Progress and challenges in R&D of high current $REBa_2Cu_3O_7$ coated conductors

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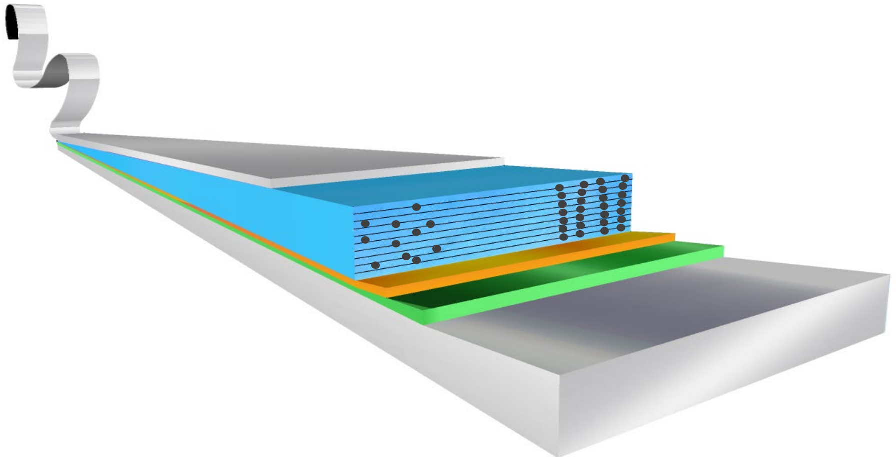
ICMAB-CSIC, Catalonia, Spain

Superconductivity News Forum (https://snf.ieeecsc.org/)



Special thanks to Prof. Teresa Puig
SNF Issues 54, 53, 47

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COST European Cooperation in Science & Technology
Ministerio de Ciencia e Innovación
Plan de Recuperación, Transformación y Resiliencia

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

ASC 24 Salt Lake City
September 1 - 6
Salt Palace Convention Center

Outline

- **REBCO coated conductors: present status, future potential and technology pull**
- **Coated Conductors: materials objectives, challenges and market requirements**
- **Fundamental aspects of coated conductor processing: towards high throughput**
- **Highest performance: vortex pinning landscape and electronic structure control**
- **Coated Conductor tapes integration into conductors**
- **Industrial scale: manufactuting and device integration**
- **Conclusions**

REBCO COATED CONDUCTORS: AT THE FRONTIER OF TECHNOLOGY

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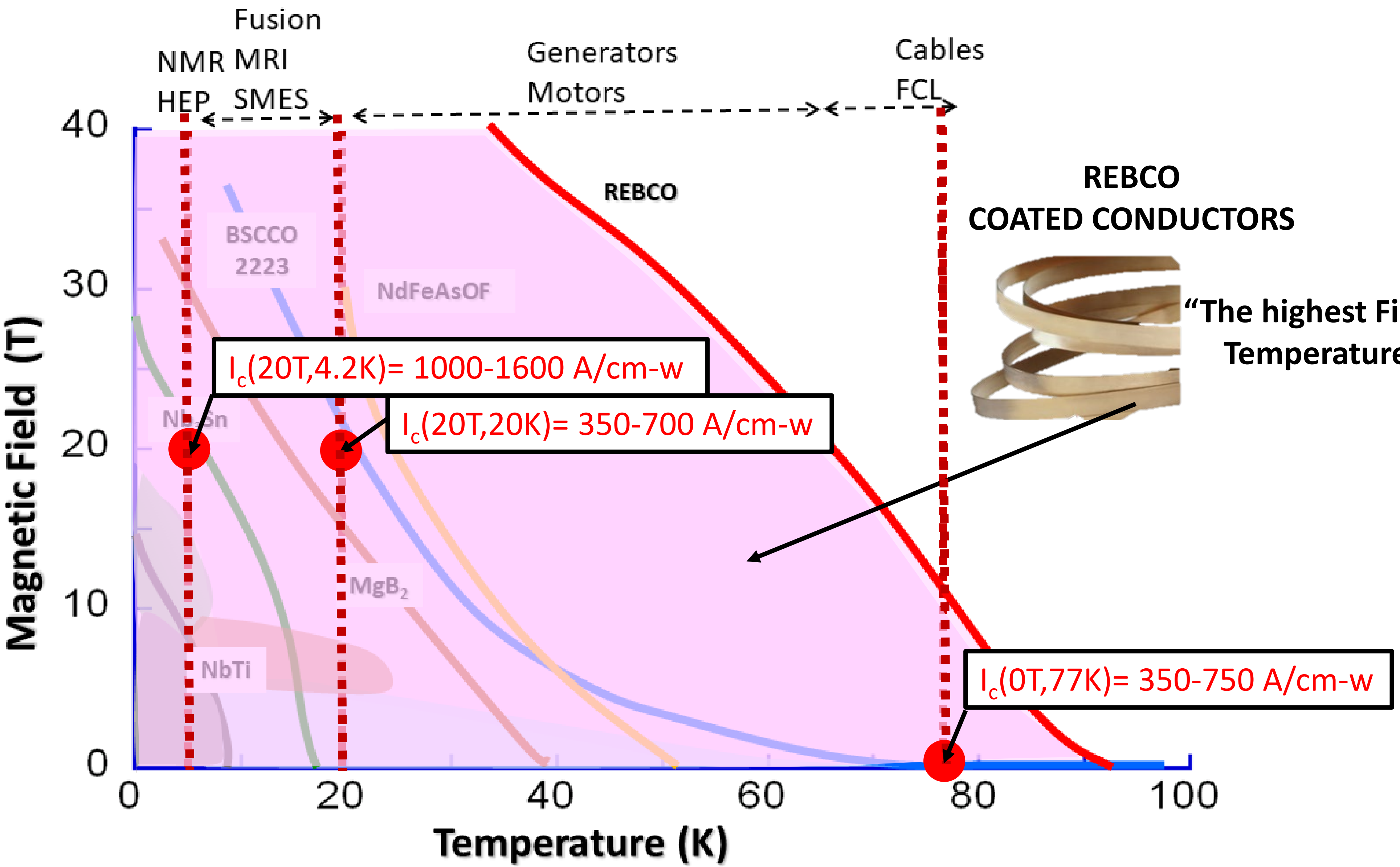

REBCO COATED CONDUCTORS

"The highest Field and highest Temperature conductor"

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MATERIALS SCIENCE

The prospects of high-temperature superconductors

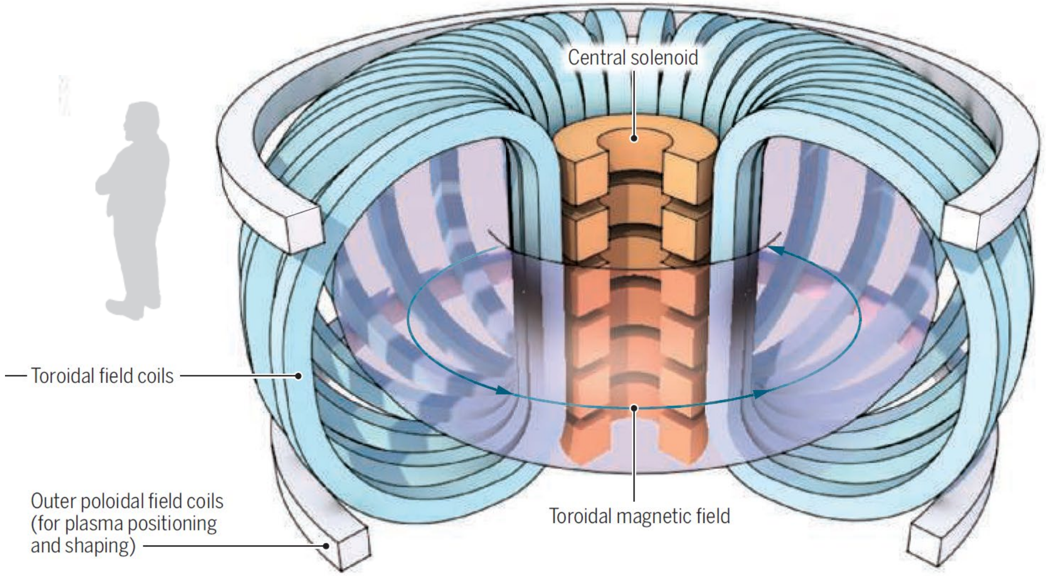
Overcoming cost barriers could make high-temperature superconductors pervasive

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

COMPACT FUSION



IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

HTS-CC NMR is already a commercial device

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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

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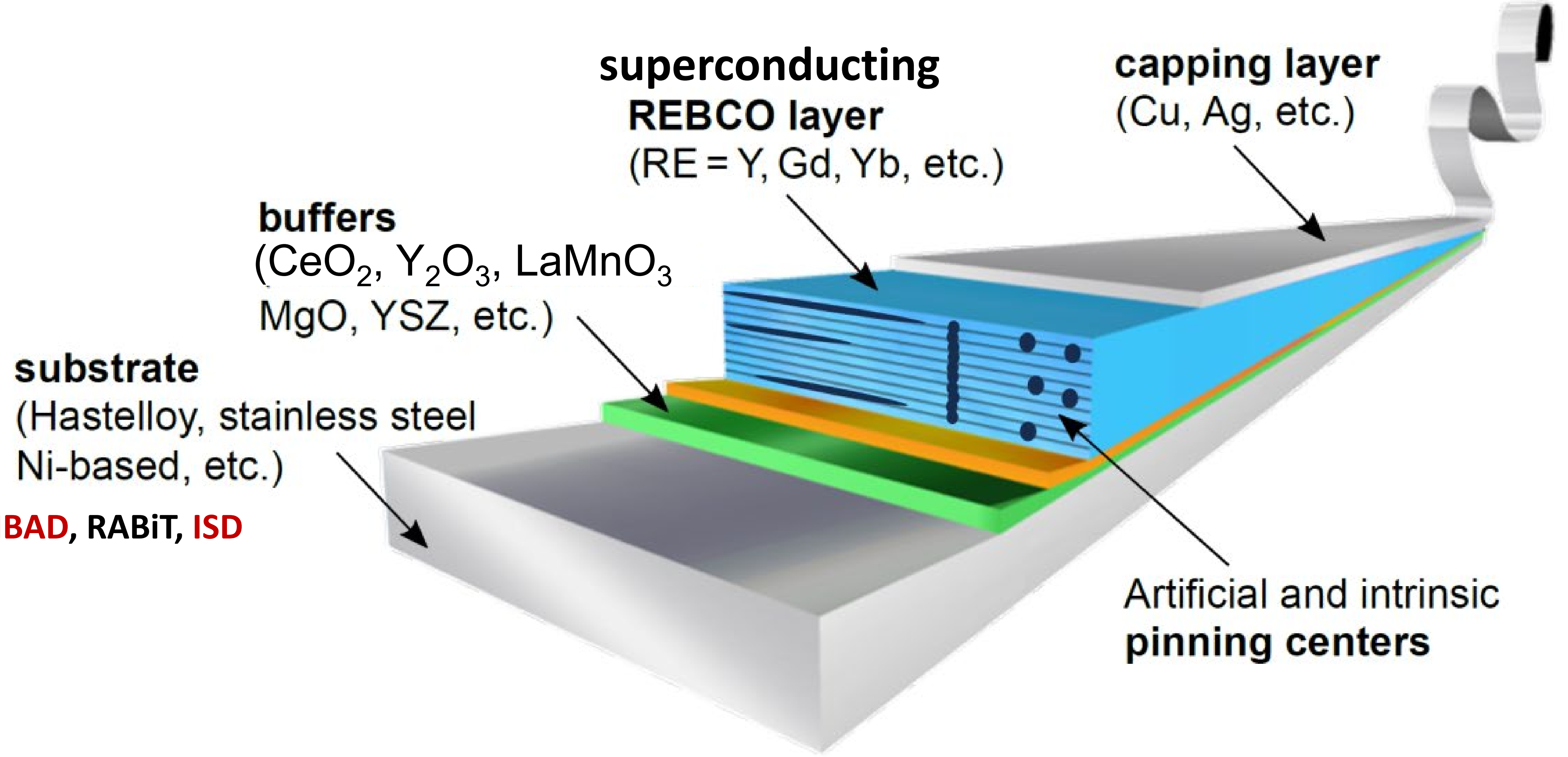

IBAD, RABiT, ISD

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

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Coated Conductors: materials objectives

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erc European Research Council Executive Agency

Coated Conductor penetration € / kA m

CHEAPER

- Ultrafast growth (G)
- Lower capital investment (€)
- Larger area manufacturing (W, L)
- Higher throughput
- Simpler processing
- Simpler architecture
- Higher yield

Low cost – High throughput

BETTER

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

Nanocomposites

Best combination

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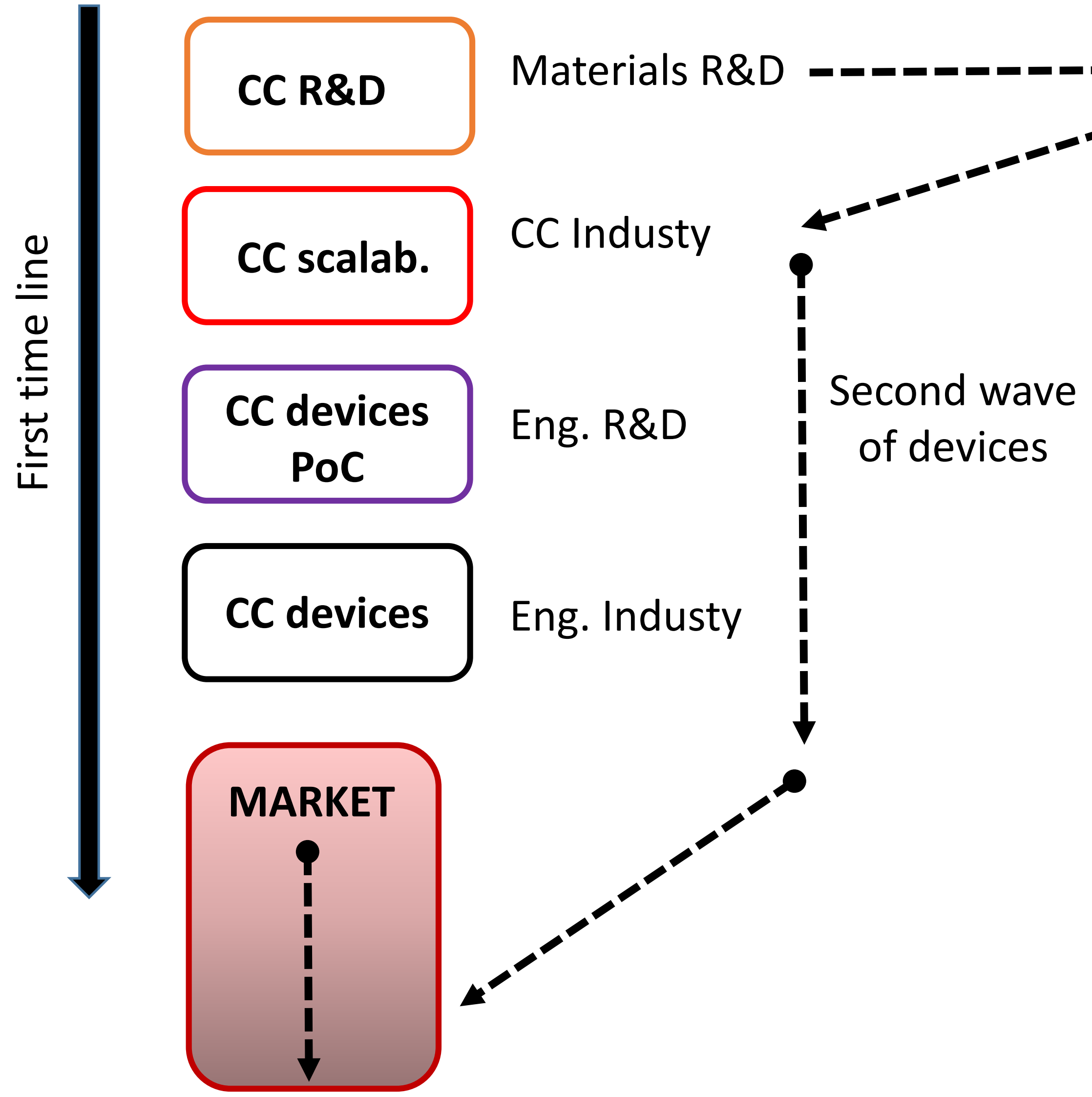
Contributions from CC Materials Research



Low-cost, High-throughput, High-performance

$$\frac{Cost}{Perfomance} = \frac{total\ cost\ per\ year}{G \ x\ L\ x\ W\ x\ J_c} = \frac{€}{kA\ x\ m}$$

- Fast growth-rate methods
- Optimization of robust vortex pinning schemes
- Growth of wide tapes

High-throughput experimentation can be of great help

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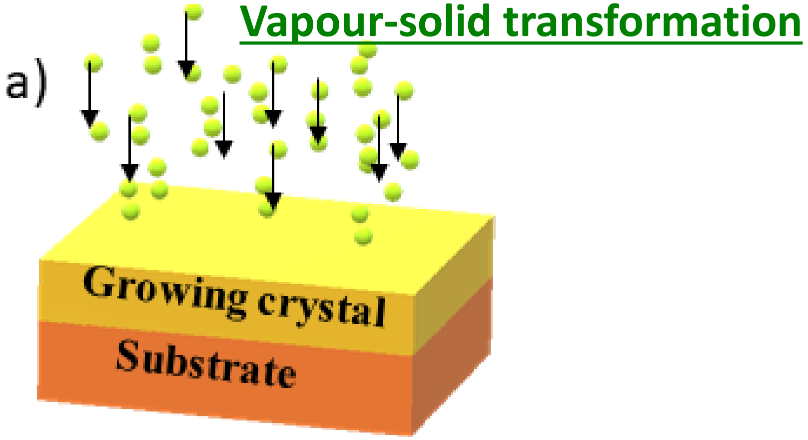
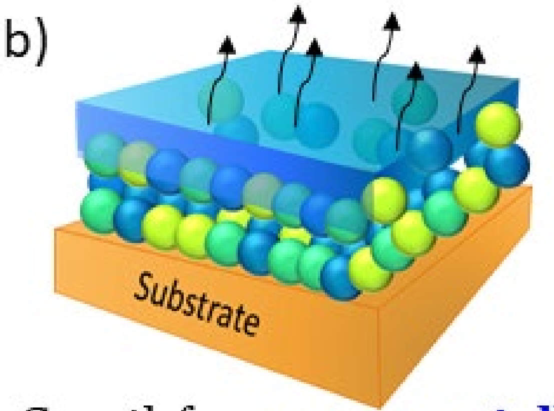
CSIC

REBCO growth processing

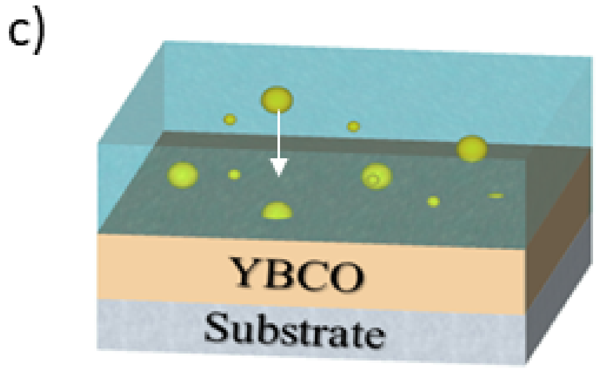
Supersaturation, σ, is the driving force for crystallization: σ ∝ G (growth rate)



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



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



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

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

$\sigma = f\,(\ln (P_{HF}^2 / P_{H_2O}))$

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

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

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

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

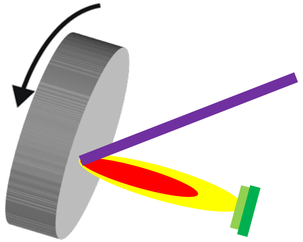
T. Puig, X. Obradors et al, Nat Rev Phys (2024), J. Driscoll et al, Nat Rev Mat (2021), X. Obradors et al, Superc Sci Technol (2024)

Transient Liquid Assisted Growth (TLAG)

A new high throughput non-equilibrium kinetically controlled growth process

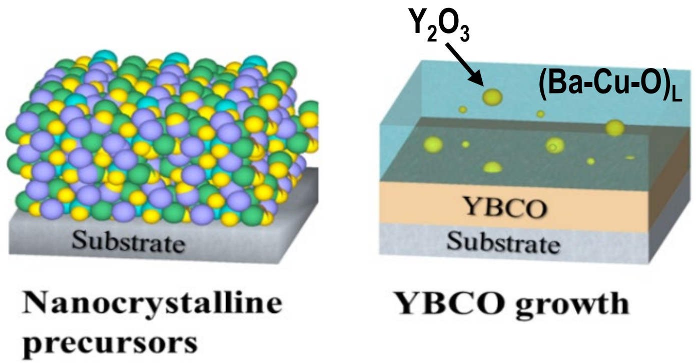
CSD

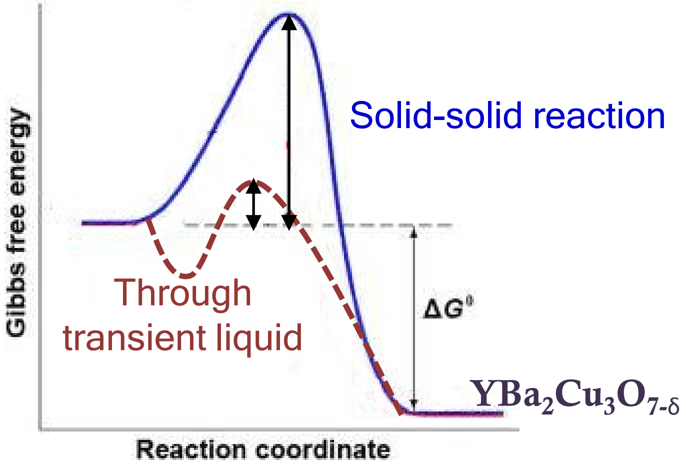
L. Saltarelli et al, ACS Appl. Mat. & Interf. (2022)



Low Temp PLD

A. Queralto et al, SUST (2023)



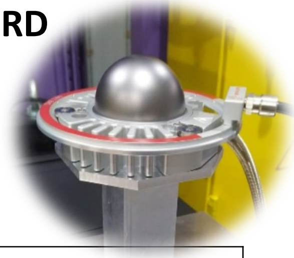


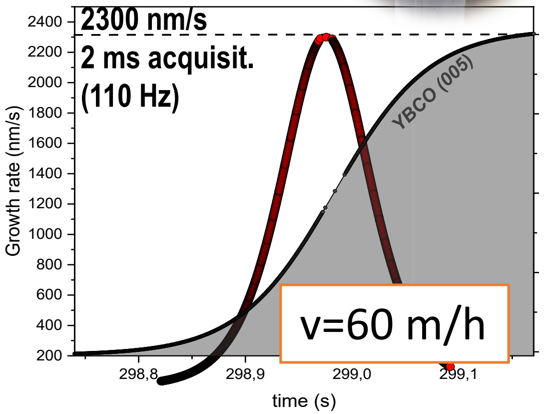
- High performance (3 MA/cm^2 at 77K)
- High throughput
- **High growth rate** (2.300 nm/s)
- Simple reactor
- Large area processing
- Low cost/performance method

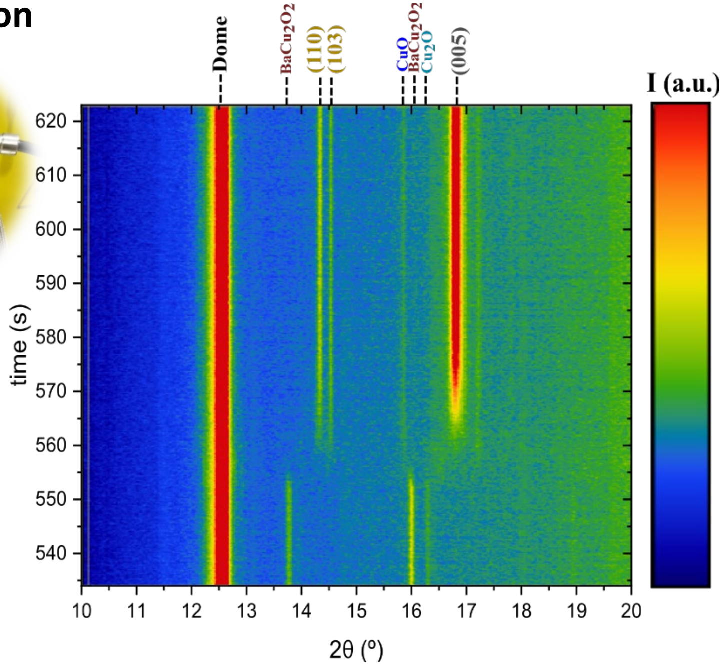
100 nm/s by **ultrafast-PLD** EuBCO/BHO (transient liquid growth at high T PLD)

Y. Wu, Materials & Design 224 (2022)

In-situ synchrotron XRD







L. Soler et al., Nat Comm (2020), S. Rasi, et al, Advance Science (2022); L. Saltarelli et al, ACS Mat Int (2024)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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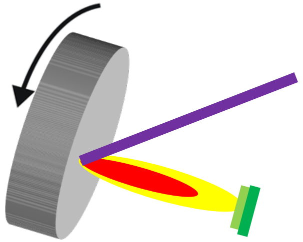
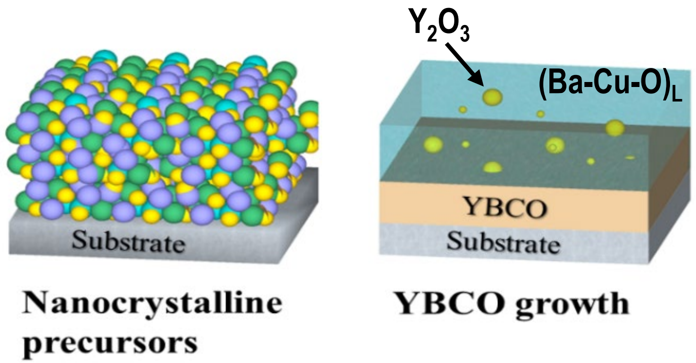
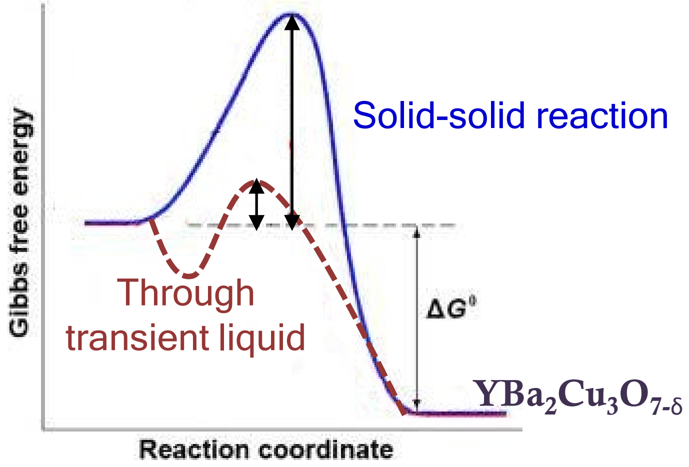


Low Temp PLD

A. Queralto et al, SUST (2023)





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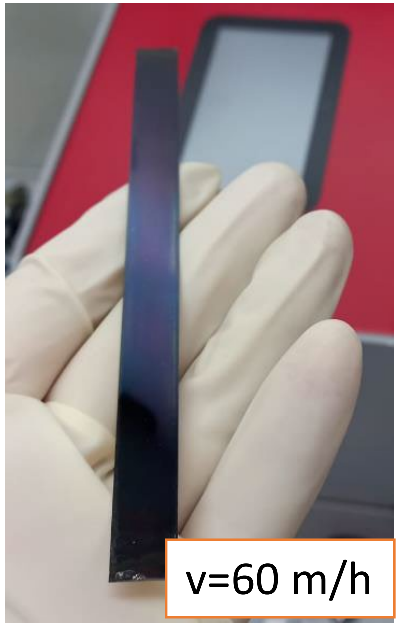
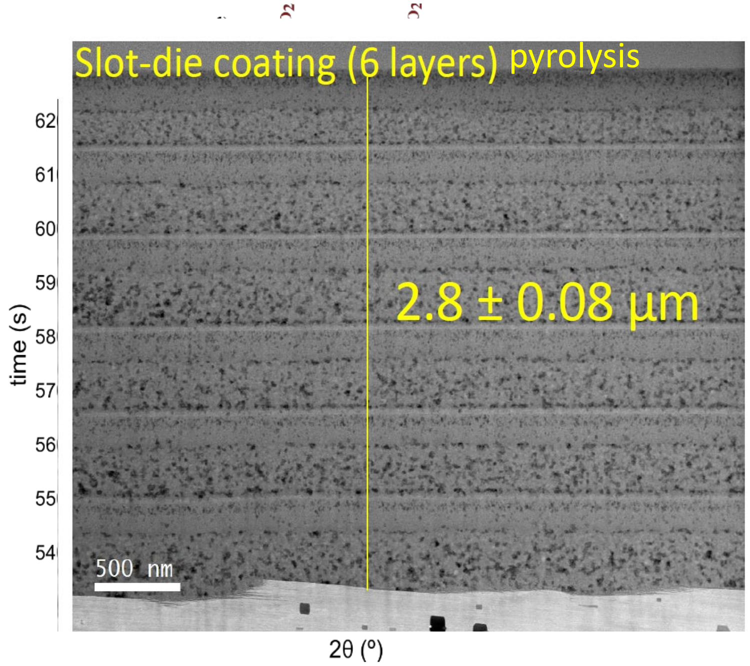




100 nm/s by **ultrafast-PLD** EuBCO/BHO (transient liquid growth at high T PLD)

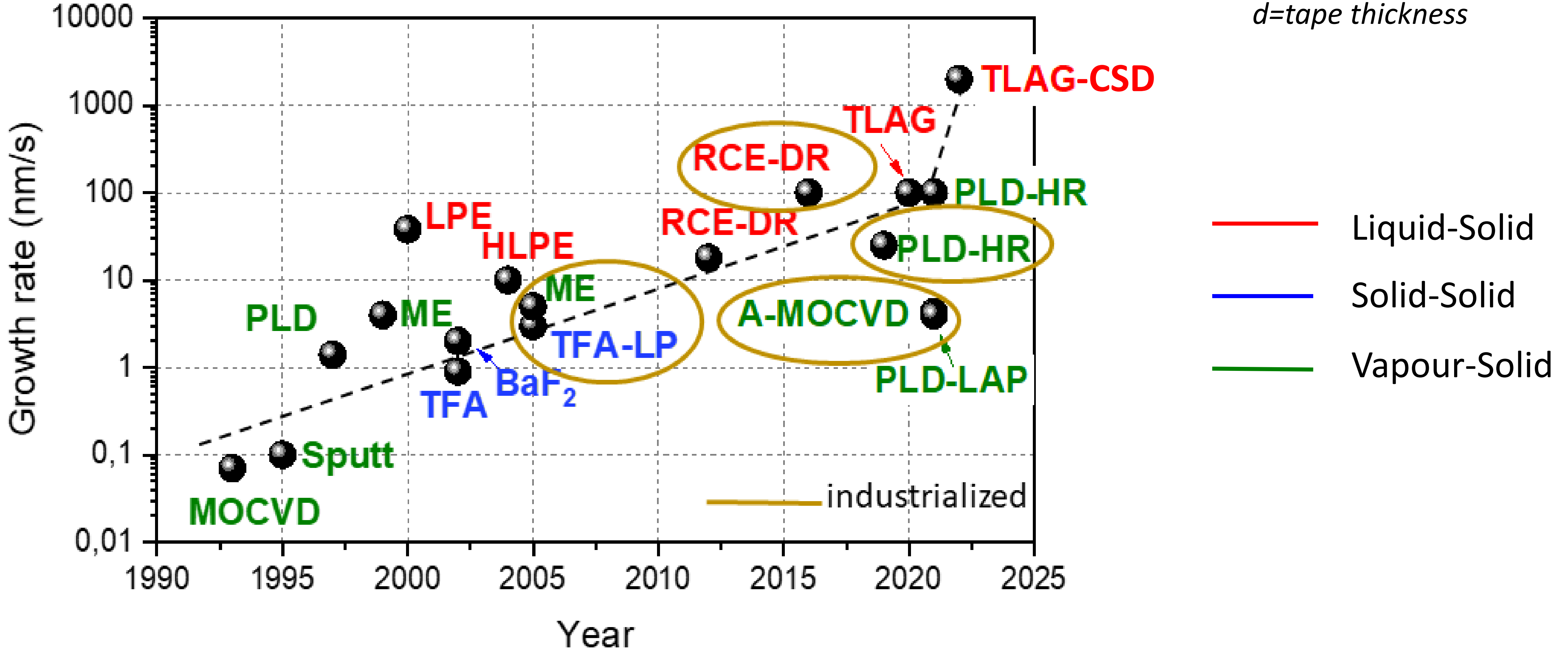
Y. Wu, Materials & Design 224 (2022)

L. Soler et al., Nat Comm (2020), S. Rasi, et al, Advance Science (2022); L. Saltarelli et al, ACS Mat Int (2024)

Reaching high Growth Rate: A path towards cost reduction

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

G= growth rate
W= tape width
L= tape length
d=tape thickness



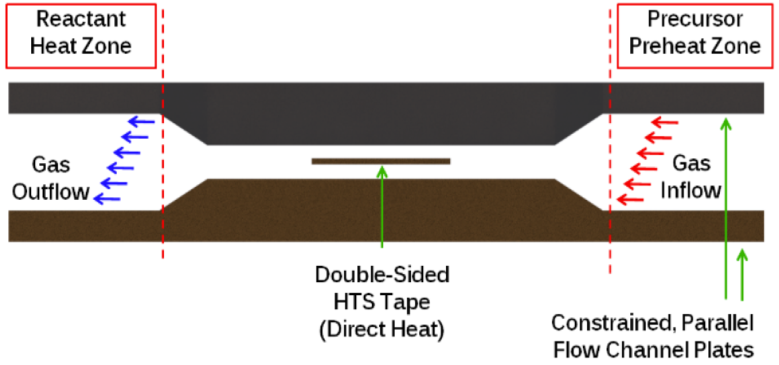
T. Puig, X. Obradors et al, Nat Rev Phys (2024)

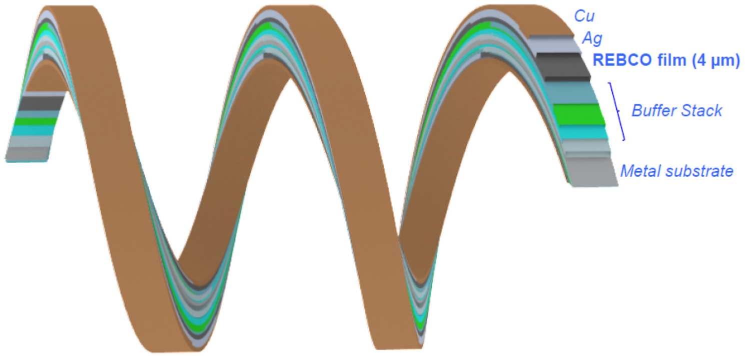
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Large area deposition: width, double side CC

Double-sided REBCO tapes by Advanced MOCVD

TcSUH AMPeers





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*** **(3.5 x I_c commercial tape)**

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

SuNAM
上创超导 Shanghai Creative Superconductors
THEVA

x 2.5 production capacity 125 mm wide tapes	Seed layer : PLD system Thick REBCO layer: RCE-DR system
New production line for 40 mm wide tapes	x 7 production capacity increase in 2025
Tape width 4 × 80 -100 mm	Capacity: 2500+ km$_{12}$

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40 mm solution deposition slot die	CSD TLAG growth under development

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Large area deposition and patterning (Fusion sterallator)

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IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), June 2023.
Presentation given at Coated Conductors for Applications Workshop, Houston, TX, USA, April 2023.

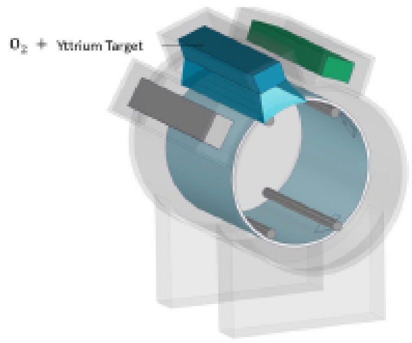
...and simplify HTS manufacturing

F. Volte and A. Usoskin

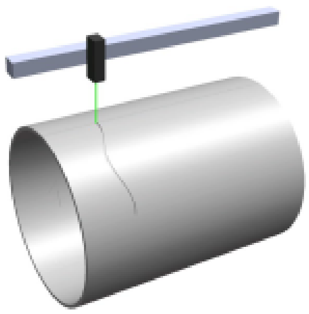
SNF Issue 53

MOCVD, 1 m wide cylinder

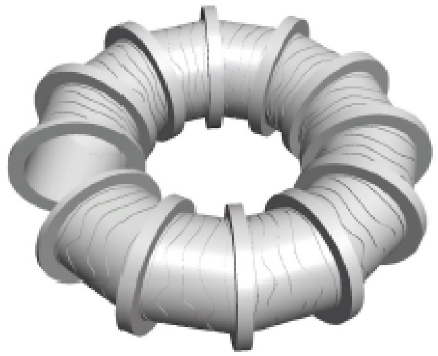
Deposition



Patterning



Assembly



2 machines instead of 7

7x faster process

Multi-layer

3D → two 1D movements

Portable sub-assemblies (cryostat + vessel + coil-set)

Patents pending

RENAISSANCE FUSION

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Nanocomposites: The best Artificial Pinning Centres

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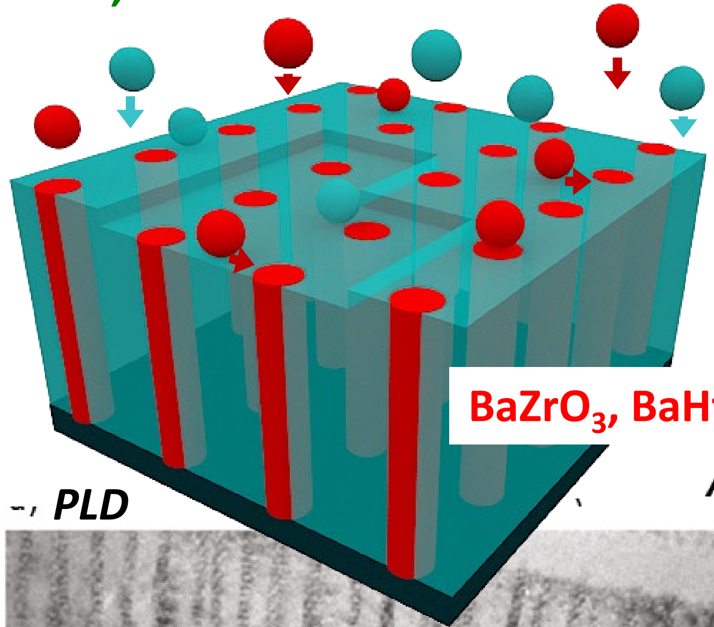
See SUST Special issue on APC 2018

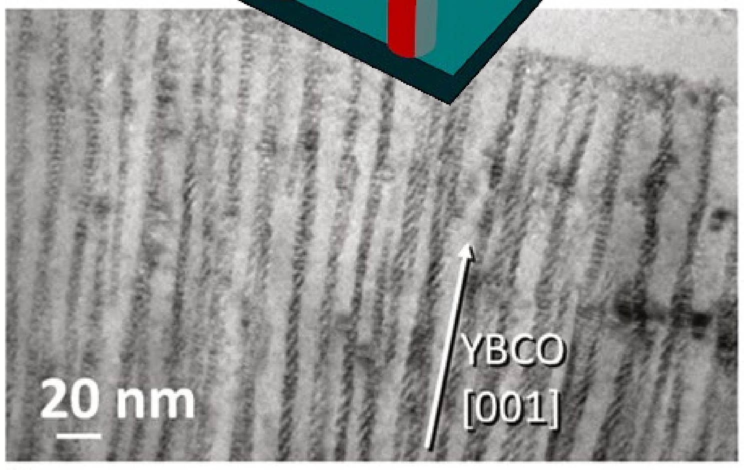
Simultaneous nanocomposite growth method

PLD, MOCVD



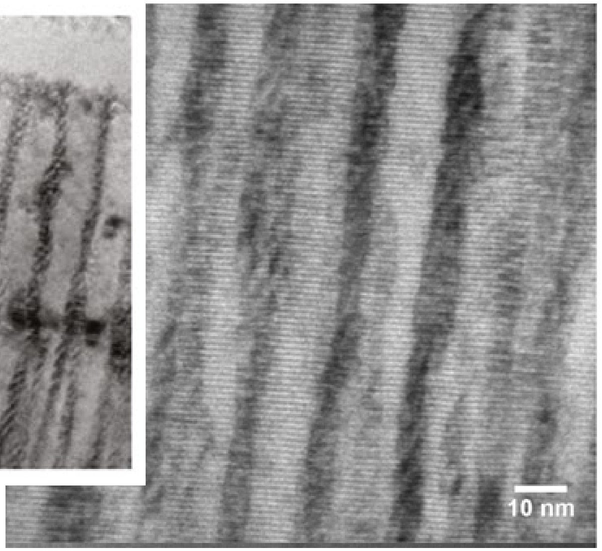
- Ad-atoms deposition, absorption, surface diffusion
- Self-assembly of epitaxial nanorods while epitaxial REBCO growth

PLD



C. Cantoni et al , ACSNano (2011)

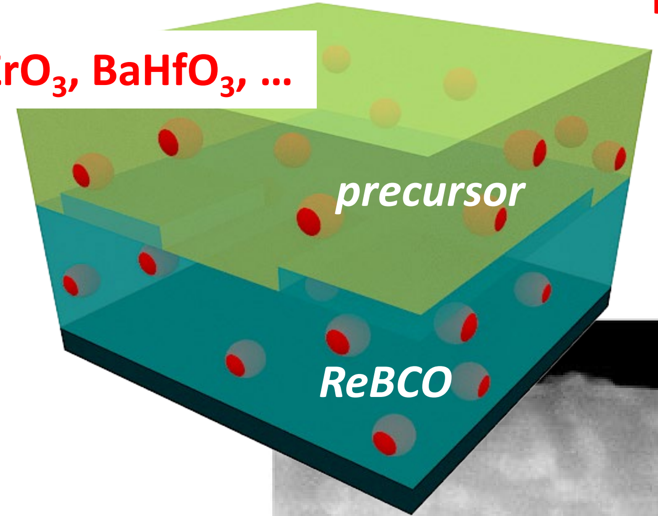
A-MOCVD



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

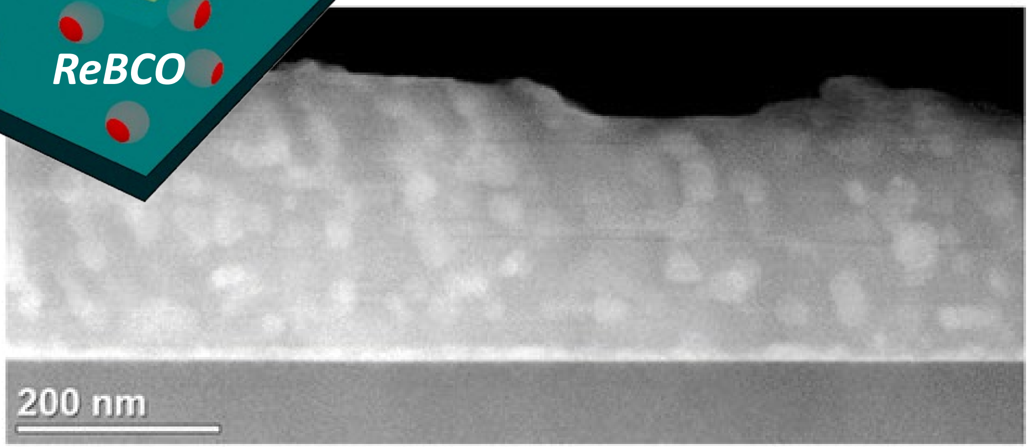
Sequential nanocomposite growth method

TFA-MOD, RCE-DR, TLAG-CSD

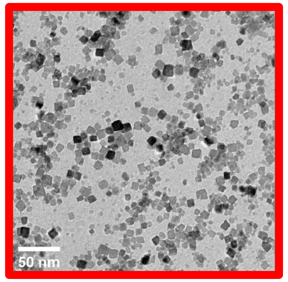


- Precursor deposition
- Np are spontaneously segregated or pre-formed
- ReBCO epitaxial growth traps random Np

TFA-MOD



A. Llordes, Nat Mat (2012)



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

N. Chamorro, RSC Adv. (2020)

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Simultaneous growth of Nanocomposites
Low versus high growth rate

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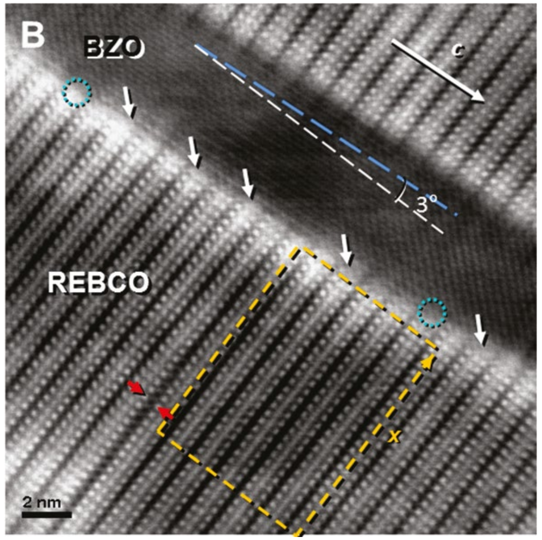
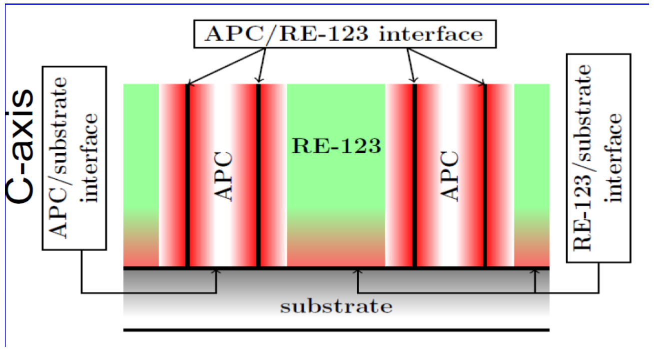
High growth rates (10-50 nm/s)

Grown at 0.6 nm/s



C. Cantoni et al , ACSNano 2011

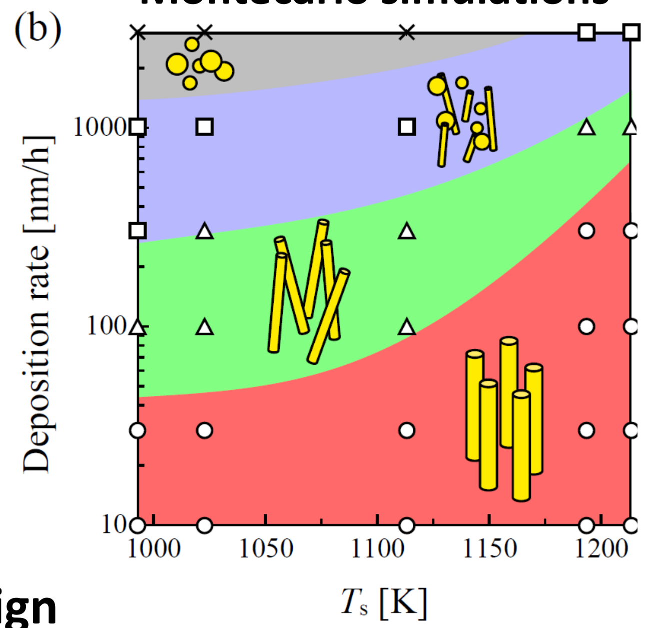
Elastic Strain energy model



Wu, et al, SUST 30 (2017)

Engineering landscape by design

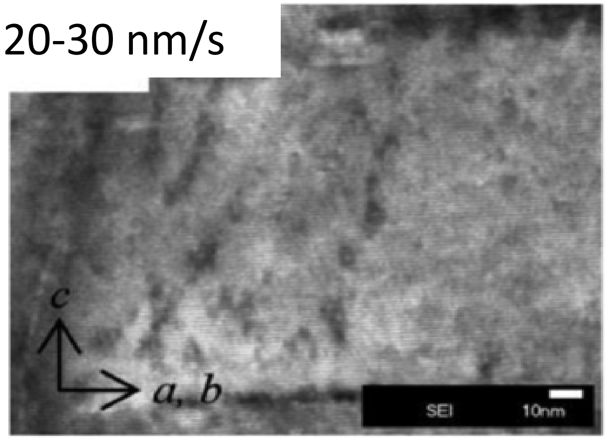
Montecarlo simulations



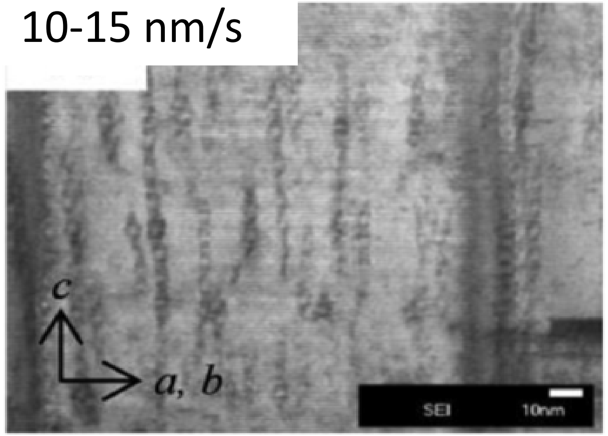
Y Ichino et al J.JAP 56 (2017)

EuBCO + $HfBaO_3$ nanorods

20-30 nm/s

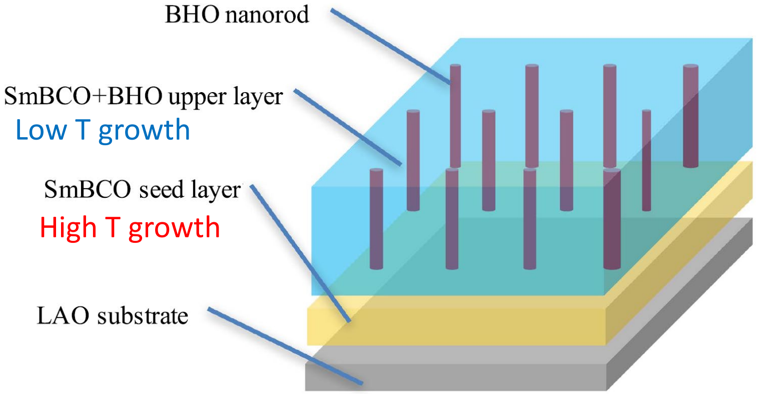


10-15 nm/s

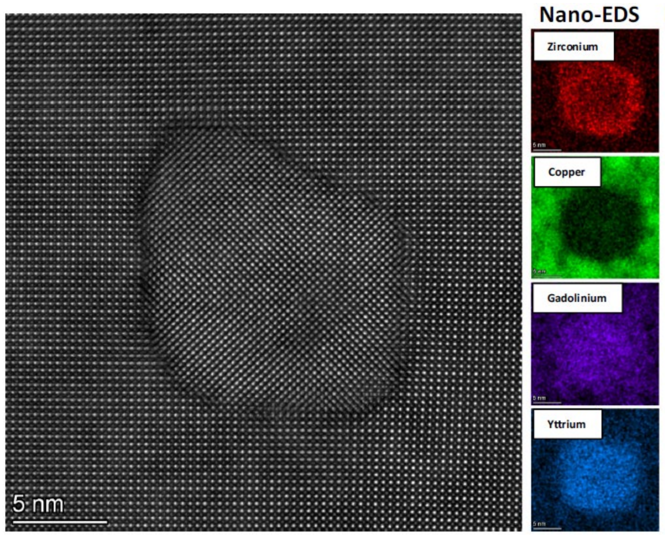


Fujita, S. et al. IEEE TAS 29 (2019)

LTG – PLD method



Y. Yoshida et al, SUST 30 (2017)

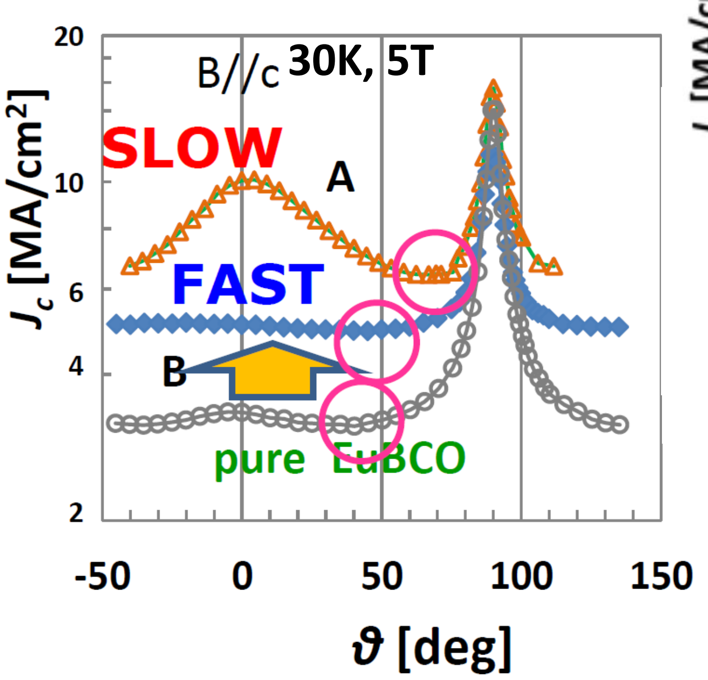


A. Goyal et al, Nat Comm (2024)

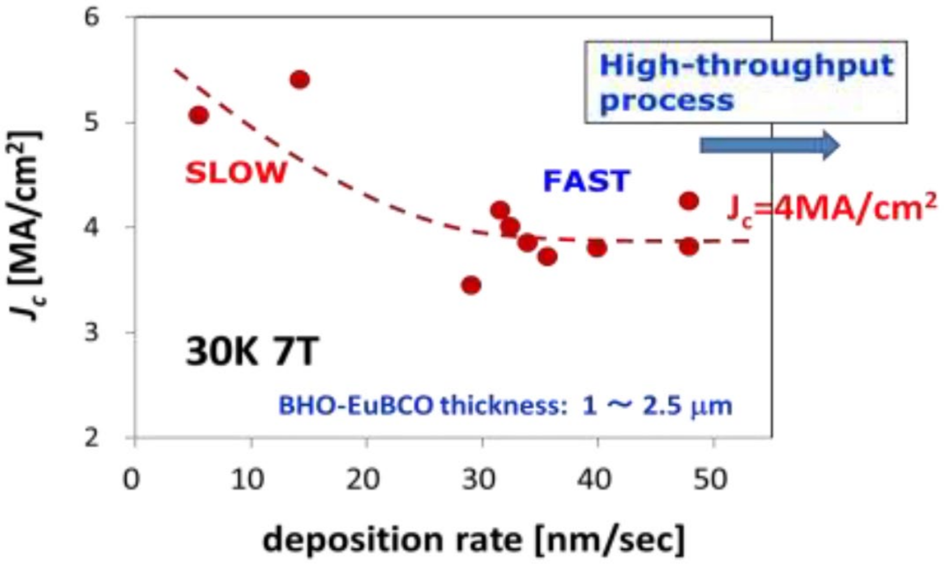
Vortex pinning consequences at high growth rate: PLD-HR

"Tsunagu" Technology Fujikura

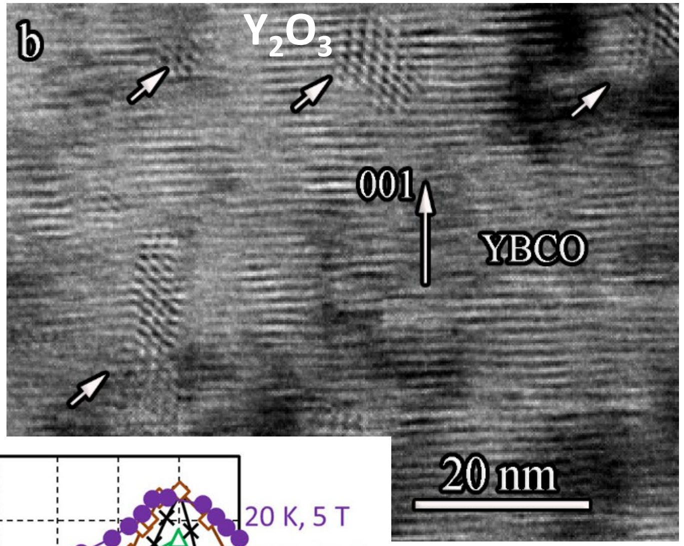
EuBCO + $HfBaO_3$ nanorods

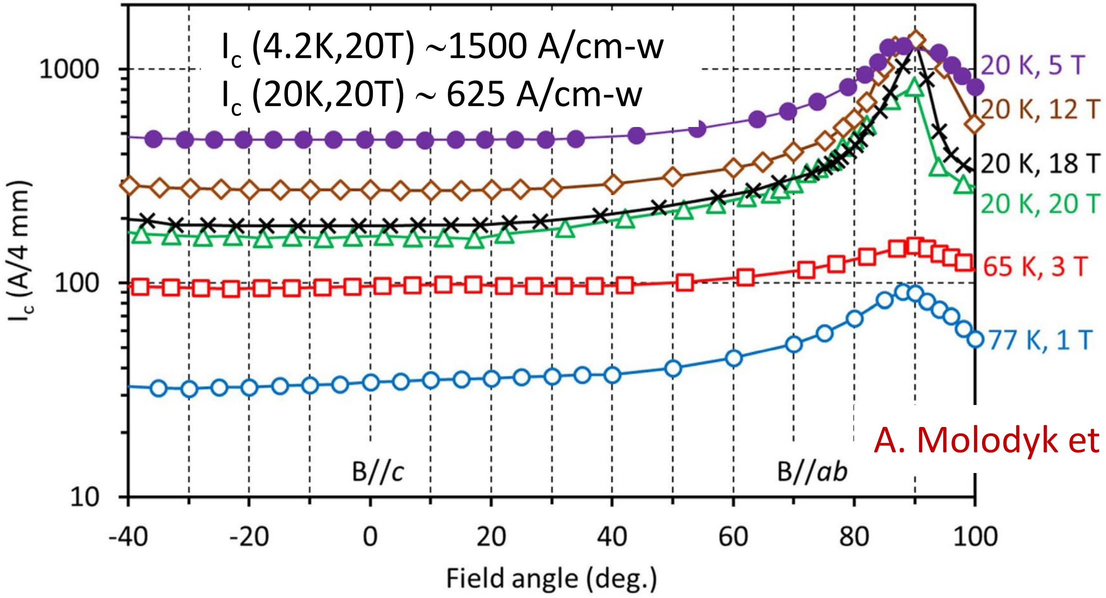


Y. Iijima, SNF Issue 53



YBCO + Y_2O_3 nanoparticles



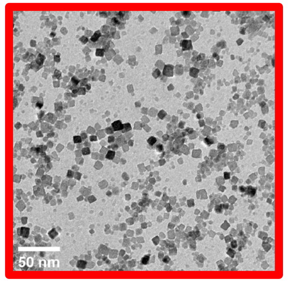


A. Molodyk et al, Sci. Rep 11 (2021)

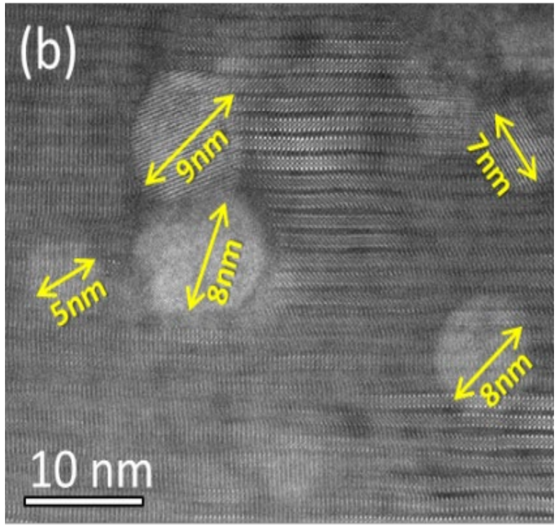
Aligned long nanorods are not essential at low T - high H

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

TFA-MOD (0.5-1 nm/s)



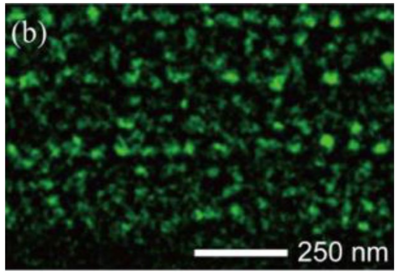
Fast heating with preformed Np

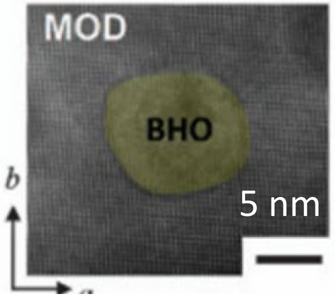


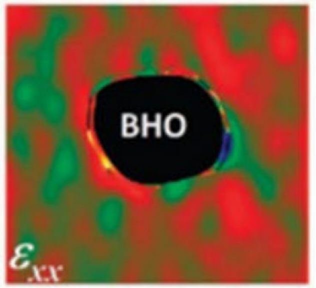
Small randomly oriented Np are obtained V ~ 7.7 %

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

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







UTOC: ultrathin multicoating to avoid Np coarsening

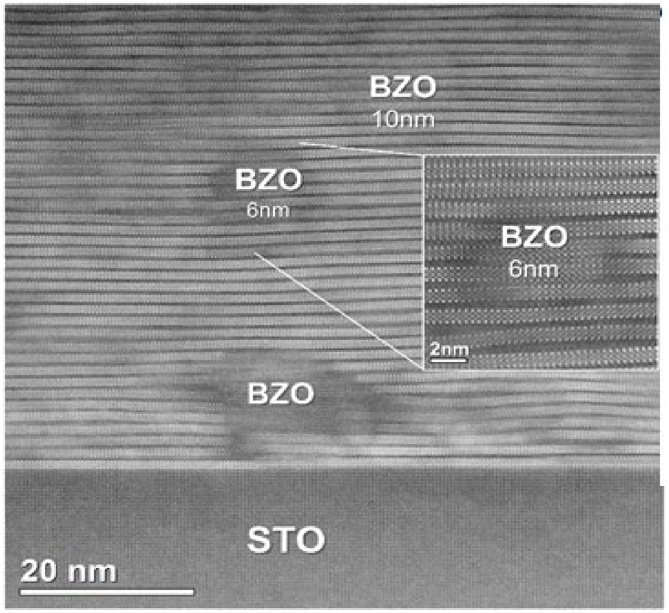
J_c (77K, sf)~ 5.5 MA/cm^2

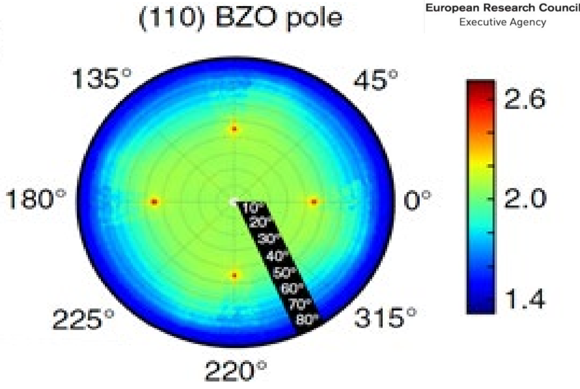
J_c (26K, 6T)~ 11 MA/cm^2

T. Izumi, K. Nakaoka, SUST., 31 (2018)

M. Miura et al, NPG Asia Materials 9 (2017)

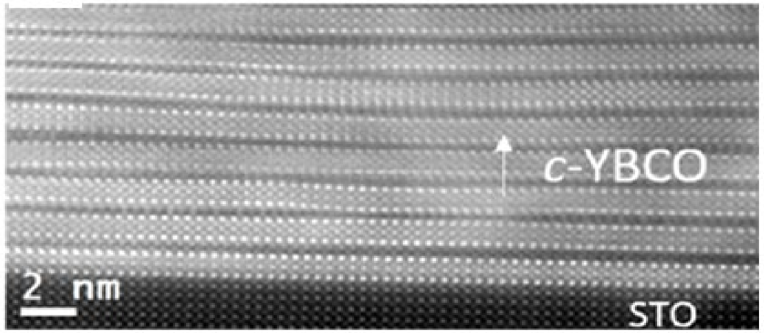
TLAG-CSD (50-2000 nm/s)





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)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Vortex pinning consequences at high growth rate: TLAG-CSD

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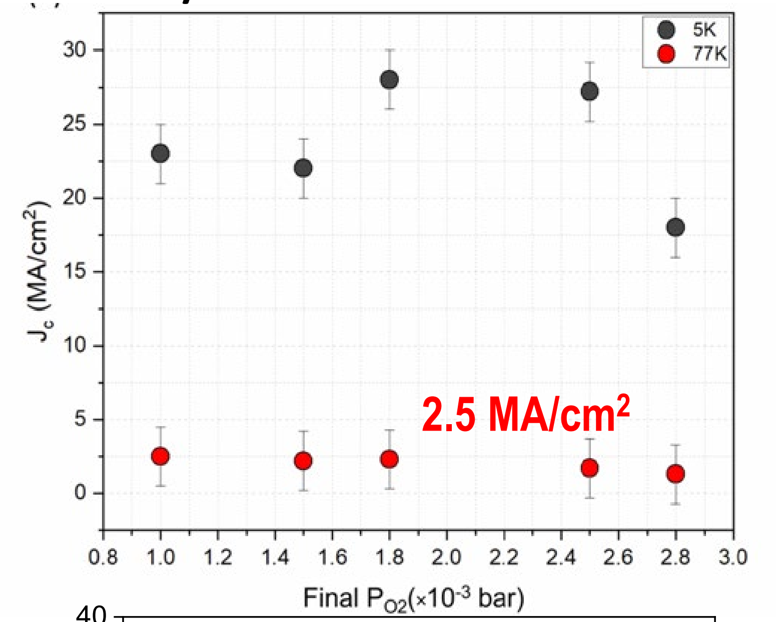
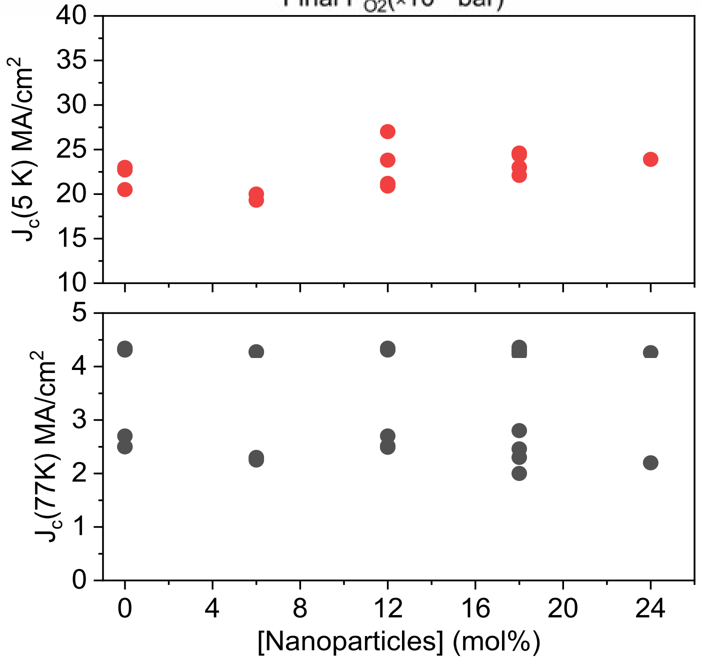
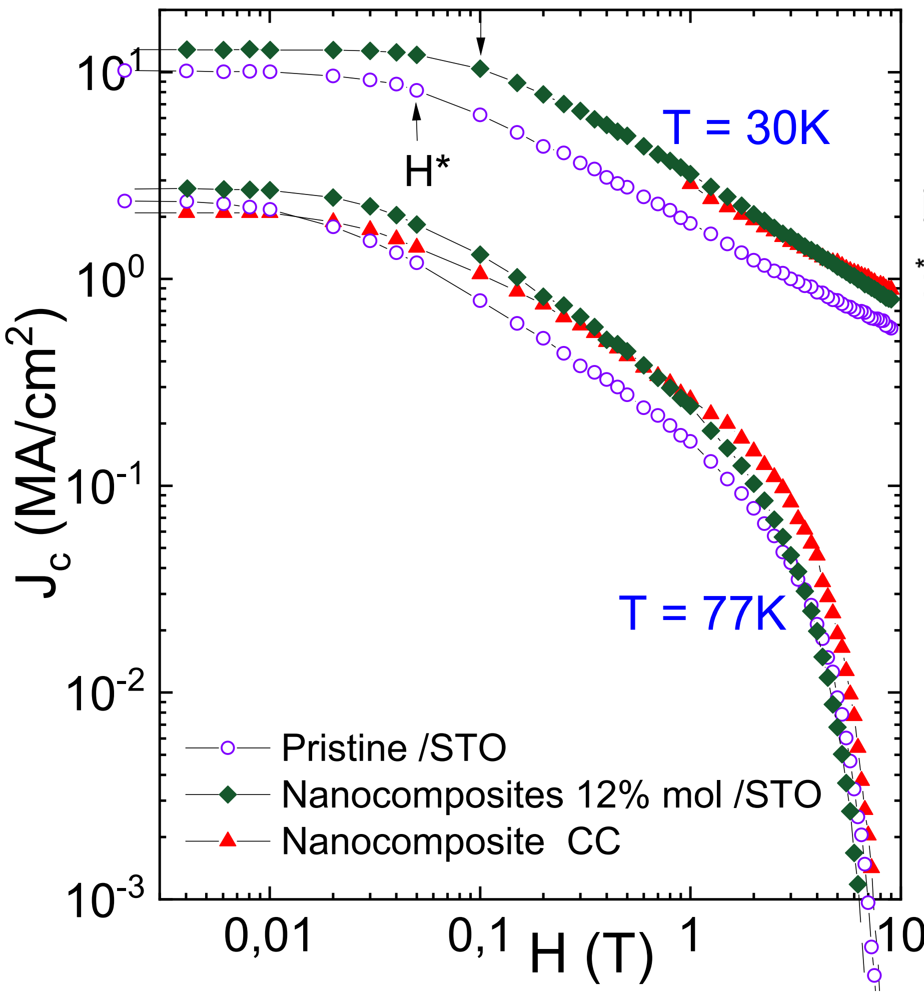
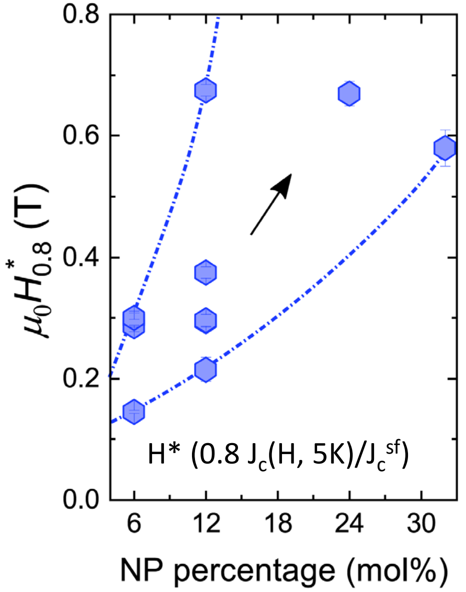
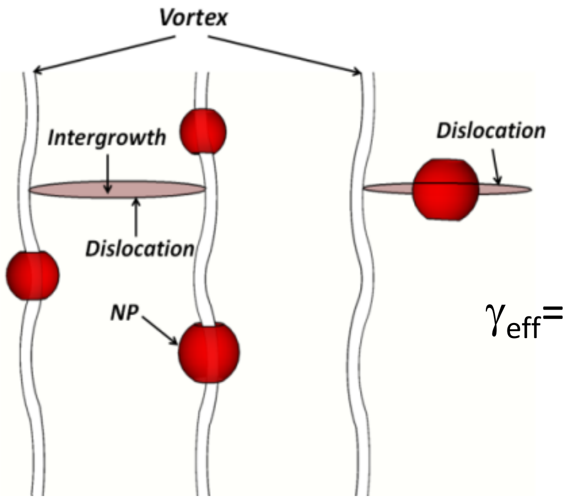
50 nm/s → 1500 nm/s









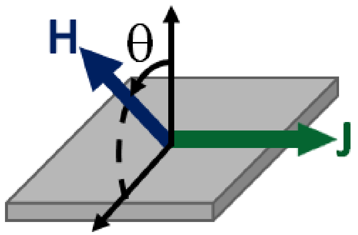


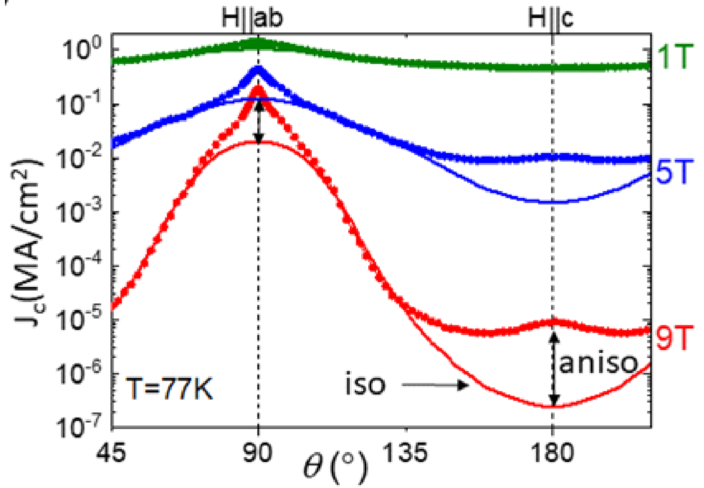
γ_{eff}= 2-2.5

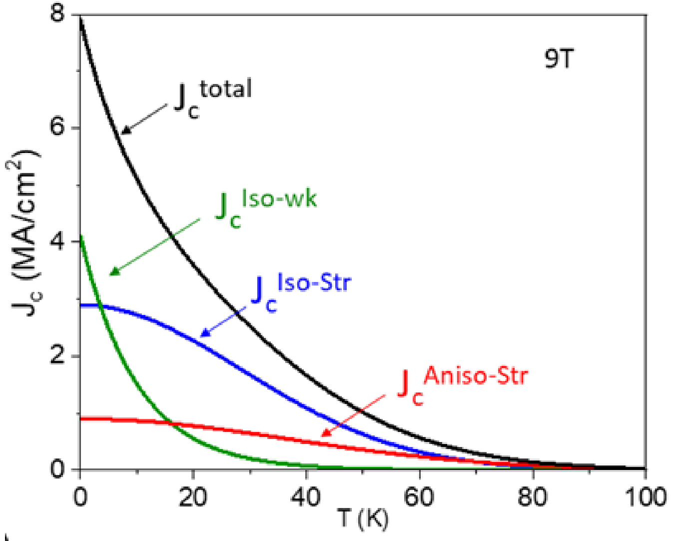
Rich vortex pinning determined by the defect microstructure of high growth rates

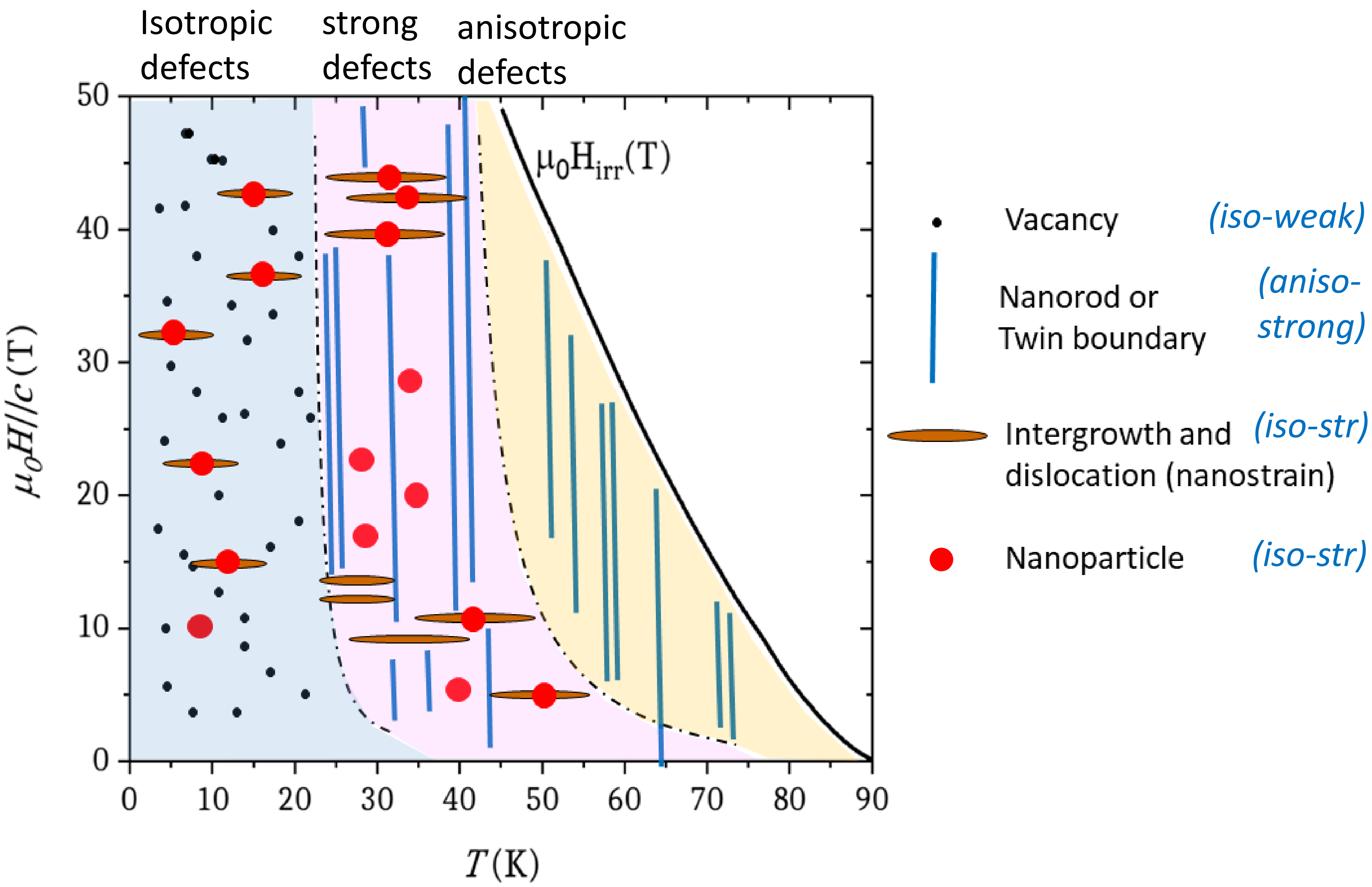
L. Soler et al., Nat Comm (2020), S. Rasi et al, Advance Science (2022)

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 (2024)

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

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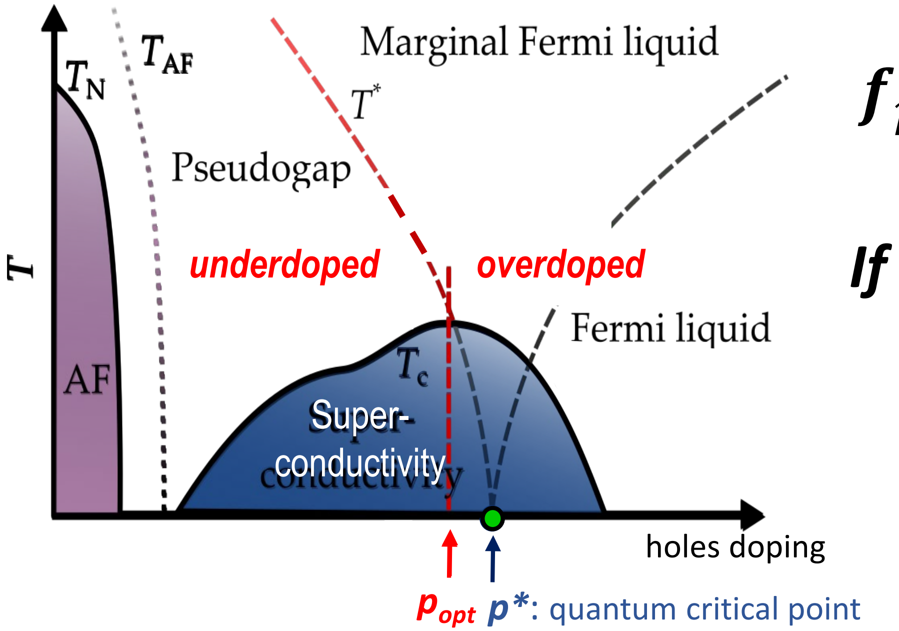
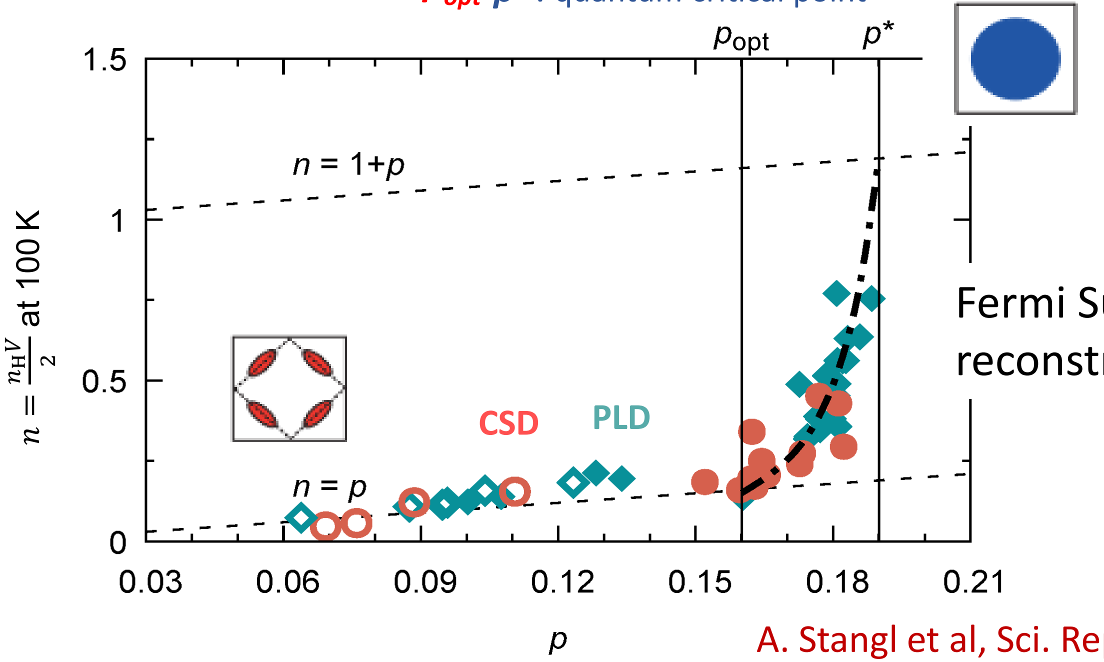


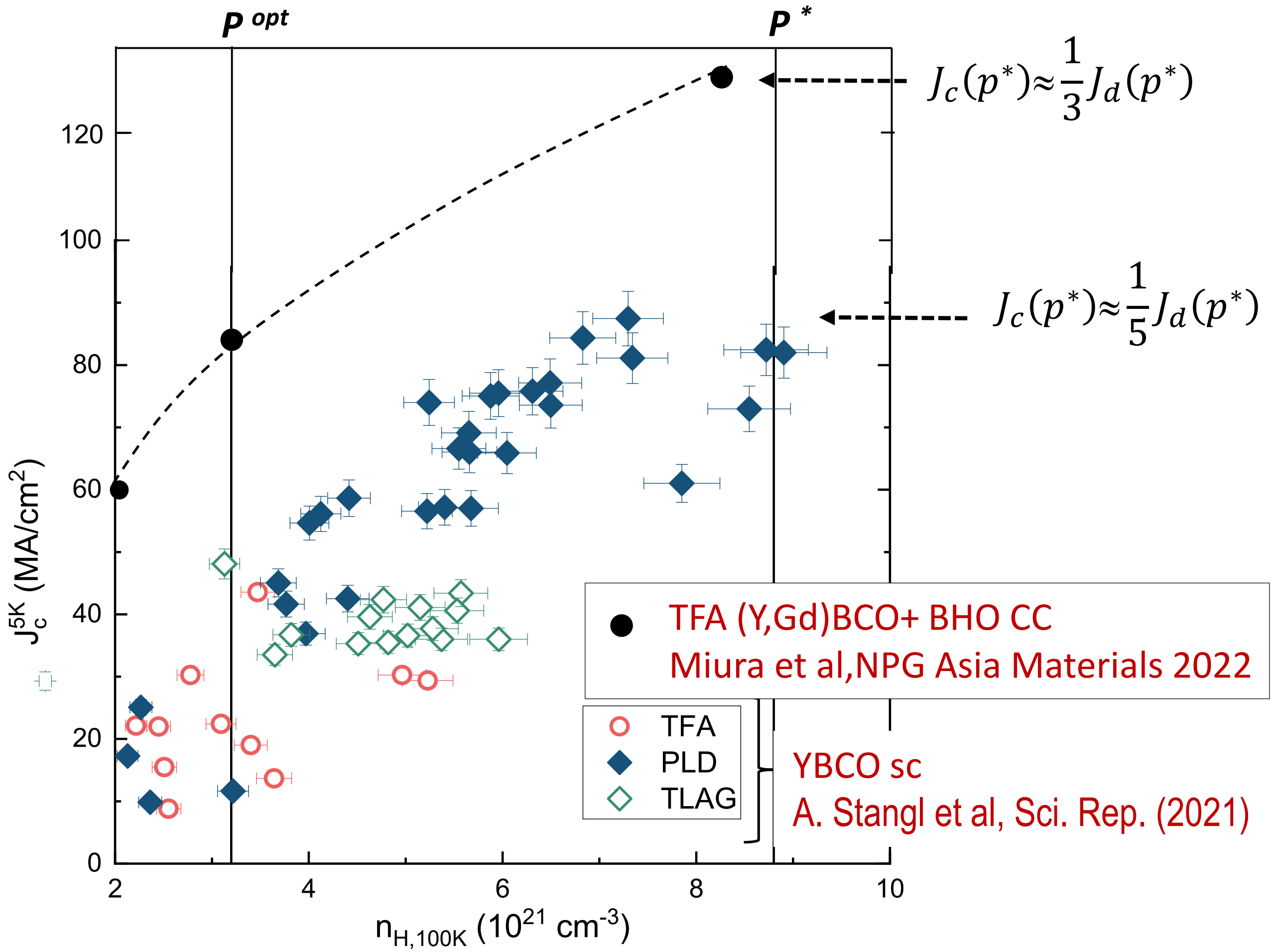
$$f_p \propto E_c \propto n_H$$

$$\text{If } n_H \square\!\rightarrow \; J_c\square$$



Fermi Surface reconstruction

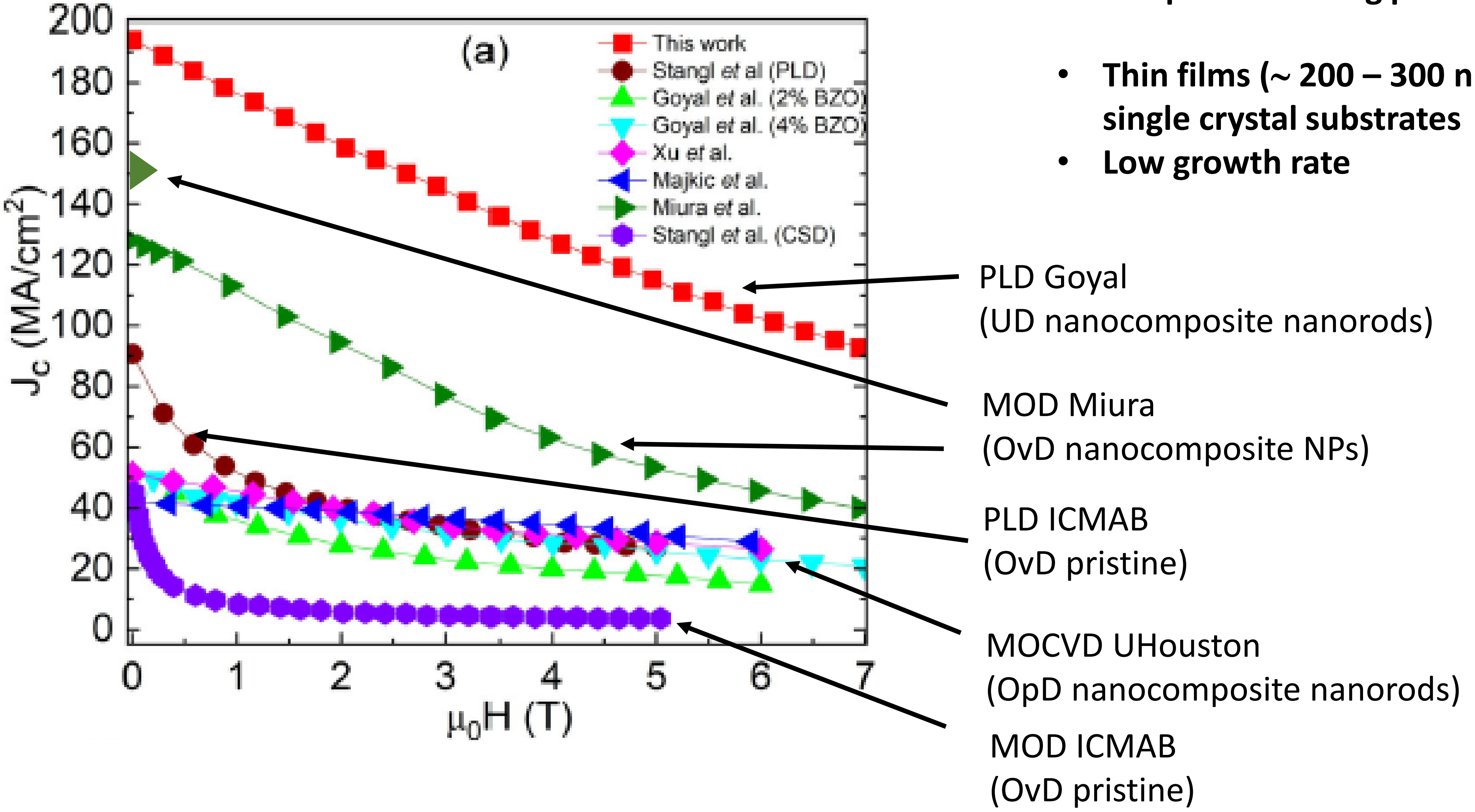
A. Stangl et al, Sci. Rep. (2021)



Interest in combining high throughput and nanocomposite CC in overdoped state

Record values of superconducting performance in REBCO CCs

T = 4.2K, H//c



Best superconducting performance at 4.2 K

- **Thin films (~ 200 – 300 nm) on IBAD or single crystal substrates**
- **Low growth rate**

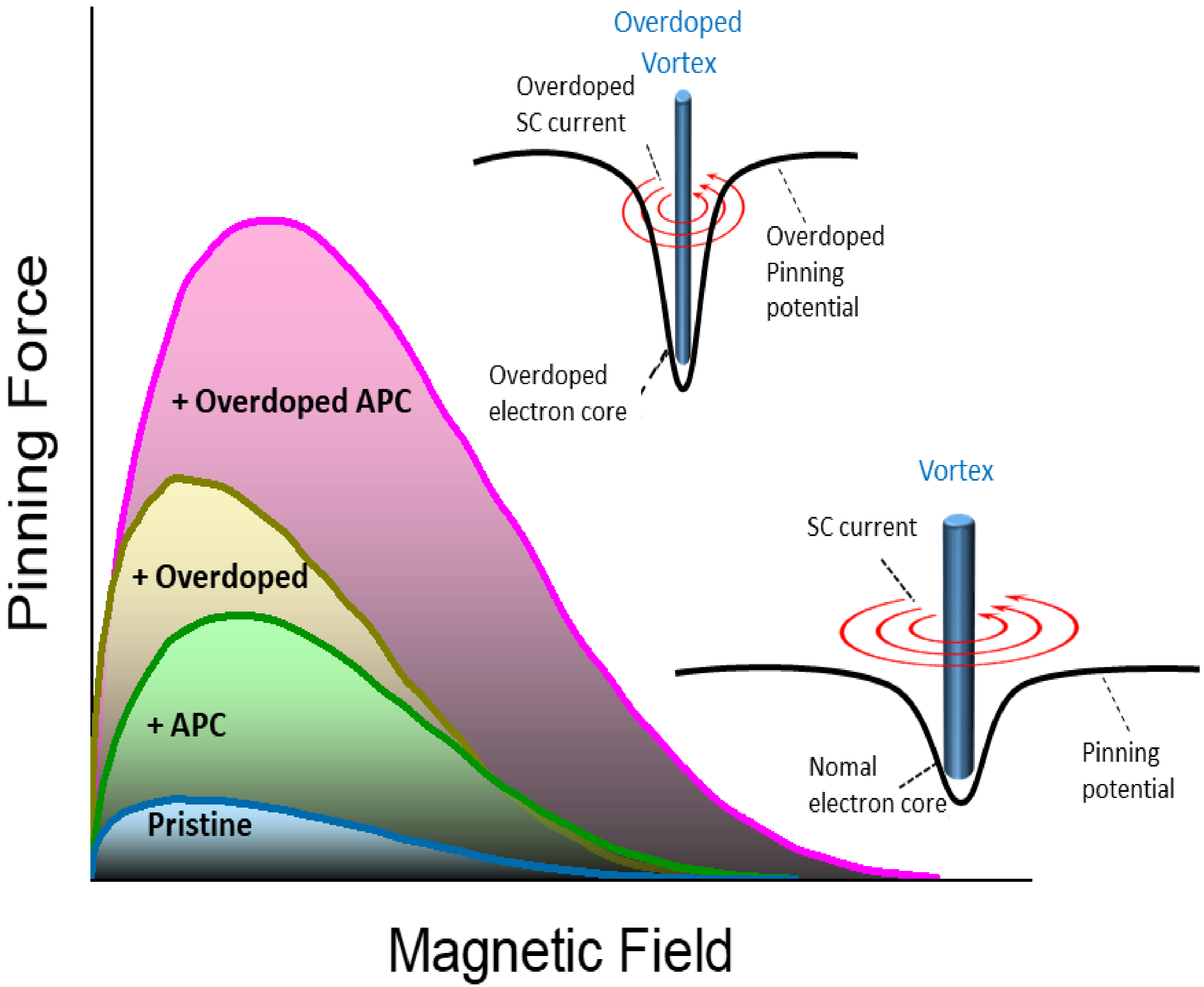
A. Stangl et al, Sci. Rep. (2021); M. Miura et al, NPG Asia (2022); Majkic et al, SUST (2018); Goyal et al, Nat Comm (2024)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Record values of superconducting performance in REBCO CCs

Performance enhancement

1. First thrust: biaxially textured CCs (pristine) (optimally doped)
2. Second thrust: Artificial pinning Centers (optimally doped)
3. Third thrust: synergy enhanced carrier concentration (overdoped) and APCs



X. Obradors, T. Puig, "Pin the vortex on the superconductor", Nature Mater. News and Views (2024, in press); M. Miura et al, NPG Asia (2022); M. Miura et al., Nat Mat (2024) for IBS

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Summary materials processing challenges

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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						To demonstrate
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

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Other application driven relevant materials aspects: from CC to conductor

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Coated Conductor tape:

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

Conductor wire:

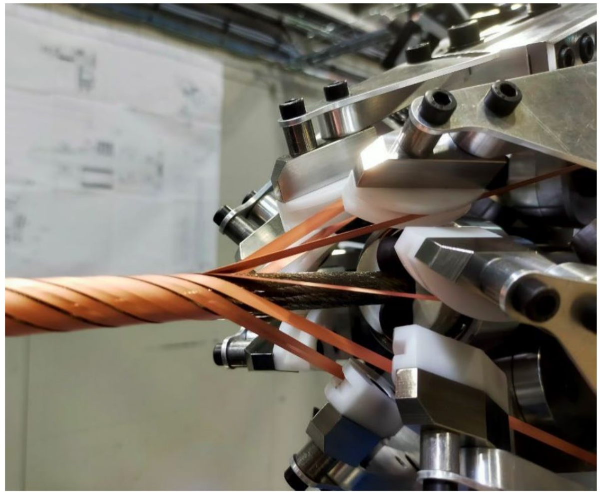
- Conductor configuration (current sharing, transposition, …)
- Conductor bending radius
- Winding methodologies (impregnation, winding guides,…)
- Insulated, non-Insulated, partially insulated wiring
- Thermal stress, mechanical resilience, quench management, ac-losses, ….

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

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

S. Kar et al, SUST 33 (2020)

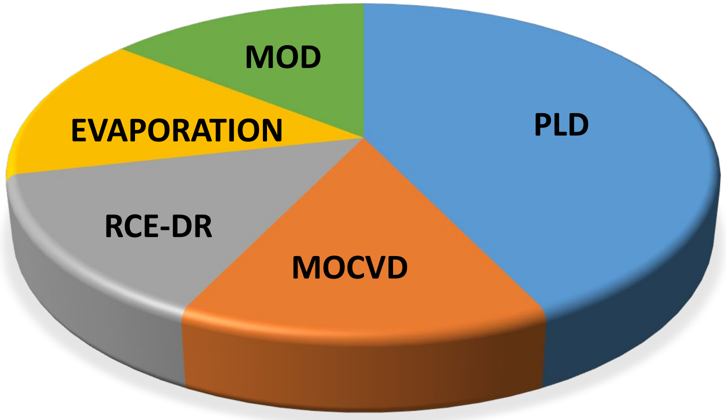
N Yanagi et al J. Phys.: Conf. Ser. 2545 (2023)


A. Ballarino, HiTAT Workshop, Geneva, March 2023

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Status of CC fabrication at Industrial scale

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 Shanghai Superconductor Technology	PLD	IBAD	YBCO	BZO nanorod
SuperPower Inc.	MOCVD	IBAD	(Y,Gd)BCO	BZO nanorod
			HM prod.	
THEVA	ME	ISD	GdBCO	
SuNAM	RCE-DR	IBAD	GdBCO	
上创超导 Shanghai Creative Superconductors	CSD	IBAD	YBCO	BZO nanoparticle



R&D product

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

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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 m² unit $I_c L$ = 1 GA-m/year for 2024

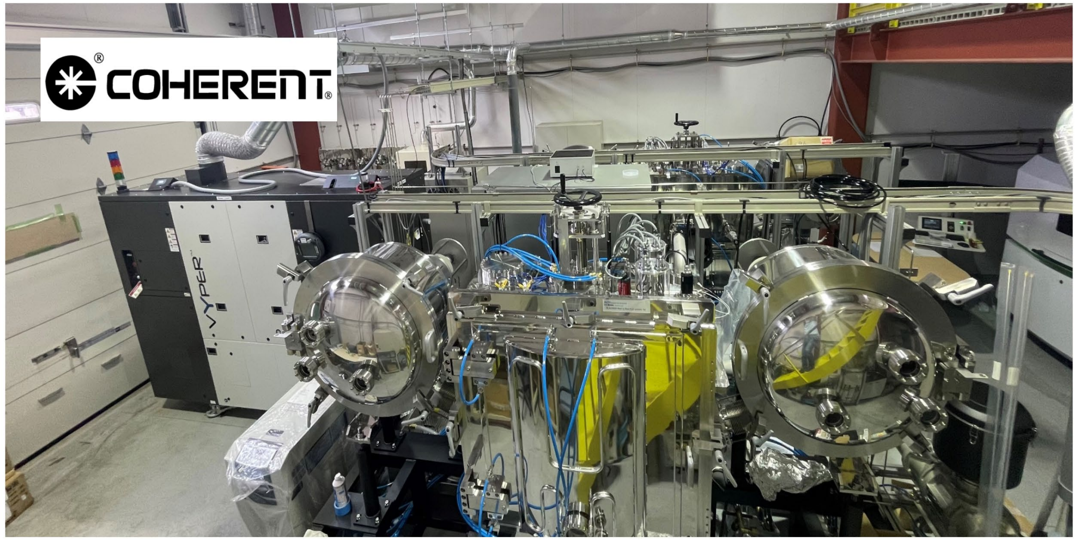
(2500 tapes x 600 A (20T, 20K) x 700 m) *(12 mm eq.)*

We are up to build more modular plants as demand unveils

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

25000 km/yr (12 mm) in 2028

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

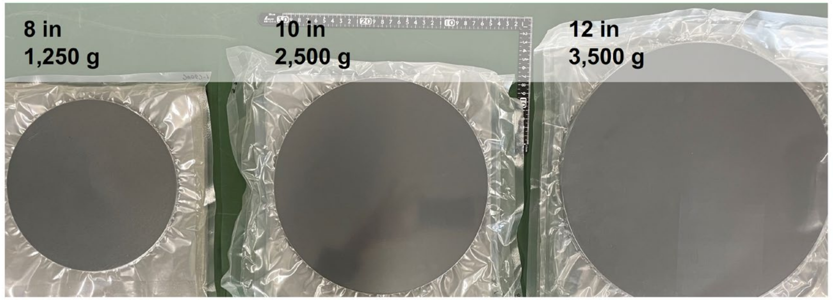


February – received equipment, April – started operation

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

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

Scaling up PLD major raw materials (PLD targets)



IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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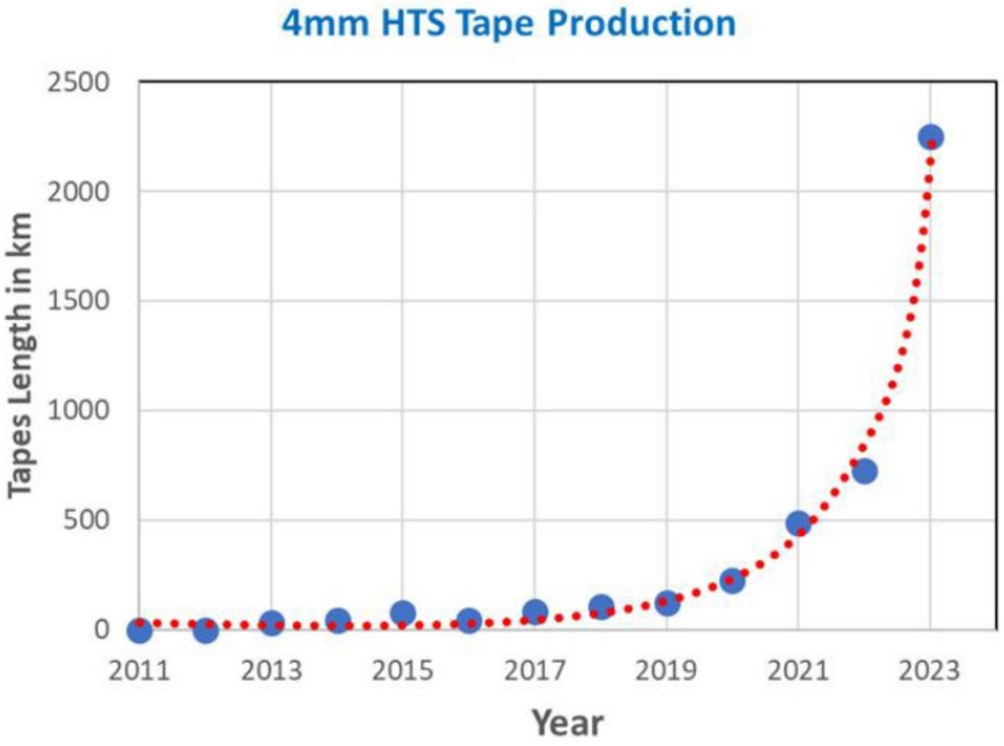

5000 m^2 unit $I_c L$ = 1 GA-m/year for 2024

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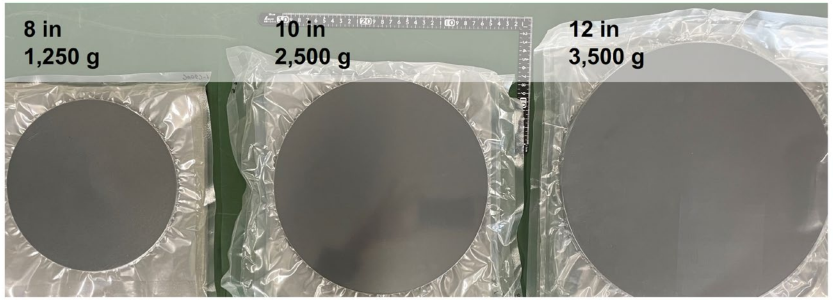
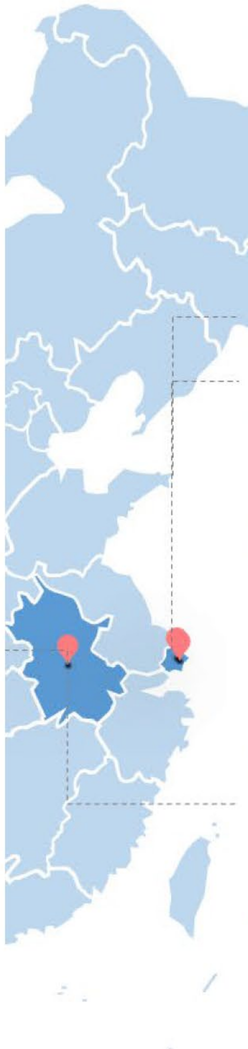
Scaling up PLD major raw materials (PLD targets)



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

25000 km/yr (12 mm) in 2028

Shanghai Superconductor Technology (SST) (PLD method)



Plant #1 (Upgrading of existing plant)

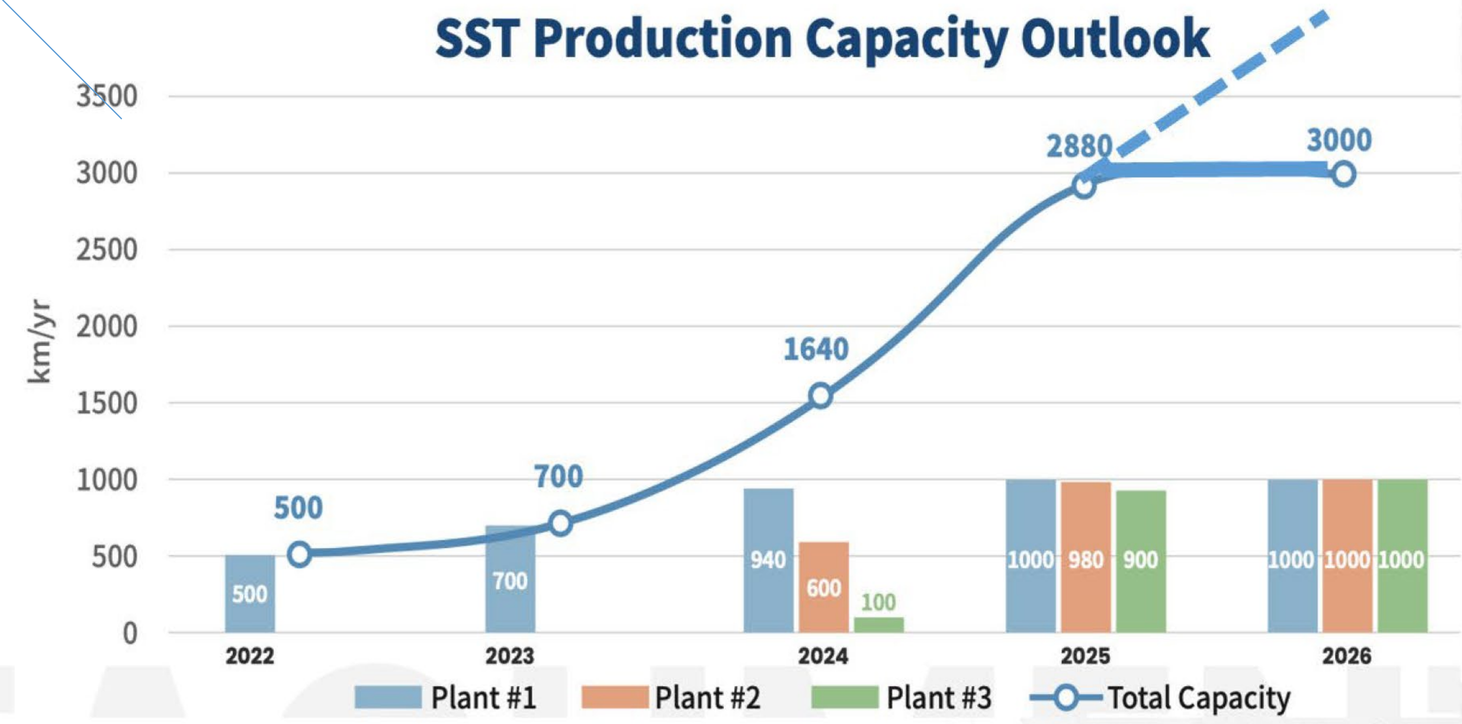
Zhangjiang Hi-tech Park, Shanghai

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.)*

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

Shanghai Creative Superconductors, SCSC

上创超导 Shanghai Creative Superconductors

Industrial production lines (TFA-MOD method)

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

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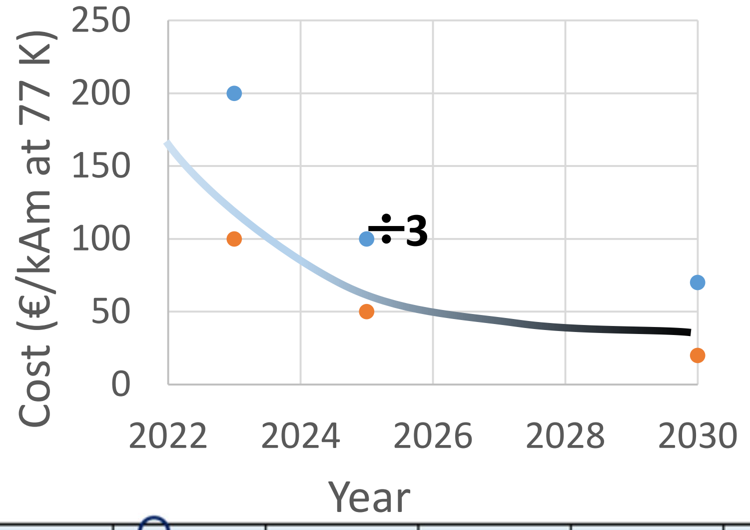
Status of CC materials at industrial scale and prospects

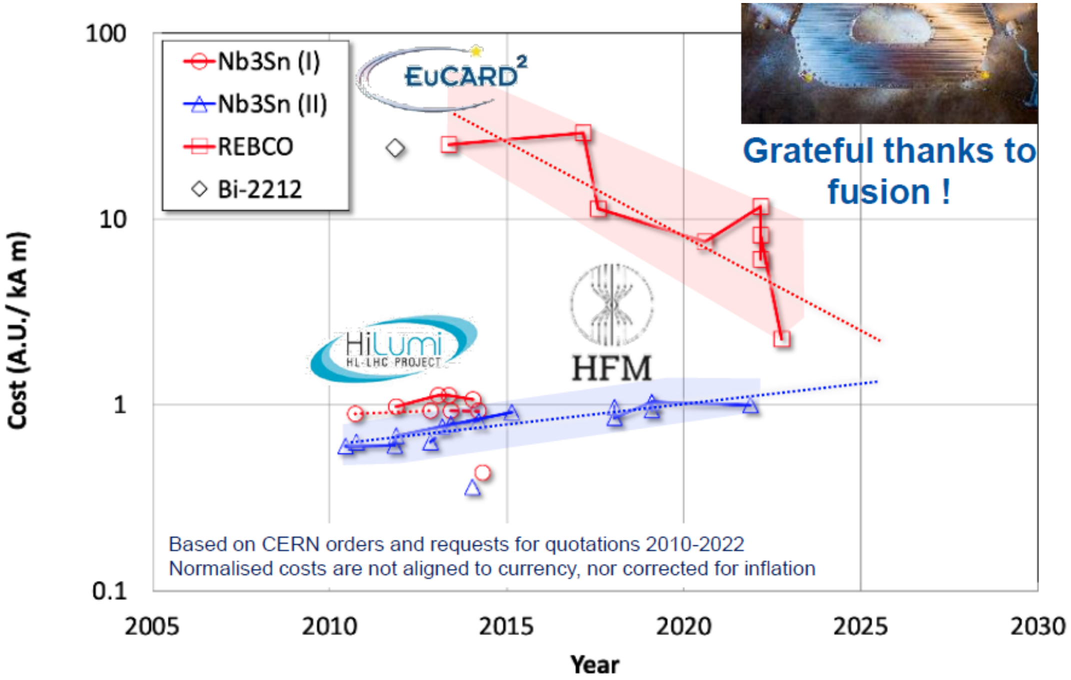
Cost …

7 consolidated companies

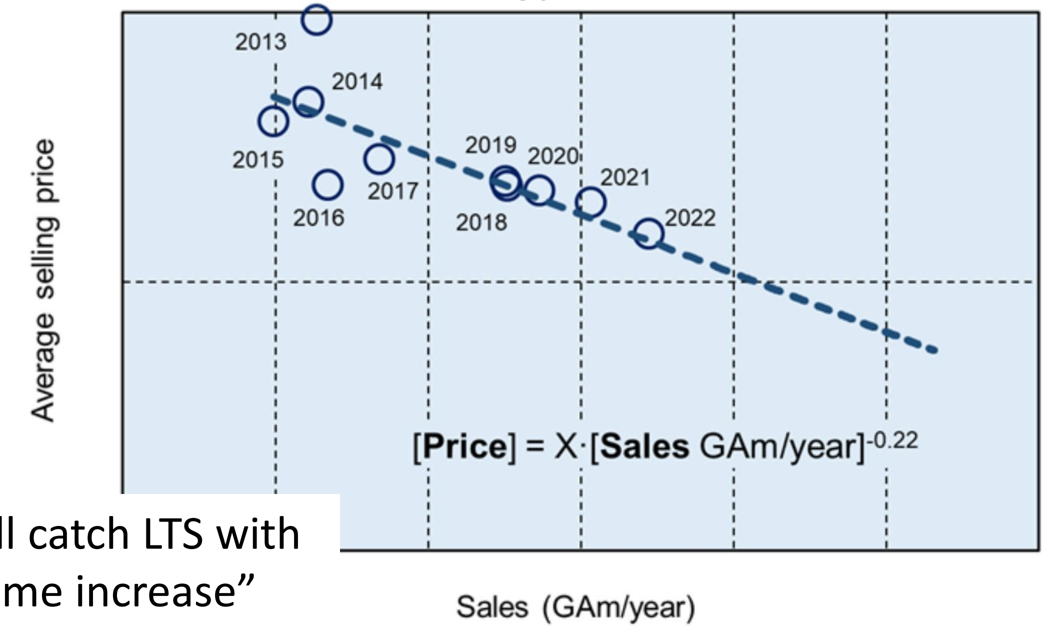
Magnitude	At present	Target for 2025	Target for 2028
Length (km)	0.5 – 1	1 – (5)	
Width (mm)	2, 3, 4, 6, 12	40, 80, 100, 125	
Production (km/yr) *12 mm equiv.*	3000 - 5000	6000 -10000	+40000 (+25000 Faraday)

S. *Lee, Faraday Group,* SNF Issue 53





L. Bottura, CERN, SNF Issue 52



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

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

CC Industry application target

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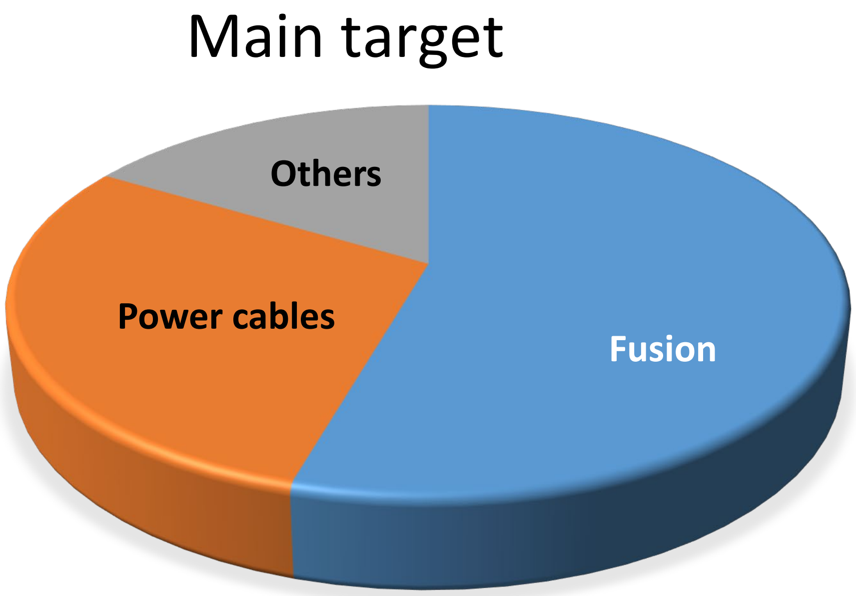
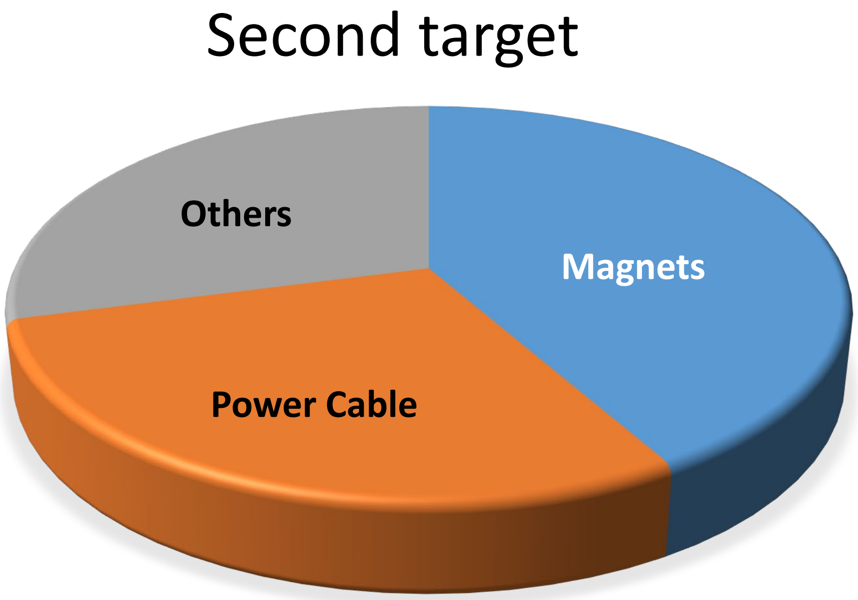
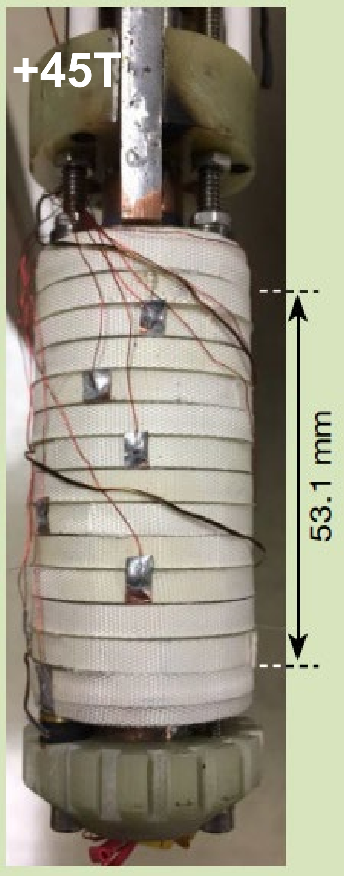
7 consolidated companies





NATIONAL HIGH MAGNETIC FIELD LABORATORY



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

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

https://cfs.energy/technology

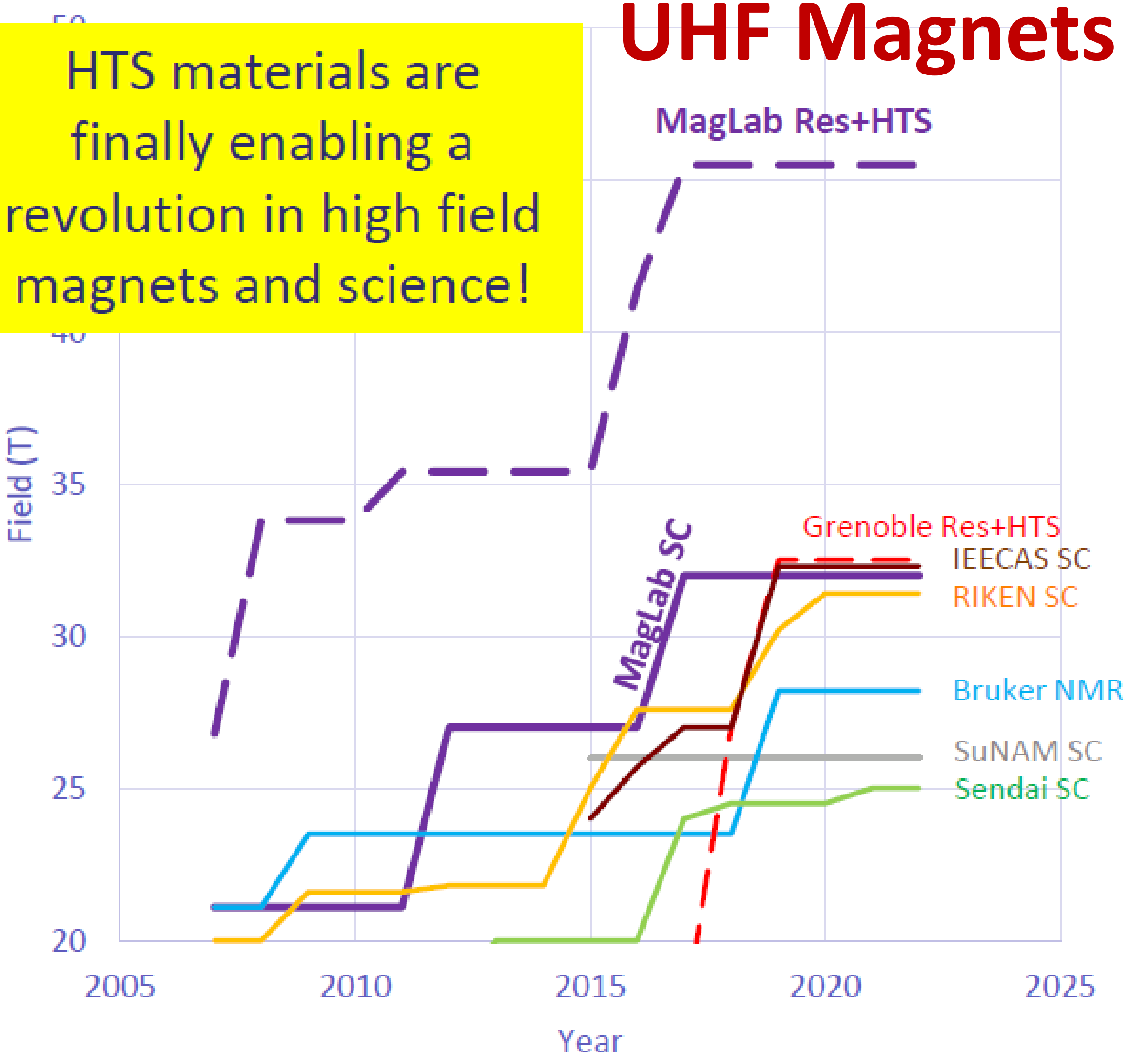
Summary

Dr. Mark D. Bird, *SNF Issue 53*

NATIONAL HIGH MAGNETIC FIELD LABORATORY

UHF Magnets

HTS materials are finally enabling a revolution in high field magnets and science!



NMR = Nuclear Magnetic Resonance.

There are now > 7 organizations worldwide developing HTS coils for service at Ultra-High Fields.

- All SC magnets >25 T use REBCO.
  - SC magnets are presently available at 28 – 32 T for condensed matter physics.
  - NMR magnets are operating at 28.2 T (1.2 GHz).
  - >4 groups are pursuing 30 – 35 T SC.
  - 2 groups are pursuing 30.5 T (1.3 GHz) NMR.
  - ~4 labs are pursuing 40 T SC.
- Variability of properties, effects of screening currents, and quench protection remain important challenges.

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Compact fusion with Ultra High Field Magnets

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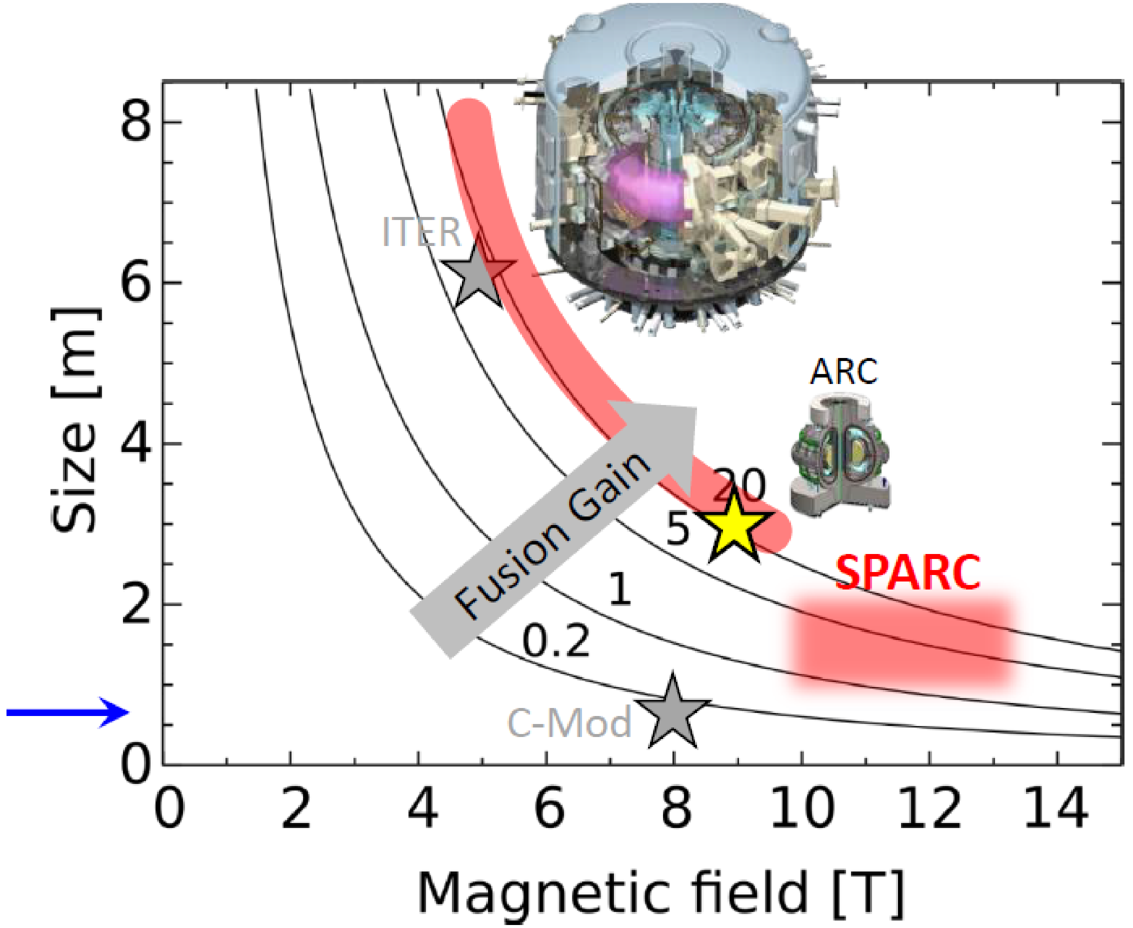
SPARC: Smallest Possible Affordable, Robust, Compact



500 MW reactors, 10^8 °C

COMMONWEALTH FUSION SYSTEMS

tokamak energy — a faster way to fusion

Massachusetts Institute of Technology

- Huge R&D efforts worldwide with public and private partners and investment (tens of new companies)
- Reactors in 2030?
- Fusion could generate 20-30 % of renewable worldwide energy
- Very low land use (÷ 100 vs PV)

J.K. Noland et al., Scientific Reports 12, 21280 (2022)

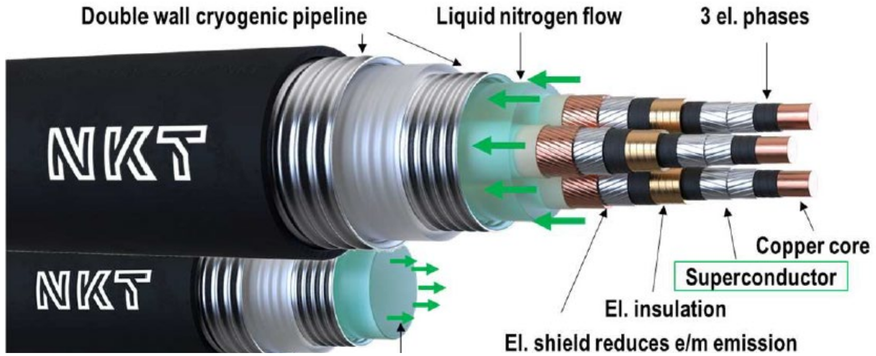
- **High field with HTS (B ~ 12T): much lower volume (÷ 100 ITER and DEMO) (~ few M$)**
- **Coils REBCO ~ 2-3 m at 20 T and 20 K, P$\propto$B^4 (x 16)**
- **CC demand: 10.000 km (2024) / 20.000 km/device / demand x 10-20 in 10 years**

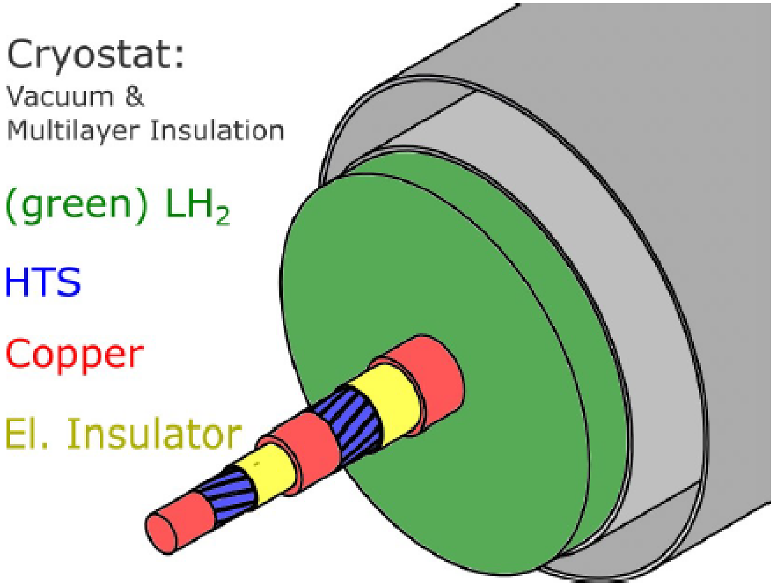
Special Issue of the IEEE TRANS APPL SUPERC, vol. 34. March (2024)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Smart grids: superconductor cables and fault current limiters

- Power increase in urban zones with environmental restrictions (undergrown)
- AC cables with reduced voltaje (+1.2 km / 110 kV / 500 MVA). Superlink Project: 15 km (Munich)
- No losses in DC cables (< 35 kV / +2.4 km). Transport, railway, data centers, busbars for industry electrolysis, ...
- Low social aceptance of HV grids: Undergrown HVDC cables is a solution for (Supernode Project, 1 GW, renewables integration)
- Overhead transmission lines, smaller rights of way and lower cost (VEIR)
- Reduced use of transformers (lower voltage) and FCL integration
- Hybrid Energy pipelines (LH_2 fuel + HTSC electricity / 25 K). TransHyde Project (Germany)





T. Arndt, SNF Issue 52

M. Noe et al, Roadmap HTS cables, SUST (in press)

Electrical airplanes: HTS CCs are key elements

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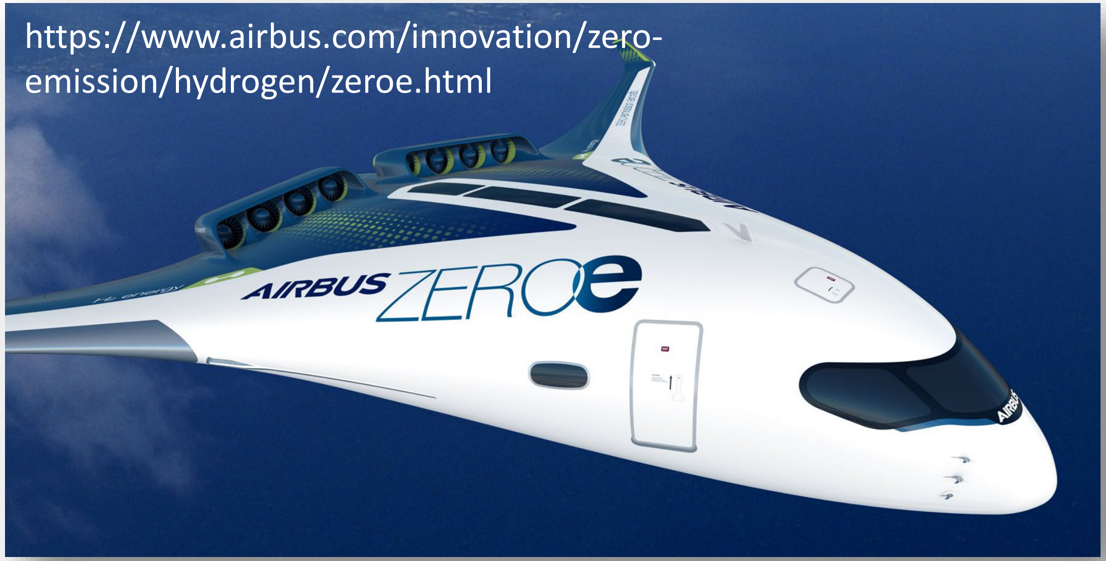
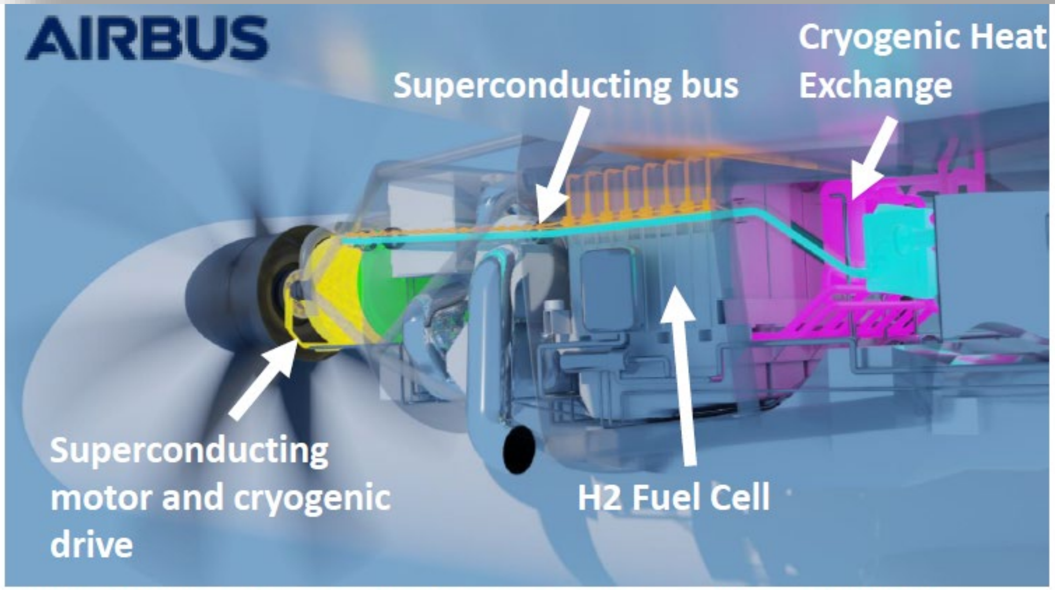


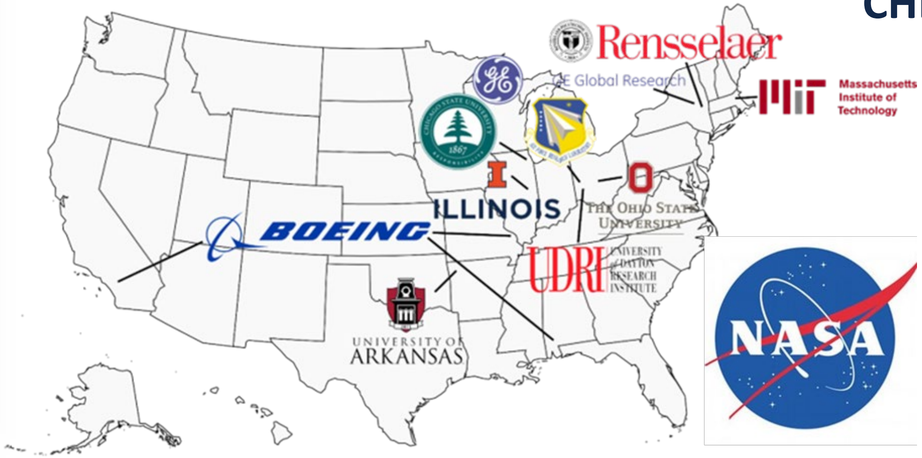


https://www.airbus.com/en/newsroom/press-releases/2024-05-airbus-takes-superconductivity-research-for-hydrogen-powered

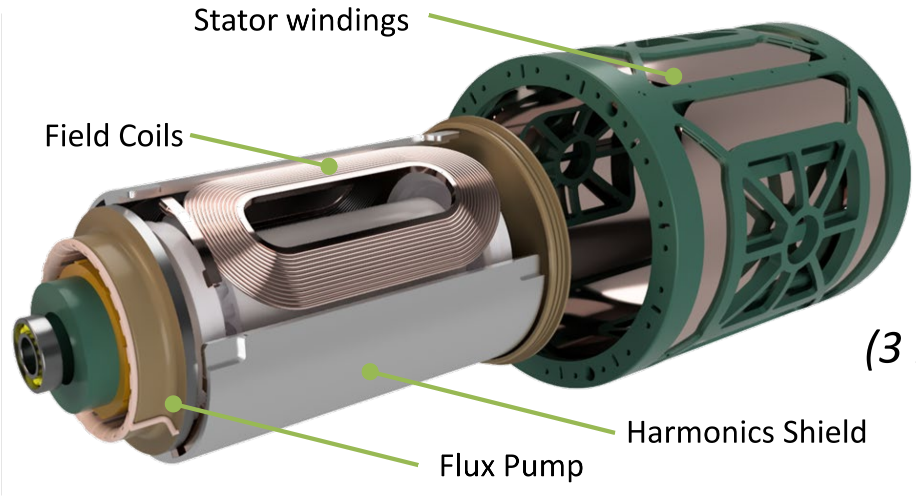
- **Minimize weight of components (motors, generators, cables)**

[Center for High-Efficiency Electrical Technologies for Aircraft]()

CHEETA members



Cables
Motors
Generators



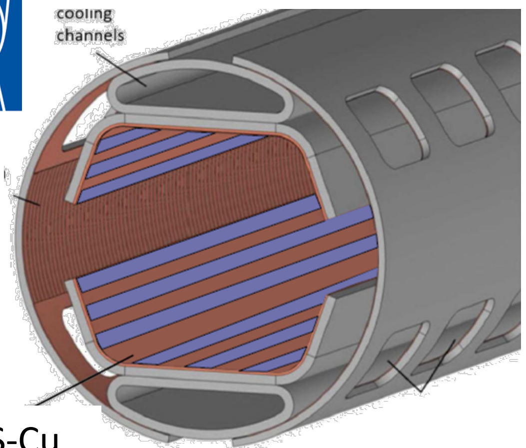
(3 MW motor))

R.A. Badcock et al, Robinson Res Inst, *New Zealand SNF Issue 56*

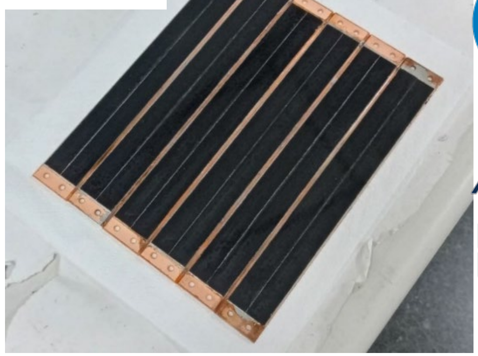
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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

High energy circular Collider Beam screen

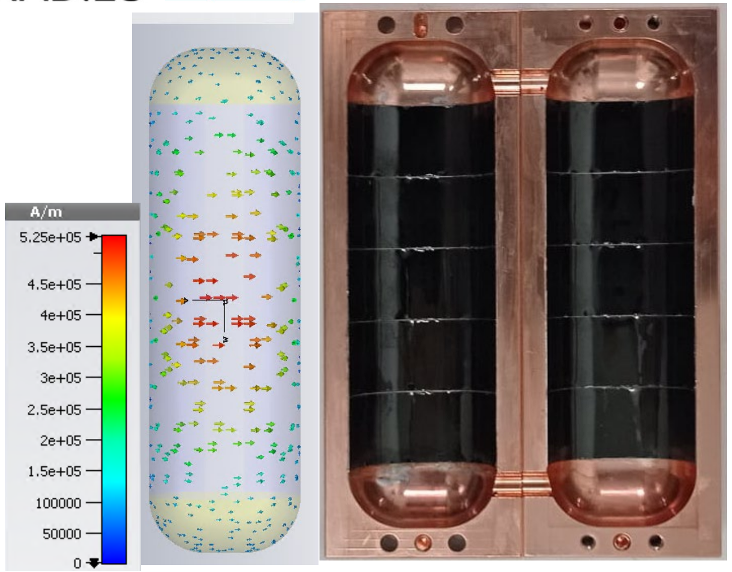


HTS-Cu hybrid coating



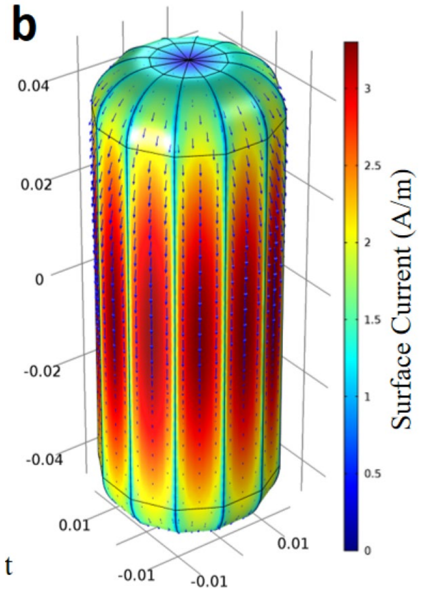
G. T. Telles et al, SUST 36 (2023)

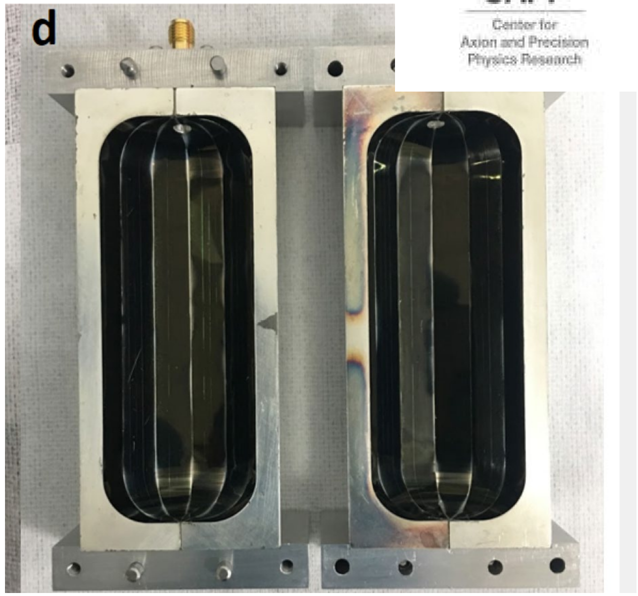
High-Q RF cavities at high H for Dark Matter search (Axion haloscopes)



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

J. Gutiérrez et al, SNF Issue 55

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Conclusions

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- Coated conductors are unique superconducting materials that are set to enable numerous applications
- 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, power cables, magnets (HEP), electrical transportation are ready to make the necessary pull
- R&D in CC must persist to help improve the capabilities, robustness and reduce figure of merit "cost/performance" and push the market penetration in several enabling technologies
- Strengthen academic – industry collaboration should be pursued as well as lobbying to become a clean and efficient energy technology

公益社団法人 低温工学・超電導学会

Cryogenics and Superconductivity Society of Japan.

EUROPEAN SOCIETY FOR APPLIED SUPERCONDUCTIVITY

IEEE CSC Council on Superconductivity

Superconductivity News Forum (https://snf.ieeecsc.org/)

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