Advanced characterization to underpin the mechanisms of ultrafast *Transient Liquid Assisted Growth* (TLAG) of superconducting epitaxial layers

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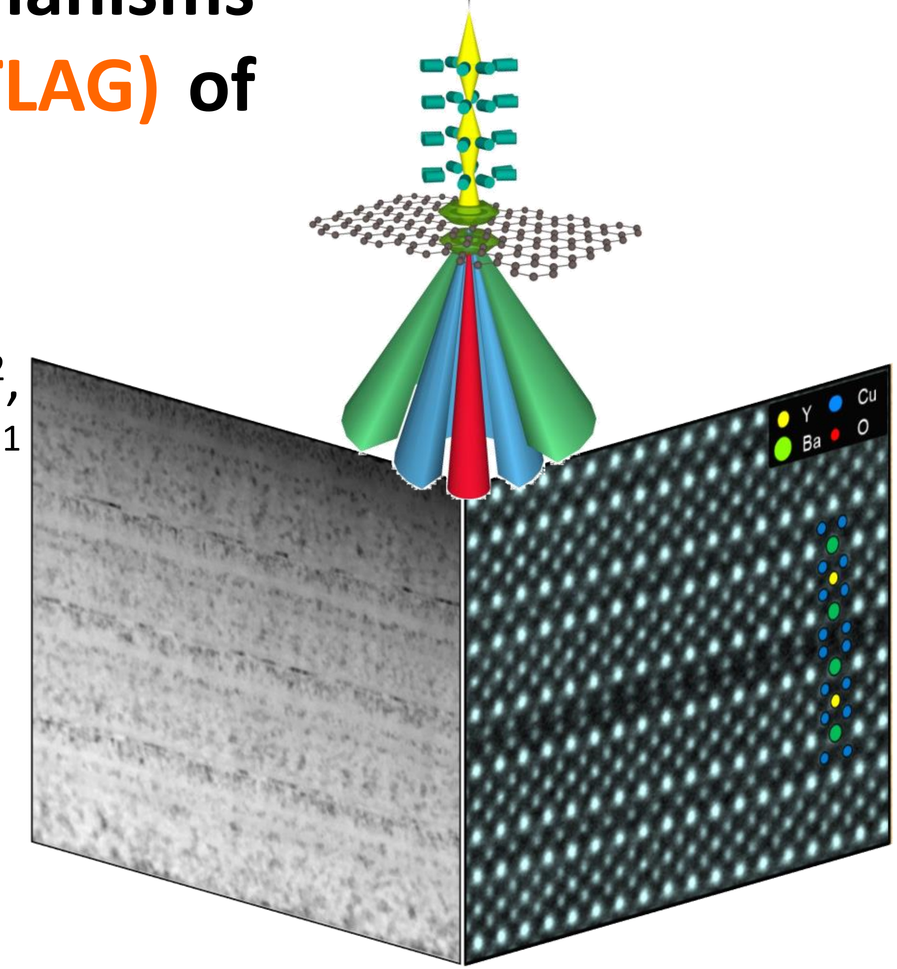
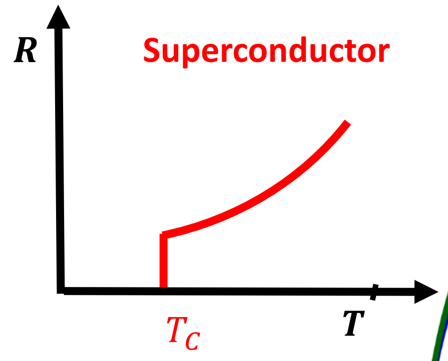
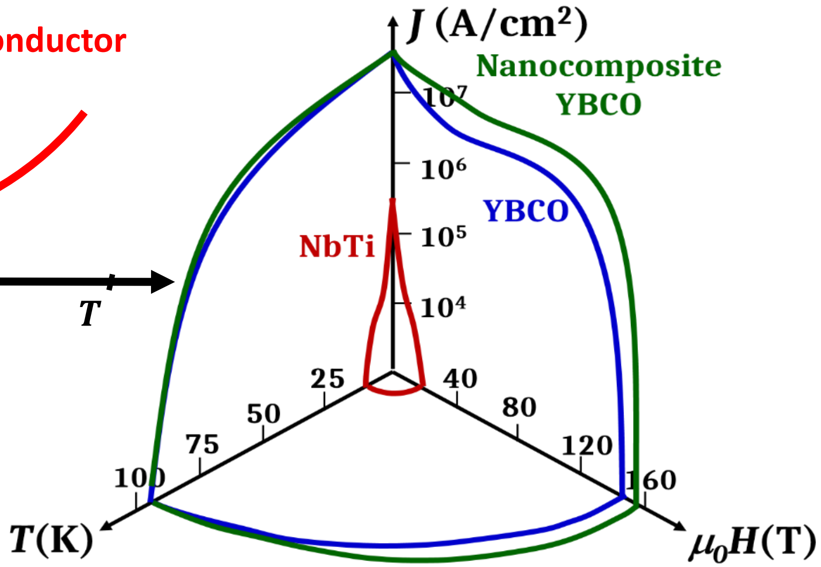


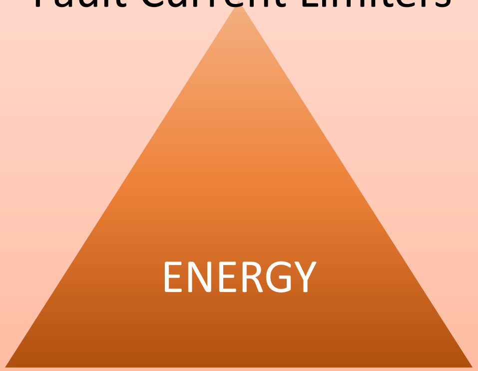
High Temperature Superconductors for Energy Transition





Devices with:
-low losses
-high magnetic fields
-low weight, volume

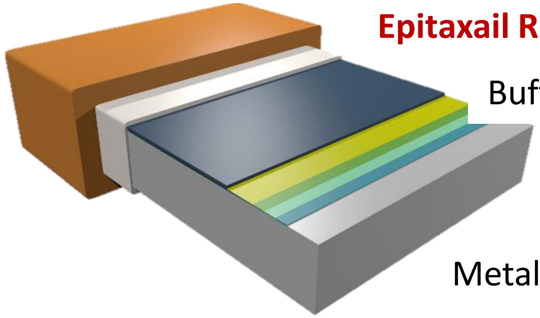
Distribution
Cables
Fault Current Limiters



Generation
Wind generators
Compact Fusion

Transportation
motors and generation
in electrical aircrafact

Long length Coated Conductor (CC)



Protective Cu + Ag layers

Epitaxail REBCO (1 – 3 μm) → Low cost, High throughput, Scalability

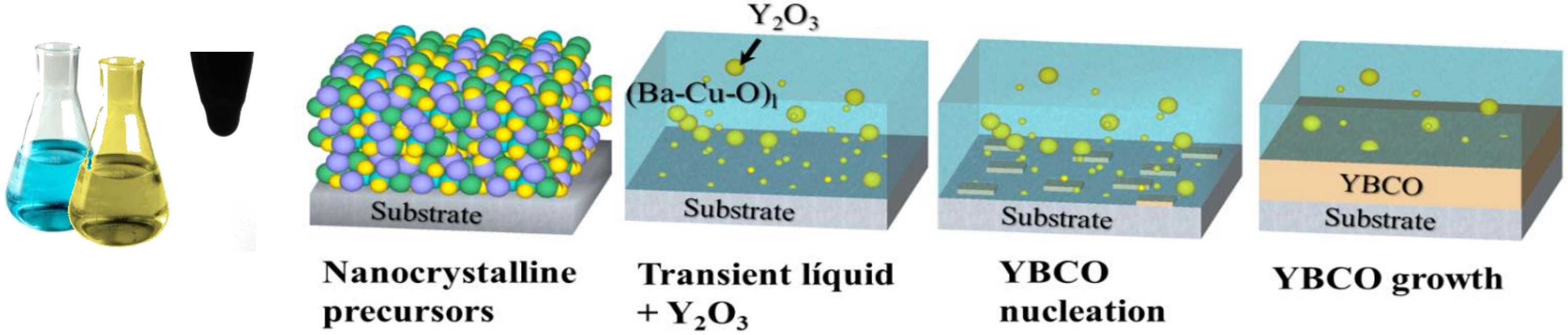
Buffers (0.2 – 1 μm)

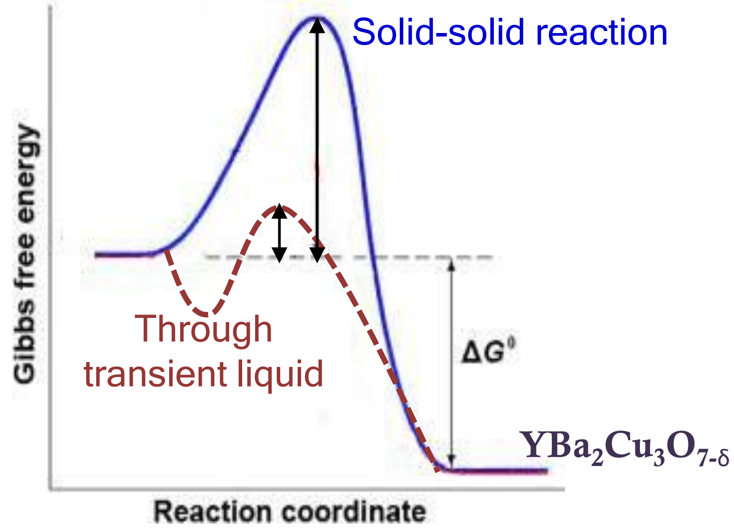
Metallic substrate (30 - 100 μm)

-PLD (5-15 nm/s)
-MOCVD (1-10 nm/s)
-Evaporation (5 nm/s)
-TFA- Chemical Solution Deposition (1 nm/s)

TRANSIENT LIQUID ASSISTED GROWTH: TLAG

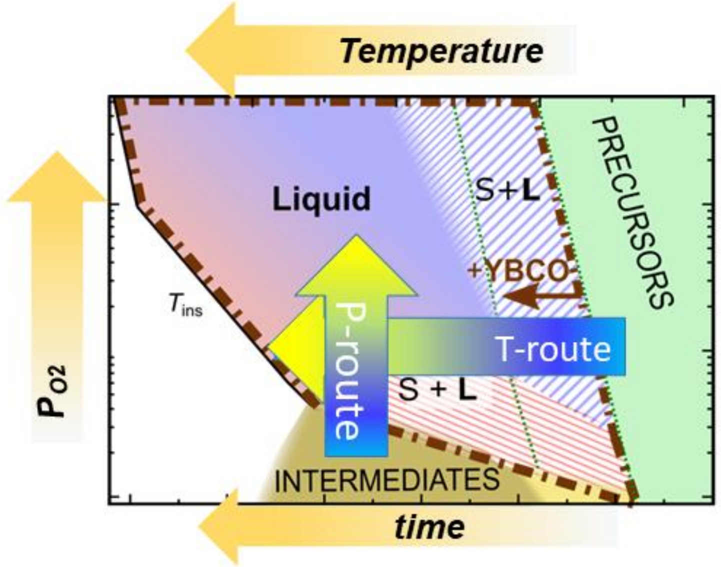
A non-equilibrium kinetically controlled process for ultrafast growth





(M-Prop) →

$$\mathbf{BaCO_{3(s)} + CuO_{(s)}} + Y_2O_{3(s)} \longrightarrow \mathbf{(Ba - Cu^{I/II}\text{-}O)_{(l)} + Y_2O_{3(s)}} \longrightarrow YBa_2Cu_3O_{7-\delta}$$



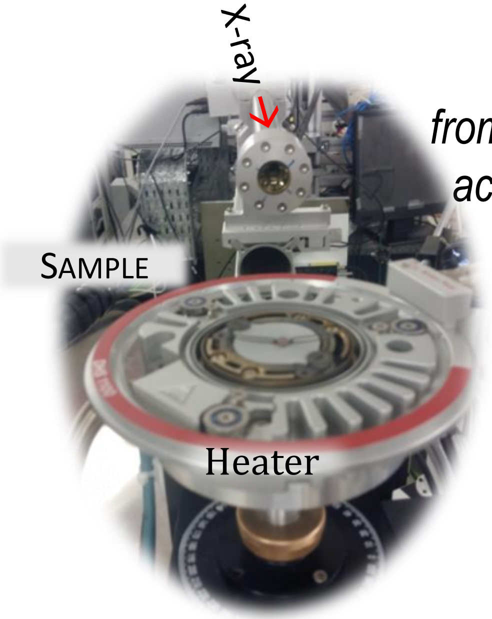
- Ultrafast growth rate, G, up to 2000 nm/s demonstrated
- Large area deposition, simple reactor
- High throughput
- Low cost

But,

- Kinetic growth mechanism need to be elucidated
- Nano-microstructure is crucial because it determines performance

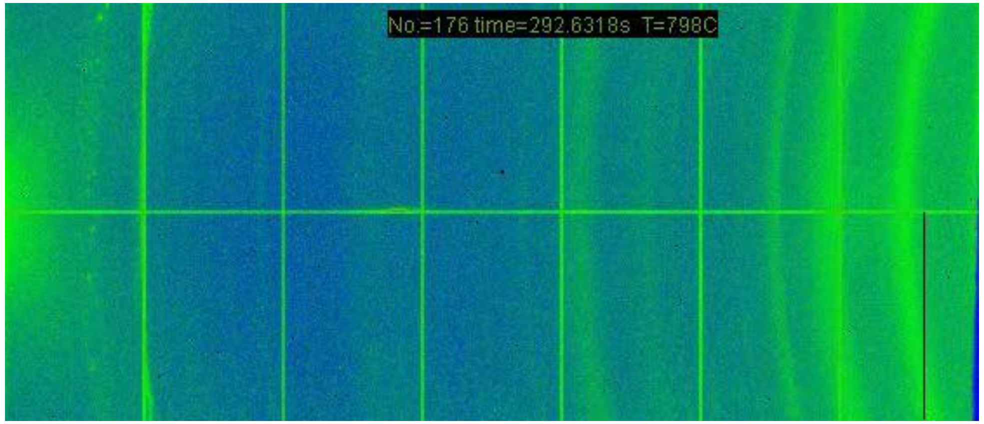
L. Soler et al., Nat Comm (2020)
S. Rasi, et al, Advance Science (2022)
L. Saltarelli et al, ACS Appl. Mat. & Interf. (2022)
A. Quetalto et al, SUST (2023)

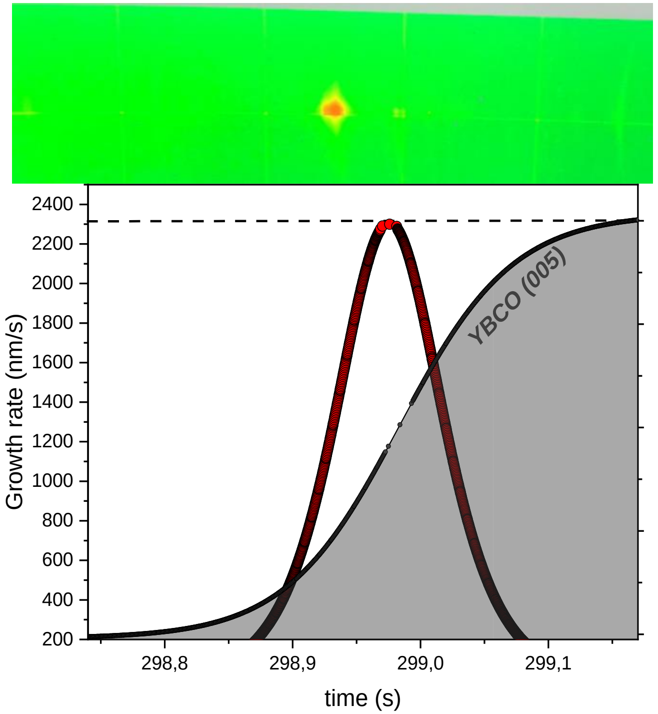
TLAG in-situ growth evaluation



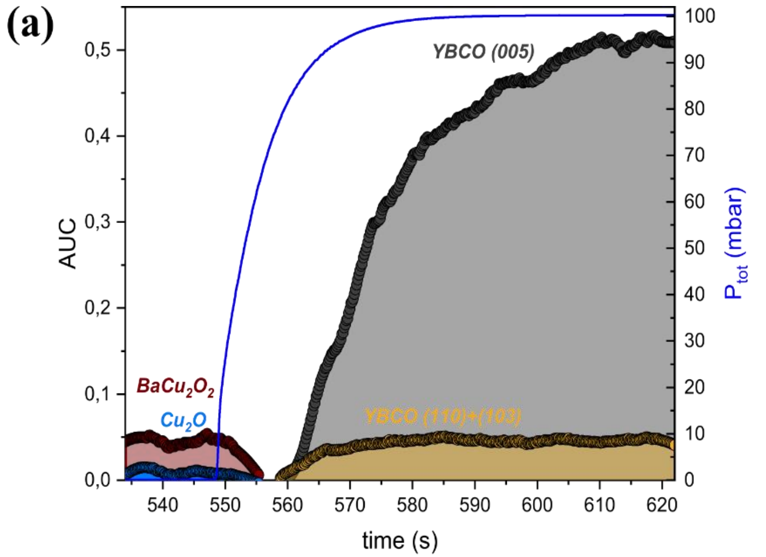
from 100 ms down to 2 ms acquisition time

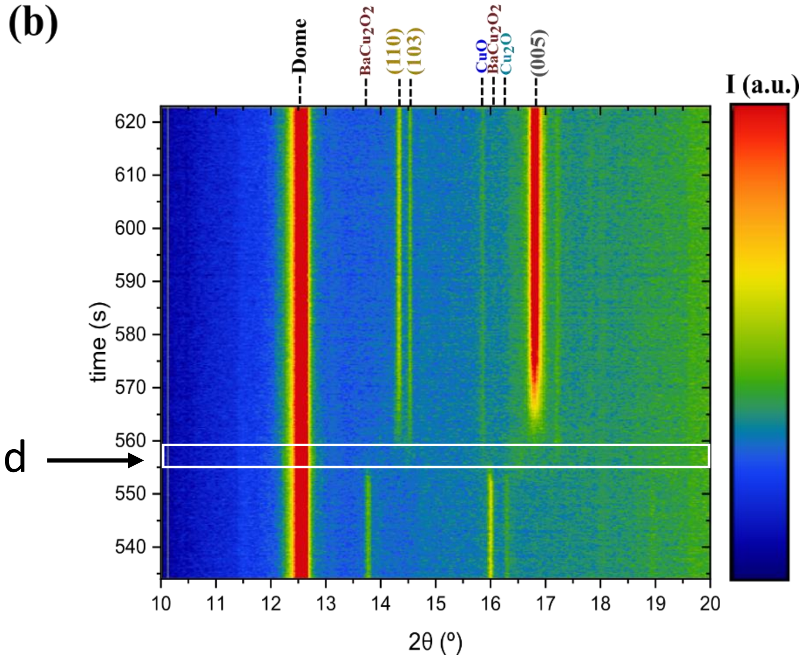
In-situ growth XRD synchrotron experiments





2300 nm/s for 400 nm films
2 ms acquisit. (110 Hz)





Transient liquid →

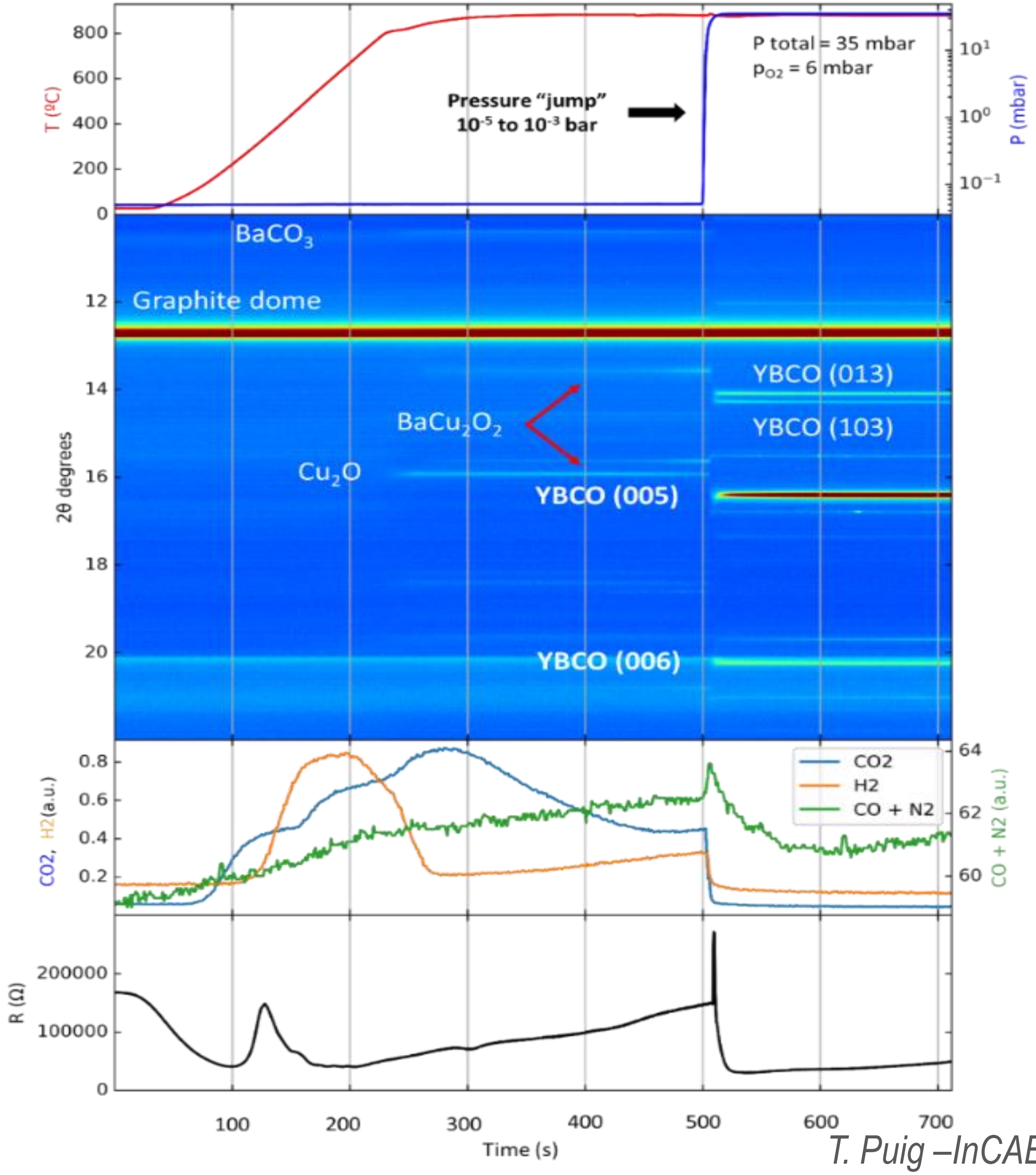
L. Soler et al Nat Comm (2020), S. Rasi, et al, Advance Science (2022)

In-Situ ALBA Synchrotron installation

NCD-SWEET BEAMLINE

GIWAXS detector

Heating stage



Experiment conditions

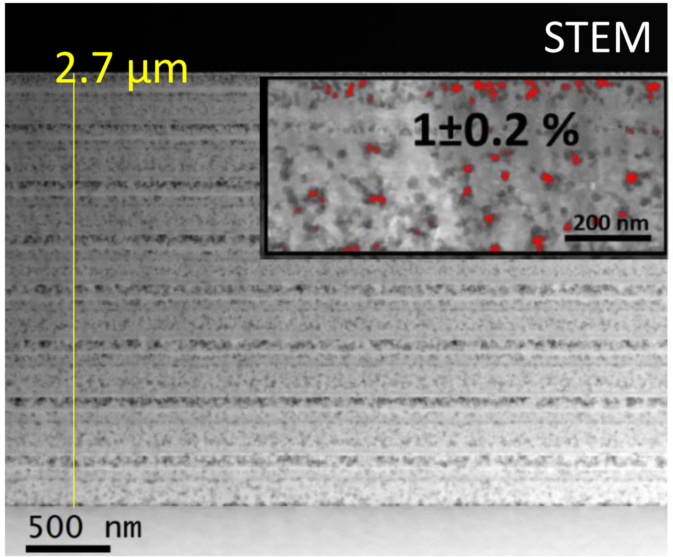
Synchrotron XRD

Mass spectroscopy

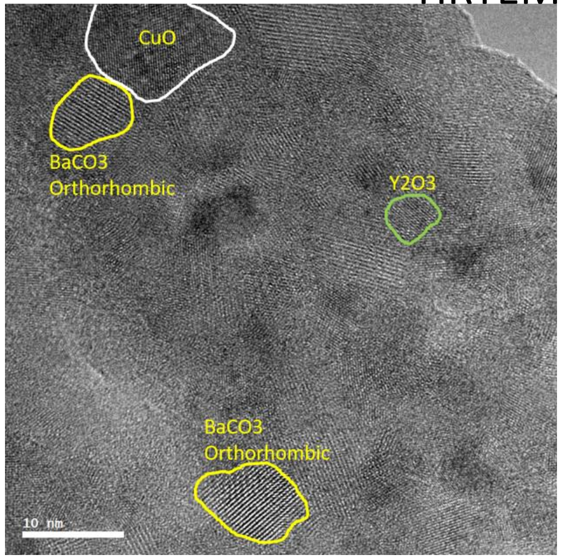
Resistivity

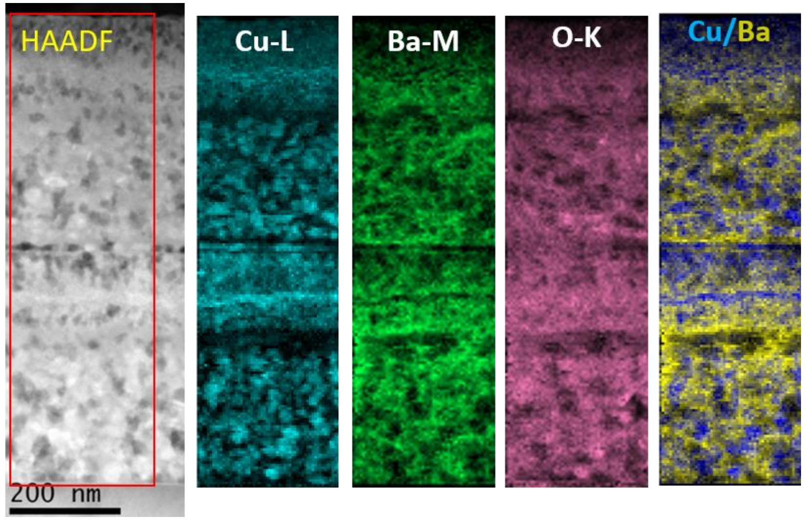
YBCO TLAG FILMS: Requirements for epitaxial growth

Nanoscale homogeneous and low porosity precursor films



HRTEM

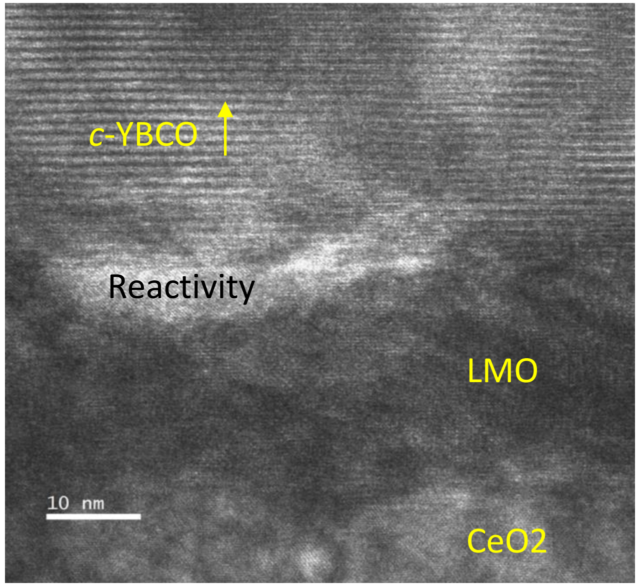




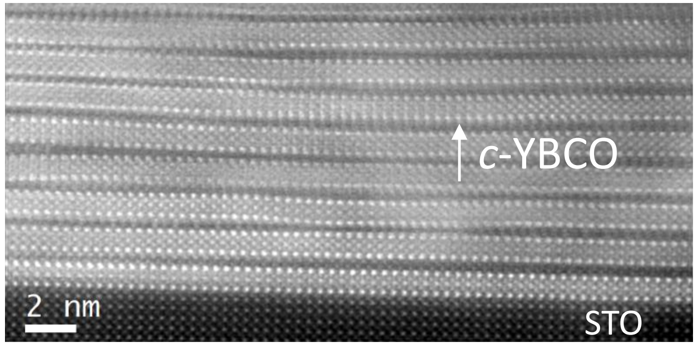
EELS Elemental maps

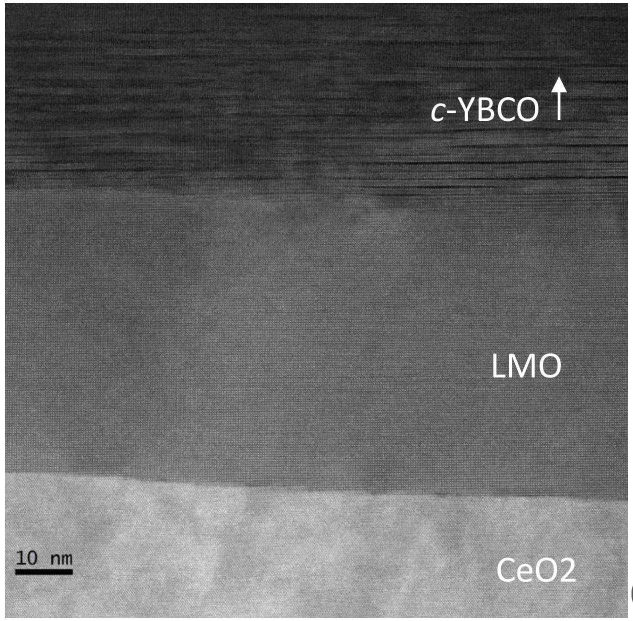
TLAG nucleation and growth

HRTEM



HR-STEM





L. Saltarelli, K. Gupta et al, ACS Appl. Mat. & Interf. (2022)

Reorientation of small randomly oriented YBCO crystals: correlations between in-situ XRD and TEM

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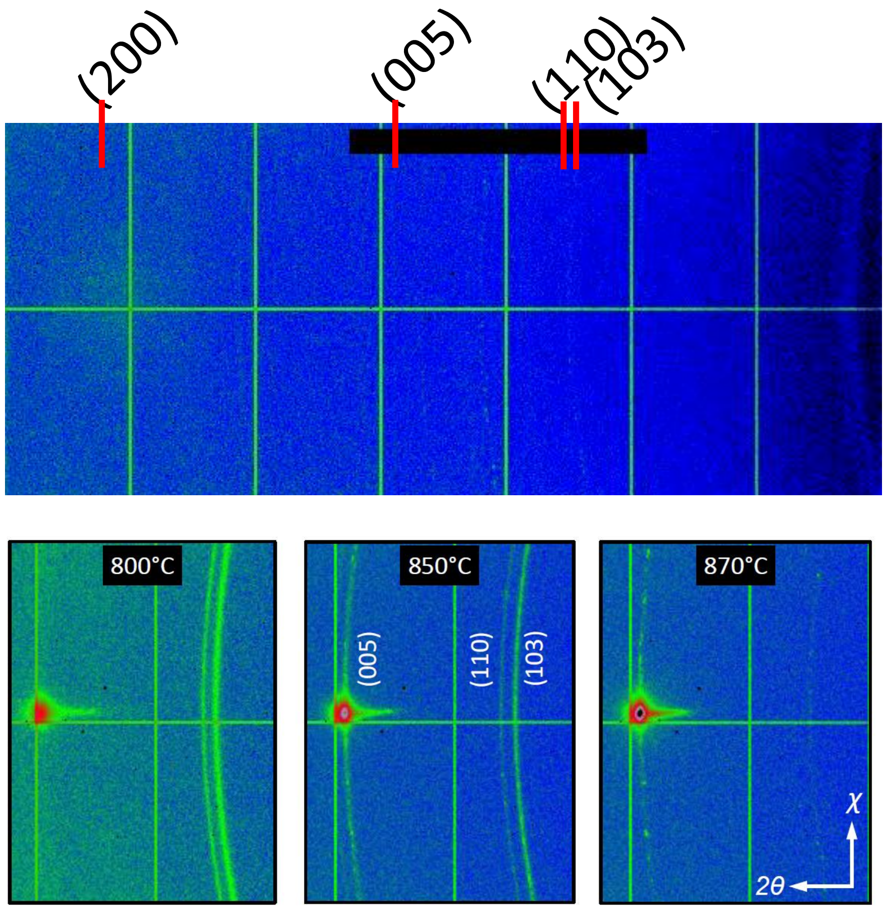
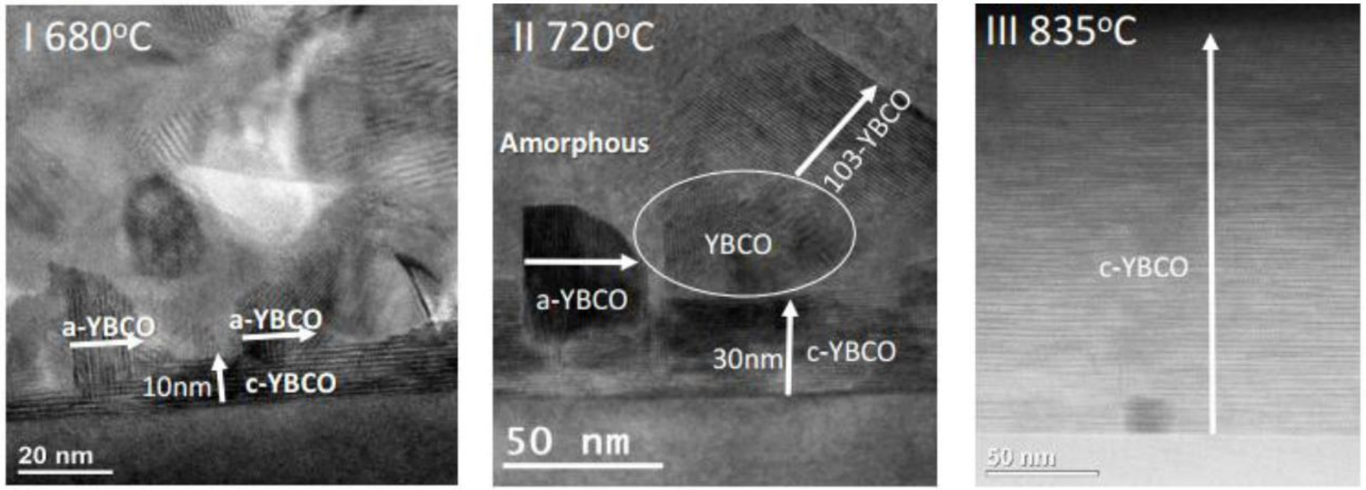
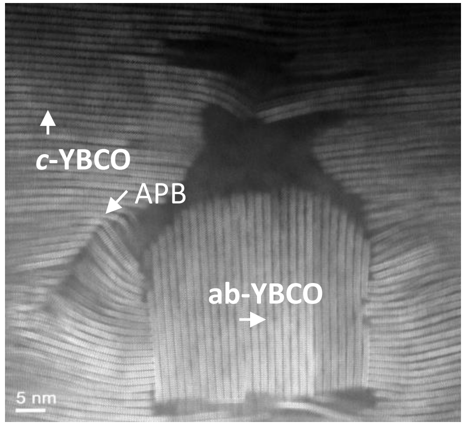


TLAG has the capacity to reorient randomly nucleated YBCO crystals depending on their size and liquid composition



We are able to track the transformation of the random YBCO phase to the epitaxial orientation

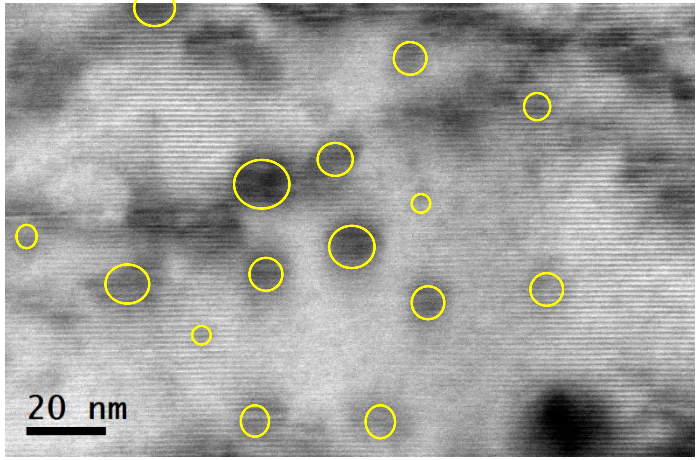


STEM

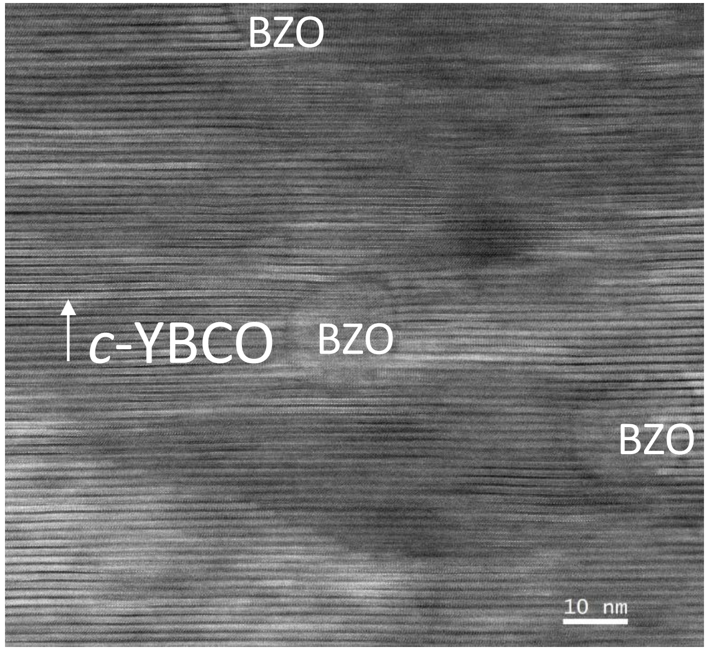
K. Gupta et al, in preparation

YBCO TLAG NANOCOMPOSITE FILMS:
Atomic defects landscape for high field performance

STEM-BF

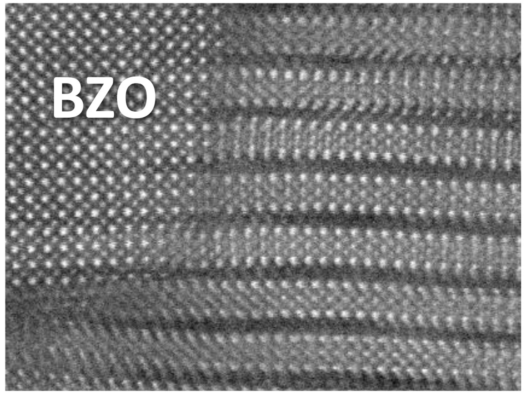


STEM-ADF

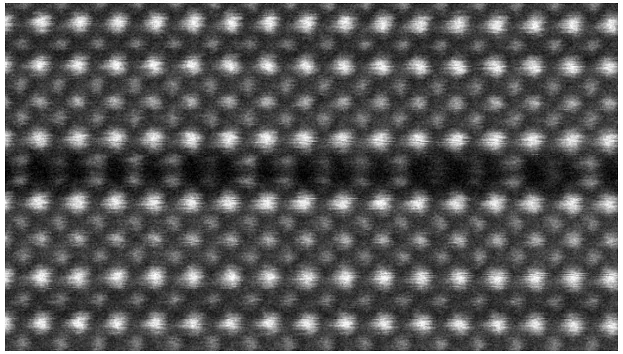


K. Gupta et al, in preparation

HR-STEM / Annular Dark Field

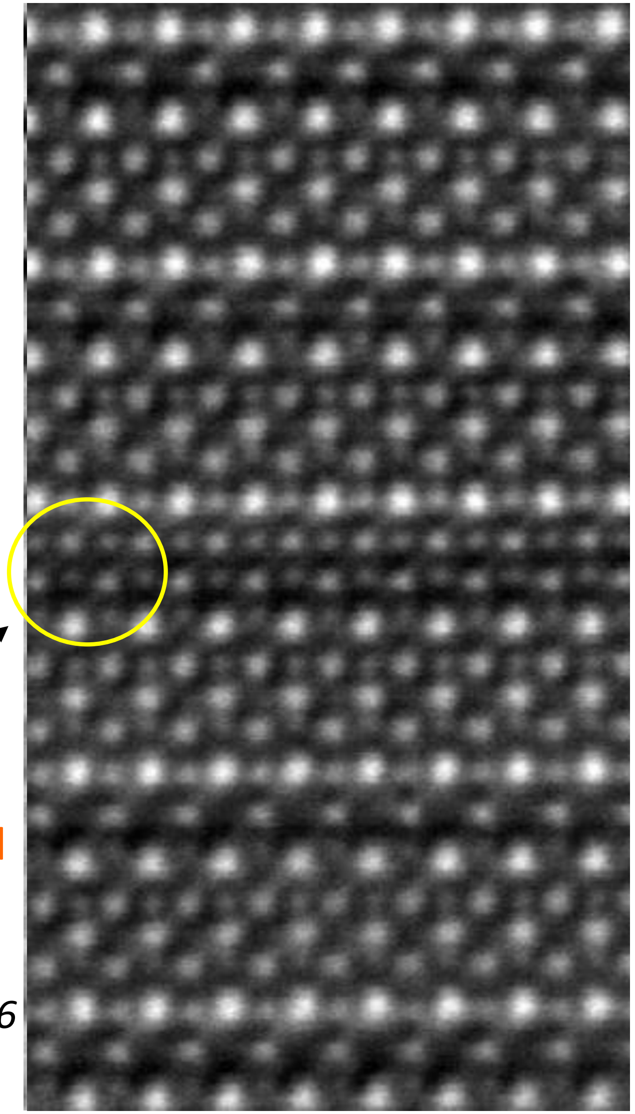


Intercalation of additional CuO planes



L.Soler, R. Guzman et al, Nat Comm (2020)

HR-STEM Inverse Annular Bright Field



Clusters of $2V_{Cu}+3V_{o-}$ identified (supported by EELS)

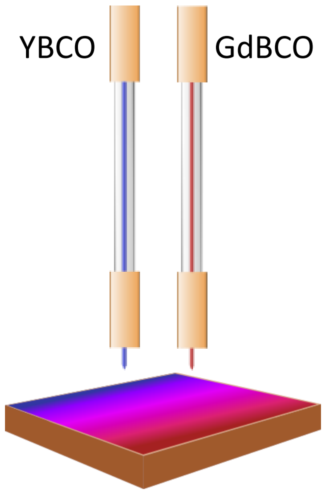
J. Gazquez et al, Adv. Science 2016

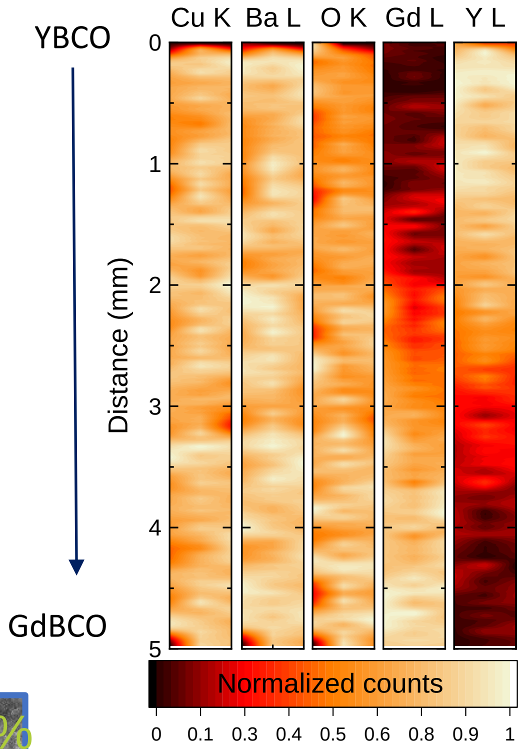
B. Mundet et al, Nanoscale 2020

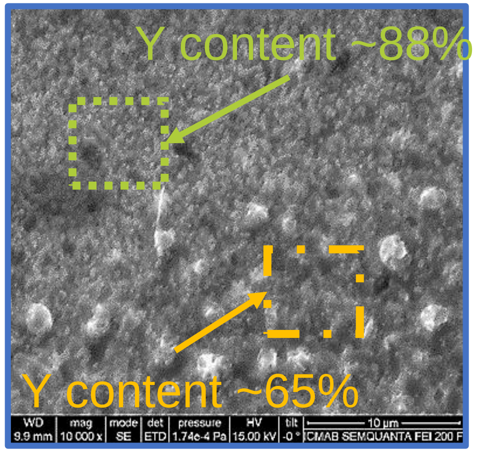
High Throughput experimentation:

Fast optimization of CC using Compositional Gradients

Combinatorial DoD Ink Jet Printing





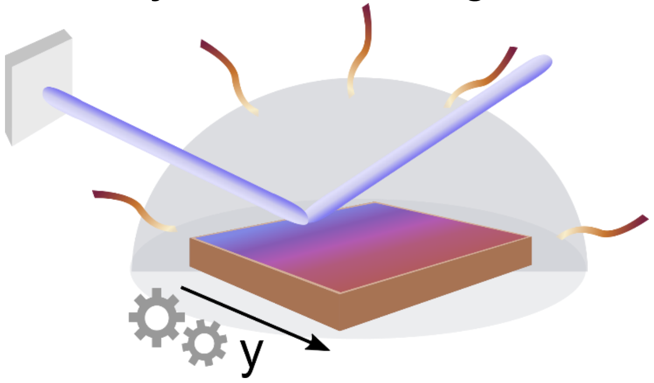


A. Queralto et al., ACS Appl. Mater. Interfaces (2021)

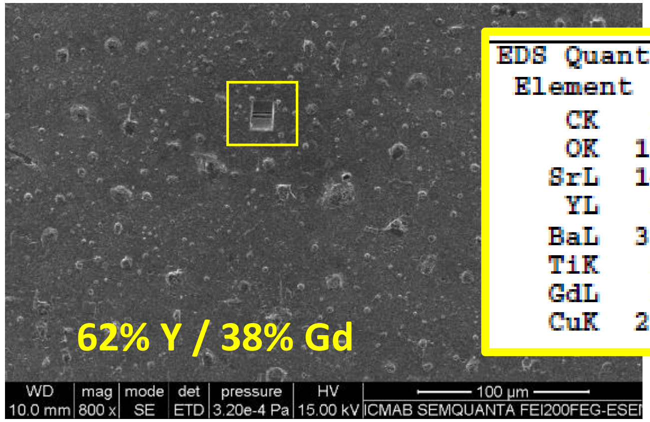
Machine Learning approaches initiatives are underway

Advanced Characterization

In-situ synchrotron XRD gradients evaluation



FIB-cut and TEM evaluation in selected places



EDS Quantitative Results

Element	Wt%	At%
CK	3.35	13.85
OK	12.52	38.87
SrL	14.02	7.94
YL	5.08	2.84
BaL	31.33	11.33
TiK	5.57	5.77
GdL	5.53	1.75
CuK	22.59	17.65

Conclusions

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- TLAG is a non-equilibrium ultrafast growth process that allows to achieve high performance Coated Conductors at with low cost, high throughput and high scalability

- In-situ Synchrotron XRD experiments are essential to understand the kinetic growth mechanisms and obtain epitaxial layers at ultrafast growth rates

- Probe-corrected Transmission Electron Microscopy and Spectroscopy have proven to be crucial for the identification of the atomic defects that determine superconducting performance

- The combined use of these advanced tools should contribute to the understanding of the TLAG process and its application in industry. We are strongly interested in their use