High Performance HTS Tapes for High Field Magnet Applications

V. Selvamanickam

Department of Mechanical Engineering

Texas Center for Superconductivity

University of Houston, Houston, TX, USA

Presented at CERN, September 14, 2015

Outline

- Thin film technology for HTS coated conductor manufacturing
- Improving performance of HTS tapes in high magnetic fields
- Addressing consistency in in-field performance of HTS tapes
- Multifilamentary HTS tapes
- Manufacturing scale up of improved HTS tape technologies

High Temperature Superconductors can impact a broad range of industries

Energy

Cables
Transformers
Generators
Energy Storage
Grid Protection

Medical

MRI
Proton Beam Therapy

Industry

NMR
Fault Current Limiters
Motors
Induction heaters
Magnetic Separation

Defense

Airborne generators
All-electric ship
Degaussing cables
Rail Gun

Transportation

Maglev trains
Electric aircraft
All electric ship
Rocket propulsion

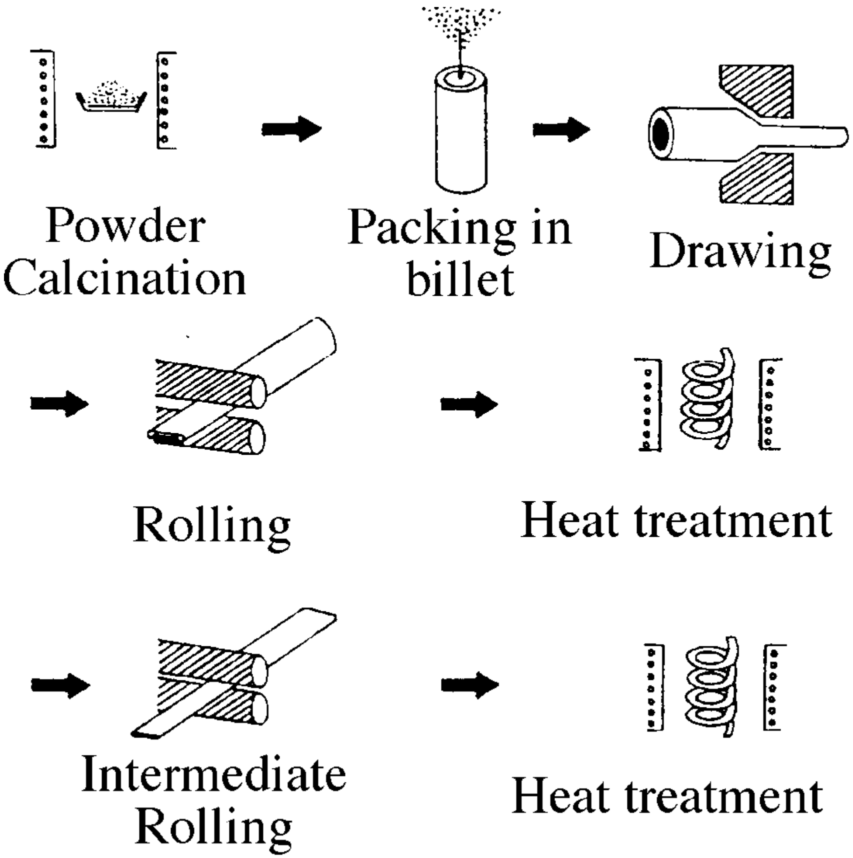
Research

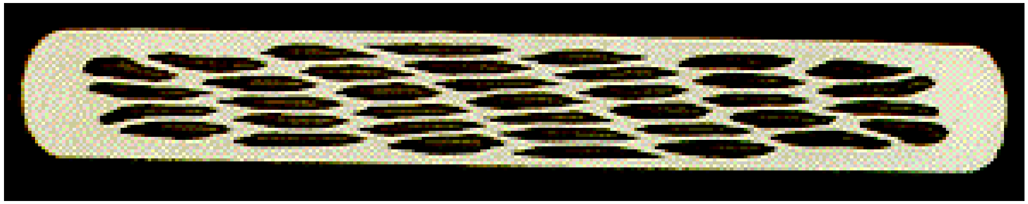
High-field magnets
High Energy Physics
Fusion reactors
Drug discovery

Thin film technology for HTS coated conductor manufacturing

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

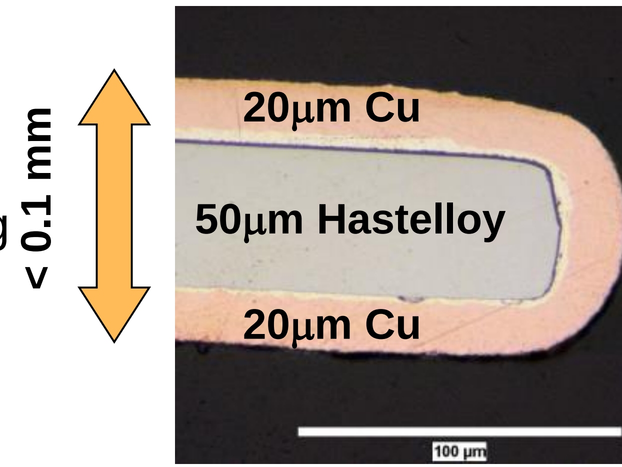
- High-temperature superconductors are ceramic materials and are inherently brittle. Challenge is to produce them in a flexible wire form in lengths of kilometers
- Two approaches to produce HTS in flexible tape form:
  - First-generation (1G) HTS - HTS is encapsulated as filaments in a silver sheath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

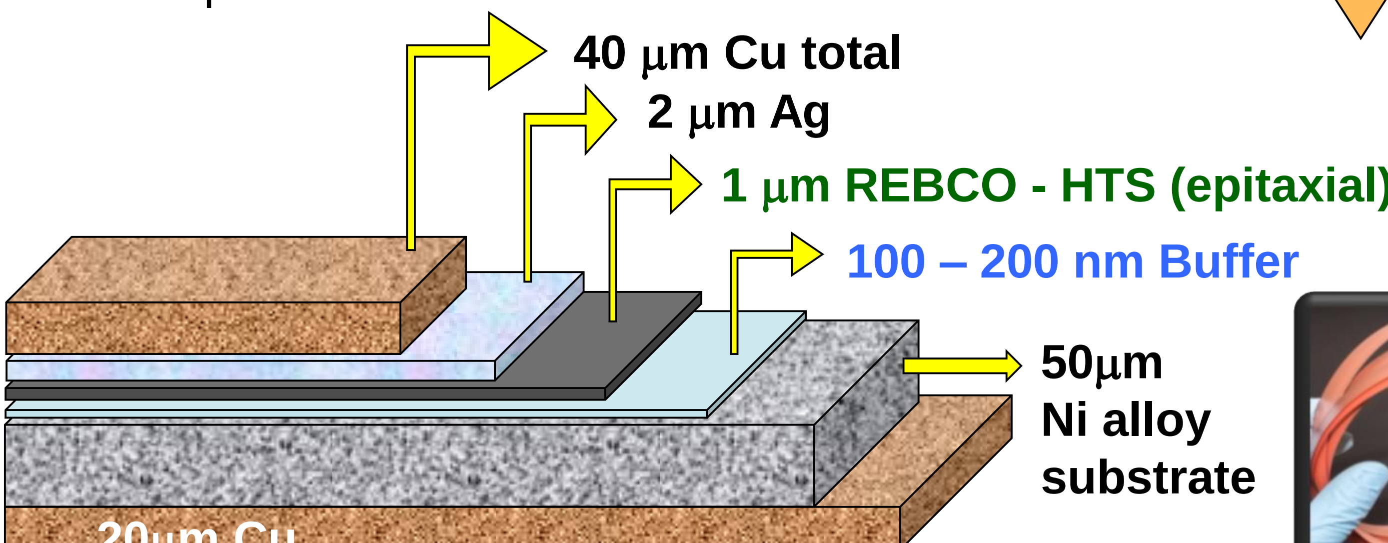




Thin film (2G) HTS tape manufacturing approach

- 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



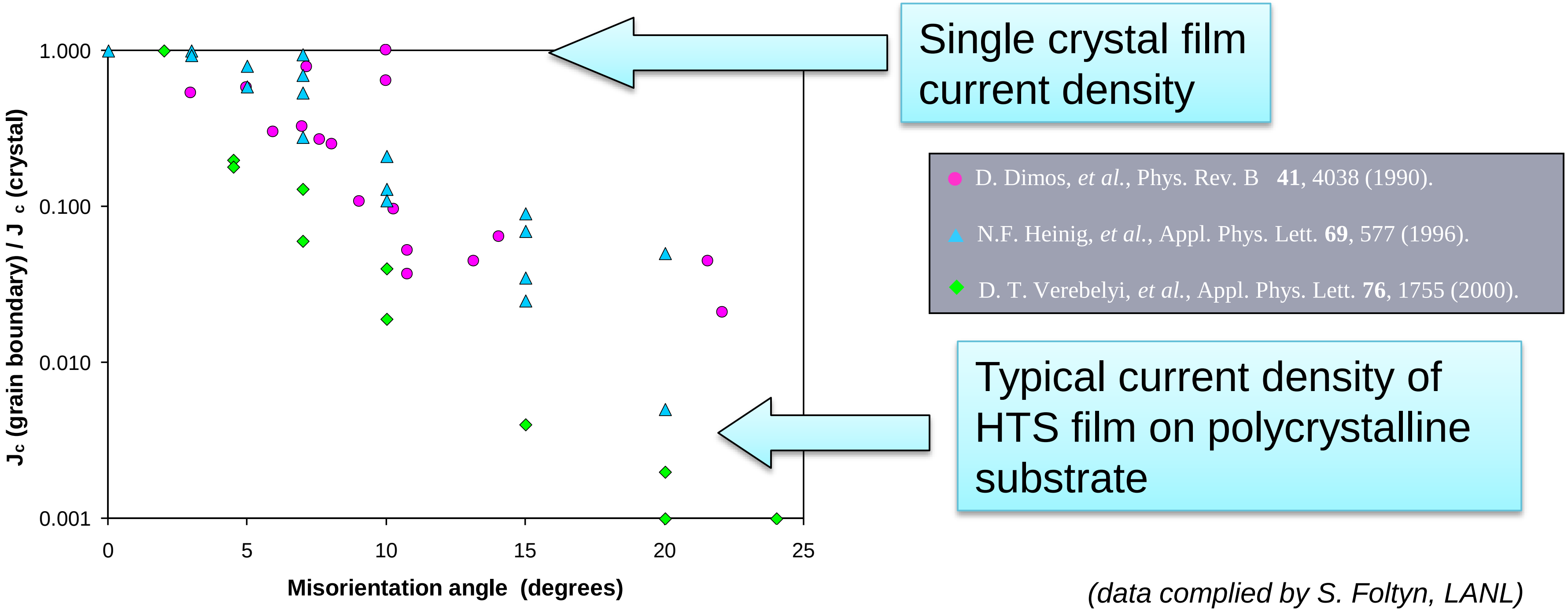


Fundamental challenge in thin film HTS tapes

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



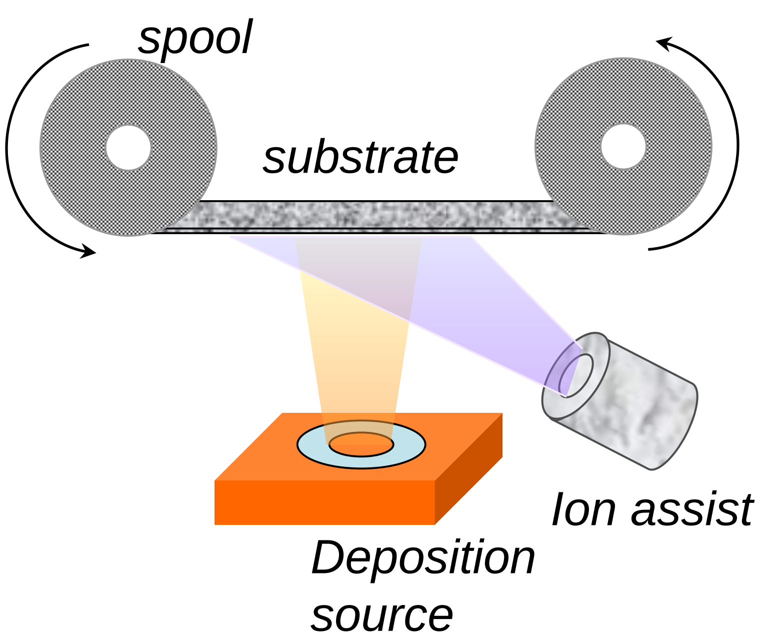
(data complied by S. Foltyn, LANL)

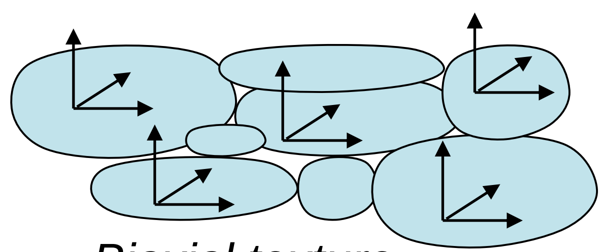
Cannot make kilometer lengths of HTS thin film wire on single crystal substrates.

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 !



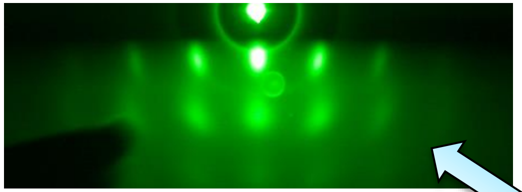


Biaxial texture

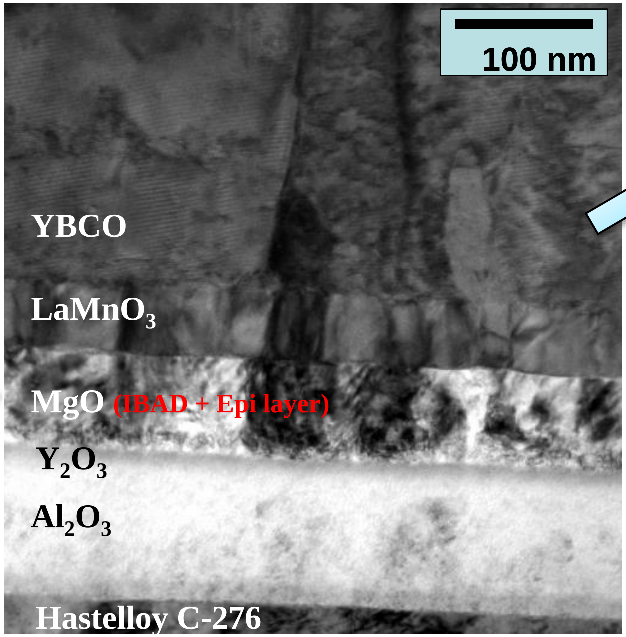
Grains in the IBAD film are arranged in a 3-dimensional aligned structure with grain-to-grain misorientation in any axis less than 5 degrees – essentially a near-single crystalline structure

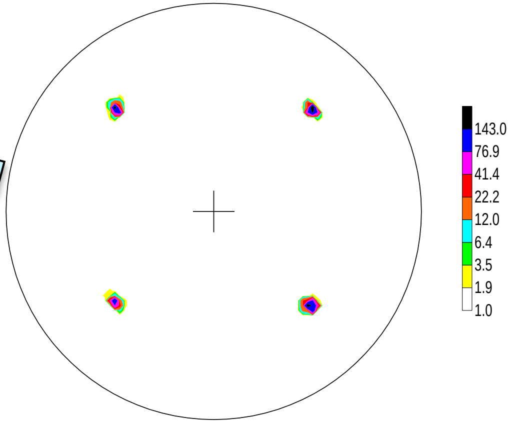
Epitaxial single crystalline-like films on polycrystalline or amorphous substrates based on IBAD

- 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

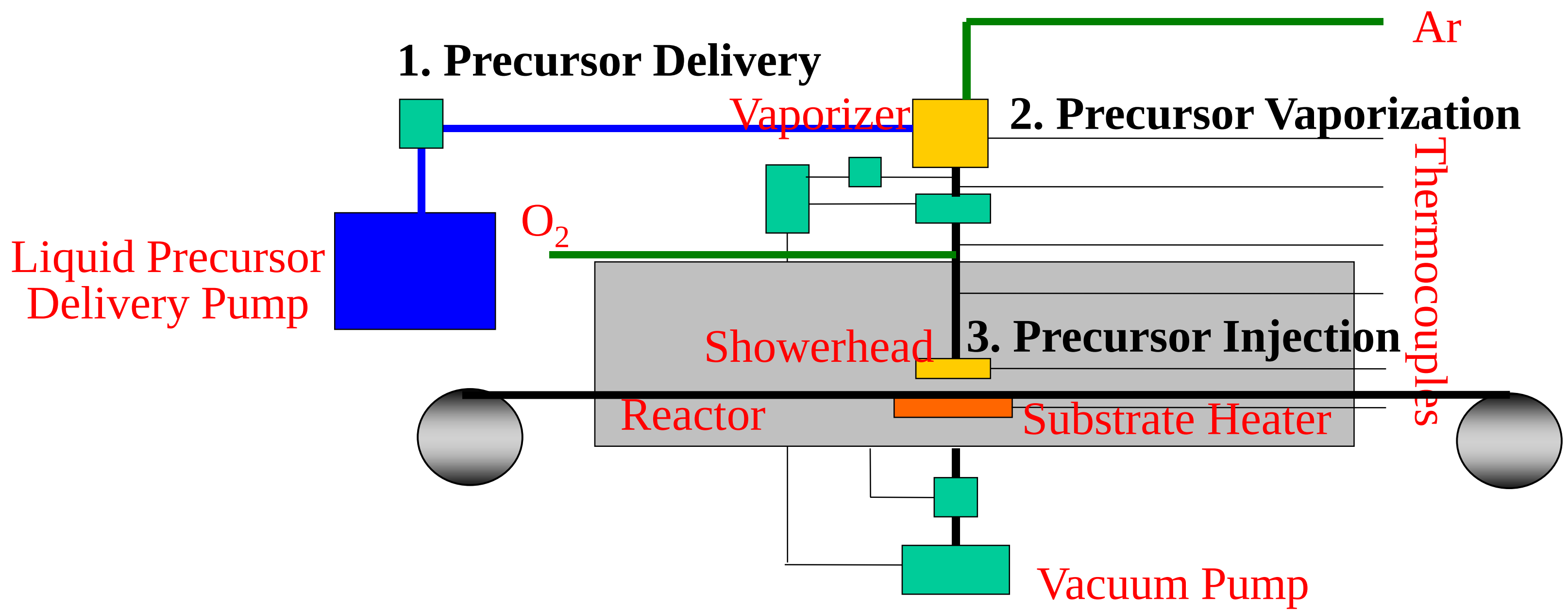




YBCO(113)

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)



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

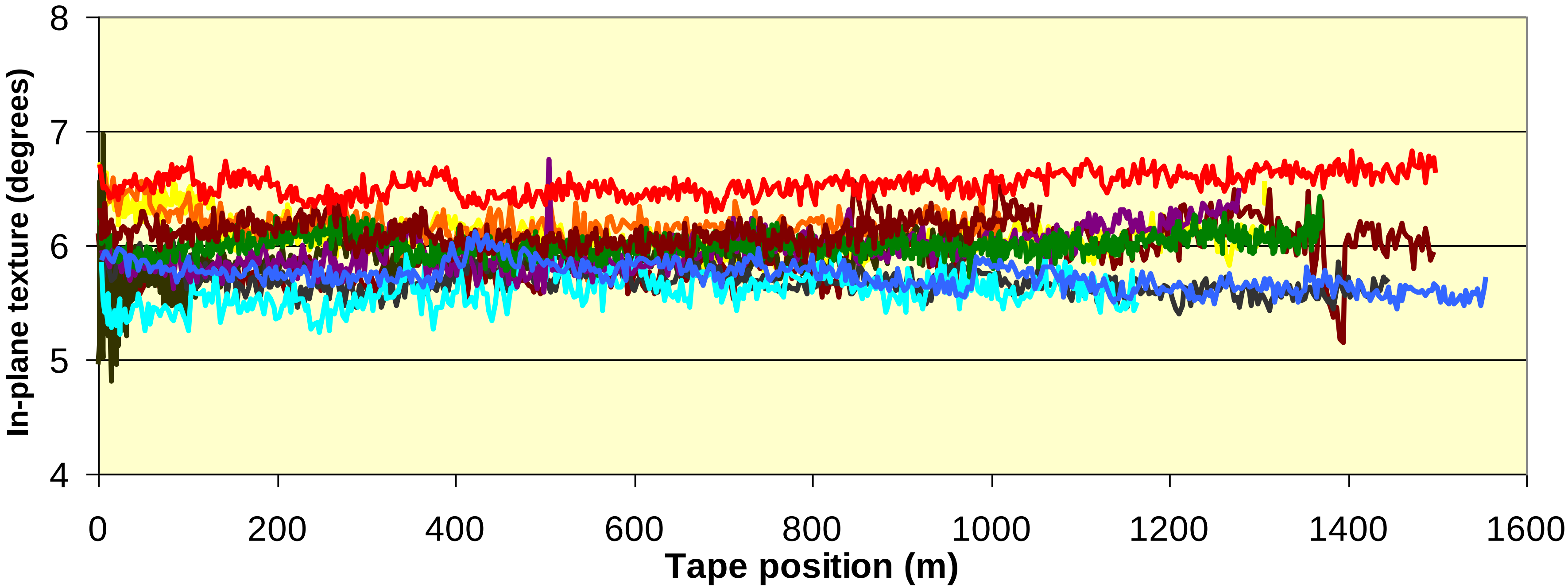
thd = (2,2,6,6-tetramethyl-3,5-heptanedionate) = $OCC(CH_3)_3CHCOC(CH_3)_3$

Immense challenge in scaling up 2G HTS tape fabrication from R&D to manufacturing

- **Epitaxial thin film growth over kilometer**
  - Never been accomplished in any material system
- **Uniform critical current over kilometer lengths**
  - Uniform stoichiometry of superconductor over kilometer lengths
  - Uniform thickness of 5-layer buffer stack without imperfections (porosity, scratches…) over a kilometer with buffer thickness as small as 7 nm
- **High-rate vapor deposition** of complex, multi-component films over 1 μm in thickness **over large deposition area**.
- **Stable deposition conditions over 40 hours** with temperature, precursor deposition uniformity over 100 cm × 15 cm deposition area

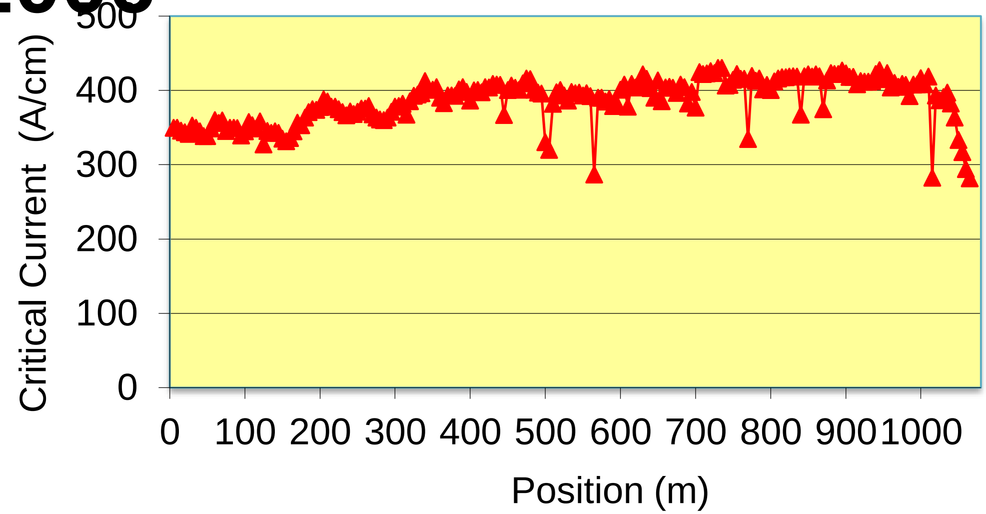
Numerous advances in materials science, processing, and equipment engineering were needed for scaling up to kilometers

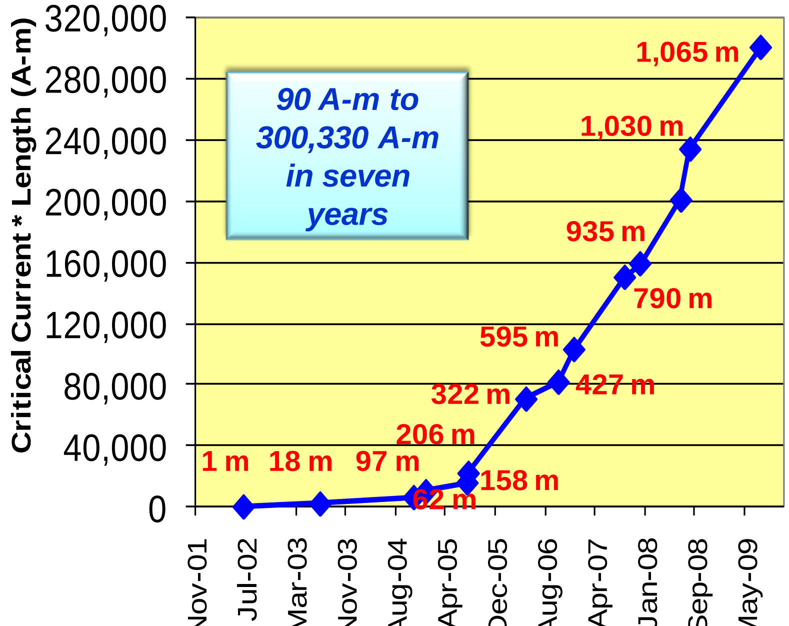
Routine manufacturing of kilometer lengths of full 5-layer IBAD buffered tape



Tapes with complete 5-layer buffer stack have been produced in lengths of 1,300 m to 1,500 m with in-plane texture of 5 – 7 degrees and excellent uniformity of ~ 2%

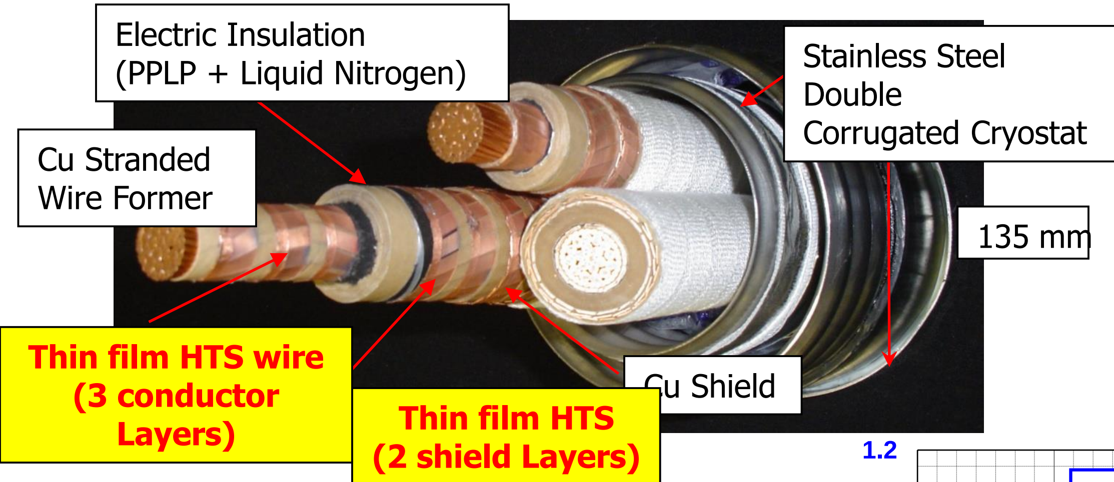
2G HTS tape was scaled to pilot manufacturing in 2006

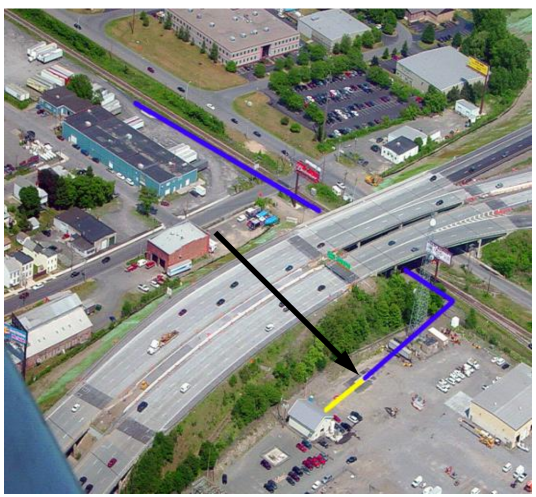


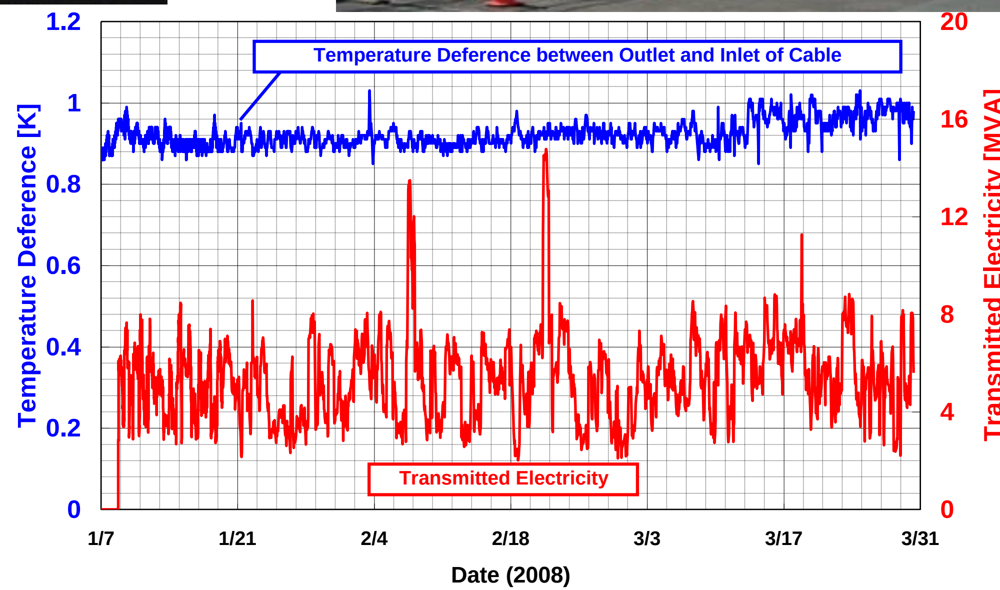


2G HTS tape is now routinely produced up to **kilometer lengths** with **300 times** the current carrying capacity of copper wire

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



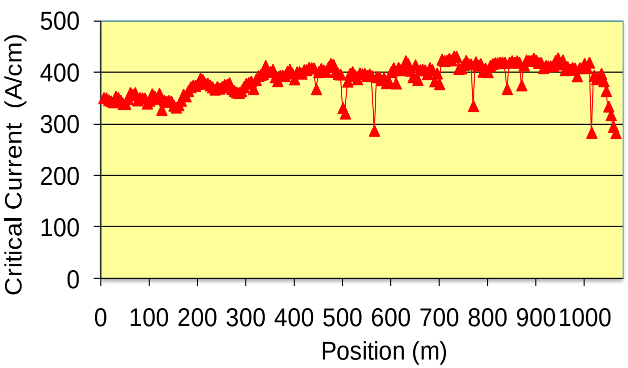




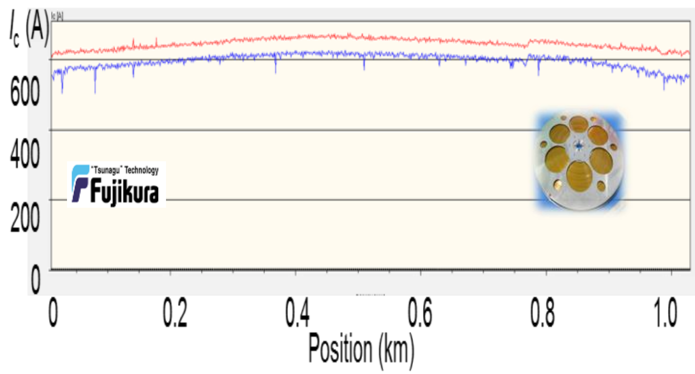
350 m cable made with 30 m segment of 2G HTS thin film wire was energized in the grid in January 2008 & supplied power to 25,000 households in Albany, NY

2015: At least 5 companies producing 500 – 1000 m lengths of 2G HTS tapes

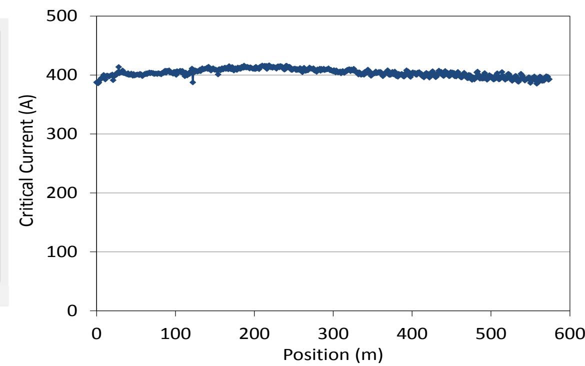
SuperPower



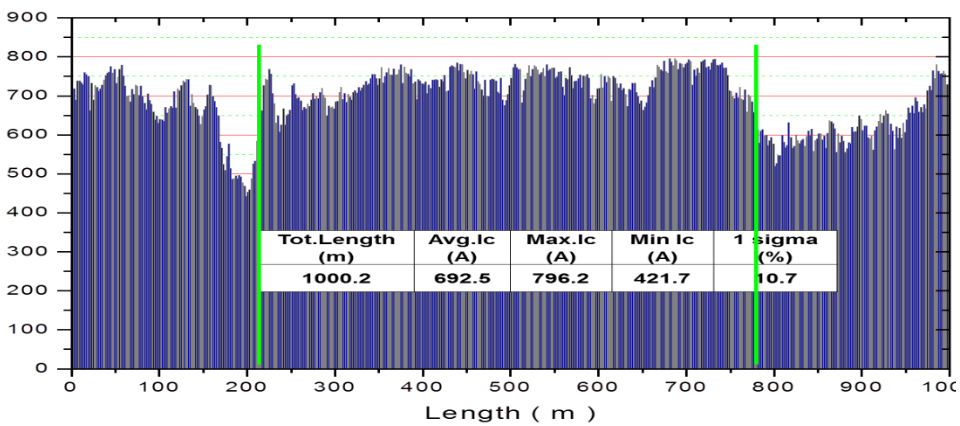
Fujikura



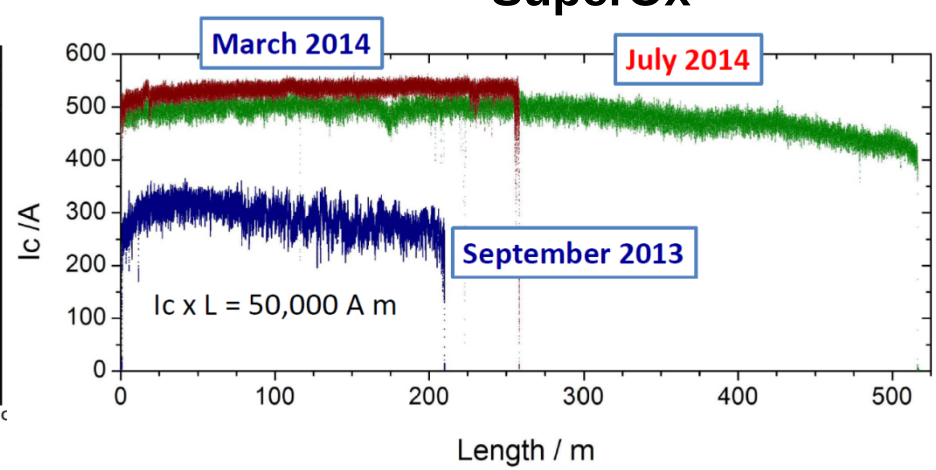
AMSC



SuNAM



SuperOx



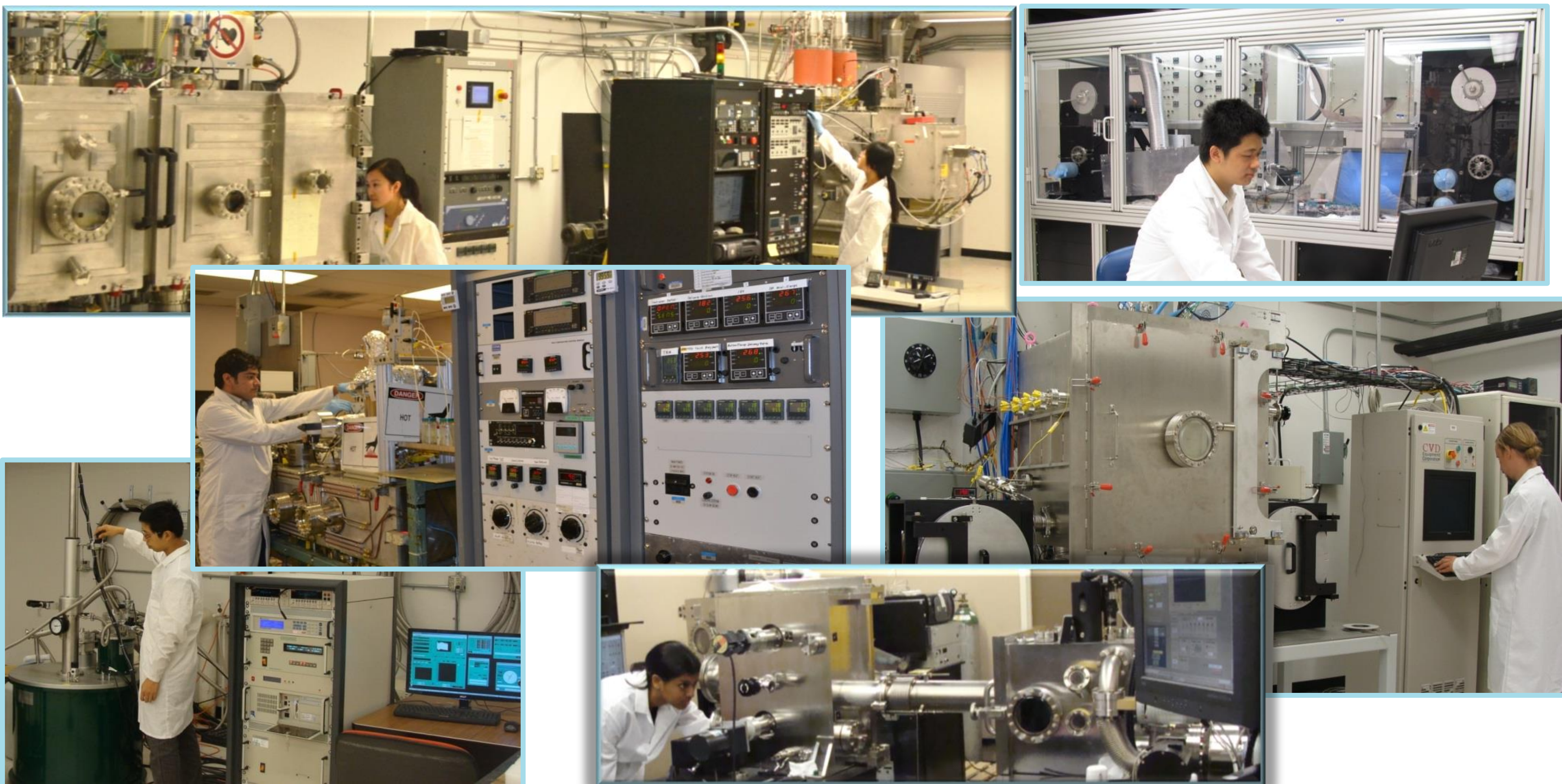
Improving performance of HTS tapes in high magnetic fields

2G HTS tape requirements for applications

High performance Uniformly high amperage (Ic) High in-field performance
High production capacity, Long piece lengths, On-time Delivery High throughput Thinner layers
Customer driven wire architectures Stabilization, low resistance joints, low ac loss
Low cost product Higher yield (simplicity – simpler process, fewer layers, on-line monitoring) Lean use of materials (more efficient conversion of raw material to film), high throughput

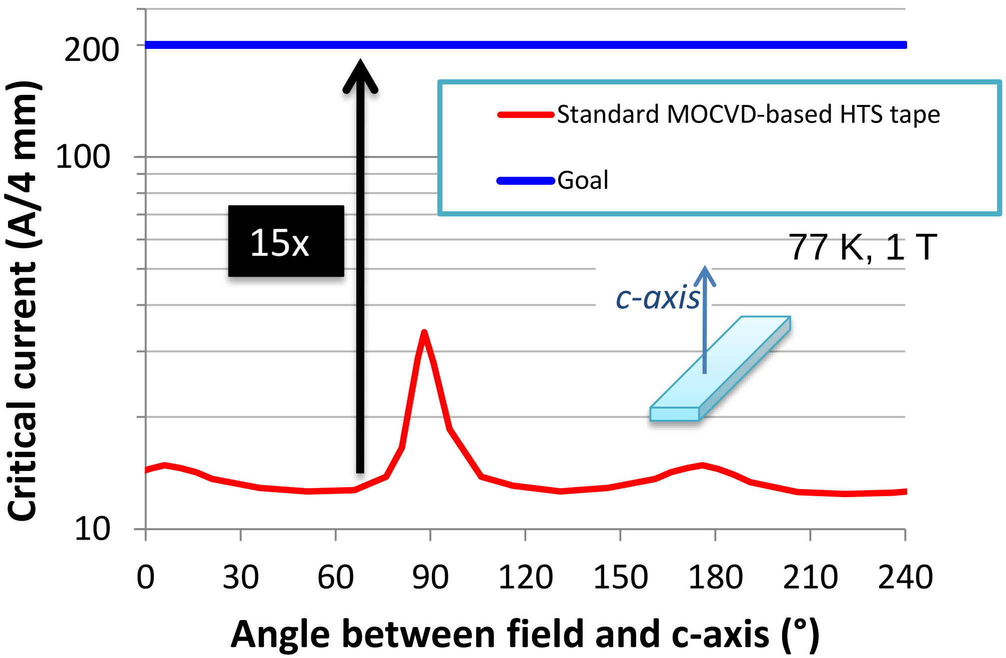
HTS Wire R&D program at Univ. Houston

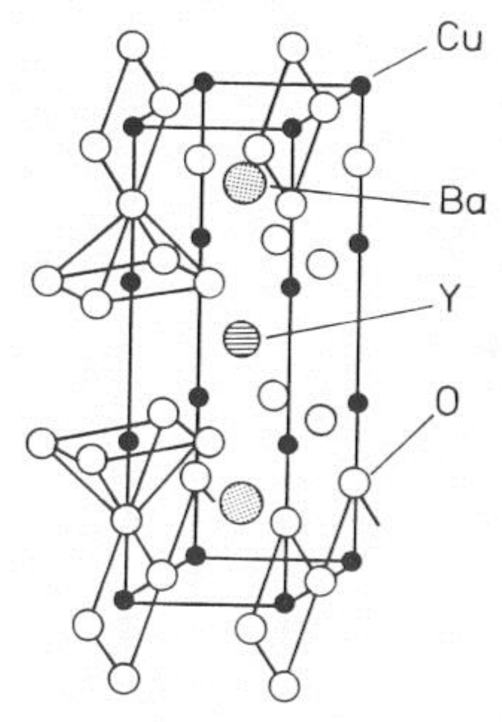
- State-of-the-art equipment for thin film wire processing & testing
- Technology advances already transitioned from UH to manufacturing
- Applied Research Hub created in UH Energy Research Park



In-field I_c improvements in thin film HTS

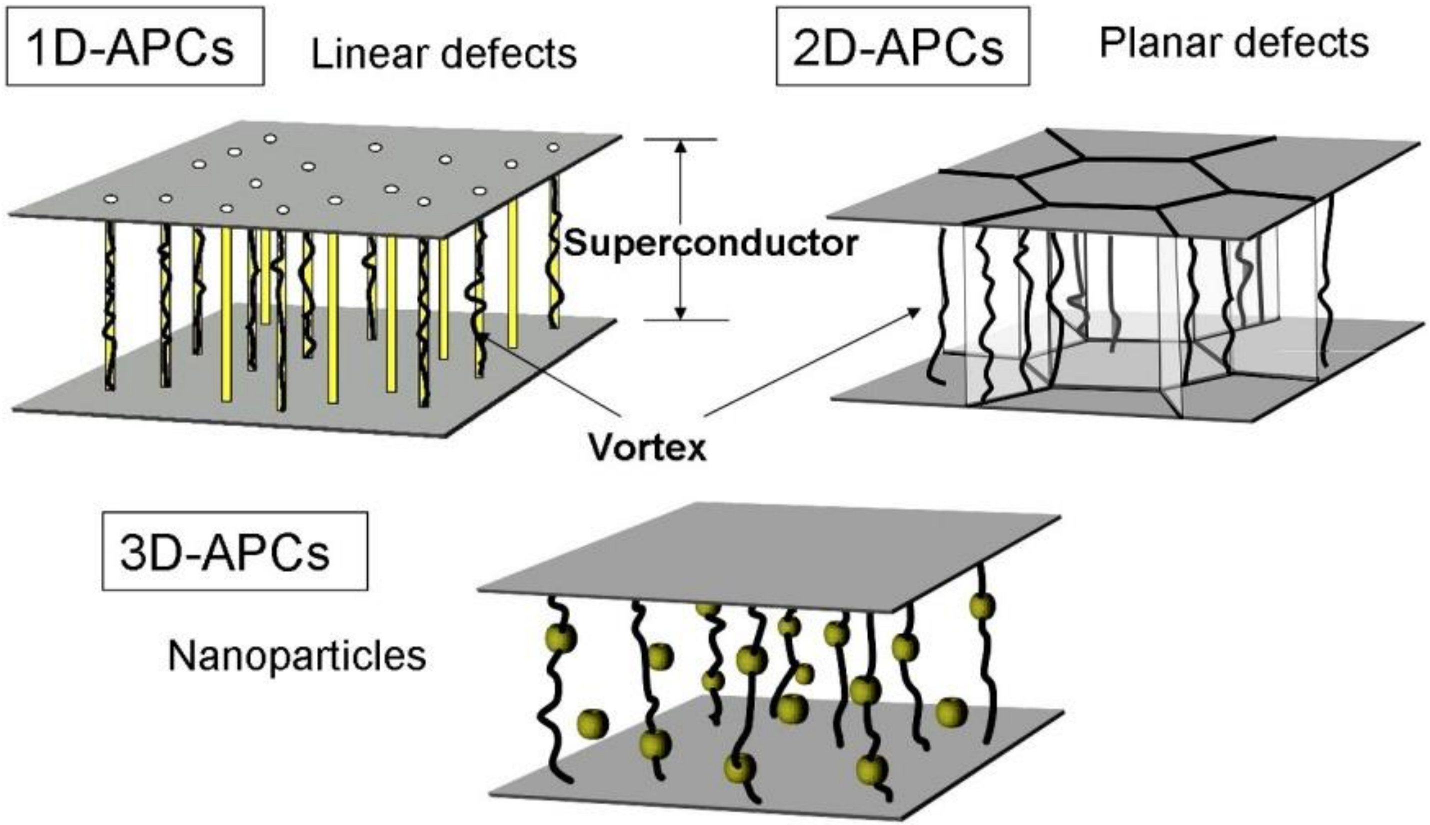
- Even though HTS tapes have good critical current properties at zero field, their performance reduces rapidly in an applied magnetic field at higher temperatures.
- Critical current of HTS tapes are very anisotropic and the minimum current value limits use.





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

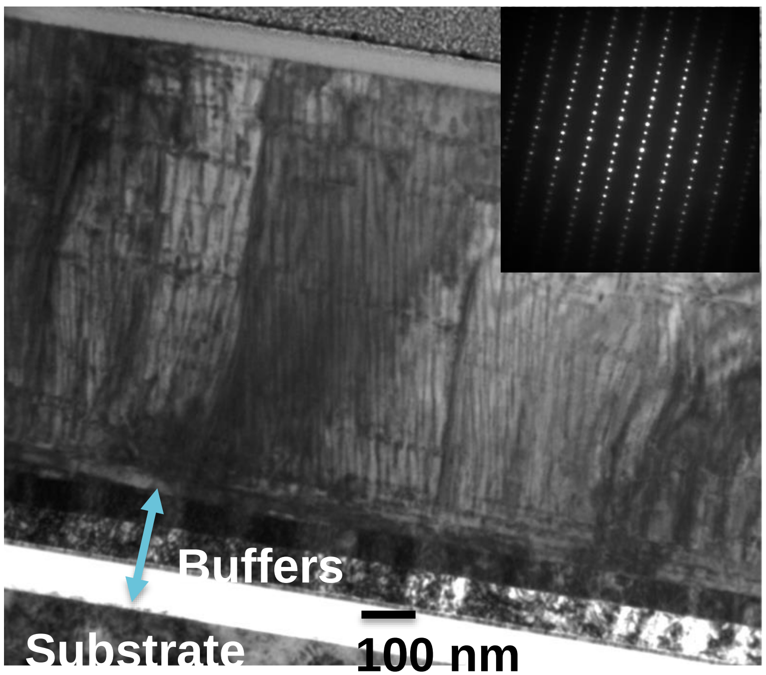
Nanoscale defects for pinning flux lines

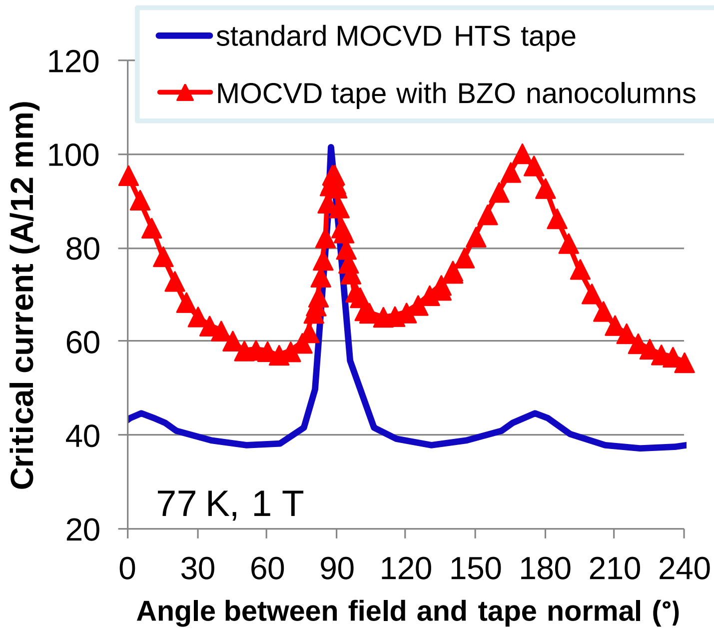


From Matsumoto

Improved pinning by Zr doping of MOCVD HTS conductors

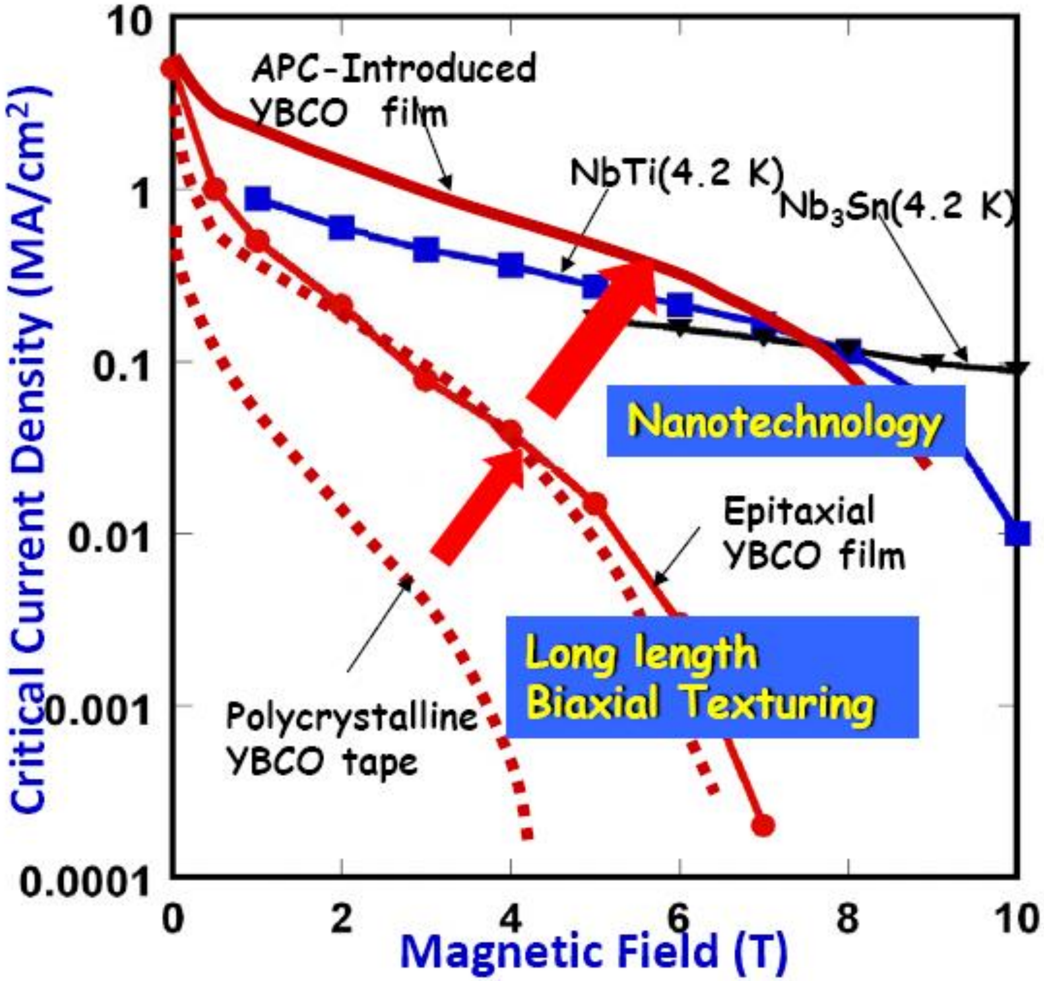
- *5 nm sized, few hundred nanometer long $BaZrO_3$ (BZO) nanocolumns with ~ 35 nm spacing created during in situ MOCVD process with 7.5% Zr*
- Two-fold improvement in critical current at 77 K, 1 T achieved by **7.5%** Zr addition in MOCVD films





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

Nanotechnology enabled improved critical current density in HTS tapes



K. Matsumoto and P. Mele, Supercond. Sci. Technol. 23 (2010) 014001

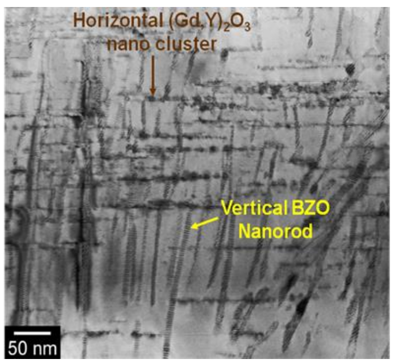
UNIVERSITY of HOUSTON

SuperPower Inc. A Furukawa Company

TcSUH

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

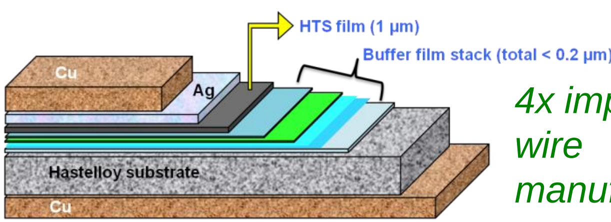
- University of Houston-led ARPA-E REACT program with SuperPower, TECO-Westinghouse, Tai-Yang Research and NREL targeted on 10 MW wind generator using advanced HTS wire



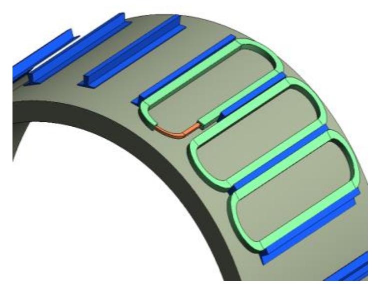
Technology Impact

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

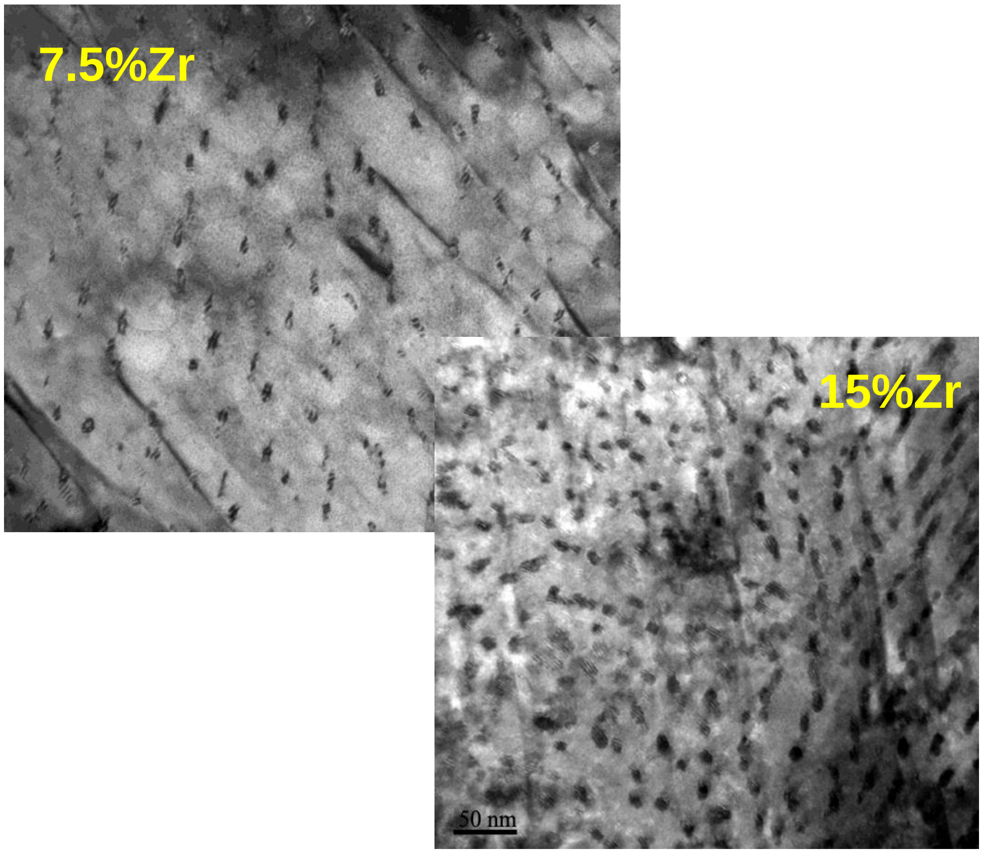
NREL NATIONAL RENEWABLE ENERGY LABORATORY

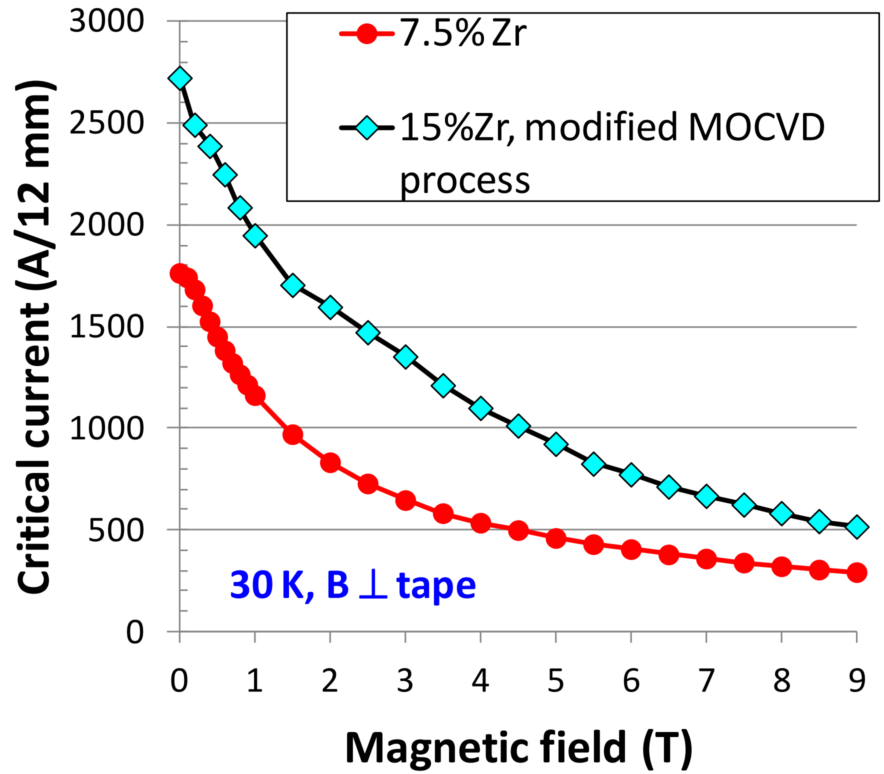
4X HTS conductor can enable commercial feasibility of HTS devices

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.

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



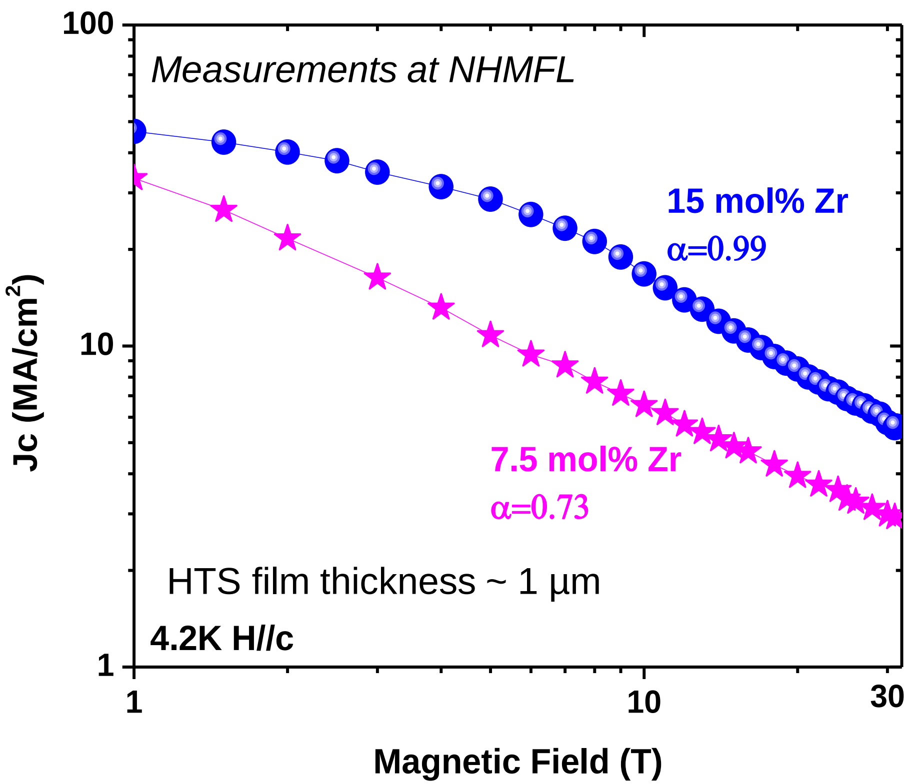


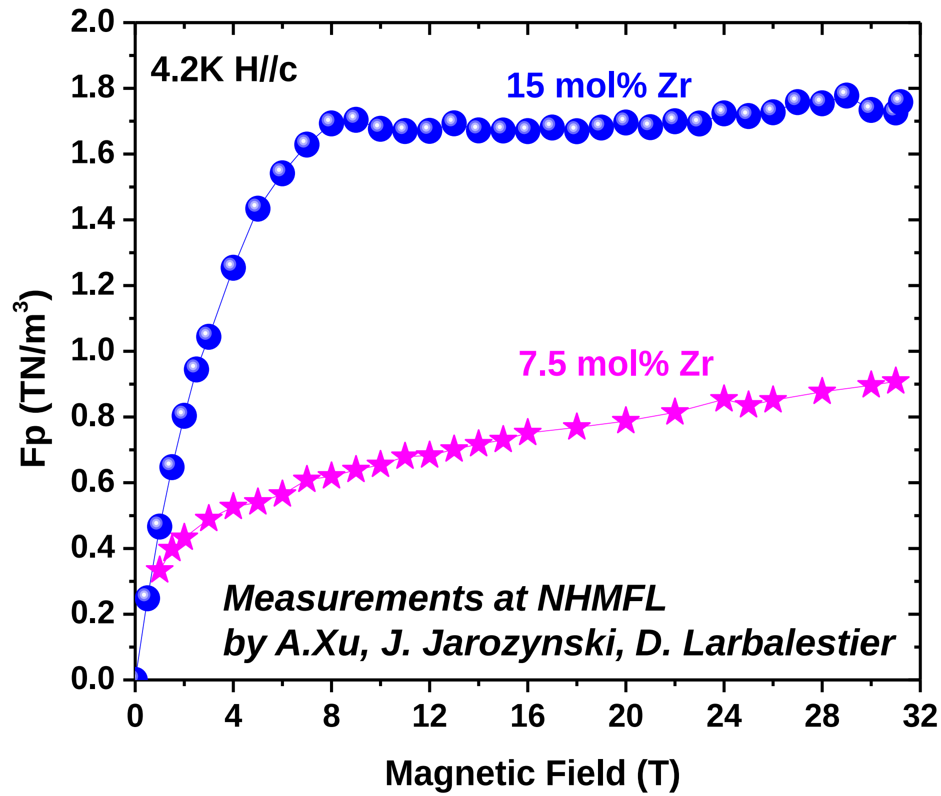
Supercond. Sci. Technol. **26** (2013) 035006

- *Critical current of 15% Zr-added film* ***~ 1384 A/12 mm (*** $\boldsymbol{J_c}$ ***= 12.5 MA/cm²)*** *at 30 K, 3 T, B||c*
- *Lift factor at 30K, 3 T, B||c improved by >100% to* ***~ 4.4***

UNIVERSITY of HOUSTON

Far superior pinning in 15%Zr tape at 4.2K compared to the best 7.5%Zr tape to date

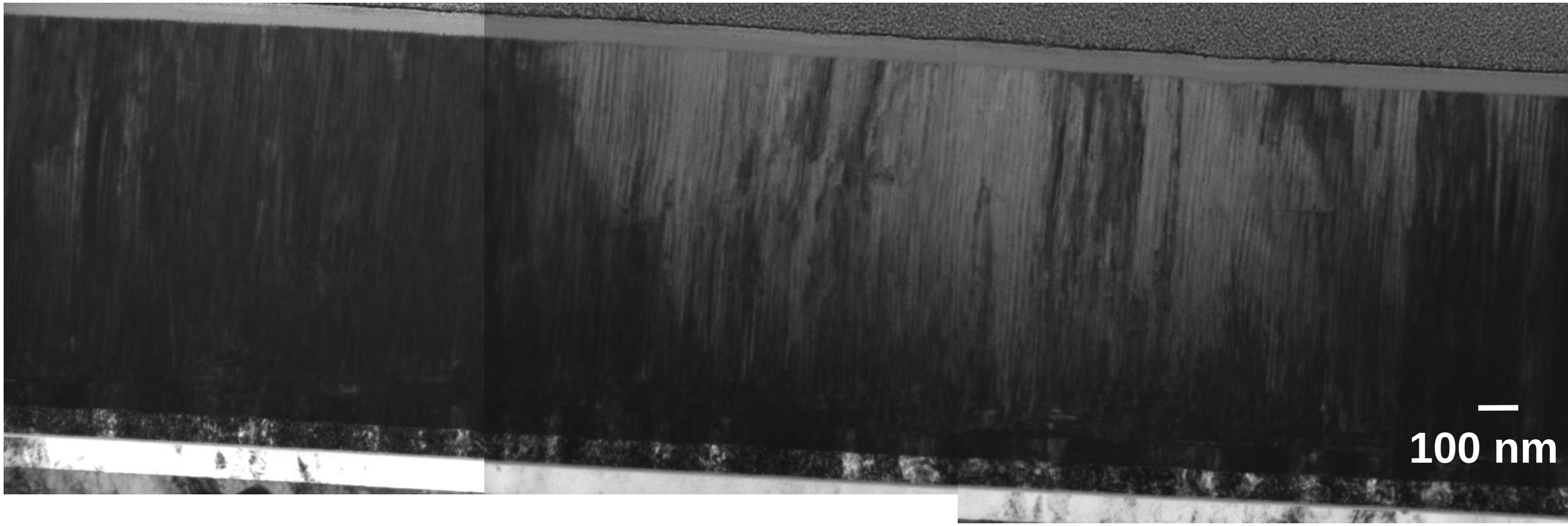


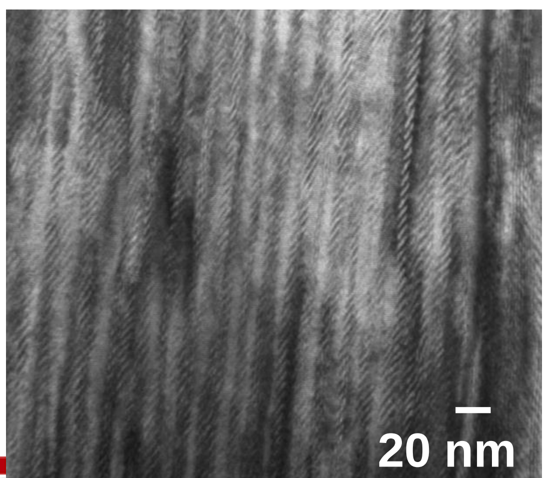


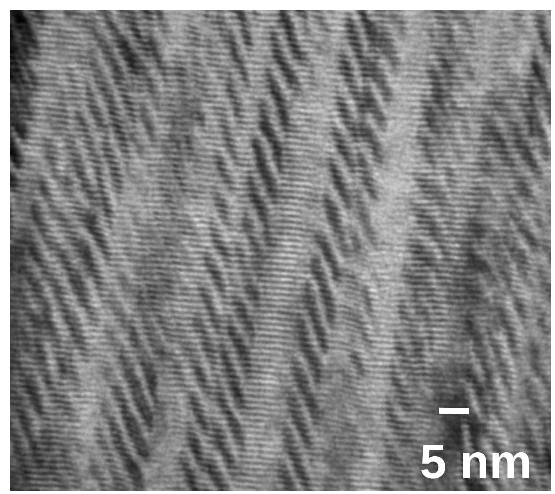
- *2.5X higher Jc in 15%Zr at 4.2 K, 10 T and 2.1X higher Jc in 15%Zr at 4.2 K, 20T*
- *The max pinning force increases from 0.9 TN/m^3 in 7.5%Zr to 1.7 TN/m^3 in 15%Zr*
- *Pinning force in 15%Zr nearly constant 1.7TN/m^3 from 8 to 31 T*
- *α = 0.99 indicate huge weak pinning in 15%Zr at 4 K (in addition to pinning by nanocolumns)*

TcSUH

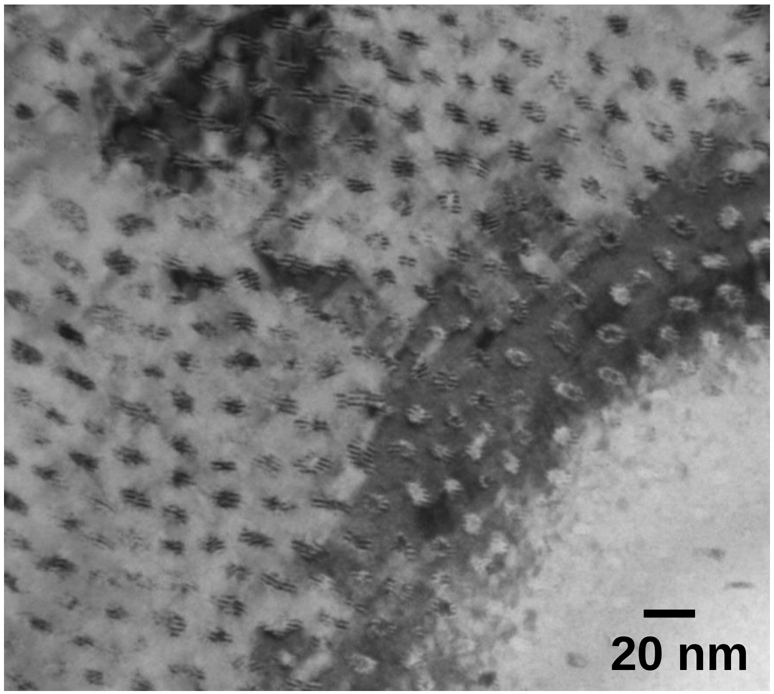
Even higher density of extended BZO nanoscale defects in 25%Zr-added tapes

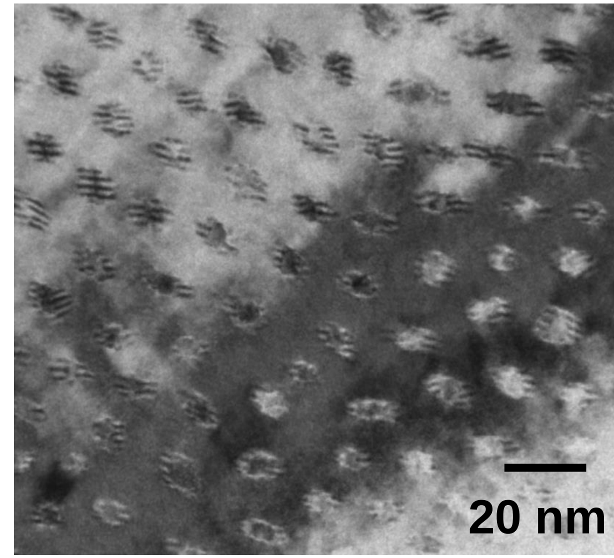


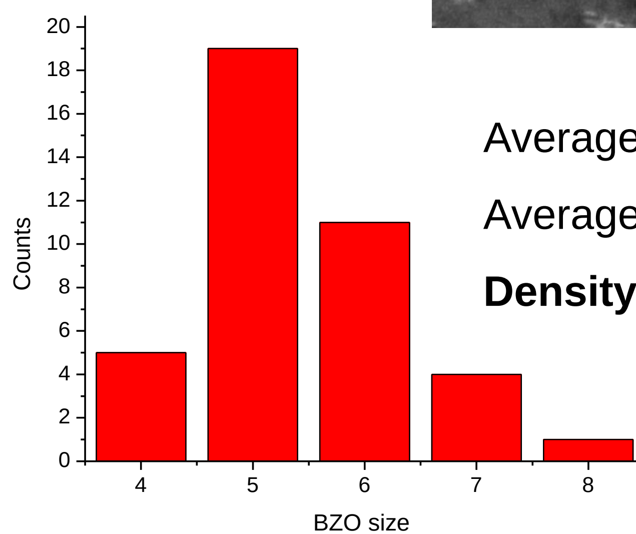




High density of extended BZO nanoscale defects in 25%Zr-added tapes





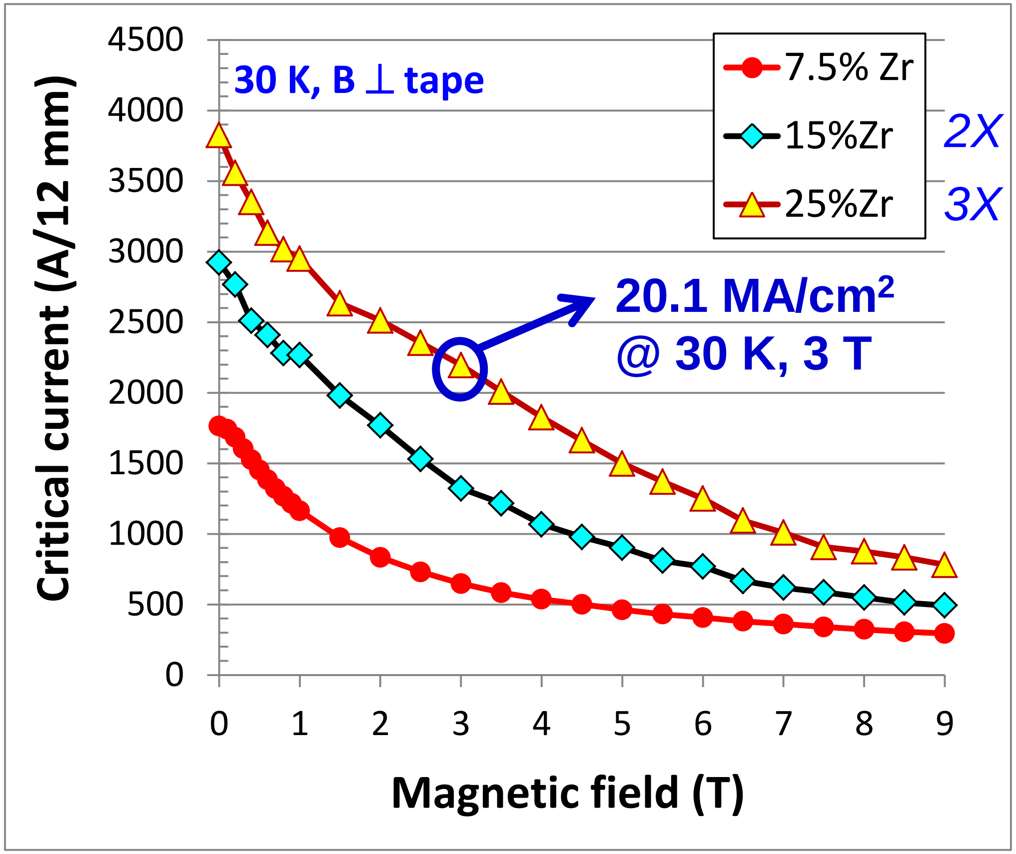


Average BZO size 5.5 nm

Average spacing ~ 12 nm

Density = 6.9 × 10^{11} cm^{-2}!

3X improvement in in-field performance in the last 2 years



2X higher

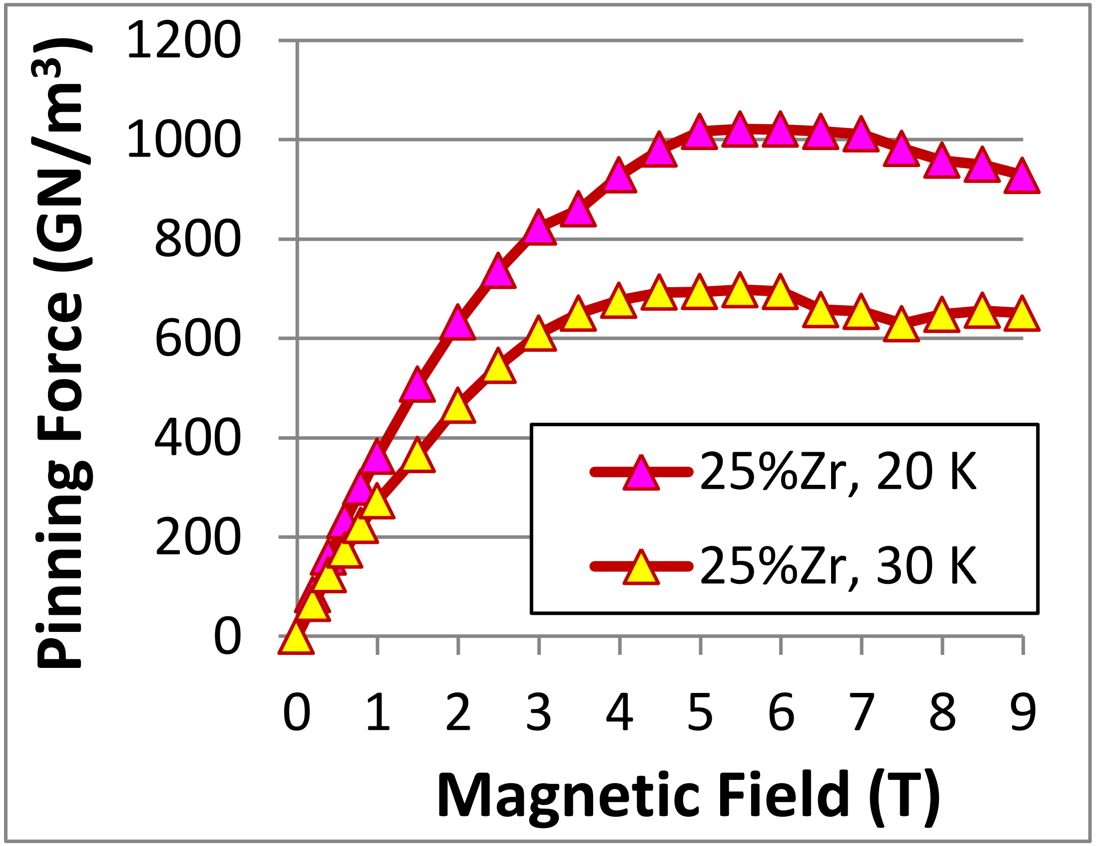
3X higher

- *Critical current of 25% Zr-added tape at 30 K, 3 T, B||c* ***~ 2172 A/12 mm*** ***J_c = 20.1 MA/cm², Pinning force = 603 GN/m³***
- *Lift factor at 30K, 3 T, B||c* ***~ 6.4 (200% improvement!)***

- Enabled 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

TcSUH

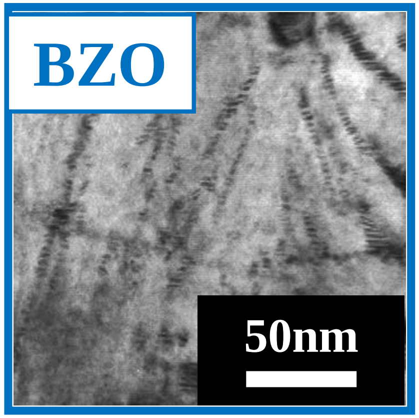
Very high pinning forces in 25%Zr-added tapes: above 1000 GN/m^3 at 20 K!



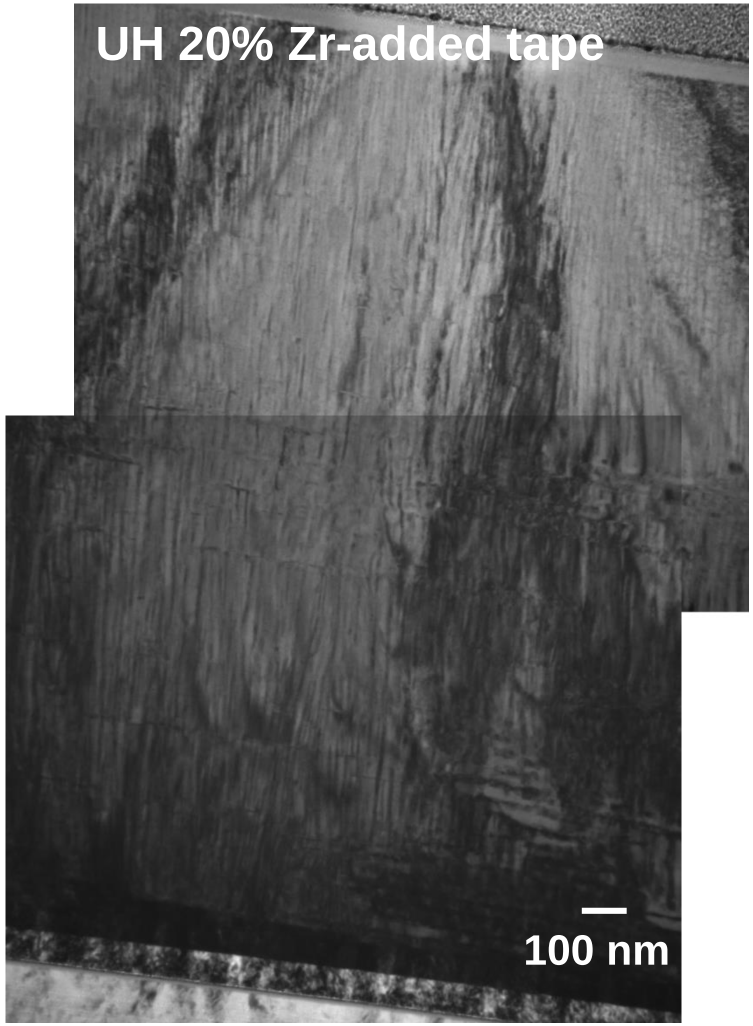
Appl. Phys. Lett. **106**, 032601 (2015)

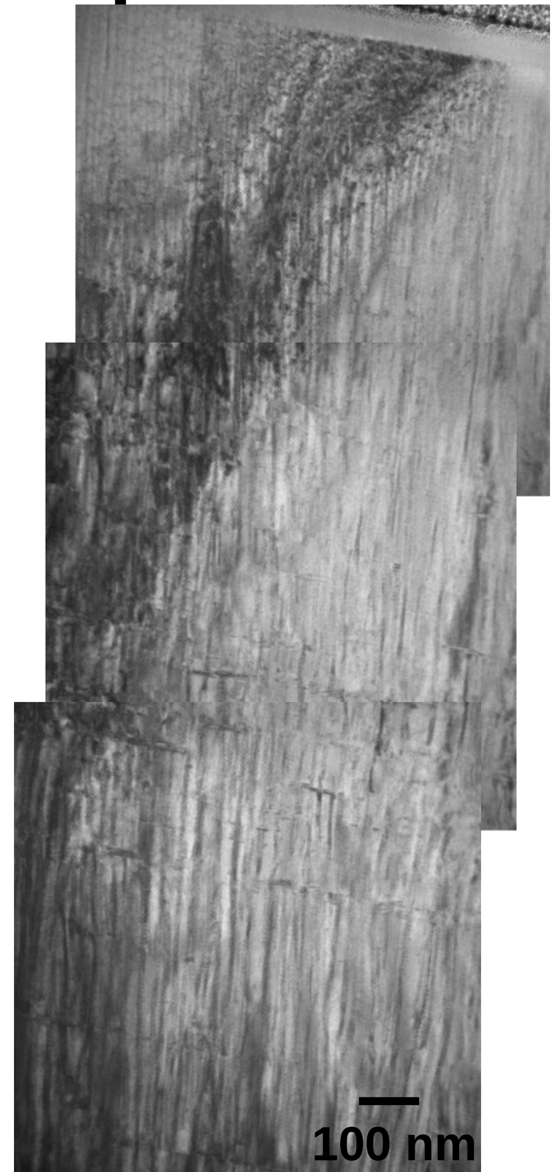
- *Maximum pinning force at 30 K: 698 GN/m^3*
- *Maximum pinning force at 20 K: 1021 GN/m^3*

Continuous BZO growth along 2.2 µm thick 20%Zr-added GdYBCO tape



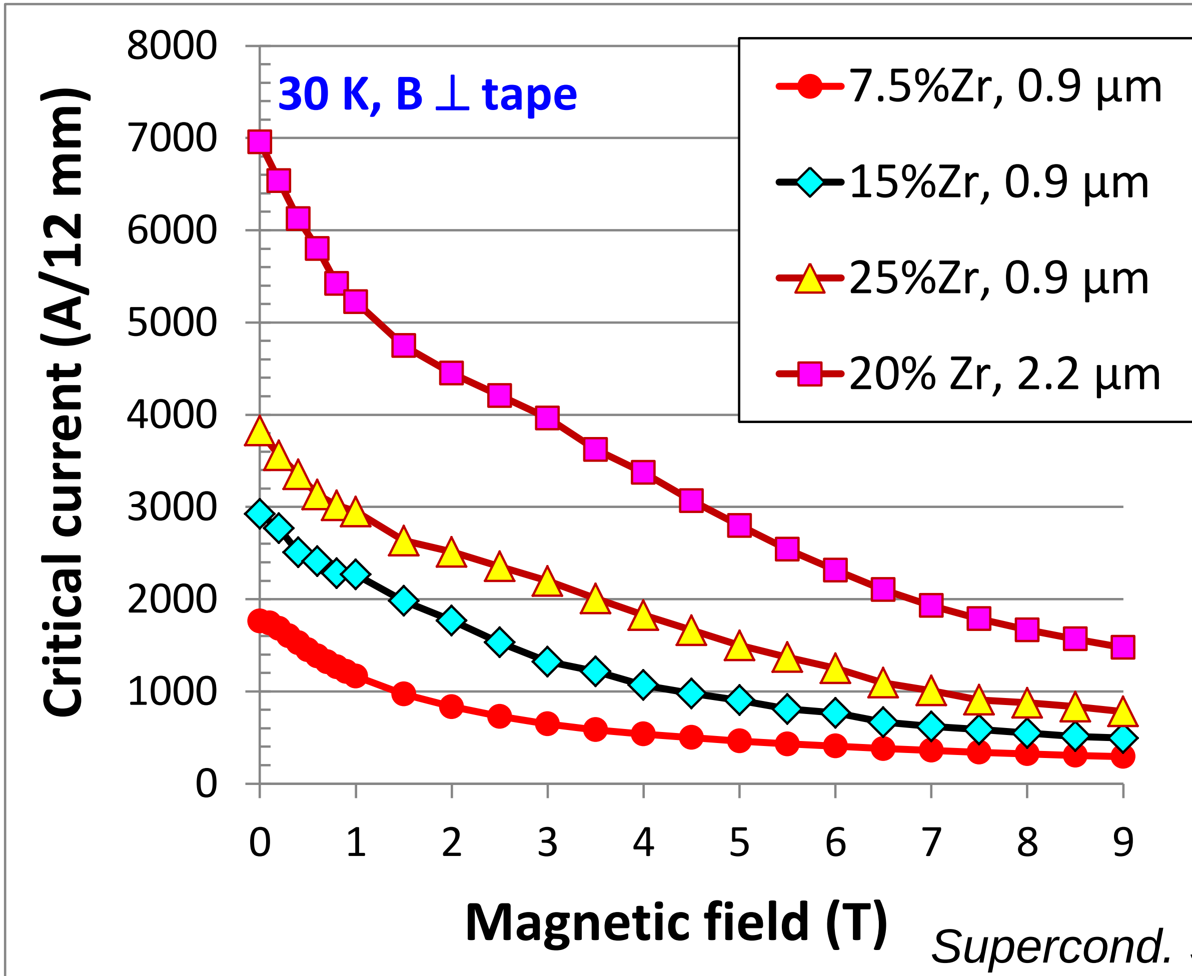
Loss of BZO alignment reported by ISTEC in their BZO-doped thick films made by PLD





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

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

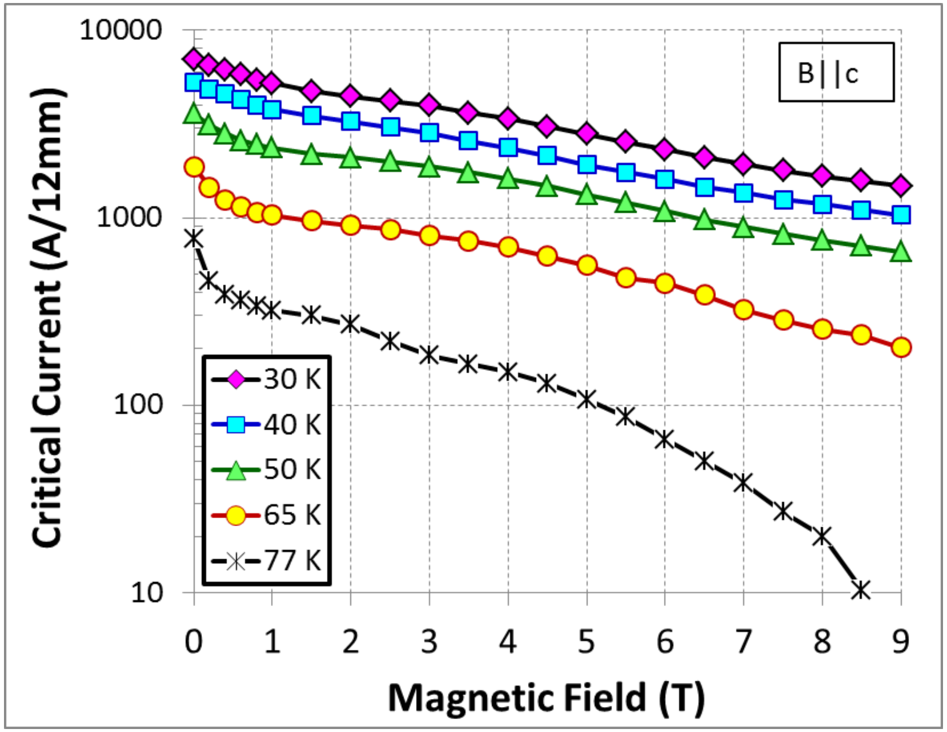


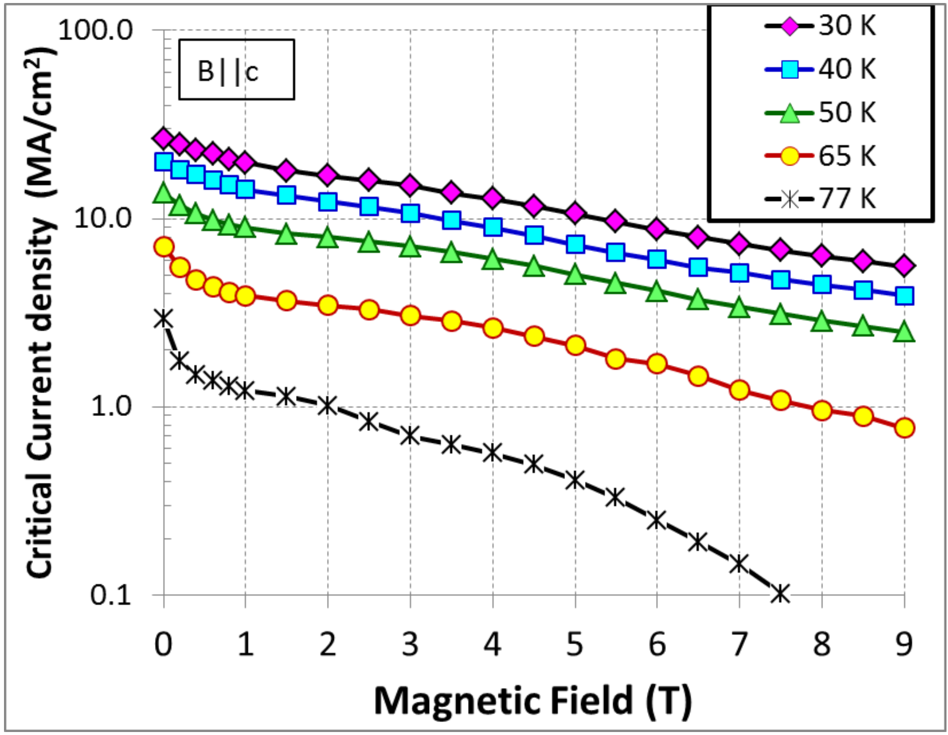
Supercond. Sci. Technol. **28**, (2015) 072002

- *Critical current of 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***
  - ‼ *at 30 K, 2.5 T, B||c,*
    I_c = 4206 A/12 mm
    J_c ~ 16 MA/cm^2
    *Lift factor ~ **5.4***

Exceeded ARPA-E REACT program goal of 3000 A/12 mm at 30 K, 2.5 T, B||c by a wide margin! Goal: 4X Ic at 30 K, 2.5 T; Achieved 5.6X Ic

Very high critical currents in 2.2 µm thick 20% Zr-added tapes over a broad temperature range

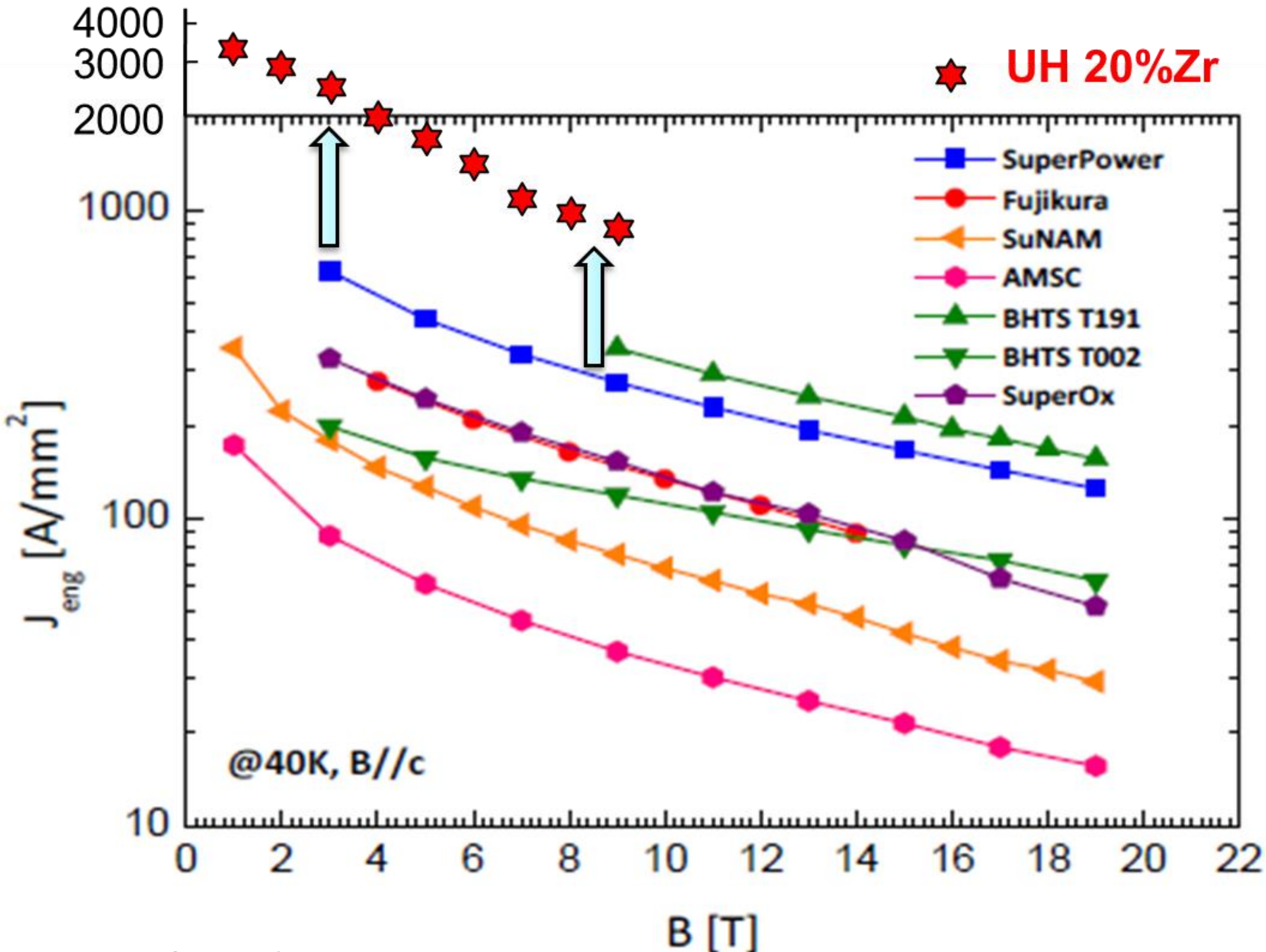




Supercond. Sci. Technol. **28**, (2015) 072002

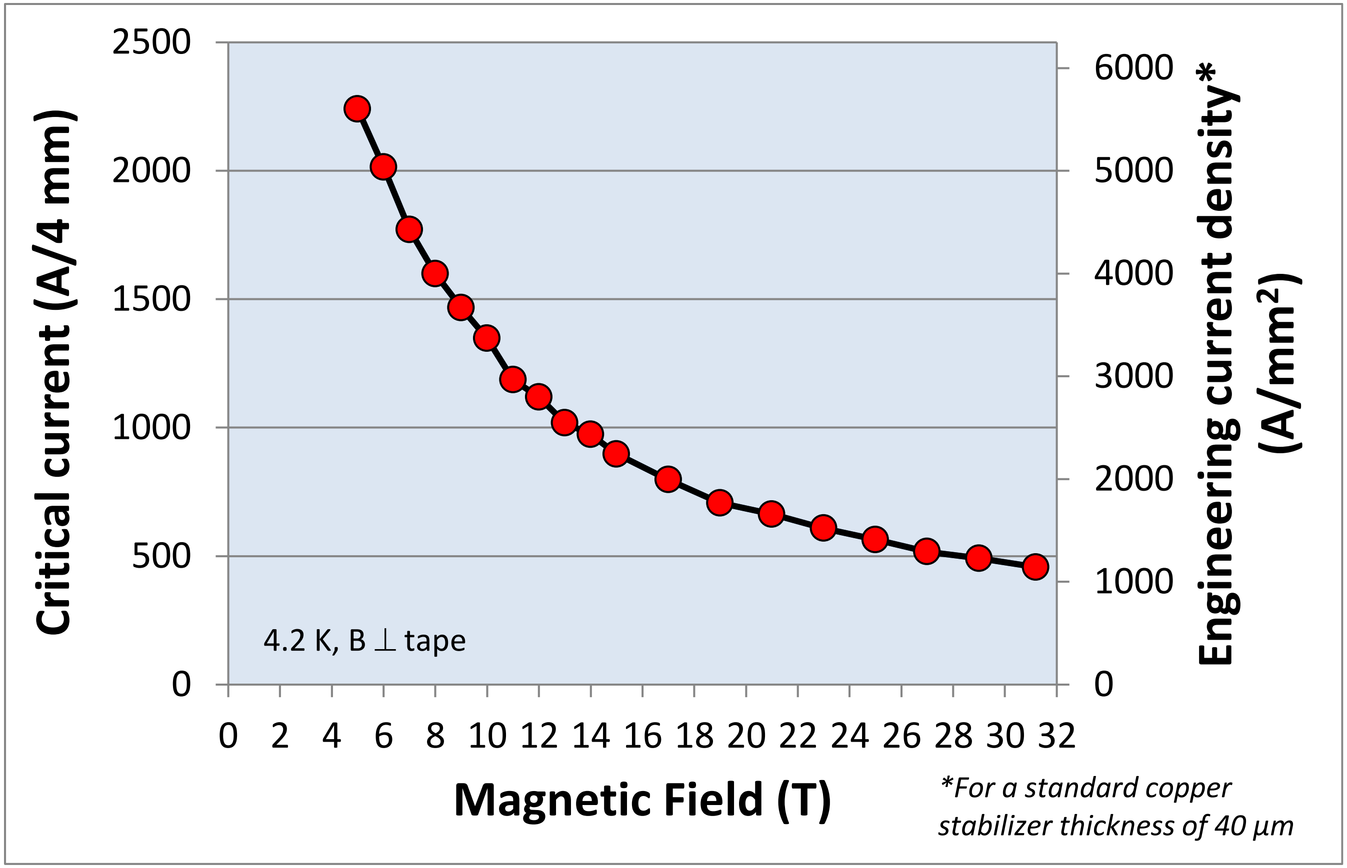
	30 K, 3 T	40 K, 3 T	50 K, 3 T	65 K, 3 T	77 K, 3 T
I_c (A/12 mm)	3963	2833	1881	805	184
J_c (MA/cm^2)	15	10.1	7.1	3.1	0.7

J_e of 20% Zr-added tapes 3X – 4X higher than SuperPower's production AP wire at 40 K



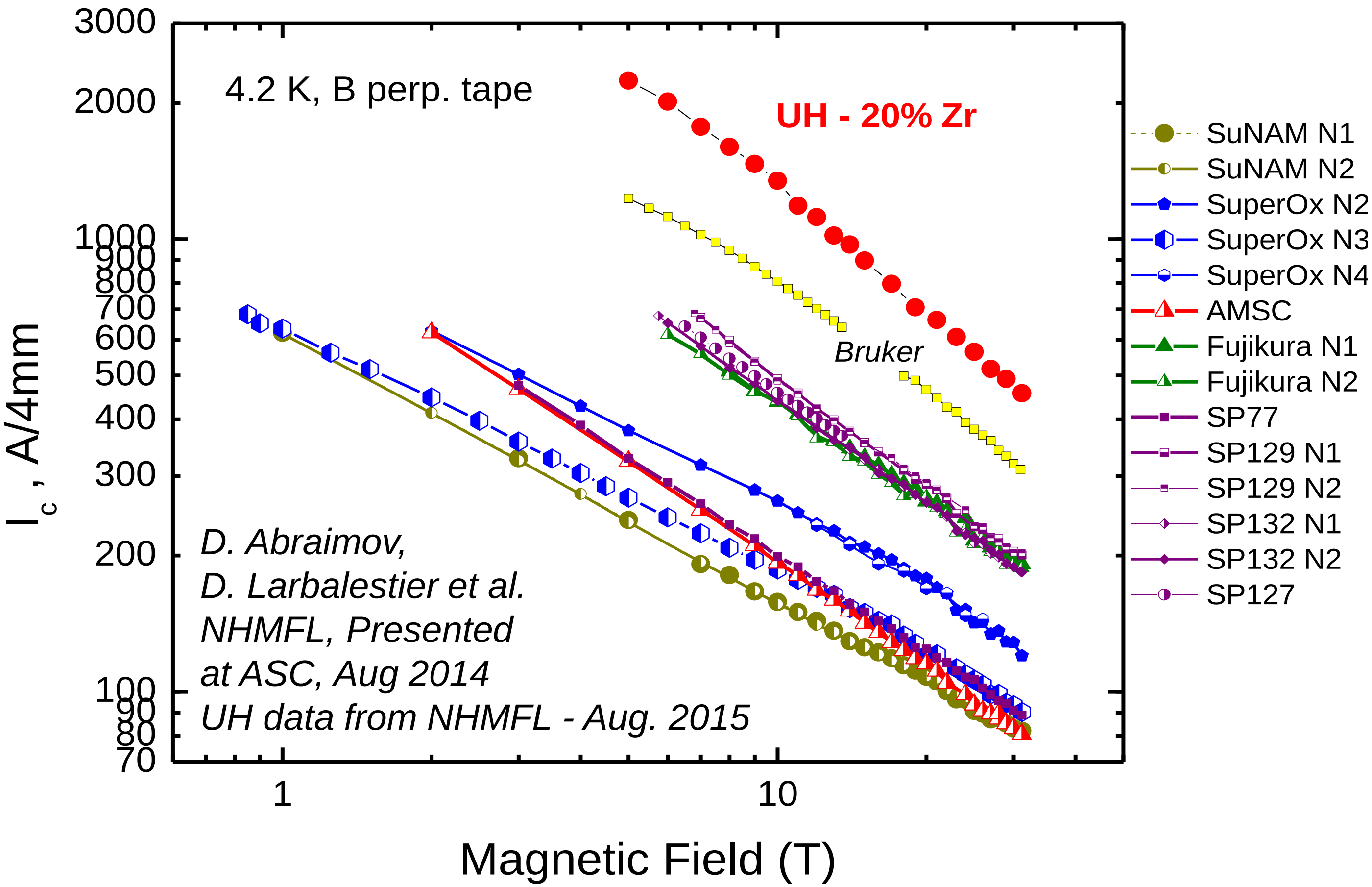
Data of industry 2G HTS wire performance
Presented by C. Senatore at the 1st Workshop on Accelerator Magnets in HTS, 21-23 May 2014, Hamburg, Germany

Very high I_c and J_e in 3.3 µm thick 20%Zr tape at 4.2 K



At 4.2 K, 21 T, I_c = 663 A/4mm, J_e = 1658 A/mm^2

Ic of 20%Zr-added tapes 2.5X higher than SuperPower's production AP wire at 4.2 K, 15 T

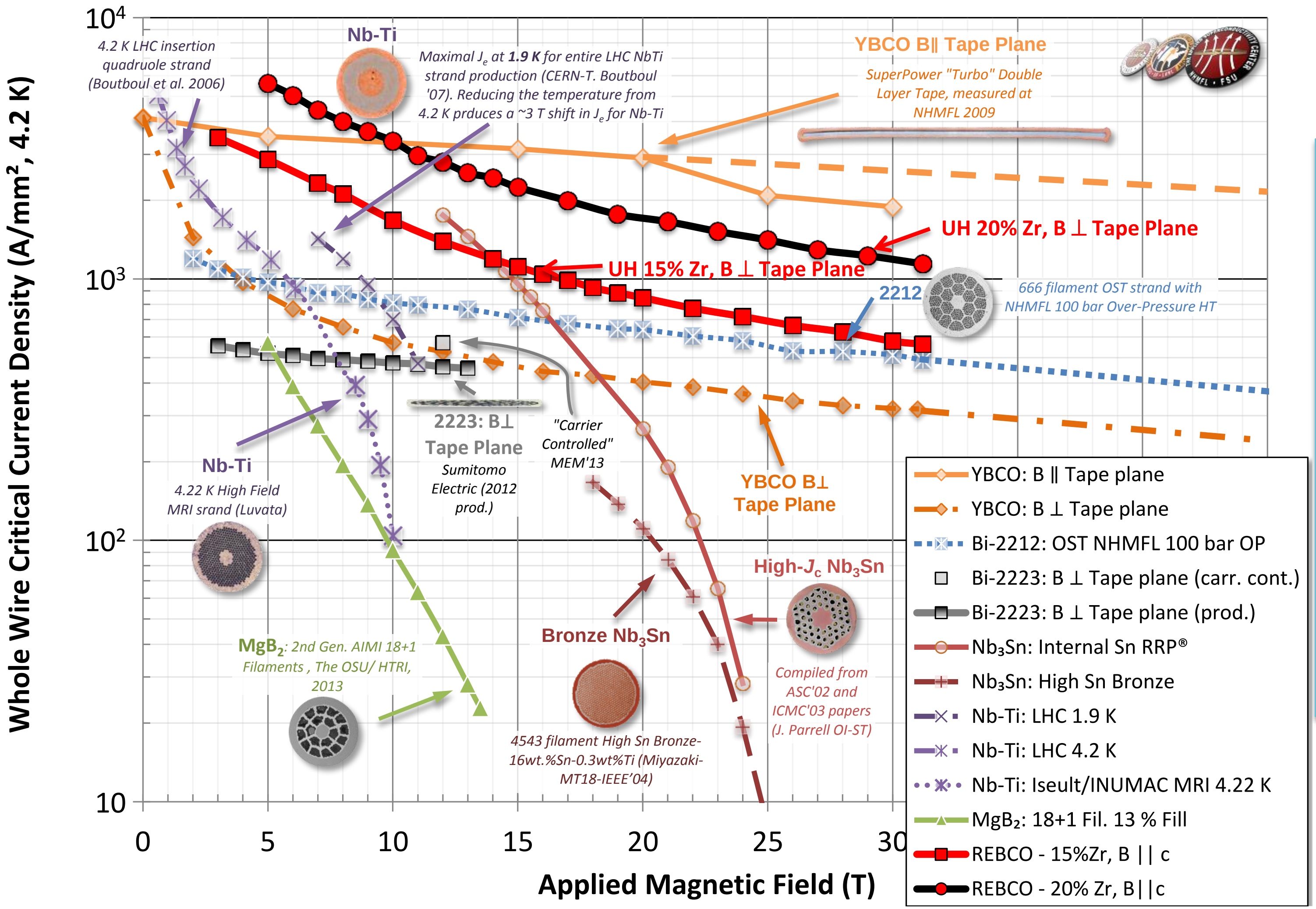


Wire optimized for 30 K performance maintains its superior performance over a wide range of temperatures and fields → impacts several HTS applications

UNIVERSITY of HOUSTON

TcSUH

15%Zr & 20%Zr tape performance at 4.2K better than all wires even in field perpendicular to tape



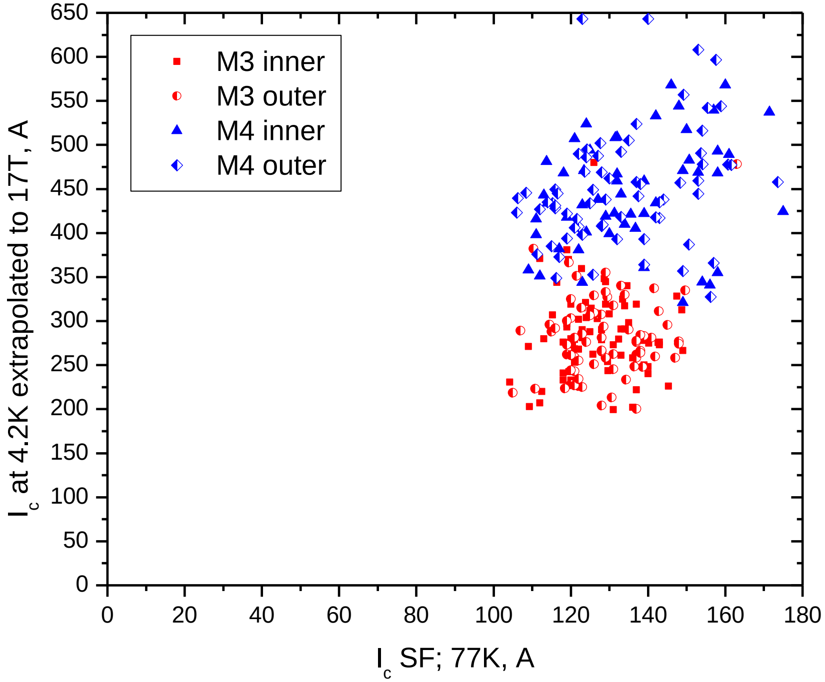
J_e of 20% Zr
2.3X Nb_3Sn
@ 15 T
6.4X Nb_3Sn
@ 20 T

J_e of 20% Zr
3.1X Bi-2212
@ 15 T
2.7X Bi-2212
@ 20 T

Data maintained by Peter Lee, NHMFL, http://fs.magnet.fsu.edu/~lee/plot/plot.htm
UH data on 15%Zr tapes from *APL Materials* **2,** 046111 (2014)

Addressing consistency in in-field performance of HTS tapes

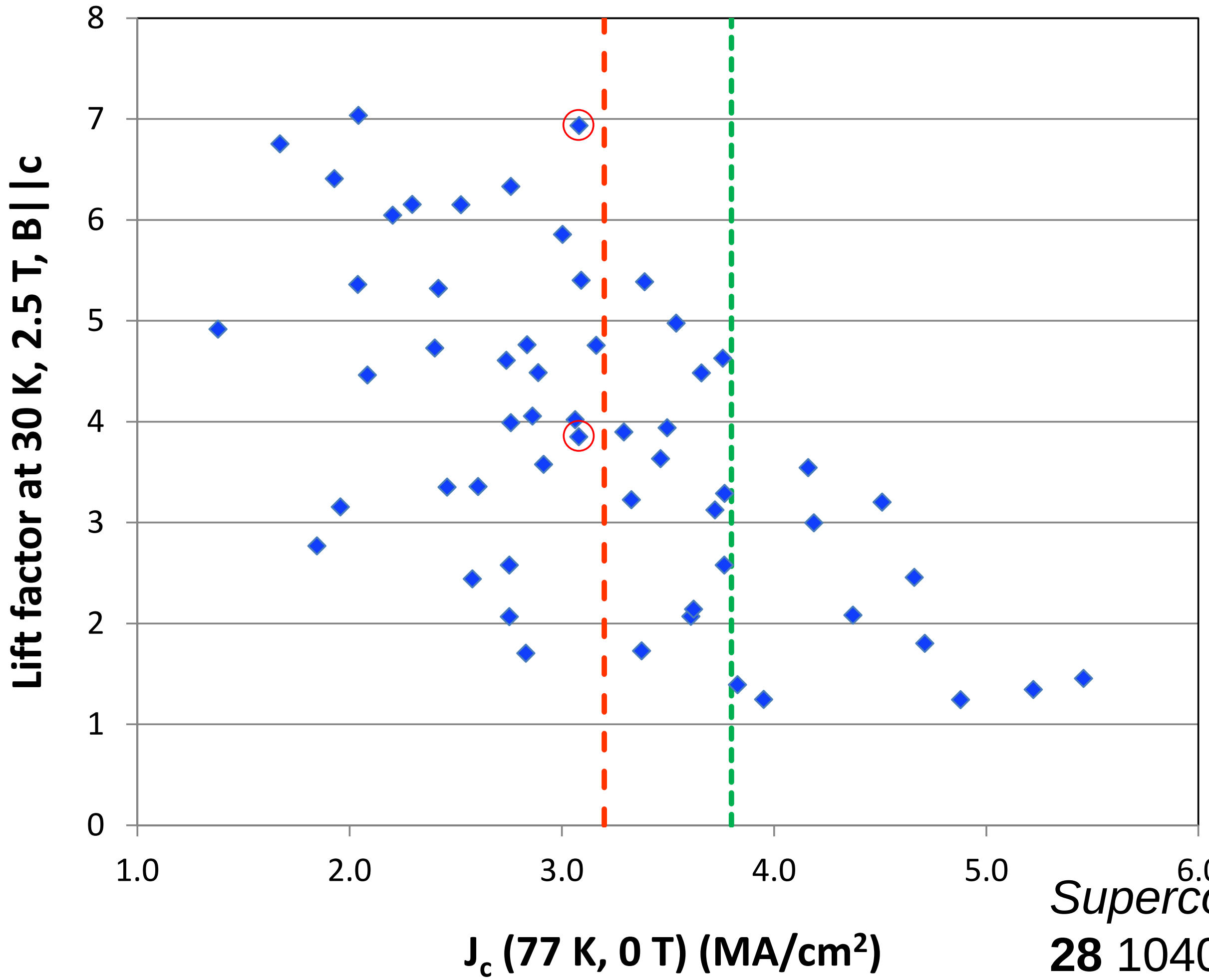
Manufacturing Challenge: Wide scatter in I_c in high fields at lower temperatures



D. Abraimov et al. NHMFL, reported at WAM-HTS, Hamburg, May 2014

- 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

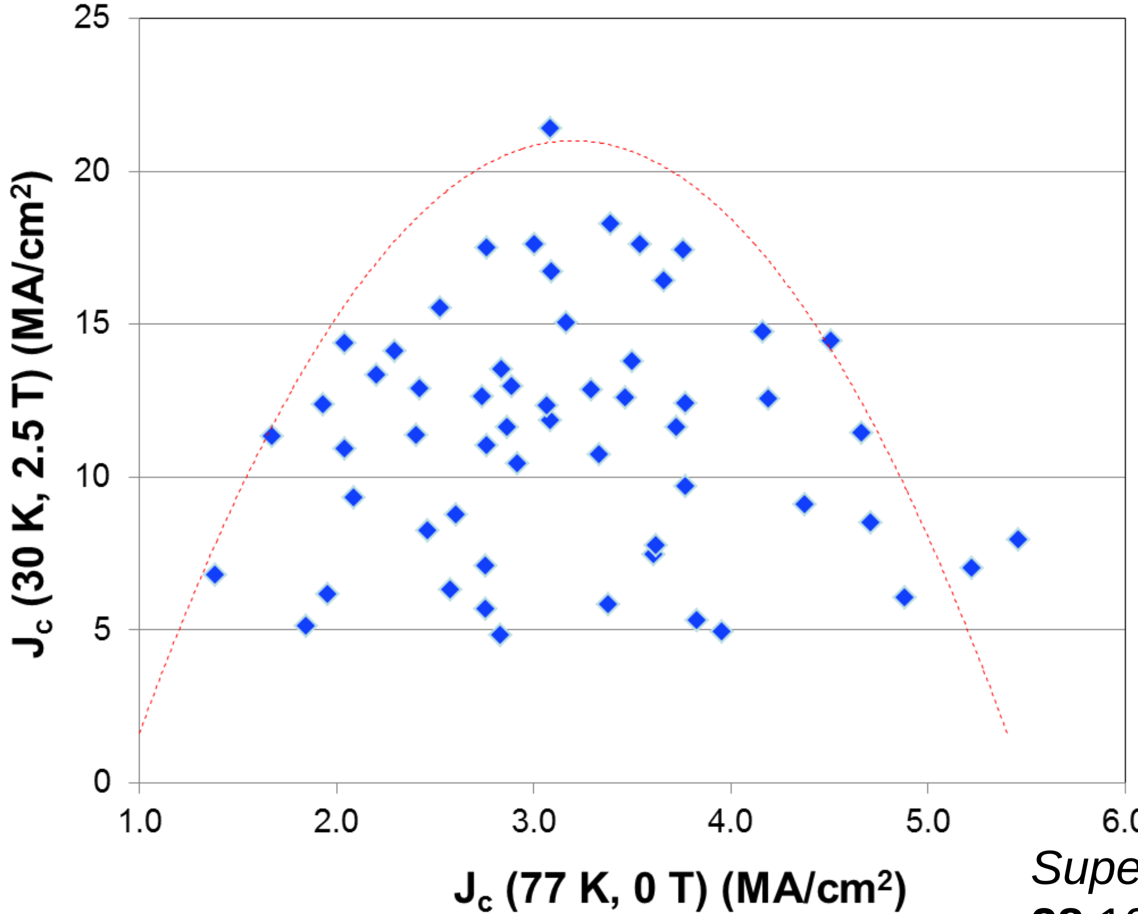
Inverse correlation between J_c at 77 K, 0 T and lift factor at 30 K



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

Jc < 3.2 MA/cm^2 at 77 K, 0 T needed for lift factor above 6 at 30 K, 2.5 T

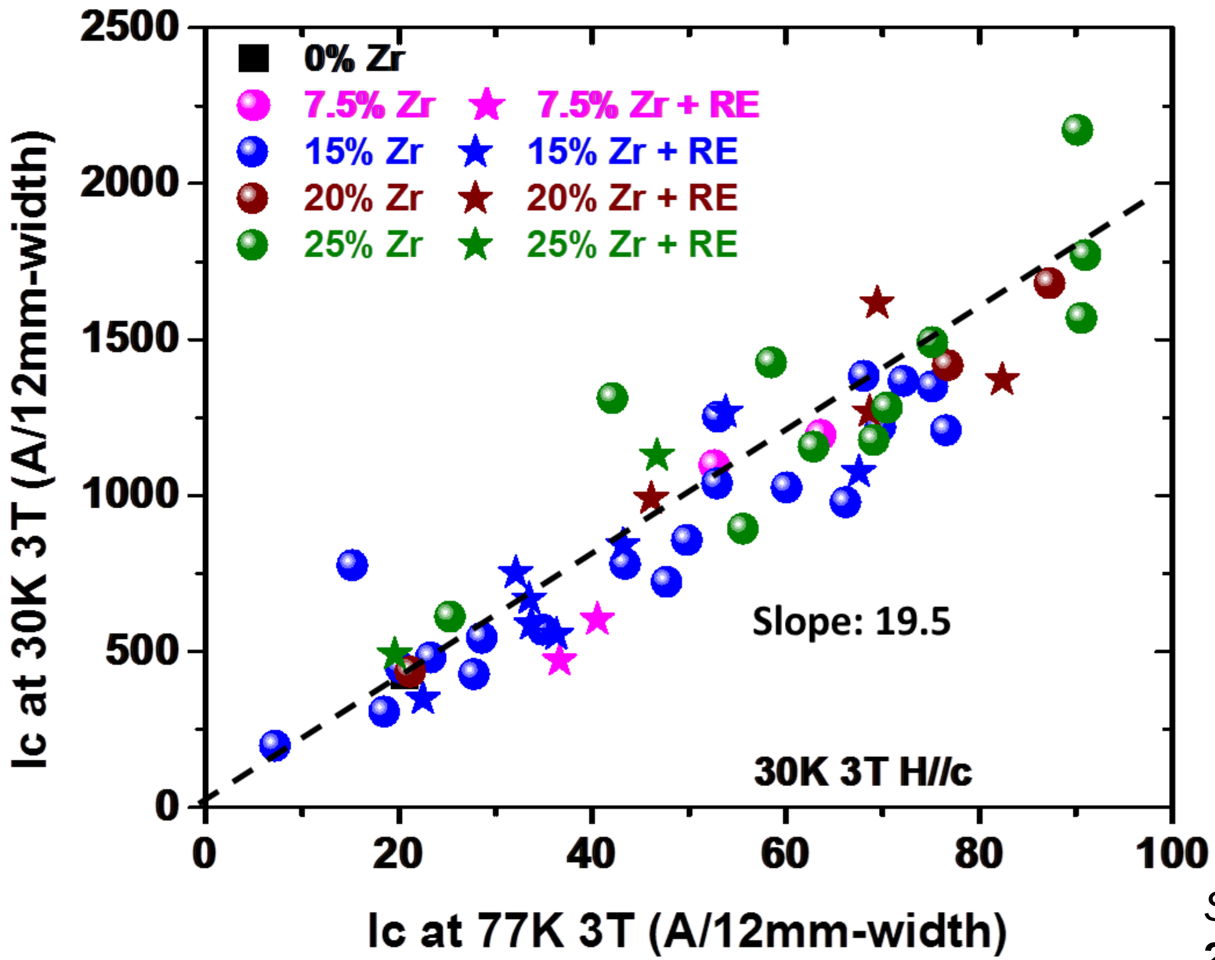
Optimal window of J_c at 77 K, 0 T for high J_c (> 15 MA/cm^2 at 30 K, 2.5 T)



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

Jc at 77 K, 0 T needs to be between 2.4 and 3.8 MA/cm^2 at 77 K, 0 T for Jc > 15 MA/cm^2 at 30 K, 2.5 T

Good correlation between I_c at 77 K, 3 T at in-field I_c at 30 K

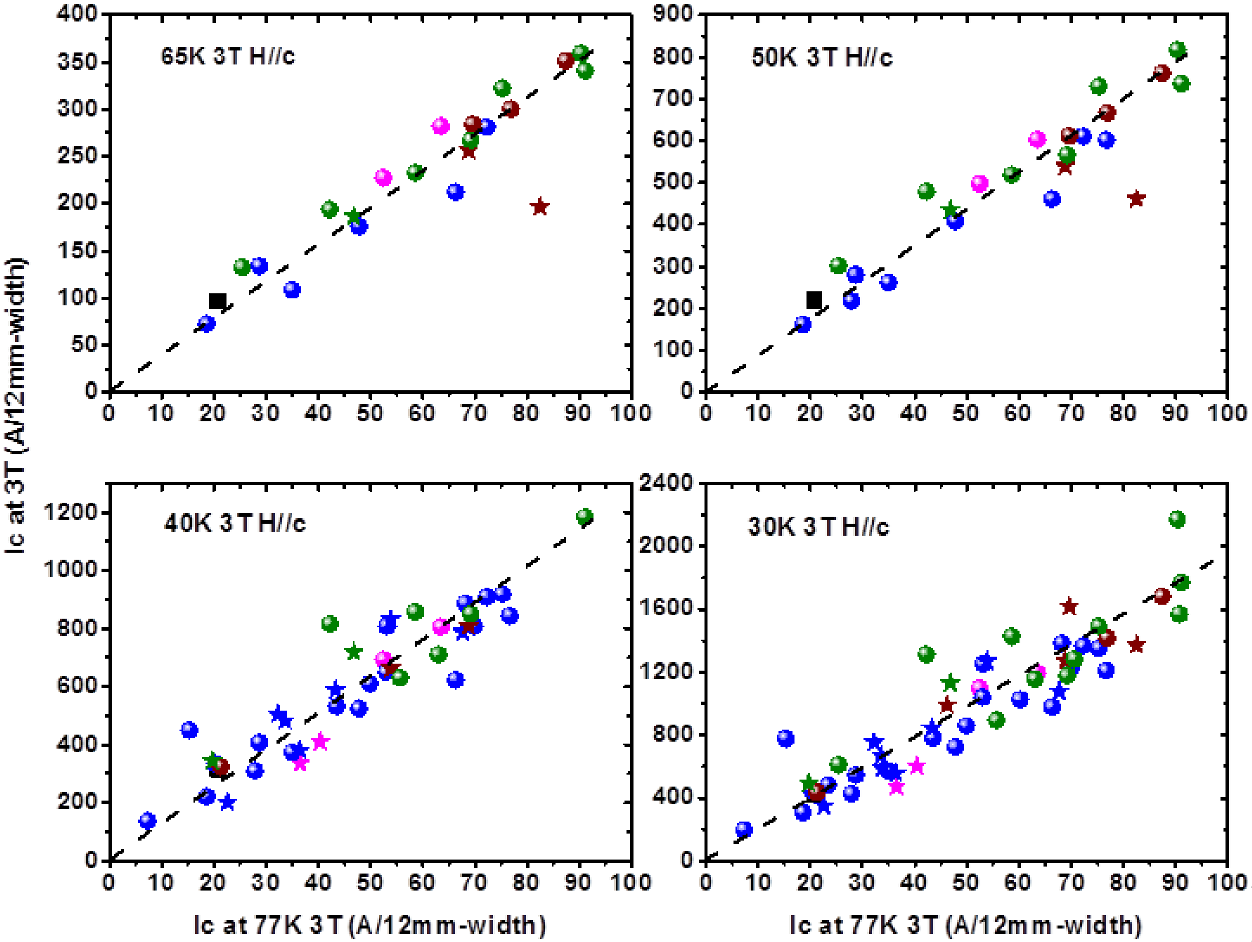


Typical film Thickness = 0.9µm

Supercond. Sci. Technol. **28** 082001(2015)

I_c at 77 K, 3 T at B||c is good predictor of I_c at 30 K, 3 T at B||c

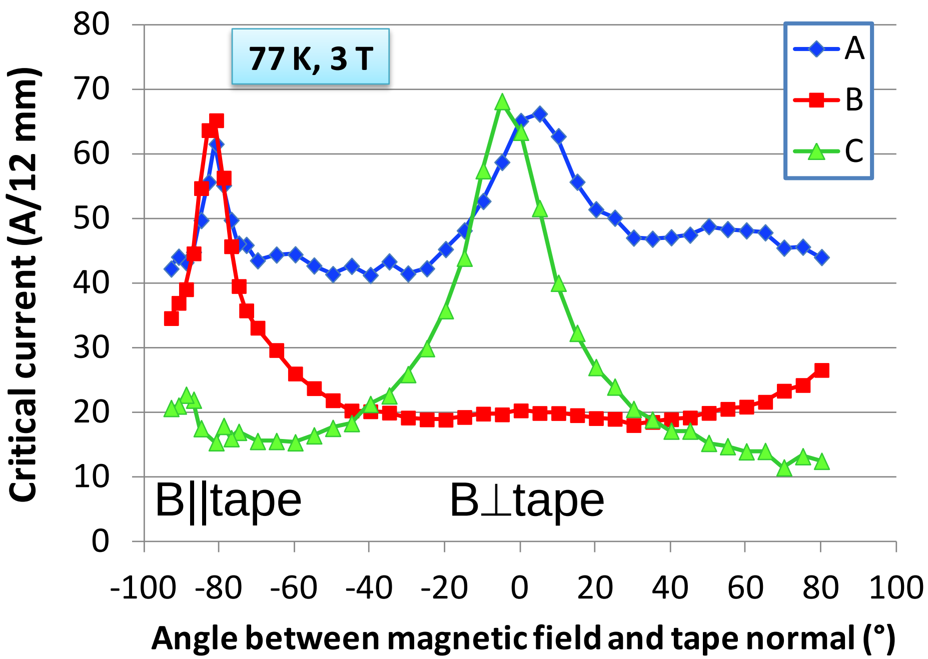
Good correlation between I_c at 77 K, 3 T and in-field I_c at 30, 40, 50 and 65 K

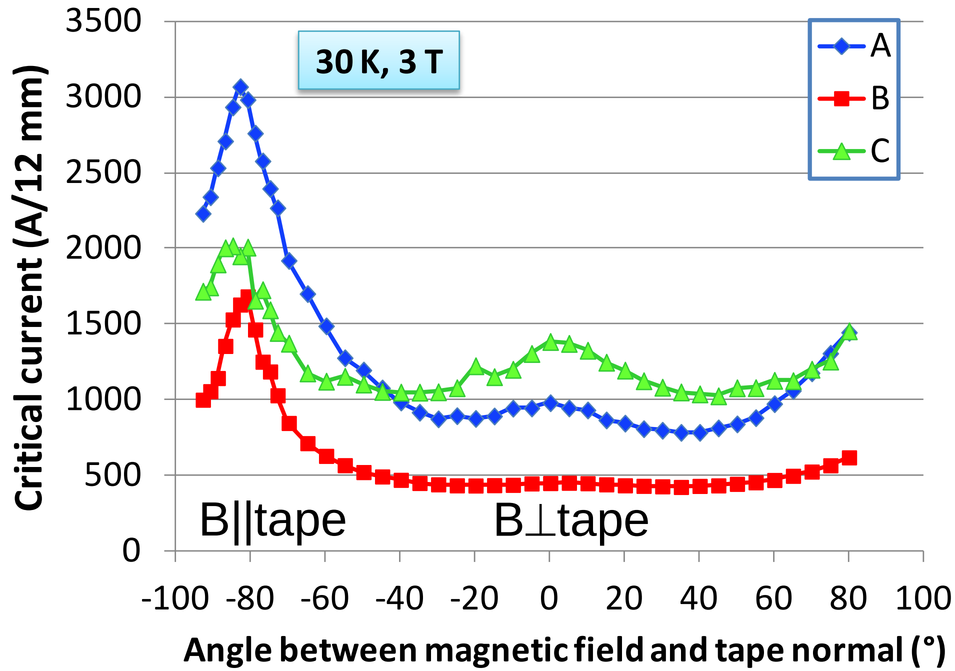


Supercond. Sci. Technol. **28** 082001(2015)

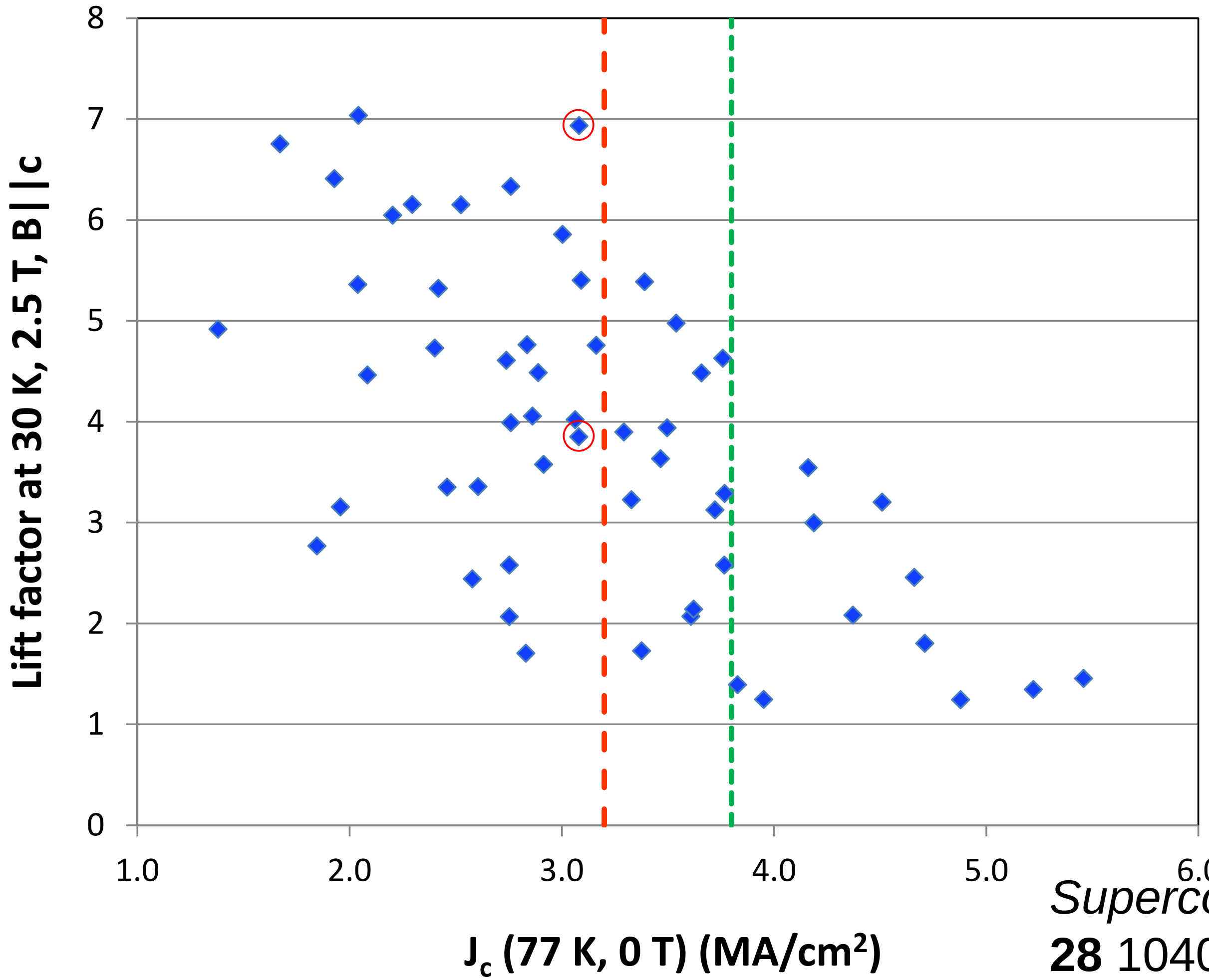
Critical current measurements at 77 K, 3 T is a good Quality Assurance metric for in-field performance at lower temperatures

Discovered that angular dependence characteristics at 77 K, 3 T are predictors of performance at 30K, 3T



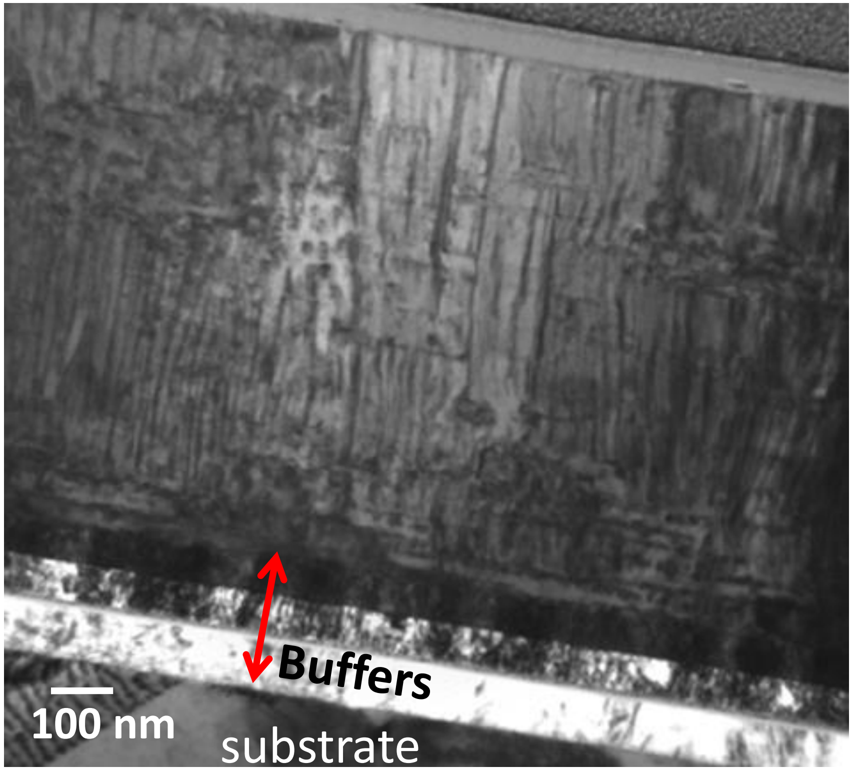


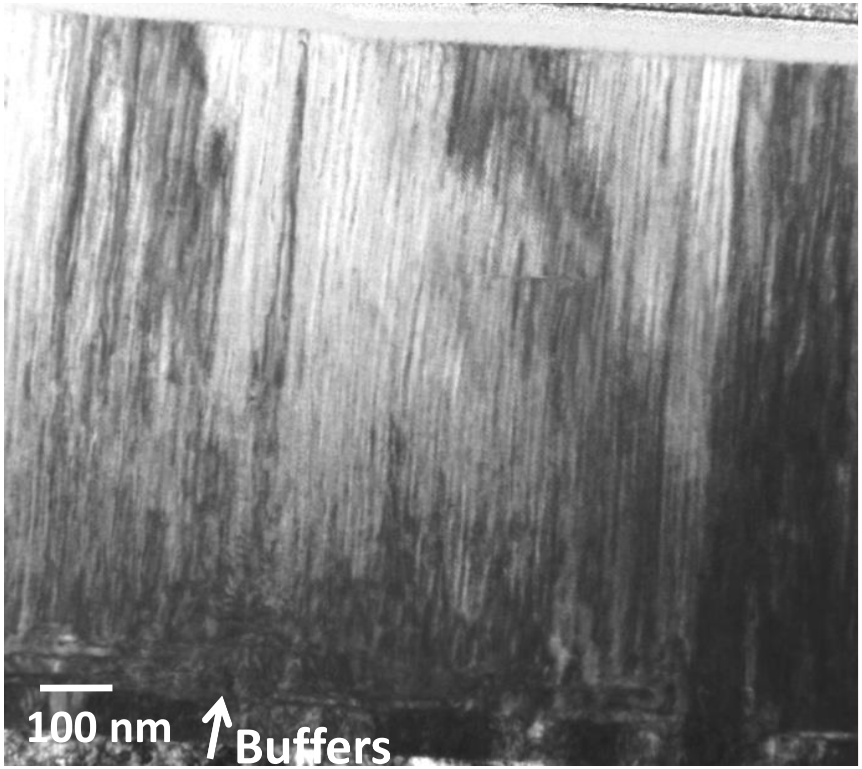
What is reason for scatter in in-field Ic at 30 K?



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

Continuous-aligned nanocolumns essential for high in-field J_c

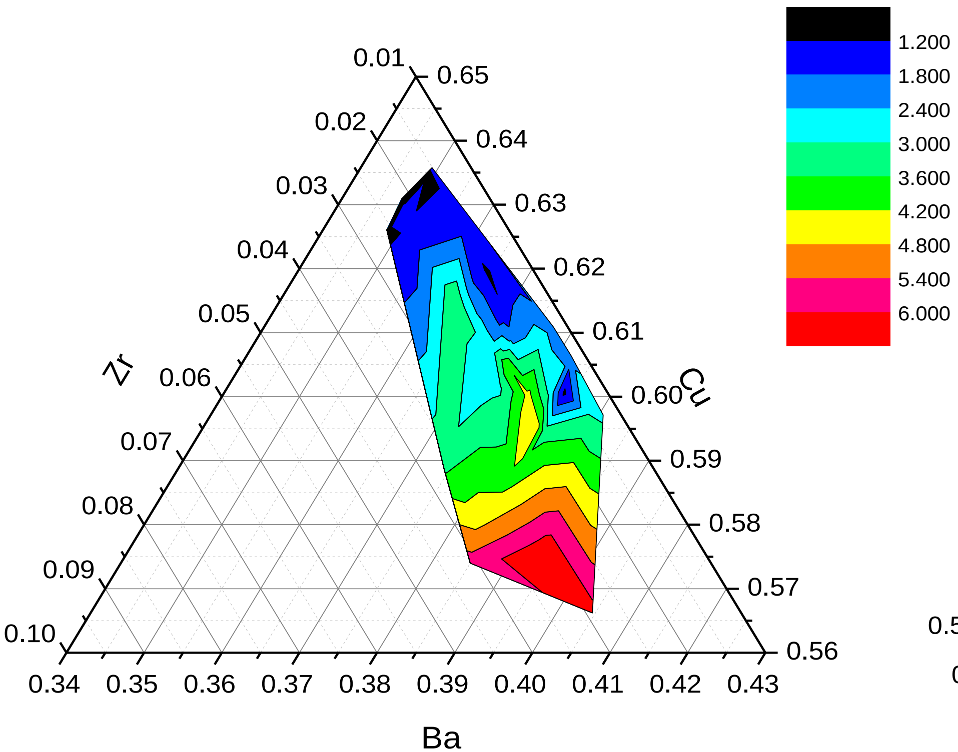




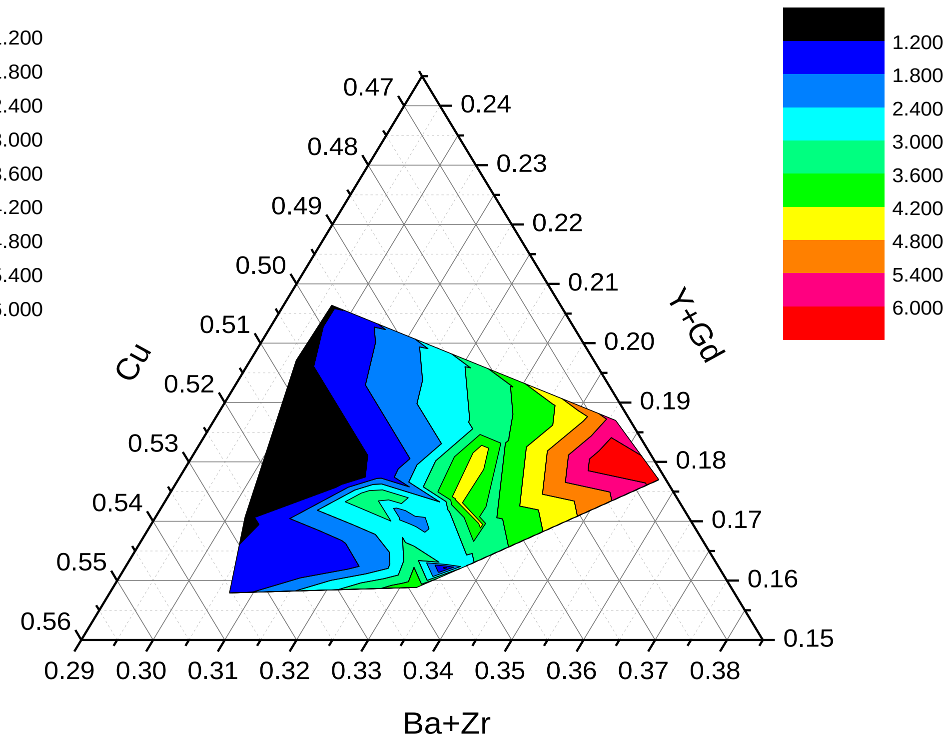
J_c (77 K, 0 T) = 3.08 MA/cm^2
(Ba+Zr)/Cu = 0.675
Lift factor @ 30 K, 2.5 T = 3.85
J_c (30 K, 2.5 T) = 11.86 MA/cm^2

J_c (77 K, 0 T) = 3.08 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

Compositional control important for achieving high lift factor at 30 K, 3 T



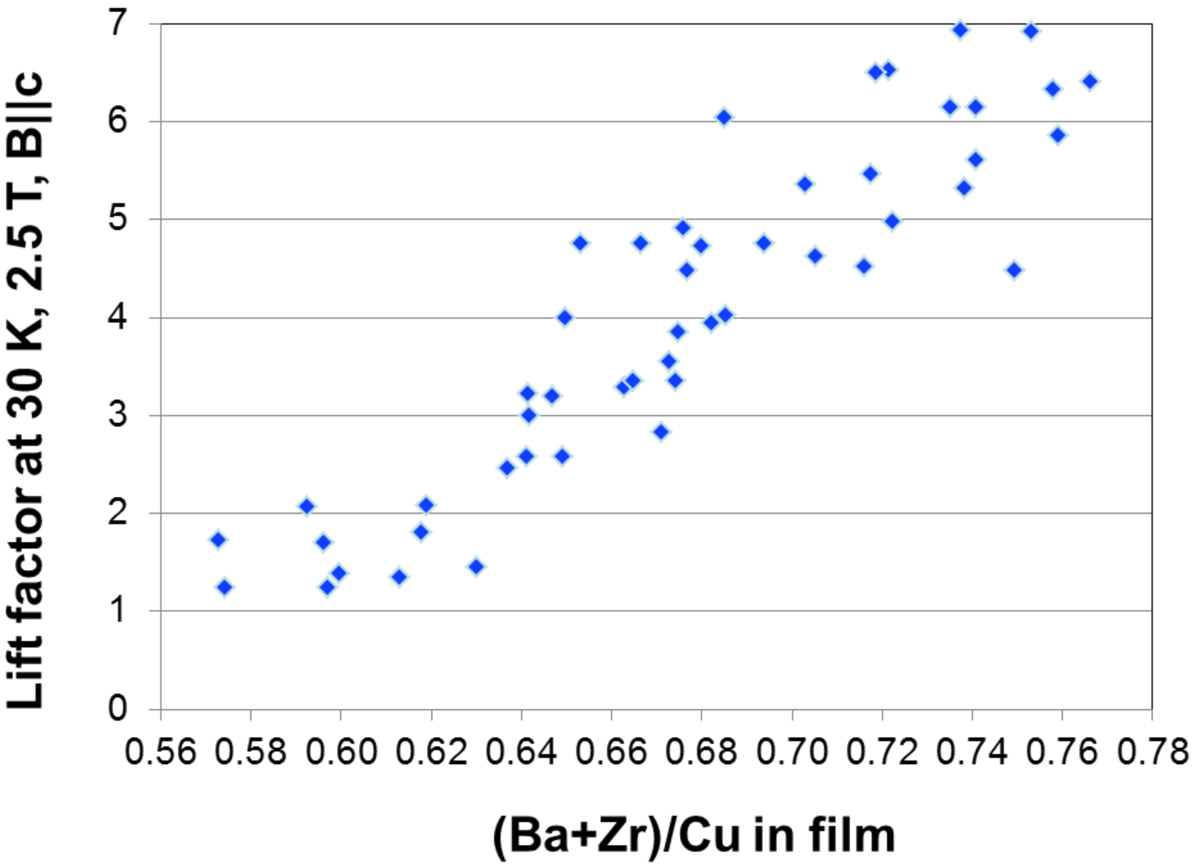
Appl. Phys. Lett. **106**, 032601 (2015)



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

Need to control the film composition within the optimum window consistently from run to run and uniformly over long run

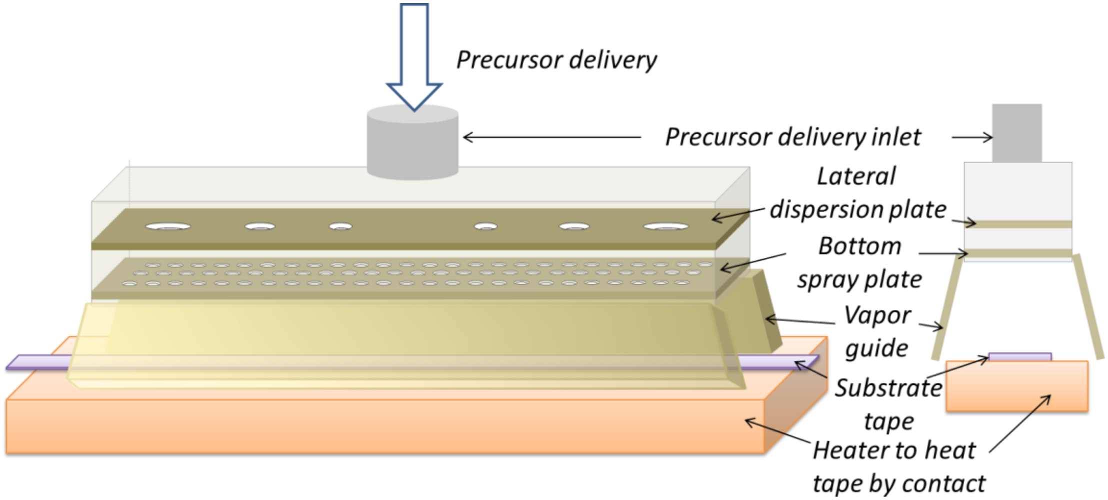
Compositional control important for achieving high lift factor at 30 K, 3 T

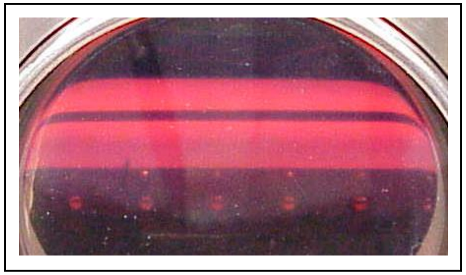


Supercond. Sci. Technol. **28** 104003 (2015)

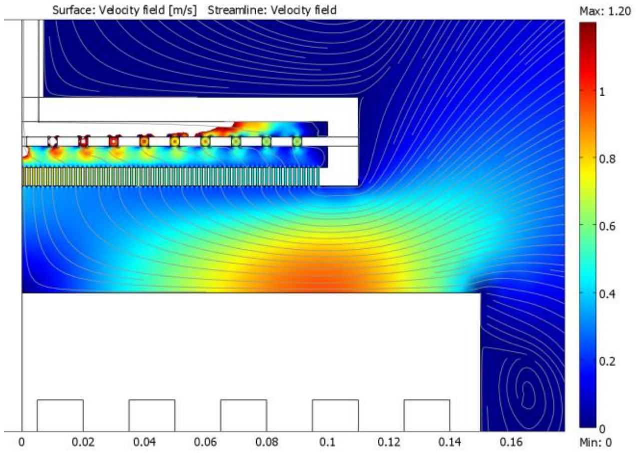
Need to control the film composition within the optimum window consistently from run to run and uniformly over long run

Deficiencies of conventional MOCVD reactor: Challenge in fine-scale composition control





Contact heating in conventional MOCVD



- Temperature control of tape is critical to control film composition in a narrow range for high in-field I_c, but tape temperature is not directly monitored or controlled in all existing MOCVD systems
- Apart from uniform heating, precursor flow non uniformities cause non uniform temperatures

Existing MOCVD system design is not suitable for needed level of temperature control for consistent composition that is critical for uniform in-field I_c

Deficiencies of existing MOCVD reactor: Precursor waste and capacity limitation

- MOCVD precursor cost is 25% of total wire cost and is the one that will increase with increasing wire amperage
- Precursor material conversion efficiency of today's MOCVD process is only 15% which is limited by equipment
- Another limitation is in decomposition of –thd ligands at the growth interface

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

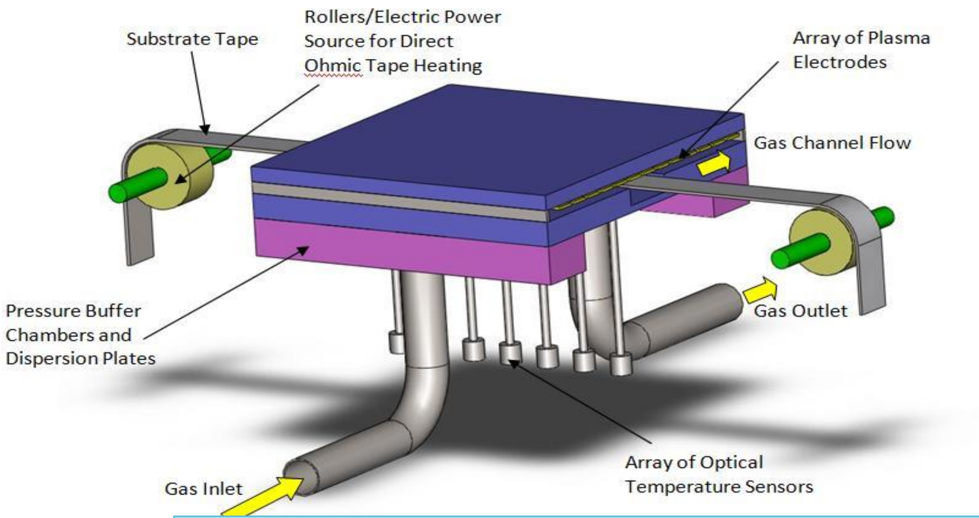
thd = (2,2,6,6-tetramethyl-3,5-heptanedionate) = $OCC(CH_3)_3CHCOC(CH_3)_3$

- Now, only thermal activation to break down the large –thd ligands at the growth interface. Not sufficient.

Tripling precursor to film conversion efficiency would reduce HTS materials cost 3x, decrease process time by 3x, and triple capacity

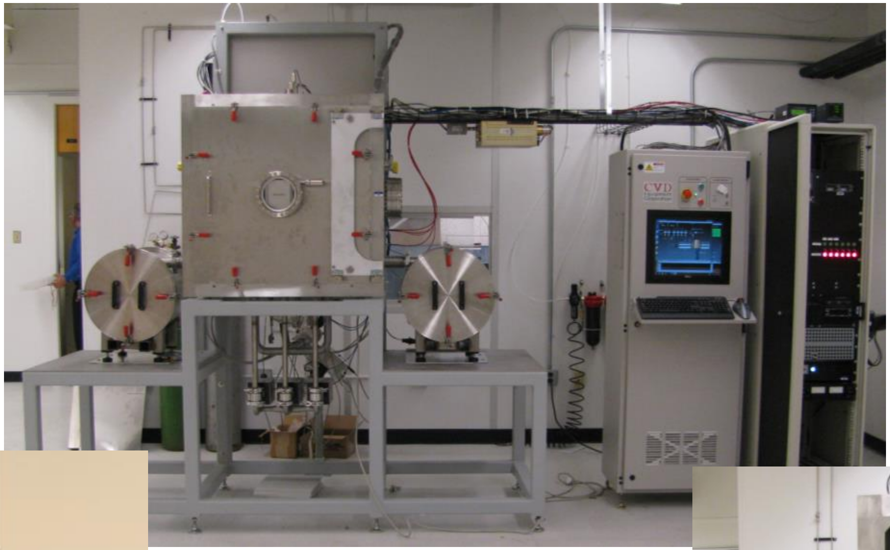
New Advanced MOCVD tool for better control of process variables

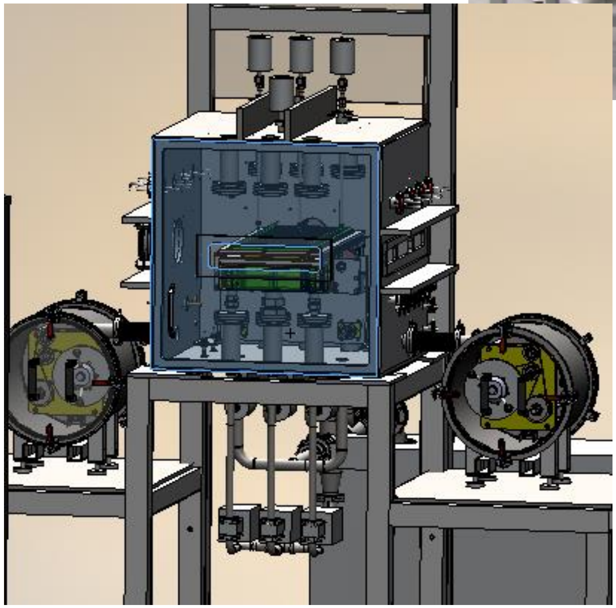
- New reactor to address all deficiencies of current production tools designs
  - Derived from modeling
  - Low volume, laminar flow design for uniform temperature, flow, higher conversion efficiency of precursor to film
  - Direct tape heating, direct tape temperature monitoring
  - Stable precursor delivery system
  - Plasma enhancement for enhanced reaction kinetics

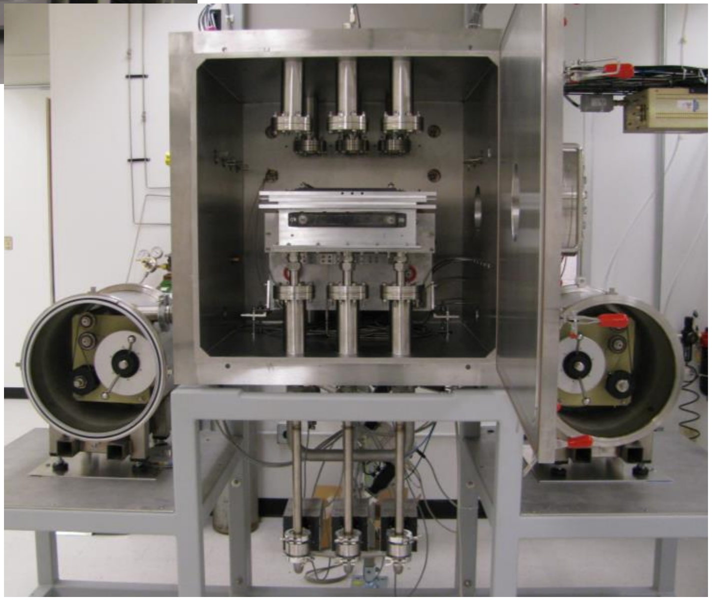


Several new innovative designs implemented in new MOCVD design derived from modeling

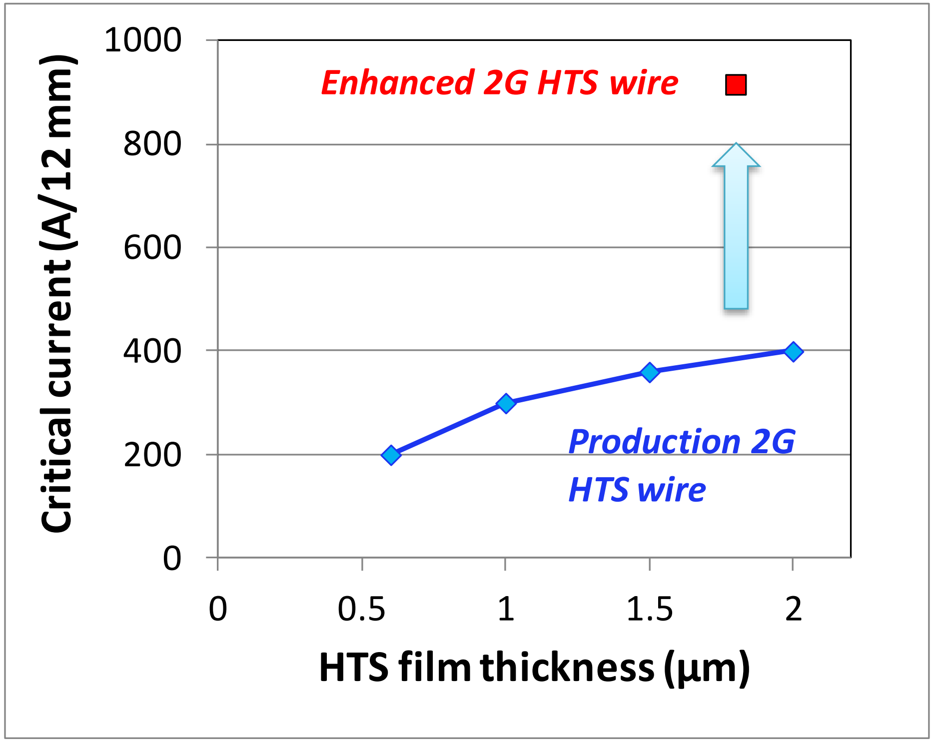
Advanced MOCVD system with completely new reactor design constructed and tested

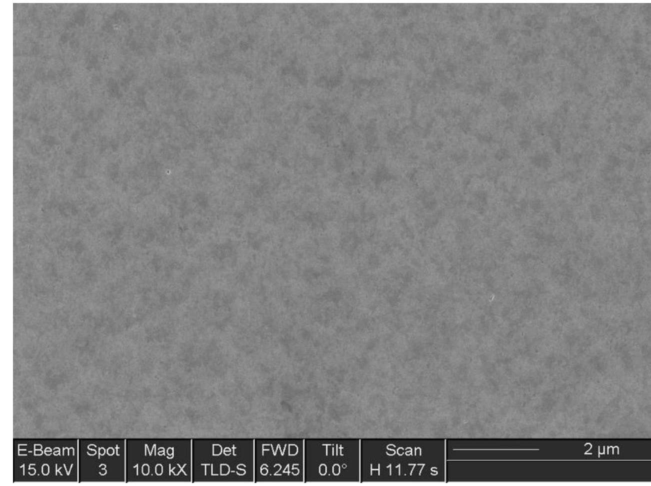




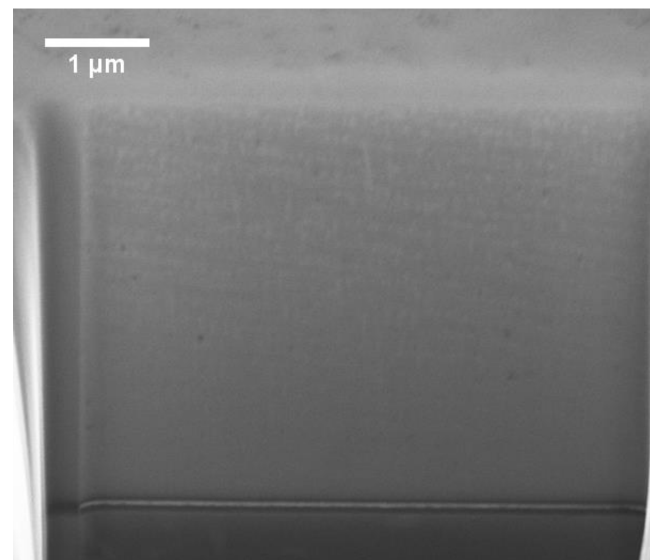


2.4X higher wire performance, 40% improved growth rate with Advanced MOCVD reactor





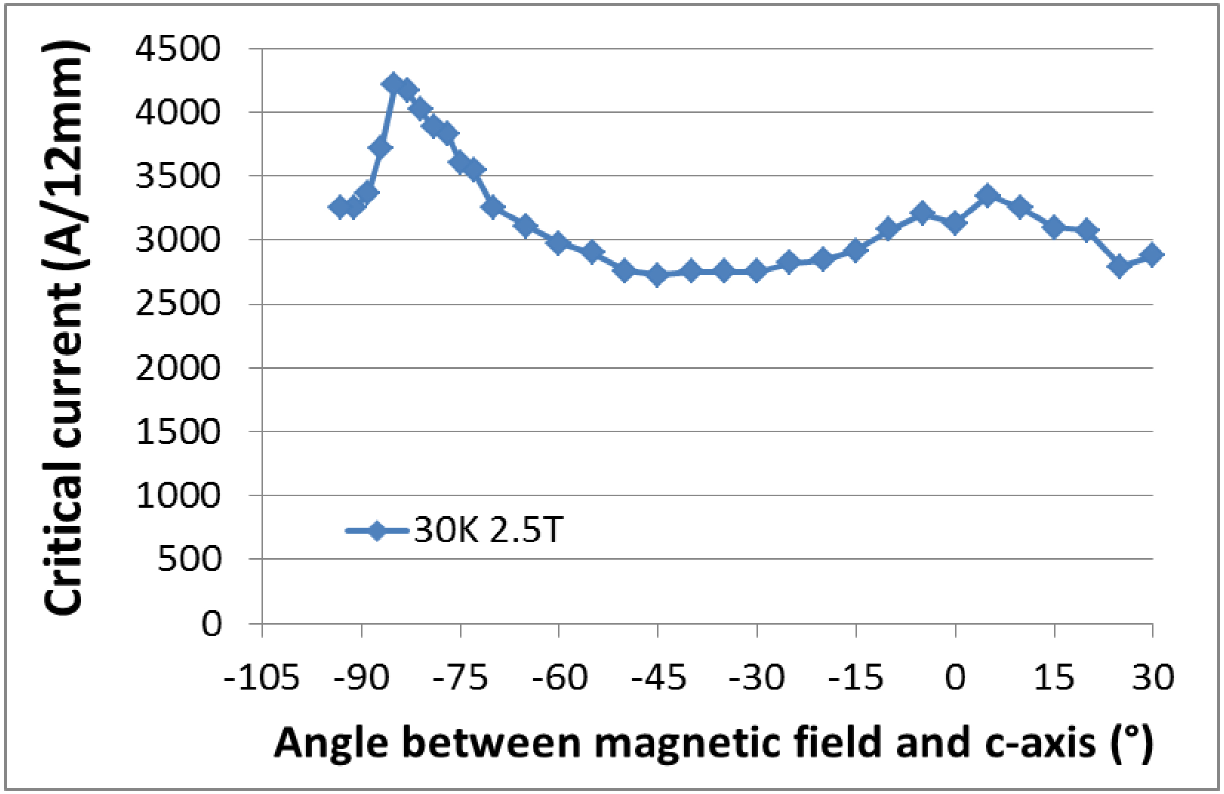
2 µm thick film – Enhanced wire



5 µm thick film – Enhanced wire

- *No a-axis grains even in 5 µm thick films made with Advanced MOCVD reactor*
- *Over 900 A achieved with Advanced MOCVD reactor by improving thick film microstructure*
- *Growth rate increased by 40% by improved flow dynamics*

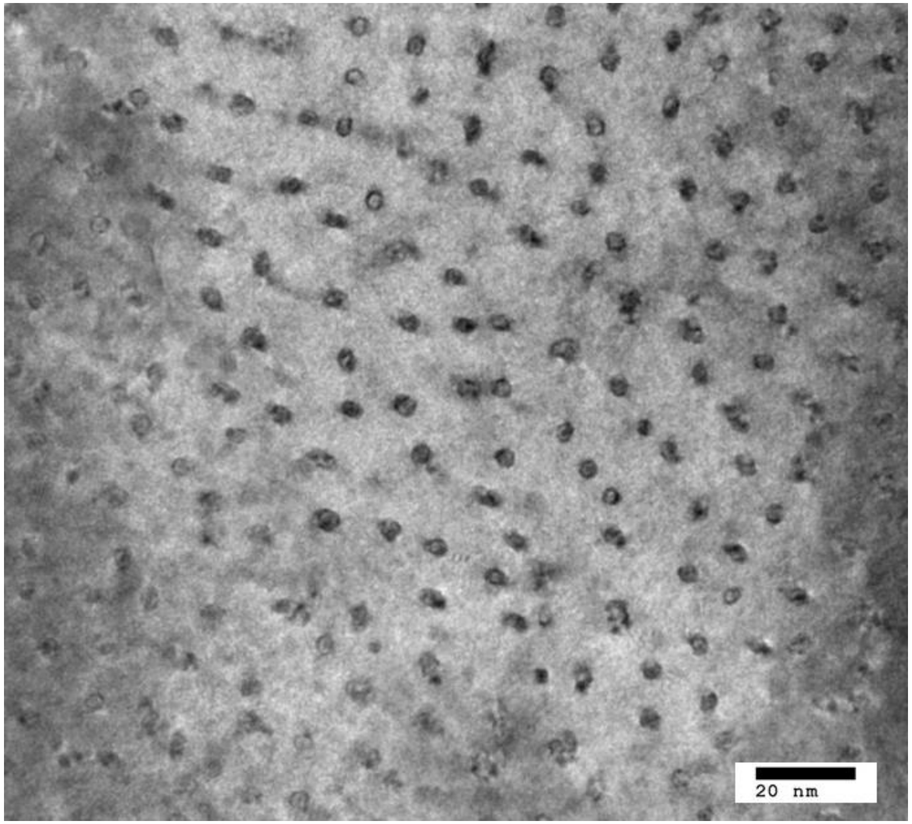
4X Ic achieved in 20% Zr-added tape made in Advanced MOCVD System

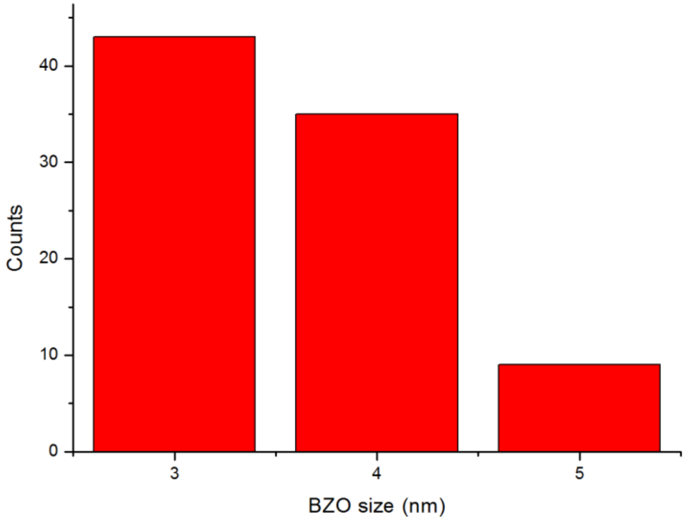


Ic ~ 3346 A/12 mm @ 30 K, 2.5 T, B||c

Lift factor ~ 9 (new record! much higher than the best value of 7 in tapes made in conventional MOCVD system)

Much finer-sized BZO in 20% Zr-added tape made in Advanced MOCVD System with lift factor of 8.5 @ 30 K, 2.5 T





BZO size mostly 3 nm
Spacing 12 nm

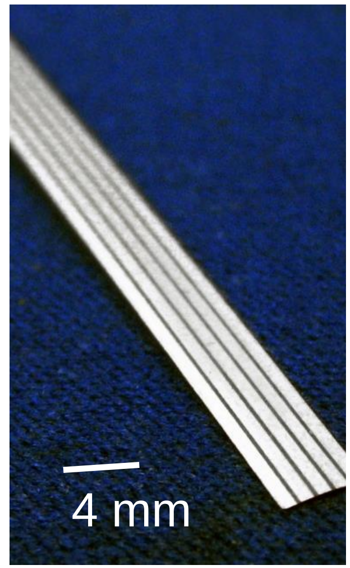
Typical size of BZO in high lift factor tapes made in conventional MOCVD system: 5 – 6 nm

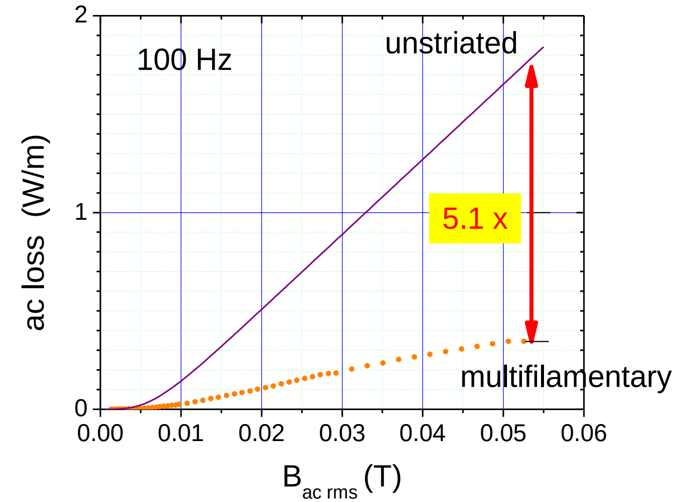
Great opportunities for further improvements in performance of REBCO Coated Conductors through nanoscale defect engineering and thick films

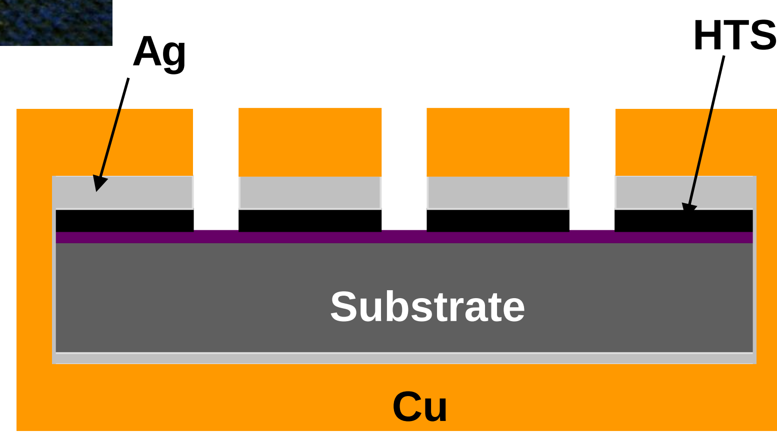
Multfilamentary tapes

Multifilamentary coated conductors for low ac loss applications

- Filamentization of coated conductors is desired for low ac loss applications.
- Maintaining filament integrity uniform over long lengths (no Ic reduction)
- Minimum reduction in non superconducting volume (narrow gap) and fine filaments
- Striated silver and copper stabilizer (minimize coupling losses)

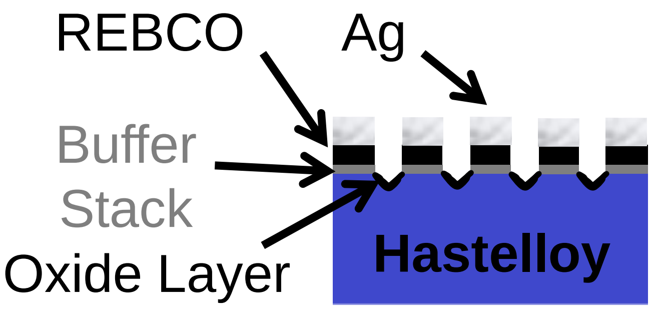


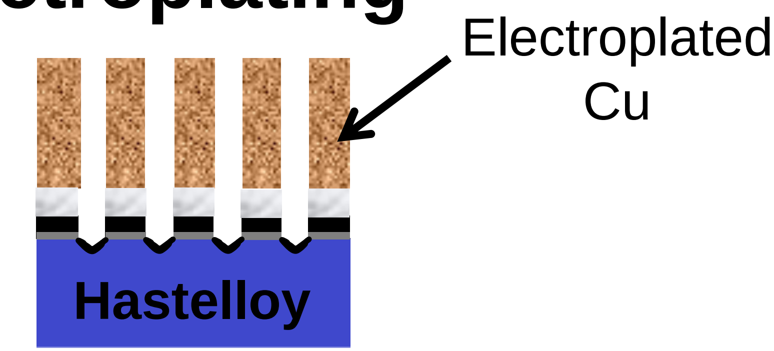




A fully filamentized coated conductor would need to have 20 – 50 µm of copper stabilizer striated !

Fully-filamentized conductor by Laser Striation and Selective Electroplating





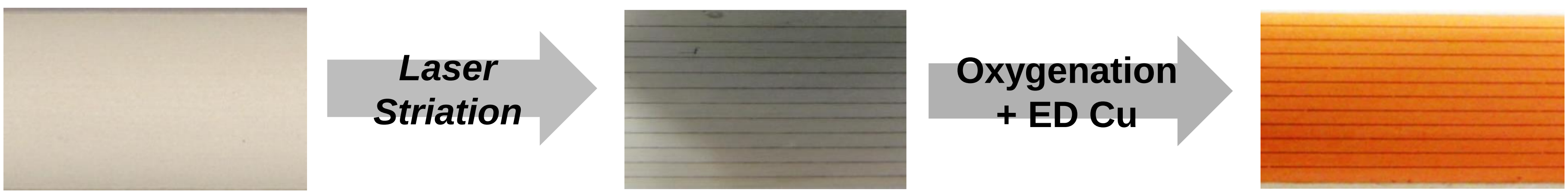
Laser Striation + oxygenation

Selective Cu Electroplating

Non-striated
12 mm wide Ag sputtered tape

12-filament ,
12 mm wide tape

12-filament tape with electroplated Cu

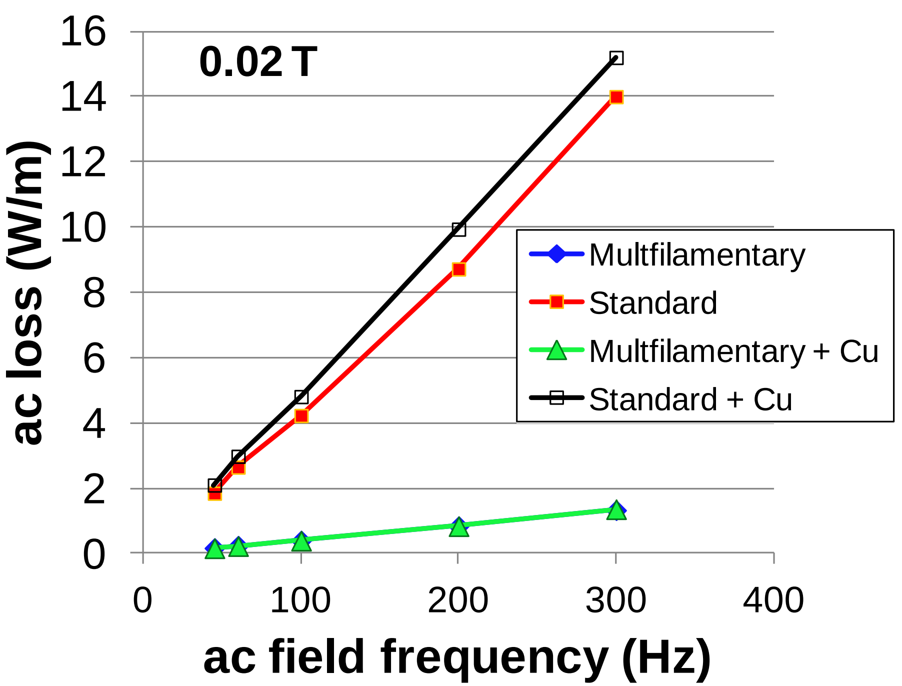


I. Kesgin, G. Majkic, and V. Selvamanickam, “A simple, cost effective top-down method to achieve fully filamentized low AC loss 2G HTS coated conductors” , *Physica C.* **486,** 43–50 (2013)

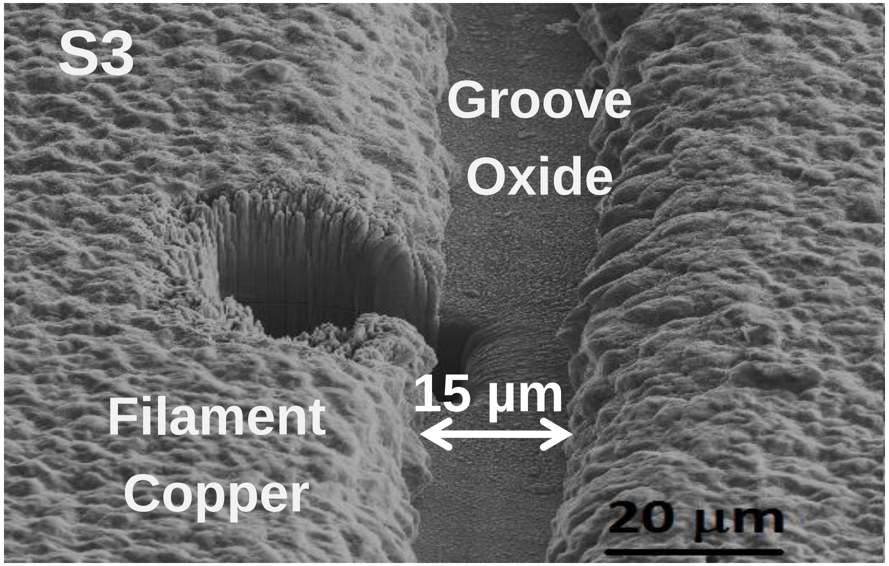
Significant ac loss reduction in full-filamentized conductor with copper stabilizer

- Critical current of standard conductor = 207 A
- Critical current of 12-filament conductor = 197 A
- Critical current of 12-filament conductor after 10 μm copper stabilizer = 200 A

*AC loss of 12-fiament conductor at 60 Hz is **11 times** lower than that of unstriated conductor without copper stabilizer and **13 times** lower with copper stabilizer, at higher fields*

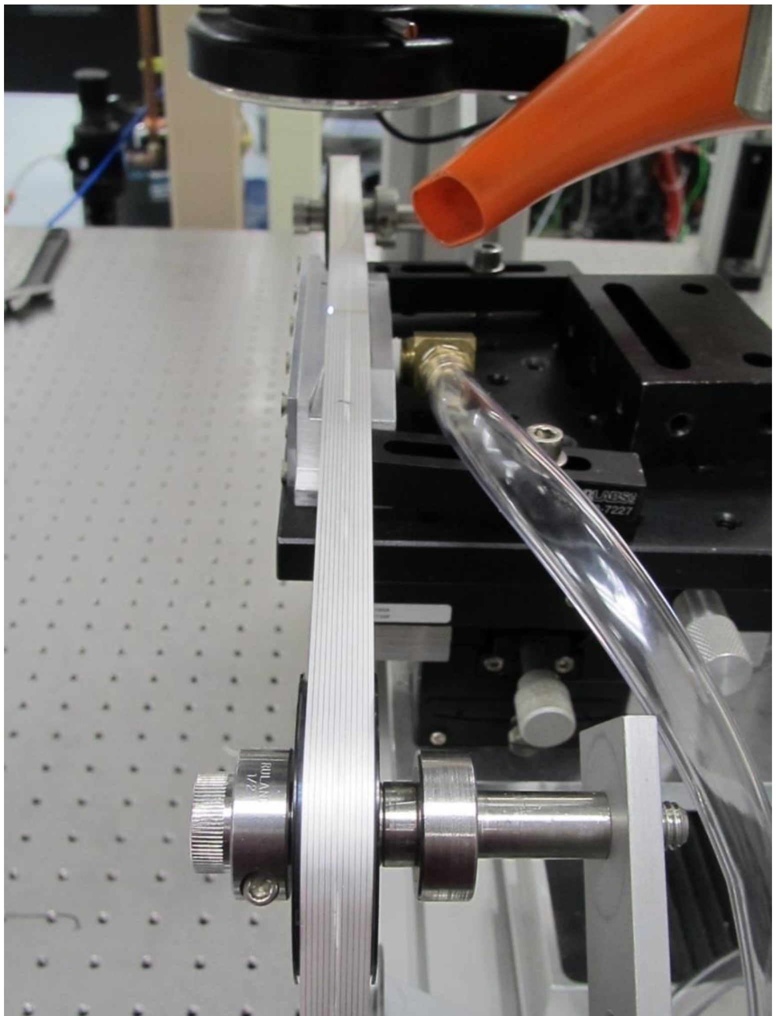


Fully filamentized wire with fully decoupled filaments made with even 30 µm thick stabilizer



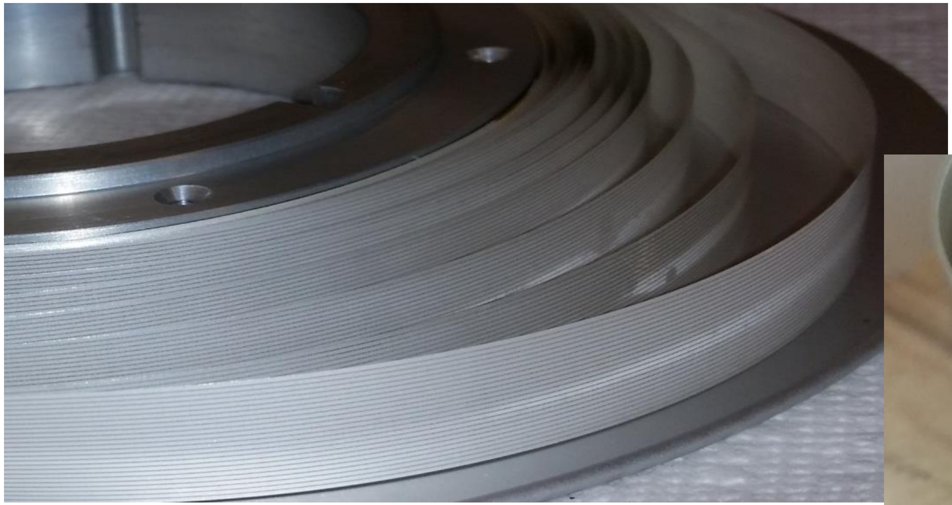
No coupling
Mechanically scribed, oxidized and Cu plated **(~ 30 µm)**

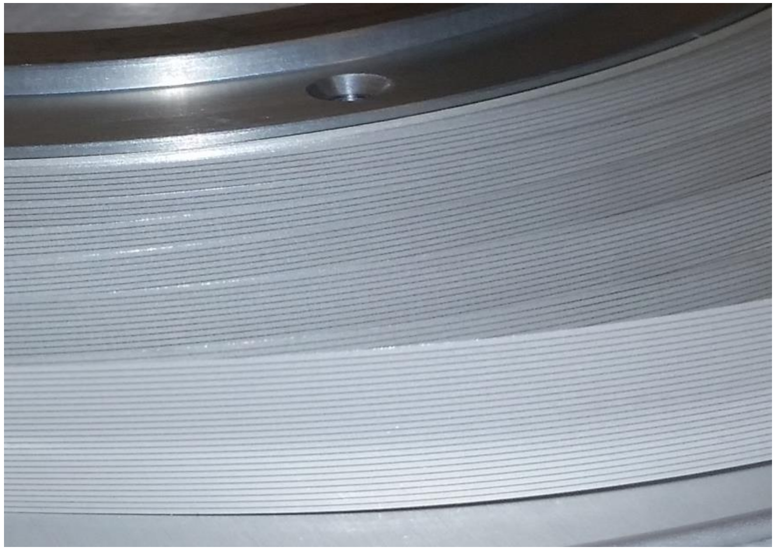
Long-length fabrication of multifilamentary coated conductors



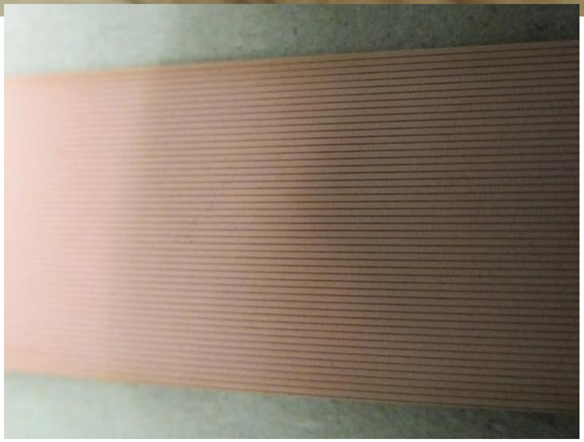
Higher filament count coated conductors

24-filament conductor

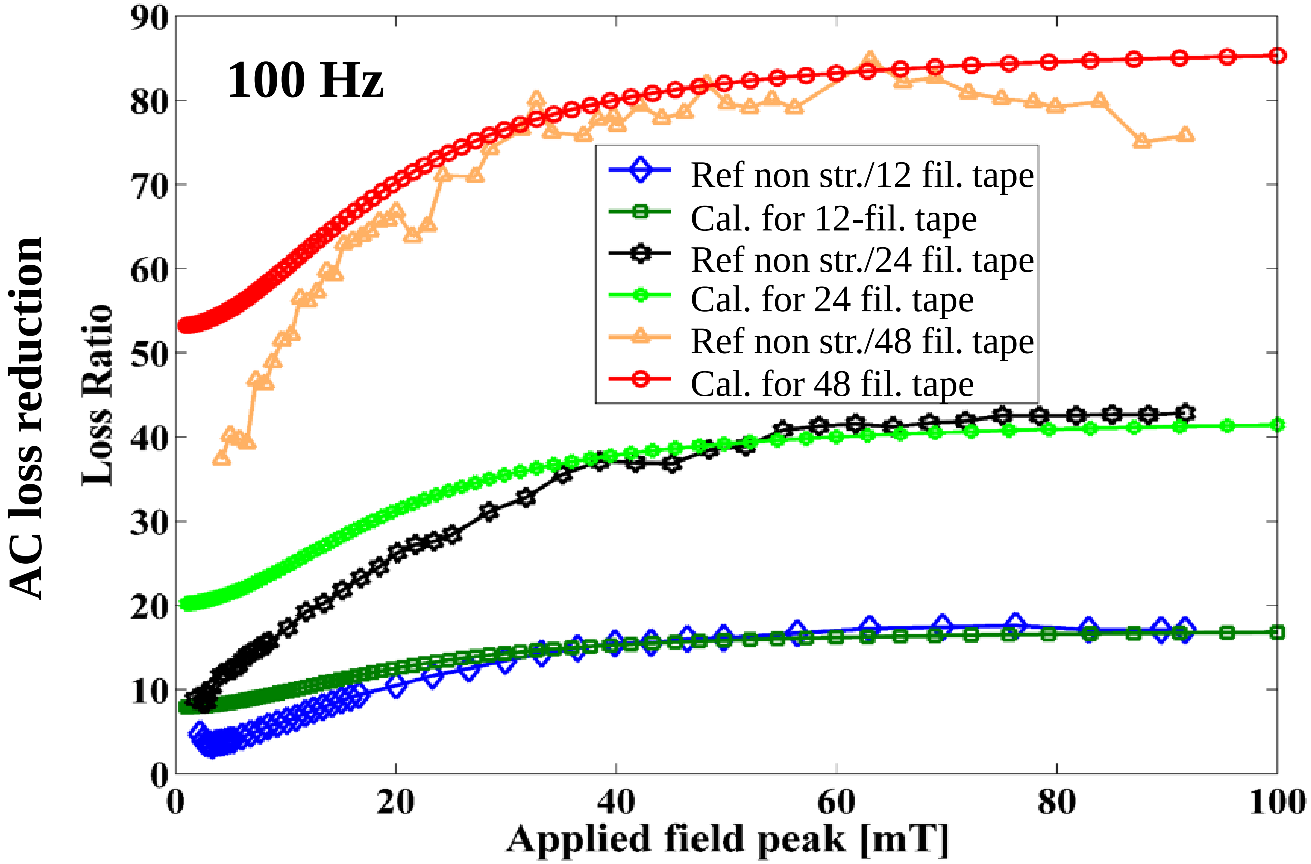




48-filament conductor



Significant ac loss reduction with multifilamentary coated conductors



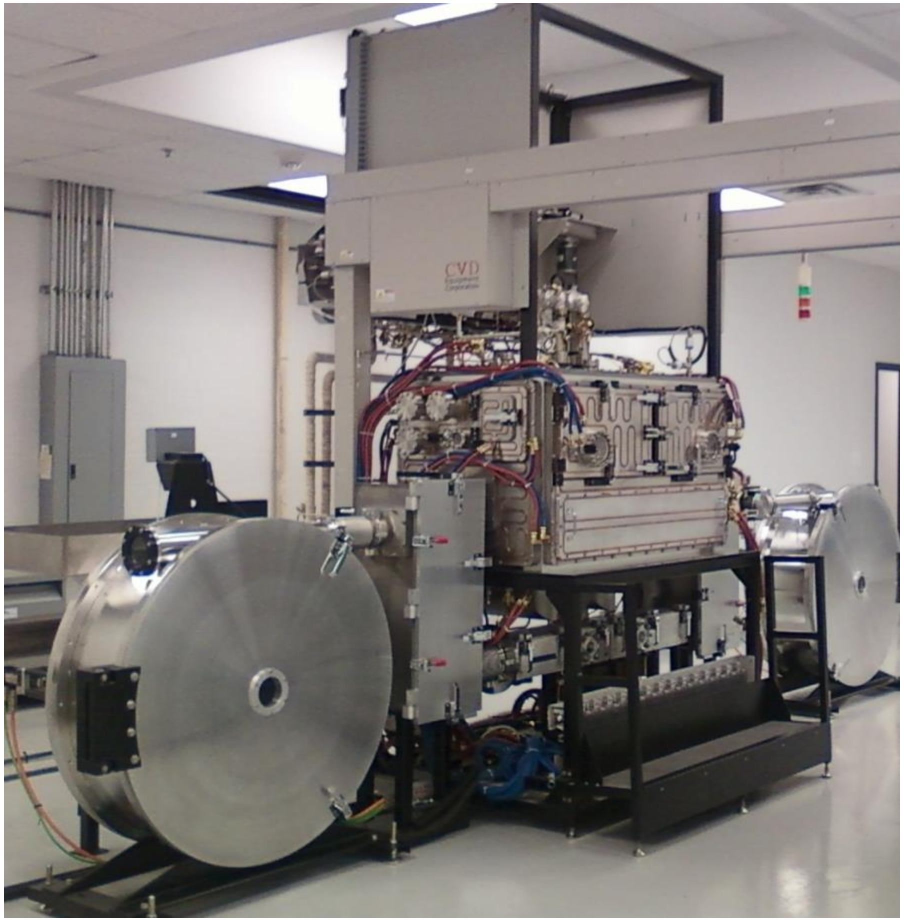
I. Kesgin, G. Levin, T. Haugan and V. Selvamanickam, "Multifilament, copper-stabilized superconductor tapes with low alternating current loss" *Appl. Phys. Lett.* **103,** 252603 (2013)

These are the highest reported values of AC loss reduction in coated conductors fabricated with a thick copper stabilizer.

Manufacturing scale up of improved HTS tape technologies

UH Energy Research Park operation to accelerate technology transfer and manufacturing innovation

- Pilot Superconductor Manufacturing facility established in 2012 at the UH Energy Research Park operation begun to transfer technologies developed at UH to manufacturing, conduct manufacturing research, construct and test HTS devices.
- New pilot-scale MOCVD system procured through $3.5 M award from the state's Emerging Technology Fund.
- UH plans to provide its partners prototype quantities of long tapes (tens of meters) with the latest advances



Rapid transfer of technology advances to manufacturing to accelerate commercialization of HTS for energy and other applications

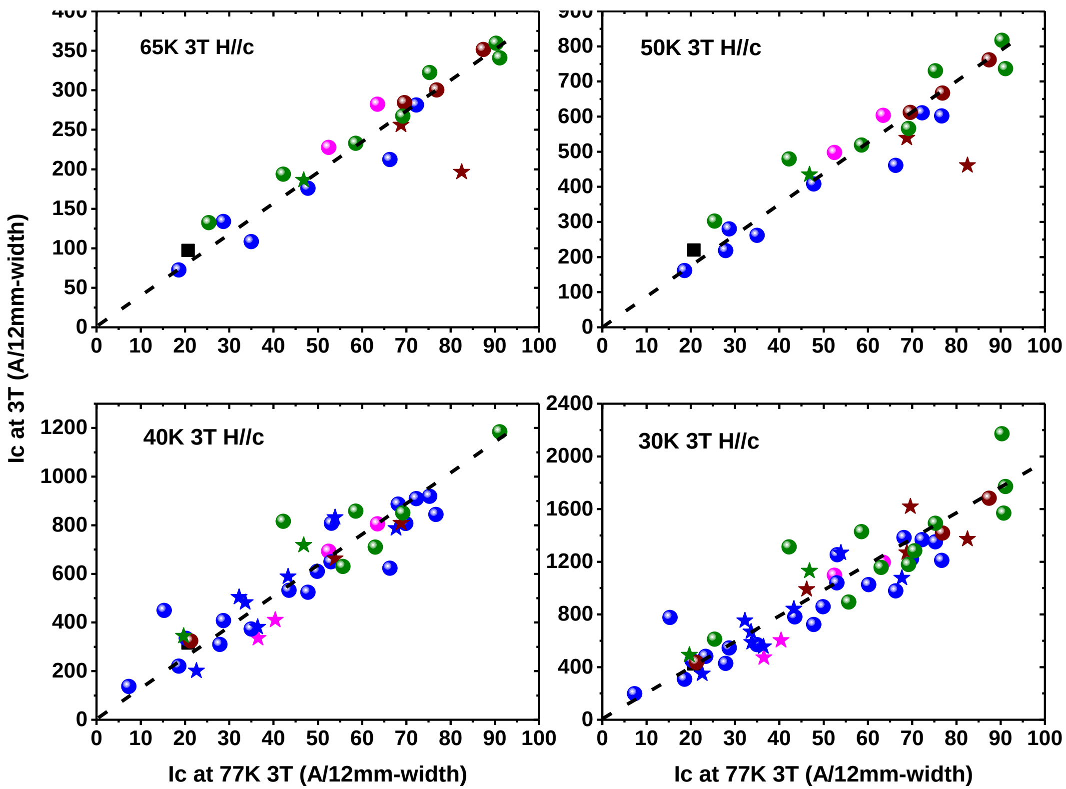
UNIVERSITY of HOUSTON

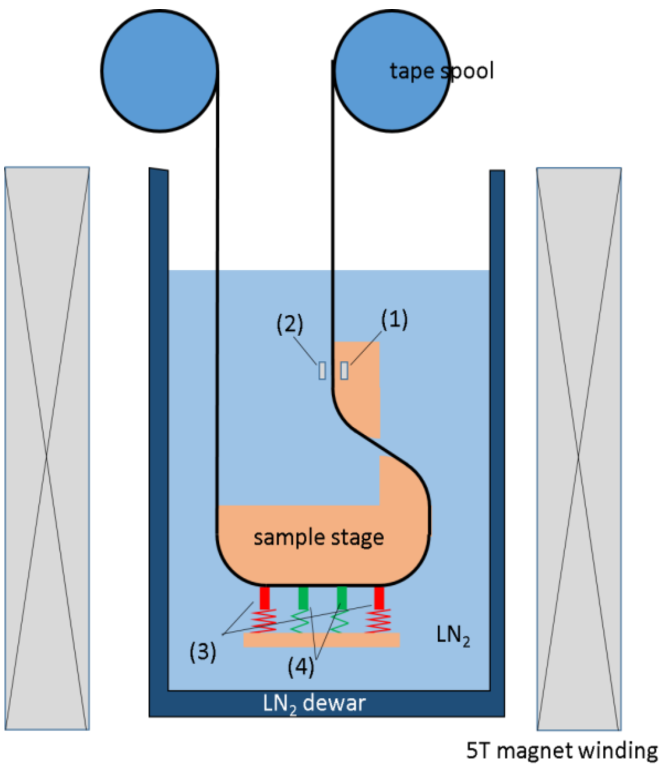
TcSUH

ERP facility: Test bed for new QA/QC tools, process control tools for manufacturing

Reel-to-reel, in-field critical current measurement system:

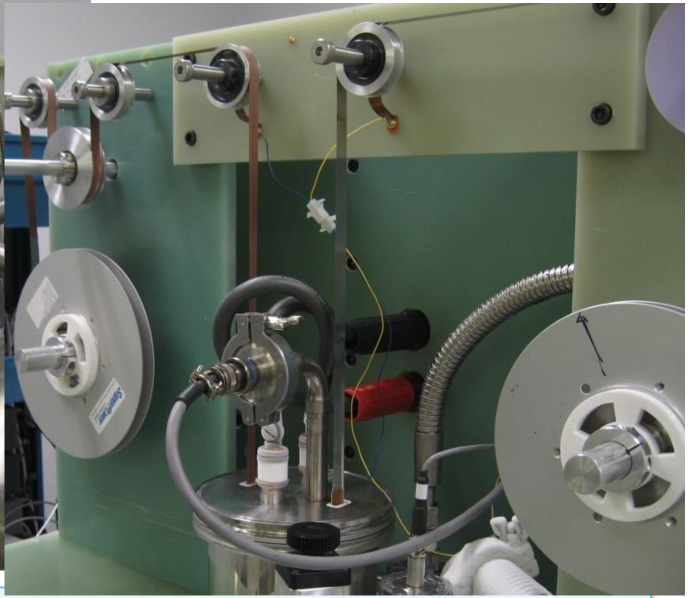
- Good correlation between Ic at 77 K, 3 T at Ic at high fields, low temp
- We have designed, built and commissioned a reel-to-reel in-field Ic measurement system with a 150 mm bore, 5 T magnet





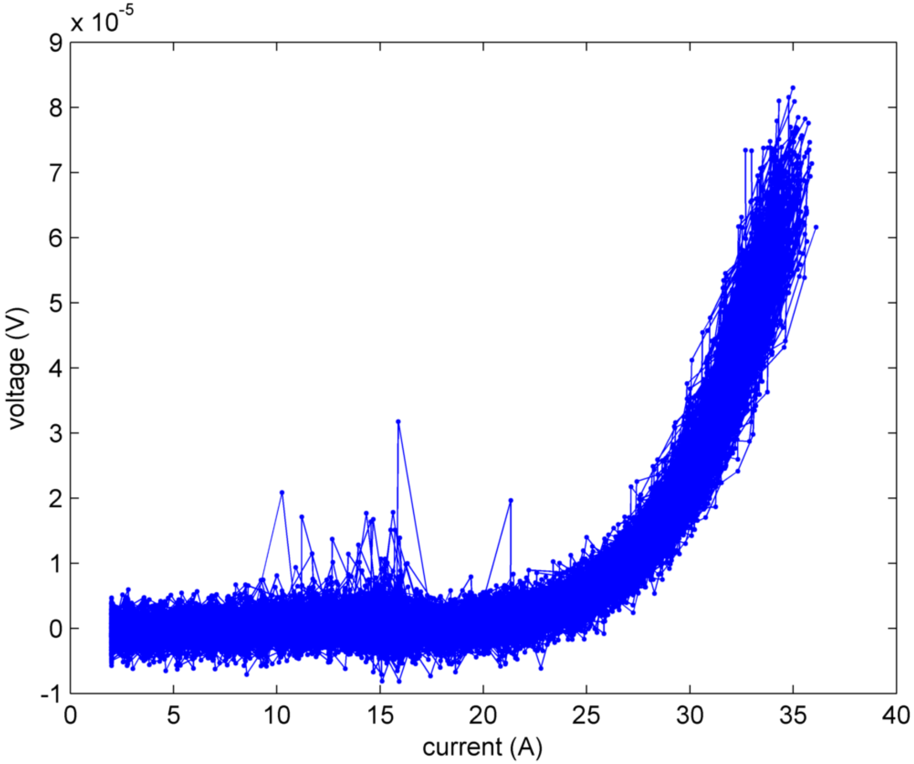
Reel-to-reel testing system to rapidly qualify consistency and uniformity of I_c in a magnetic field of 3 T

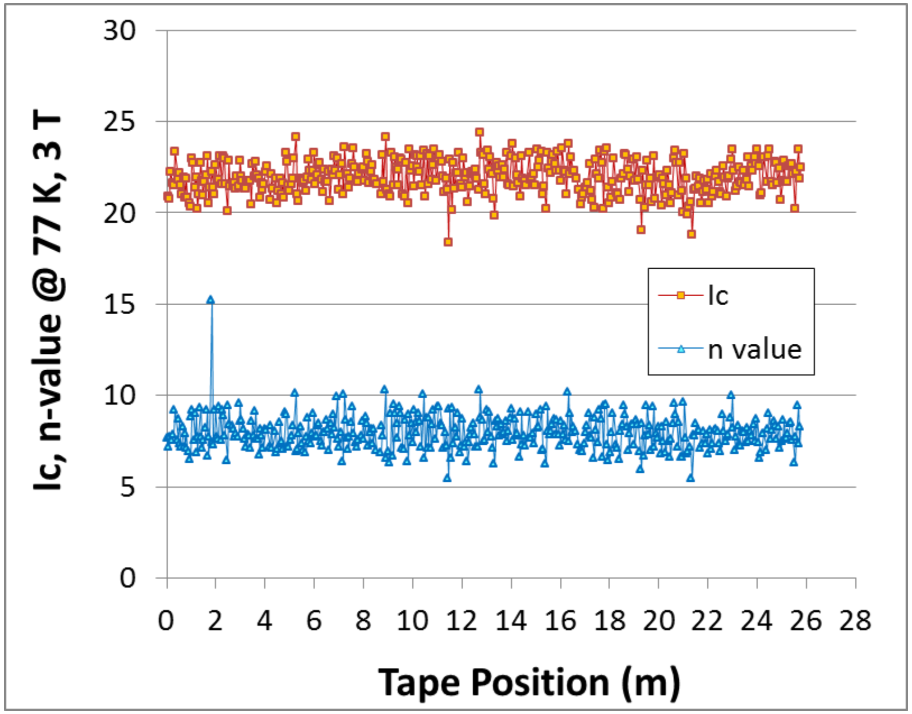
- Based on our finding of a strong correlation between I_c at 77 K, 3 T, B||c and low temperature in-field I_c, we have developed a design for a reel-to-reel in-field I_c measurement system
- System has been constructed and has been commissioned into operation.



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

Reel-to-reel testing system as a tool to qualify consistency and uniformity of in-field performance of HTS tapes





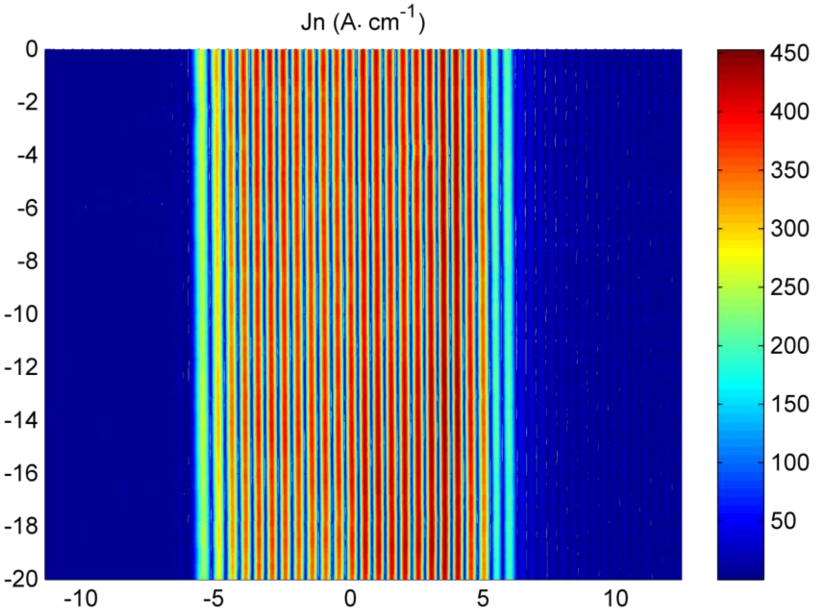
426 I-V curves at 77 K, 3 T every 5.7 cm of 26 m long tape

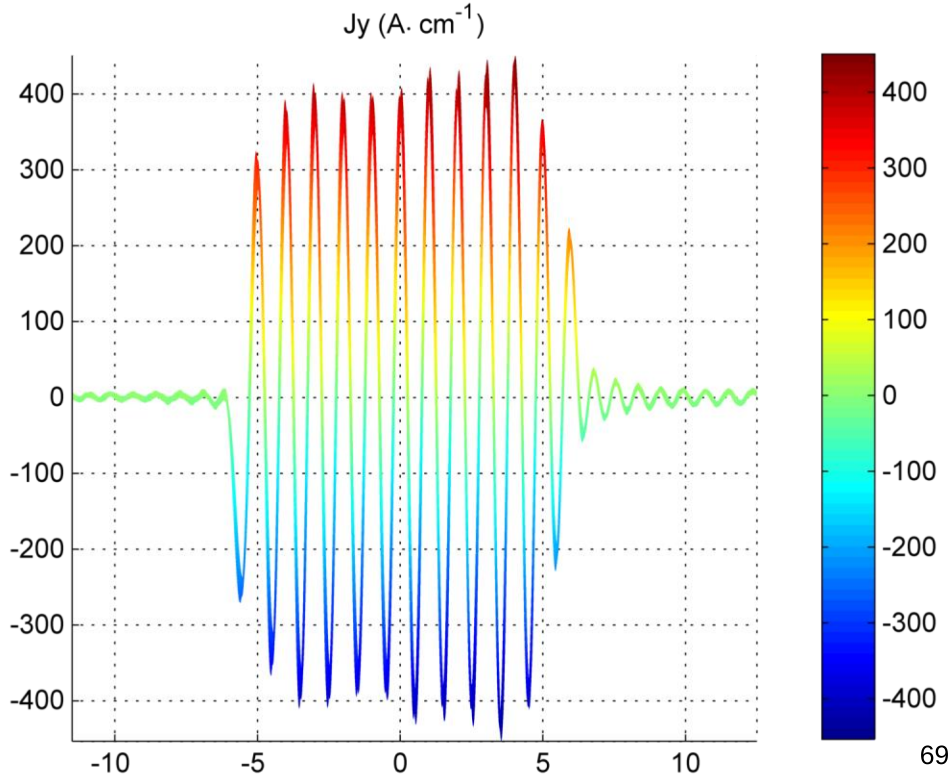
Standard deviation in Ic at 77 K, 3 T ~ 4%
Standard deviation in n value at 77 K, 3 T ~ 9%

ERP facility: Test bed for new QA/QC tools, process control tools for manufacturing

Reel-to-reel, Scanning Hall Probe Microscopy system:

- To visualize critical current uniformity on a sub-millimeter scale to identify defects that cause critical current drop outs.
  - Valuable for high yield manufacturing & for multifilamentary wires





Summary

- Major improvements in coated conductor performance in high magnetic fields at low temperatures with high levels of Zr addition (15 -25%)

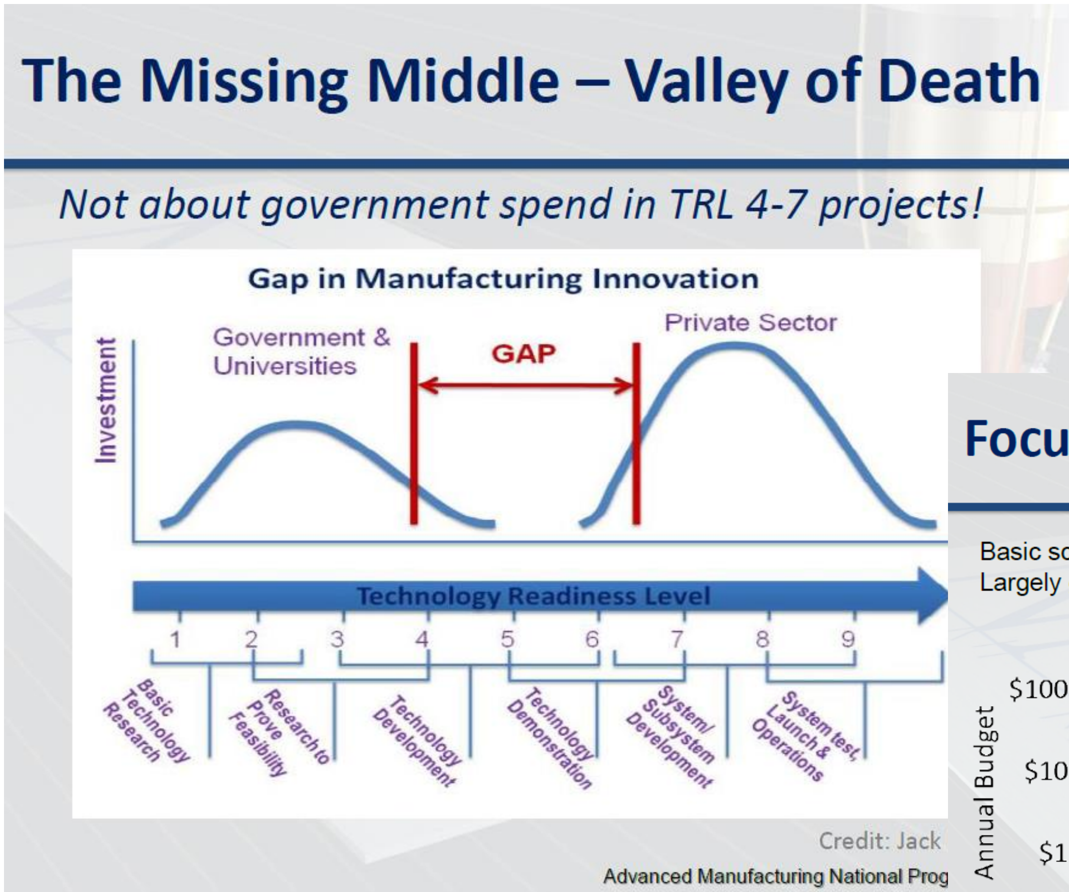
  In 25%Zr-added tapes, at 30 K, 3 T,
  - **I_c = 2172 A/12 mm: J_c = 20.1 MA/cm^2**
  - **Pinning force = 603 GN/m^3 , Lift factor = 6.4 at 30 K, 3T (B||c) → 3X higher**
  - **Pinning force at 20 K > 1000 GN/m^3**
- Very high performance achieved in 2.2 µm thick 20%Zr-added tapes
  - At 30 K, 3 T, ***I_c = 3963 A/12 mm , J_c = 15 MA/cm^2,*** *Lift factor* ***~ 5.1***
  - At 40 K, 3 T, ***I_c = 2833 A/12 mm , J_c = 10 MA/cm^2 → ~ 4X better than production wire***
- Very high performance achieved in 3.3 µm thick 20%Zr-added tapes
  - At 4.2 K, 20 T, ***I_c = 685 A/4mm , J_e = 1710 A/mm^2 → ~ 2.6X better than Bi-2212***
- Control of (Ba+Zr)/Cu composition and alignment of BZO defects key to achieve high lift factor
- Advanced MOCVD system developed for better process control
  - ***Lift factor = 9 at 30 K, 2.5 T (better than best lift factor of 7 in conventional MOCVD)***
- Facility at UH Energy Park established for manufacturing scale up of new technologies for high performance HTS tapes

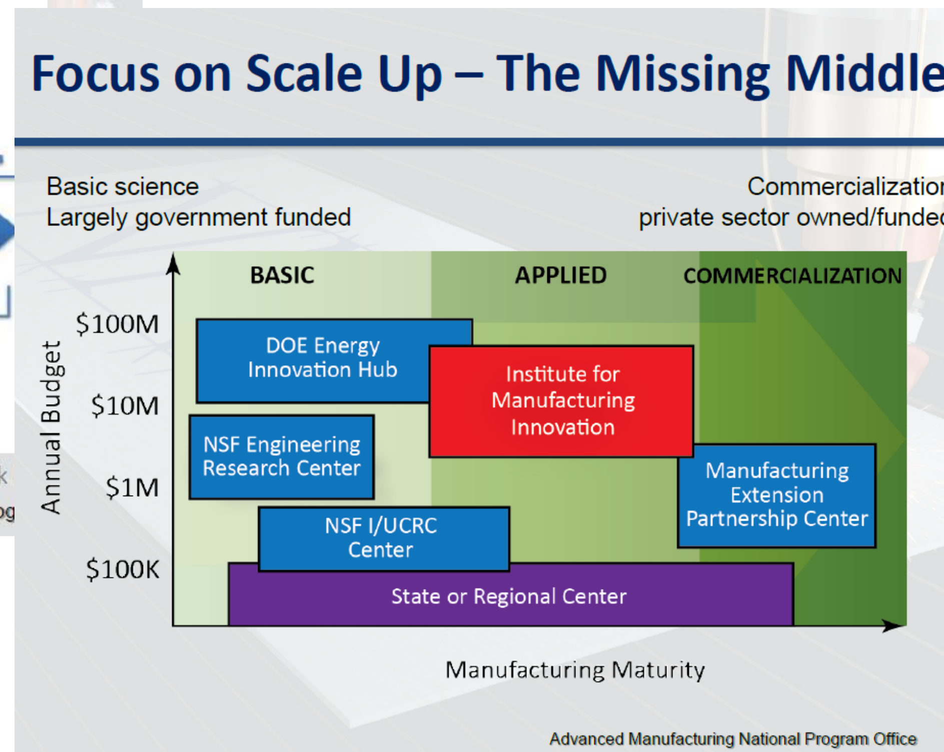
Rapid progress in high-field performance HTS tapes in past three years; opportunities for HTS tapes to make strong impact in high-field applications

Advanced Superconductor Manufacturing Institute

Advanced Manufacturing: Multi-agency Initiative

National Network of Manufacturing Institutes to address gaps in Manufacturing Innovation





Source: “National Network for Manufacturing Innovation” by S. Smith & B. Kinsley, GUIRR, 4 June 2013

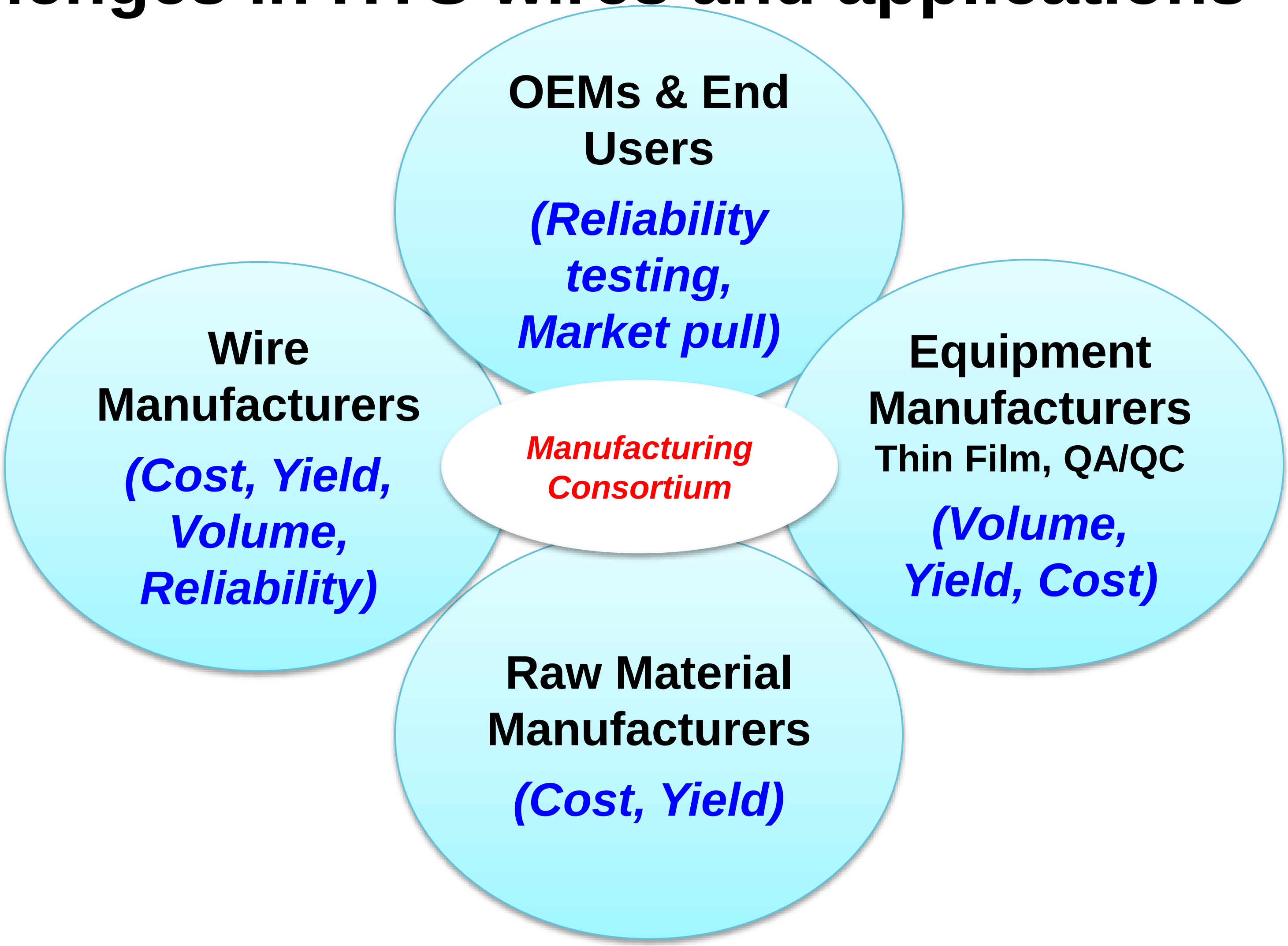
Six Manufacturing Institutes created; several more on the way

- America Makes: National Additive Manufacturing Innovation Institute (NAMII) Lead: Case Western Reserve University, Carnegie Mellon University
- Digital Manufacturing & Design Innovation (DMDI) Institute – Lead: UI Labs (formed from University of Illinois in 2013)
- Lightweight & Modern Metals Manufacturing Innovation (LM3I) Institute – Lead: Edison Welding Institute
- Next Generation Power Electronics National Manufacturing Innovation Institute – Lead: North Carolina State University
- Clean Energy Manufacturing Innovation Institute for Composites Materials and Structures – Lead: University of Tennessee
- Integrated Photonics Institute for Manufacturing Innovation – Lead: SUNY

Federal funding of $ 70 - $ 120 M available over 5 – 7 years

45 Manufacturing Institutes planned in the next 10 years

Consortium needed to bring industry together to comprehensively address manufacturing challenges in HTS wires and applications



UH facilitating an industry-driven effort to form a Manufacturing Institute

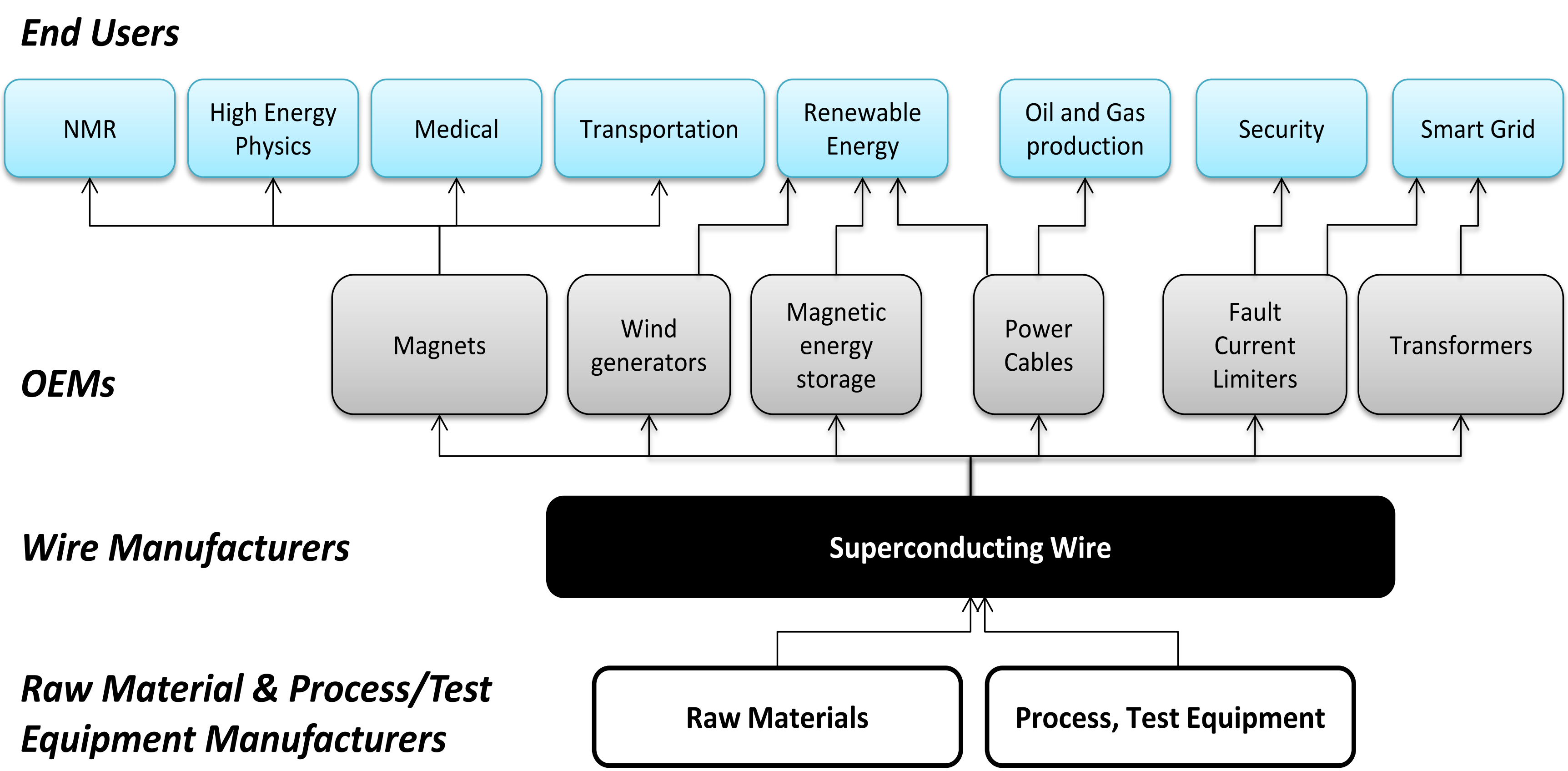
Superpowering America—

The Advanced Superconductor Manufacturing Institute

Superconductor technologies have significant benefits that span a broad range of applications in the U.S. economy. Advanced manufacturing is needed to help realize these benefits and capitalize on more than a billion dollars in research and development.

- Workshop in October ‘13 at the University of Houston: Strong and broad participation of superconductor industry (~ 30 companies)
  - Consensus built around an industry-driven Institute
- Steering committee of 12 industry members formed in February 2014 and whitepaper on an Advanced Superconductor Manufacturing Institute was created.

ASMI will address the entire value chain & broad range of superconductor applications



Objectives of ASMI

- Address the “missing middle” in advanced superconductor manufacturing innovation to bridge the gap between manufacturing of superconductor prototypes to commercialization.
- Enable industry for high-yield, low-cost manufacturing of HTS wires
- Develop and deploy innovative in-line tools guided by modeling and simulation for high-throughput processing, QA/QC and testing of HTS wire and components.
- Establish an ‘industry commons’ to test concepts close to maturity and to be a test-bed for comprehensive testing of homogeneity and reliability of HTS wires and power devices.
- Workforce development and training in superconductor manufacturing at all education levels.
- Engage and assisting small and medium enterprises to address manufacturing impediments to commercialization while reducing associated manufacturability risk during adoption of this new technology platform.

Established ASMI as a Texas entity; Received AMTech Funding from NIST

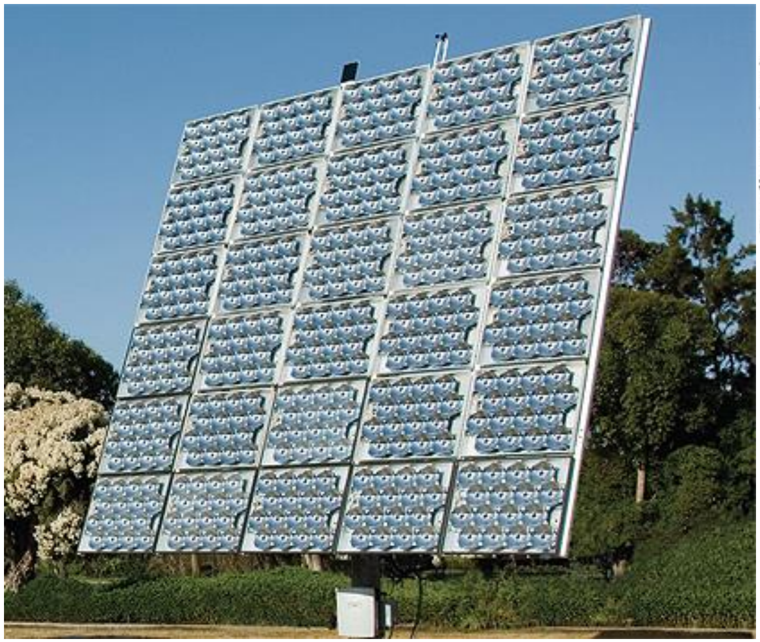
- ASMI created as a not-for-profit entity in Texas.
- Responded to NIST's AMTech Program planning awards FFO to fund this entity for building a consortium

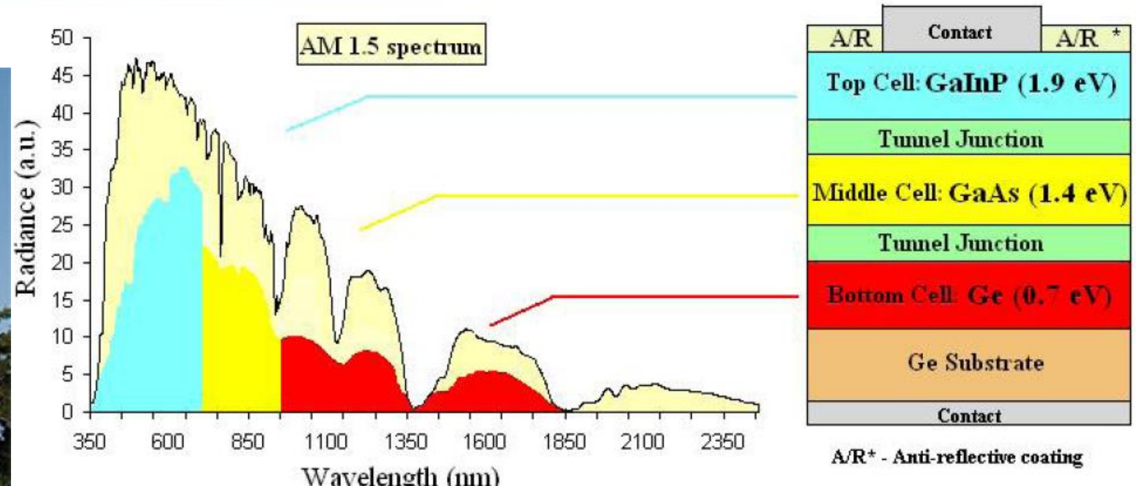
Advanced Manufacturing Technology Consortia (AMTech) Program

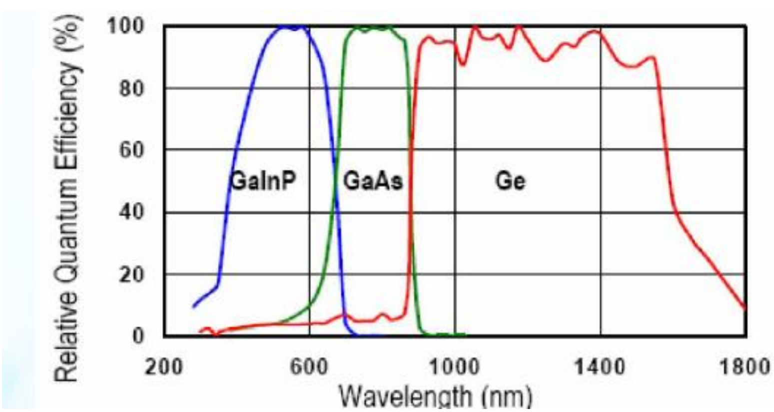
- Over 30 companies have committed to participate in consortium
  - Through the entire value chain: Manufacturers of Process and Test Equipment, Superconductor Wire, Materials and Components, Superconductor Power Equipment OEMs, End users
- Trade Organizations, Academia and National Laboratory also committed to participate in consortium
- UH's AMTech proposal awarded a $ 500 K grant for an 18-month roadmapping effort; – one of 16 recipients among 118 applicants
- First significant step towards an eventual National Manufacturing Institute.

III-V Compound Semiconductors for High Efficiency, Low-cost Solar Cells

III-V compound semiconductor solar cells are made on expensive single crystal substrates



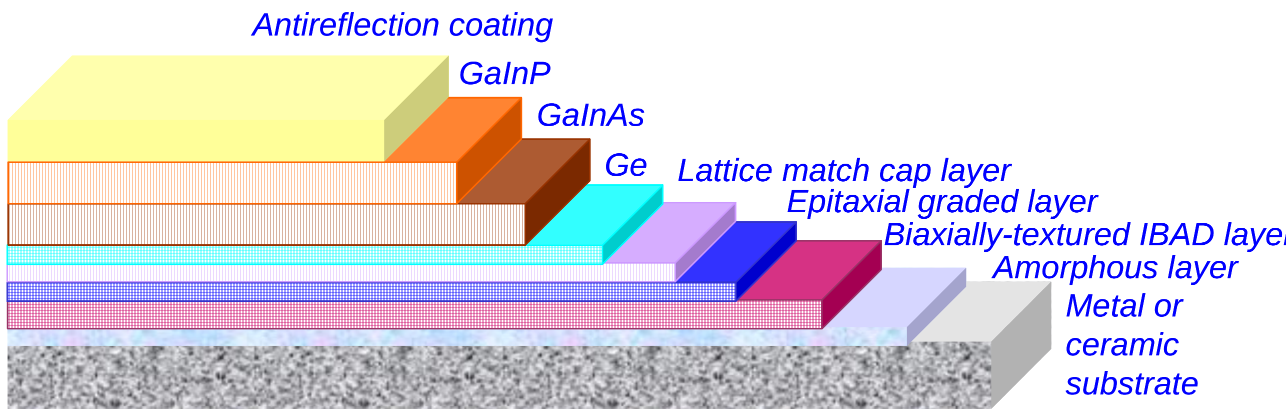




Cost of single crystal Ge or GaAs substrate itself is about ½ of entire module cost. Due to high cost, III-V solar cells are used mainly for space and concentrated PV applications

Novel photovoltaic thin film technology for high performance, lower cost solar cells

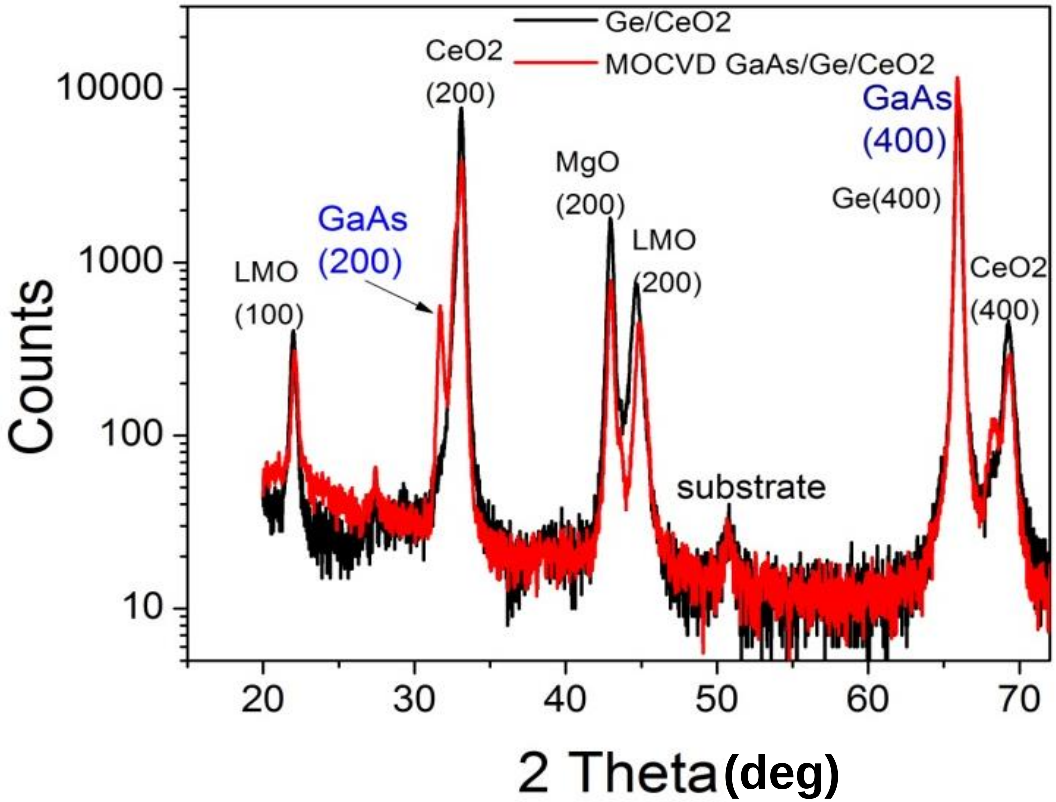
- Our approach is to fabricate high efficiency PV cells based on foundation technology of inexpensive flexible, practical substrates that have been developed for superconducting tapes.

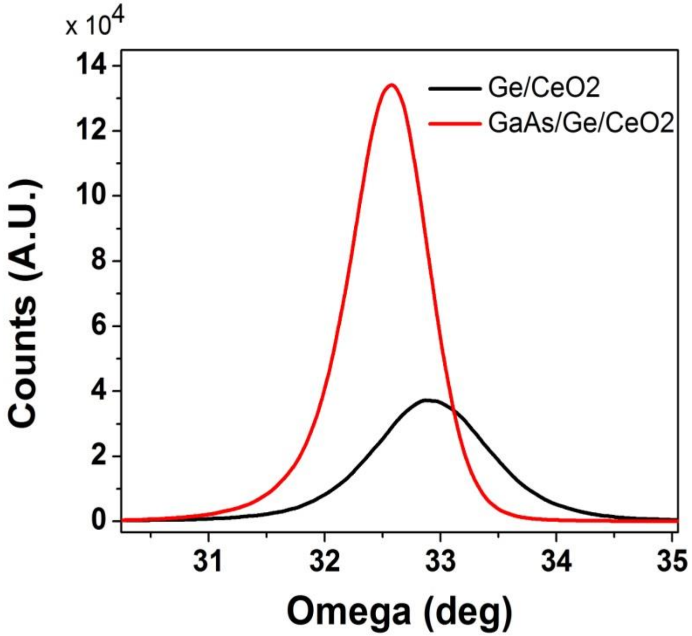


Proof of concept demonstrated in early-stage demonstration project

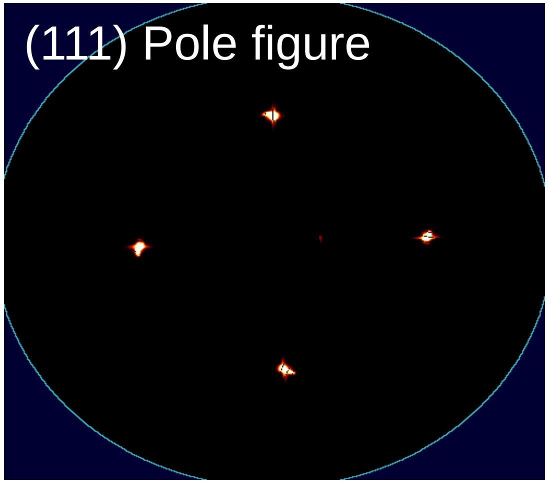
UNIVERSITY of HOUSTON

Epitaxial GaAs by MOCVD on Ge template on flexible metal substrates

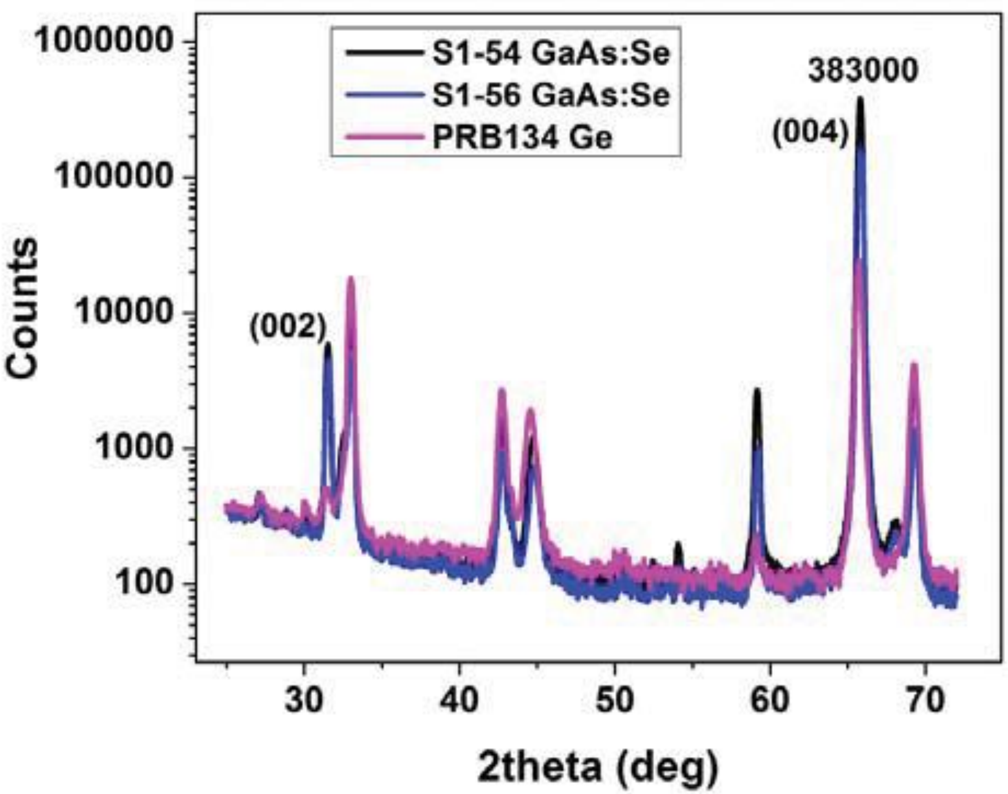




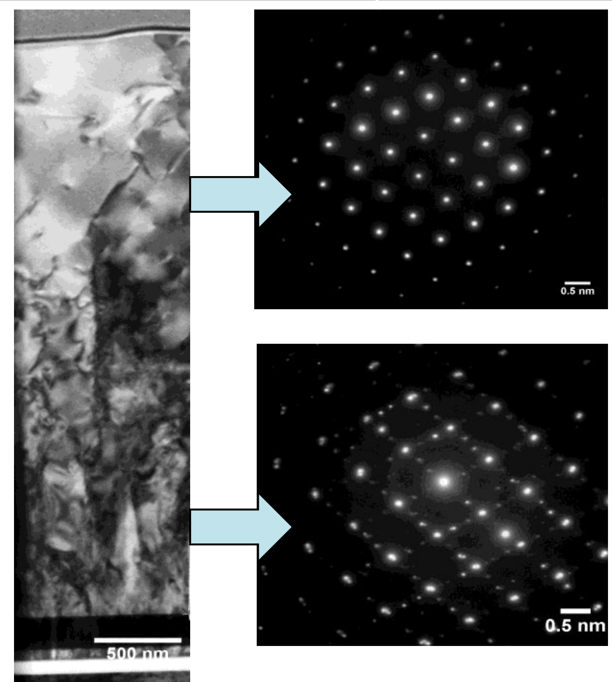
Sample	FWHM
Ge flexible substrate	4100 arcsec
GaAs/Ge	2800 arcsec



Mobility > 860 cm^2/Vs achieved on Se-doped GaAs thin film on metal substrate



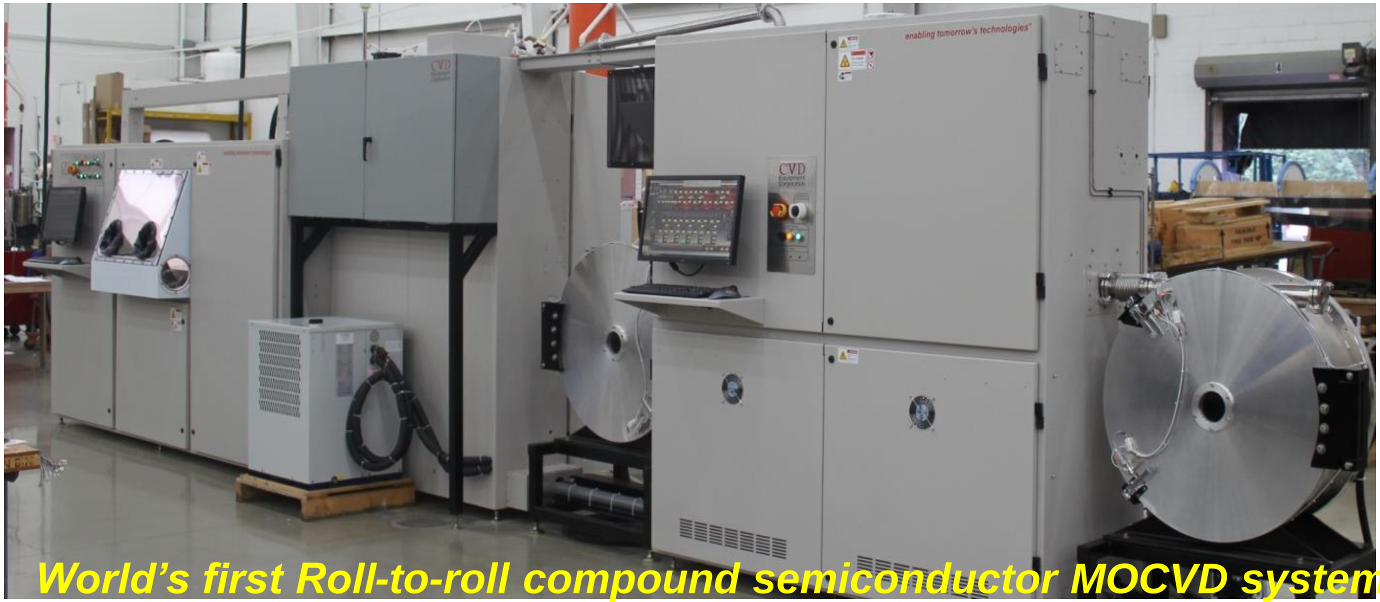
Carrier concentration (cm^{-3})	Mobility ($cm^2/V\text{-}s$)
- 2.55 x 10^{18}	860
- 5.0 x 10^{19}	530
- 1.58 x 10^{18}	860-872



- Highly (00l) aligned Zn-doped GaAs
- Out-of-plane texture: 0.63 – 0.82 degrees FWHM
- Defect density in the Se-doped GaAs films was in range of (1 – 5) × 10^7 cm^{-2}

Energy Devices Fabrication facility established in UH Energy Research Park

- 13,000 sq. ft. Energy Device Fabrication facility established at the ERP to extend facilities on campus
- Unique roll-to-roll process equipment, device fabrication tools and metrology tools set up for high-performance, low-cost energy and electronics devices in this facility

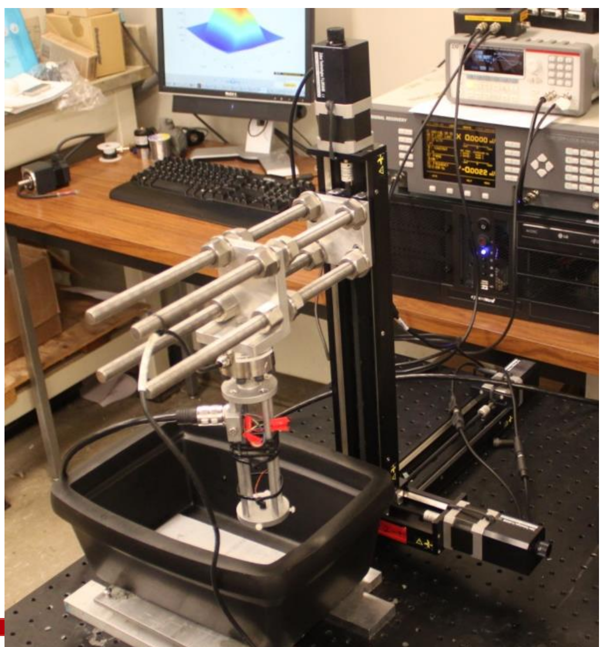


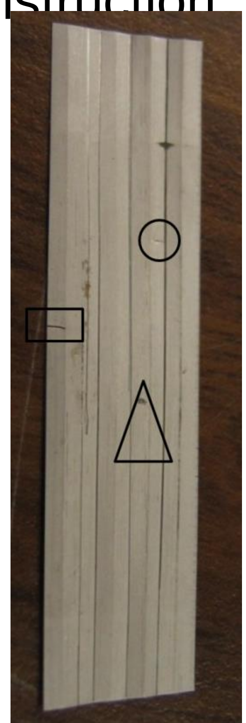
World's first Roll-to-roll compound semiconductor MOCVD system

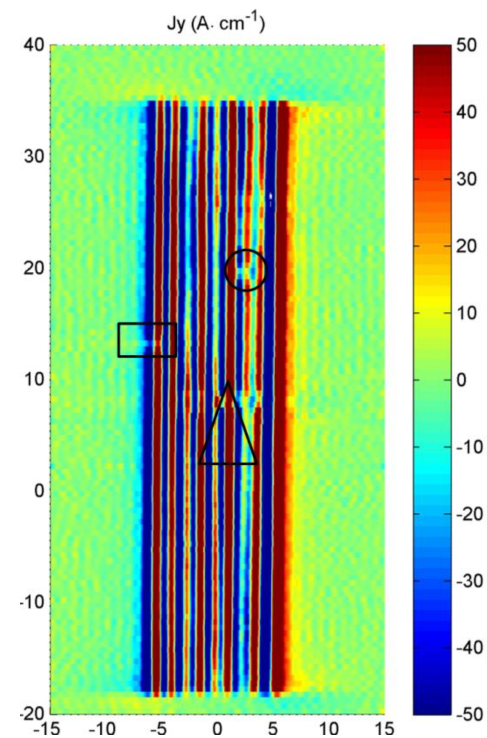
ERP facility: Test bed for new QA/QC tools, process control tools for manufacturing

Reel-to-reel, Scanning Hall Probe Microscopy system:

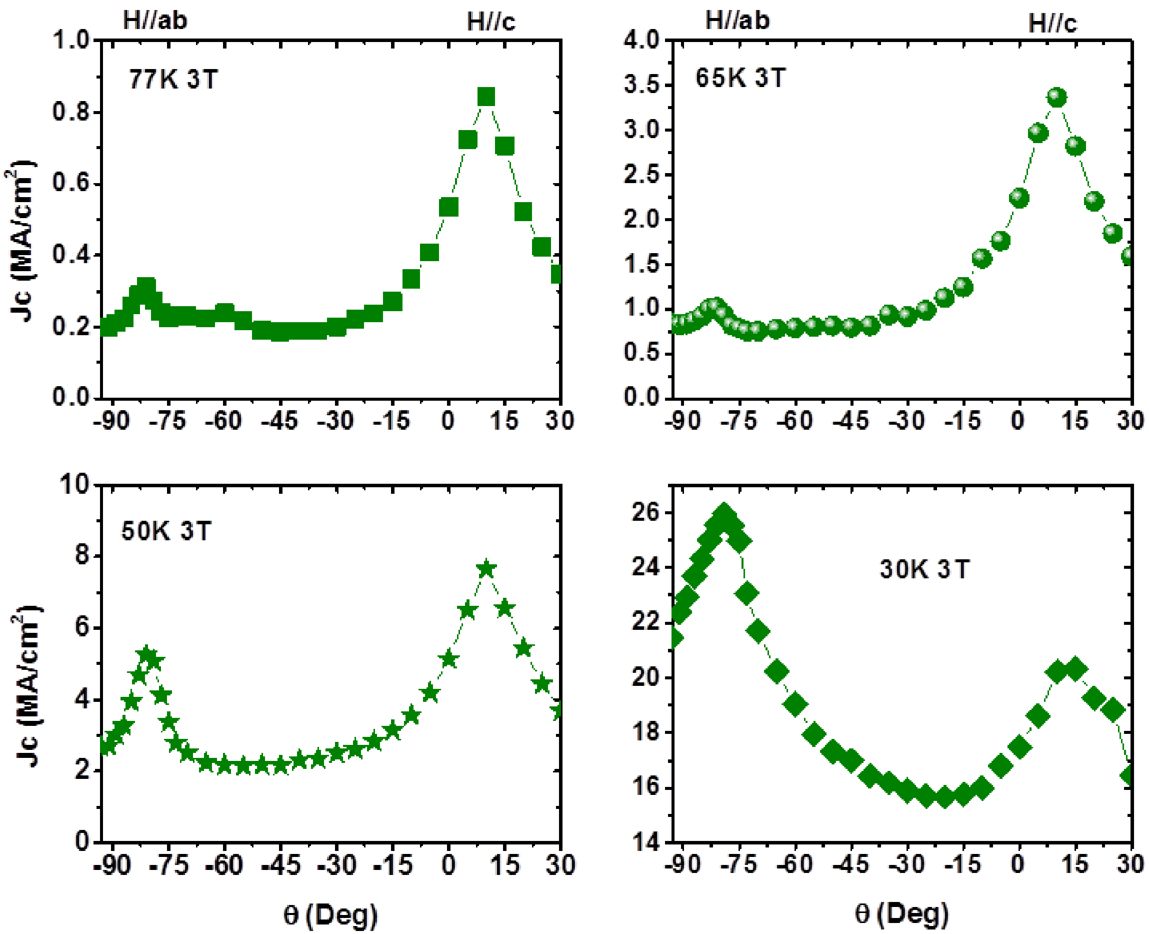
- To visualize critical current uniformity on a sub-millimeter scale to identify defects that cause critical current drop outs.
  - Valuable for high yield manufacturing & for multifilamentary wires
  - System designed and is in construction



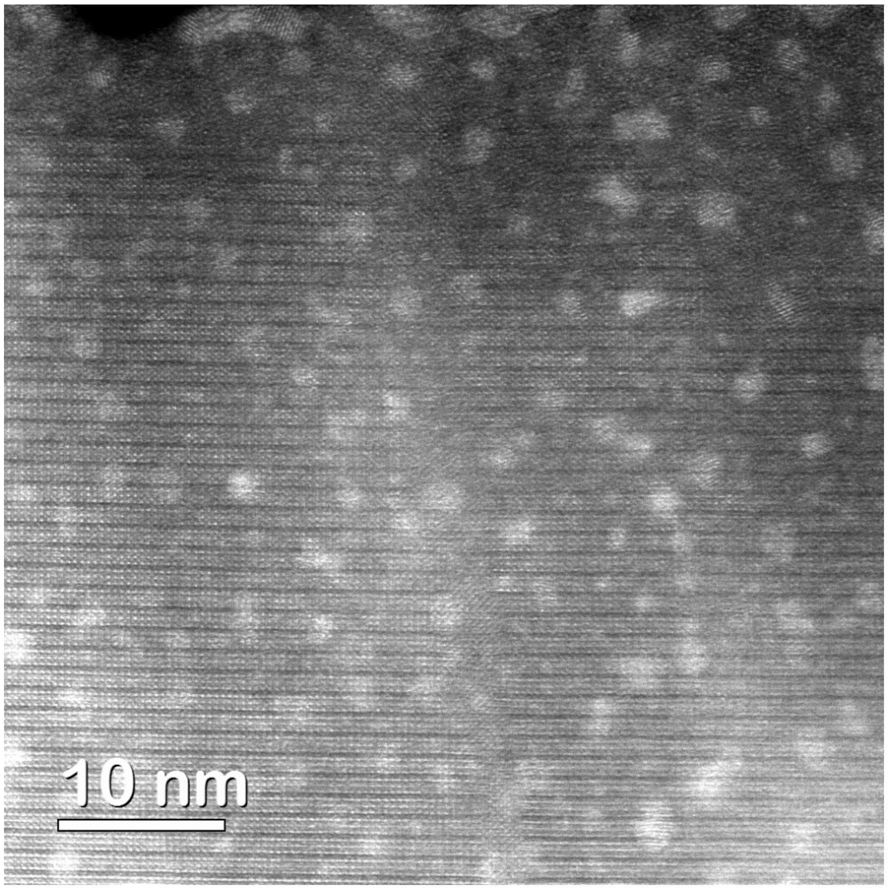


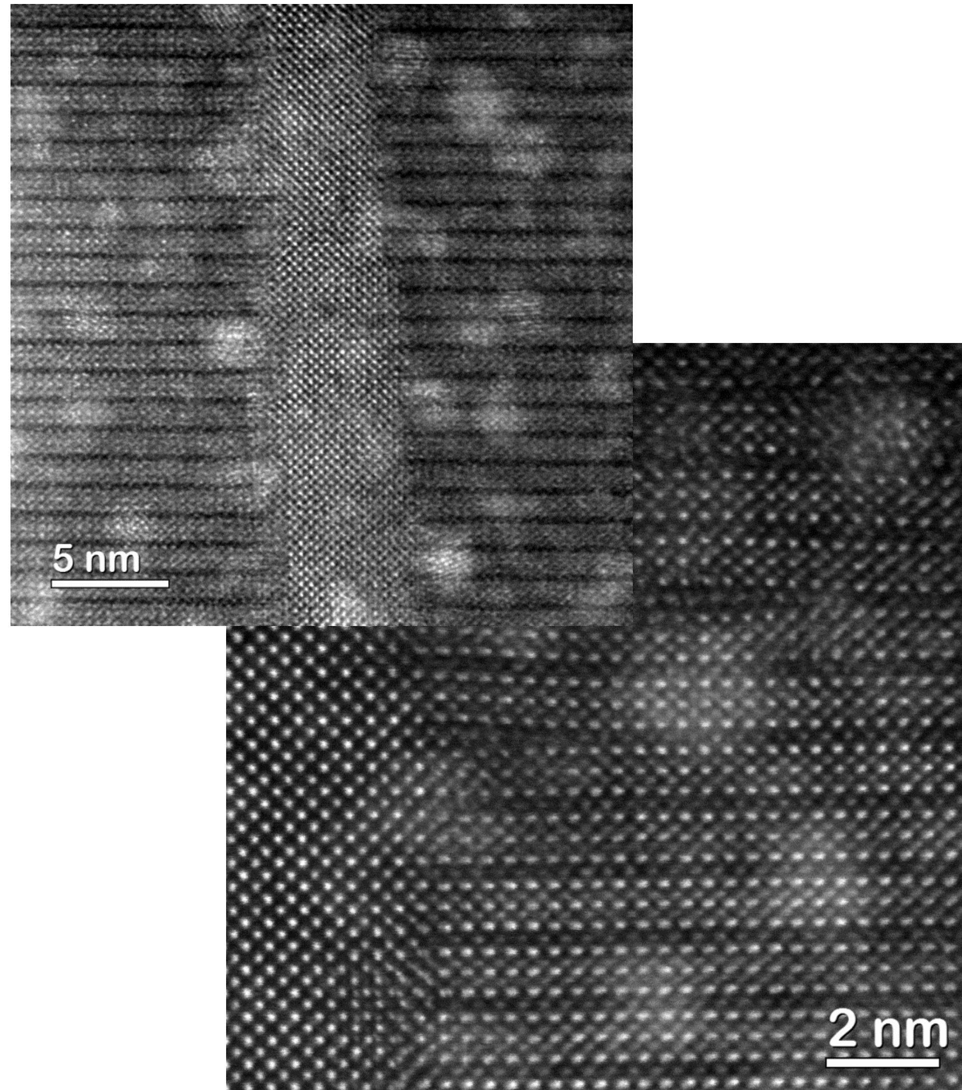


Multiple pinning mechanisms in high Zr-added tapes evident in changes in angular dependence characteristics with temperature



2 – 3 nm sized particles adjacent to BZO nanorods in high Ic 25% Zr-added tape





TEM by Claudia Cantoni, ORNL

Cu-Zr nanoparticles in high Ic 25% Zr-added tape