics. The consensus was that *additional* funds for cryogenics would be very helpful, but not at the expense of the SPI projects.

Coated Conductors and Fundamental Issues: There are three subcategories here: textured templates, the superconductor itself, and issues related to scale-up/manufacturing.

a) Pertaining to textured templates, the main discussion was about IBAD and RABiTS -- it is not clear that we even know *why* these methods work. That opens the door to suggestions of using inclined-substrate deposition, and bases other than YSZ or MgO (Sumitomo has had some success here).

The largest issue relating to RABiTS is the need for something stronger than nickel *and* non-magnetic, to reduce AC losses. If nickel is to be used, AC losses will be very significant: With a 2-mil nickel substrate, the AC loss in a transmission line is high, but it is less of a problem in applications where the magnetic field is higher in the first place.

We need a fundamental understanding of how to produce texturing in alloys. Also, with RABiTS, the buffer-layer architecture determines the epitaxy of the superconducting layer. Accordingly, we need a reproducible process for making good buffer layers.

b) For the superconductor itself, grain boundaries are the most important issue. Large-angle grain boundaries need to be eliminated. This in turn involves a cost trade-off and it affects the choice between deposition methods. Grain *size* may also be an important determinant of Jc. The macroscopic texture does <u>not</u> uniquely determine the outcome; the FWHM does not tell the whole story. There can be a wide variety of grain-boundary misorientation angles; and the current can meander along an irregular path.

Furthermore, it was noted that Jc is influenced by the *thickness* of the HTS layer. In thick films, Jc is down by a factor of 5 from what can be achieved in *thin* films; and yet, in a magnetic field of 3 to 5 T, Jc is greater in thick films. So studying Jc <u>in field</u> needs to be done. Los Alamos so far has tested samples up to 2 μm thick. A related question is that of flux-pinning. We seek a processing system with optimum flux-pinning, but there are some very fundamental questions unanswered. Nobody understands why some films are so very good; indeed, the best thin films are distinctly better than single crystals.

Alternate deposition processes were discussed, especially the BaF_2 method. It was noted that dip-coating can be easily scaled up, as Kodak has done for years. The trick with YBCO is to understand how the deposition rate affects the microstructure.

c) Scale-up/manufacturing include giving attention to increasing Je: double-sided coating is desirable, but that is hard to manufacture. There are also difficult issues with joining technology, buckling of film, compression/tension effects, etc. Deposition processes and deposition rates can be controlled with in-situ monitoring, but the national labs are not currently geared up to address such measurements; which have to be left to industry.

Concerning the problem of manufacturing heated continuous tapes, it was agreed that this is difficult to solve over long lengths. The question was posed: is a one-meter continuous tape good enough for the labs to hand off this technology to industry? (The general consensus was "no".)

AC losses, as well as Neodymium compounds, were discussed by this group. It is possible that Nd might be easier to use than standard YBCO, but the window of tolerance will be smaller for Nd compounds.

Manufacturing cost was not discussed very much by this group, except to note that the issues are about the same as they were last year. It was agreed that the cost analysis can best be

done by the wire manufacturers, but industry does not feel that this technology is far enough along yet to warrant a cost analysis at this time.

In the discussion session, getting the cost down was the major topic. Martin Maley noted that we have to put more emphasis on cost-related issues; as an example, he cited the deposition of HTS material by faster and more economical methods, such as Bob Hammond's electron beam.

WRAP-UP

Jim Daley made some concluding remarks: The findings of the break-out groups will be assembled along with the proceedings, and mailed out to all participants. He thanked the representatives of Basic Energy Sciences and High Energy Physics for attending, and expressed hope that we will continue to strengthen relations with those parts of DOE. Jim noted that EPRI continues to be a strong backer of the program, which it has been from the start.

The Superconducting Partnership Initiatives are proceeding well. The proposals for this year have been evaluated, and notifications to bidders have been sent out. This part of the program will occupy center-stage for the rest of this year.

Finally, Jim Daley announced that the Annual Peer-Review meeting will be held in Washington DC at Loew's L'Enfant Plaza Hotel on July 20-22, 1998.

APPENDIX A

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