Manufacture of REBCO tape for high-field applications: present technology and future challenges

To create magnetic field with superconductors, you use NbTi. Unless you can't.

Then you use Nb3Sn. Unless you can't.

Then you use REBCO.

David Larbalestier

S H O R T C U T

- Why REBCO is so desired for applications

  *Very high critical field *Tc above LN2 *Possibility of high fields above LHe

- Why REBCO is so difficult to make into a useful conductor

  *Brittle ceramics by the mile *High anisotropy *Need for biaxial texture

- How REBCO is made into a useful conductor

  *Template *REBCO itself *High field properties

- Fusion hatches the egg for HTS

  *And mutually vice versa

- Oh boy is this difficult!

  *Prominent examples of things gone wrong

- Clever use of imperfect material

  *Prominent examples of clever use

- Future directions

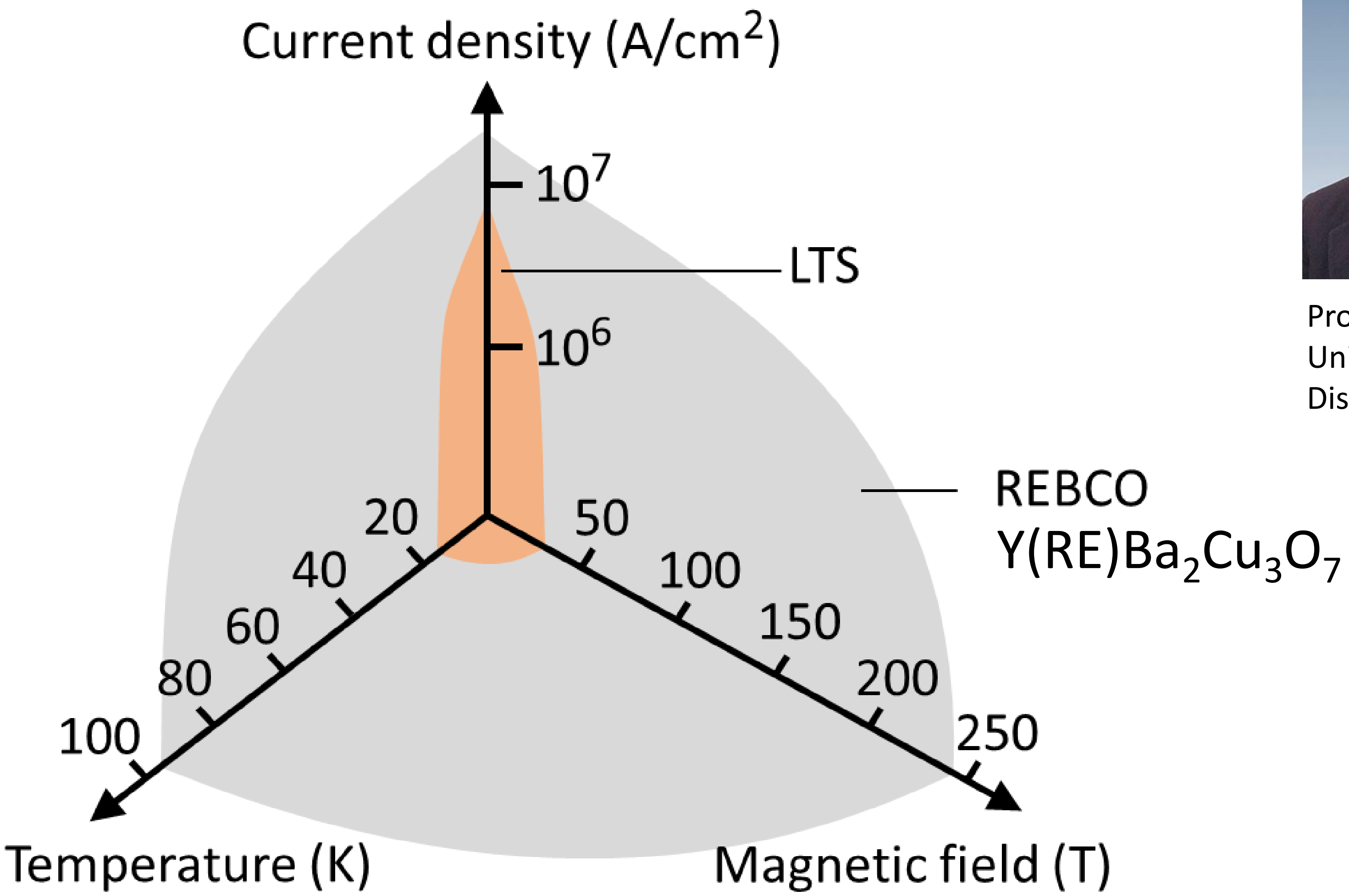
  *Improve on everything---that is, on everything that is important

- We did not cover everything

  *AC loss *Cost/price *…

Why REBCO is so desired for applications

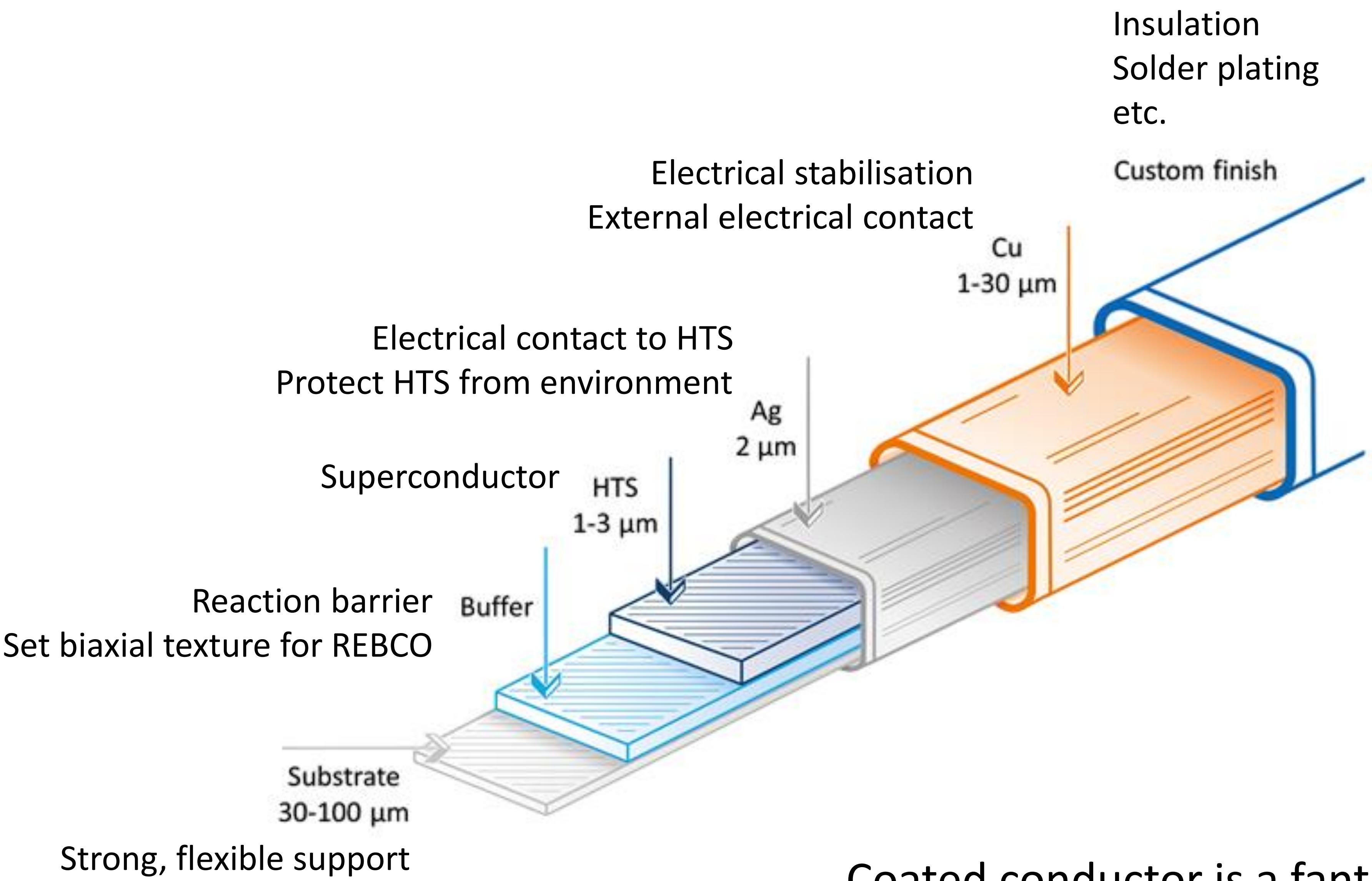
*Very high critical field *Tc above LN2 *Possibility of high fields above LHe



Prof. Paul Chu
University of Houston
Discovered REBCO (YBCO) in 1987

Why REBCO is so difficult to make into a useful conductor

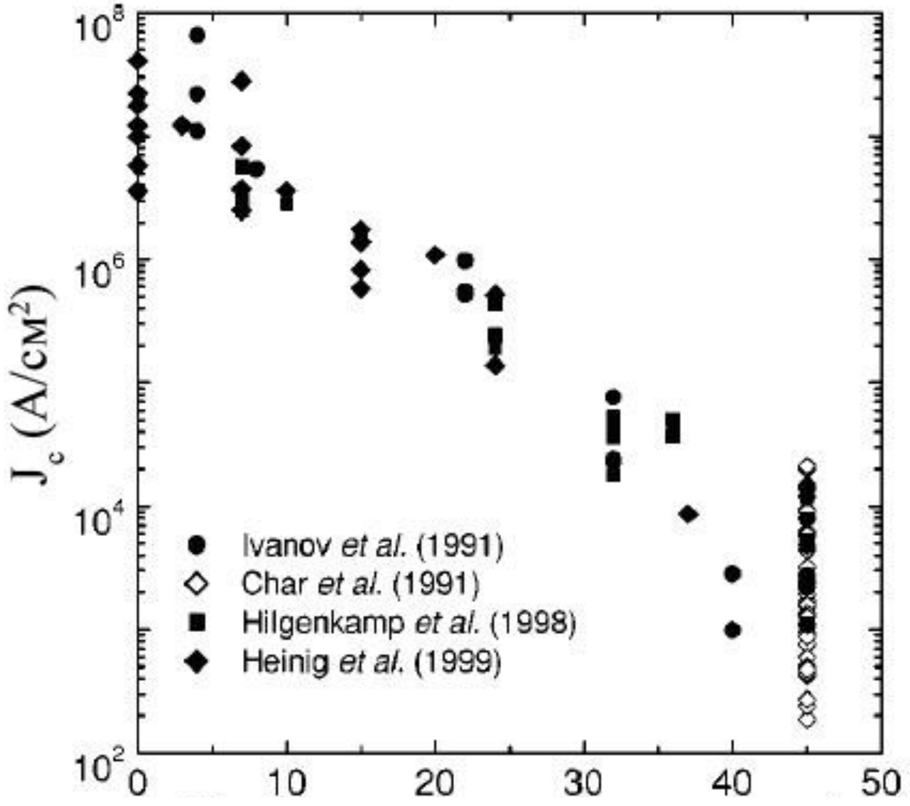
*Brittle ceramics by the mile   *High anisotropy   *Need for biaxial texture



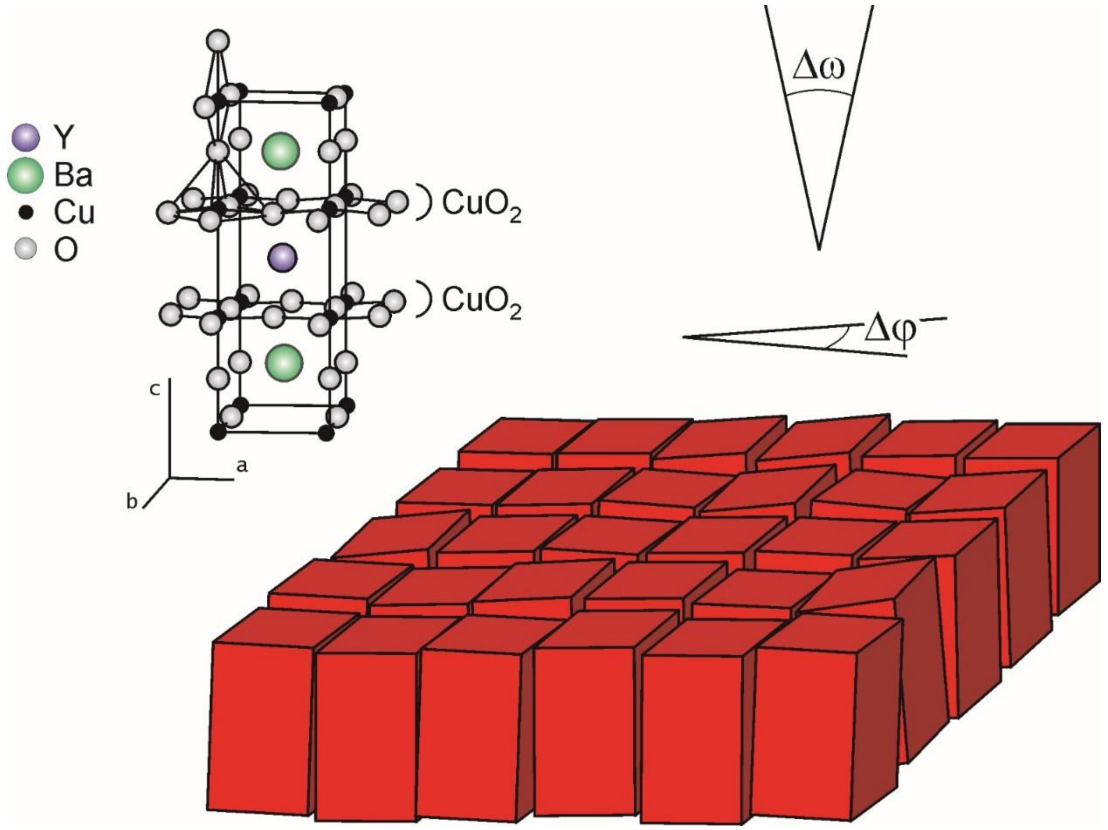
Coated conductor is a fantastic beast

Why REBCO is so difficult to make into a useful conductor

*Brittle ceramics by the mile *High anisotropy *Need for biaxial texture



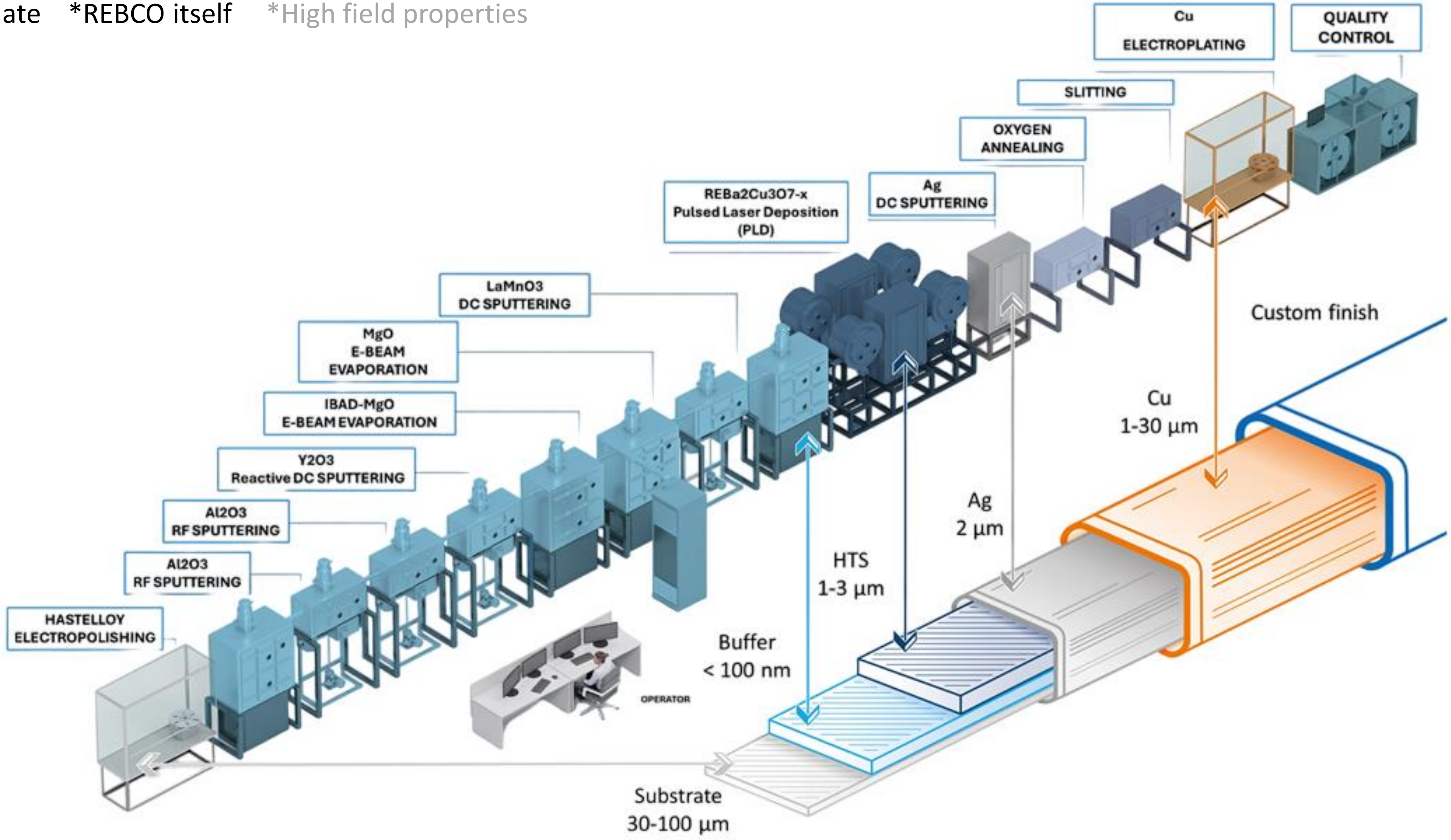
Crystal grain misalignment (deg.)



Not just ceramics, but single crystal by the mile

How REBCO is made into a useful conductor

*Template *REBCO itself *High field properties

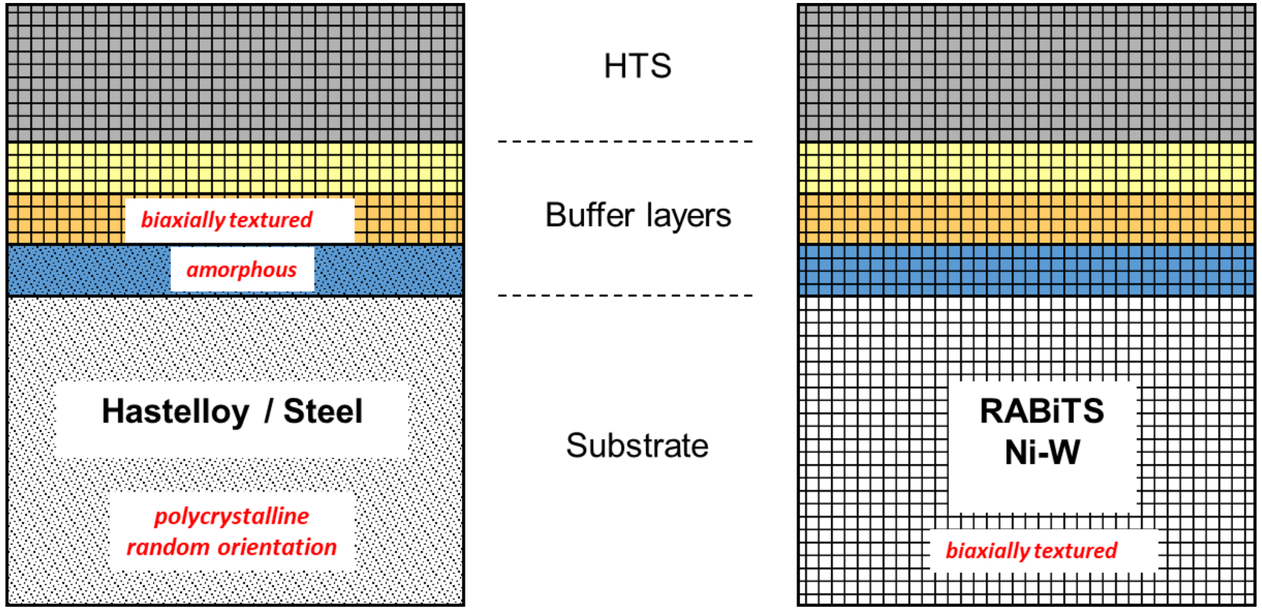


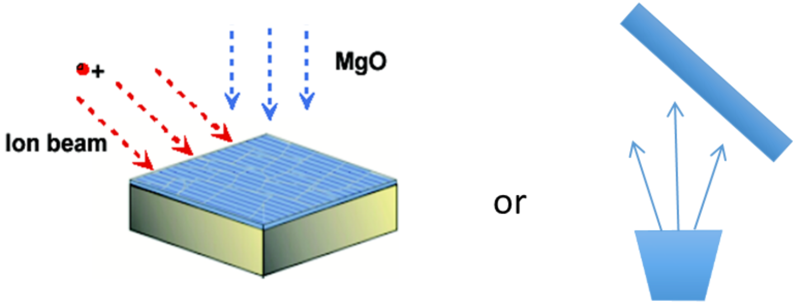
How REBCO is made into a useful conductor

*Template   *REBCO itself   *High field properties

IBAD: Ion-Beam Assisted Deposition
Iijima 1991: IBAD-YSZ
Hammond 1997: IBAD-MgO

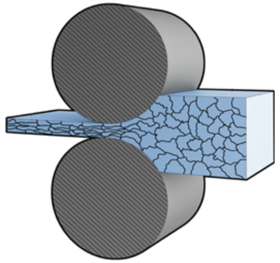
ISD: Inclined Substrate Deposition
Hasegawa 1996: ISD-MgO





IBAD   ISD

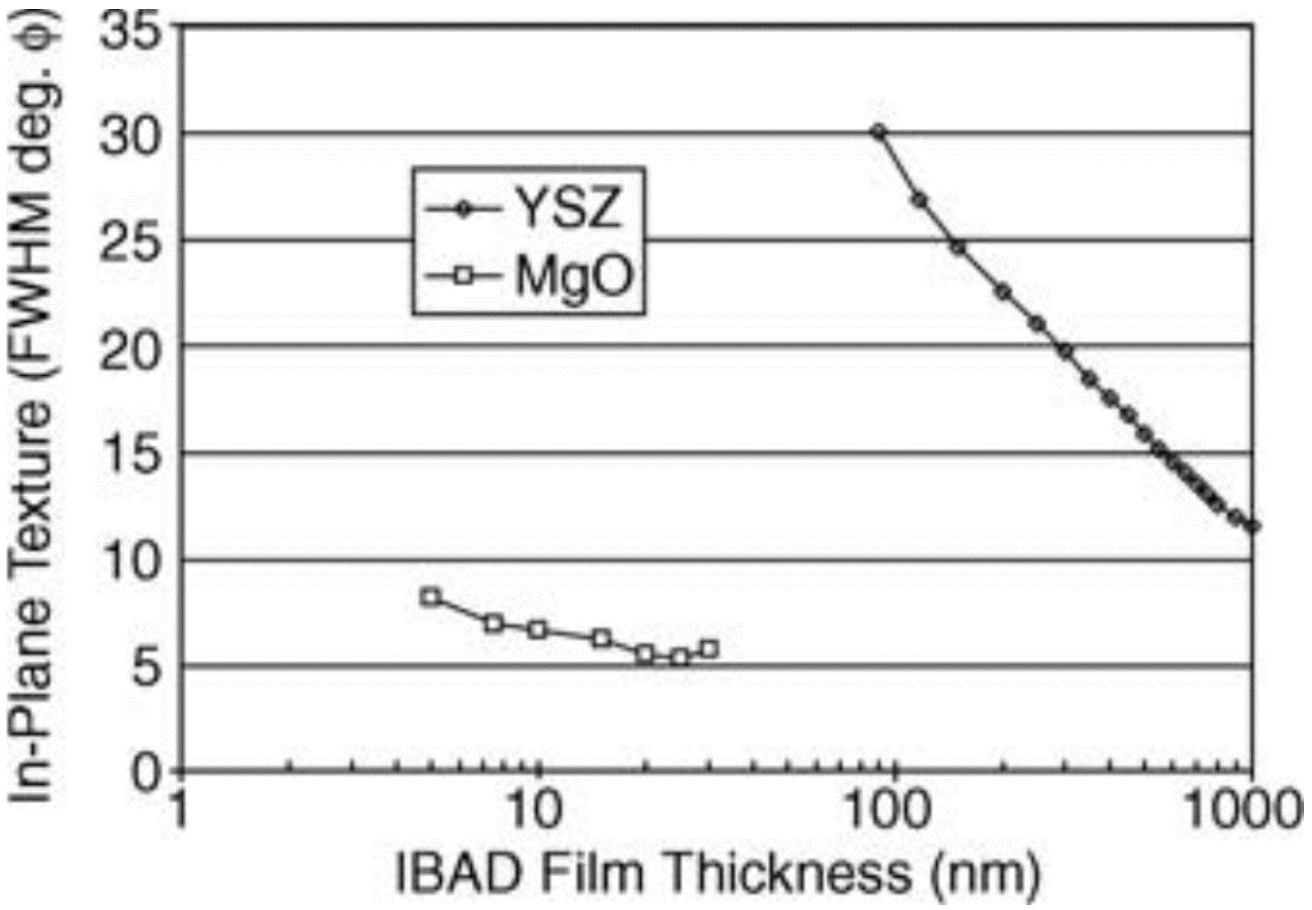
RABiTS:
Rolled-Annealed Biaxially Textured Substrates
Goyal (ORNL) 1995-96



Poorer texture
Not as strong substrate
Magnetic substrate

How REBCO is made into a useful conductor

*Template   *REBCO itself   *High field properties



RABiTS: AMSC

ISD-MgO: THEVA

IBAD-MgO: ALL OTHERS

IBAD-ISZ (and ISD-MgO): thick layers required for adequate texture.
IBAD-MgO: a few nm / seconds is enough. High throughput is possible.

How REBCO is made into a useful conductor

*Template   *REBCO itself   *High field properties

Chemical deposition methods

Starting materials are chemically different from the material in the film

Metal Organic Chemical Vapour Deposition (MOCVD)
Chemical Solution Deposition (CSD)
Metal Organic Deposition (MOD)

Physical deposition methods

Starting materials are the same as the material in the film

Physical Vapour Deposition (PVD)
Pulsed Laser Deposition (PLD)

Reactive Co-Evaporation (RCE)

In-situ deposition methods

The material in the film forms during the deposition

MOCVD
PLD

RCE—cyclic

Ex-situ deposition methods

1st Deposit a 'precursor' film
2nd React to form the final material

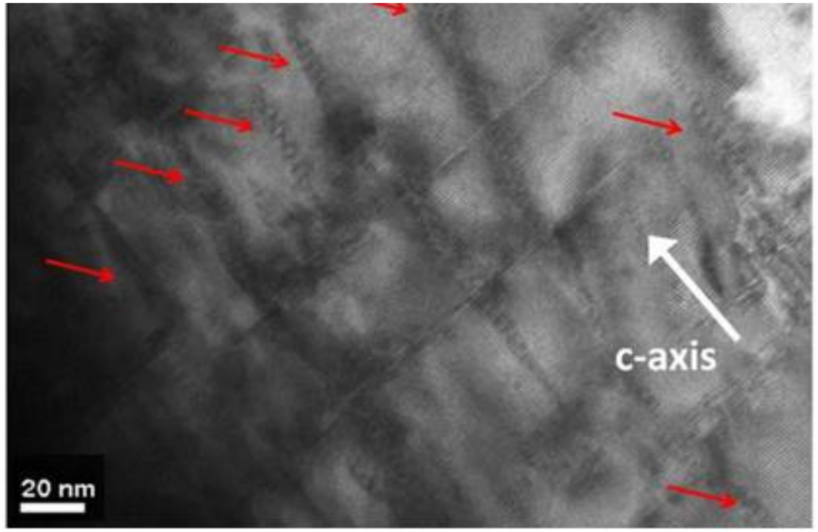
CSD/MOD
RCE—deposition-reaction (DR)

How REBCO is made into a useful conductor

*Template *REBCO itself *High field properties: pinning enhancement

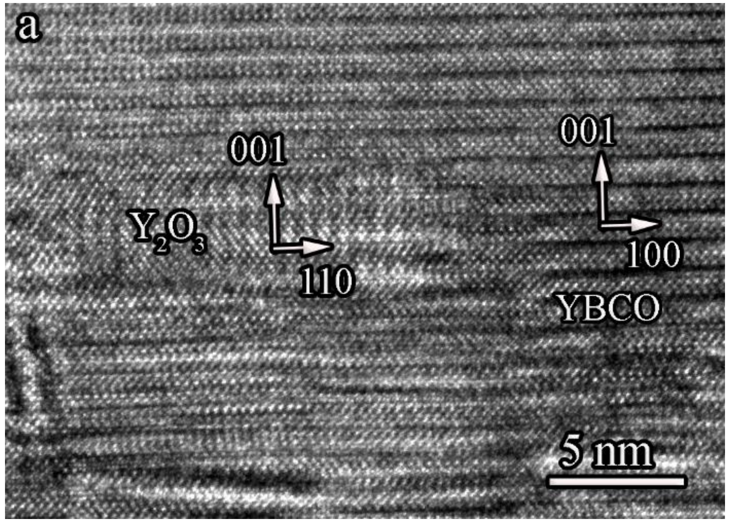
(Artificial) pinning centres (APC): nanoparticles that generate many even smaller defects in REBCO---the real pinning centres.

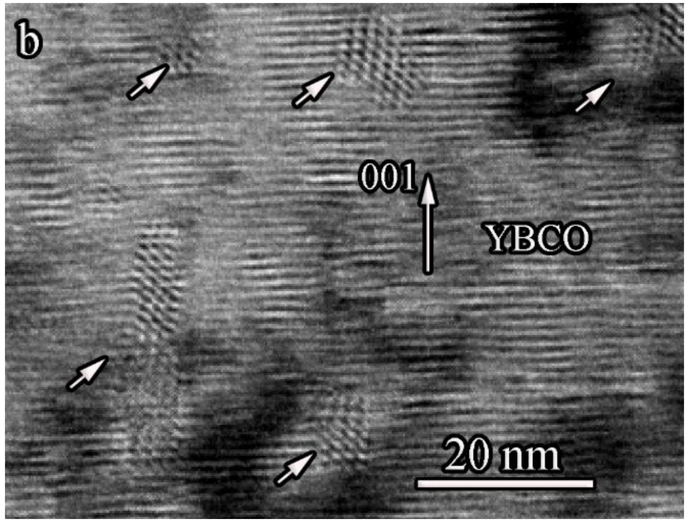
Extrinsic nano-particles (e.g. $BaZrO_3$), often correlated along REBCO *c*-axis



doi.org/10.1038/srep02310

Intrinsic Y_2O_3 nanoparticles in YBCO, uniformly distributed



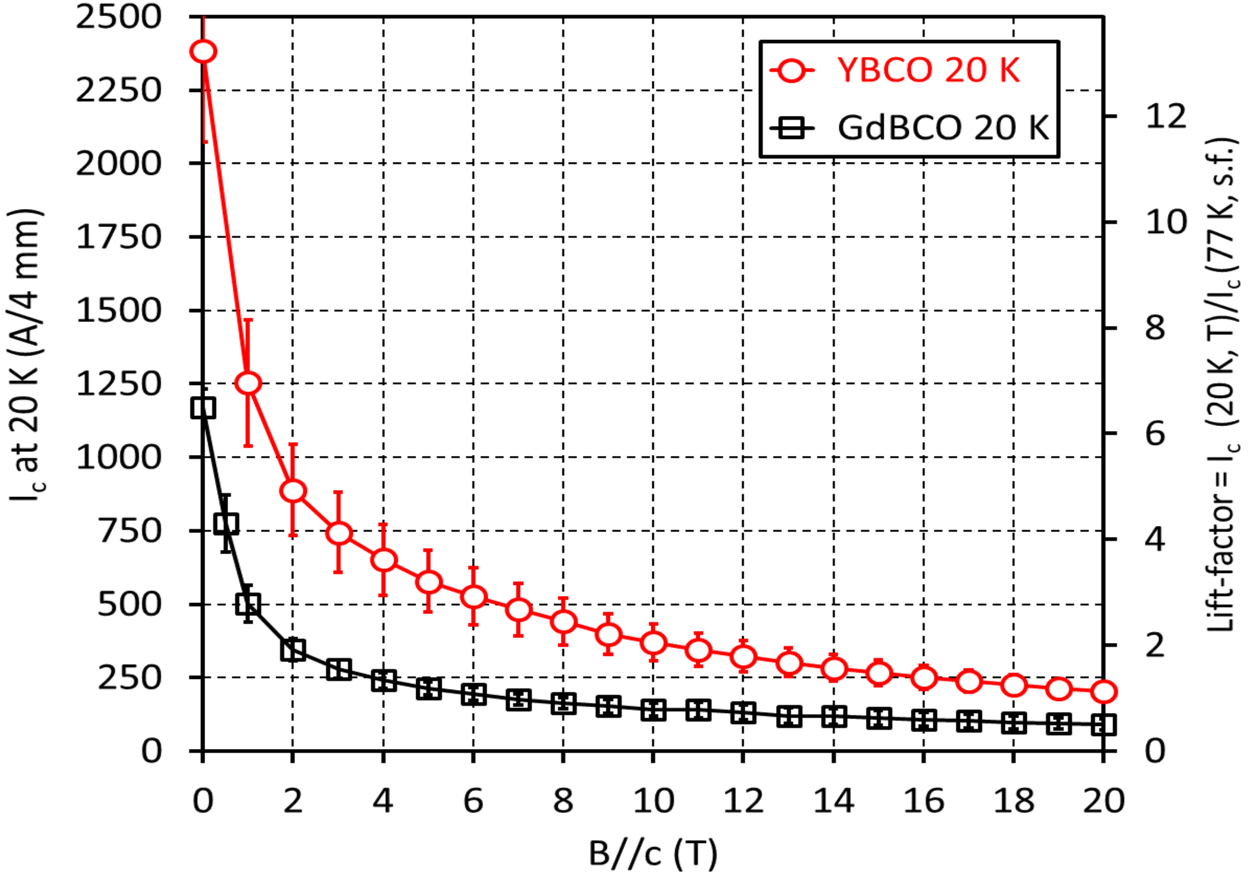


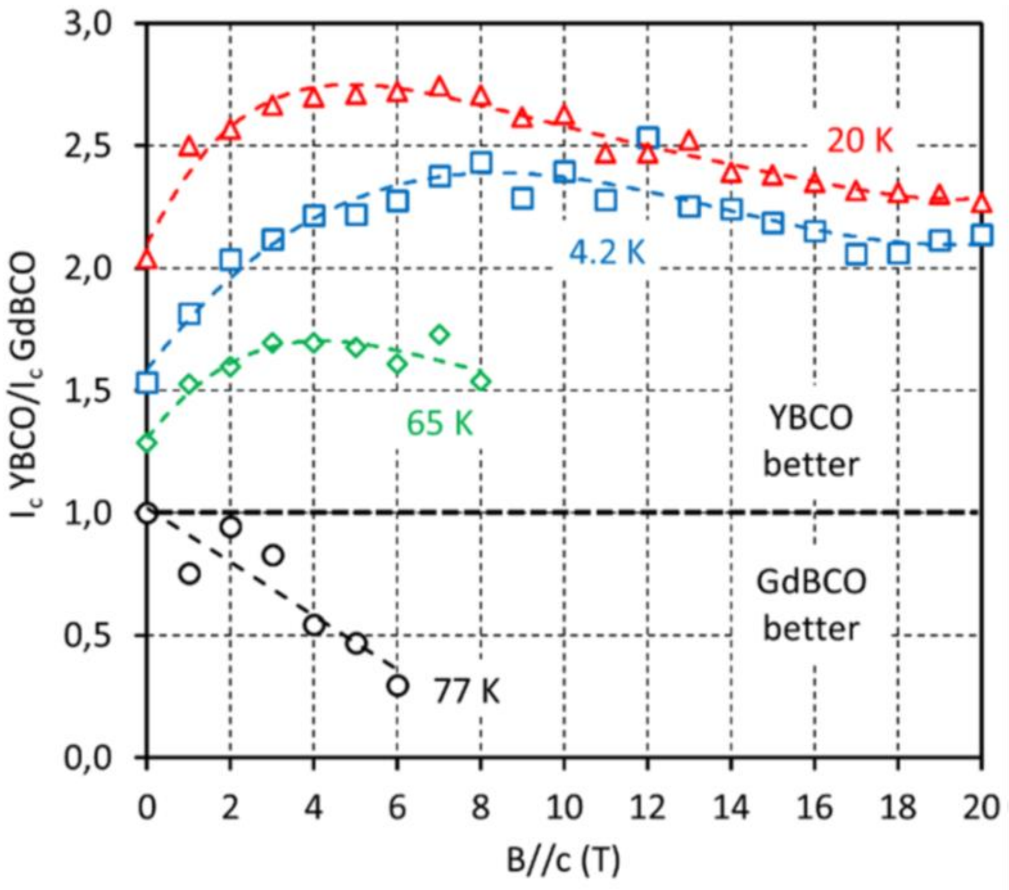
doi.org/10.1038/s41598-021-81559-z

How REBCO is made into a useful conductor

*Template *REBCO itself *High field properties: pinning enhancement

REBCO with APC vs. REBCO without APC



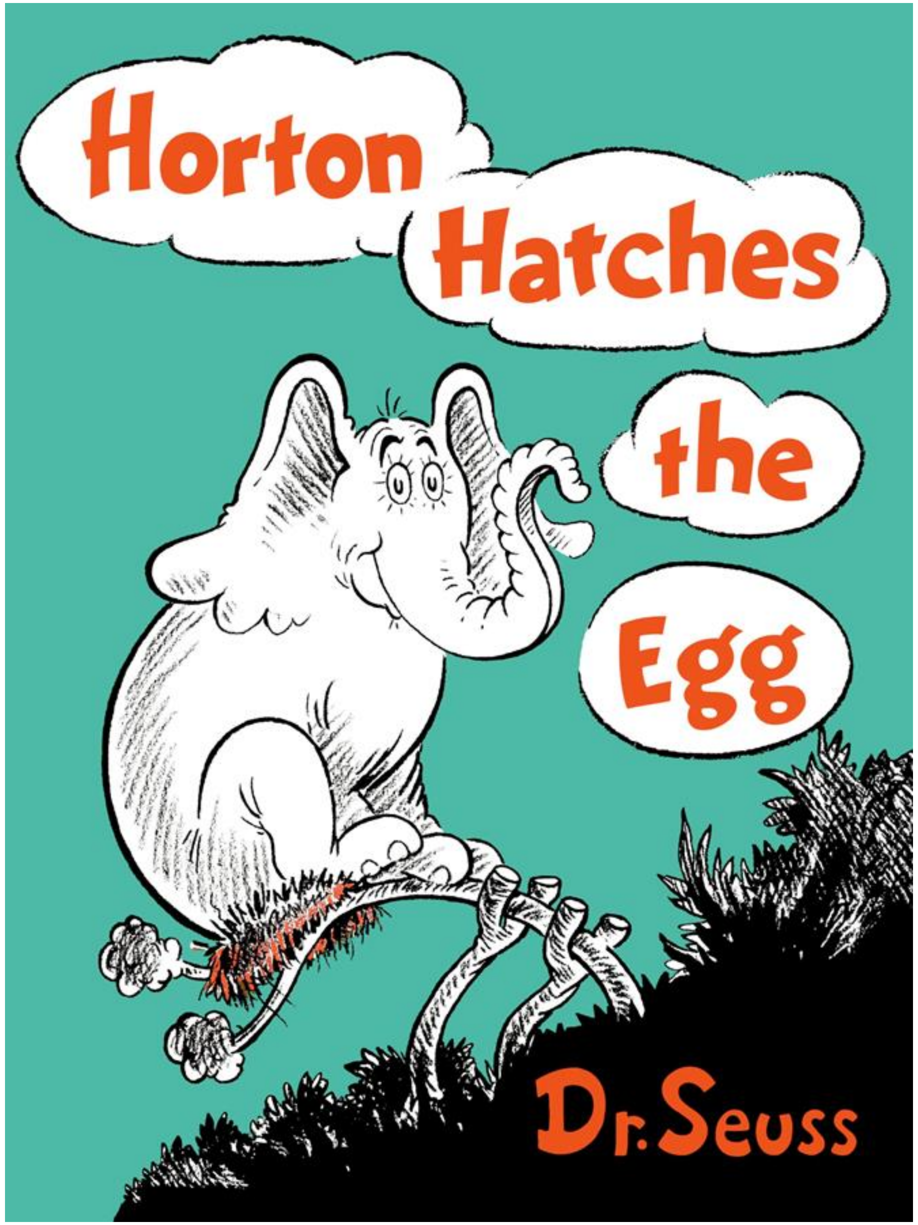


doi.org/10.1038/s41598-021-81559-z

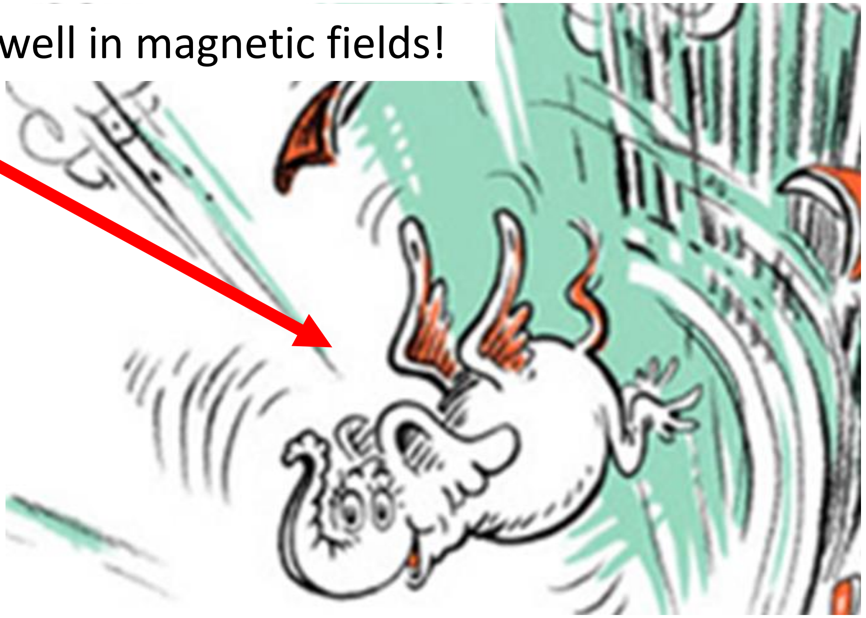
Who makes REBCO into a useful conductor

Manufacturer (A-Z)	Template	HTS method	REBCO	Pinning
AMSC	RABiTS	MOD	YBCO	
Faraday Factory Japan (FFJ)	IBAD-MgO	PLD	YBCO	Y_2O_3
Fujikura	IBAD-MgO	PLD	EuBCO	$BaHfO_3$ (BHO)
Furukawa/SuperPower	IBAD-MgO	MOCVD	(Y, Gd)BCO	$BaZrO_3$ (BZO)
Shanghai Superconductor Technology (SST)	IBAD-MgO	PLD	EuBCO	BHO
SuNAM	IBAD-MgO	RCE-DR	GdBCO	
THEVA	ISD-MgO	RCE-cyclic	GdBCO	BHO

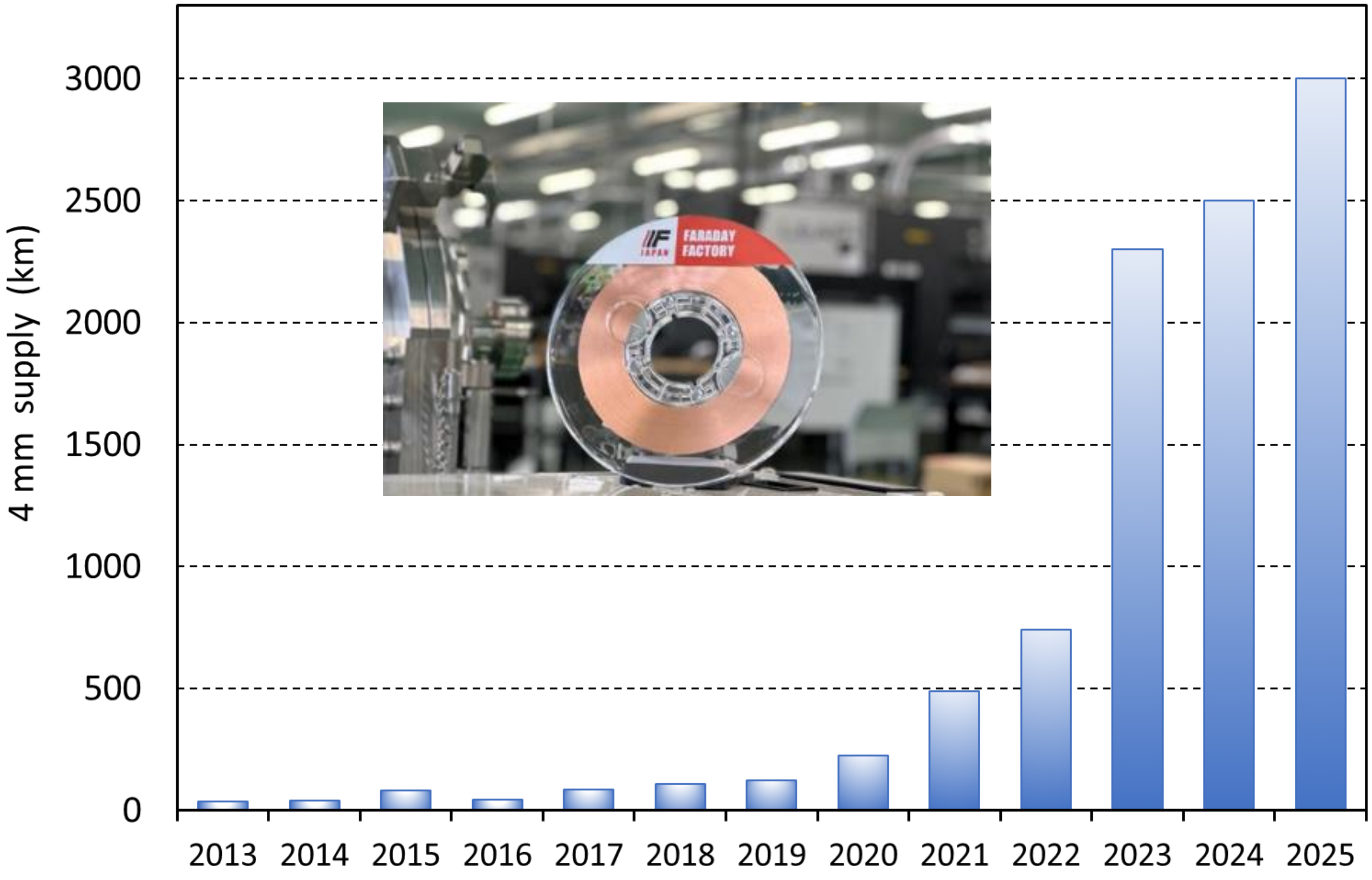
Fusion hatches the egg for HTS



This chick flies well in magnetic fields!

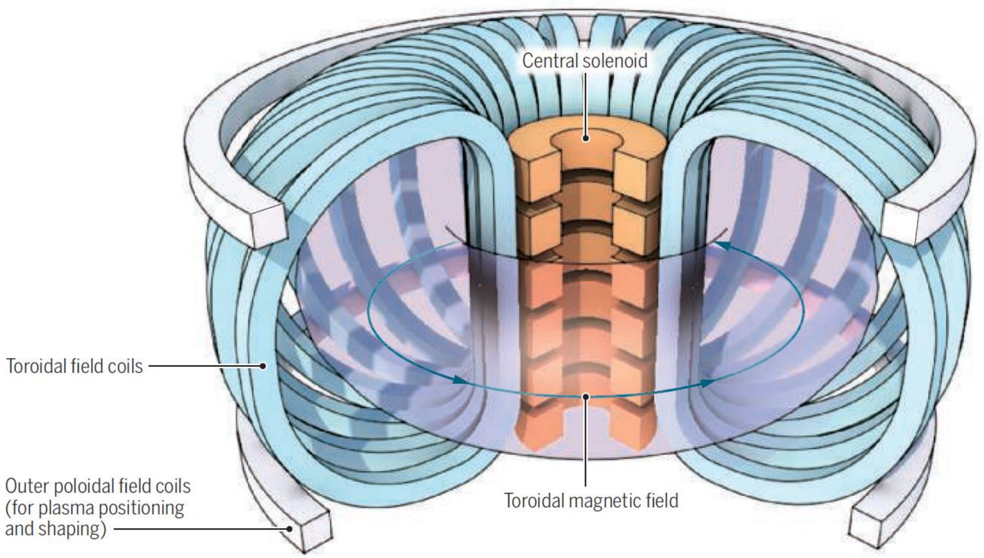


Fusion hatches the egg for HTS

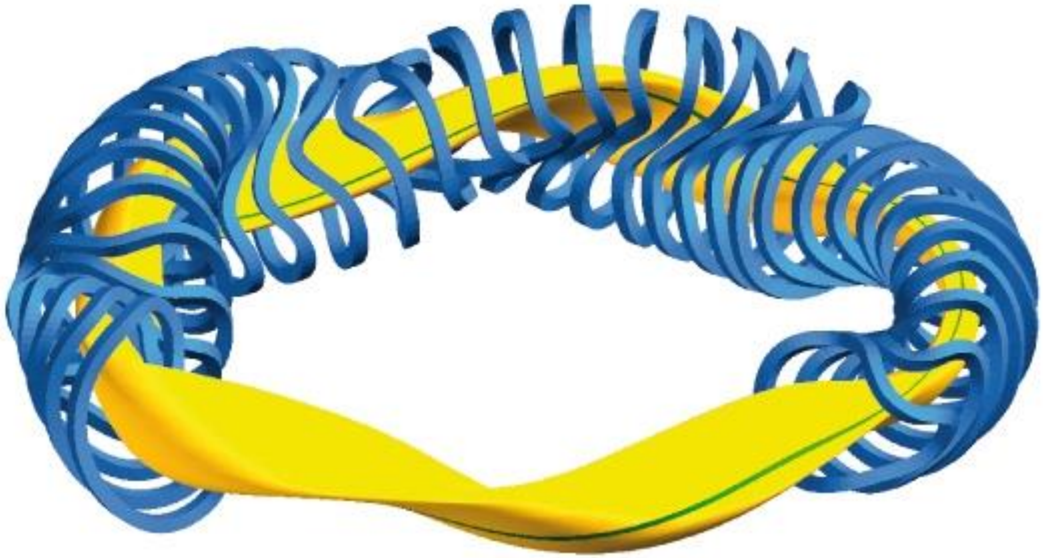


HTS hatches the egg for Fusion

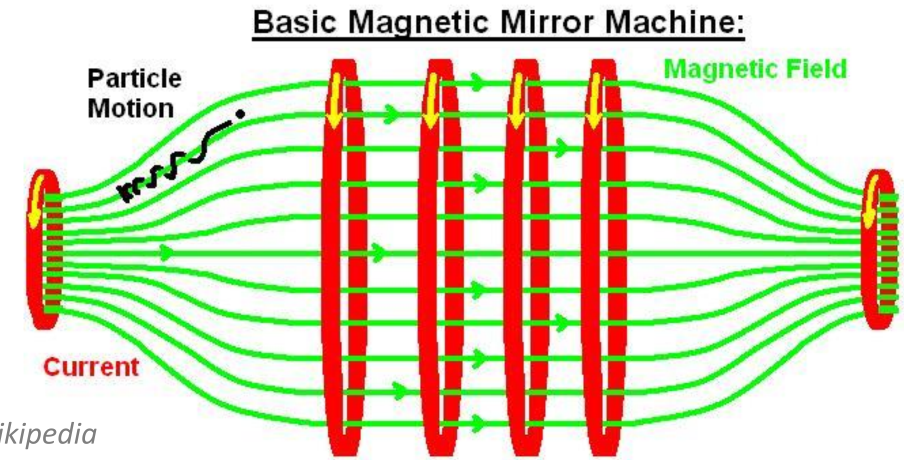
HTS has been incorporated into magnets for every magnetic confinement fusion concept



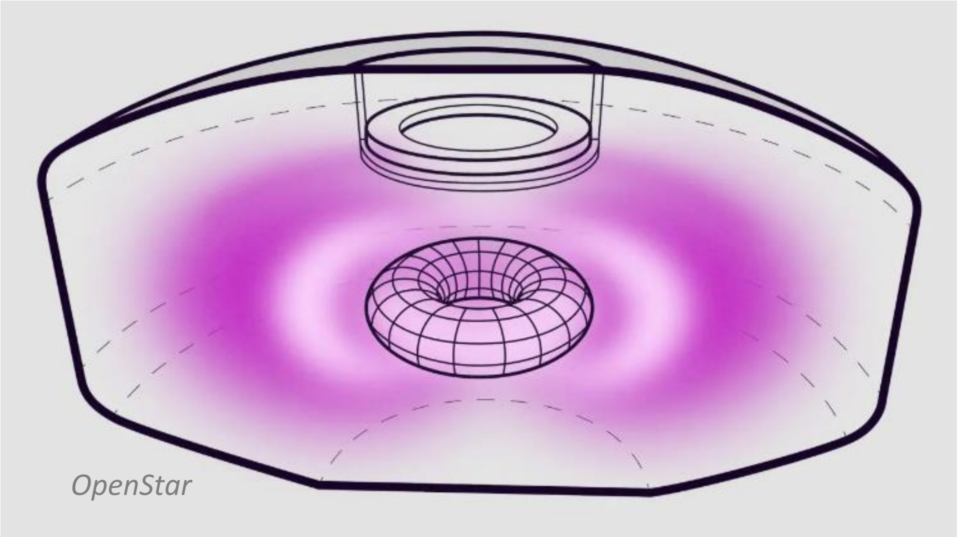
10.1126/science.abq4137



Wikipedia



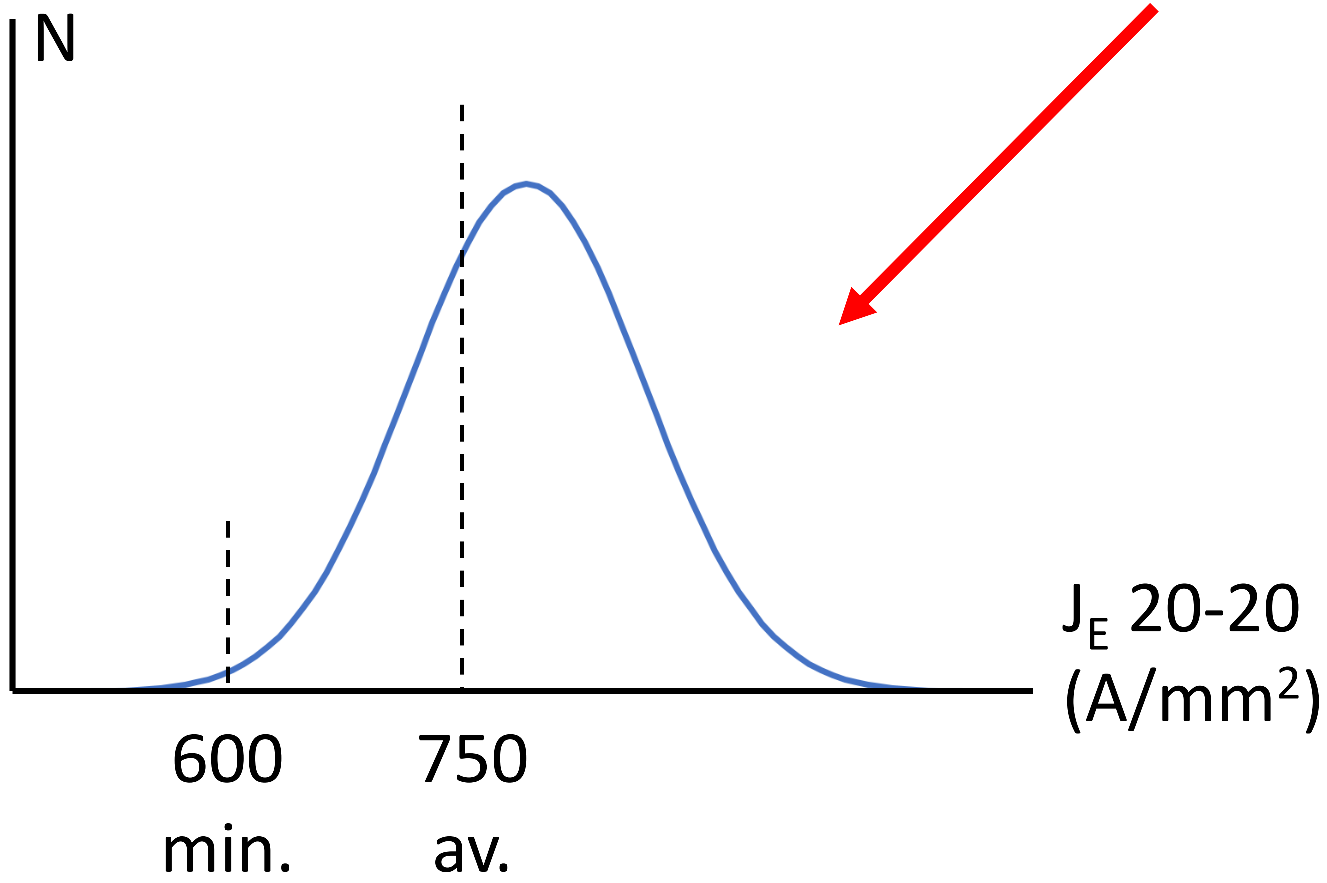
Wikipedia



OpenStar

Useful REBCO conductor of today

This chick flies well in magnetic fields!



Oh boy is this difficult!

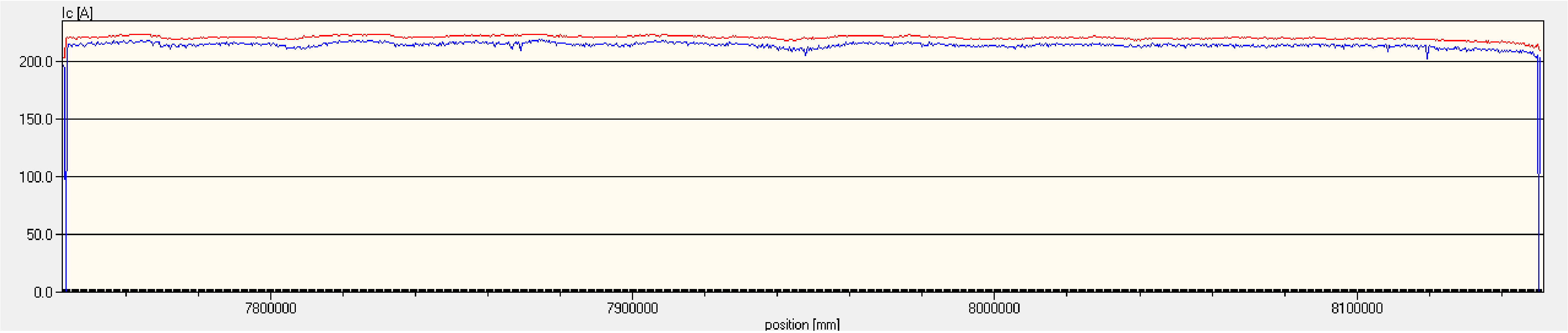
*Prominent examples of things gone wrong

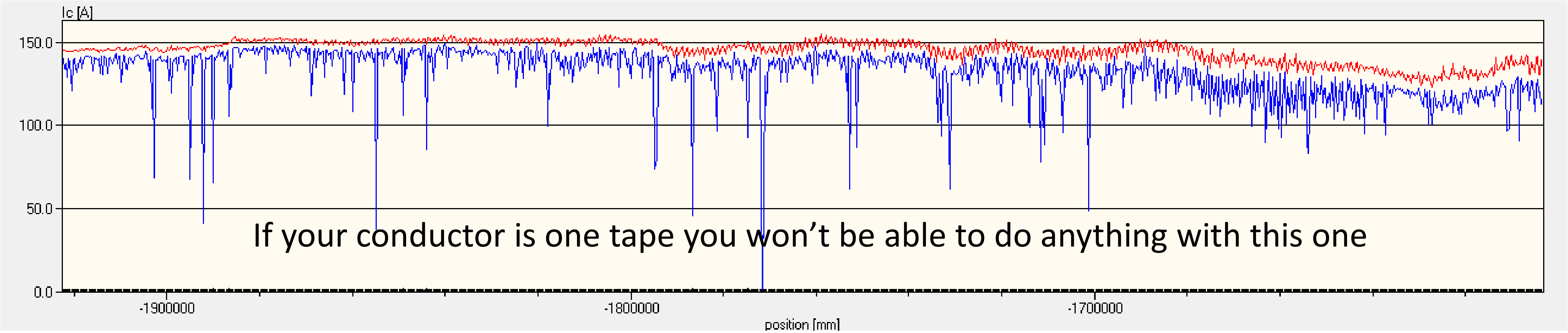
REBCO coated conductor is not its cartoon.

David Larbalestier

Oh boy is this difficult!

*Prominent examples of things gone wrong: I_c dropouts





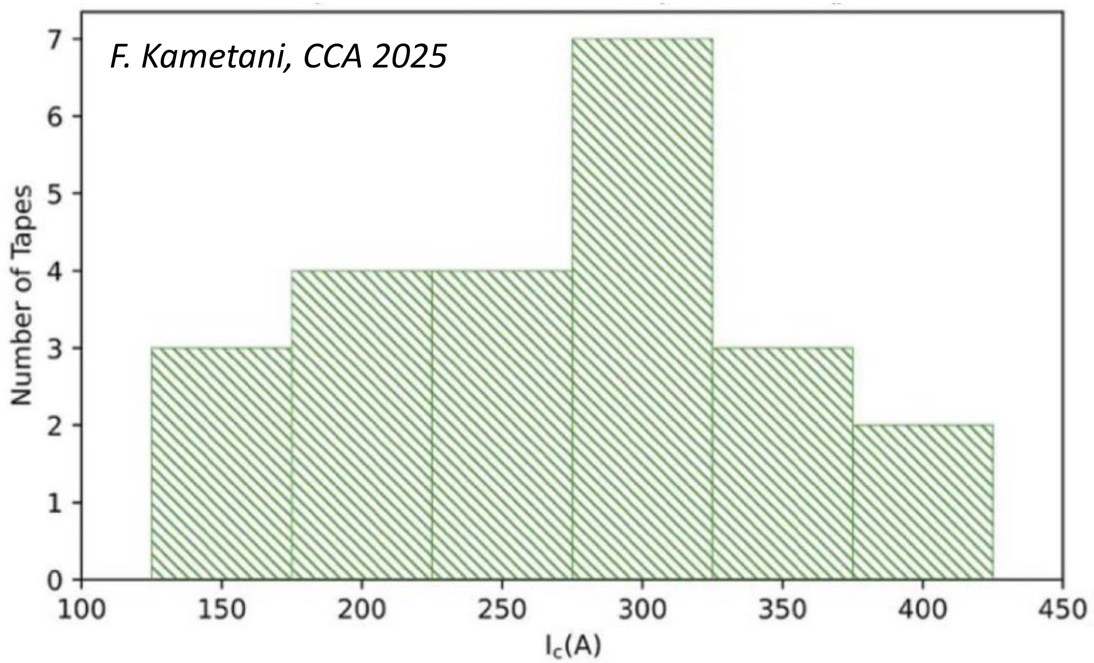
If your conductor is one tape you won't be able to do anything with this one

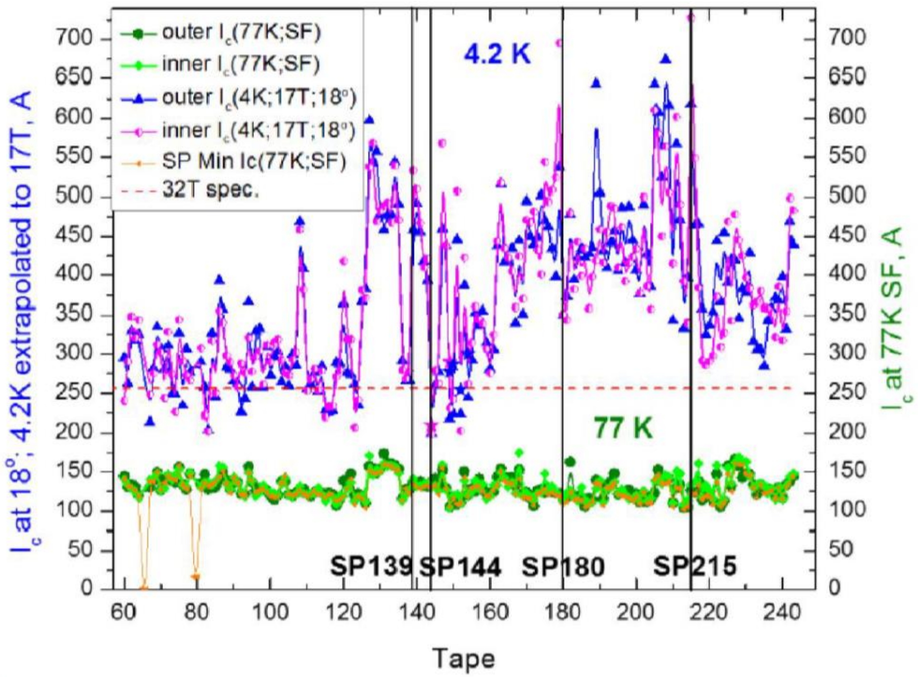
Cure:

- Improve process control at all manufacturing steps
- Clever use of imperfect material (listen on)

Oh boy is this difficult!

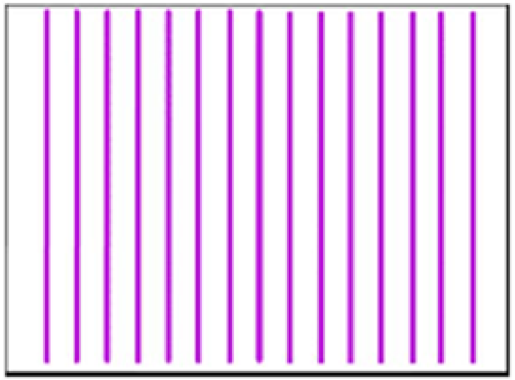
*Prominent examples of things gone wrong: uncontrolled variation of in-field I_c/nanostructure



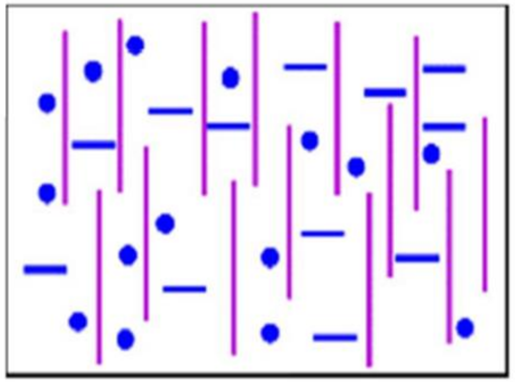


doi.org/10.1088/1361-6668/aa90d1

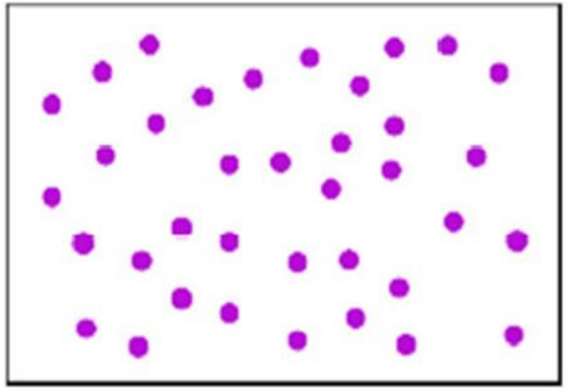
Columnar APC regime



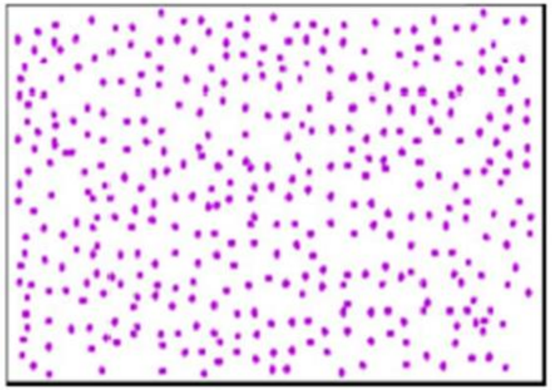
Mixed defect regime



3D defect regime



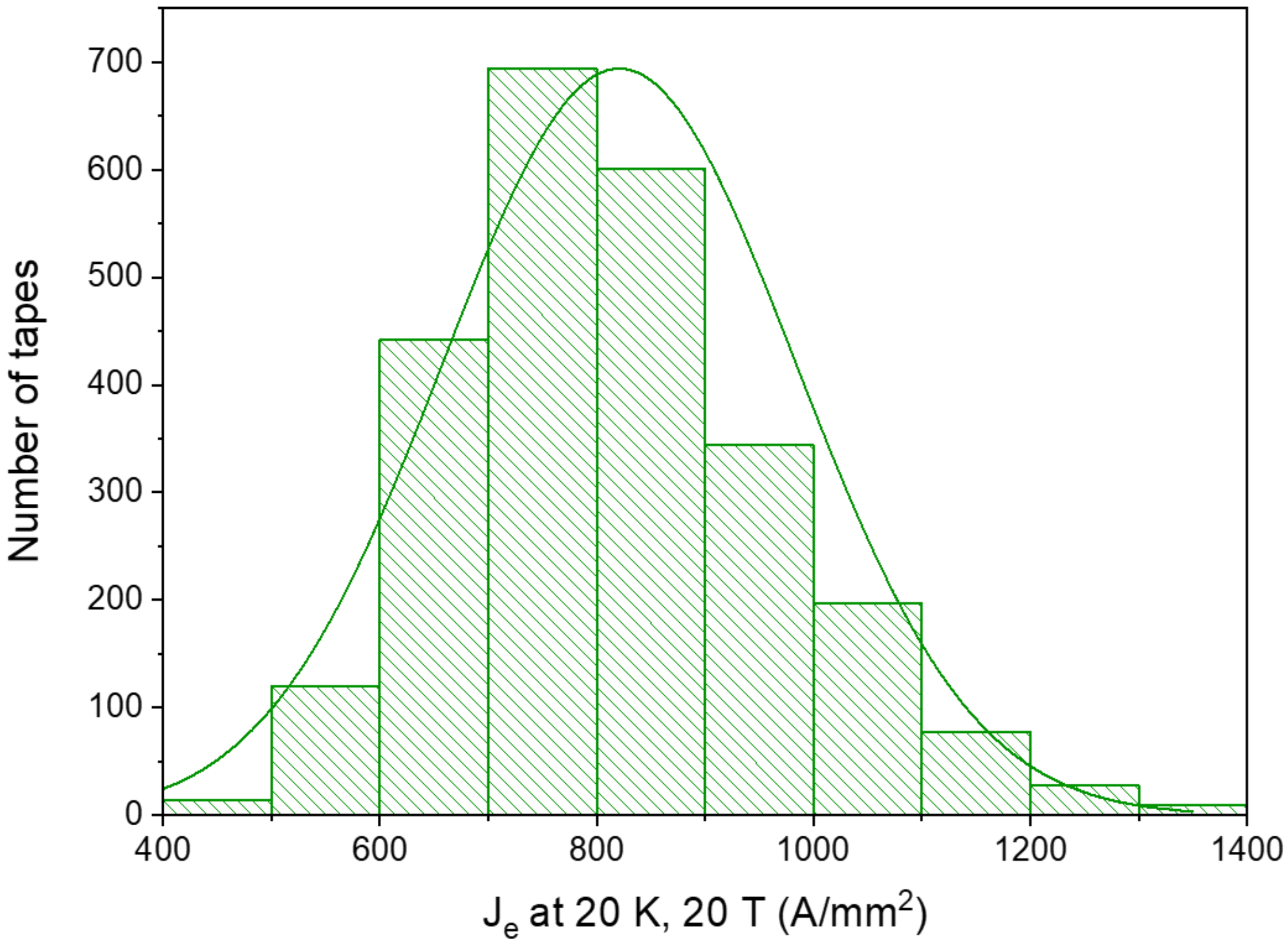
0D defect regime

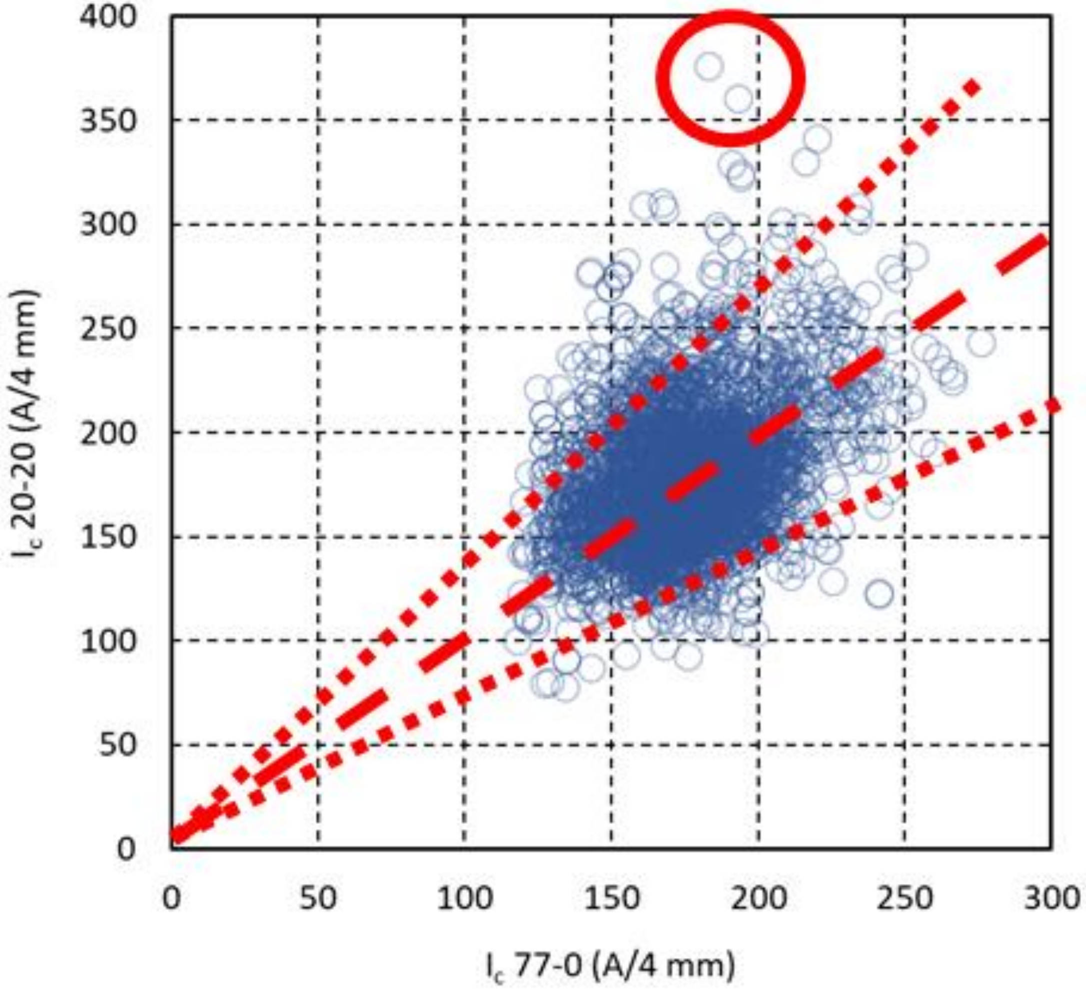


Uncontrolled process variations switch dominating nanostructure patterns---especially for extrinsic columnar APC

Oh boy is this difficult!

*Prominent examples of things gone wrong: less wild variation of in-field I_c (intrinsic APC)

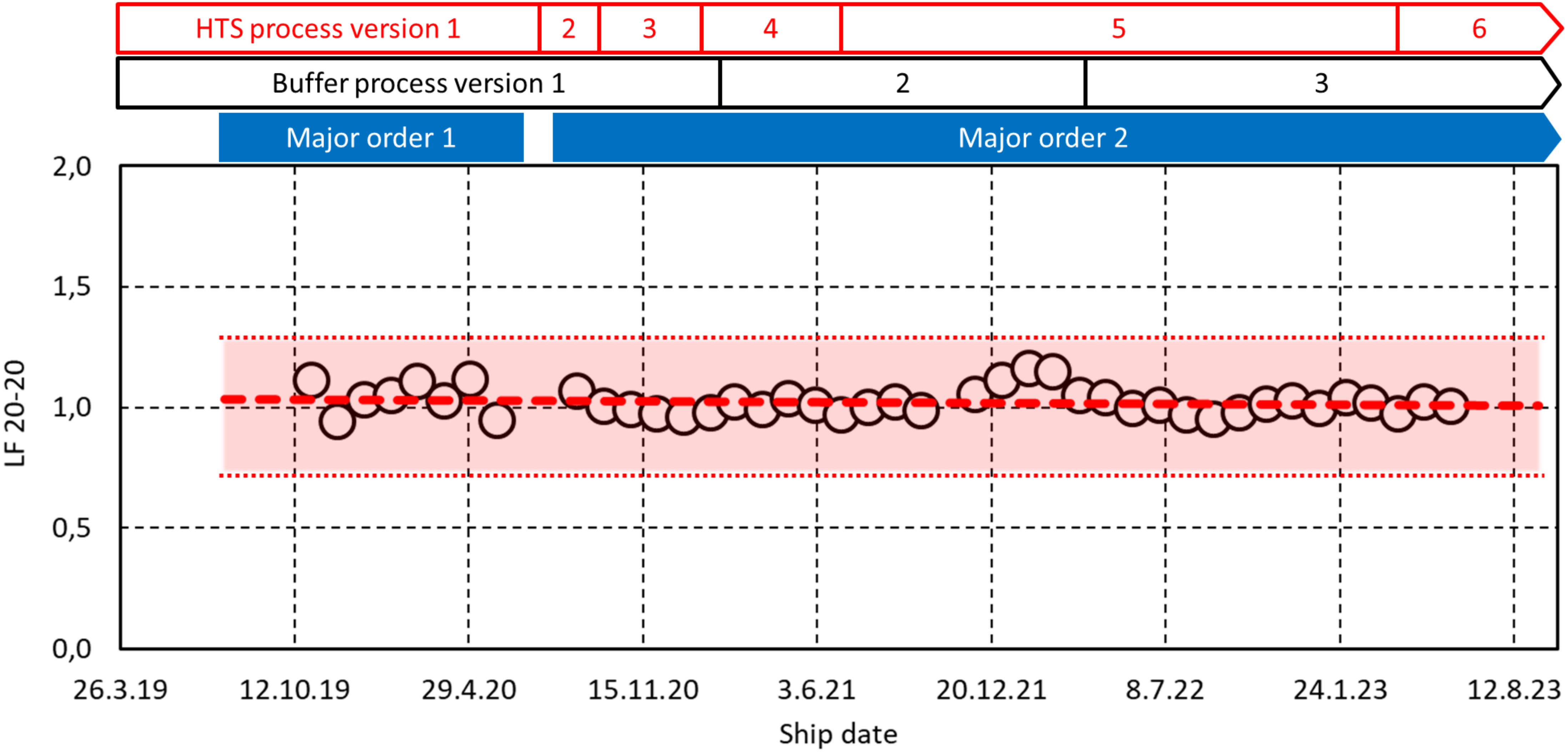




Important: statistical spread of in-field I_c among different tapes is similar to that within one tape

Oh boy is this difficult!

*Prominent examples of things gone wrong: less wild variation of in-field I_c (intrinsic APC)



Even better: for this type, the average performance and deviation stay constant over the years

Oh boy is this difficult!

*Prominent examples of things gone wrong: delamination

REBCO coated conductors are oxide multilayers
As such they have intrinsically relatively low adhesion between the layers
When things go wrong, adhesion may drop almost down to zero

Mechanical fracture in solids is a probabilistic process like electric breakdown
There is very low but non-zero probability that fracture occurs at a very small load
The proper way of quantifying this is statistical (the Weibull distribution)

Cure:

- Improve process control at all manufacturing steps
- Find correlations of process and adhesion and feedback to process
- Perform routine measurements to build statistics
- Single measurements are non-informative as they can return random value; they are local and destructive

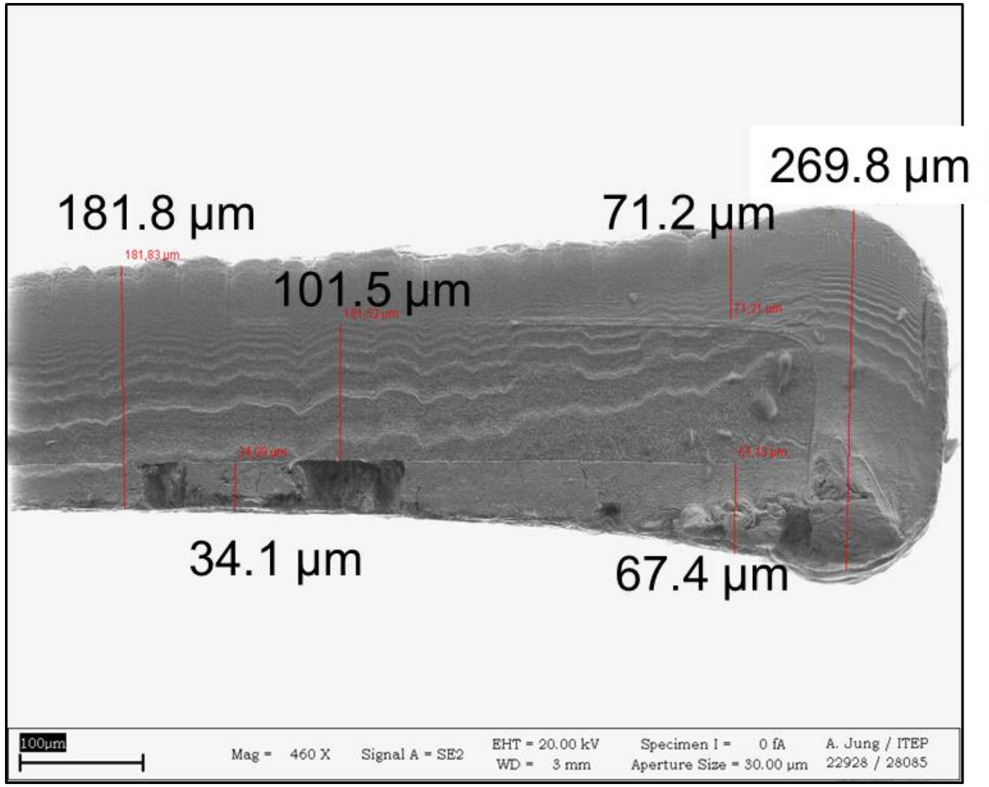
doi.org/10.1088/0953-2048/28/4/045011

Oh boy is this difficult!

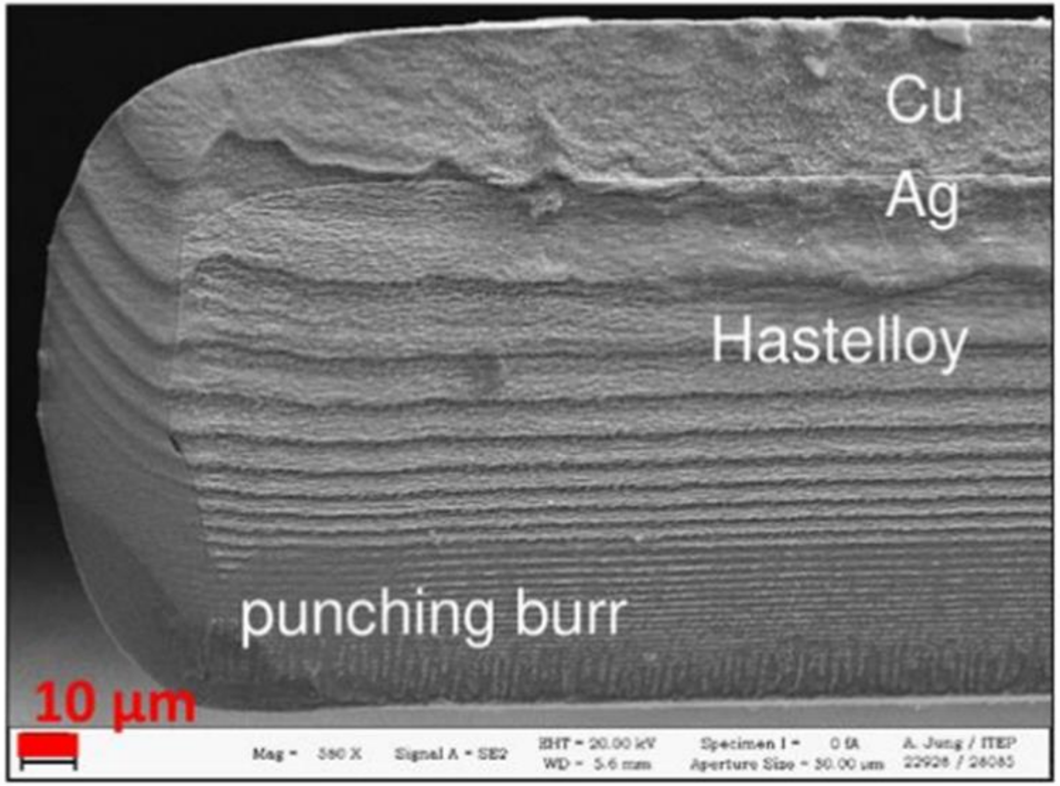
*Prominent examples of things gone wrong: electroplated copper dog-boning

Non-uniform electroplated copper at tape edges is a natural result of the non-uniform geometry and electric field
Thus it cannot be avoided completely
The degree of the coating non-uniformity can be reduced by process improvement

Severe case



Not so bad



A. Kario, EUCARD2 reports

Clever use of imperfect material

REBCO is not yet perfect, but it may be good enough.

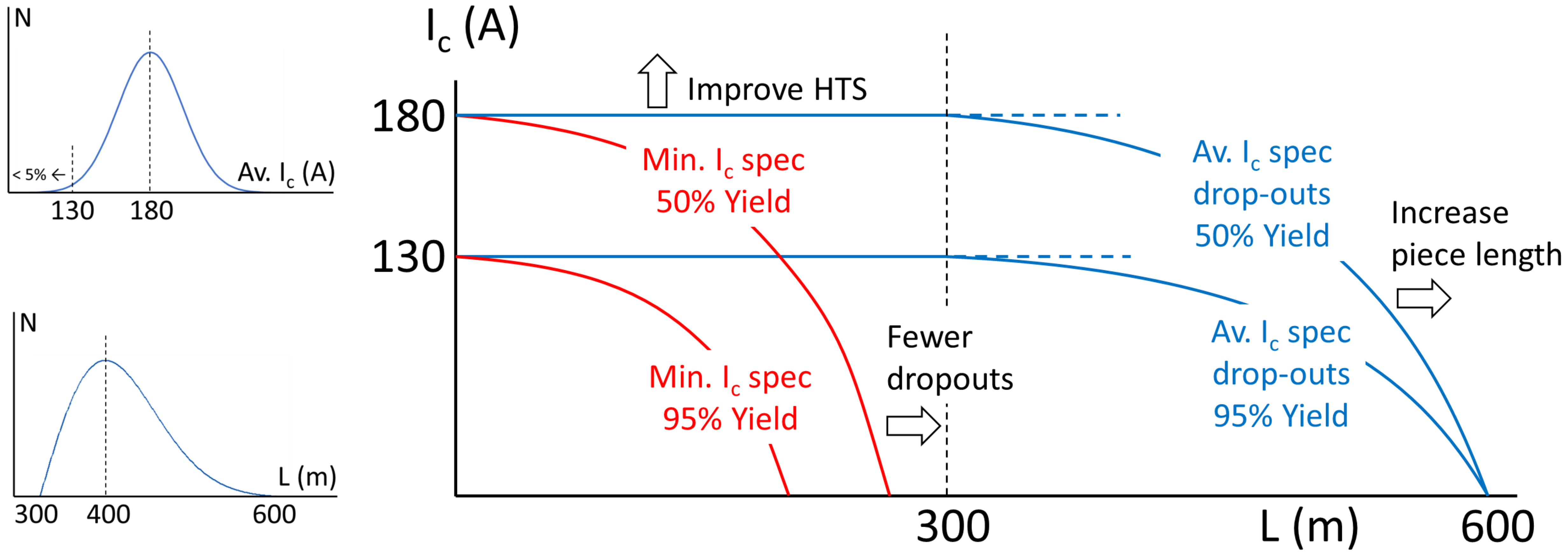
Let’s learn how to use it and use it!

David Larbalestier

Clever use of imperfect material

HTS availability explained

- Semi-quantitative sketch below
- Qualitatively, the same trend for any manufacturer

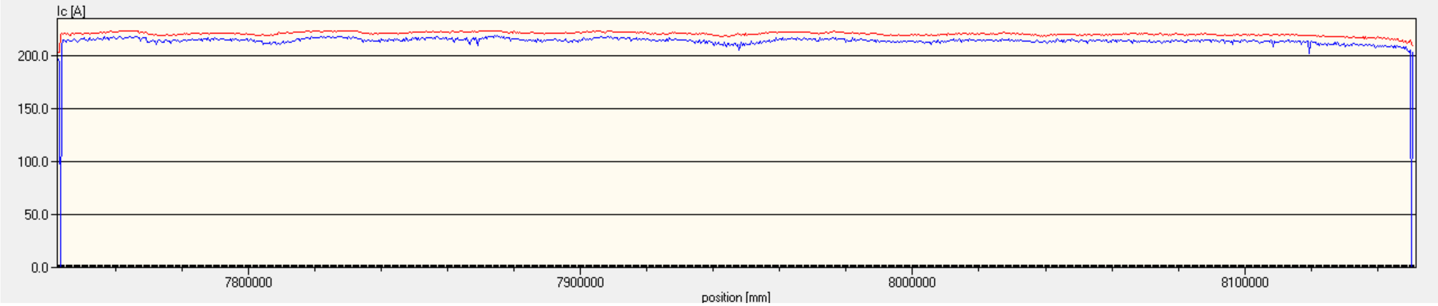


Clever use of imperfect material

*Prominent examples of clever use: niche use of perfect material at a premium price

Requirements to ReBCO coated conductors for UHF NMR application

- Key technical requirements to ReBCO coated conductors for UHF NMR magnets:
  - Uniform properties along entire piece lengths (Ic, copper, insulation,...)
  - Long piece lengths (typically 300 m to 900 m) without Ic drop-outs (I_c dips)
  - High Ic values at high magnetic fields and low temperatures (I_c at 4 K and 10 T B||c: ~350 A to >500 A for 4 mm width)
  - Excellent mechanical properties (Hastelloy substrate,...)



Ascend 1.2 GHz
(HTS/LTS hybrid, 2 K)

Ascend Evo 1.0 GHz
(HTS/LTS hybrid, 4.2 K)

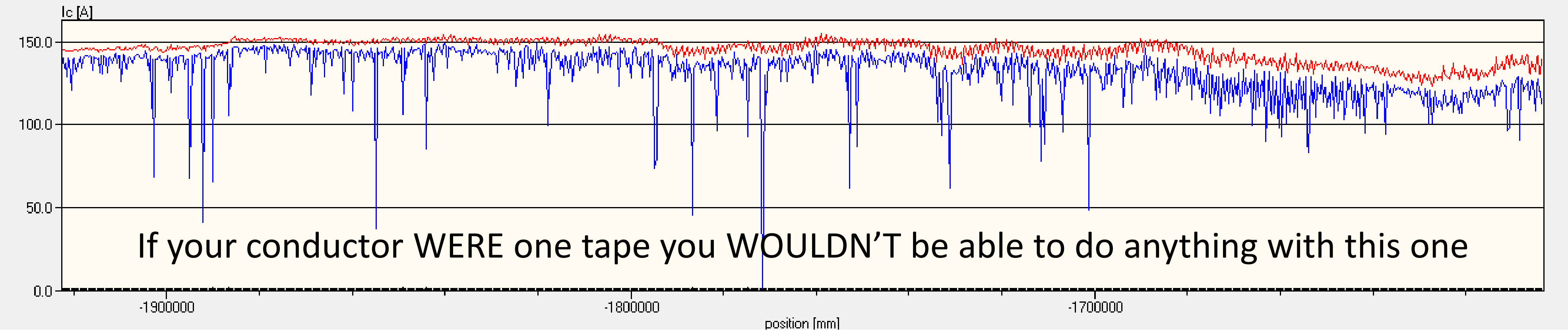
Clever use of imperfect material

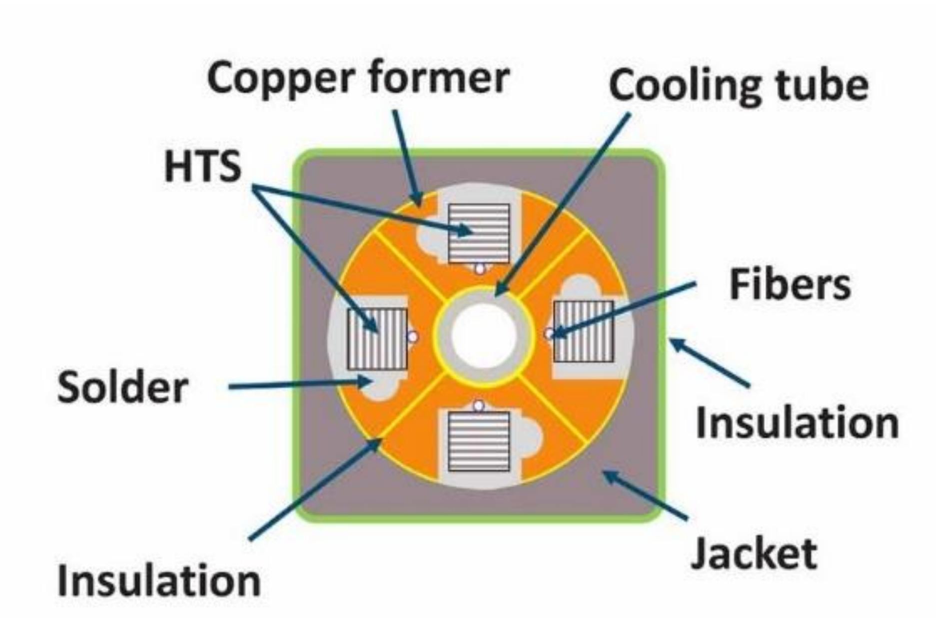
*Prominent examples of clever use: non-insulated (NI) coils

Tokamak Energy drilled 4 or 5 holes in their NI coil in operation before they saw signs of performance degradation

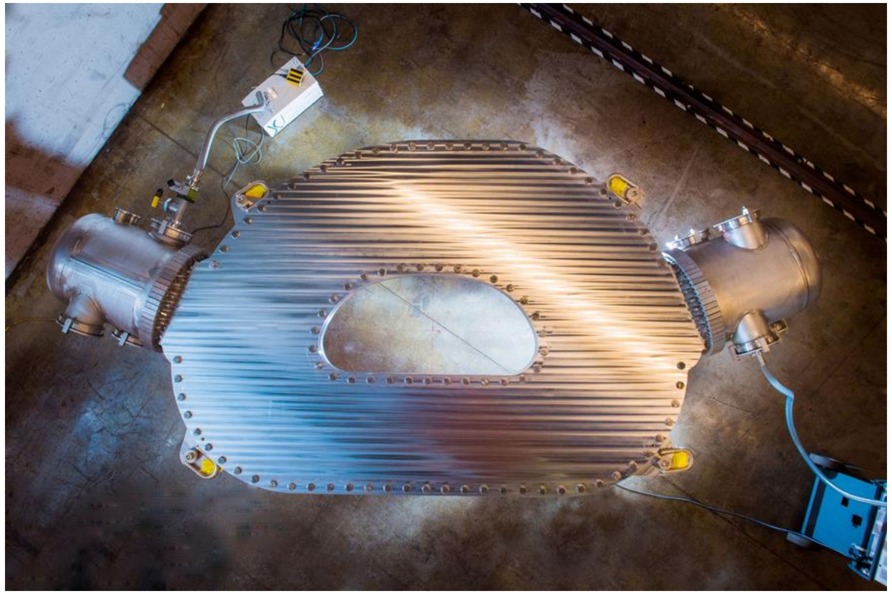
Clever use of imperfect material

*Prominent examples of clever use: multi-strand cables with current sharing





CFS: PIT VIPER cable for CS



CFS: HTS stack cable for TF coils

doi.org/10.1088/1361-6668/ad7efc

doi.org/10.1109/TASC.2023.3332613

Future directions

*Improve on everything---that is, on everything that is important

Make REBCO much closer to commodity than today

More mature industrial production

Better overall quality---in-line QC/QA tools

Fewer dropouts

Longer piece lengths

Do customers really need even higher in-field I_c/J_e in large volume?

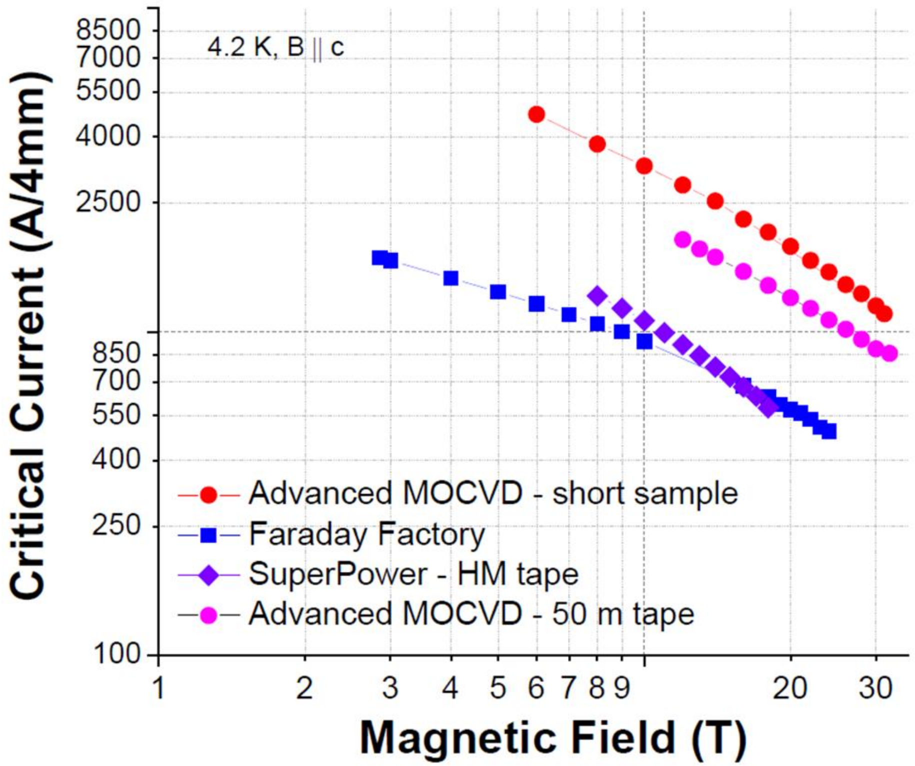
Do customers want to outsource integration of tape into cables and other elements?

Future directions

*Improve on everything---that is, on everything that is important

Do customers really need even higher in-field I_c/J_e in large volume?
Advanced R&D teams prove this is not impossible.

Expectation: there may be a healthy niche segment for such tape.

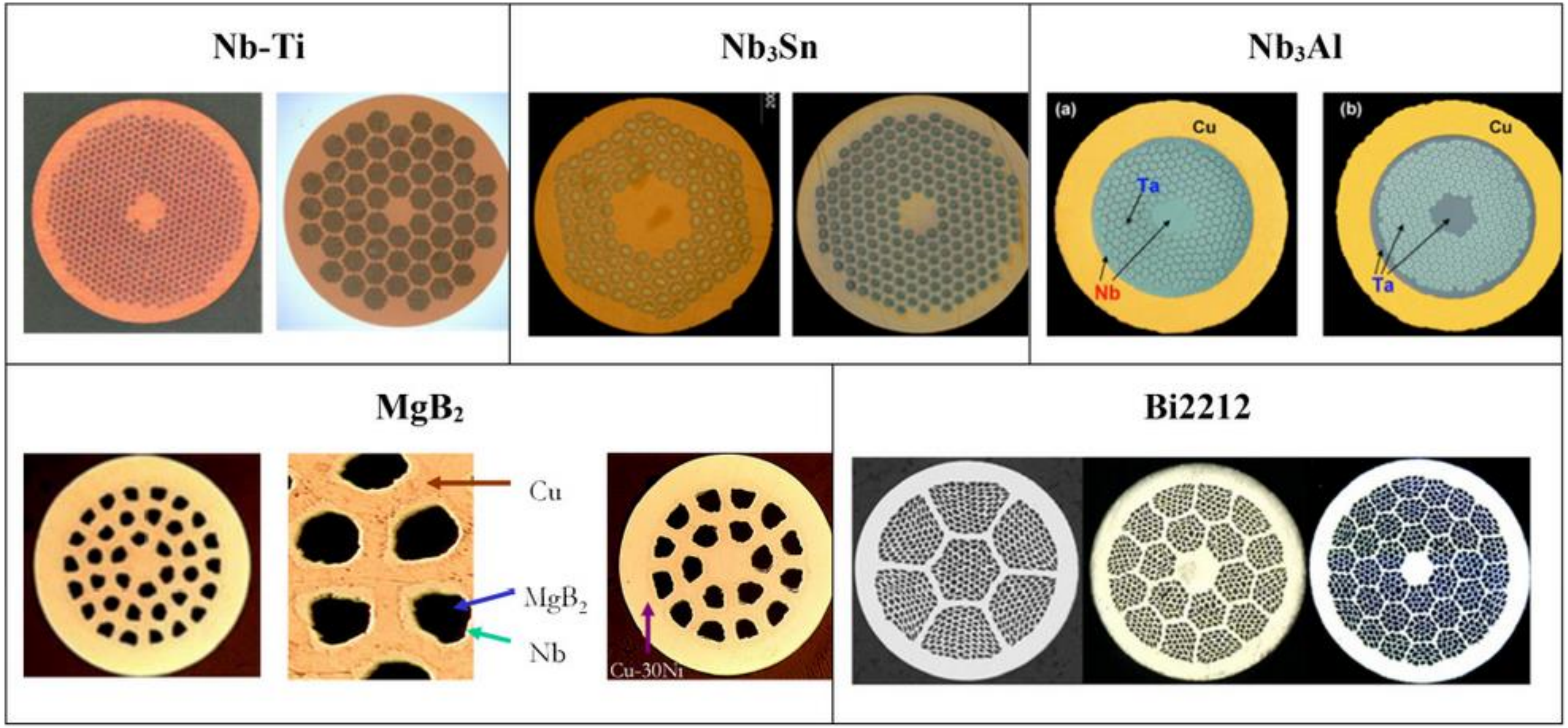


Venkat Selvamanickam

…while even higher performance would be nice, the present performance is sufficient, and we prefer high volume, reproducible quality and low price.
Brandon Sorbom

We did not cover everything

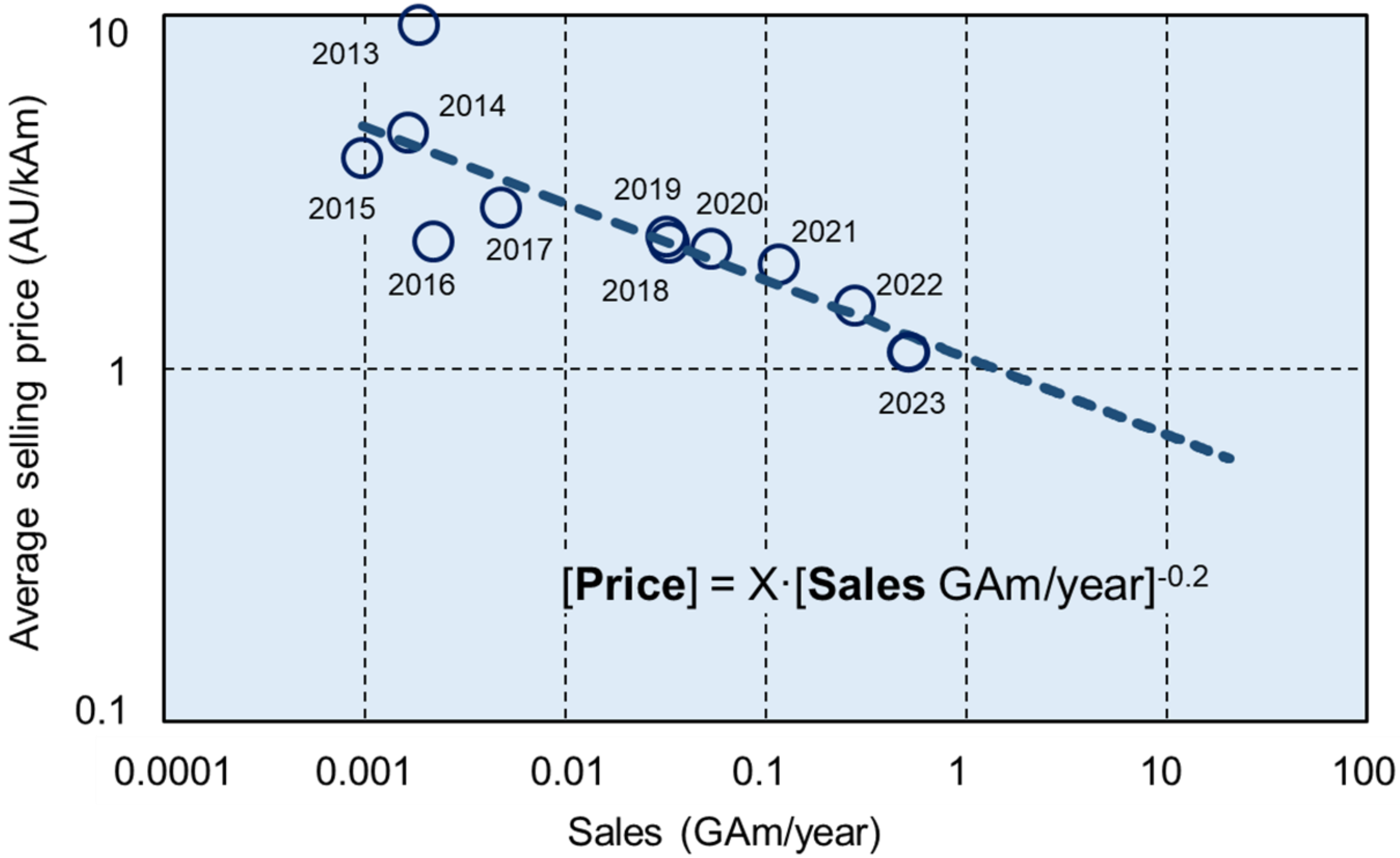
*AC loss   *Cost/price   *…



I am at a loss

We did not cover everything

*AC loss *Cost/price *...



To sustain this trend, we need continuous industrial R&D, to improve throughput of production units

S H O R T C U T

- Why REBCO is so desired for applications
  *Very high critical field   *Tc above LN2   *Possibility of high fields above LHe
- Why REBCO is so difficult to make into a useful conductor
  *Brittle ceramics by the mile   *High anisotropy   *Need for biaxial texture
- How REBCO is made into a useful conductor
  *Template   *REBCO itself   *High field properties
- Fusion hatches the egg for HTS
  *And mutually vice versa
- Oh boy is this difficult!
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*AC loss   *Cost/price

*… Please ask