UNIVERSITY of HOUSTON

AMI ADVANCED MANUFACTURING INSTITUTE

Development of High Temperature Superconductors for Wind Energy

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TcSUH

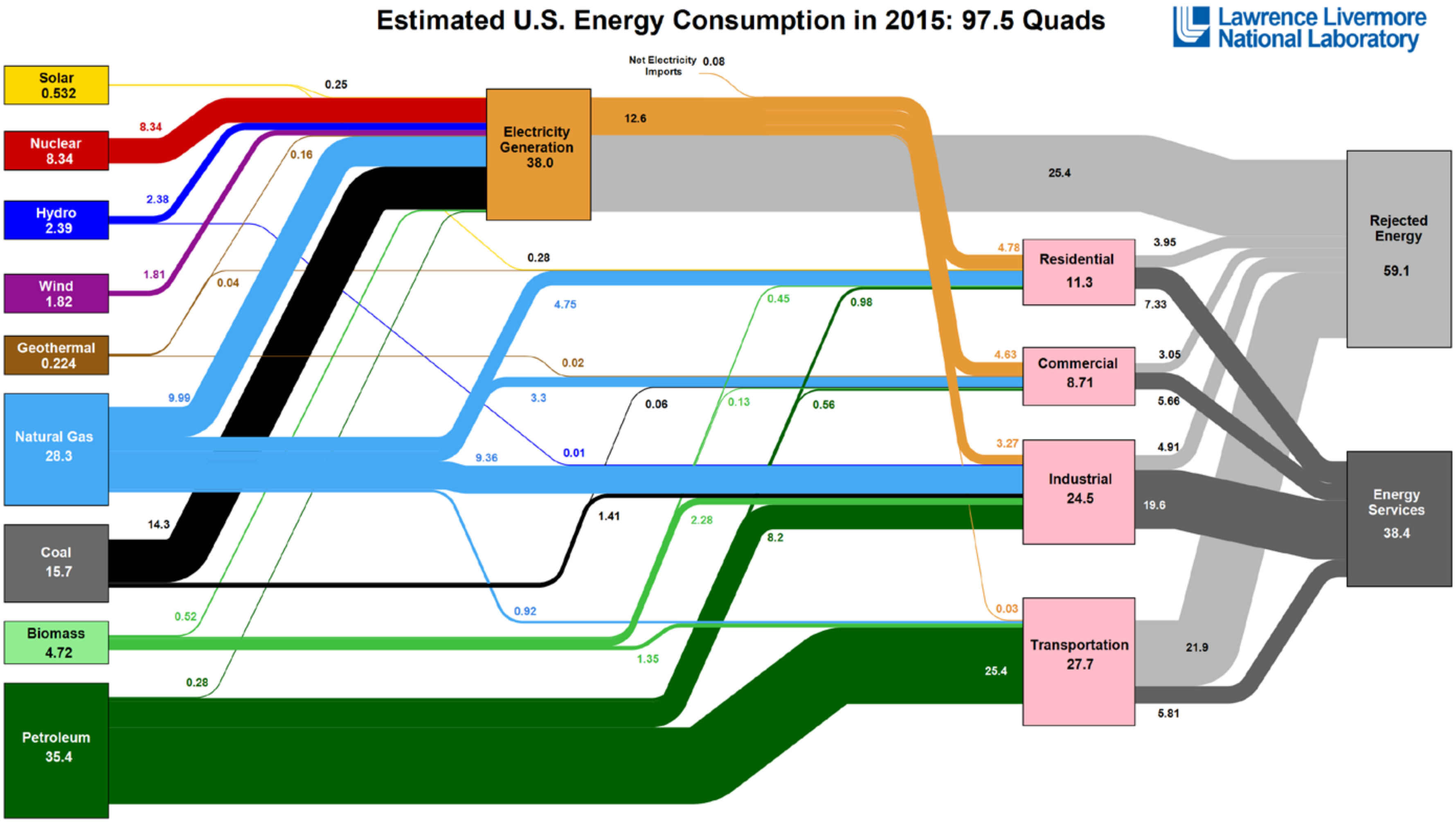
Iowa State University, February 6, 2017

Outline

- Superconductors for energy applications
- High Temperature Superconductor Wire Manufacturing
- Enhanced HTS Wire for Wind Energy and other Applications
- Path Forward: High-yield Manufacturing of High Performance Superconductors

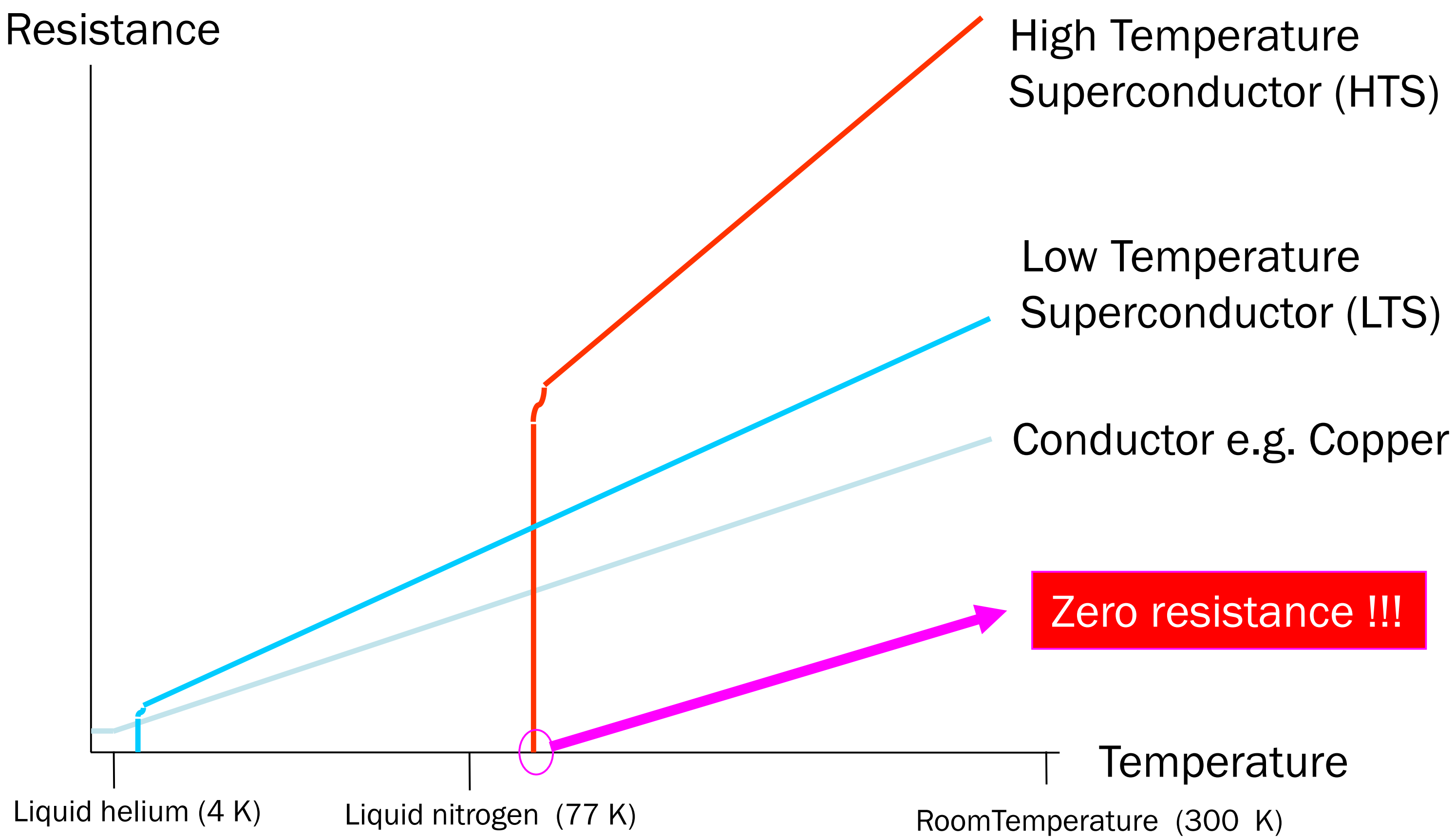
Superconductors for energy applications

Two-thirds of primary energy is lost in electricity generation/use



https://flowcharts.llnl.gov/

High temperature superconductors : Unique materials with great potential

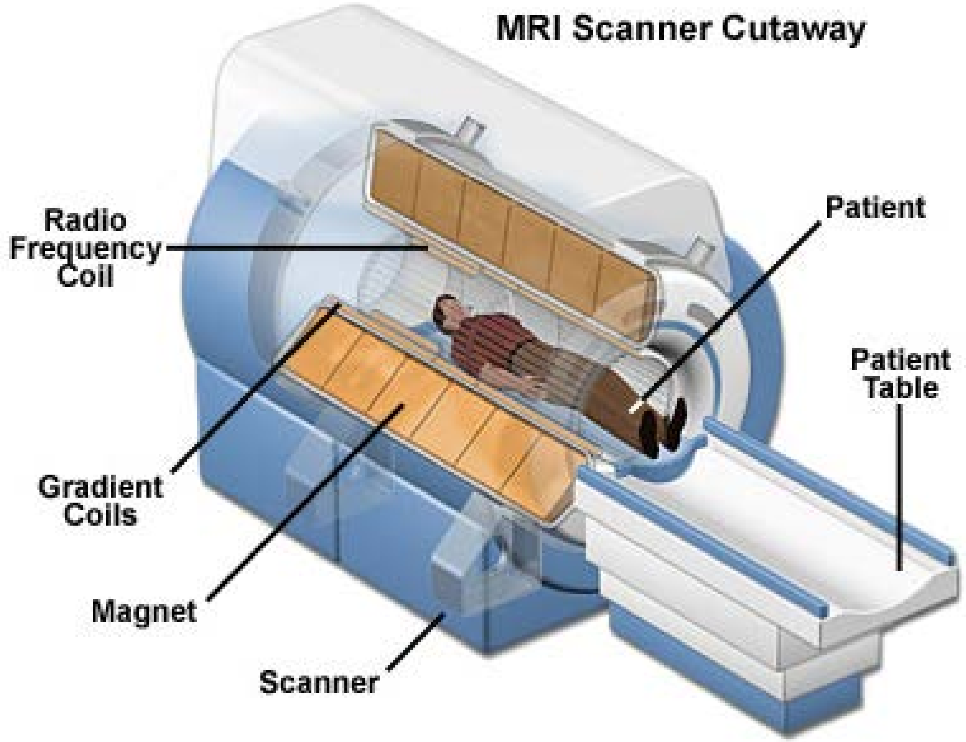


Current carrying capability of copper ~ 100 A/cm^2

Current carrying capability of superconductor ~ 5,000,000 A/cm^2

Low Temperature Superconductors are widely used in medical applications

Medical Devices: MRI

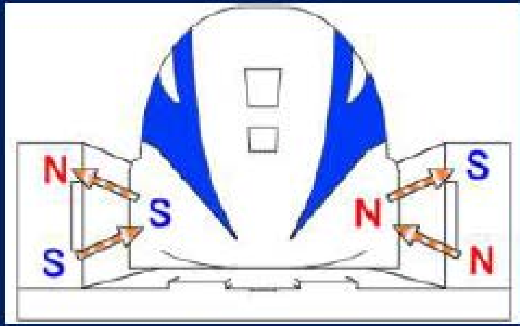


http://www.magnet.fsu.edu/education/tutorials/magnetacademy/mri/index.htm

MRI is a $ 3B industry enabled by superconductors.

Low Temperature Superconductors enable Maglev transportation

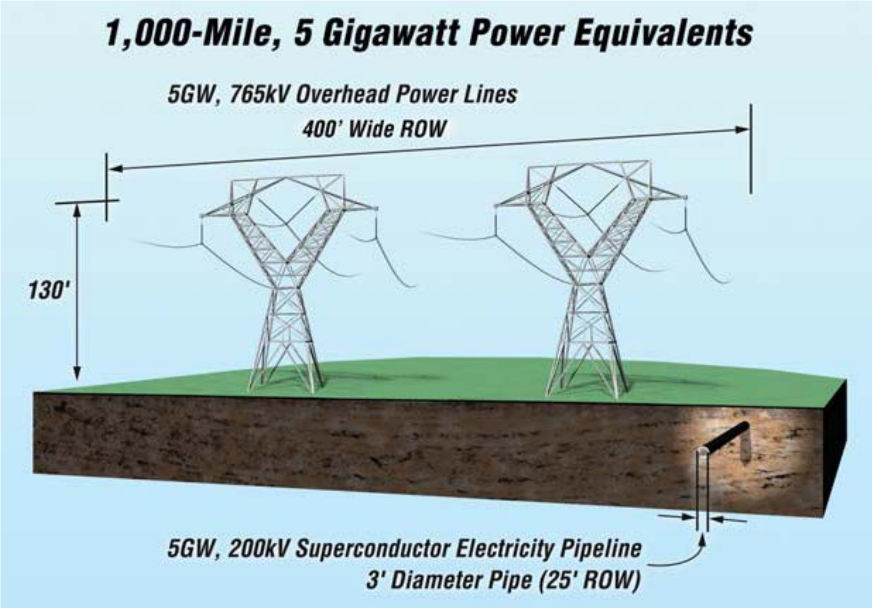
- JR-Maglev since 1969 pushed forward, records at 580 km/h, nominal 500 km/h
- Summer 2011 : Now first passengers track will be built, very important!
- From Tokyo via Nagoya (in 2027) to Osaka (in 2045) in 1h (now 2h25)



Courtesy of Herman ten Kate

Superconducting powerlines for long distance transmission of renewable energy

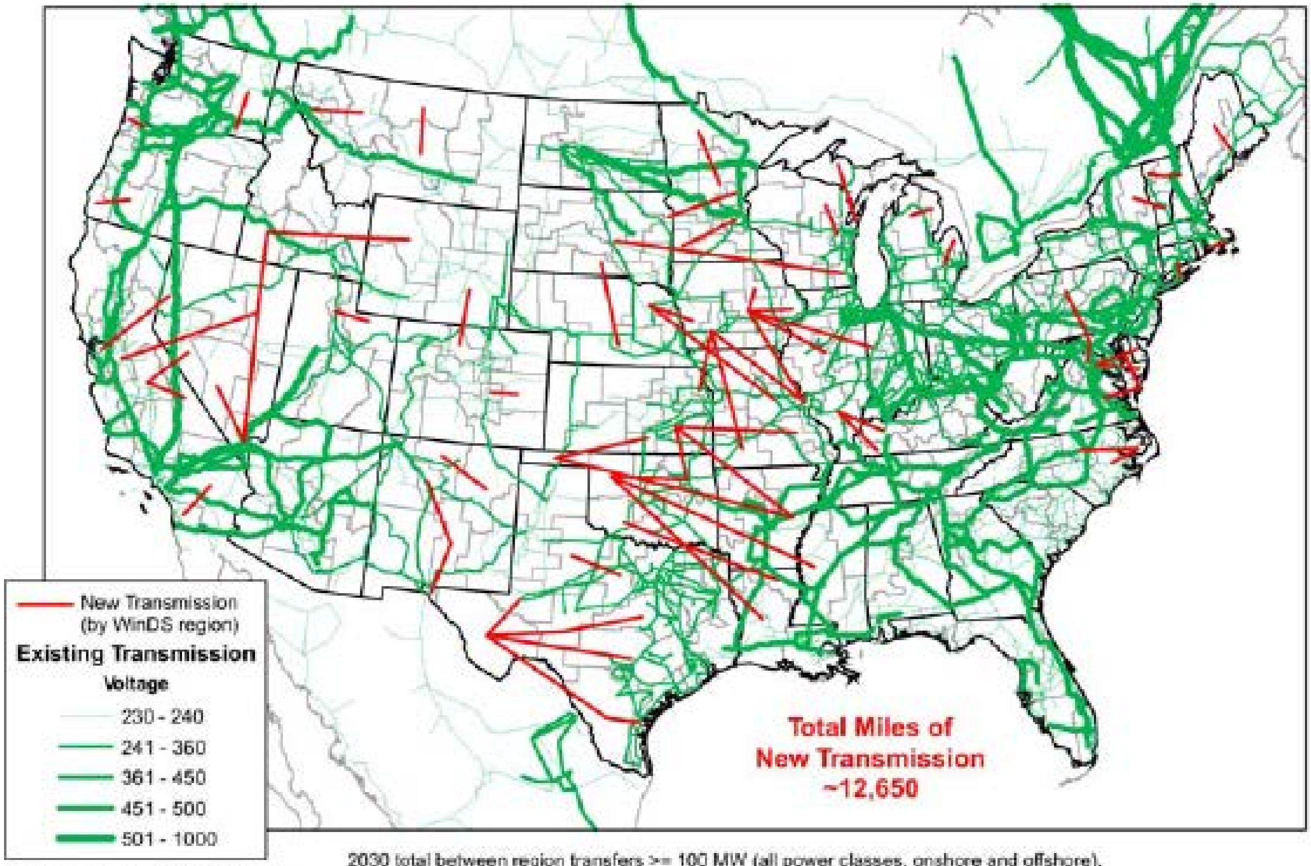
- 5 to 10 times more capacity than comparable conventional cables
  - *Can be used in existing underground conduits → saves trenching costs*
- Much reduced right of way (25 ft for 5 GW, 200 kV compared to 400 feet for 5 GW, 765 kV for conventional overhead lines)



12,000 miles of new transmission lines needed for 20% Wind Energy

Figure 4-10. Conceptual new transmission line scenario by WinDS region

2030 - New Transmission Lines - WinDS Region Level - Simplified Corridors >= 100 MW

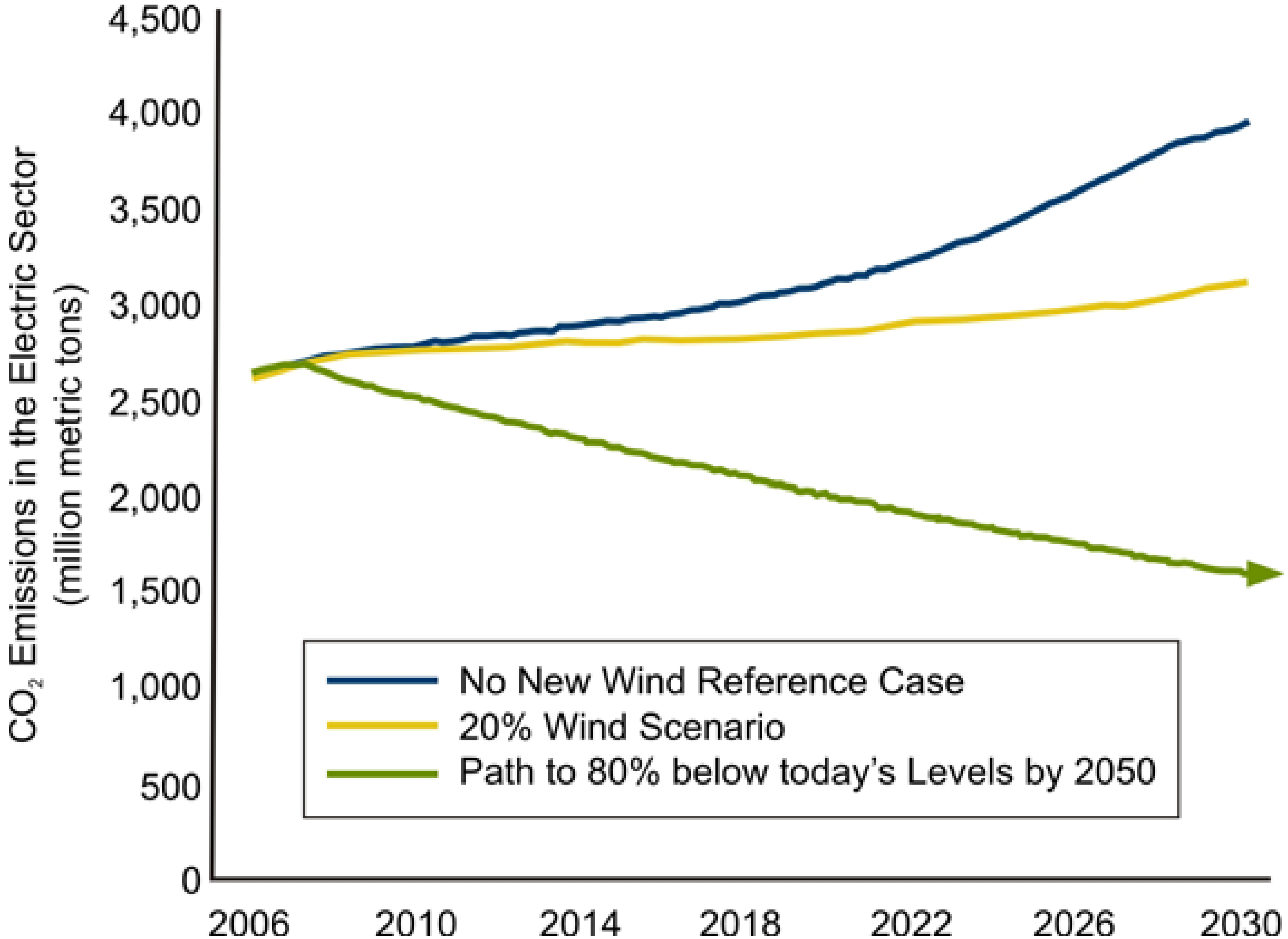


Existing Transmission Data: POWERmap. powermap.platts.com ©2007 Platts. A Division of The McGraw-Hill Companies

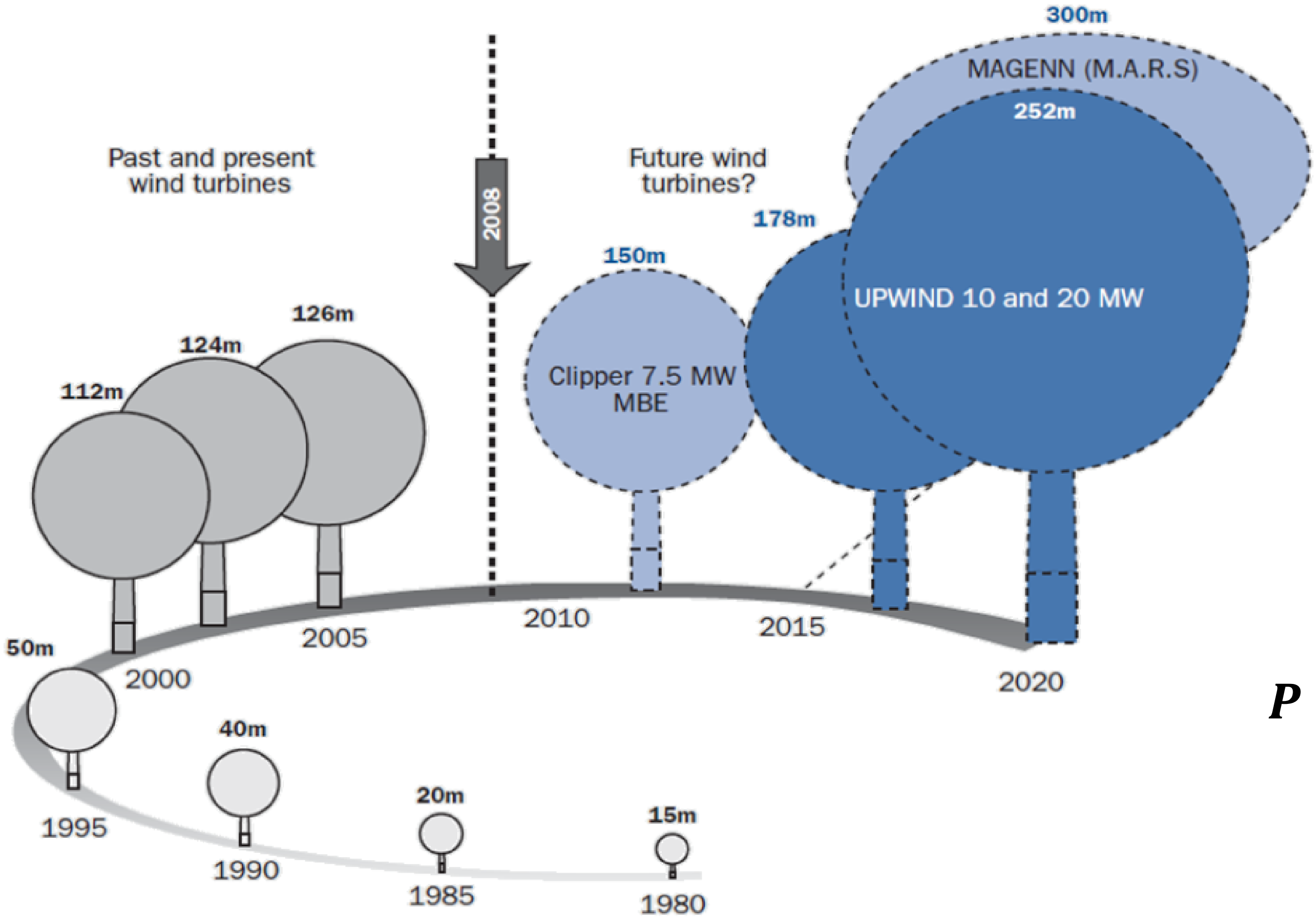
2030 total between region transfers >= 100 MW (all power classes, onshore and offshore), visually simplified to minimal paths. Arrows originate and terminate at the centroid of the region for visualization purposes; they do not represent physical locations of transmission lines.

20% Wind 06-19-2007

Significant opportunities for CO_2 reductions by wind energy



Large and high power wind turbines preferred for reducing cost of wind energy

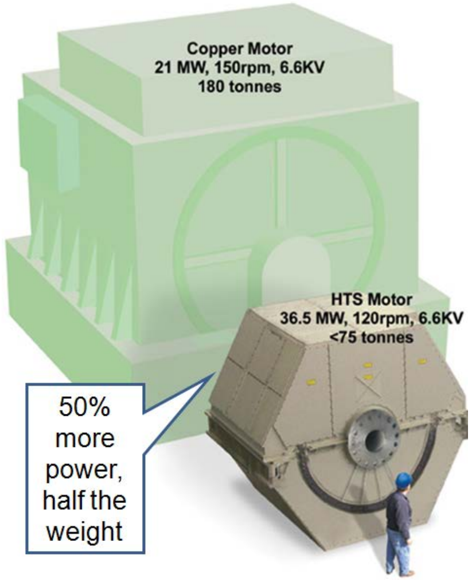


$$P = R_{blade}^{5}$$

Ref: Garrad Hassan

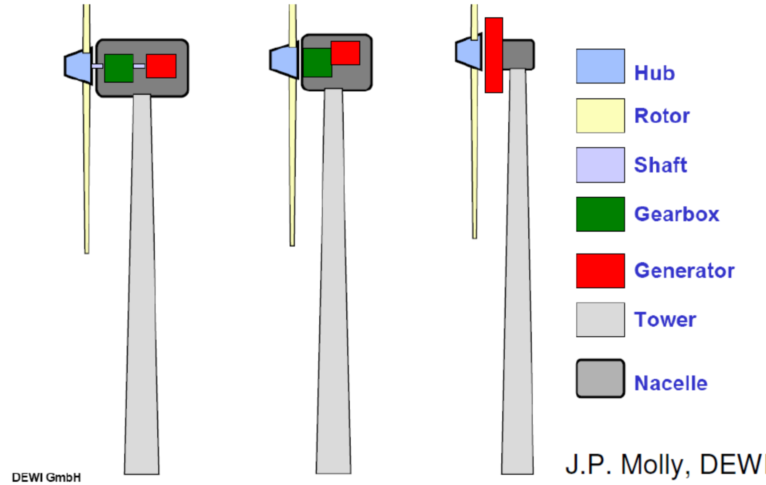
Superconducting generators for wind energy

- Superconducting generators can be beneficial in high power density systems
  - *Reduce generator weight & volume by 50% or more (< 500 tons for 10 MW compared to ~ 900 tons for conventional direct drive)*
  - *More efficient, especially at part load*
  - Cooling of superconductors consumes about 6 kW (< 0.1%). Single-stage cryocoolers weigh < 0.5 ton



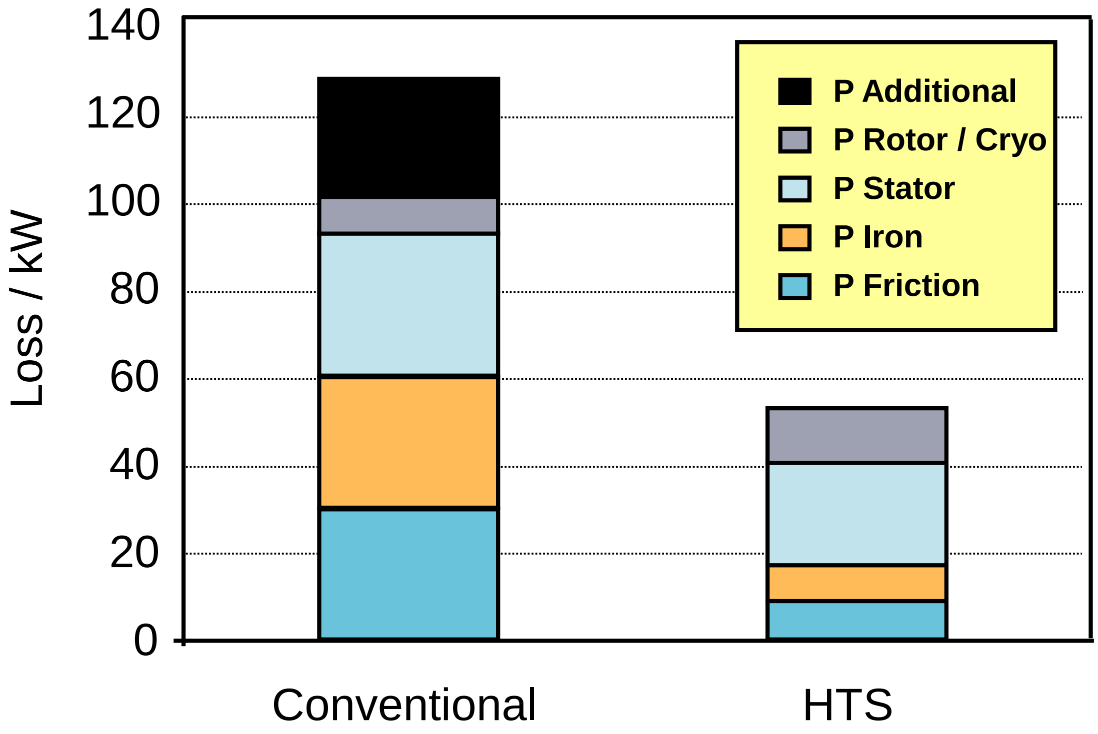
- Superconducting generators for light-weight, higher-power, direct drive turbines
  - Preferred for off-shore wind energy for economy & less maintenance
  - More efficient, especially at part load

- **Conventional :** **15 RPM → 1:100 gearbox → 1500 RPM gen.**
- **Hybrid:** **15 RPM → 1:6 gearbox → 90 RPM gen.**
- **Multi-pole:** **15 RPM direct drive**



J.P. Molly, DEWI 2007

2% efficiency improvement in Siemens' 4 MVA HTS Generator



Picture: Siemens

Efficiency at rated operation

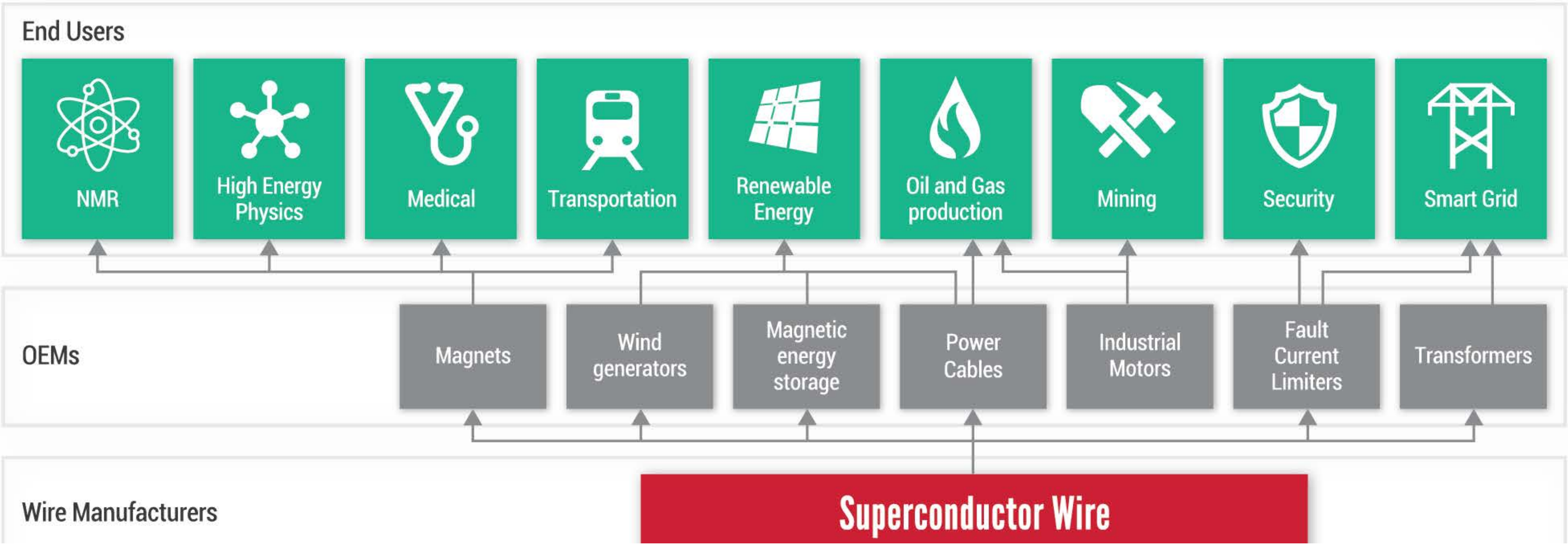
cos φ	Conv.	HTS
0.8	96.1 %	98.4
1.0	97 %	98.7

- Higher power density → higher magnetic field in armature winding → less Cu and steel → less overall losses

Klaus et al. Design Challenges and Benefits of HTS Synchronous Machines, *IEEE Transactions* 2007

Multi-pronged impact of Superconductors can be realized in clean energy applications

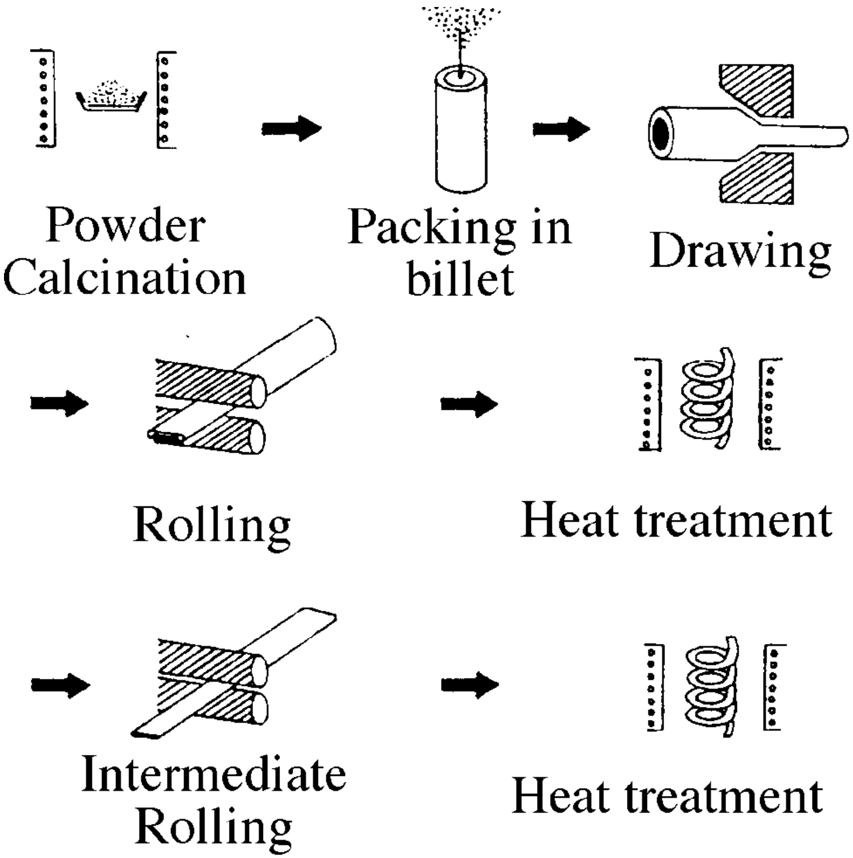
- Enhanced energy efficiency
- High power density
- Less CO_2 emission
- Better power quality
- Better security of electric power grid



High Temperature Superconductor Wire Manufacturing

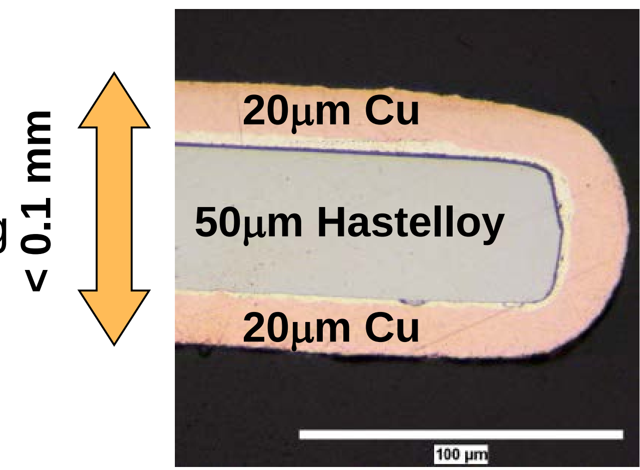
Challenge is to produce HTS in form of a flexible wire/tape

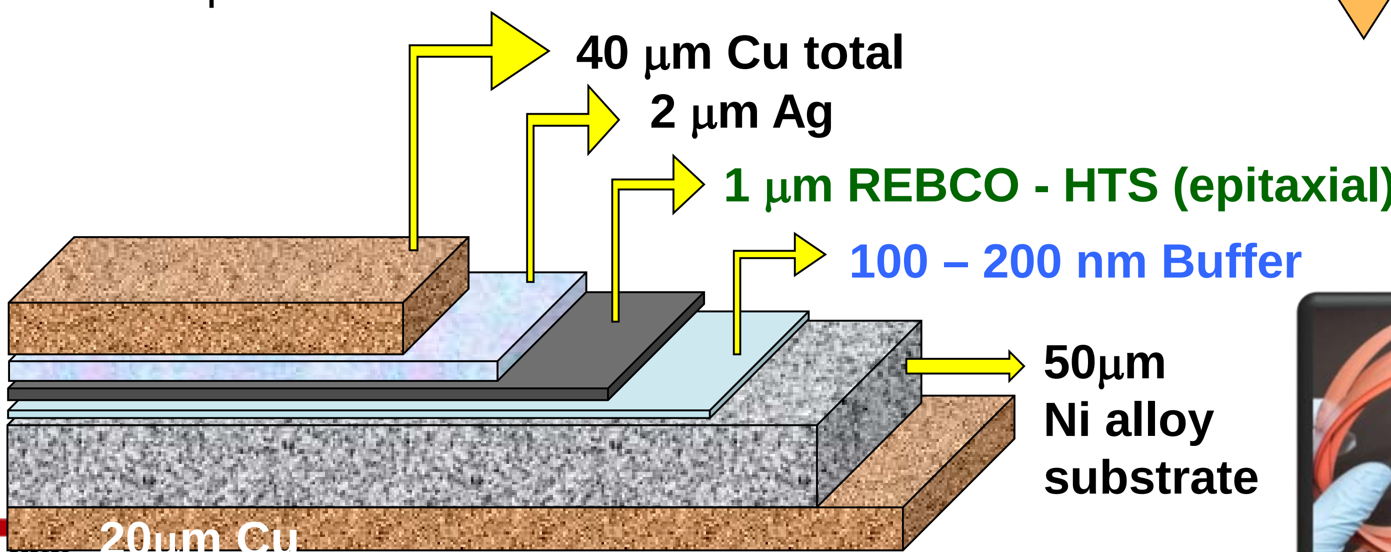
- High-temperature superconductors are ceramic materials and are inherently brittle. Challenge is to produce them in a flexible wire form in lengths of kilometers
- Two approaches to produce HTS in flexible tape form:
  - First-generation (1G) HTS - HTS is encapsulated as filaments in a silver sheath
    - expensive materials, labor intensive, performance limitations
    - Inferior performance in high magnetic fields



Thin film (2G) HTS tape manufacturing approach

- 2G HTS tape is produced by thin film vacuum deposition on a flexible nickel alloy substrate in a continuous reel-to-reel process.
  - Only 1% of wire is the superconductor
  - ~ 97% is inexpensive nickel alloy and copper
  - Automated, reel-to-reel continuous manufacturing process



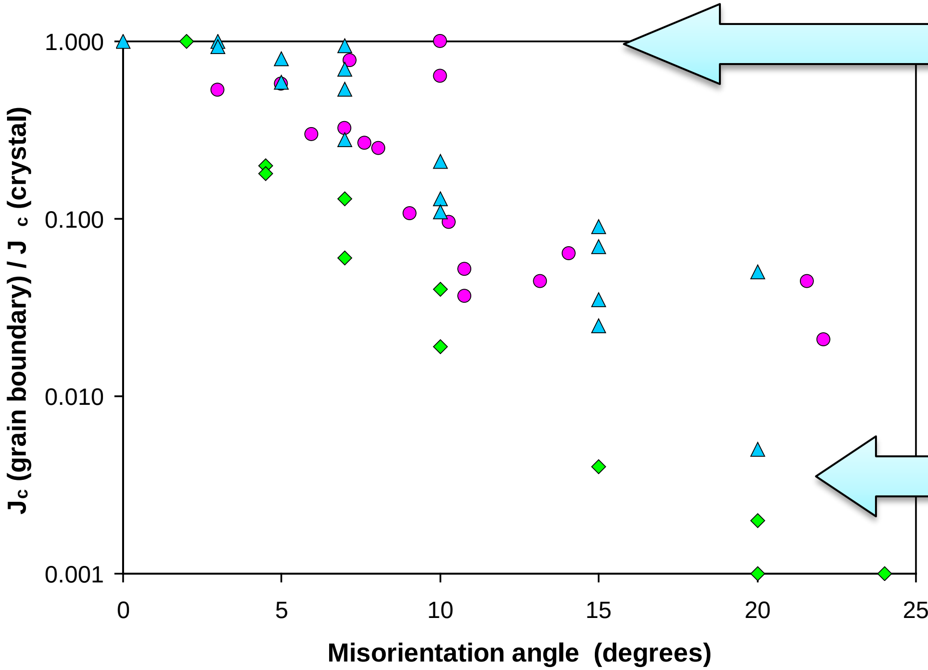


Fundamental challenge in thin film HTS tapes

Current density of epitaxial thin film of HTS on single crystal substrate ~ 5 MA/cm^2

Current density of thin film of HTS on polycrystalline substrate ~ 0.01 MA/cm^2

Grain-to-grain misorientation in a polycrystalline HTS thin film is responsible for low current density



Single crystal film current density

● D. Dimos, *et al.*, Phys. Rev. B **41**, 4038 (1990).

▲ N.F. Heinig, *et al.*, Appl. Phys. Lett. **69**, 577 (1996).

◆ D. T. Verebelyi, *et al.*, Appl. Phys. Lett. **76**, 1755 (2000).

Typical current density of HTS film on polycrystalline substrate

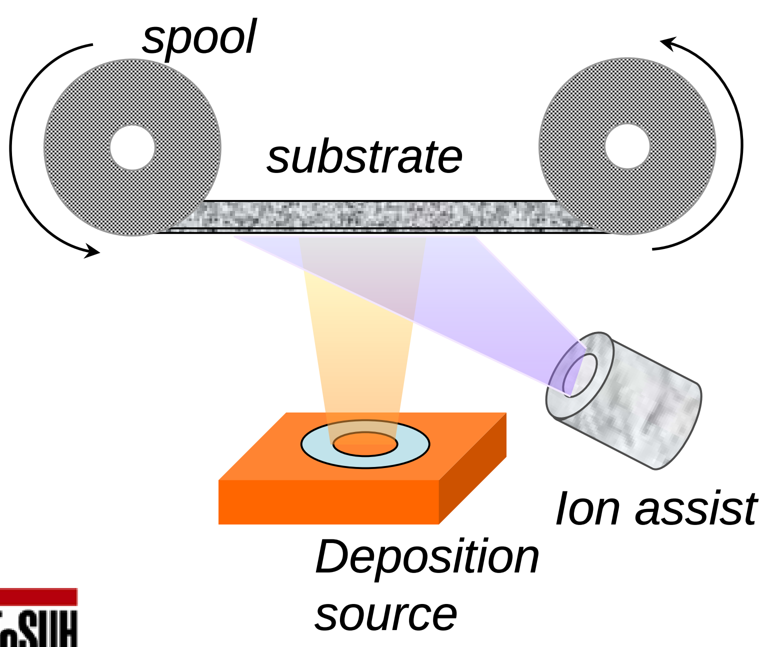
(data complied by S. Foltyn, LANL)

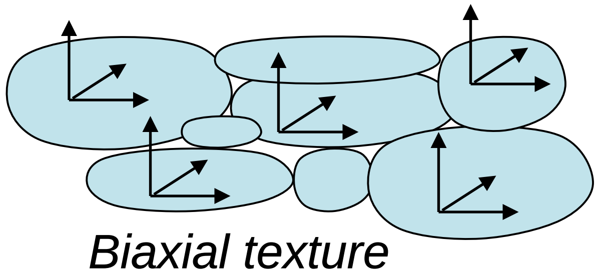
Cannot make kilometer lengths of HTS thin film wire on single crystal substrates.

Need a way to produce single crystalline like HTS thin films on practical, polycrystalline flexible substrates

Ion Beam Assisted Deposition (IBAD) – A technique to produce near single crystal films on polycrystalline or amorphous substrates

- Essentially, any substrate can be used – stainless steel, nickel alloys, glass, polymer …(room temperature process)
- Biaxial texture achieved in certain conditions of ion bombardment resulting in grain-to-grain misorientation in film plane of about 5 degrees !
- Only 10 nm of IBAD film is needed – very fast process !

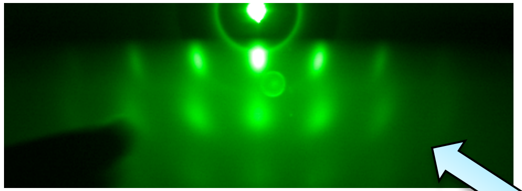




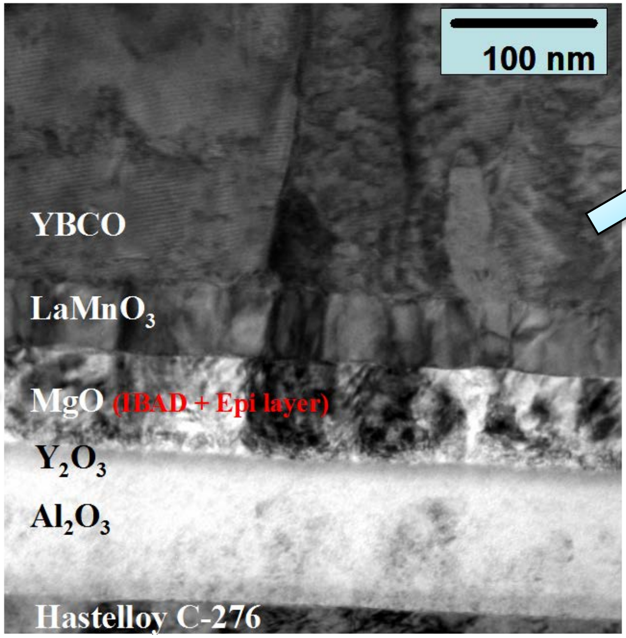
Grains in the IBAD film are arranged in a 3-dimensional aligned structure with grain-to-grain misorientation in any axis less than 5 degrees – essentially a near-single crystalline structure

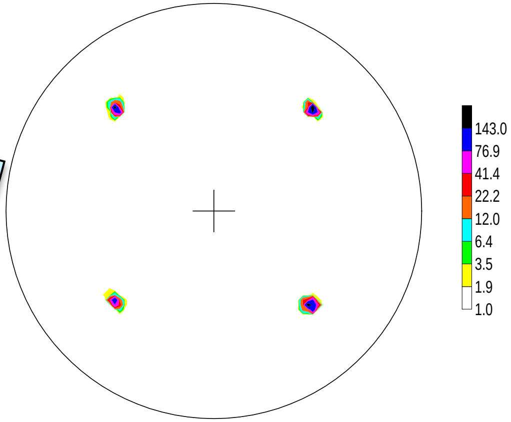
Epitaxial single crystalline-like films on polycrystalline or amorphous substrates based on IBAD

- A near single crystalline film is achieved by IBAD under specific conditions.
- Once a template is created, this near-single-crystalline structure can be transferred epitaxially to many other films.



Reflection High Energy Electron Diffraction of growing IBAD film showing biaxial texture development within a few nanometers

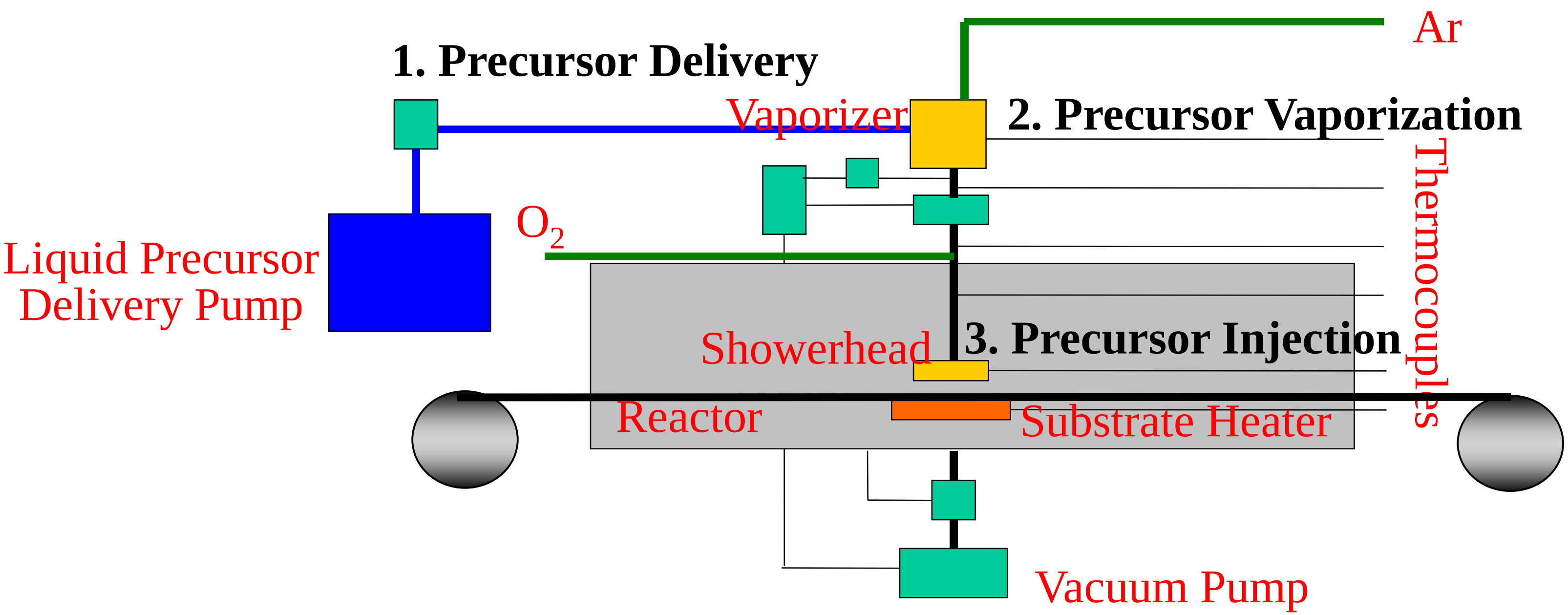




YBCO(113)

X-ray polefigure showing a high degree of biaxial texture in a superconducting $YBa_2Cu_3O_x$ film grown epitaxially on a IBAD MgO film even though the lattice mismatch is about 8%

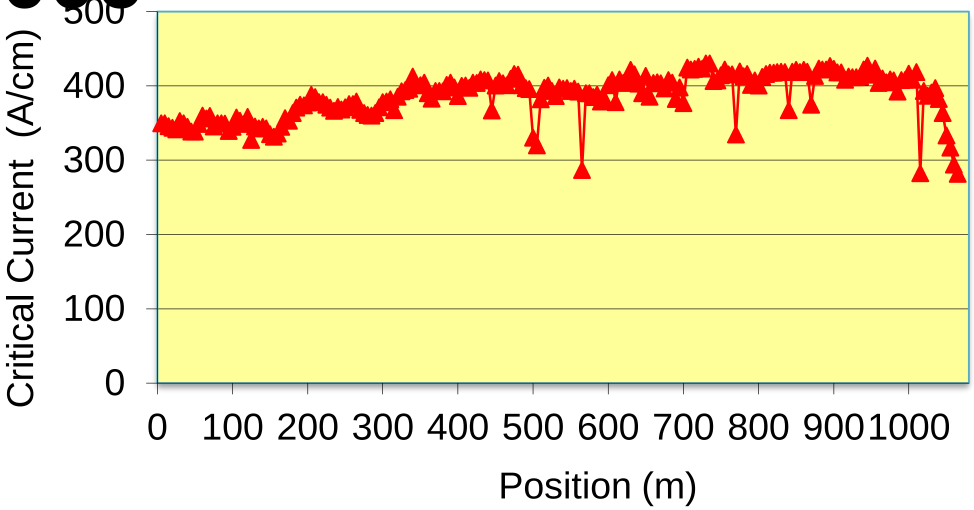
Superconductor film deposition by metal organic chemical vapor deposition (MOCVD)



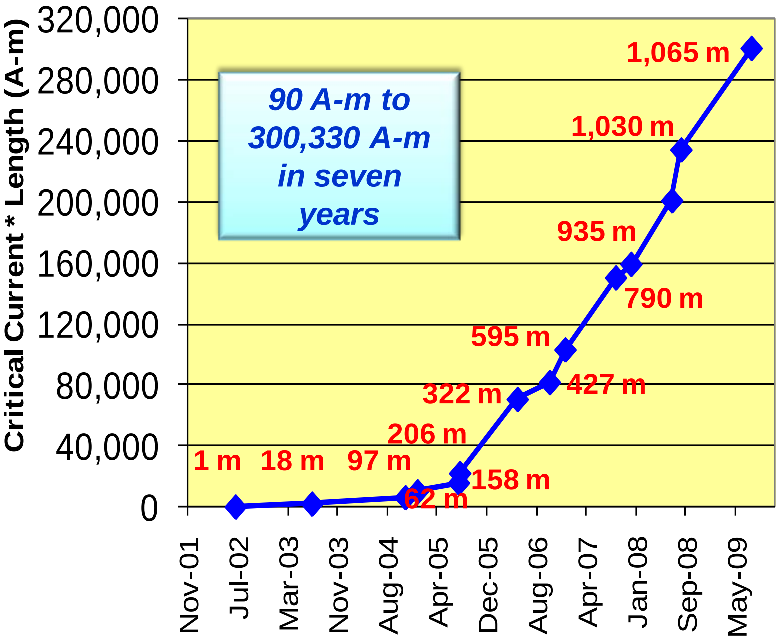
$$Y(thd)_3 + Ba(thd)_2 + Cu(thd)_2 \rightarrow YBa_2Cu_3O_7 + CO_2 + H_2O$$

thd = (2,2,6,6-tetramethyl-3,5-heptanedionate) = $OCC(CH_3)_3CHCOC(CH_3)_3$

2G HTS wire was scaled to pilot manufacturing in 2006



2G HTS wire is now routinely produced up to **kilometer lengths** with **300 times** the current carrying capacity of copper wire



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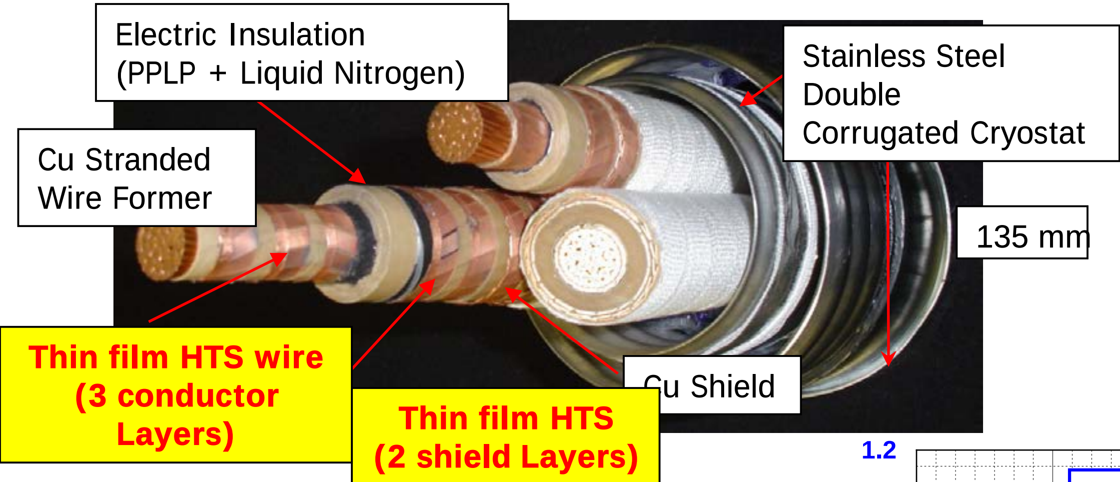
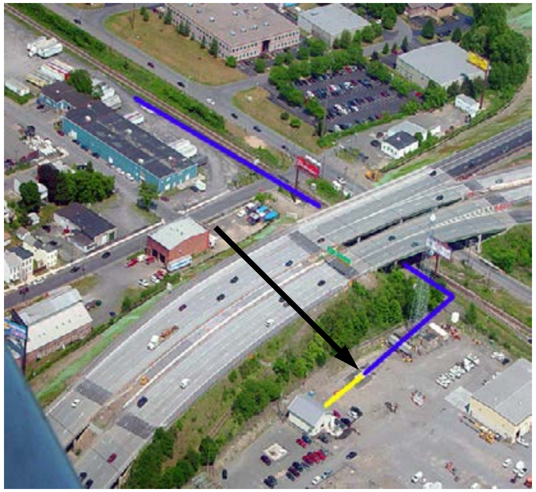
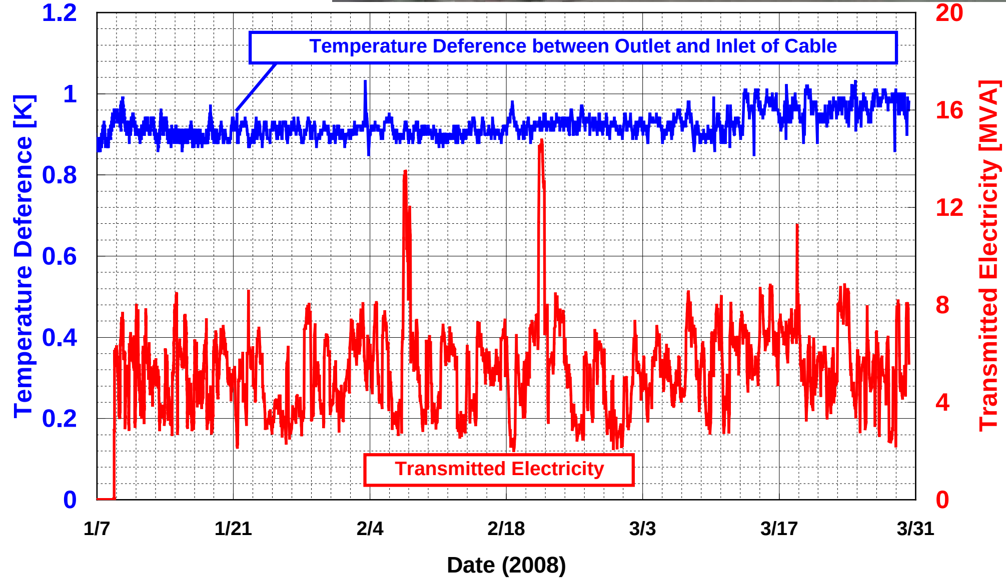
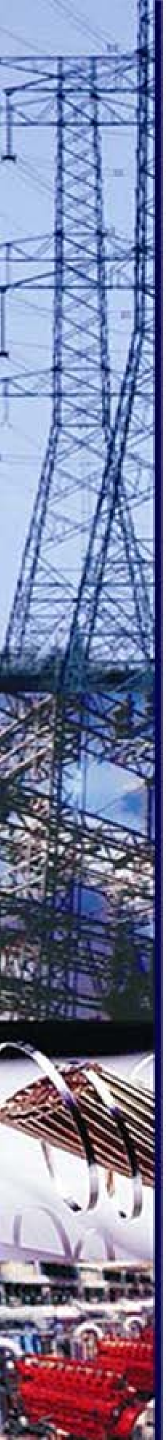
Demonstration of the world's first device with 2G HTS thin film wire in a live power grid







350 m cable made with 30 m segment of 2G HTS thin film wire was energized in the grid in January 2008 & supplied power to 25,000 households in Albany, NY



U.S. HTS Cable Installations

National Grid, Albany, NY
34.5 kV, 800 A, 48 MVA,350 m
Cable by Sumitomo Electric
Cryogenics by Linde

Bixby station, American Electric Power, Columbus
13.2 kV, 3000 A, 69 MVA, 200 m
Cable by Southwire & NKT cables
Cryogenics by Praxair

Long Island Power Authority
138 kV, 574 MW, 600 m
Cable by Nexans
Cryogenics by Air Liquide

12 companies producing thin film HTS wire

SuperPower Inc. A Furukawa Company

amsc

2006: Only the two US companies manufactured 2G HTS wire

SuNAM
Korea

SuperOx
Russia

Fujikura
Japan

2016: 9 of 12 wire companies are overseas!

BRUKER
Germany

THEVA
Germany

上海超导科技股份有限公司 Shanghai Superconductor Technology Co., Ltd.
China

STI
USA

Germany

Shanghai Creative Superconductor Technologies Co., Ltd.
China

中国科学院苏州纳米技术与纳米仿生研究所
China

Enhanced HTS Wire for Wind Energy and other Applications

High Performance, Low Cost Superconducting Wires and Coils for High Power Wind Generators

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SuperPower Inc. A Furukawa Company

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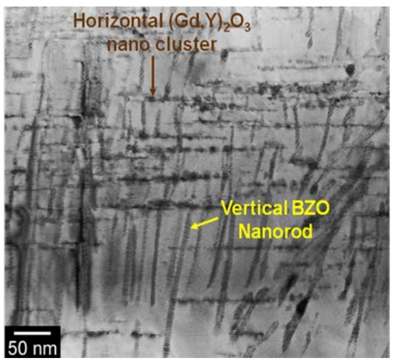
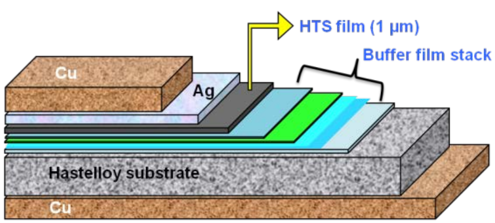
- University of Houston-led ARPA-E REACT program with SuperPower, TECO-Westinghouse, Tai-Yang Research and NREL targeted on 10 MW wind generator using advanced HTS wire



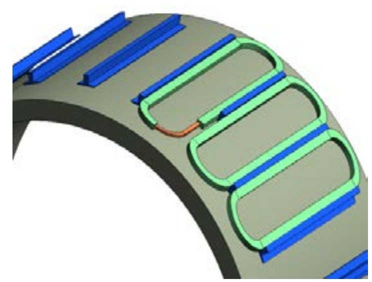
Technology Impact

Present-day superconducting wire constitutes more than 60% of the cost of a 10 MW superconducting wind generator. By quadrupling the superconducting wire performance at the generator operation temperature, the amount of wire needed would be reduced by four which will greatly enhance commercial viability and spur a tremendous growth in wind energy production in the U.S.

Engineered nanoscale defects



4x improved wire manufacturing



High-power, Efficient Wind Turbines

Lower cost Generator coils

Quadrupling Superconductor Wire Performance for Commercialization of 10 MW Wind Generators and will enable other high-field applications

Tai-Yang Research

TECO Westinghouse

NREL NATIONAL RENEWABLE ENERGY LABORATORY

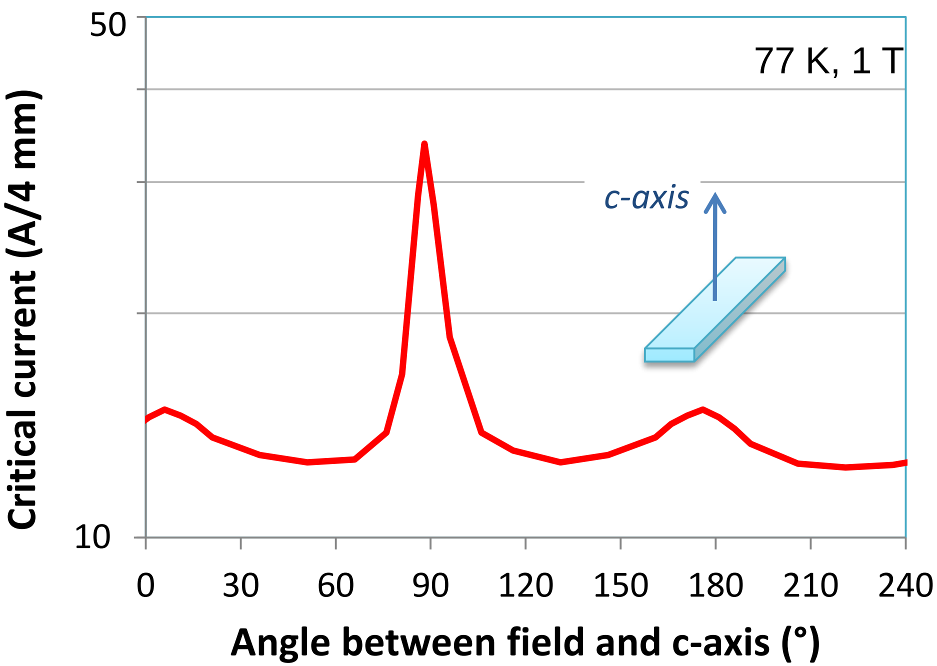
4X HTS conductor can enable commercial feasibility of HTS devices

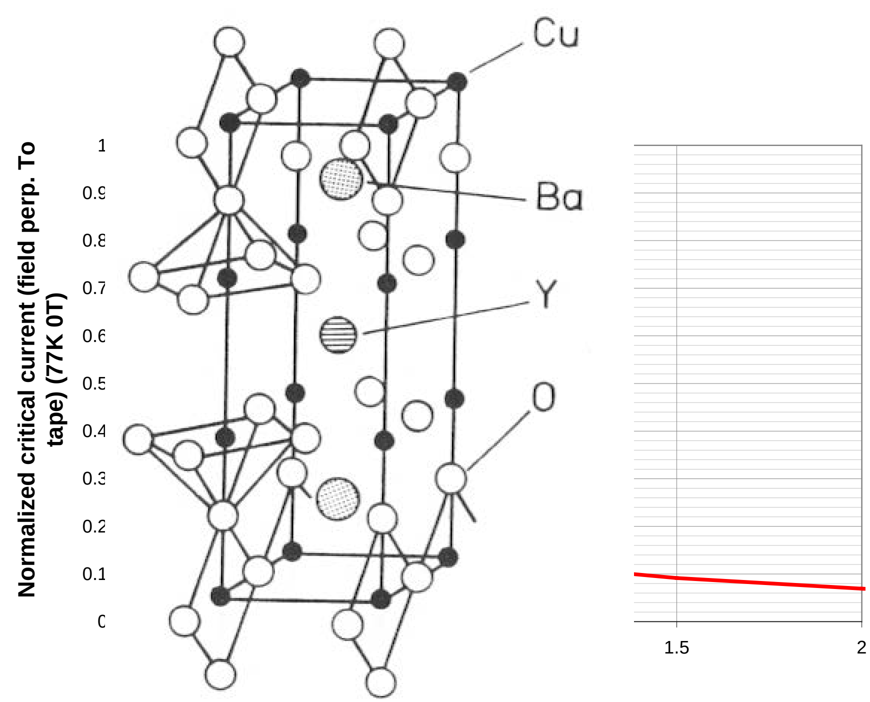
Metric	Start of project	End of project
Critical current at 30 K, 2.5 T (A/12 mm) (device operating condition)	750	~3000
Wire price at device operating condition ($/kA-m)	144	36
Estimated HTS wire required for a 10 MW generator (m)	42,785	10,700
Estimated HTS wire cost for a 10 MW generator $ (,000)	6,000	1,500

- Quadruple the critical current performance to **3,000 A** at 30 K and 2.5 T
  - **Doubling the lift factor** (ratio of I_c at operating temperature and field to I_c at 77 K, zero field) in I_c of coated conductors at 30 K, 2.5 T by *engineering nanoscale defect structures in the superconducting film.*
  - Additional near **doubling of critical current by thicker superconducting films** while maintaining the efficacy of pinning by nanostructures.

Improvement of critical current of HTS wires in high magnetic fields

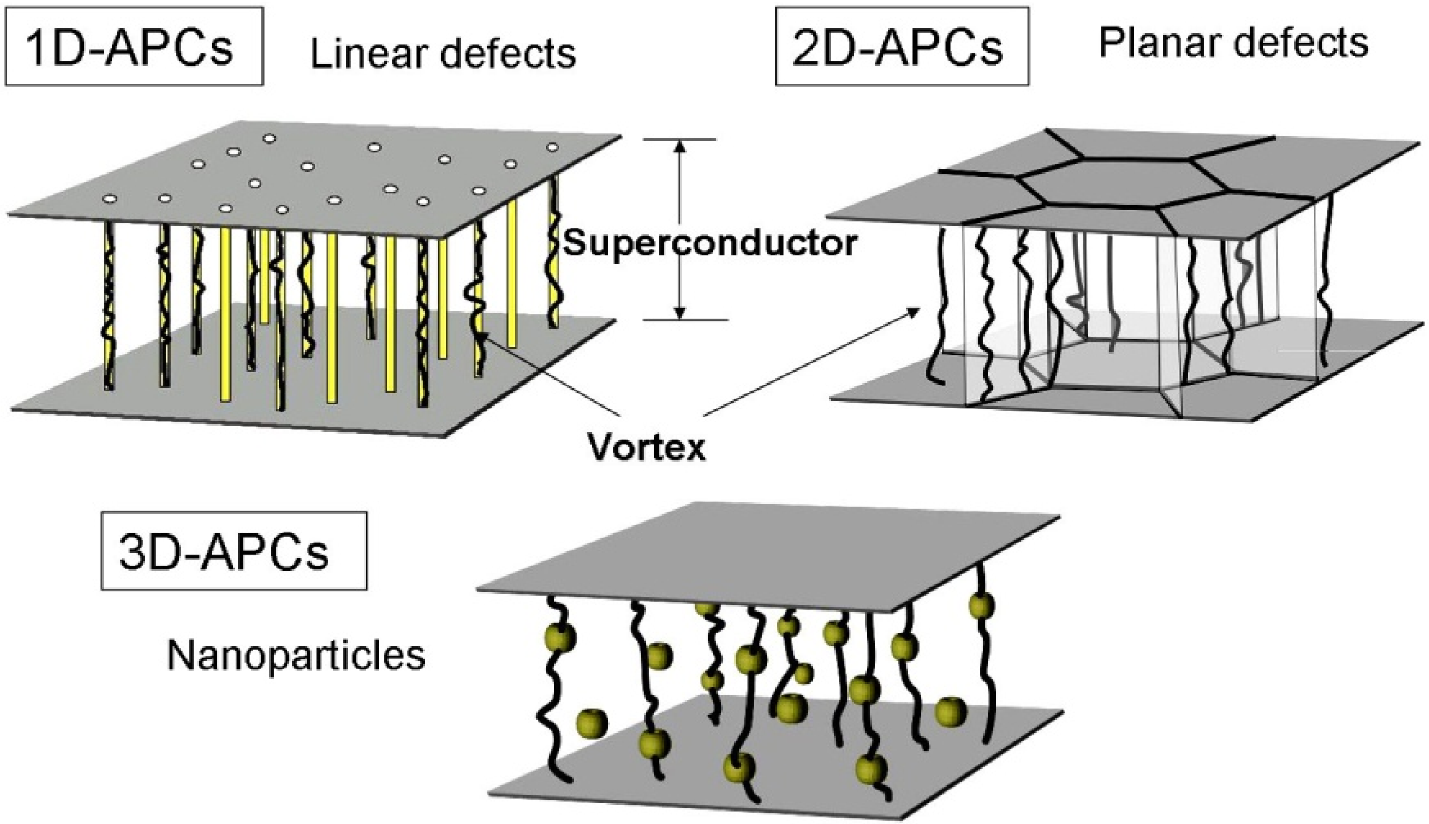
- Even though HTS tapes have good critical current properties at zero field, their performance reduces rapidly in an applied magnetic field at higher temperatures.
- Critical current of HTS tapes are very anisotropic and the minimum current value limits use.





Nanoscale defect structures need to be introduced to achieve isotropic and strong flux pinning and thereby improve critical current of HTS wires

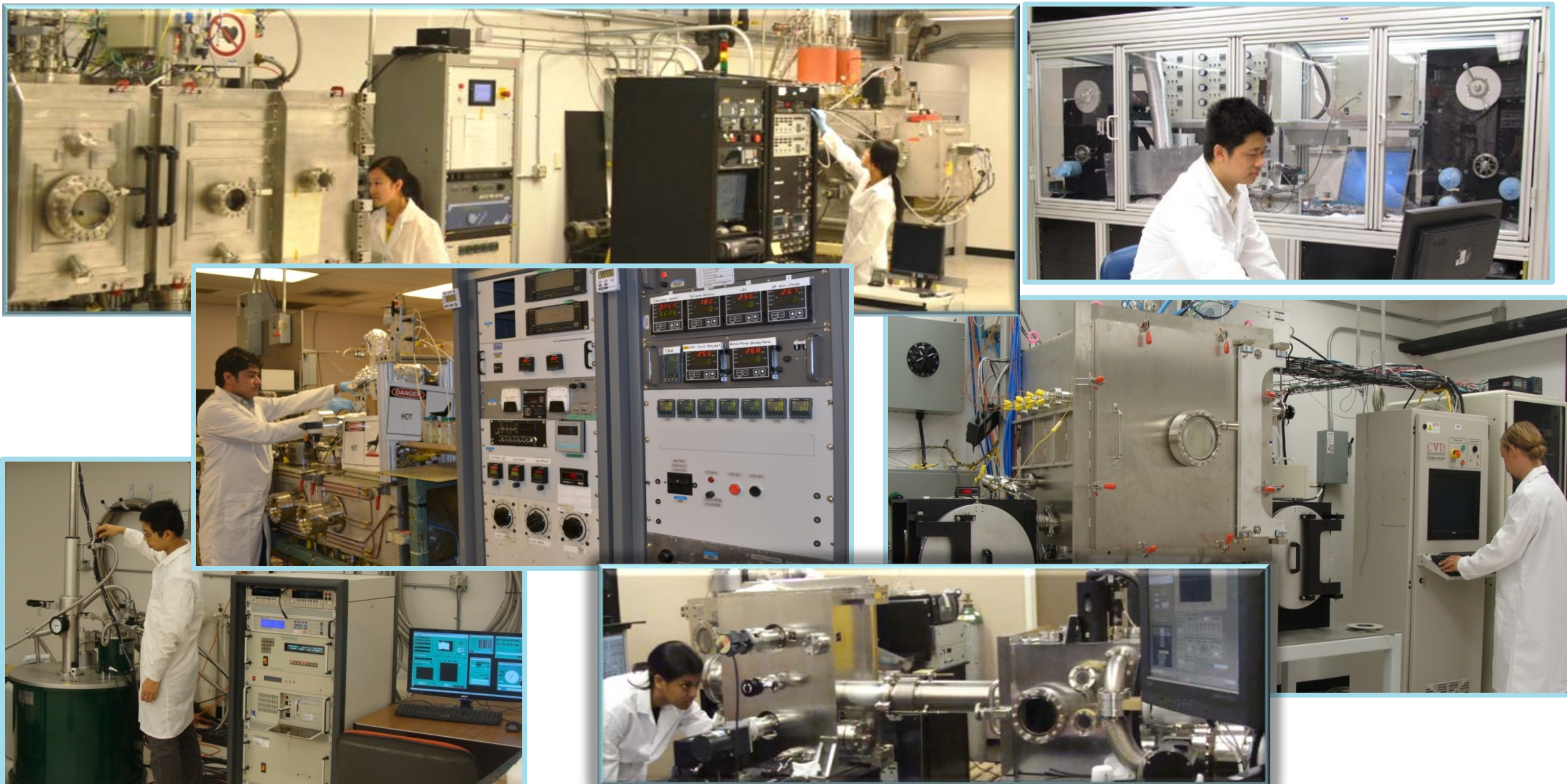
Nanoscale defects for pinning flux lines



From Matsumoto

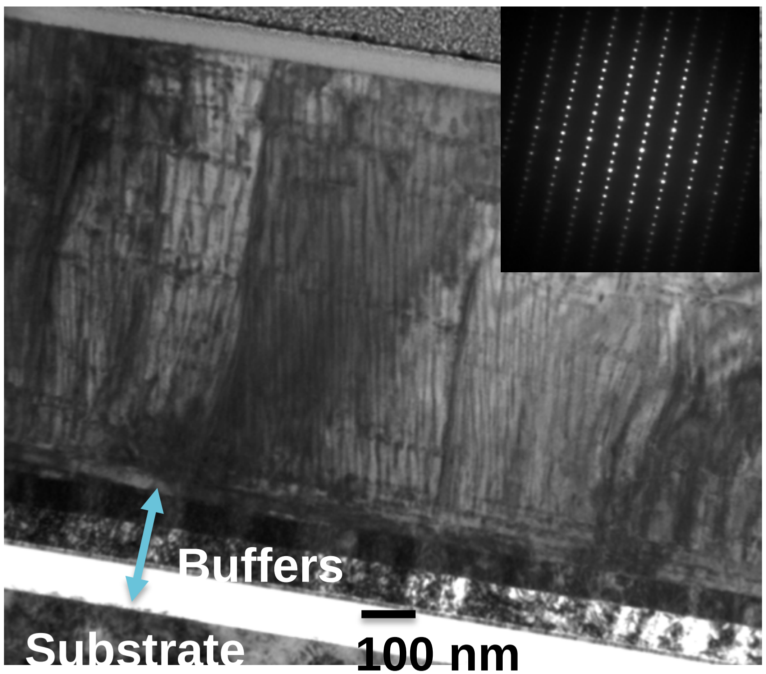
HTS Wire R&D program at Univ. Houston

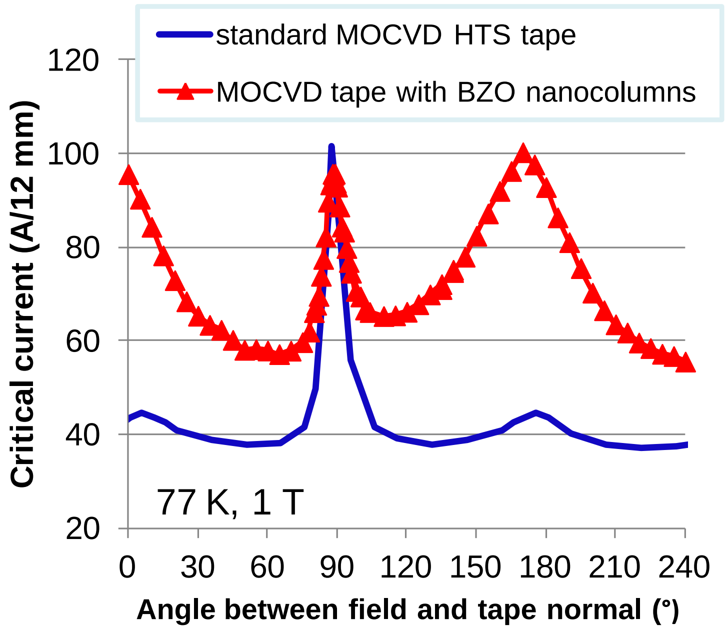
- State-of-the-art equipment for thin film HTS wire processing & testing
- Technology advances already transitioned from UH to manufacturing
- Applied Research Hub created in UH Energy Research Park



Improved pinning by Zr doping of MOCVD HTS conductors

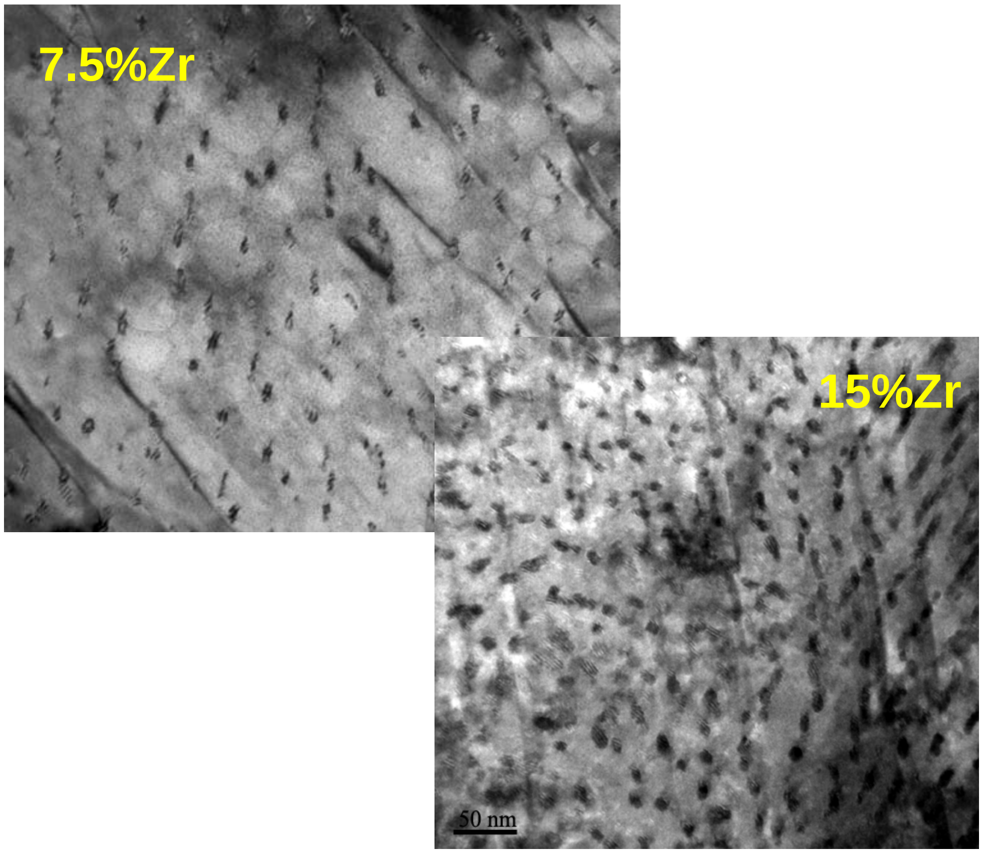
- *5 nm sized, few hundred nanometer long $BaZrO_3$ (BZO) nanocolumns with ~ 35 nm spacing created during in situ MOCVD process with 7.5% Zr*
- Two-fold improvement in critical current at 77 K, 1 T achieved by **7.5%** Zr addition in MOCVD films

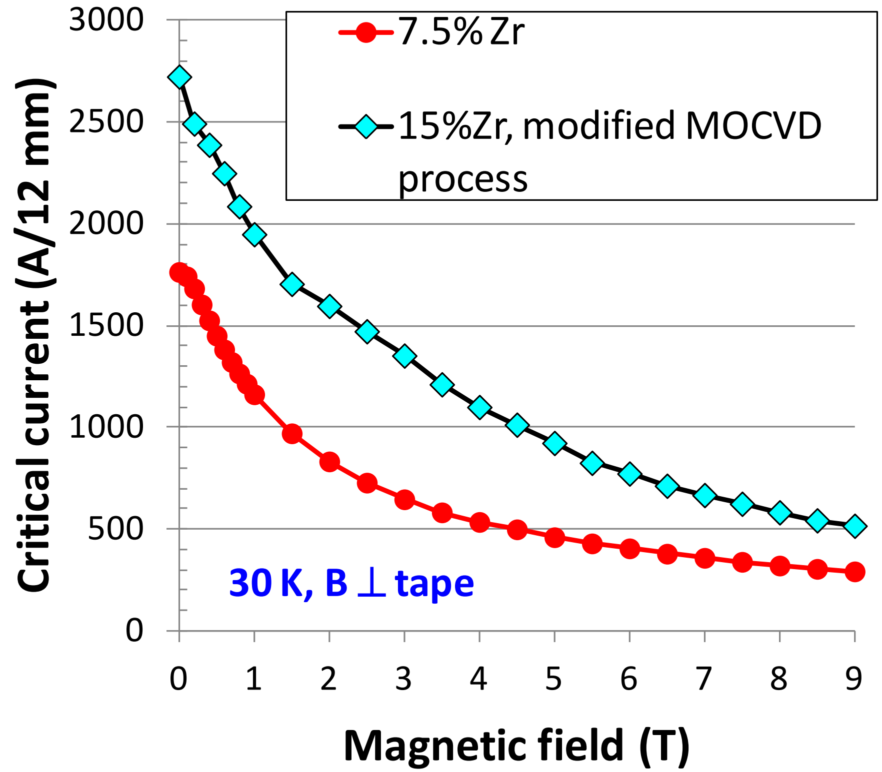




Process for improved in-field performance successfully transferred to manufacturing in industry – standard product in the last five years

2X improvement in in-field performance with 15% Zr-added tapes

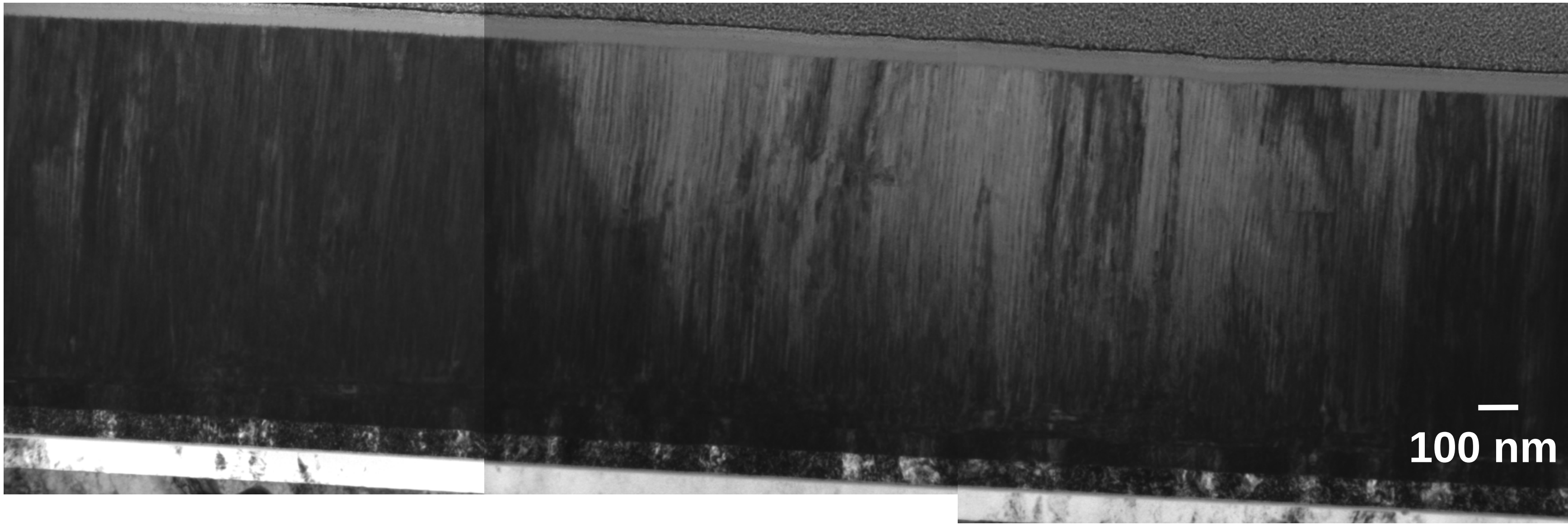


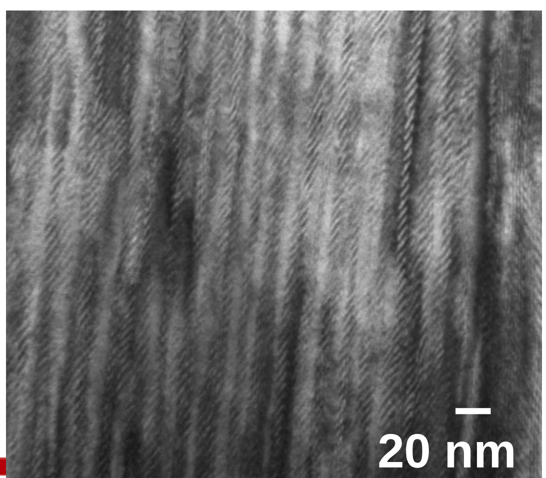


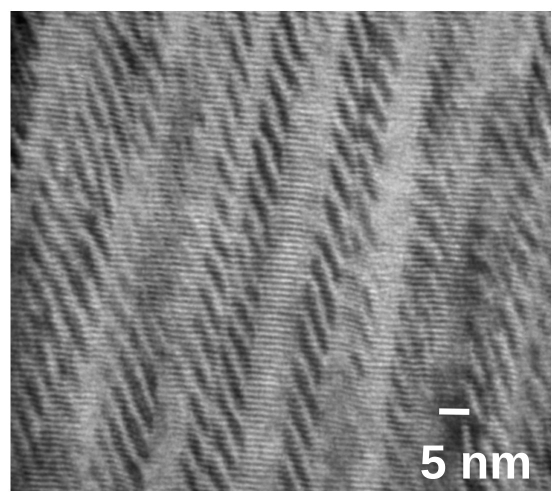
Supercond. Sci. Technol. **26** (2013) 035006

- *Critical current of 15% Zr-added film ~* ***1384 A/12 mm (J$_c$ = 12.5 MA/cm^2)*** *at 30 K, 3 T, B||c*
- *Lift factor at 30K, 3 T, B||c improved by >100% to ~* ***4.4***

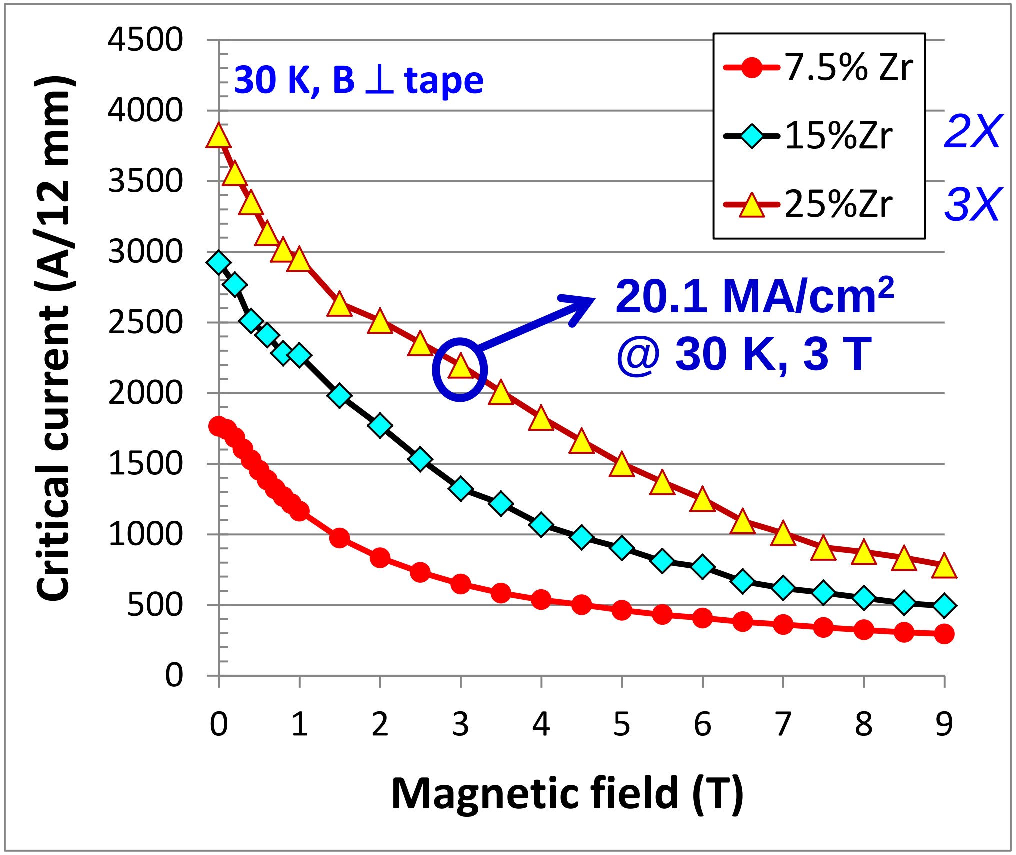
Even higher density of extended BZO nanoscale defects in 25%Zr-added tapes





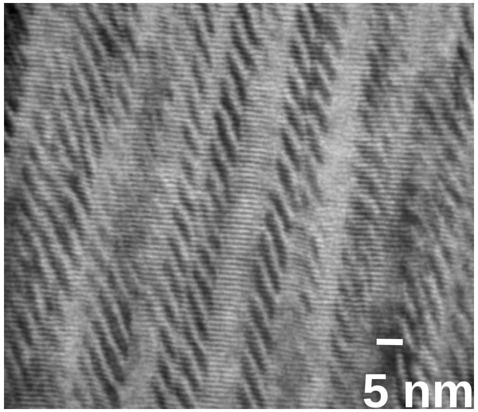


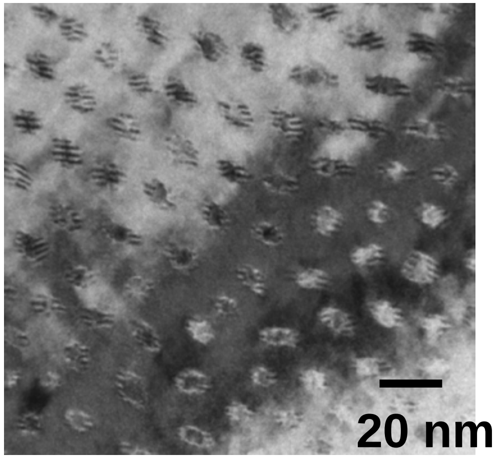
3X improvement in in-field performance in the using heavily-doped HTS tapes



2X improvement

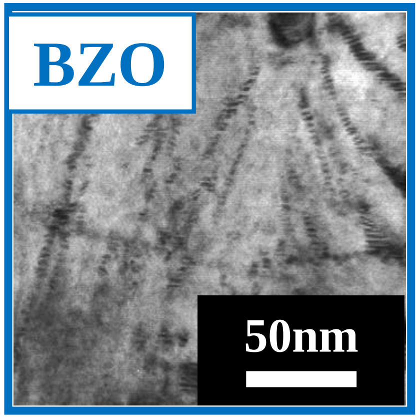
3X improvement



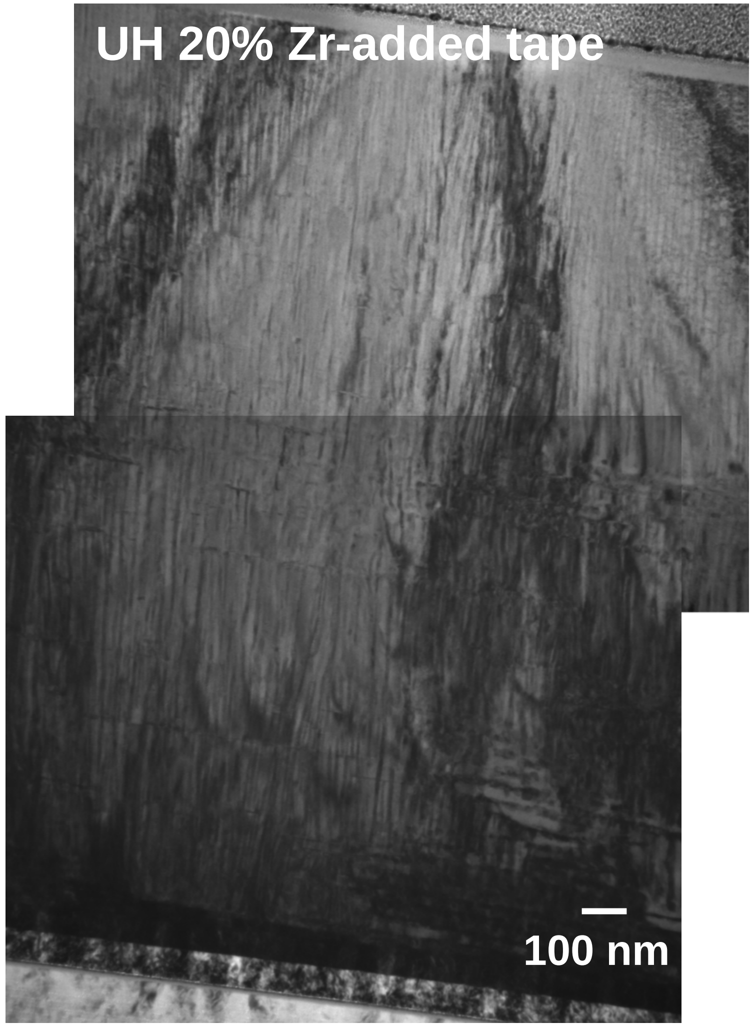


- Enable by engineering a high density of nanoscale defects while maintaining high crystalline quality of the superconductor films
- 7.5% Zr wire manufactured in long lengths since 2010 (AP wire)
- 15% Zr wire being scaled up to manufacturing

Combining heavy Zr addition with thick HTS films

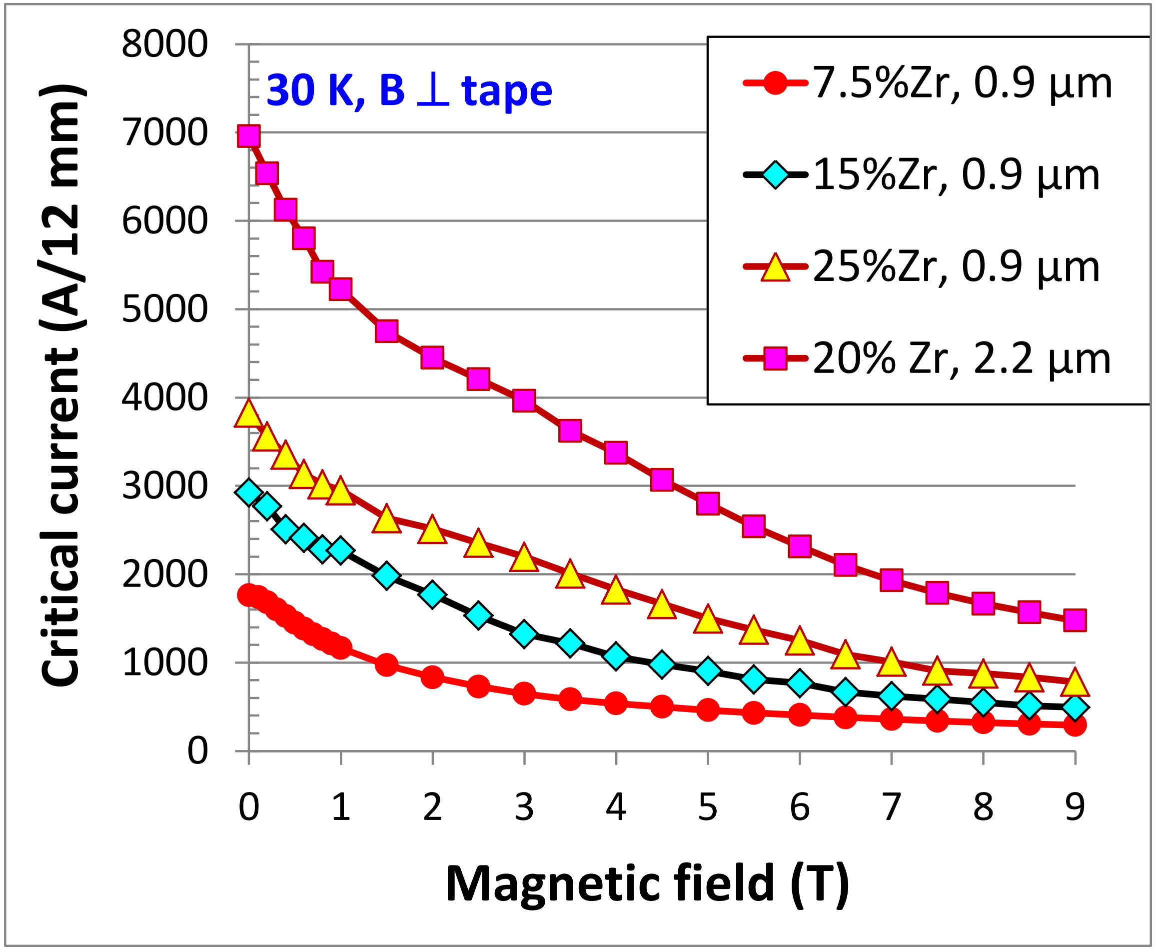


Loss of BZO alignment reported by ISTEC in their BZO-doped thick films made by PLD



No loss of BZO alignment in 2.2 µm thick films by MOCVD

High critical currents in 2.2 μm thick 20% Zr-added tapes at 30 K



Supercond. Sci. Technol. **28**, (2015) 072002

20% Zr-added tape with 2.2 μm HTS film at 30 K, 3 T, B||c,

I_c = 3963 A/12 mm ; J_c = 15 MA/cm^2** ; Lift factor ~* ***5.1

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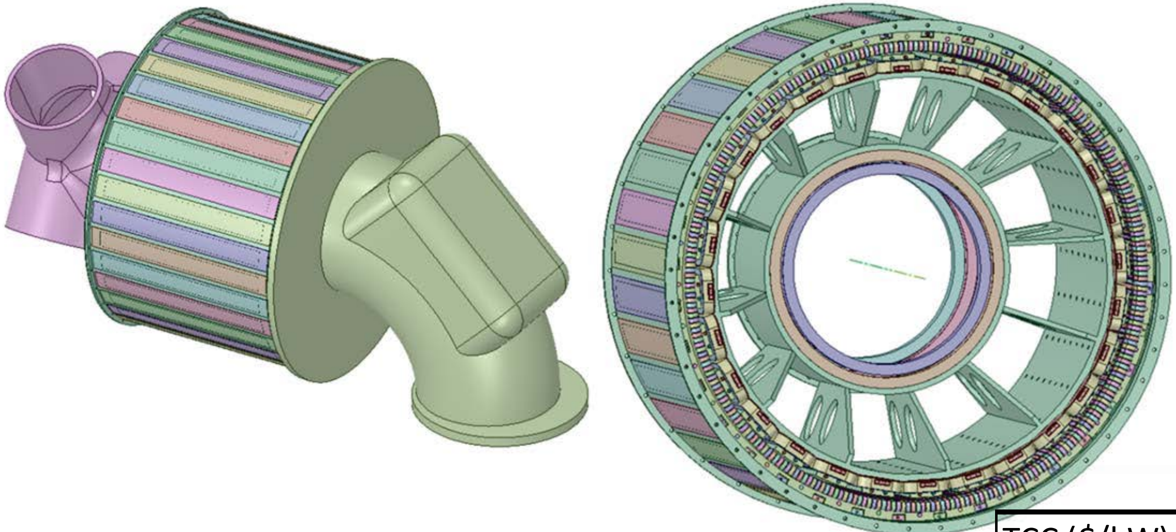
Significant reduction in Generator cost using 4X improved HTS wire

Electromagnetic, mechanical, and thermal design of a 10 MW generator developed based on 4X wire



Whole Machine

Rotor + Stator

Wire quantity for 10 MW generator reduced from 42 km to ~10 km → Generator cost reduced by 2.24X

	Baseline 2G HTS	4x 2G HTS
TCC ($/kW)	2,031	1,541
BOS ($/kW)	2,820	2,820
Soft Costs ($/kW)	1,574	1,415
O&M ($/kW)	170	170
AEP (MWh/MW)	4,194	4,194
FCR	14%	14%
LCOE ($/kWh)	**$0.255**	**$0.233**
Drive Train LCOE ($/kWh)	**$0.046**	**$0.030**

TcSUH SuperPower Inc. A Furukawa Company TECO Westinghouse e2P Energy to Power Solutions NREL NATIONAL RENEWABLE ENERGY LABORATORY

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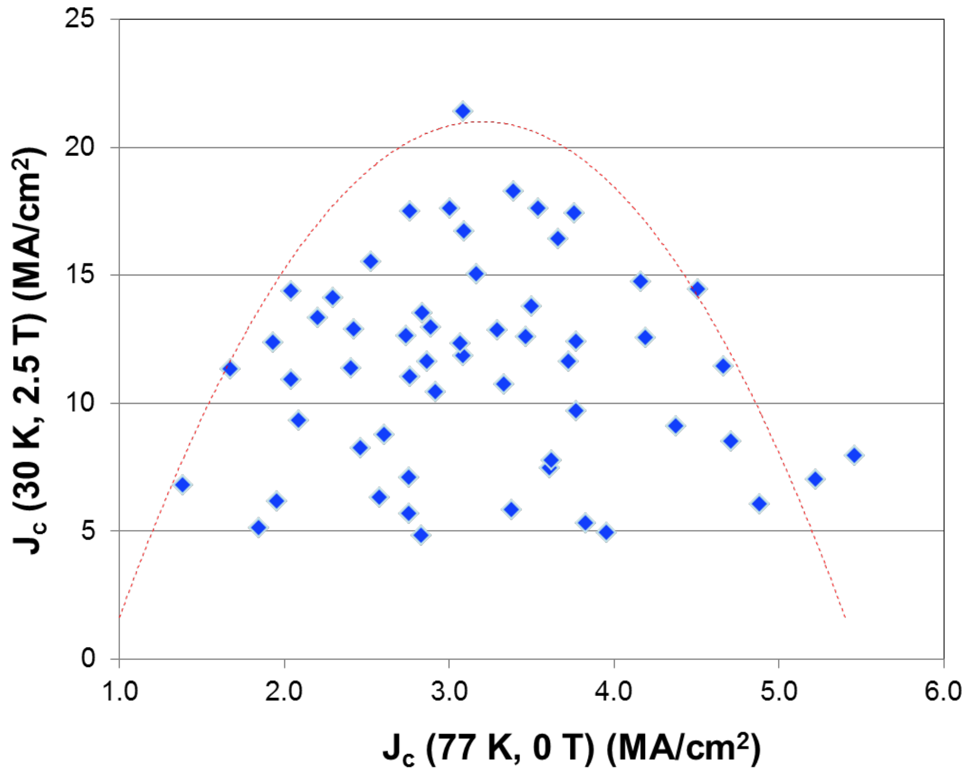
Path Forward: High-yield Manufacturing of High Performance Superconductors

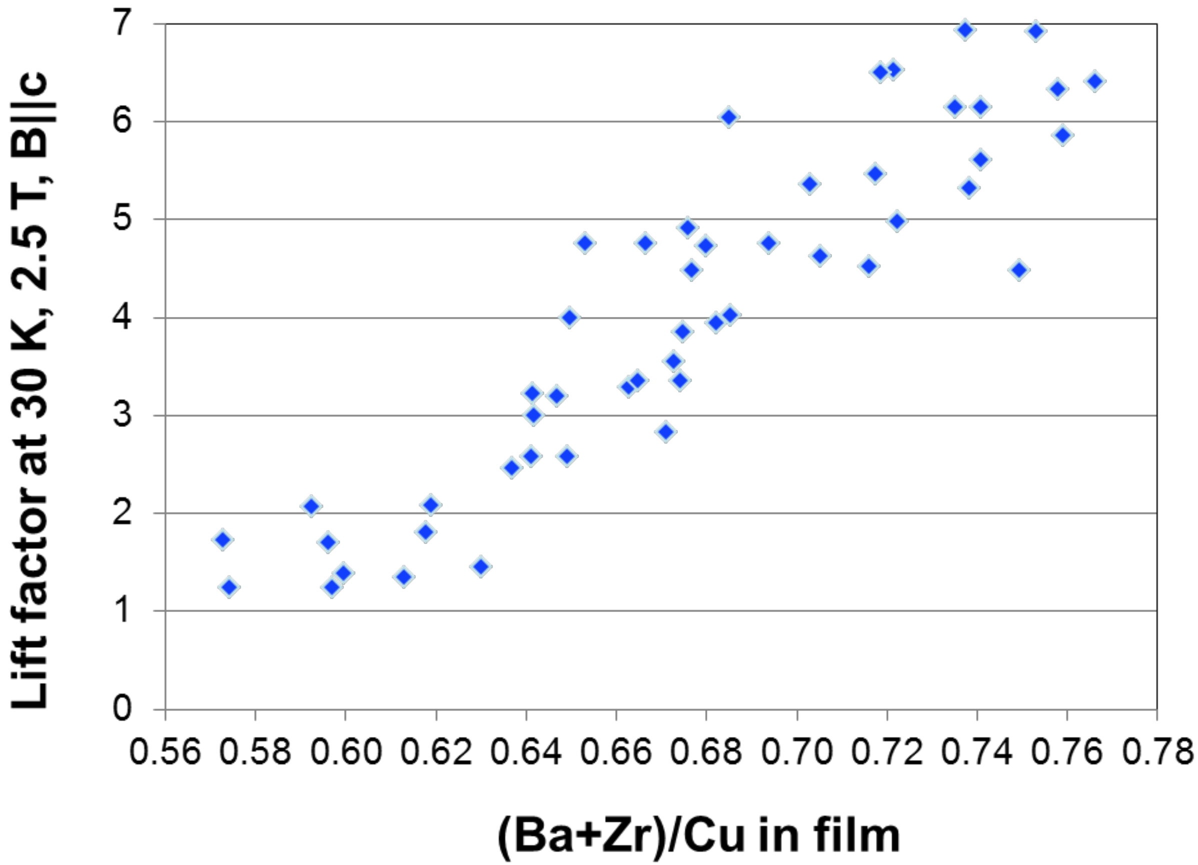
TcSUH

Manufacturing Challenge: Wide scatter in I_c in high fields at lower temperatures



- A primary driver of cost is manufacturing yield.
- For high yield manufacturing, consistent wire performance is needed
- Uniformity of Ic at 77 K, 0 T does not guarantee consistency in in-field performance

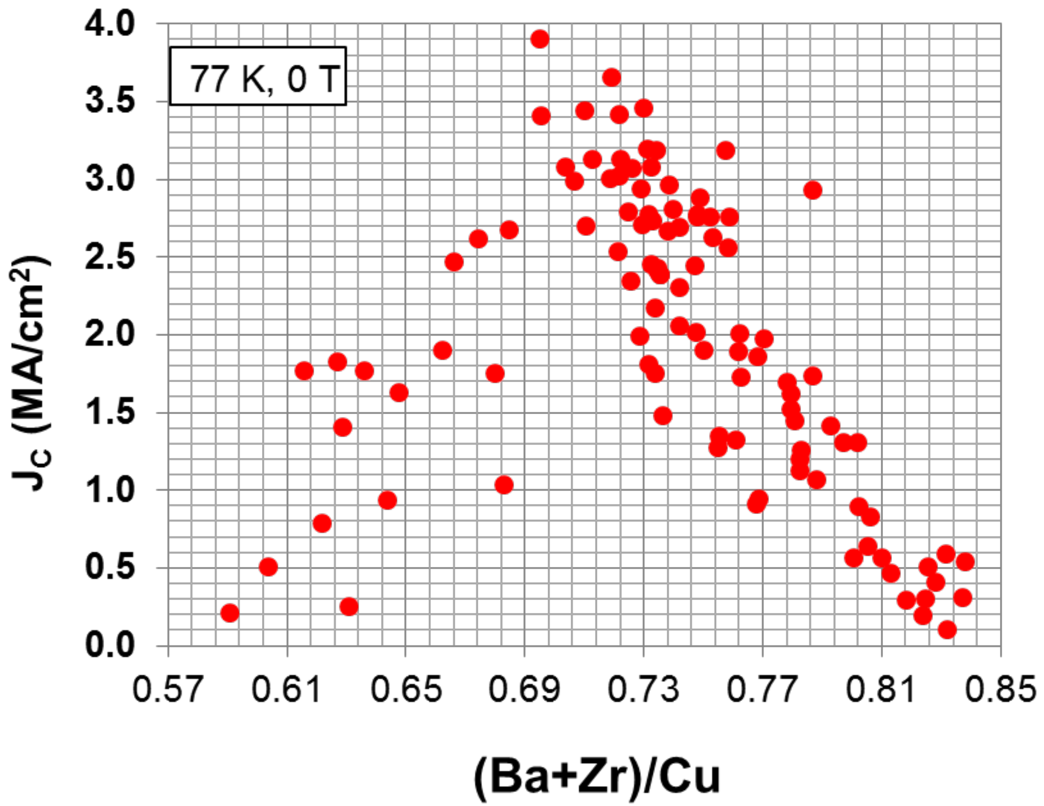
Compositional control important for achieving high lift factor at 30 K



Supercond. Sci. Technol. **28** 104003 (2015)

Lift factor > 4 at 30 K, 2.5 T for (Ba+Zr)/Cu > 0.69

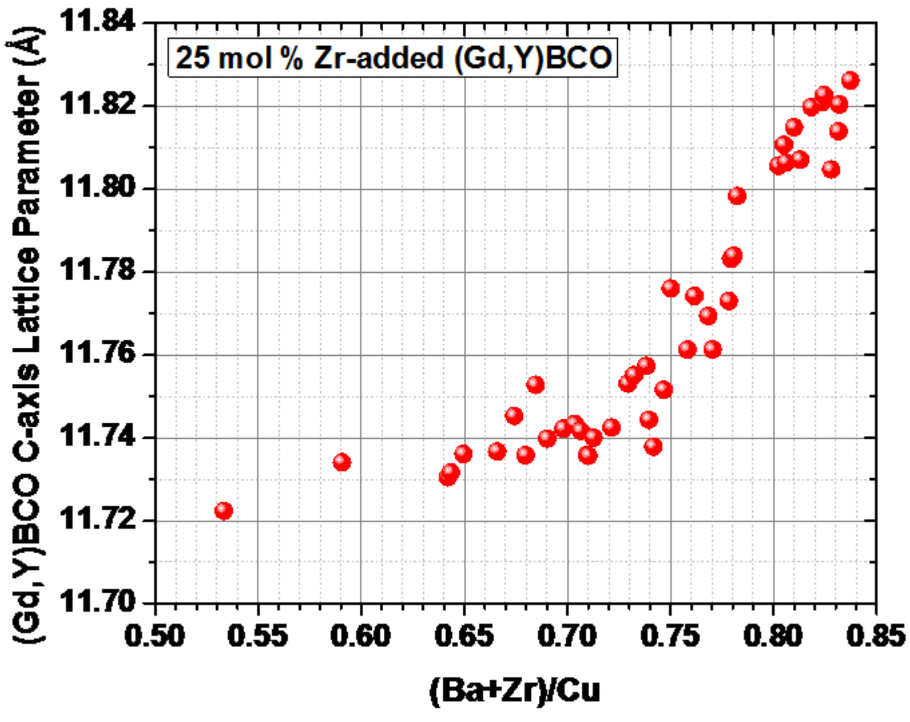
J_c at 77 K, 0 T decreases with increasing (Ba+Zr)/Cu beyond 0.69

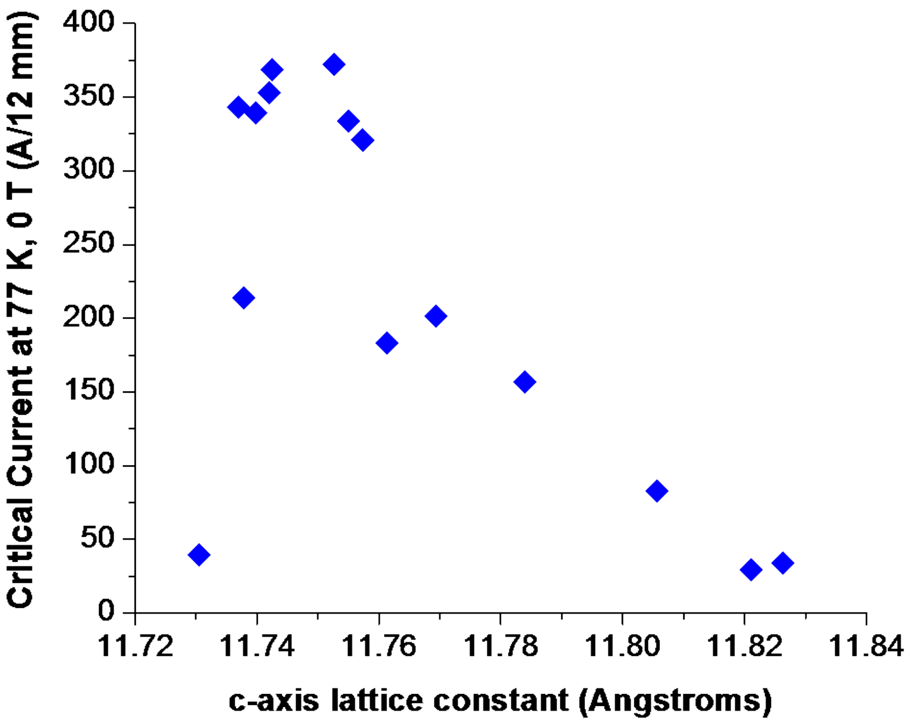


For high I_c at 30 K, 3 T, need a combination of good I_c at 77 K, 0 T and a high lift factor at 30 K, 3 T

Need to control (Ba+Zr)/Cu in REBCO film in a narrow range!

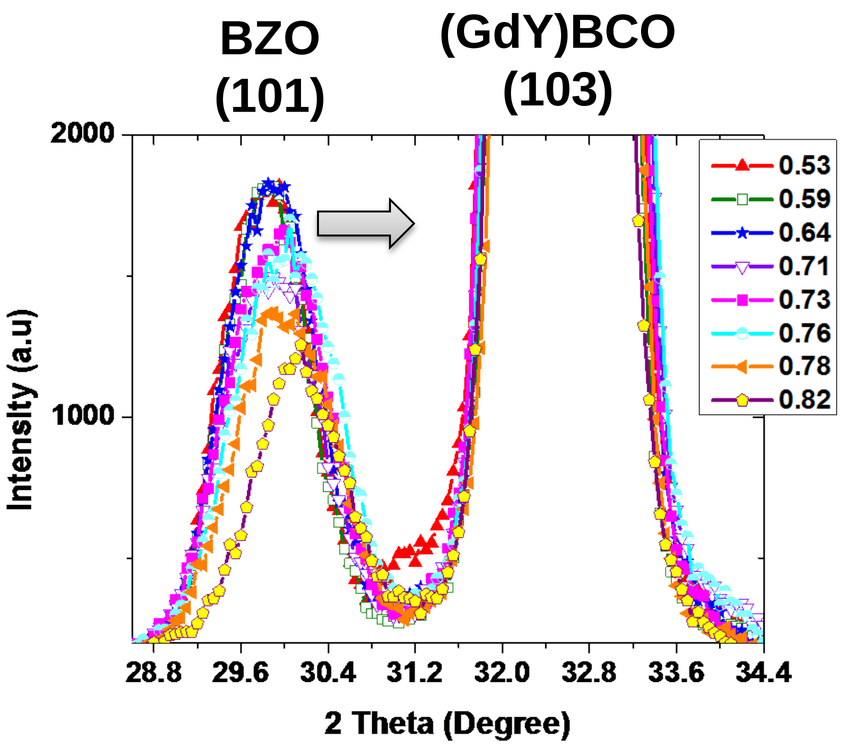
Found increase in c-axis lattice parameter with increasing (Ba+Zr)/Cu composition in tape

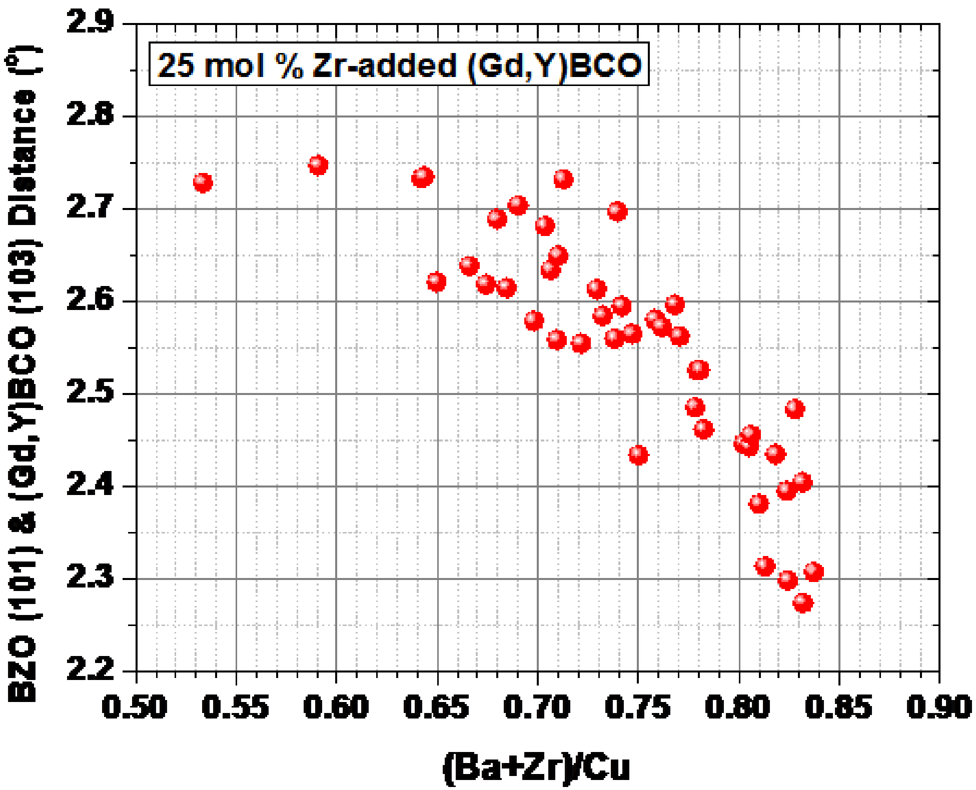




As (Ba+Zr)/Cu content in the tape increases, the lattice parameter of the superconductor film increases towards that of BZO

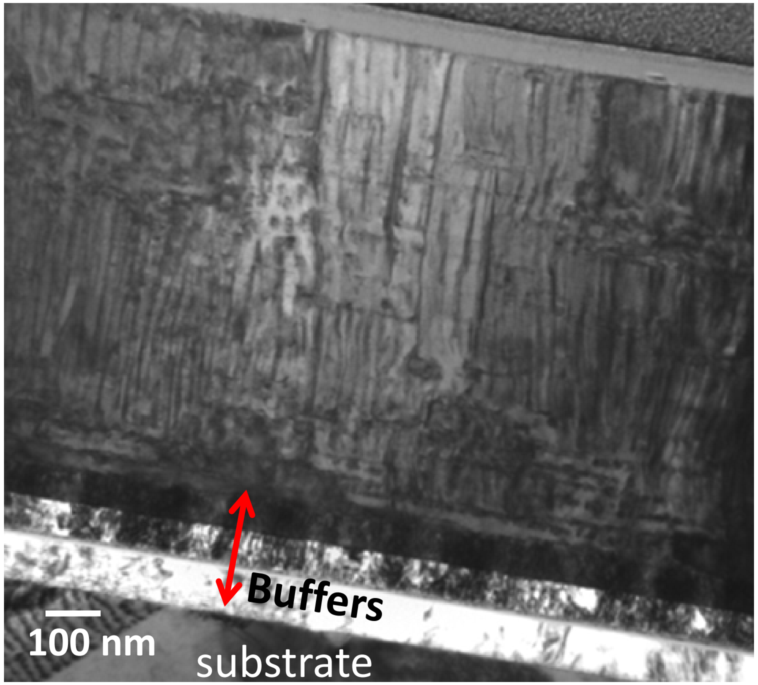
BZO lattice shrinks towards REBCO lattice with increasing (Ba+Zr)/Cu content





Transition to continuous-aligned nanocolumns at high (Ba+Zr)/Cu

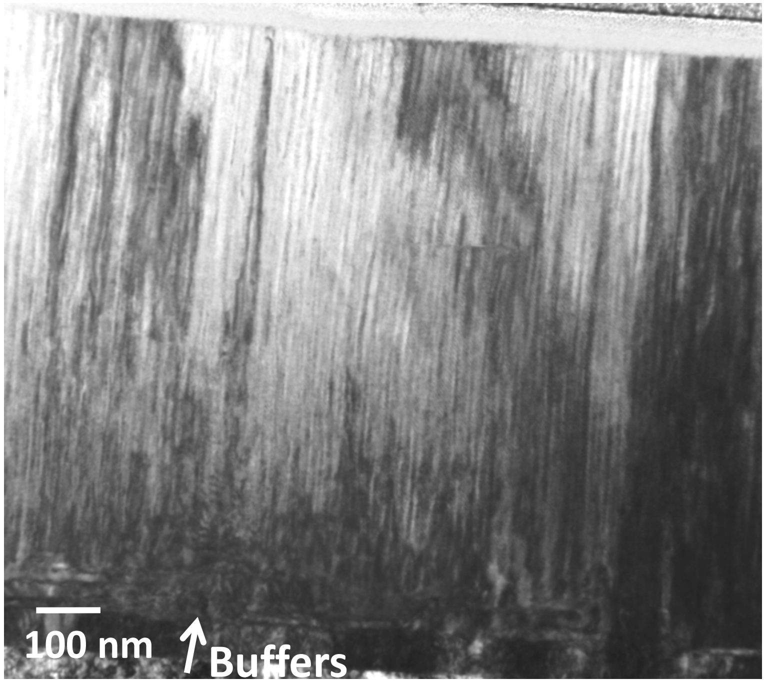
(Ba+Zr/Cu) ↑ → REBCO lattice expands & BZO lattice shrinks to match each other → BZO nanocolumns become continuous



(Ba+Zr)/Cu = 0.675

Lift factor @ 30 K, 2.5 T = 3.85

J_c (30 K, 2.5 T) = 11.86 MA/cm^2

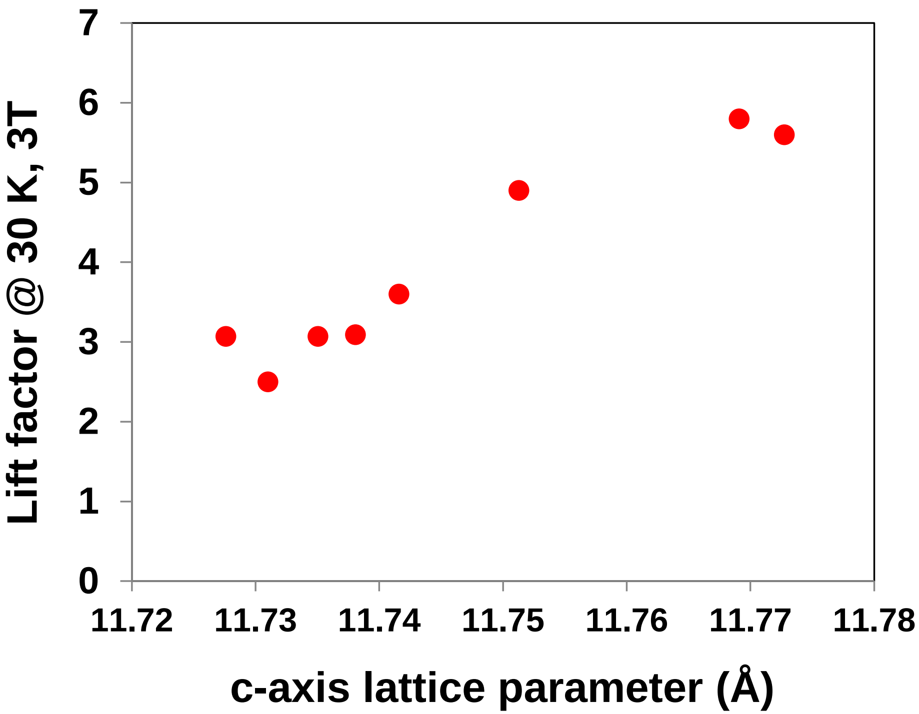


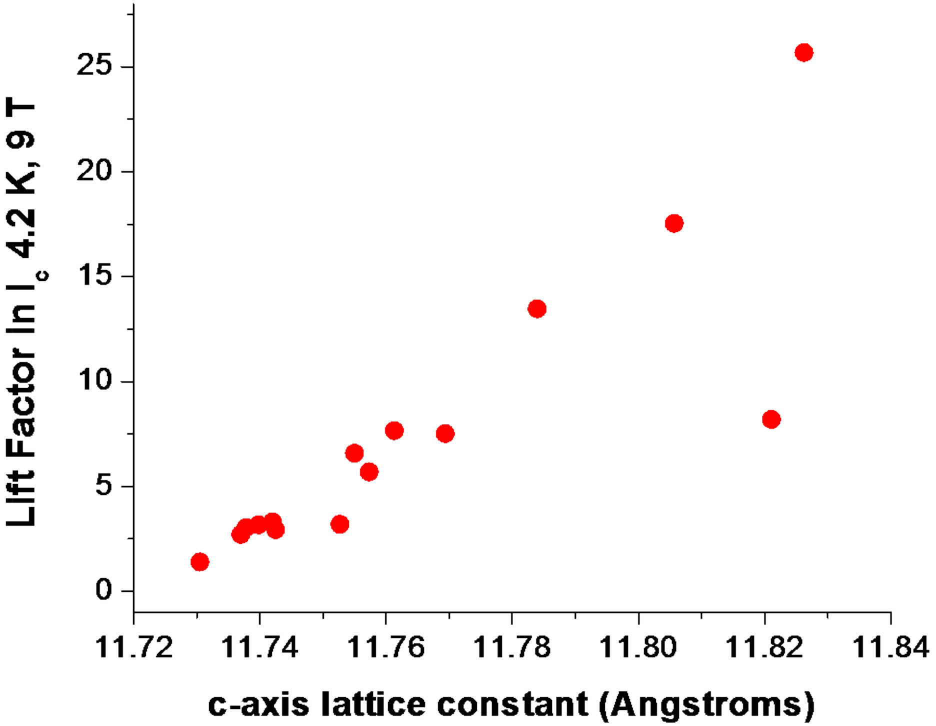
(Ba+Zr)/Cu = 0.737

Lift factor @ 30 K, 2.5 T = 6.93

J_c (30 K, 2.5 T) = 21.34 MA/cm^2

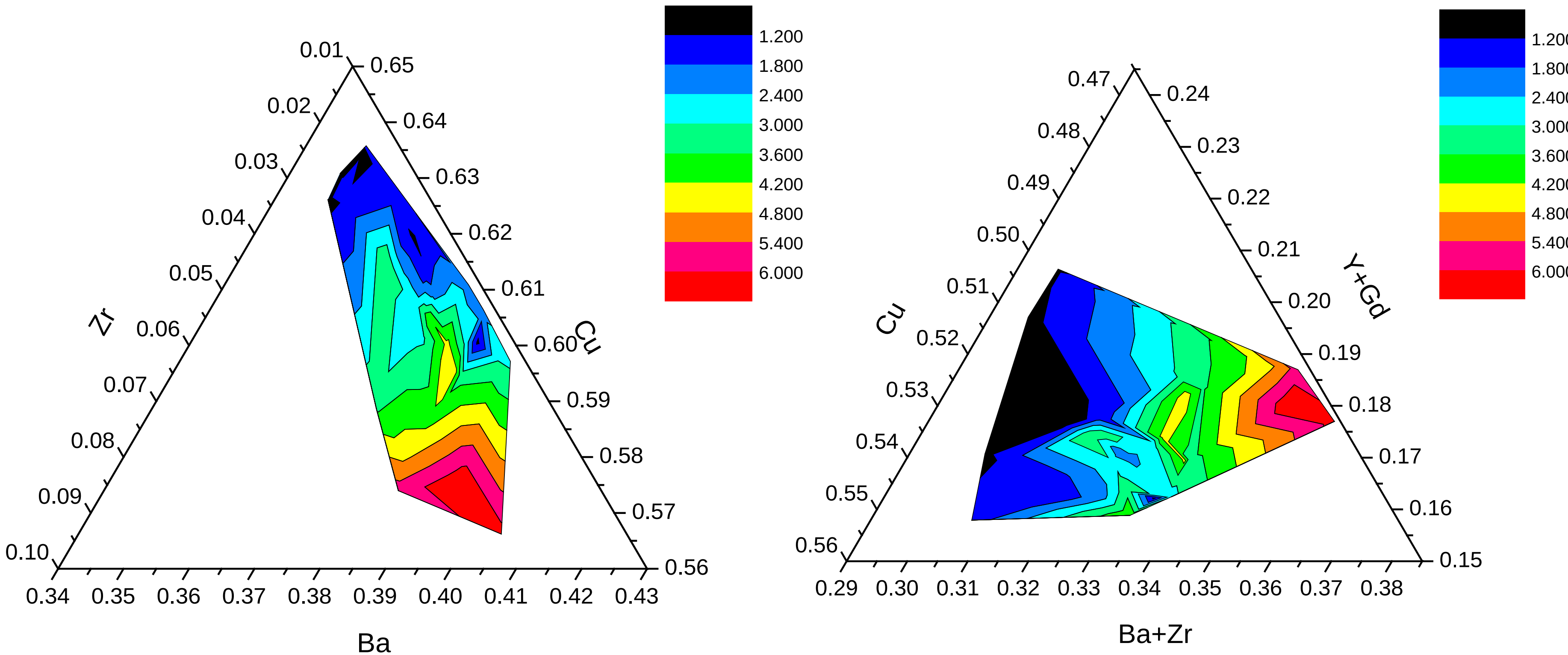
Correlation between c-axis lattice parameter and lift factor at 30 K, 3 T





Improvement in lift factor when c-axis lattice constant > 11.74 Å.

Compositional control important for achieving consistently high lift factor

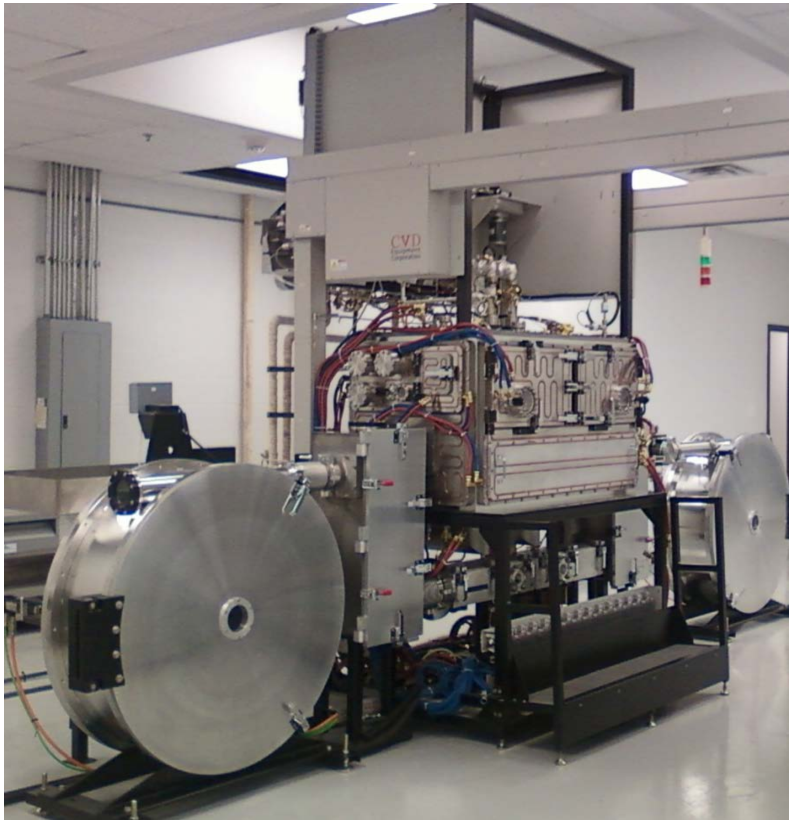


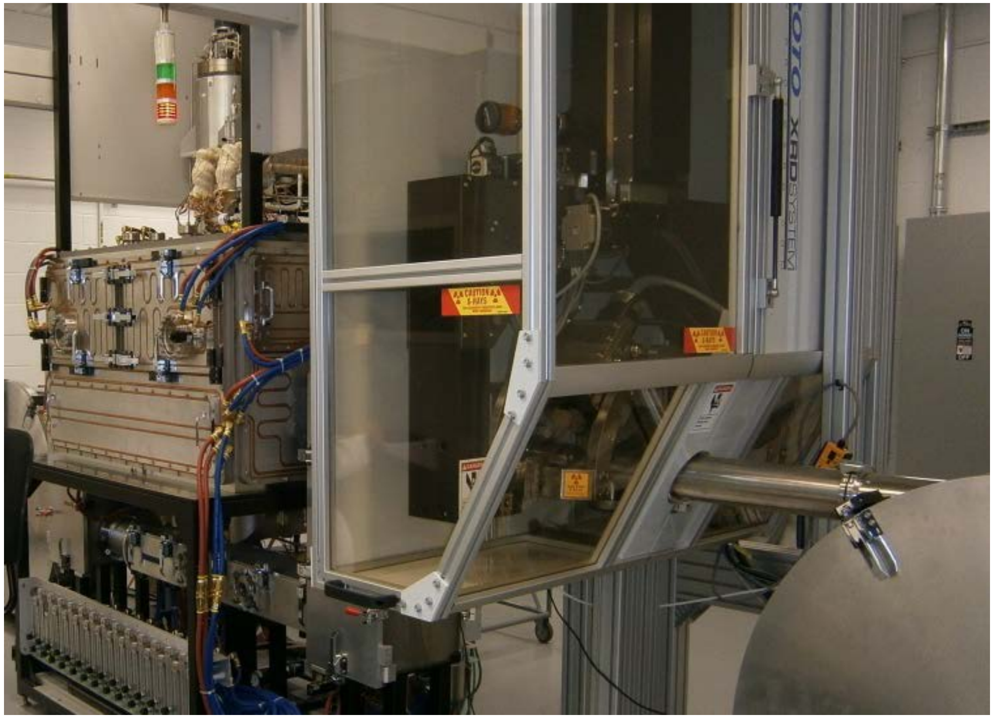
Appl. Phys. Lett. **106**, 032601 (2015)

<u>Opportunity</u>: In-line process control and QC tools to control the film composition within the optimum window uniformly over long run

Use of in-line XRD system in pilot MOCVD tool

- For real-time monitoring of shift in c-axis lattice parameter as a tool to enable consistency in film quality for consistent in-field performance





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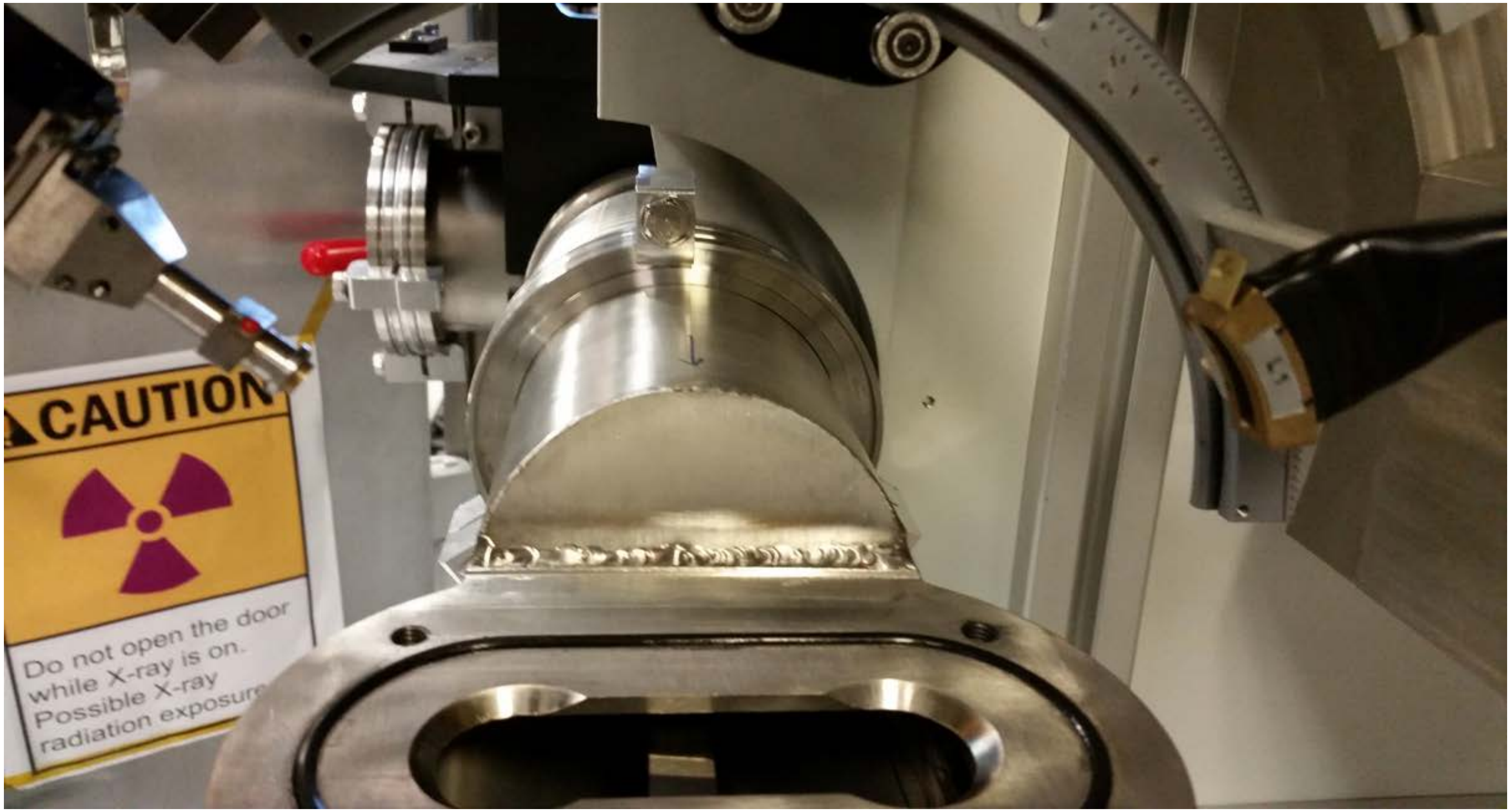
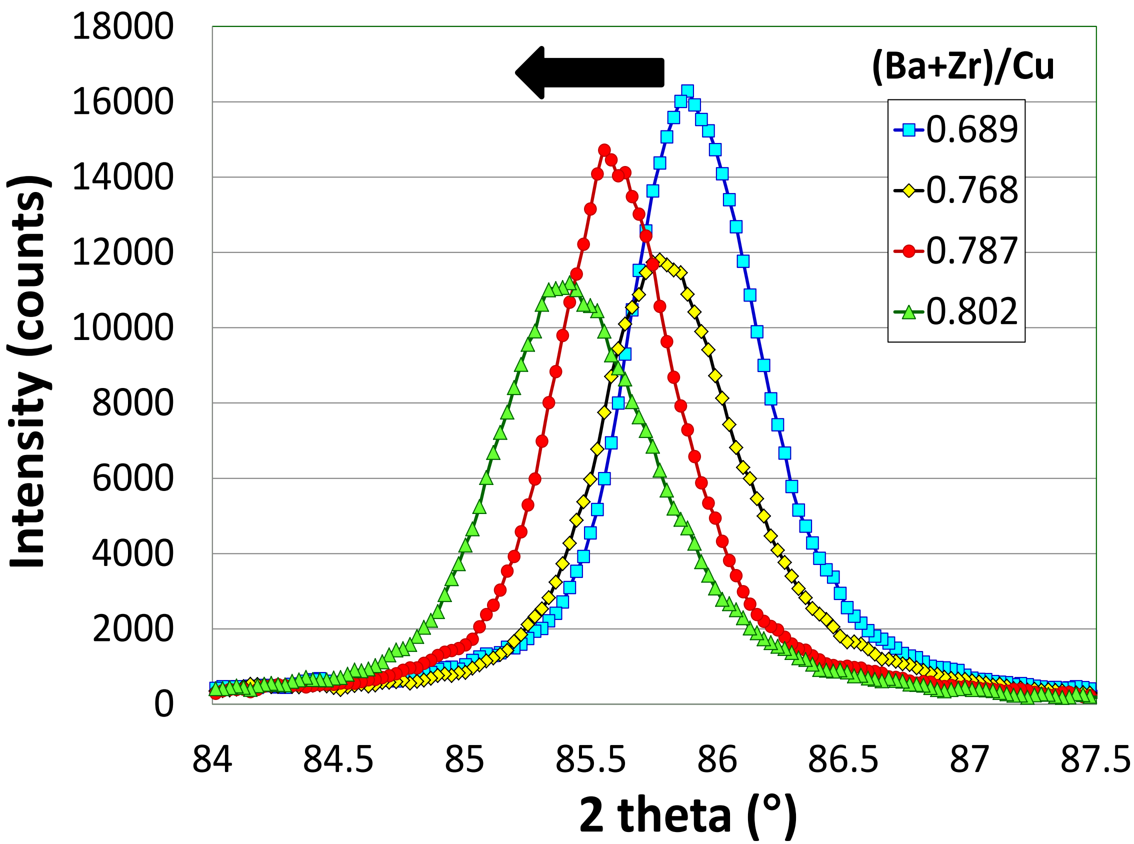
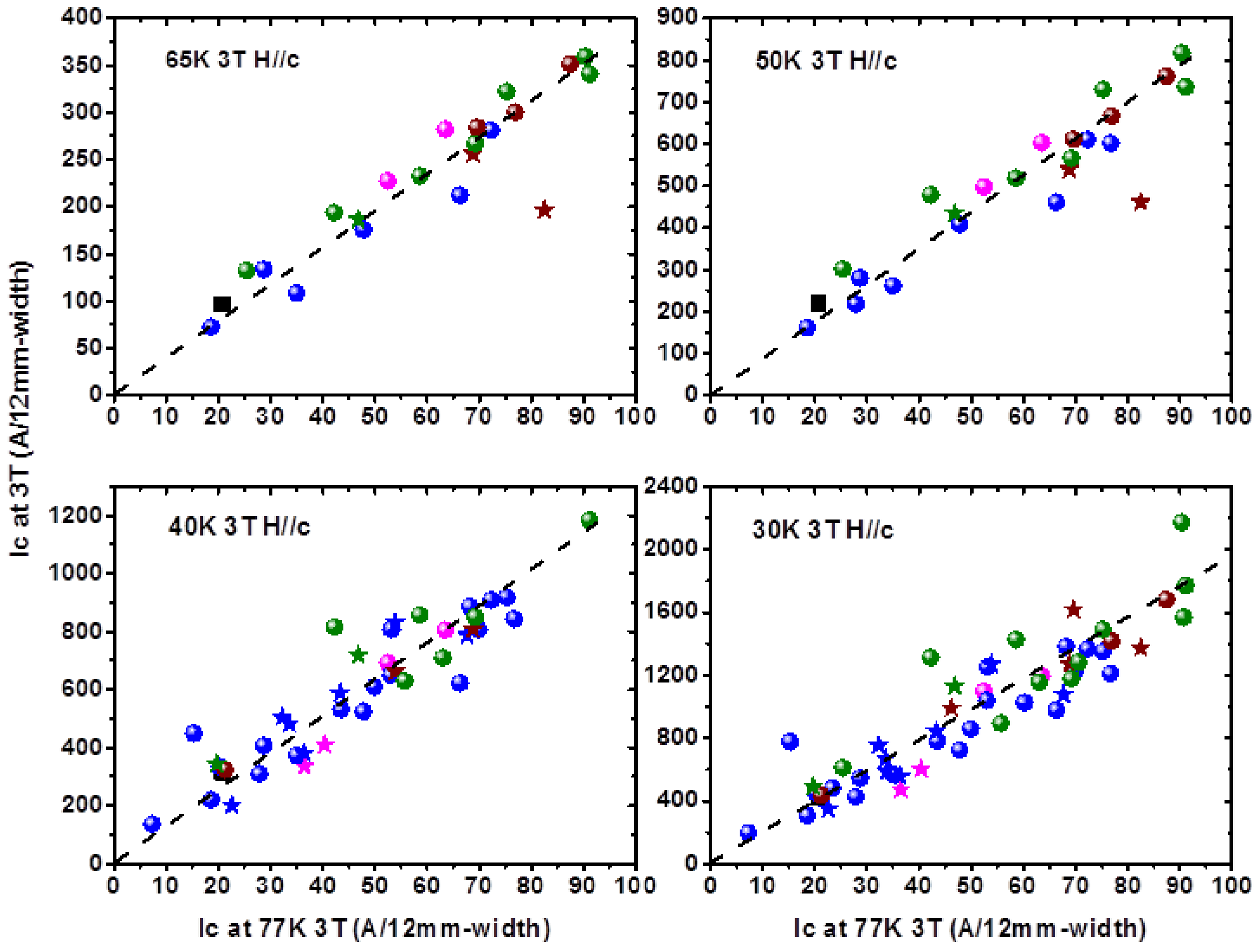


C-axis peak shift method used in the in-line XRD system in MOCVD tool to discern variation in (Ba+Zr)/Cu



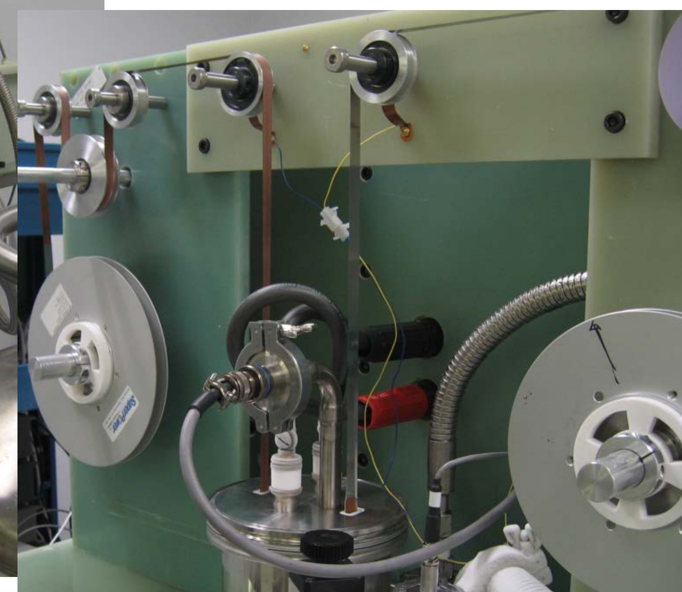
Good correlation between I_c at 77 K, 3 T and in-field I_c at 30, 40, 50 and 65 K



Critical current measurements at 77 K, 3 T is a good Quality Assurance metric for in-field performance at lower temperatures

Reel-to-reel testing system to rapidly qualify consistency and uniformity of I_c in a magnetic field of 3 T

- Based on our finding of a strong correlation between I_c at 77 K, 3 T, B||c and low temperature in-field I_c, we have developed a design for a reel-to-reel in-field I_c measurement system
- System has been constructed and has been commissioned into operation.



Goal: To verify consistency and uniformity in in-field performance of long tapes and assess ability to control nanoscale defects in microstructure over tens of meters

3.6 MW Superconducting Wind Turbine under development in Europe

ECOSWING Project (H2020, ecoswing.eu)

- Objectives
  - Design, develop and manufacture a full scale multi-megawatt direct-drive superconducting wind generator
  - Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark (3.6 MW, 14 rpm, 128 m rotor)
- Project partners
  - Envision, Eco5, Theva, FhG, U Twente, SHI, DNV-GL, Jeumont Electric, Delta Energy Systems
- Duration
  - March 2015-March 2019
- Project cost
  - EUR 13,846,594, EU contribution EUR 10,591,734

High Temperature Superconductors are being implemented for clean energy applications

- Advanced thin superconductor wire technologies developed for high power wind generators
- Superconducting wind turbines under implementation

For more information contact

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- E-mail : selva@uh.edu
- Web site : http://www2.egr.uh.edu/~vselvama/
- Phone : (713) 743 4044

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