ORNL – SuperPower CRADA: Development of IBAD-Based 2G Wires

Oak Ridge National Laboratory

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SuperPower, Inc.

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FY 2006 Funding: 800 K

ORNL-SuperPower CRADA Objectives

Assist SuperPower in the development of high performance IBAD-MOCVD-based 2G wires for the commercial application of HTS technology.

Approach

Carry out R&D support to achieve an improved understanding of the fundamental properties of the IBAD-MgO templates as well as MOCVD-REBCO to manufacture robust & high performance 2G wires.

FY 2006 CRADA Plans

- **Assist SuperPower in transferring LMO technology from short lengths to pilot-scale type production lengths.**
  - **Demonstrate > 300 A/cm on LMO type buffers.**
  - **Produce robust IBAD-MgO/LMO templates in 250 m lengths.**
- **Simplify buffer structure for IBAD-MgO suitable for MOCVD (in conjunction with LANL CRADA).**
- **Provide characterization to optimize pinning in MOCVD-HTS films produced on IBAD-MgO templates.**
- ***(NEW)* SuperPower assistance in transferring MOCVD equipment to establish REBCO deposition capabilities at ORNL.**
- **Understand the role of copper (Cu) surround -stabilization in the operational stability limits REBCO coated conductors.**
- **Evaluate ac loss in stacks of narrow-width coated conductors and compare to equivalent 4 mm-wide wire.**
- **Determine if improvement observed in the high voltage performance of copper surround-stabilized 2G tapes translates from fundamental geometries to practical geometries.**

Presentation Outline

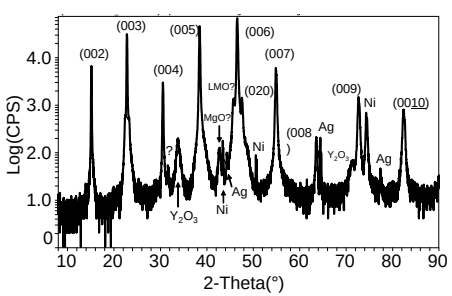
- **FY 2006 Results**
  - **Development of simplified buffer layer strategies** **(Dominic)**
  - **Microstructure-property correlations of MOCVD REBCO films on IBAD-MgO**
  - **MOCVD technology transition**
  - **AC loss** **(Robert)**
  - **Stability**
  - **Dielectrics**
  - **Integration of LMO technology with IBAD-MgO MOCVD conductors** **(Selva)**
- **FY 2006 Performance & FY 2007 Plans** **(Selva)**
- **Research Integration**

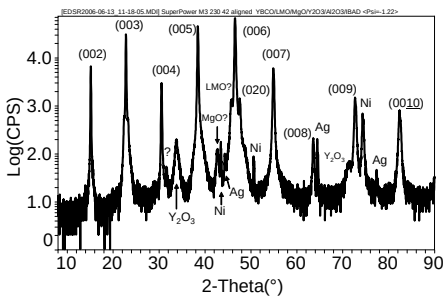
FY06 Plan: Assist SuperPower to transfer LMO technology from short to pilot-scale type production.

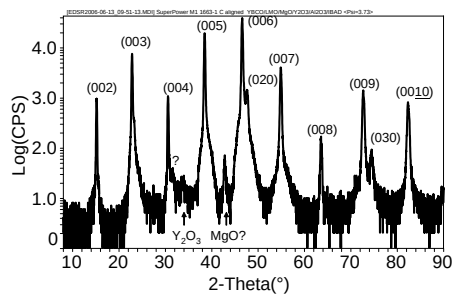
- **Building on FY05 success, SuperPower has integrated the LMO buffer into its production operation.**
- **High quality and uniformly textured IBAD-MgO/LMO substrates have been manufactured in long lengths (Selva).**
- **High J_c-I_c samples have been obtained on these substrates:**

0.9 μm	1.4 μm	2.8 μm	2.1 μm
234 A/cm-w	293 A/cm-w	441 A/cm-w	557 A/cm-w
2.6 MA/cm^2	2.1 MA/cm^2	1.6 MA/cm^2	2.6 MA/cm^2

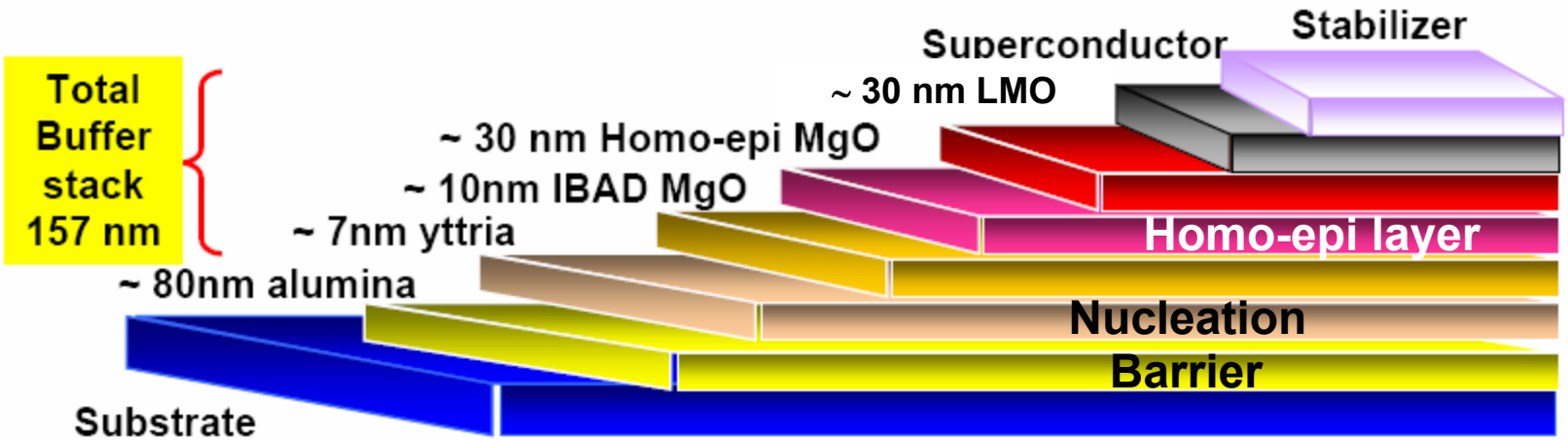
Typical REBCO: >96% cube, $\Delta\omega$ ~ 1° - 1.5°, $\Delta\phi$ ~ 3° - 4°, some a-perp.







FY06 Plan: Simplified buffer structures for low-cost and improved IBAD-MgO performance.



Objective: **To replace or remove one or more layers in the current SuperPower buffer stack.**

Approach:

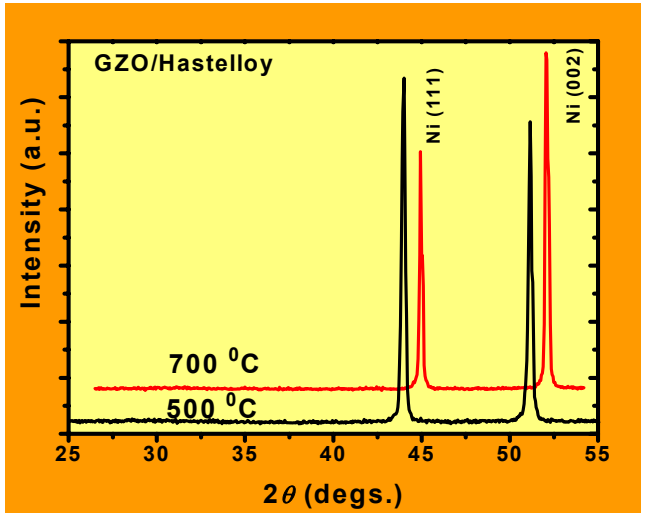
1) **Replace possibly Al_2O_3 barrier & Y_2O_3 nucleation layer with a low-cost, high throughput single amorphous MOD layer:**

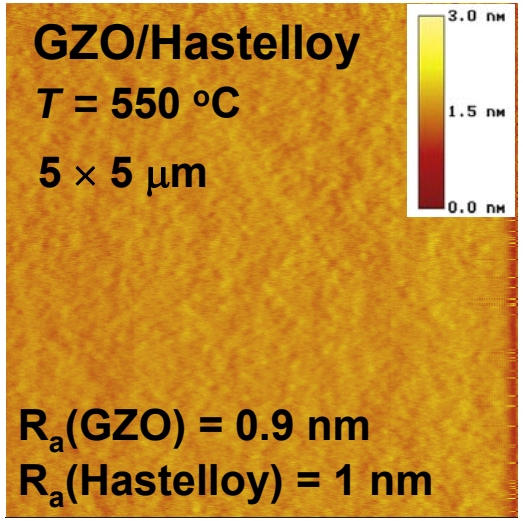
   Candidates: $RE_2Zr_2O_7$, Al_2O_3, Nitrides, RE_2O_3,…

2) **Eliminate homo epitaxial MgO, & deposit LMO layers directly on IBAD-MgO.**

Nanocrystalline/Amorphous solution (MOD) based $RE_2Zr_2O_7$ layers have been deposited on e-polished hastelloy substrates.

Nanocrystalline/amorphous $Re_2Zr_2O_7$ phase can be achieved @ $T \leq 700$ °C





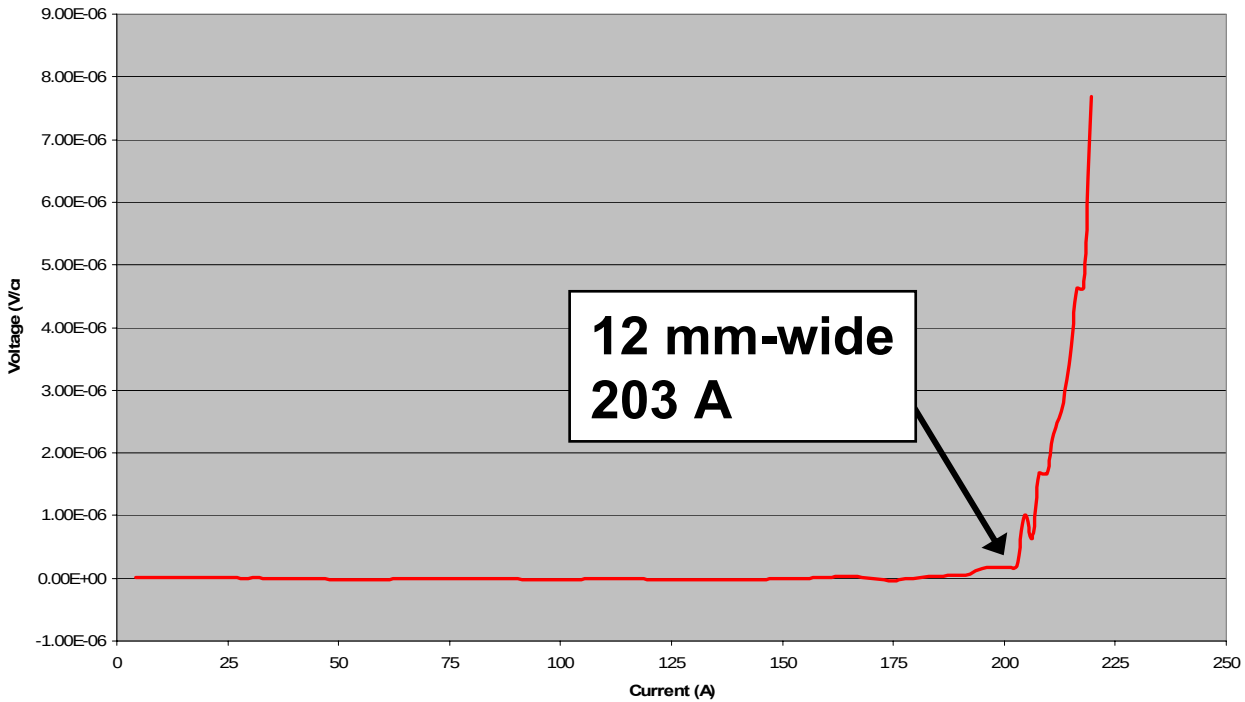
- **MOD approach yields smooth & dense films.**
- **Initial IBAD-MgO texture obtained on these layers is promising.**
- **On GZO layers: IBAD-MgO $\Delta\phi$ = 7.4.**
- **On LZO layers: IBAD-MgO $\Delta\phi$ = 7.8.**

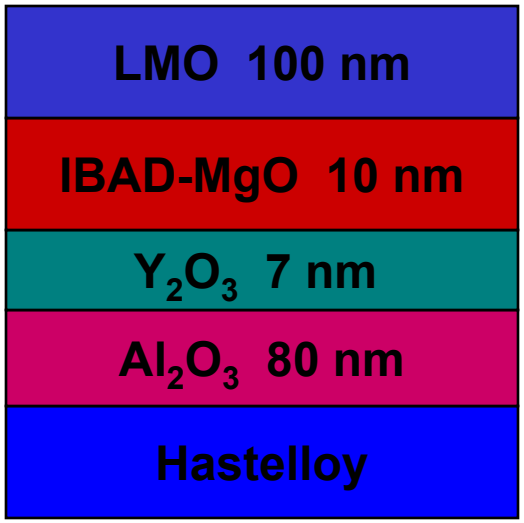
MOCVD-YBCO films with good I_c achieved on 100 nm thick LMO layers deposited directly on IBAD-MgO.

\YBCO/LMO/MgO(IBAD)/Y_2O_3/Al_2O_3/metal

I_c = 169 A/cm-w

LMO texture: $\Delta\omega$ = 3°, $\Delta\phi$ = 9°





FY06 Plan: Provide characterization to optimize pinning in MOCVD-HTS films produced on IBAD-MgO templates

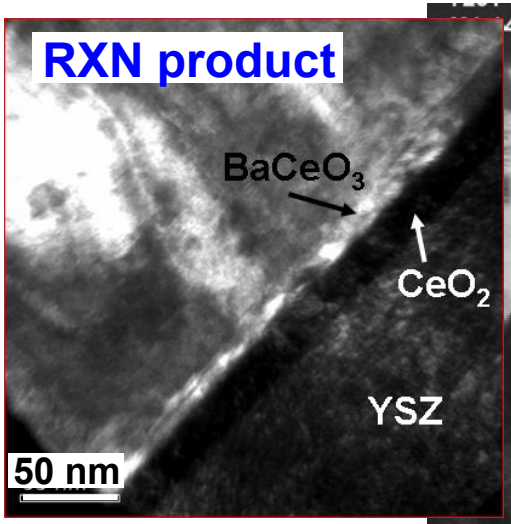
SuperPower Goal: To increase J_c from ~ 2 MA/cm^2 to 3 MA/cm^2 at 77K, self-field, in SuperPower's thick REBCO on IBAD substrates.

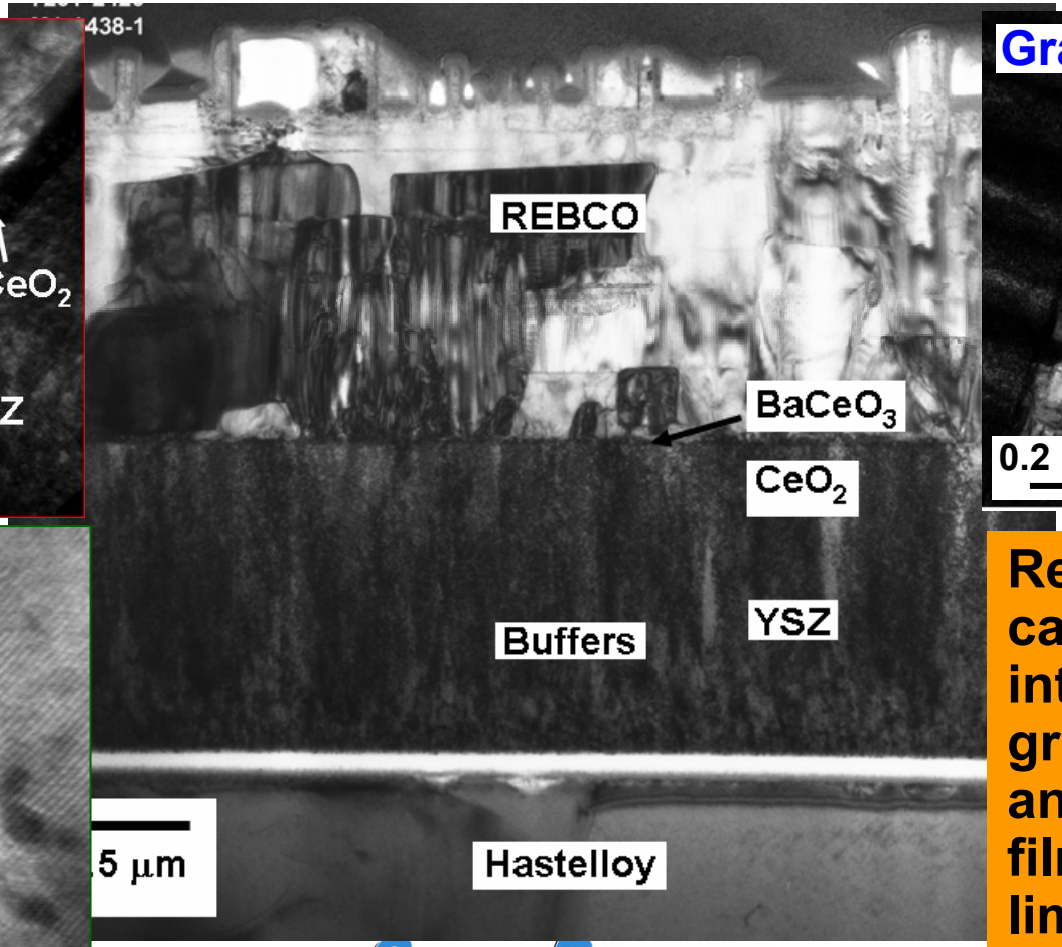
Approach: To determine what defects are limiting the J_c by analyzing the texture, microstructure and reactions at interfaces.

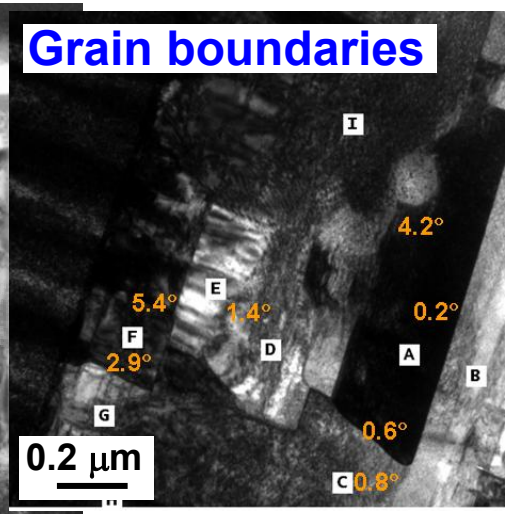
FY 2005: Microstructure-property correlations in REBCO MOCVD films on IBAD YSZ substrates.

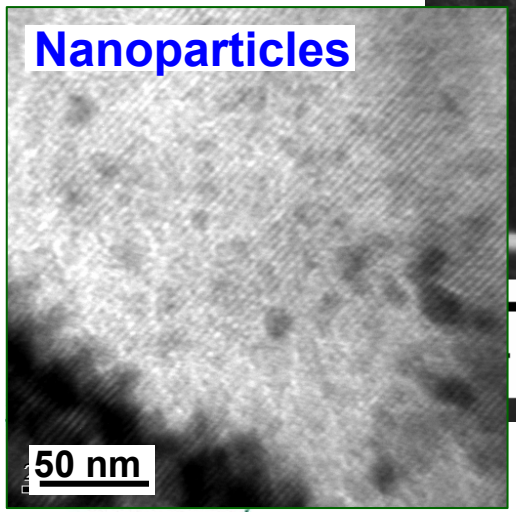
Standard 1.1 μm R-R processed BEBCO tape from SuperPower.

REBCO: $\Delta\omega$ = 1.82° FWHM $\Delta\phi$ = 4.90° FWHM
I_c = 244 A/cm J_c = 2.2 MA/cm^2









Reaction at the cap-layer / HTS interface, a-perp. grains & higher-angle GB's in the film could all be limiting the J_c

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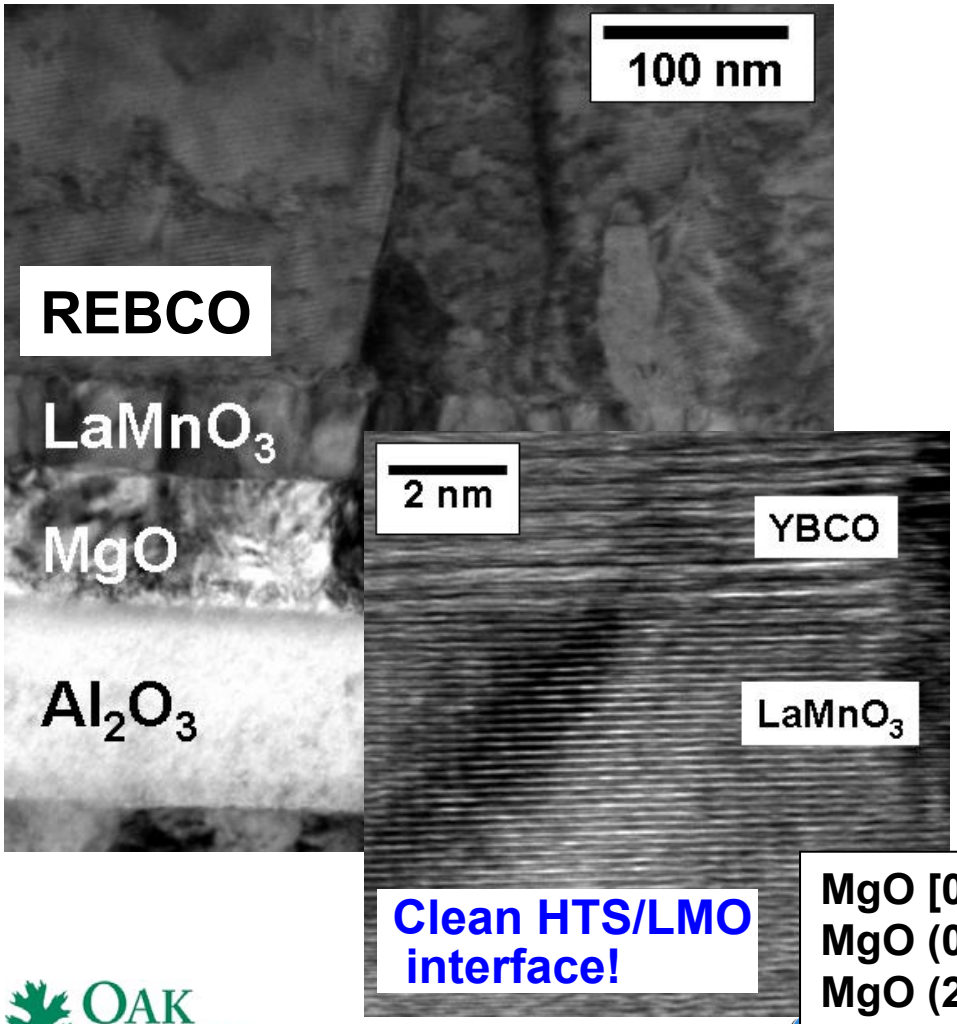
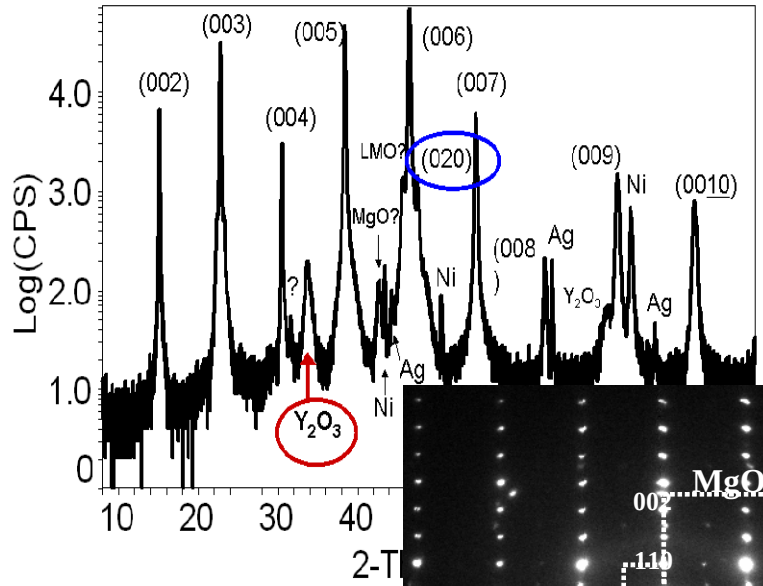
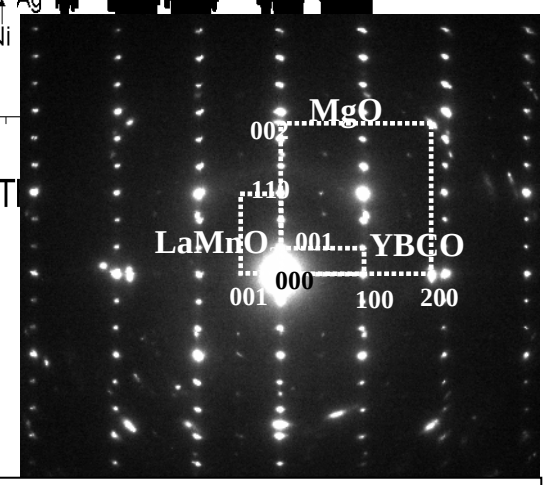
FY 2006: Microstructure-property correlations in 0.9 μm REBCO MOCVD films on IBAD MgO substrates.

REBCO: > 96% cube, $\Delta\omega$ = 1.48° FWHM, $\Delta\phi$ = 3.14° FWHM







MgO [010] || $LaMnO_3$ [-110] || YBCO [010] (zone axes)
MgO (002) || $LaMnO_3$ (110) || YBCO (001)
MgO (200) || LaMnO3 (001) || YBCO (100)

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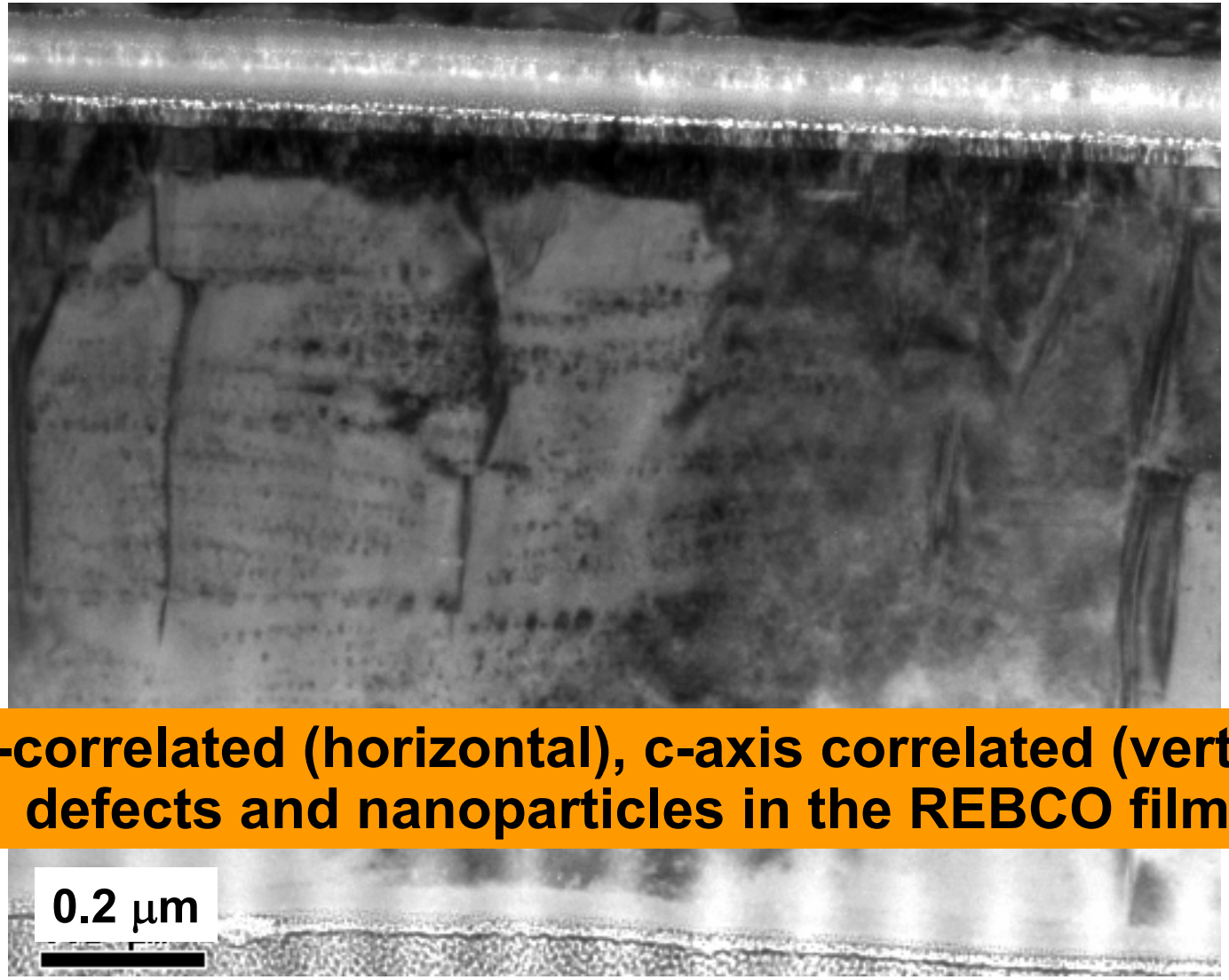
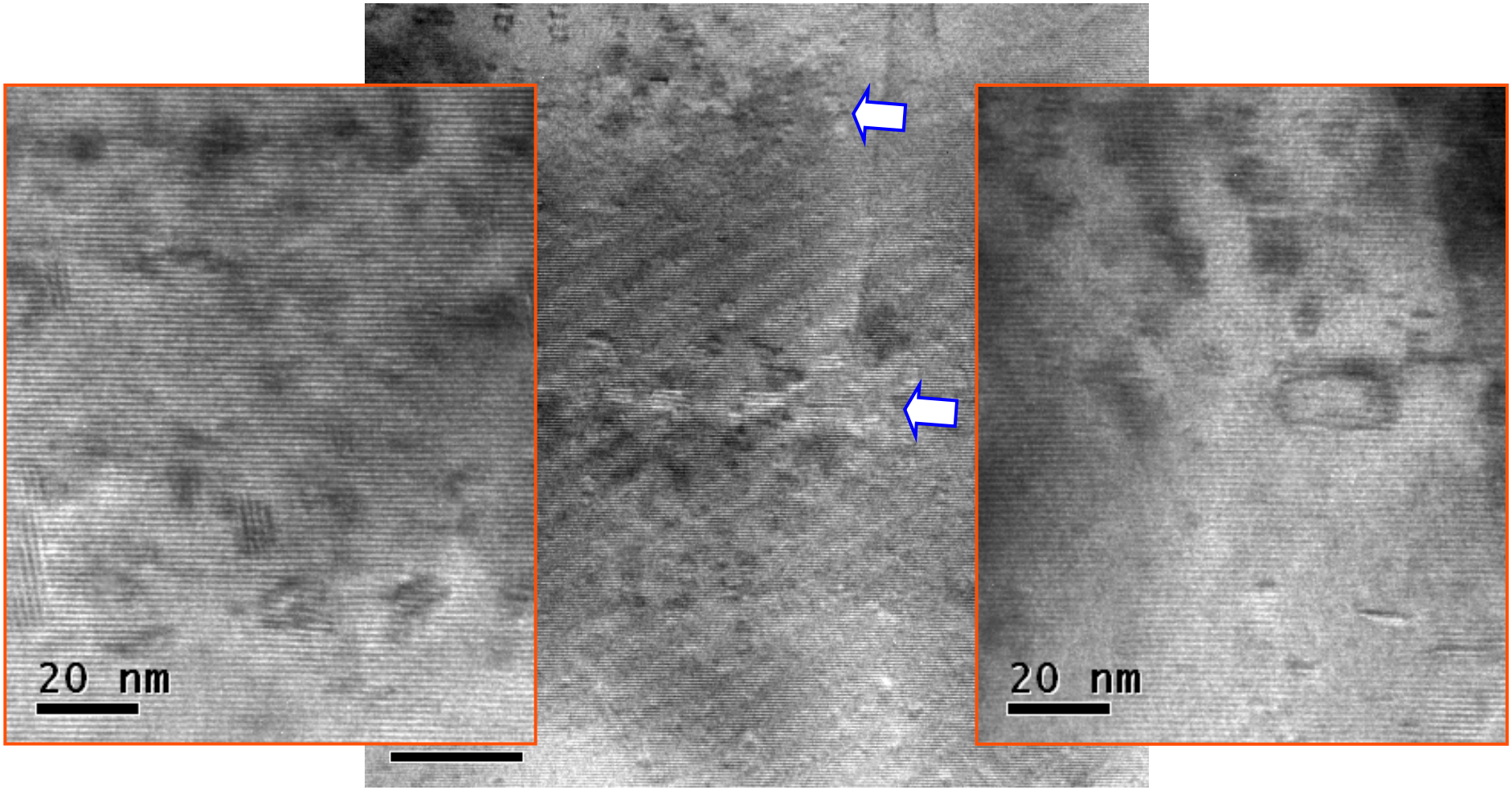
What are the microstructural features of "standard" 0.9 μm thick MOCVD films on IBAD MgO in FY06?

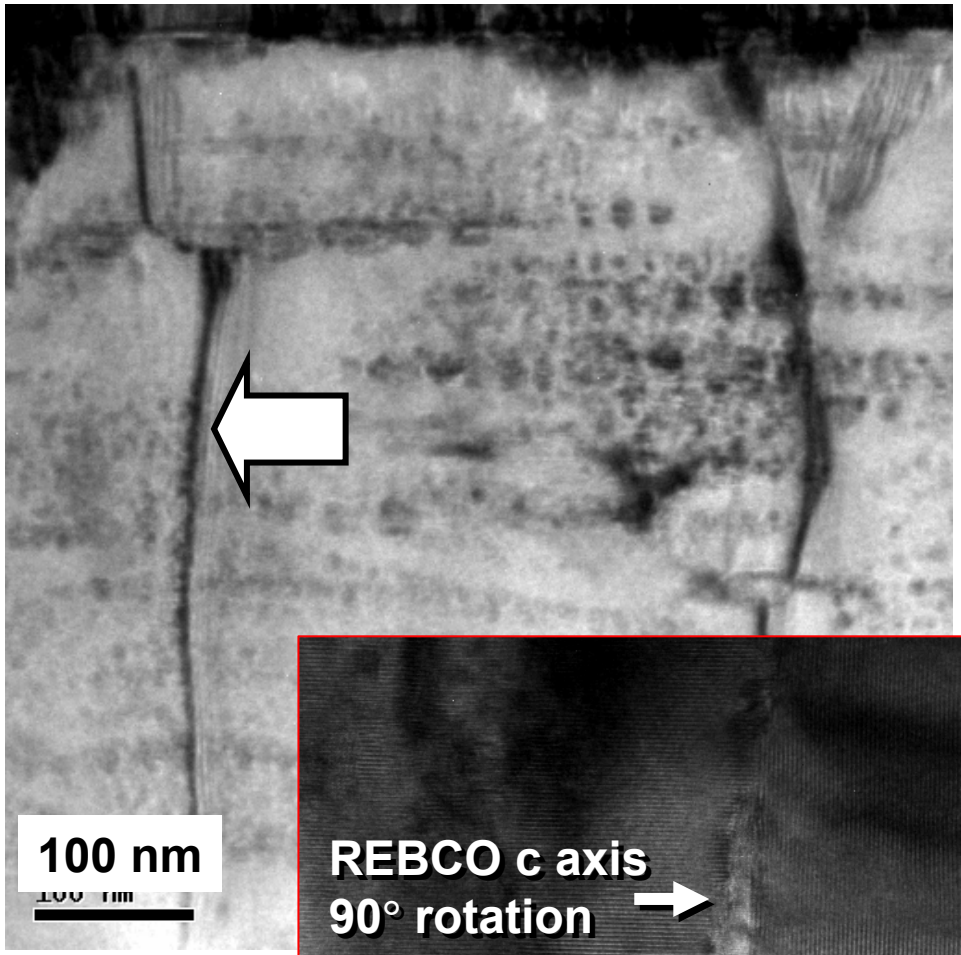


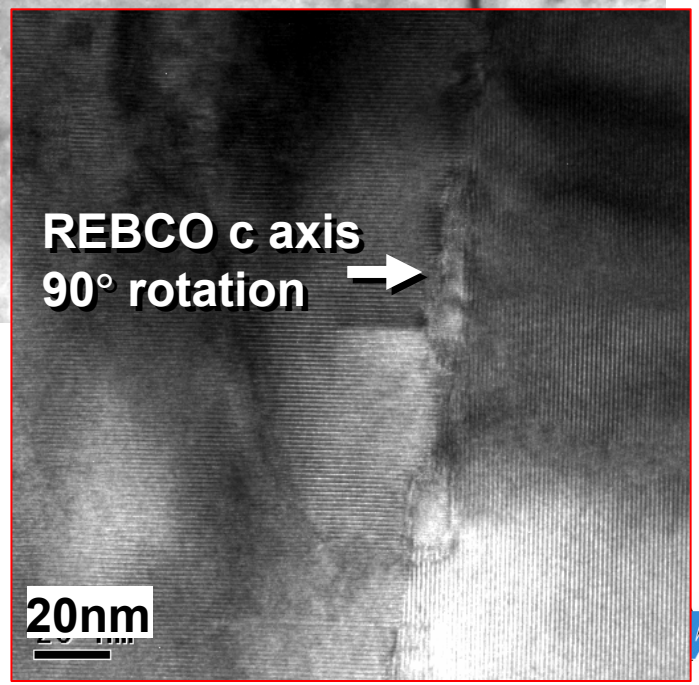
ab-correlated (horizontal), c-axis correlated (vertical) defects and nanoparticles in the REBCO film!

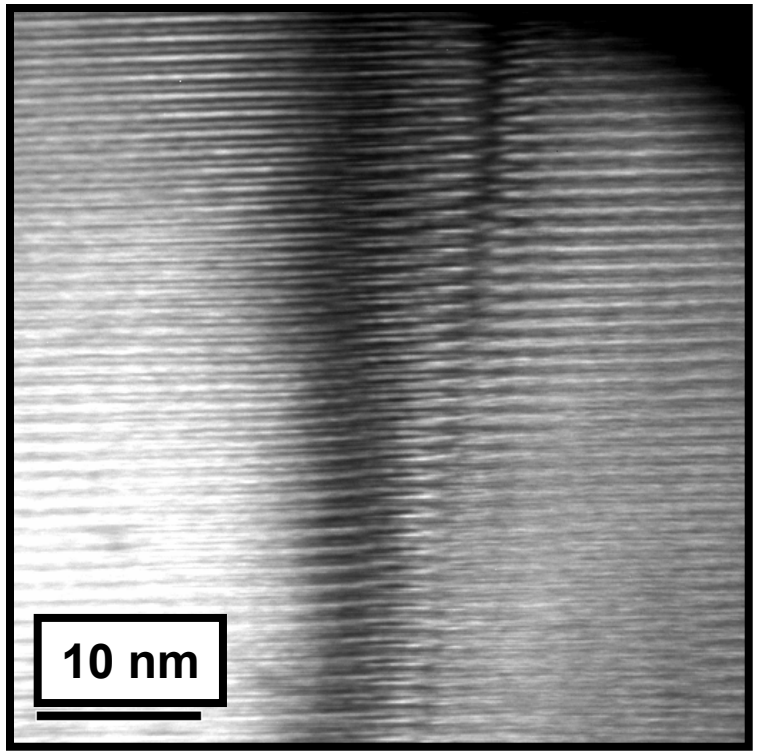
Horizontal defects are clusters of stacking faults. Y_2O3 nanoparticles are seen throughout the film.



Vertical defects are bundles of anti-phase boundaries!



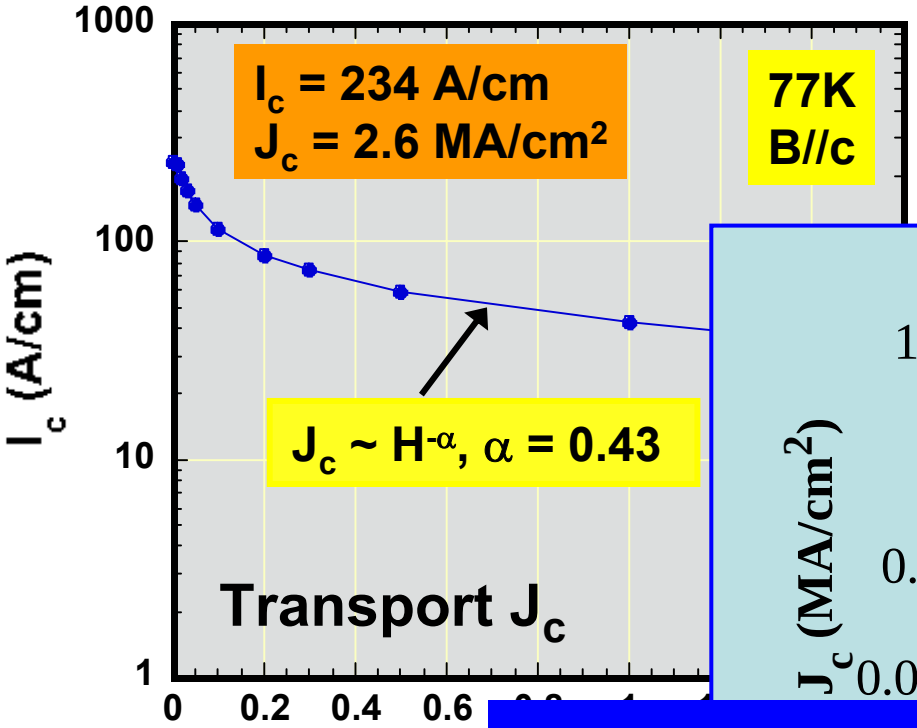


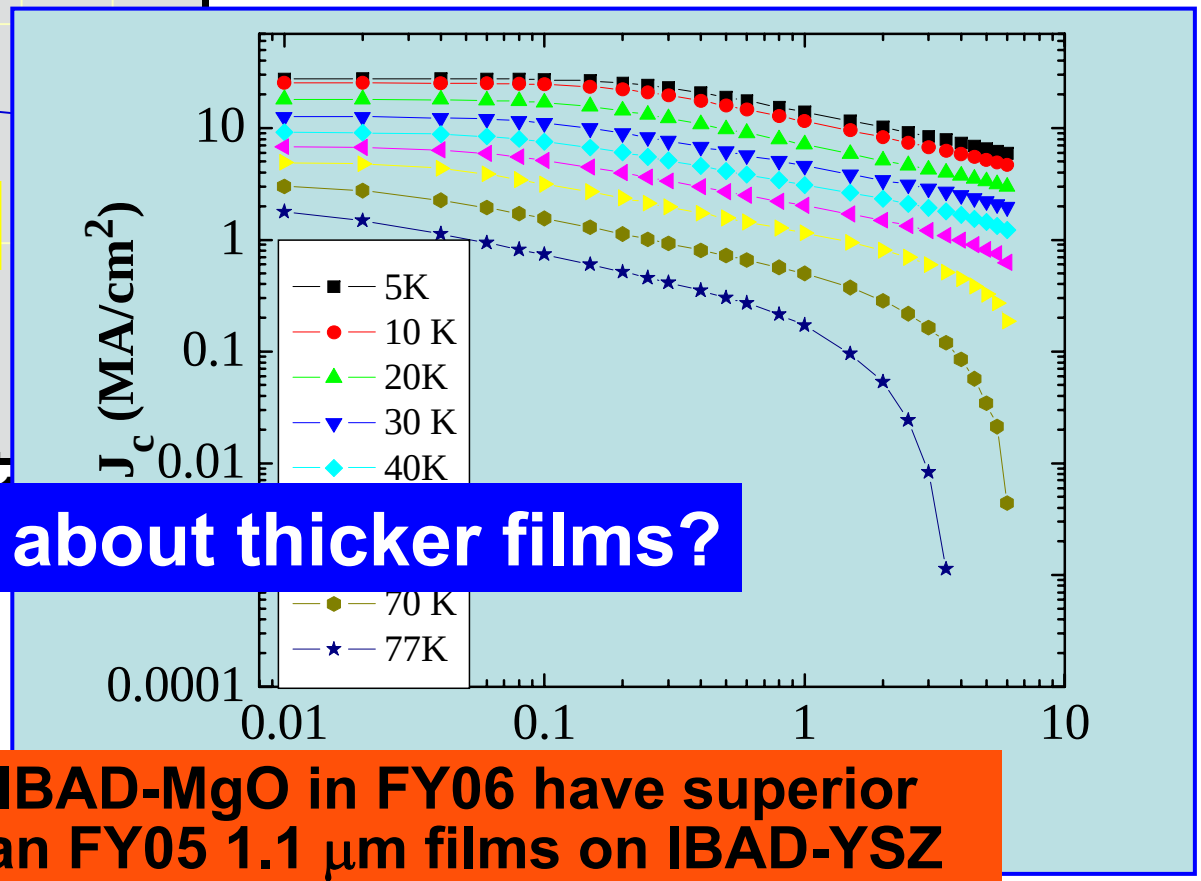


No J_c-limiting microstructural features except small amount of a-axis grains.

Should possess high J_c .

J_c of SuperPower's FY06 standard long length R-R MOCVD/IBAD-MgO are better than FY05.





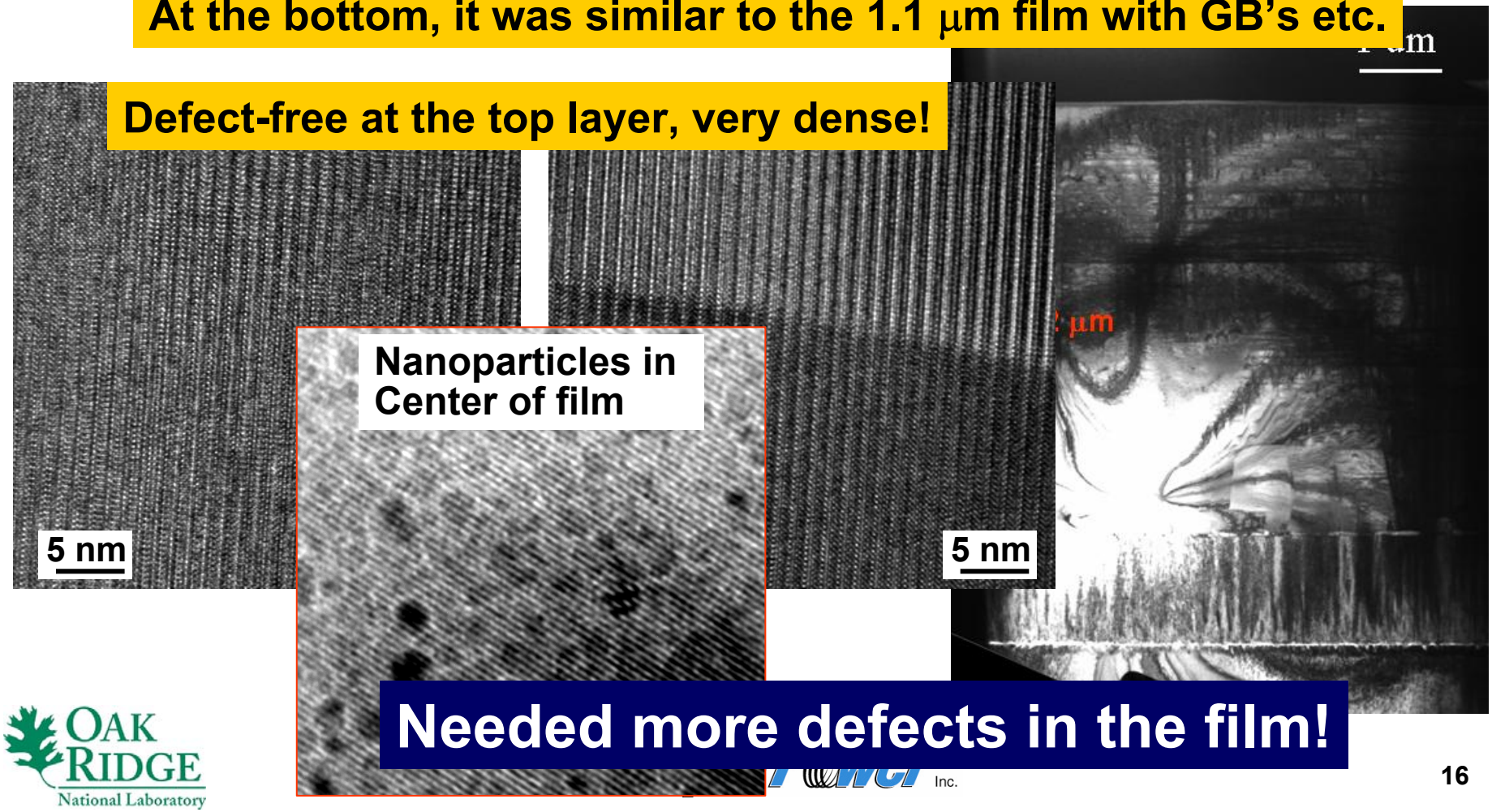
What about thicker films?

0.9 μm films on IBAD-MgO in FY06 have superior performance than FY05 1.1 μm films on IBAD-YSZ
→ Consistent with defect structures observed.

FY 2005: 5.2 μm thick MOCVD film on IBAD-YSZ has excellent texture through the cross-section.

REBCO: $\Delta\omega$ = 3.21° FWHM $\Delta\phi$ = 4.01° FWHM
I_c = 407 A/cm J_c = 0.8 MA/cm^2

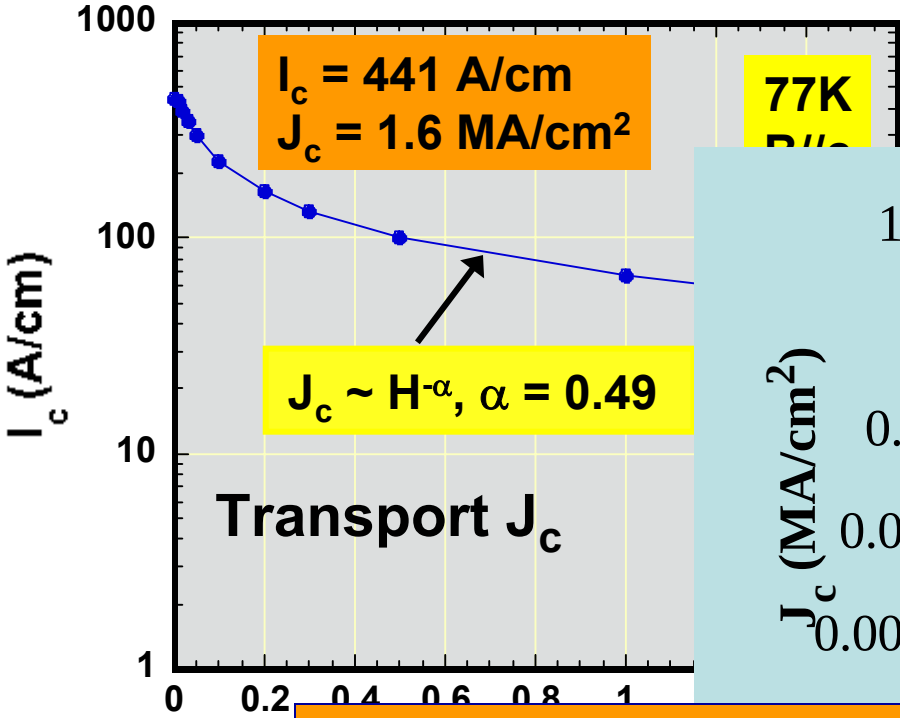
At the bottom, it was similar to the 1.1 μm film with GB's etc.



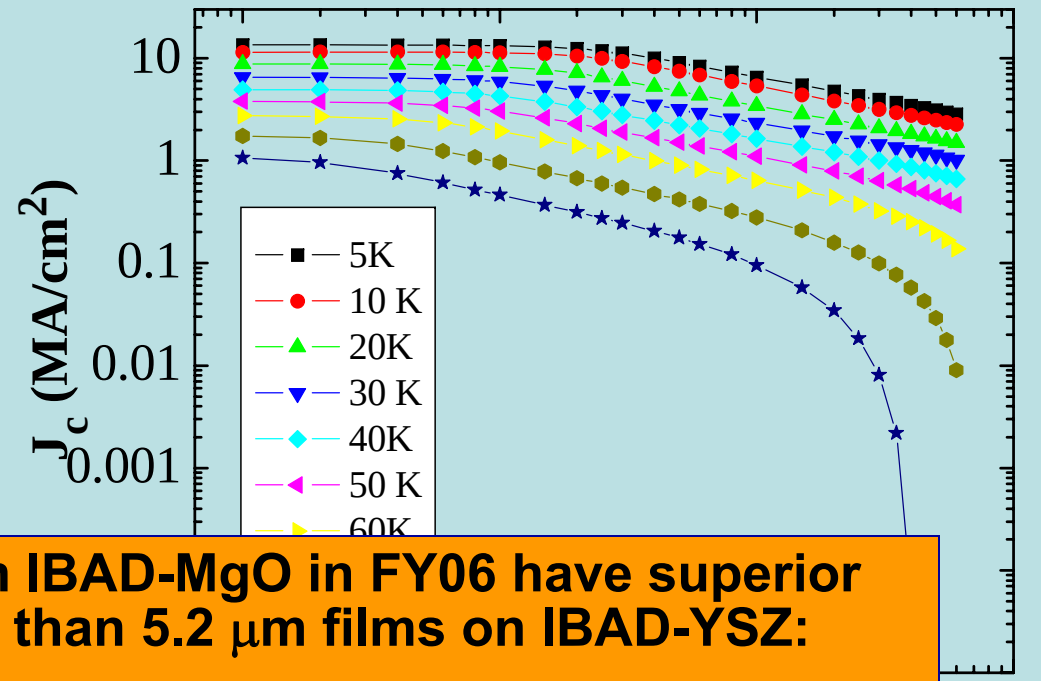
Needed more defects in the film!

FY 2006: 2.8 μm REBCO MOCVD film on IBAD-MgO has higher J_c than last year's 5.2 μm film.

REBCO: > 96% cube, $\Delta\omega$ = 1.22° FWHM, $\Delta\phi$ = 3.82° FWHM



Magnetization J_c



2.8 μm films on IBAD-MgO in FY06 have superior performance than 5.2 μm films on IBAD-YSZ:

→ 441 A/cm-w vs. 407 A/cm-w.
Higher I_c, Half the thickness!

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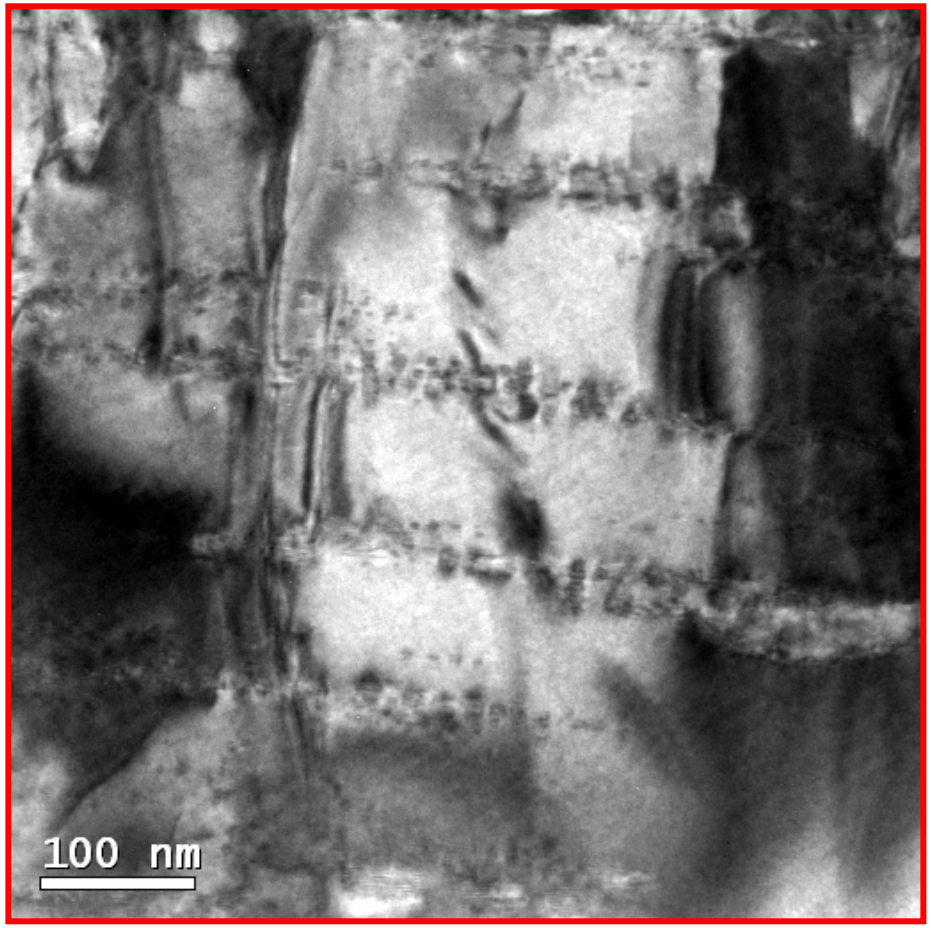
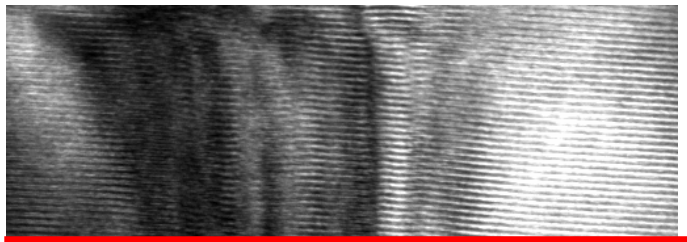
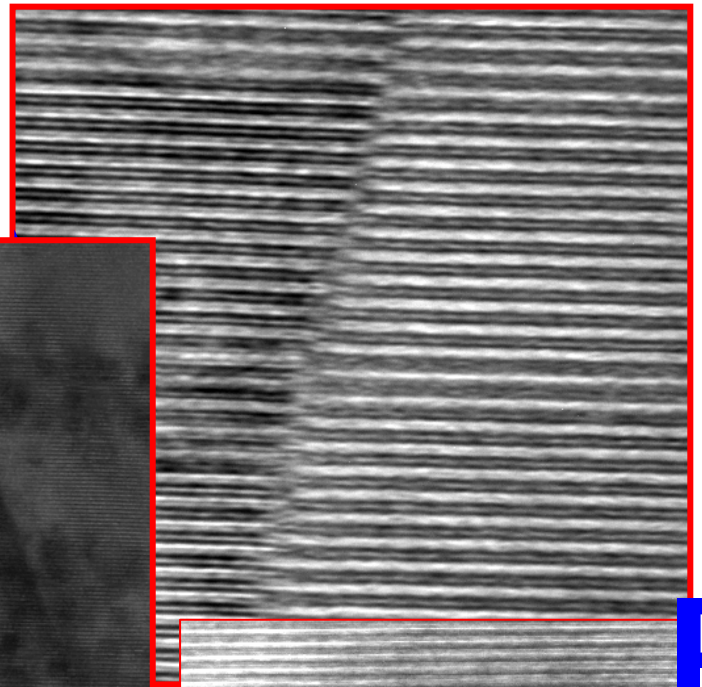
What are the microstructural features of "2.8 μm" SuperPower films in 2006?

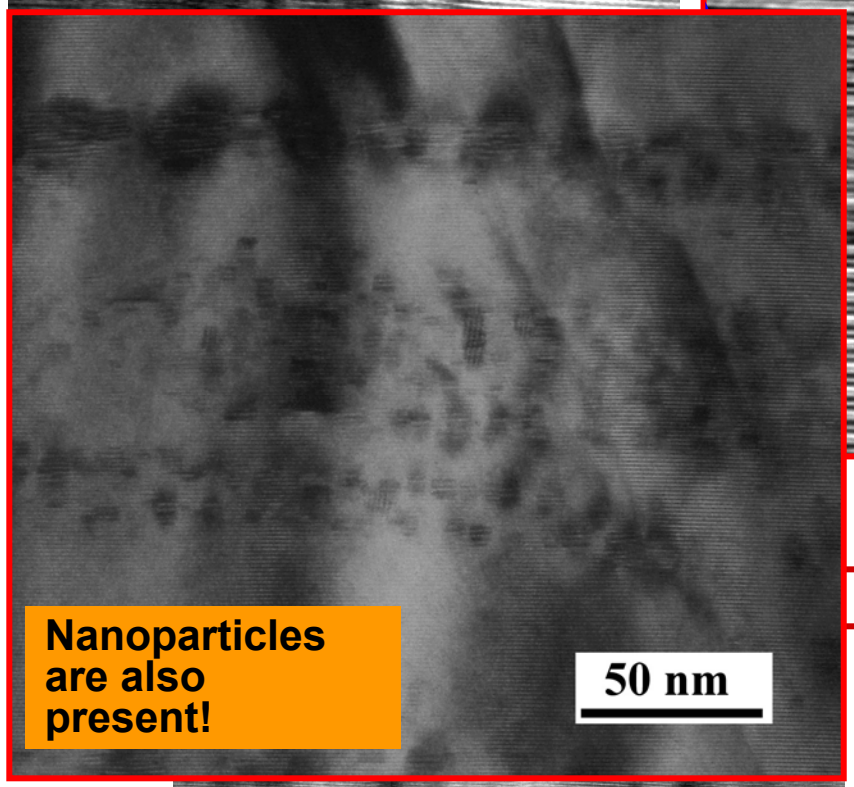
Both vertical and horizontal defects observed <u>throughout entire thickness</u>



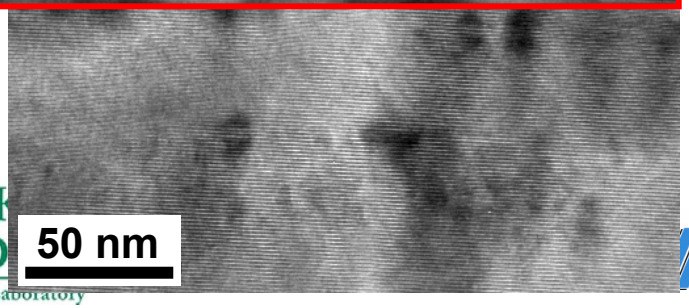
Same types of defects as thinner films.

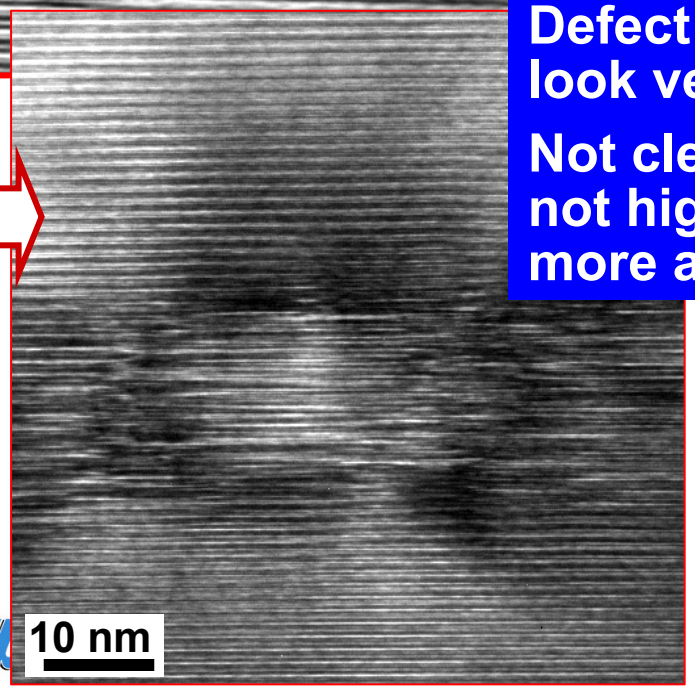






Nanoparticles are also present!





Vertical defects are bundles of anti-phase boundaries.

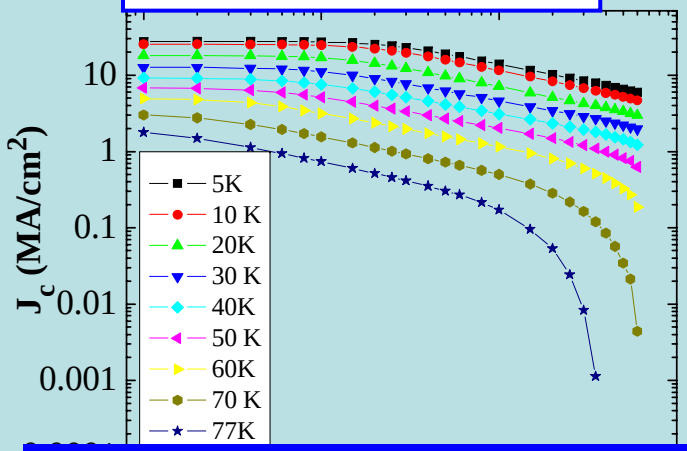
Horizontal defects are localized bundles of stacking faults.

Defect structures look very good!

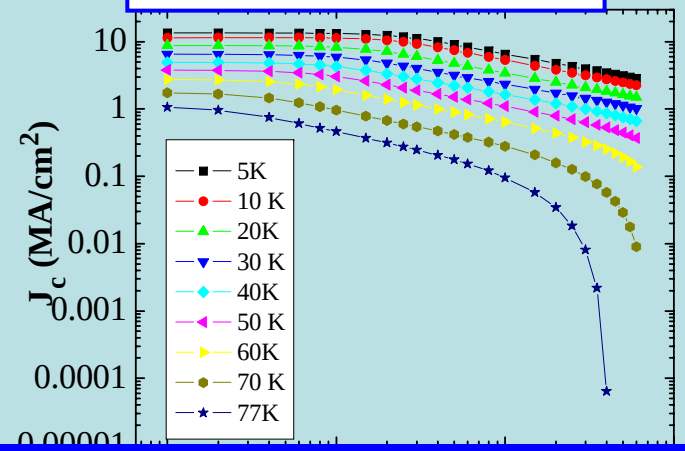
Not clear why J_c is not higher – need more analysis.

Magnetization data at lower temperatures & higher fields shows that pinning is strong at all (H, T).

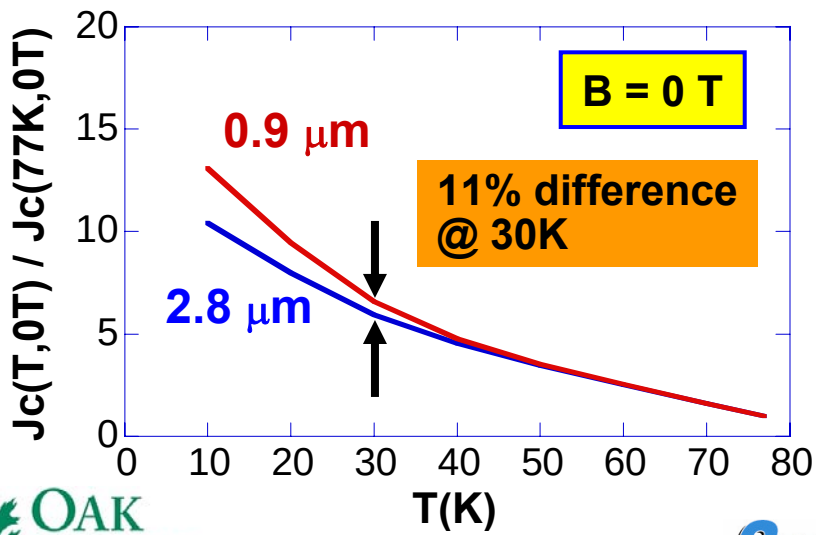
0.9 μm: 2.6 MA/cm²

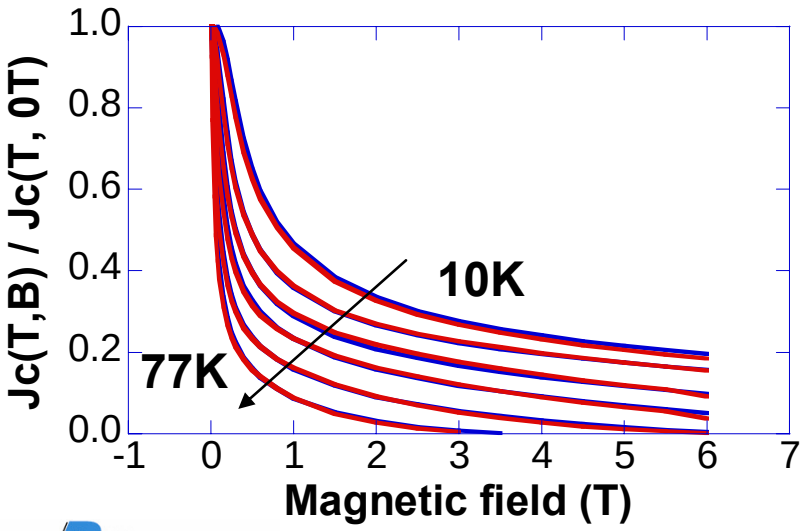


2.8 μm: 1.6 MA/cm²



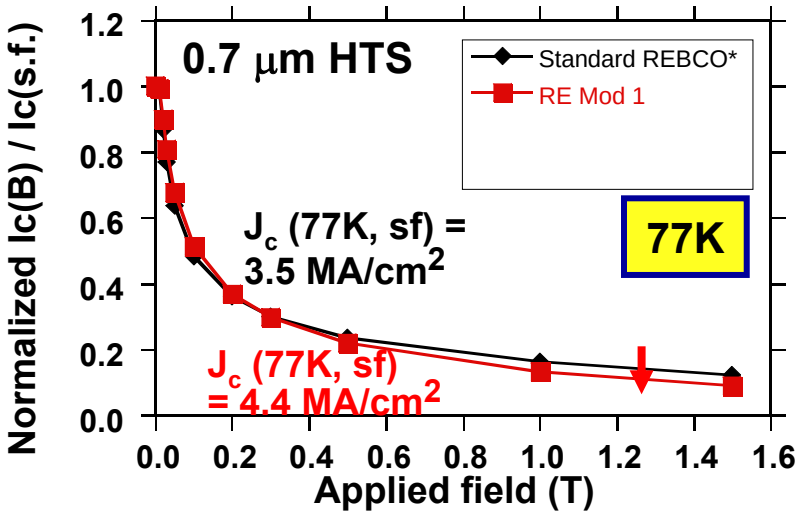
Same Precursor → Same Processing → Same Pinning

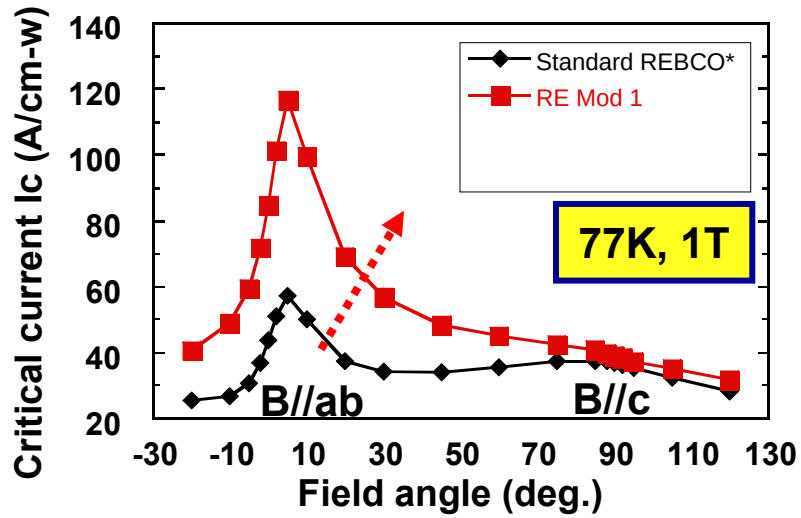


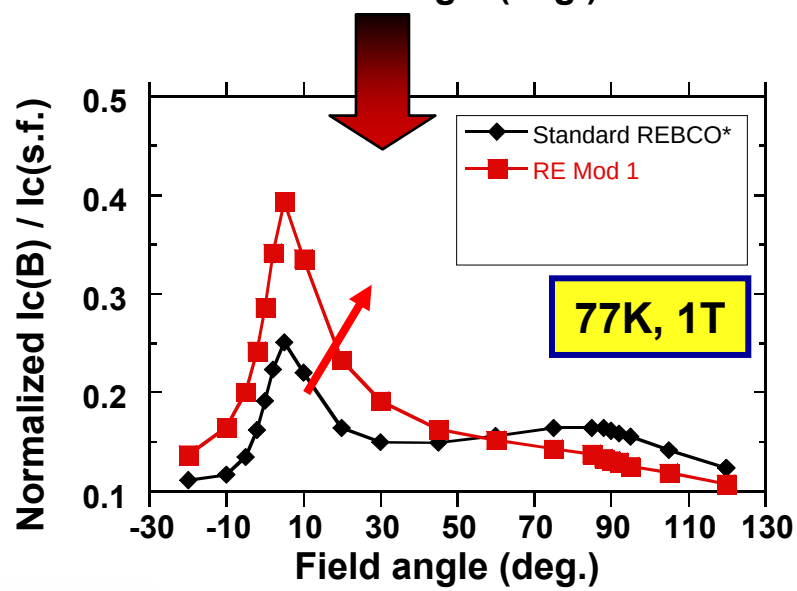


Experiments underway to introduce more pinning centers!

Rare-earth Modification 1 …



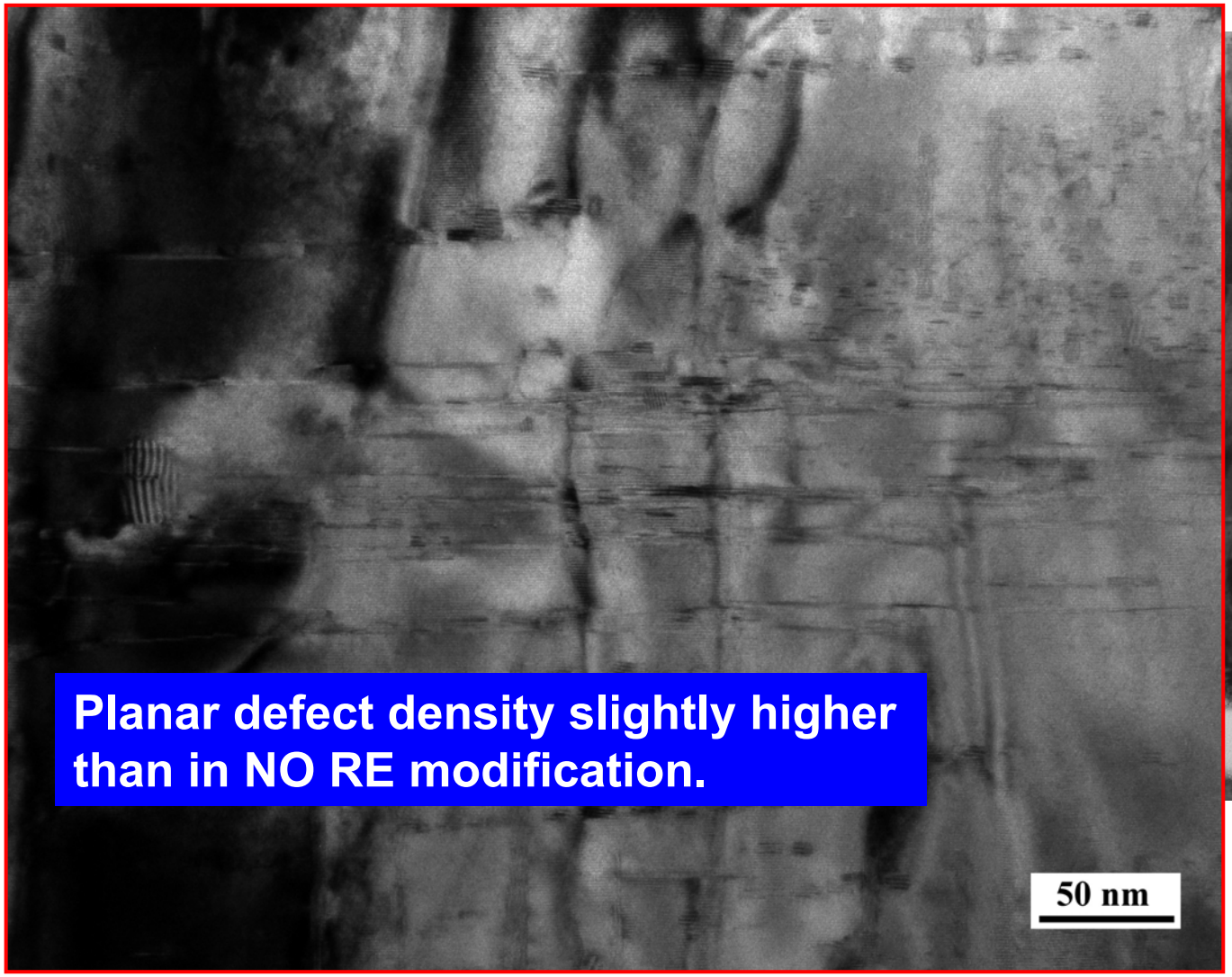




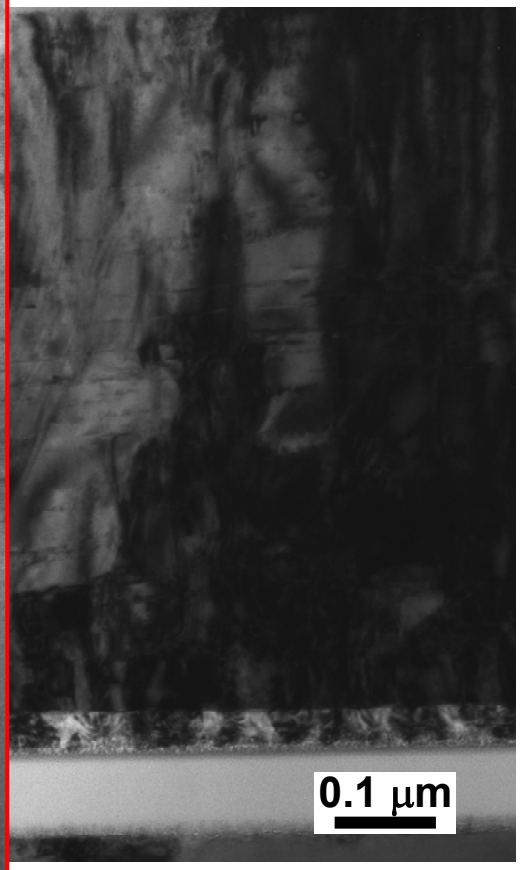
Resulted in at 77K:

- **Substantial increase in I_c(B//a-b).**
- **Improvement in I_c(0°-60°),**
- **Slight decrease in I_c(B//c).**

RE Modification 1 sample also has high densities of both a-axis & c-axis correlated defects.

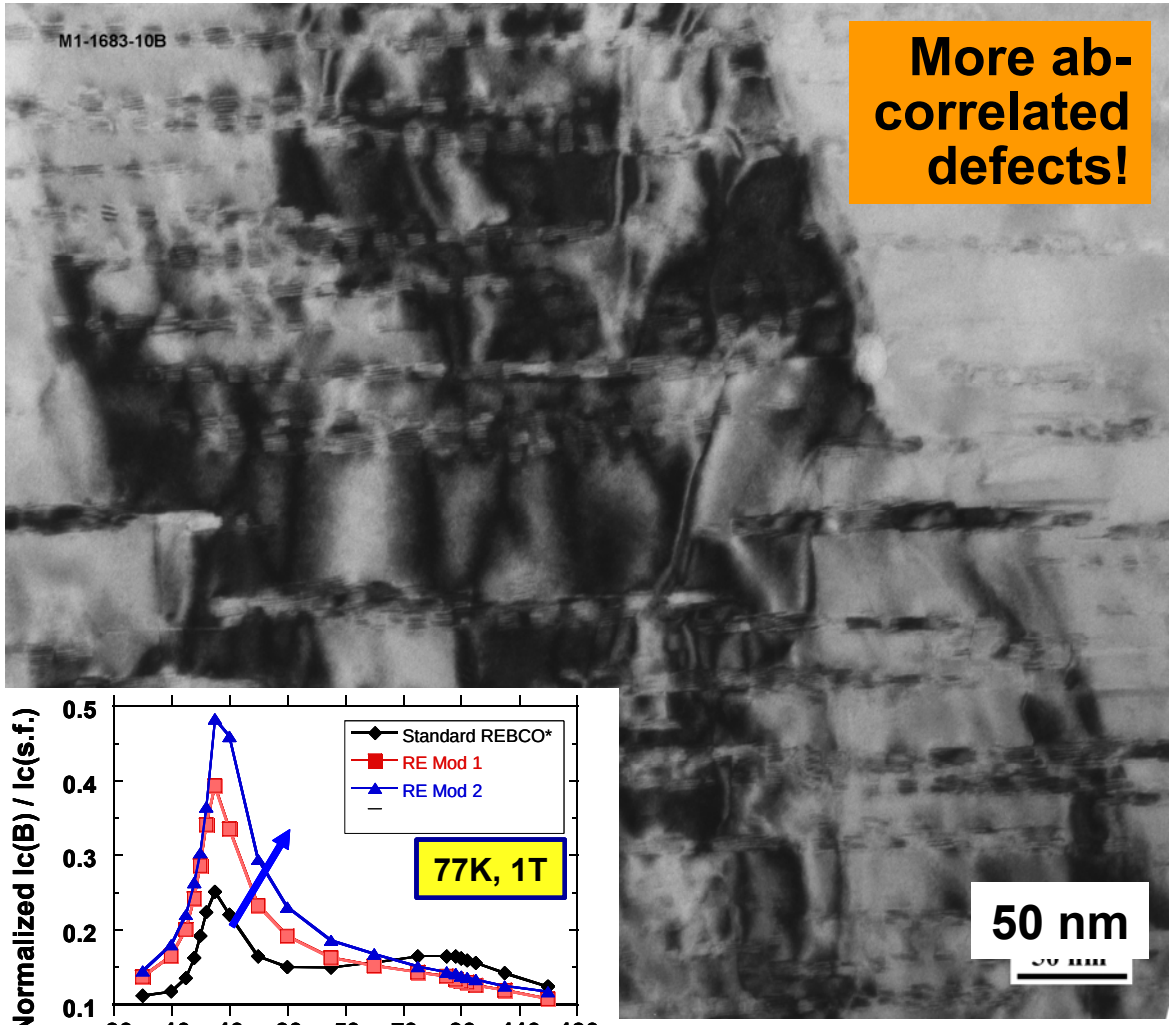


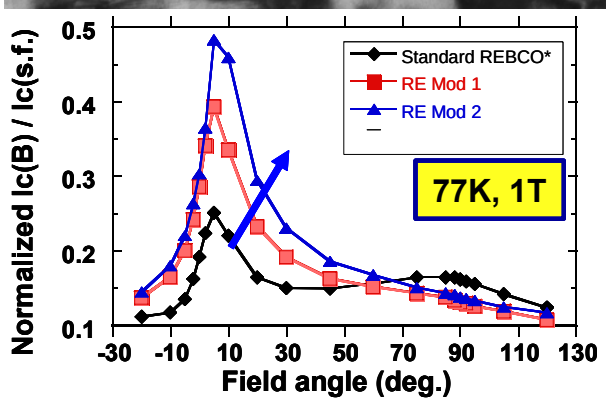
Planar defect density slightly higher than in NO RE modification.



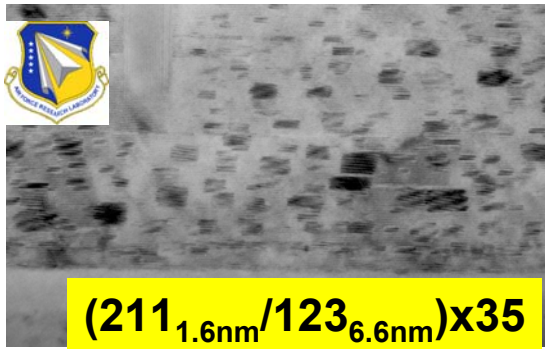
Other RE modifications have also been performed.

Rare-earth Modification 2 …

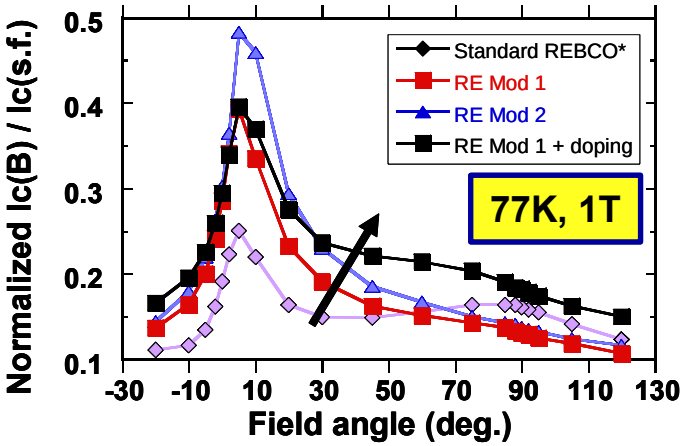




Reminiscent of micro-structure found for 211 Island growth in 123/211 multi-layered composites by ARL:



Efforts in doping to enhance J_c(H//c) also underway: (Mod 1 + doping)



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SuperPower transferred research MOCVD-REBCO capability to ORNL.

- **SuperPower and ORNL have decided that more exploratory work on precursor modifications should be included in the CRADA.**
- **To be as effective and efficient as possible, processing at ORNL should closely resemble the SuperPower operation.**

- **(*New FY 2006 Plan Added*): Establish "SuperPower" MOCVD-REBCO capability at ORNL.**

Tech transfer from Industry to Lab based on Collaboration, Integration and Trust developed in the CRADA!

- **ORNL scientist visited SuperPower for planning & training activities.**
- **Research MOCVD system revitalized & tested.**
- **J_c = 2.5 MA/cm^2 obtained.**

- **SuperPower research MOCVD system transferred & installed at ORNL**

Oak Ridge National Laboratory

SuperPower Inc.

Presentation Outline

- **FY 2006 Results**
  - Development of simplified buffer layer strategies (Dominic)
  - Microstructure-property correlations of MOCVD REBCO films on IBAD-MgO
  - MOCVD technology transition
  - **AC loss** (Robert)
  - **Quench and Stability**
  - **Dielectrics**
  - **Integration of LMO technology with IBAD-MgO MOCVD conductors** (Selva)
- **FY 2006 Performance & FY 2007 Plans** (Selva)
- **Research Integration**

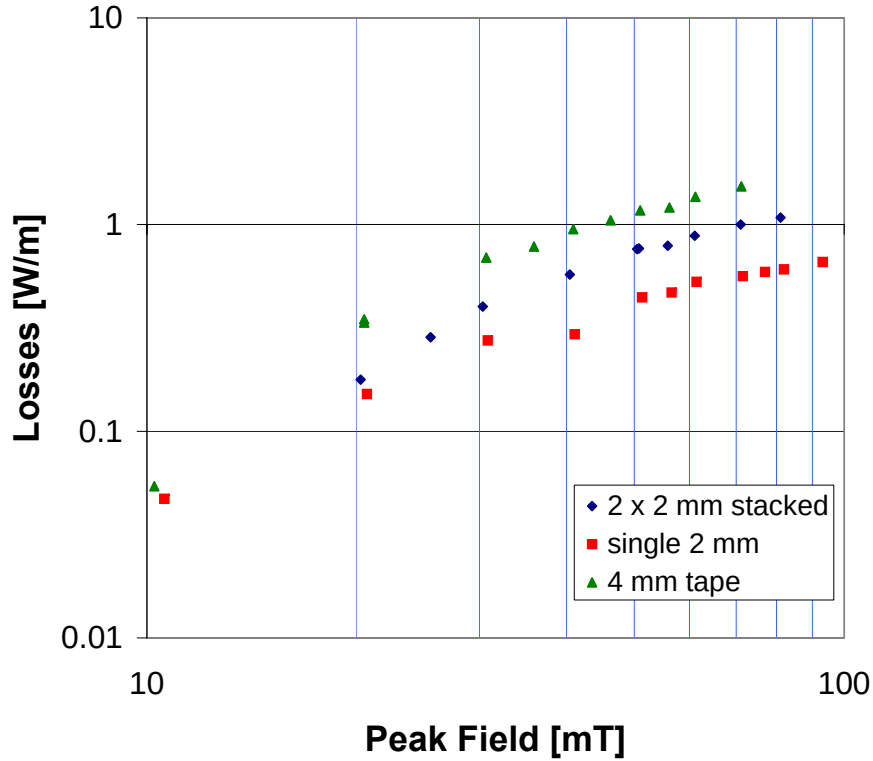
In addition to the materials effort, fundamental characterization of the conductor was carried out

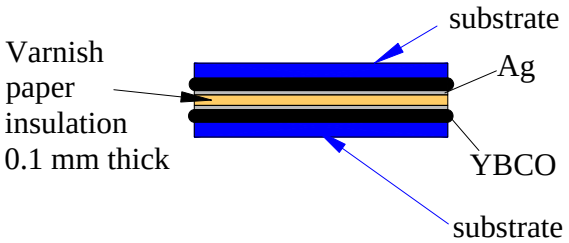
- **AC loss**
  - **Basic properties of ac losses as a function of width**
  - **Exploration of alternative assembled conductor geometries**
- **Quench and Stability**
  - **Determine how amount of copper stabilization affects:**
    - » **Thermal runaway (I = constant)**
    - » **Ultimate limits ($I > I_c$)**
    - » **Normal zone propagation**
- **Dielectrics**
  - **How conductor stabilization (surround stabilizer) effects high voltage properties**

FY2006 Plan: Evaluate ac loss in stacks of narrow width coated conductors.

Stacks of narrow width conductors show reduced ac loss in perpendicular field.

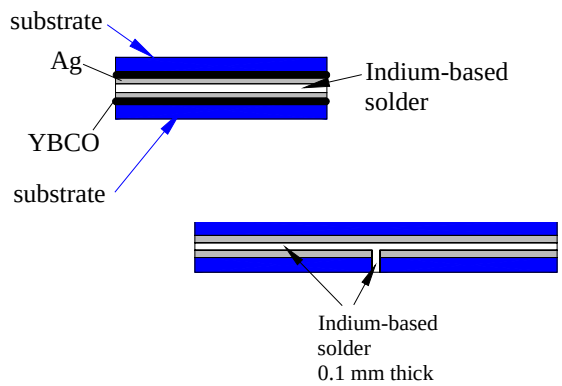
- Motivation – Explore alternative methods to reduce ac loss not associated with filamentization
- YBCO tape specifications provided by Superpower
  - 2 mm and 4 mm wide
  - I_c (2 mm, 77 K) = 30 A
  - I_c (4 mm, 77 K) = 60 A
  - No Cu-surround stabilizer
- Stack of two 2-mm wide conductor has lower losses than a 4-mm wide conductor with similar critical current density
- Drop in ac losses almost matches drop in engineering current density



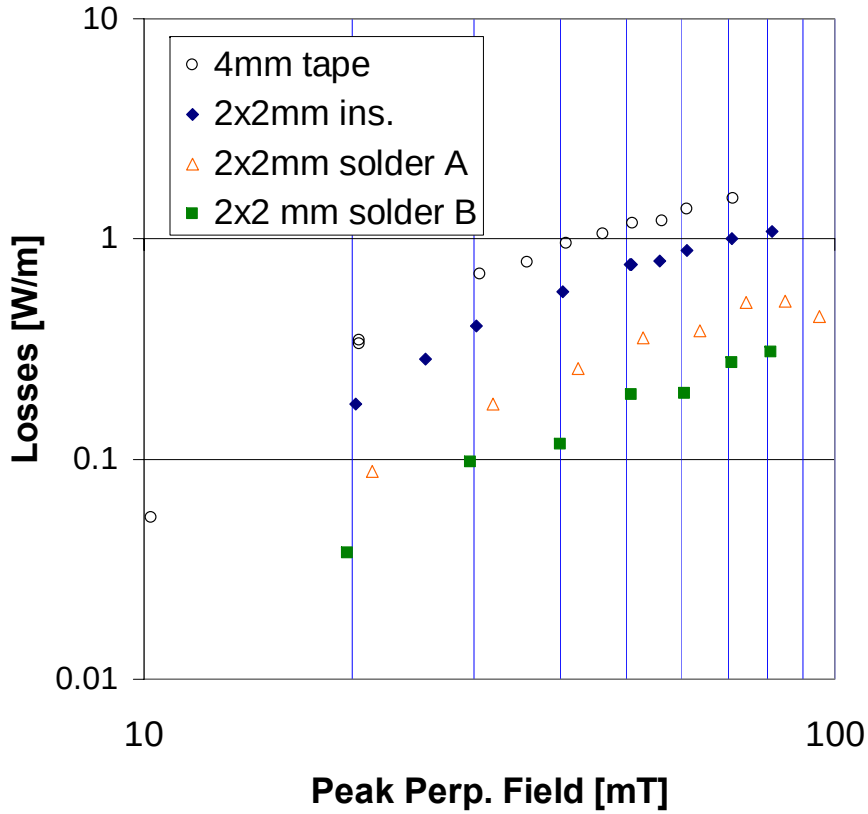


AC loss in 2 mm spliced tapes reduce losses further

- In a stack of two, 2-mm wide tapes, one tape was cut in two and the tapes were soldered to create low resistance joint
- Samples examined with different indium-based solders



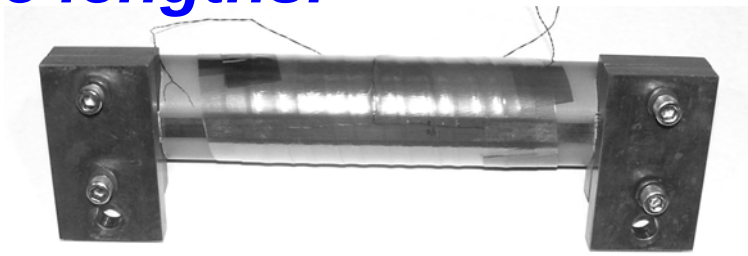
- Drop in ac losses in applied perpendicular field outpaced drop in engineering current density



FY 2006 Plan: Understand the role of Cu surround-stabilization in operational stability.

Short length stability study examines different issues with limited sample lengths.

- Copper stabilization thickness
  - Stability improve with thicker coatings
  - J_e as thickness increases
  - Eddy current losses become an issue
- Current waveform
  - Constant
  - Impulse



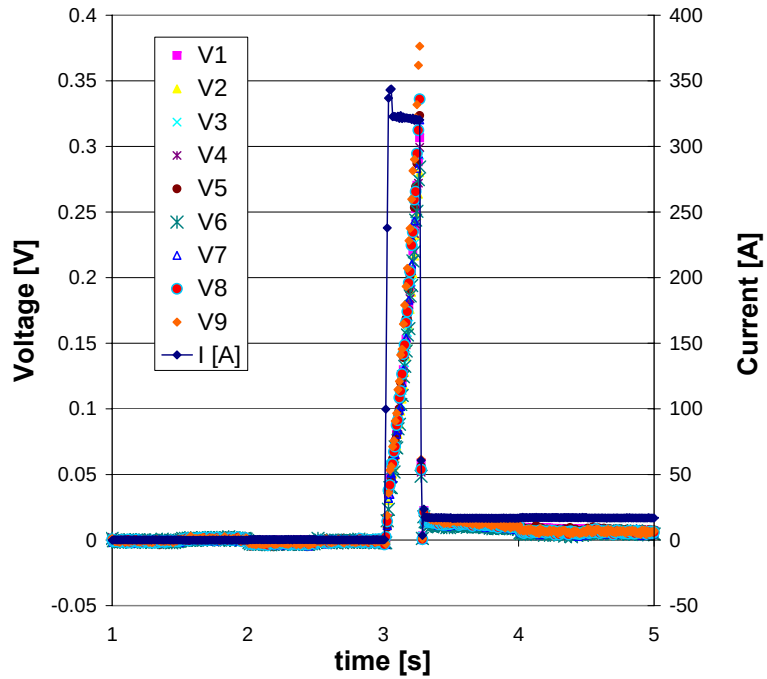
Insulated 77 K bath

Sample specifications

- 4-mm wide SuperPower YBCO tapes
- Copper surround stabilizer of 0, 20 μm , and 38 μm (0, 40 μm, and 76 μm total)
- Tape lengths: 30 cm and 1 m
- Voltage taps evenly spaced along length to watch normal zone formation and recovery

Impulse limit directly tied to Cu surround stabilizer thickness

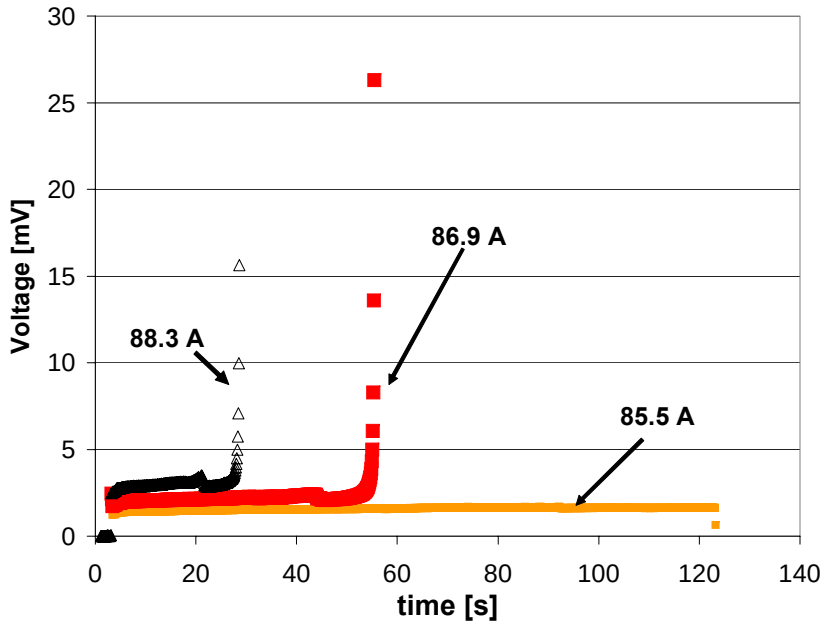
- Impact on Cu surround stabilizer on ultimate limits of YBCO tape
  - Two-stage waveform, first 0.25 s at $I>I_c$ followed by $I < I_c$ for 30 s to 60 s



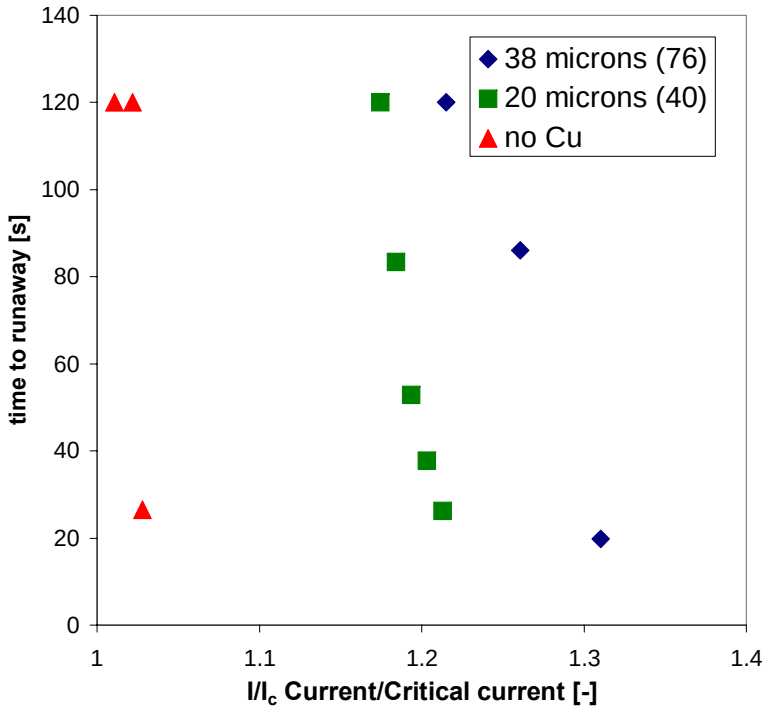
Cu surround thickness [μm]	I_c [A]	I_{pulse} [A]	I_{pulse}/I_c [-]	R/l (300 K) [Ω/m]	$C = (R/l) *(I_{pulse}/I_c)$
0	64	76.7	1.20	0.61	0.70
20	72	262.3	3.64	0.094	0.34
38	68	432	6.35	0.055	0.35

Addition of Cu surround stabilizer increases thermal runaway currents by at least 20%

- Runaway more dominated by thermal properties than sample resistance

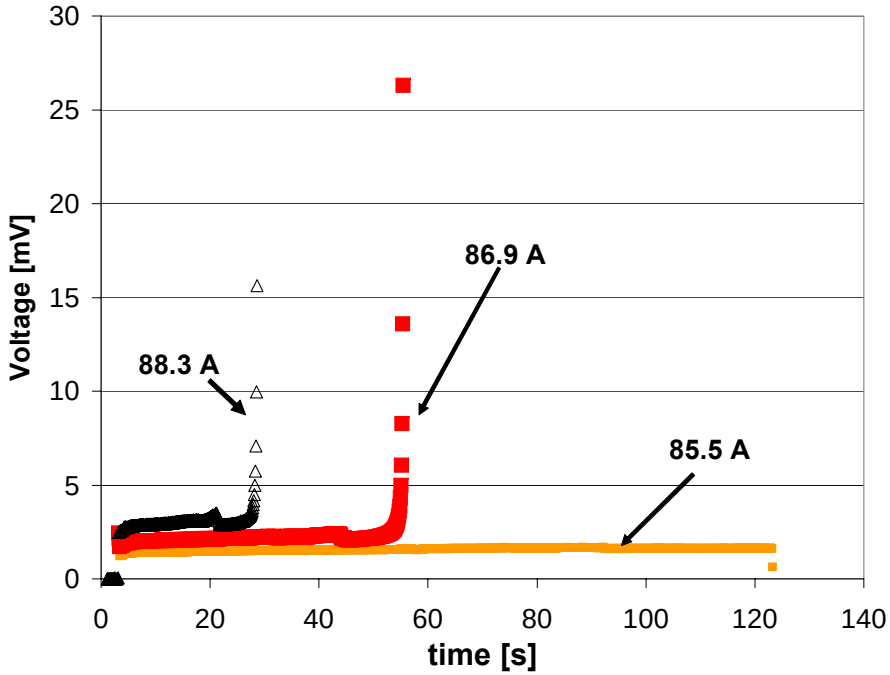


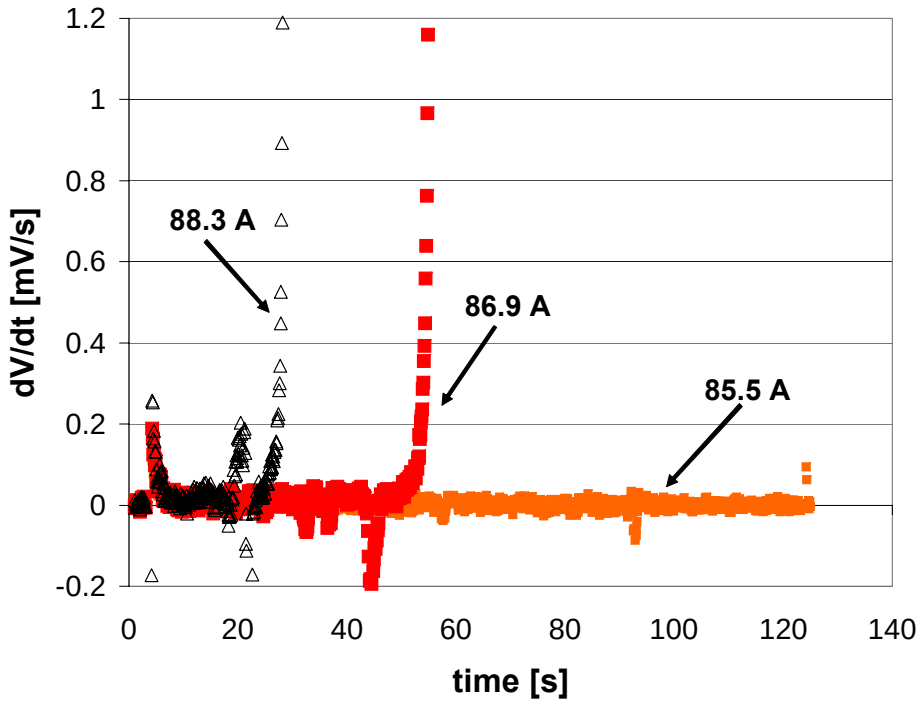
Example of thermal runaway in 20 μm of Cu surround stabilizer



Thermal runaway current at different surround copper thicknesses

Transition from stability to thermal runaway is extremely rapid even at 77 K



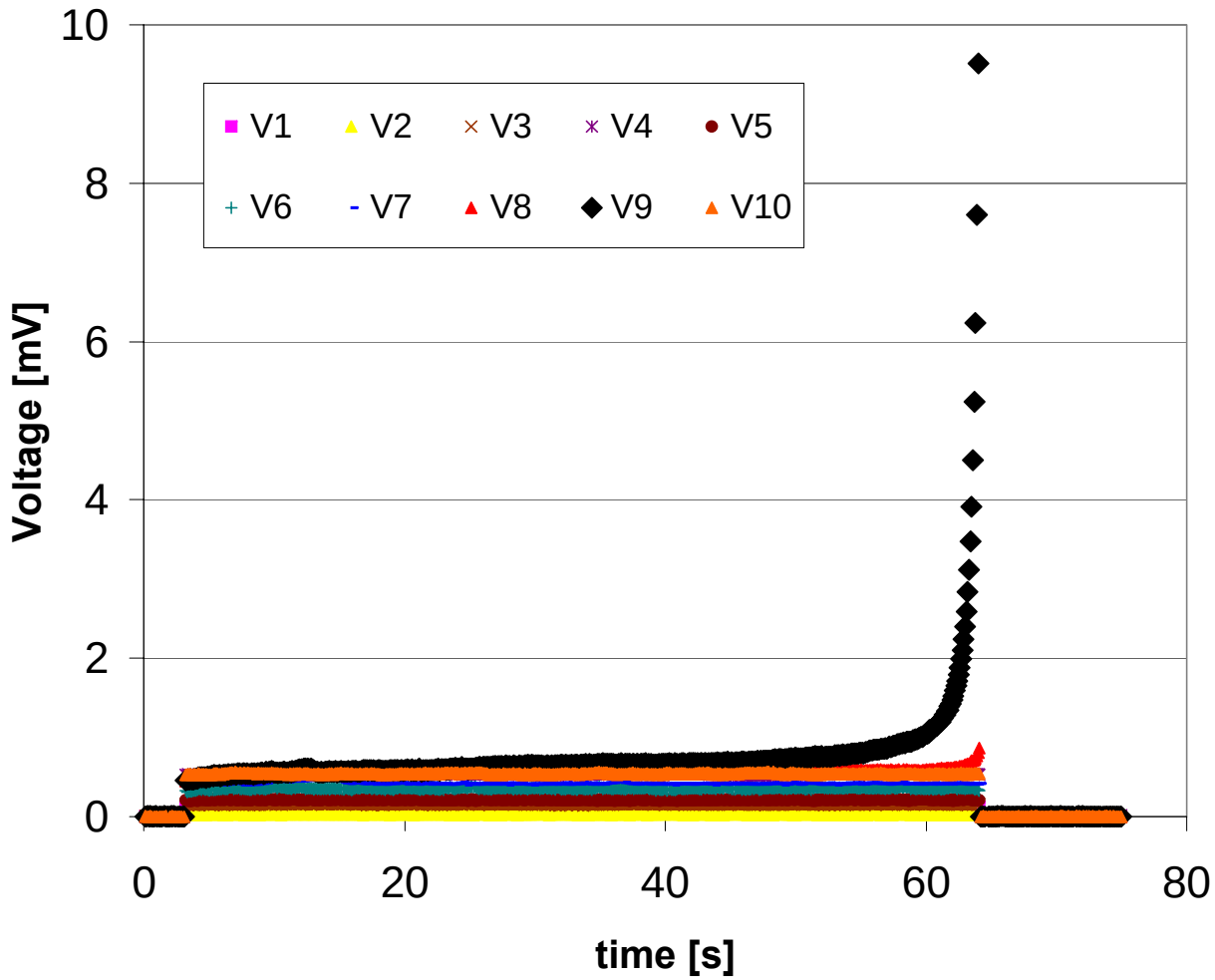


End-to-end voltages associated with thermal runaway at different currents for sample with 20 μm of Cu surround stabilizer

With the rate of voltage increasing of 0.1 mV/s to 1.0 mV/s in less than 1 second, detection of normal zone could be difficult in noisy environment

This thermal runaway is extremely localized

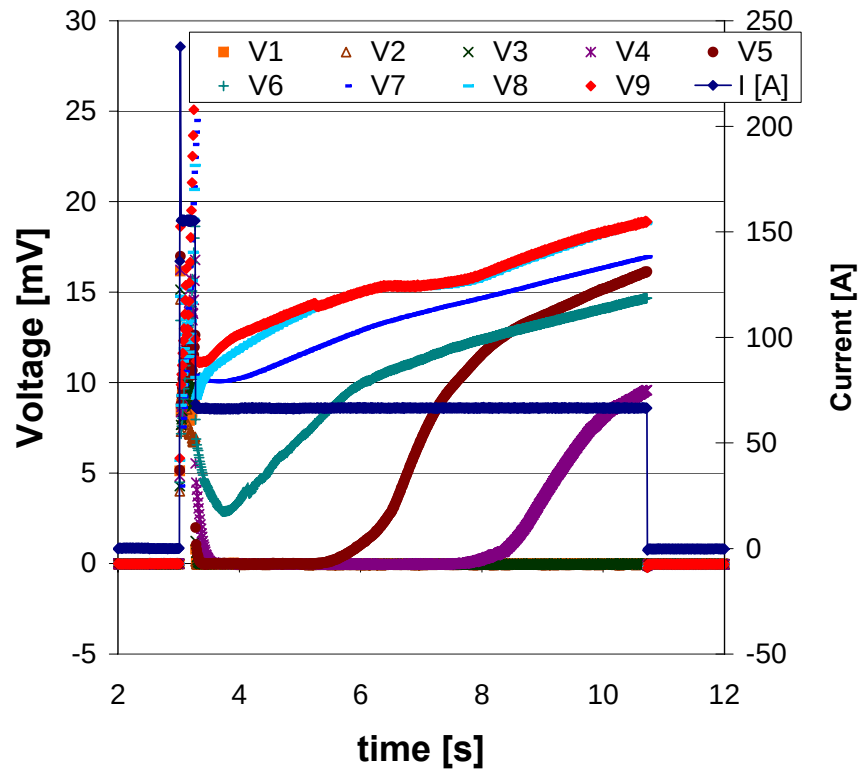
- Thermal runaway shown in 38 μm Cu-surround stabilizer
- With each voltage tap 1.5 cm apart, only 30% of length exhibits runaway
- For both 20 μm and 38 μm cases, uniformity of critical current over length extremely important



Normal zone propagation speeds less than 1 cm/s observed for 38 µm case

- Manipulation of the pulse current and the operating current that follows can produce propagation
- Non-uniformity of critical current over 2 cm had to be greater than 10% to localize heating in sample
- Operating current more of factor in propagation speeds than impulse current

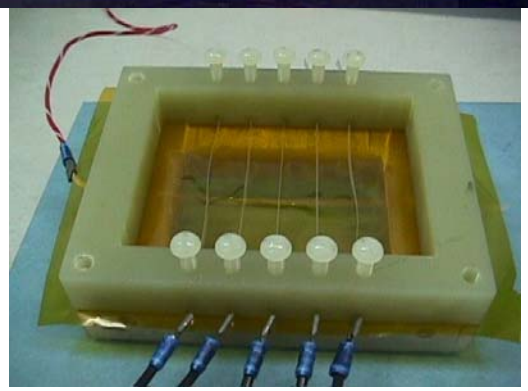
I_{pulse} [A]	I_{pulse}/I_c [-]	I_{op} [A]	I_{op}/I_c [-]	Propagation speed [cm/s]
155.2	2.28	66.6	0.98	0.58
157.1	2.30	66.6	0.98	0.70
165.0	2.43	59.8	0.87	0.46
165.0	2.43	56.4	0.82	0.27
165.0	2.43	53.2	0.78	0.19



FY 2006: Determine if improvement in HV performance translates to practical geometries.

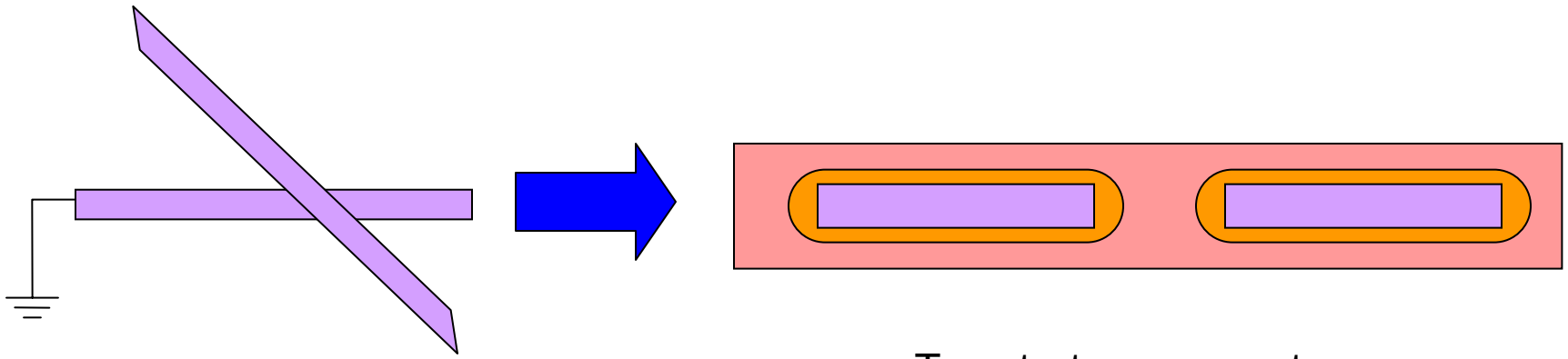
Copper stabilization can influence fundamental high voltage behavior.

- A pair of samples with and without Cu surround stabilization were placed in a cross configuration separated by a 25 μm thick piece of kapton
- After sample was placed in a room temperature oil bath, ac voltage was applied until discharge observed



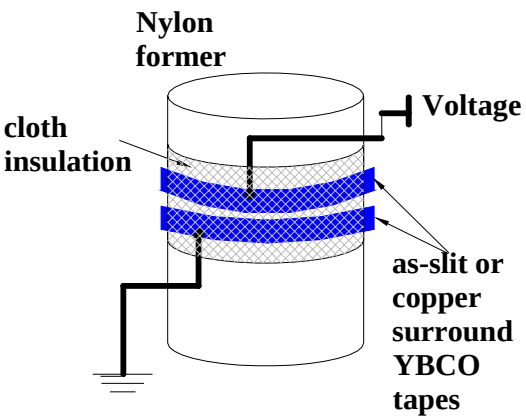
Sample	As-slit YBCO	Cu surround stabilized YBCO
Avg. Breakdown voltage	**6.1 kV +/- 2.2 kV**	**6.7 +/- 0.2 kV**
10% probability breakdown	**2.1 kV**	**6.5 kV**

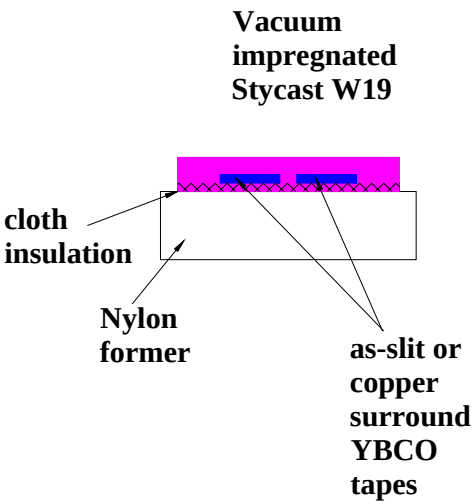
Can the effects of Cu-surround stabilizer be carried into application geometries?

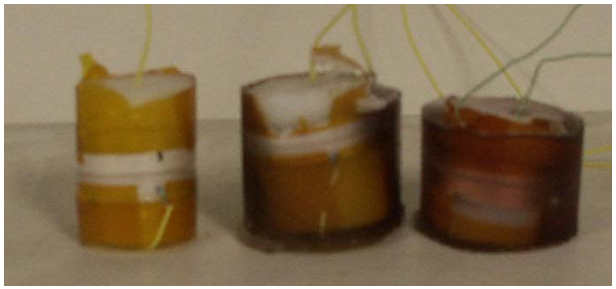


Fundamental geometry

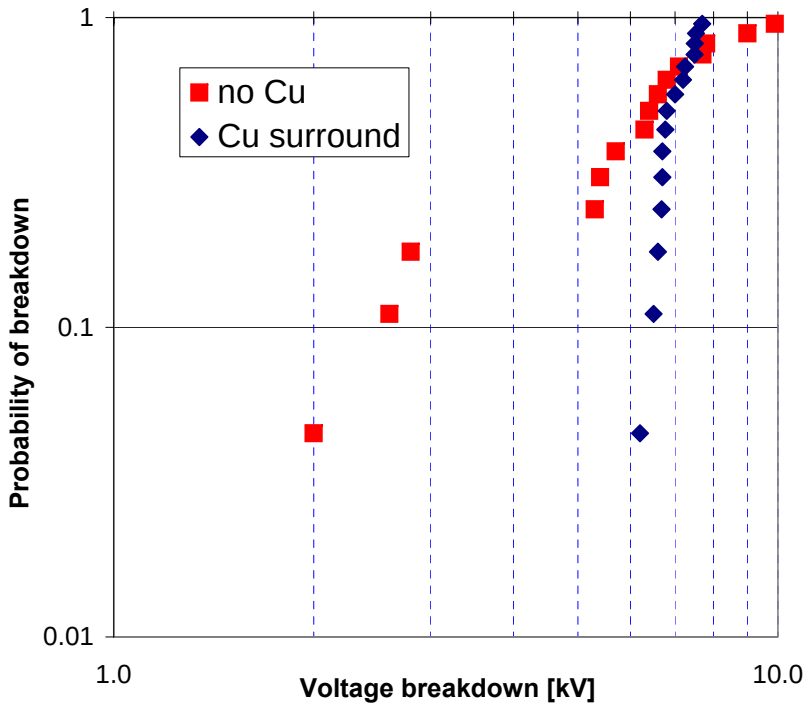
Turn-to-turn geometry



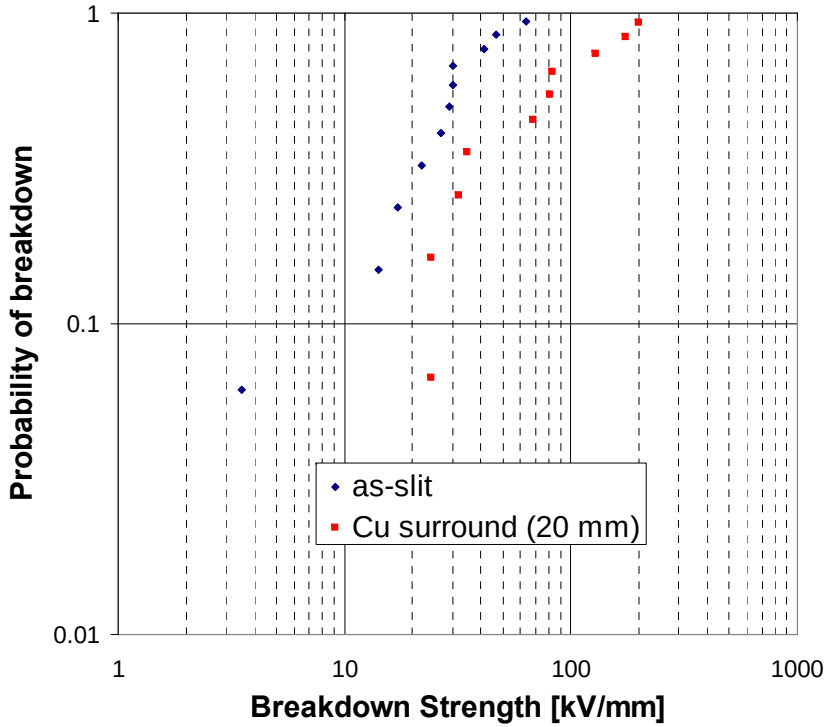




Surround Cu stabilizer increases the breakdown voltage for turn-to-turn testing



Cross configuration breakdown profile



Turn-to-turn breakdown profile

- **Cu surround stabilizer still has a better breakdown profile when compared to as-slit conductor**
- **Additional factors with respect to epoxy uniformity could be difference**

Presentation Outline

- **FY 2006 Results**
  - Development of simplified buffer layer strategies (Dominic)
  - Microstructure-property correlations of MOCVD REBCO films on IBAD-MgO
  - MOCVD technology transition
  - AC loss (Robert)
  - Quench and Stability
  - Dielectrics
  - **Integration of LMO technology with IBAD-MgO MOCVD conductors (Selva)**
- **FY 2006 Performance & FY 2007 Plans (Selva)**
- **Research Integration**

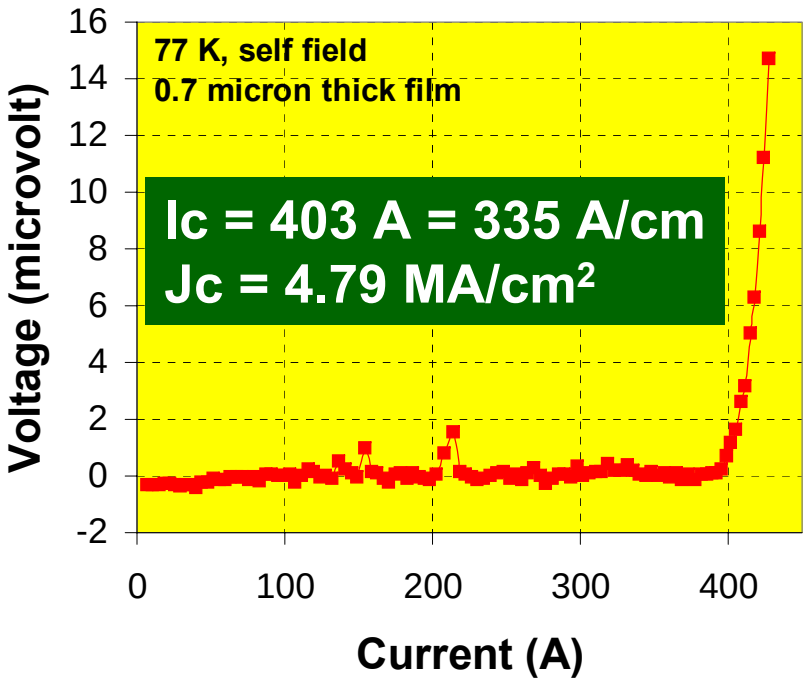
FY 2005: ORNL developed LMO technology on SuperPower IBAD-MgO templates.

LMO is an excellent alternative to STO especially in combination with reactively sputtered MgO and MOCVD REBCO

Advantages of LMO:

- **Higher deposition rate even with *rf*-sputtering.**
- **Wider processing window than STO.**
- **LMO layers can be thin (only 25 nm).**
- **Availability of La-Mn alloy targets for reactive sputtering, whereas Sr-Ti alloys are not available.**
- **Higher I_c performance than STO.**

REBCO/LMO/*homo*-epi MgO/IBAD MgO



Close collaboration with ORNL has enabled SuperPower to significantly improve IBAD MgO-MOCVD based conductors in an expedited manner.

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SuperPower Inc.

FY06 Plan: Assist SuperPower to transfer LMO technology from short to pilot-scale production

- ✓ **In FY 2006, SuperPower has completed the transition from IBAD-YSZ to high throughput IBAD MgO.**
- ✓ **LMO buffer has been integrated into SuperPower's conductor manufacturing operation.**
- ✓ **Optimization of LMO sputtering conditions has led to substantial increase in buffer deposition linear speed:**

FY 2005: 10 m/h → FY2006: up to 80 m/h ; routinely 40 m/h

- ✓ **The ability to deposit LMO rapidly will enable the sequential deposition of 2 buffer layers on IBAD MgO.**

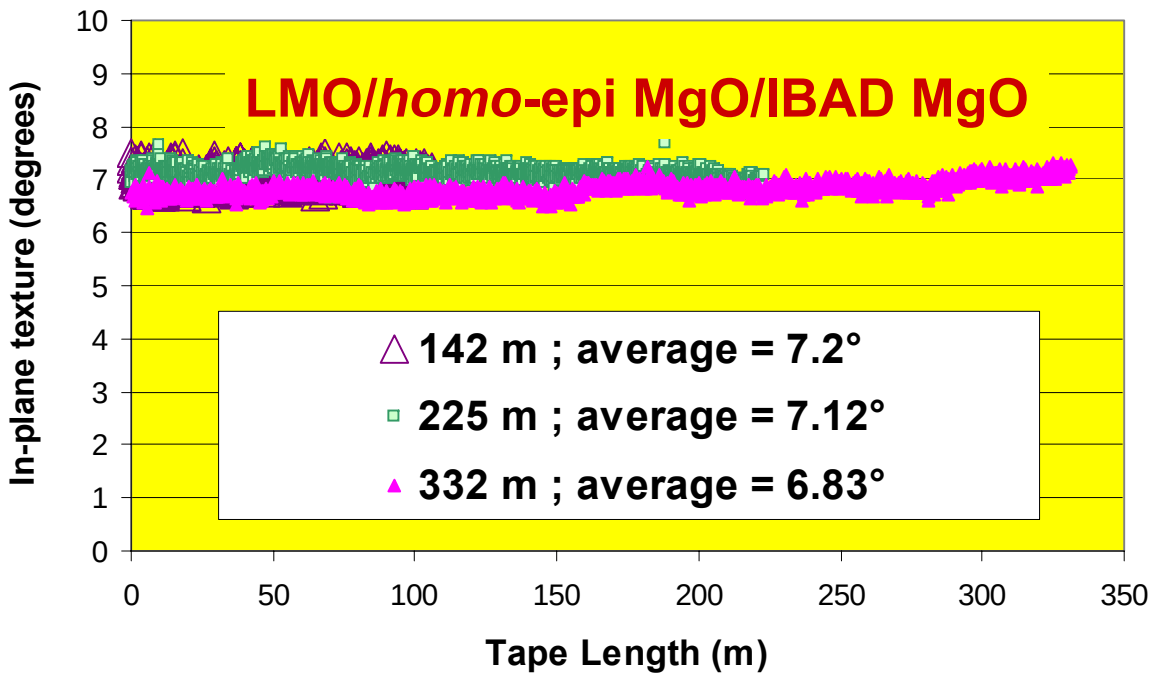
Expected tape speed for sputtering of both layers simultaneously = 160 m/h of 12 mm wide tape i.e. 480 m/h of 4 mm wide tape.

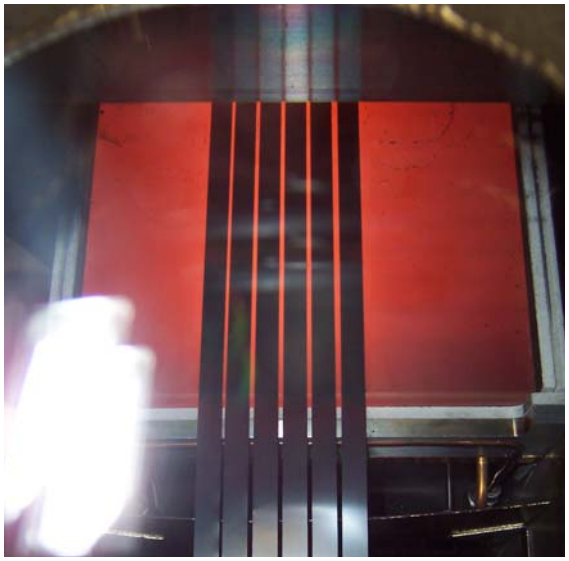
Oak Ridge National Laboratory

SuperPower Inc.

Highly uniform IBAD-MgO/LMO substrates have been produced in long lengths.

300+ m long *LMO/homo-epi MgO/IBAD-MgO* tape produced in Pilot buffer system at linear speed of 40 m/h was determined to be very uniform.





SuperPower helix tape system

Close collaboration with ORNL in fundamental materials understanding expedited SuperPower efforts to scale up of LMO for IBAD MgO-MOCVD based conductors

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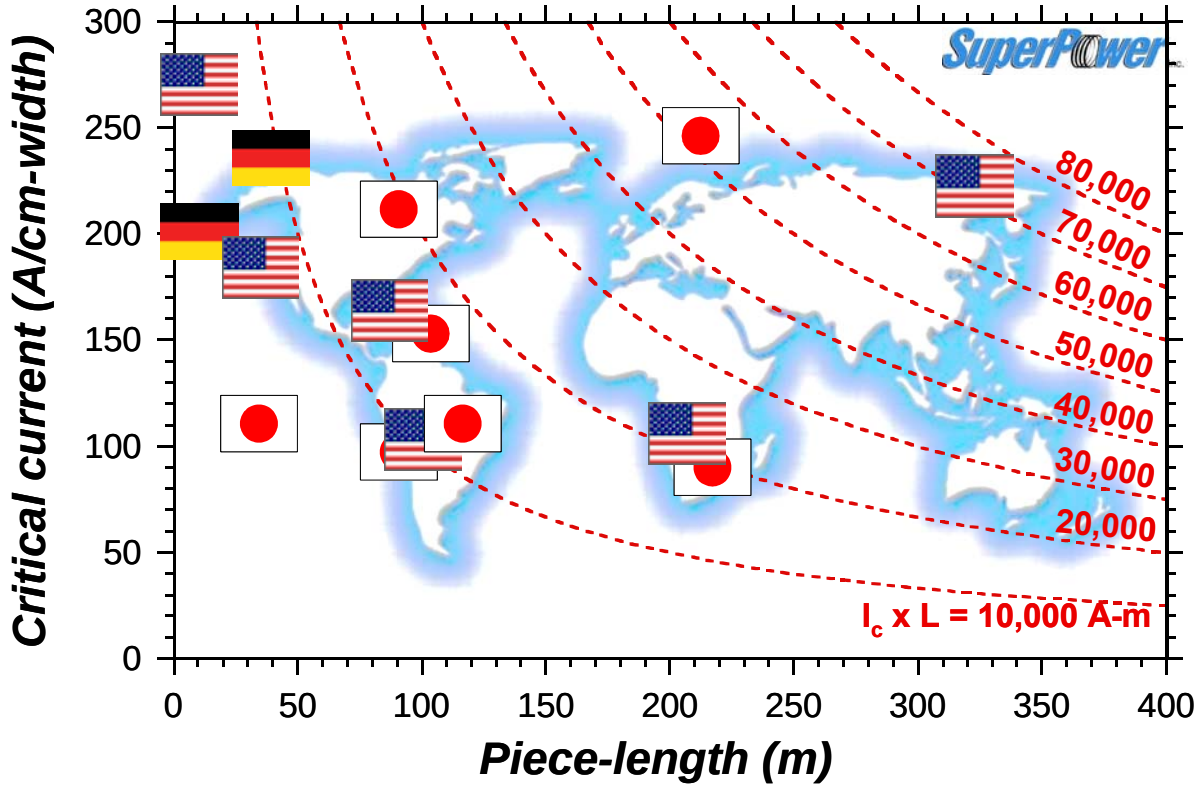
SuperPower Inc.

Availability of uniformly textured high-quality substrates in long lengths has enabled SuperPower to achieve World Record 2G wire performance

<u>322 m-long</u> *MOCVD-REBCO/LMO/homo-epi MgO/IBAD-MgO* 2G wire carried 219 A/cm-w

I_c X L = 70,518 Amp-meters
(a 220% increase in one year)



SuperPower Inc.

FY 2006 Performance (Scoring Criteria)

FY2006 Plans	FY2006 Performance
• Assist SuperPower in transferring LMO technology from short to pilot-scale type length.	☑ Assisted in understanding of the fabrication of high-quality long-length IBAD-MgO/LMO. ☑ SuperPower has integrated LMO into its manufacturing operation. ☑ 332 m-long IBAD-MgO/LMO with 6.8° in-plane FWHM. ☑ High performance wires have been obtained on these substrates: ➢ J_c as high as 4.79 MA/cm^2 (0.7 μm) ➢ I_c as high as 557 A/cm-w (2.1 μm).
Produce robust IBAD-MgO/LMO templates in 250-m lengths.	☑ SuperPower fabricated World Record performance 2G wire 322-m long that carries 219 A/cm-w (I_c X L = 70518 A-m).
• Simplify buffer architecture of IBAD-MgO suitable for MOCVD-HTS.	☑ Deposited smooth, dense & crack-free MOD-amorphous/nanocrystalline films on Hastealloy. ☑ IBAD-MgO deposited on these films show ~ 7.5° in-plane FWHM. ☑ Substrates with LMO deposited directly on IBAD-MgO show good texture (NO homo epi-MgO) : Obtained I_c = 169 A/cm-w by MOCVD-REBCO.

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SuperPower Inc.

FY 2006 Performance (Scoring Criteria)

FY2006 Plans	FY2006 Performance
• Provide characterization to optimize pinning in MOCVD-HTS films on IBAD-MgO.	☑ Studied the transport and magnetization properties on numerous samples. ☑ Correlated enhanced performance in SuperPower "standard" samples with horizontal (ab correlated) stacking fault bundles, vertical (c-axis correlated) anti-phase boundaries clusters, and nanoparticles. ☑ Assisted in understanding the effects of precursor modifications on performance-microstructure relationship. ☑ High I_c obtained on ORNL-nanoparticle surface decorated IBAD with MOCVD-REBCO.
• *(New)* Establish "SuperPower" MOCVD-HTS deposition capability at ORNL.	☑ ORNL personnel was trained in SuperPower research MOCVD unit operation and precursor preparation. ☑ Revitalized research MOCVD system demonstrated short sample J_c of 2.5 MA/cm^2. ☑ SuperPower research MOCVD system installed at ORNL in July 06.

Oak Ridge National Laboratory

SuperPower Inc.

FY 2006 Performance (Scoring Criteria)

FY2006 Plans	FY2006 Performance
• Understand the role of copper (Cu) surround stabilization in the operational stability limits REBCO coated conductors.	☑ Measurements indicated that thickness of Cu surround stabilizer has more of an impact during current impulses than for constant currents. ☑ Thermal runaway & impulse limits measured at 77 K as function of Cu surround stabilizer thickness. In addition, normal zone propagation speeds < 1 cm/s were observed for 4-mm wide REBCO with 38 μm surround stabilizer.
• Evaluate ac loss in stacks of narrow width coated conductors and compare to equivalent 4 mm wide REBCO.	☑ Alternative splice geometries and stacks of 2-mm wide YBCO tapes have shown reduced ac losses at 60 Hz perpendicular peak fields.
• Determine if high voltage improvement from Cu surround stabilizer is valid in practical geometries.	☑ In turn-to-turn geometry, REBCO tapes with Cu-surround stabilizer increased the breakdown voltage when compared to as-slit REBCO tape for similar probabilities.

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FY 2007 Plans (Scoring Criteria)

- **Continue ORNL assistance to SuperPower in fabricating robust IBAD-MgO templates in a pilot-scale production level: <u>500-meters length</u>.**
- **Development of improved buffer architectures leading to improved IBAD-MgO template performance and/or reduced manufacturing cost.**
- **Continue characterization and optimization of pinning mechanisms in thick REBCO films produced in the manufacturing system:**
  - **I_c = 750 A/cm-width in thick films.**
  - **Increase J_c of 2.8 μm HTS wire to that of 0.9 μm level.**
- **Investigate the efficacy of pinning enhancement in thick MOCVD-REBCO through RE and other modifications.**
- **Transfer the knowledge learned from the MOCVD system regarding REBCO thick film growth located at ORNL to SuperPower.**
- **Continue examination of ac loss in multiple spliced conductors and stack configurations as a function of field and field orientation.**
- **Over-current testing, ac loss measurements, and identification of stability & protection issues related to filamentary REBCO/IBAD tapes.**
- **Construct and examine stability & ac loss of 2T coil made from 4 mm-wide 2G wire at different temperatures (30K – 77K) and cooling conditions (conduction vs. bath).**

Research Integration (Scoring Criteria)

- **Regular weekly conference calls.**
- **Frequent sample exchanges.**
- **Joint development and joint materials evaluation & testing.**
- **CRADA meetings.**
- **Technical staff from SuperPower routinely visited ORNL to perform IBAD-MgO/LMO buffer evaluation studies and detailed REBCO characterizations.**
- **ORNL staffs visited SuperPower in planning and training activities in order to transfer the SuperPower research MOCVD capability to ORNL.**
- **Interacted with LANL through SuperPower on nanocrystalline/ amorphous buffer studies.**
- **Several joint presentations and 2 joint publications in preparation.**
- **Joint invention disclosures filed.**

Close collaboration and interaction between ORNL and SuperPower has resulted in significant advancement in process understanding and subsequently development of a robust manufacturing process at SuperPower

Joint publications

1. **Growth of thick $YBa_2Cu_3O_{7-\delta}$ films carrying an I_c of 272 A/cm on $LaMnO_3$-buffered ion-beam assisted deposition MgO substrates using Metal-organic chemical vapor deposition - M. Paranthaman, T. Aytug, and A. Goyal (ORNL) and X. Xiong, Y. Chen, J. Reeves, and V. Selvamanickam (SuperPower) (in preparation).**

2. **Transport, structural and microstructral characterization of epitaxial $Y_{0.9}Sm_{0.1}Ba_2Cu_3O_7$ thick films on IBAD YSZ on Hastelloy substrates - A. Goyal, J. Li, E. D. Specht, P. M. Martin and M. Paranthaman (ORNL) and V. Selvamanikcam and J. Reeves (SuperPower) (submitted).**