Can we reach fast growth methods for Coated Conductors at competitive costs ?

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Acknowledgements

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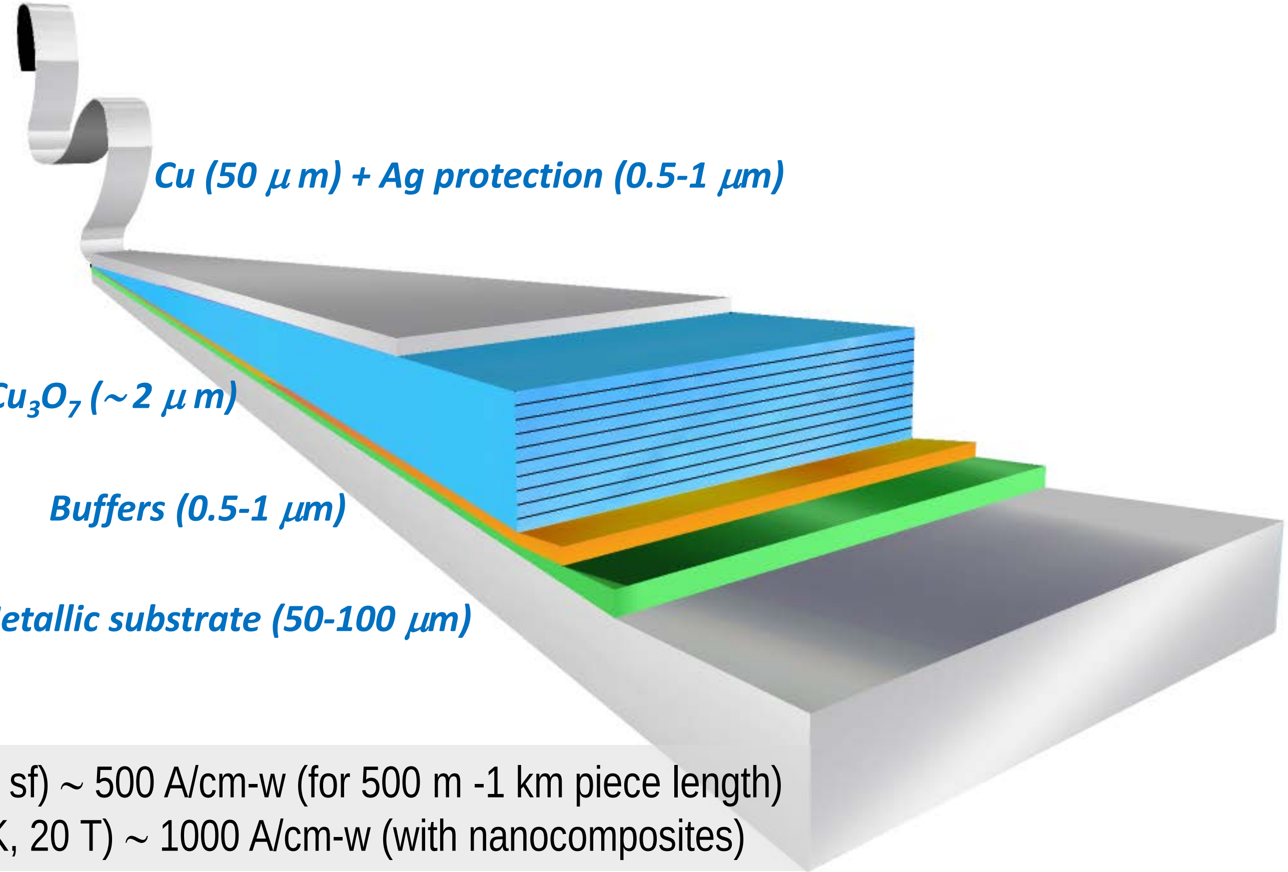
REBCO is the opportunity and the challenge at high magnetic fields



I_c (77K, sf) ~ 500 A/cm-w (for 500 m -1 km piece length)
I_c (4.2 K, 20 T) ~ 1000 A/cm-w (with nanocomposites)

25-yr of Coated Conductor technology development

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Pros:

- High T_c
- High H_{c2}
- High J_c
- High IL

Cons:

- Grain boundaries
- Anisotropy
- Small coherence length (nanometric pinning centres)
- High thermal excitations
- Robustness

- **Biaxial texture ⇒ high cost**

Cost= €/ kA-m

How to decrease cost of Coated Conductors

What would be an aceptable cost ?

COST
€ / kA m
$I_c = J_c \cdot t$

CHEAPER ← → **BETTER**

CHEAPER:
- Fast growth
- Simple processing
- Simple architecture
- High yield

- Low capital investment

BETTER:
- High performance J_c(B, T)
- Thick REBCO films
- Good homogeneity
- Mechanically robust
- Thin substrates (J_E)

- Customized for Applications

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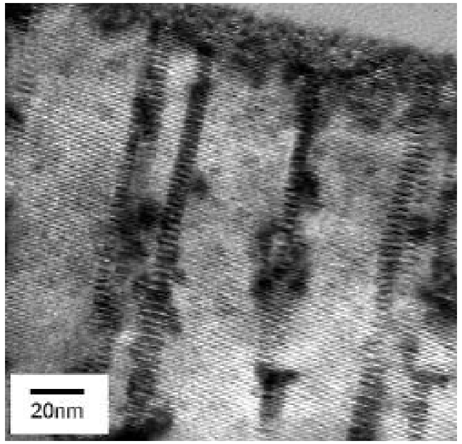
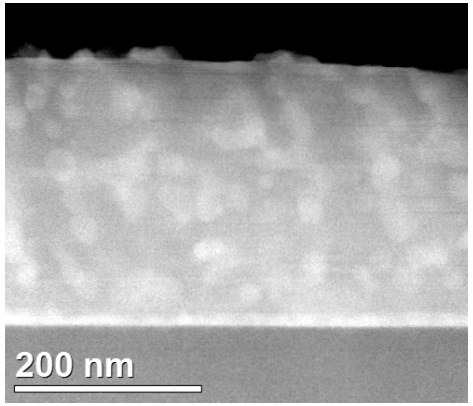
NANOCOMPOSITES

PLD (also for MOCVD)



CSD



S. Kang, Science 311 (2006), J. Guiterrez, Nat Mat 11 (2007)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Invited presentation 1-MO-CS-02I given at EUCAS, 01 - 05 September 2019, Glasgow, UK.

Present state in Industrial Coated Conductor growth

	MOCVD	PLD	Evapora-tion	RCE-DR	TFA-CSD	TLAG-CSD
Nanocomposite growth feasibility	[green]	[green]	[red]	[red]	[green]	[green]
Throughput (m/h)	[orange]	[green]	[orange]	[green]	[orange]	[green]
Fabrication costs	[orange]	[orange]	[orange]	[orange]	[green]	[green]
Growth rate (nm/s)	[red]	[orange]	[red]	[green]	[red]	[green]

Transient Liquid Assisted Growth - CSD

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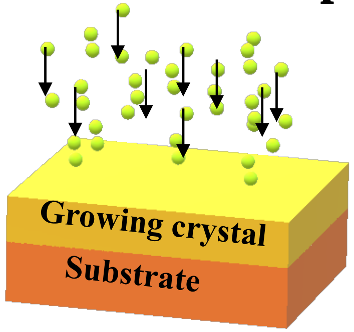
Growth mechanisms for epitaxial REBCO films crystallization

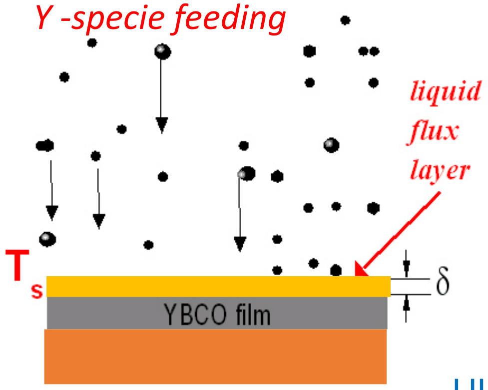
Growth from **vapour** phase



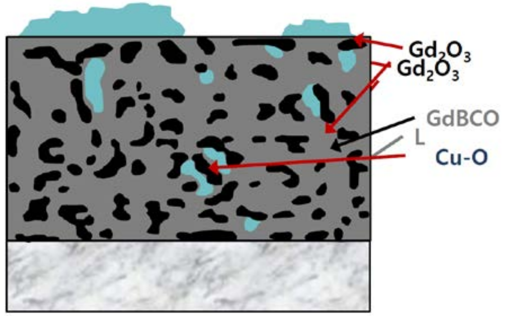
- PLD
- MOCVD
- Evaporation

PLD : 5-12 nm/s (Superox), 14 nm/s (SST)
A-MOCVD:3 nm/s (U. Houston), Evapor.: 4 nm/s (THEVA)

Growth from high temperature supersaturated **equilibrium liquids**



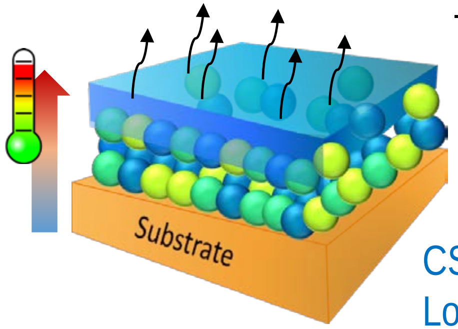
- HLPE, VLS, TPE



-RCE-DR (ex-situ)

HLPE: ~10 nm/s (UCAM)
RCE-DR: 30-100 nm/s (SUNAM)

Growth from **amorphous precursor solids**



- CSD (ex-situ)

CSD : ~1 nm/s
Low cost

Growth from **transient liquids** derived from amorphous precursor solids

- **TLAG-CSD (ICMAB)**

Growth rates from liquids : ~100 nm/s
Scalable and low cost

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Fast growth processing of CC and its compatibility with high currents

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Instrinsic factors: → **High growth rates**

- Growth mechanisms
- Materials growth rate (YBCO, GdBCO,..)

Extrinsic factors: → **High manufacturing rates**

for ***in-situ growth methods*** *(PLD, MOCVD, evaporation)*

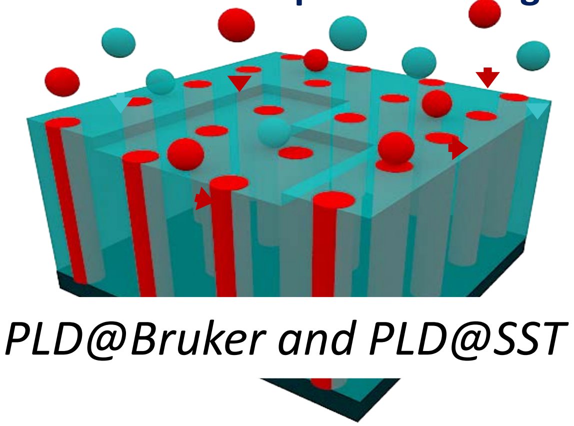
- High deposition velocity
- High deposition area
- Multi-plume
- Multi-lane
- PLD high power and frequency laser,…
- Nanocomposites might be compromised

for ***ex-situ growth methods*** *(RCE-DR, CSD, TLAG-CSD)*

- Independent deposition and growth processes
- Multi-turn deposition
- Furnaces dimensions
- High deposition area
- Nanoparticles may not be compromised
- Some high growth rate processes are being used

In-situ growth methods

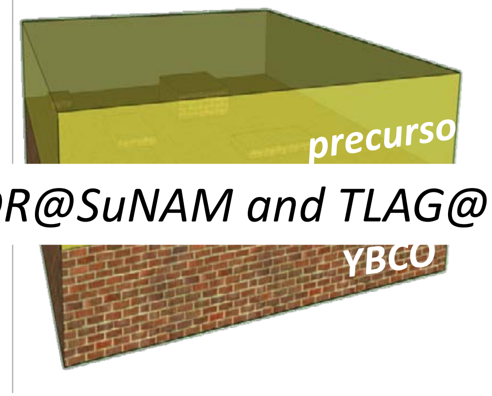
Simultaneous deposition and growth



PLD@Bruker and PLD@SST

Ex-situ growth methods

Sequential deposition and growth



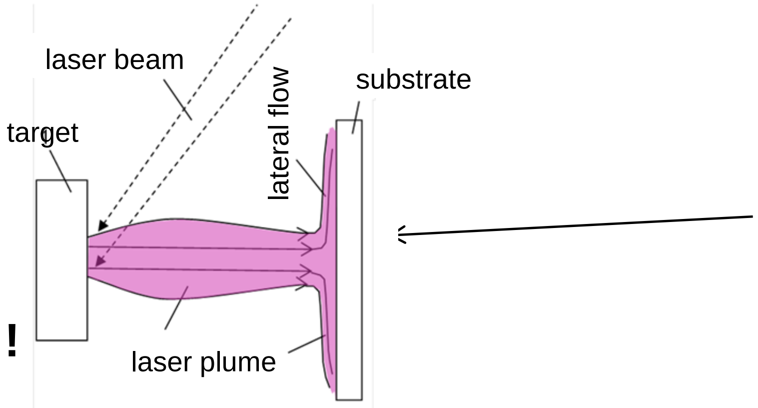
RCE-DR@SuNAM and TLAG@ICMAB

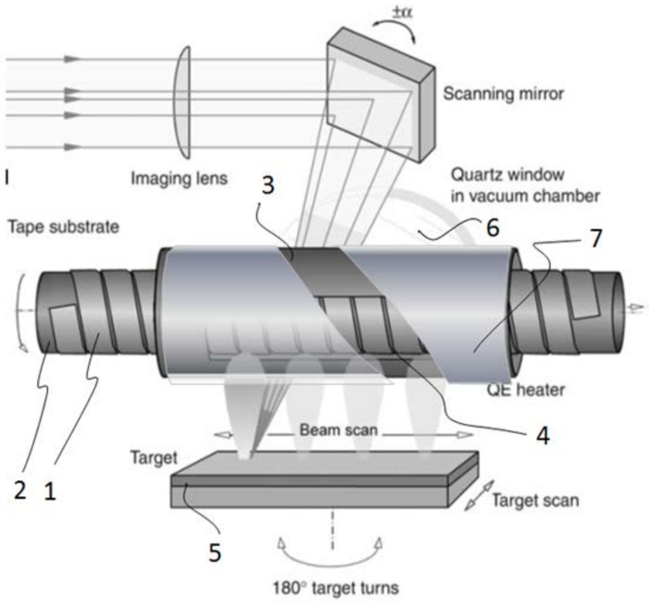
BRUKER HTS GmbH

- The processing speed of long length **DD YBCO films** by Pulsed Laser Deposition is performed in a **dynamic mode**. Main impact factors on the processing speed are:
  - Target properties
  - **Beam scan** parameters
  - **Substrate rotation** and movement
  - Process environment (T, p)
- The **deposition rate in the static mode exceeds** **150 nm/s** at the maximum of the local film thickness distribution

Multi-plume, multi-turn, high power and high frequency laser

I_c=1200 A/cm-w at 4.2 K @ 20 T !





Strategy for "fast growth" in PLD at SST

上海超导

Multi-plume- Multi-lane PLD: typical growth rate in a mass-production is Average rate= **20nm/sec** between 10-50nm/sec (**tape speed 120m/hr**)

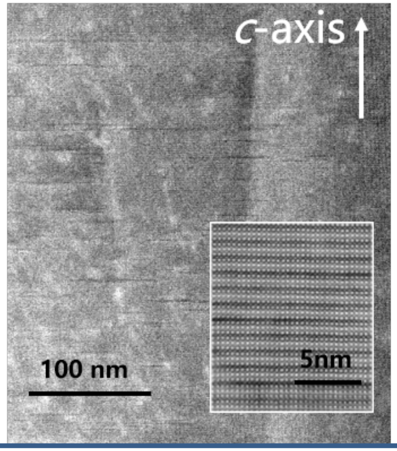
Need to balance between I_c and production speed

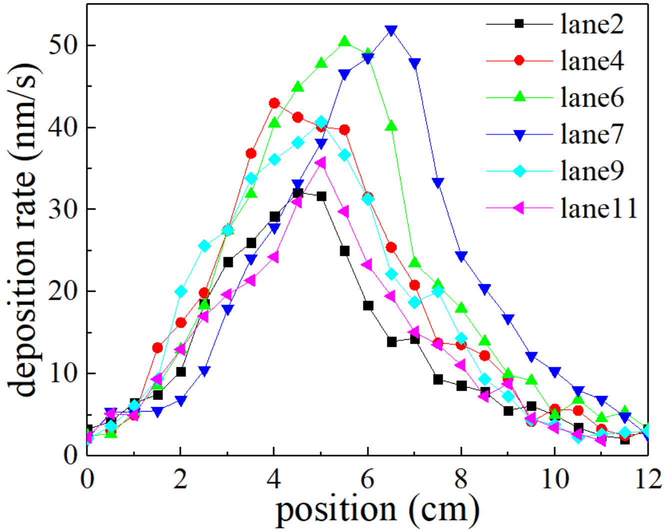
High deposition rate makes more stacking faults and high I_c at low temperatures. → favorable for realistic industry operation

High I_c with SF without columnar structutre

I_c=1200 A/cm-w at 4.2 K @ 17 T !

Material: Y→Gd (production speed was doubled.)



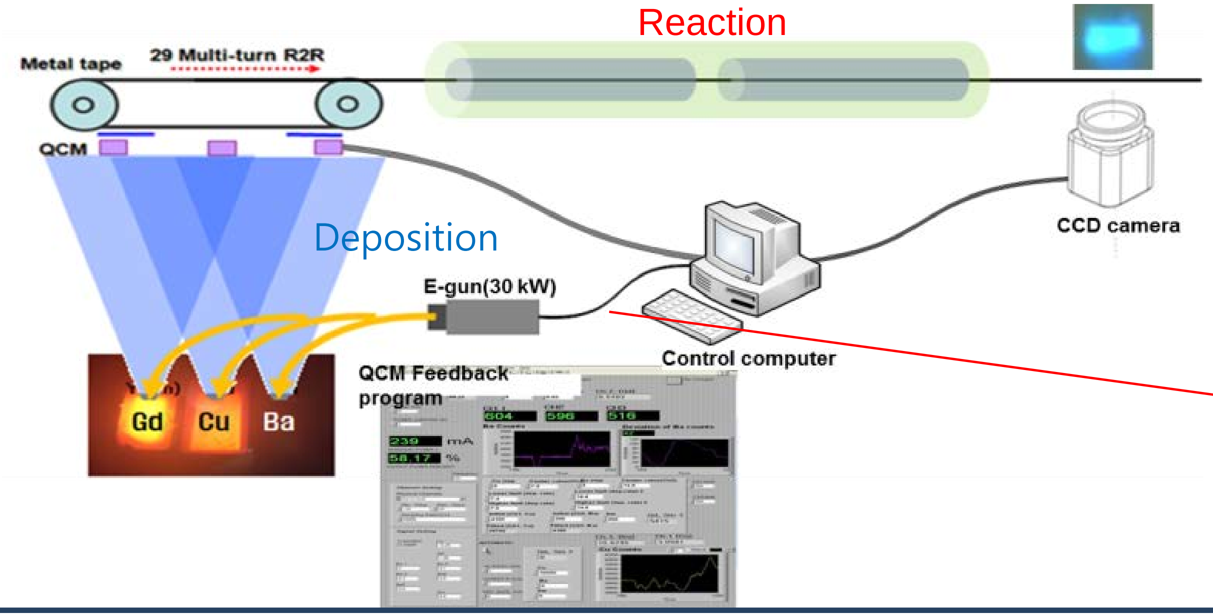


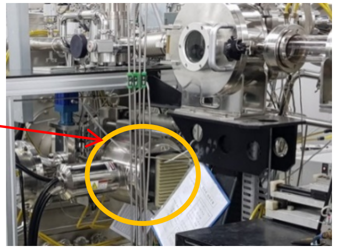
Compromised between rate and area

Next strategy:

Material: Y→Gd, APC → Re-survey for high rate, wide temp. range, PO2 (stability in production) → Next MBCO+APC'

Introduction of RCE-DR process & system





- RCE-DR : Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R)
- **High rate co-evaporation at low temperature & pressure** to the target thickness(> 1 μm) at once in deposition zone (**6 ~ 10nm/s**) – **120 m/h tape speed**
- **Fast conversion(up to 100 nm/sec)** from amorphous glassy phase to superconducting phase at high temperature and oxygen pressure in reaction zone
- Simple, high deposition rate & area, low system cost
- Easy to scale up :single path
- Verified for Gd, Y, Sm, … …

I_c=750 A/cm-w at 77 K,sf !

SuNAM

Superconductor,
Nano & **A**dvanced **M**aterials

	PLD	RCE-DR	TLAG-CSD
Growth rate (nm/s)	5-10 (16 for LA-PLD*)	~100	100
Deposition velocity	High power laser Multi Plum Multi-lane Drum	6-10 nm/s multiturn evaporation	Multi-lane pyrolysis & furnace length
Deposition area	High	High	High
Reel-to-reel adaptation	Achieved	Achieved	Easy
Tape speed	120 m/h (SST)	120 m/h Limited by deposition speed	60 m/h (pyrolysis) 700 m/h (growth)
Average manufacturing rate	150 nm/s (BRUKER) 20 nm/s (SST)		100 nm/s x number of parallel tapes

** Cambridge Liquid-assisted PLD variant*

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YBCO-CSD Growth methods

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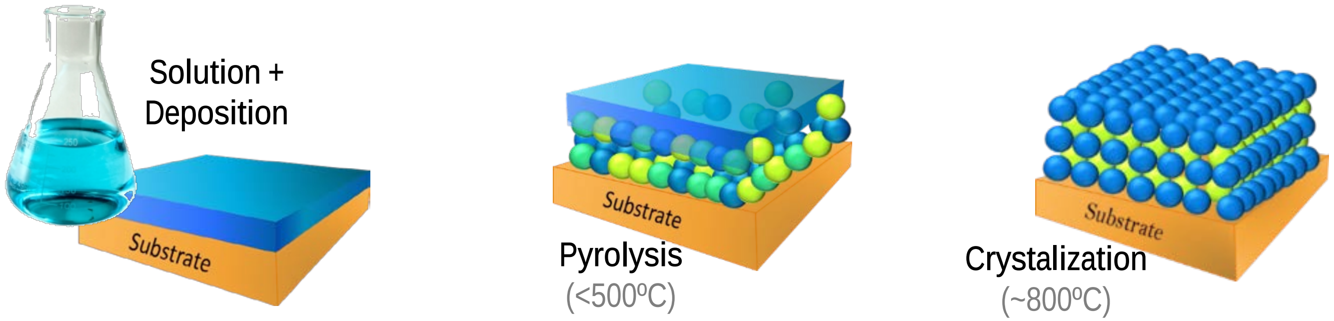
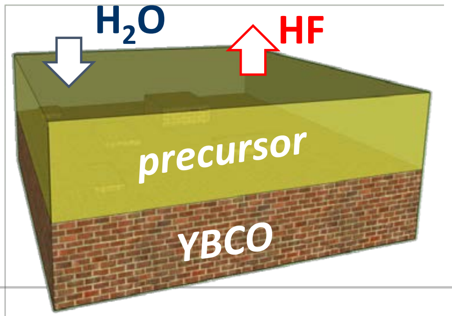


Decoupled processes

TFA- route

Trifluoroacetate based precursors

$Ba_{1-x}Y_xF_{2-y}O_y$ + CuO + Y_2O_3

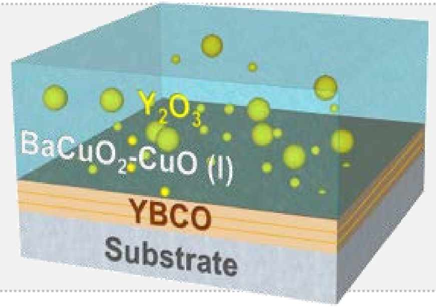


- ❖ *Gas-solid conversion reaction*
- ❖ *Slow growth rates (~1 nm/s)*
- ❖ *Slow HF removal – complex reactor*

TLAG- route

Fluorine Free based precursors

$BaCO_3$ +CuO + Y_2O_3



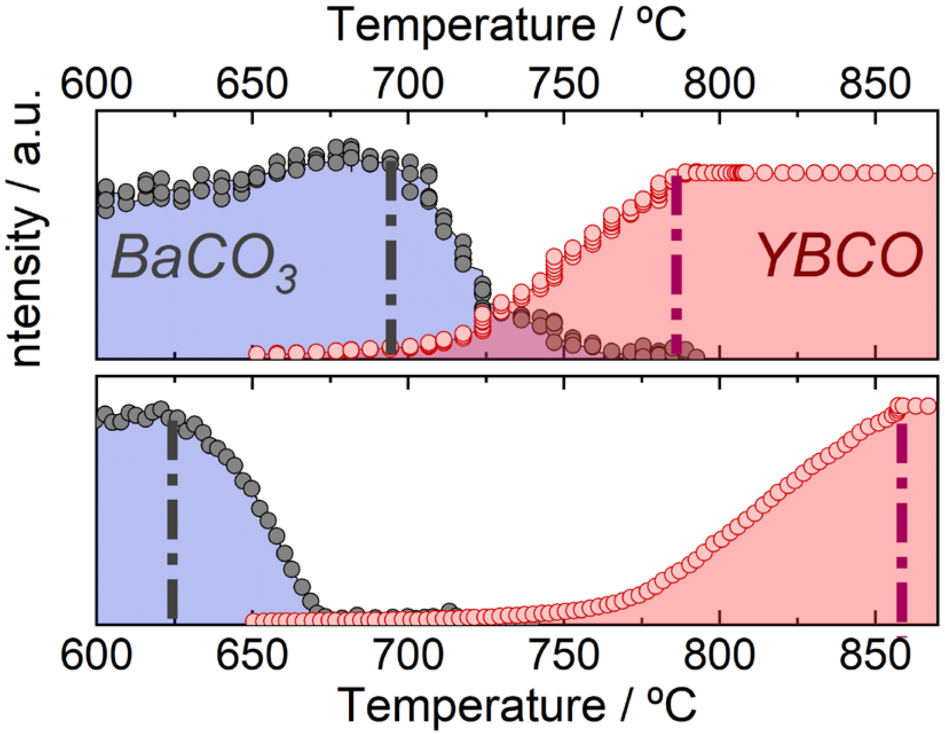
- ❖ *Liquid-solid conversion reaction*
- ❖ *Fast growth rates-100 nm/s*
- ❖ *Dependent on $BaCO_3$ decomposition*
- ❖ *Simple reactor –environment friendly*

TLAG = Transient Liquid Assisted Growth

TLAG-CSD
$BaCO_3$ decomposition is not an issue

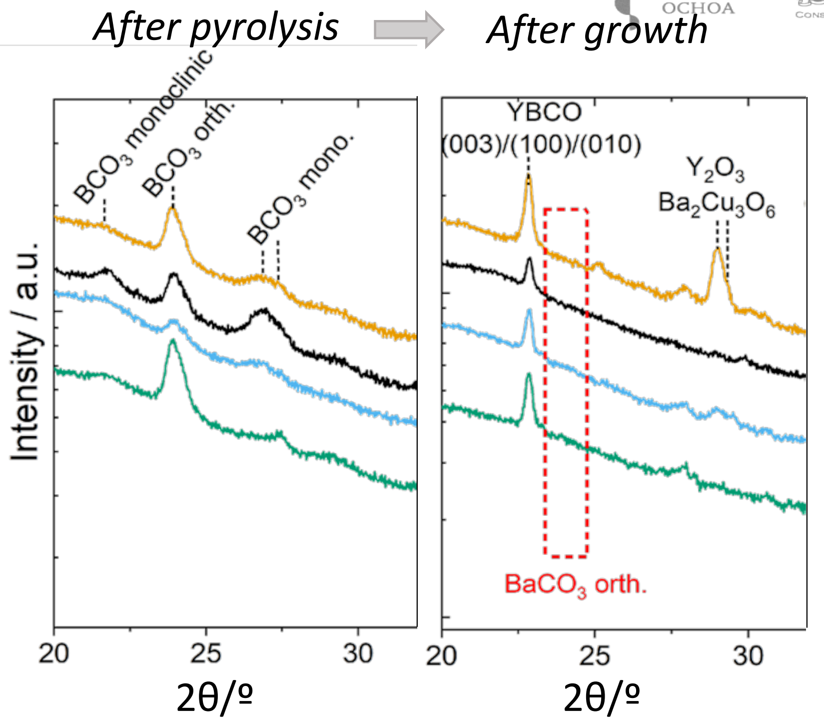
(T, P_{O2}, P_{total}, heating ramp, composition…)

In-situ XRD at Soleil sync.

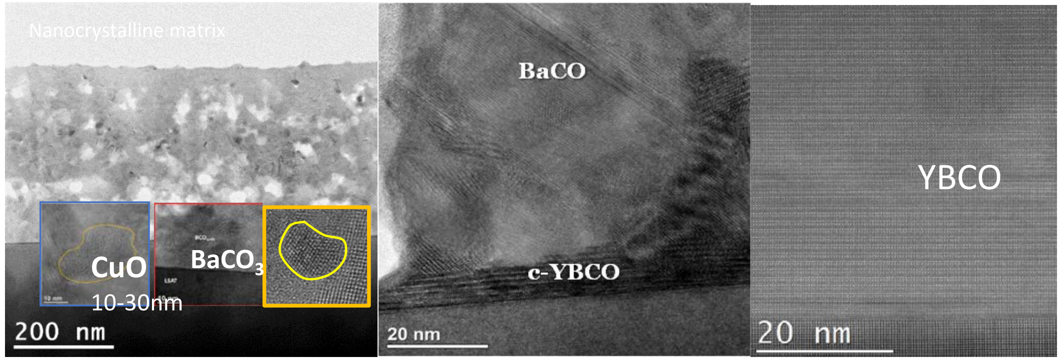


Decomposition in seconds at high heating rates

See 3-MO-CU-02S (J. Bancheswki), 3-MO-CU-04S (S. Rasi)



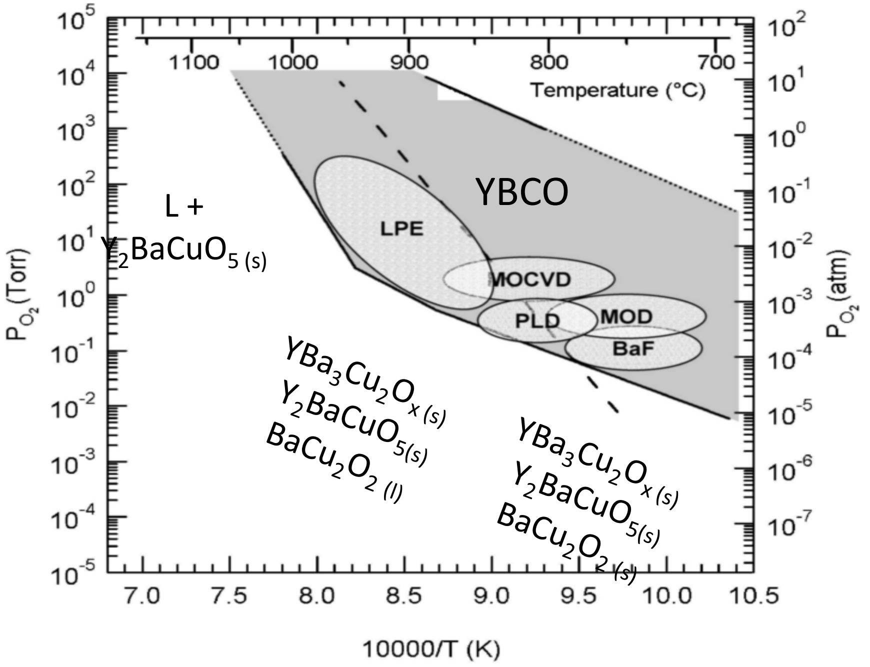
1 µm thick epitaxial layers

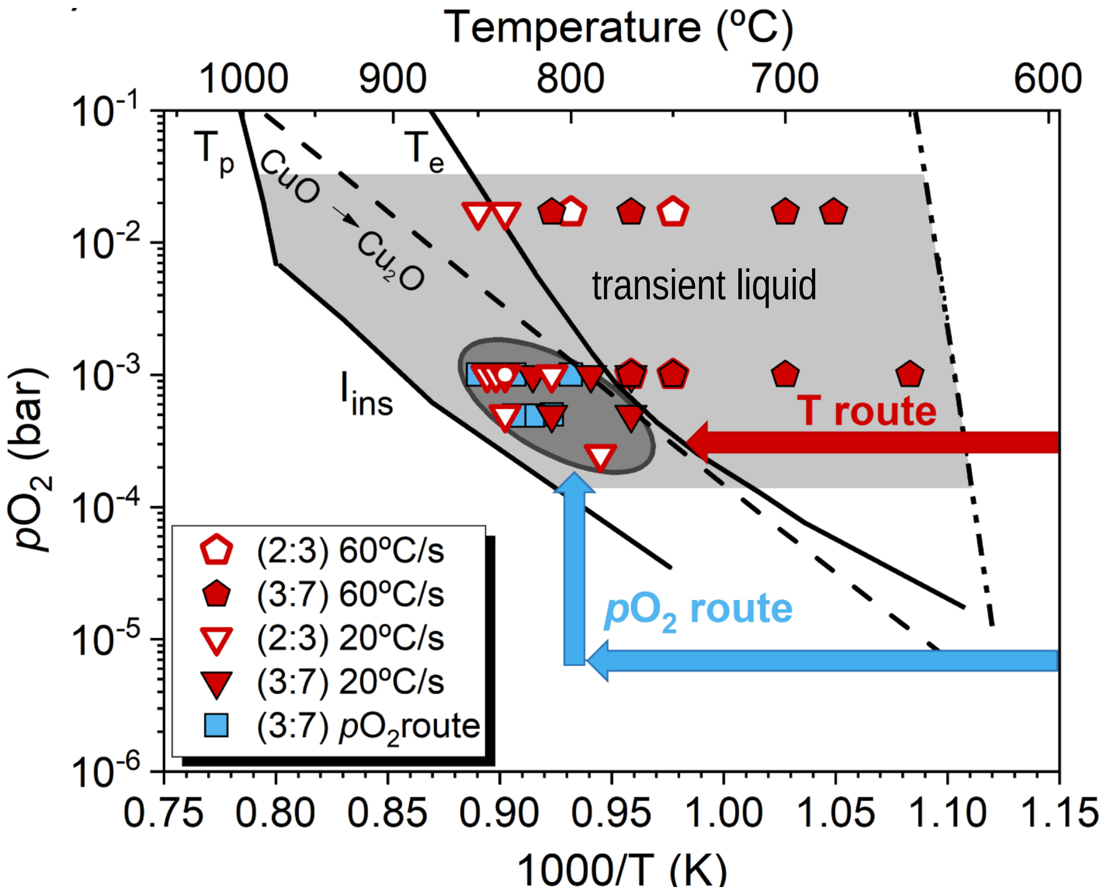


Transient Liquid Assisted Growth: TLAG-CSD

$2BaCO_3(s) + 3CuO(s) + 1/2Y_2O_3 \rightarrow [2BaCuO_2 + CuO](l) + 1/2Y_2O_3 + 2CO_2(g) \rightarrow YBa_2Cu_3O_{6.5} + yO_2(g)$

$YBa_2Cu_3O_{7-x}$ phase diagram





- Transient liquids ($BaCuO_2$-CuO) form much faster than the equilibrium solid phase (YBCO)
- No need of equilibrium liquid phases in the phase diagram
- Kinetically driven growth process

Very wide area of YBCO c-axis nucleation if heating rates > 20ºC/s (RTA furnaces)

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TLAG-CSD: $[2BaCuO_2 + CuO](l) + 1/2Y_2O_3 + 2CO_2(g) \rightarrow YBa_2Cu_3O_{6.5} + yO_2(g)$

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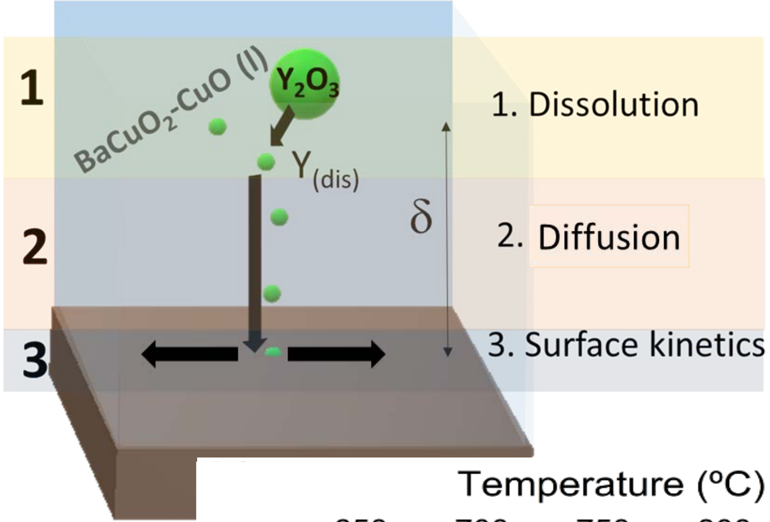
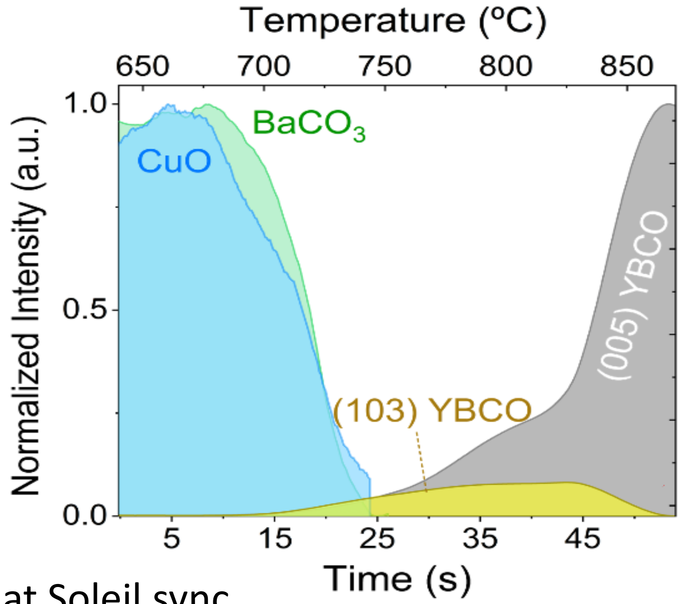
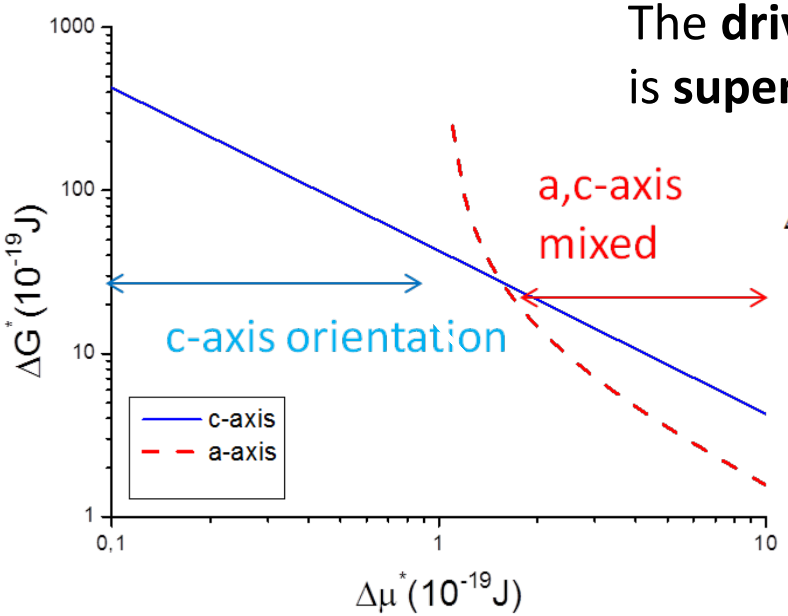


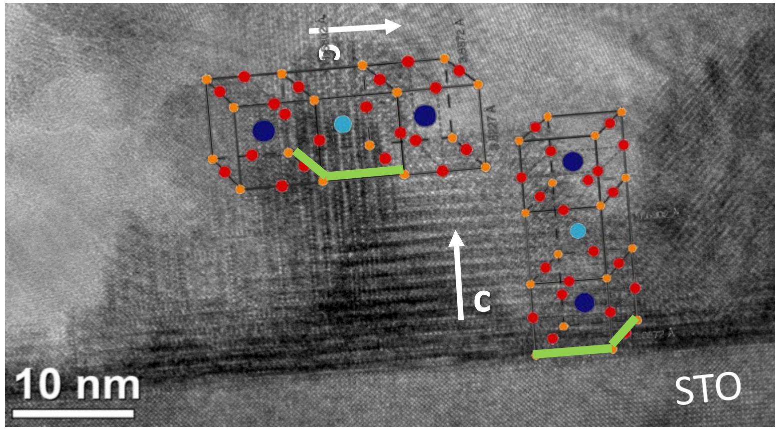


In-situ XRD at Soleil sync.



The **driving force** for nucleation is **supersaturation:**

$$\Delta\mu = kTln\frac{C_\delta}{C_e} = kTln(\sigma + 1)$$



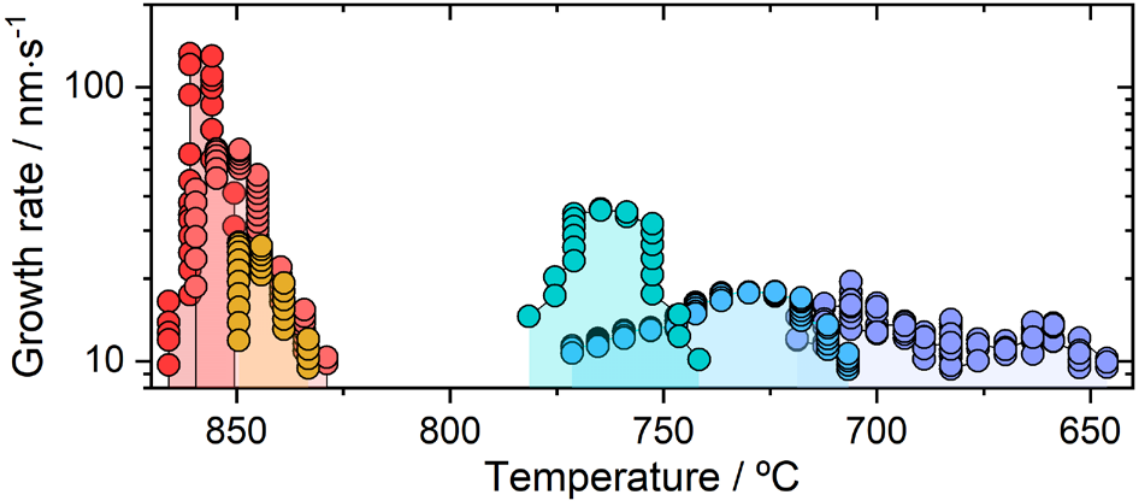
For YBCO c-axis growth, low supersaturation is needed

(Y (RE) concentration & solubility, liquid composition)

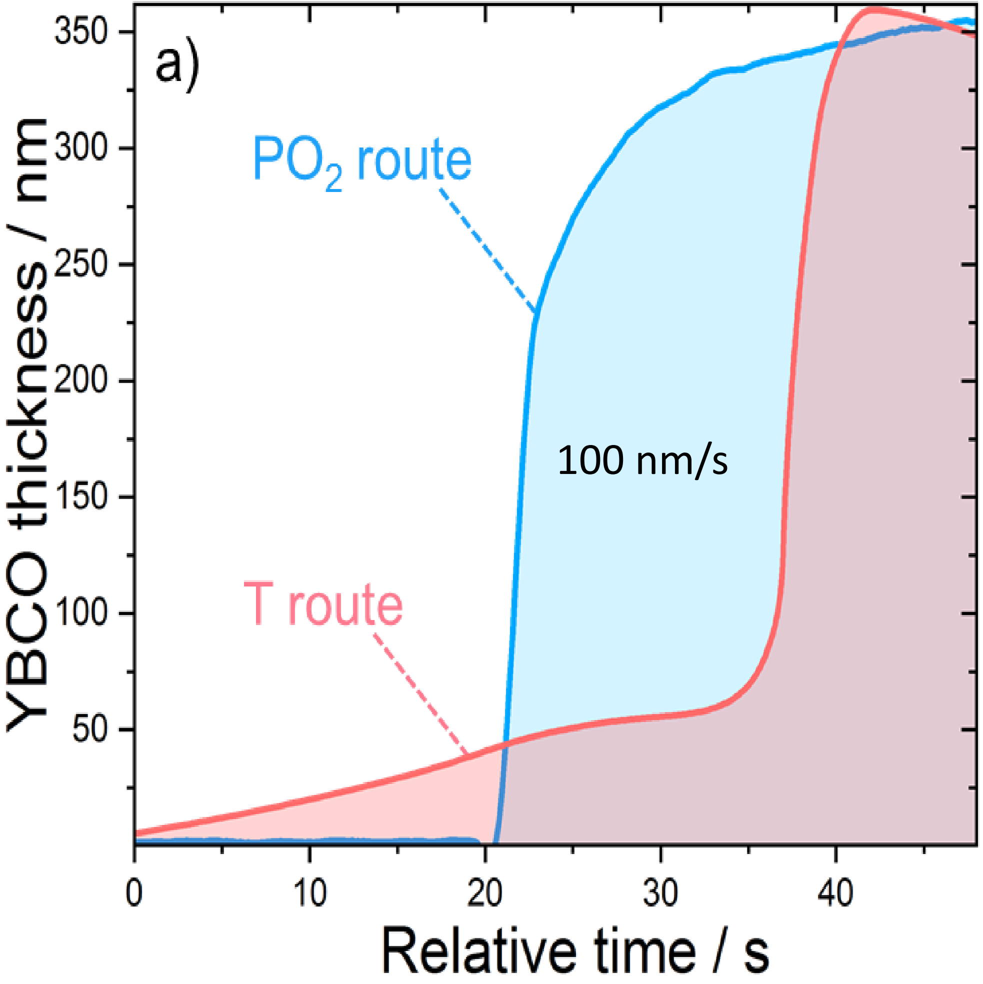
Ultrafast growth by TLAG-CSD

In-situ XRD at Diffabs
(*col. C. Mocuta*)

100 ms acquisition time



See 3-MO-CU-02S (J. Bancheswki)



L. Soler et al, submitted

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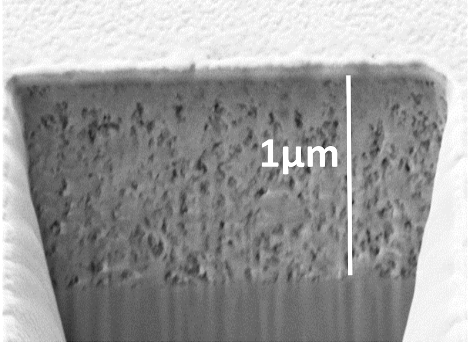
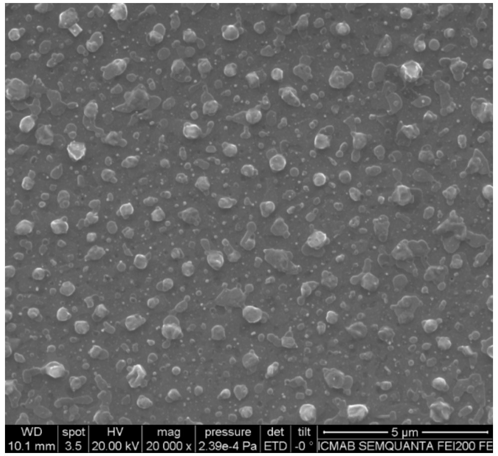
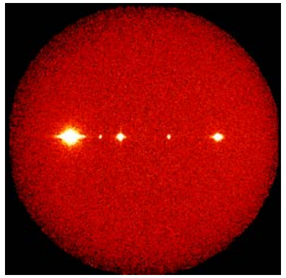
Transient Liquid Assisted Growth (TLAG-CSD) films

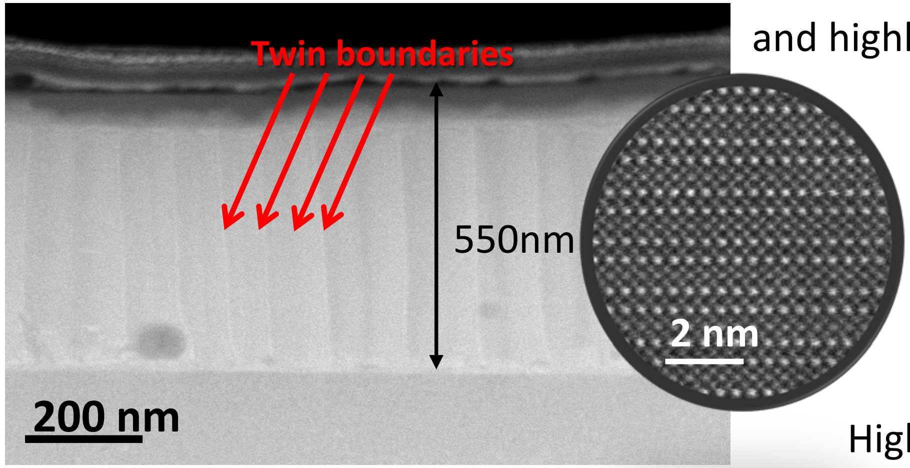


Homogeneous pyrolysis and compatible with IJP

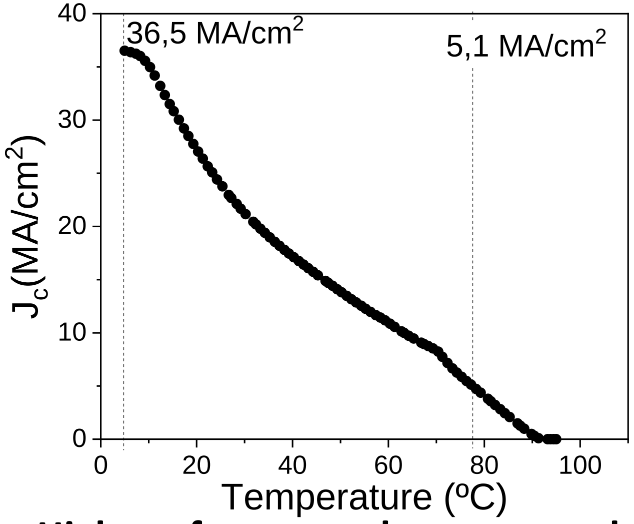




Extremely low porosity and highly epitaxial



High quality growth



High performance demonstrated
J_c(77K)~ 5 MA/cm^2
T_c ~ 90 K

L. Soler et al, to be published

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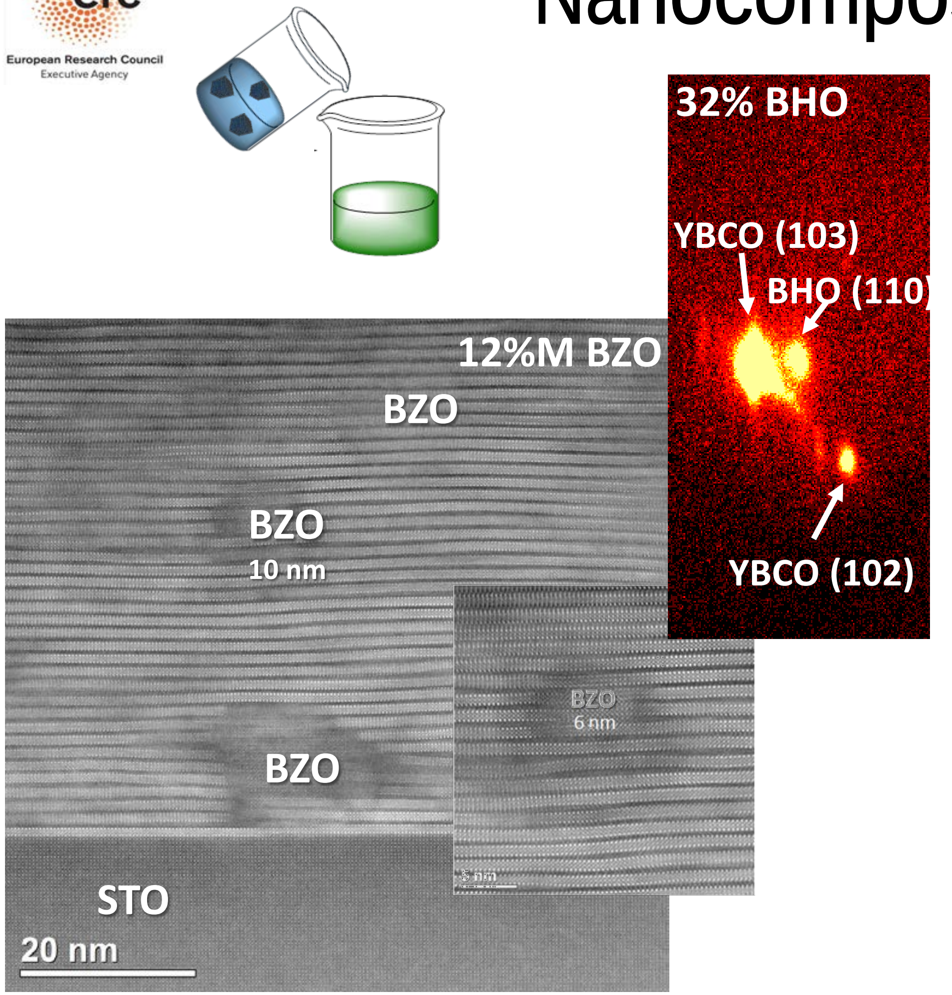
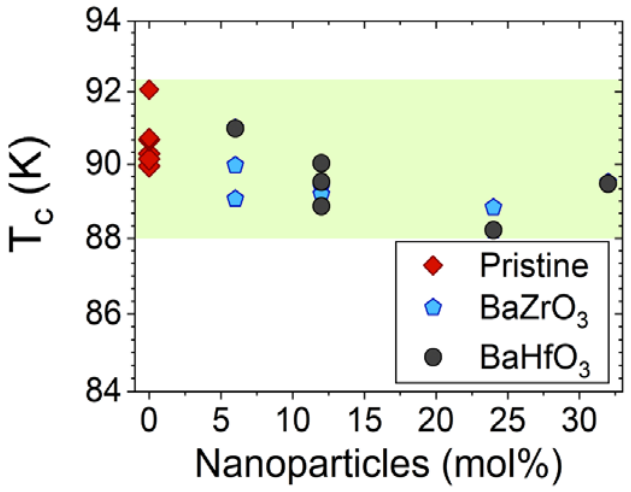
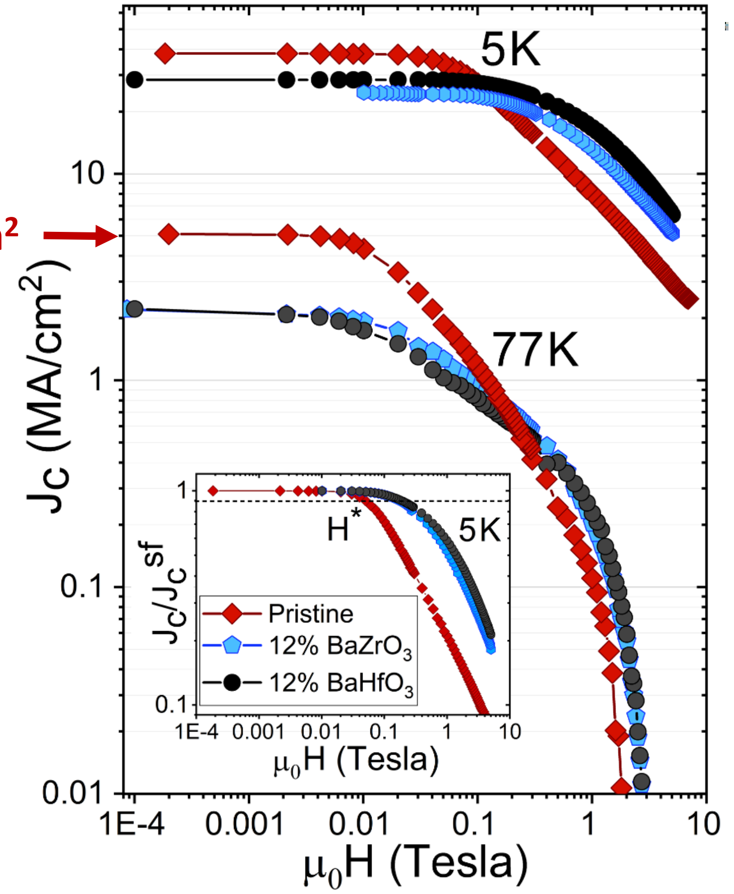
European Research Council
Executive Agency

Nanocomposites by TLAG-CSD



Very high density of defects and small epitaxial nanoparticles in nanocoposites





In-field performances of TLAG nanocomposite outperform pristine films

L. Soler et al, submitted

See 2-MO-FP1-05S (X. Obradors) and 1-MPCC1-102 (A. Queralto) for opportunities with Ink Jet Printing

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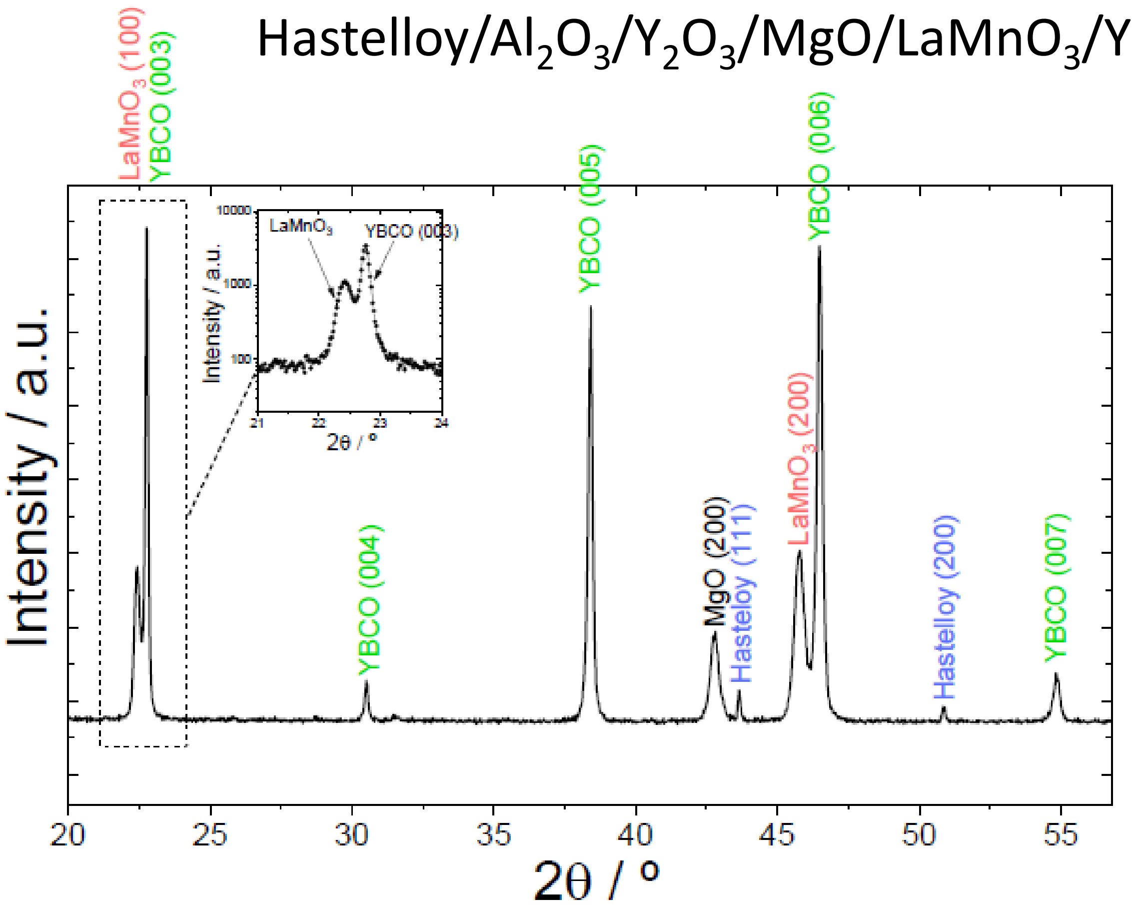
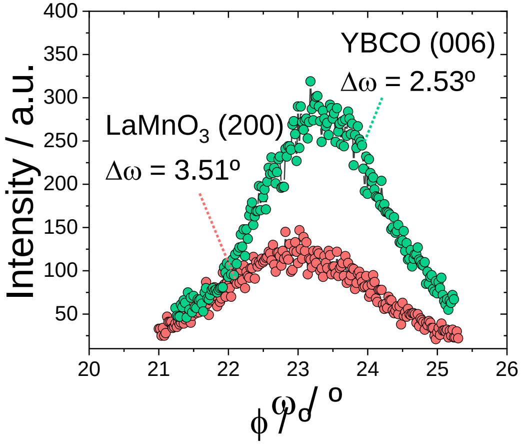
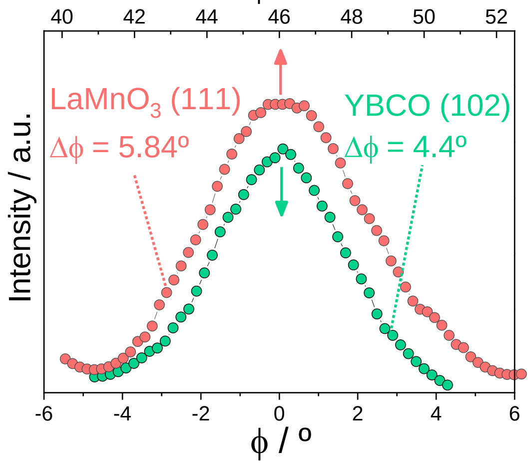
TLAG-CSD Coated Conductors

SUNAM IBAD substrates:

Hastelloy/Al_2O_3/Y_2O_3/MgO/$LaMnO_3$/YBCO







High texture quality , no interfacial reaction

Colab. between SuNAM, OXOLUTIA and ICMAB within Impact ERC-PoC

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TLAG YBCO coated conductor

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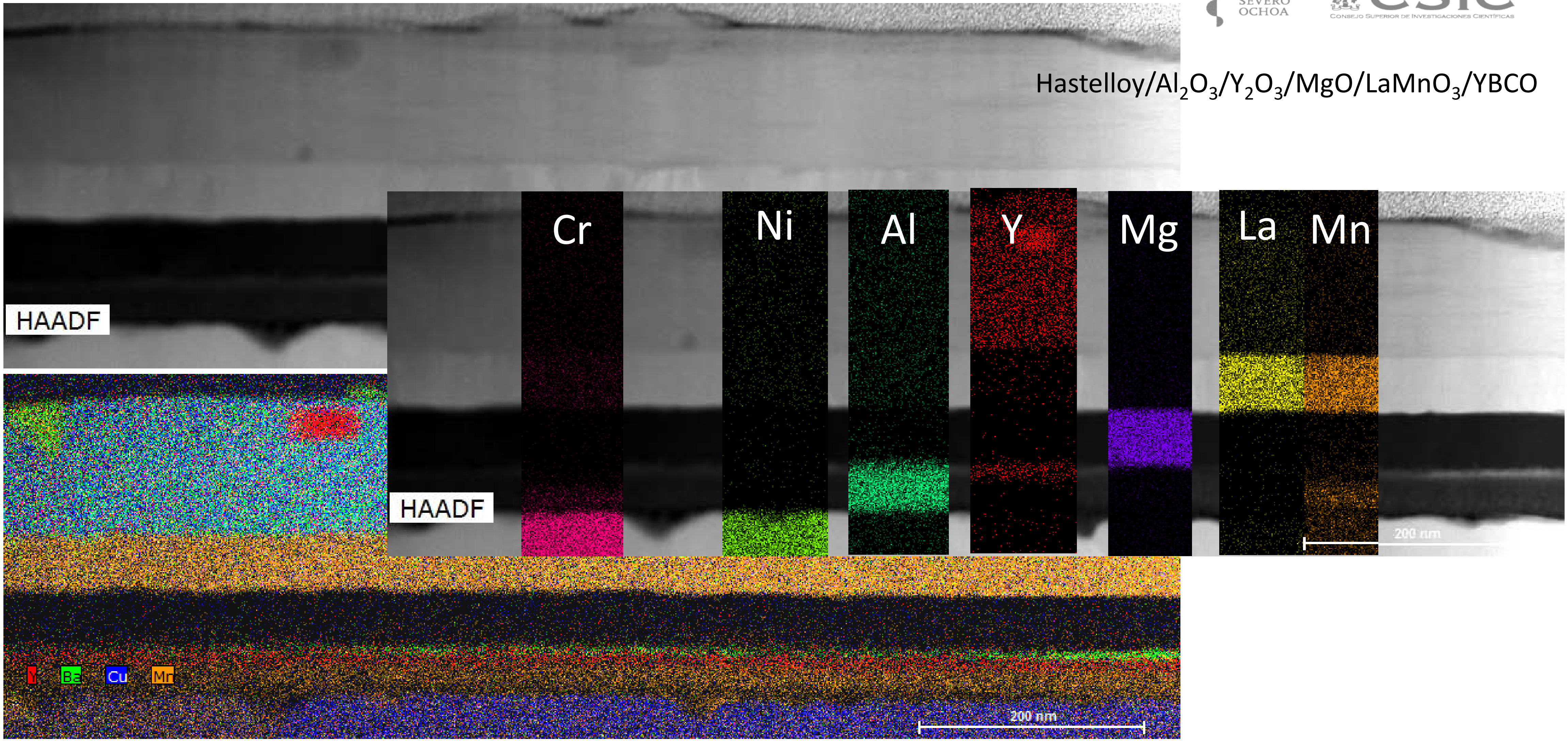
TEM-EDX analysis: Homogeneous layers and clean interfaces without reactivity

Hastelloy/Al_2O_3/Y_2O_3/MgO/$LaMnO_3$/YBCO



Conclusions and prospectives

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- ❑ HTS coated conductors have reached impressive performances also at high magnetic fields
- ❑ Strategies are being followed to decrease cost/performance ratio. In particular by:
  1. Increasing manufacturing rates
  2. Using high growth rate processes like those assisted by liquids
- ❑ Very good prospectives are envisaged for PLD, RCE-DR and TLAG-CSD concerning fast fabrication rates
- ❑ TLAG-CSD is a new opportunity combining very high growth rates of 100 nm/s with CSD methods and nanocomposites growth