Overview on progress, challenges and frontier research of coated conductors for application

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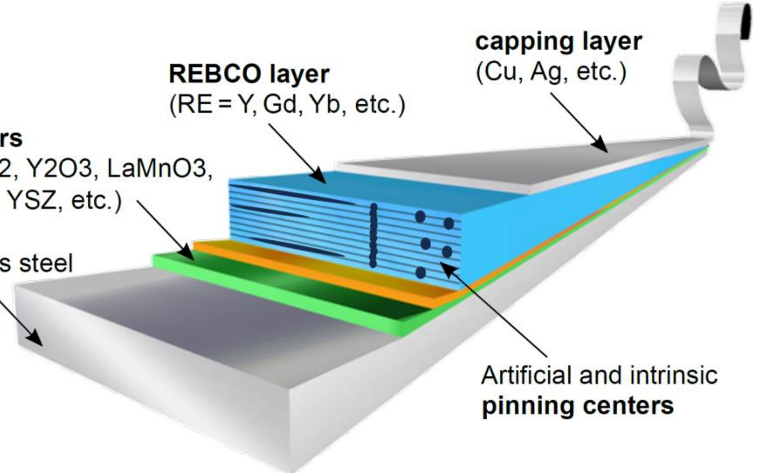

Work is supported by

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H. Lee, S. Moon, Sunam Co, Ltd
C. Cai, Shanghai Creative Superconductors Co, Ltd

… and entire Coated Conductor community

Outline

- Introduction
- Fundamental aspects of coated conductor (CC) processing: towards high growth rate
- Capacity for tuning vortex pinning landscape
- Applications driven relevant materials aspects
- Status at industrial scale, prospects and challenges
- Materials R&D challenges and initiatives
- Conclusions and take away message

MATERIALS: An enabling technology for the welfare society

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SUPERCONDUCTIVITY

CLIMATE CHANGE MITIGATION

CIRCULAR ECONOMY

CRITICAL MATERIALS MINIMIZATION USE

Successful healthcare
Cutting-Edge diagnosis systems & therapy treatments

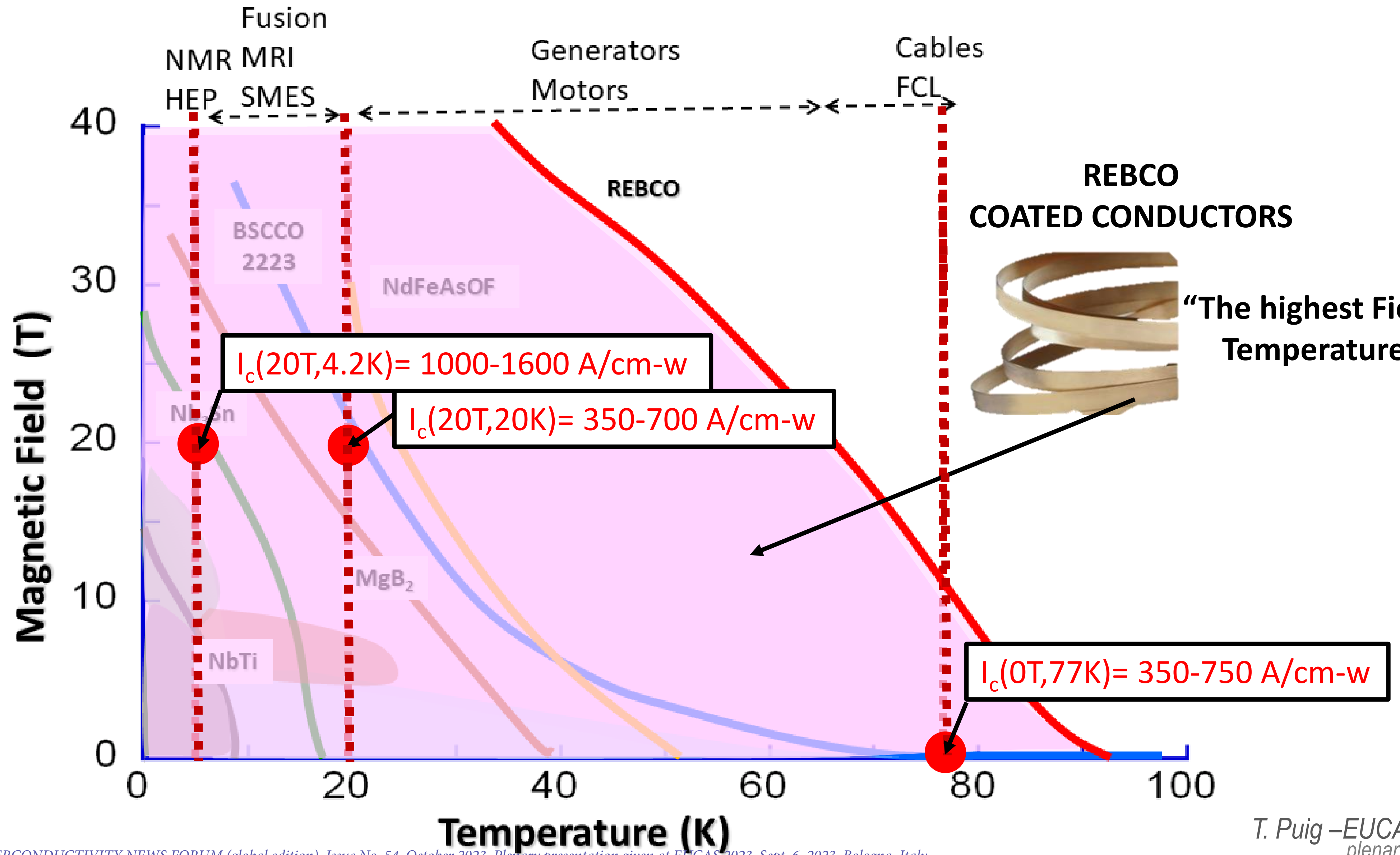
Energy transition
Electrical transportation
Industry 5.0

Smart electronics, communications & computing

Basic science at the frontier of knowledge

PLANET SUSTAINABILITY

SUPERCONDUCTING MATERIALS:
AT THE FRONTIER OF TECHNOLOGY



REBCO COATED CONDUCTORS

"The highest Field and highest Temperature conductor"

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 54, October 2023. Plenary presentation given at EUCAS 2023, Sept. 6, 2023, Bologna, Italy

MATERIALS SCIENCE

The prospects of high-temperature superconductors

Overcoming cost barriers could make high-temperature superconductors pervasive

By **Alexander Molodyk**[1] *and*
David C. Larbalestier[2]

"…the present outlook for high-temperature superconductor materials and their industrial applications is historic…"

Science, 380, 1220, 2023

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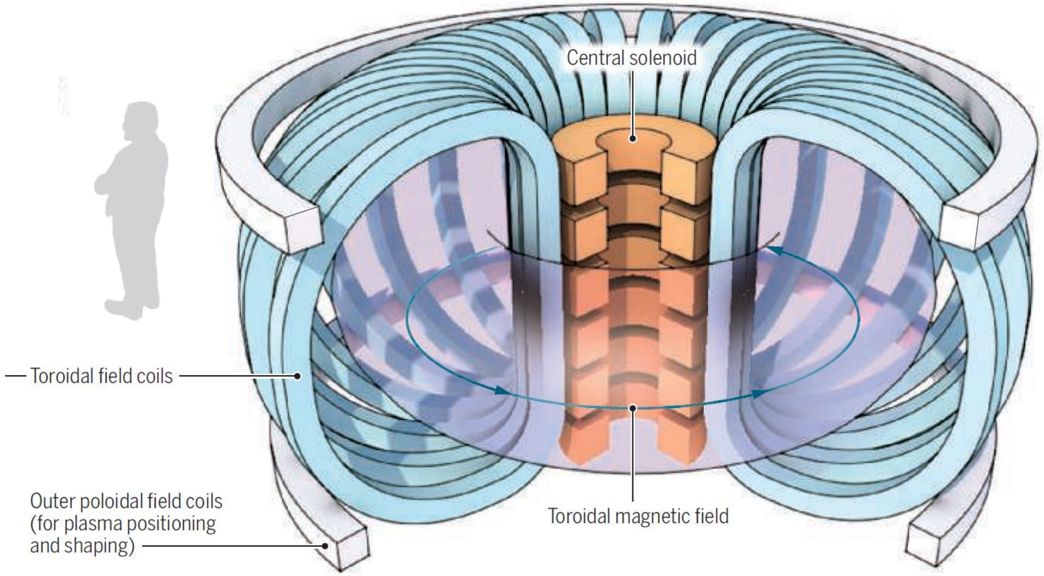
COMPACT FUSION



HTS-CC NMR is already a commercial device

High-field (25.9 T LTS+HTS) Bruker Analytical NMR

https://www.bruker.com

Strong pull for:

Electric aviation: Rotating machines

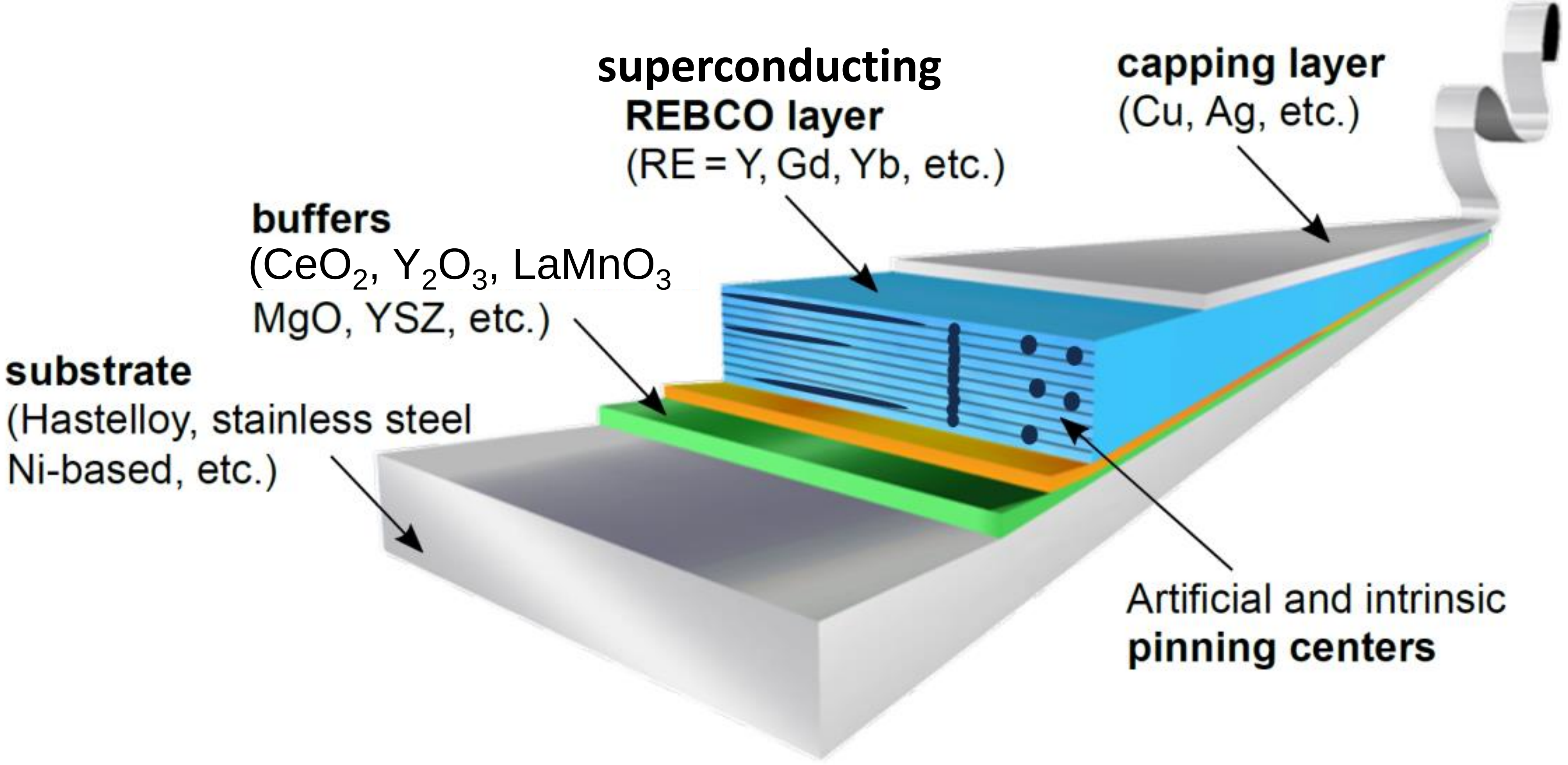
Smart grid: Power cables, FCL, SMES

https://www.theva.com/superlink
https://www.nkt.com
110 kV, 12 km, 500 MVA

Accelerator physics: Complex high field magnets operating at higher temperatures

Feather M2 HTS dipole accelerator magnet   L. Rossi, C. Senatore, Instruments 5(1), 8 (2021)

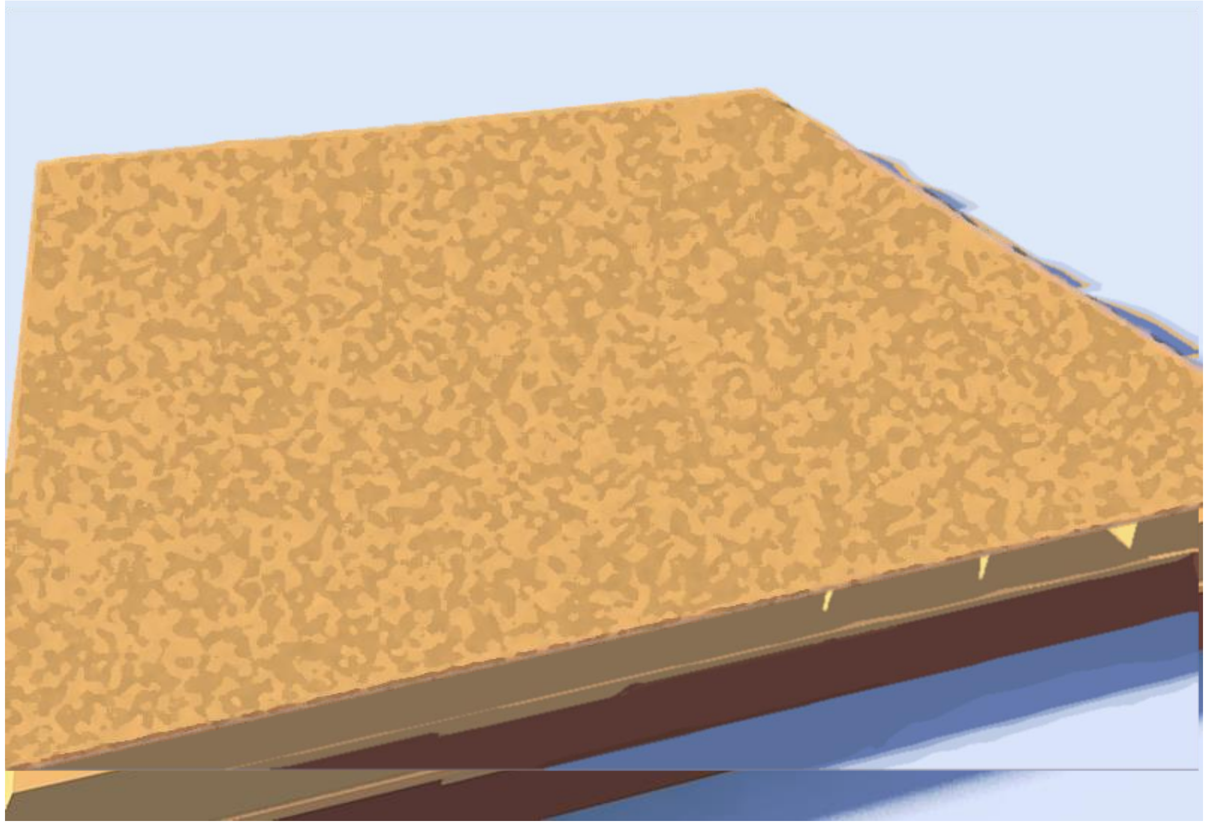
COATED CONDUCTOR, CC



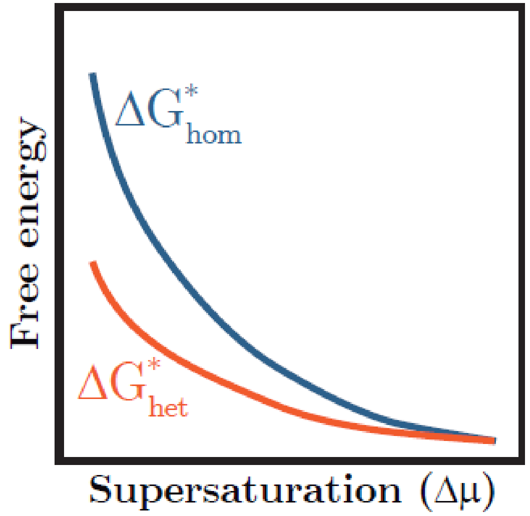
(Long length and thick) epitaxial superconducting layer on a multilayer flexible architecture

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 54, October 2023. Plenary presentation given at EUCAS 2023, Sept. 6, 2023, Bologna, Italy

Fundamental aspects of CC film growth

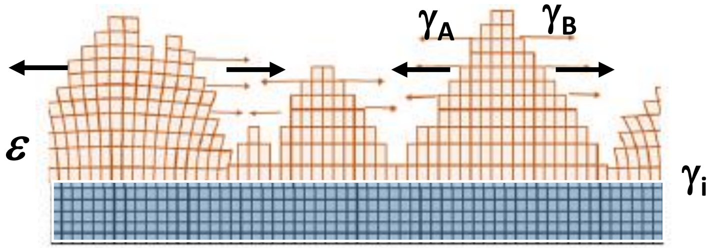


1. **Nucleation**
2. **Coarsening**
3. **Coalescence**
4. **Grain boundary zipping**
5. **Continuous film**



Nucleation rate

$$\dot{N} \propto \exp\left(-\frac{\Delta G^*}{k_B T}\right)$$



Surface energy: γ_A, γ_B
Interface energy: γ_i
Elastic strain energy: ε

X. Obradors, T. Puig, et al, Chem. Soc. Rev, 2014

REBCO growth processing

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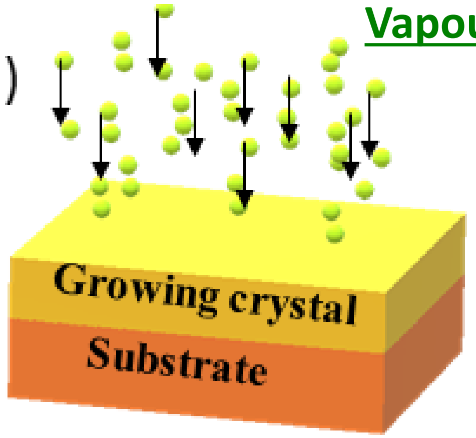
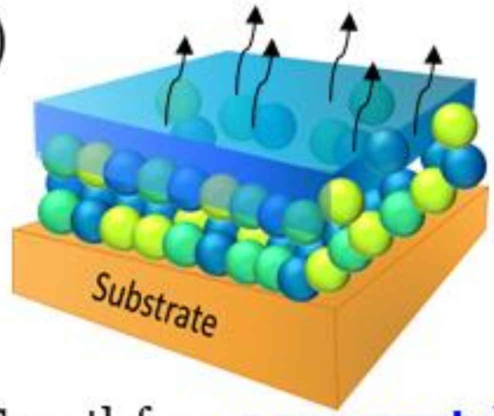
Vapour-solid transformation | **solid-solid gas mediated** | **Liquid-solid**

a)



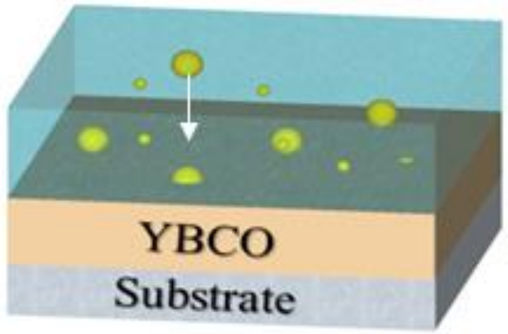
Growth from **vapour phase**
PLD, MOCVD, ME, MBE, Sputt

b)



Growth from **nanocrystalline solids**
TFA,-**MOD, BaF_2**

c)



Growth from **liquid phase**
TLAG-CSD, RCE-DR, HLPE , **VLS**

Supersaturation, σ, is the driving force for crystallization: **$\sigma \propto$ G** (growth rate)

$\sigma = (P_{ad} - P_{ad,e}) / P_{ad,e}$ Deposition rate
High vacuum environ.

$P_{ad,e}$ = ad-atoms equilibrium pressure at surface growth front
P_{ad} = ad-atoms pressure at surface growth front

$\sigma = f\,(\ln (P_{HF}^2 / P_{H2O}))$

P_{HF} = HF partial pressure
P_{H2O} = water partial pressure

$\sigma = (C_\delta - C_e) / C_e$ RE solubility,
Ba-Cu-O liquid

C_e = RE equilibrium concentration in the liquid
C_δ = RE actual concentration

Growth rate: **G= 0.5-25 nm/s** | **G= 0.5-5 nm/s** | **G=10-1000 nm/s**

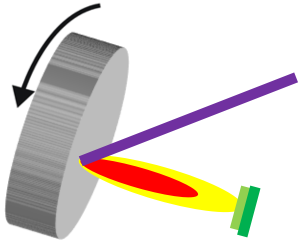
T. Puig et al, Nat Rev Phys (2023, accepted), J. Driscoll et al, Nat Rev Mat (2021)

Transient Liquid Assisted Growth (TLAG)

A new high throughput non-equilibrium kinetically controlled growth process

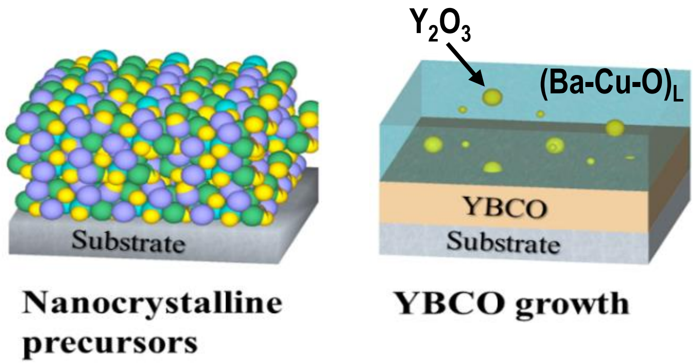
CSD

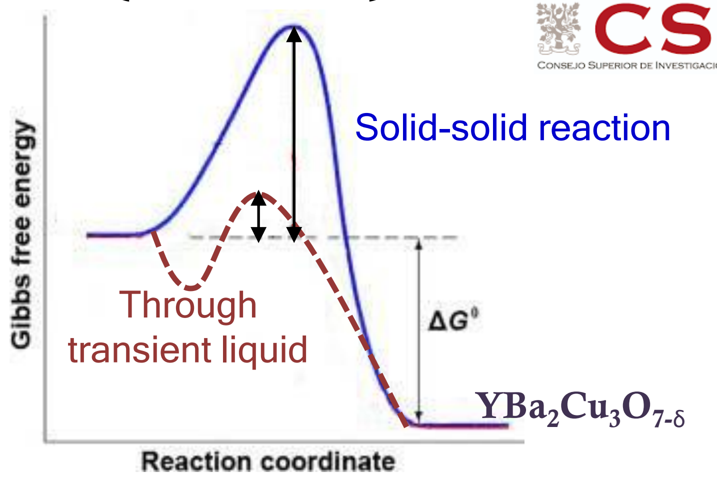
L. Saltarelli et al, ACS Appl. Mat. & Interf. (2022)



Low Temp PLD

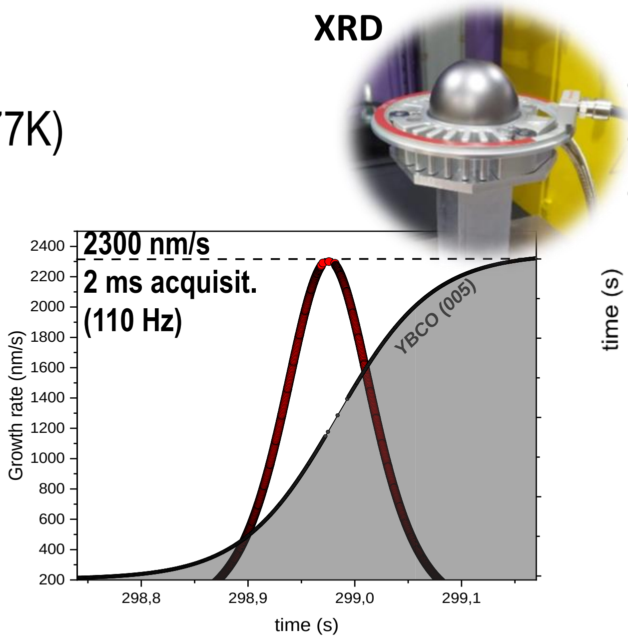
A. Quetalto et al, SUST (2023)

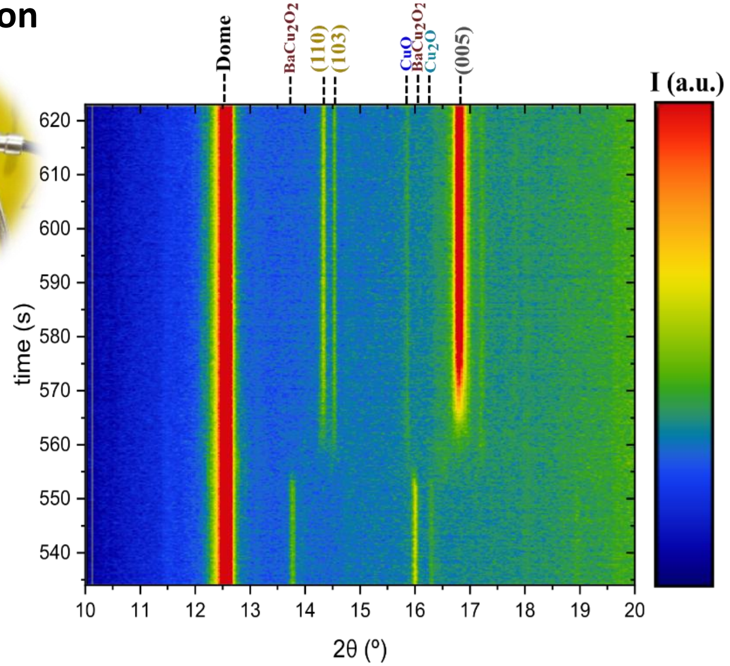




- High performance (3 MA/cm^2 at 77K)
- High throughput
- Simple reactor
- Large area processing
- Low cost/performance method

In-situ synchrotron XRD





100 nm/s by **ultrafast-PLD** EuBCO/BHO (transient liquid growth at high T PLD)

Y. Wu, Materials & Design 224 (2022)

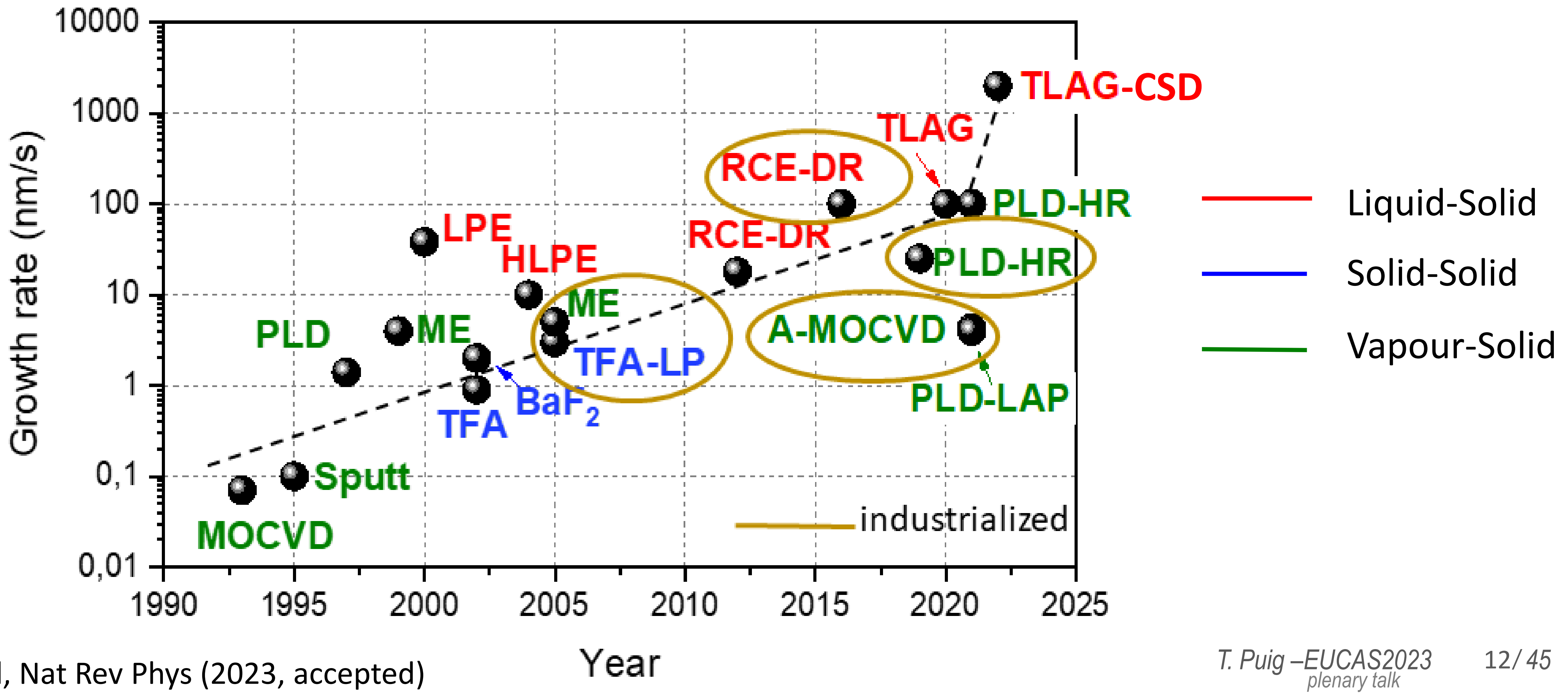
L. Soler et al., Nat Comm (2020), S. Rasi, et al, Advance Science (2022)

T. Puig –EUCAS2023 plenary talk

Reaching high Growth Rate: A path towards cost reduction

Figure of merit: $$\frac{Cost}{Perfomance} = \frac{total\ cost\ per\ year}{G\ x\ L\ x\ W\ x\ (I_{c-w}/d)} = \frac{€}{kA\ x\ m}$$

W= tape width
L= tape length
d=tape thickness



T. Puig et al, Nat Rev Phys (2023, accepted)

Materials processing challenges

to decrease cost/performance ratio

	PLD	MOCVD	ME	TFA-CSD	RCE-DR	TLAG-CSD
High performance						
High homogeneity in long length						To demonstrate
Large area processing						
High thickness (> 3 µm)						To demonstrate
High growth rate						
Low cost equipment						
High manufacturing yield						To demonstrate

Different growth methods have adopted different approaches to achieve competitiveness

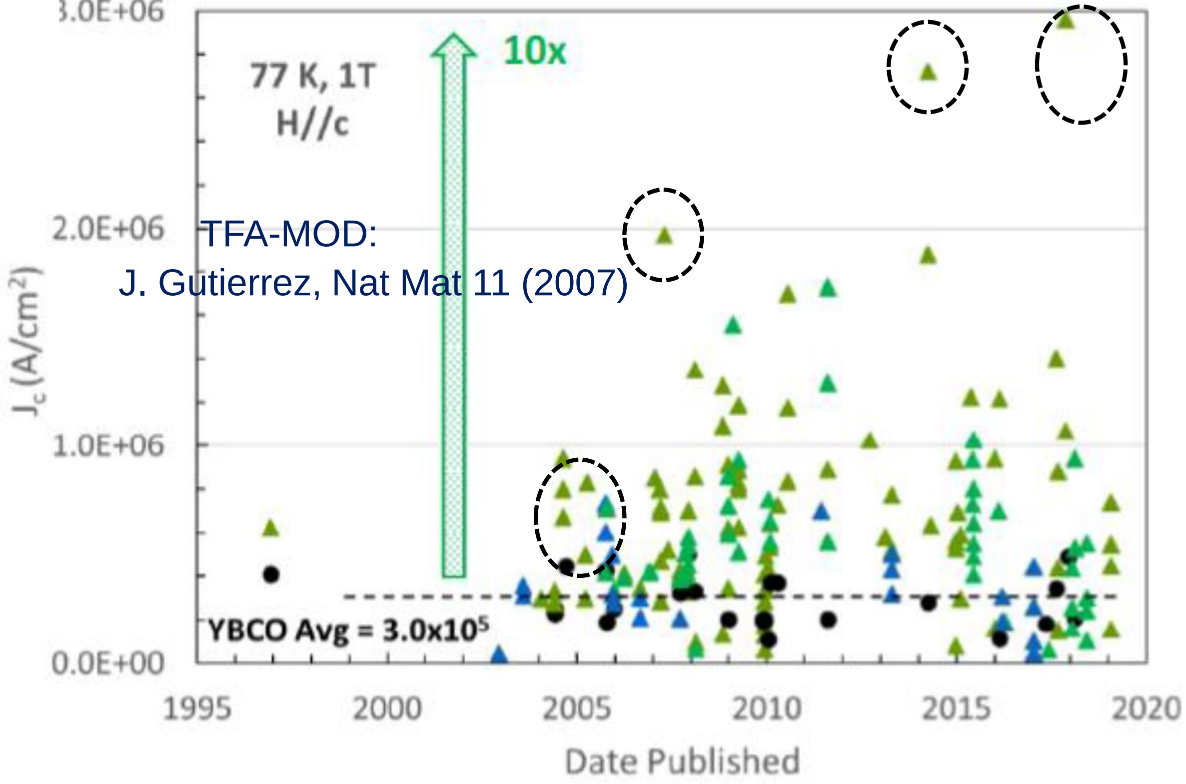
Flux pinning progress J_c(77K, 1T, 5T), 1995 to 2020

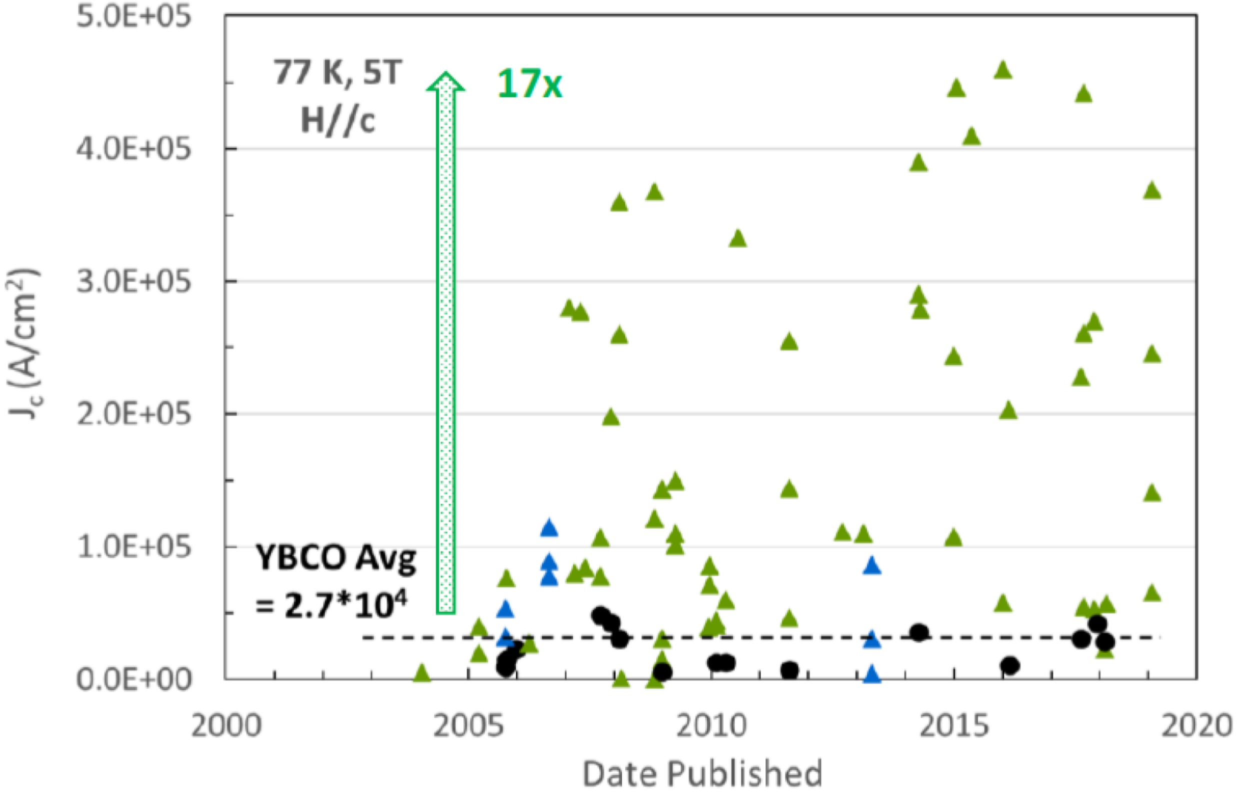
Historical progress of APC
(from 87 top papers)

PLD: A. Tsuruta, SUST 27 (2014)

TFA-MOD:
Miura, NPG Asia Materials (2017)

TFA-MOD:
J. Gutierrez, Nat Mat 11 (2007)





PLD: J. Driscoll, Nat. Mat. 3 (2004)
T. Haugan, Nature 430 (2004)
Y. Yamada, APL 87 (2005)
S. Kang, Science 311 (2006)

Courtesy from Timothy J. Haugan, AFRL

Capacity for tuning vortex pinning depends on type of defect, size, chemical composition, orientation, strength and dimensionality

$$F_L = J_c \times B = F_p \qquad F_p = \sum_{i}^{N_p} f_{p,i}(B,T) \qquad f_p = Up/\xi$$

$$S = -\frac{d(lnJ)}{d(lnt)}$$

Vortex creep effects at high T

S. Eley et al, Nat Mat 16 (2017)

Time-dependent Ginzburg-Landau simulations for visualizing pinned states of quantized vortices by nanorods or nanoparticles

Simulated by Kaname Matsumoto, Aug. 20, 2023

Kyushu Institute of Technology
TOBATA | IIZUKA | WAKAMATSU

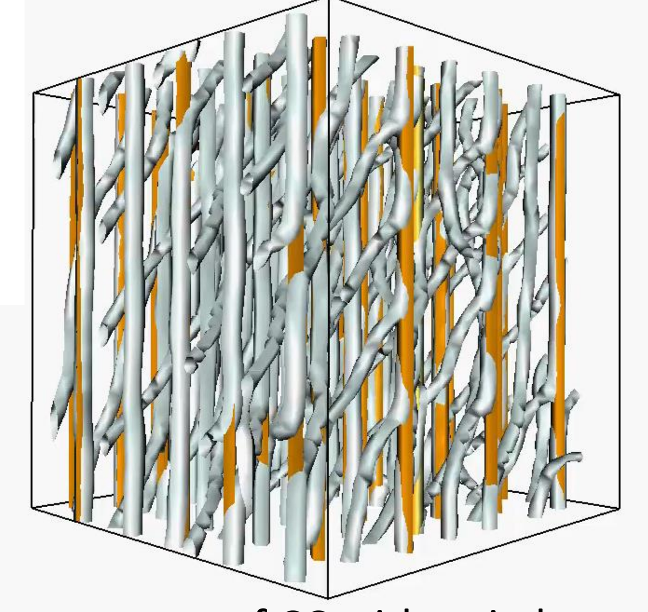
Tc = 90 K
Temp = 10 K
B ~ 12 T
Θ = 30 deg.

ξ_0 = 1.5 nm
GL κ > 100
Anisotropy parameter = 7

120 nm × 120 nm × 120 nm

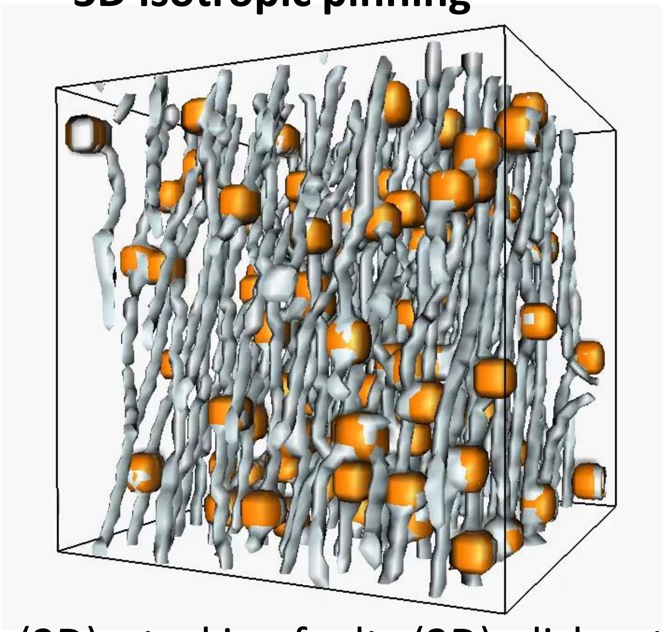
Nanorod diameter ~ 6 nm
Volume fraction ~ 2.5 %

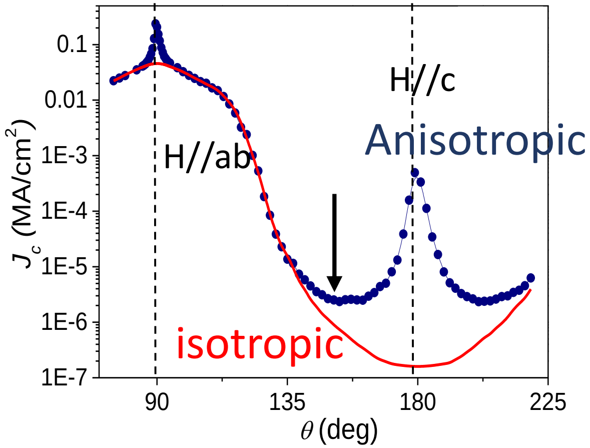
1D anisotropic pinning



Nanoparticle diameter ~10 nm
Volume fraction ~ 2.5 %

3D isotropic pinning





The complex microstructure of CC with twin boundaries (2D), stacking faults (2D), dislocations (1D), nanostrain (3D), oxygen vacancies (0D), and APC defines $J_c(\theta, H, T)$

R. Willa et al , SUST 31 (2018), I.A. Sadovskyy et al, PNAS 116 (2019), F. Valles, Comm Mat 3 (2022)

Nanocomposites: The best Artificial Pinning Centres

See SUST Special issue on APC 2018

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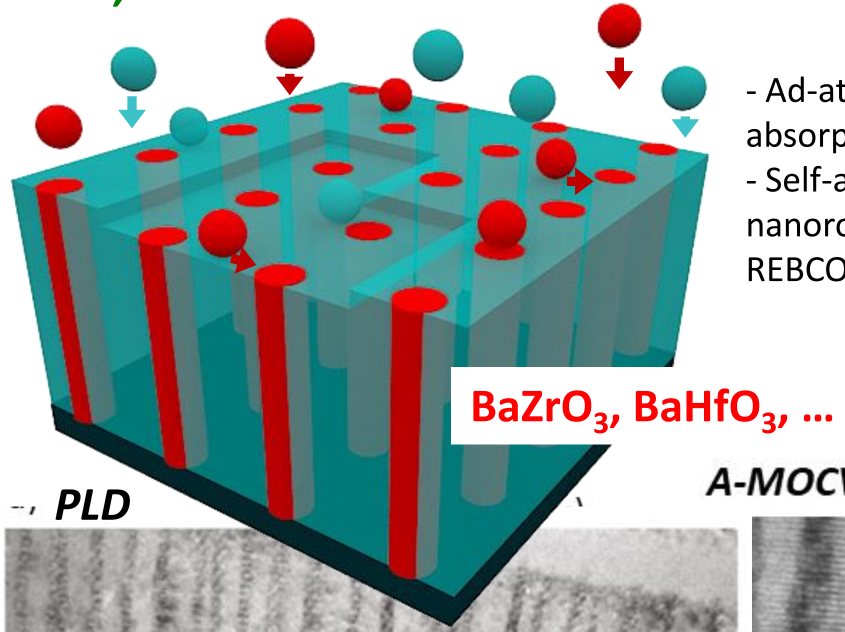
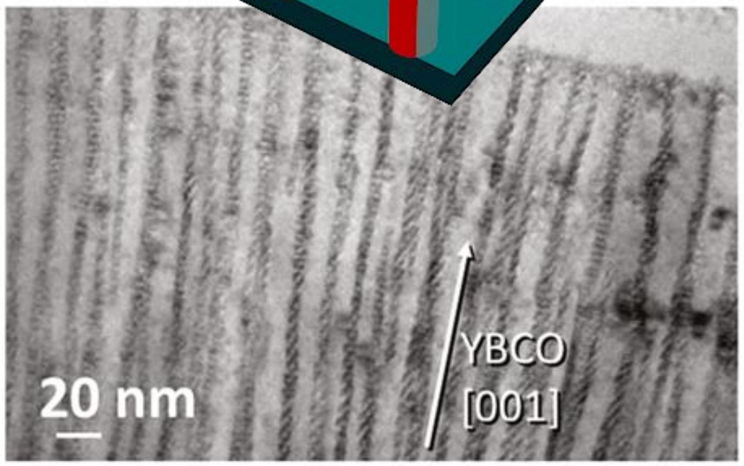
Simultaneous nanocomposite growth method

PLD, MOCVD



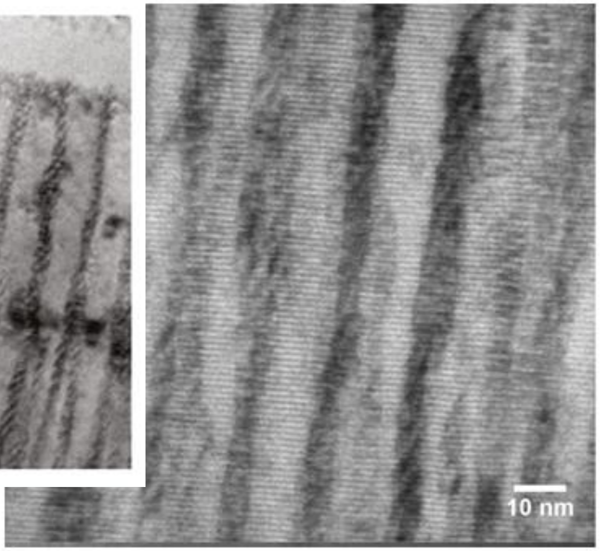
- Ad-atoms deposition, absorption, surface diffusion
- Self-assembly of epitaxial nanorods while epitaxial REBCO growth

PLD



C. Cantoni et al , ACSNano (2011)

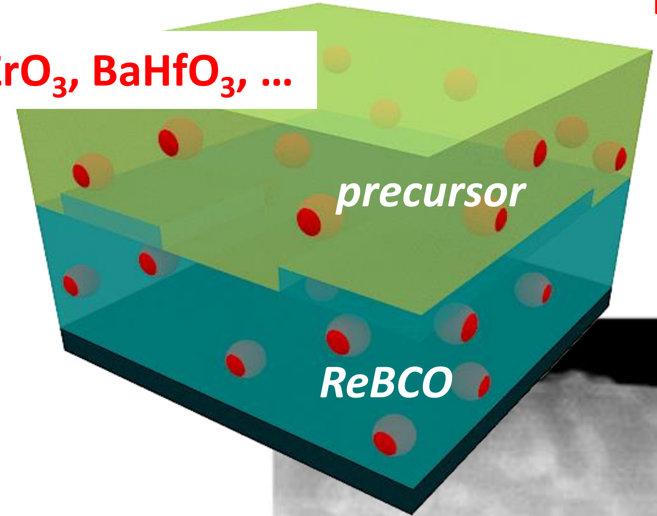
A-MOCVD



Majkic, G. *et al*. *SUST* **33** (2020)

Sequential nanocomposite growth method

TFA-MOD, RCE-DR, TLAG-CSD

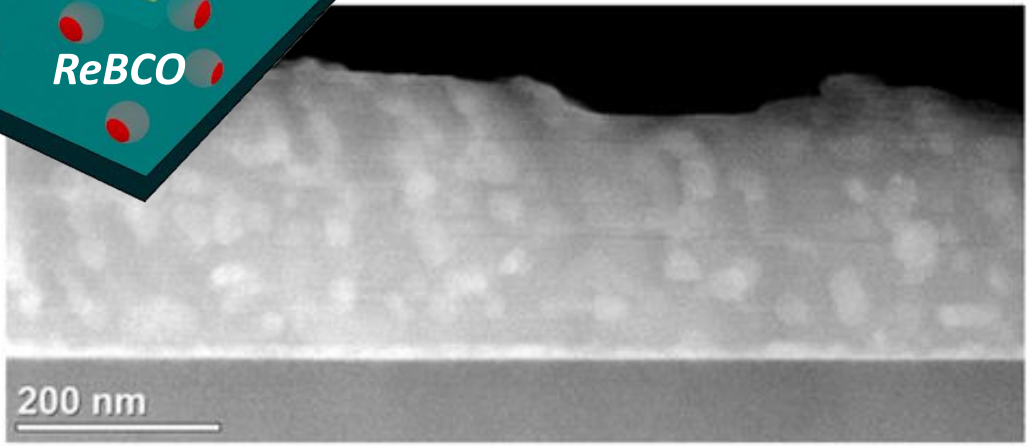


-Precursor deposition

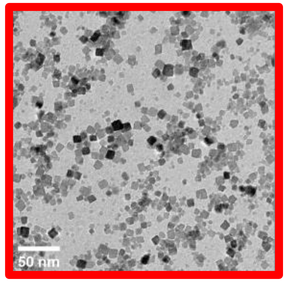
-Np are spontaneously segregated or pre-formed

-ReBCO epitaxial growth traps random Np

TFA-MOD



A. Llordes, Nat Mat (2012)

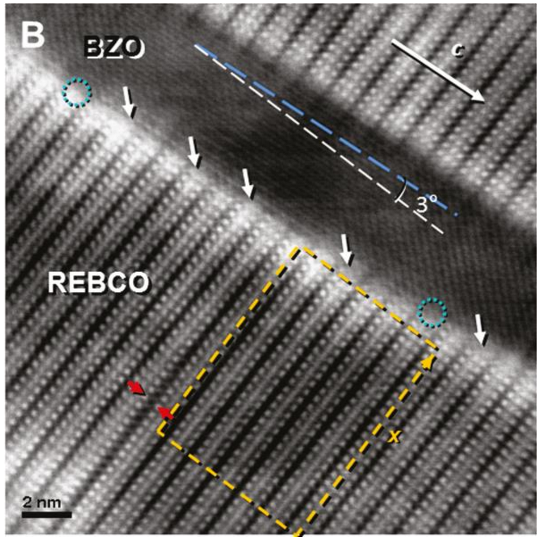


Pre-formed Np with a fine control of size, composition

N. Chamorro, RSC Adv. (2020)

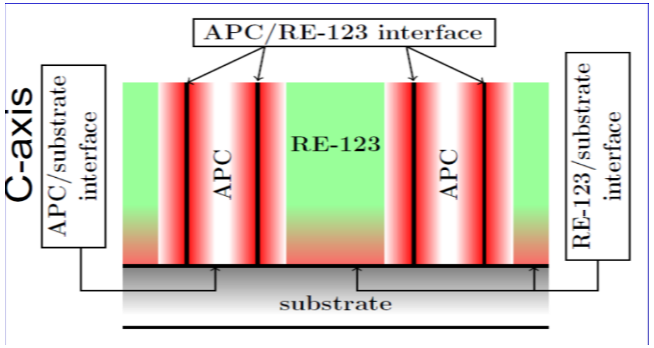
Simultaneous growth of Nanocomposites
Low versus high growth rate

Grown at 0.6 nm/s



C. Cantoni et al , ACSNano 2011

Elastic Strain energy model

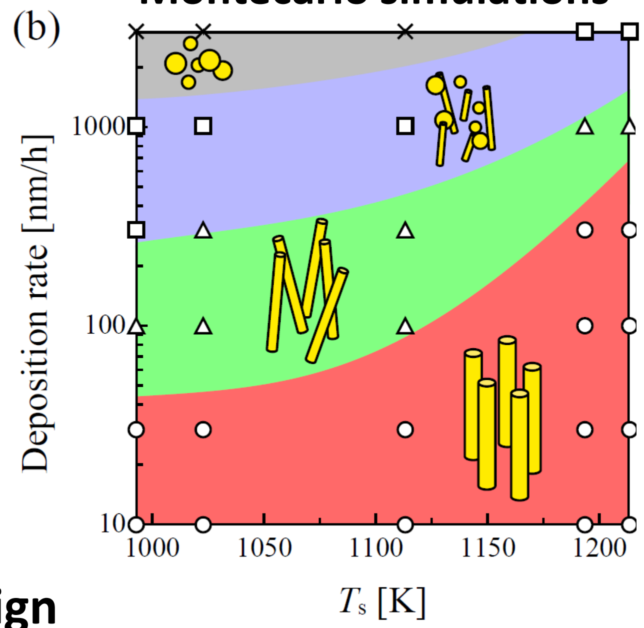


Wu, et al, SUST 30 (2017)

Engineering landscape by design

High growth rates (10-50 nm/s)

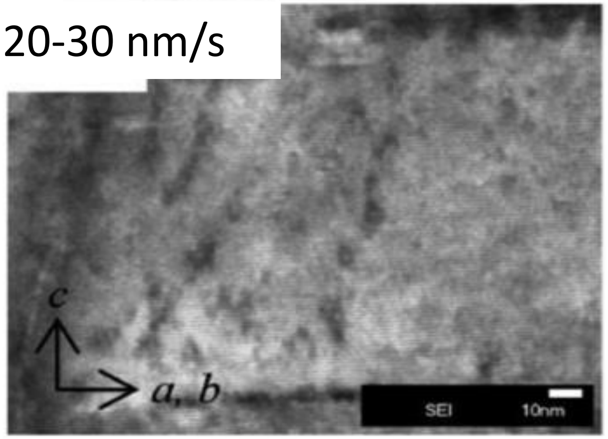
Montecarlo simulations



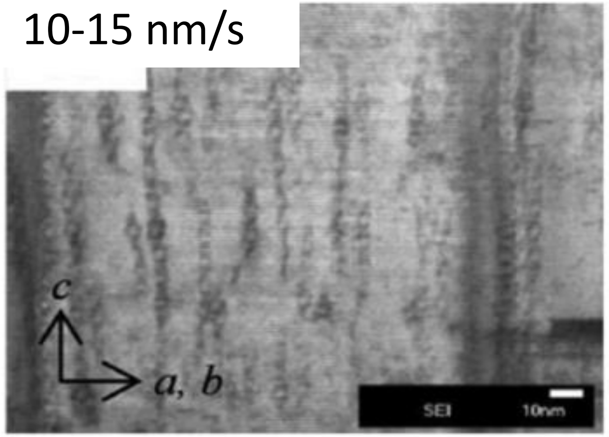
Y Ichino et al J.JAP 56 (2017)

EuBCO + $HfBaO_3$ nanorods

20-30 nm/s

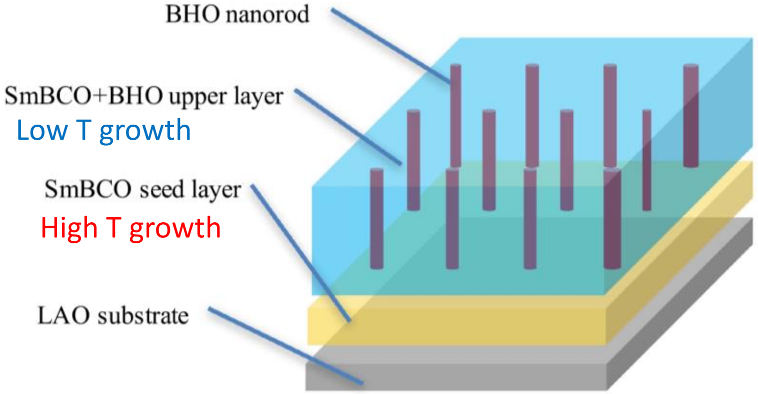


10-15 nm/s



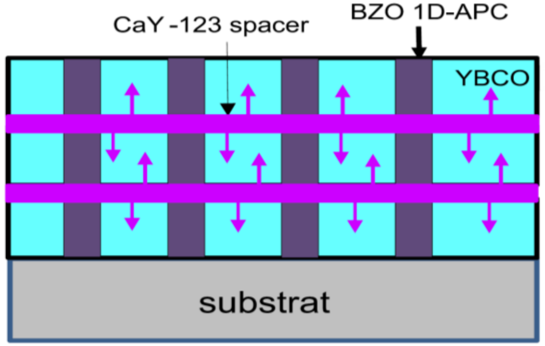
Fujita, S. et al. IEEE TAS 29 (2019)

LTG – PLD method



Y. Yoshida et al, SUST 30 (2017)

dynamic control of nanorod / YBCO interface



Wu, et al, SUST 35 (2022)

Vortex pinning consequences at high growth rate: PLD-HR

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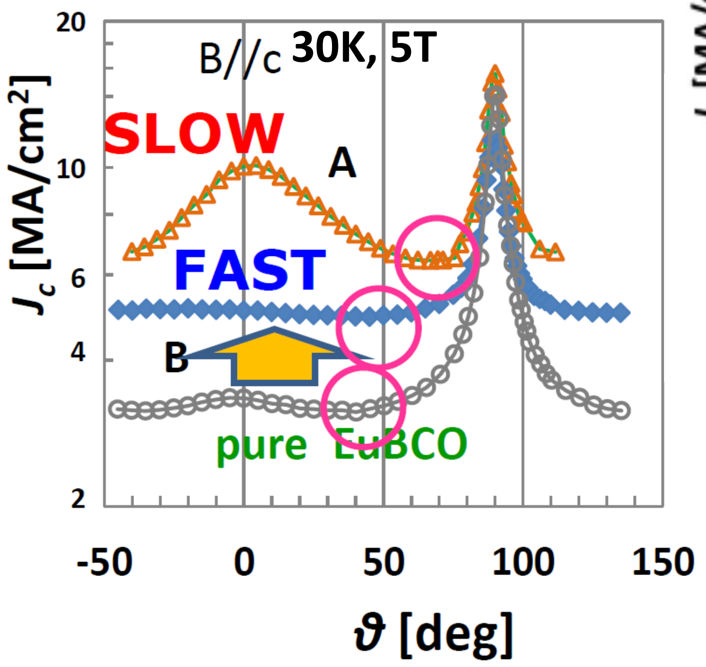
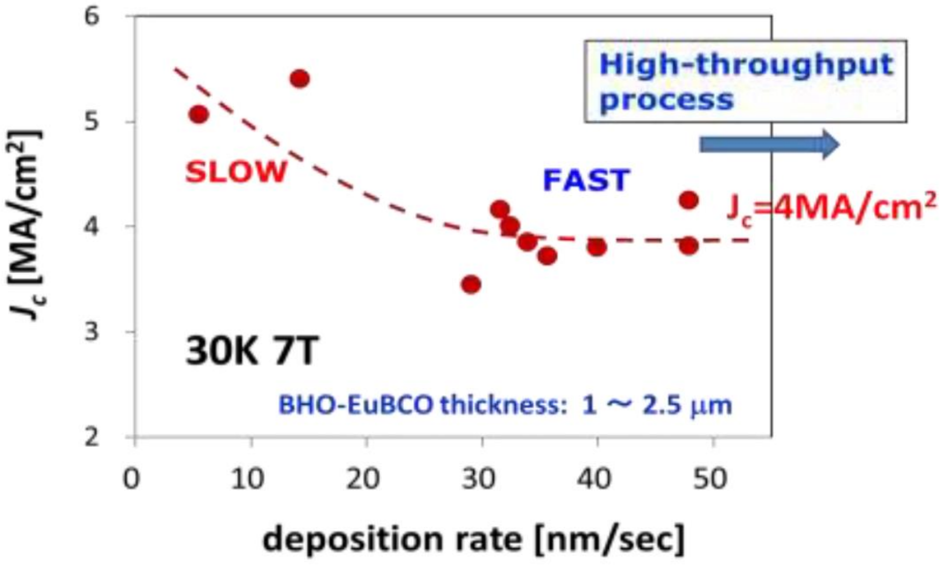
"Tsunagu" Technology Fujikura

EuBCO + $HfBaO_3$ nanorods

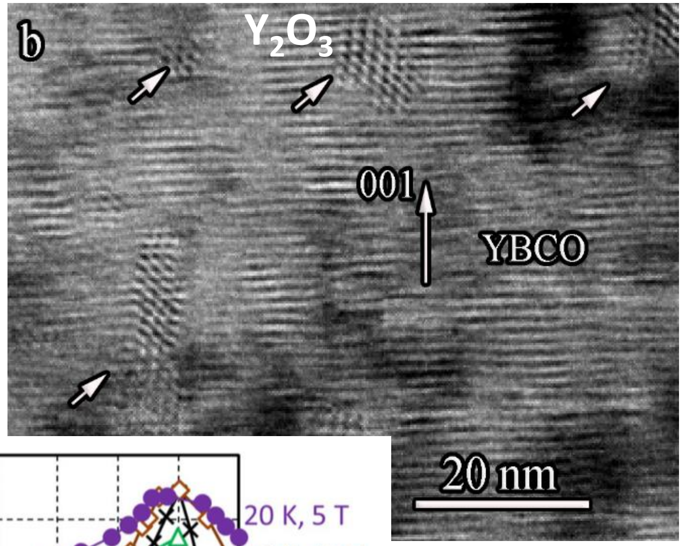


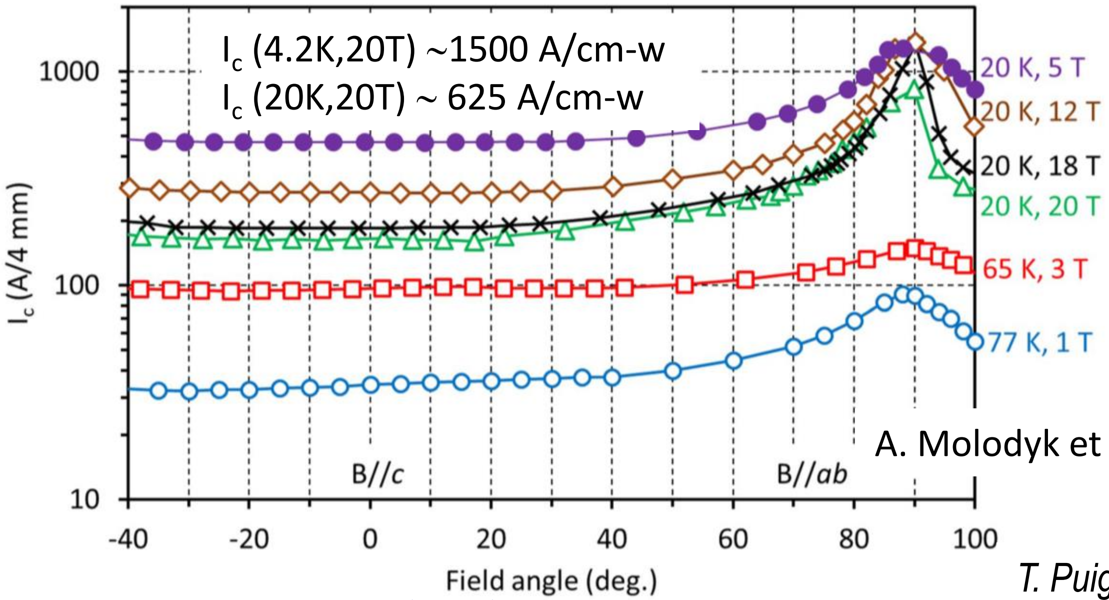
Y. Iijima, CCA 2023



FARADAY FACTORY JAPAN

YBCO + Y_2O_3 nanoparticles





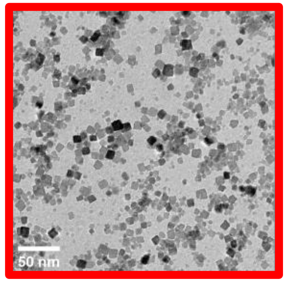
A. Molodyk et al, Sci. Rep 11 (2021)

Aligned long nanorods are not essential at low T - high H

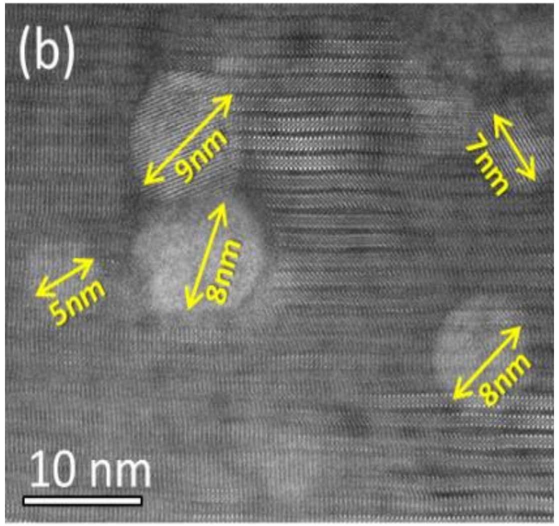
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 54, October 2023. Plenary presentation given at EUCAS 2023, Sept. 6, 2023, Bologna, Italy

Sequential growth of Nanocomposites at high growth rate: TFA vs TLAG

TFA-MOD (0.5-1 nm/s)



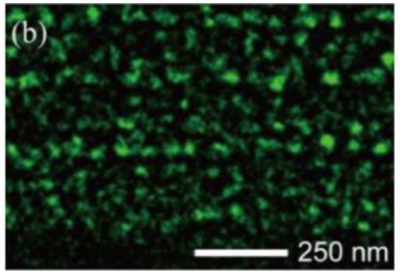
Fast heating with preformed Np

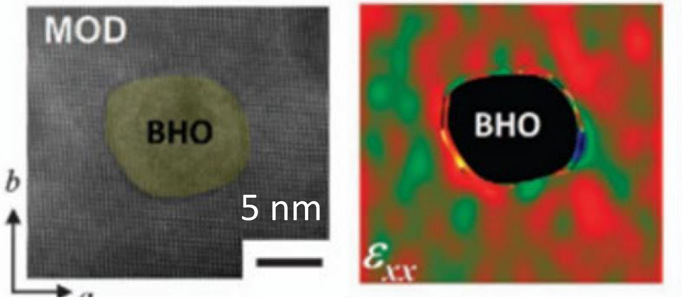


Small randomly oriented Np are obtained

Z.Li et al, Sci. Rep 9 (2019)

J_c (77K, sf)~ 5 MA/cm^2



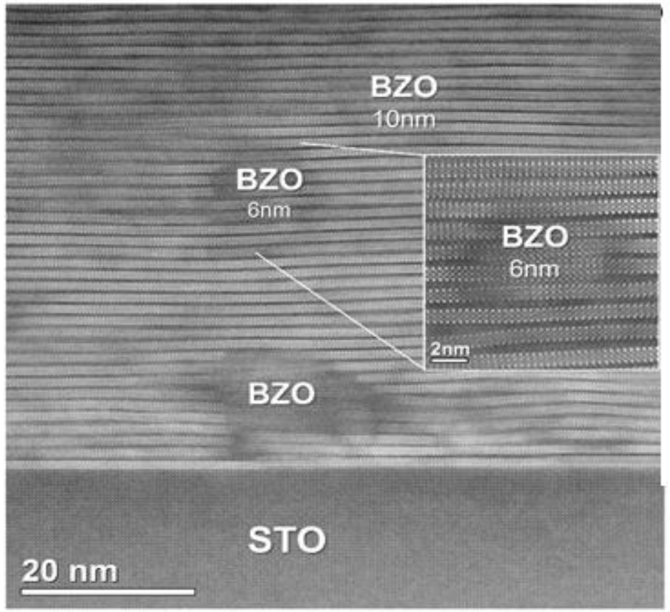


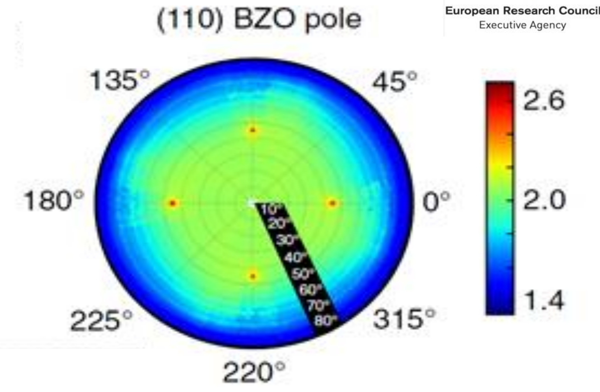
UTOC: ultrathin multicoating to avoid Np coarsening

J_c (77K, sf)~ 5.5 MA/cm^2
J_c (26K, 6T)~ 11 MA/cm^2

T. Izumi, K. Nakaoka, SUST., 31 (2018)
M. Miura et al, NPG Asia Materials 9 (2017)

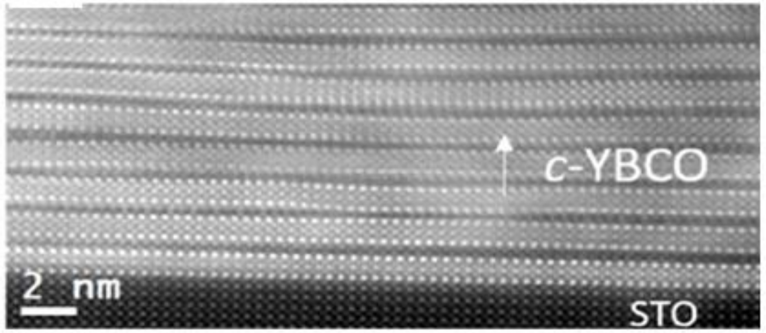
TLAG-CSD (50-2000 nm/s)





Small epitaxial oriented Np and high defect density are reached

Pristine YBCO film



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

Vortex pinning consequences at high growth rate: TLAG-CSD

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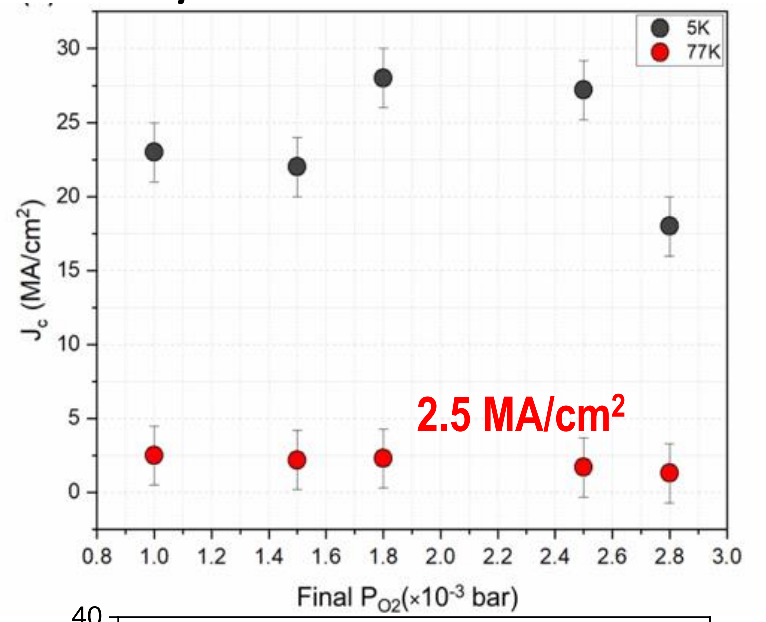
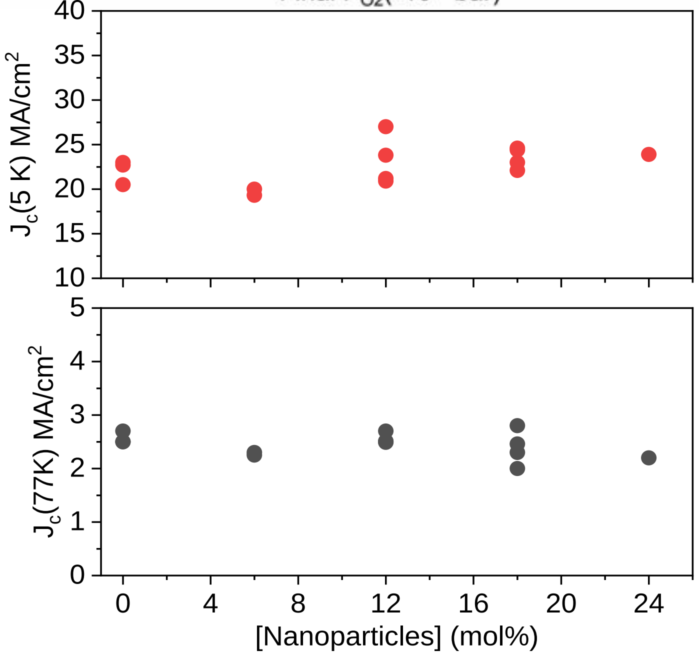
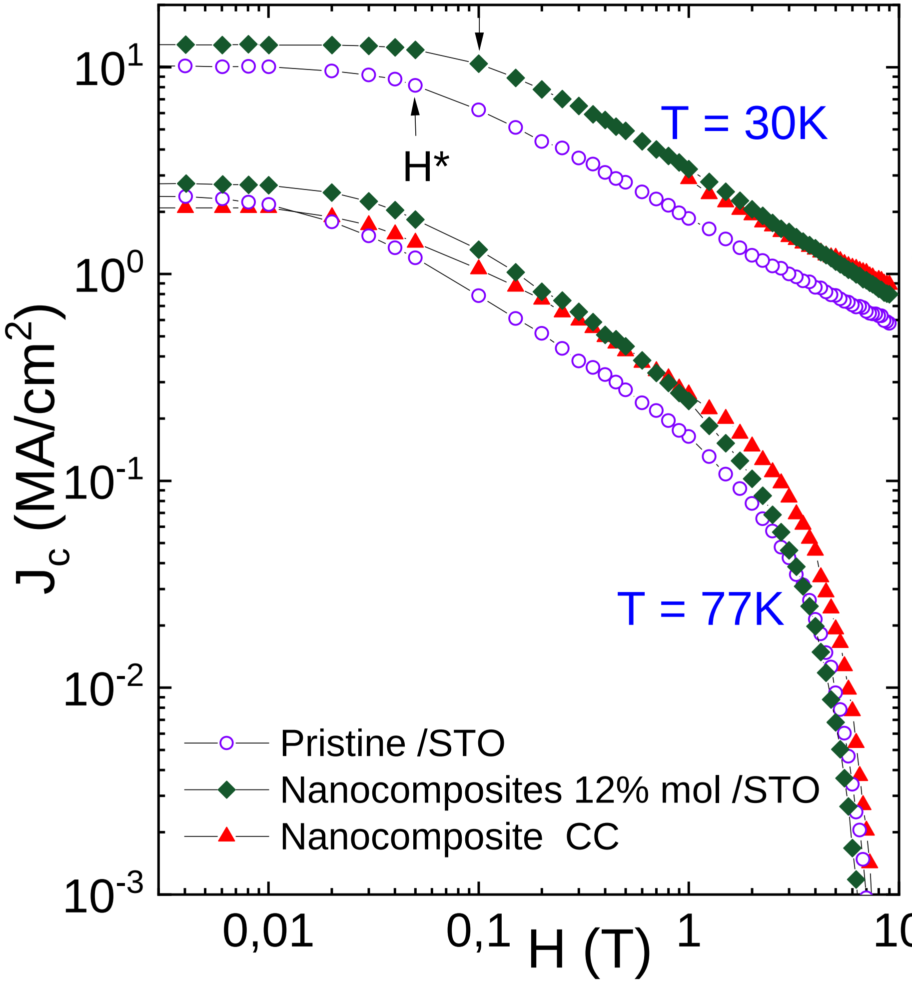
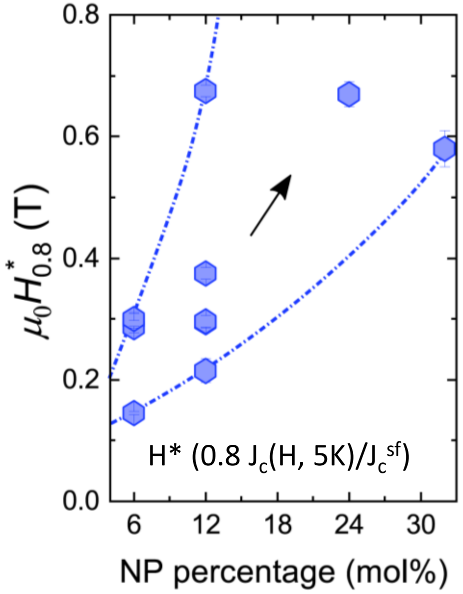
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
erc European Research Council Executive Agency
SUMITOMO ELECTRIC

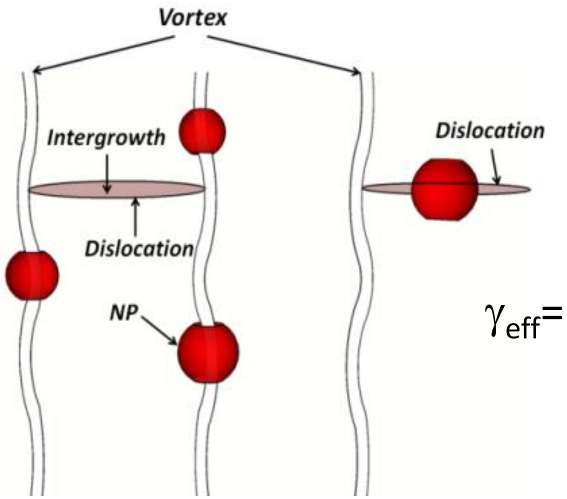
50 nm/s → 1500 nm/s









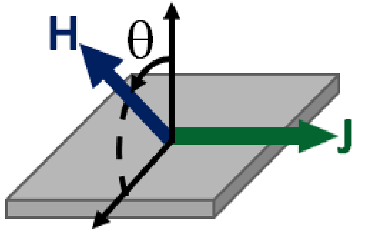


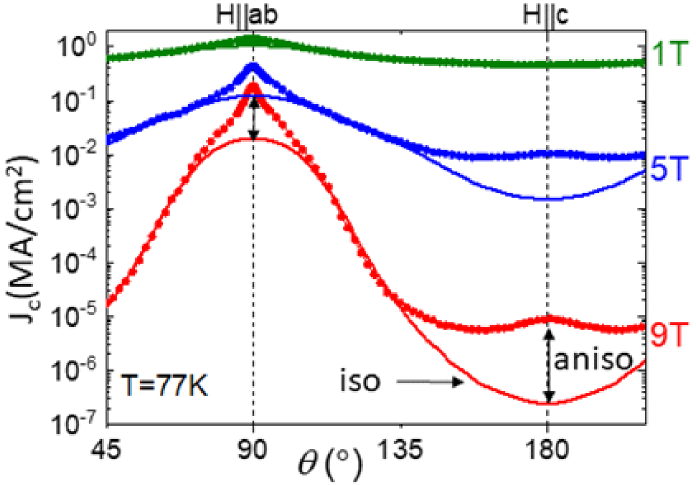
γ_{eff}= 2-2.5

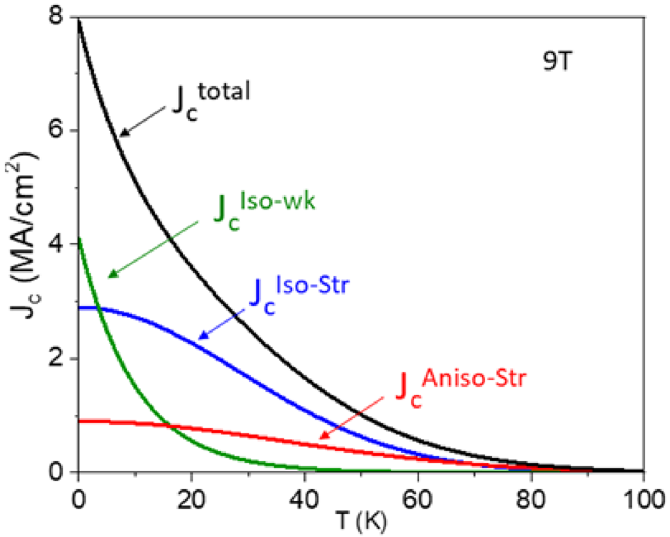
Rich vortex pinning determined by the defect microstructure of high growth rates

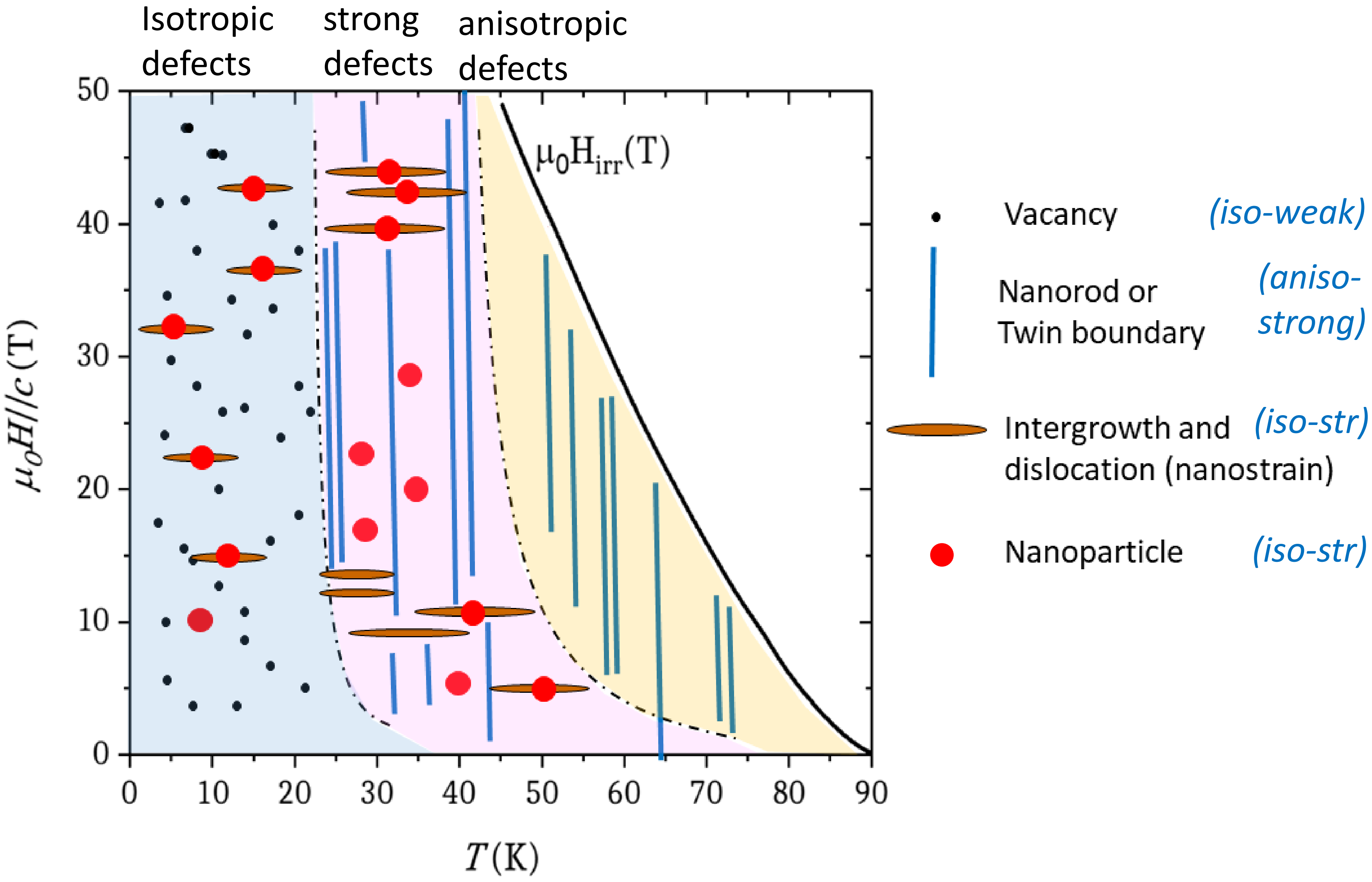
L. Soler et al., Nat Comm (2020), S. Rasi, et al, Advance Science (2022)

Vortex pinning landscape of CC, $J_c(\theta, H, T)$









F. Valles et al, Comm Mat 3(2022) T. Puig et al, Nat Rev Phys (2023, accepted)

$J_c(n_H, T, H)$ in the Overdoped state: where Condensation energy and charge carrier density increases

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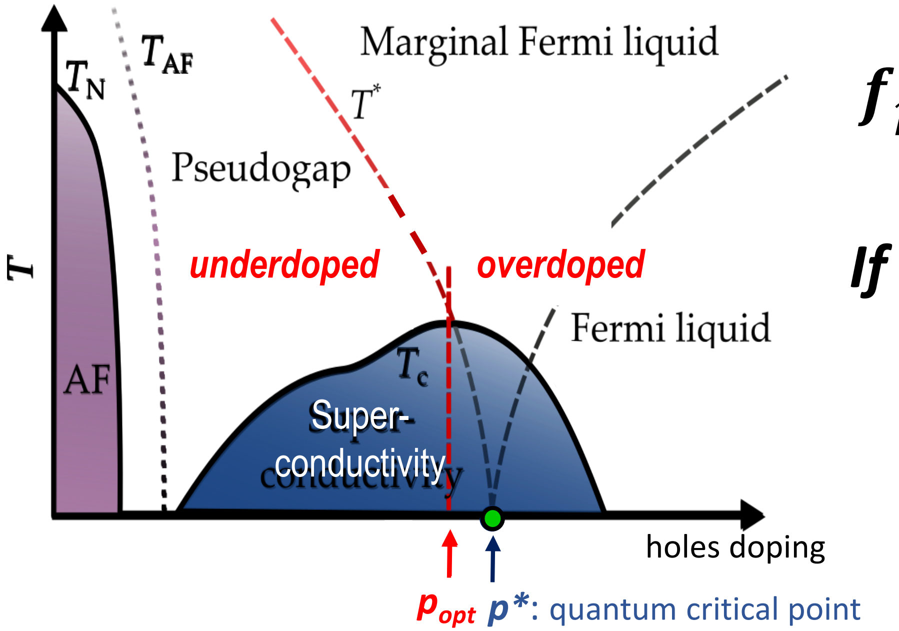
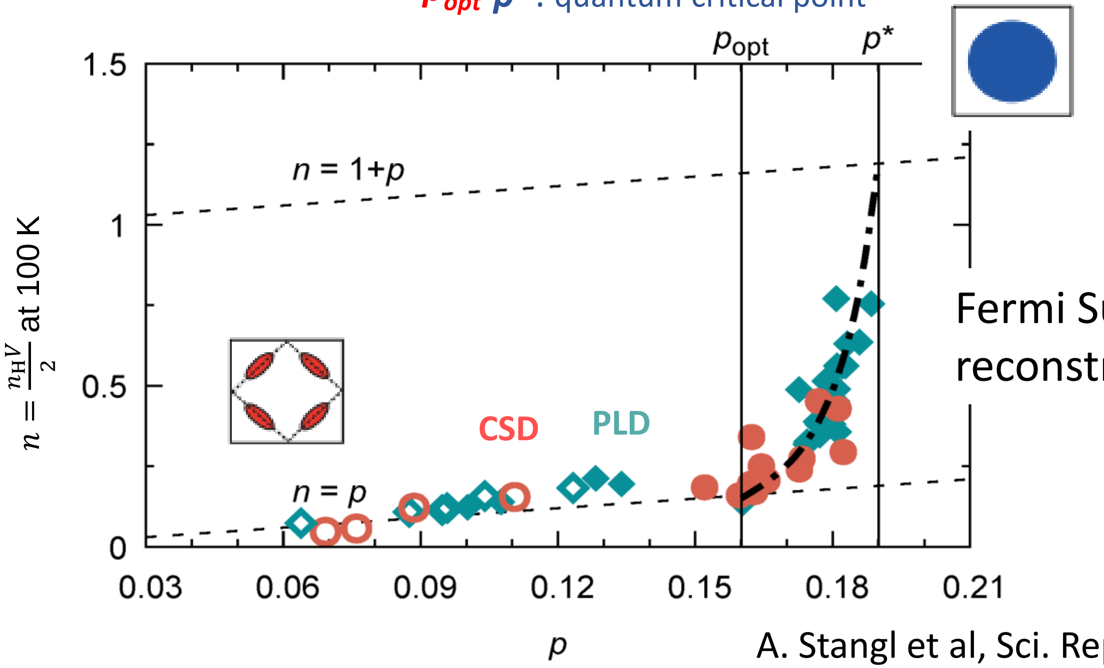


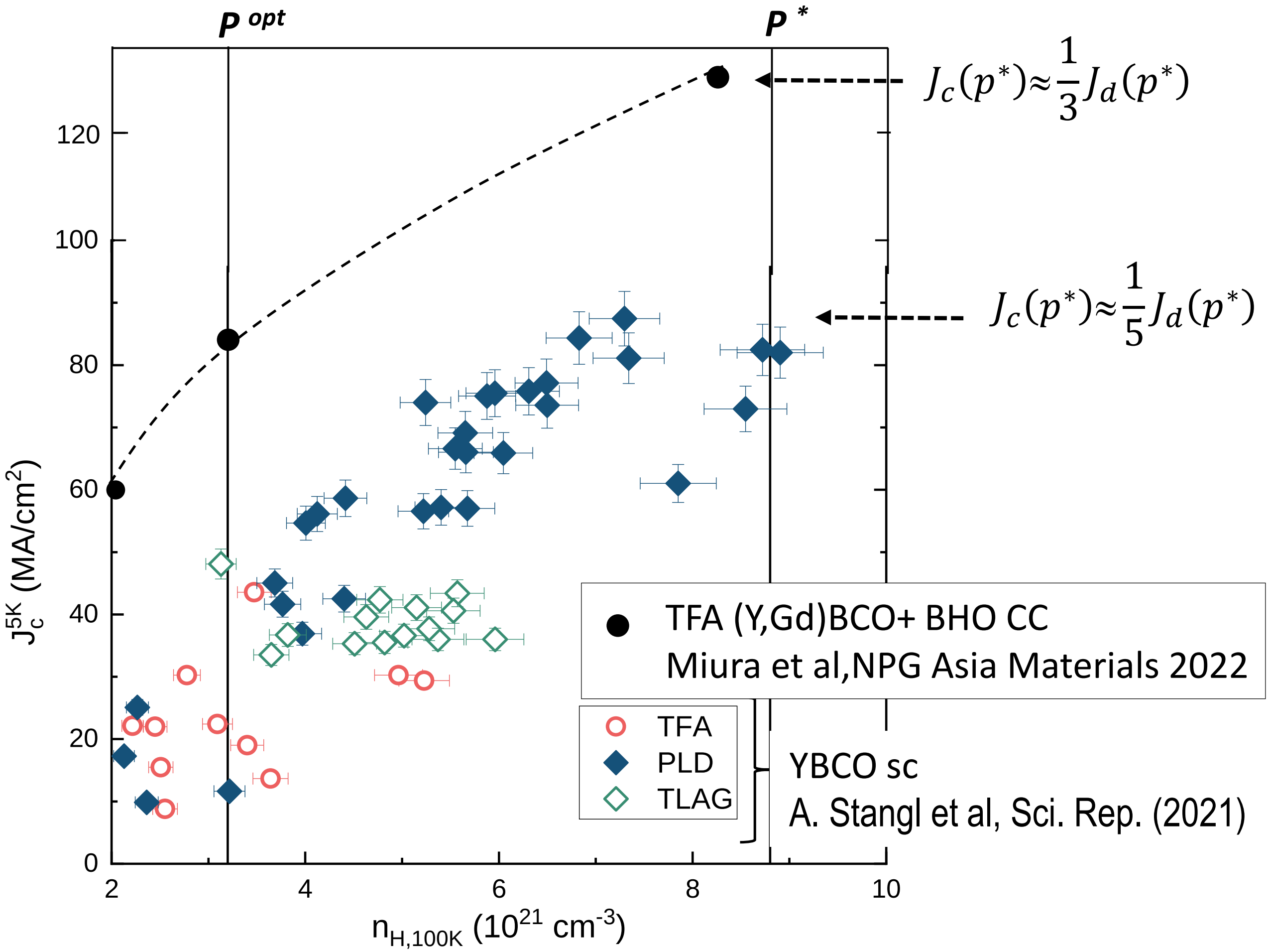
$$f_p \propto E_c \propto n_H$$

$$\text{If } n_H \uparrow \rightarrow J_c \uparrow$$



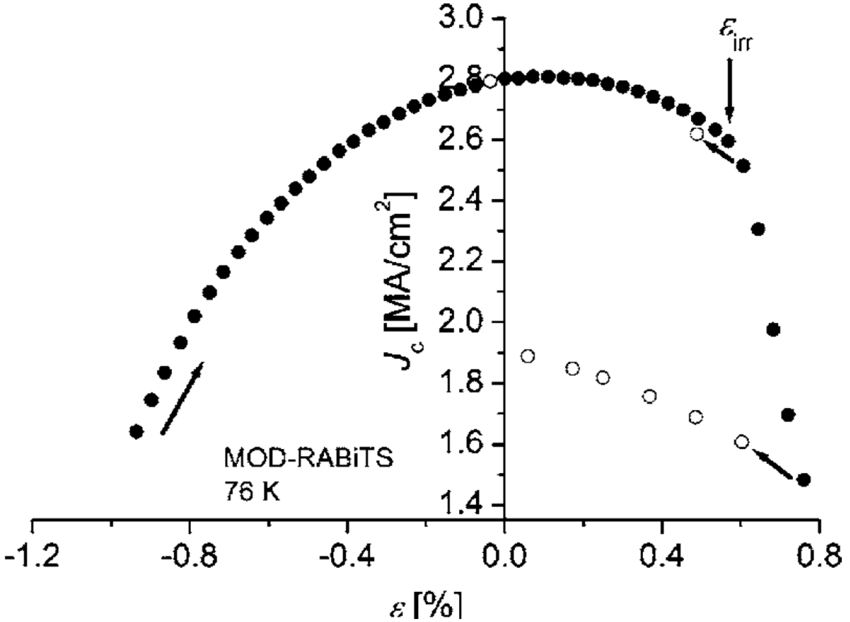
Fermi Surface reconstruction

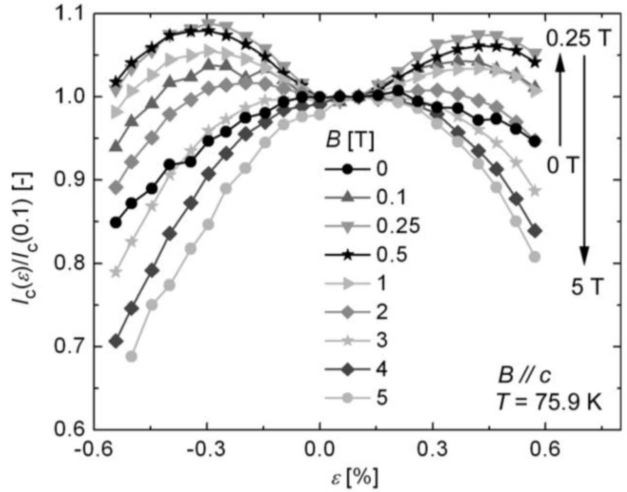
A. Stangl et al, Sci. Rep. (2021)



Interest in combining high throughput and nanocomposite CC in overdoped state

J_c(T, H, ε) dependence on axial strain in the complex pinning landscapes of CC



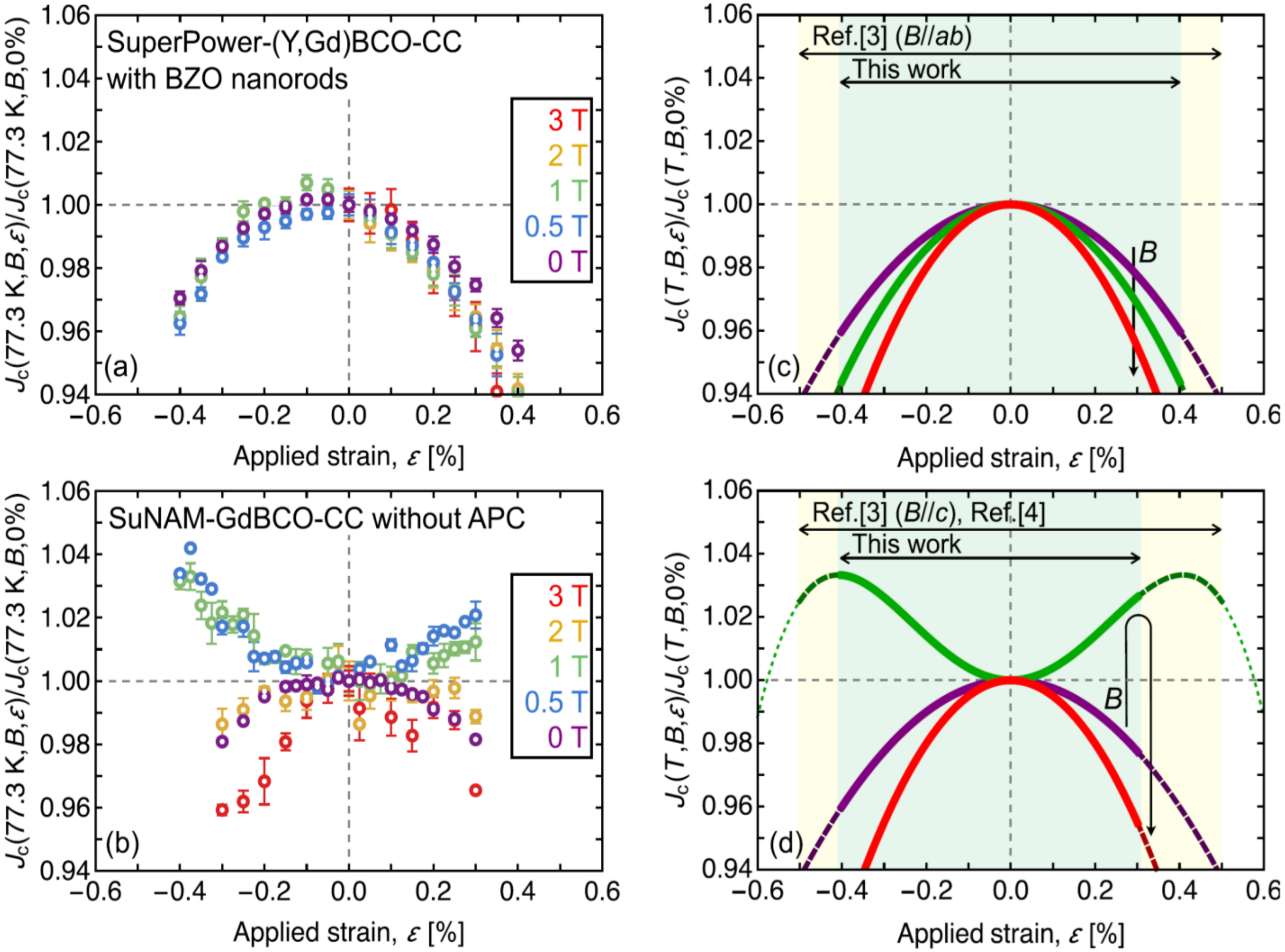


D C Van der Laan et al, APL 90 (2007)

D C Van der Laan et al, SUST 23 (2010)

Anisotropic Correlated pinning

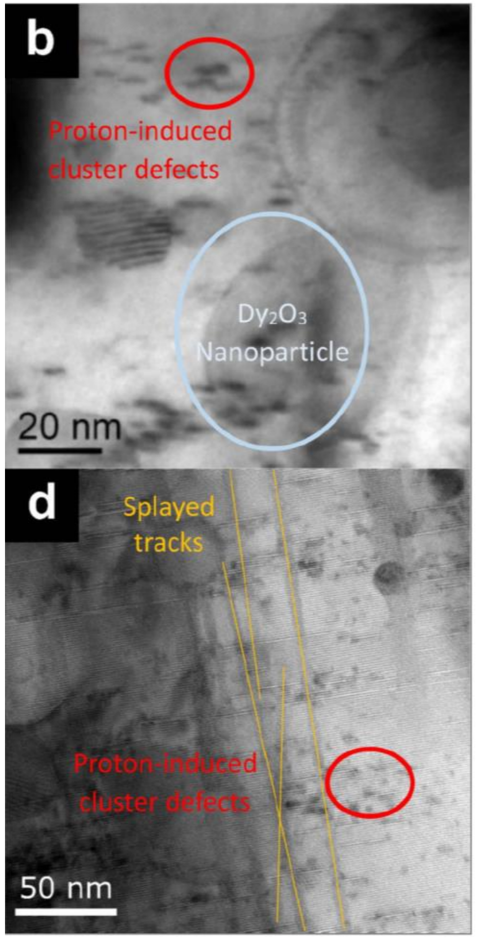
Isotropic Random pinning

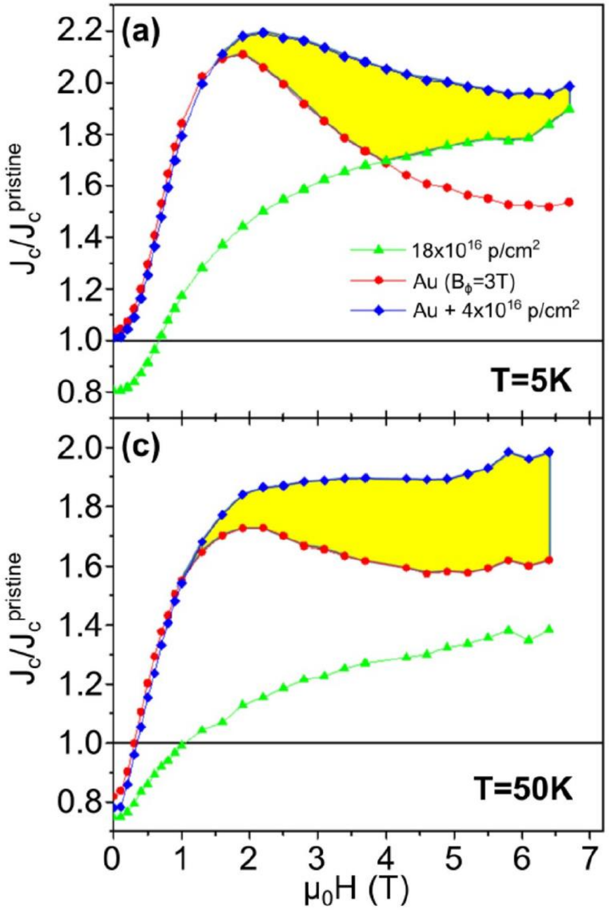


T. Okada et al SUST 33 (2020)

$J_c(D_o, H, T)$ dependence on particles irradiation of CC: effect on complex microstructures

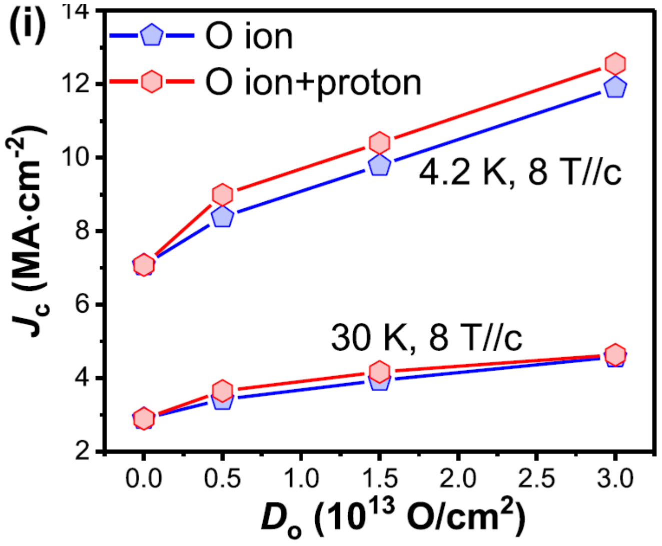
250 MeV Au ions + 4 MeV protons in AMSC MOD nanocomposite films





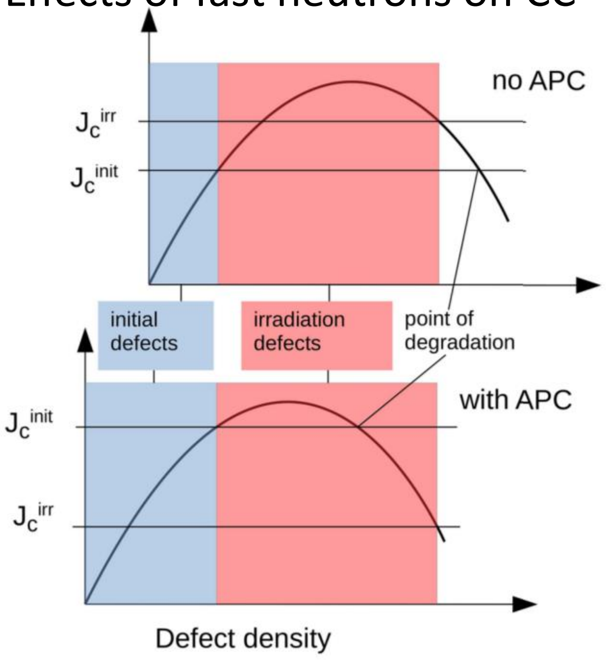
K J Kihlstrom et al SUST 34, (2021)

60 keV protons + 250 MeV O-ion in PLD GdBCO SST films



D. Huang et al, SUST 36, (2023)

Effects of fast neutrons on CC



D.X. Fischer et al, SUST 31 (2018)

Irradiation effects are very relevant for Fusion application (refer to S. Speller talk Tu.)

Other application driven relevant materials aspects: from CC to conductor

Coated Conductor tape:
- Engineering current density, J_e
- Homogeneity and uniformity
- Mechanical strength
- Fatigue
- Splicing
- Quench protection
- Ac losses
- Radiation damage, …

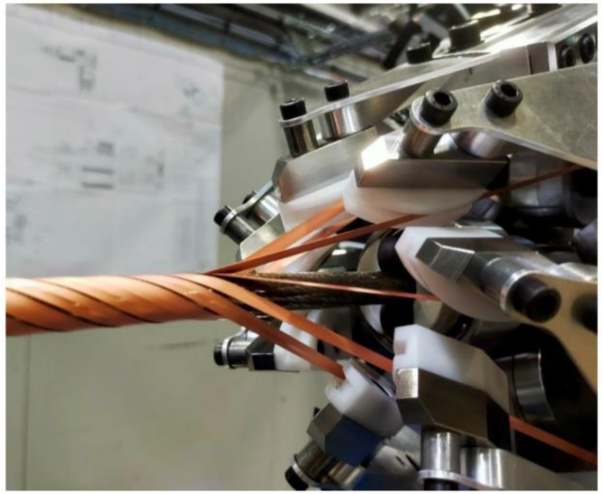
Conductor wire:
- Conductor configuration (current sharing, transposition, …)
- Conductor bending radius
- Winding methodologies (impregnation, winding guides,…)
- Insulated, non-Insulated, partially insulated wiring
- Thermal stress, mechanical resilience, quench management, ac-losses, ….

D. Van der Laan et al, SUST 34 (2021)

S. Kar et al, SUST 33 (2020)

N Yanagi et al J. Phys.: Conf. Ser. 2545 (2023)

Z.S. Hartwig et al, SUST 33 (2020)


A. Ballarino, HiTAT Workshop, Geneva, March 2023

Status of CC fabrication at Industrial scale

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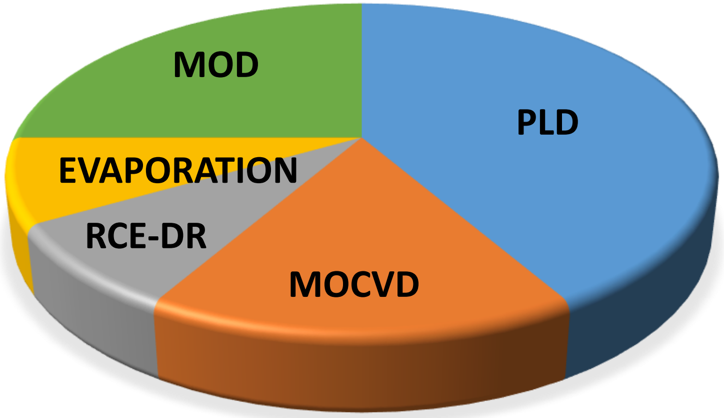
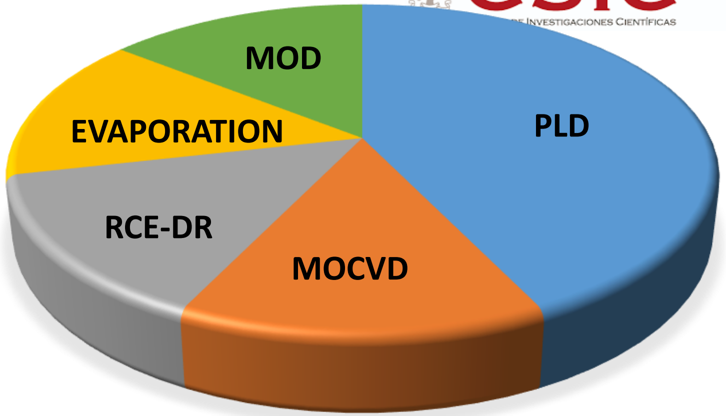
Consolidated product	Growth method	Textured substrate	REBCO materials	Main APC
FARADAY FACTORY JAPAN	PLD	IBAD	YBCO	Y_2O_3 nanoparticle
			GdBCO	
"Tsunagu" Technology Fujikura	PLD	IBAD	EuBCO	BHO nanorod
			GdBCO	
上海超导 Shanghai Superconductor Technology	PLD			
SuperPower Inc.	MOCVD			
THEVA	ME			
SuNAM	RCE-DR			
上创超导 Shanghai Creative Superconductors	MOD	IBAD	YBCO	BZO nanoparticle





R&D product

HTS HIGH TEMPERATURE SUPERCONDUCTORS	PLD
SuNAM	PLD
SWCC GROUP	MOD
SUMITOMO ELECTRIC	MOD
METOX	MOCVD

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 54, October 2023. Plenary presentation given at EUCAS 2023, Sept. 6, 2023, Bologna, Italy

New horizons at Faraday Group (PLD method)

FARADAY FACTORY JAPAN

Multi GA-m factories vision (mid-2020's)

Fits well into standard logistics center

5000 m^2 unit $I_c L$ = 1 GA-m/year for 2024

(2500 tapes x 600 A (20T, 20K) x 700 m) *(12 mm eq.)*

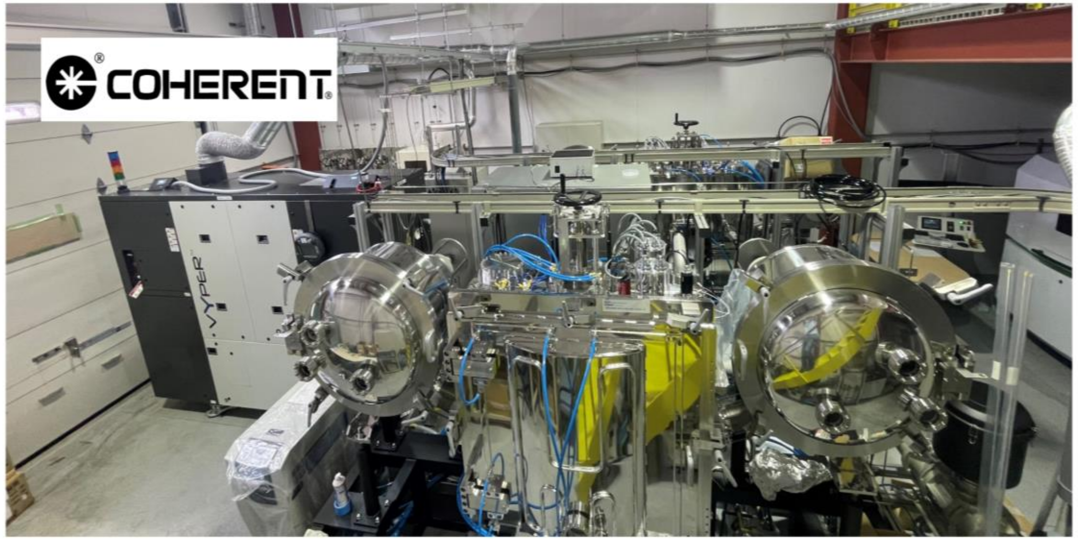
We are up to build more modular plants as demand unveils

CCA-2023, University of Houston, UH Hilton, Texas, USA, 3-6 April 2023

1300 km/yr (12 mm) in 2023

25000 km/yr (12 mm) in 2028

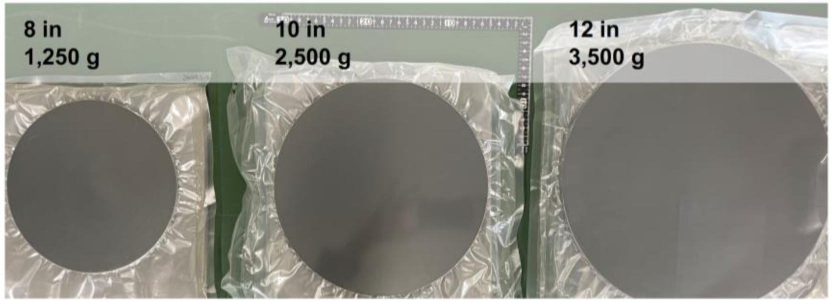
Next-gen production unit (600W laser + 2 chambers)



February – received equipment, April – started operation

If R&D successful, there's potential to reach **1 GA-m/year with only 5 units**

Scaling up PLD major raw materials (PLD targets)



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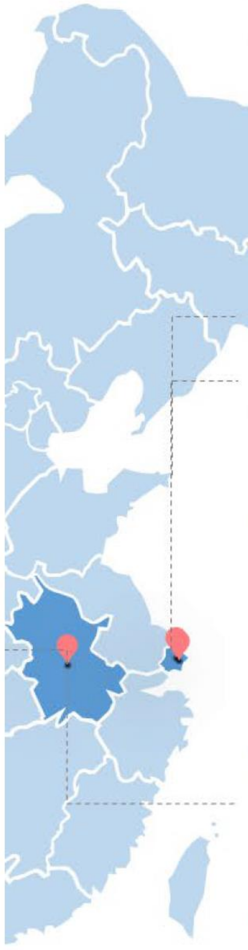
上海超导

Shanghai Superconductor Technology (SST) (PLD method)



Plant #1 (Upgrading of existing plant)

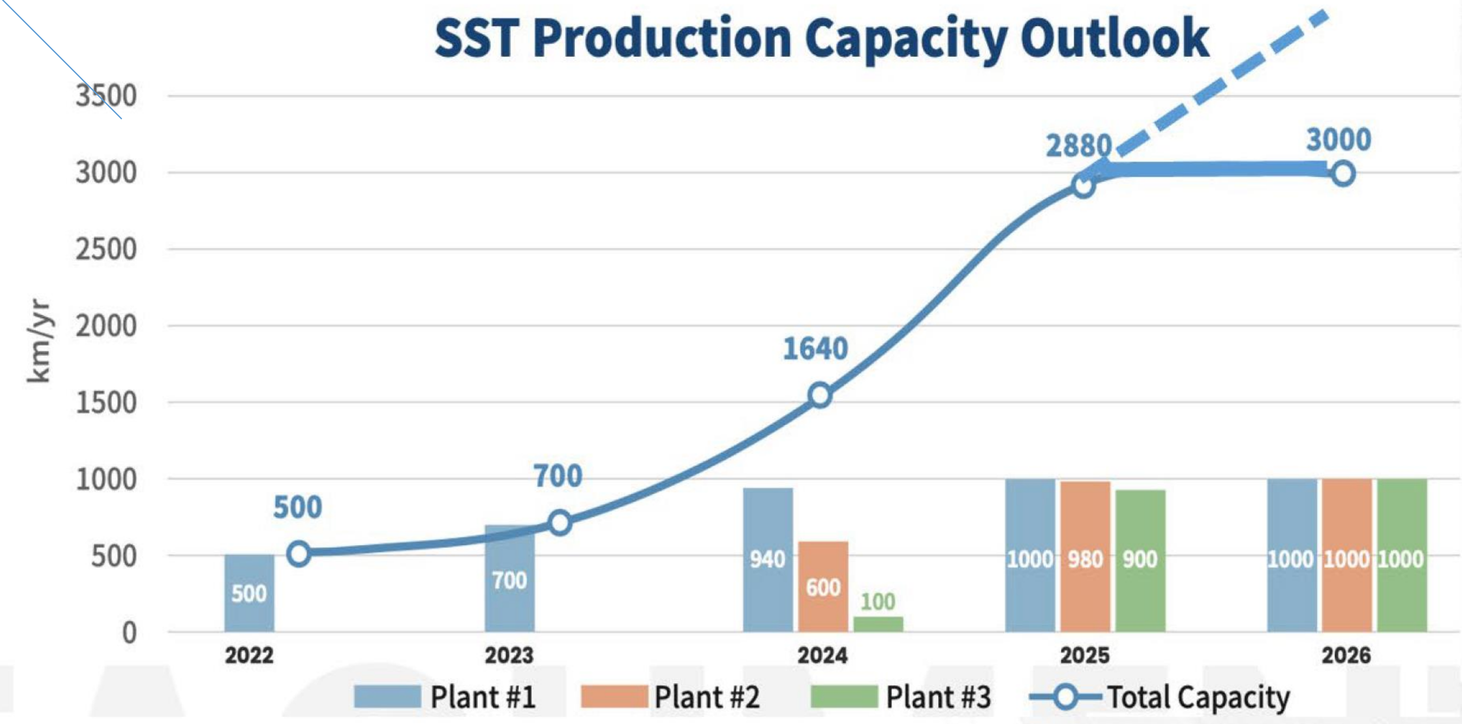
Zhangjiang Hi-tech Park, Shanghai

Plant #2 (New)

Kangqiao Industrial Park, Shanghai

Plant #3 (New)

Aviation Harbour Demonstration Park, Hefei



3 years Expansion

3 Plants

3000 km/yr Capacity *(12 mm eq.)*

Prospects for Fujikura (PLD-Hot wall method)

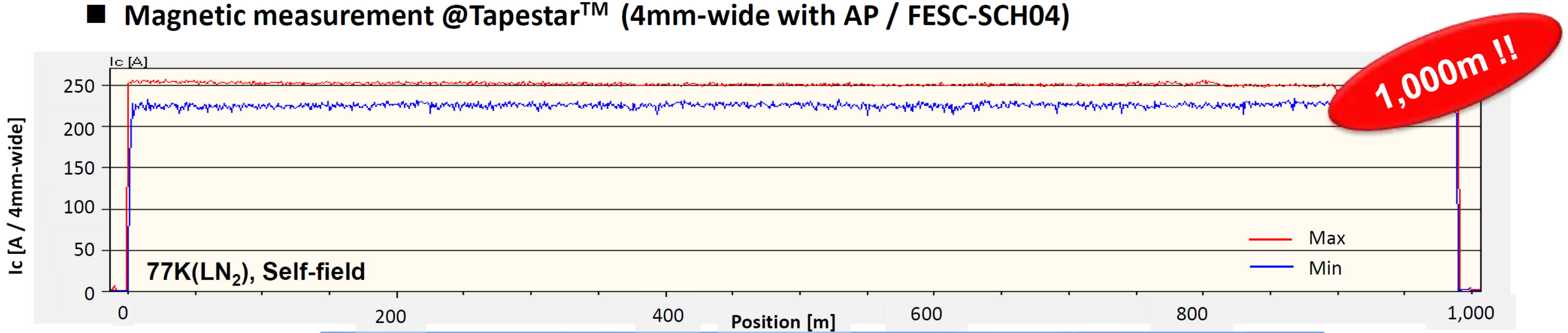
"Tsunagu" Technology Fujikura

Annual production more than double for 2025

- Increase growth rate
- Increase number of production units
- Improve modernization of production managements

Uniformity needs to be mantained

■ **Magnetic measurement @Tapestar™ (4mm-wide with AP / FESC-SCH04)**



quite uniform I_c with artificial pinning tape and ~ 1,000 m are obtained

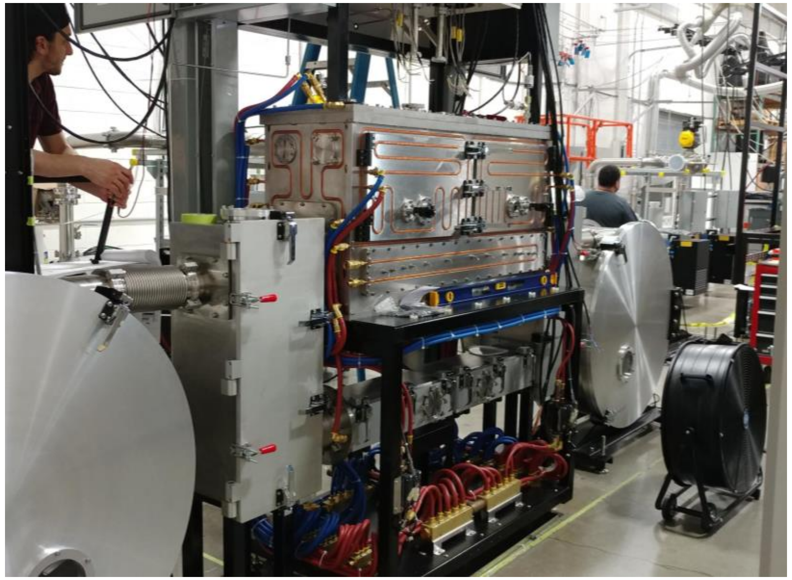
SuperPower's new wire manufacturing facility in Glenville, New York, US (MOCVD method)

New IBAD system

At present: ~**200 km/yr.** (4mm eq.)

Phase 1 expansion (end of 2023):
~**600 km/yr.** (4mm wide eq.)

New MOCVD systems



Phase 2 expansion (~end of 2025):
~**1,200 km/yr.** (4mm wide eq.)

Current development progress in SuNAM (RCE-DR method)

RCE-DR system

120 mm-w Electro-polishing

PLD system

Present: 400 km/yr (4 mm eq.)

Target 2025: x 2.5 production capacity
125 mm wide tapes

Real-time (AI) is used for CC surface analysis

Development of a new process:
→ Seed layer : PLD system
→ Thick REBCO layer: RCE-DR system

SuNAM

Shanghai Creative Superconductors, SCSC
Industrial production lines (TFA-MOD method)

EUCAS2023 Bologna, Italy 3rd-7th September

上创超导 Shanghai Creative SuperConductor

Polishing

Buffer layer texturing

Present:
400 km/yr (4 mm)

New production line under construction for 40 mm wide tapes

x 7 production capacity increase in 2025

Coating and growth of the Superconducting layer

Packaging

FUTURE: PRODUCTION SCALING (e-beam evaporation method)

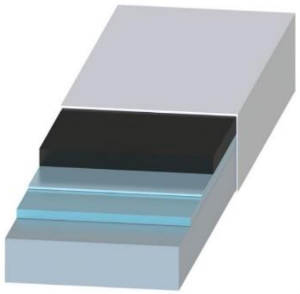
Sole remaining European HTS wire supplier

THEVA

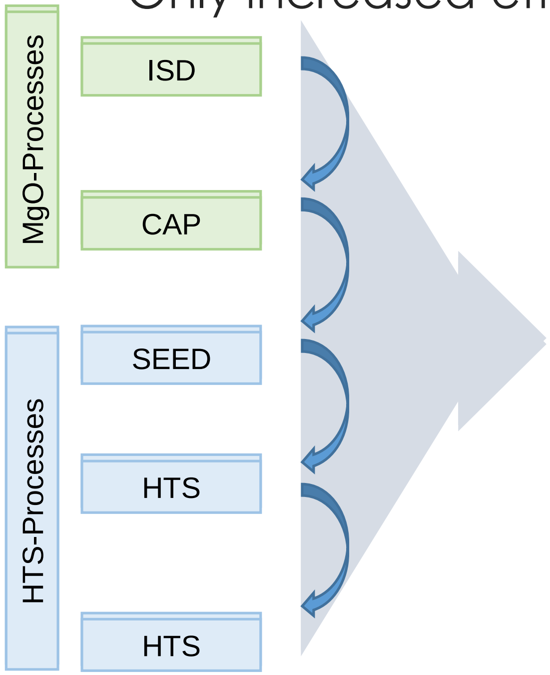
THEVA Pro-Line

Scaling means more than cloning of current equipment

Only increased efficiency and productivity can reduce **unit cost**



Very simplified architecture



ALPHA ⇒ BETA

100% ⇘ 25%

MgO buffer	HTS & Ag

Tape width 12 mm

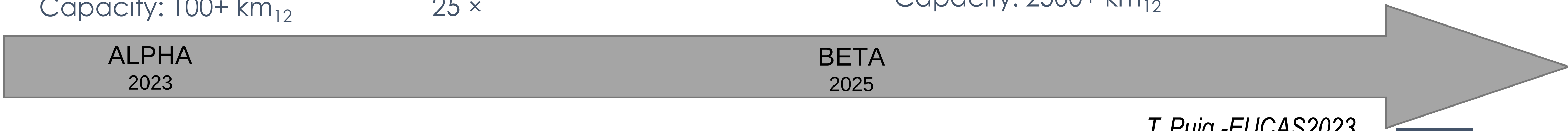
Capacity: 100+ km_{12}

Going wide

25 ×

Tape width 4 × 80 -100 mm

Capacity: 2500+ km_{12}



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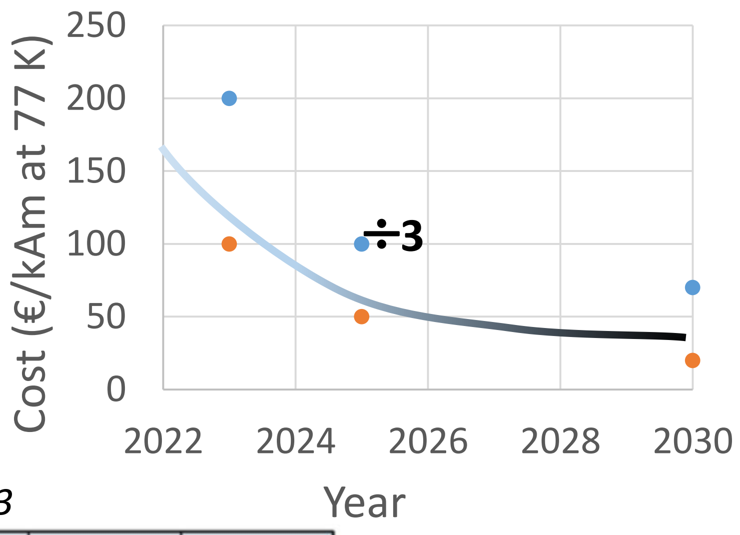
Status of CC materials at industrial scale and prospects

7 consolidated companies

Magnitude	At present	Target for 2025	Target for 2028
Length (km)	0.5 – 1	1 – (5)	
Width (mm)	2, 3, 4, 6, 12	40, 80, 100, 125	
Production (km/yr) *12 mm equiv.*	3000 - 5000	6000 -10000	+40000 (+25000 Faraday)

Cost …



S. Lee, Faraday Group, CCA 2023

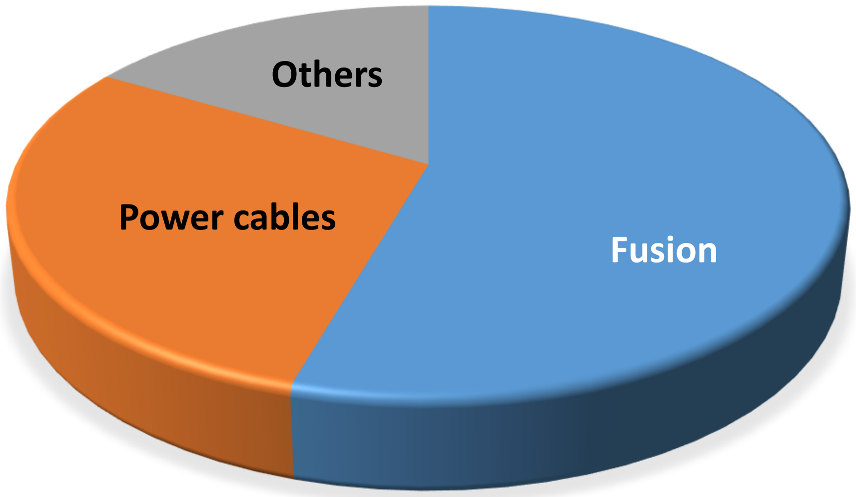
"HTS price will catch LTS with a 10-fold volume increase"

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 54, October 2023. Plenary presentation given at EUCAS 2023, Sept. 6, 2023, Bologna, Italy

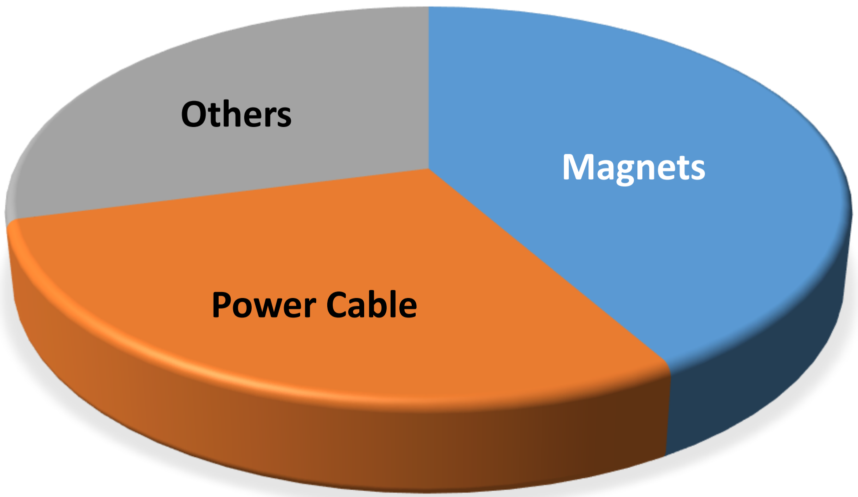
CC Industry application target

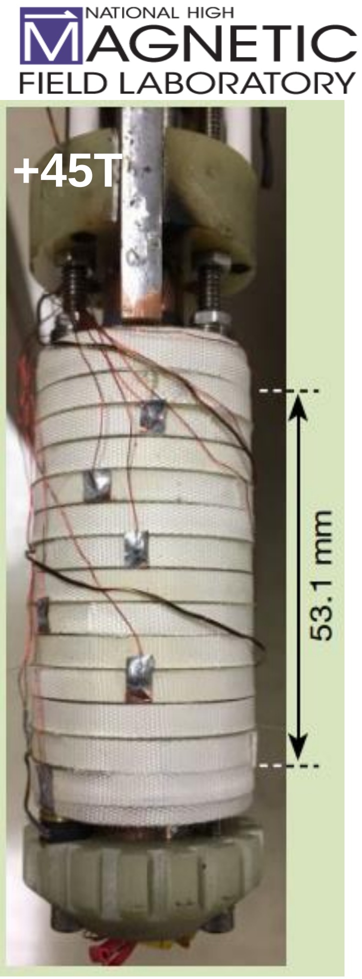
7 consolidated companies

Main target



Second target



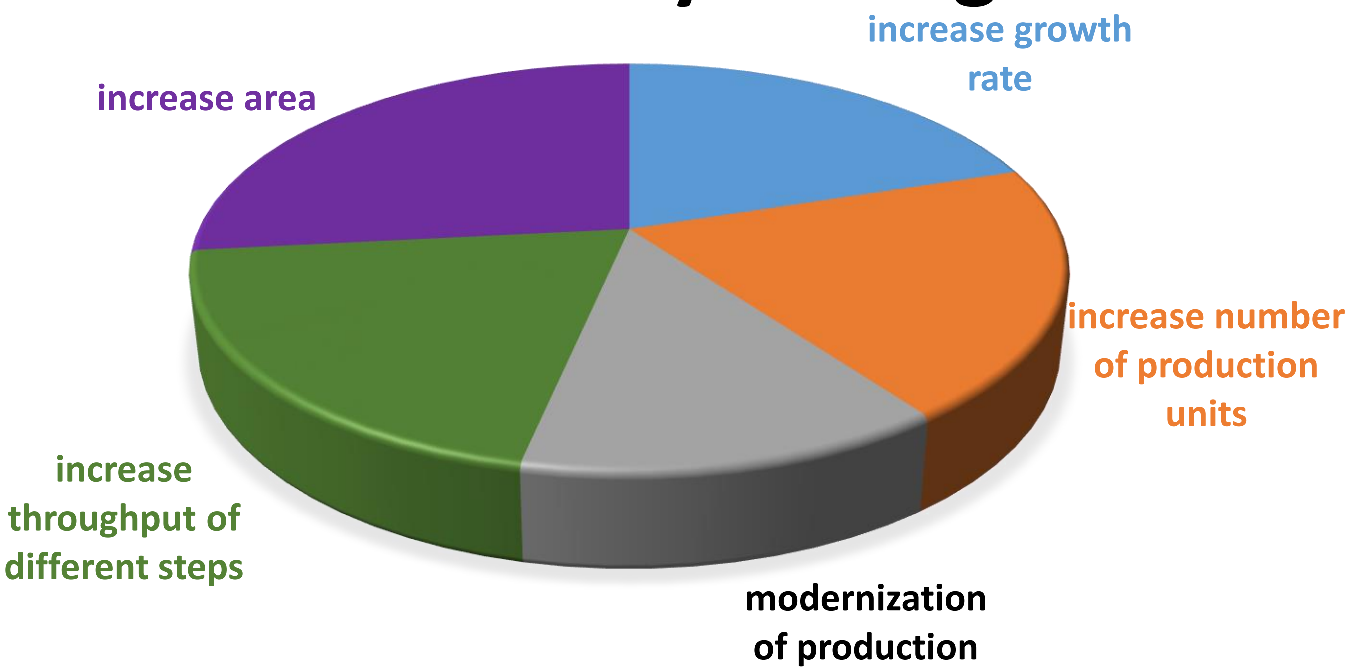


https://cfs.energy/technology

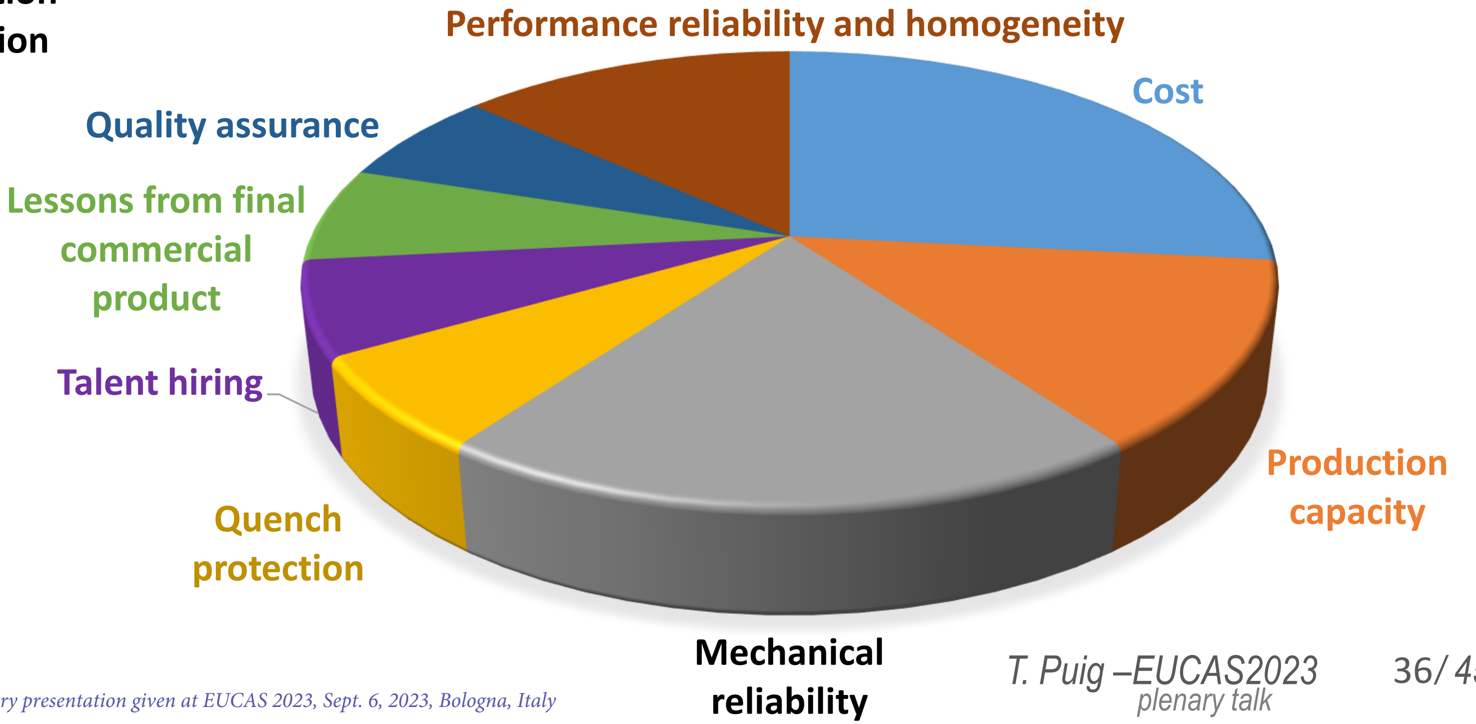
https://www.theva.com/superlink
https://www.nkt.com

S. Hahn et al, Nature 570, 496 (2019)

Industry strategies



Industry challenges



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The industrial vision of CC in a sentence

“Coated conductors would advance steadily as the unique practical wires available for emerging applications used in really large field, or severe thermal conditions”

“Prospective sustainable market of HTS materials and applications promises numerous public benefits for much human activity in energy production, distribution, and use; medicine; transportation; and research”

“Innovative manufacturing technology is the key to scale up the production and reduce the cost”

“Faster, Higher, Stronger – Together (Olympic motto). Citius, Altius, Fortius - Communis.
What is the final goal for you instead of Gold Medal?”

“In the long run, coated conductor HTS will become a commodity product, opening up the opportunity to fuel a wide market of energy applications rather than just a few very special, experimental prototypes”

“New paradigm designer of electric energy”

“The superconductor is hard to resist, but the harder is more valuable. The latest progress on superconducting coated conductors is realizing our dream for various superconducting applications”

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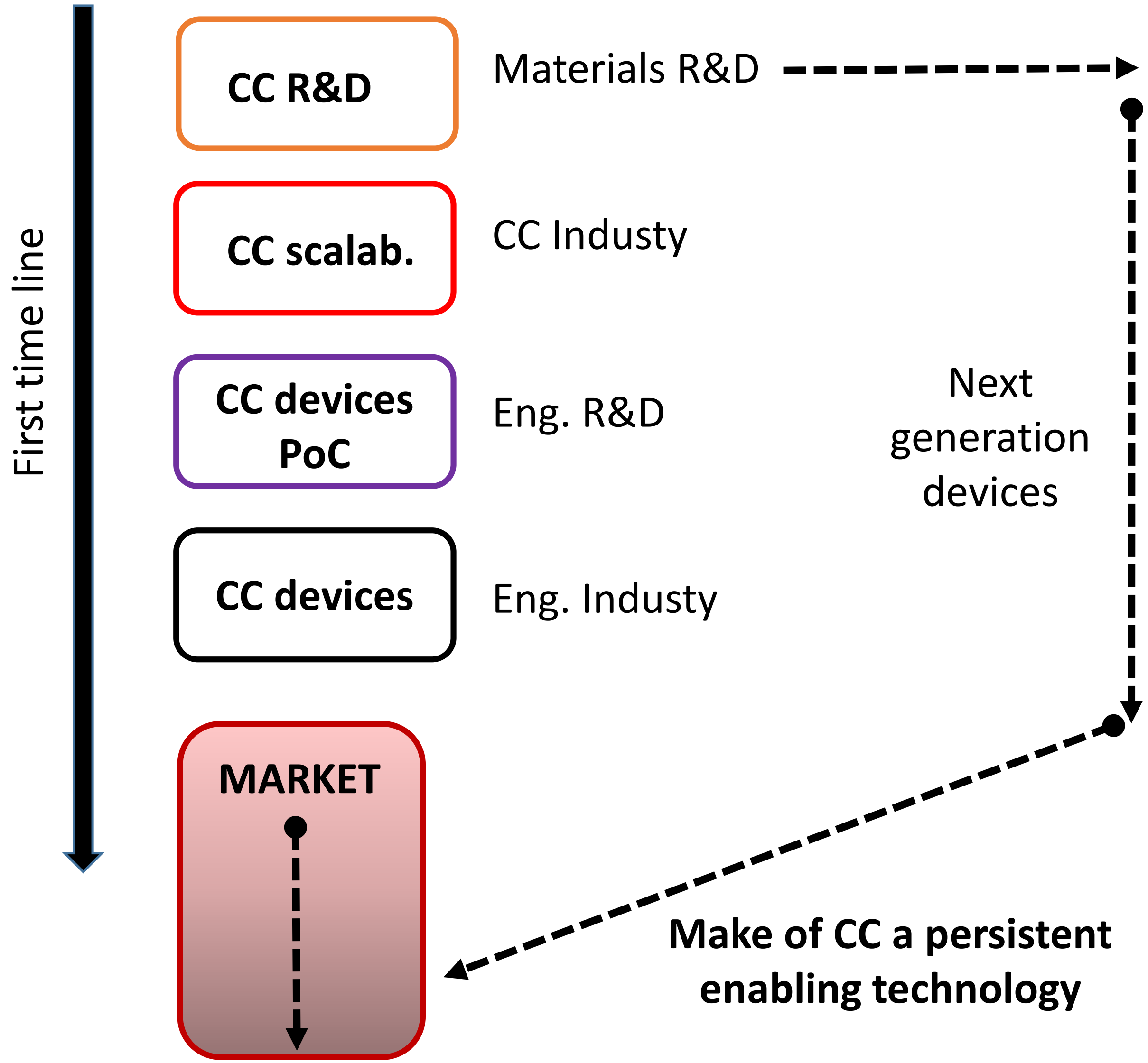
Materials R&D challenges and initiatives

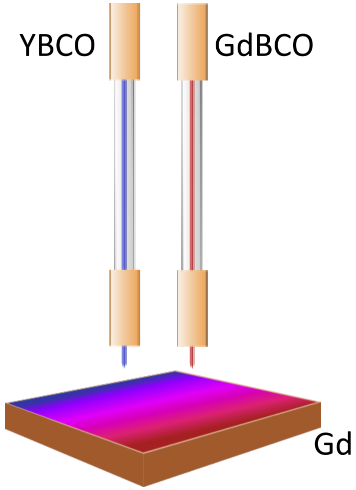


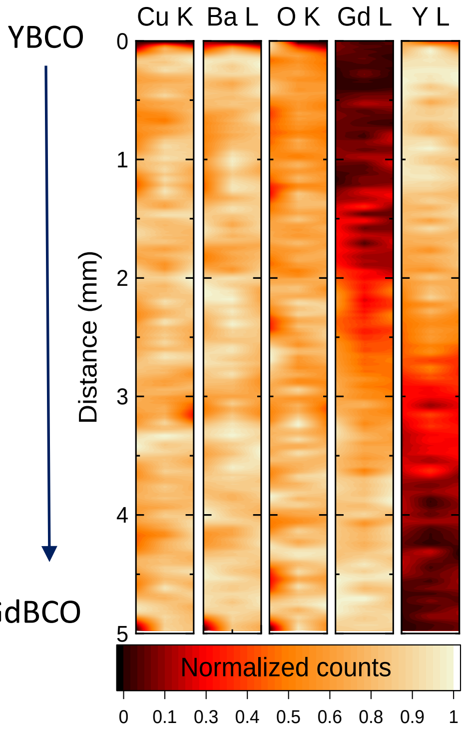
Joining the CC industry to develop further:

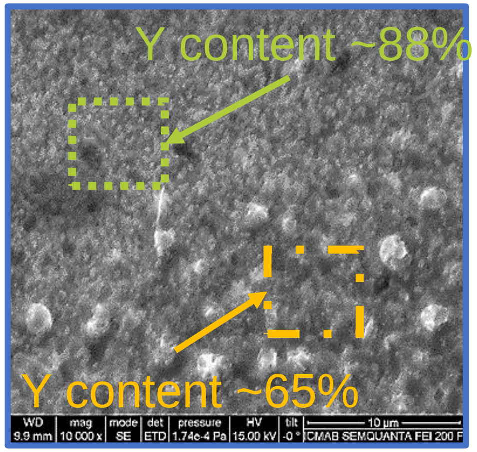
- Novel High-Throughput methods and processes
- Fast screening methodologies and machine learning approaches
- Semi-industrial R&D scales
- Databases and standarization of wide range of CC properties
- …

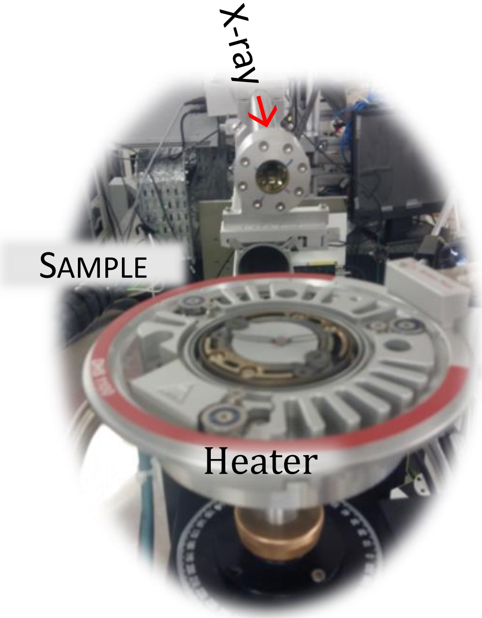
High Throughput Experimentation using Compositional Gradients and TLAG growth

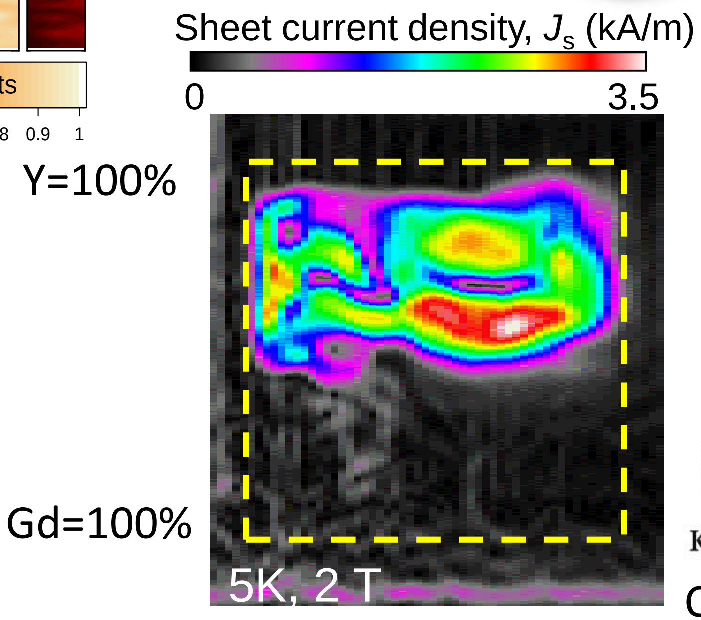
Combinatorial DoD Ink Jet Printing



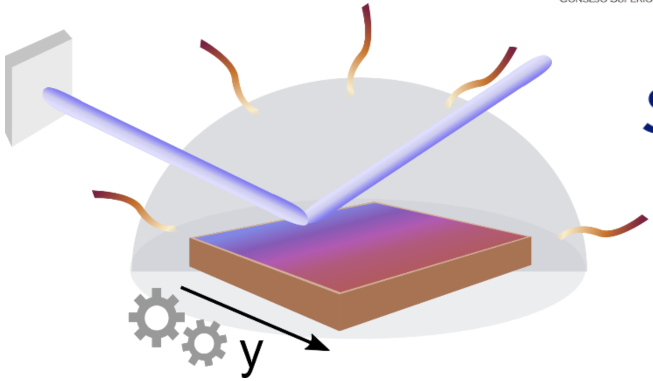




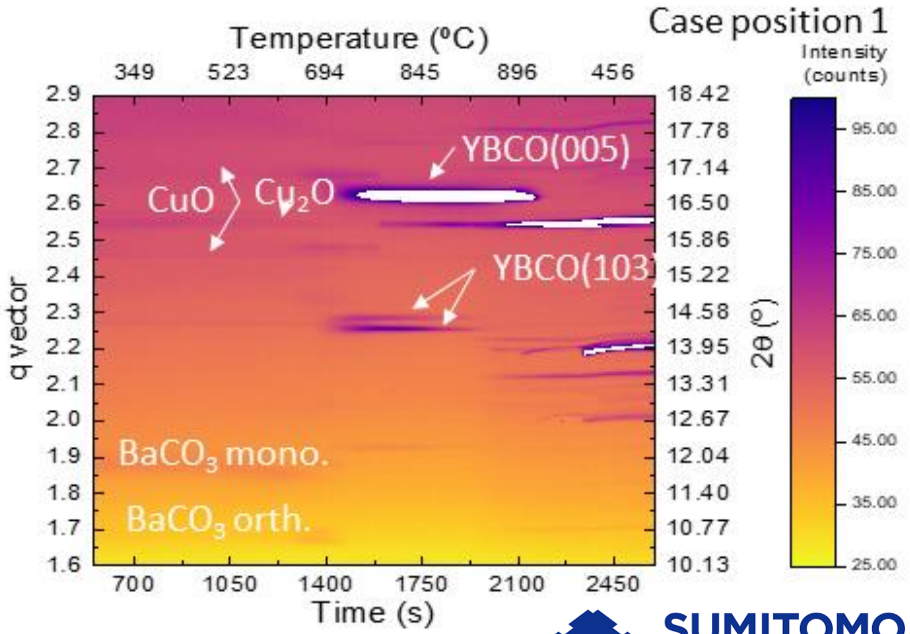




in-situ synchrotron XRD

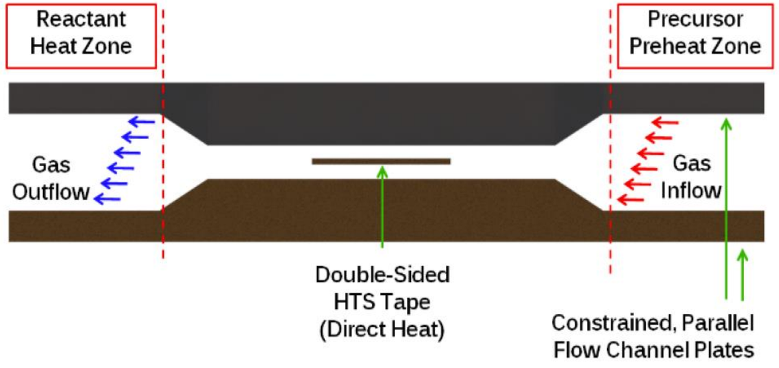


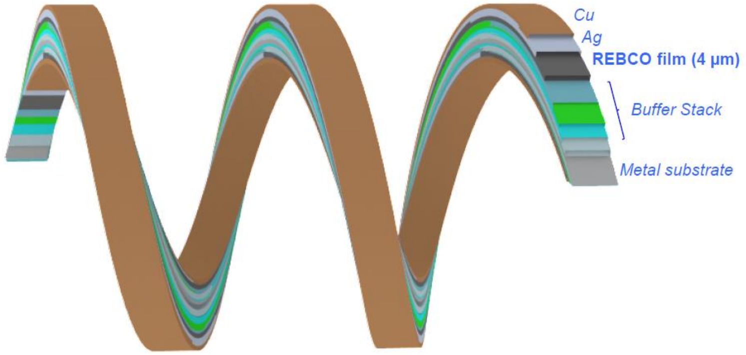
Data is segmented by positions for analysis



Colab. T. Kiss

Double-sided REBCO tapes by Advanced MOCVD

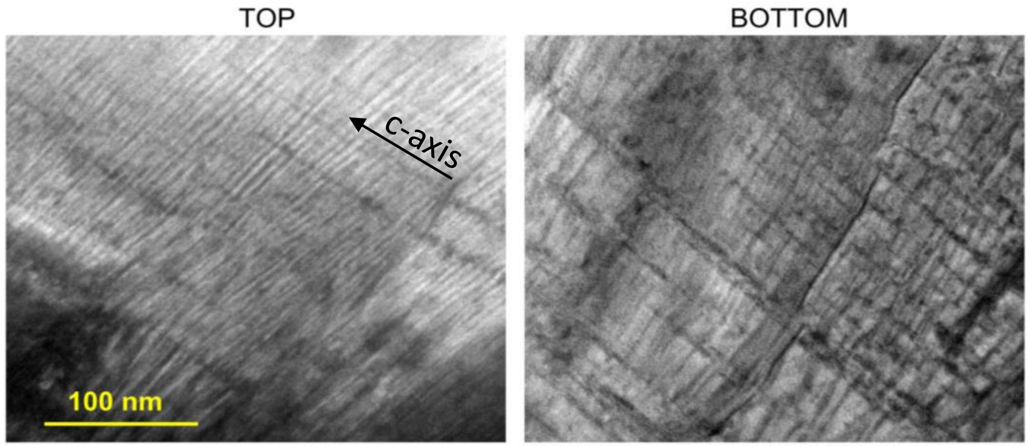




Reduced tape quantity per device
Reduced raw chemicals
Increase I_c
Reduced cost

Double-sided REBCO 2x 2.5 μm thick film in a ***single step:*** ***I_c*** **> 500 A/4mm at 20 K, 20 T, 15cm (3.5 x I_c commercial tape)**

Double-sided REBCO 2x 5 μm thick film
10 x I_c commercial tape



- 20 m good quality textured buffered double-sided substate
- Similar nanorods microstructure in both sides (15%Zr)
- Comparable mechanical properties as single side (~ 575 MPa)
- Current sharing can be fostered to promote defect-tolerance

Towards double-sided 50 m tapes
Next 500 m @ $10/kA-m at 20K, 20T

AMPeers

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 54, October 2023. Plenary presentation given at EUCAS 2023, Sept. 6, 2023, Bologna, Italy

Data driven approach coupling high throughput measurement and ML

Methodology to model CC production process

Input

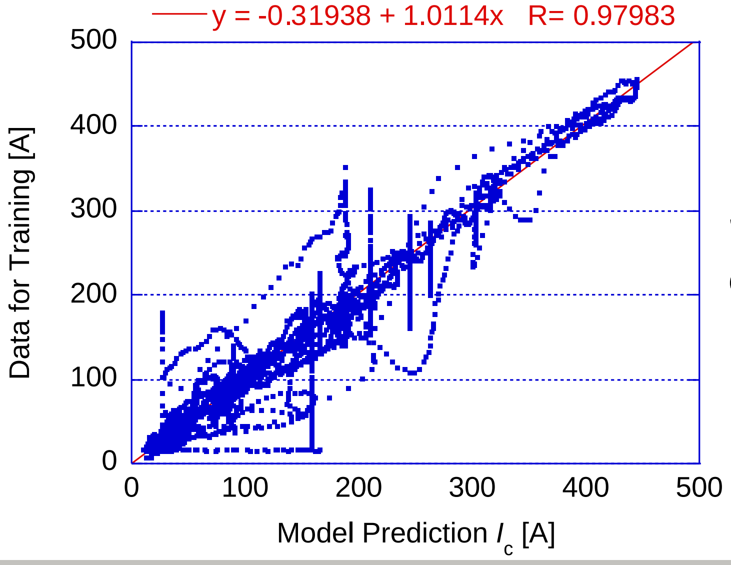
Output

Unknown governing equations
due to complex processes

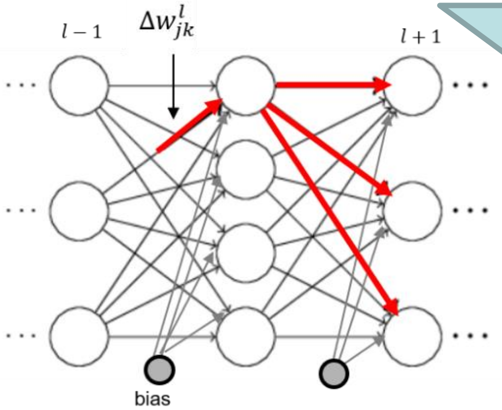
Control Parameters
- Subst. Temp.
- Laser Power
- Pressure
- Wire Traveling Speed
- And more …

$x_{1,i},\ x_{2,i}\ x_{3,i}\dots$

Combinatorial long length sample

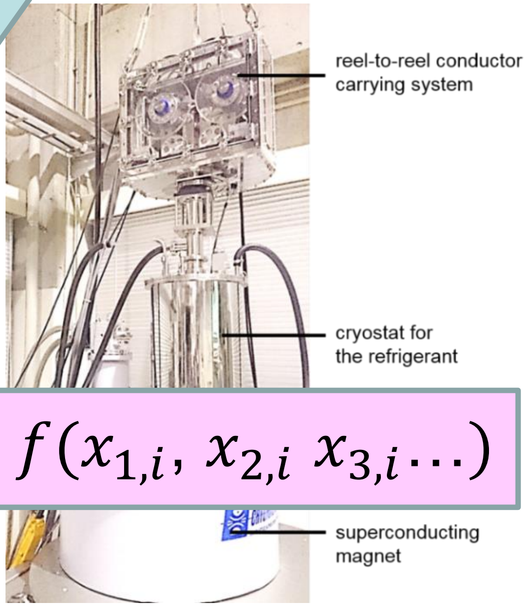


Deep Neural Network Architecture



Size of training data set: **11,222**

Critical Current, I_c (Performance)



$$I_c = f(x_{1,i},\ x_{2,i}\ x_{3,i}\dots)$$

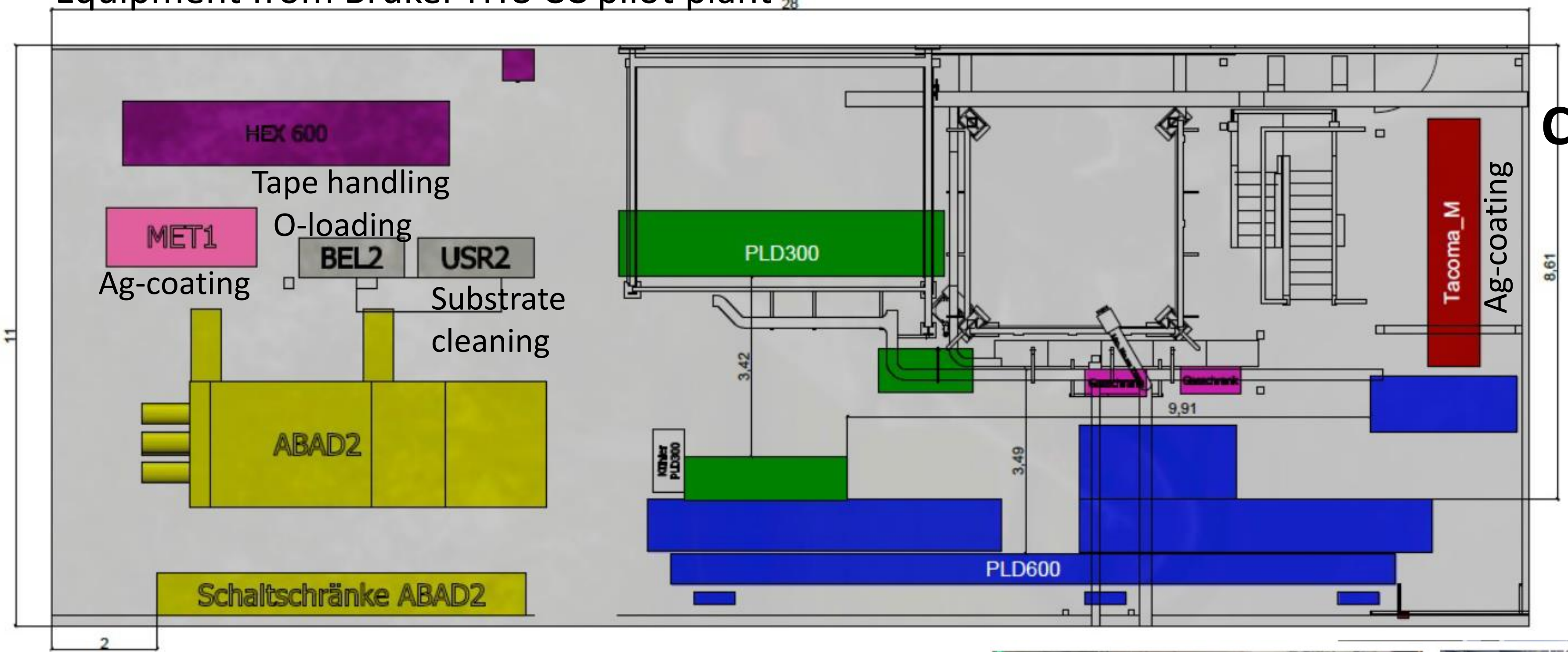
High throughput operando measurement

T. Puig -EUCAS2023 Plenary talk

KYUSHU UNIVERSITY
JAPAN

KC4: KIT-CERN Collaboration on Coated Conductor

Equipment from Bruker HTS CC pilot plant



Core KC4 Lab space > 500 m²

A joint, Open Lab Foundry of HTS CC synthesis:
Gap bridge between small scale materials research on CC and larger scale tailored, high quality full Coated Conductor architectures

PLD600
Batch vacuum coating

R2R electroplating

ABAD vacuum coater

T. Puig -EUCAS2023
Plenary talk

2022 — 2023 — 2024 — 2027

Intermediate 20m length scale

Extension to 100m+ length scale

Need of Standardization and Open databases of CCs

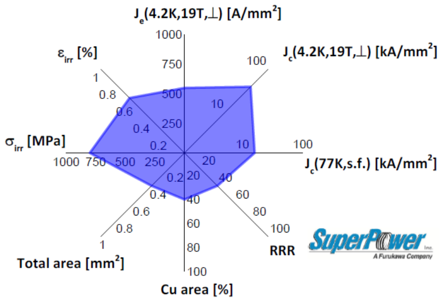
Robinson Research Institute High-Temperature Superconducting Wire Critical Current Database, $J_c(T,H,\theta)$- S. Wimbush

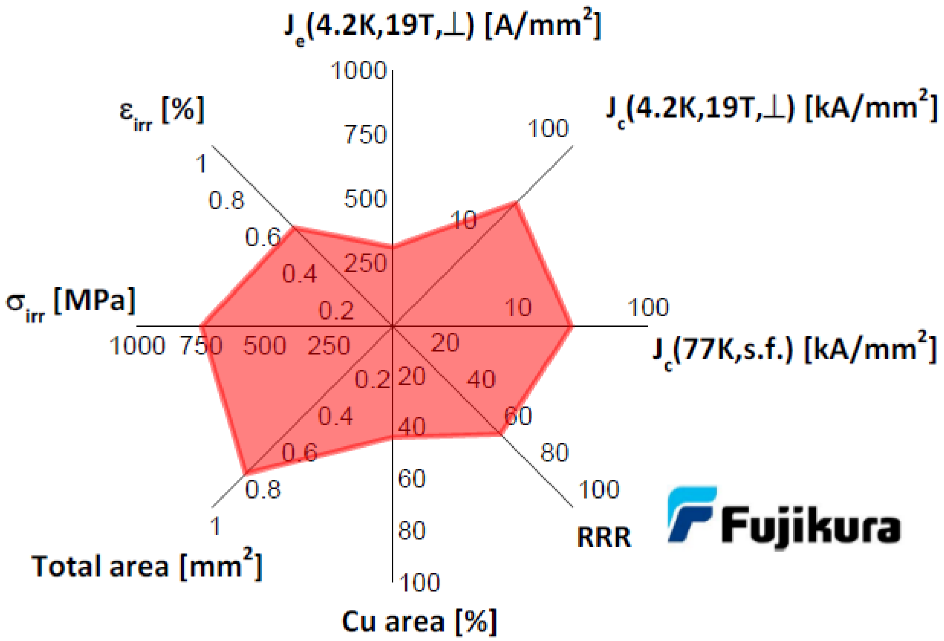
http://www.victoria.ac.nz/robinson/hts-wire-database

https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

P. Lee, D. Abramimov

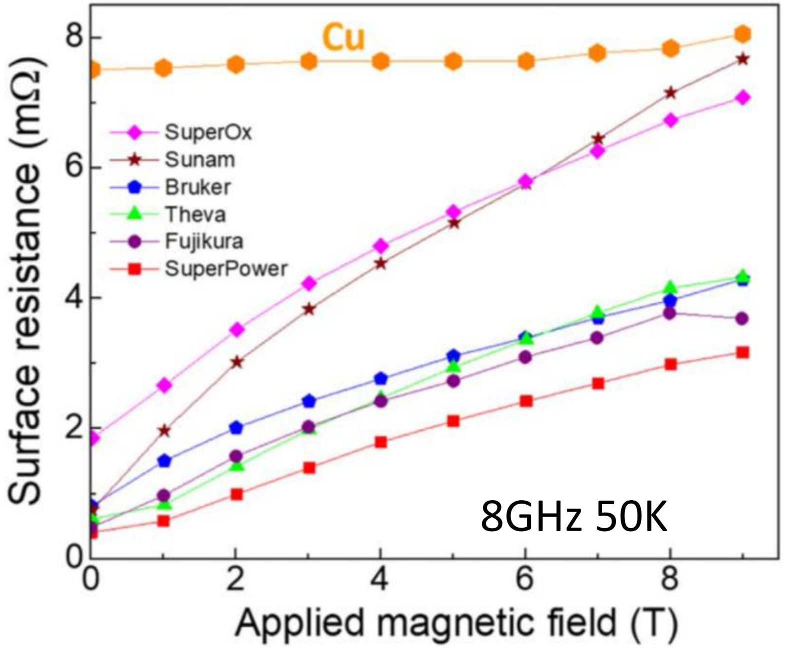
C. Senatore (2017)





L. Rossi, C. Senatore, Instruments 5(1), 8 (2021)

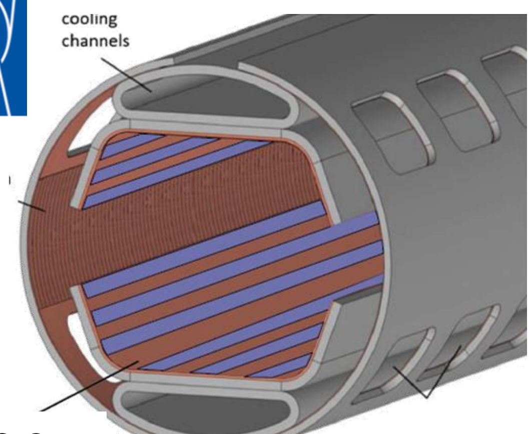
Towards high field HTS RF cavities



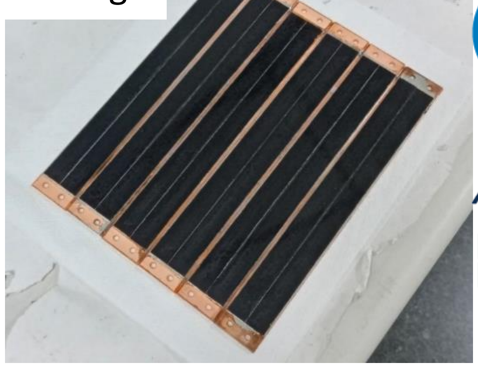
T Puig et al, SUST 32 (2019)
A. Romanov et al, Sci Rep 10 (2020))

Additional opportunities for CC
Case of RF cavities at high magnetic fields for HEP

High energy circular Collider Beam screen

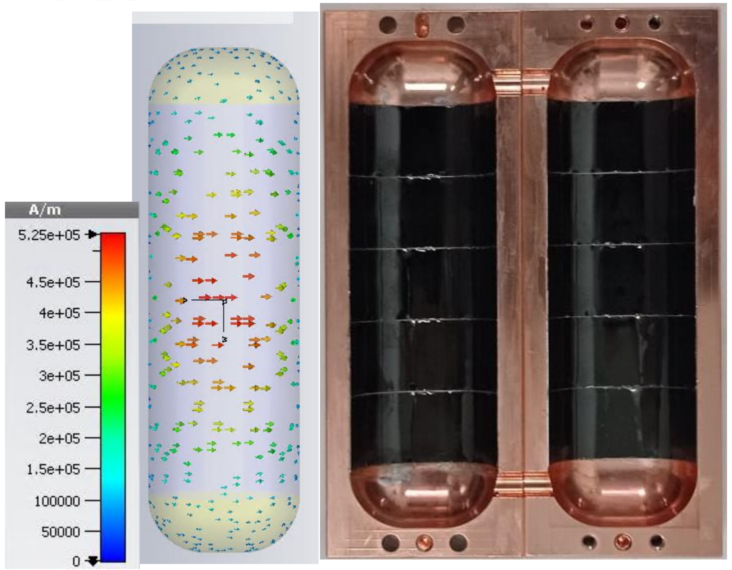


HTS-Cu hybrid coating



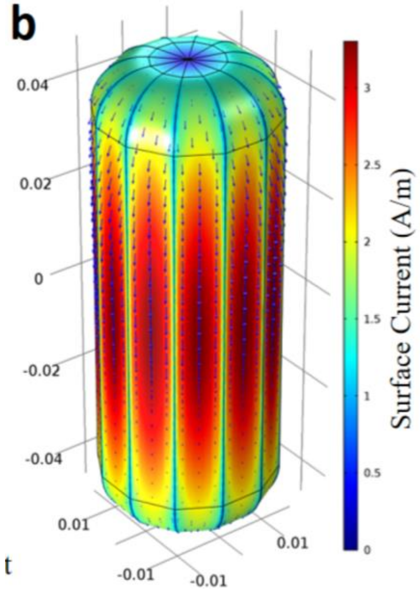
G. T. Telles et al, SUST 36 (2023)

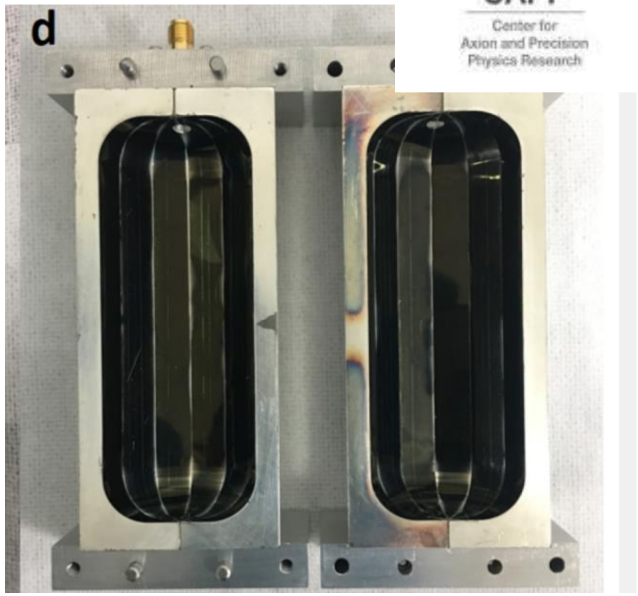
High-Q RF cavities at high H for Dark Matter search (Axion haloscopes)



J. Golm et al, IEEE TAS 32 (2022)

Q ~ $6x10^4$ @ 11T, 4.2 K (8 GHz)





D. Ahn et al, Phys Rev Appl 17 (2022)

Q ~ $3.3x10^5$ @ 8T, 4.2 K (6.9 GHz)

Q ~ $1.3x10^7$ @ 8 T, 150 mK (5.4 GHz)

(200 x Q_{cu})

Opportunities in Muon collider

Conclusions and take away message

- Coated conductors are unique superconducting materials that are set to enable numerous applications for our welfare society
- Only with an understanding of materials, vortex physics and engineering properties can superconducting devices emerge
- After 20 years of R&D on coated conductors, the CC industry is ready to take the big step to scale up production
- Applications such as fusion, NMR and power cables, but also electrical transportation are quite ready to make the necessary pull
- R&D in CC must persist to help improve the capabilities, robustness and cost of next generation devices and make of CCs a persistent enabling technology
- **We started 20 years ago chasing a dream and we didn't give up. We are here to make it come true, and now we are very close, we feel it in the ambience**

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 54, October 2023. Plenary presentation given at EUCAS 2023, Sept. 6, 2023, Bologna, Italy