State of Coated Conductor Industry

REBCO Roundtable *November 2023*

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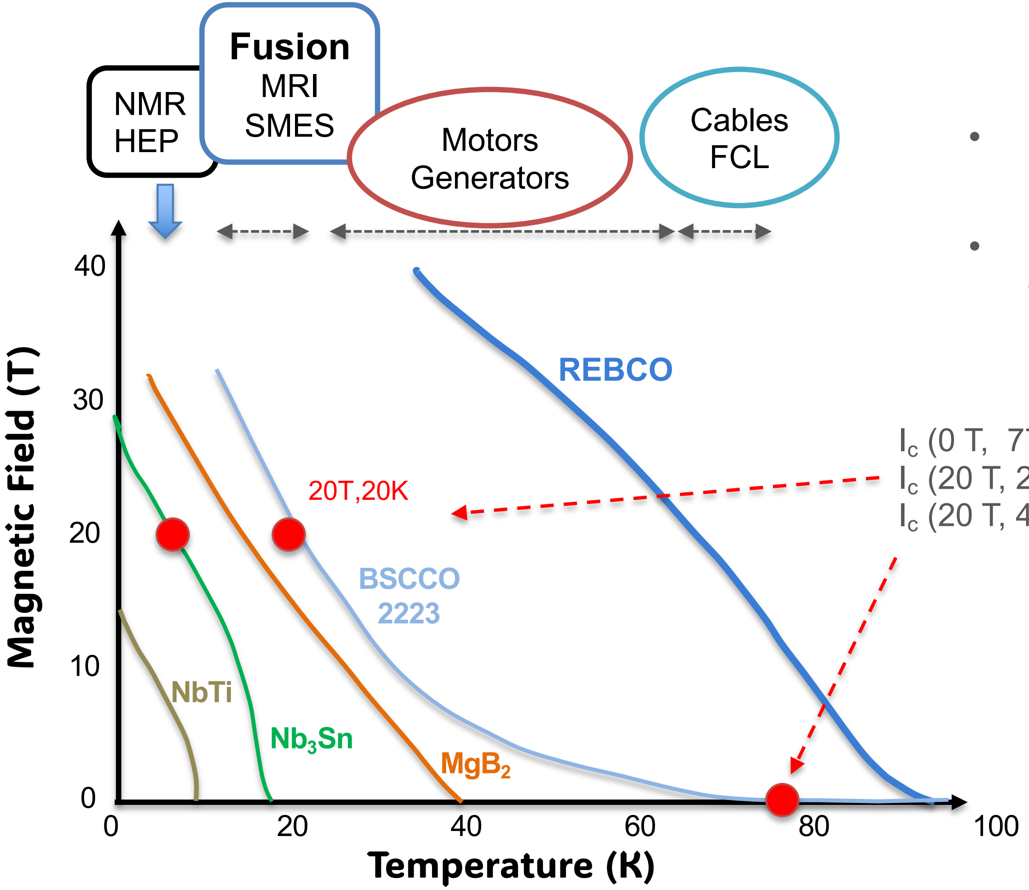
Outline

- Overview of CC with a bit of history
- Current CC (REBCO tape) manufacturers
- Various processes and low-T performance
- Cost and price issues

Coated Conductors are the Highest Performing Superconductors Today

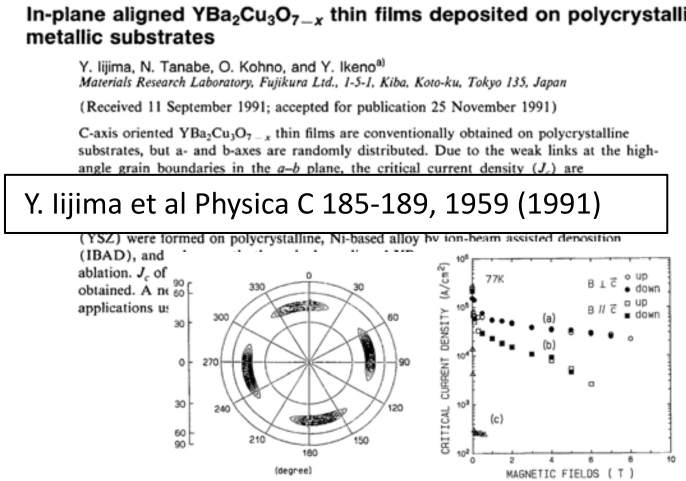


- Biggest current demand is in Fusion generating 10x higher CC production than 5 years ago
- Fusion customers are currently willing to pay the high price for CC

- CC Manufacturers typically make several versions of their REBCO Tape products depending on the specific operating temperature and magnetic field of the application
- Performance continues to improve, esp. as manufacturers make thicker REBCO

Brief History of Coated Conductors – 32 years

- How to make a 'single crystal by the mile'
- Started with Yasuhiro Iijima at Fujikura, 1991



In-plane aligned $YBa_2Cu_3O_{7-x}$ thin films deposited on polycrystalline metallic substrates

Y. Iijima, N. Tanabe, O. Kohno, and Y. Ikeno[a]
Materials Research Laboratory, Fujikura Ltd., 1-5-1, Kiba, Koto-ku, Tokyo 135, Japan

(Received 11 September 1991; accepted for publication 25 November 1991)

C-axis oriented $YBa_2Cu_3O_{7-x}$ thin films are conventionally obtained on polycrystalline substrates, but a- and b-axes are randomly distributed. Due to the weak links at the high-angle grain boundaries in the a–b plane, the critical current density (J_c) are

(YSZ) were formed on polycrystalline, Ni-based alloy by ion-beam assisted deposition (IBAD), and

ablation. J_c of

obtained. A n

applications u

Y. Iijima et al Physica C 185-189, 1959 (1991)

First CC

ORNL RABiTS

IBAD-MgO Stanford

LANL first 1 meter CC

AMSC first commercial CC

SuperPower 10km to Sumitomo

AMSC sells 3000 km CC

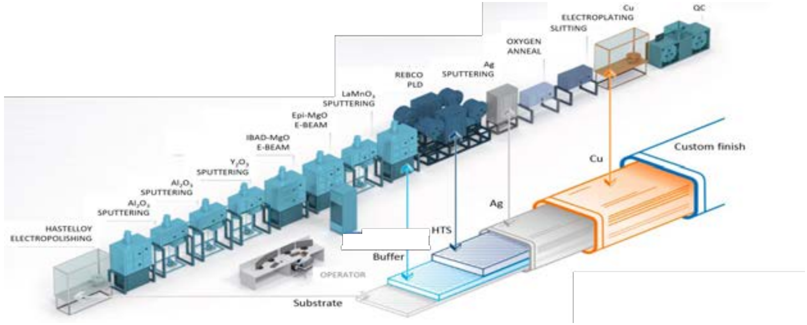
Cable, FCL, Magnets

6 Companies producing CC

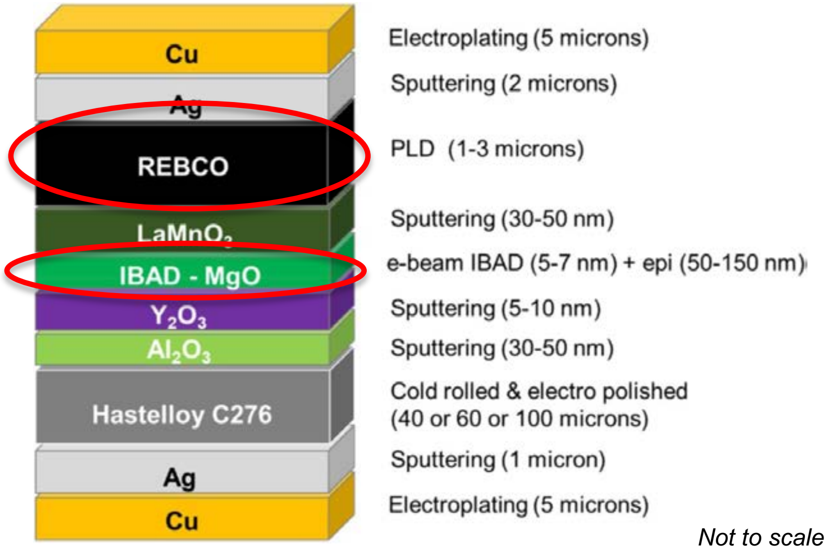
Compact fusion application

1991 1996 2001 2006 2011 2016 2021

CC's Complicated Layering Processes: Two key parts



Most common layer architecture:



Not to scale

Molodyk et al., Scientific Reports (2021) 11: 2084

- Epitaxial REBCO superconducting films (1-5 μm) but with many other layers
- Two key parts:
  - **REBCO layer**
  - **Single-crystal-like template**
- Single-crystal-like template has been somewhat standardized with the Stanford IBAD-MgO (but much more could be done); some are using RABiTS or ISD
- REBCO growth can be done *In situ* or *Ex situ* depending on when the growth occurs

How do you grow epitaxial films of REBCO?

1) ***Ex situ***

Deposit constituent elements first and then react to form the compound: **Two step** process

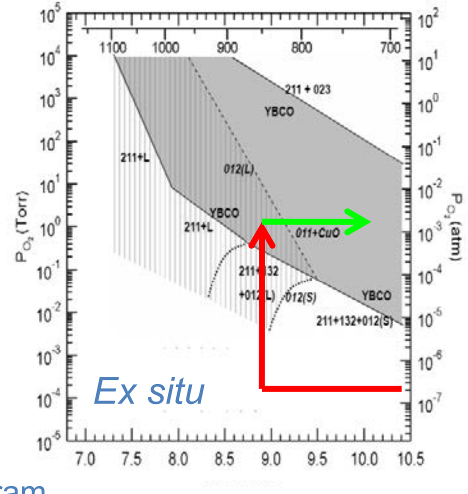
2) ***In situ***

Deposit constituent elements and form the structure during deposition: **One step** process

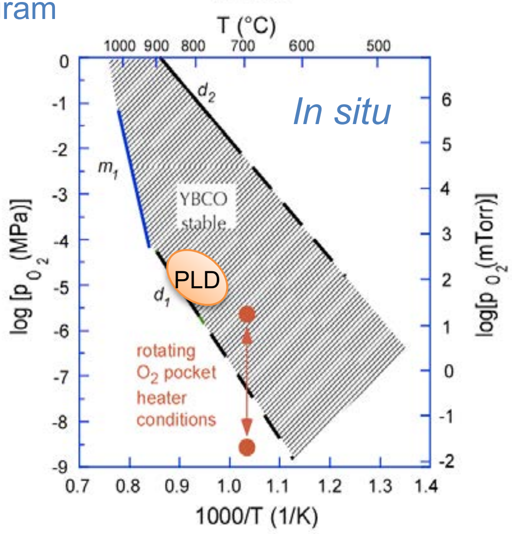
Challenge: Need oxygen; Stability diagram for YBCO phase: Hammond-Bormann line

- Each REBCO tape manufacturer has chosen their own path for REBCO growth

Pulsed Laser Deposition (PLD), Metal-Organic Chemical Vapor Deposition (MOCVD), Reactive Coevaporation (RCE) and Metal Organic Deposition (MOD) non-vacuum



REBCO
Stability diagram



Matijasevic et al *IEEE Trans. Appl. Supercond.* (1993)

Coated Conductor (REBCO Tape) Manufacturers

2023

Top Producers (for Low T, High B):

SuperOx, FF
Russia/Japan
(IBAD+PLD)

Fujikura,
Japan
(IBAD+PLD)

Shanghai Superconductor
Shanghai, China
(IBAD+PLD)

SuperPower, NY,
USA/Japan
(IBAD+MOCVD)

Theva GmbH,
Germany
(ISD+RCE)

Addl Producers:

SuNAM Co. Ltd,
Korea
(IBAD+RCE)

American Superconductor, Inc
Devens, MA, USA
(RABiTS+MOD)

Shanghai Creative Superconductor,
Shanghai, China
(IBAD+MOD)

Eastern Superconductor
ETERN/SAMRI/CAS,
Suzhou, China
(IBAD+MOCVD)

Currently Building Production Equipment:

Metox Technologies, Inc.
Houston, TX USA
(IBAD+MOCVD)

High Temperature Superconductors, Inc.
Santa Barbara, CA USA
(IBAD+PLD)

Future:

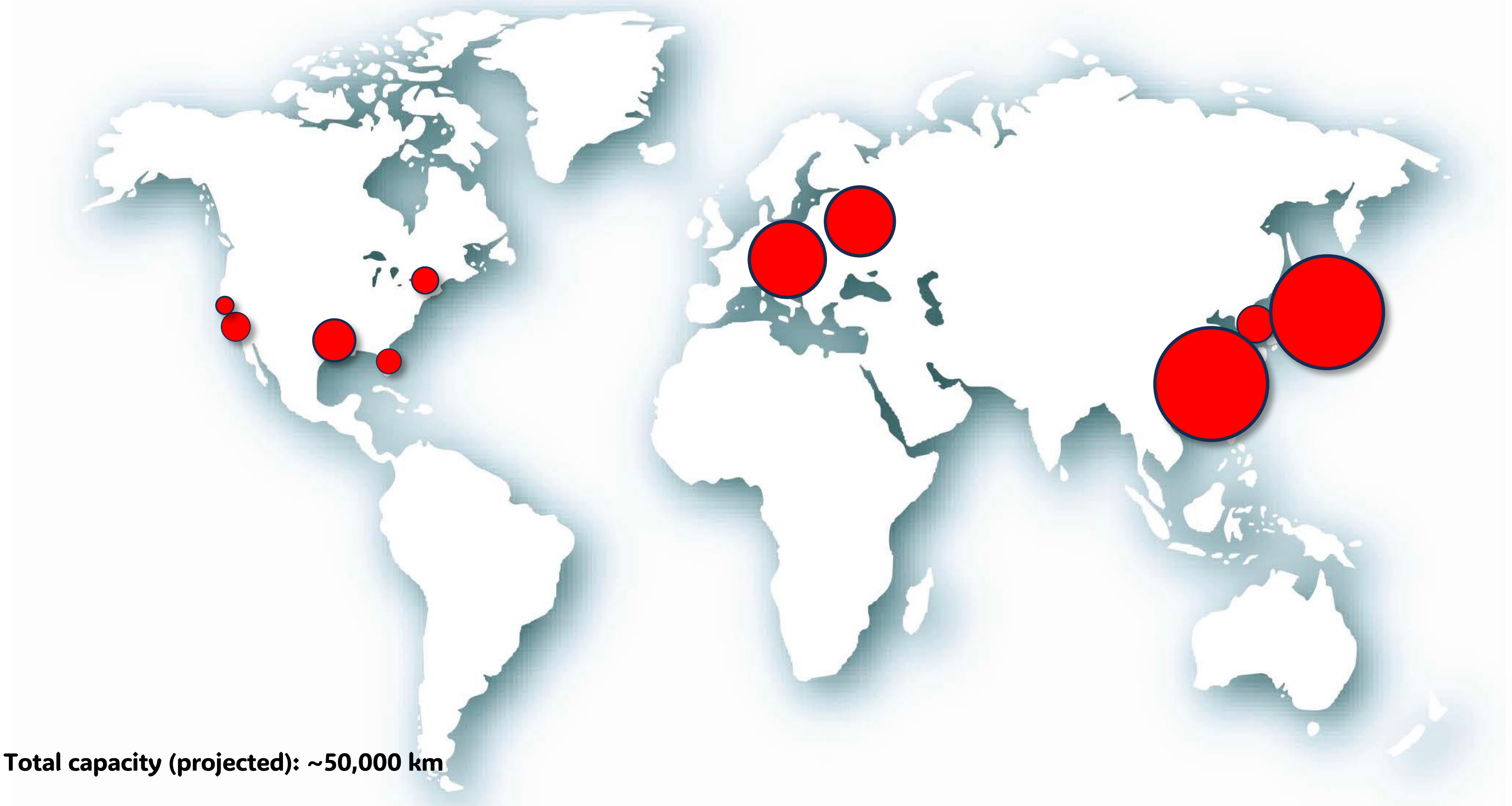
Sumitomo, Japan
(RABiTS+MOD)

Showa, Japan
(RABiTS+MOD)

Coated Conductor World Map

Total annual production (est): 6,000 km
Total capacity (claimed): 14,000 km

Coated Conductor World Map – in 2026



Total capacity (projected): ~50,000 km

Summary of Coated Conductor Producers (Q4 2023)

Company		Process	Capacity 4MME	Future
Faraday Factory Japan 20/20	Japan	IBAD + PLD	4000 km	5500 km (2024)
Fujikura 20/20	Japan	IBAD + PLD	?	>double (2025)
Shanghai Superconductor Tec 20/20	China	IBAD + PLD	2000 km	9000 km (2026)
SuperPower 20/20	USA	IBAD + MOCVD	200 km	1200 km (2025)
Theva 20/20	Germany	ISD + RCE (CDR)	360 km	7500 km (2025)
SuNAM	Korea	IBAD + RCE (LATS)	700 km	1000 km (2025)
Shanghai Creative SuperConductor	China	IBAD + MOD	400 km	3000 km (2025)
Eastern Superconductor	China	IBAD + MOCVD	3000 km	6000 km (2024)
High Temperature Superconductors	USA	IBAD + PLD		2025
MetOx Technologies	USA	IBAD + MOCVD		2025
Sumitomo Electric Industries	Japan	RABiTS/IBAD + MOD		2026
SWCC Showa	Japan	IBAD + MOD		

Summary of Different Processes Utilized

REBCO / Template	*In situ* growth			*Ex situ* growth	
	PLD	**MOCVD**	**RCE-CDR**	**RCE-LATS (DR)**	**MOD**
IBAD (MgO)	FARADAY FACTORY JAPAN Fujikura 上海超导科技股份有限公司 Shanghai Superconductor Technology Co., Ltd. SST	SuperPower Inc. A Furukawa Company Eastsuper		SuNAM	上创超导 Shanghai Creative SuperConductor SCSC
RABiTS					amsc
ISD			THEVA		

Pinning in REBCO Superconductors

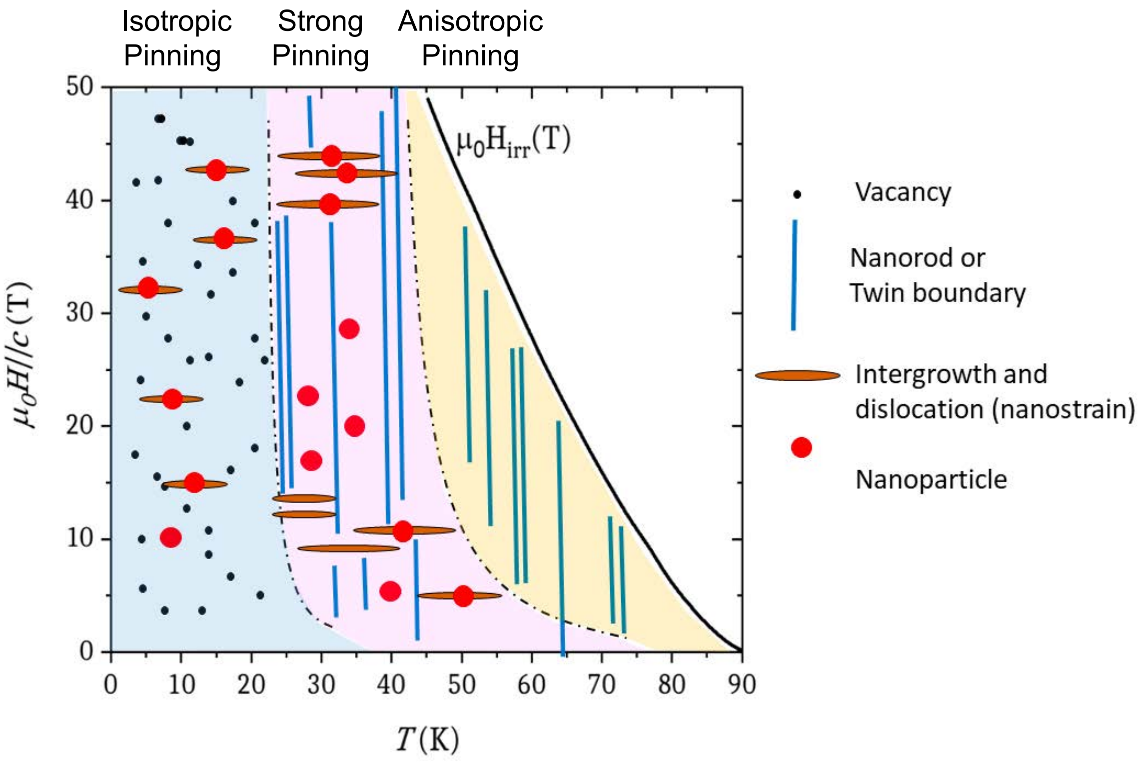
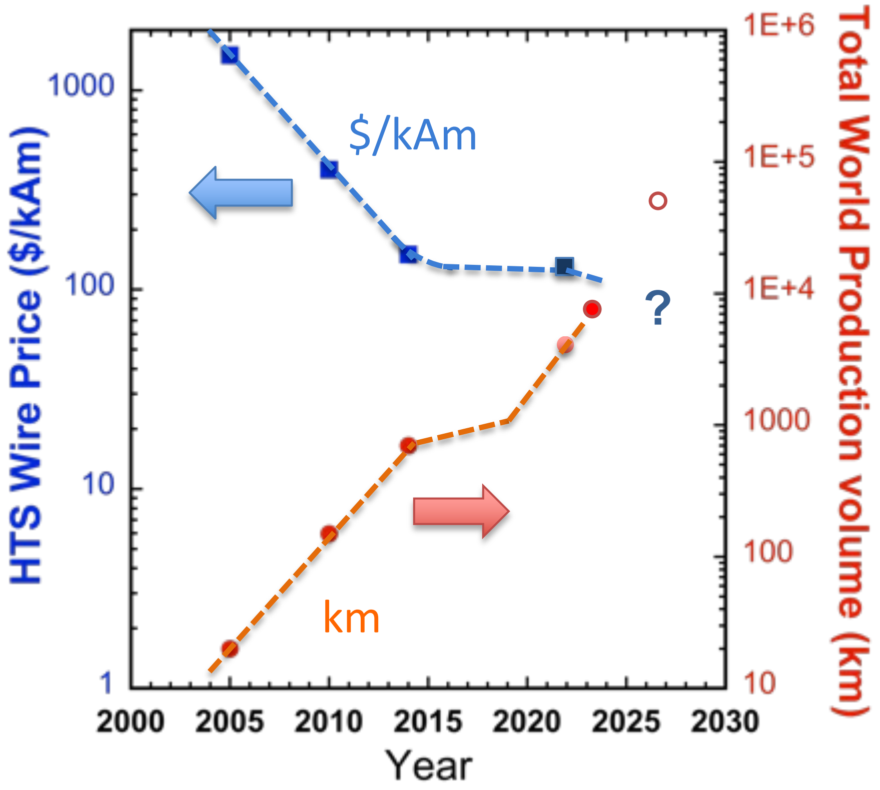


Figure from T. Puig ICMAB, 2023

- At higher temperatures long linear pinning centers are beneficial due to thermal fluctuations of vortices, typically produced by APC nanocolumns
- At low temperatures point defects are more beneficial for pinning
- *In situ* REBCO growth provides more easily the 0D point defects
- *In situ* grown films have been shown to have higher J_c in field at low T
- *Ex situ* growth should be able to provide such defects as well, but typically provides cleaner, defect-free, materials due to high temperature kinetics and liquid-assist nature

CC Cost and Price Trends

- Low-cost CC are inherently possible
- At present CC Production volume is increasing quite a bit, but price is decreasing only slightly
- Companies are ramping up production *without* significant reduction in production cost (*cloning production systems*)
- Manufacturers announced in September 2023 a ramp up to ~50,000 km by 2026
- Competition is expected to lower the price somewhat in the next few years
- Not yet clear how production costs will come down
- Cost is dominated by REBCO deposition and growth cost



V. Matias and R.H. Hammond, Phys Procedia 36, 1440, 2012

Conclusions

- Technical and manufacturing progress on Coated Conductors for applications has been considerable in the last decades
- Vibrant industry: 12+ companies are producing or intending to produce coated conductors
- Fusion application, led by CFS demand (2018-2024), has revitalized the field and ramped up production (>10x), but mostly in one manufacturer (SuperOx/Faraday Factory)
- Current CC production is dominant in Russia and Japan; future production should also be much more in China and USA
- However, price is still high for large-scale adoption for many applications. Post-2024 price should come down more with increased competition, but assuming demand will continue to grow.
- More Production R&D is needed for CC cost reduction with scale up (new ARPA-E program)
- Suggestions for the Magnet community:
    - Utilize the large number of suppliers available; currently not in the US, but there will be 3 in US
    - Specifications are still evolving; need to work with the suppliers (mostly small companies) who are eager to learn from customers
    - Start with large magnets that are less demanding on performance uniformity (eg current sharing)