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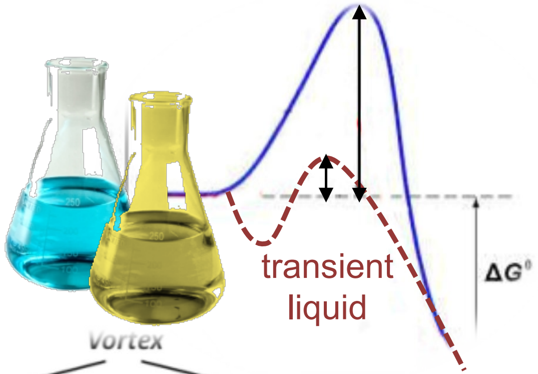
Work is supported by

Materials opportunities to boost HTS-CC
Example of Transient liquid Assisted Growth



Teresa Puig, Xavier Obradors

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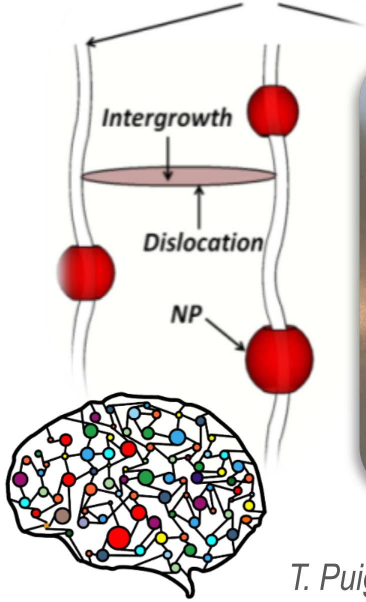
Collaborators: S. Rasi[1,2], A. Queralto[1], K. Gupta[1], L. Saltarelli[1], D. Garcia[1, 3], A. Pacheco[1], R. Vlad[1], A. Kethamkuzhi[1], J. Banchewski[1], L. Soler[1], J. Jareño[1], R. Guzmán[1], N. Chamorro[3,1] J. Gutierrez[1], S. Ricart[1], J. Farjas[2], P. Roura[2], C. Mocuta[4], R. Yanez[3], J. Ros[3]

1 ICMAB 2 UdG 3 UAB Universitat Autònoma de Barcelona 4 SOLEIL SYNCHROTRON



Materials Science opportunities for CC

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Decrease the cost/performance ratio

1. **Decrease the cost/performance ratio by developing high throughput growth methods:**
   Transient Liquid assisted growth, TLAG-CSD process (100-1000 nm/s)

2. **Use of High Throughput Experimentation strategies for fast optimization of processes:**
   Combinatorial approaches and Machine Learning algorithms

3. **Foster higher critical currents by engineering the vortex pinning landscape for each application:**
   Understanding the (H,T,θ) pinning landscape for engineered nanocomposites

4. **Increase pinning force by increasing charge carrier density:**
   Tune charge carrier density by oxygen overdoping

1. TLAG-CSD process

An opportunity for high-throughput, scalable and low cost production of Coated Conductors at **ultrafast growth rate**

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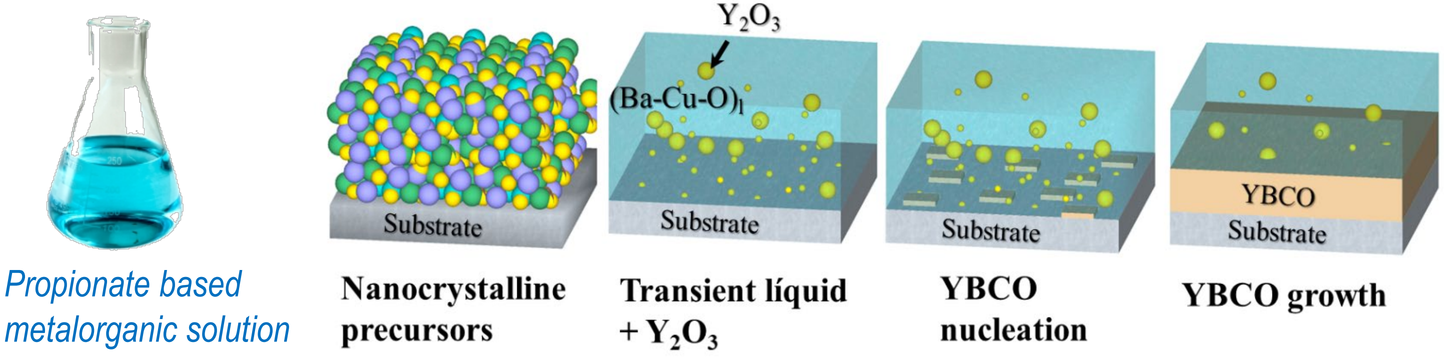
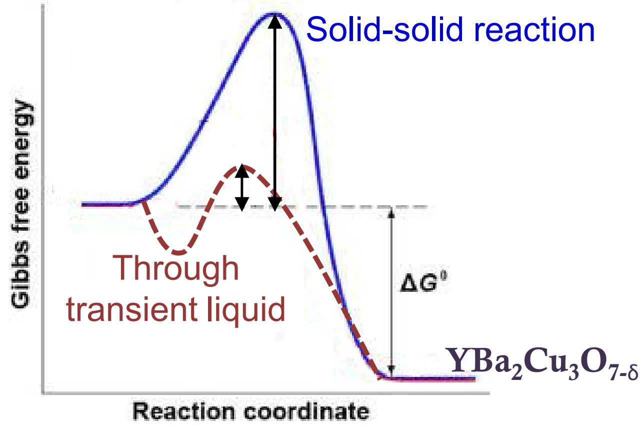




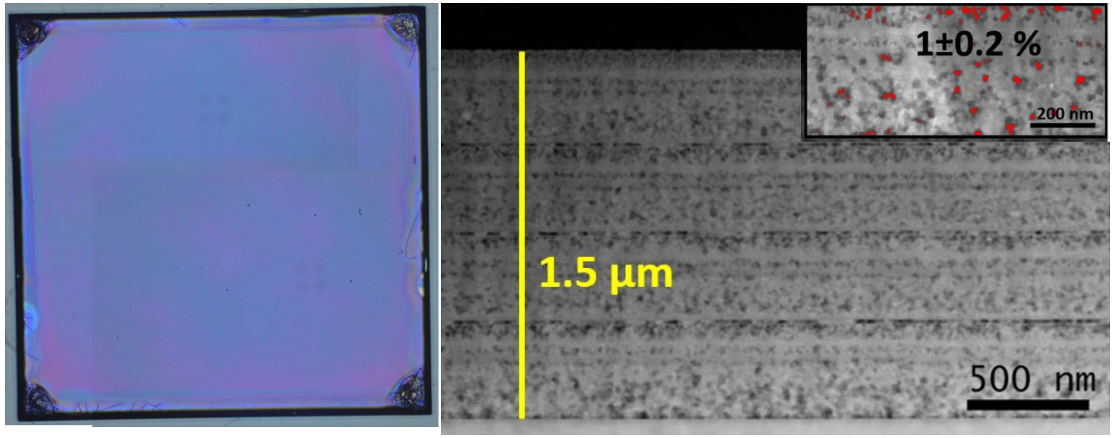
$$BaCO_{3(s)} + CuO_{(s)} + Y_2O_{3(s)} \longrightarrow (Ba - Cu^{I/II}\text{-}O)_{(l)} + Y_2O_{3(s)} \longrightarrow YBa_2Cu_3O_{7-\delta}$$

Transient liquid

- Non-equilibrium process kinetically controlled by supersaturation reaching ultrafast growth rates 100 nm/s – 1000 nm/s from a **transient liquid-solid reaction**
- **Supersaturation** is the driving force for nucleation, controls liquid properties, substrate wettability and c-axis window. It can be modified by: Ba-Cu-O liquid composition, RE solubility, T and PO_2 ramps and (T, PO_2) values reached
- Environmentally friendly **fluorine free precursors** based on $BaCO_3$- CuO reaction
- Well-matched with **large area** deposition, simple and large area reactor of low cost investment

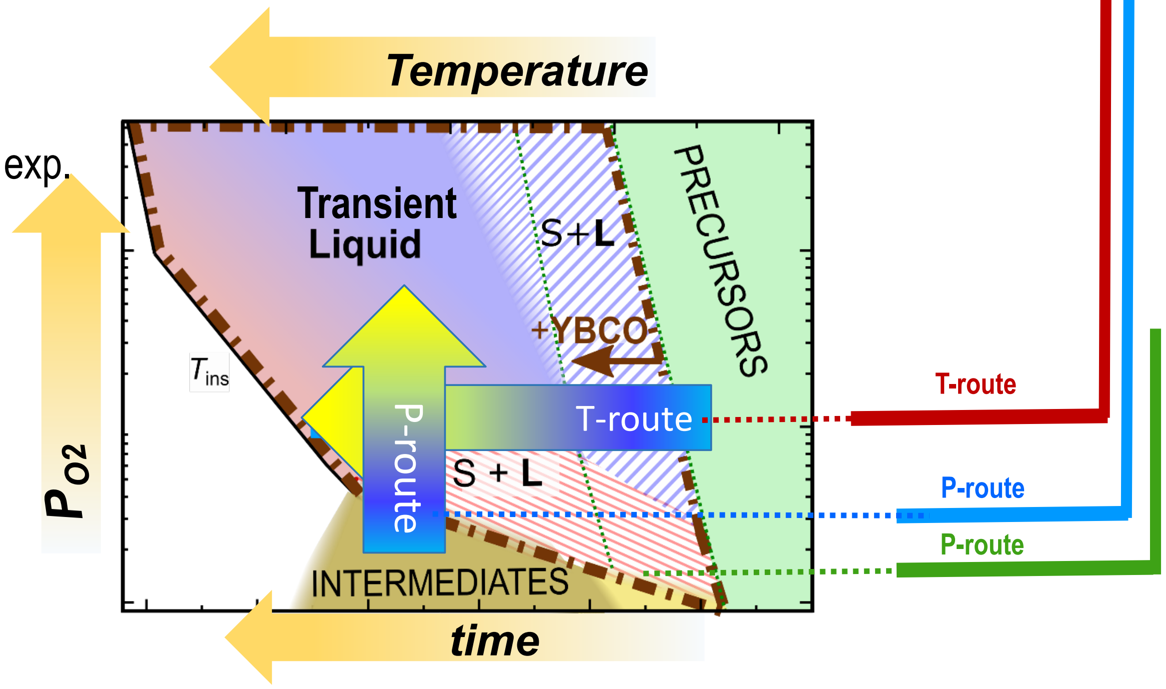
L. Soler et al., Nat Comm (2020), S. Rasi et al., J. Phys Chem C (2020), A. Queralto et al., ACS Appl. Mater. Interfaces (2021)

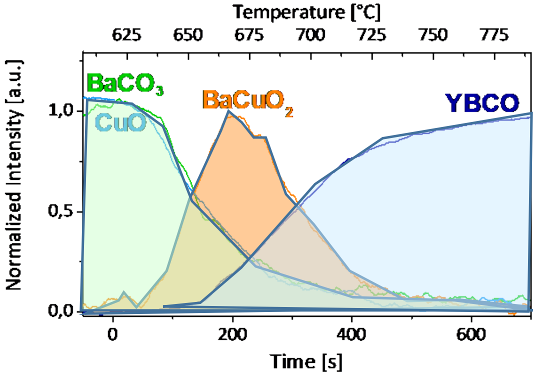
Pyrolyzed films and intermediate phases

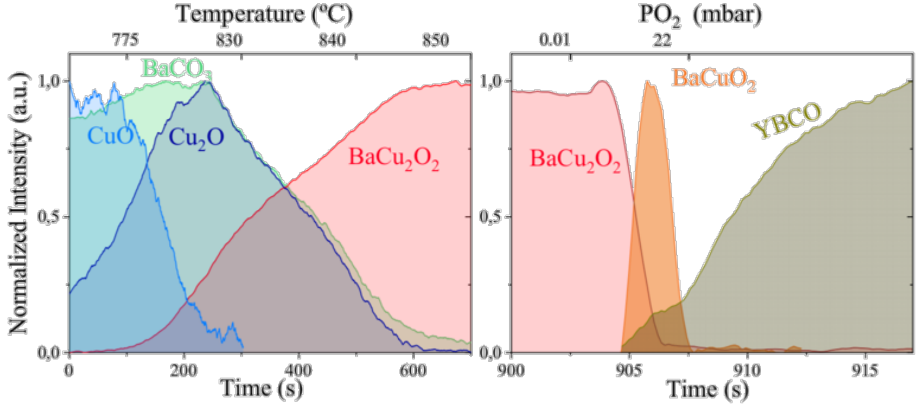


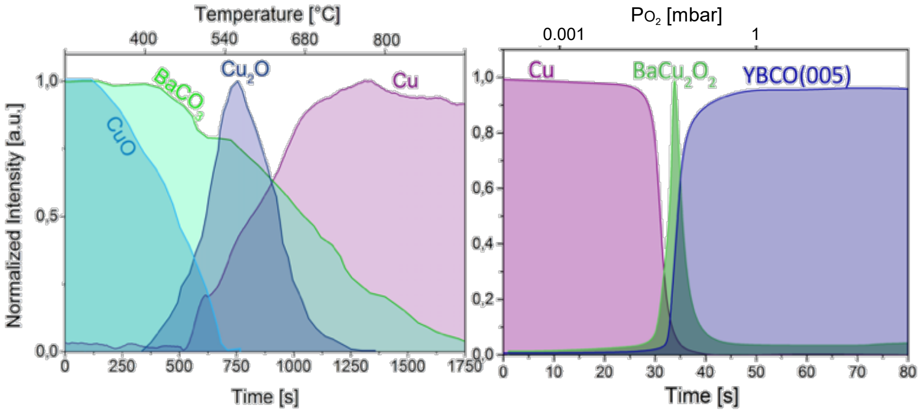
$BaCO_3$ decomposition verified in 2.5 µm thick pyrolyzed layers

In-situ XRD synchrotron exp.

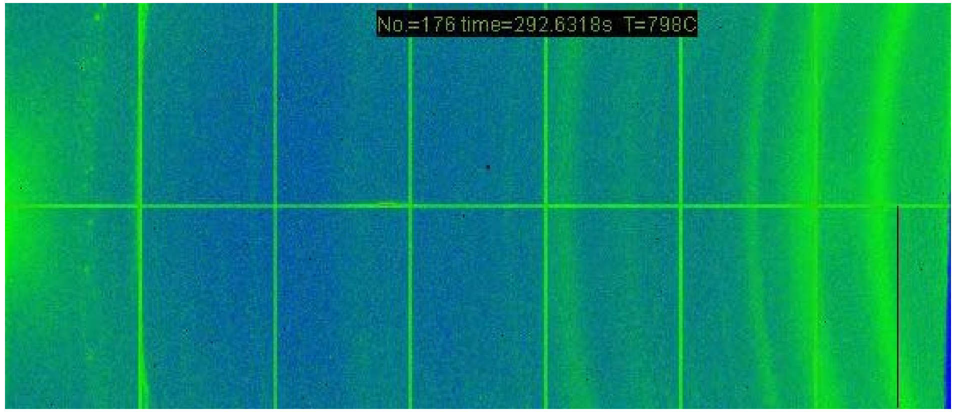


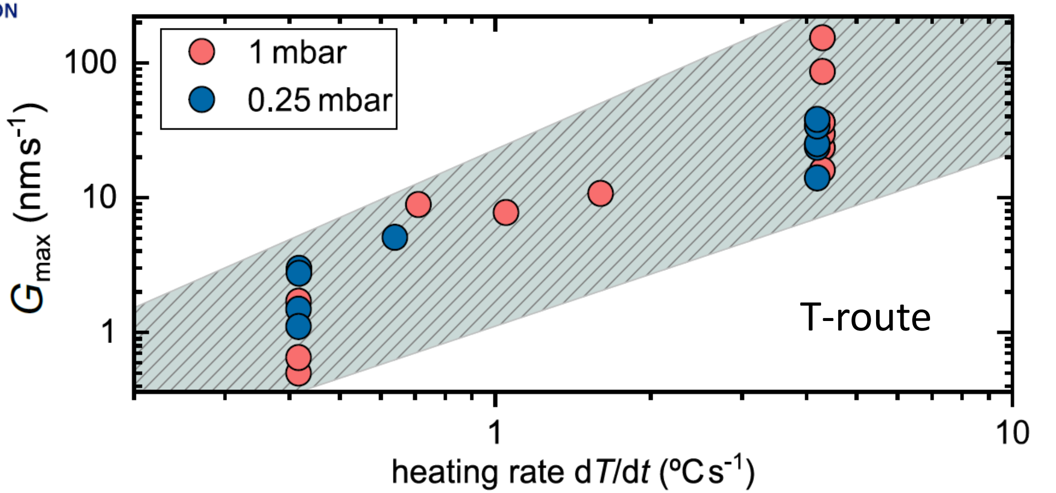




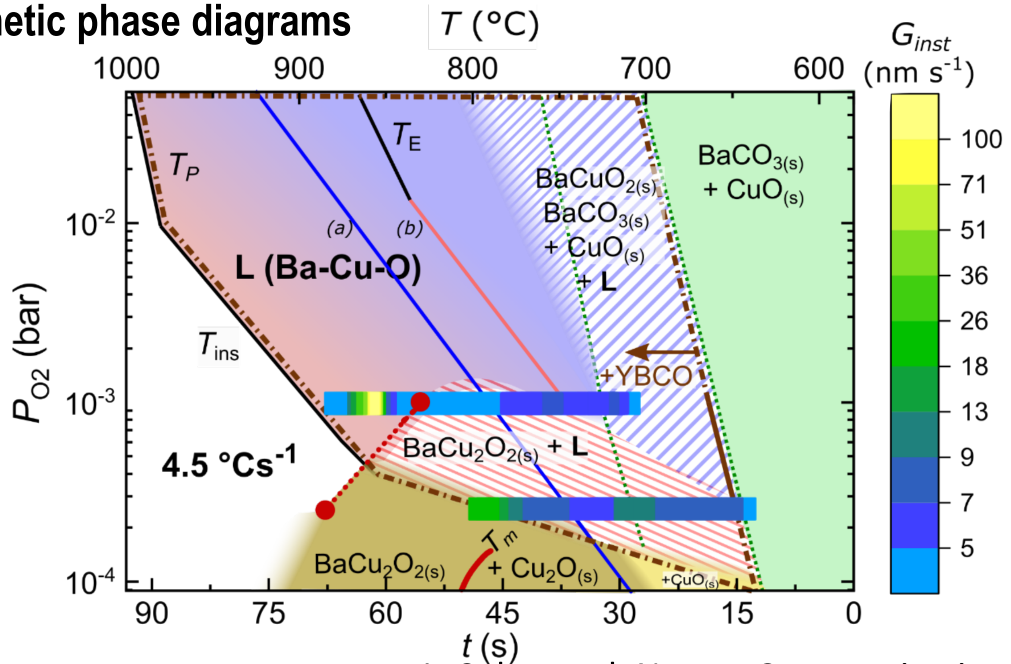


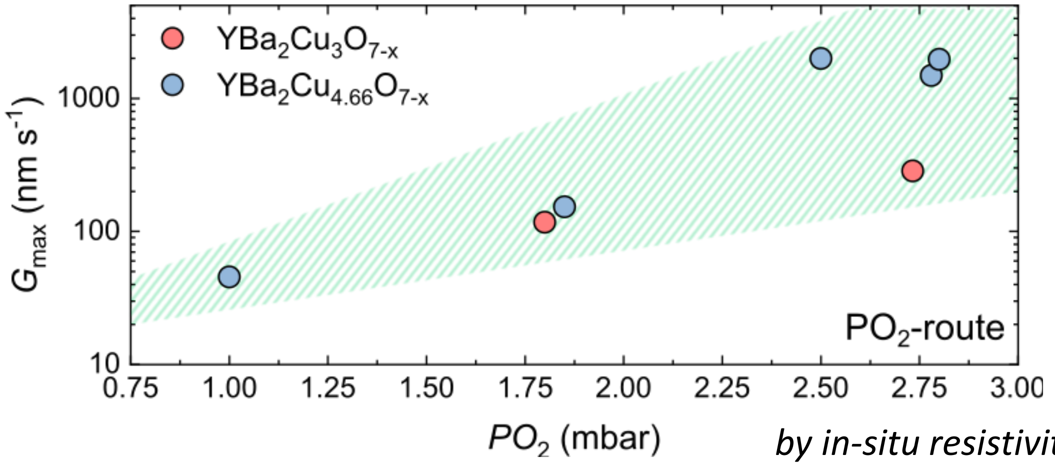
Ultrafast (non-equilibrium) growth by TLAG-CSD





Kinetic phase diagrams





by in-situ resistivity

L. Soler et al, Nature Communications (2020), S. Rasi & A. Queralto et al, in preparation

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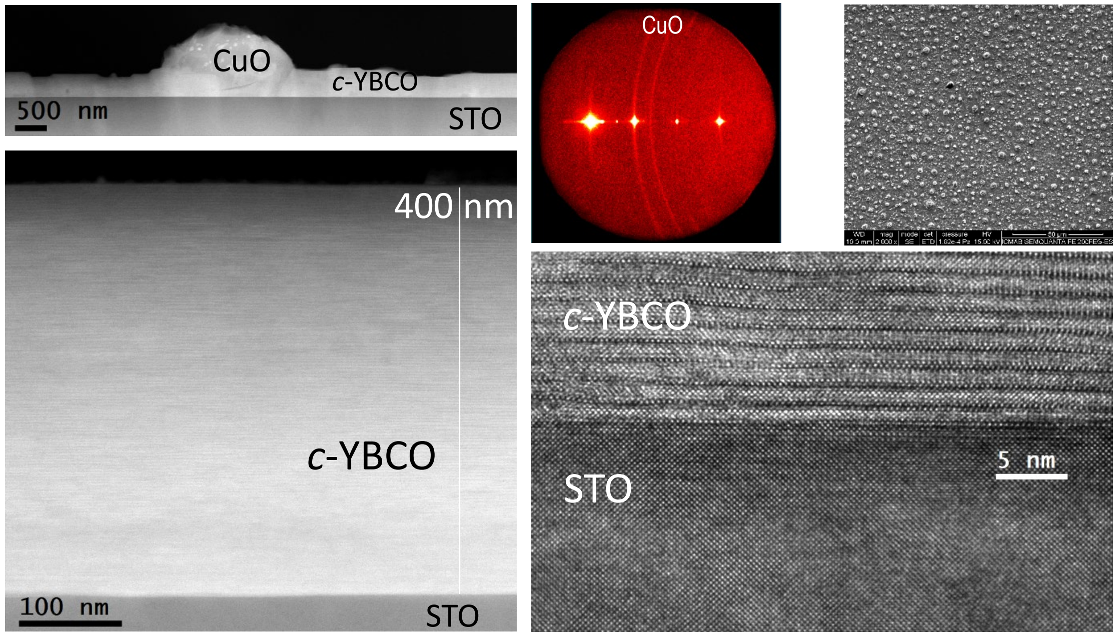
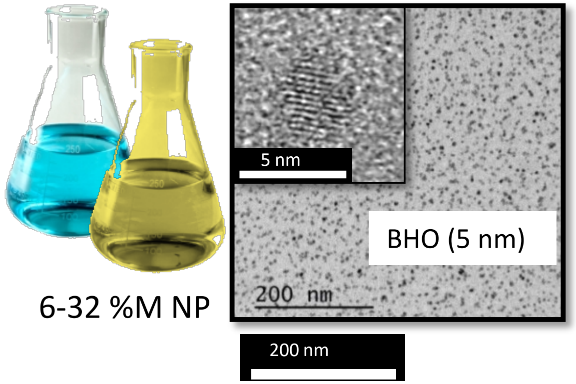
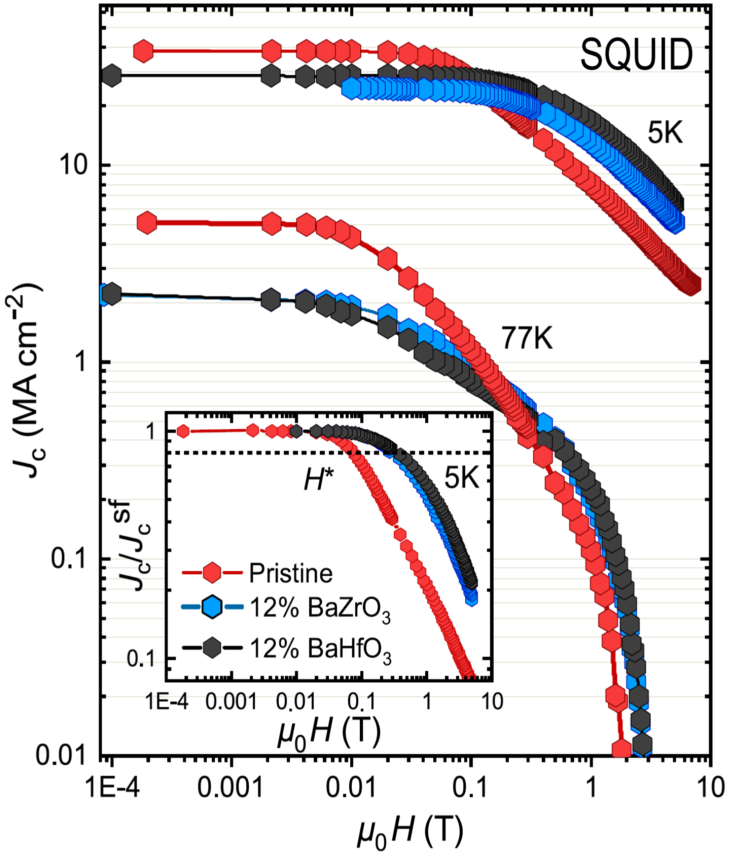
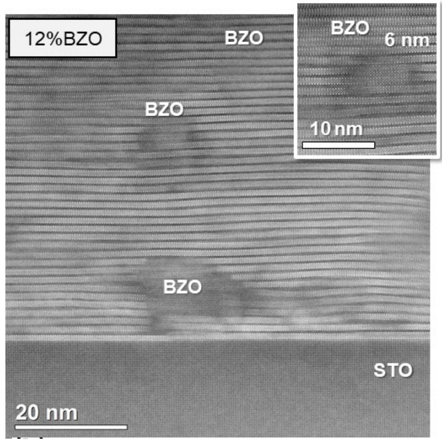
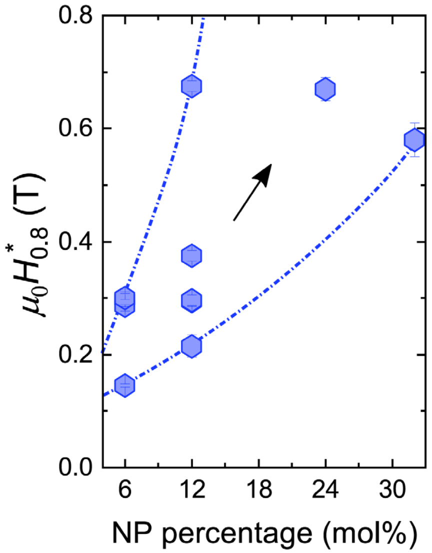
TLAG-CSD films properties











J_c (77K, sf) = 2-5 MA/cm^2 and higher in-field performance in TLAG nanocomposite

L. Soler et al, Nature Communications (2020), N. Chamorro, RSC Adv (2020)
L. Saltarelli et al (to be published), J. Banchewski et al, to be published

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TLAG Coated Conductors

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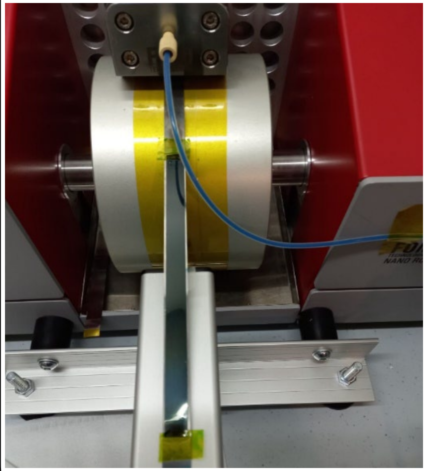
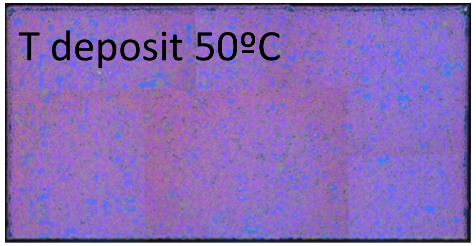
Slot-die coating deposition

15 cm, 1 µm pyrolyzed film (2 layers)

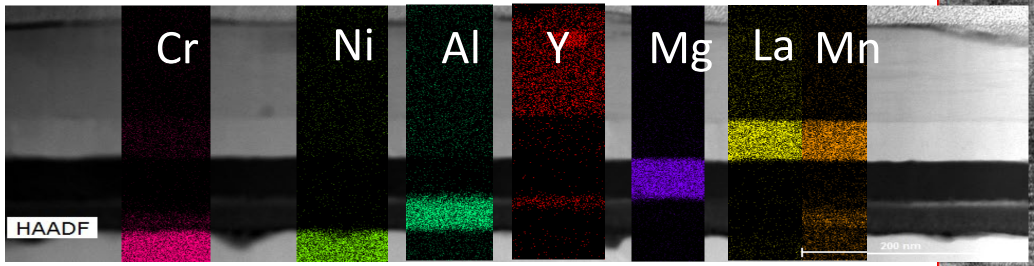


IJP deposition

1 µm pyrolyzed film (1 layer)

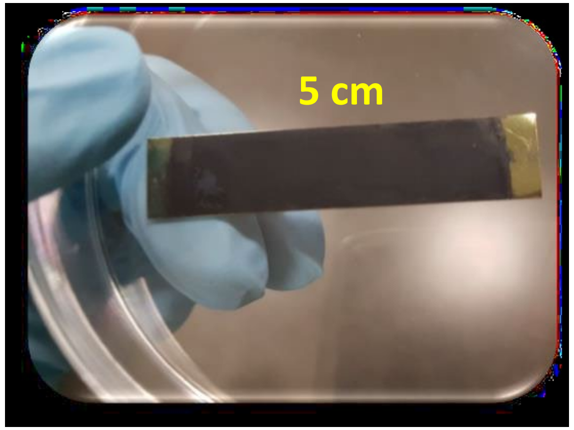


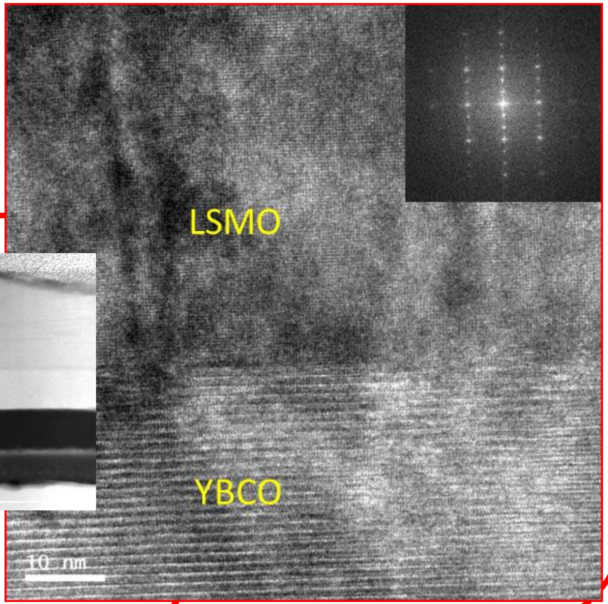
- Homogenenous depositions and pyrolysis



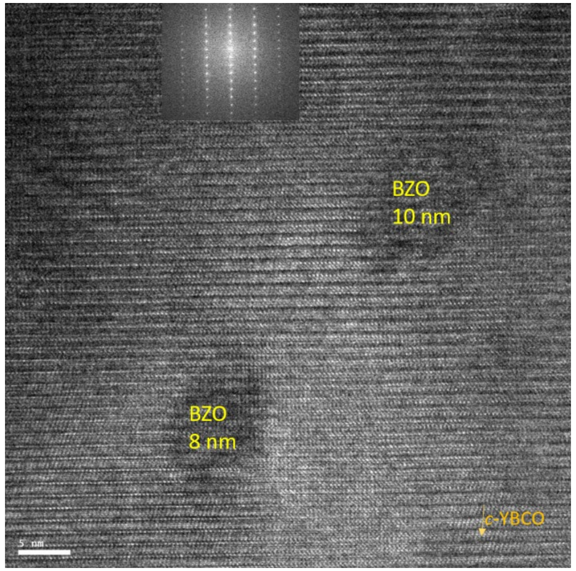
- Smooth interfaces
- J_c~1 MA/cm^2 at 77 K for 500 nm

TLAG CC growth on provider 1 (5 cm long tapes tested)- P-route



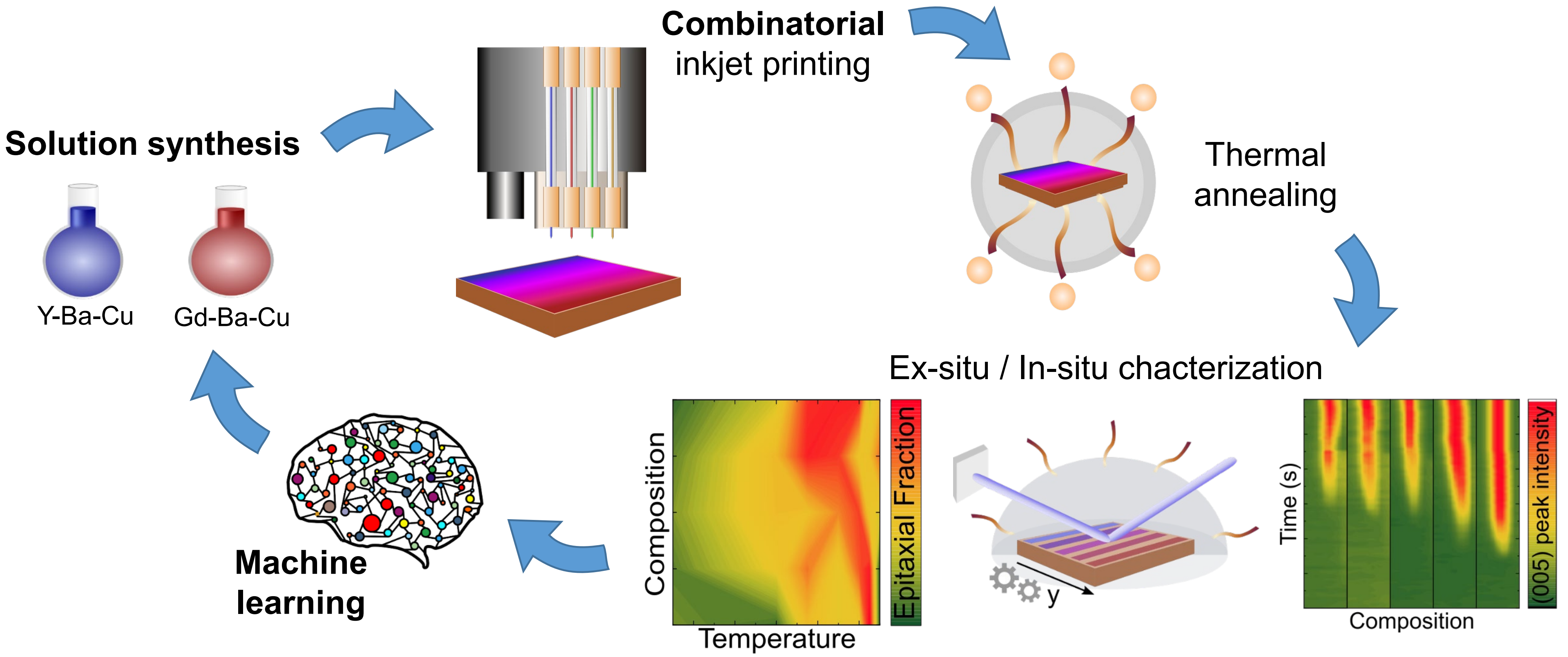


TLAG CC growth of nanocomposites provider 2 – T-route



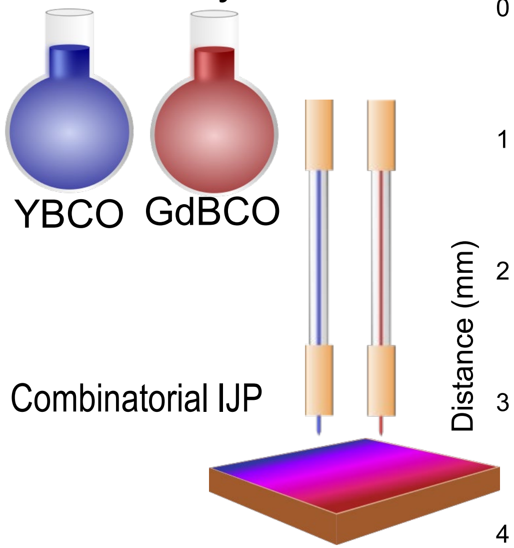
- Small NPs (8-10 nm)
- Epitaxial and dispersed BZO NPs

2. High Throughput Experimentation by combinatorial approaches and Machine Learning algorithms

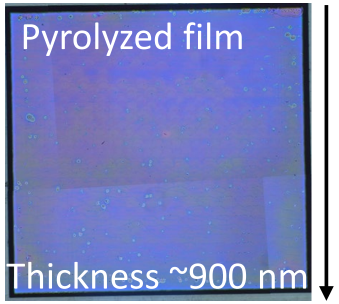


Fast optimization using compositional gradient samples

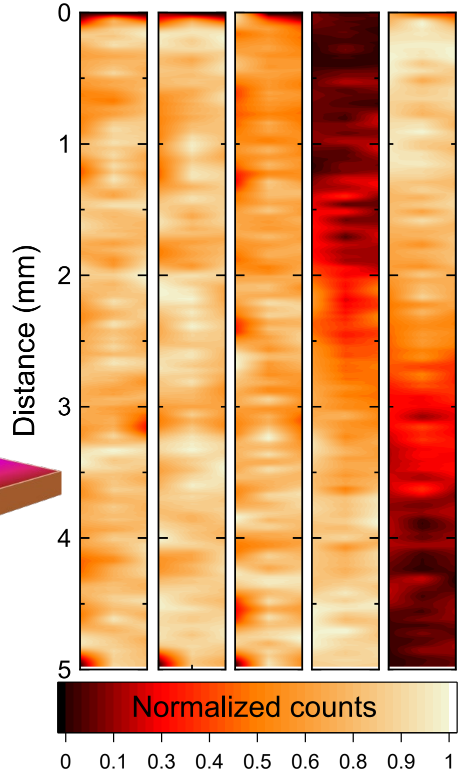
Solution synthesis

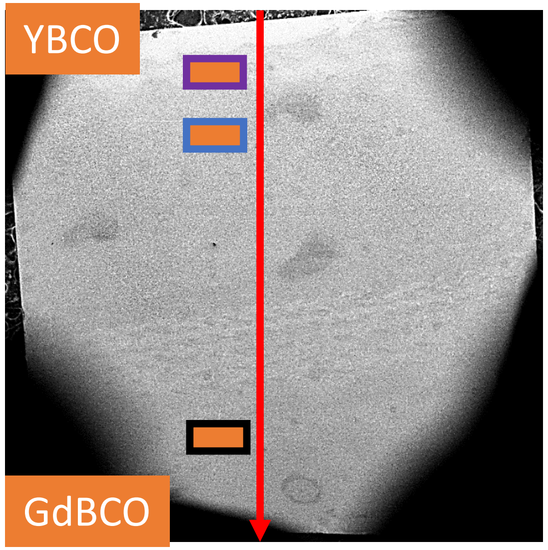


YBCO (0 mm)

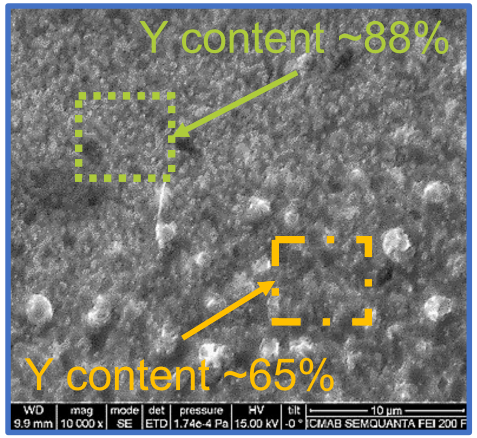


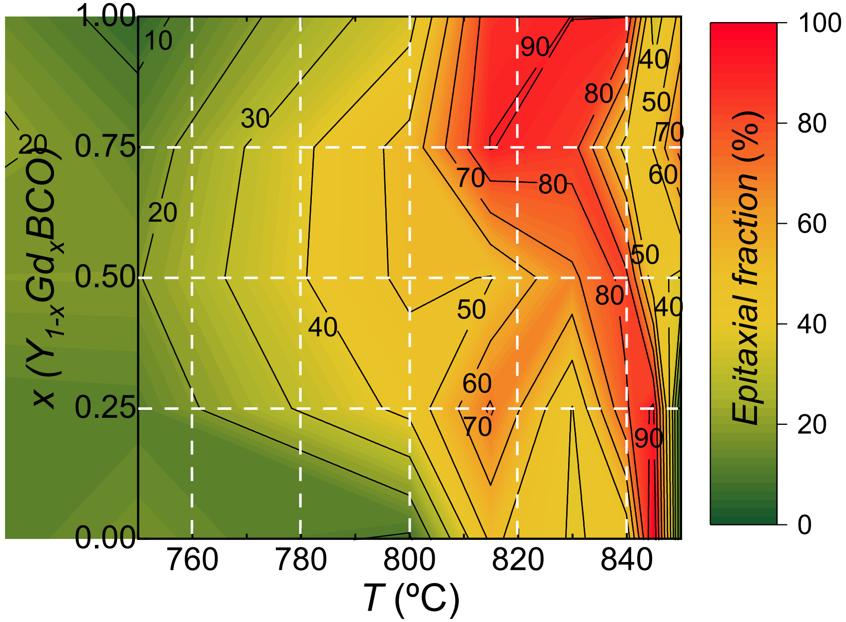
GdBCO (5 mm)





Morphological changes





13 combinatorial samples were used instead of 78 regular samples to reach the same mapping resolution

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

Machine learning for predicting process magnitudes

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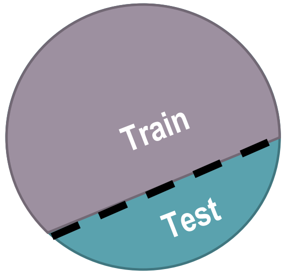
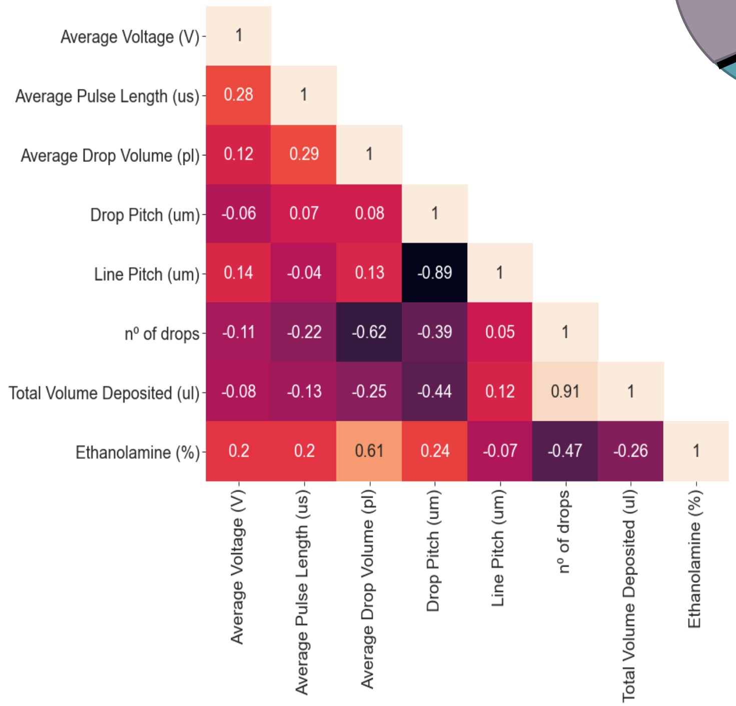
Case: Predicting the Total Volume Deposited

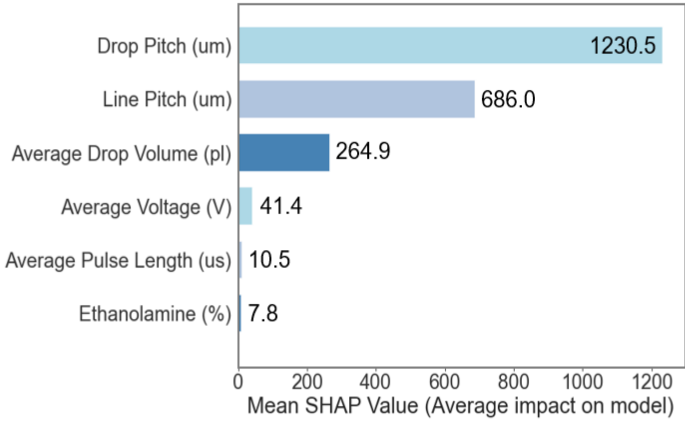
IJP deposition data of 231 samples

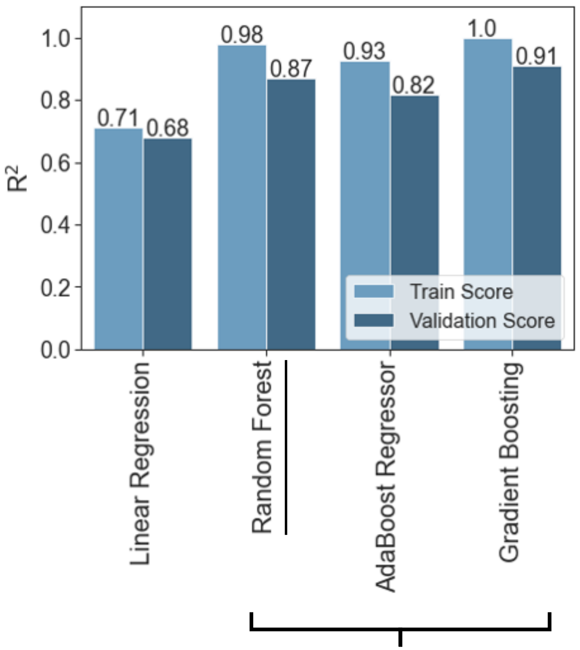


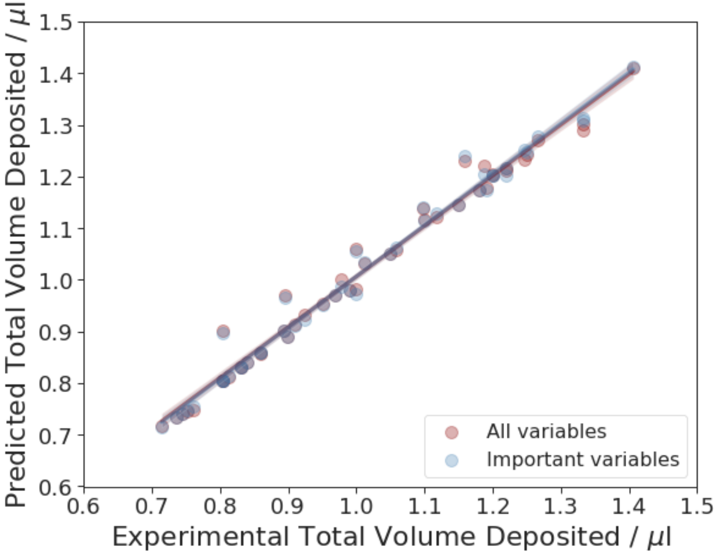
train/test splits
80/20

Correlation matrix









A Queralto et al, to be published

Tree-based ensamble algorithms

3. Understanding the (H,T,θ) pinning landscape for engineered nanocomposites

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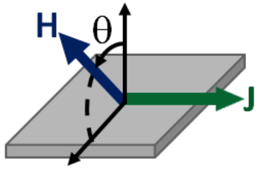


$$J_c(T) = J_c^{iso\text{-}wk}(T) + J_c^{iso\text{-}str}(T) + J_c^{aniso\text{-}str}(T)$$

$J_c^{iso\text{-}wk}/J_c$

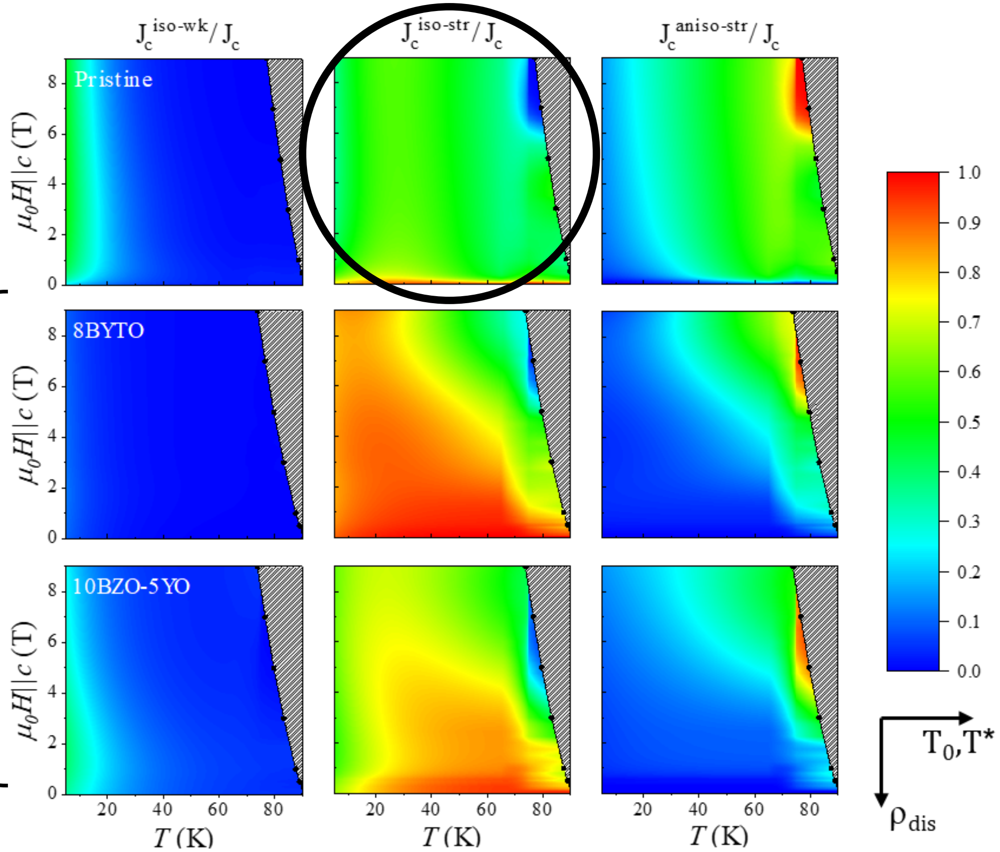
$J_c^{iso\text{-}str}/J_c$

$J_c^{aniso\text{-}str}/J_c$

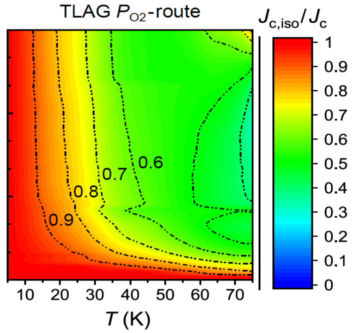
- defect dimensionality
- orientation
- size

TFA Pristine

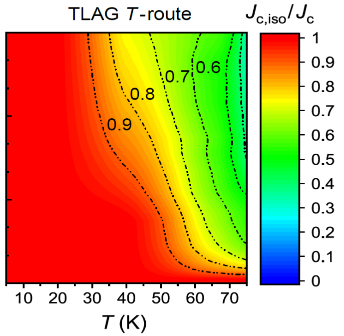
TFA Nanocomposites



TLAG Pristine (P-route)



TLAG Pristine (T-route)



J. Banchewski et al, to be published

Lot's of opportunities for TLAG Nanocomposites

J. Gutierrez et al, Nat Mat (2007), A. Llordes et al, Nat Mat (2021), A. Palau et al, SUST (2018), J. Blanchewski et al, to be published

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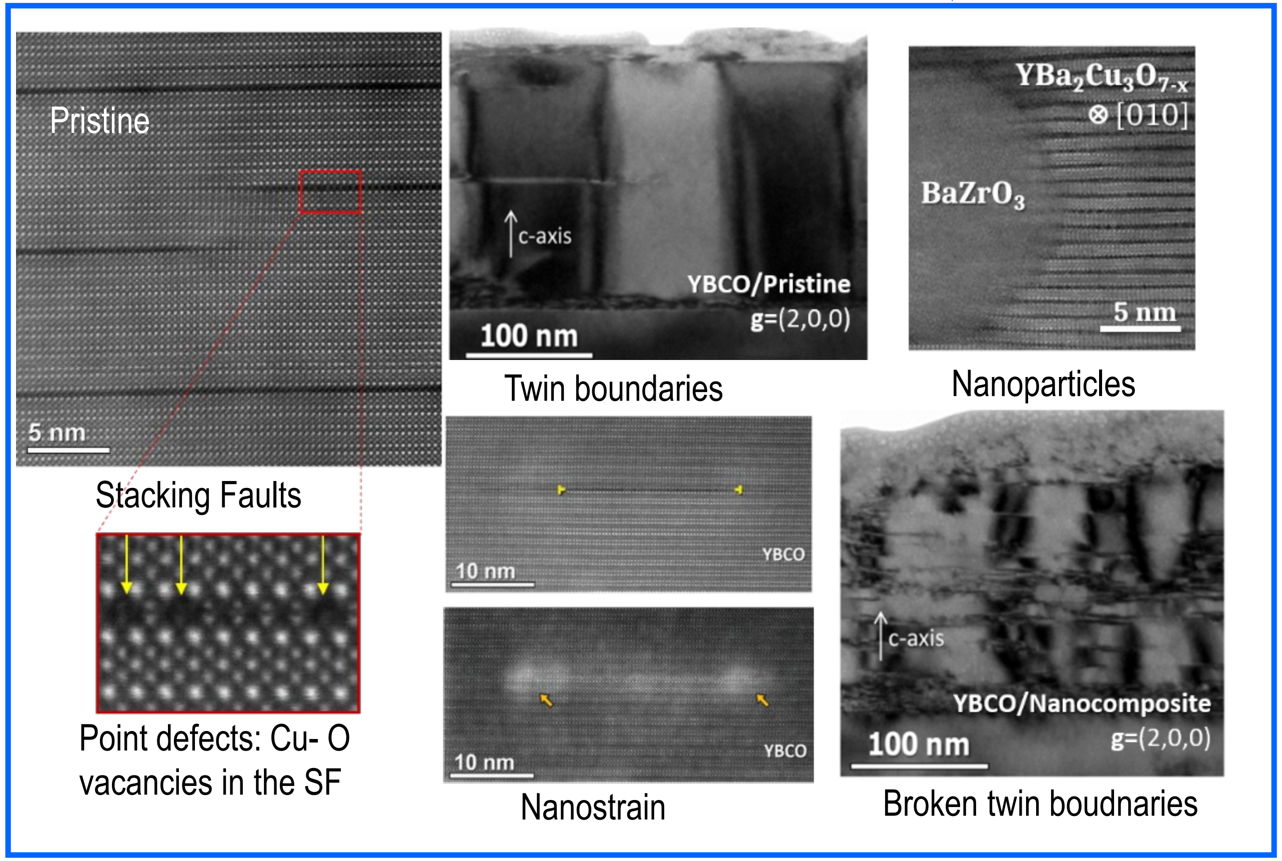
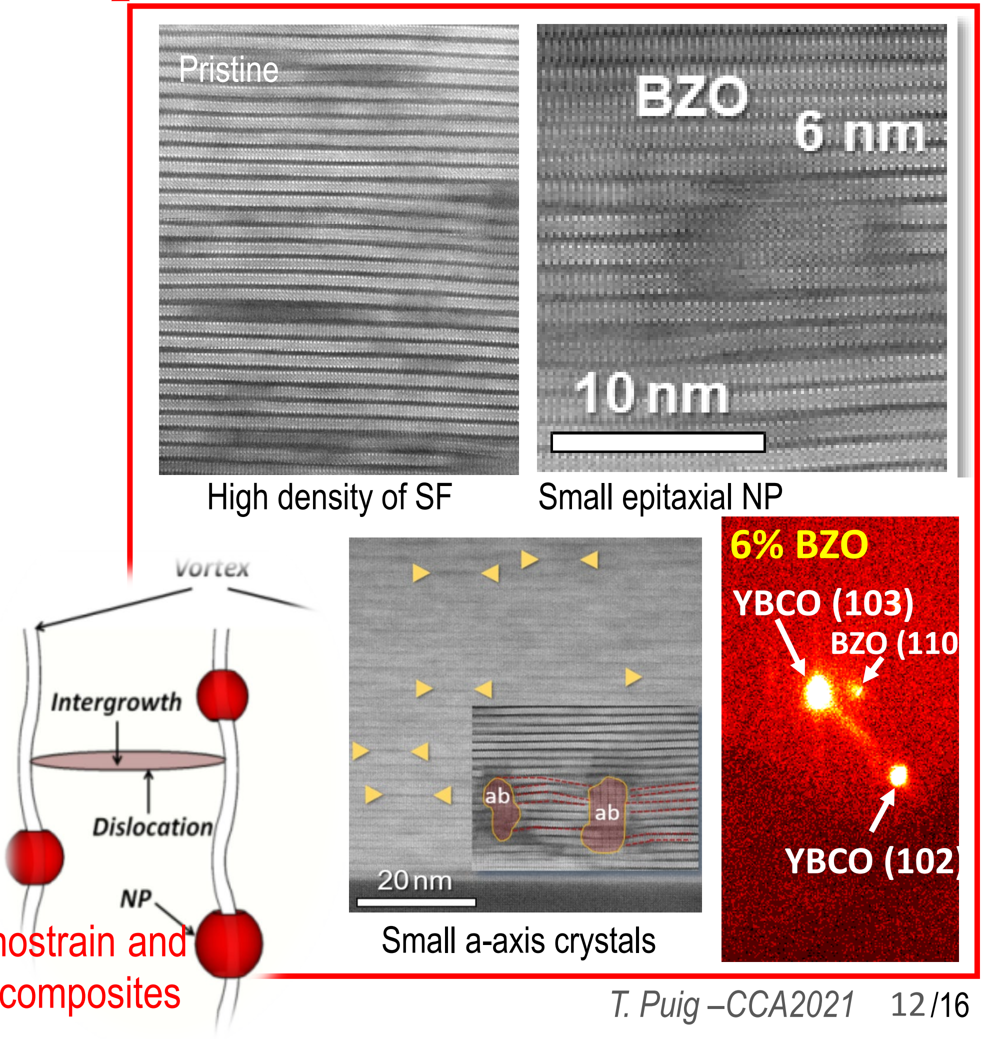
Vortex pinning defects in TFA/TLAG - CSD films





J. Gutierrez et al, Nat Mat (2007)
A. Llordés et al, Nat Mat (2012)
A. Palau et al., SUST (2018)
Z. Li et al, Sci Rep. (2019)
L. Soler et al, Nat Comm (2020)
J. Gazquez et al., Adv. Sci. (2016)
R. Guzman et al, APLMat (2017)
S.T. Hartman et al, PRMat (2019)

Synergistic effect of nanostrain and small NP in TLAG nanocomposites

Optimized pinning landscapes

Low and intermediate T - Intermediate and high H

14 years of measurements

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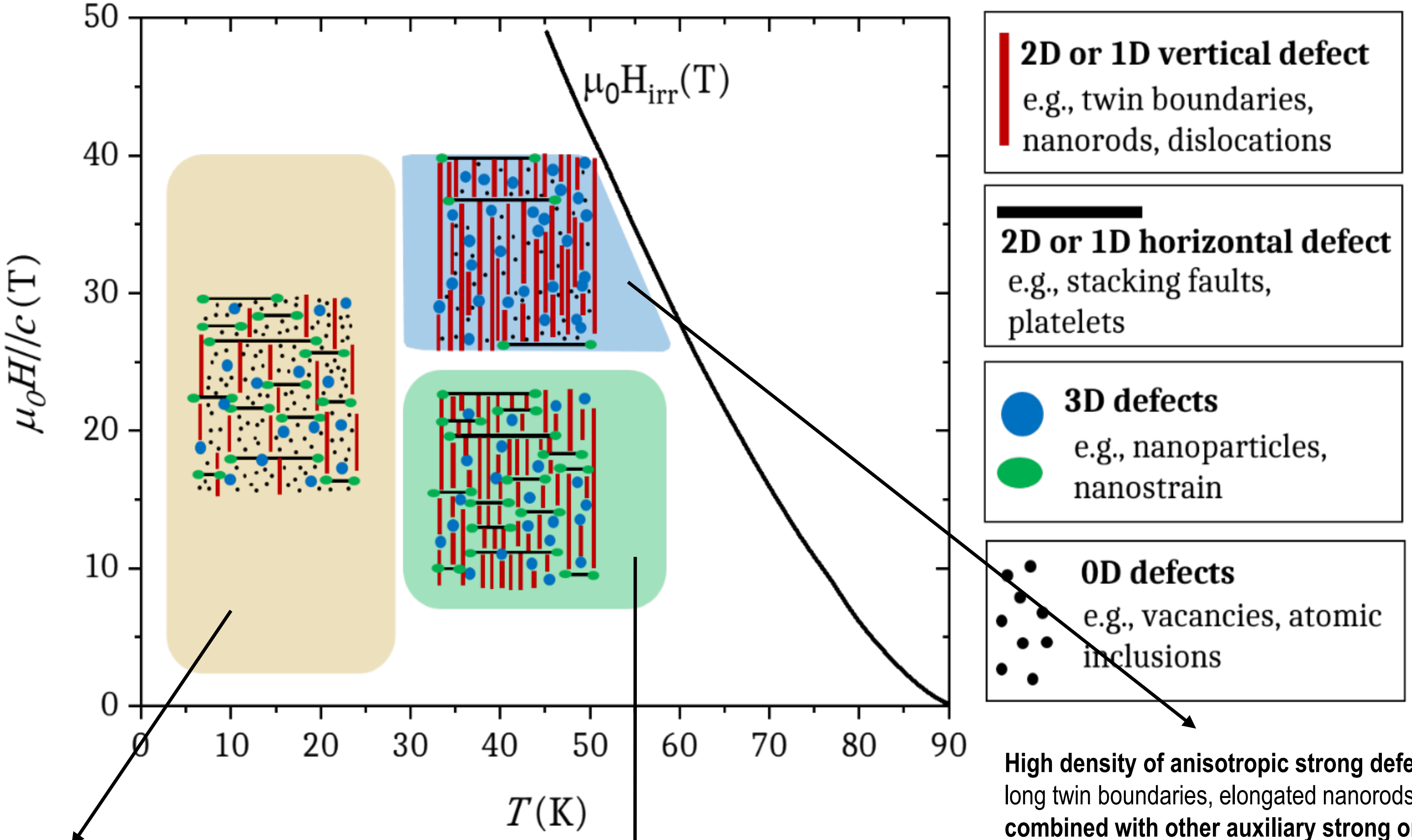
NATIONAL HIGH MAGNETIC FIELD LABORATORY
D. Abraimov
J. Jaroszynski
D. Larbalestier



High density of isotropic defects: Cu-O vacancies, short SF, small NP (better Np than nanorods)

Large density of strong isotropic and anisotropic defects with long vertical coherence: nanoparticles, nanostrain, long nanorods, long twin boundaries (Nanorods and nanoparticles will add effects)

High density of anisotropic strong defects with very long vertical coherence: long twin boundaries, elongated nanorods, thick CSD nanocomposites **combined with other auxiliary strong or weak isotropic defects to lessen vortex creep excitations** (1D-2D mandatory but all defects will help to diminish creep)

F. Valles et al, *to be published*

4. Tune charge carrier density by oxygen overdoping

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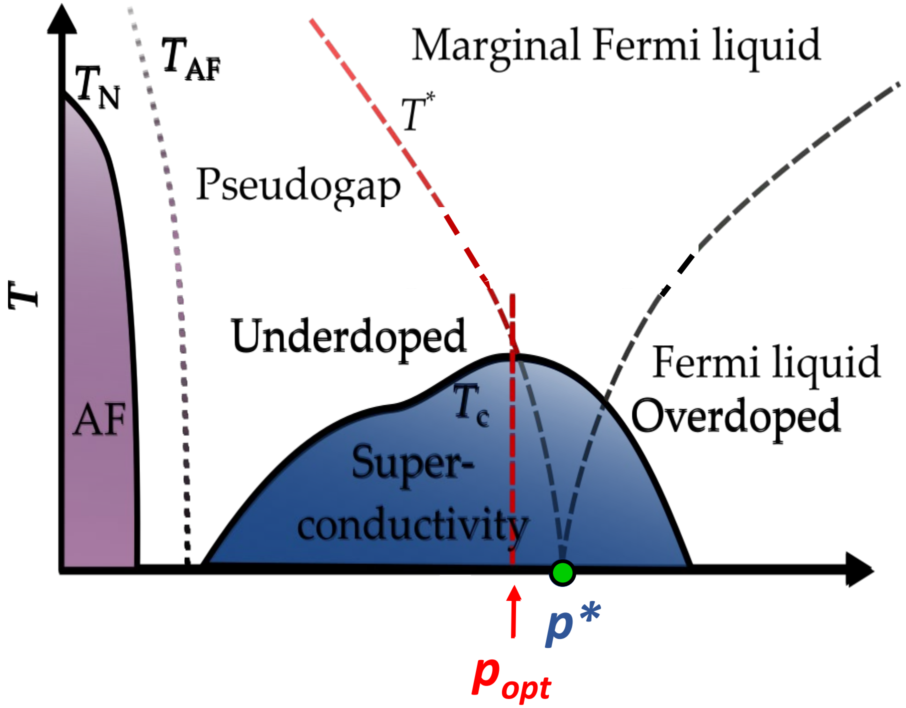


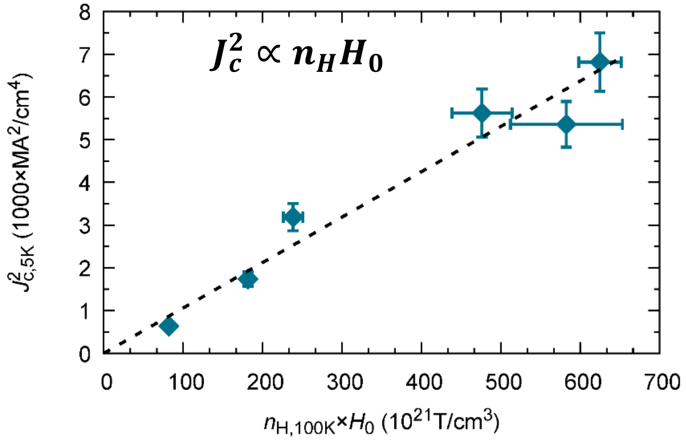
p_{opt} = 0.16 holes/CuO_2-plane: optimal doping for maximum T_c
p^*= 0.19 holes/CuO_2-plane: Critical doping (QCP)

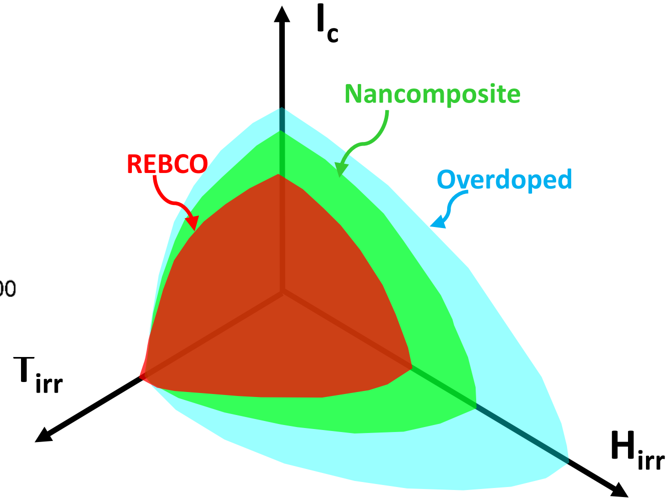
Pinning force $F_p = \sum_i^{N_p} f_{p,i}(B,T) \propto J_c$

$f_p \propto E_c$ condensation energy

$J_d^2 \propto n_s E_c \longrightarrow J_c^2 \propto n_H H_0$ (H_0 from in-plane magnetoresistance)

(three independent experimental parameters)





n_H and E_c increases in the overdoped state, and consequently J_c should increase

A. Stangl et al, Sci. Rep. (2021)

Strong increase of J_c in the overdoped state

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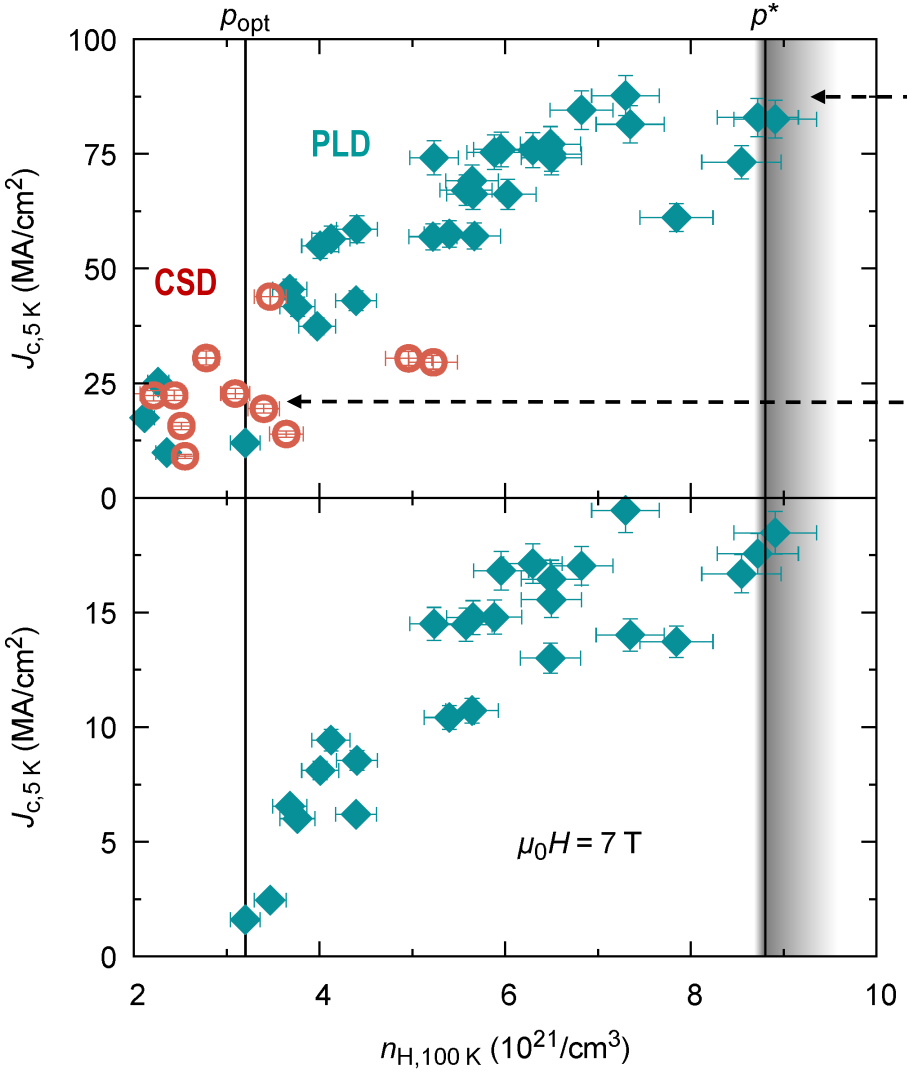


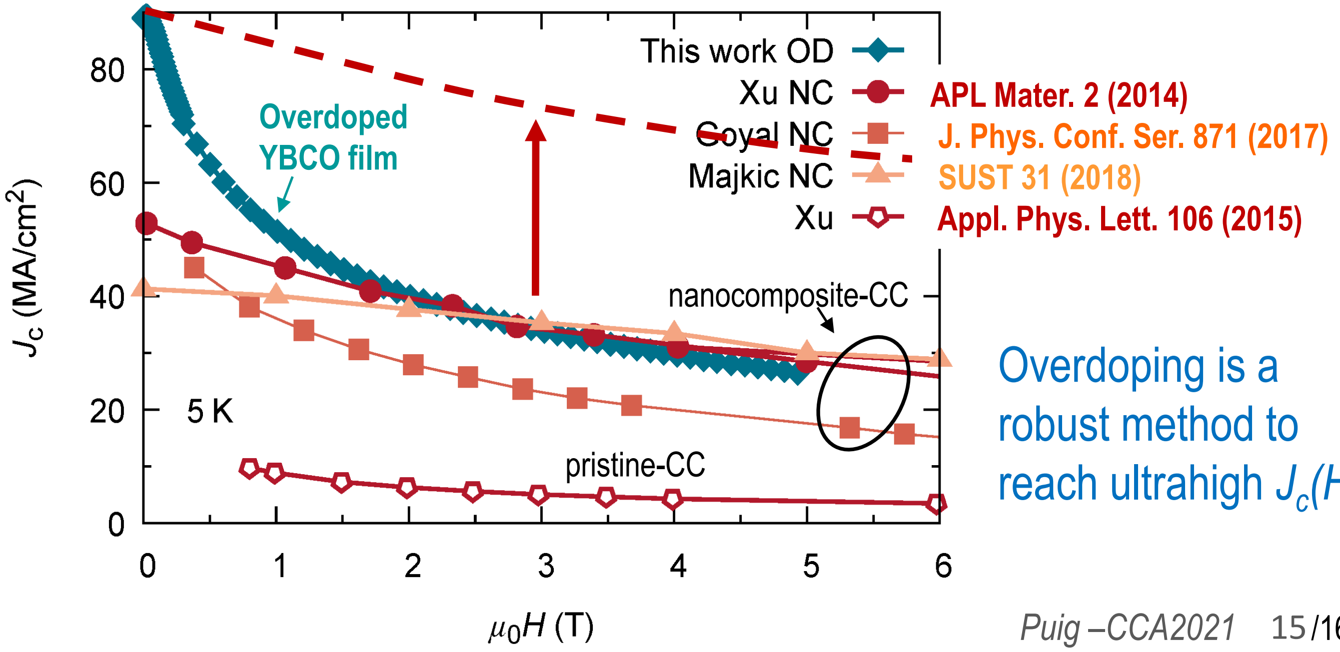
$$J_c(p^*) \approx \frac{1}{5} J_d(p^*) = 90\ MA/cm^2$$

$J_d(p^*) \approx$ 500 MA/cm²

$$J_c(p^{opt}) \approx \frac{1}{10} J_d(p^{opt})$$

$J_d(p^{opt}) \approx$ 330 MA/cm²

Strong increase of J_c with n_H
(x4 from p_{opt} to p*)



Overdoping is a robust method to reach ultrahigh $J_c(H)$

A. Stangl et al, Scientific Reports (2021)

CONCLUSIONS

- Material science should help Coated Conductors to reach the market
- Cost / Performance ratio needs to decrease and high-throughput low cost growth processes with high critical current strategies can be employed
- TLAG-CSD is a non-equilibrium growth method able to grow high performance YBCO nanocomposites using low cost CSD methods at ultrafast growth rates
- Nanoengineering combinations of different defects should be used to optimize pinning landscape for each application
- Overdoping can be a robust and feasible way to further increase J_c in nanoengineered Coated Conductors