New Directions in the Deposition of Fluorine-Free HTS Materials

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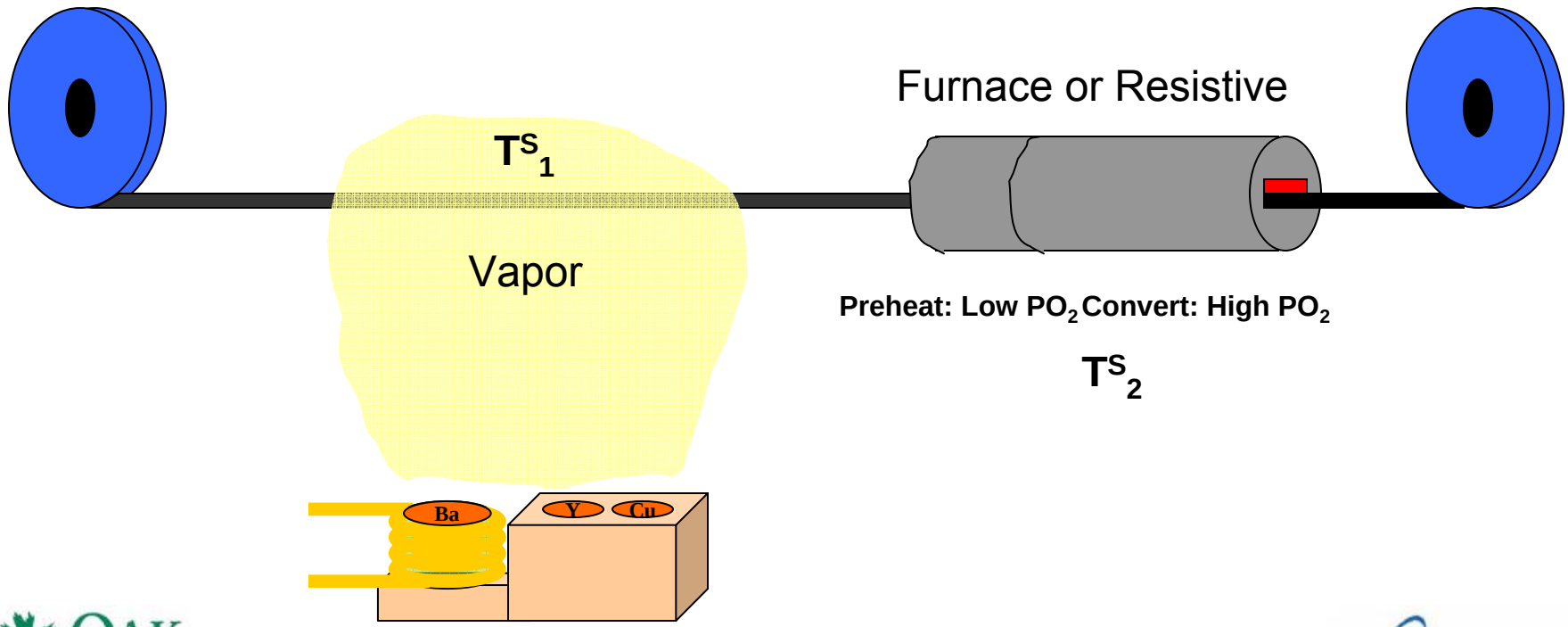
***speaker**

ORNL: $200k
LANL: $400k
Stanford: $75k

Superconductivity for Electric Systems 2006
Annual Peer Review
July 25-27, 2006

Why another YBCO Process?

- **Faster process by eliminating the N_2/H_20 furnace conversion as in BaF_2**
- **Cheaper feedstock materials**
- **Potentially wider buffer choice than ceria - no HF**
- **Can match deposition speeds and conversion - one pass YBCO.**



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Metals are the most economical feedstock

ORNL: PLD from oxide target for elucidating materials issues.

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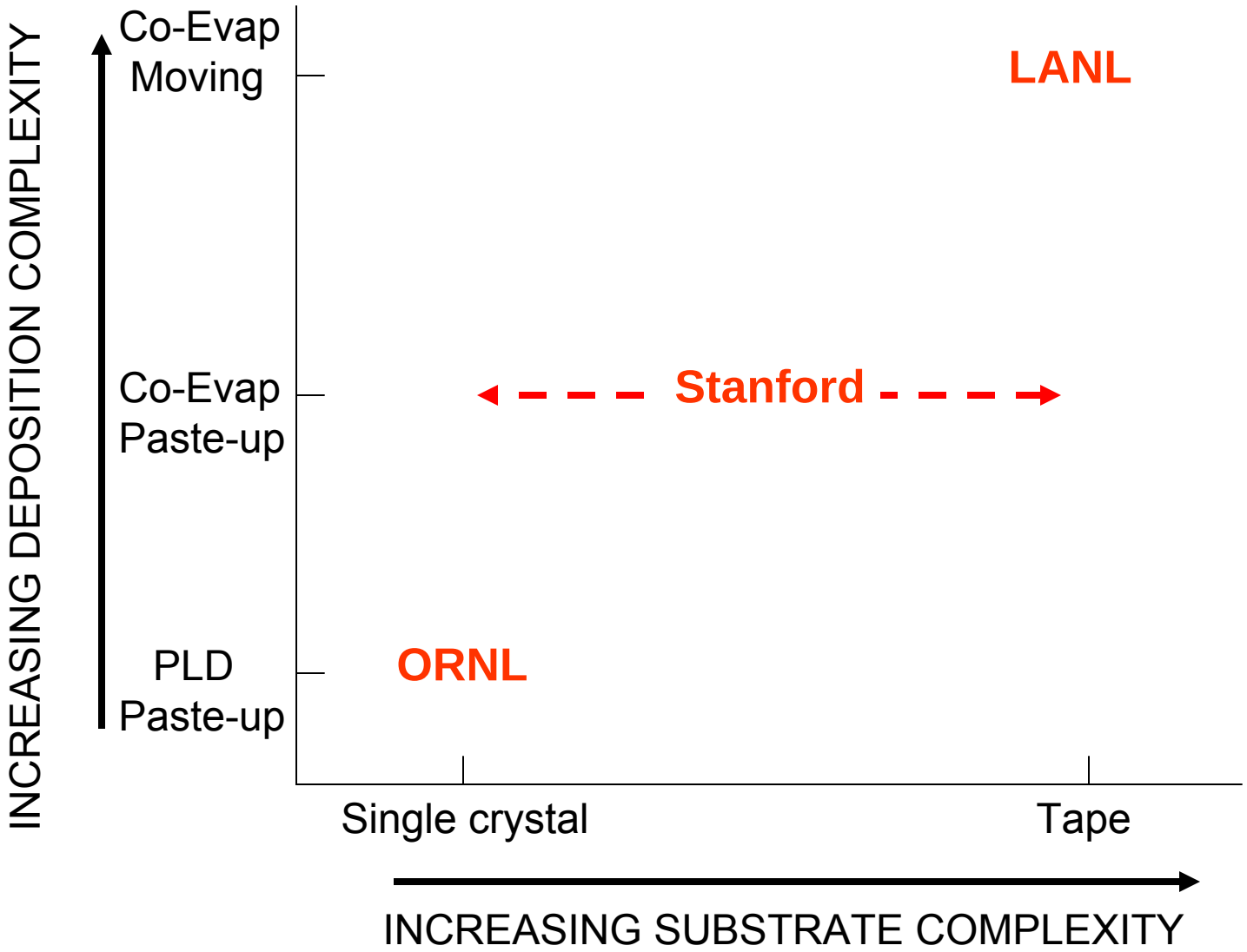

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Material Science of YBCO Growth by Liquid Assisted Reaction of Amorphous Precursors.

Jeong-uk Huh, Gertjan Koster, M.R. Beasley, T.H. Geballe, R.H. Hammond

Outline:

- **YBCO Stability , Phase Diagram, and Liquid.**
- **Overview of Best Region in P, T, for Growth.**
  - **Precursor and Paths to Reaction Region Explored.**
  - **Summary of Results: Growth Morphology Too Perfect!!!**
    - » **<u>NEED DEFECTS !</u>**

- **Review: How These Conclusions Were Reached:**

  FTIR during Deposition—In-situ Optical Properties

  XRD-dome: Development in P, T, time of YBCO from precursor.

- **Summary and Future Tasks**.

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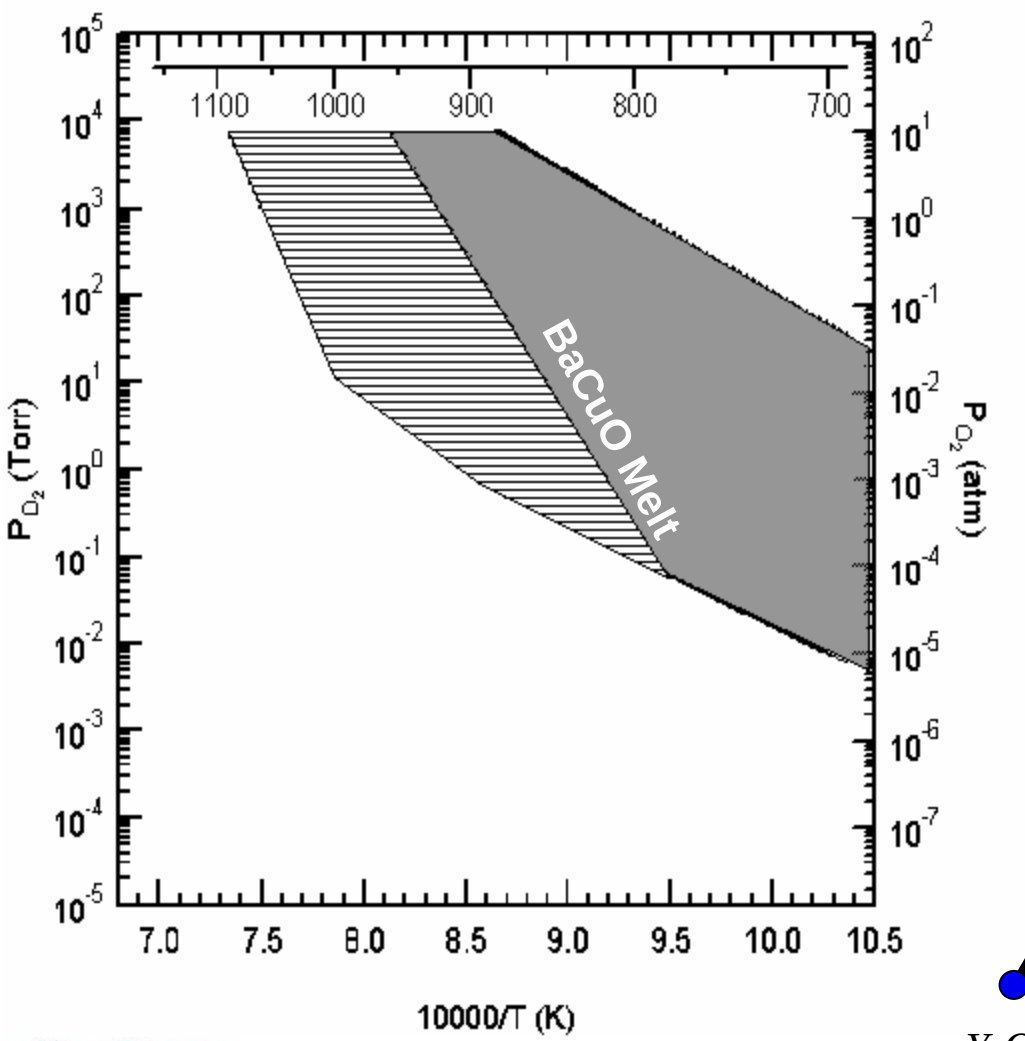
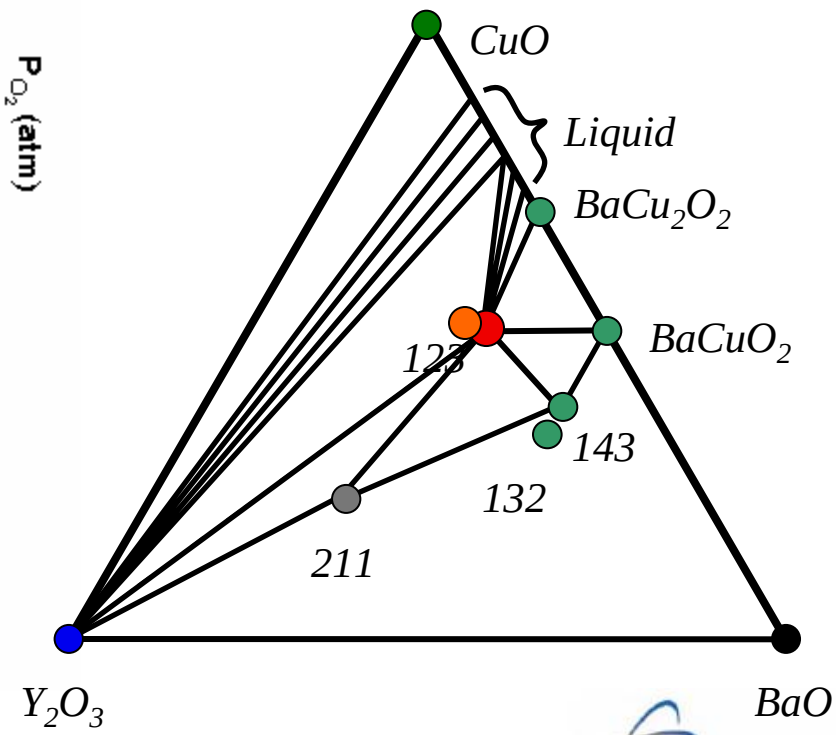
YBCO stability diagram



- The region where YBCO is stable (P,T)
- Line where liquid Ba-Cu-O transition;
  $(L)BaCu_2O_2 \rightarrow (S)CuO + (S)BaCuO_2$
- Conjectured phase relationships:



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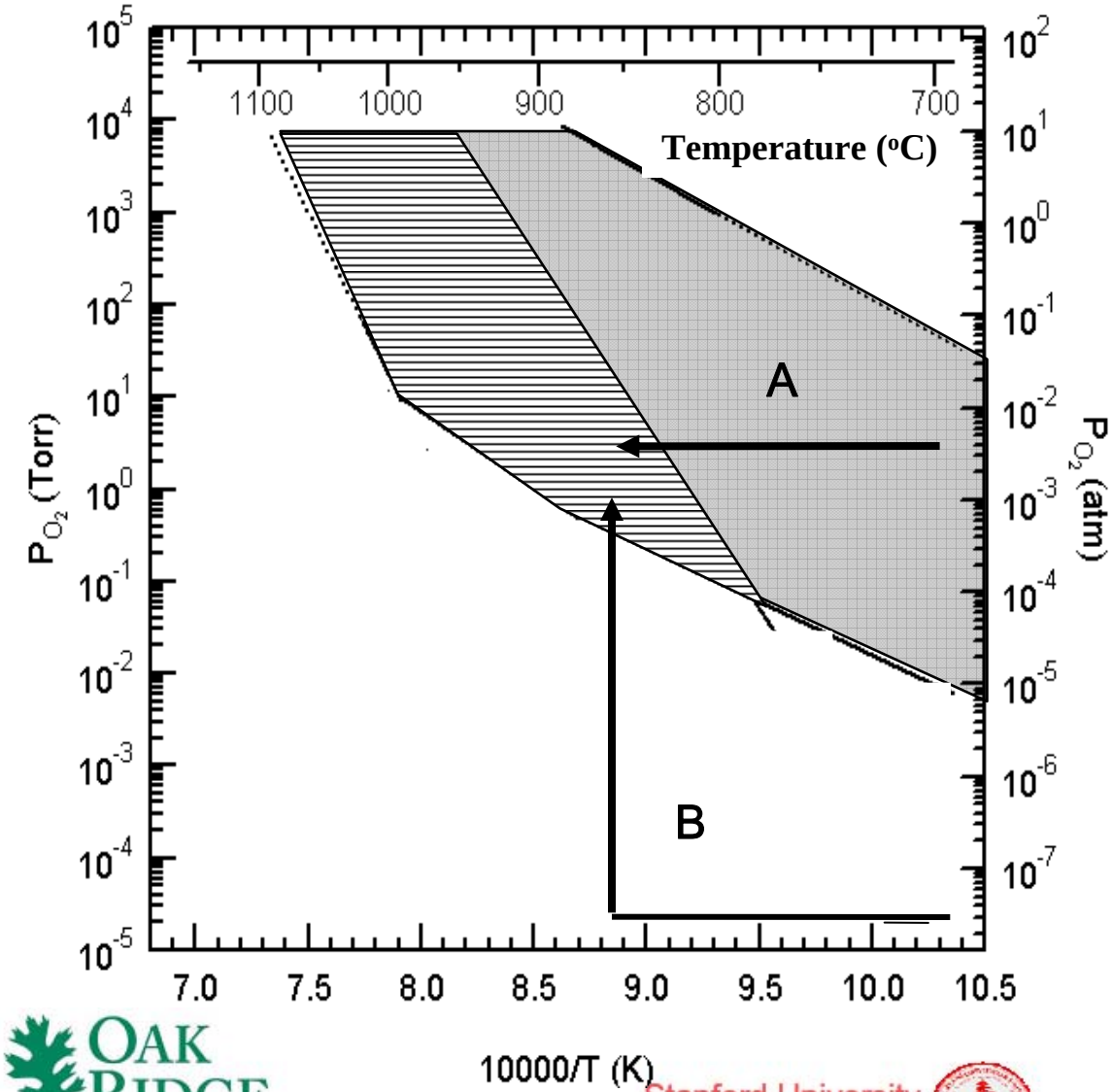
Precursor Paths to Reaction Explored:

Growth of YBCO from precursors



Precursors:

PLD: 100 mTorr at 300 C & RT

Electron Beam: 5×10^{-5} Torr at 830 C and 300 C.

2 paths:

A-constant P_{O_2}, Temp driven.

B-Constant T, P_{O_2} driven.

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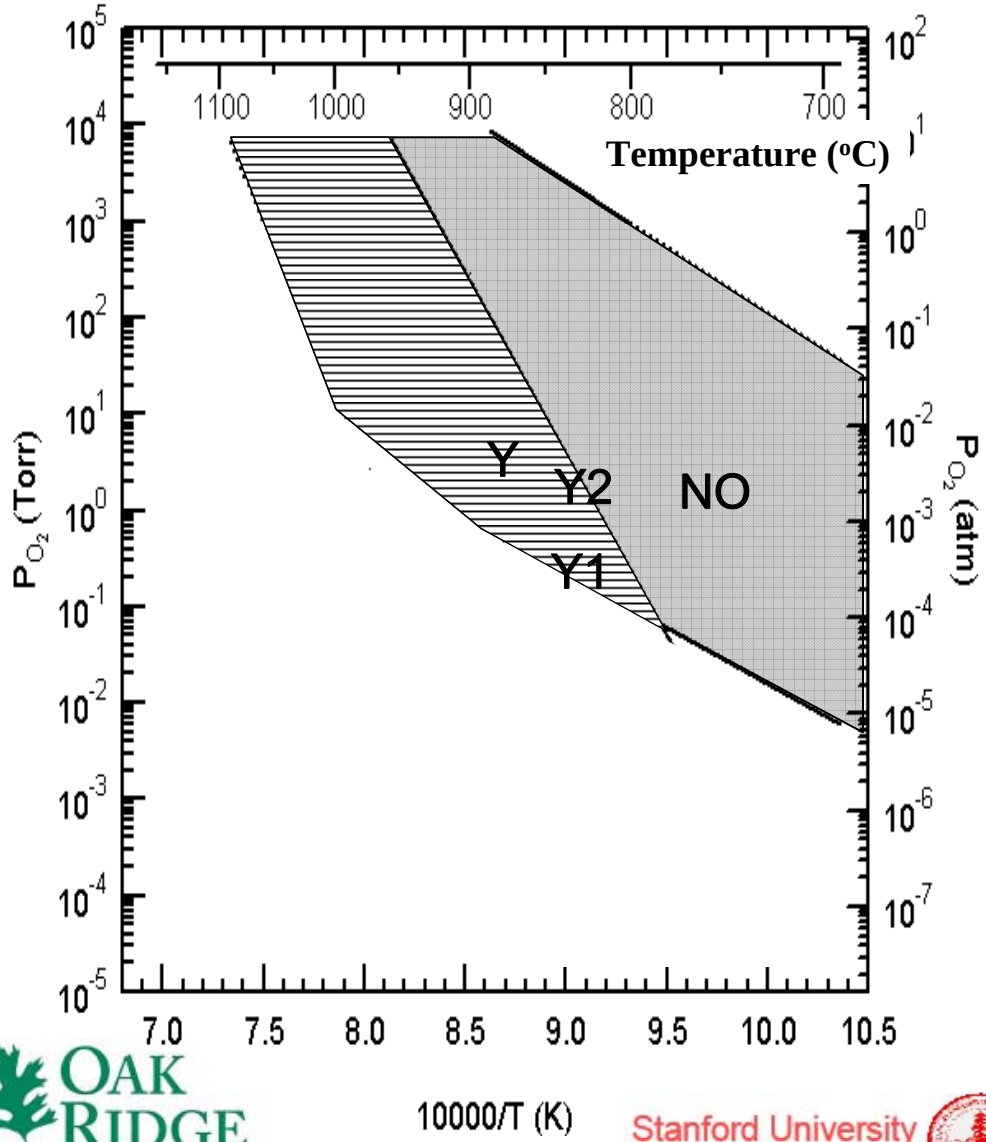
Overview: Summary of General Results



<u>Growth in different regions</u>:

Y (yes):

Good c-axis epitaxy.

Y1—slow growth, sec to minutes.

Y2—faster growth, seconds.

NO:

Some “a” axis and some (103).

In General for all:

Dependence on Buffer-surface

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Overview :

Growth Morphology:

In general, too perfect c-axis growth:

- **Oxygenation of chains very slow.**
- **J_c(H) low---no pinning.**

Need defects:

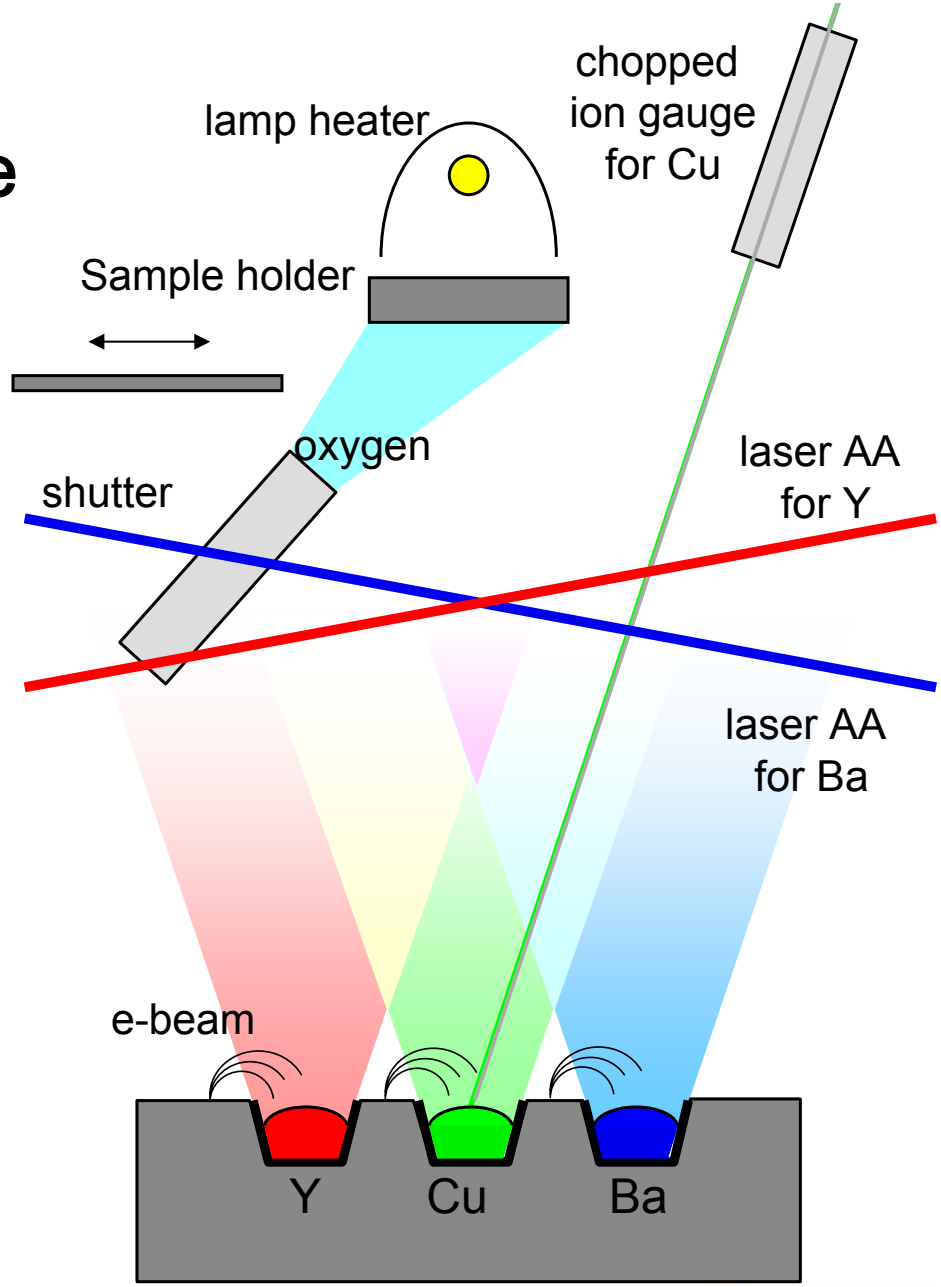
- **Artificial Pinning Centers (APC)---nano particles. Example $BaZrO_3$, Y_2O_3.**
- **Defects due to rapid supersaturated growth:--small grains, but still c axis.**
- **Composition clusters: (spinodal decomposition?): Seen in bulk—so called "peak effect", Murakami. Recently seen in PLD films—Yoshida and Matsumoto,**

  $Sm_{1+x}Ba_{2-x}Cu_3O_y$, and Nd123ss

Review: How we got here

Film growth method

- **Electron-beam reactive co-evaporation**
  - Composition control
    - laser AA: Y & Ba
    - chopped ion gauge: Cu
  - Deposition rate
    - 100 ~ 300 Å/s
  - Deposition pressure
    - 5×10^{-5} Torr oxygen



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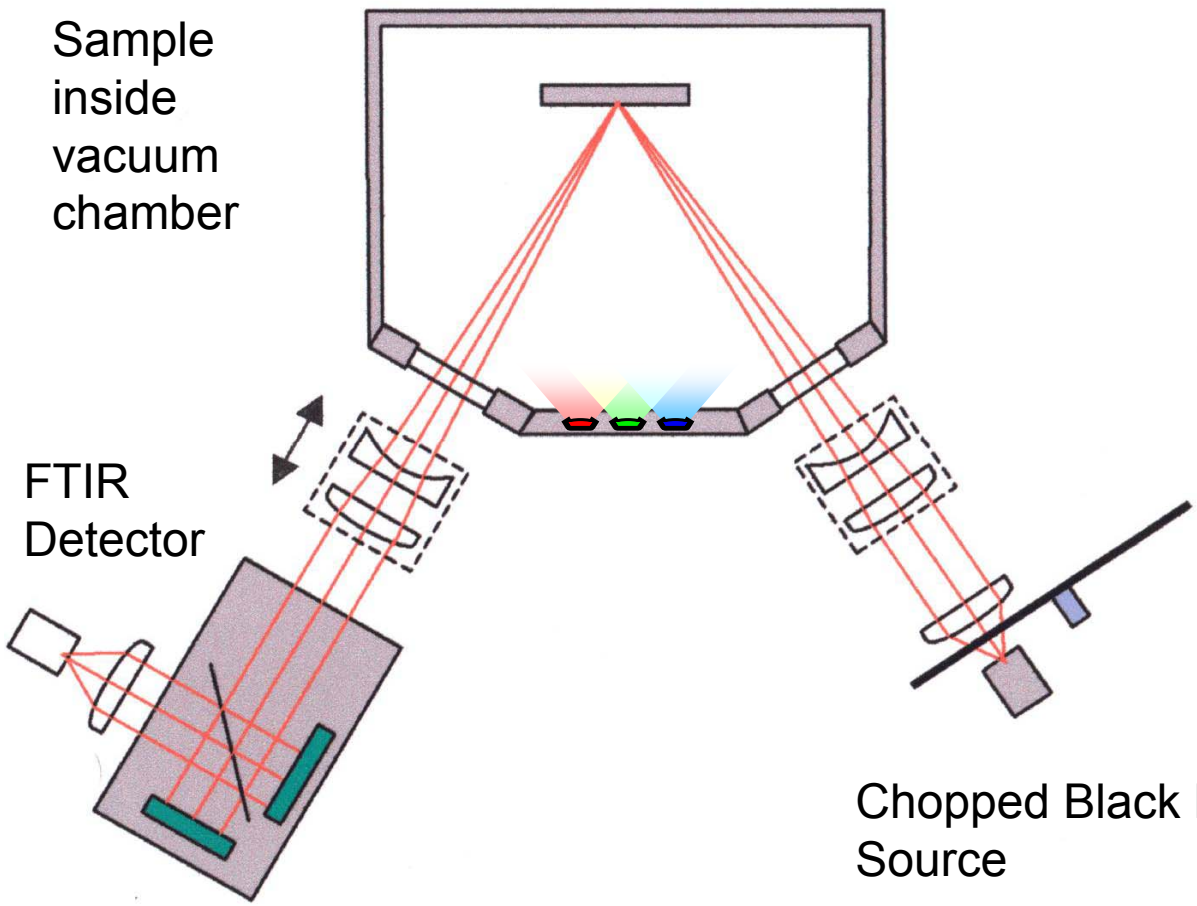
Fourier Transform InfraRed set up

Used to monitor dielectric properties during and post deposition
wave lengths 500 to 6000cm^{-1}, ~ 1.5 to 15 microns.



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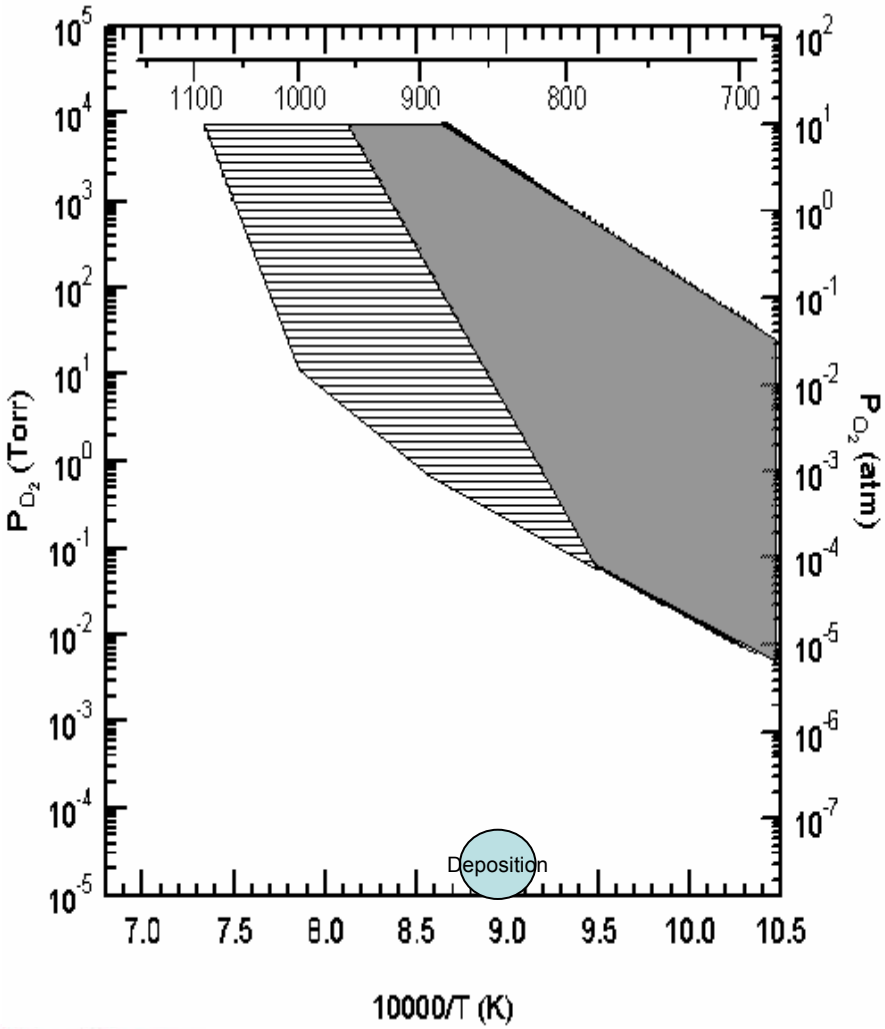
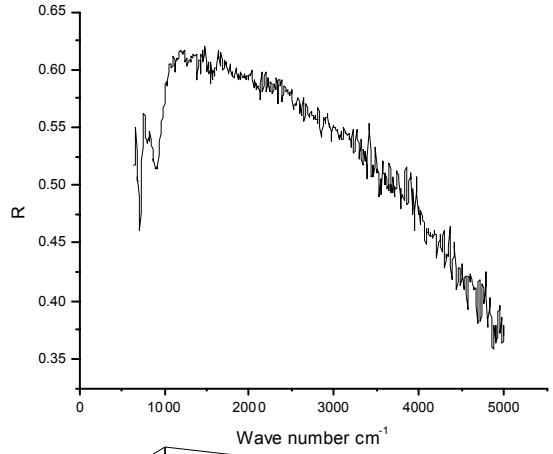
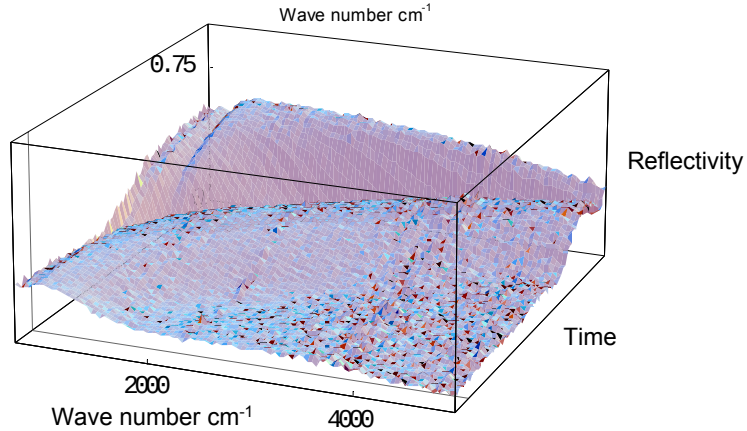
FTIR During Deposition

(on RABiTS)







- Deposit at 5×10^{-5}Torr O_2, 830°C
- Interference fringe period changes as film gets thicker. More opaque.

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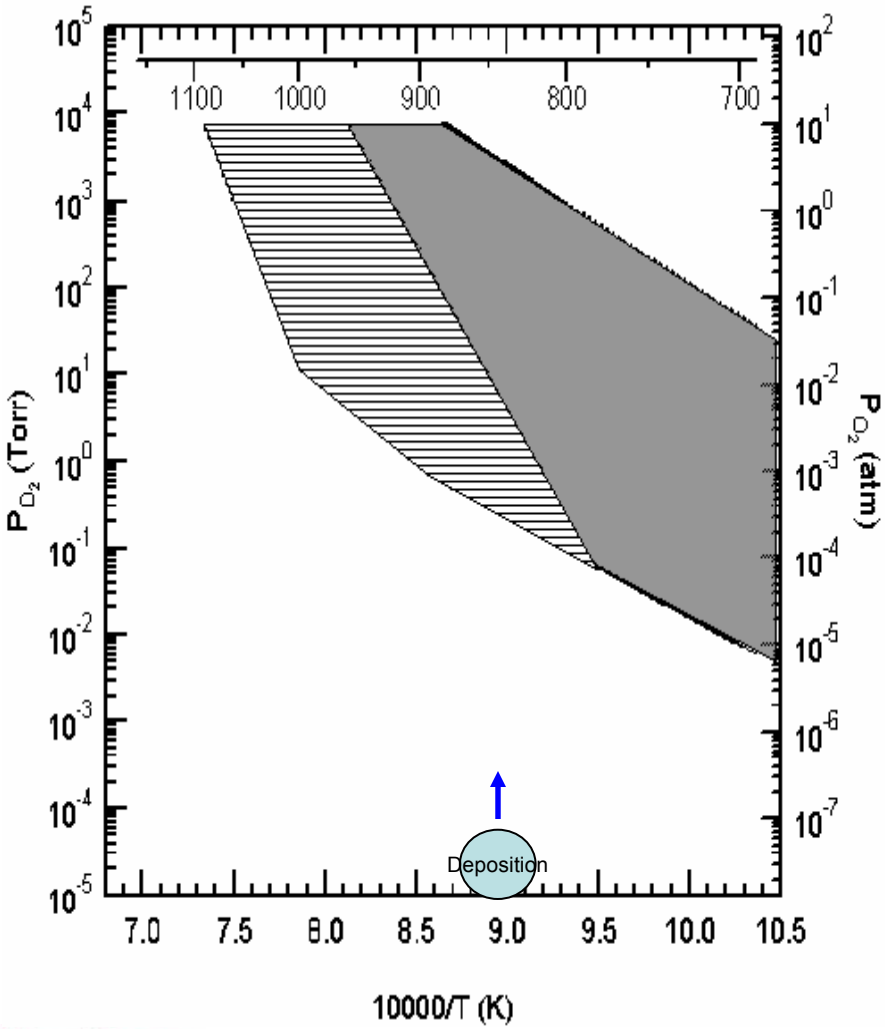
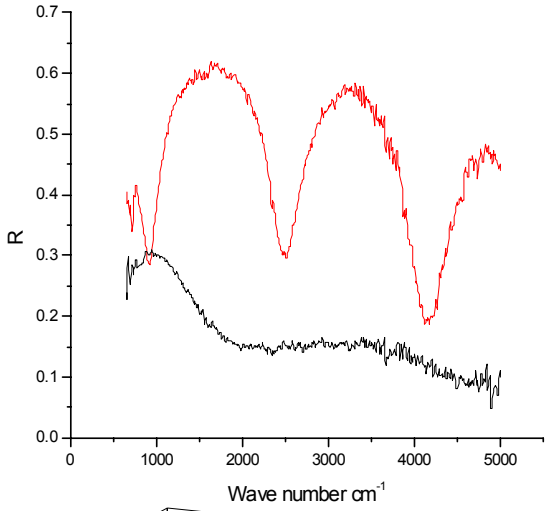
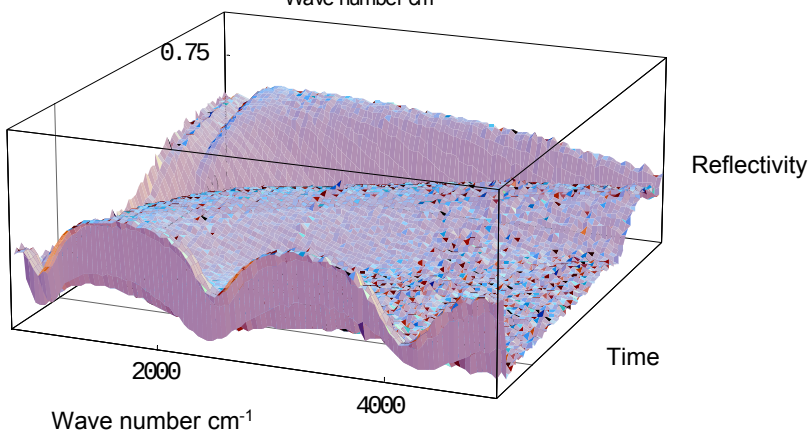
FTIR after pressurization

(on RABiTS)







- Introduce oxygen to 2 - 3 mTorr
- Interference fringes intensity jumps- more transparent.

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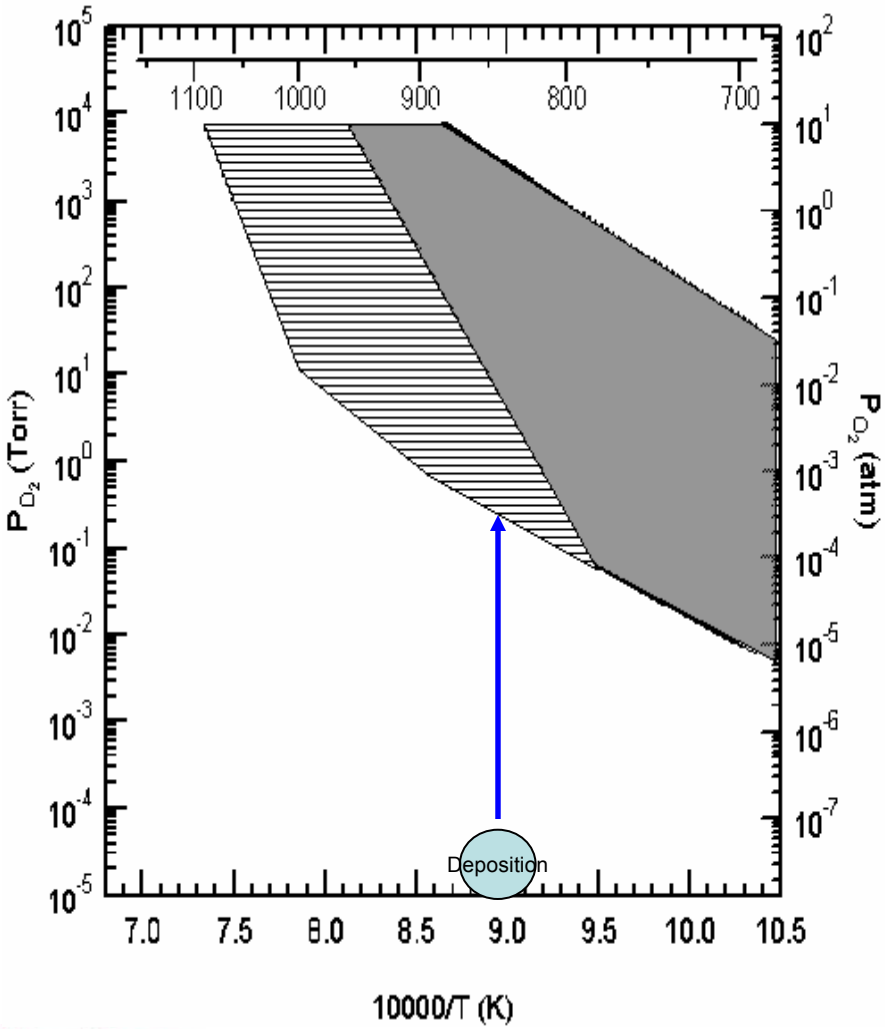
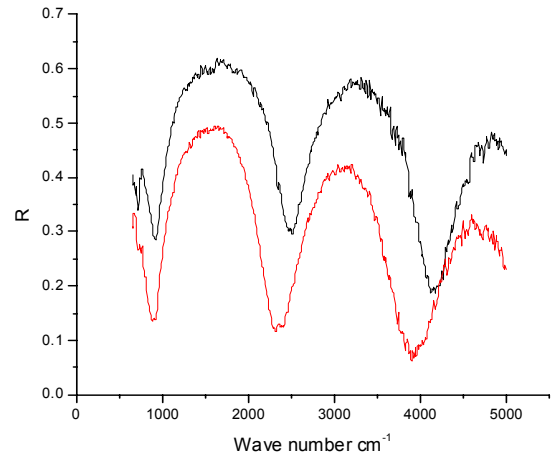
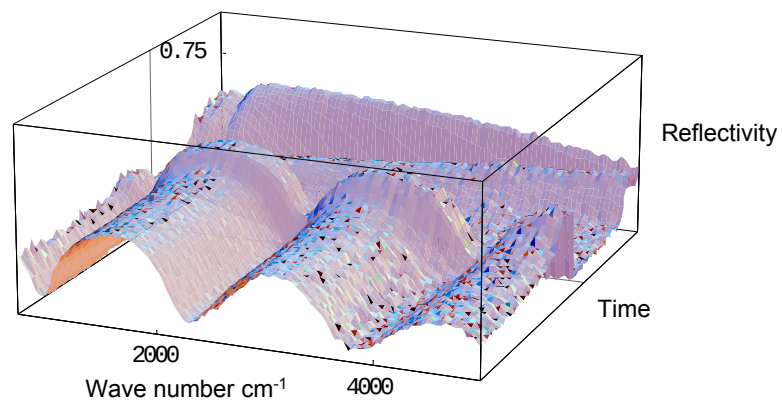
FTIR during YBCO growth

(on RABiTS)







- YBCO grows
- Interference intensity decreases as enter the growth region

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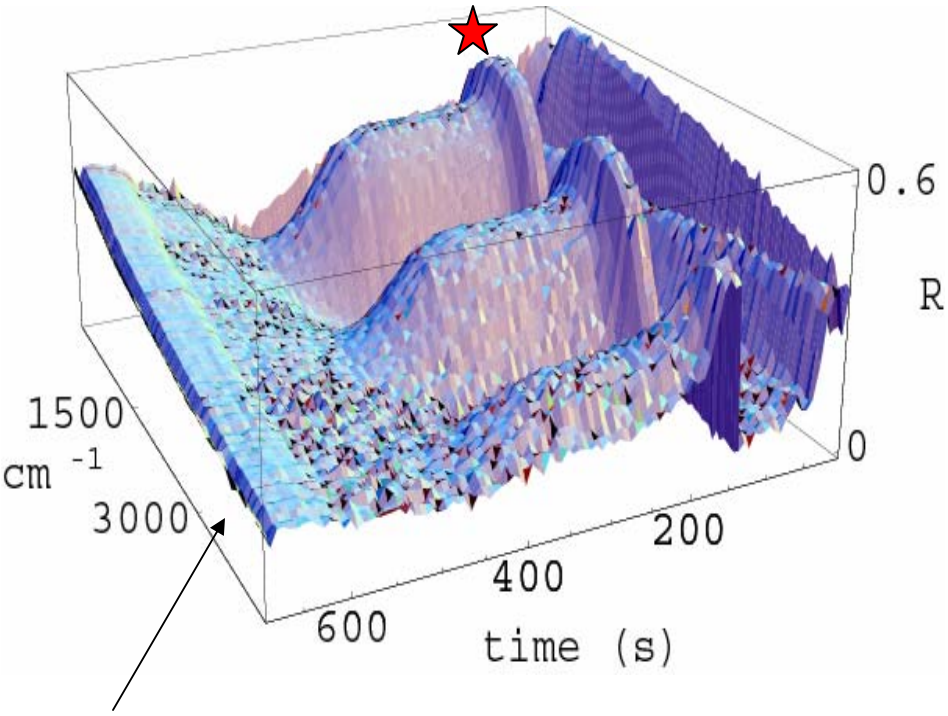
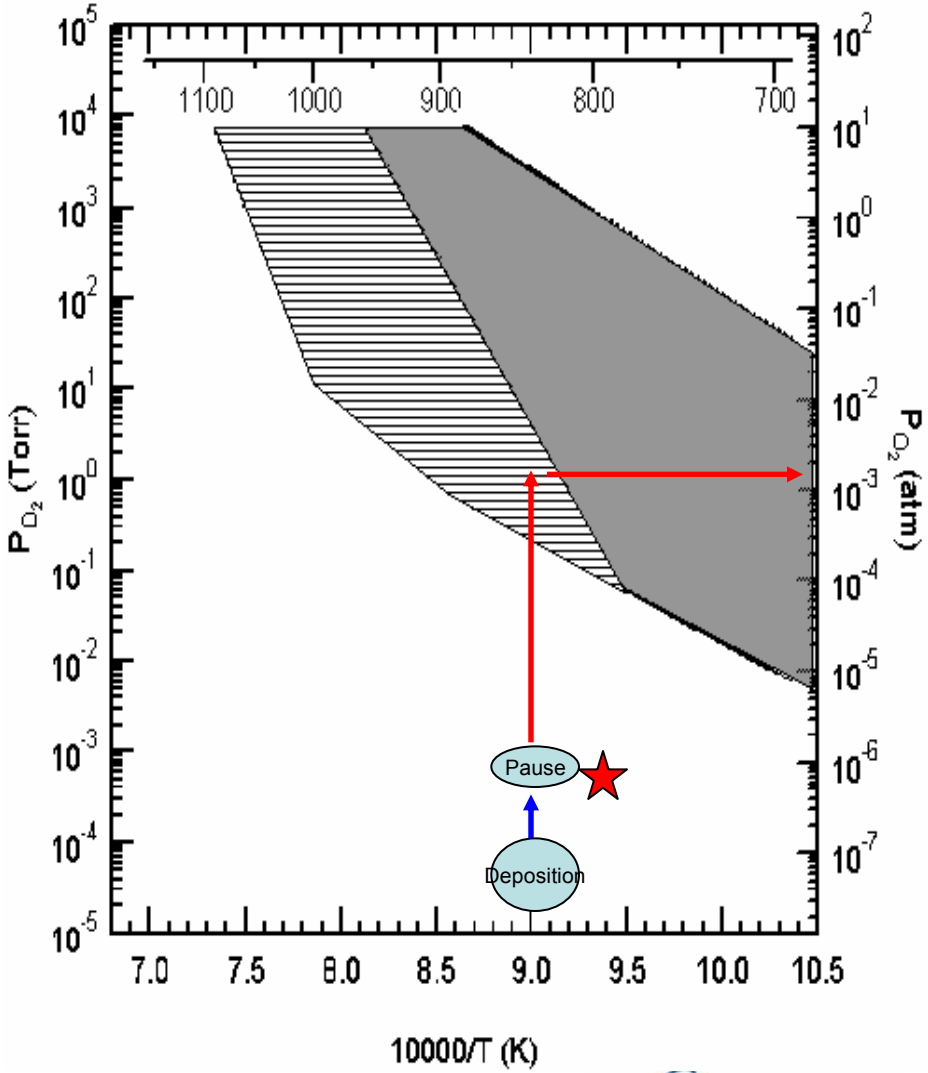
FTIR during and after YBCO Deposition



Drude metallic YBCO



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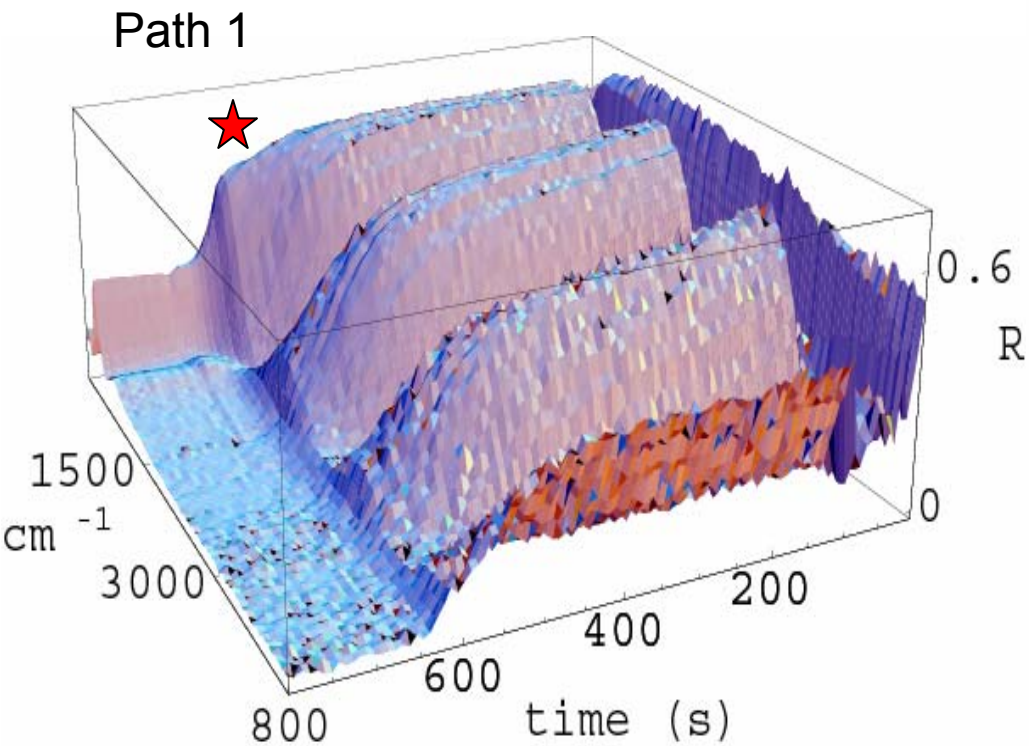
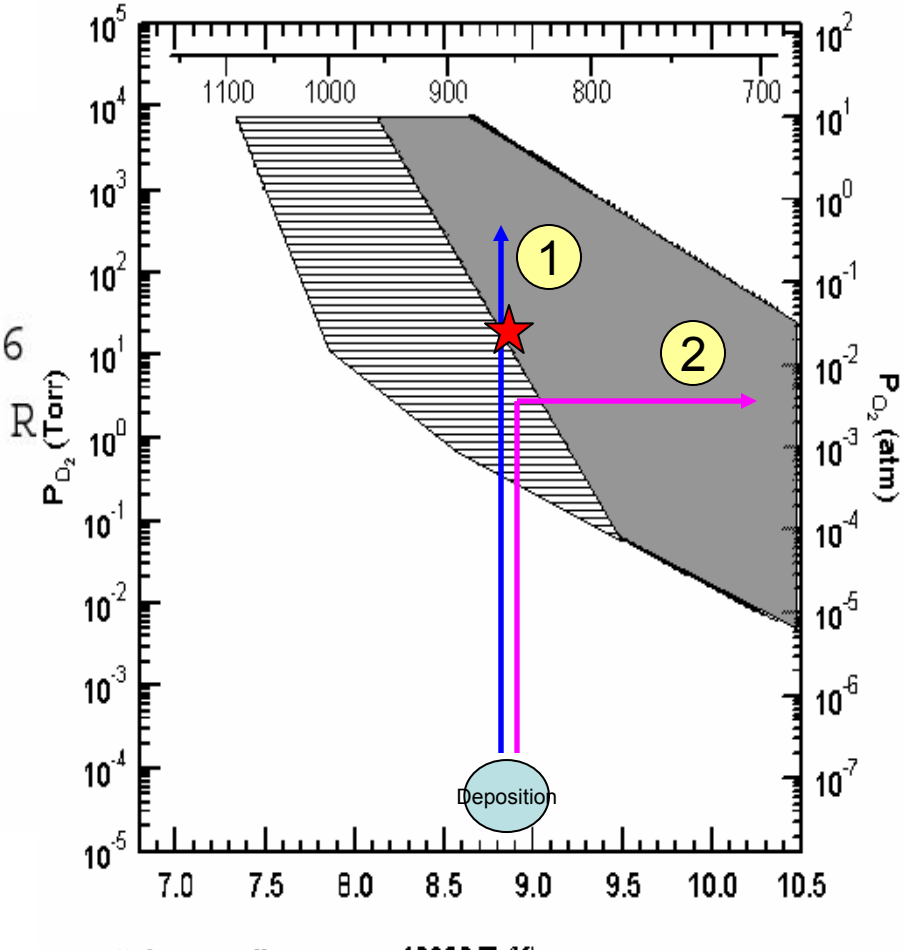
FTIR of Ba-Cu-O

Determination of liquid Ba-Cu-O decomposition: $BaCu_2O_2 \rightarrow CuO(s) + BaCuO_2(s)$





Path 2 - No change till ~ 650°C: supercool liquid → "Glass" solid

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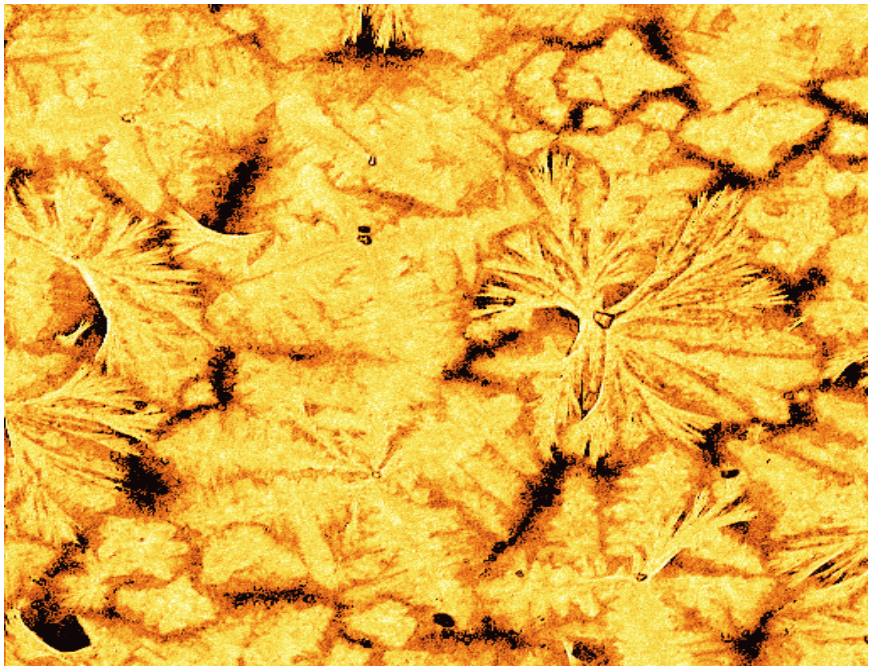
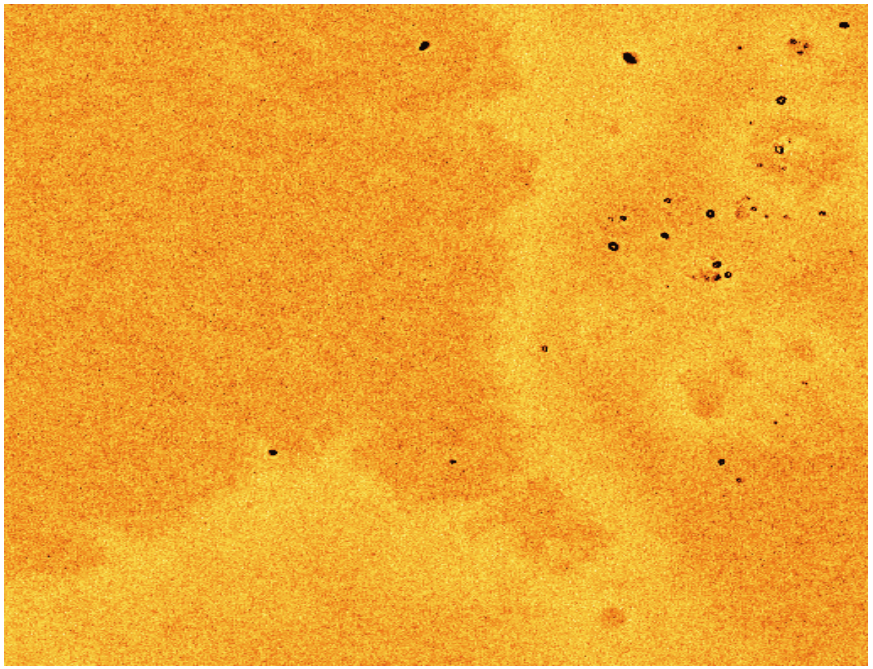
Ba-Cu-O Layer

Showing result of transformation $BaCu_2O_2(L) \rightarrow CuO\ (S) + BaCuO_2(S)$ on surface of YBCO.





Bob Jones

YBCO + Liquid grown in liquid region
Then cooled across line.

Grown out side liquid region

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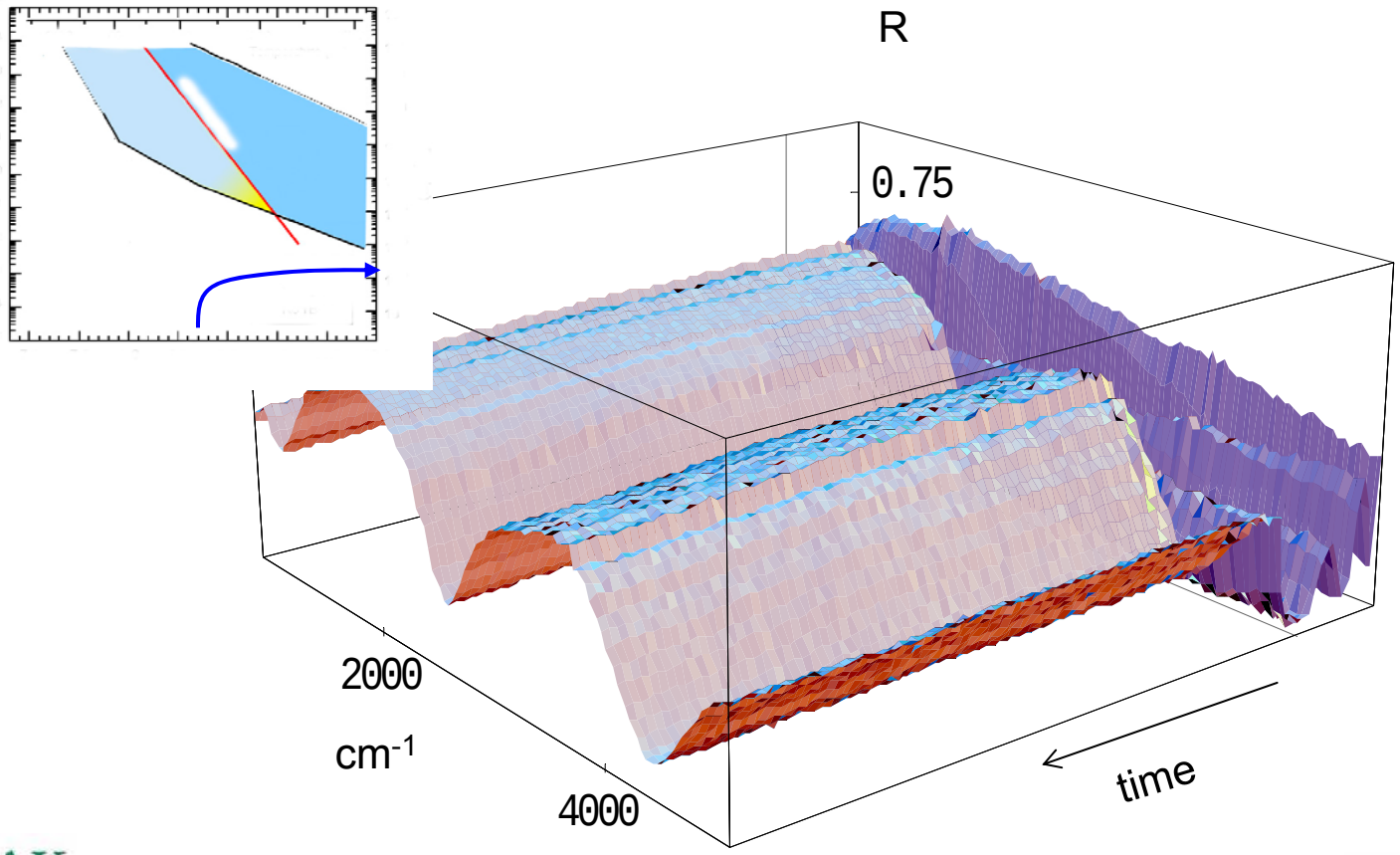
FTIR of YBCO precursor:

- deposited at 830˚C, $5x10^{-5}$ Torr O_2,
- oxygenated to 3mTorr,
- cooled.

Note no change in response as cooled down to room temperature.



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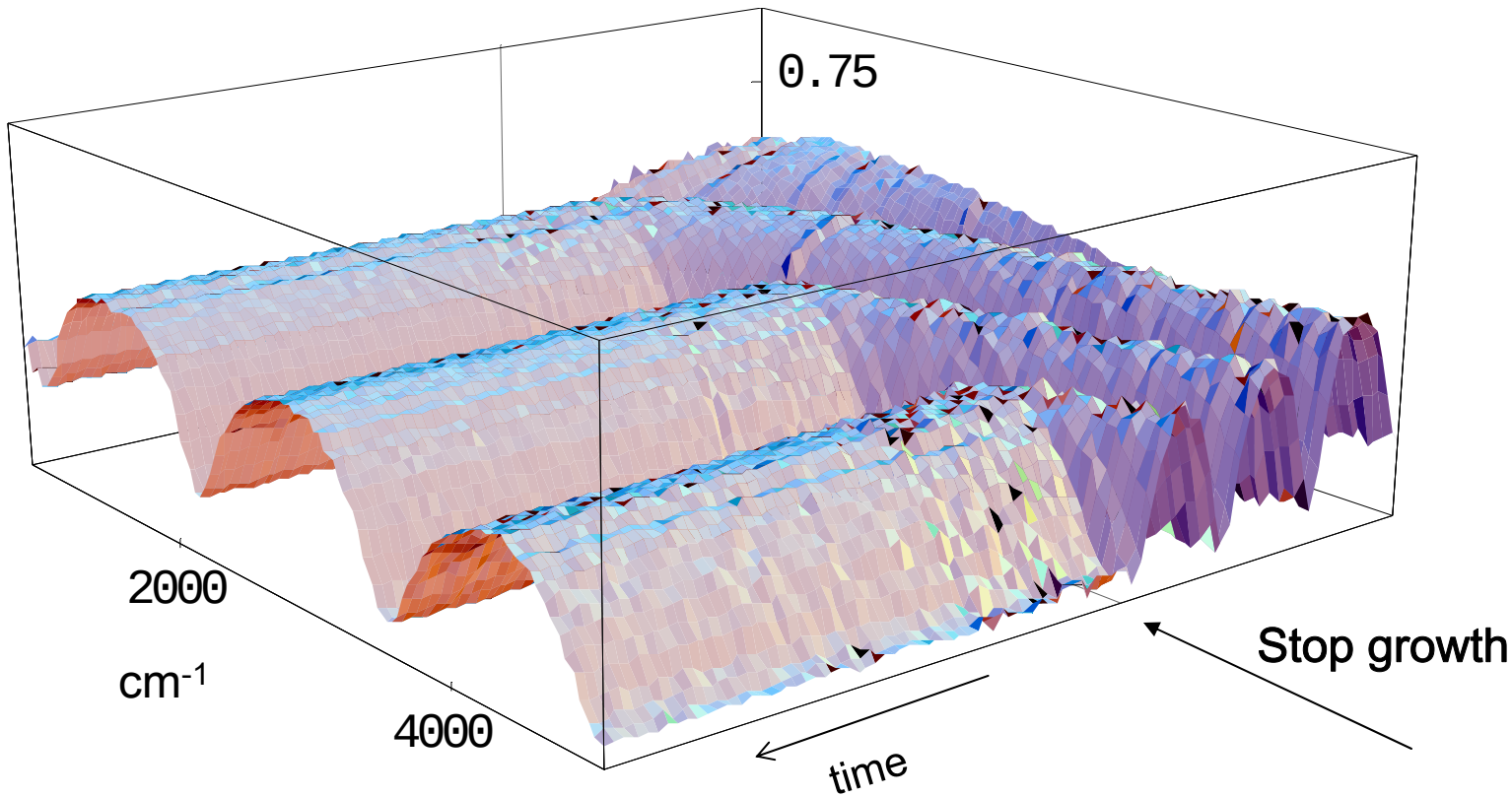
FTIR for YBCO precursor

•deposited at 300˚C, $5x10^{-5}$ Torr O_2
showing full fringe amplitude of the "glass" state during deposition and later.



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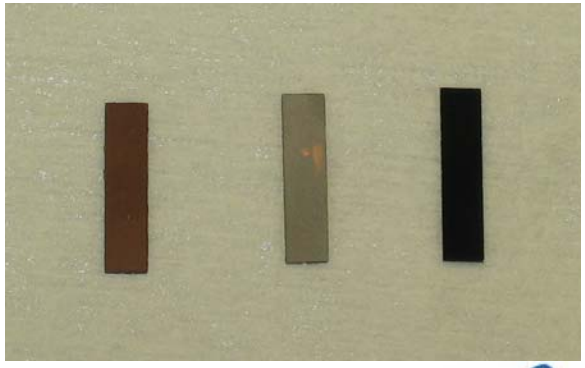
X-Ray Diffraction (XRD) Dome

XRD heating dome (6 cm diameter)

Capable of taking XRD real-time measurements while heating the sample under a certain gas environment

Put the “glassy” precursor into the Dome at different pressure and heat up to various temperatures

Great way to find the post-deposition Condition for YBCO



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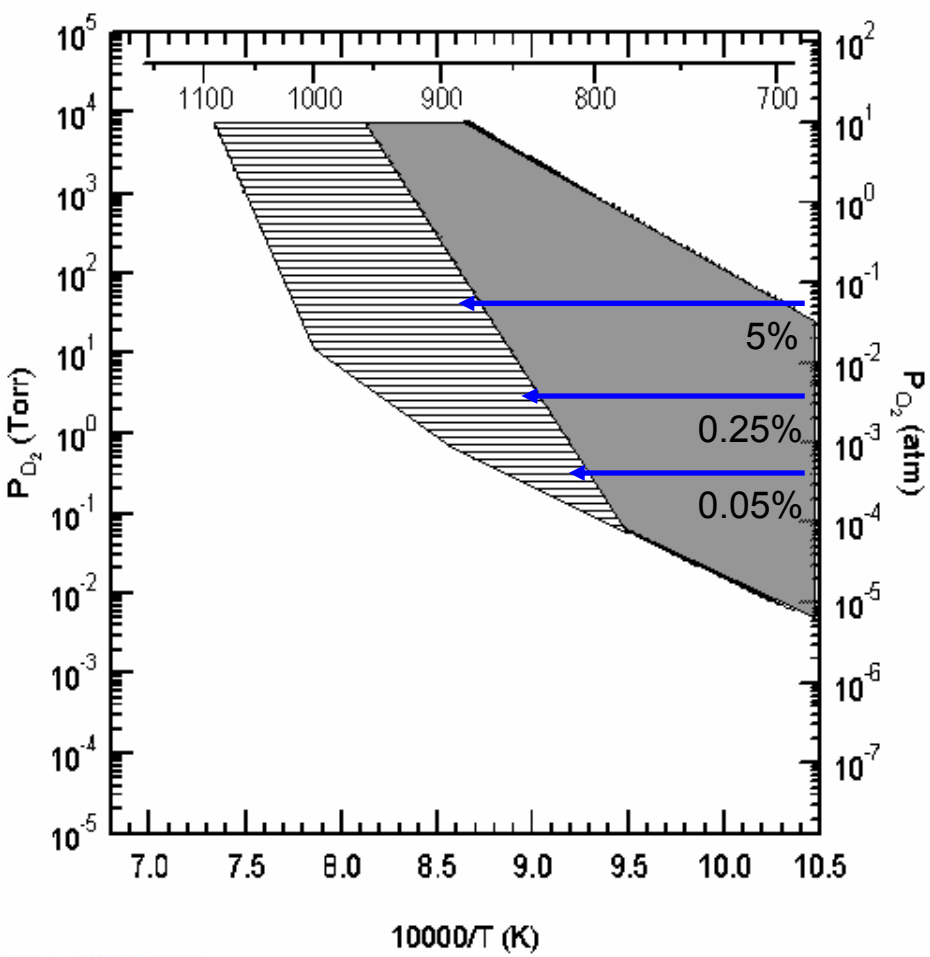
Examples of XRD Taken in Dome:

Growth of low temperature precursor

Investigate where in Po_2, T growth occurs



- Samples made at 300°C in 5×10^{-5}Torr O_2 on $LaAlO_3$
- Mount in dome heat to 650°C in Argon
- Heat in three different Po_2

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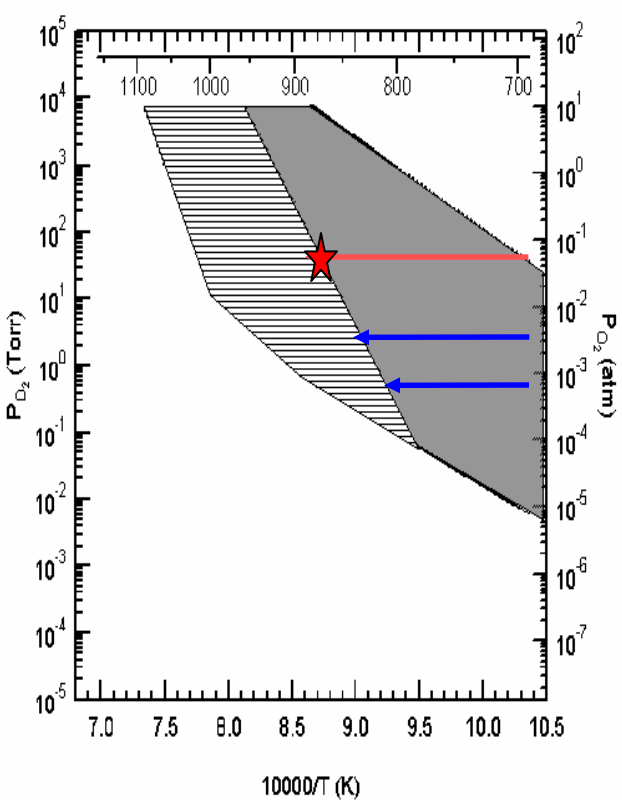
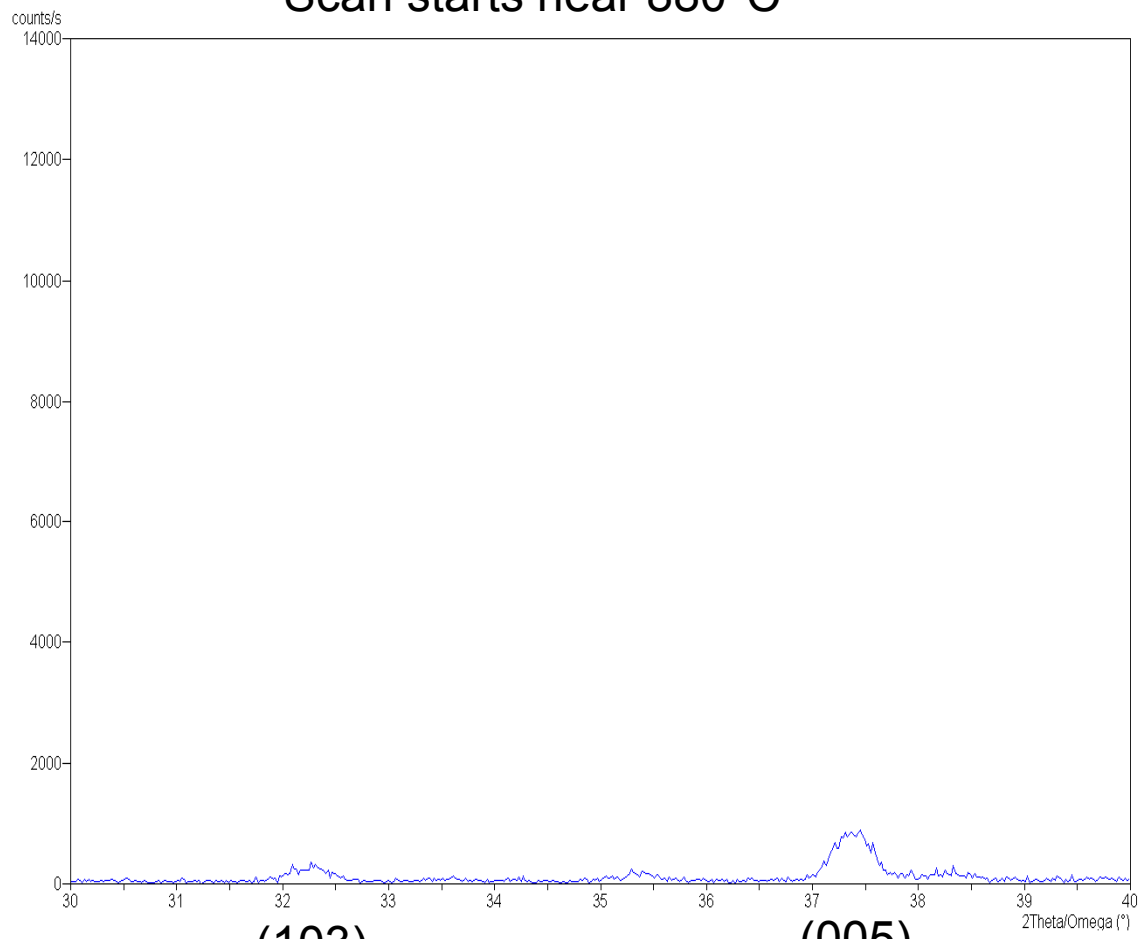
Heating in 5% Po_2



Scan starts near 880°C



(103) (005)

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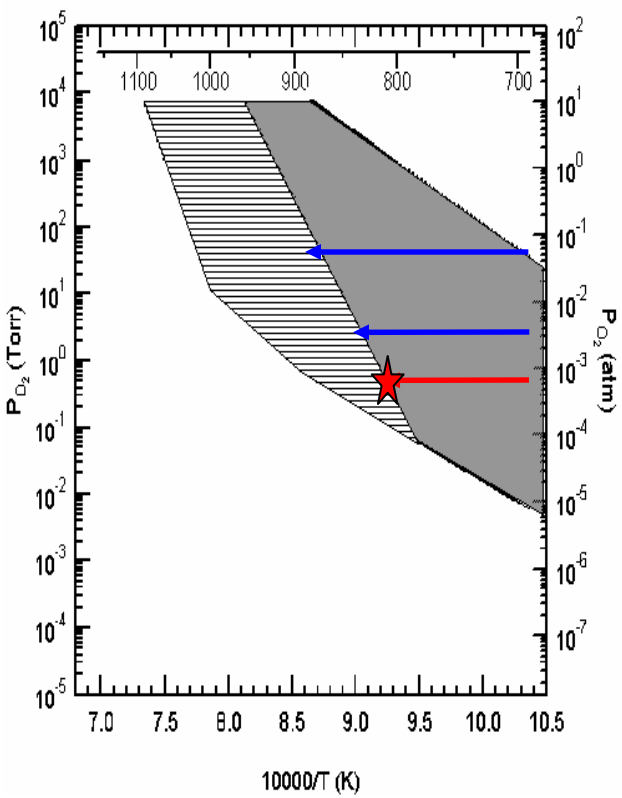
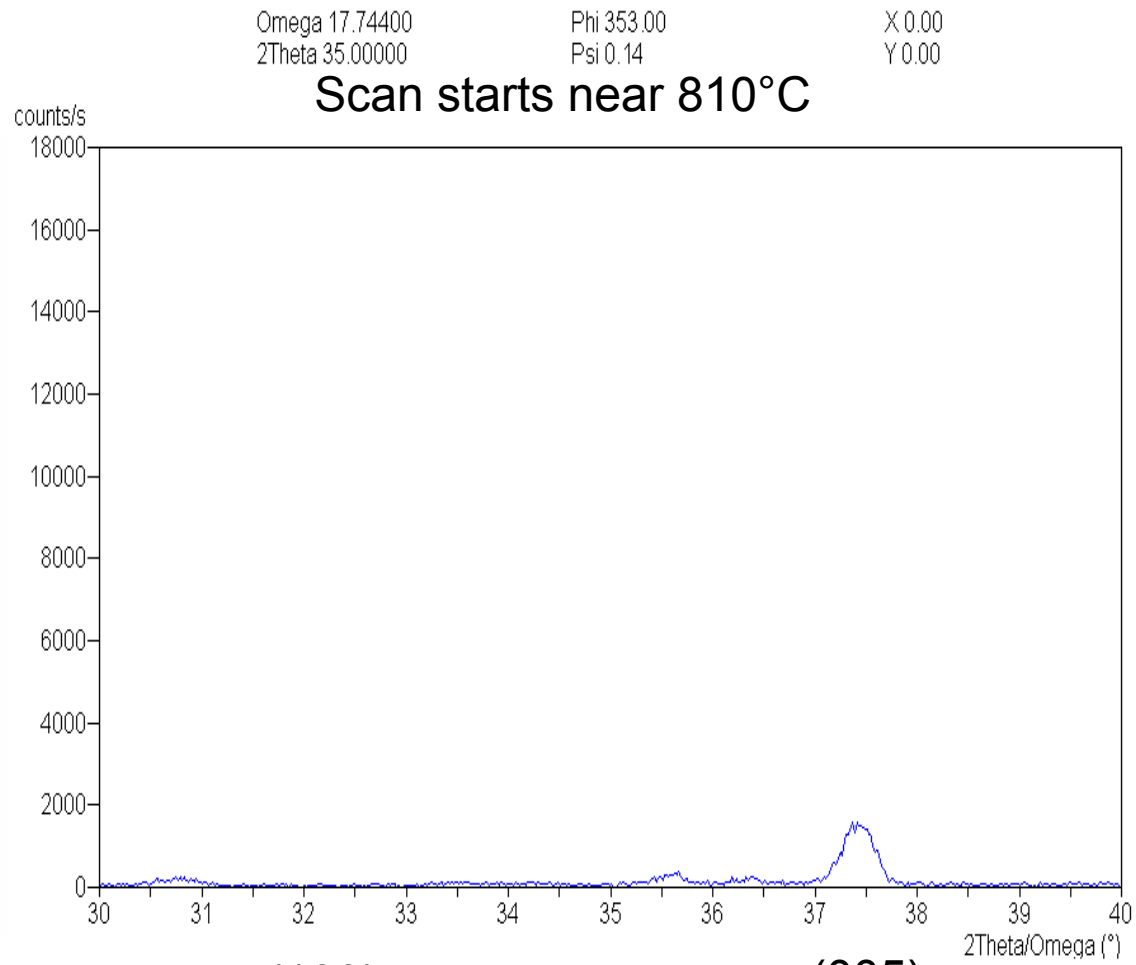
Heating in 0.05% Po_2





(103) (005)

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Dome Results

Sample #	% O_2	Rapid Growth Temp	Time for Growth	(005)/(103)
489A1	5	880°C	2 min	13
489A6	0.25	830°C	5 min	25
492A1	0.05	810°C	8 min	110

On $LaAlO_3$

- Conclusions:
  - Majority of growth occurs near liquid line
  - Rate of growth higher PO_2, higher temperature
  - (103) less at low growth rate, low temperature
  - R-T looks promising but need annealing

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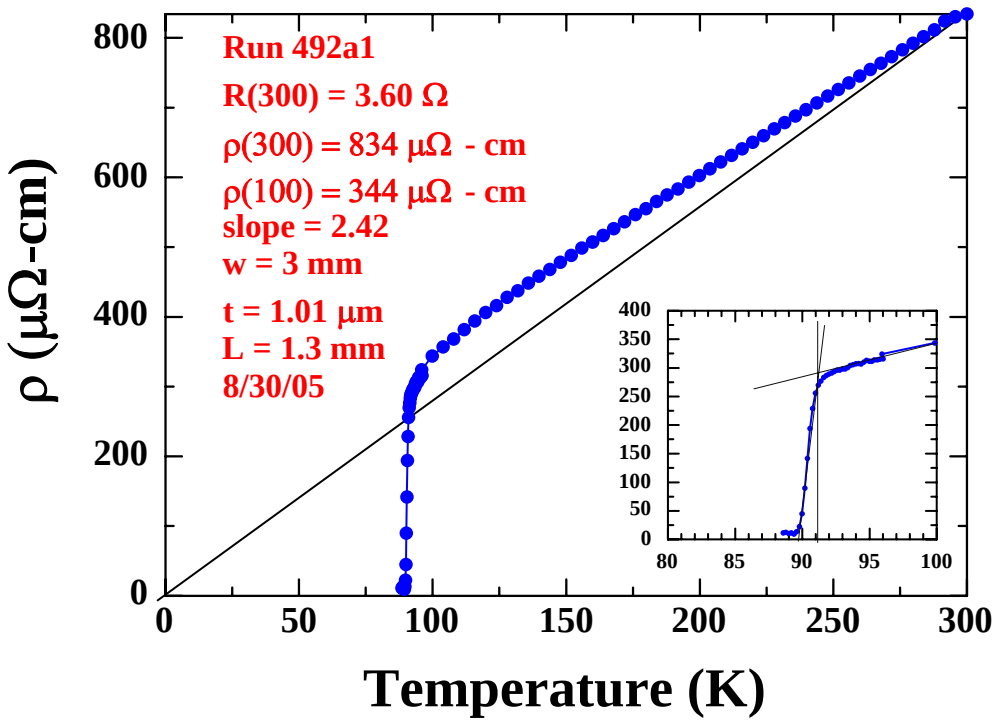
Resistivity-temperature curve of a sample grown on LAO with 0.05% oxygen partial pressure.
The slope runs above the extrapolation line from 0 to 300K,which indicates the sample might be lacking oxygen



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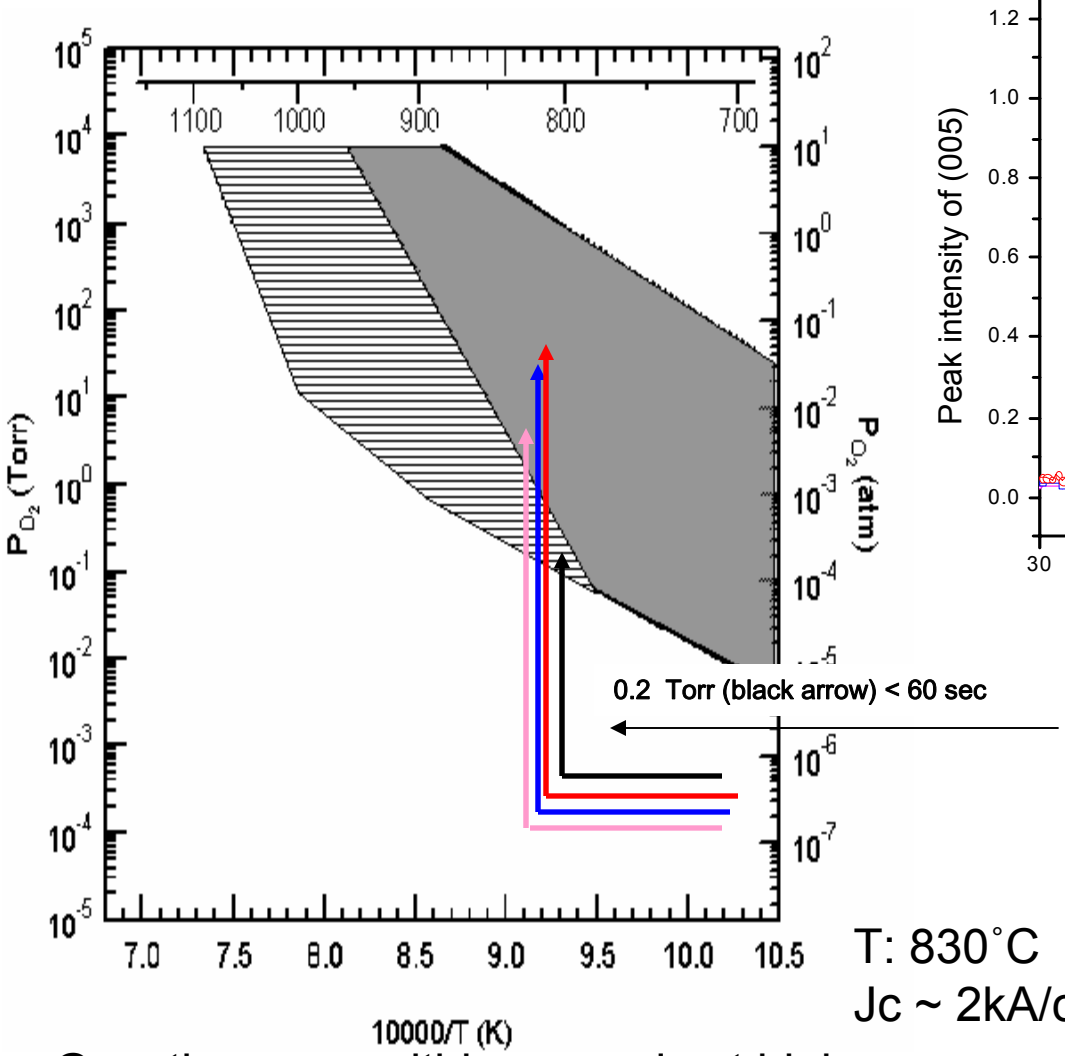
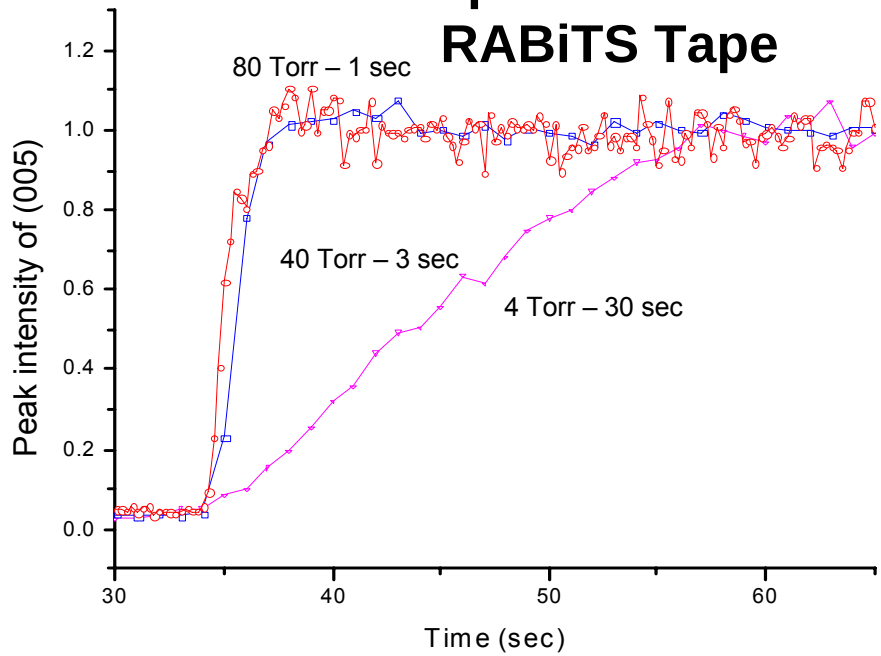
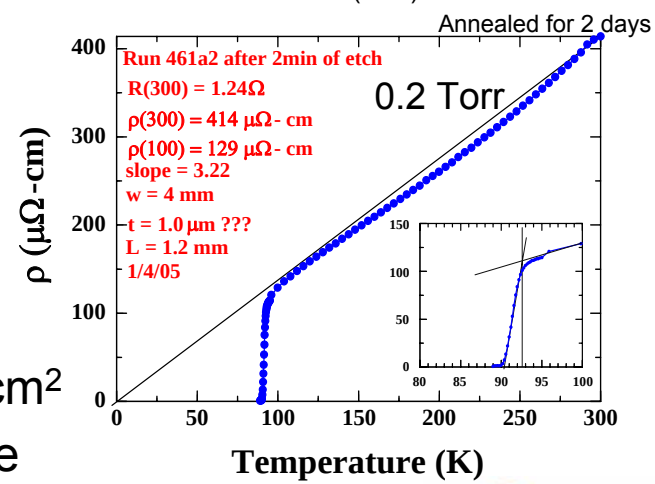
Example of XRD Dome:

Traces of temperature and pressure with the dome experiment:







T: 830˚C

Jc ~ 2kA/cm^2

Growth occurs within seconds at higher pressure

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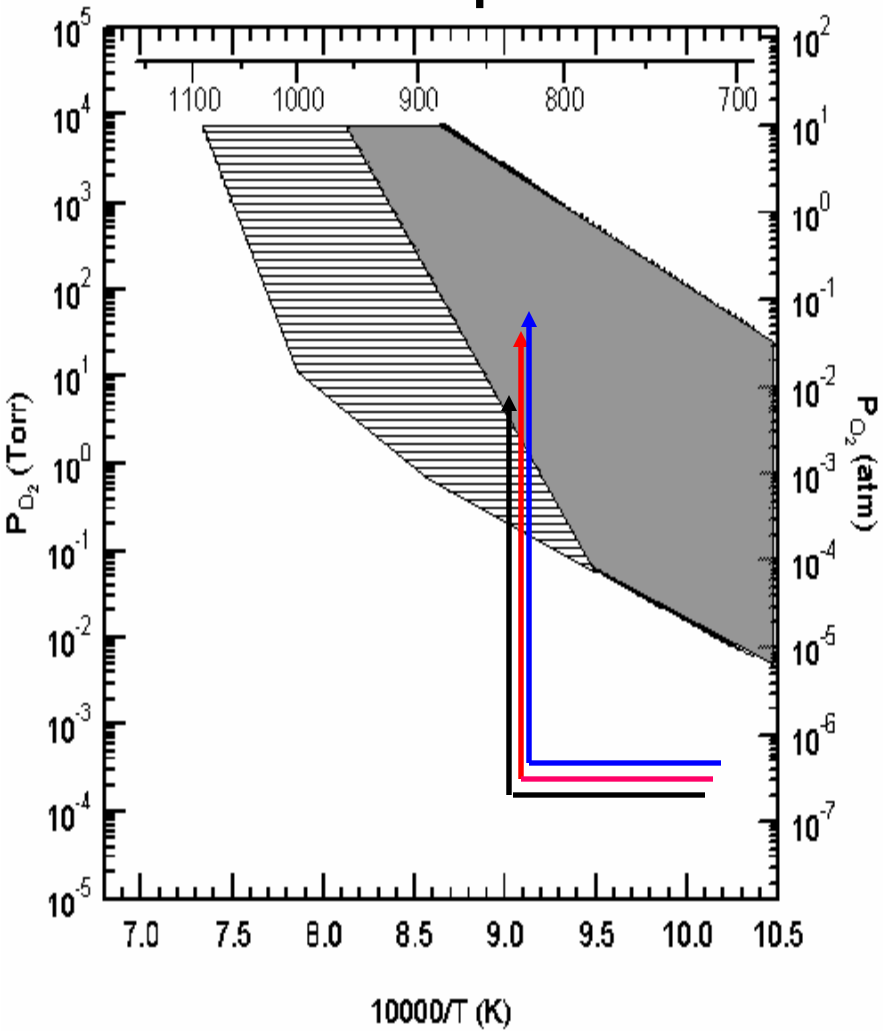
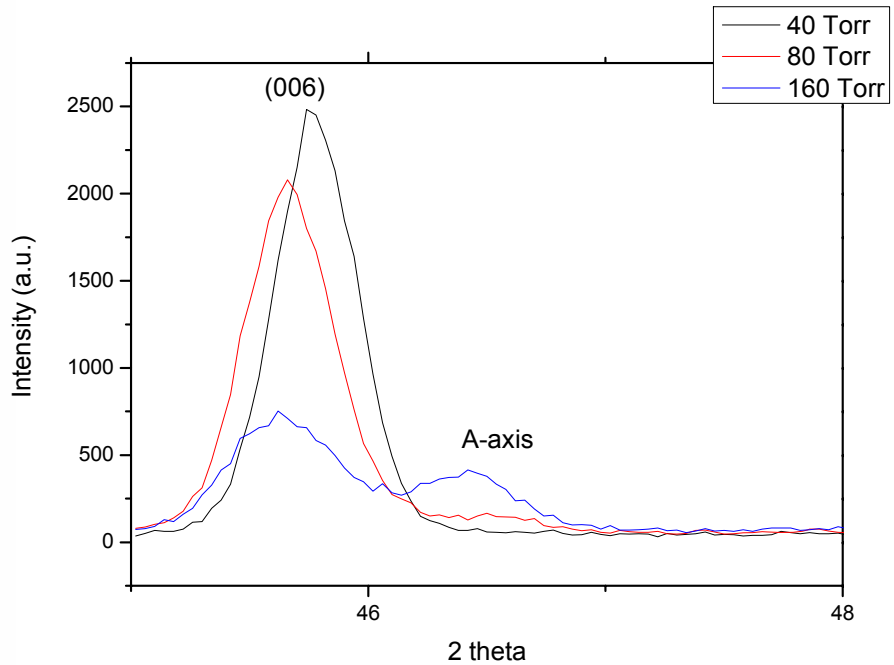
Example of XRD Dome: Traces of temperature and pressure with the dome experiment:

RABiTS Tape





- A-axis growth increases as pressure increases
  - Agreement with single crystal

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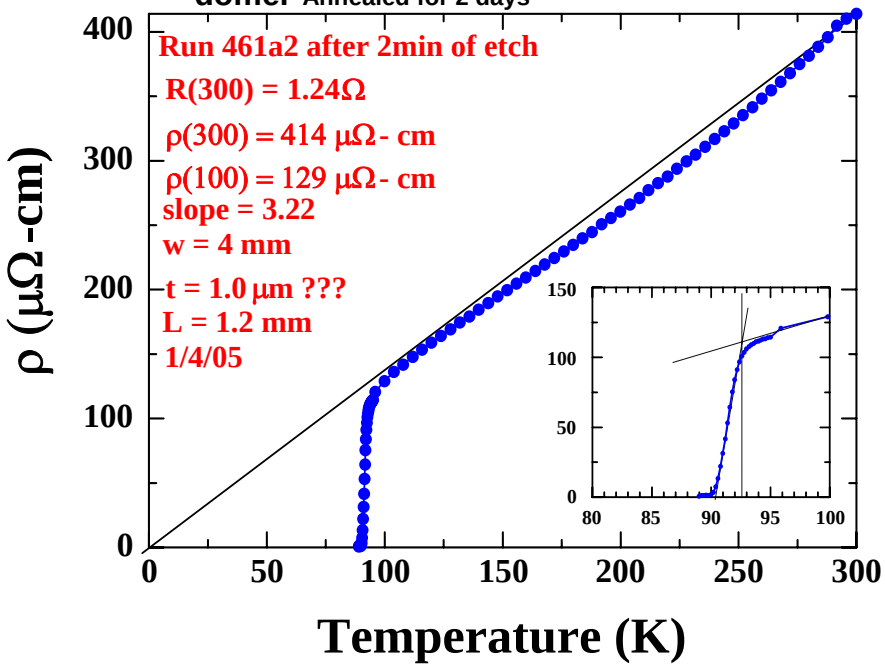
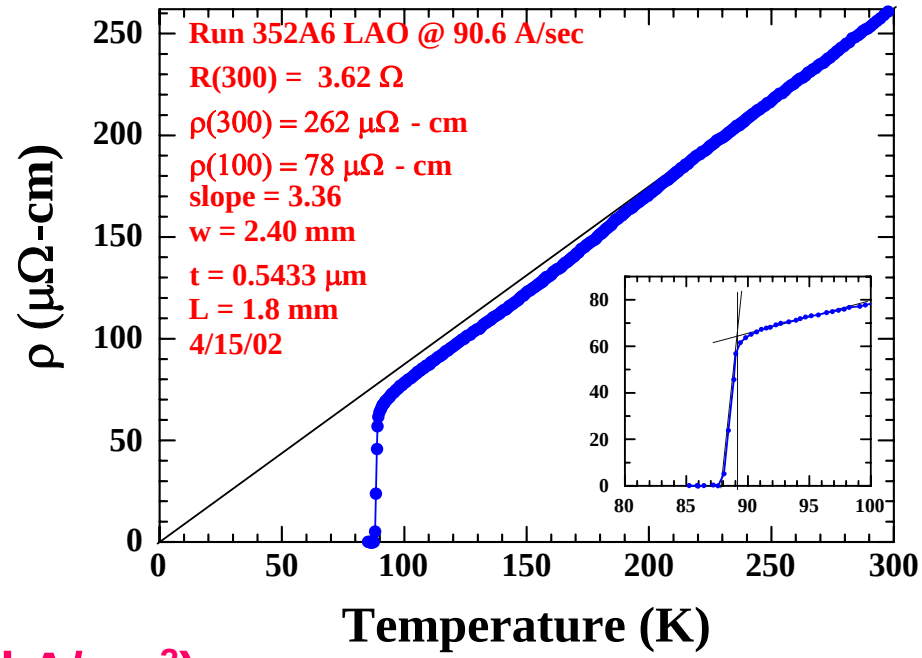
Resistivity-Temperature Curves

RABiTS : Pressurized to 0.2 Torr, in XRD-dome. Annealed for 2 days



LAO : 2-step In-situ: ΔP+cool



Jc = 2.5MA/cm²

- XRD Dome sample had **low Jc (2 kA/cm²)**
- Ideally resistivity at 300K ~ 250μΩ-cm
  - High resistivity of Dome sample could be from misplaced contacts or…
  - Cross section partially blocked or…
  - Contaminated by silver paint organics

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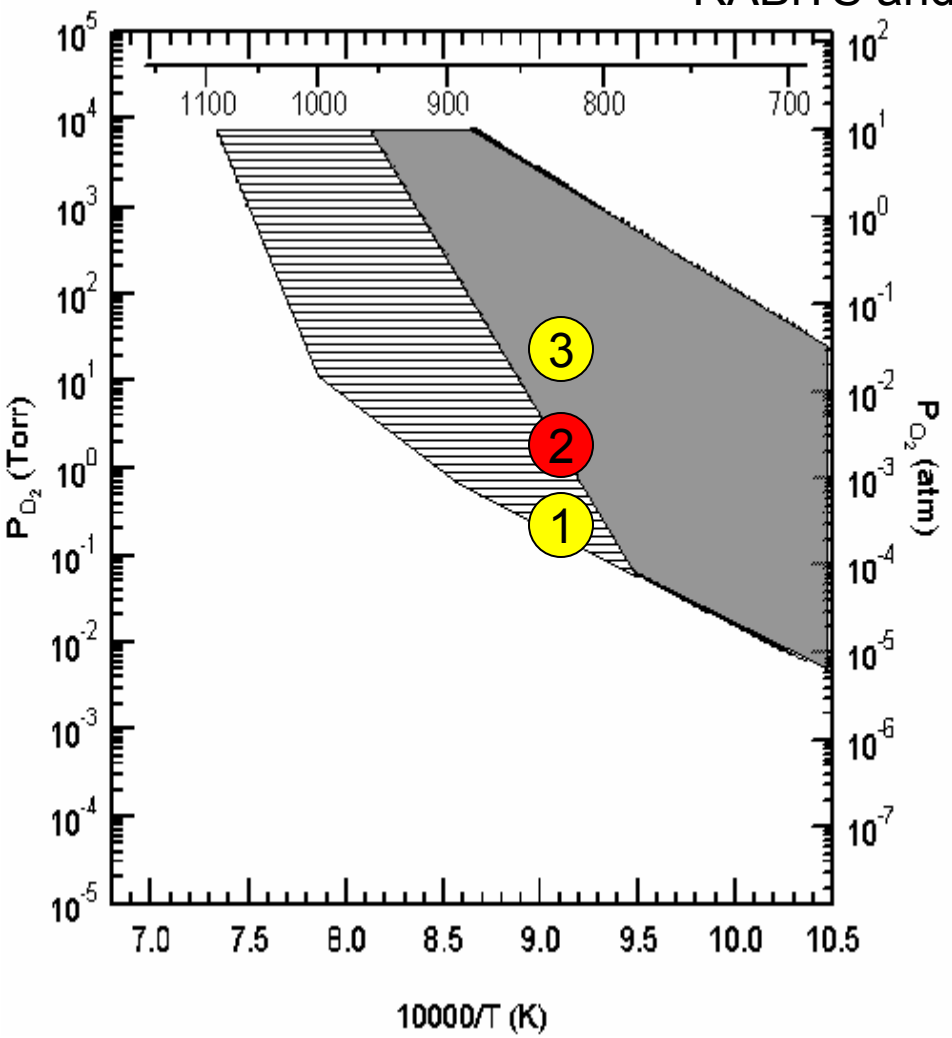
Summary of XRD Dome Results

RABiTS and Single Crystal



- Region 1
  - Slow growth
    - minutes to hours on $LaAlO_3$
    - Seconds to minutes on RABiTS
  - "Perfect" c-axis ?
  - Hard to get O_2 in
  - No pinning << 1MA/cm^2
- **Region 2**
  - **Faster growth**
  - **RABiTS – Predominantly C-axis**
  - **$LaAlO_3$ – small (103)**
- Region 3
  - Tends to be polycrystalline
  - Very rapid growth < 1sec
- All need extra annealing
- Candidate for nano-engineering

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ORNL: Basic studies toward F-free precursors for *ex situ* HTS coatings

K. Kim, Y. Zhang, R. Feenstra, H. M. Christen, S. Cook,
F. A. List, J. Tao, S. J. Pennycook, Y. Zuev

- Controlled deposition of F-free (also C-free) precursors by PVD
- Potential advantages as *ex situ* precursors:
  - No processing by-products (e.g., no need to control HF removal)
  - Batch processing possible (spool up in large furnace)
  - Compatibility with wide range of buffer materials

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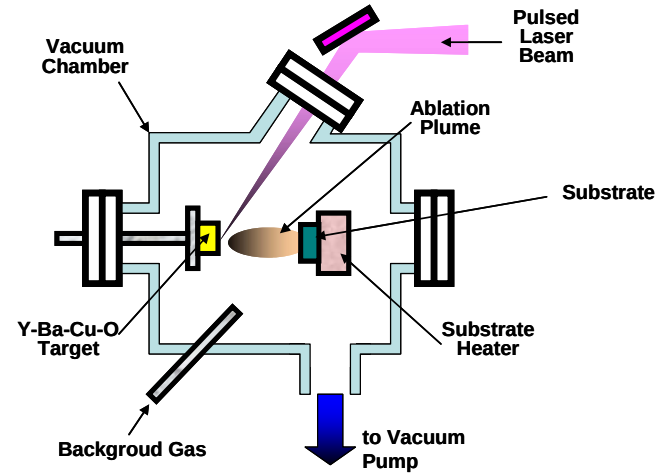
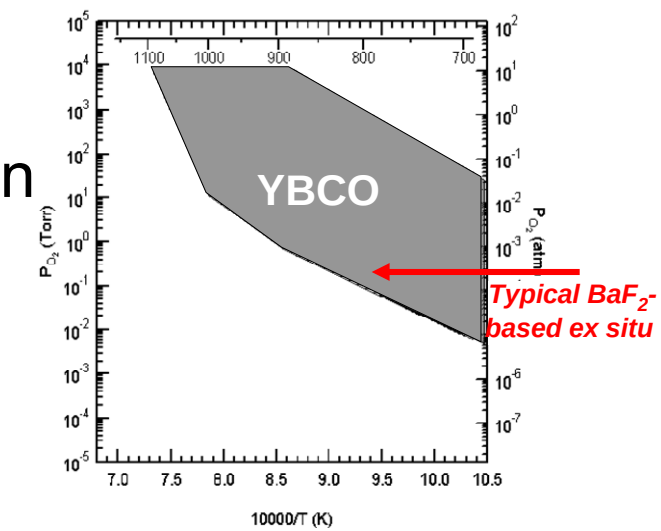
Approach: baseline controlled synthesis/properties

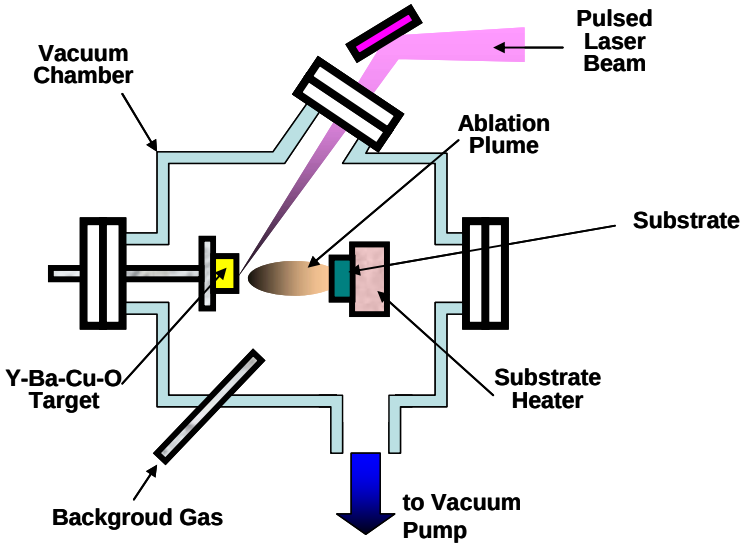
- Deposit thin precursor films on single crystal substrates at room-T by PLD
  - $LaAlO_3$ and $SrTiO_3$ substrates
  - YBCO and YBCO/2%$BaZrO_3$ PLD targets
- Process precursors both *in deposition chamber* (no air exposure) and *ex situ* (air exposure, but surface passivated)
- Properties characterization and iteration
  - ICP (composition)
  - XRD (structure, epitaxy)
  - SEM, TEM (nanostructure)
  - Magnetic and transport (T_c, J_c)





Precursors:

- Deposition:
  - Substrates at room temperature
  - 100 mTorr O_2 ambient
  - Thickness 0.1 – 0.5 μm



- ICP shows near 1:2:3 stoichiometry

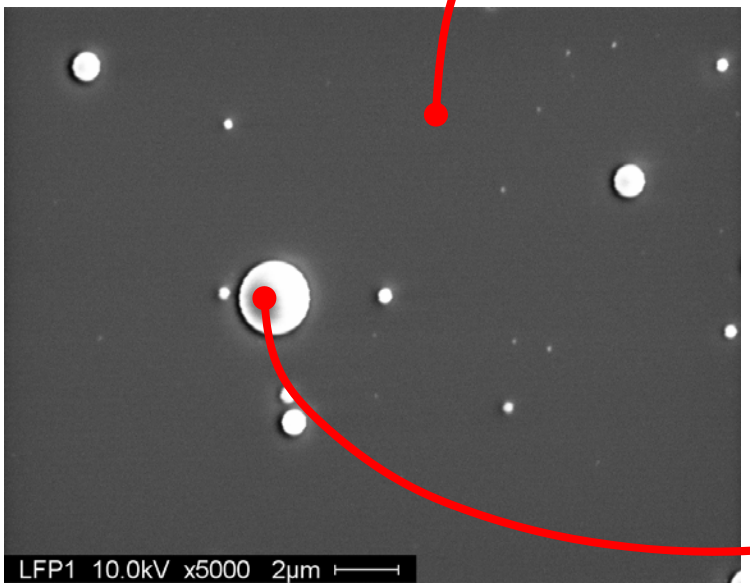
- XRD → pseudo-amorphous (no Bragg peaks)

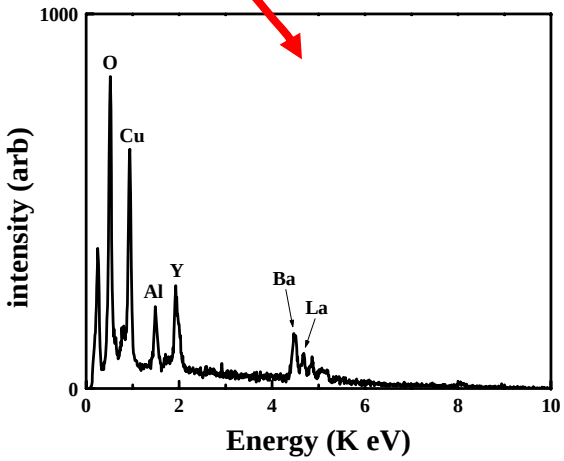
- Passivated against atmospheric exposure (~100 nm Ag cap layer for *ex situ* processing)

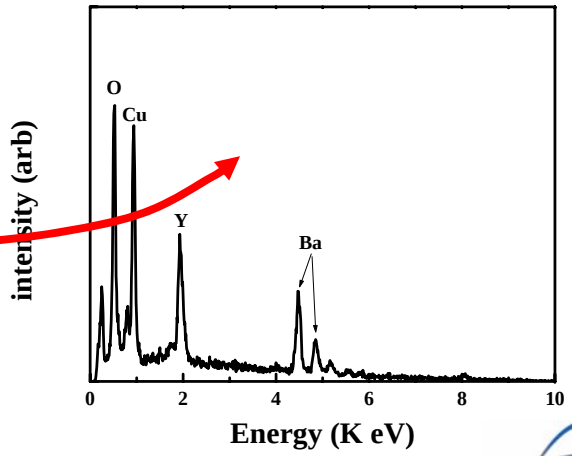
Precursor:

- Smooth, with some particulates
- Composition uniform (EDS→Y:Ba:Cu ratios same)

as-deposited precursor film on $LaAlO_3$ @ RT, P_{O2} 1.0×10^{-1} Torr







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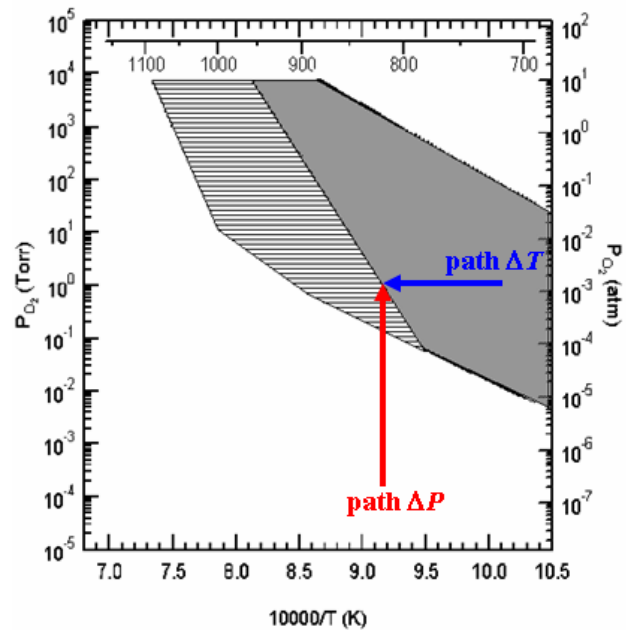
Conversions:

- Evaluated large array of parameters along processing paths "ΔP" and "ΔT"
  - Conversion temperature and $P(O_2)$
  - For ΔP path, ambient during T-ramp of precursor
  - Proximity to "012" liquid line



precursor growing					heating-up		processing					
temp.	gas	press.	E	shots	gas	press.	temp.	h/r	gas	press.	O press.	duration
RT	O_2	1.0E-01	320	4000	O_2	1.0E-01	780	16.8	O_2	1.0E-01	1.0E-01	10
RT	O_2	2.0E-04	330	5000	O_2	1.0E-01	780	19.9	O_2	1.0E-01	1.0E-01	10
RT	vacuum	1.5E-08	330	5000	O_2	1.0E-01	780	19.4	O_2	1.0E-01	1.0E-01	10
RT	O_2	1.0E-01	410	5000	O_2	1.0E-01	700	21.1	O_2	1.0E-01	1.0E-01	8
RT	O_2	1.0E-01	410	5000	O_2	2.0E-01	850	21.2	O_2	2.0E-01	2.0E-01	20
RT	O_2	1.0E-01	420	5000	O_2	3.0E-01	700	21.8	O_2	3.0E-01	3.0E-01	30
RT	O_2	1.0E-01	410	5000	O_2	3.0E-01	850	22.3	O_2	3.0E-01	3.0E-01	30
RT	O_2	1.0E-01	400	7000	O_2	3.0E-01	850	75.0	O_2	3.0E-01	3.0E-01	25
RT	O_2	1.0E-01	400	5000	O_2	4.0E-01	980	19.1	O_2	4.0E-01	4.0E-01	30
300	O_2	5.0E-05	400	7000	O_2	3.8E-01	810	35.7	O_2	3.8	3.8E-01	8
RT	O_2	5.0E-05	420	7000	O_2	3.8E-01	850	15.9	O_2		3.8E-01	30
RT	O_2	1.0E-01	400	7000	$99O_2/H_2O$	1.0E-02	700	24.1	$99O_2/$		9.9E-03	30
RT	O_2	1.0E-01	400	7000	$99O_2/H_2O$	1.0E-02	710	26.4			9.9E-03	30
300	O_2	1.0E-01	400	5000	O_2	3.0E-01	850	3			3.0E-01	30
RT	O_2	5.9E-02	400	5000	$9.8O_2/H_2O$	6.5E-02					5.9E-02	10
BF_2 pre cursor film					$9O_2/H_2O$	1.0E-01				1.0E-01	9.0E-02	30
RT	O_2	1.0E-01	420	5000	O_2/N_2		7		O_2/N_2	3.0E-01	1.5E-01	30
RT	O_2	2.0E-04	400	7000			800	29.8	O_2	1.0E-01	1.0E-01	30
RT	O_2	2.0E-04	400	7000			0	17.2	O_2	9.0E-01	9.0E-01	30
RT	O_2	1.0E-01	400				820	19.9	O_2	1.0	1.0	30
RT	Ar/H_2	1.				1.0E-01	820	22.1	O_2	9.0E-01	9.0E-01	30
RT	Ar/H_2			40		9.0E-01	820	22.1	O_2	9.0E-01	9.0E-01	30
RT	Ar/H_2			4	O_2	9.0E-01	820	22.1	O_2	9.0E-01	9.0E-01	74
RT	Ar/H_2			4000	Ar/H_2	3.0E-01	800	22.8	$O_2/Ar\text{-}H_2$	3.0E-01	1.5E-01	30
RT	Ar/H_2			4000	Ar/H_2	1.0E-01	800	23.5	$O_2/5Ar\text{-}H_2$	1.0E-01	1.7E-02	10
RT	Ar/H_2	1.	450	4000	Ar/H_2	5.0E-01	790	21.9	$O_2/5Ar\text{-}H_2$	5.0E-01	8.3E-02	72
RT	Ar/H_2	1.0E-04	460	4000	Ar/H_2	9.1E-01	810	24.5	$2O_2/Ar\text{-}H_2$	9.1E-01	6.1E-01	30
RT	Ar/H_2	1.0E-04	460	4000	Ar/H_2	1.0	820	22.9	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	30
RT	O_2	1.0E-04	460	4000	O_2	1.0E-04	800	28.0	O_2	2.7E-01	2.7E-01	15
RT	O_2	1.0E-04	460	4000	vacuum		830	26.8	O_2	4.0E-01	4.0E-01	40
RT	O_2	1.0E-04	450	4000	Ar/H_2	1.0	820	21.6	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	5
RT	O_2	1.0E-04	460	4000	Ar/H_2	1.0	850	24.5	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	10
RT	O_2	1.0E-04	440	4000	Ar/H_2	1.0	780	23.0	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	4
RT	O_2	1.0E-01	450	4000	Ar/H_2	1.0	850	23.2	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	5
300	O_2	5.0E-05	450	15400	Ar/H_2	3.8E-01	810	26.4	O_2	3.8E-01	3.8E-01	11
RT	O_2	1.0E-01	450	4000	Ar/H_2	1.0	850	25	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	15
RT	O_2	1.0E-04	460	4000	$O_2/9Ar\text{-}H_2$	1.0	820	23.4	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	5
RT	O_2	1.0E-04	450	4000	$O_2/125Ar\text{-}H_2$	1.6E-02	820	26.6	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	20
RT	O_2	1.0E-04	460	4000	Ar/H_2	8.9E-01	820	24.3	O_2	8.9E-01	8.9E-01	10
RT	O_2	1.0E-04	460	4000	Ar/H_2	1.0	820	75.7	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	10
RT	O_2	1.0E-04	450	4000	Ar/H_2	1.0	820	22.1	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	5
RT	O_2	1.0E-04	450	4000	Ar/H_2	1.0	820	22.0	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	15
RT	O_2	1.0E-04	450	16000	Ar/H_2	1.0	820	22.7	$8O_2/Ar\text{-}H_2$	1.0	8.9E-01	33

Many samples produced

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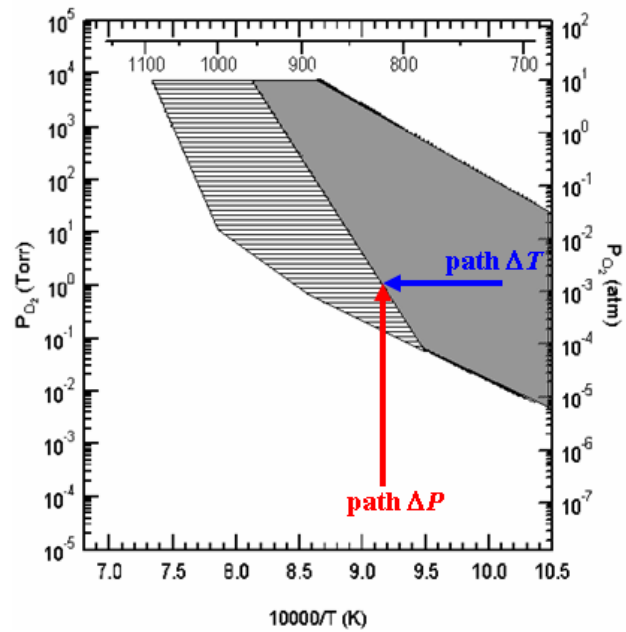
Conversions:

- Evaluated large array of parameters along processing paths "ΔP" and "ΔT"
  - Conversion temperature and $P(O_2)$
  - For ΔP path, ambient during T-ramp of precursor
  - Proximity to "012" liquid line

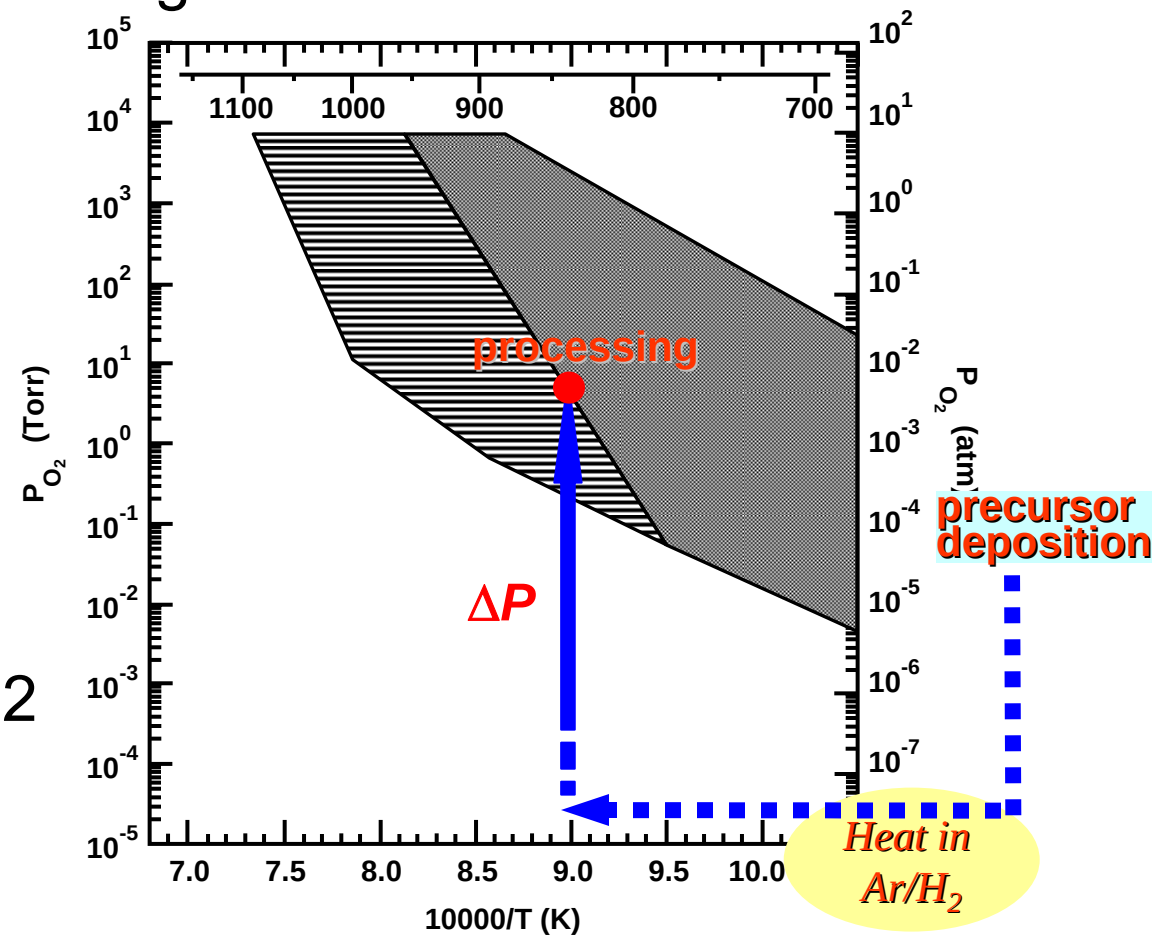


- Most conversions done *in situ* on substrate holder

- *Ex situ* conversions done at absolute $P(O_2)$ in controlled-atmosphere furnace (Ag-passivated samples)

Conversions: best results to date

- Heat precursor in reducing ambient (~1 Torr Ar/4%H_2)
- Follow path ***ΔP***
  [rapid P(O_2) ramp rate; no pause]
- Convert near the 012 melting line



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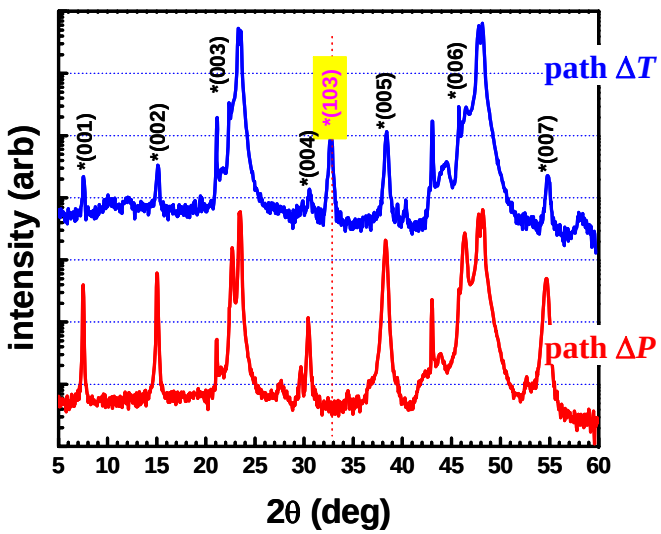
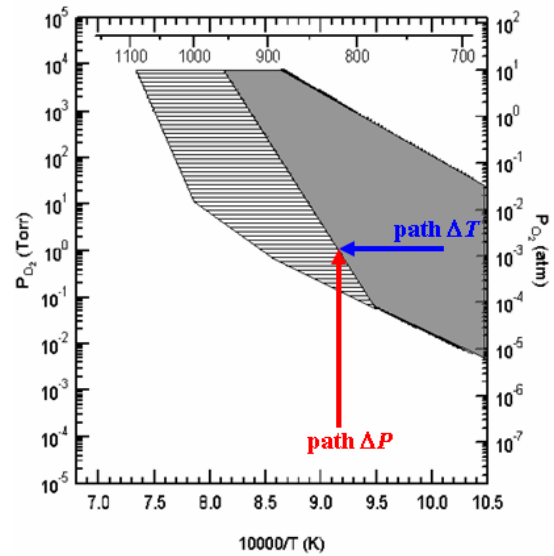
Properties:

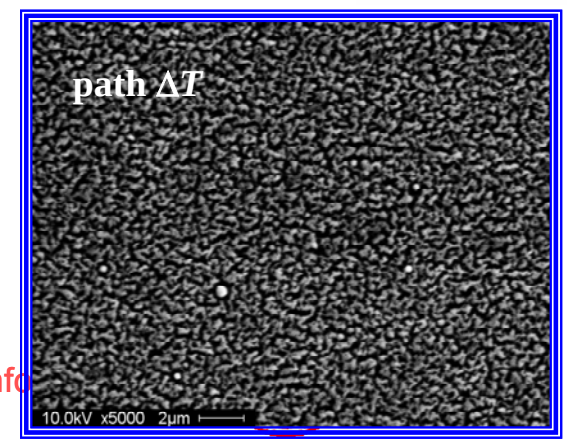
XRD of processed YBCO shows:

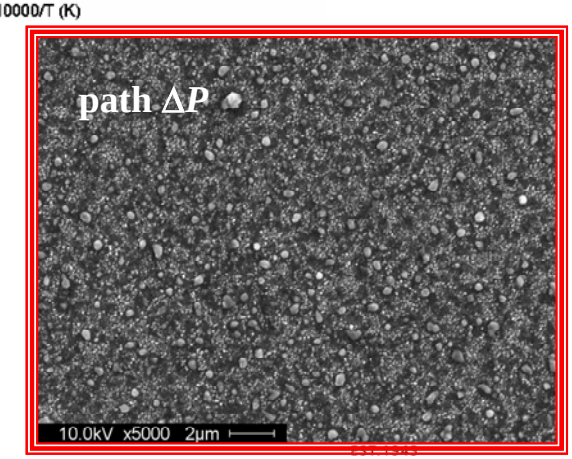
- ΔP path yields epitaxial, *c*-perp YBCO
- ΔT path produces polycrystalline YBCO component





- Related differences in surface morphology





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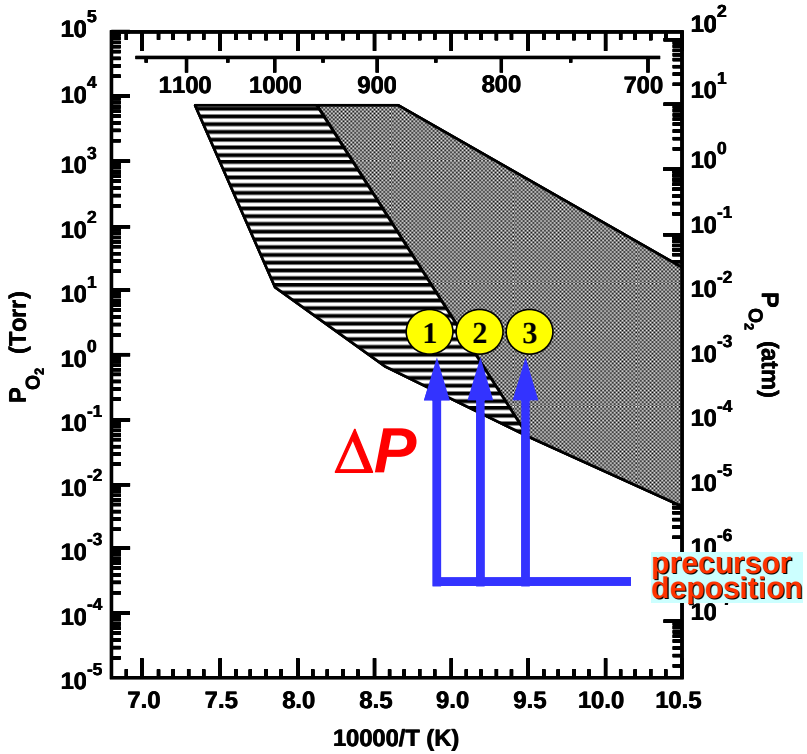
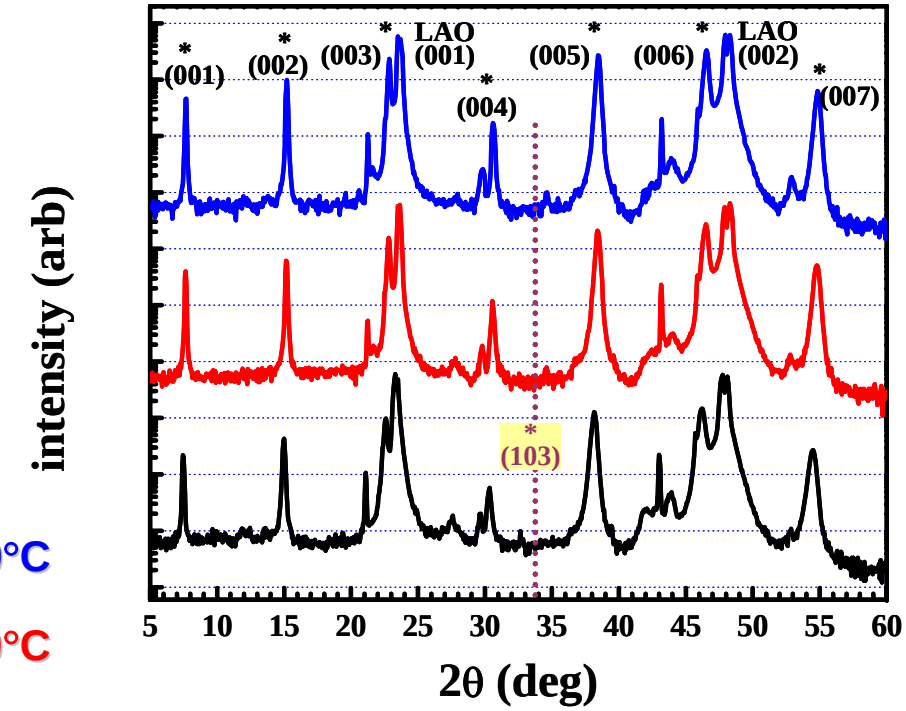
Properties:

For ΔP path, good epitaxy can be obtained at temperatures "near" the 012 melting line





1 850°C

2 820°C

3 780°C

P_{O2} = 880 mTorr

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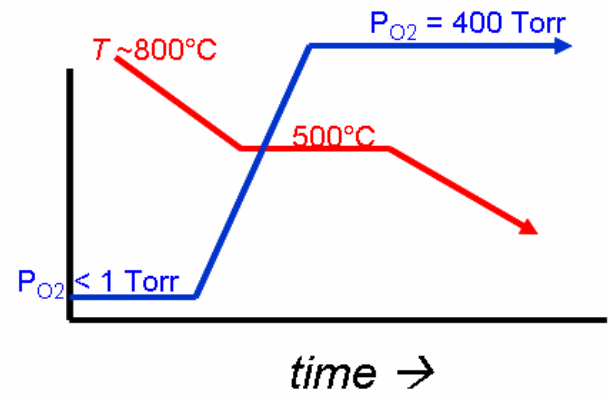
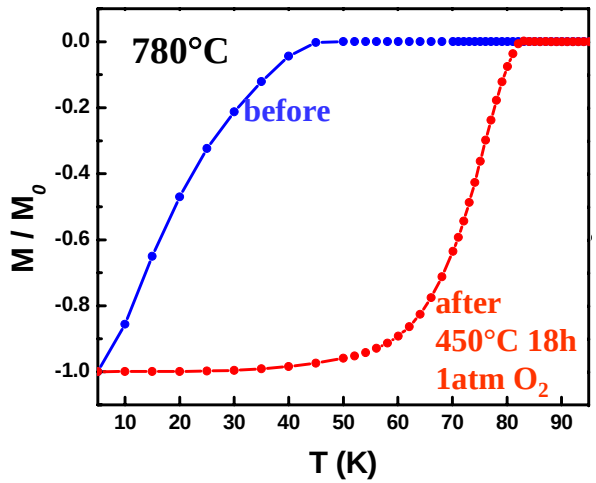
Properties:

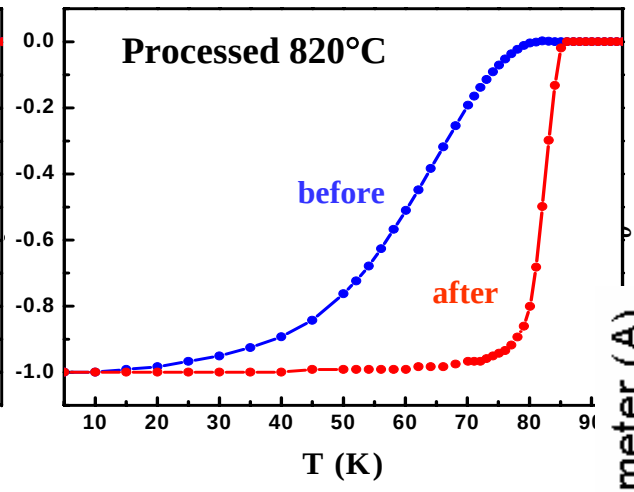
Superconducting T_c is suppressed

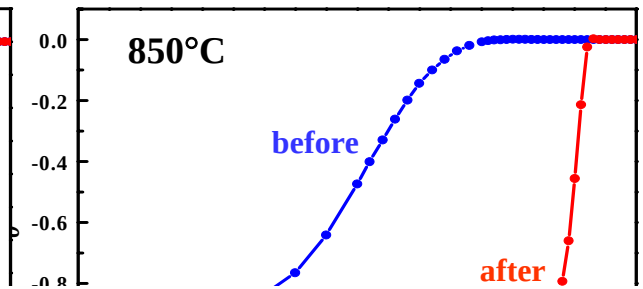
- As-processed films receive same oxygenation step as *in situ* PLD YBCO [but low T_c]



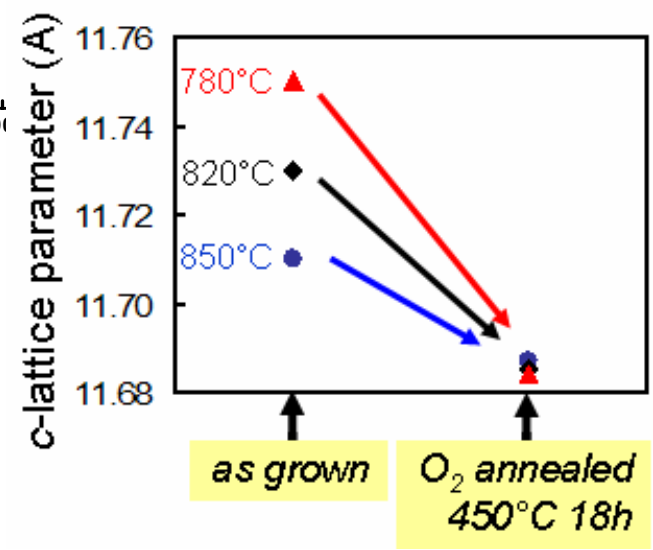
- Long oxygen anneal improves T_c







- and, *c*-lattice parameter contracts, consistent with oxygen uptake



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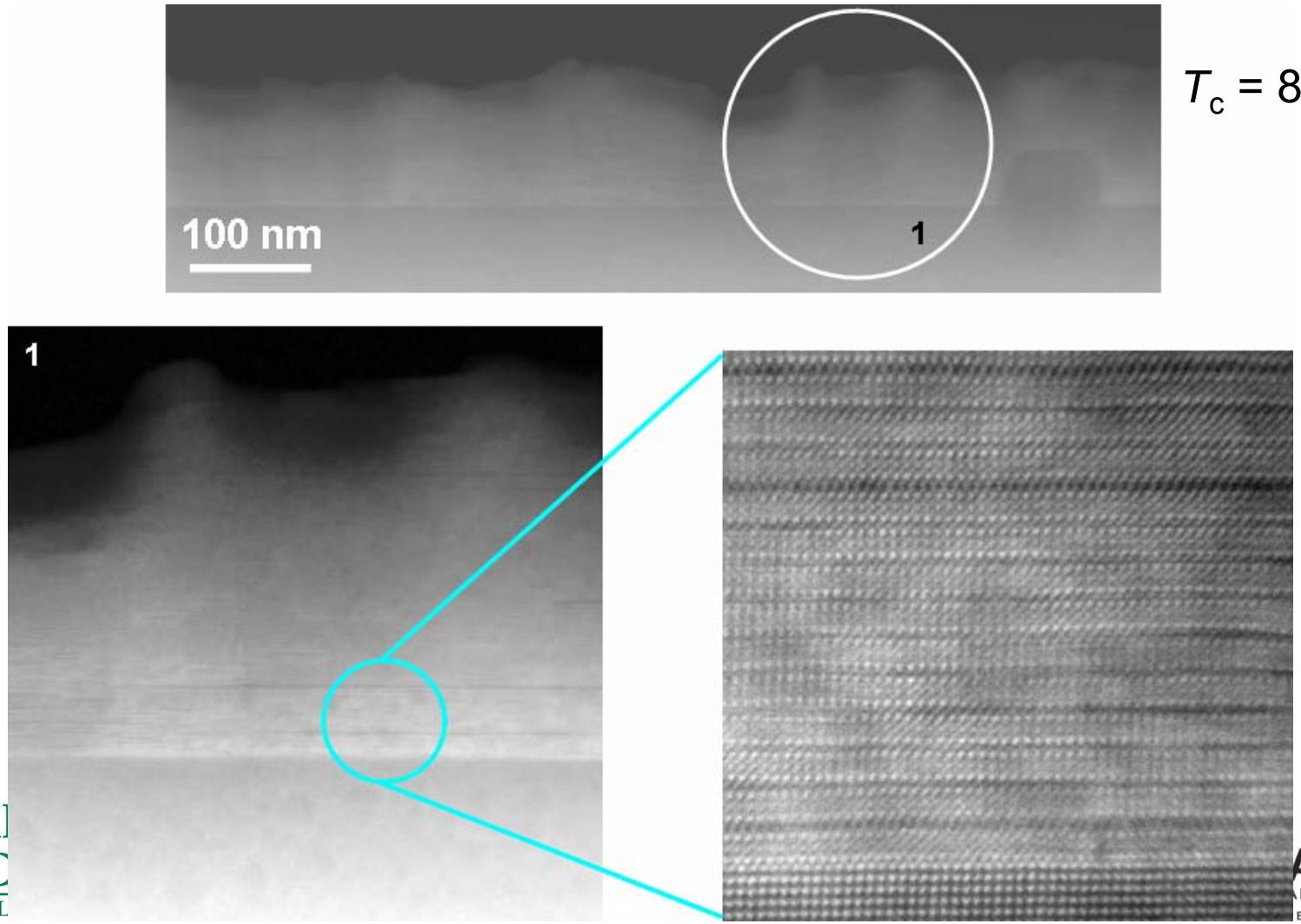
Properties:

TEM **cross-sections show few defects**

- ZSTEM images at different scales show that the F-free *ex situ* YBCO material is nearly defect free

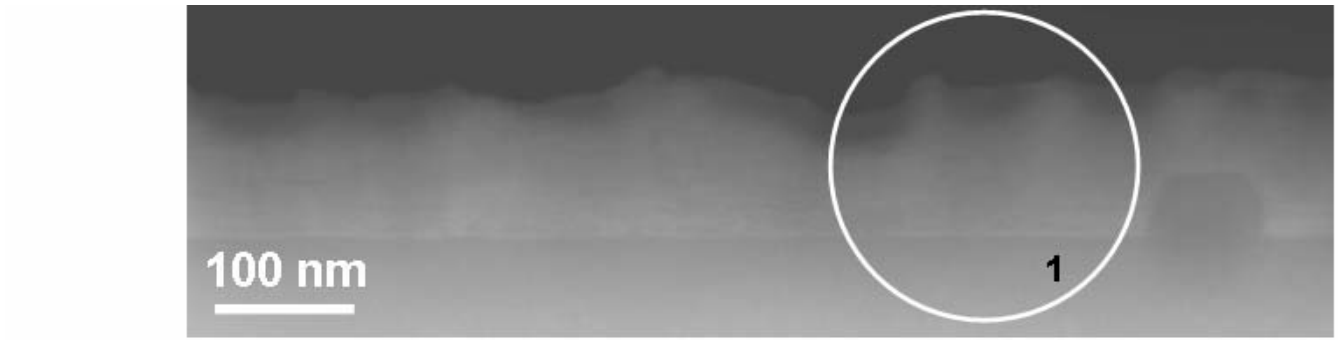


T_c = 87 K

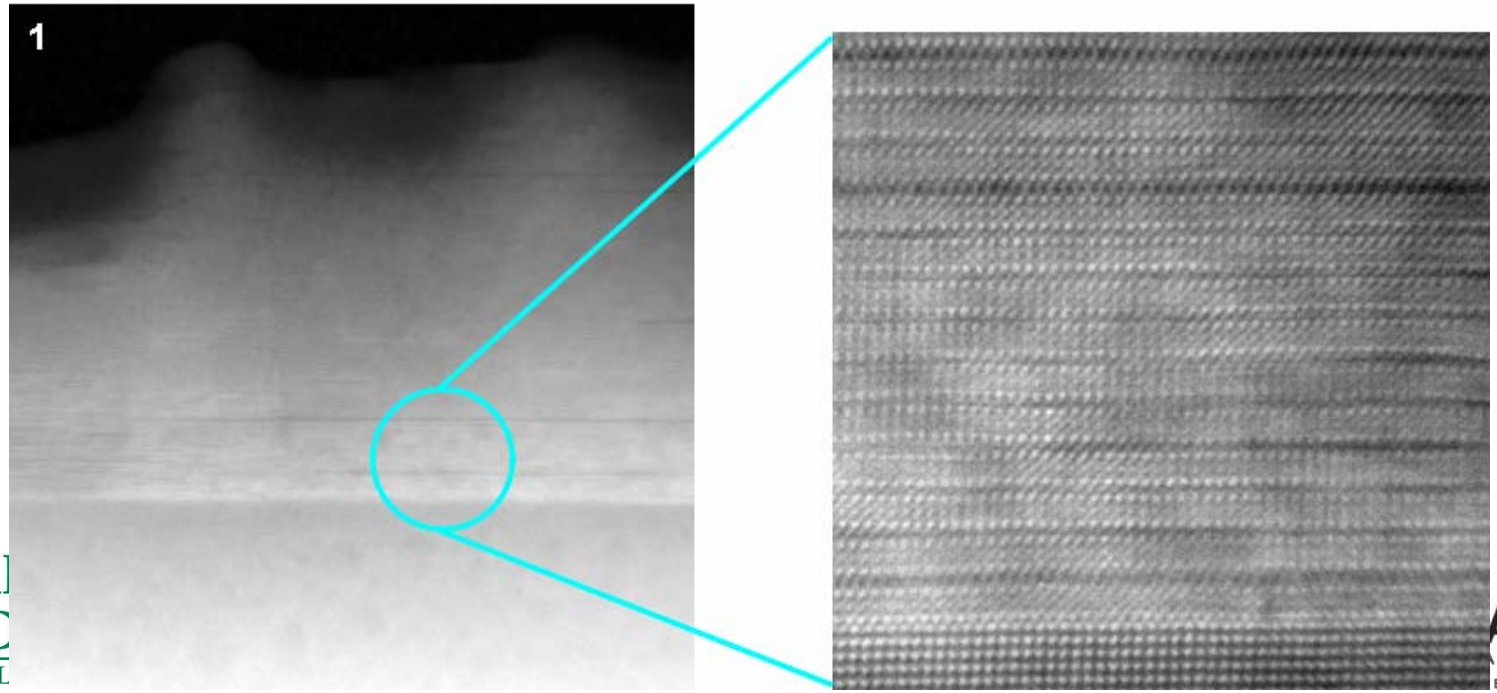
Properties:

TEM **cross-sections show few defects**

- Most “defects” are planar stacking fault intergrowth in the ~20 nm layer near the YBCO-substrate interface



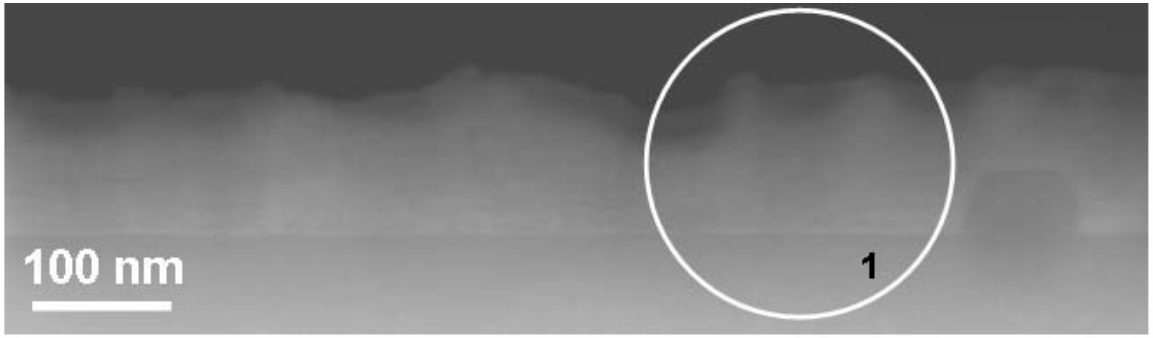
T_c = 87 K



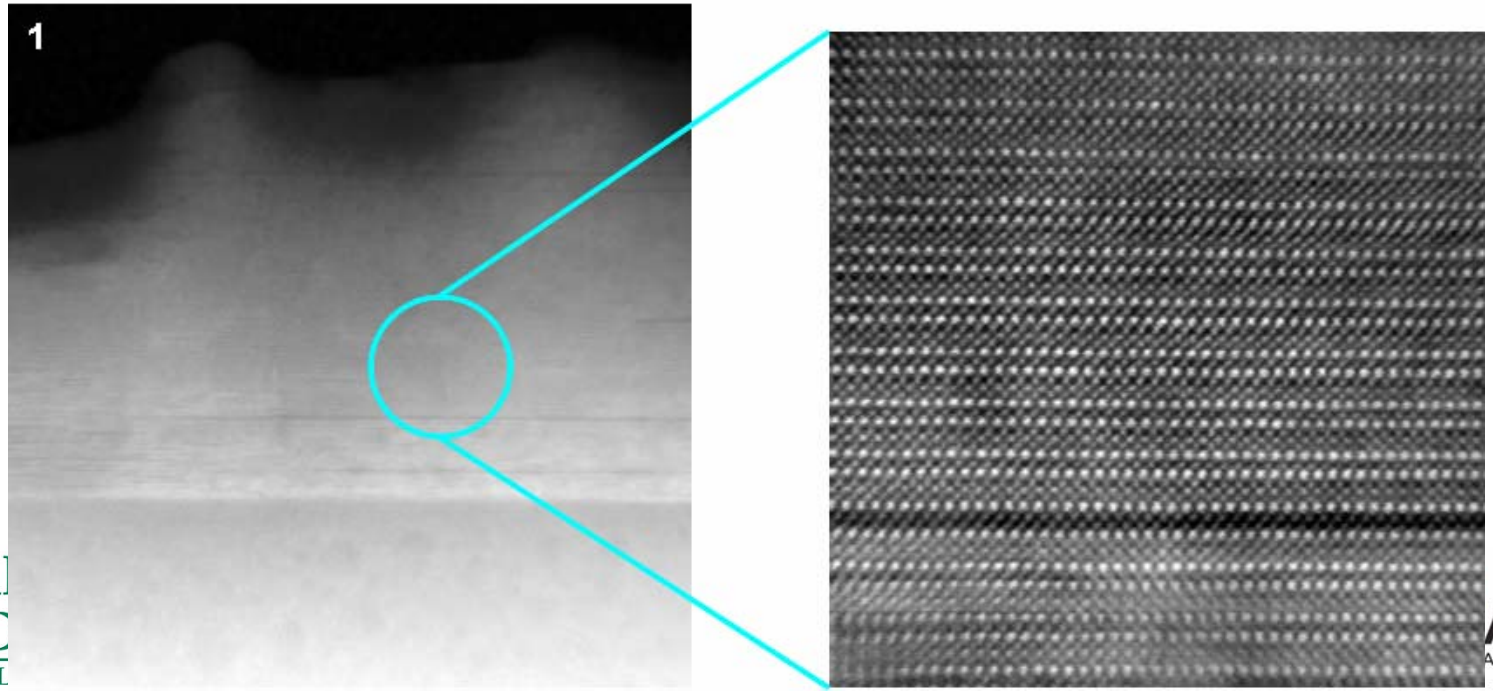
Properties:

TEM cross-sections show few defects

- Virtually no threading defects through the film thickness and improved perfection away from the substrate interface



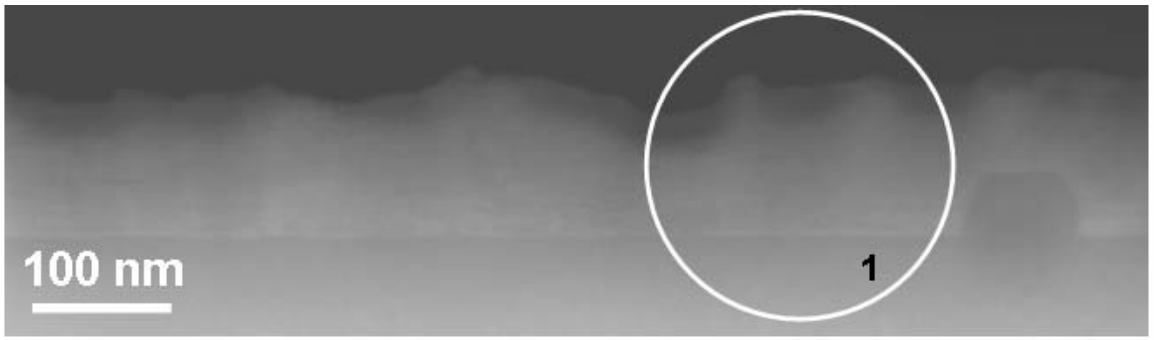
T_c = 87 K



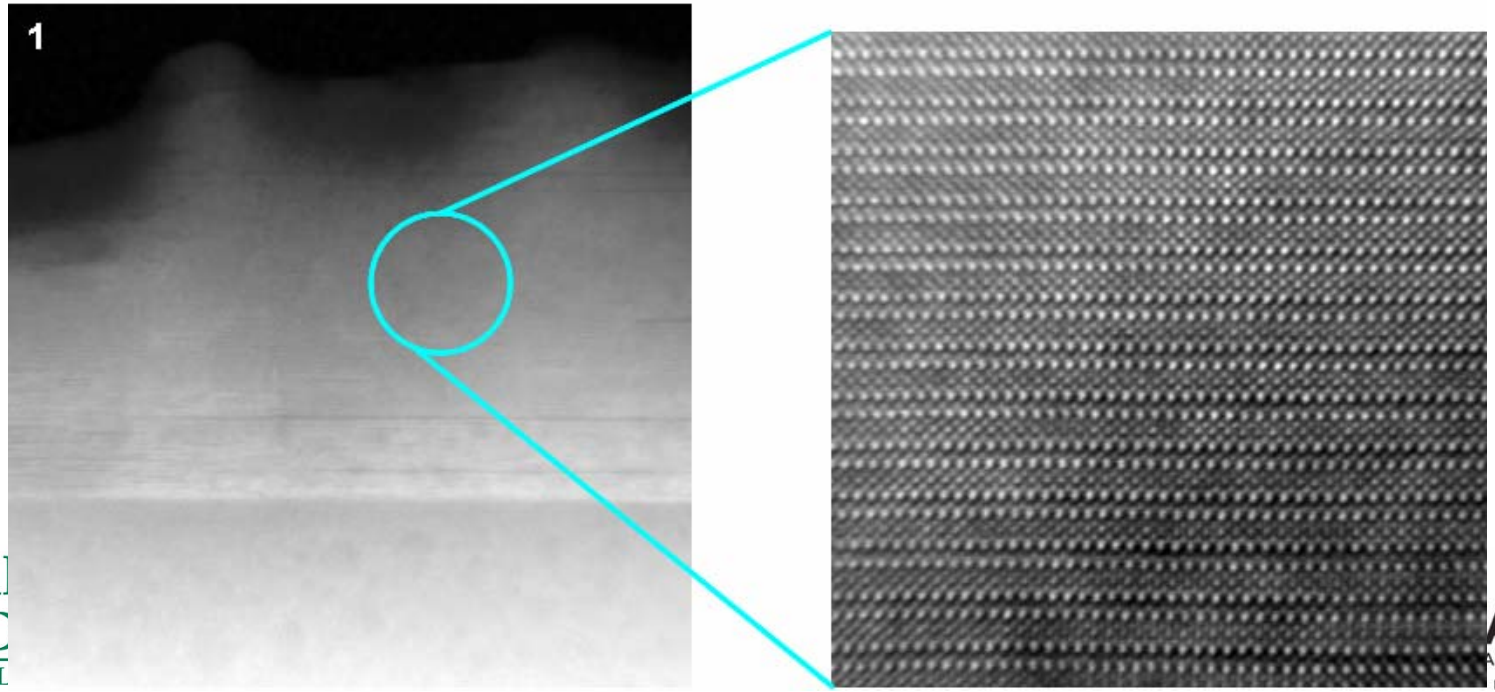
Properties:

TEM cross-sections show few defects

- The lack of visible nanoscale defects is consistent with the difficulty in oxygen uptake and the observed low flux pinning



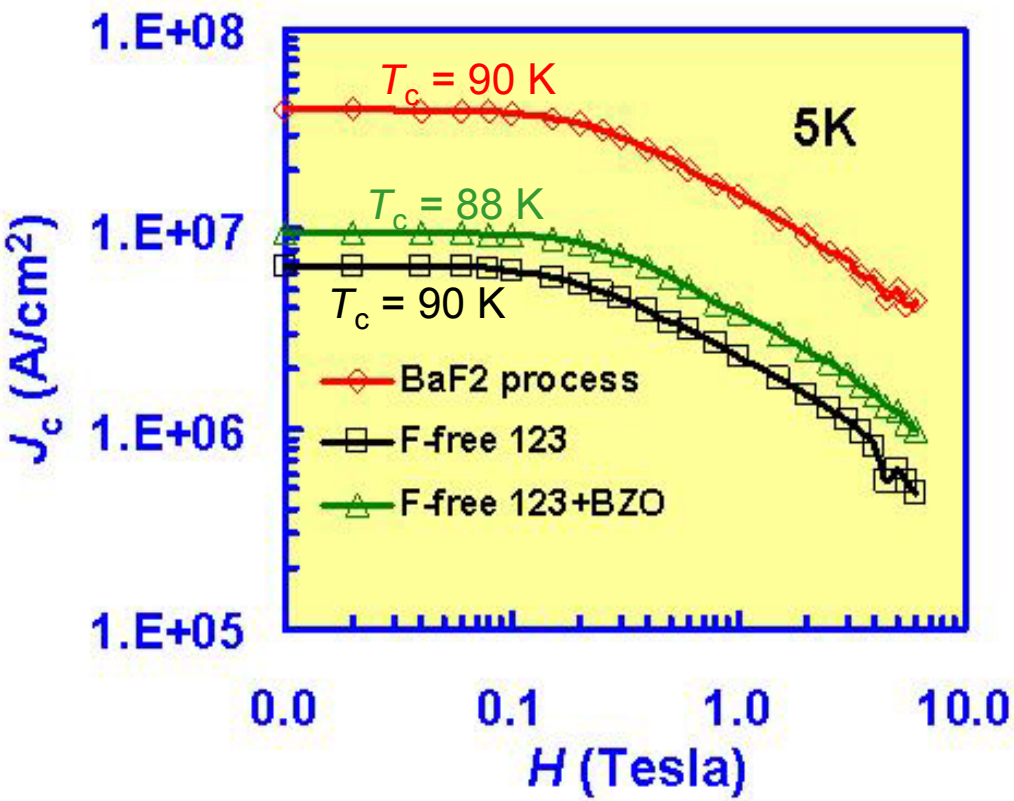
T_c = 87 K

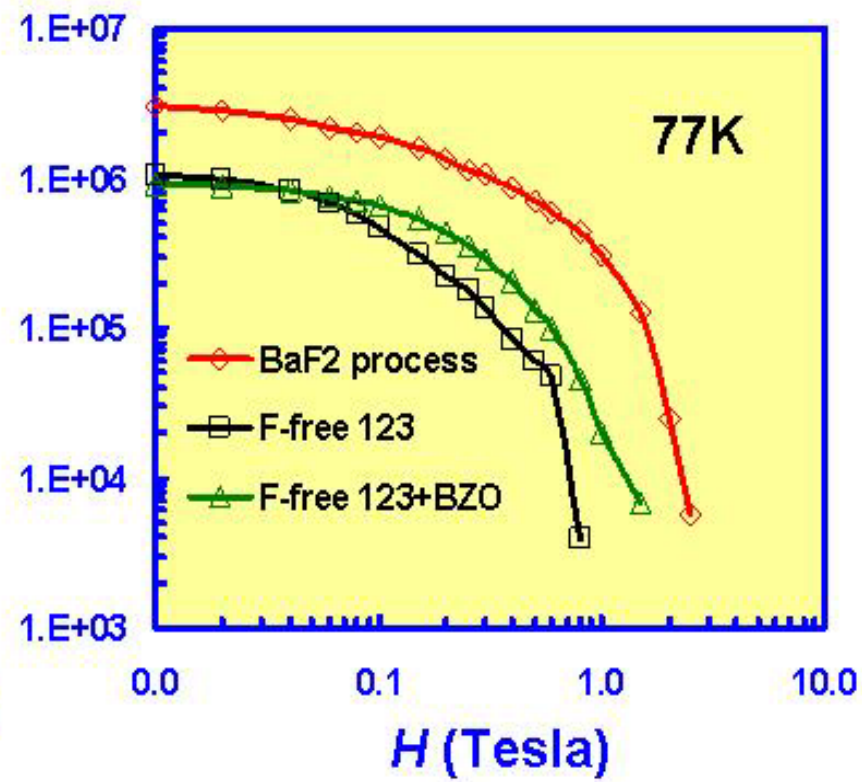


Properties:

J_c shows relatively weak flux pinning

- Magnetically-determined J_c (Bean model) values are lower than *ex situ* YBCO from comparable PVD BaF_2-based precursors
- Best results to date from BZO-doped YBCO targets (both as-grown T_c and in-field J_c)



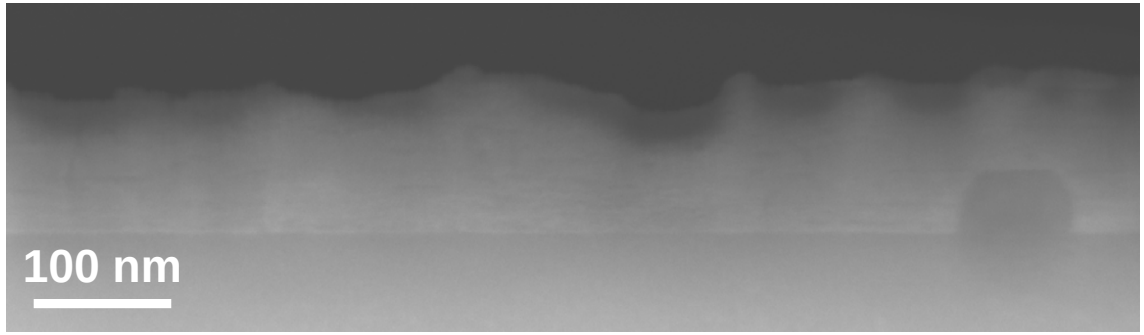


Properties:

TEM cross-sections show few defects

- Comparison with BaF_2-based film of comparable thickness

F-free *ex situ YBCO*



BaF_2 *ex situ YBCO*

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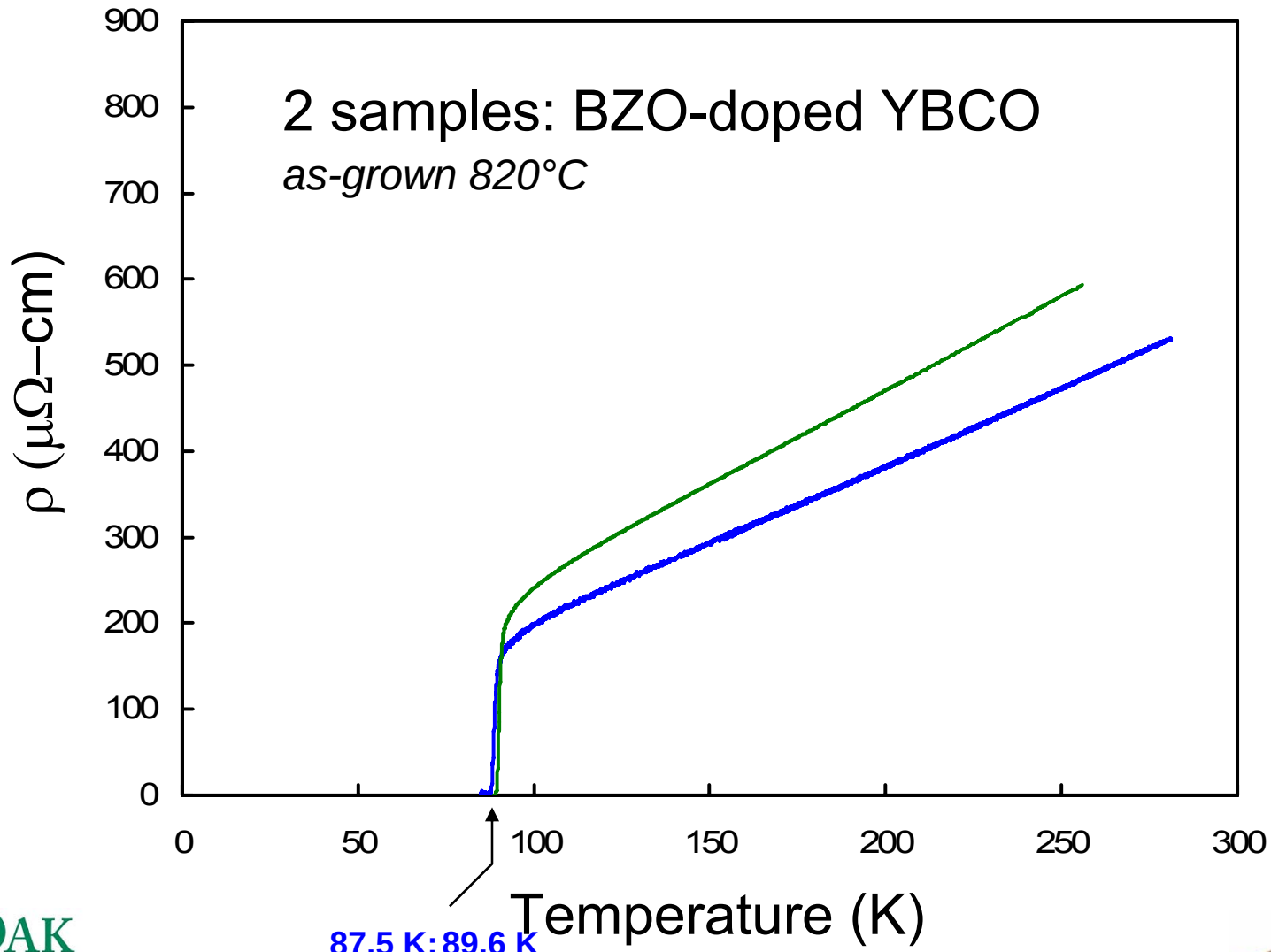
Properties:

BZO-doped normal state resistivity



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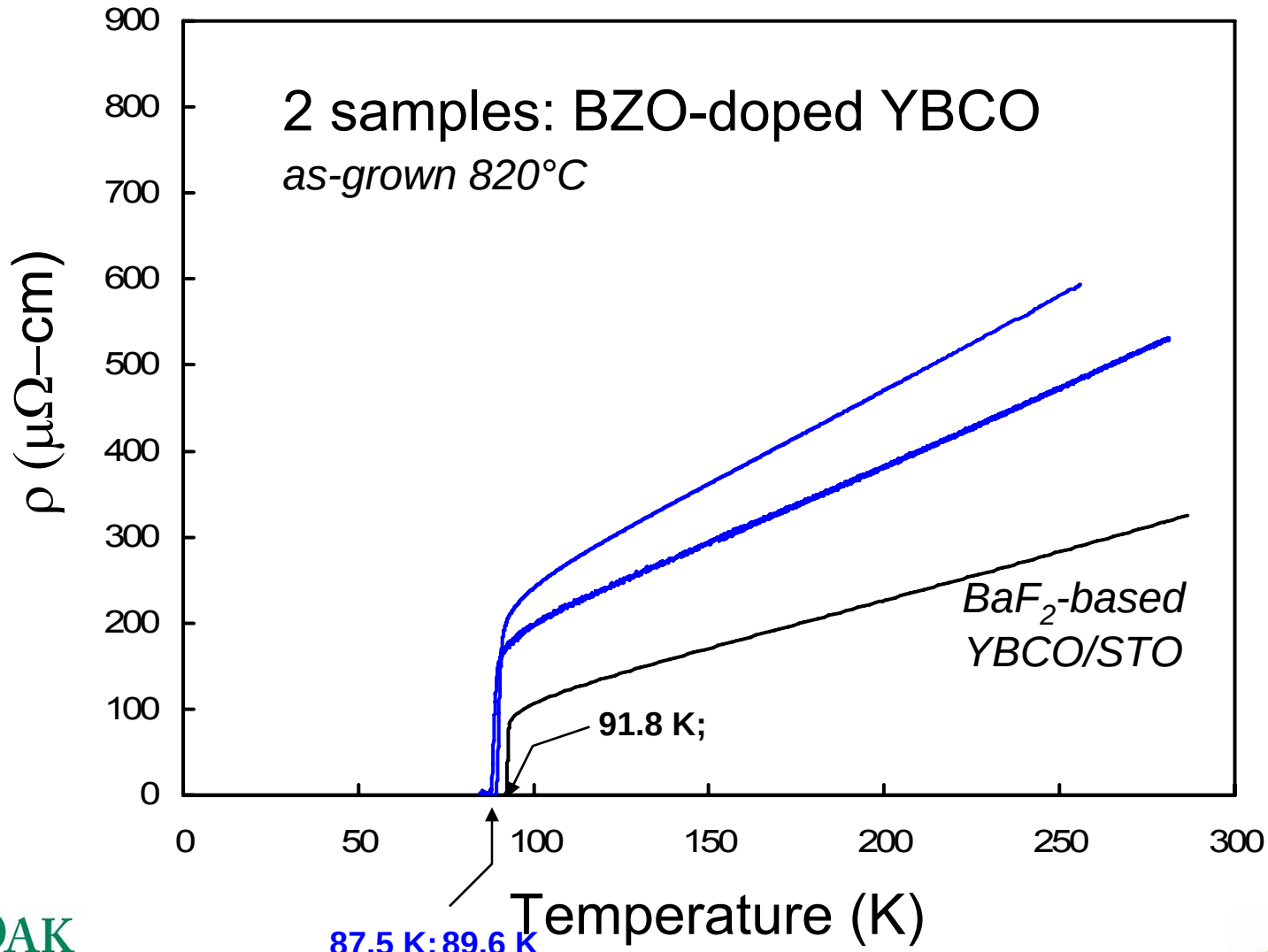
Properties:

BZO-doped normal state resistivity



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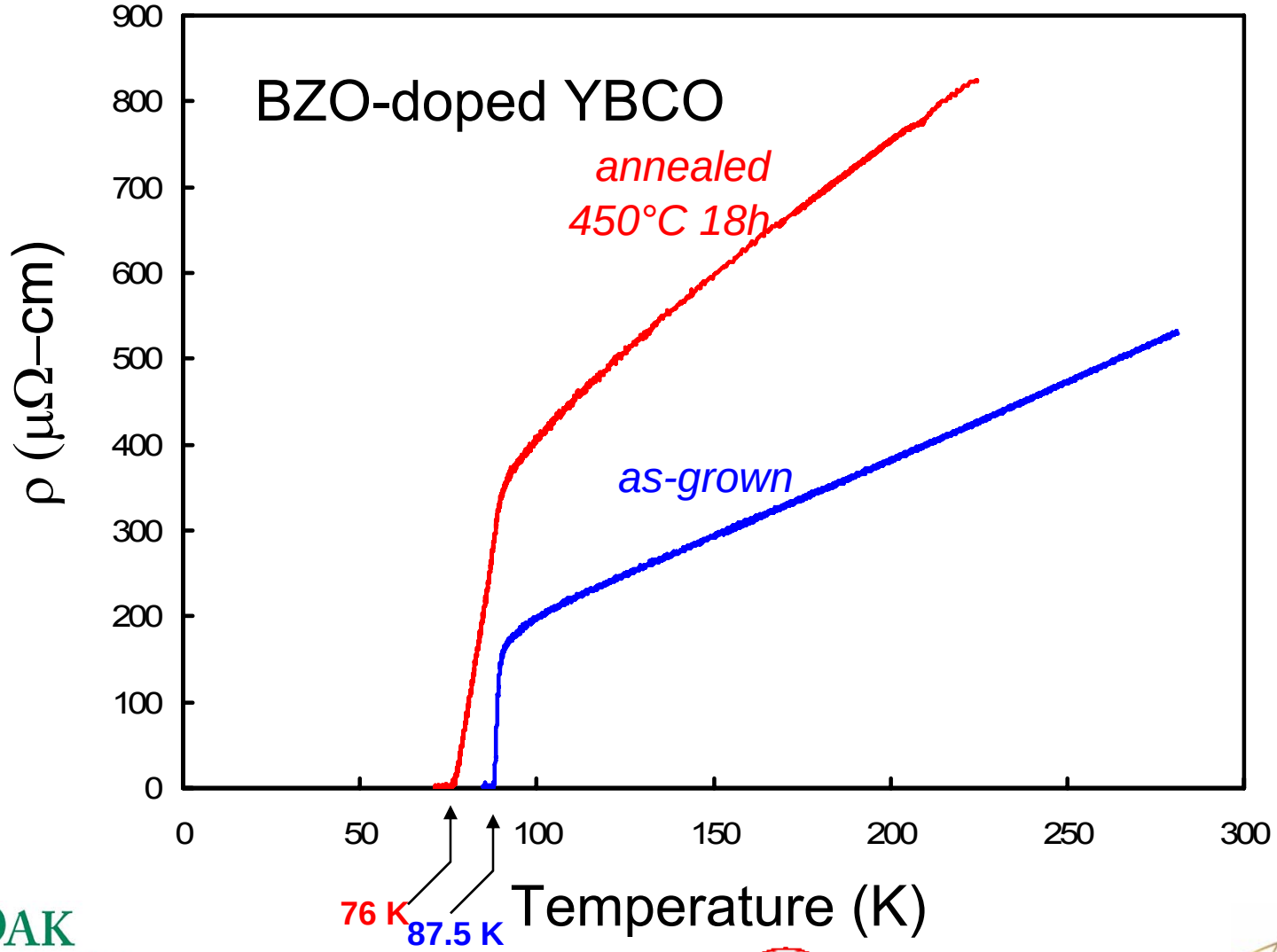
Properties:

BZO-doped normal state resistivity shows strange effects of oxygen anneal



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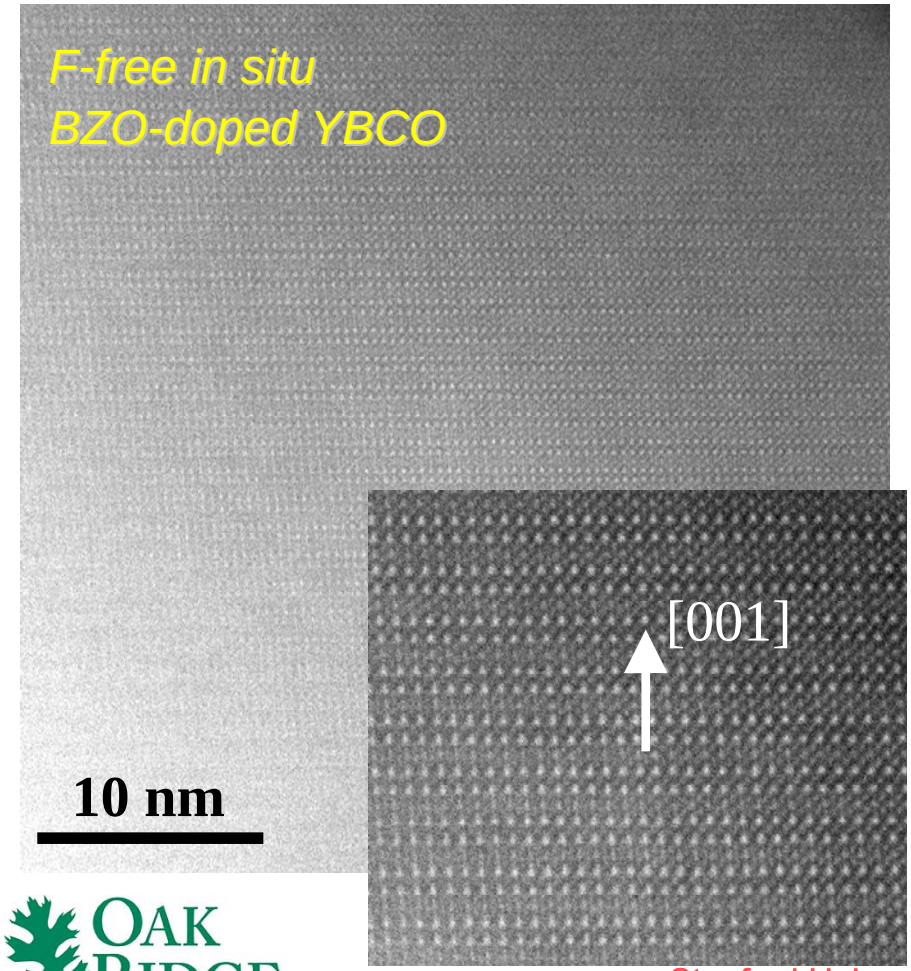
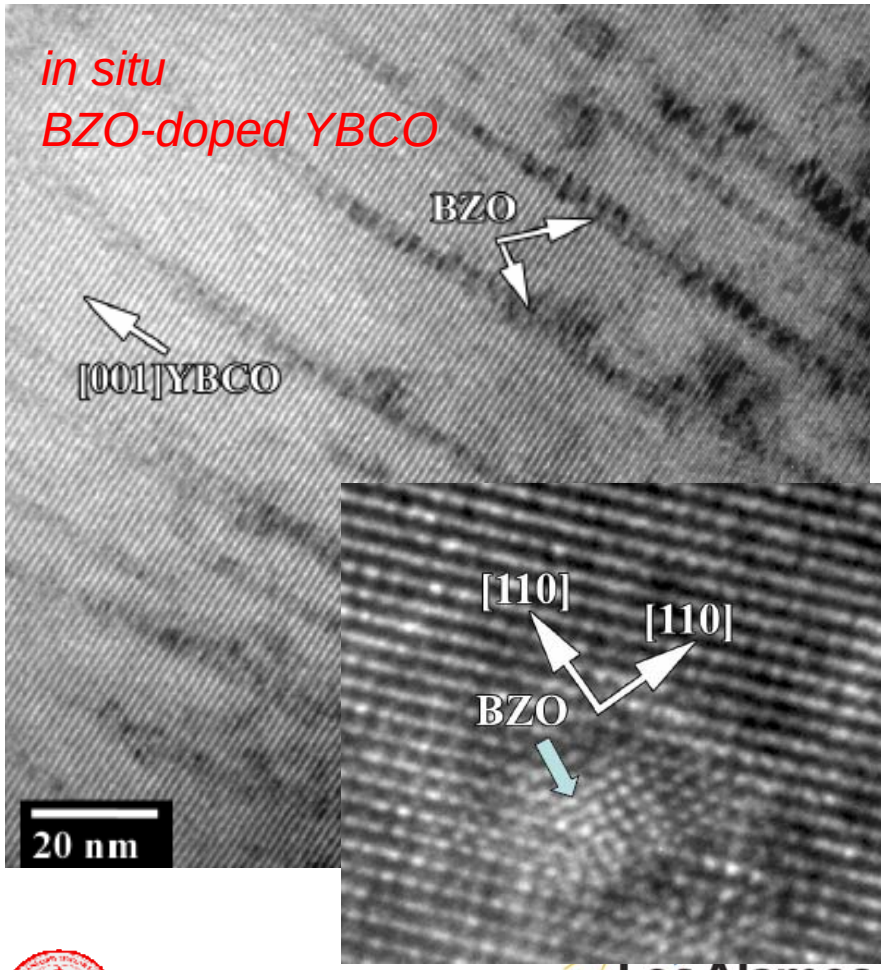
Properties:

TEM cross-sections of BZO-doped YBCO also show few defects

- Dramatic contrast between PLD *in situ* and *ex situ* BZO-doped YBCO
- **No** BZO found in *ex situ* film!





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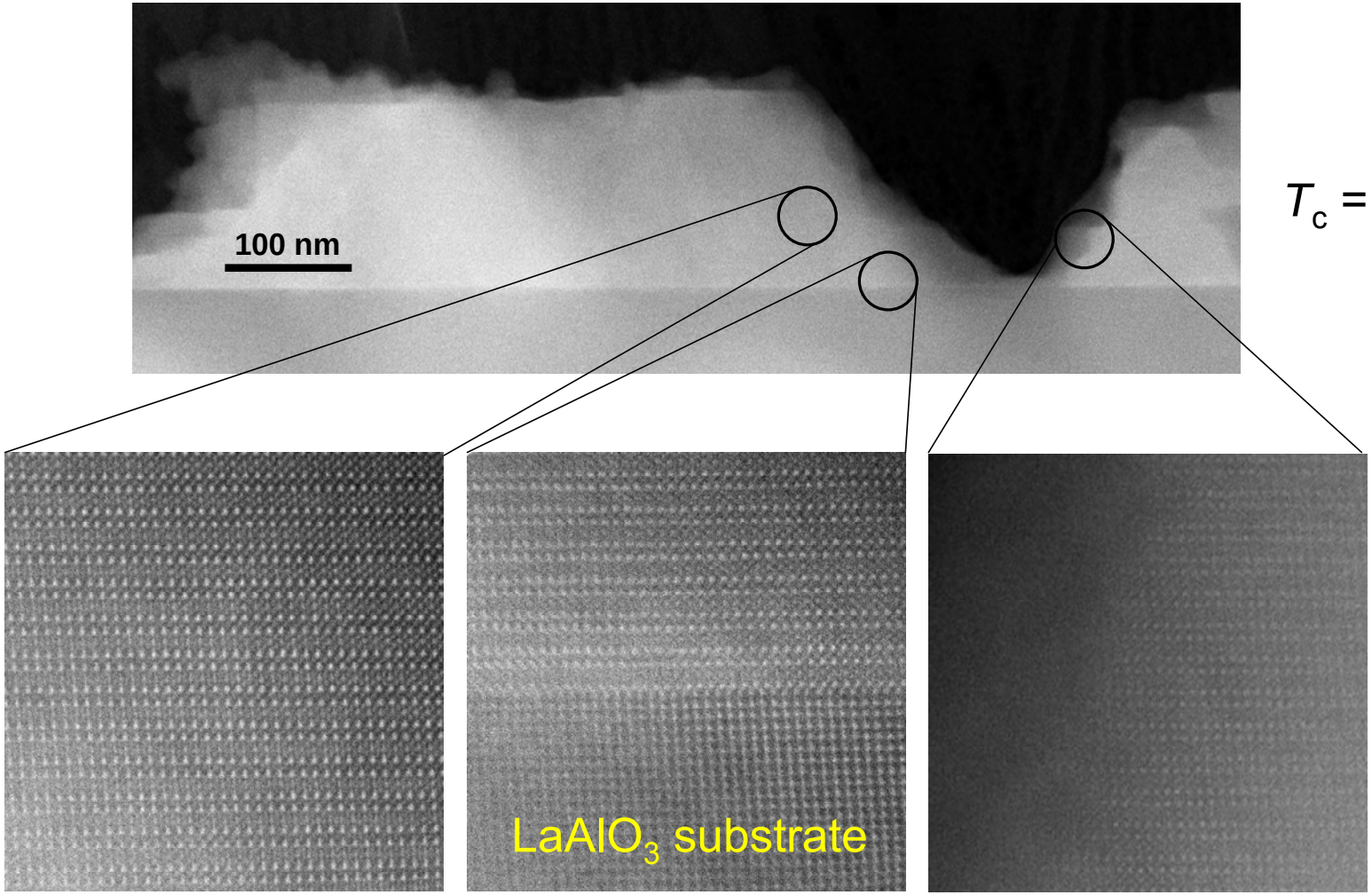
Properties: BZO-doped YBCO (processed 820°C)

No BZO observed; nearly perfect YBCO



T_c = 90 K

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Summary:

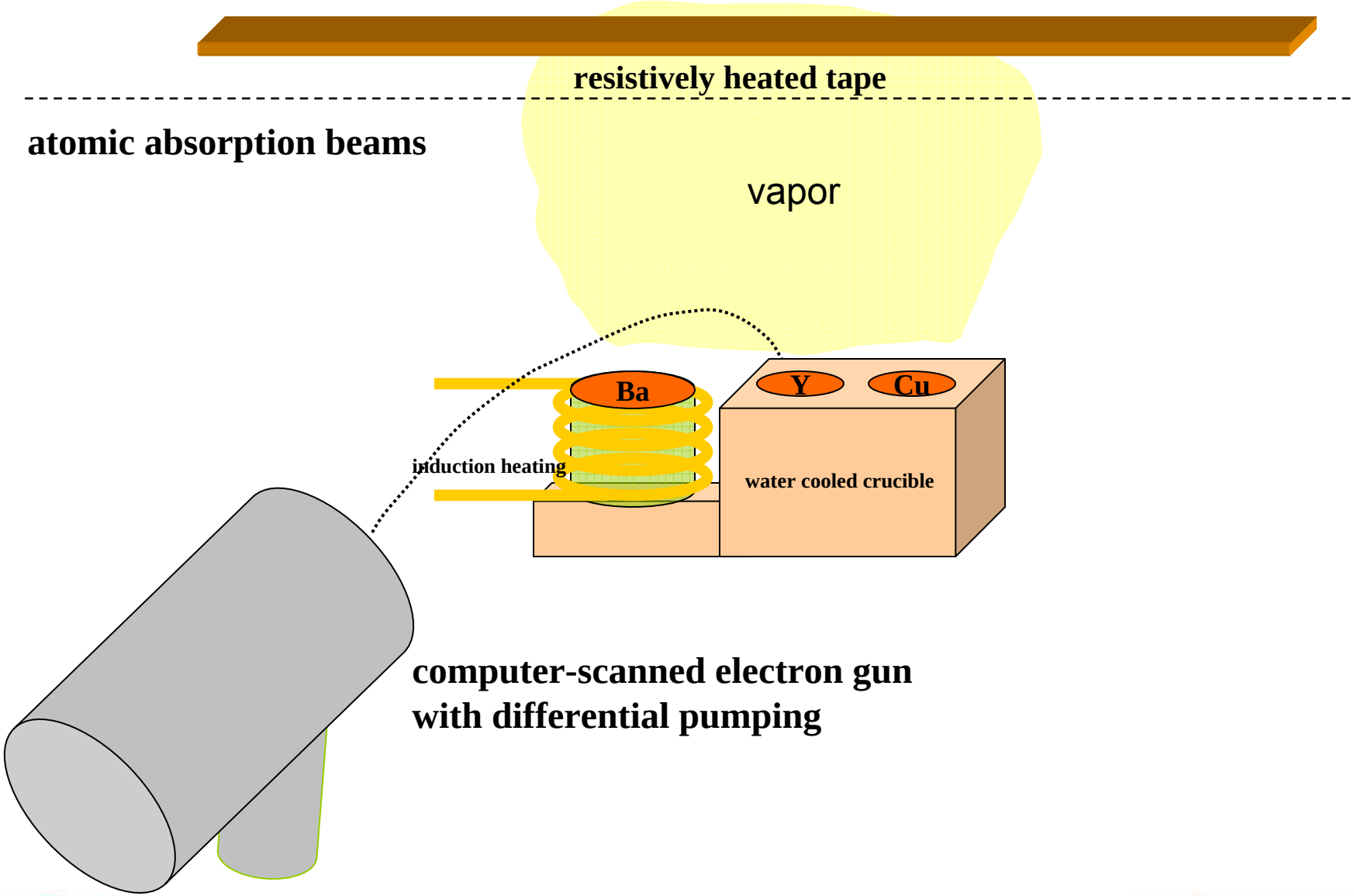
- Epitaxial thin films of YBCO and BZO-doped YBCO have been synthesized from F-free, PVD precursors

- Processing for the best materials involves raising the oxygen pressure after heating in a reducing ambient [*possibly compatible with large-scale batch processing*]

- Properties indicate materials lack appropriate level of defects needed both for oxygenation and flux pinning

- Preliminary synthesis of $BaZrO_3$-doped YBCO shows puzzling characteristics:
  - No BZO precipitates observed by TEM
  - Low-temperature oxygen uptake anneal degrades properties

LANL Co-Evaporation Schematic



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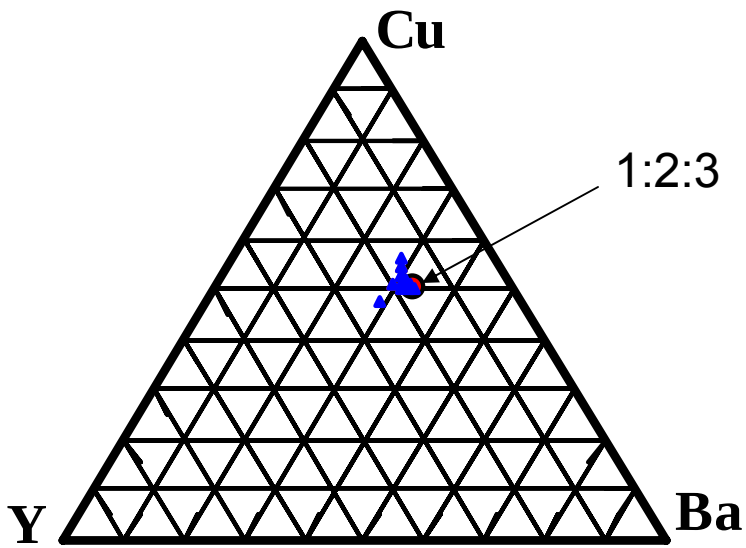
COMPOSITION CONTROL IS GOOD

Inductively Coupled Plasma composition results/ recent samples

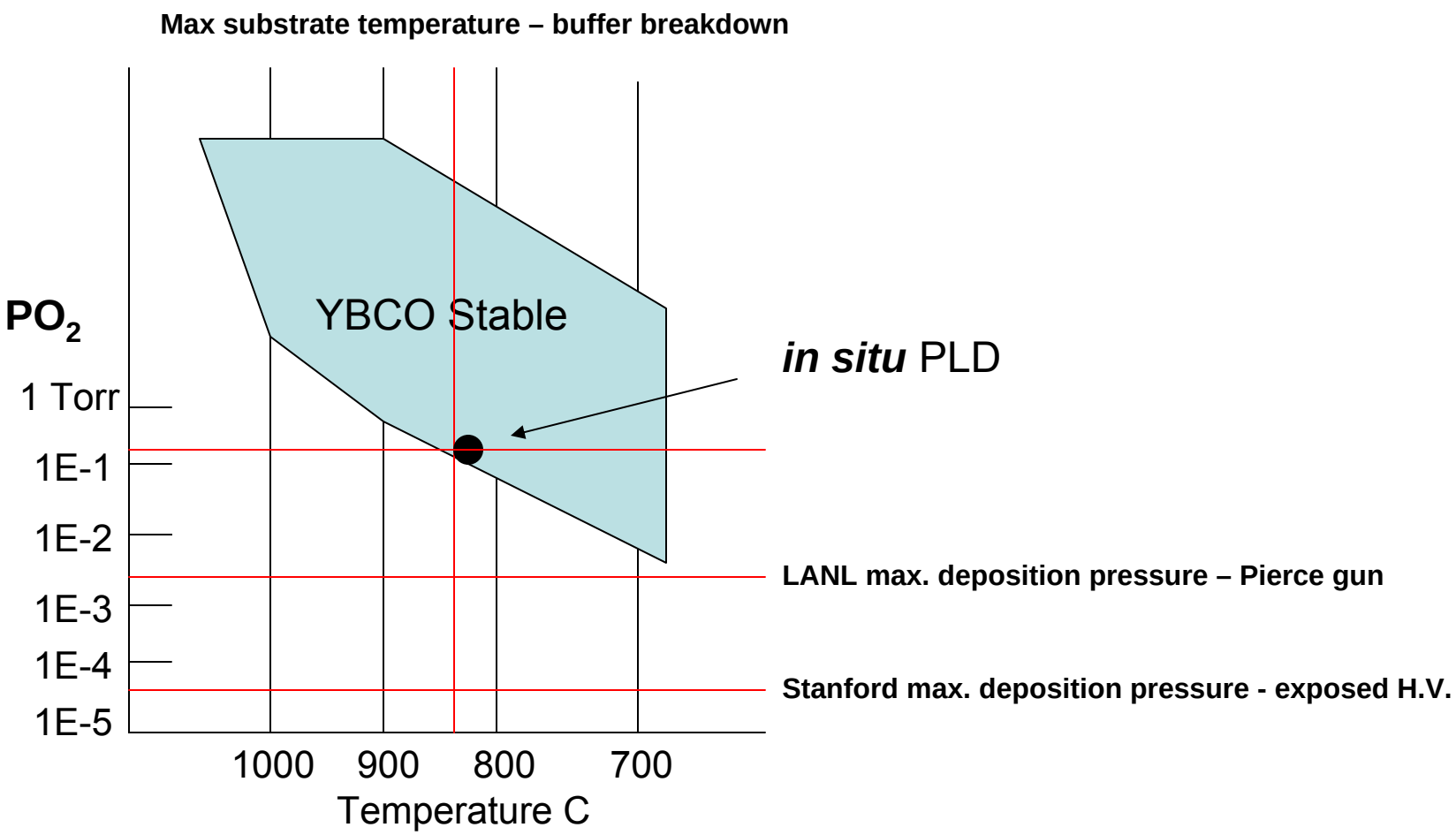


PLD for comparison

SAMPLE	yttrium	barium	copper
CE112B	17.60	29.80	52.50
CE115	23.90	29.00	47.10
CE118	17.30	32.40	50.30
CE120A	17.30	31.20	51.50
CE120B	17.50	30.20	52.30
CE121A	19.20	31.20	49.60
CE121F	19.60	29.30	51.00
CE143D	16.50	29.50	54.00
CE143E	18.50	30.50	51.00
CE144B	17.10	31.80	51.10
CE144F	15.60	28.00	56.40
Z04-134	18.8	32.2	48.9
PLDS	19.5	32.3	48
PLDS1	19.5	33.1	47.5
CE107P	20.8	32.5	46.8
CE107P2	20.9	32.9	46.2

RMS deviation from target: Co-Evap: 2.4%, PLD: 1.1%

There are limits to the available process space



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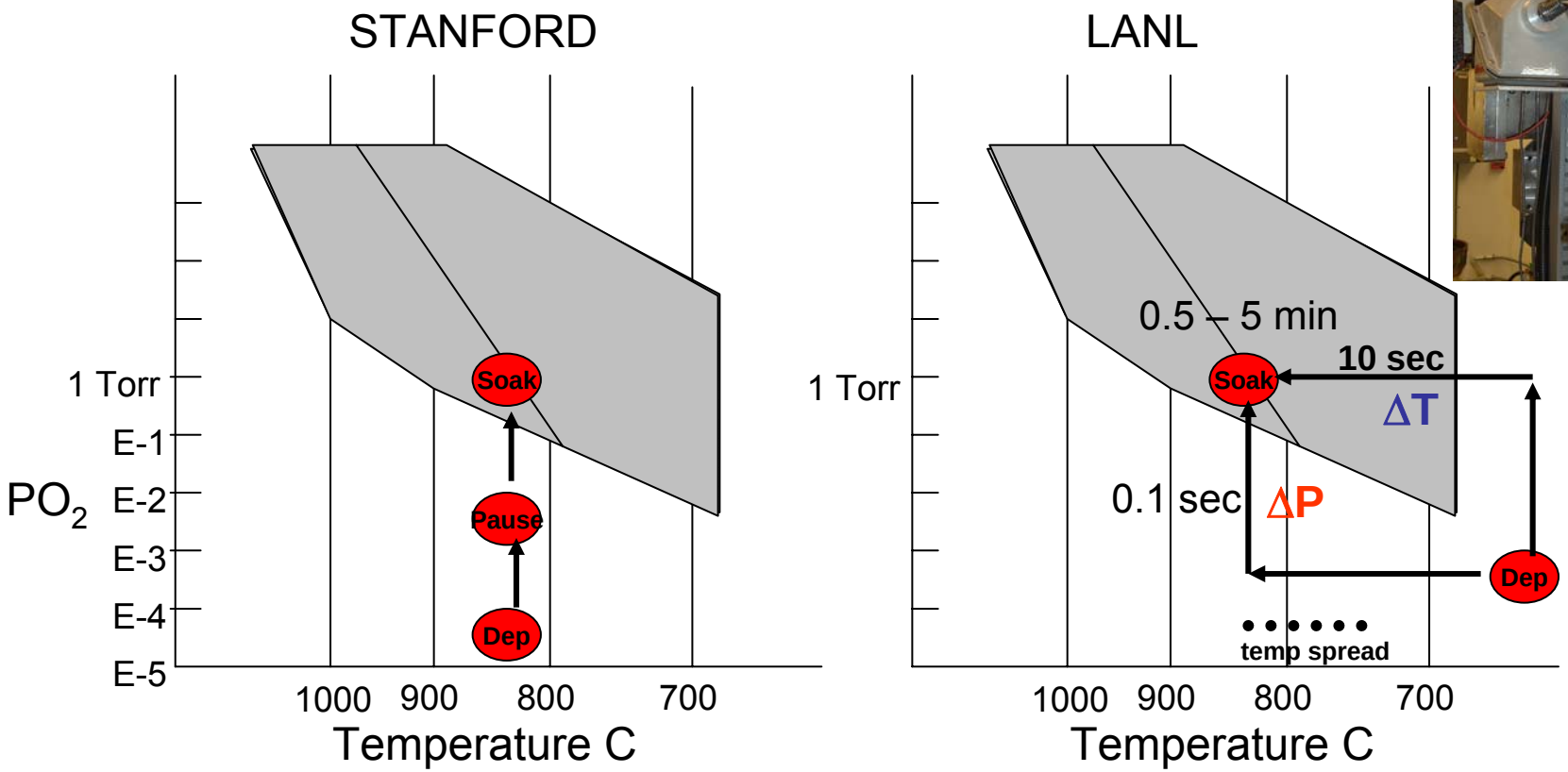
New Process uses O_2

Comparison of LANL and Stanford YBCO Processes



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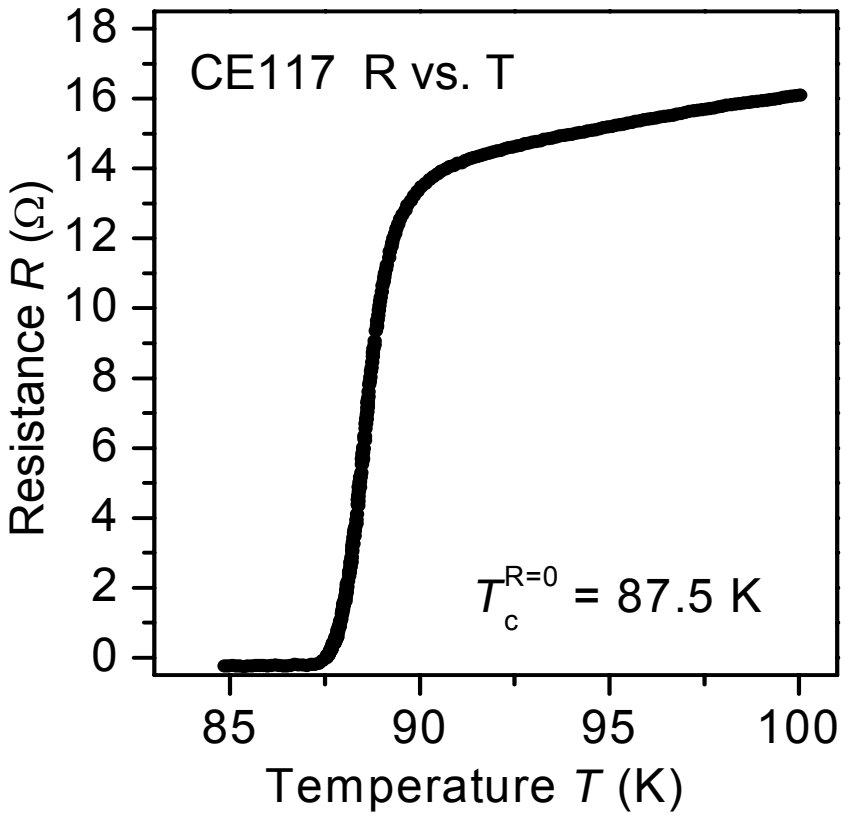
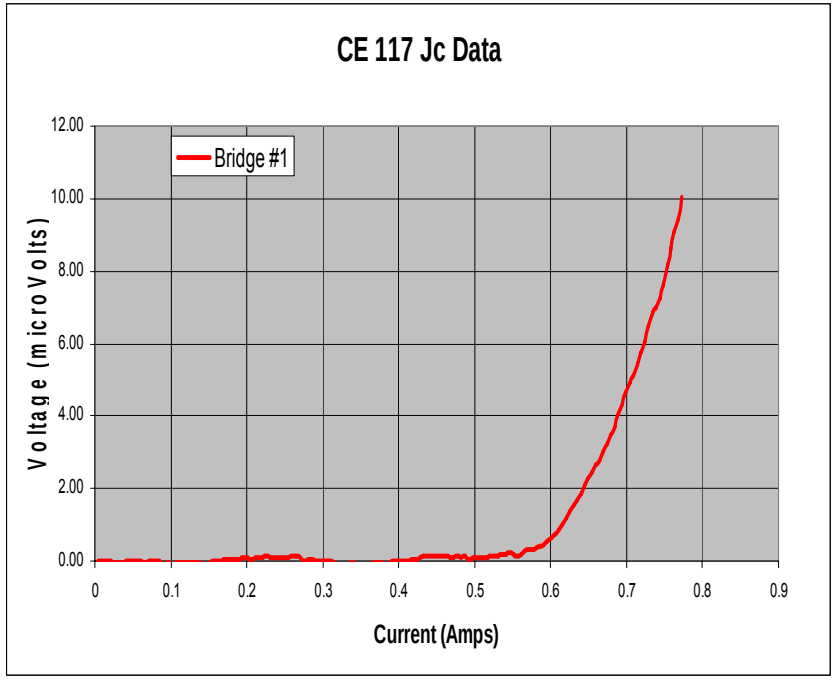
Jc = 0.11 MA/cm² (SF, 75K) on RABiTS
even though ΔT used





Jc = 0.11 MA/cm² (SF, 75K)

Wire Workshop 2006

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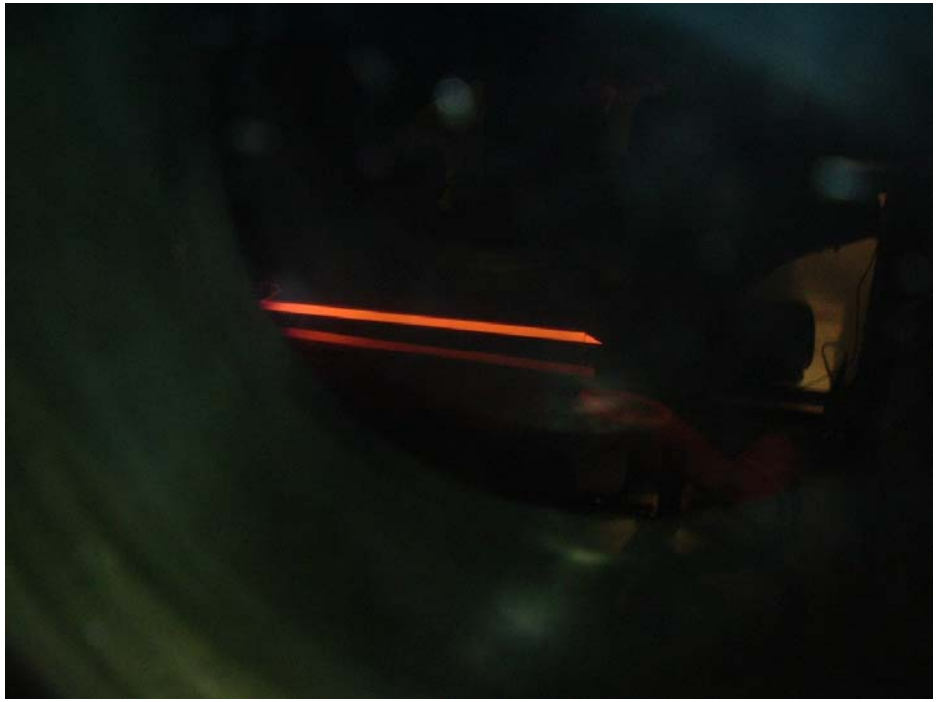
Resistively heated tape



- Heat applied directly to tape. Tape heats rapidly for high linear speed.
- No burnout of quartz bulbs or plates to coat-up.
- Width & length scalable.
- Substrate thickness variations or coating conductivity can affect temperature.
- Emissivity problem same as IR heater.
- Tapers permit combinatorial approach to temperature studies.

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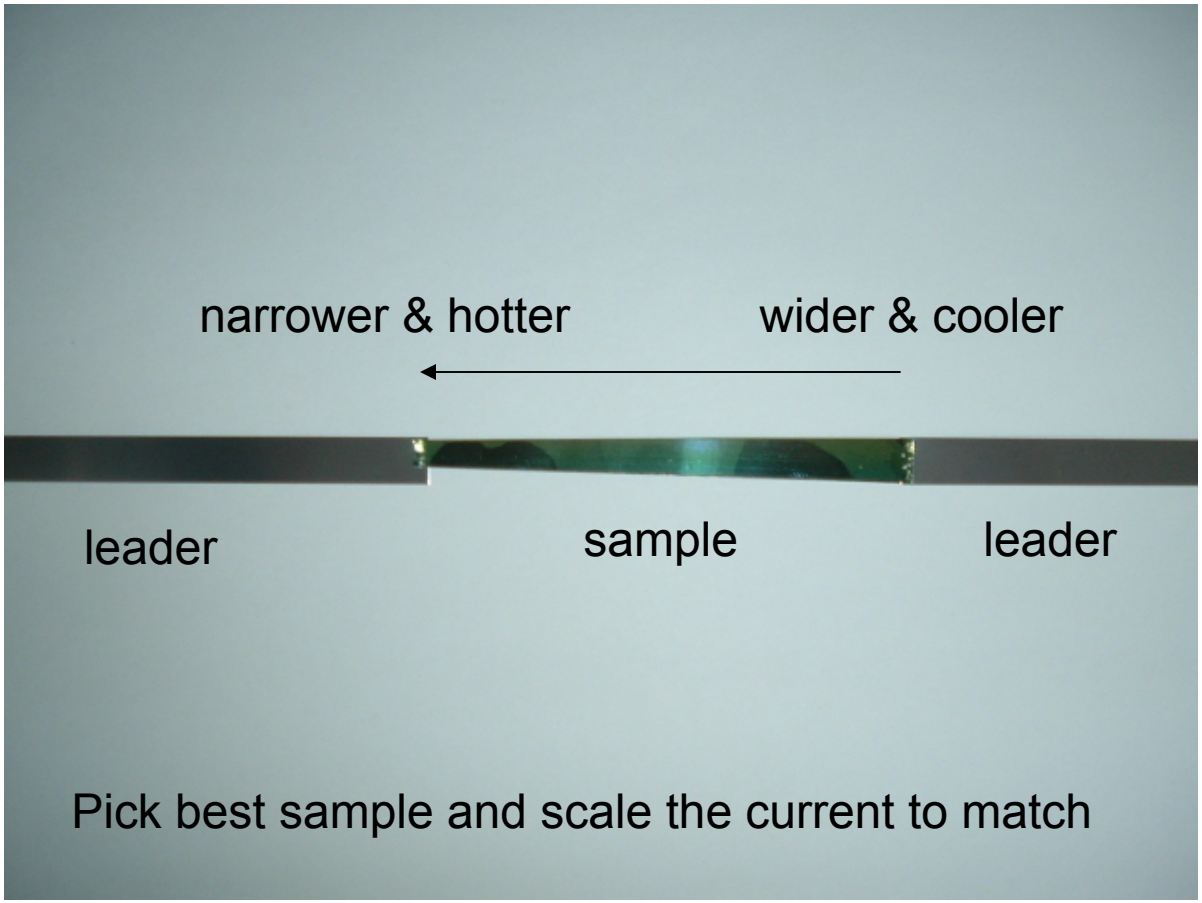
Tapered tape samples permit a combinatorial approach to substrate temperature



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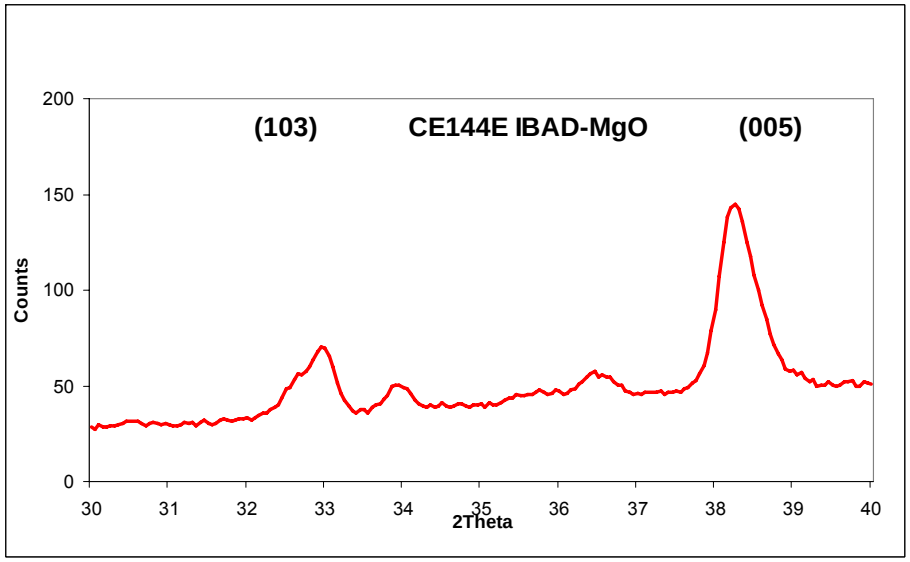
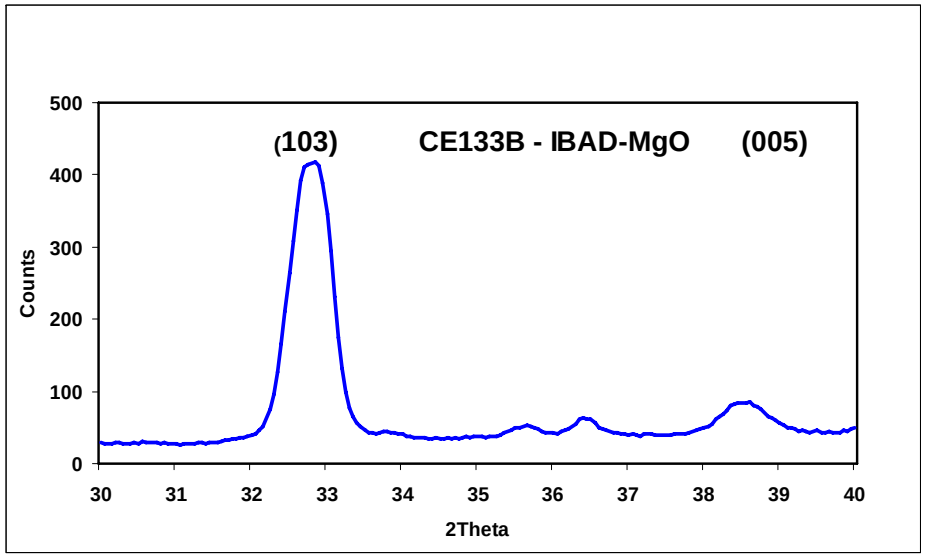
Path ΔP makes better YBCO

IBAD MgO





ΔP **ΔT**

Consistent with Stanford and ORNL findings

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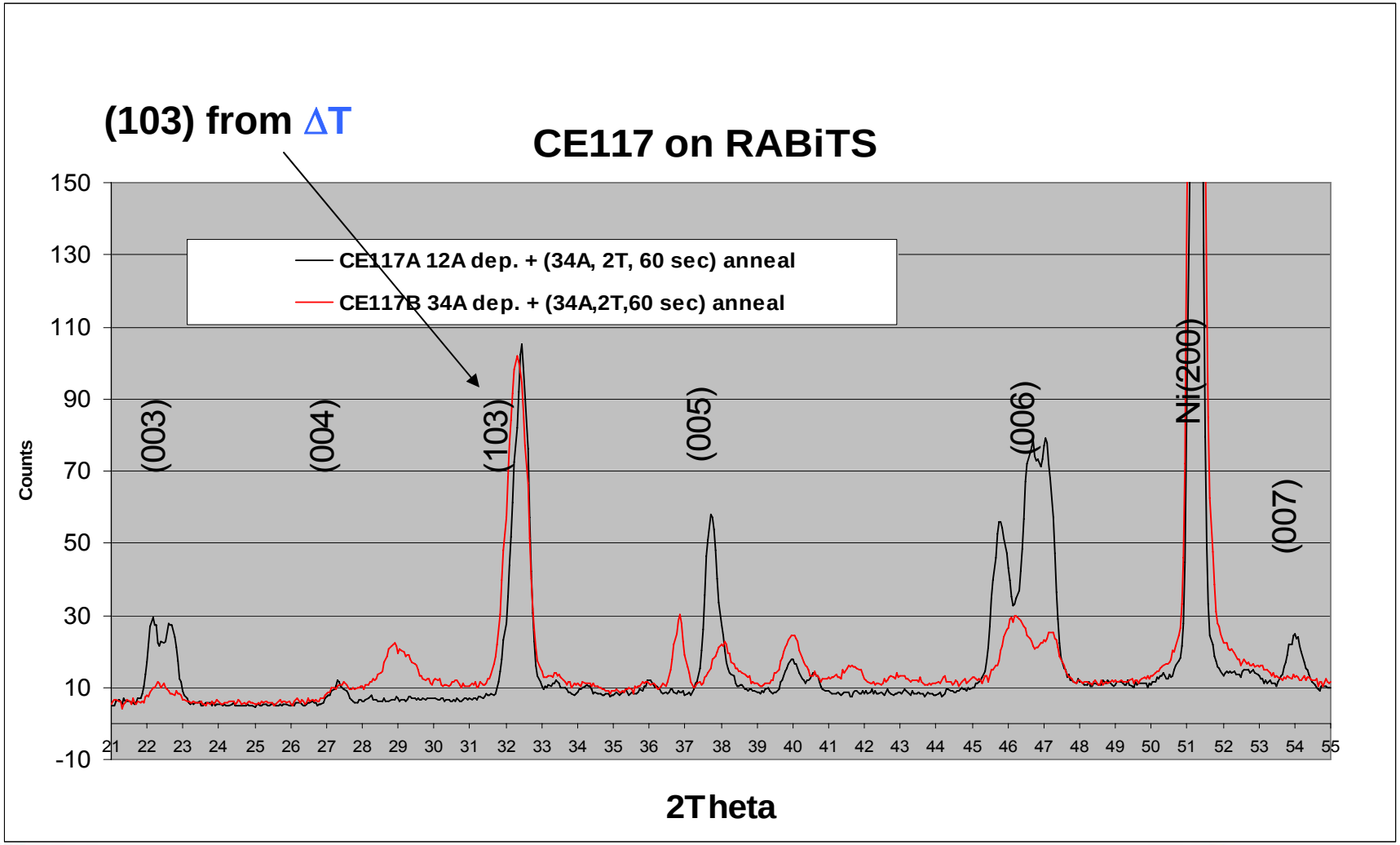
Cold deposition (T^S_1) is better



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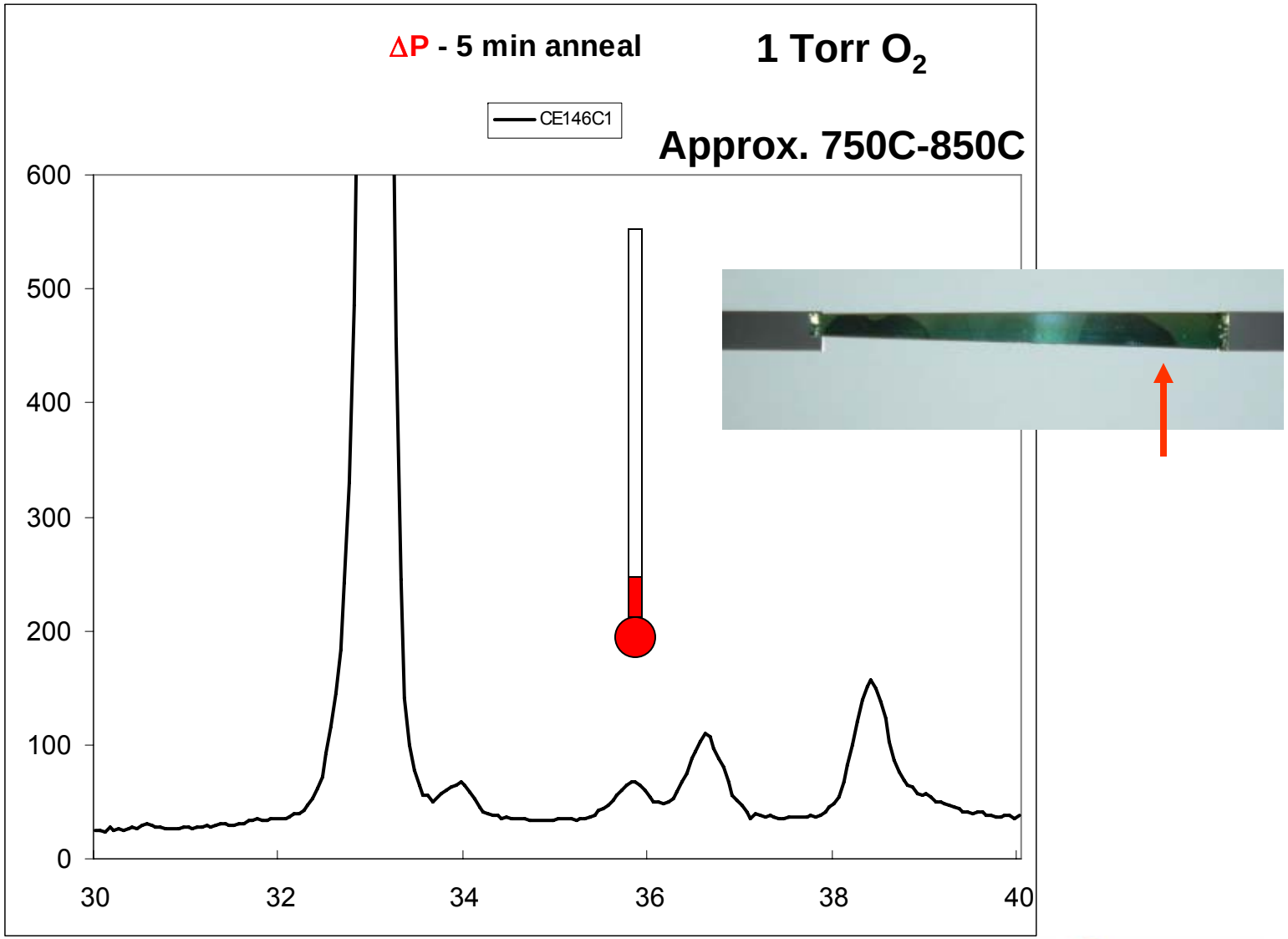
T^S_2 TEMPERATURE SEQUENCE – IBAD-MgO/CeO_2



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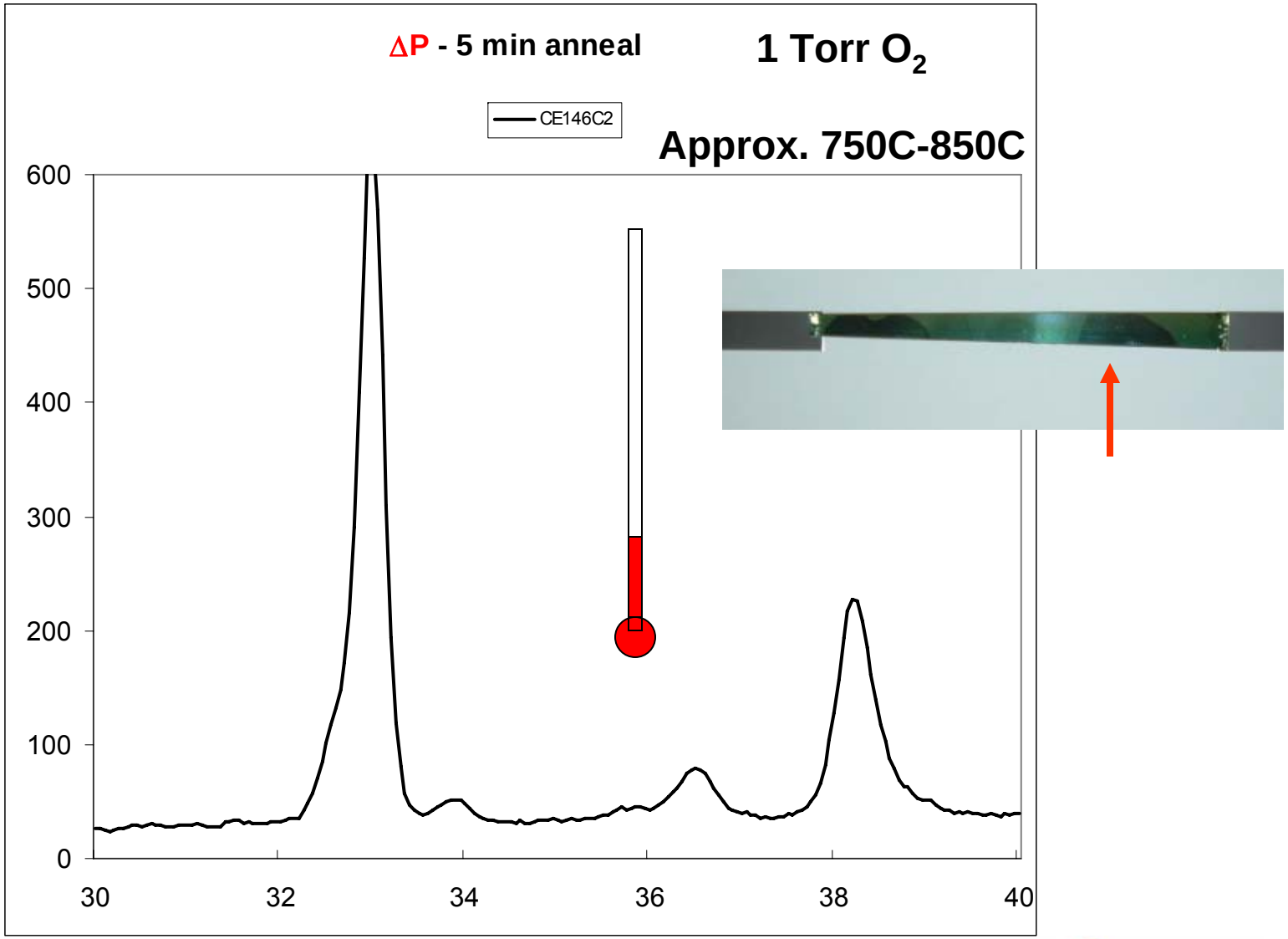

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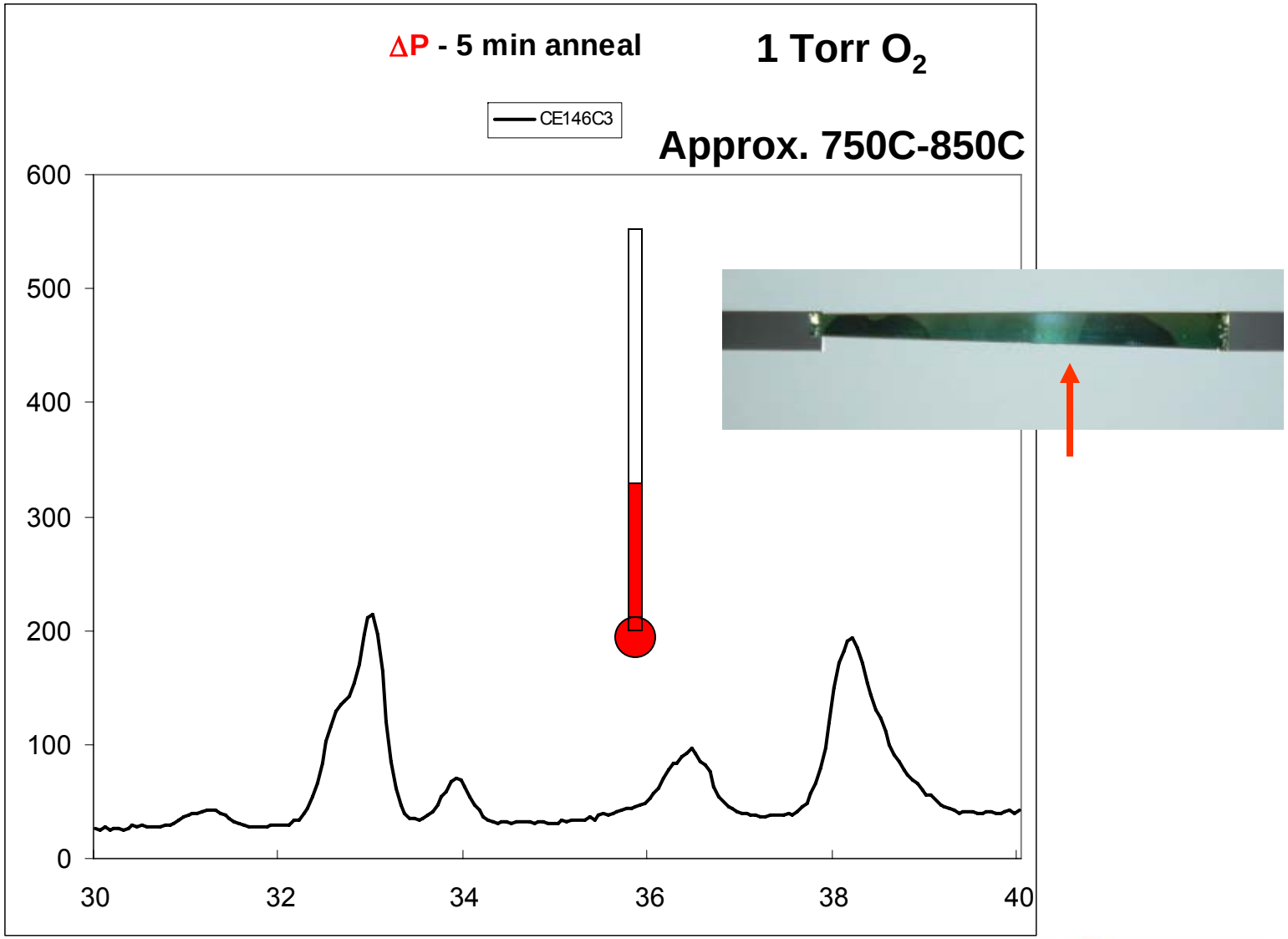

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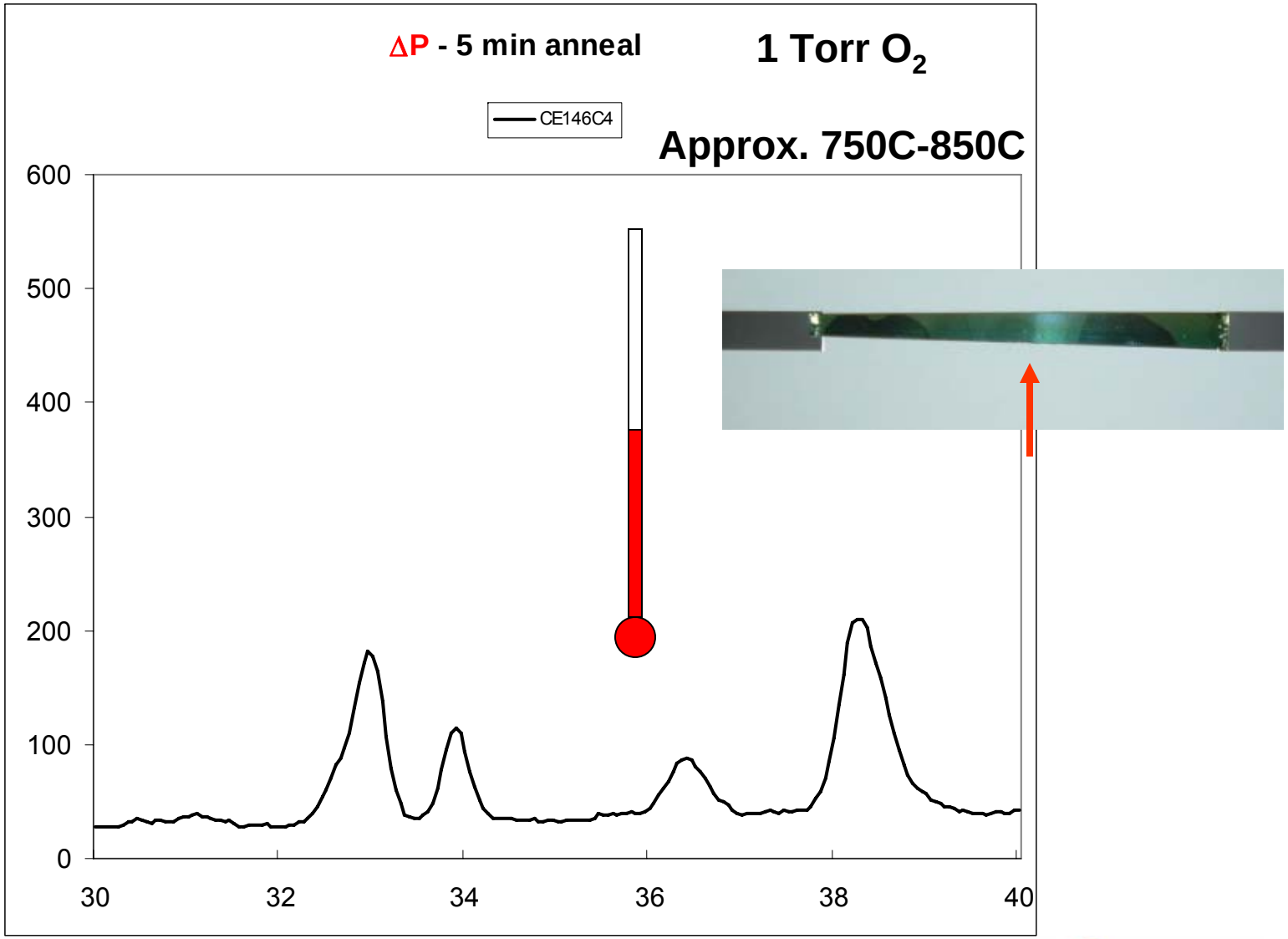

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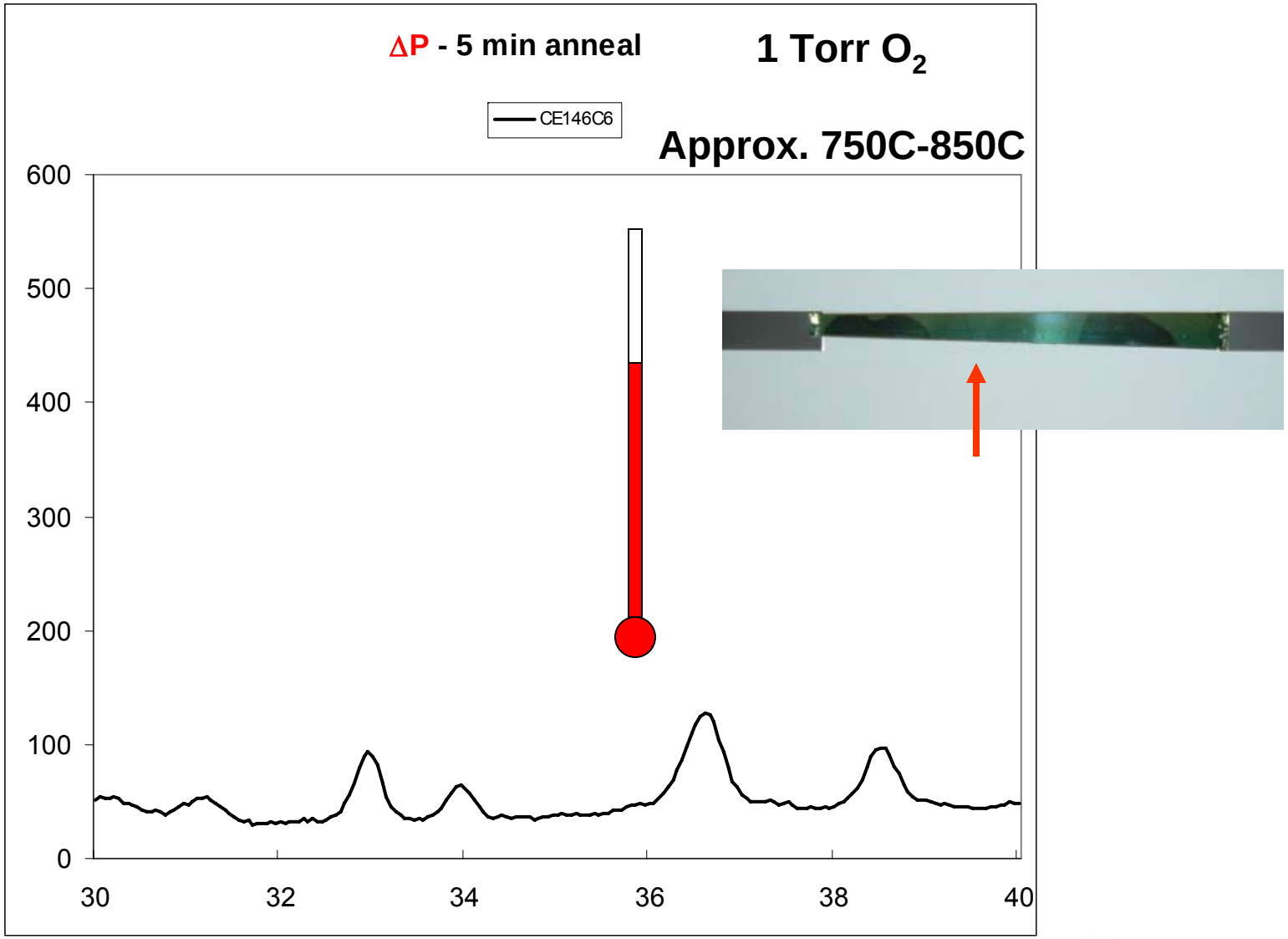

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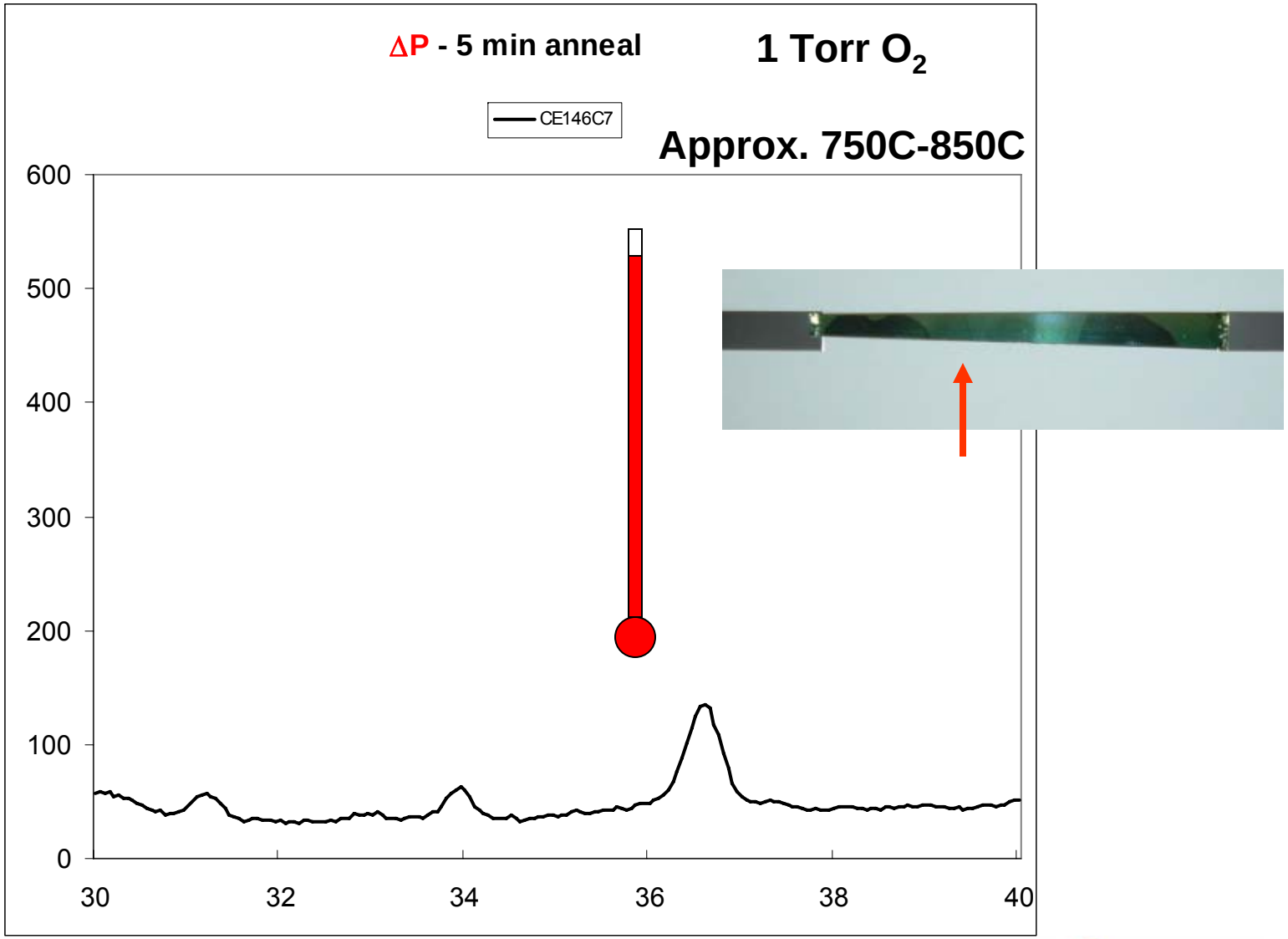

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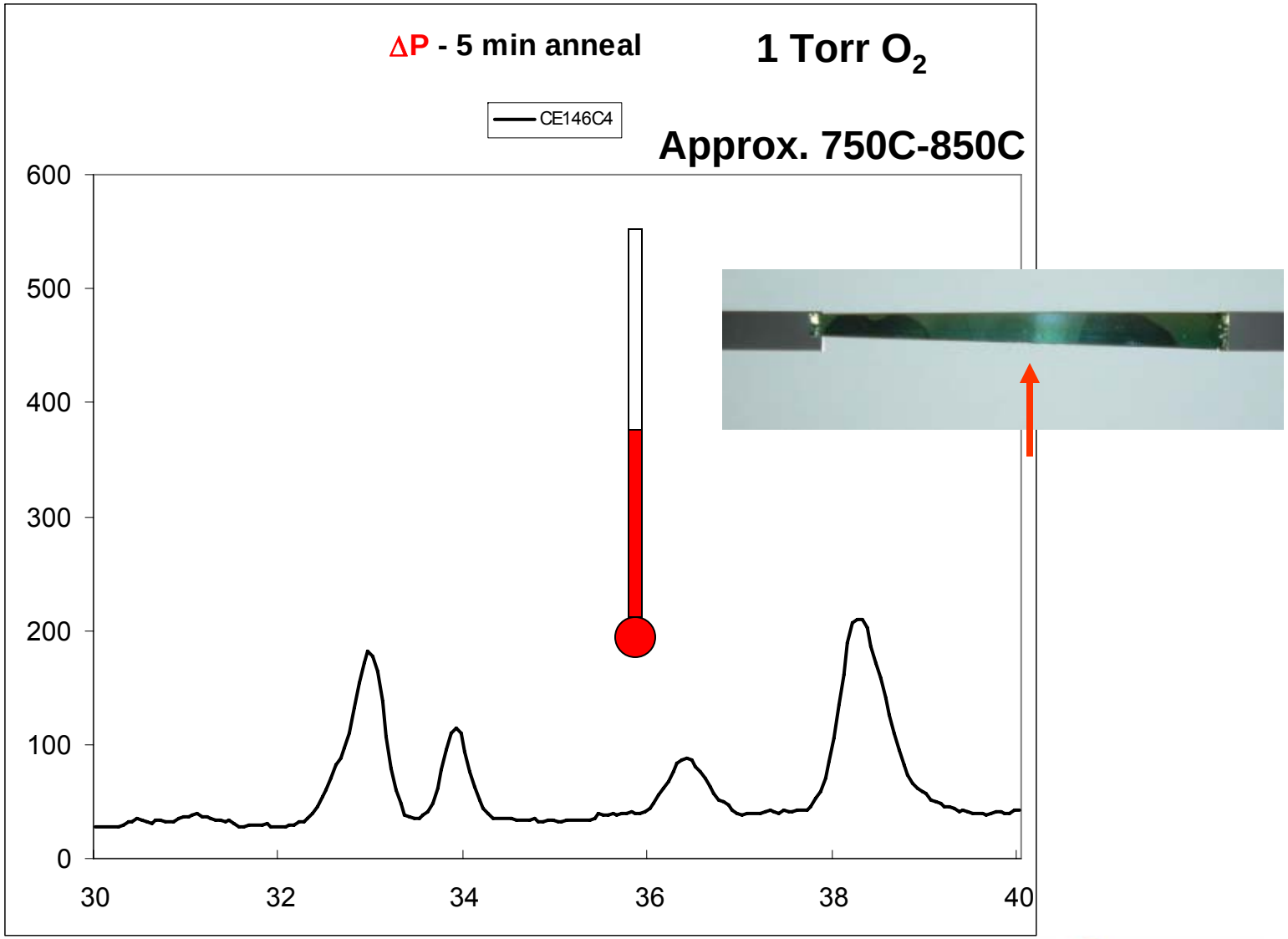

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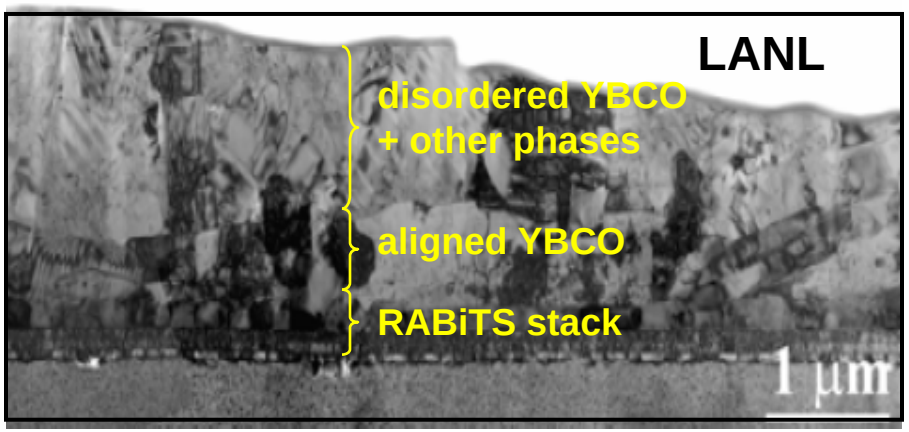
Stanford and LANL Microstructures are Similar

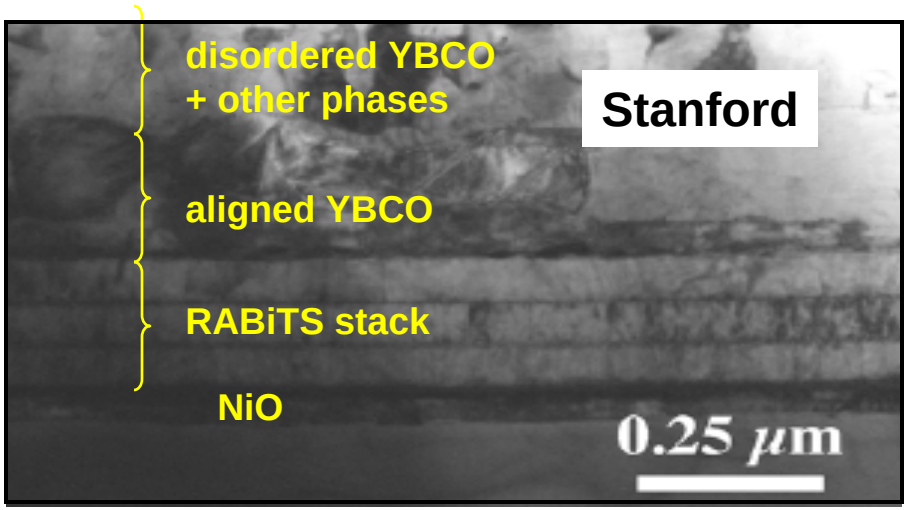
on RABiTS

Layered growth with ordered YBCO Beneath.



TEM: T. Holesinger/LANL

0.11 MA/cm^2



1.0 MA/cm^2

TEM: T. Holesinger/LANL

Why is ORNL microstructure (on LAO) different?

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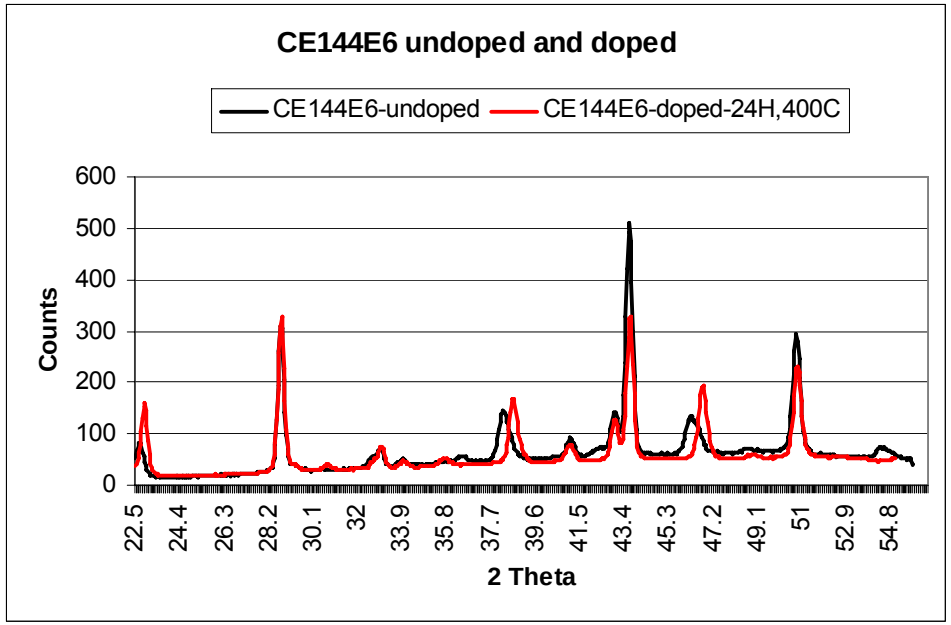
O_2 anneal is effective.

1% lattice constant decrease



(hkl)	undoped 2Th	undoped d	doped 2Th	doped d
(003)	22.7	11.742	22.9	11.641
(004)	30.55	11.695	30.75	11.621
(005)	38.25	11.755	38.7	11.624
(006)	46.3	11.756	46.8	11.637
AVERAGE		11.737		11.631

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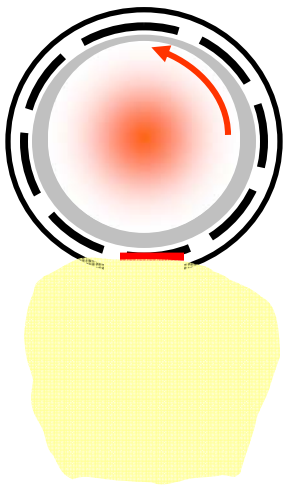
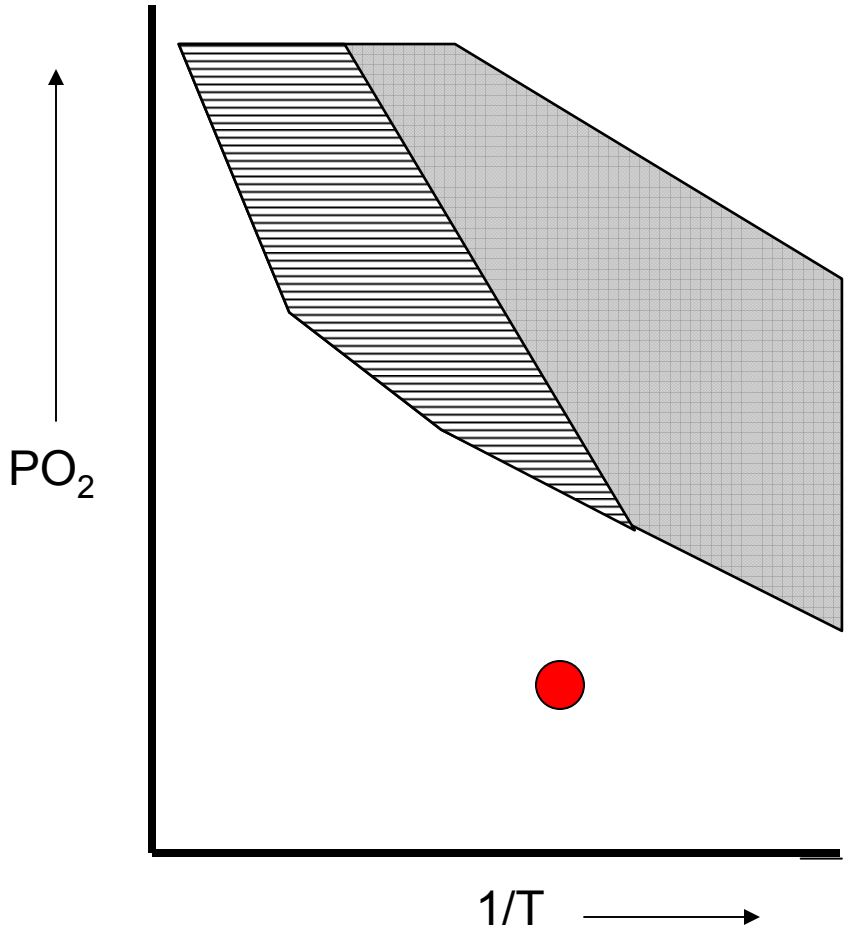
A scalable process can also be built around multiple ΔP steps.
We've built and installed a test device.

Tapes move out of page





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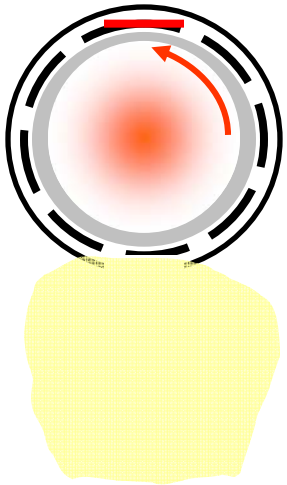

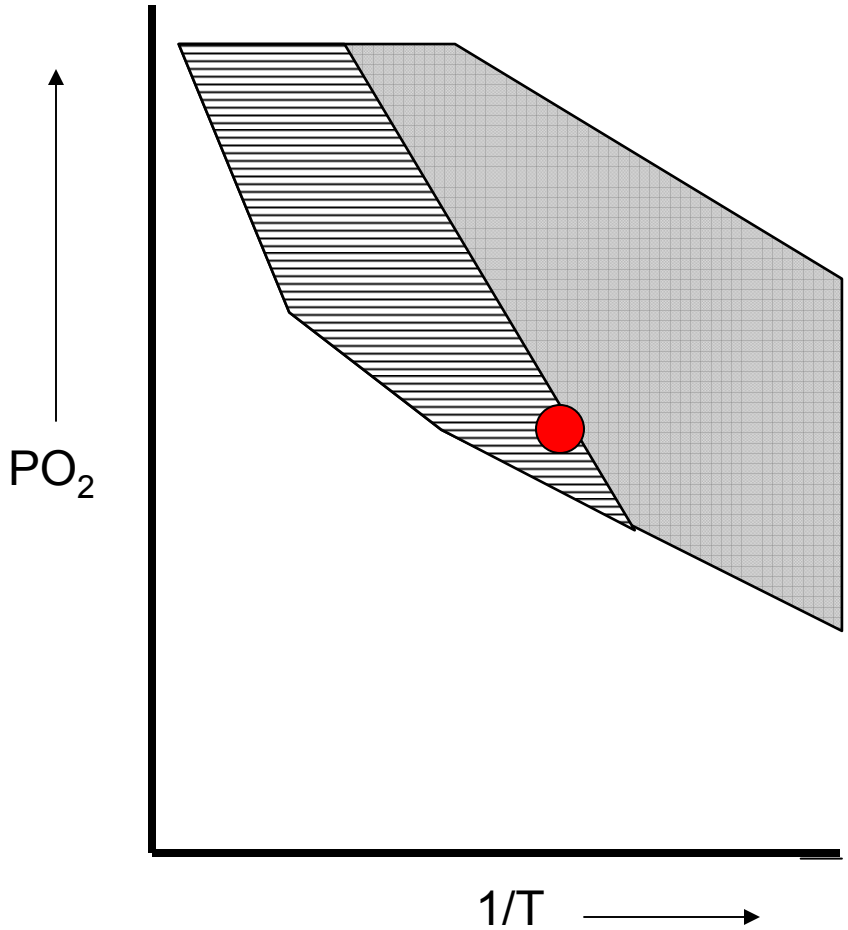

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REEL-to-REEL SUMMARY

- **A computer-driven, reel-to-reel co-evaporation system operating at 25% power has made HTS at > 100 ang/sec. It can deposit on 7.5 cm wide tapes in 100 meter lengths.**
- **The system is readily modifiable to one-pass operation.**
- **Results from the short sample work has guided the reel-to-reel development.**
- **An oxygen pocket test device is operational.**
- **A key is continued tape template availability and quality.**

Criterion: Results

- **For control studies, precursors were deposited by PLD and co-evaporation on single crystal and RABiTS substrates, and processed to yield J_c values that are low, but in the range of 1MA/cm^2**

- **Processing paths of oxygen pressure, temperature, and history were evaluated**
  - **Presently a fast and effective processing path involves a rapid increase in oxygen pressure at constant temperature.**
  - **Best conversion occurs near to the $BaCu_2O_x$ liquid-solid boundary**

- **TEM and properties show the films lack sufficient defects for both flux pinning and fast oxygenation**
  - **Results show BZO-doped YBCO shows no BZO phase**

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Criterion: Results (cont.)

- **Improved AA sensors to a point that +/- 2% composition control was routine during reel-to-reel processing.**
- **Developed "tapered sample" method in order to explore temperature dependencies.**
- **Explored Time-Temperature-Pressure trajectories to produce superconducting samples on tape templates using reel-to-reel methods**
- **J_c of 0.1 MA/cm^2 on moving 1.2 micron thick RABiTS.**
- **A new “oxygen pocket” heater was installed and operated.**

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Criterion: Performance

X **Goal: Produce 1 meter of 1 cm tape with an Ic of 100 Amperes (SF, 75K) on either RABiTS or IBAD substrate. Made 10 cm w/ J_c=0.11 MA/cm^2 on RABiTS**

✓ **Goal: Investigate post-annealing capitalizing on materials science work from Stanford. If promising, add annealing to the tape path. ORNL results also utilized. Verified ΔP method is best.**

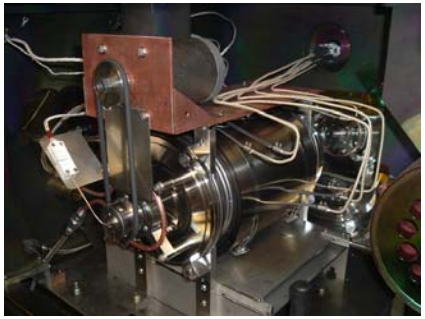
✓ **Goal: Investigate oxygenization methods:**

- **a) Activated oxygen using a microwave oxygen plasma.**
- **b) Explored higher ambient O_x pressure ~10 mT.**
- c) **Characterized O_1 using AA. > 3 x 10^{18} cm^{-2}sec^{-1}**

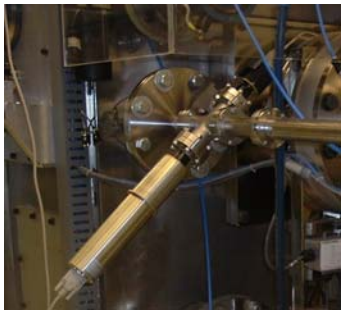
✓ **Goal: Install an "oxygen pocket" device for moving tape. Installed**

✓ **Goal: Continue to obtain & use all available tape substrates.**

Used AMSC RABiTS and LANL IBAD-MgO Tapes



"oxygen pocket"



atomic oxygen measurement

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Criterion: Research Integration

- **There is a fruitful collaboration between Stanford, LANL, and ORNL that has improved the total program capabilities. Stanford & ORNL are mapping out the pressure-temperature stability plot which is being used by LANL to demonstrate the process on moving tape.**
- **AmSuper RABiTS has been used by Stanford and LANL.**
- **Worked with Shoreline Technologies on Oxygen Pocket**
- **Collaborated with ANL on Raman Analysis of YBCO tapes**

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Criterion: 2007 Plans

Short Samples

- Continue collaboration on understanding of YBCO growth.
- Use Stanford XRD-dome for study of precursors from ORNL and LANL.
- Explore pinning additions to the "too perfect" morphology:
  - APC-BZO, Y_2O_3, other nanostructures, including substrate decoration.
  - Small grains due to rapid supersaturated growth.
  - Composition clusters in Nd123ss, and Sm123ss
- Evaluate process compatibility with alternative practical buffers (e.g., $LaMnO_3$)

Reel-to-Reel

- Produce tape with an Ic of 100 amperes/cm width (SF, 75K).
- Investigate process paths capitalizing on materials science work from Stanford & ORNL. If promising, add these to the tape path for a one-pass process.
- Produce high J_c tape with "oxygen pocket" device.

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