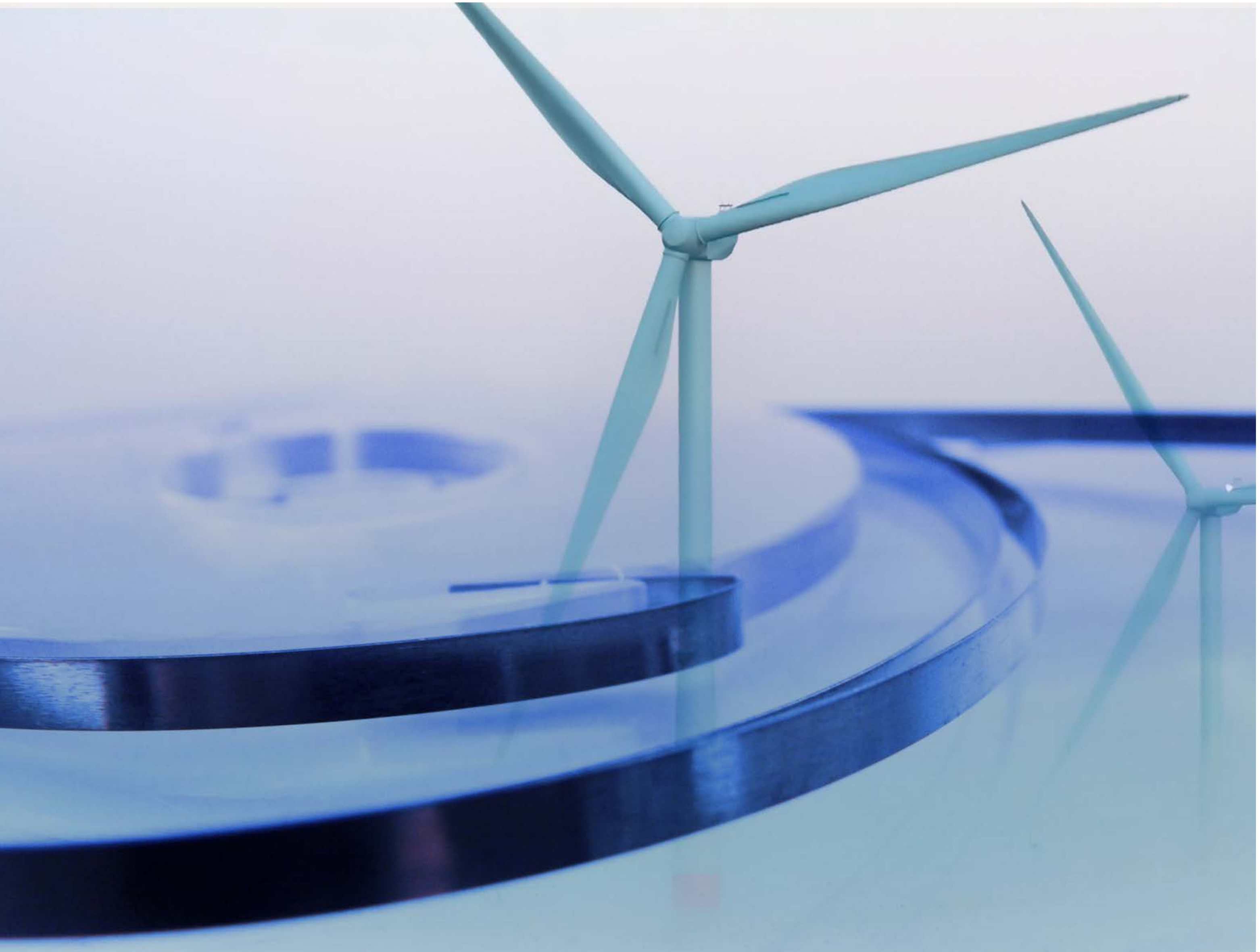
New opportunities for low cost nanostructured Coated Conductors for superconducting power applications

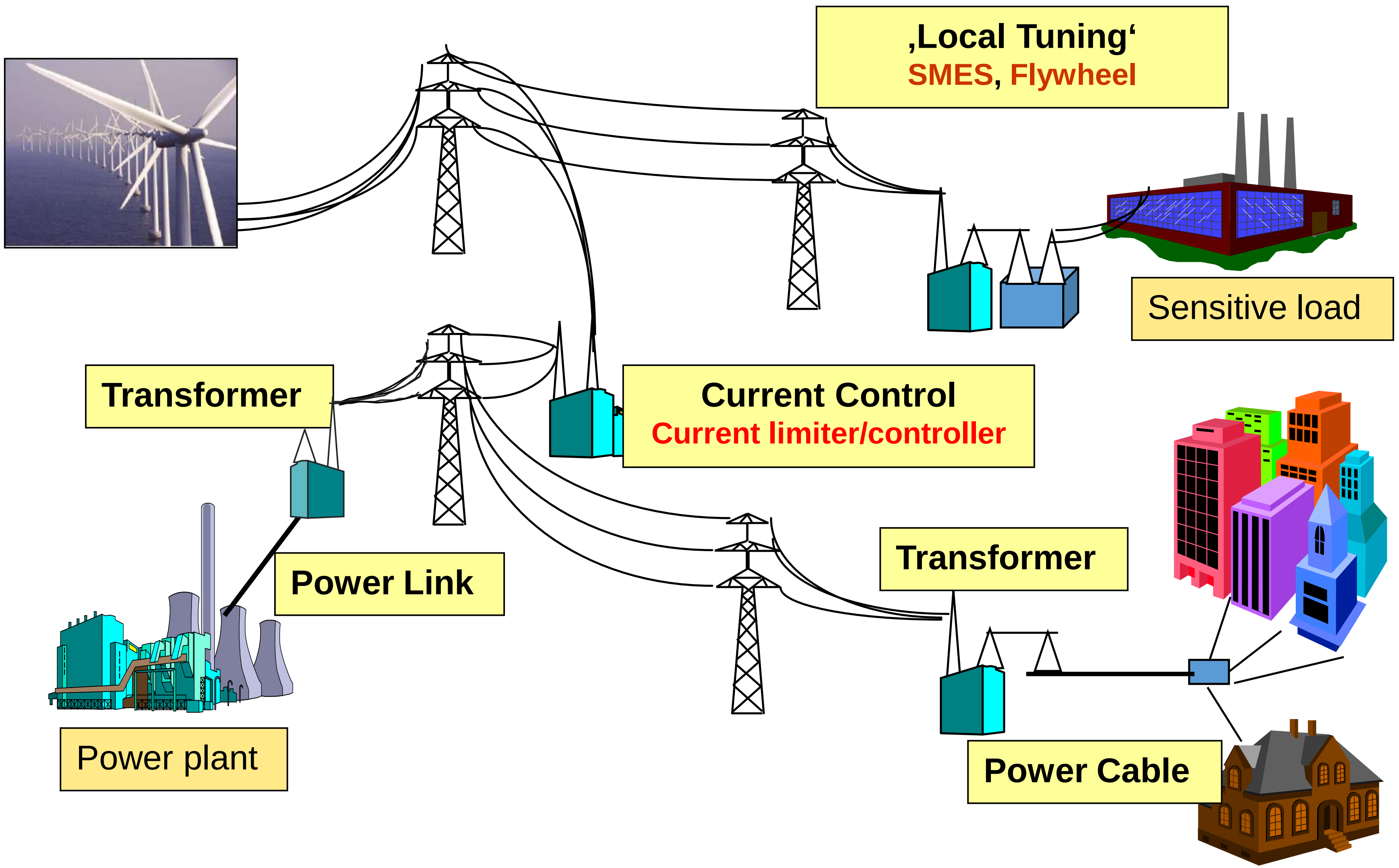


Xavier Obradors

Institut de Ciència de Materials de Barcelona, ICMAB-CSIC

Campus de la UAB, 08193 Bellaterra, Catalonia, Spain

Superconductivity: an opportunity for the smart grids



A new electricity paradigm: from the XIX century physics to that of the XXI century

Oportunity for the carbon-free energy transition!

Superconductivity and Power Applications

Power distribution, generation and storage

superconducting cables

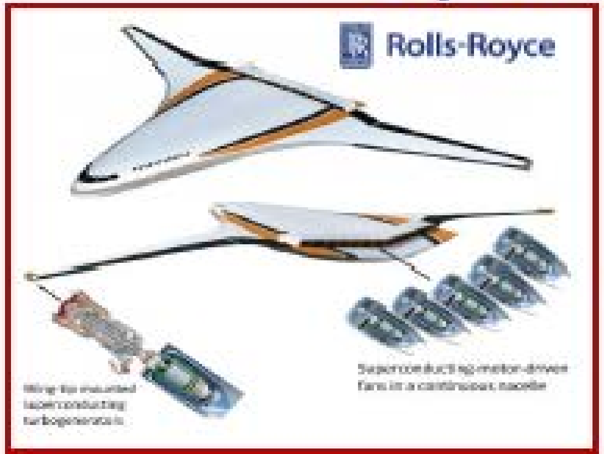
20% from renewable sources by 2020

$$E = \frac{1}{2}\frac{B^2}{\mu}$$

energy density of the magnetic field

Superconductors and transportation

High speed MAGLEV trains



Turboelectric aircrafts

GAMESA project: MINECO-RTC-Wind Generator

"Design of a new generation of wind generator and auxiliary equipment for solar energy based on superconductors"

Towards wind turbines generators based on HTS for next generation 10 MW

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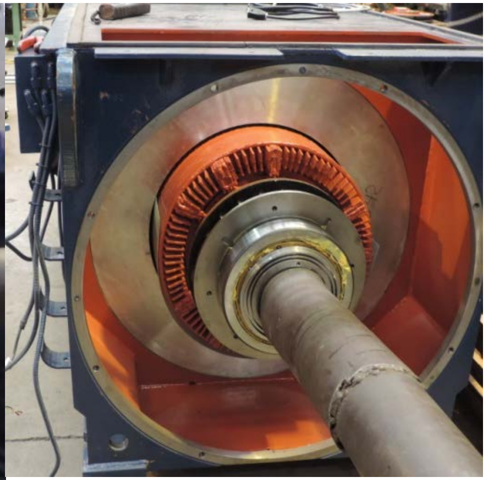
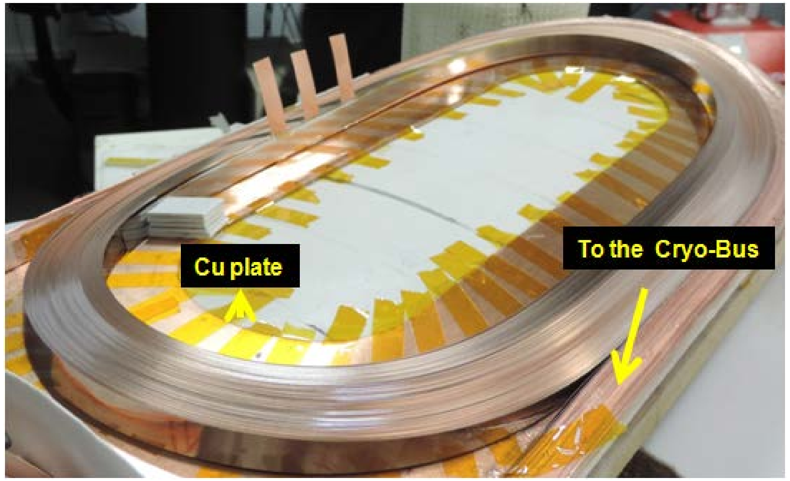
Gamesa
icma Instituto de Ciencia de Materiales de Aragón
UPC



More efficiency
Less weight
Less volume

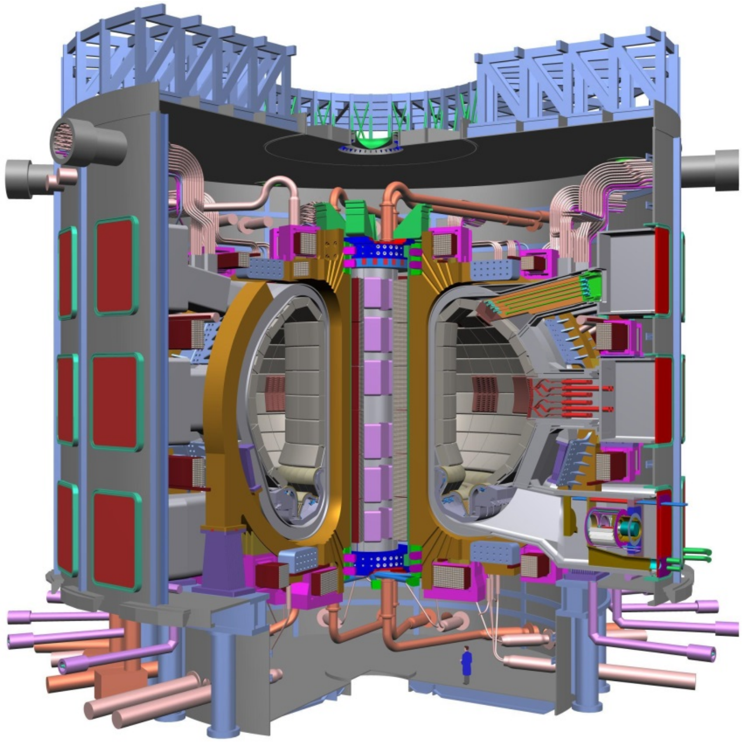


HTS coil

Patent PCT/EP2016/058934

HTS stator for wind generator of 2 MW

FUSION and Superconductivity



ITER is example of previous state-of-art in superconductor magnets

- Very large size
- > 2 years to replace interior shield
- H=10 T, coils diameter=12 m
- 500 MW fusion power

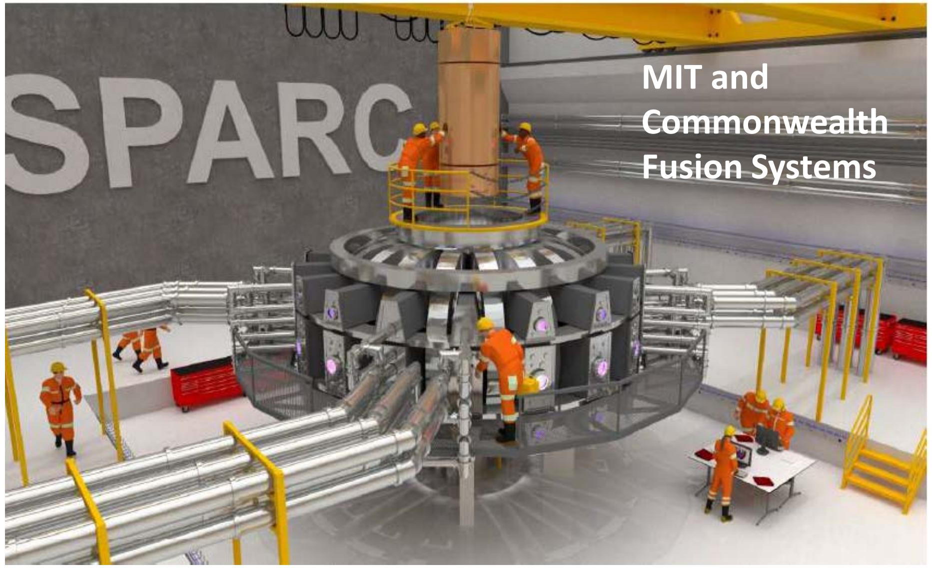
ARC is example of using new HTS magnets (Affordable, Reliable, Compact)

- Decrease volume by factor of ten!
- Modular replacement of interior
- New HTS magnet at ~20 T, 20 K
- 500 MW fusion power

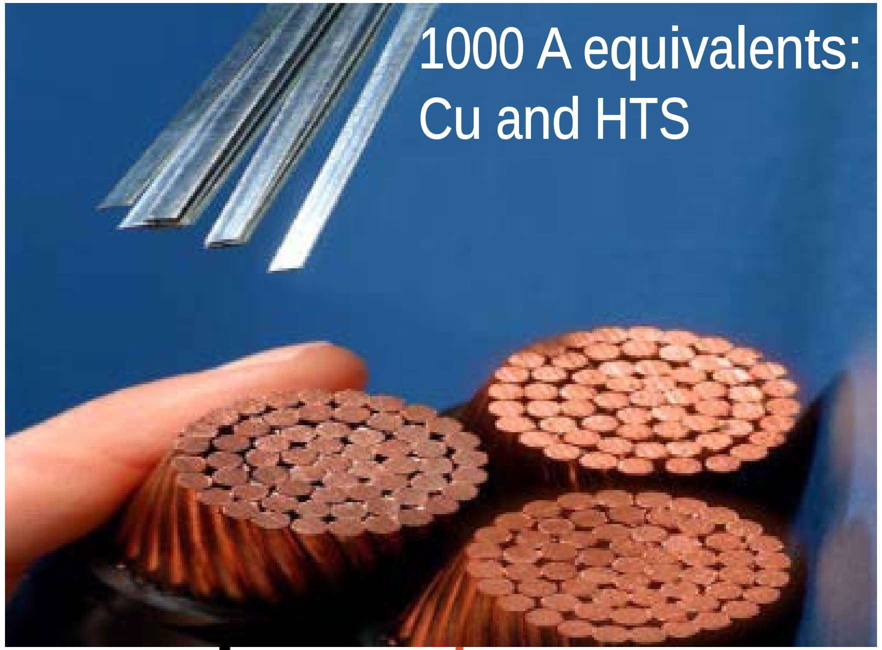
NEXT **DEMO**:
2000-4000 MW

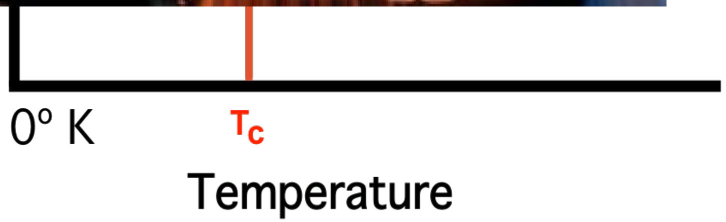
tokamak energy
a faster way to fusion

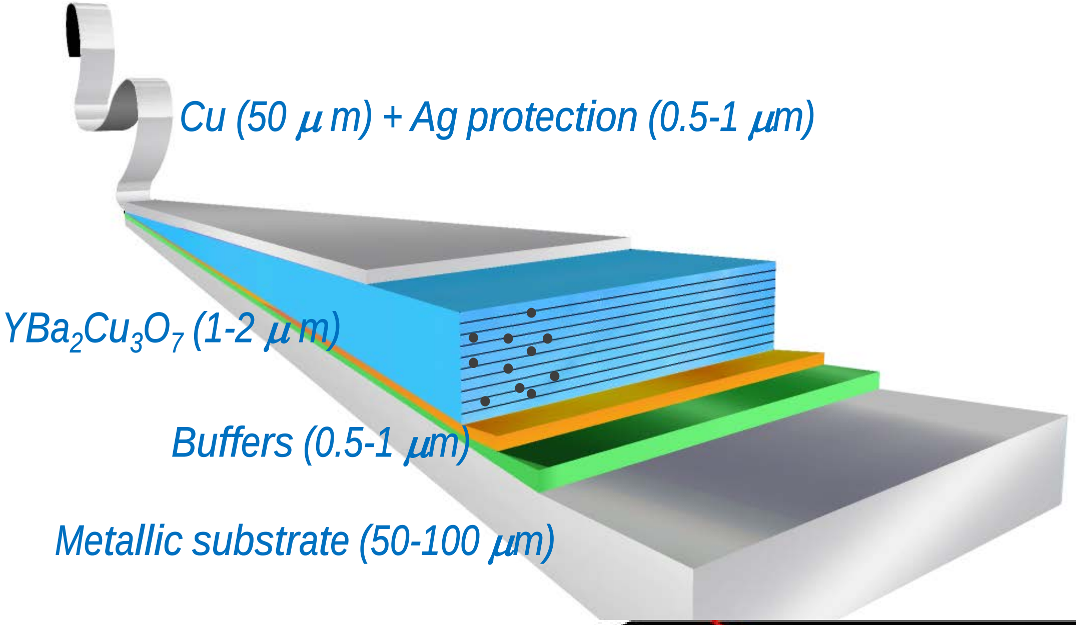
COMMONWEALTH FUSION SYSTEMS

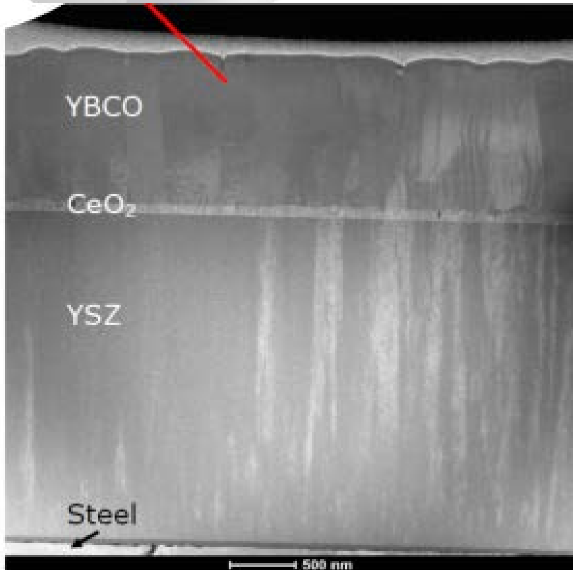


High Temperature Superconducting Coated Conductors



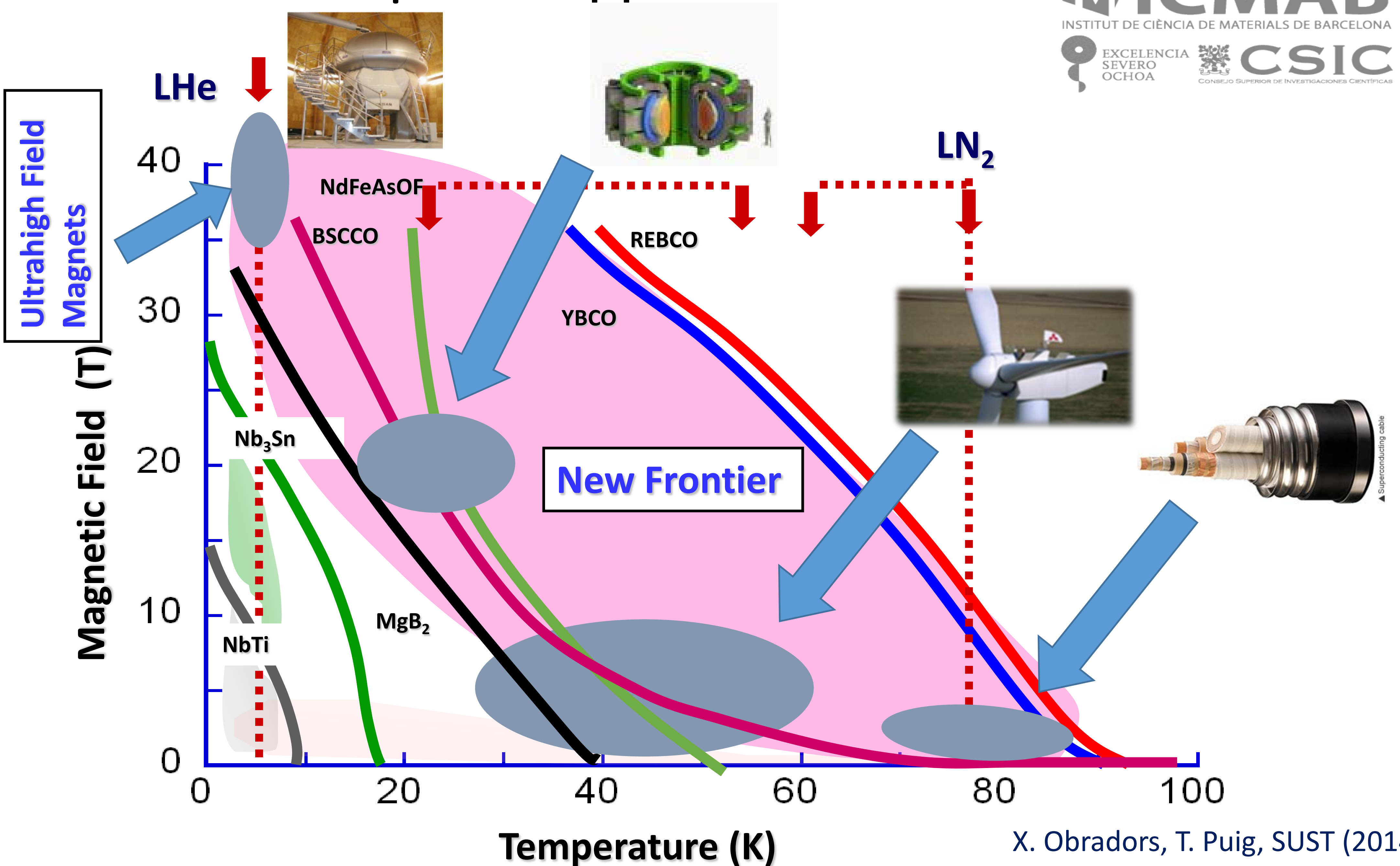






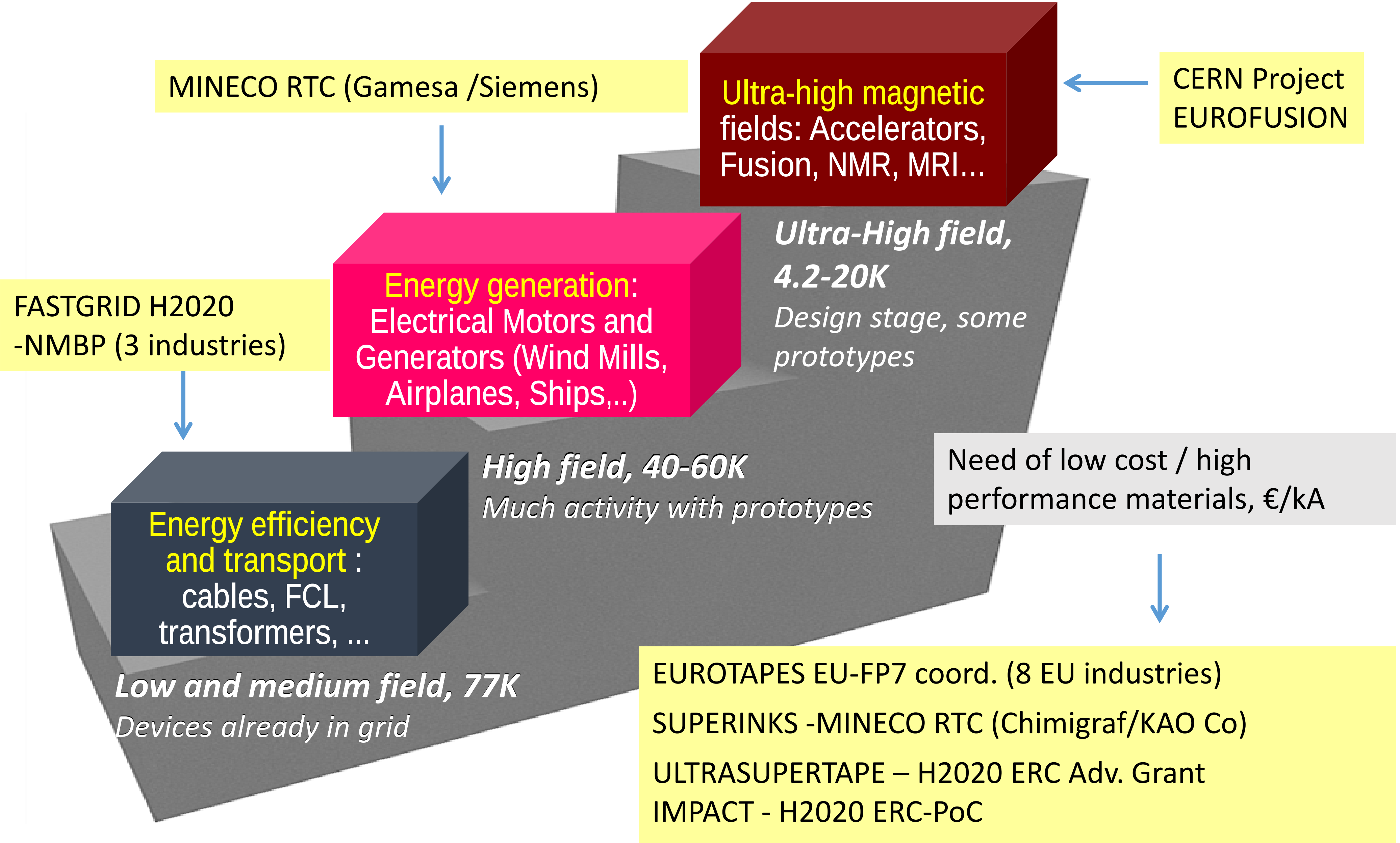
Km-length flexible epitaxial multilayer capable to carry 400 A/cm-w at 77K and 800 A/cm-w at 5 K & 30 T

HTS: New frontiers for power applications



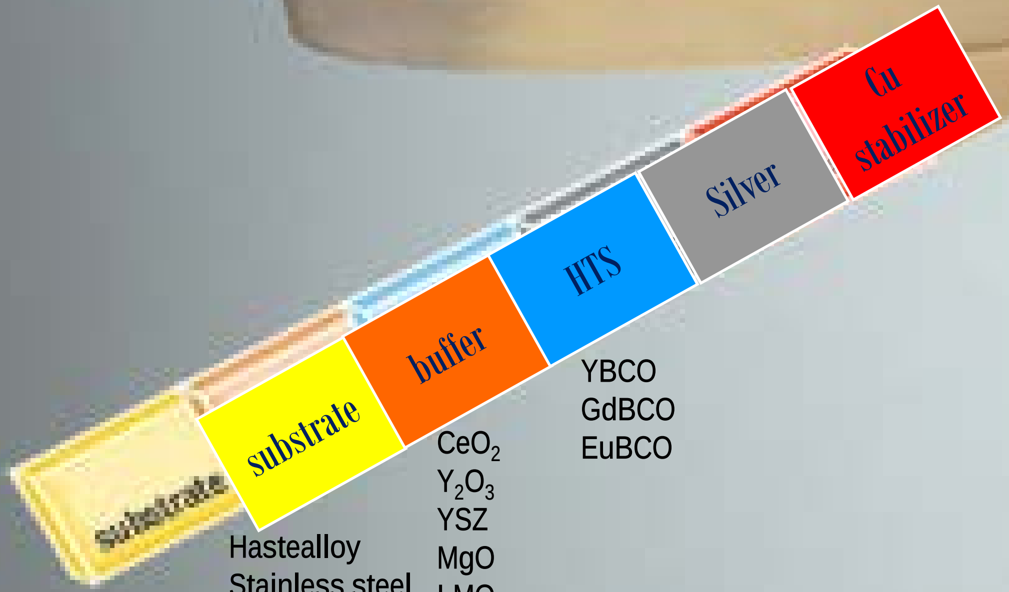
X. Obradors, T. Puig, SUST (2014)

Coated Conductors



Nowadays production is close to commercialization

We have a strong industry in CC manufacture



Hastealloy
Stainless steel
Ni-based

CeO_2
Y_2O_3
YSZ
MgO
LMO
...

YBCO
GdBCO
EuBCO

The Coated Conductor Tape

Coated Conductors: materials objectives

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erc
European Research Council
Executive Agency

Coated Conductor penetration
€ / kA m
$I_c = J_c \cdot t$

CHEAPER

- Ultrafast growth
- Lower capital investment
- Simpler processing
- Simpler architecture
- Higher yield
- Larger area manufacturing
- Higher throughput

BETTER

- Higher performance: $J_c(B, T)$
- Thicker REBCO films
- More robust
- Customized for Applications
- Thinner substrates (J_E)
- Nanostructure
- Lower ac losses

CSD - TLAG ⟷ **Best combination** ⟷ **Nanocomposites**

Chemical Solution Deposition – Transient Liquid Assisted Growth (CSD-TLAG)

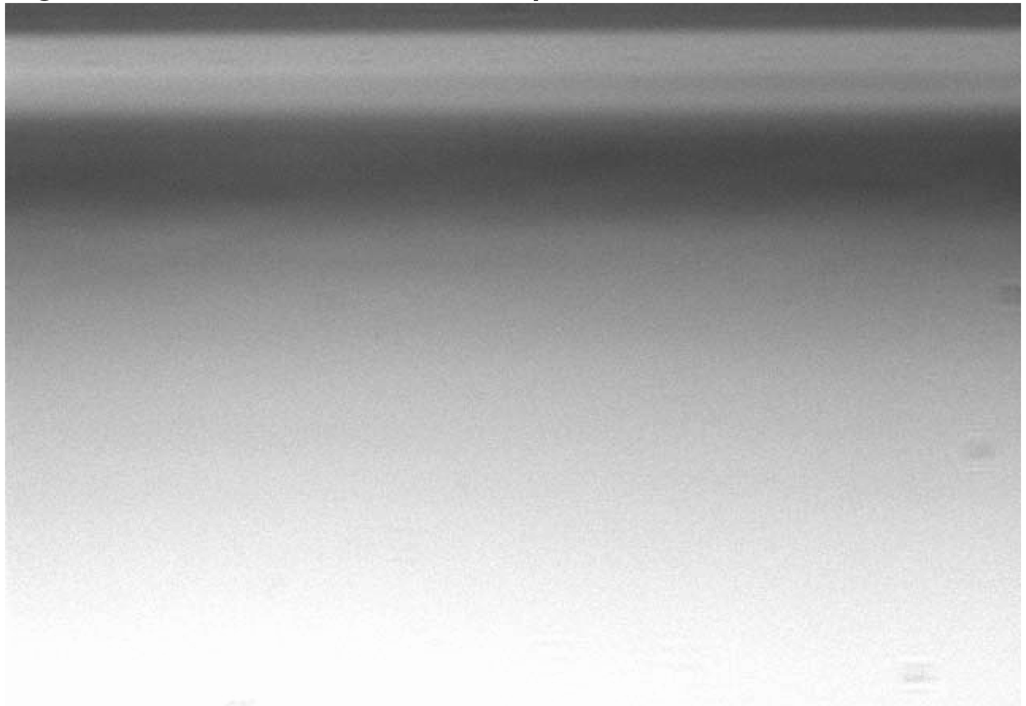
Coated Conductors at ICMAB

(> 20 years of experience)

… from fundamental knowledge on Materials & Science to process scalability and integration in devices

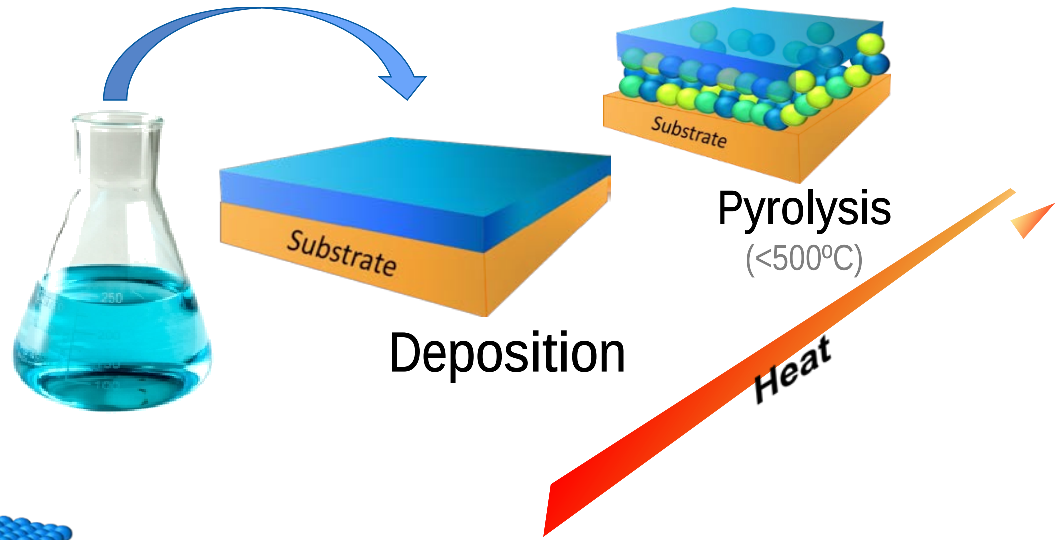
Low cost, scalable, high –throughtput / high performance materials, growth mechanisms and materials physics understanding

- Solution chemistry and nanoparticles synthesis
- Chemical solution deposition based on complex metalorganic solutions and suspensions
- Epitaxial film growth and nanocomposites
- Inkjet printing and process scalability
- Correlation between nano/micro-structure and physical mehanisms
- Electro-thermo-mechanical properties
- Integration in devices



Chemical Solution Deposition (CSD)

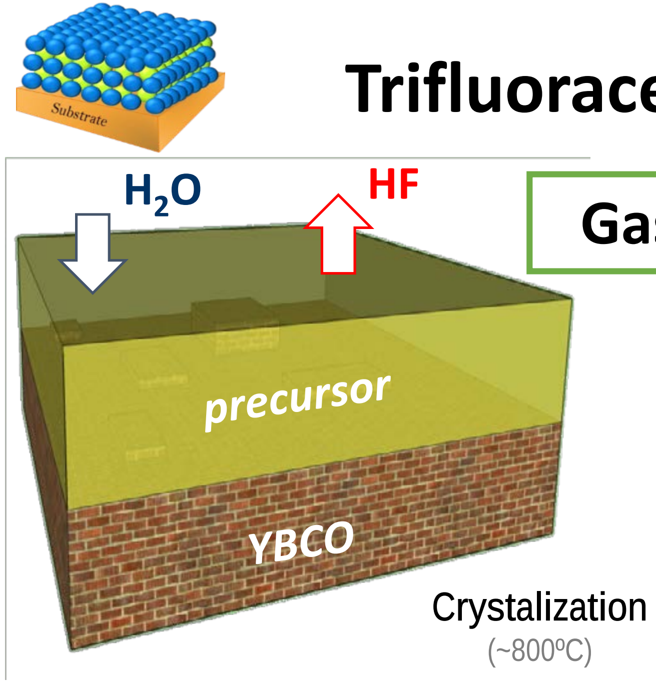
X. Obradors et al., SUST (2012); SUST (2018)
C. Pop, SUST (2019)
B. Vallejo , J Mat Chem C (2020)



First step

- Low cost solution deposition manufacturing
- Non-vaccum deposition
- Colloidal solutions for nanocomposites
- Industrially scalable (large thicknesses)

Trifluoracetate-route: Low fluorine TFA metalorganic precursors



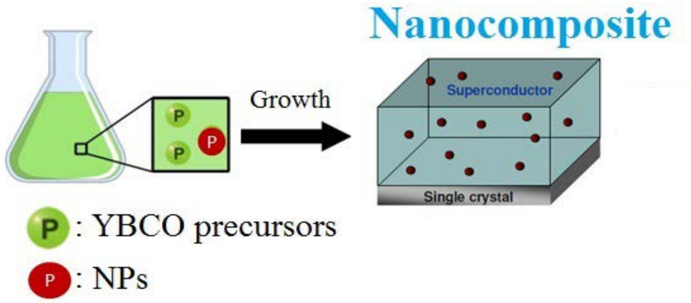
Gas-Solid reaction

Second step: film growth

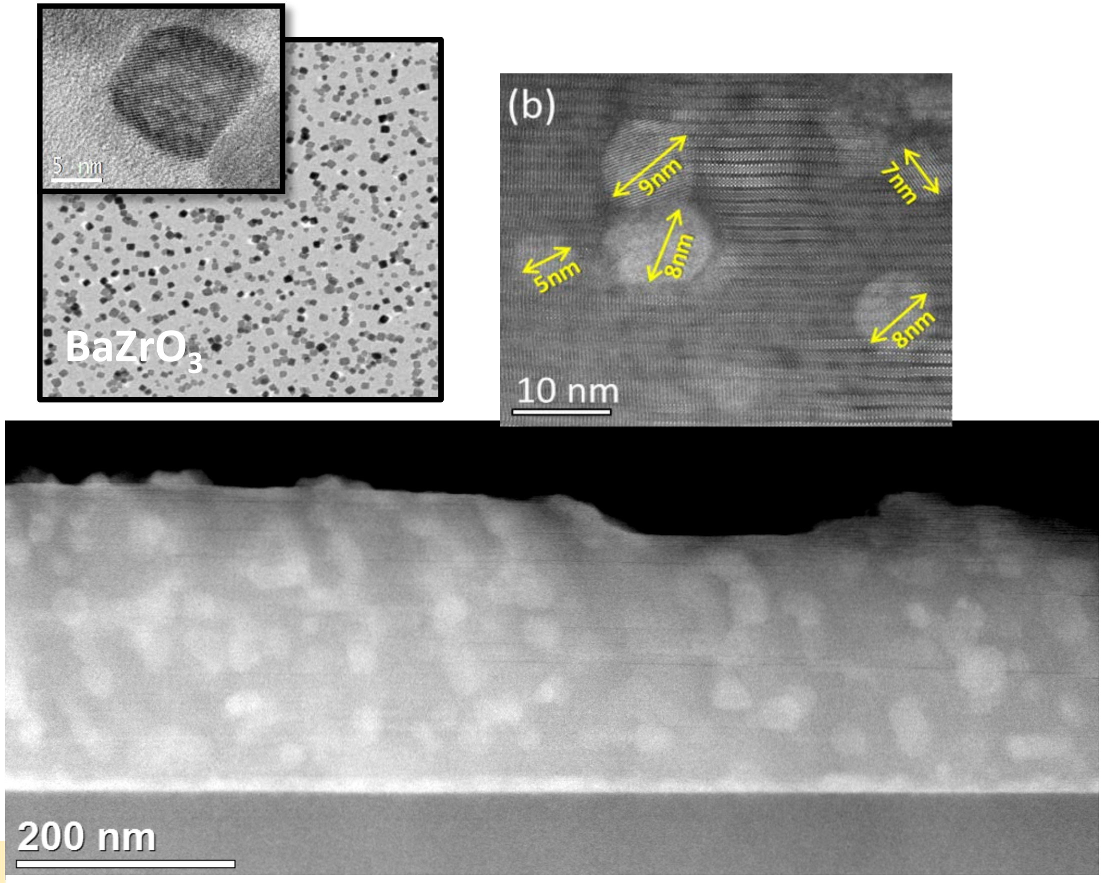
$$Ba(O_xF_y)_2 + 3/2\ CuO + 1/4 Y_2O_3 + yH_2O\ (g) \rightarrow 1/2\ YBa_2Cu_3O_{6.5} + 2yHF\ (g)$$

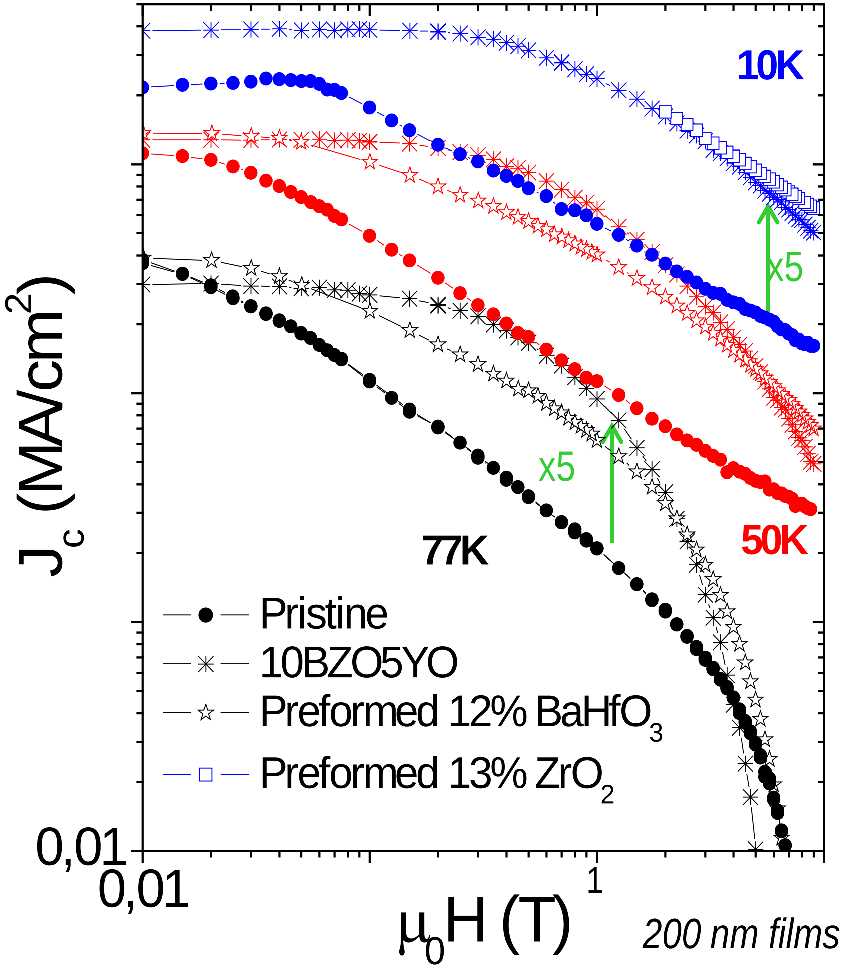
- Supersaturation conditions highly dependent on P_{HF} and P_{H2O}
- Growth rate for c-axis growth limited to 1nm/s
- High performances (I_c=400 A/cm-w)
- Complicated R2R gas flow furnaces

Nanocomposites: EUROTAPES (FP7 EU Integrated Project)



Integrating nanocomposite in coated conductors with cost effective processes for power applications and magnets





Z. Li et al, Sci Rep. (2019); J Mat Chem C (2019)

Towards growth of thick coated conductors: Scalability by innovative inks

"Development of UV inks and screen printing pastes for coated conductors"

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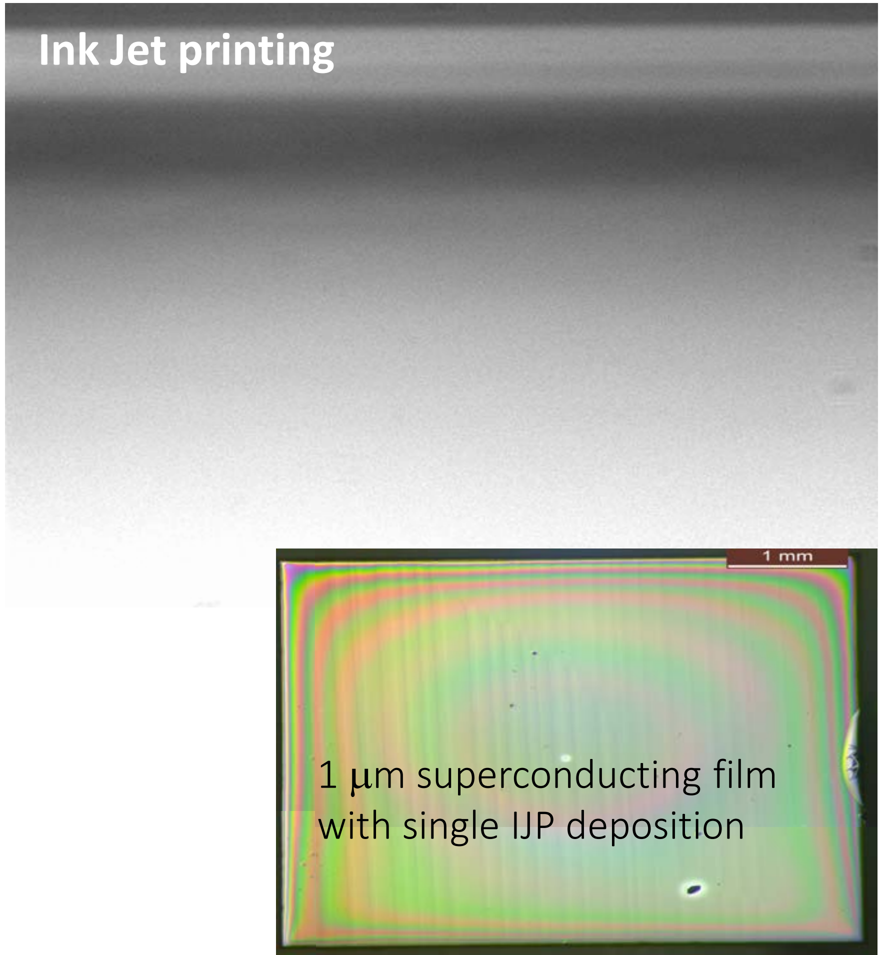
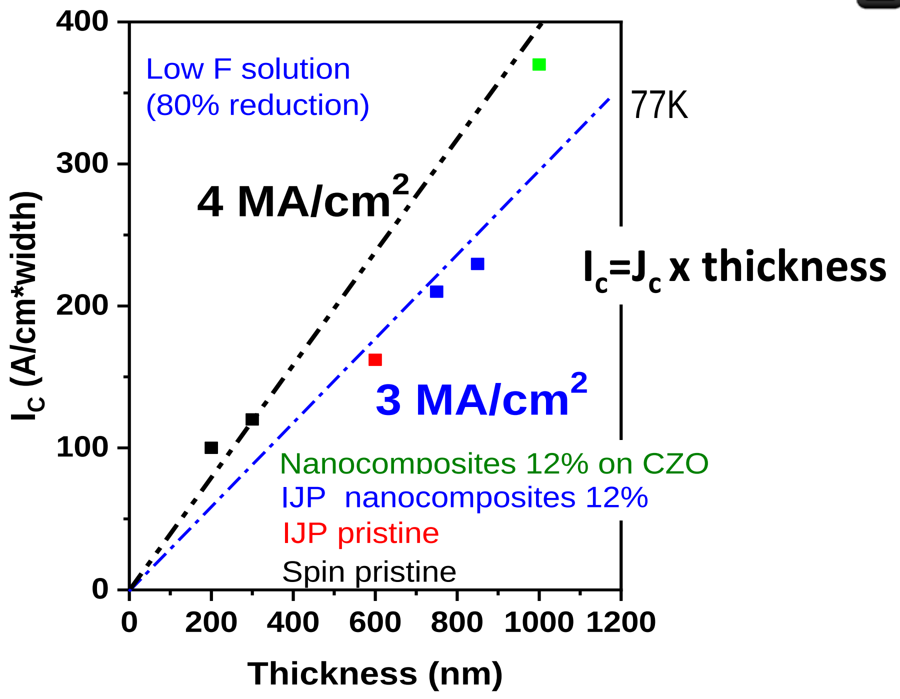
SUPERINKS: MINECO-RTC-Advanced Inks

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
CHIMIGRAF
Innovative Thinking
OXOLUTIA





Oxolutia S.L. – Spin- off

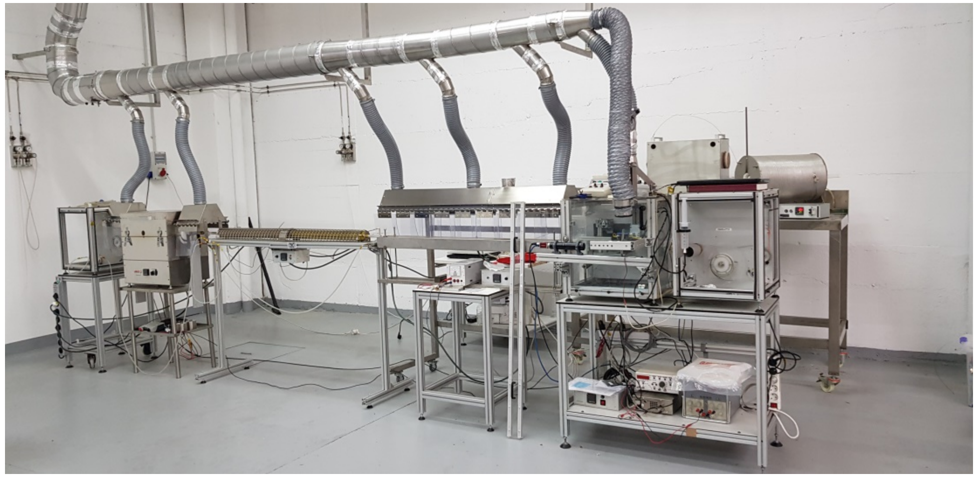
Created in 2010, 5 employees
500m^2 in a industrial park

4 ICMAB researchers co-funded
1 ex-RyC is CEO

Participated by:
La Farga Lacambra
Victoria Venture Capital

Among employees: PhD's from ICMAB

Several patents and projects in collaboration with ICMAB too



Oxide layers by CSD- ink jet printing

Main technology: Coated Conductors for sustainable development

CSD – Transient Liquid Assisted Growth

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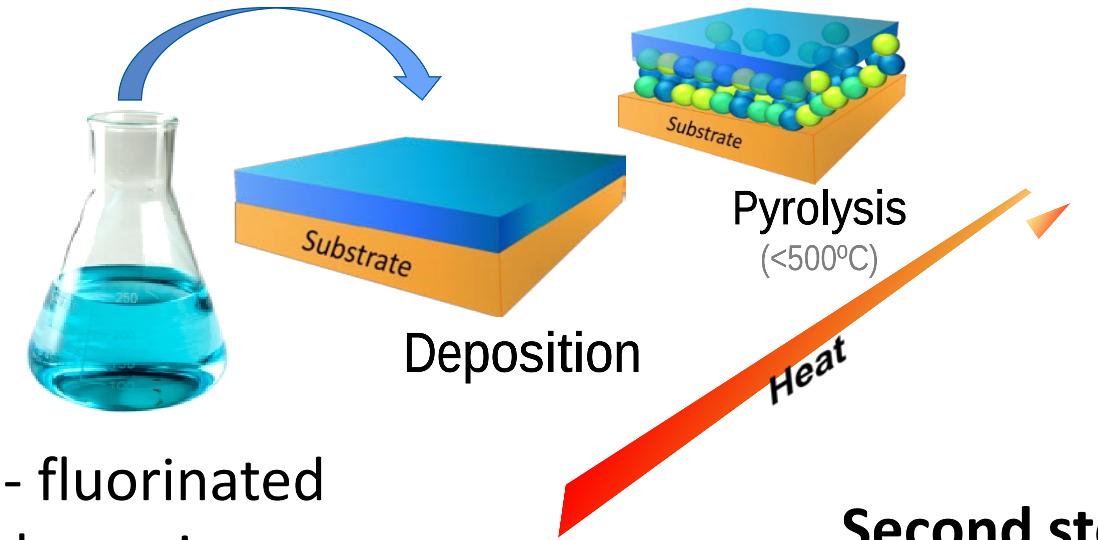


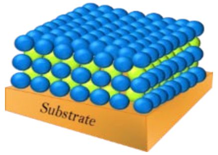
Non - fluorinated metalorganic precursors

L. Soler et al., Nat Comm (2020)
S. Rasi et al., J. Phys Chem C (2020)

First step

- Low cost solution deposition manufacturing
- Non-vaccum deposition
- Colloidal solutions for nanocomposites
- Industrially scalable (large thicknesses)

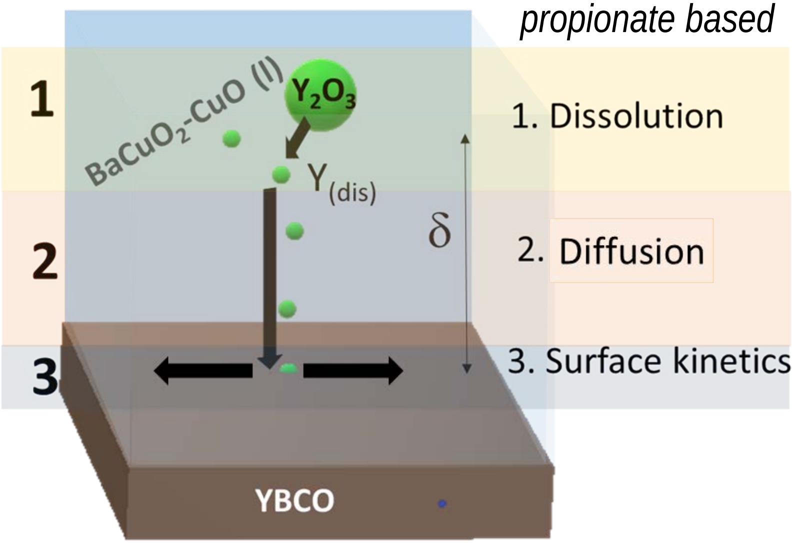
Second step: film growth



Crystalization
(~800ºC)

Metalorganic solution propionate based $\longrightarrow BaCO_{3(s)} + CuO_{(s)} + Y_2O_{3(s)} \longrightarrow (Ba - Cu_{I/II}\text{-}O)_{(l)} + Y_2O_{3(s)} \longrightarrow YBa_2Cu_3O_{7-\delta}$

Transient liquid



- ❖ *Liquid-solid conversion reaction (high atomic diffusion in liquids)*
- ❖ *Supersaturation degree can be controlled through Ba:Cu ratio*
- ❖ *Ultrafast growth rates >100 – 1.000 nm/s*
- ❖ *Simplified R2R large area reactor for industrial manufacturing*
- ❖ *Environmentally friendly*

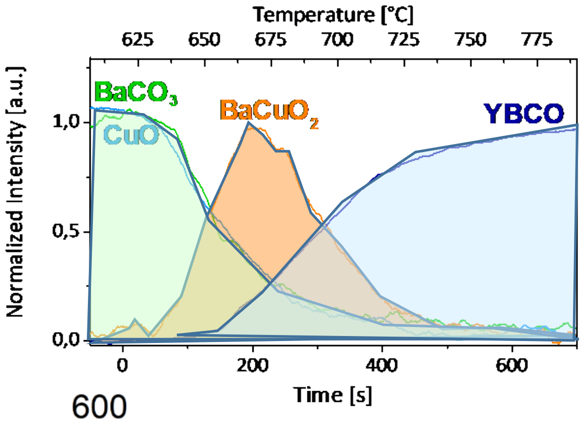
ERC-ADG ultrasupertape
erc European Research Council Executive Agency

TLAG-CSD: different growth routes

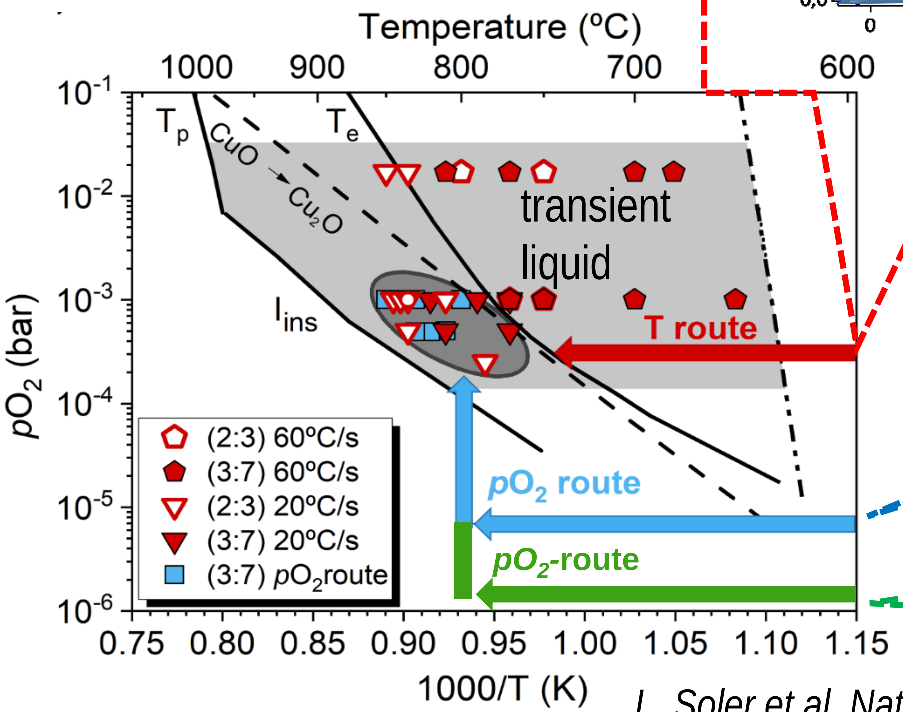
In-situ XRD synchrotron exp.

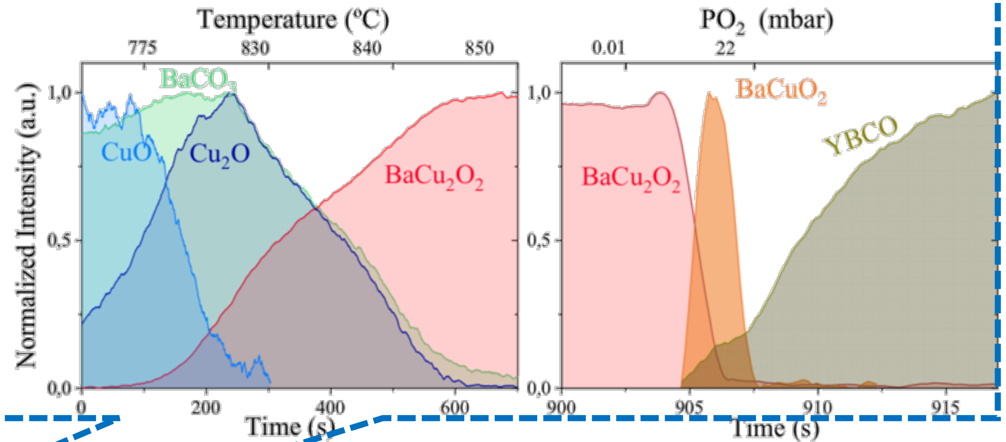
100 ms acquisition time

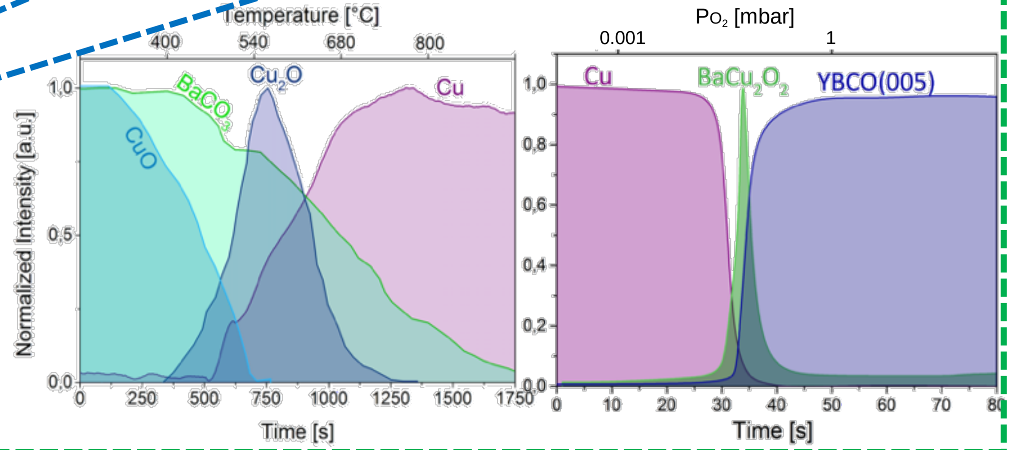
$BaCO_3(s)+CuO(s)+Y_2O_3(s) \longrightarrow [Ba\text{-}Cu\text{-}O](l) + Y_2O_3(\mathbf{s}) \longrightarrow \mathbf{YBa_2}Cu_3O_{6.5}(s)$



Kinetically driven growth by supersaturation with a wide c-axis window



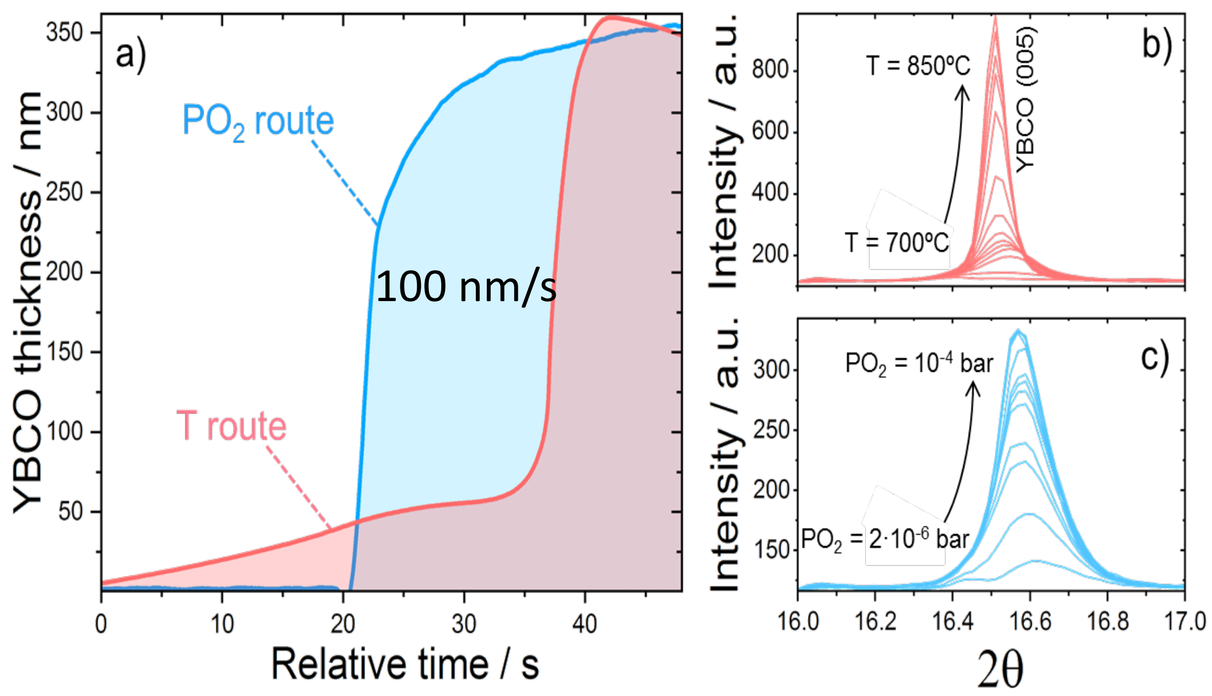


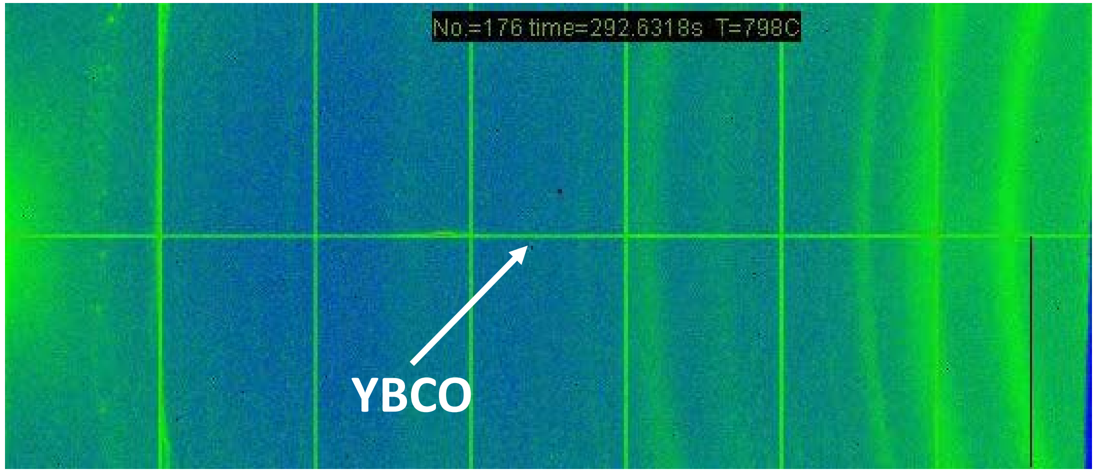


L. Soler et al, Nature Communications (2020)

S. Rasi et al., J. Phys Chem C (2020)

Ultrafast (non-equilibrium) growth by TLAG-CSD





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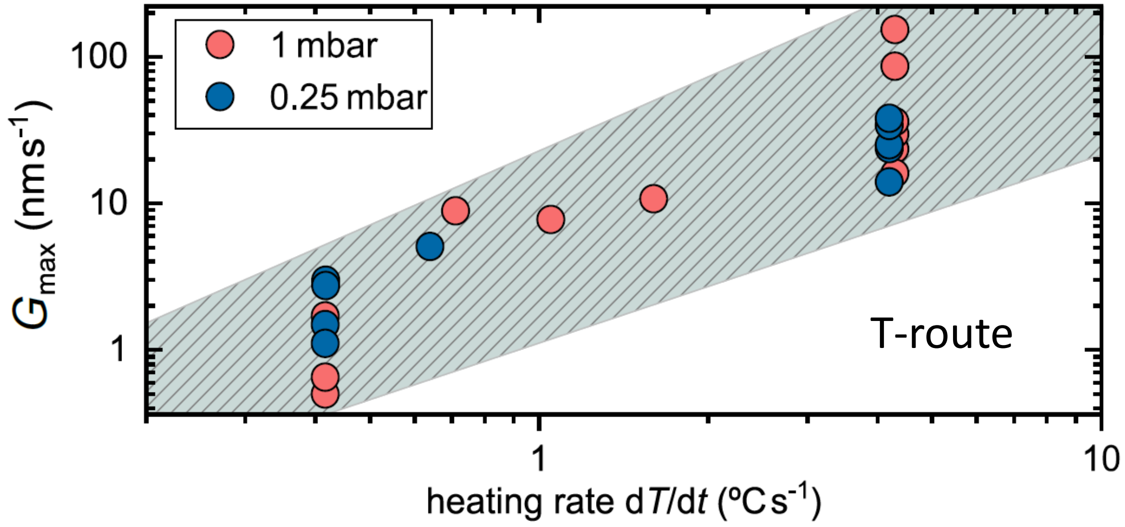
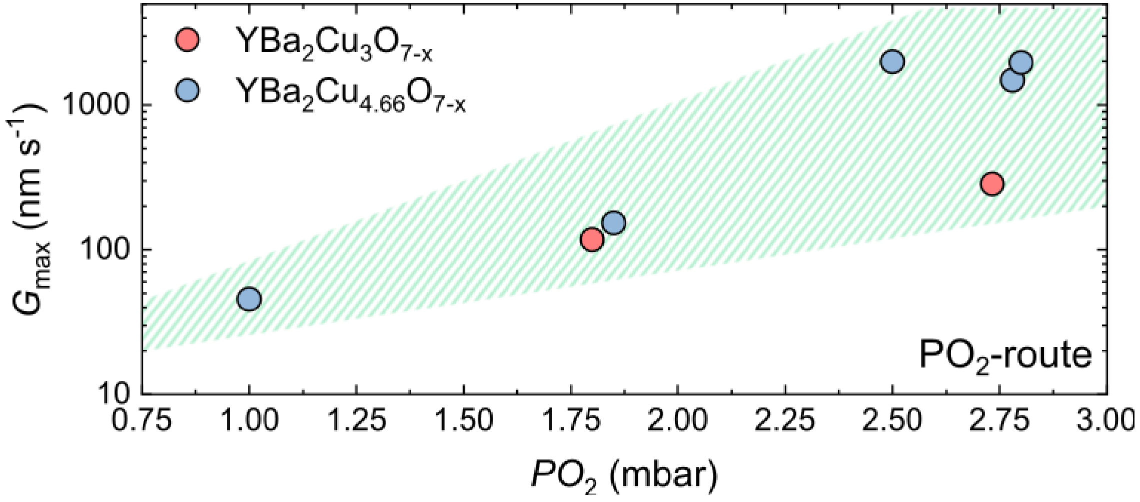
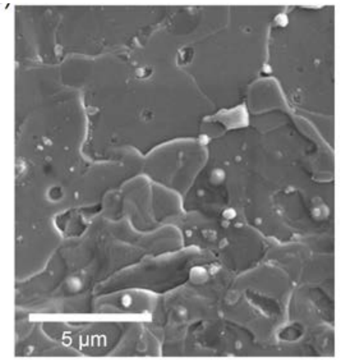


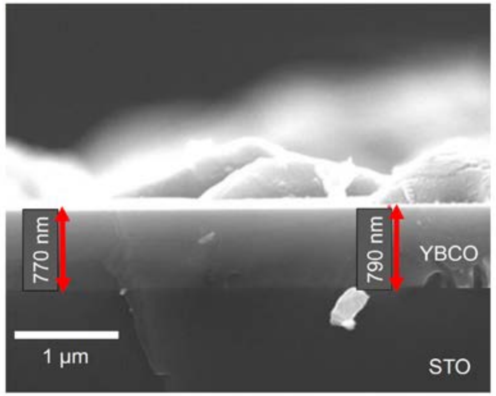


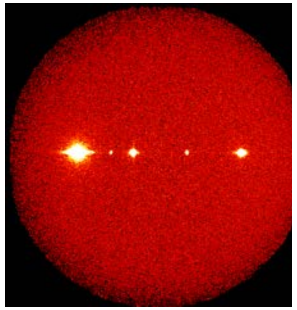
In-situ resistivity: growth rate determination

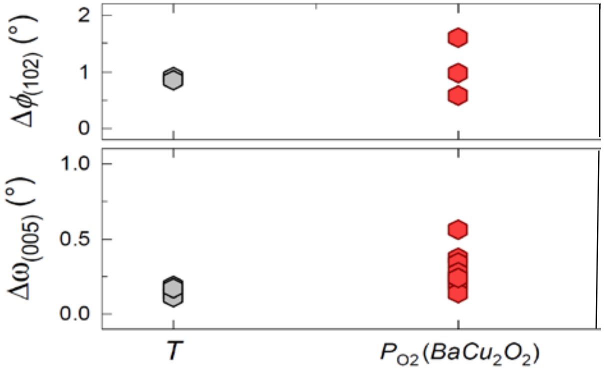
TLAG-CSD films: microstructure and properties

Extremely low porosity and highly epitaxial YBCO grown layers

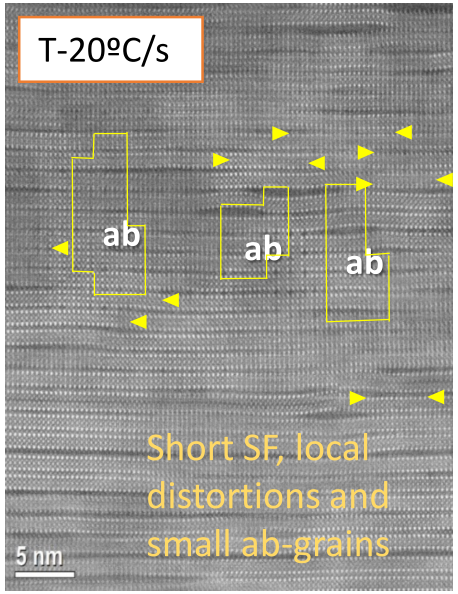


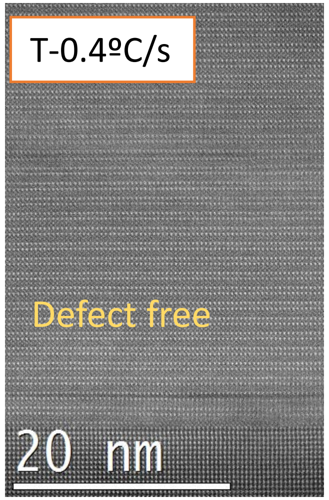


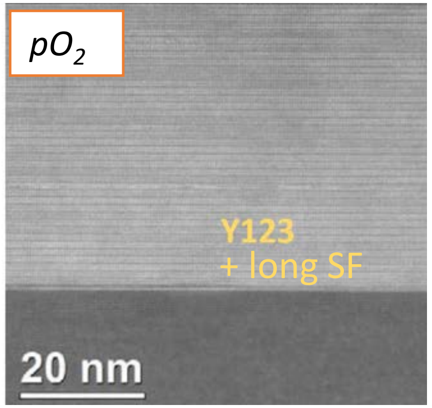




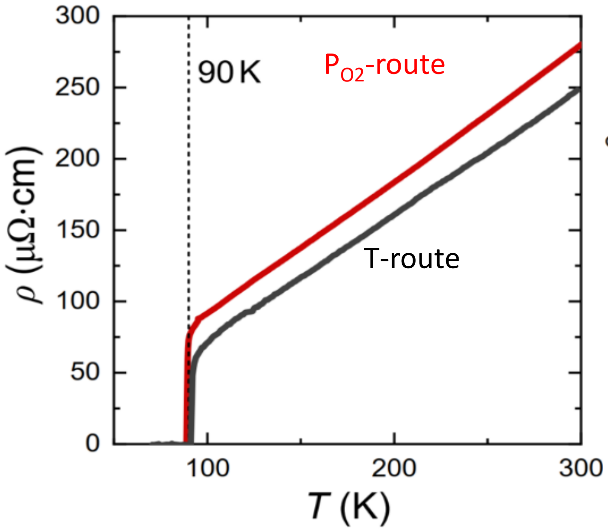
Tunable miscrostructure: depends a lot on process conditions

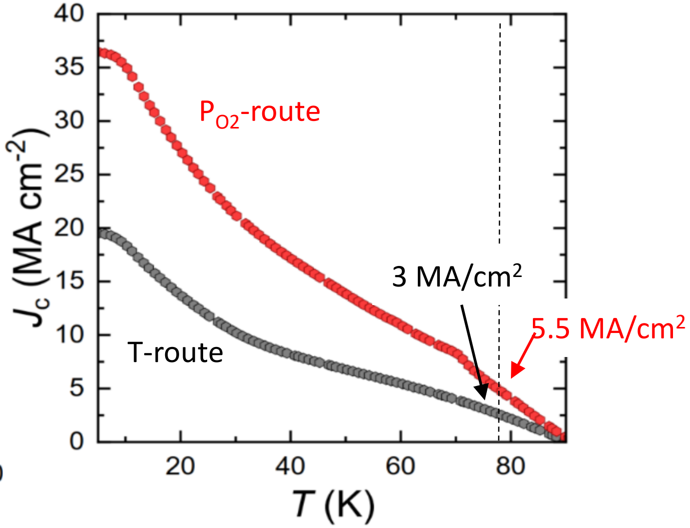






High performance demonstrated





L. Soler et al, Nature Communications (2020)

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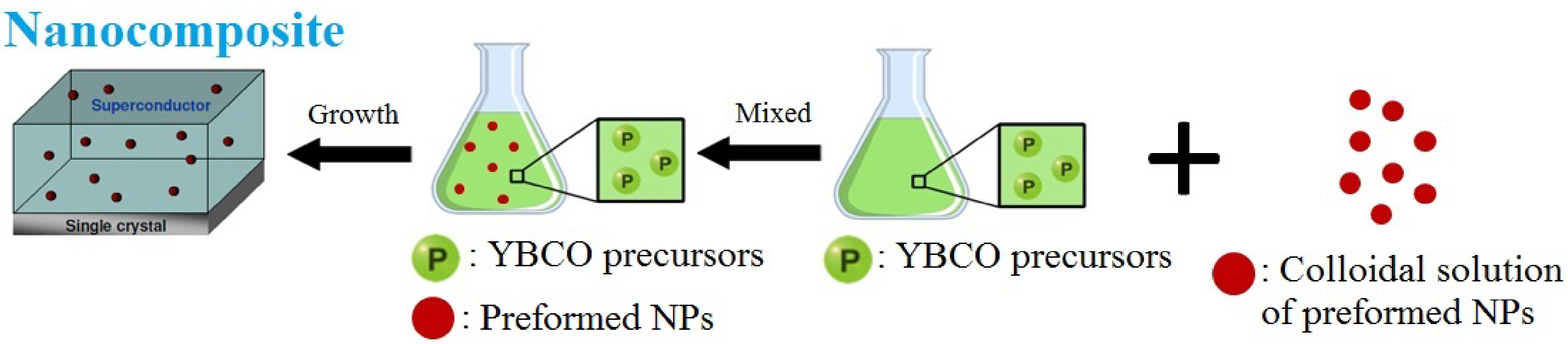
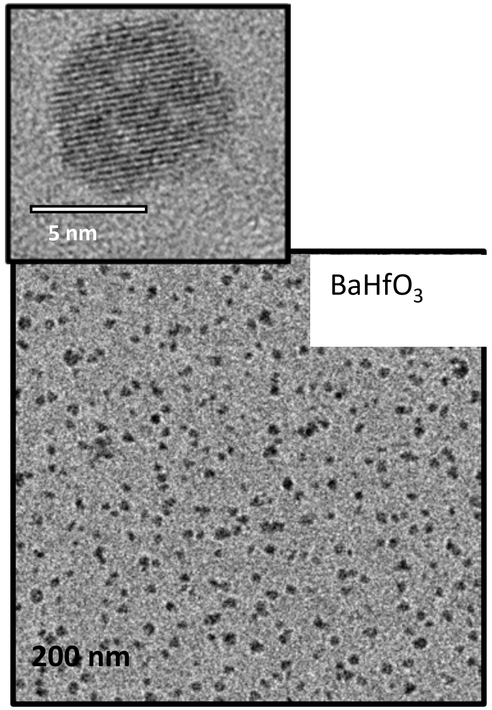
Nanocomposites: Colloidal solutions with preformed nanoparticles

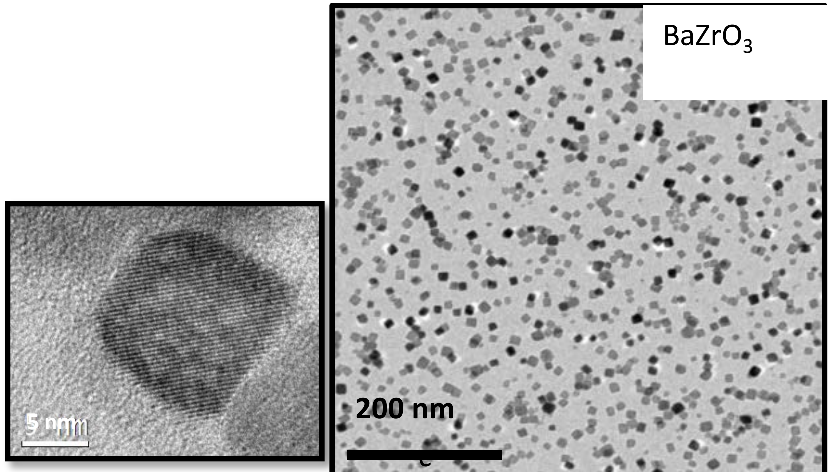
Suitable for TFA and TLAG



Need to stabilize nps in the alcoholic and ionic environment of YBCO precursor solution at high concentrations

Solvothermal synthesis – (Autoclave): 8-10 nm / 4-6 nm



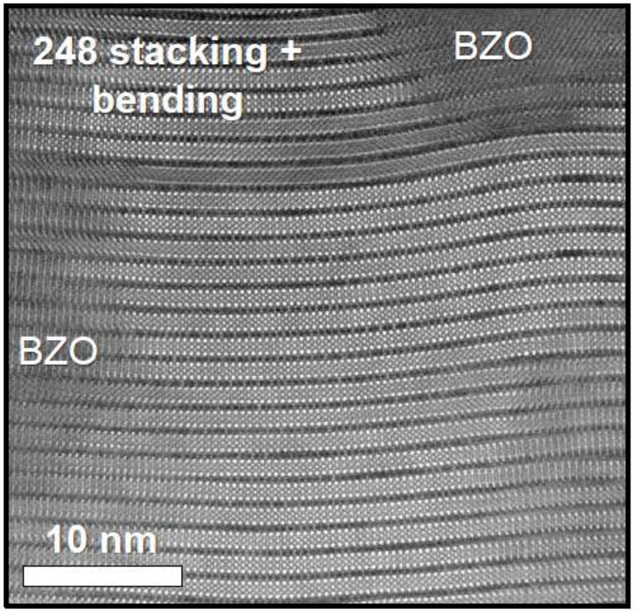


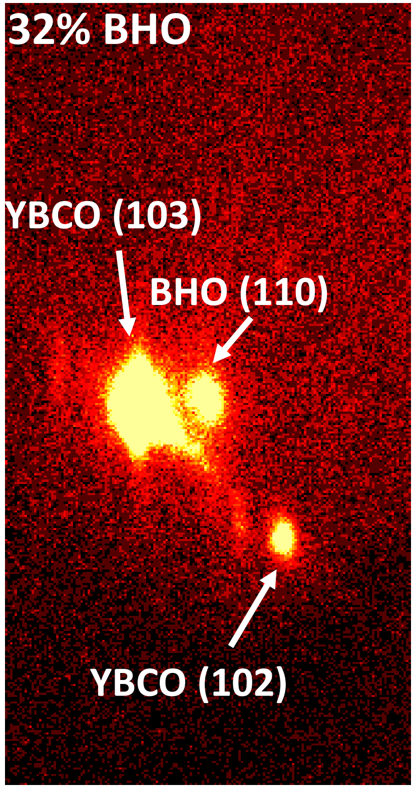
(N. Chamorro et al, RSC Adv. (2020))

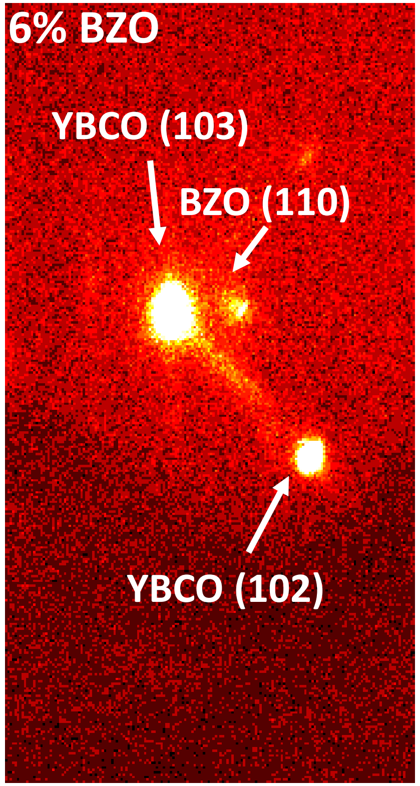
Nanoparticles orientation in TLAG

Measurement: chi: 45º, at BZO (110) most intense reflexion

Low PO_2 route

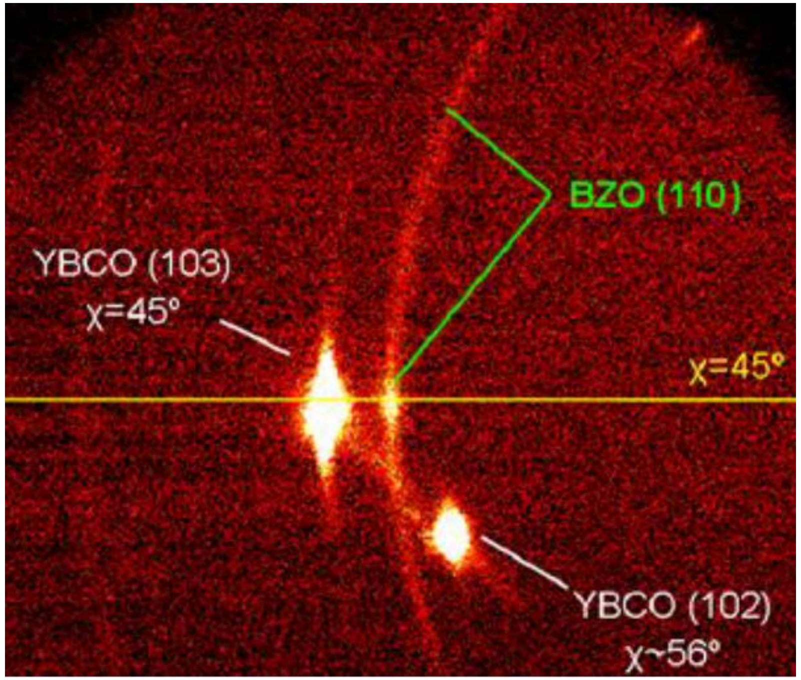






All NPs percentages:
0-10% random orientation

Example of 80% random orientation NPs (TFA)



Preformed NPs can rotate within the liquid state to reach epitaxy with YBCO matrix

L. Soler et al, Nat Comm (2020)
J. Banchewski et al, to be published

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erc European Research Council Executive Agency

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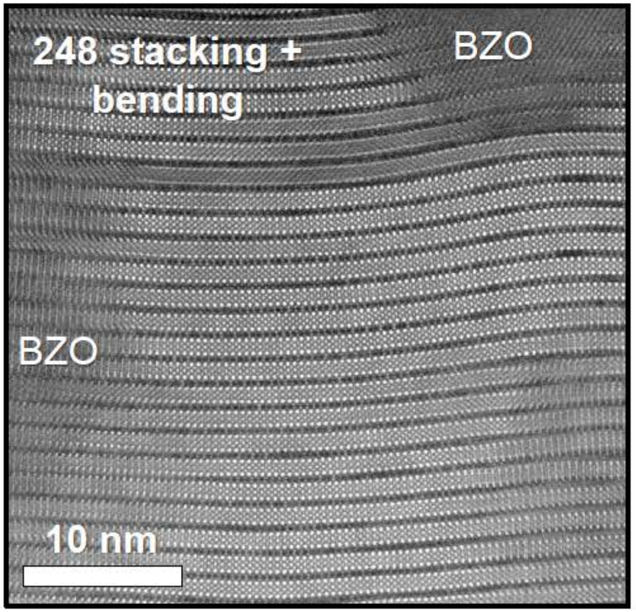

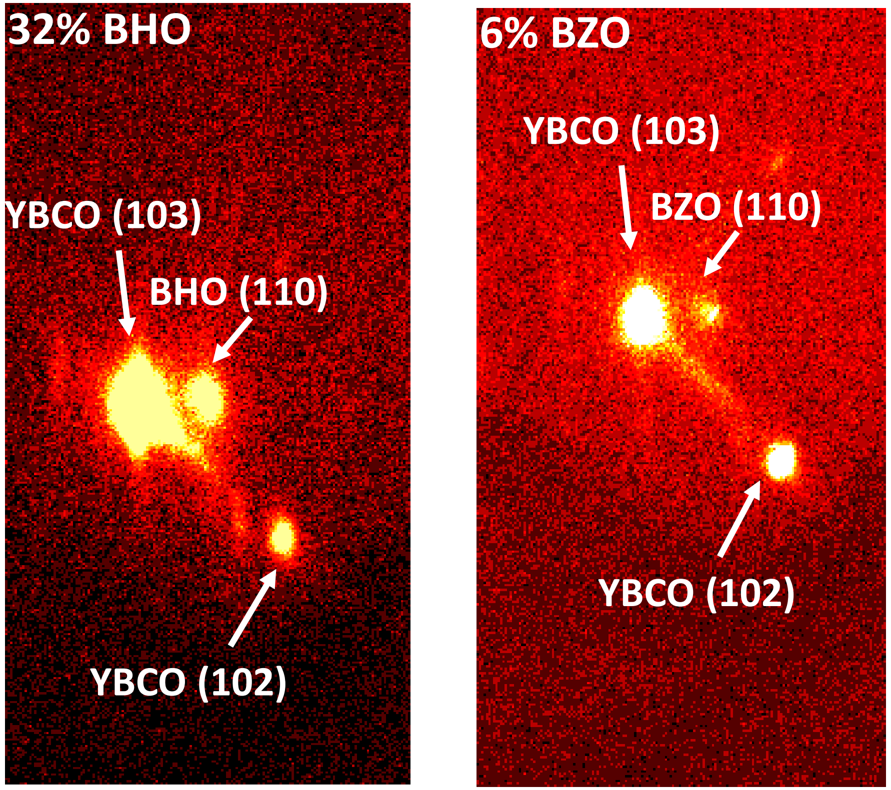

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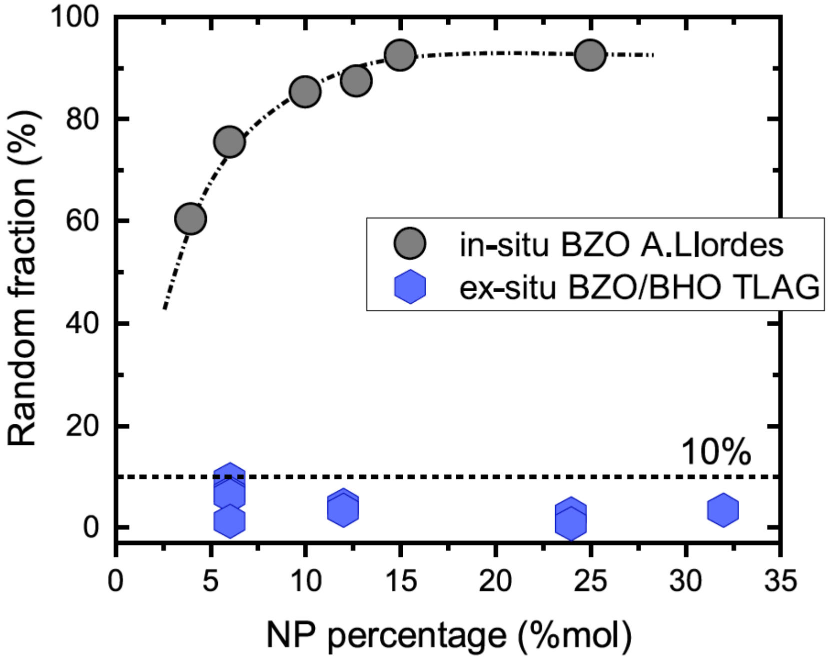
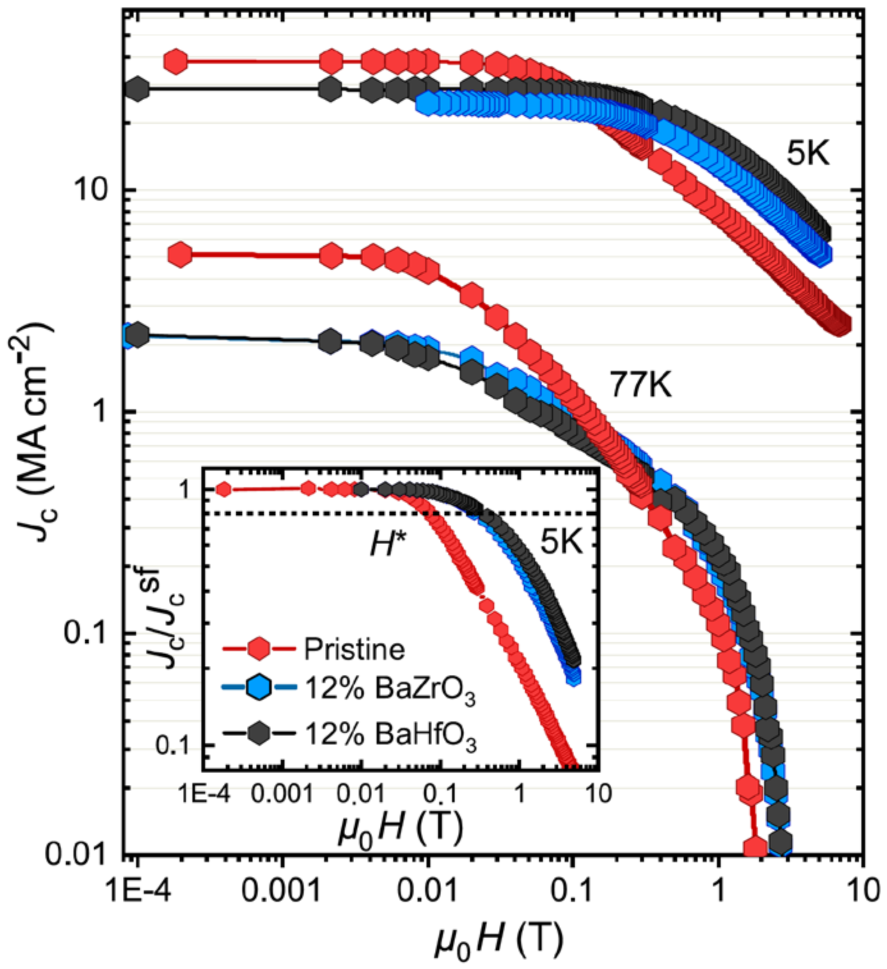
All NPs percentages:
0-10% random orientation

Example of 80% random orientation NPs (TFA)

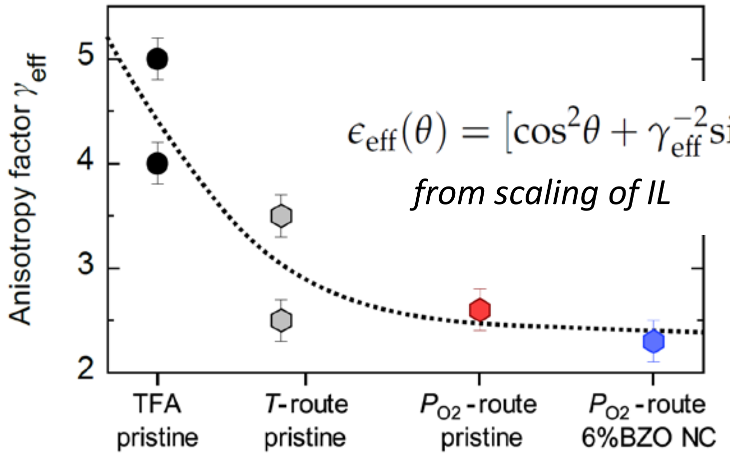


TLAG-CSD superconducting properties



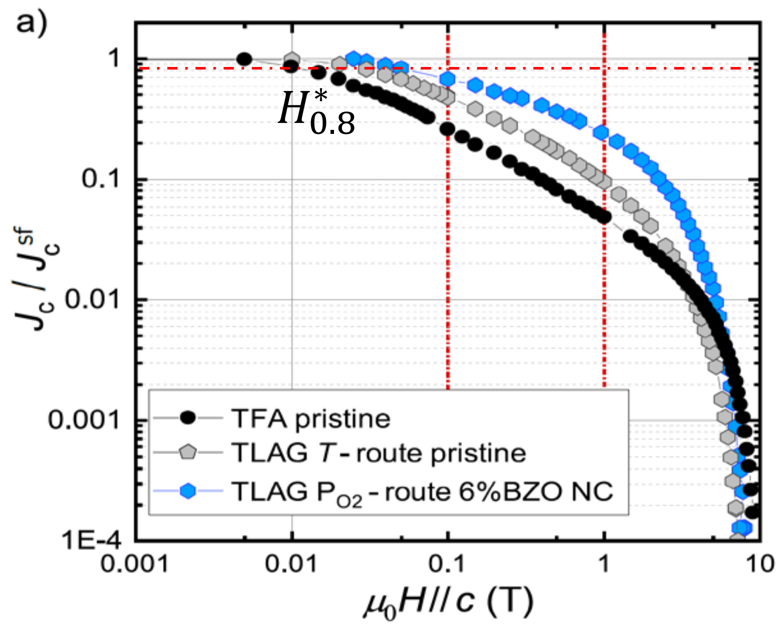
In-field performances of TLAG nanocomposite outperform pristine films

Effective anisotropy decrease due to nanostrain (SFs) and nanoparticles



$$\epsilon_{\rm eff}(\theta) = [\cos^2\theta + \gamma_{\rm eff}^{-2}\sin^2\theta]^{1/2}.$$

from scaling of IL



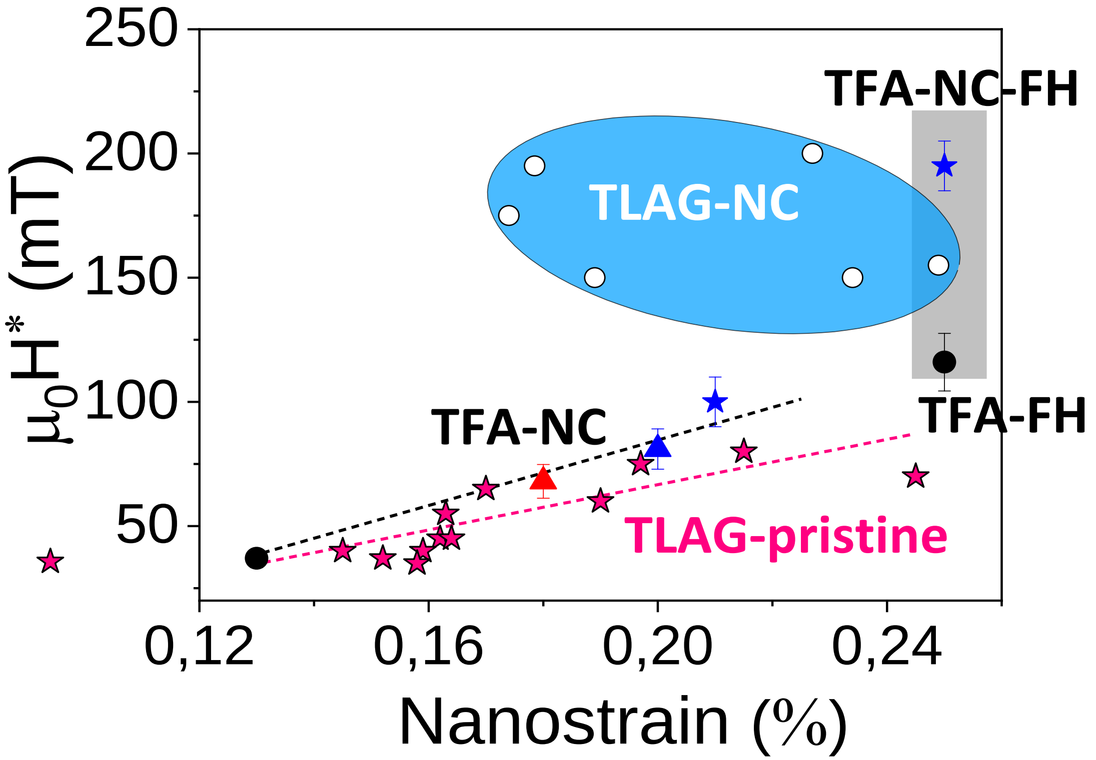
Enhanced in-field performance of TLAG nanocomposite films

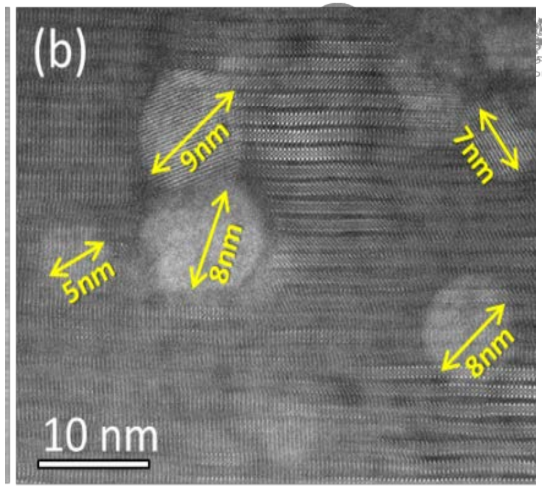
L. Soler et al, Nature Communications (2020)

J. Banchewski et al, to be published

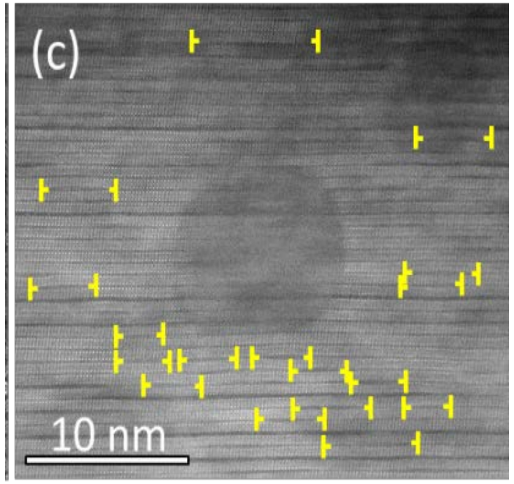
PN-Nanocomposites: TFA-FH and TLAG

TFA - Flast heating (20 ºC/s): 20%M BHO (5 nm)





$n_{np} \approx 40 \times 10^{22}\ m^{-3}$ (x2,5) (≈ 8 % vol)
NPs random fraction: 94%



Vol density partial dislocation: ≈2.3 %vol (+ 60 %)

- Fast heating strongly avoids NP coarsening (TFA and TLAG)
- High concentration of short SF: high density of partial dislocations
- NP size very close to the optimal size for vortex pinning (5-8 nm)

Synergistic combination of NPs and nanostrain also in TFA-FH and TLAG

Z. Li et al , Sci Rep. (2019); J Mat Chem C (2019); J. Banchewski et al., (to be published)
A. Palau et al., SUST (2018)

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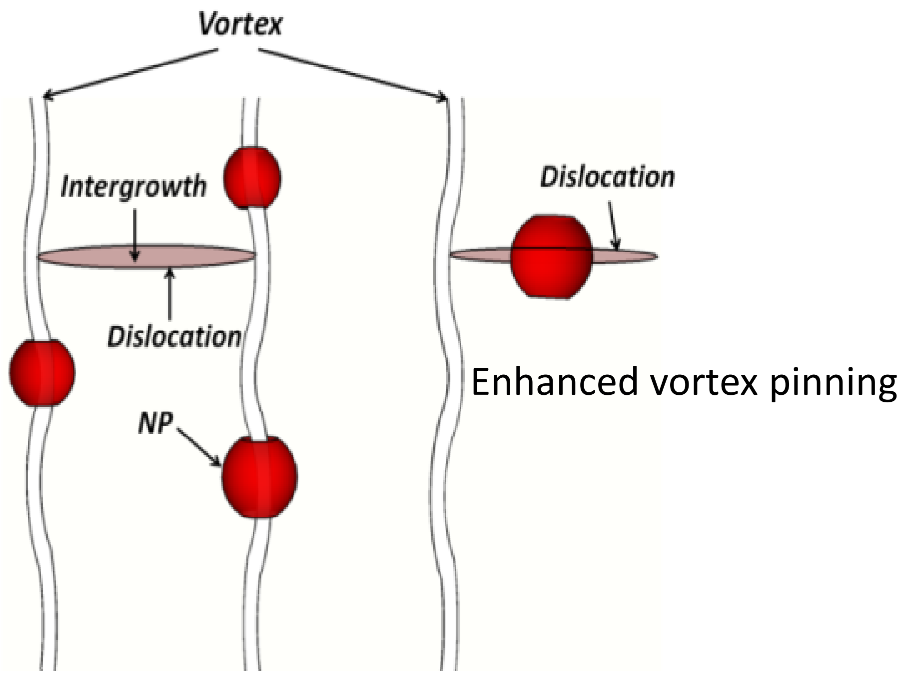

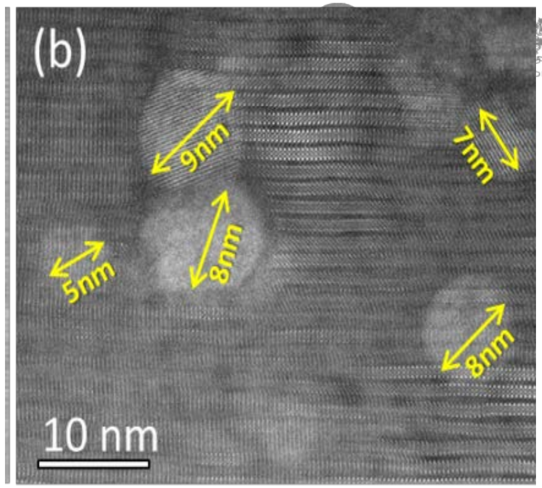

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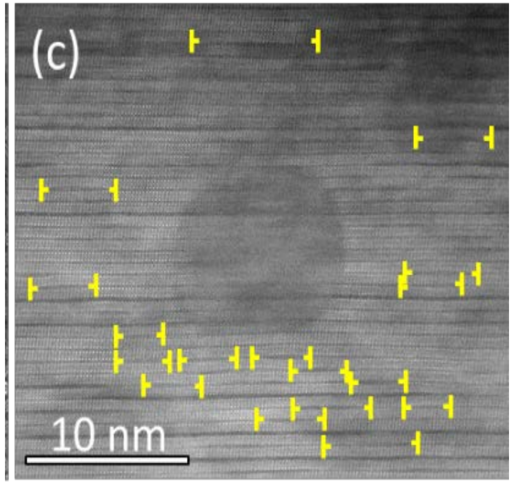

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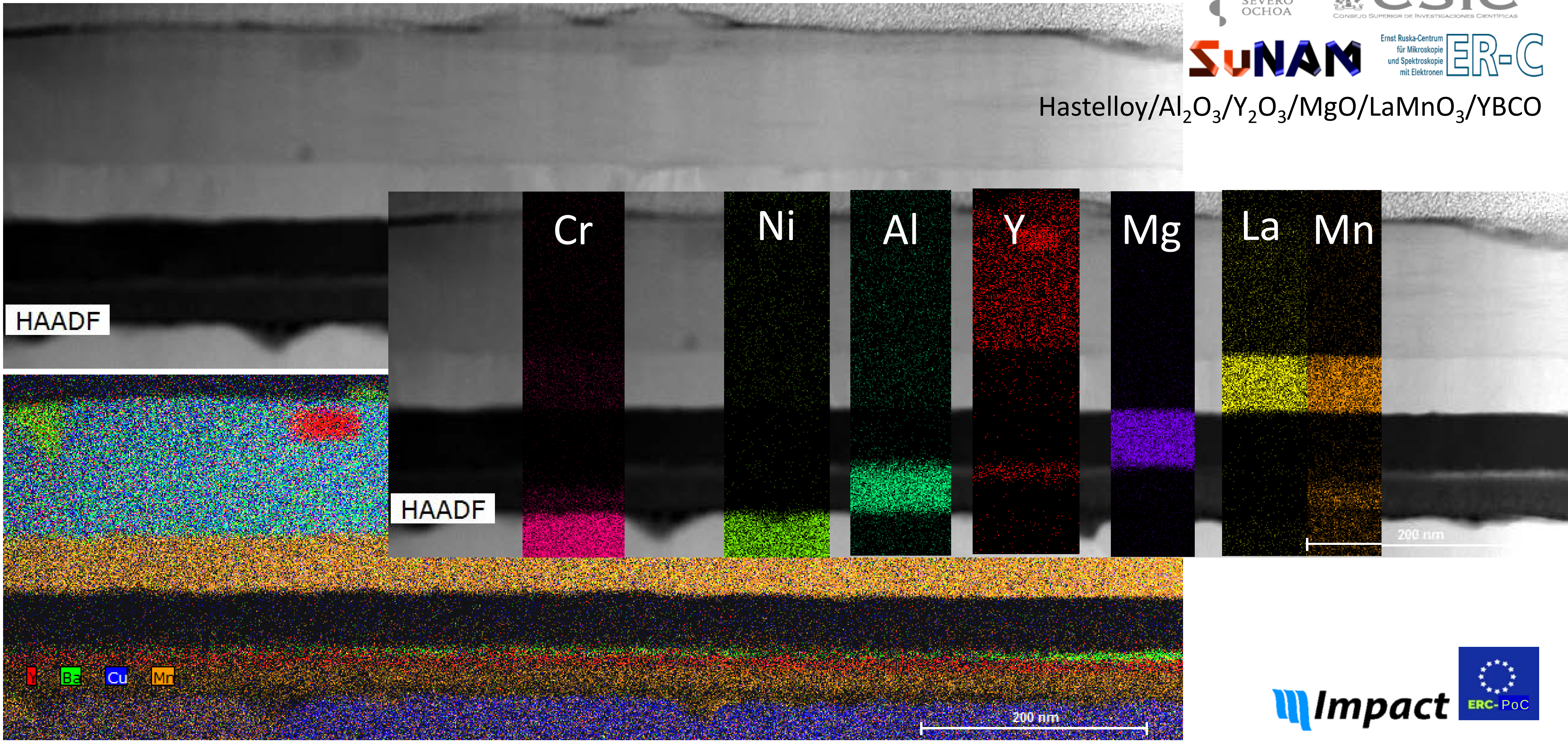
TLAG YBCO coated conductor

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

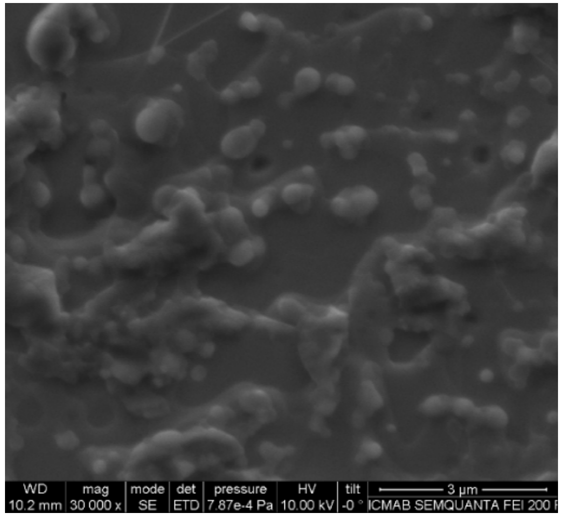
Hastelloy/Al_2O_3/Y_2O_3/MgO/$LaMnO_3$/YBCO

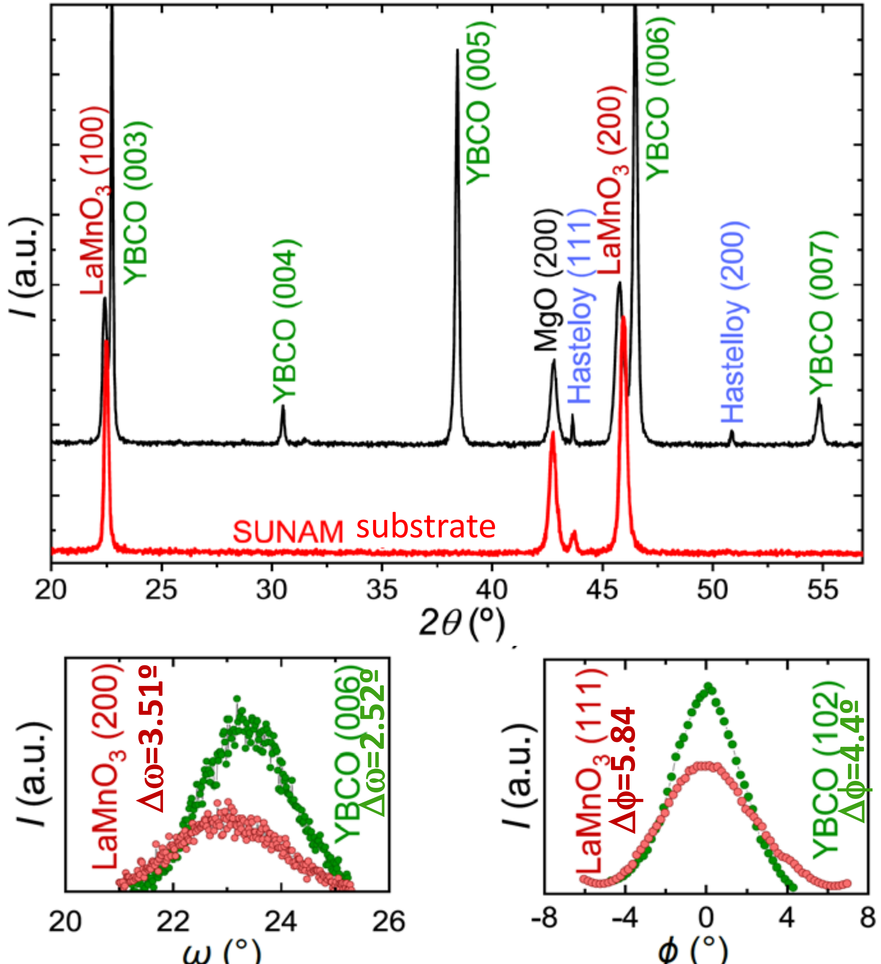


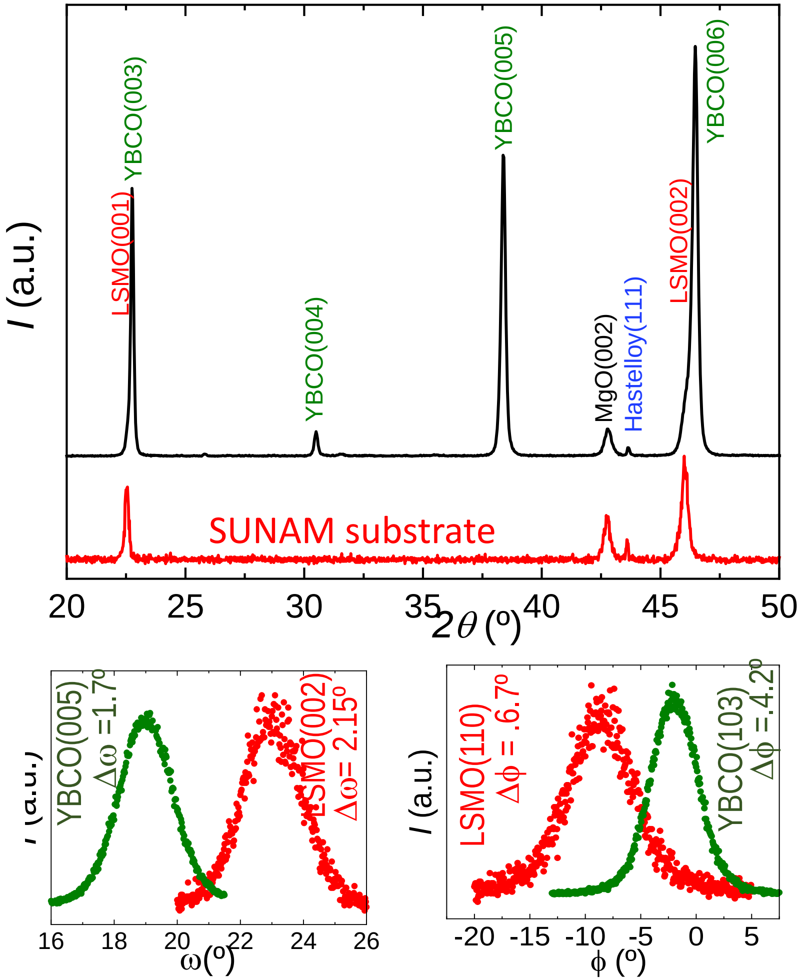
TLAG-CSD Coated Conductors

5 cm test samples of 1 µm thick homogeneous pyrolyzed YBCO deposited on SuNAM substrates

Liquid growth morphology, very high epitaxy and texture quality, with a noticeable improvement of texture of the YBCO layer







T_c =90 K

J_c (77K) = 0.5 MA/cm^2

J_c(5 K) = 6 MA/cm^2

Need to further reduce some secondary phases interrupting current percolation: tuning process conditions

Several different metallic substrates tested succesfully

CONCLUSIONS

Chemical Solution Depositon

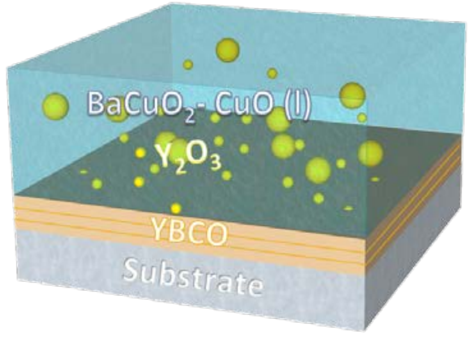
CSD-Transient liquid assisted growth

Liquid-assisted growth

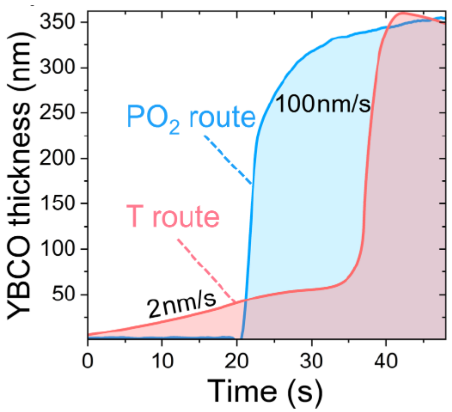
✓**Very fast growth rate**
✓Highly simplified reactor
✓More enviromentally friendly
✓Nanocomposites with PNs

✓**Large-scale**
✓**Low cost investment**
✓High deposition rates on large areas

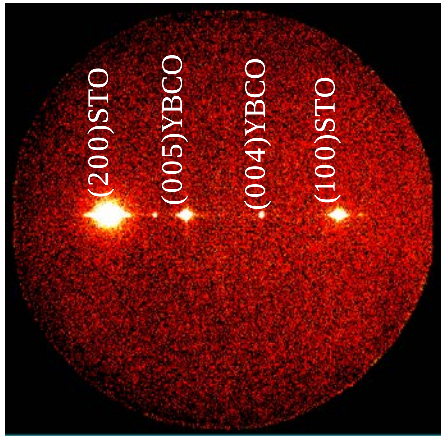
✓**Transient liquid phase achieved from metalorganic precursors**



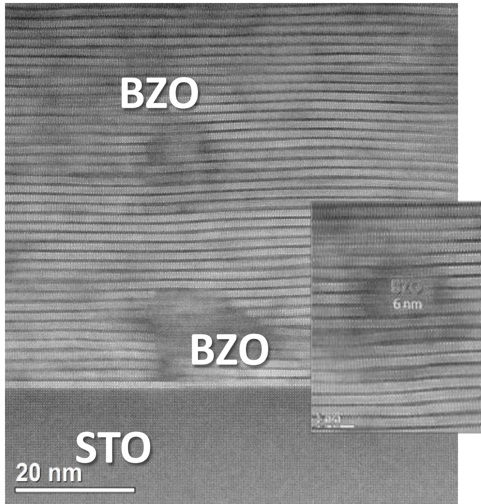
✓**Growth rate 100 nm/s**



✓**Nucleation control**



✓**Nanocomposites**



Conclusions

ICMAB

- Coated conductors are high tech materials: epitaxy at km length: **Chemical solution deposition** is a bottom-up, very versatile, low cost and scalable method to grow functional oxide epitaxial films, nanostructures and nanocomposites.

- CSD-TLAG is very promising to produce at **large scale superconducting conductors** (epitaxial multilayers on metallic substrates)

- CSD **nanocomposites** is a new class of functional materials with superior properties: vortex pinning and many other properties tuned by nanostrain can be precisely prepared.

- A novel CSD approach to YBCO nanocomposites has been developed based on **colloidal solutions** using preformed nanoparticles: a very promising approach

- We are very close to wide implementation of superconducting **power applications** and a new generation of high and ultra-high field **magnets**

A winning materials story of joint efforts

Materials **E**ngineers, **P**hysicists, **C**hemists, **E**lectrical **E**ngineers, **M**anufacturers: **The Superconducting Community**

ICMAB superconductivity team and collaborators

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

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