Status of HTS Conductor Development at University of Houston

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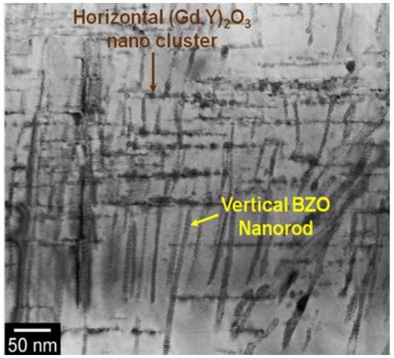
Projects funded by ARPA-E REACT, ARPA-E GRIDS, ARL, DOE , SuperPower

Outline

- Need to optimize coated conductor performance at operating conditions of coil applications (not just at 65-77 K, low fields)
  - V. Selvamanickam et al. *Supercond. Sci. Technol.* **25** (2012) 125013
- Coated conductor with high levels of Zr addition with high performance at 30 K
  - V. Selvamanickam et al. *Supercond. Sci. Technol.* **26** (2013) 035006
- Recent results with 15% Zr-added (Gd,Y)BCO tapes at 30 K and 4.2K
- Multifilamentary coated conductors with thick copper stabilizer by selective electroplating
  - Ibrahim et al. Physica C. **486,** 43–50 (2013)

4X HTS conductor performance improvement targeted for high power wind generators

- ARPA-E REACT program targeted on 10 MW wind generator operating at 30 K, 2.5 T
- Improved approaches to engineer nanoscale defects in coated conductors
- New pilot MOCVD system set up in UH Energy Research Park to rapidly scale up new technology advances to long-length manufacturing.



Engineered nanoscale defects

4x improved wire manufacturing

High-power, Efficient Wind Turbines

- *Quadrupling superconductor Performance at 30 K, 2.5 T for commercialization of 10 MW wind generators to reduce wire cost by 4x*
- *Advances will also lead to high-performance HTS conductors for other high-field applications*

Tai-Yang Research TECO Westinghouse NREL NATIONAL RENEWABLE ENERGY LABORATORY

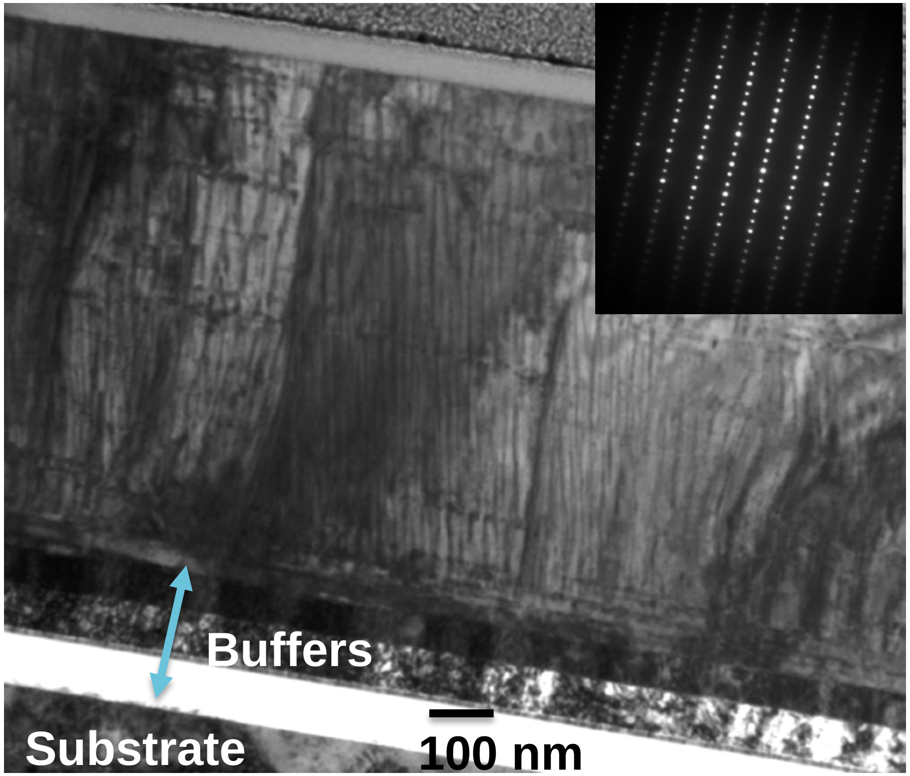
4X HTS conductor can enable commercial feasibility of HTS devices

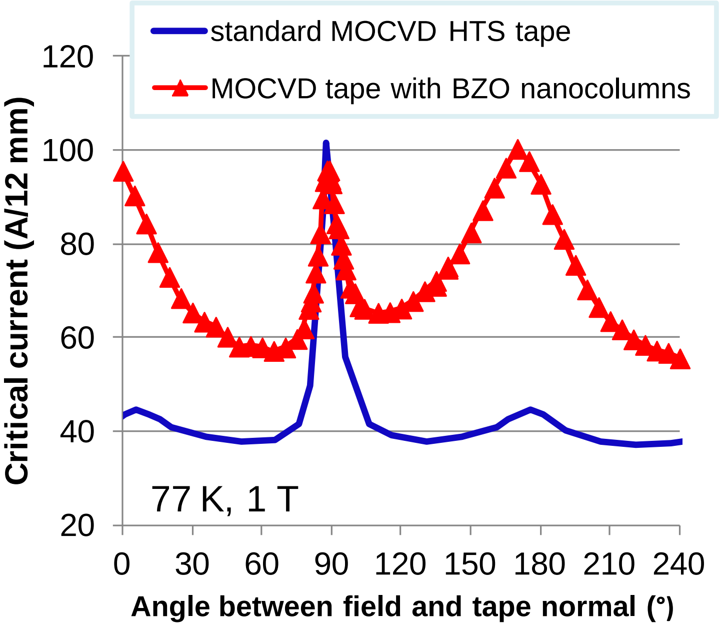
Metric	Now	End of project
Critical current at 30 K, 2.5 T (A/12 mm) (device operating condition)	750	~3000
Wire price at device operating condition ($/kA-m)	144	36
Estimated HTS wire required for a 10 MW generator (m)	65,000	16,250
Estimated HTS wire cost for a 10 MW generator $ (,000)	7,020	1,755

- 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.

Improved pinning by Zr doping of MOCVD HTS conductors

- Two-fold improvement in critical current at 77 K, 1 T achieved by **7.5%** Zr addition in MOCVD films

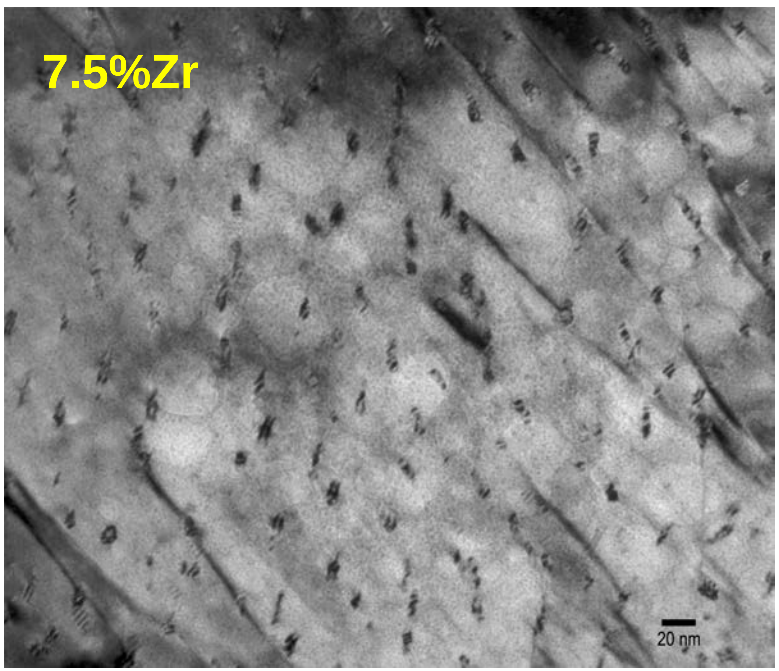


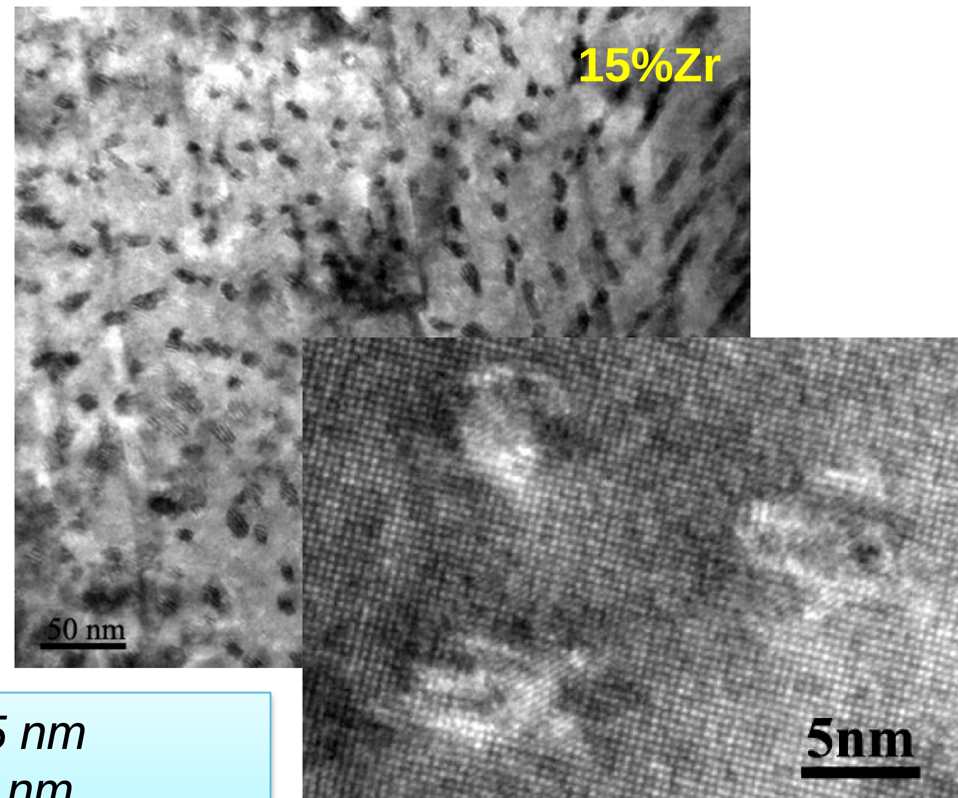


Process for improved in-field performance successfully transferred to manufacturing at SuperPower – standard product in the last two years

Opportunities to further improve pinning with higher density of BZO defects in high Zr content tapes

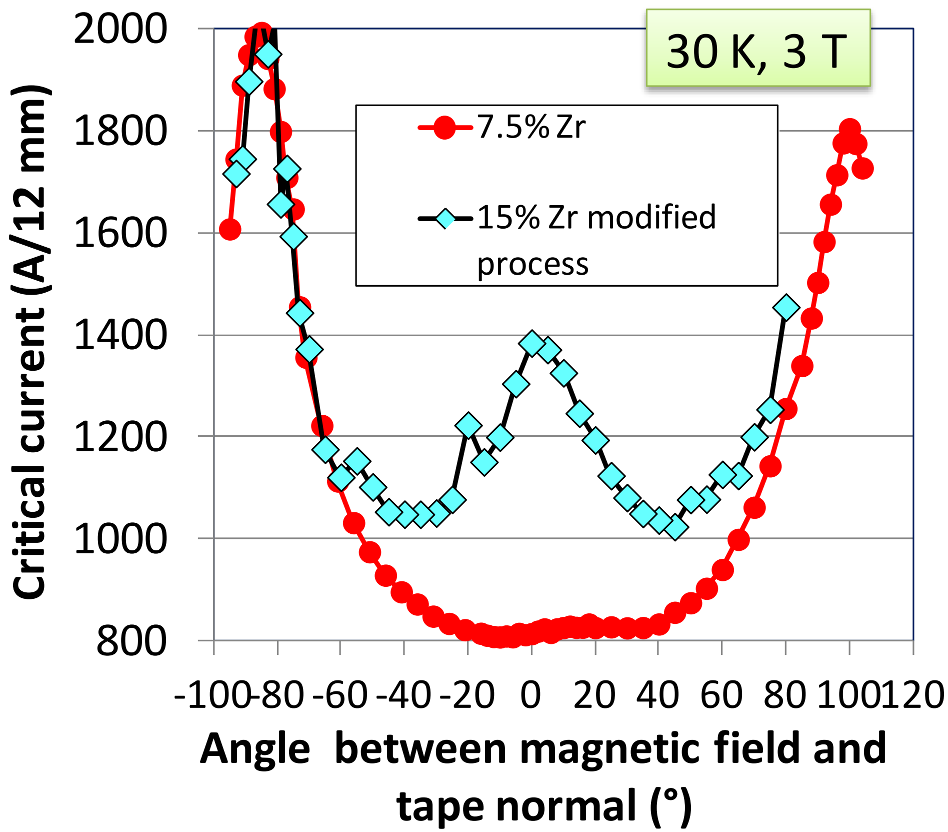
- All good Ic results reported so far with PLD, MOD and MOCVD films have been with less than 10 mol.% of second phase addition

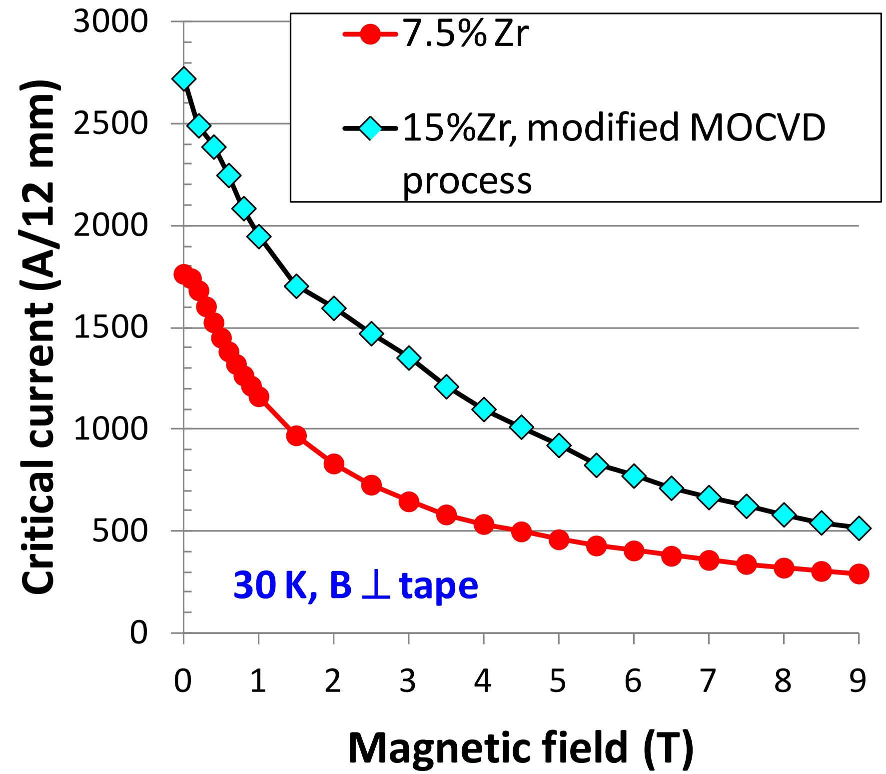




BZO spacing in 7.5%Zr sample : 35 nm
BZO spacing in 15%Zr sample : 17 nm
Average size of BZO ~ 5 nm in both

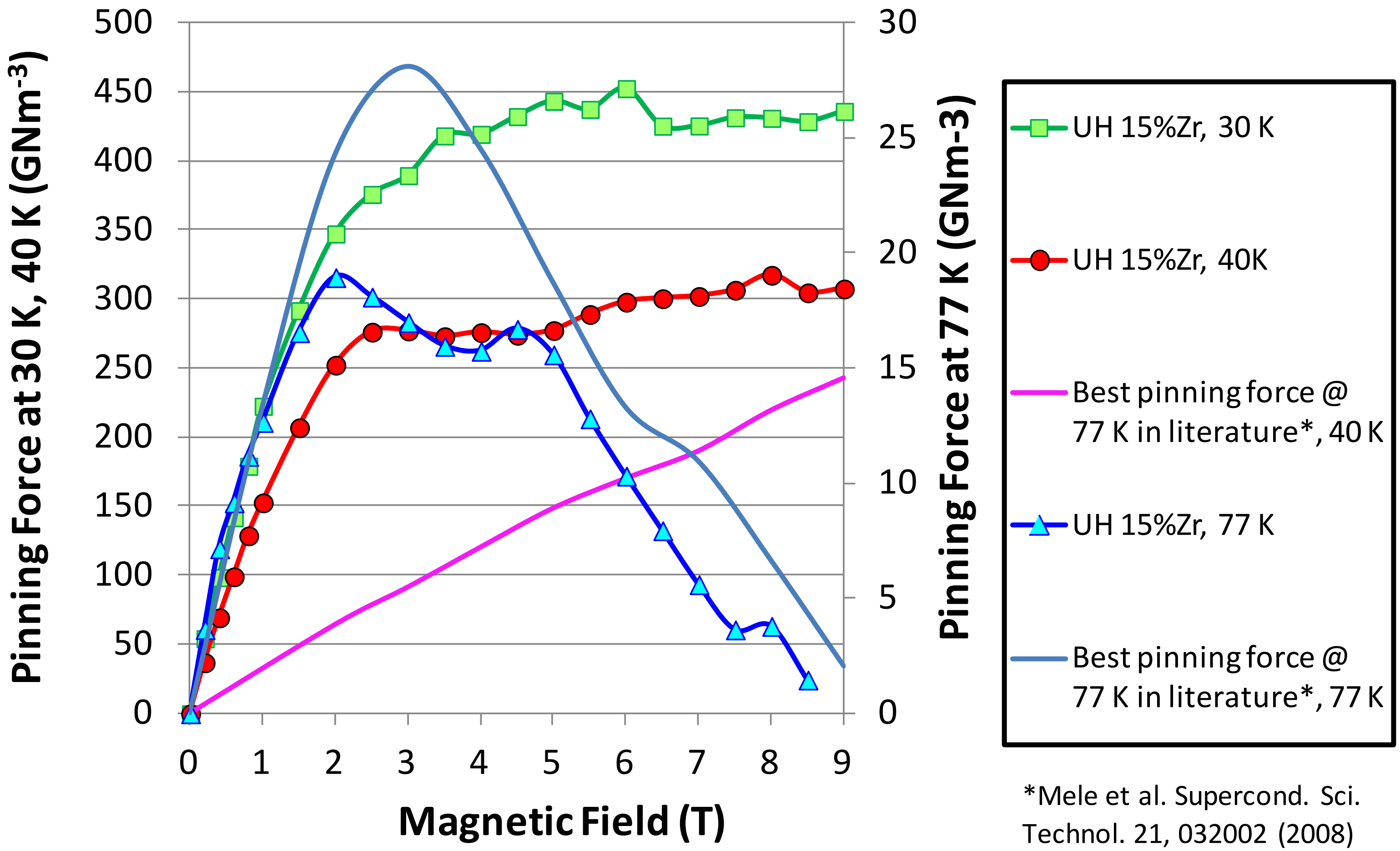
Significant improvement in performance of 15% Zr-added tapes with modified MOCVD process





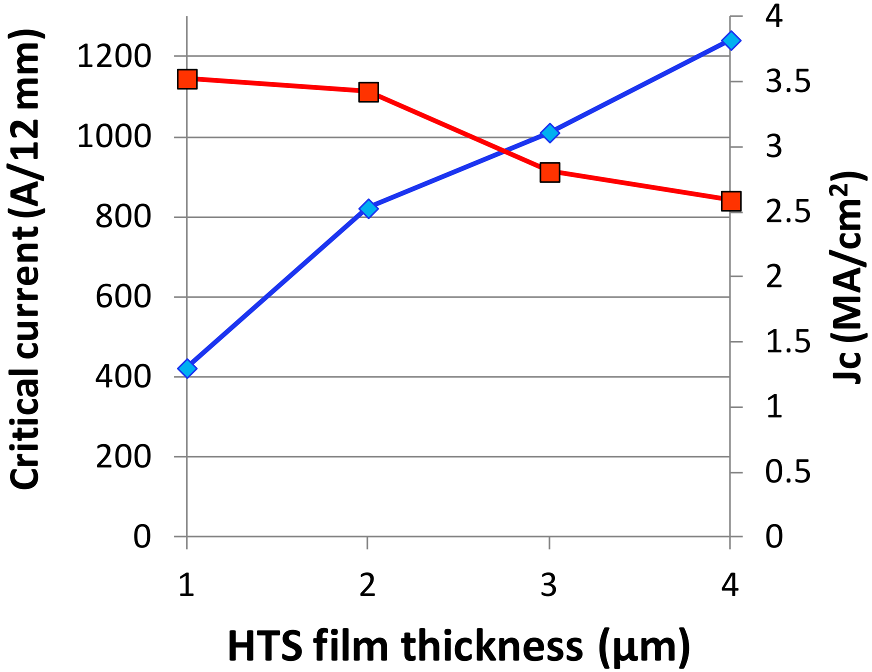
- *Critical current of 15% Zr-added film ~ **1384 A/12 mm (J$_c$ = 12.5 MA/cm^2, Pinning force = 374 GN/m^3)** at 30 K, 3 T, B||c*
- *Lift factor at 30K, 3 T, B||c improved by >100% to ~ **4.4***

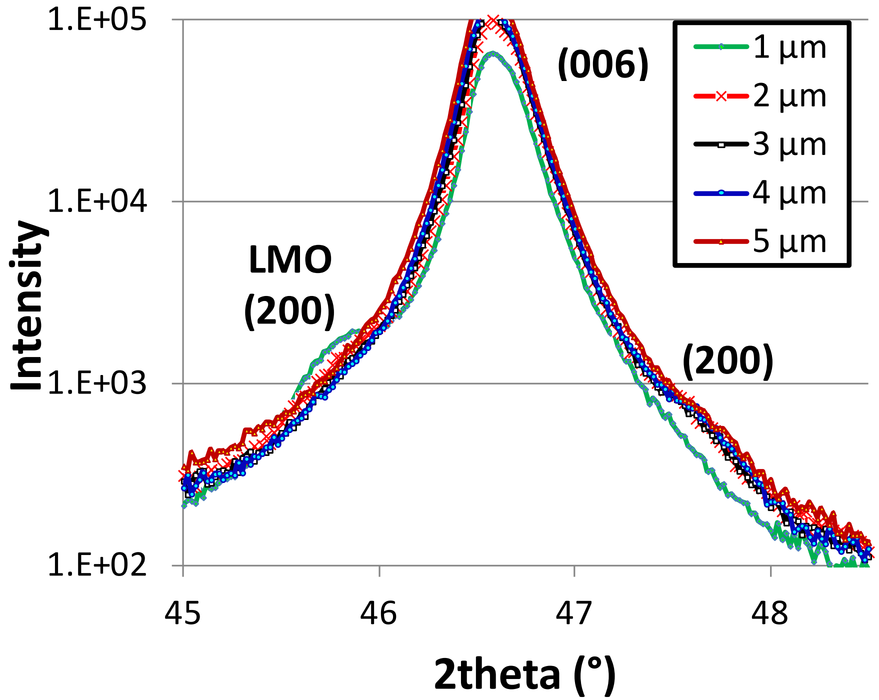
15%Zr-added tapes exhibit much higher pinning forces at 30 & 40K than best reported data



*Mele et al. Supercond. Sci. Technol. 21, 032002 (2008)

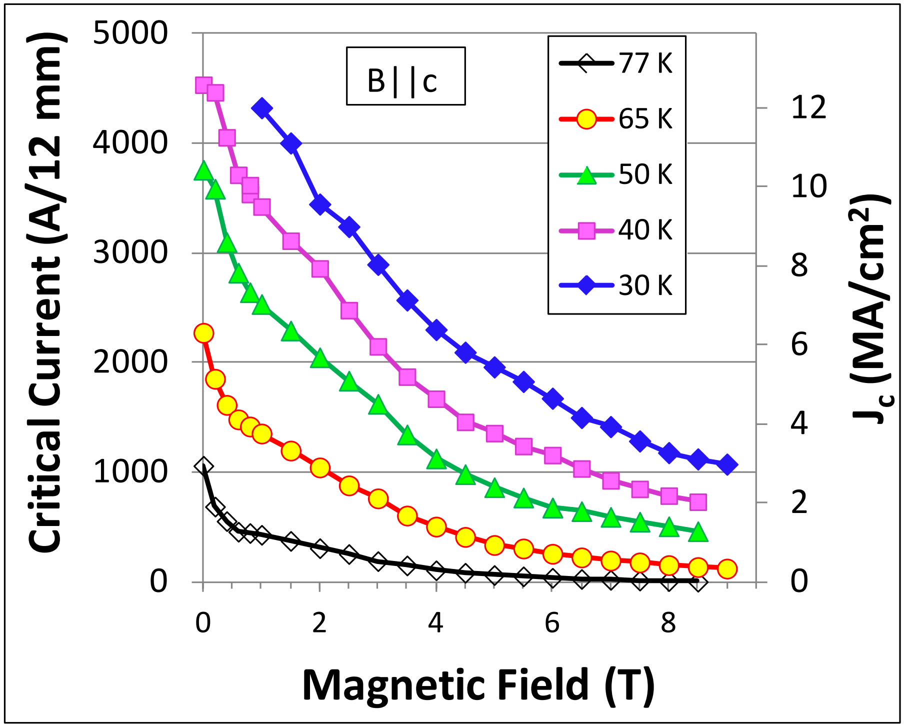
High critical currents in thick films of 15%Zr-added GdYBCO tapes

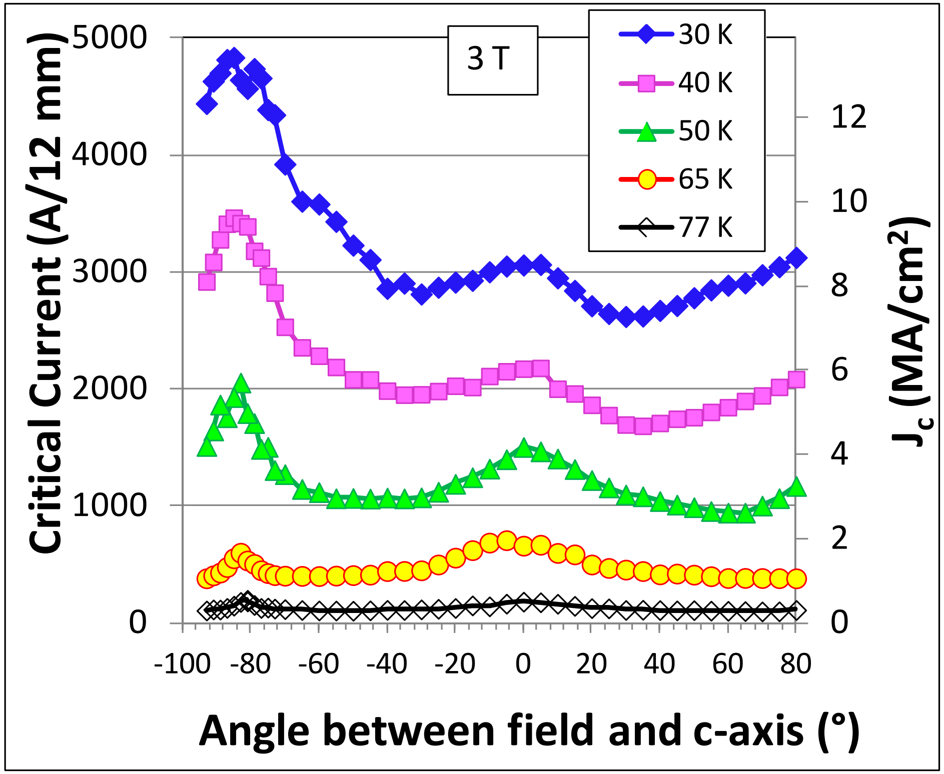




- Combining thick film and improved pinning compositions to achieve high critical currents in high magnetic fields.
- No significant a-axis oriented growth found even in 5 µm thick films
- *Critical current over 1000 A/12 mm (Jc = 2.6 MA/cm²) achieved in 3 µm films with 15% Zr addition made by modified process*

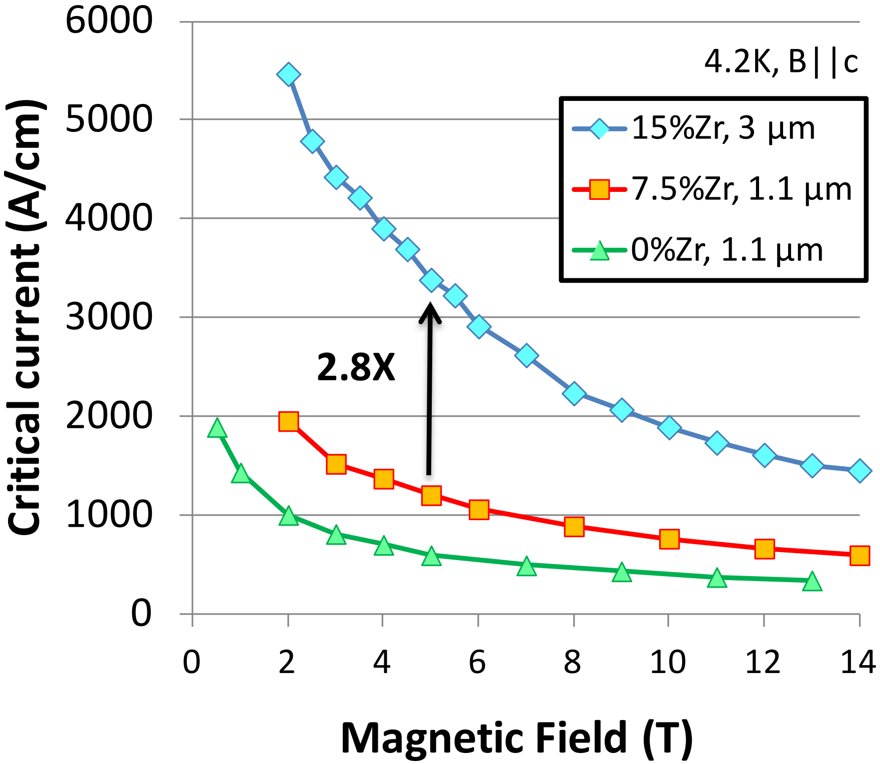
Ultra-high critical currents in 15%Zr-added 3 µm thick film tapes at 30 – 50 K in high fields

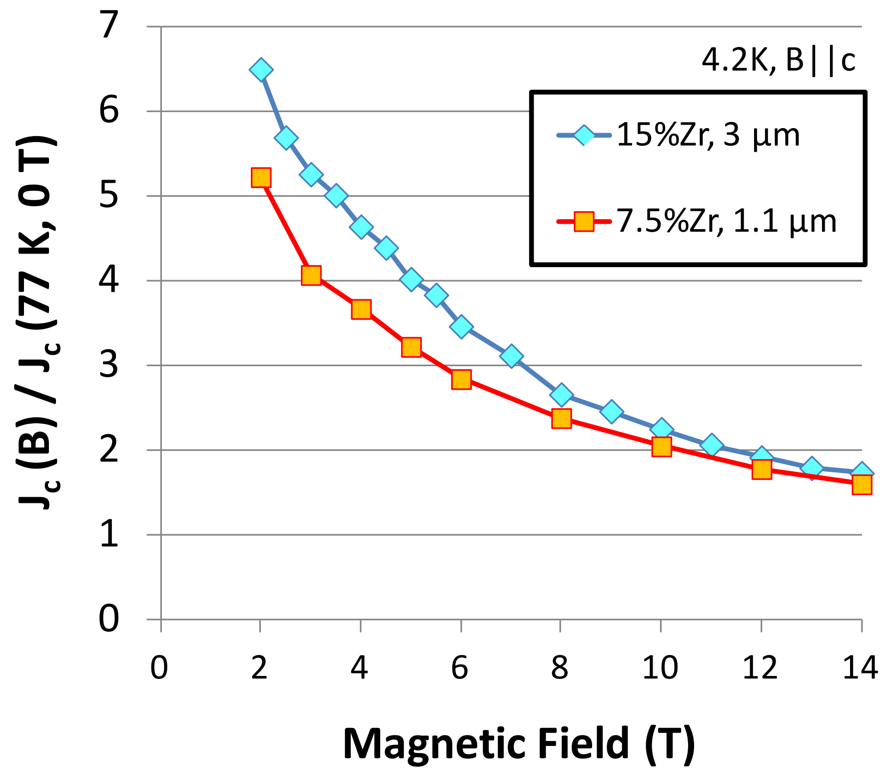




- *At 3 T, B||c,* I_c = ***2,895 A/12mm (8 MA/cm²)*** *at 30 K,*
  I_c = ***2,147 A/12 mm (6 MA/cm²)*** *at 40 K,*
  I_c = ***1,624 A/12 mm (4.5 MA/cm²)*** *at 50 K*

Ultra-high critical currents in 15%Zr-added 3 μm thick film thick film tapes in high fields at 4.2K



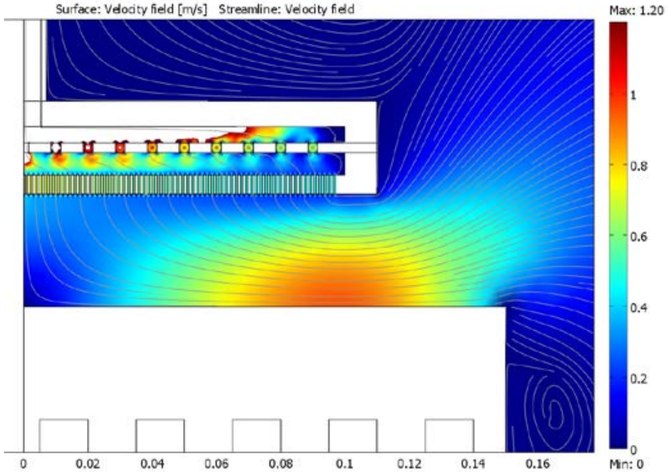


Measurements by J. Jaroszynski, D. Abraimov, X. Hu and D. Larbalestier, NHMFL

- *I_c = 3385 A/cm at 4.2 K, 5 T (B||c), 2.8 times higher than previous best*
- *Improvement from pinning (lift factor) is 25% higher in 15%Zr-tape at 4.2 K, 5 T (B||c) than previous-best 7.5%Zr-added tape*

Advanced MOCVD reactor to address deficiencies of existing MOCVD systems

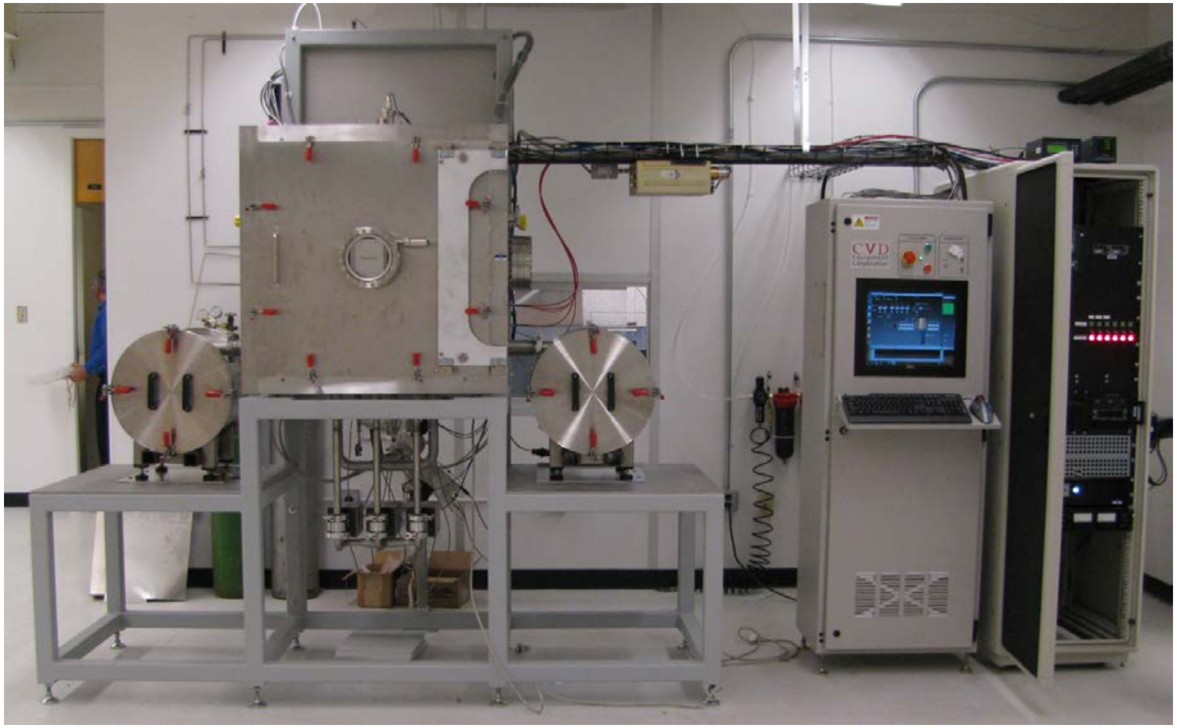
- Wire performance has been limited by MOCVD hardware design which has not been changed substantially in the last 10 years.
- Key process parameters that are key for high performance are not properly controlled and are non uniform in existing MOCVD reactors.
- Modeling of existing reactors revealed some of the deficiencies.



Existing MOCVD system design is not suitable for needed level of control and uniformity for high critical current in thick films

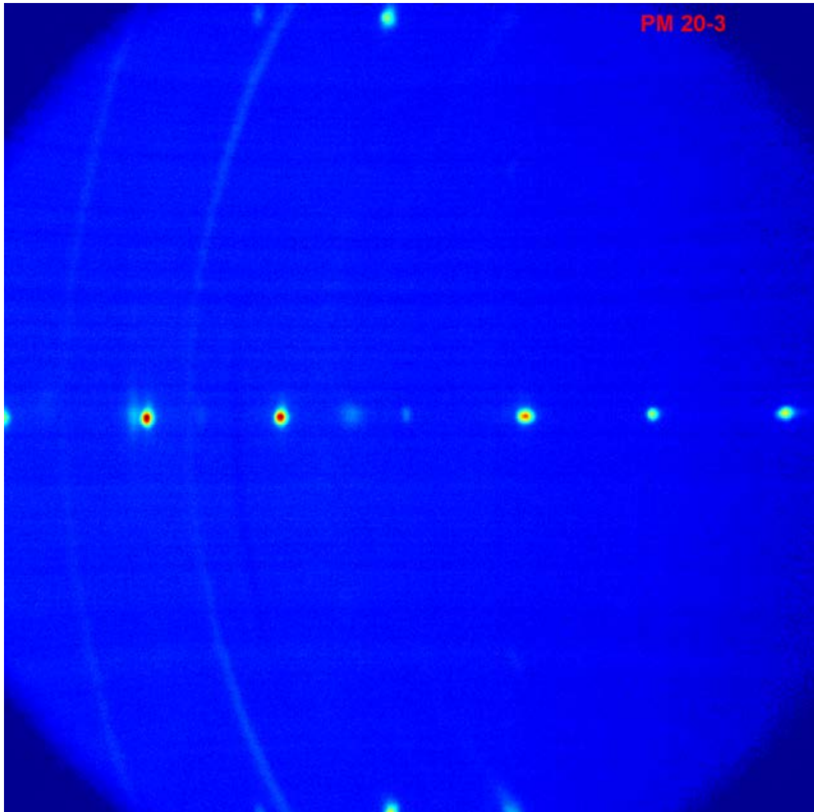
New reel-to-reel MOCVD system with advanced reactor design constructed & tested

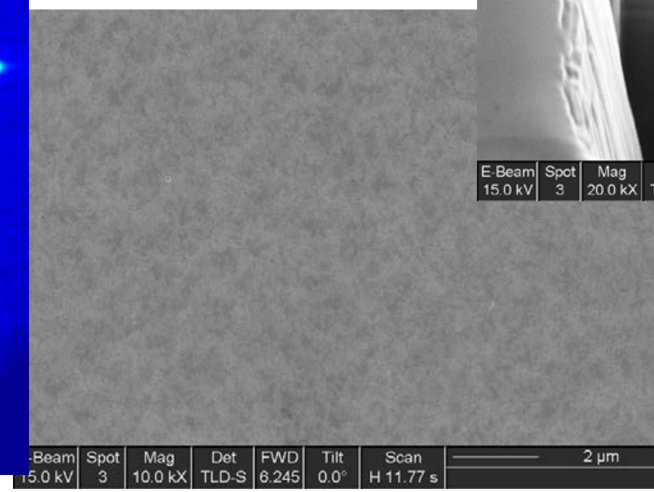
- New MOCVD reactor addresses all deficiencies of existing MOCVD reactors. Designed, constructed & tested in ARPA-E GRIDS program.

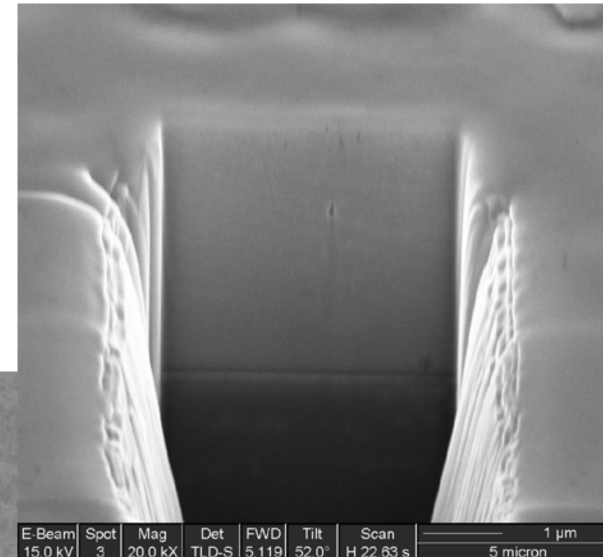


In-house capability to model, design, construct, build MOCVD reactor as well as process development and materials synthesis

HTS films with excellent microstructure and high critical current achieved with new MOCVD system



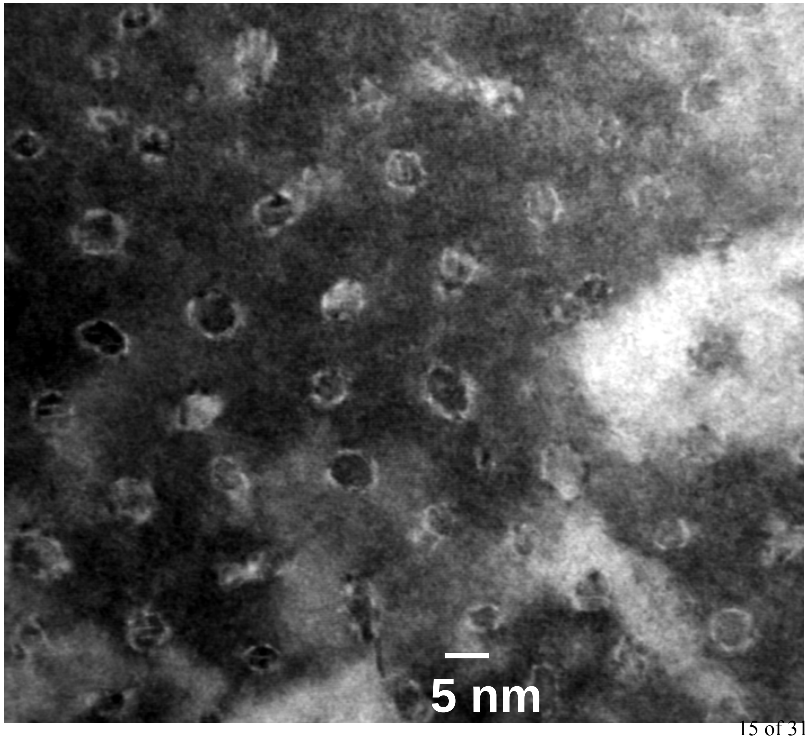


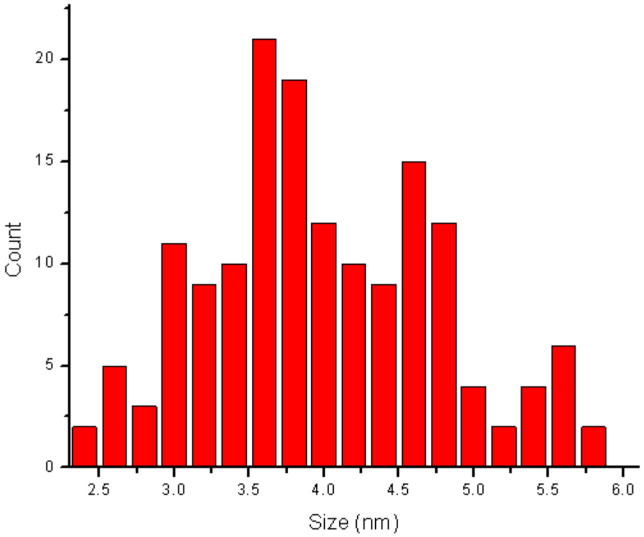


- *4 µm thick film with no a-axis grains made in new system*
- *Record-high critical current of 916 A achieved in 1.8 µm thick film made in new MOCVD system*
- *Deposition rate increased by more than 35%*

Several opportunities to further improve in-field performance

- Increase density of nanoscale defects
- Introduce nanoscale defects that are even more effective at low temperatures and high fields
- Modify growth process to *consistently and uniformly* achieve longer nanorods without interruptions





Average size 3.9nm
Average distance ~12nm

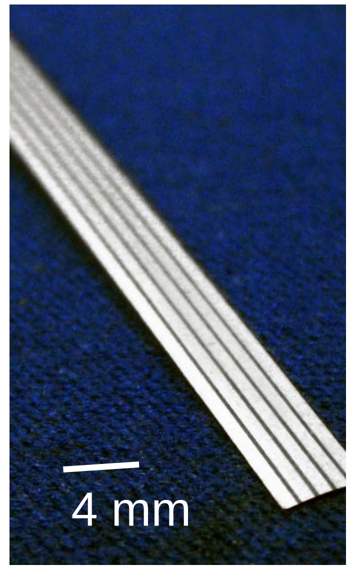
Summary: High-field HTS conductors

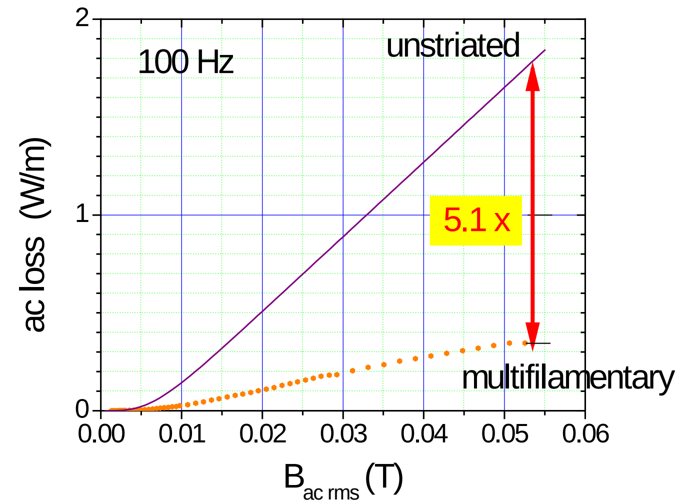
- Major improvements in coated conductor performance in high magnetic fields at low temperatures by high-density of nano-scale defects with high levels of Zr addition (15%)
  - **I_c = 1384 A/12 mm: J_c = 12.5 MA/cm^2 , Pinning force = 374 GN/m^3 Lift factor = 4.4 at 30 K, 3T (B||c) >2x typical**
- H_{irr} at 77 K of 15%Zr-added tapes increased to **14.8 T** (from 10.2 T of 7.5%Zr added tapes)
- 2.5X higher J_c in 15%Zr at 4.2 K, 10 T and 2.1X higher J_c in 15%Zr at 4.2 K, 20T compared to the best 7.5%Zr-added tapes
  - **J_c (4.2 K, 10 T) = 16.9 MA/cm^2 (J_e ~ 1690 A/mm^2)**
  - **J_c (4.2 K, 20 T) = 8.5 MA/cm^2 (J_e ~ 850 A/mm^2)**
- The max pinning force at 4.2 K increased 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

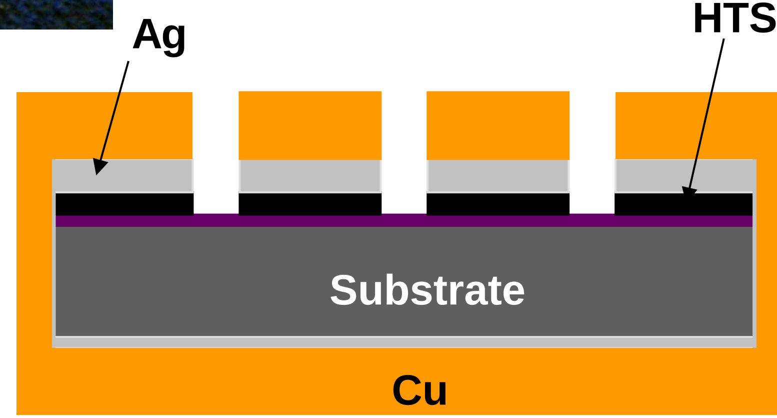
More opportunities exist for further improvement in performance of coated conductors at operating conditions of coil applications & to thereby reduce cost

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)







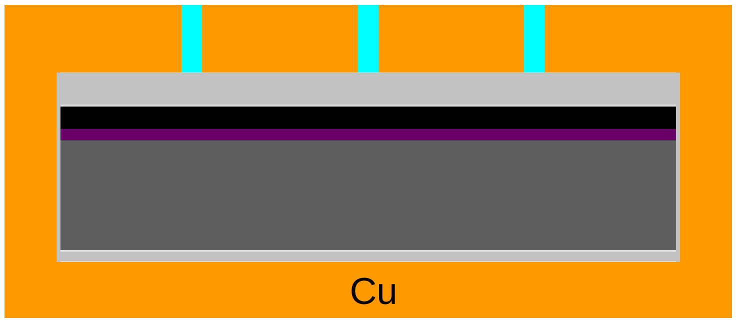
A fully filamentized coated conductor would need to have 20 – 50 µm of copper stabilizer striated !

One approach to make *fully*-filamentized coated conductor

1. Coat photoresist on silver

2. Transfer pattern from mask to photoresist

3. Electroplate copper

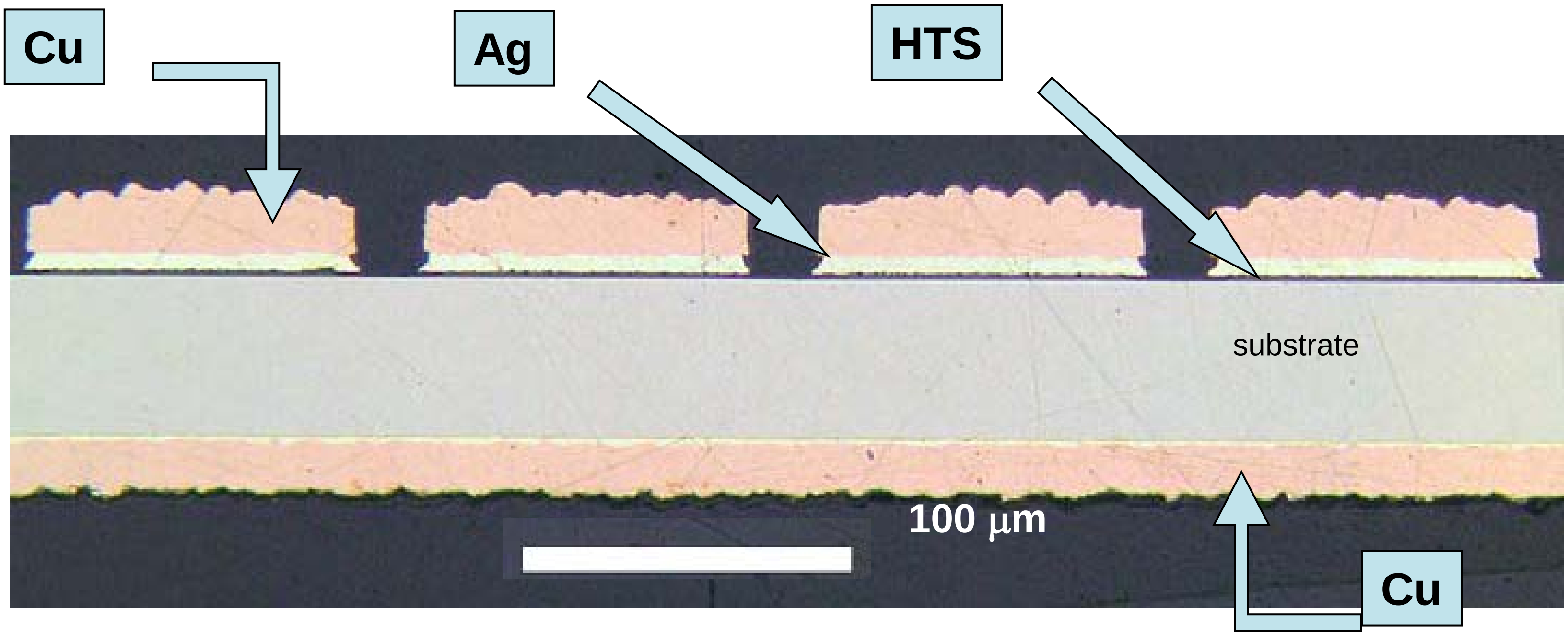


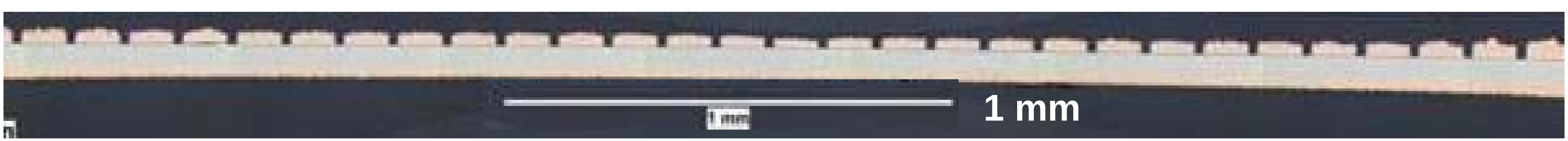
4. Remove remaining photoresist

5. Wet etch silver and HTS

X. Zhang and V. Selvamanickam, US 7,627,356

One approach to make *fully*-filamentized coated conductor

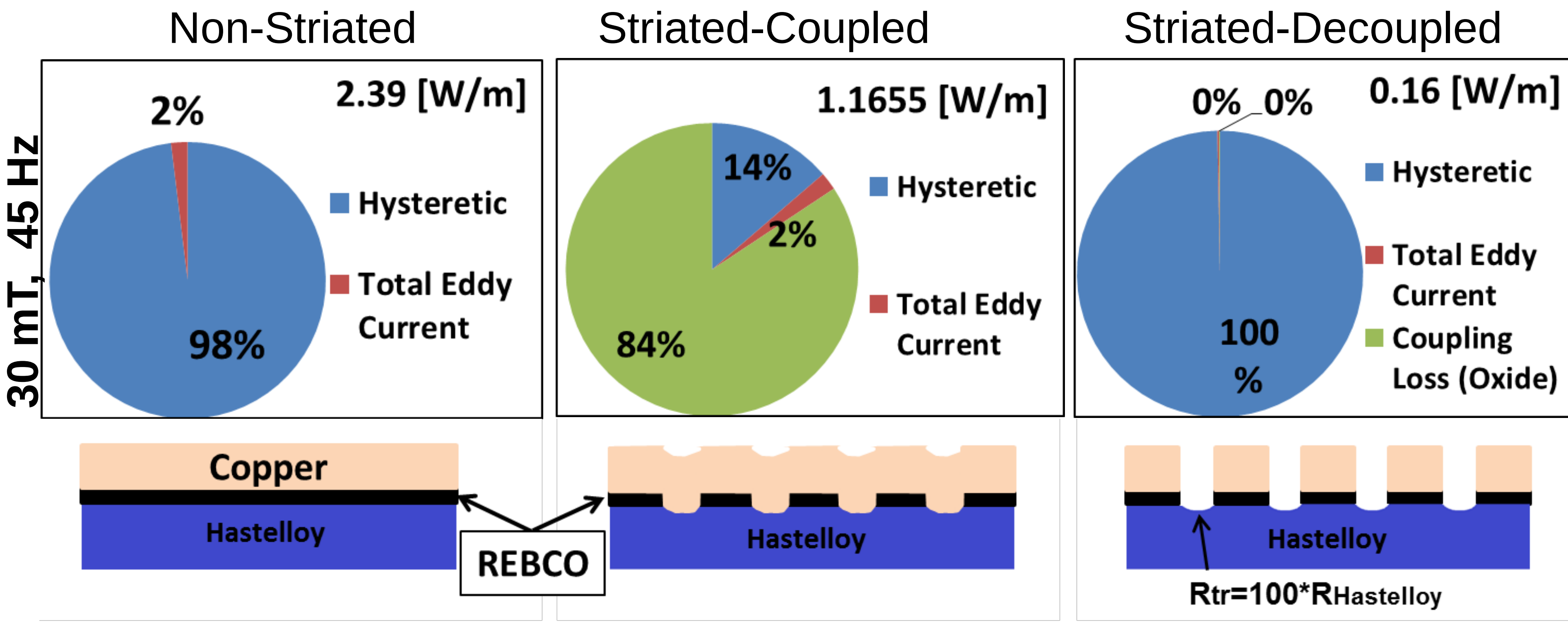




Fully-filamentized coated conductor demonstrated, but still involves etching

X. Zhang and V. Selvamanickam, US 7,627,356

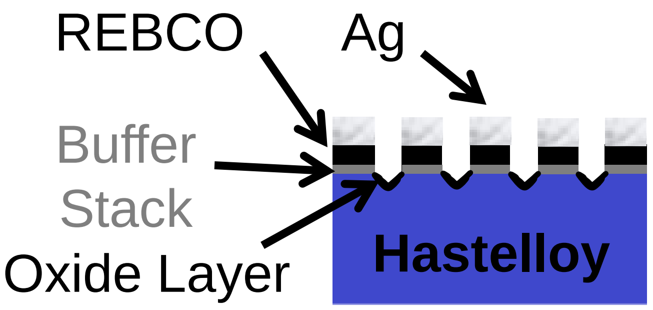
Individual Contribution of Loss Mechanisms to Total Magnetization AC Loss

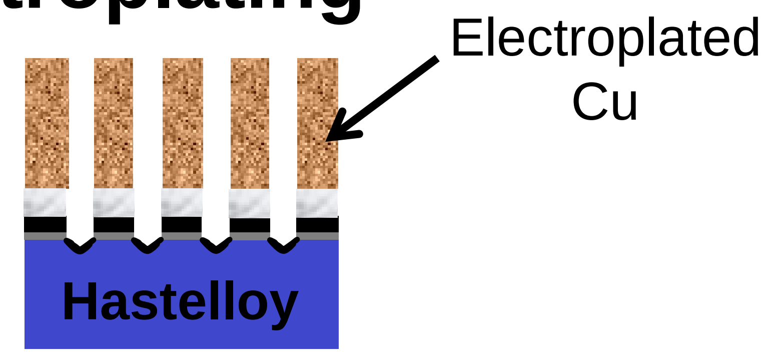


Filamentization is desired for reduction of AC loss, but coupling loss can be unacceptable. So the total loss can reach or exceed the level that is the case before striation.

This suggests that the stabilizer layer has be striated along with superconducting layer in order to prevent coupling loss

Fully-filamentized conductor by mechanical scribing and selective electroplating





Mechanical Scribing + oxygenation

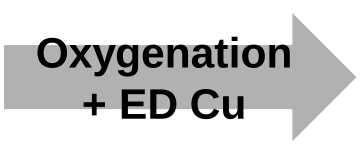
Selective Cu Electroplating

Non-striated

12 mm wide Ag sputtered tape

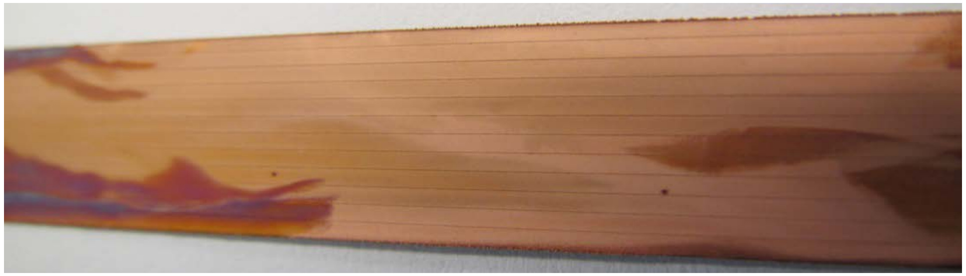
12-filament , 12 mm wide tape

12-filament tape with electroplated Cu

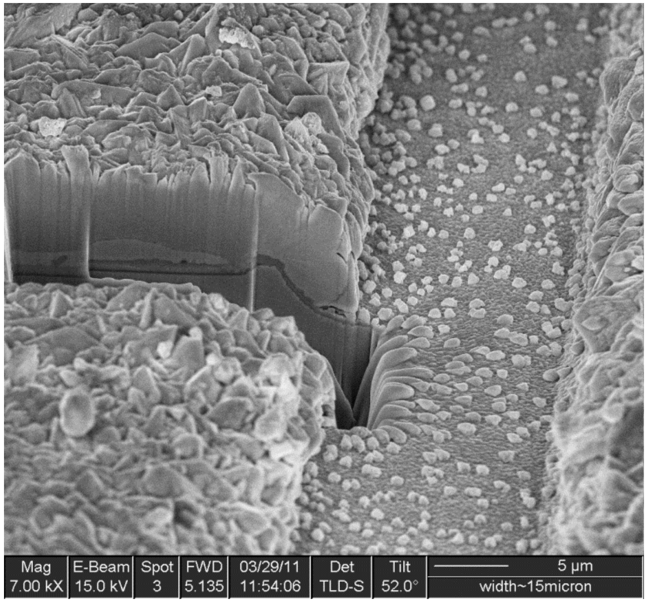


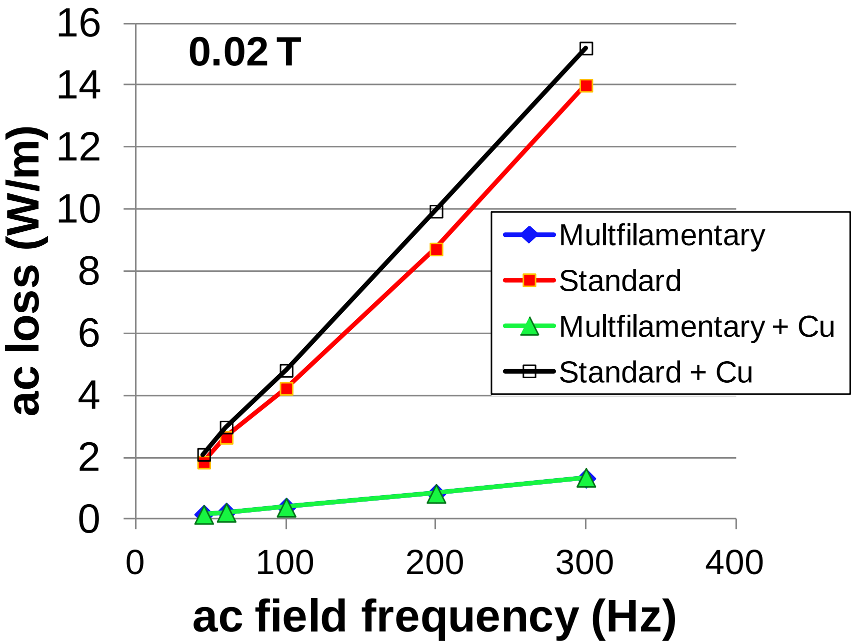
I. Kesgin, G. Majkic, and V. Selvamanickam, “A simple, cost effective top-down method to achieve fully filamentized low AC loss 2G HTS coated conductors” , *Physica C.* **486,** 43–50 (2013)

Fully-filamentized conductor show excellent ac loss reduction



12-filament wire with 10 µm thick fully striated copper stabilizer using benign copper chemistry

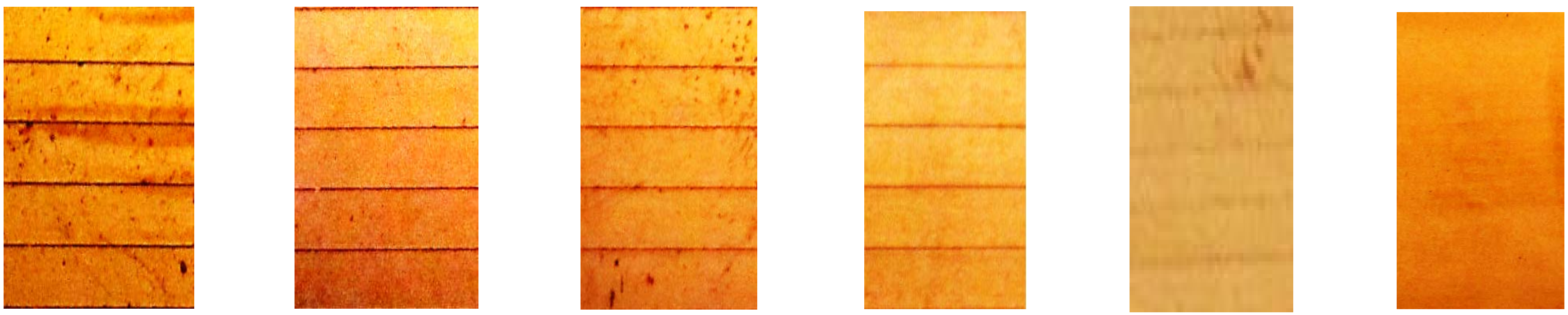




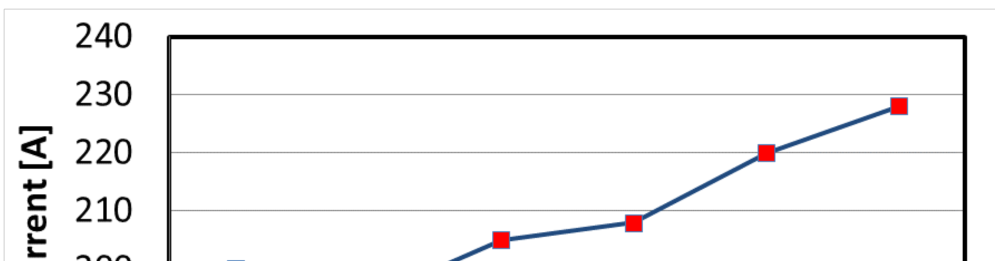
*AC loss of 12-fiament wire at 60 Hz is **13 times** lower with copper stabilizer, at higher fields*

Investigated selectively electroplated copper thickness & coupling effects

S1 S2 S3 S4 S5 S6



~10 µm ~20 µm ~30 µm ~44 µm ~36 µm ~33 µm



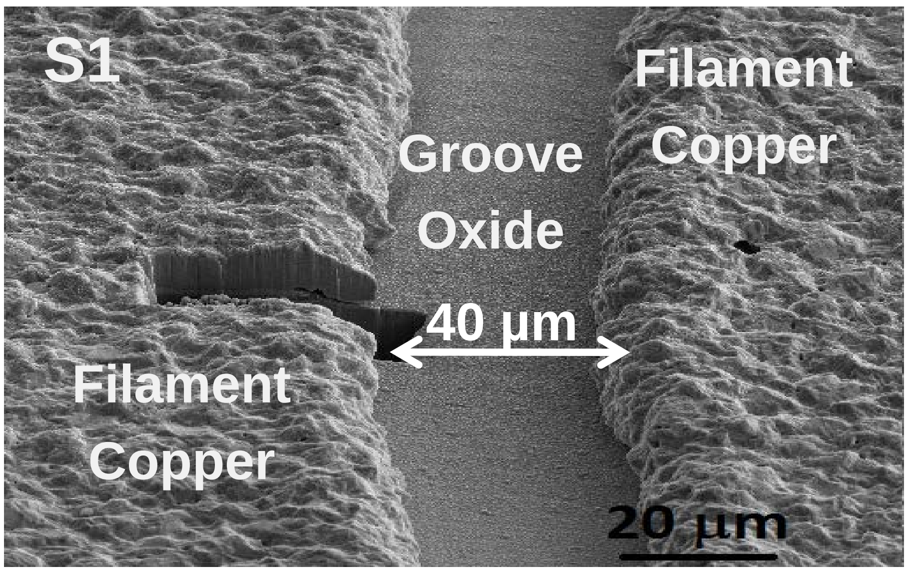
[redacted]

S5: *Fully coupled* Mechanically scribed, no oxidation and Cu plated

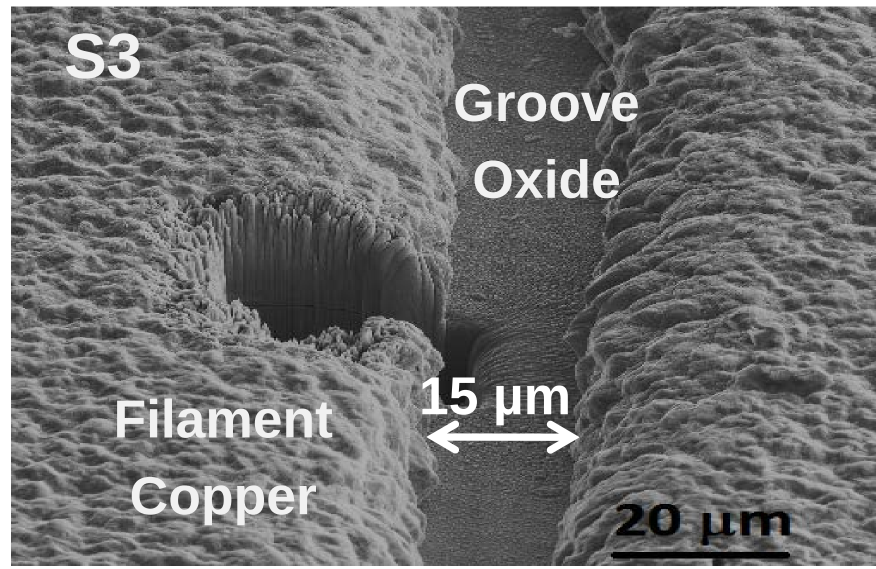
S6: *No filamentization*

I. Kesgin, G. Majkic, and V. Selvamanickam, *IEEE Trans. Appl. Supercond.* **23,** 5900505 (2013)

Sideways growth of electroplated copper reduces groove width between filaments

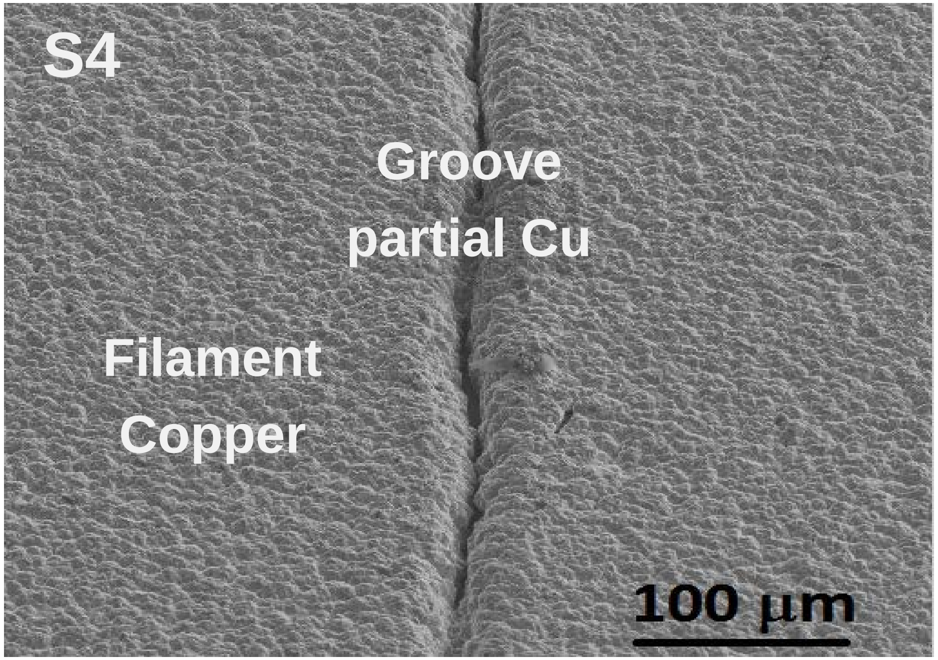


No coupling
Mechanically scribed, oxidized and Cu plated **(~ 10 μm)**

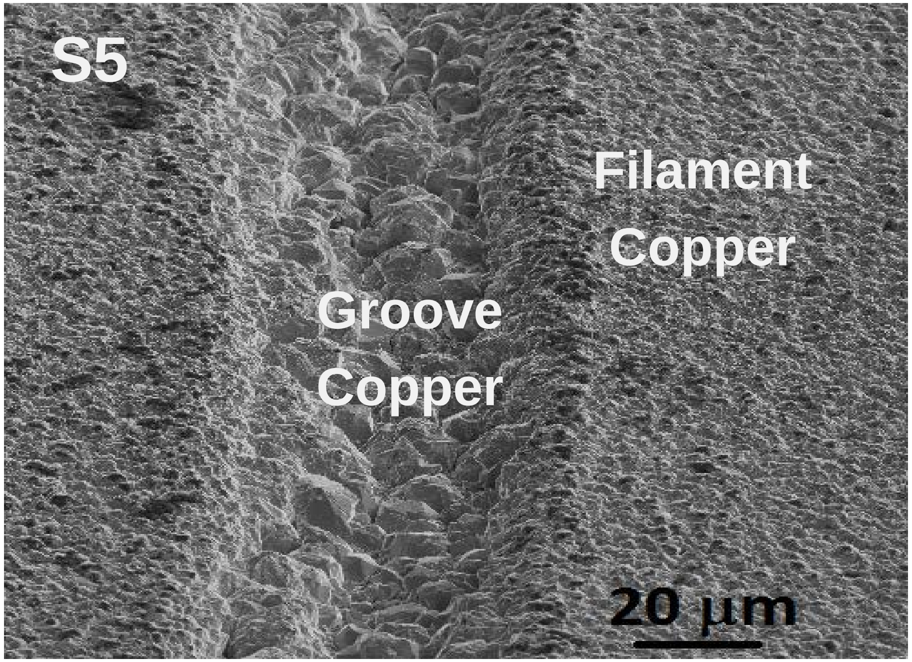


No coupling
Mechanically scribed, oxidized and Cu plated **(~ 30 μm)**

Partially and fully-coupled filamentized tape with copper stabilizer

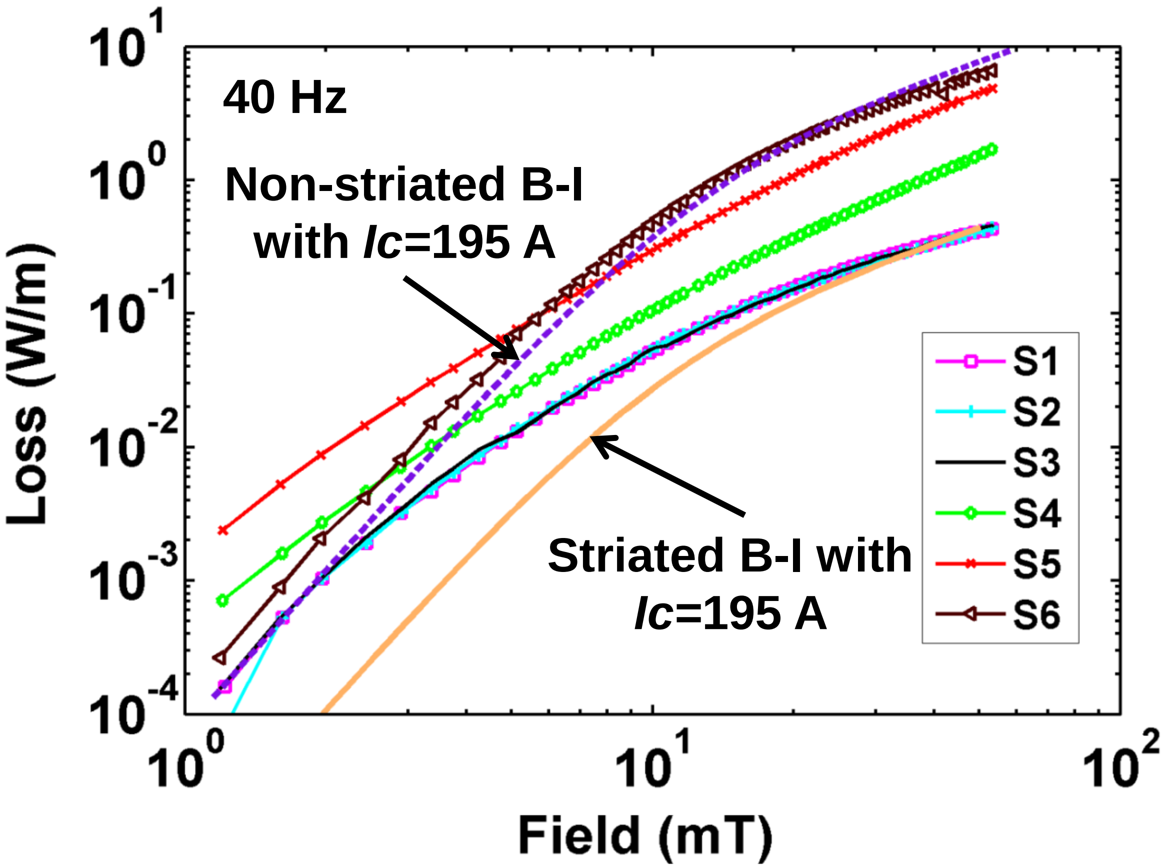


Partially coupled
Mechanically scribed, oxidized and Cu plated **(~ 44 μm)**



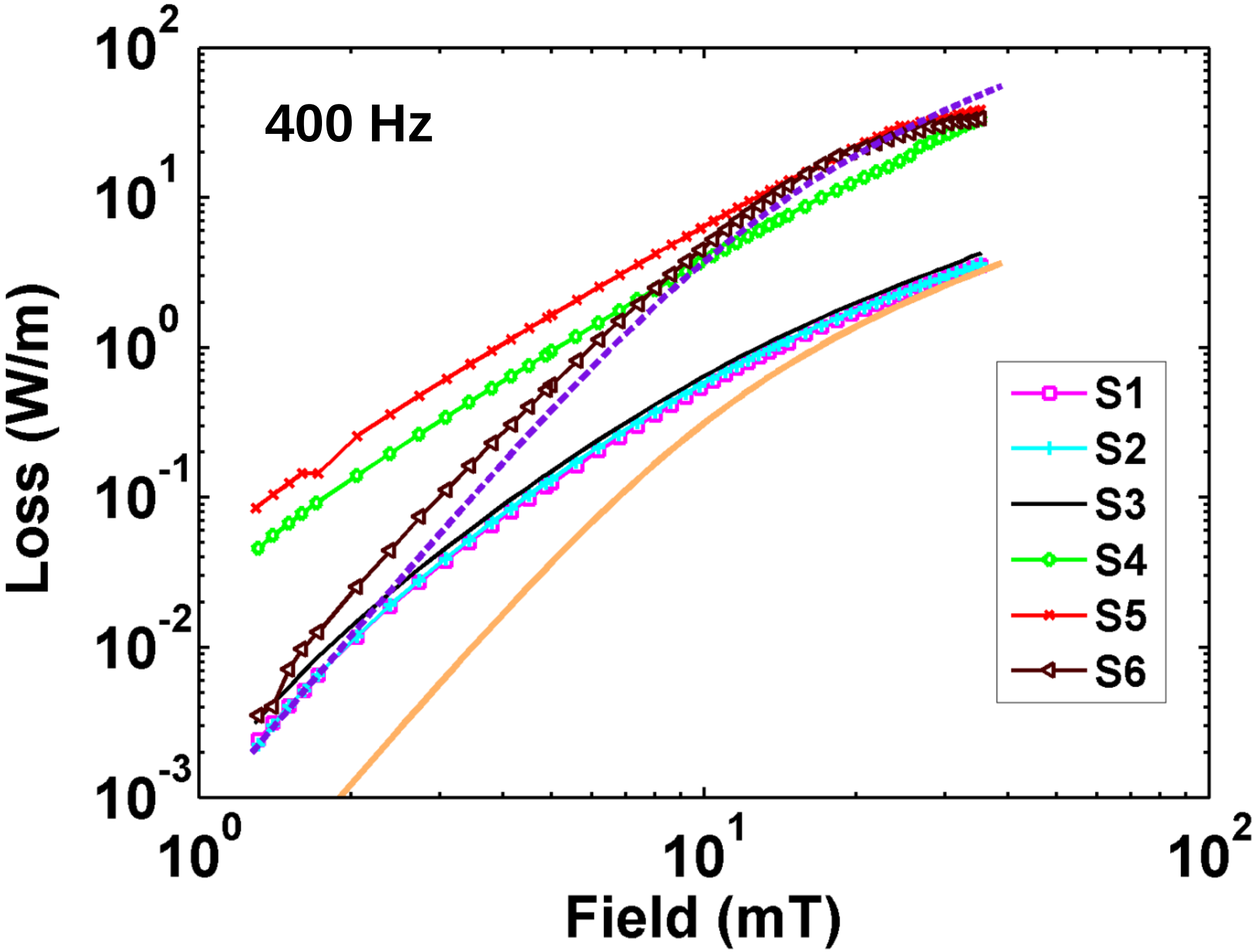
Fully coupled
Mechanically scribed, **no oxidation** and Cu plated (~ 33 μm)

No significant loss contribution up to 30 μm stabilizer in fully-filamentized conductor at 40 Hz

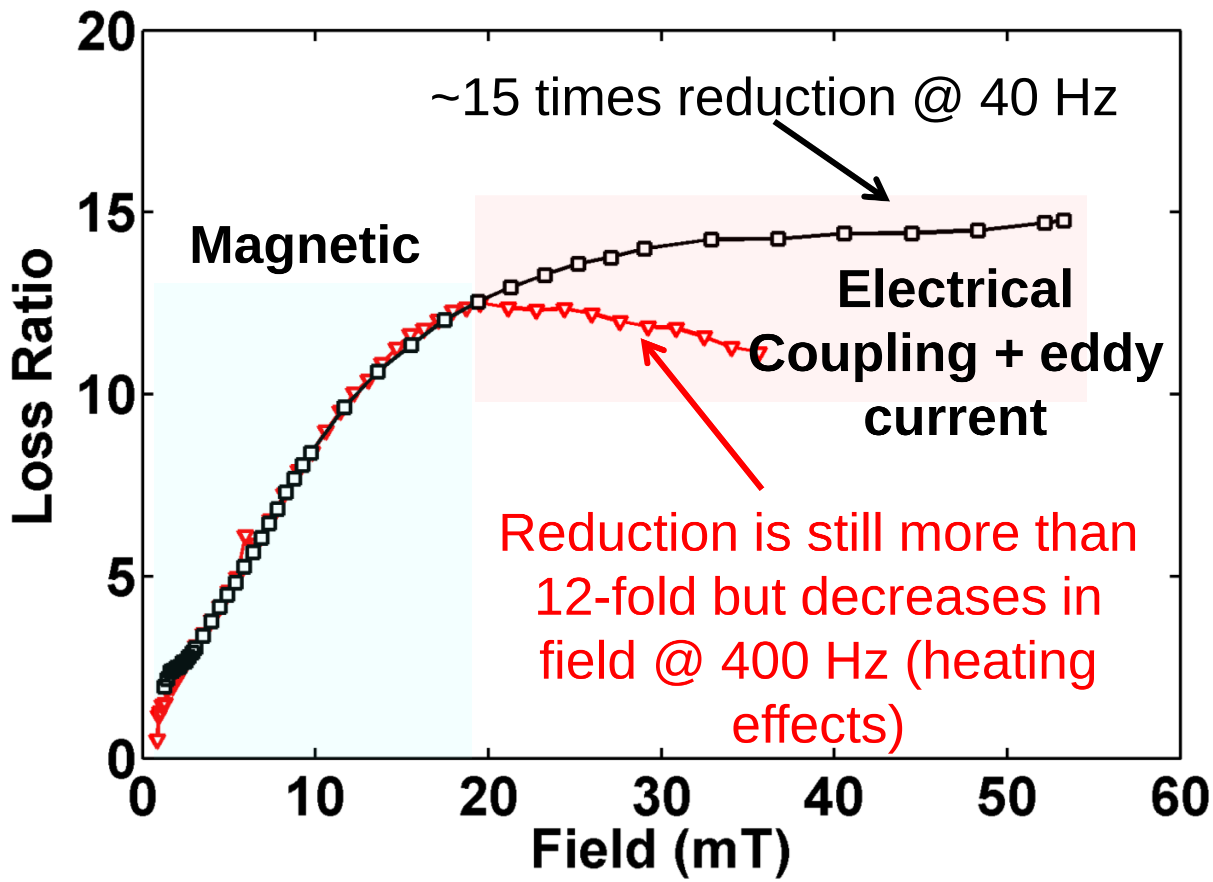


- *15-fold ac loss reduction even with 30 μm Cu stabilizer*
- *Lower ac loss reduction with 40 μm Cu stabilizer*

No significant loss contribution up to 30 μm stabilizer in fully-filamentized conductor even at 400 Hz

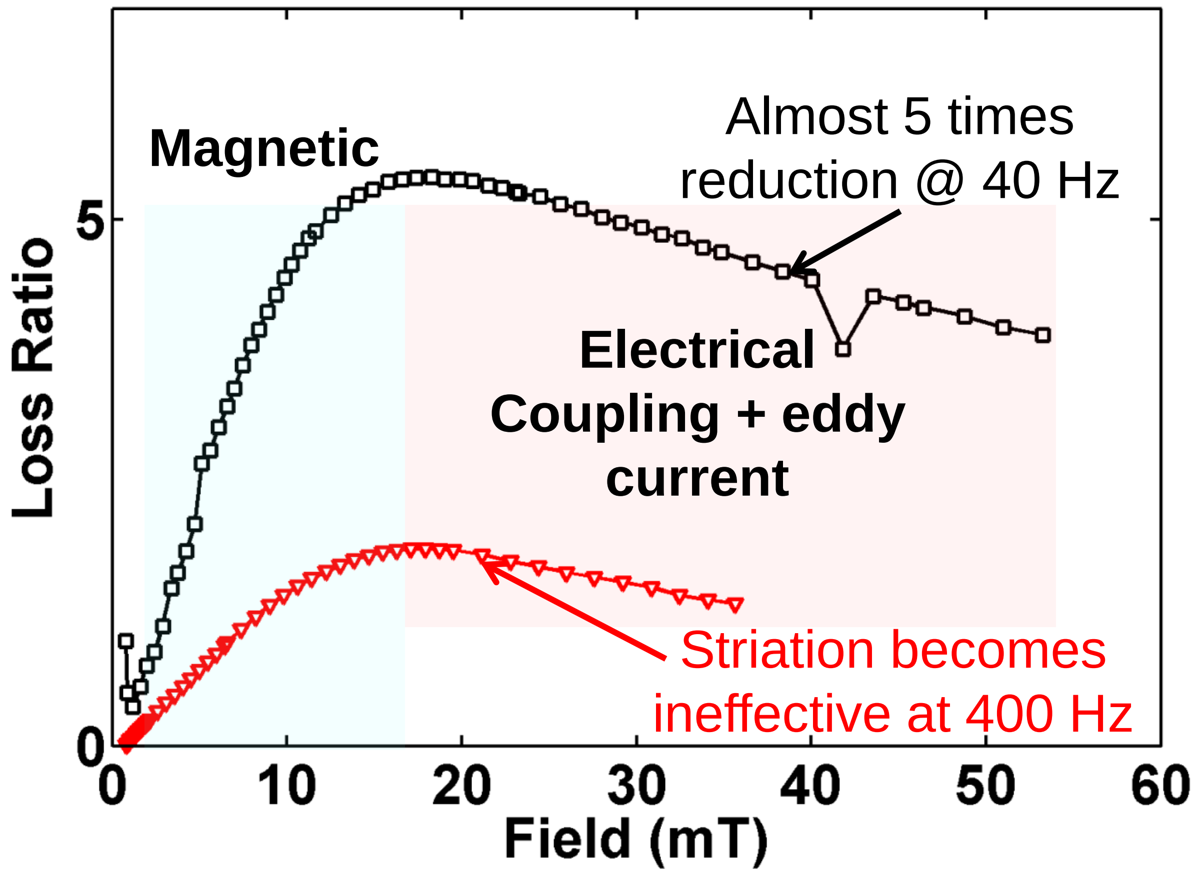


15-fold ac loss reduction in fully-filamentized conductor with up to 30 μm stabilizer



Loss ratio: ac loss of filamentized conductor S3/ac loss of non-striated conductor S6

5-fold ac loss reduction at 40 Hz even in partially-coupled filamentized conductor with 44 μm stabilizer



Loss ratio: ac loss of filamentized conductor S4/ac loss of non-striated conductor S6

Summary : Low ac loss HTS conductors

- Selective electroplating has been proven to achieve fully-filamentized coated conductor even with thick copper stabilizer.
- Coated conductor with up to 30 µm copper stabilizer can be fully-filamentized without any coupling.
  - 15-fold ac loss reduction achieved compared to reference non-striated coated conductor with ~ 30 µm copper stabilizer
- Coated conductor with 40 µm copper stabilizer can be fully-filamentized with partial coupling (due to sideways growth of copper across groove)
  - 5-fold ac loss reduction achieved at 40 Hz even with partial coupling compared to reference non-striated coated conductor
  - Fully-filamentized coated conductor with no coupling can be achieved even with thicker copper stabilizer using wider grooves
- Fully-coupled filamentized conductor (conductive material in groove) shows higher ac loss than non-striated conductor: in this case striation makes the situation worse!

We are continuing to advance HTS coated conductors to overcome challenges in commercial applications

Challenge	Advancements underway
Decrease wire cost	Enable industry to improve wire performance Enable industry to improve process efficiency
Increase production volume	Innovative manufacturing equipment
Improve manufacturing yield	Novel process control, Quality control tools Quality Assurance tool development
Product reliability	Test facilities for wires and devices

For more information :

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