U.S. Department of Energy

Office of Electricity Delivery and Energy Reliability

Recent HTS Activities in the US

IEA HTS Executive Committee Meeting
Milan, Italy
June 19, 2014

Debbie Haught
Program Manager
Office of Electricity Delivery and Energy Reliability (OE)

Overview

Major HTS wire manufactures

- AMSC (YBCO 2G coated conductors)
- SuperPower (YBCO 2G coated conductors)
- STI (YBCO 2G coated conductors)
- Oxford Instruments Superconducting Technology (Bi-2212 wires)
- Hyper Tech (MgB_2 wires)

DOE Projects

- Office of Electricity OE: Smart Grid HTS-FCL transformer
- Office of Energy Efficiency and Renewable Energy EERE: Offshore wind generator
- Advanced Research Projects Agency Energy ARPA-E: wires for wind generators, superconducting magnetic energy storage
- Office of Science: High Energy Physics HEP, Fusion Energy Sciences FES, Small Business Innovative Research SBIR: wires and magnets

Other Federal Agencies

- DHS, Army, Air Force, Navy, NSF, NASA, NIH

State Agencies

- NYSERDA

Application Optimized Amperium Wire

Focus on Operating Conditions and Mechanical Requirements

Sec. 1 — LN_2/Low Field AC Applications

Power Cables

Stand-Alone FCL

- Brass and SS lamination for cables and FCLs
- Optimized for I_c in self-field and AC loss
- Mechanicals for cable-wind tolerance

New 1.2 μm HTS layer + Optimized Heat Treatment (HT) for Higher Current

Sec. 2 — Low Temperature/High Field DC Applications

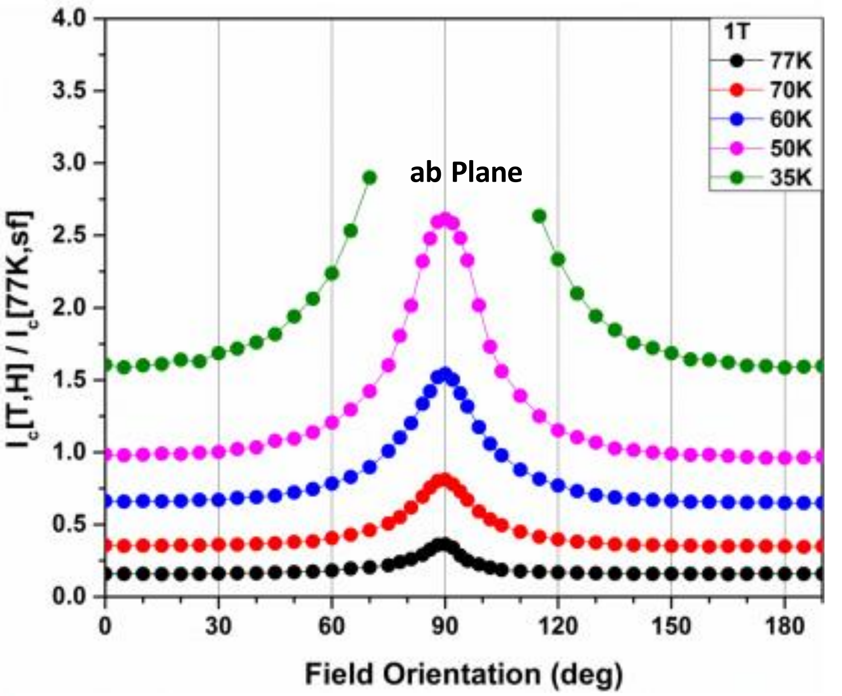
Motors

Wind Turbines/Generators

- Copper lamination for rotating machines
- I_c optimized for (30K, 1.5-2 T)
- Mechanicals for high c-axis strength

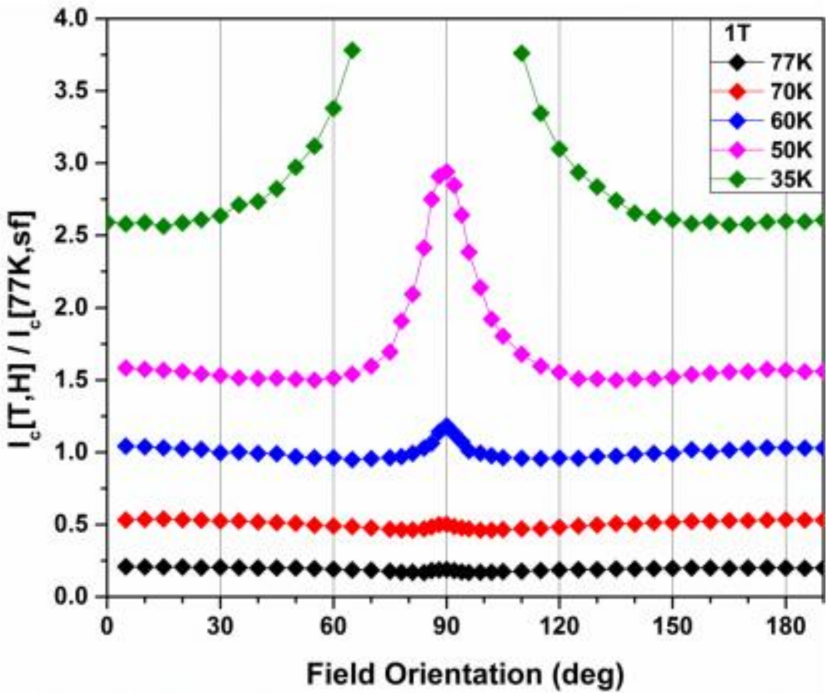
New 1.2 μm HTS Wires Optimized for Application Specific Operating Conditions

1.2 μm Cable Wire



High temperature, low field applications

1.2 μm Coil Wire

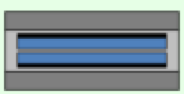
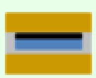


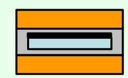
Low temperature , perpendicular field applications

N. Strickland
Callaghan Innovation (previously IRL)

Amperium Wire Architectures

Application specific mechanical packaging

Wire Type	Architecture	
Standard Amperium Wires *See www.AMSC.com*		
SS Laminated 12		**Single HTS, 3-layer 12 mm wide 75 µm thick SS**
SS Laminated 12 Double Insert		**Double HTS, 4-layer 12 mm wide 75 µm thick SS**
Brass Laminated 4.4		**Single HTS, 3-layer 4.4 mm wide 150 µm thick brass**

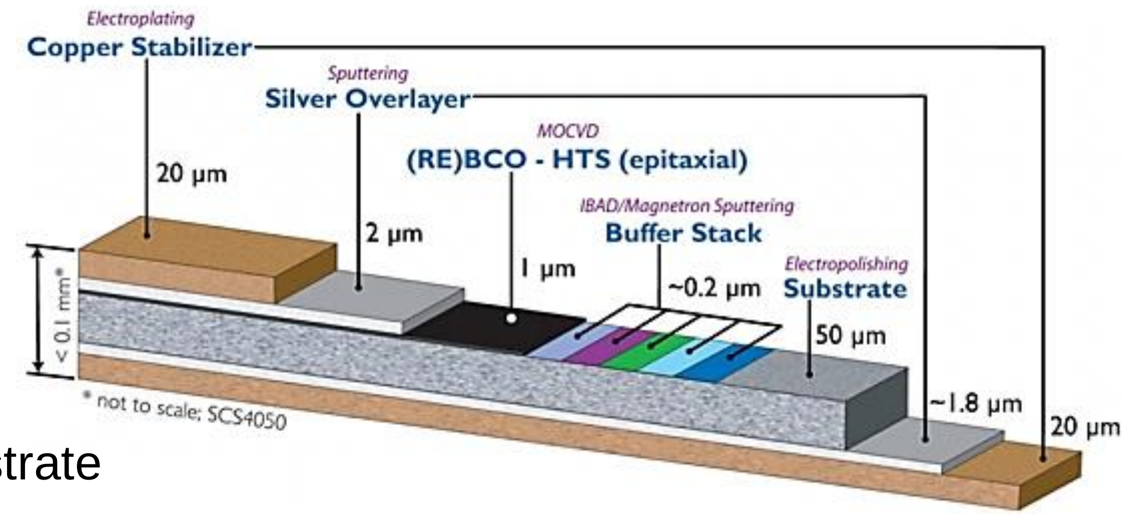
Wire Type	Architecture	
Standard Amperium Wires *See www.AMSC.com*		
Copper Laminated 4.8		**Single HTS, 3-layer 4.8 mm wide 50 µm thick copper**
Copper Laminated 12		**Single HTS, 3-layer 12 mm wide 50 µm thick copper**

Amperium® Wire Summary

- **Resistive FCL Wire**
  - Single and double HTS architectures
  - Range of currents: ~250A and ~500A
- **Cable Wire**
  - Short length wires demo’d with RABiTS c
  - 1.2μm HTS + HT Optimization for I_c >160A
  - Low ac loss at low current with Non Magnetic Substrate
  - Resilient to simulated cable winding
- **Coil Wire**
  - 1.2μm HTS + HT Optimization for 20-30% boost in I_c 30K, 1-2T
  - Compatible with high I_c long length production process
  - Tolerant to c-axis stress up to 40 MPa - Not prone to delamination

SuperPower's ReBCO superconductor with artificial pinning structure provides a solution for demanding applications

- **Hastelloy® C276 substrate**
  - high strength
  - high resistance
  - non-magnetic
- **Buffer layers with IBAD-MgO**
  - Diffusion barrier to metal substrate
  - Ideal lattice matching from substrate through ReBCO



- **MOCVD grown ReBCO layer with BZO nanorods**
  - Flux pinning sites for high in-field I_c
- **Silver and copper stabilization**
- **Configurations can be tailored to specific applications**
  - Substrate thickness
  - Ag/Ag alloy and copper thickness
  - HTS composition (Advanced pinning (AP) / Cable formulation (CF)

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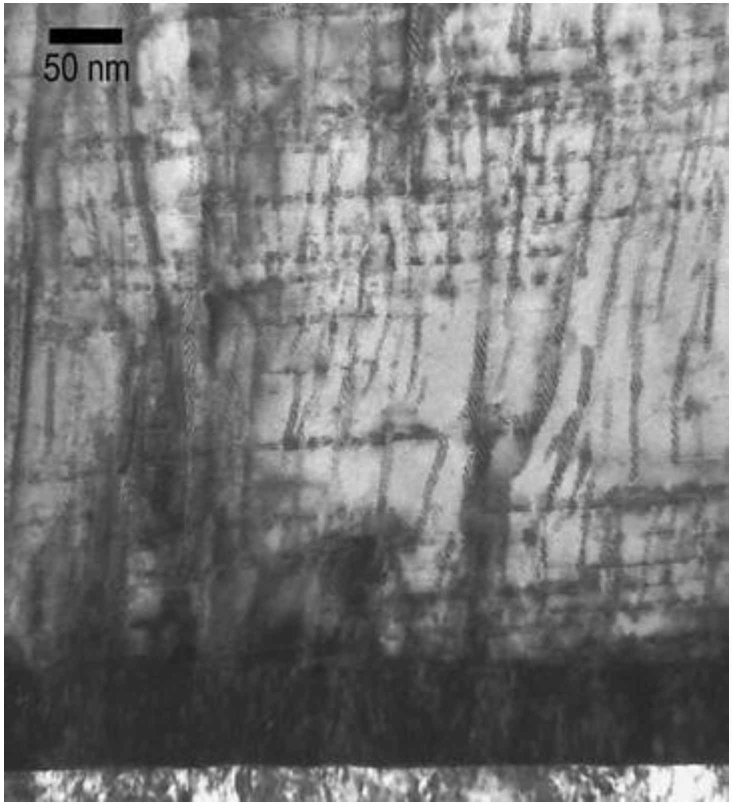
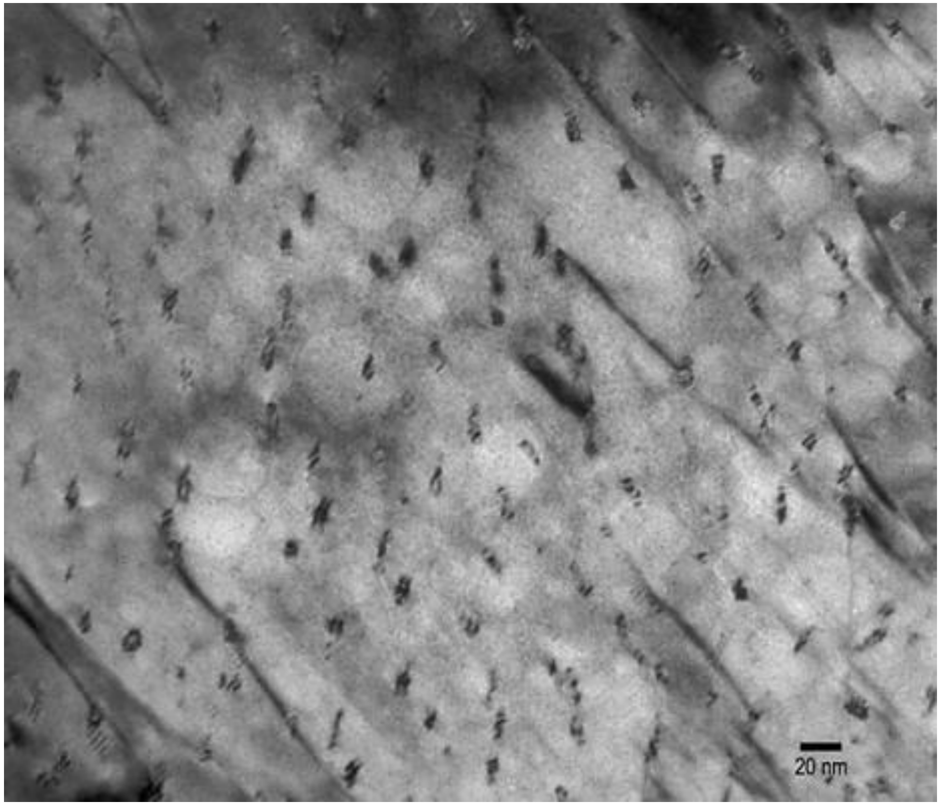
Microstructure of production MOCVD HTS wires with standard 7.5% Zr doping

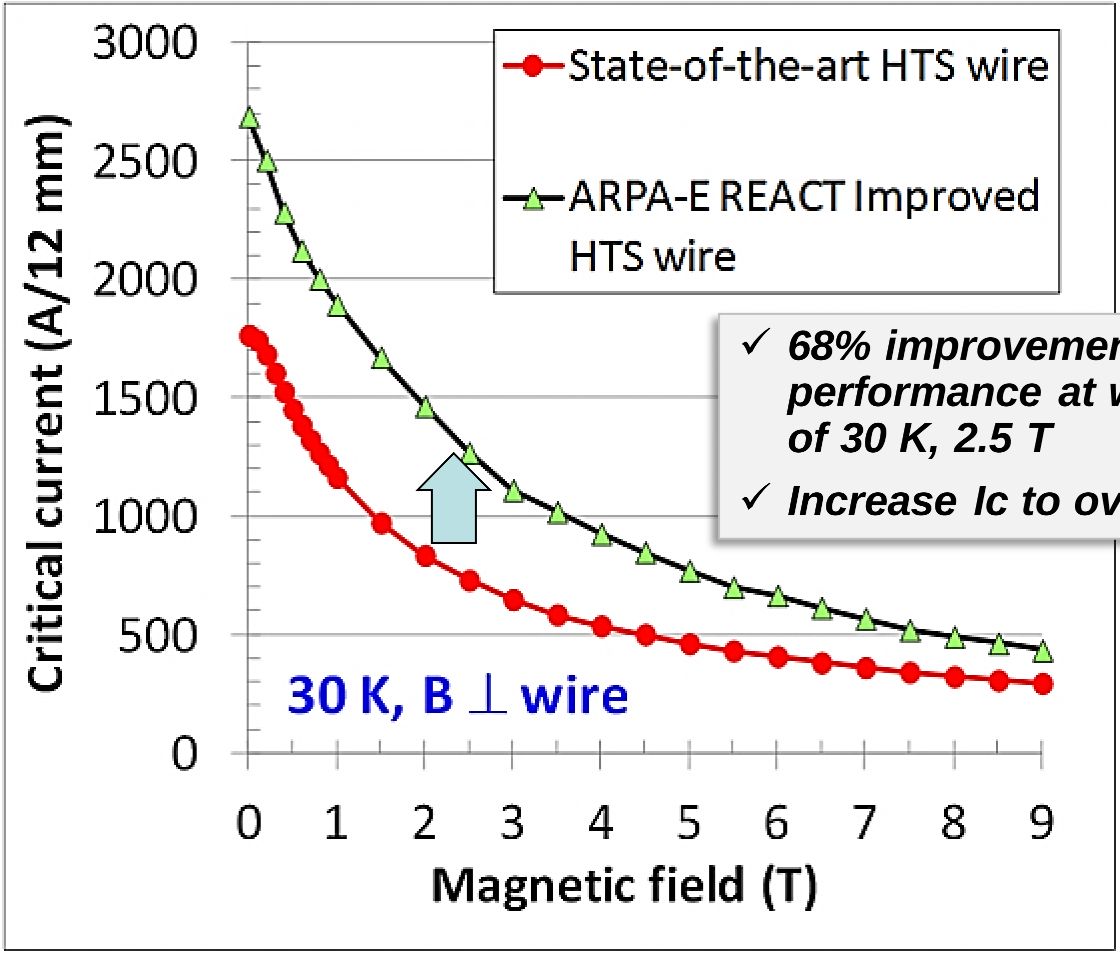




5 nm sized, few hundred nanometer long BZO nanocolumns with ~ 35 nm spacing created during in situ MOCVD process with 7.5% Zr

Technology development programs are focused on next level of product improvements

- Increase base I_c
- Increase lift factor
- Increase wire strength
- Reduce ac losses



- ✓ *68% improvement demonstrated in wire performance at wind generator operating condition of 30 K, 2.5 T*
- ✓ *Increase Ic to over 1,500A (demo in mid 2014)*

Structured, well-timed process for transfer of these advancements into production (by end of 2014)

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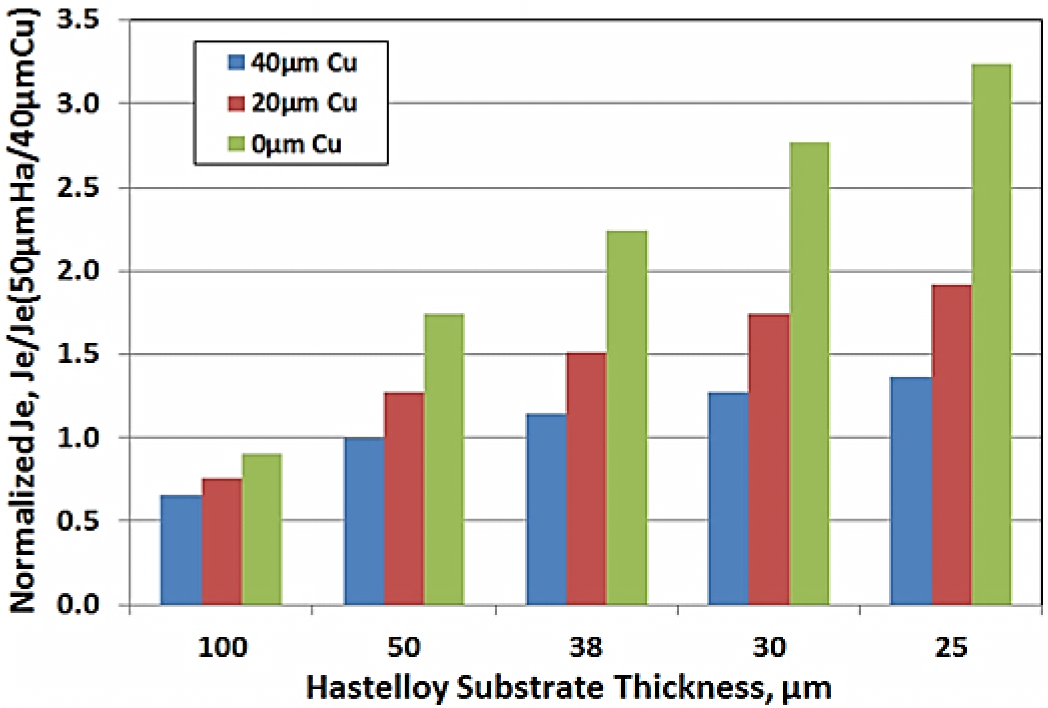
Thinner substrates offer improved current density while still providing strong mechanical support

- **Current 2G HTS production material based on either 50 or 100μm Hastelloy® C276 substrate**
  - For standard Cu thickness of 40μm total, the conductor thickness of current production 2G HTS conductor is ~ 0.095mm.
- **Thinner Hastelloy® C276 of 25, 30 and 38μm thicknesses are being evaluated**
  - For standard Cu thickness of 40μm total on a 25μm Hastelloy® C276 substrate, conductor thickness is reduced to ~70μm
  - This implies a 36% increase in current density
- **Available second half of 2014**



Baseline is 40 micron thick copper stabilizer

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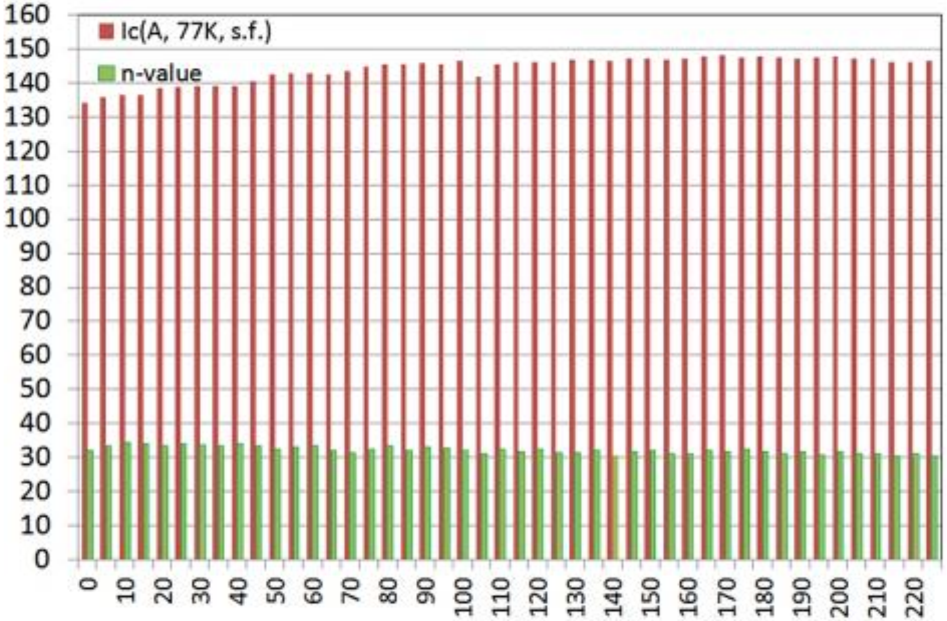
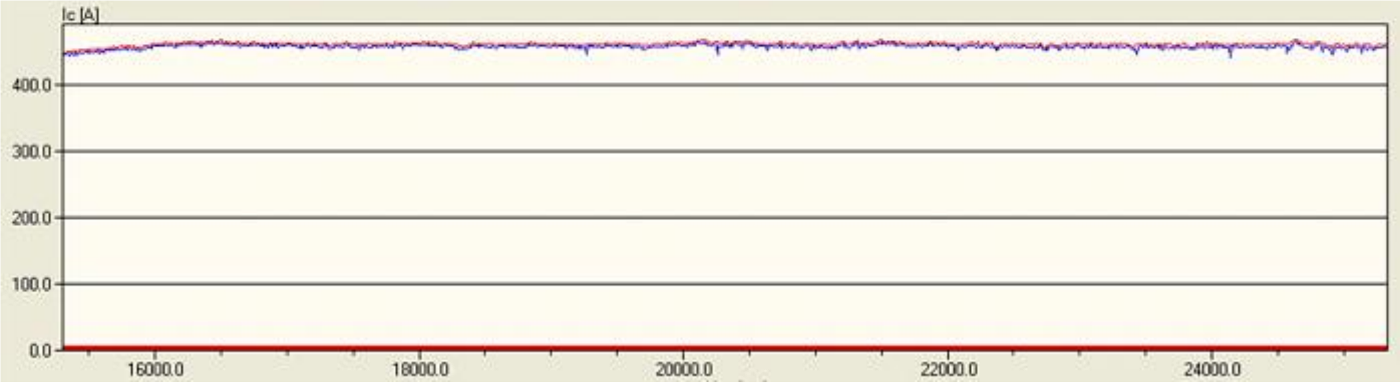
Precision process control led to highly uniform performance

I_c uniformity along length, 4mm tape (4-probe transport measurement)



I_c uniformity along length (TapeStar), 12mm tape

- Magnetic, non-contact measurement
- High spacial resolution, high speed, reel-to-reel
- Monitoring I_c at multiple production points after MOCVD
- Capability of quantitative 2D uniformity inspection



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Leading Superconducting Innovation

Attacking large opportunity with Conductus® wire strategic initiative

1987

High Temperature Superconducting (HTS) Technology Development

Key competitive advantage

HTS Product Release

Only company to successfully commercialize HTS products for RF electronics. Established leadership with best-in-class HTS products

HTS Manufacturing High Volume

Advanced proprietary HTS deposition process in full scale manufac-turing production. 6,000 systems deployed with Verizon Wireless and AT&T

Conductus® HTS Wire Production, New Manufacturing Facility in Austin, TX

Manufacturing of second generation (2G) HTS wire with industry leading performance

CONDUCTUS® Superconducting Wire

Today

Technology Transfer and Partnerships

Wireless Product Business

Resonant LLC

Cryogenic Cooler Business

2012 and Beyond

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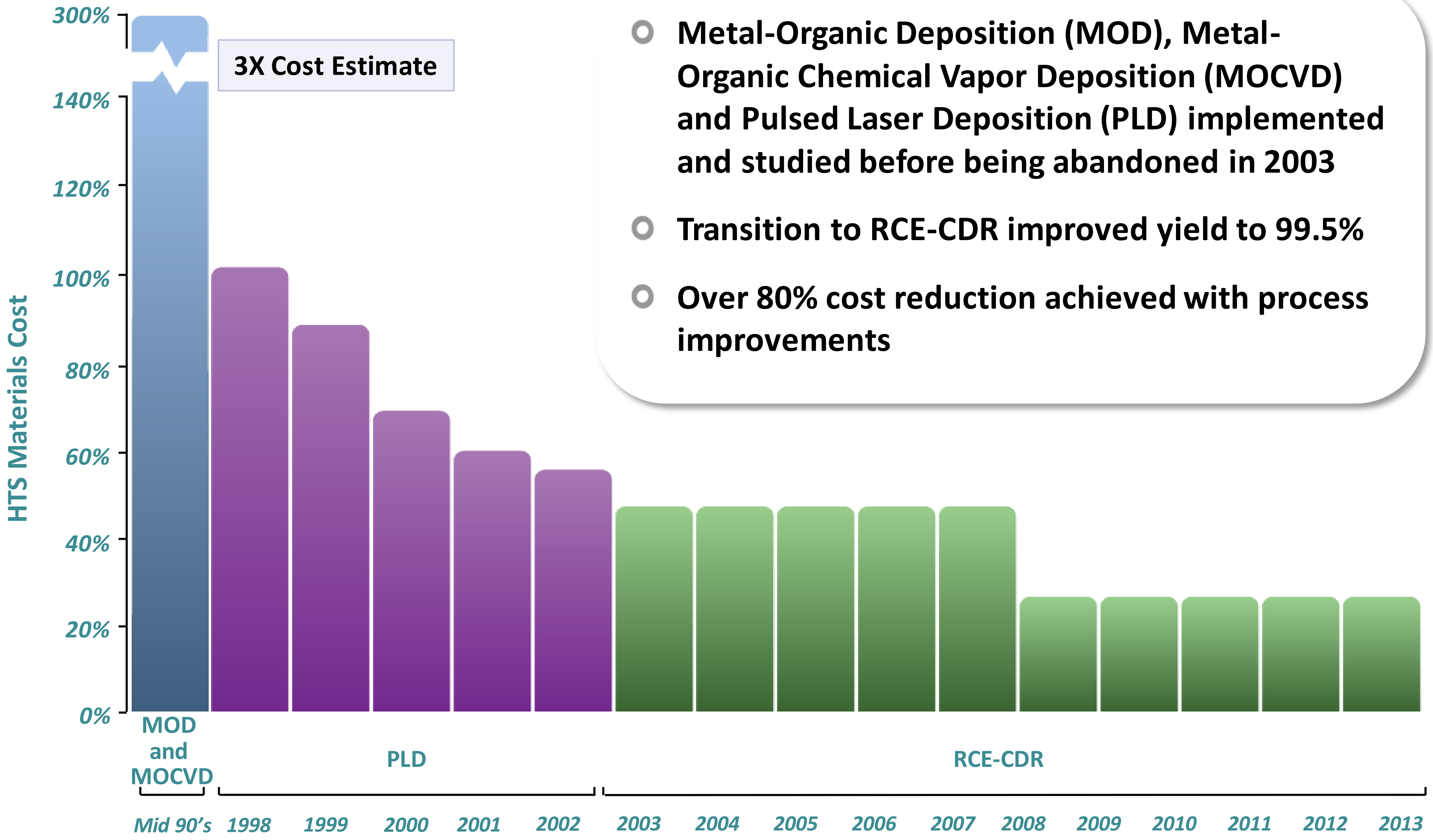
STI SUPERCONDUCTOR TECHNOLOGIES INC.

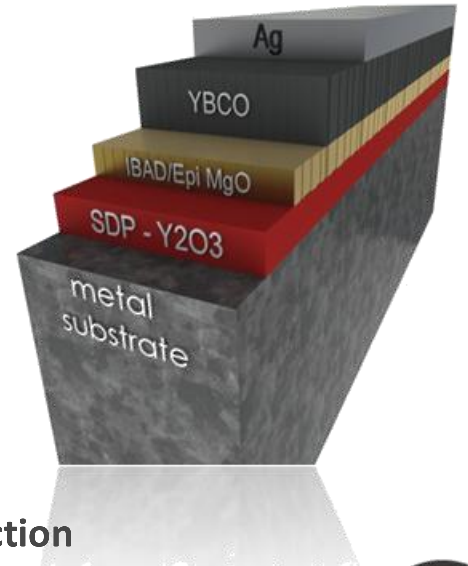
HTS Materials Cost Reduction Over Time



- **Metal-Organic Deposition (MOD), Metal-Organic Chemical Vapor Deposition (MOCVD) and Pulsed Laser Deposition (PLD) implemented and studied before being abandoned in 2003**
- **Transition to RCE-CDR improved yield to 99.5%**
- **Over 80% cost reduction achieved with process improvements**

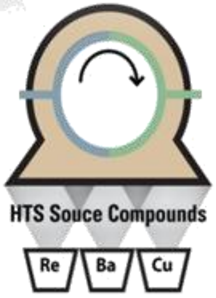
STI's Conductus Wire - Three Step Approach

- **SDP – Solution deposition planarization**
  - **Atmospheric wet coating which provides an amorphous ceramic overlayer**
  - Low-cost solution process
  - Diffusion barrier and planarization layer
  - No need to polish metal substrate tape
  - Compatible with many alloys



- **IBAD + Epi MgO – Ion beam assisted deposition**
  - **The thinnest, fastest template formation**
  - Requires only 50 nm MgO layers for crystallinity
  - Fast process
  - In-situ process in a 2 chamber deposition system

- **RCE-CDR – Reactive coevaporation / cyclic deposition and reaction**
  - STI has developed the RCE-CDR technique for >15 years in wireless filters and
  - shown it to be a low-cost & high-yield production technique for HTS deposition
  - Enables growth directly on MgO layer and can be used with optional buffer
  - In-situ process in a single deposition system
  - Elemental raw material - low cost
  - Large-area deposition



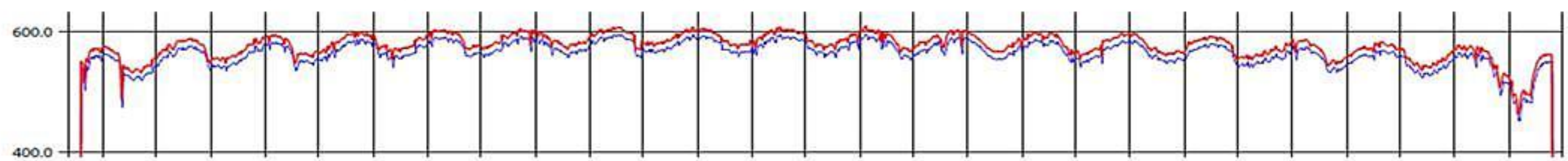
Low-Cost HTS Coated Conductor Scale Up

- **STI's Coated Conductor is inexpensive, high-yield, and scalable**
  - Piece lengths and current continue to increase
  - Great compositional uniformity
- **Conductus wire production in 2014 – Project funded to capacity of 750,000m/yr**
  - SDP and IBAD production systems – Complete
  - 1000M RCE System is being built now – Production ramp in 2H2014

SUPERCONDUCTOR TECHNOLOGIES INC.

Superconductor Technologies Inc. Achieves Conductus Wire Performance Milestone

AUSTIN, Texas, April 29, 2014- STI successfully completed a full pilot production run of Conductus® wire achieving a minimum current of 500 Amps per centimeter (A/cm) width at 77k.



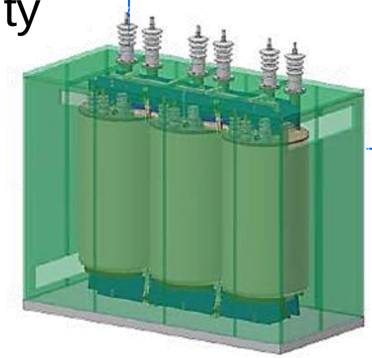
HTS Fault Current Limiting Transformer

SuperPower Inc. A Furukawa Company

Program: OE Smart Grid
Award: $ 10.7 Million USD ($21.5 Million USD Tot)
Duration: Feb '10 – Feb '15
Partners: SuperPower, SPX Waukedha, Univ. Houston, Southern Cal Edison

Goal: Design, develop, manufacture and install a SmartGrid-compatible SFCL Transformer on a live grid utility host site

- 28 MVA 3-phase FCL medium power utility transformer (69 kV / 12.47 kV)
- To be situated within Southern California Edison's Smart Grid site in Irvine, CA – expecting 2 years of grid operation
- First transformer to use significant amounts of 2G superconducting wire



✓ Conductor design and winding technology have advanced to the point where phase winding will begin in the first half of 2014.

✓ Transformer design is completed. Vendors are being sourced or have already been signed to deliver components.

DHS' Resilient Electric Grid (REG) ConEd System

amsc

- Sponsored by DHS as a way to increase urban grid resiliency
  - Successfully tested proving 50% fault current reduction
  - Rated 13.8kV, 95MVA, 4000A
- Phase 1: Develop & prove fault current limiting cable technology
  - Completed
- Phase 2: In grid demonstration cable
  - In process

Homeland Security

Southwire®

Photo courtesy US DOE Oak Ridge National Laboratory

Project Hydra Cable in Type Test

Commercialization requires a significant installation

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Phase II Hydra Project Summary

- HT**S** FCL Cable passed all Industry Qualification tests
- 25 meter cable test results validated FCL performance model predictions
- Equipment procurement and manufacture progressing
- Below grade construction package out for bid
- Construction expected to start in early 2014, followed by equipment installation and commissioning tests
- Operational demonstration will connect two Con Edison substations enabling 13.8kV asset sharing in the power network

Applied Materials SCFCL at Central Hudson

- Applied Materials' SCFCL was recently installed on the Central Hudson grid New York (under a NYSERDA Grant)
  - Commissioning planned for early June
  - Press release has been issued
- 115/14.4kV Substation in Downtown Poughkeepsie, NY (22MVA @ peak)
  - Experiences ~10 faults per year

System Layout – Central Hudson

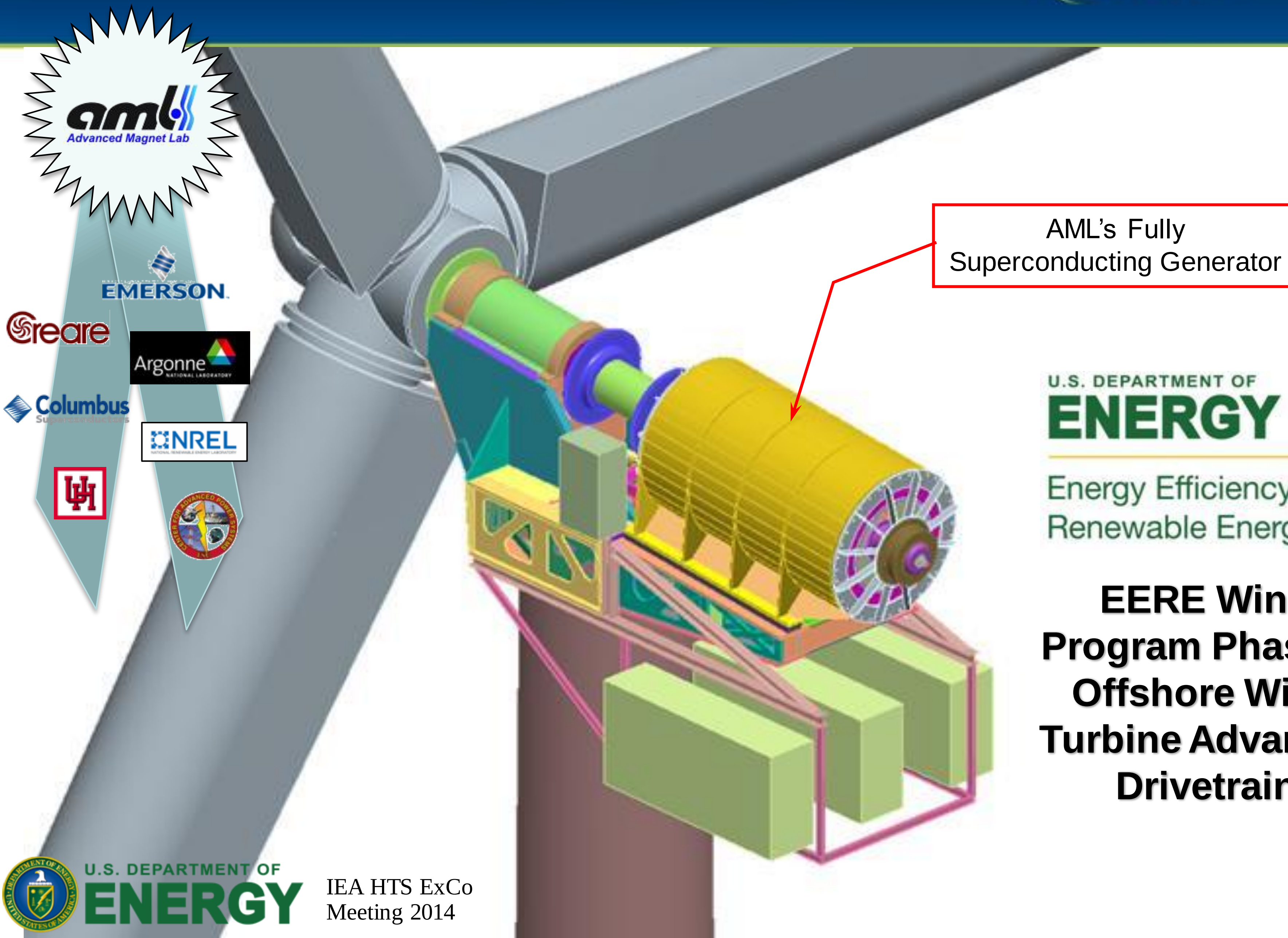
Refrigeration Units (2)
- N+1 Redundant
- Environmental enclosure
- Modular system

Reactor (+CT/PT)
- Installed by Central Hudson
- AMAT monitoring T3 (and T1 for reference)

Superconducting Unit
- Tested at KEMA
- Redundant safety features
- Environmental Cover
- Optimized boil-off

10+ MW Wind Turbine Generator Team

AML Superconductivity and Magnetics



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Energy Efficiency & Renewable Energy

EERE Wind Program Phase II: Offshore Wind Turbine Advanced Drivetrain

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Advanced Research Projects Agency – ARPA-E

Launched in 2009, ARPA-E aims to advance high-potential, high-impact energy technologies that are too early for private-sector investment.

REACT – *Rare Earth Alternatives in Critical Technologies*

Develop cost-effective alternatives to rare earths for motors and generators and encourage existing technologies to use them more efficiently.

GRIDS – *Grid-Scale Rampable Intermittent Dispatchable Storage*

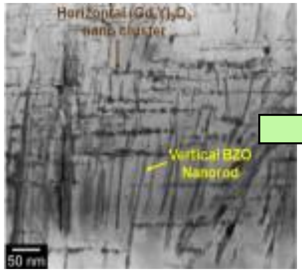
Develop flexible, large-scale storage technologies that can store renewable energy for use at any location on the grid at an investment cost less than $100 per kilowatt hour.

Low-Cost Superconducting Wire for Wind Generators

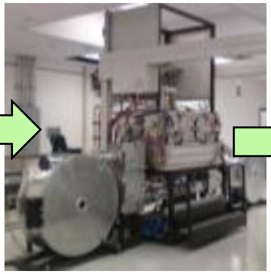
Goal: 4X 2G HTS conductor performance improvement for high power wind generators operating at 30K, 2.5T.

- New pilot MOCVD system set up in UH Energy Research Park to rapidly scale up new technology advances to long-length manufacturing.

Program: ARPA-E REACT
Award: $ 4 Million USD
Duration: Feb '12 – Dec '14
Lead: Univ. Houston
Prof. Venkat Selvamanickam
vselvama@Central.UH.EDU
Partners: SuperPower, NREL
TECO-Westinghouse,
Tai-Yang Research



Engineered Nanoscale defects



4x improved wire manufacturing

High-power, efficient wind turbines

- *Quadrupling 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 for other high-field devices.*

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SuperPower Inc. A Furukawa Company · NREL · Tai-Yang Research · UNIVERSITY of HOUSTON · TECO Westinghouse · arpa·e

4x HTS conductor can enable commercial feasibility of devices

Metric	Now	End of project
Critical current at 30 K, 2.5 T (A/12 mm) (device operating condition)	750	~3,000
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

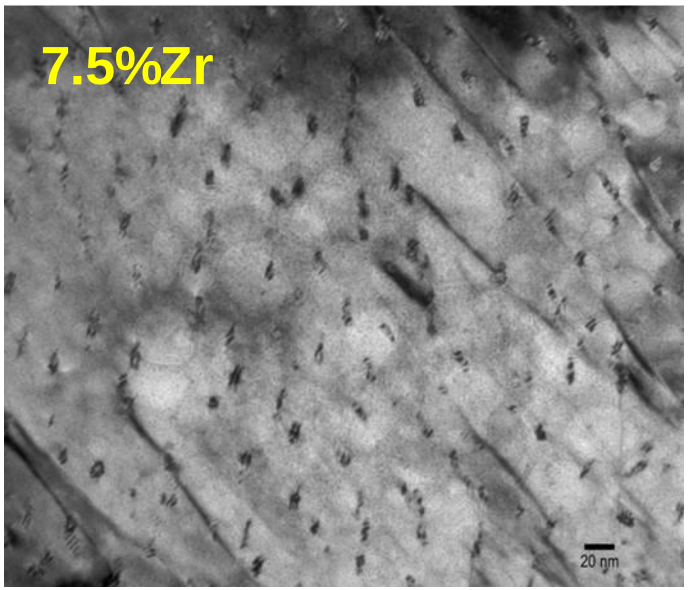
Technical Approach

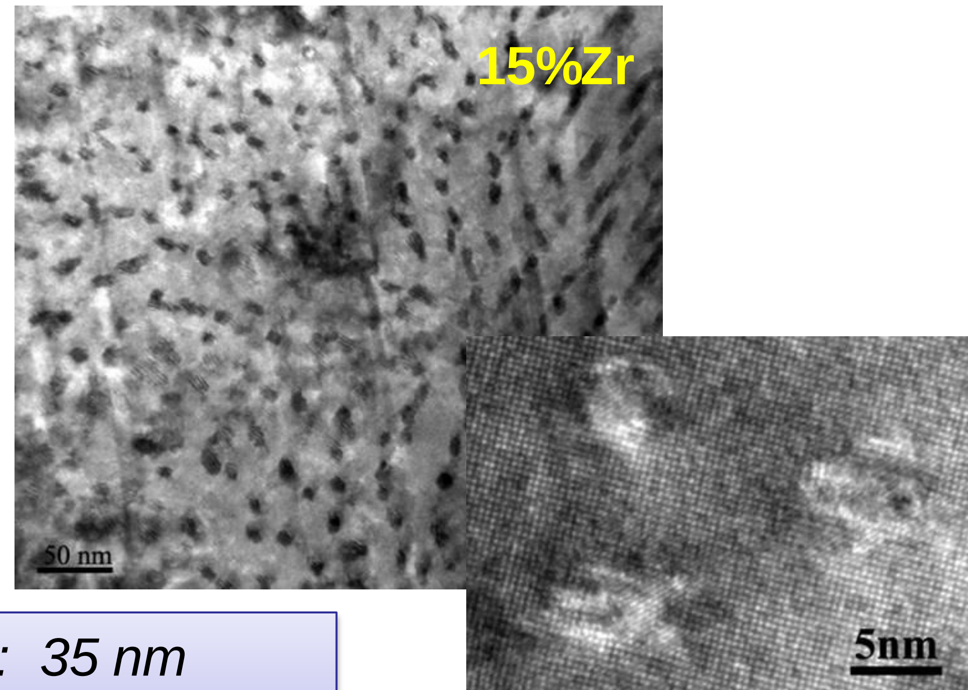
- Quadruple the critical current performance to **3,000 A** at 30 K, 2.5 T:
  - **Doubling the lift factor** [Ic (T, H) / Ic (77K, s.f.)] in I_c of coated conductors at 30 K, 2.5 T by *engineering nanoscale defect structures in the superconducting film.*
  - Additional near **doubling of critical current by thicker supercon0-ducting films** while maintaining the efficacy of pinning by nanostructures.

Increased nanoscale defect density in high Zr content wires

TcSUH

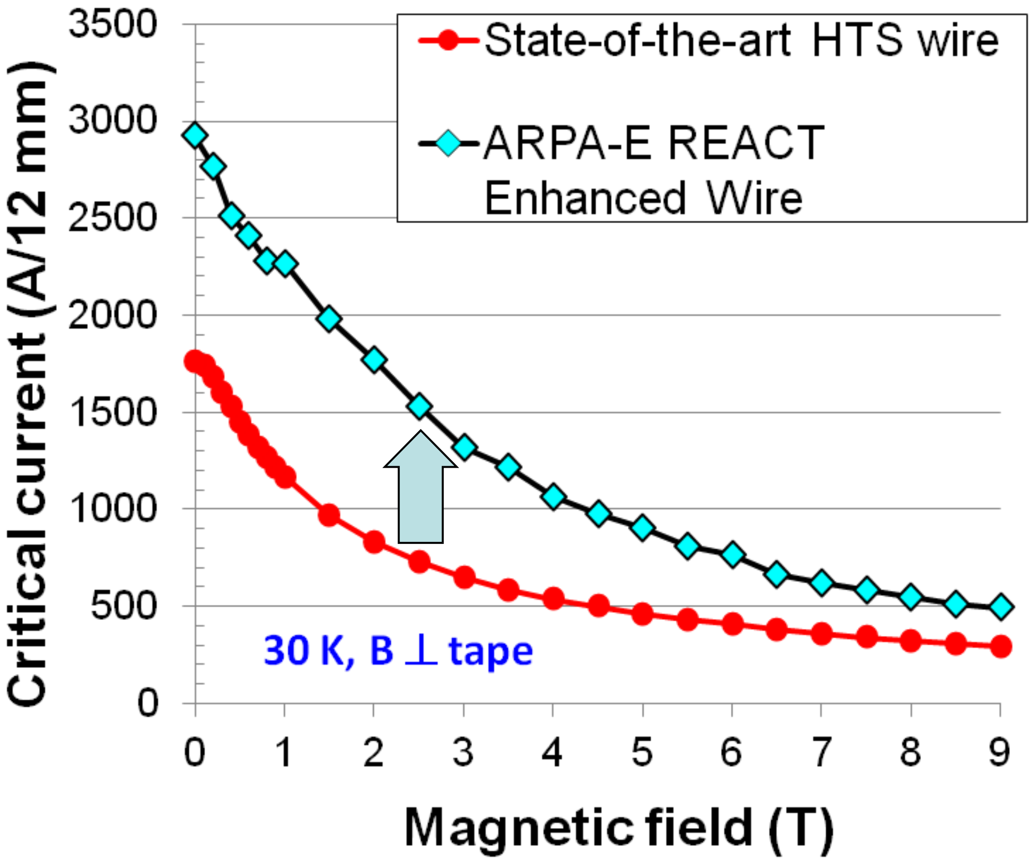
- All good critical current results reported so far have been with less than 10 mol.% of second phase addition.
- High Zr content (> 15%) wires developed to increase nanoscale defects





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

Two-fold improvement in Ic developed in ARPA-E program with 15% Zr-added 2G wire



- ✓ 15% Zr-added wire at 30 K, 2.5 T, B||c: I_c > 1500 A, J_c = 13.6 MA/cm^2, Pinning force = 340 GN/m^3
- ✓ Lift factor at 30K, 3 T, B||c improved by >100% to ~ 4.4

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Superconducting Wires for Direct-Drive Wind Generators

Goal: 4X 2G HTS conductor J_c improvement over state-of-the-art wire for high power wind generators

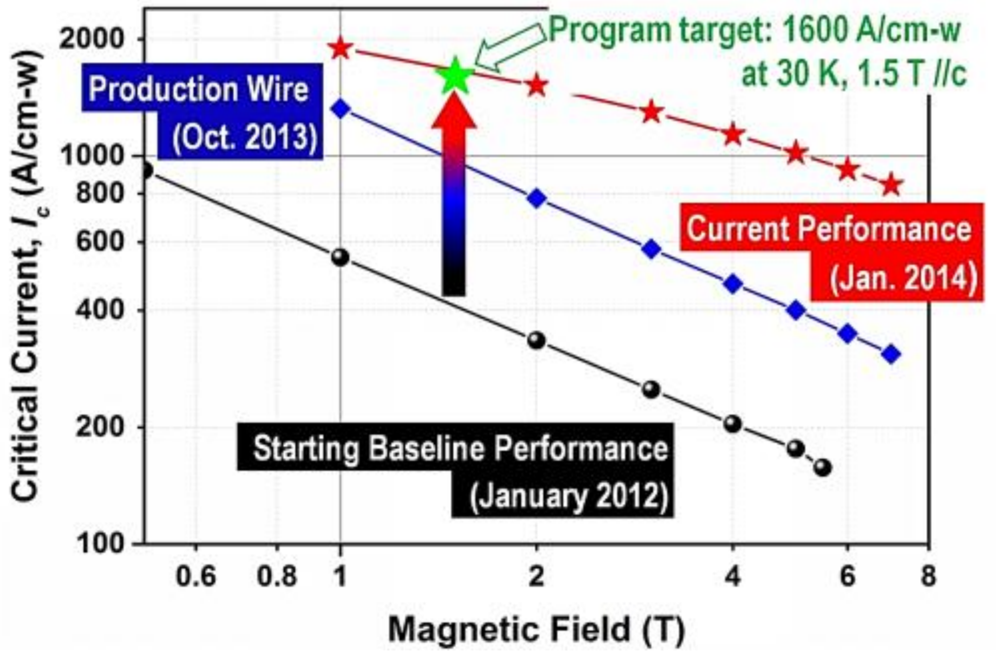
Technical Approach: Combine optimized pinning design (BNL) with a low-cost, long-length wire process (AMSC)

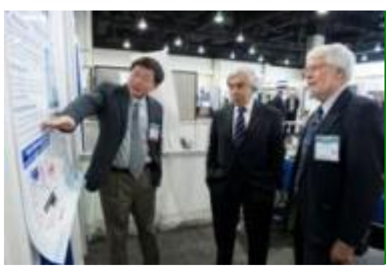
Impact: Enabling motors and generators with significant performance and cost advantage over the permanent magnet technology, and reduce the use of rare-earth materials by over 1000 times and overall system cost.

Program: ARPA-E REACT
Award: $ 1.5 Million USD
Duration: Jan '12 – June '14
Plus-Up: $ 975 K USD extended to Dec. '15
Lead: Brookhaven NL
Dr. Qiang Li qiangli@bnl.gov
Partner: AMSC

Achieved program target of 1,600 A/cm-width at 30K, 1.5T, B//c

Performance of superconducting wires





BNL scientist Qiang Li discusses next-generation superconducting wires with US Energy Secretary Ernest Moniz at February 2014 ARPA-E Energy Innovation Summit

- ✓ Developed analytical probes at BNL to provide quantitative guidance for improving I_c in R&D and production wires at AMSC.
- ✓ Over 200% I_c enhancement achieved in commercial production wire.
- ✓ Over 400% I_c enhancement achieved with optimized pinning landscape.

http://www.bnl.gov/newsroom/news.php?a=24697

HTS Superconducting Magnetic Energy Storage (SMES)

Goal: Develop HTS cable design and fabricate high-power, low-cost cable for SMES hybrid with battery for renewable energy storage.

Program: ARPA-E OPEN 2012
Award: $ 2,7 Million USD
Duration: Feb '13 – Feb '16
Lead: Tai-Yang Research Company,
Dr. Chris Rey
cmrey@tai-yang.com
Partners: North Carolina State, Univ. Houston

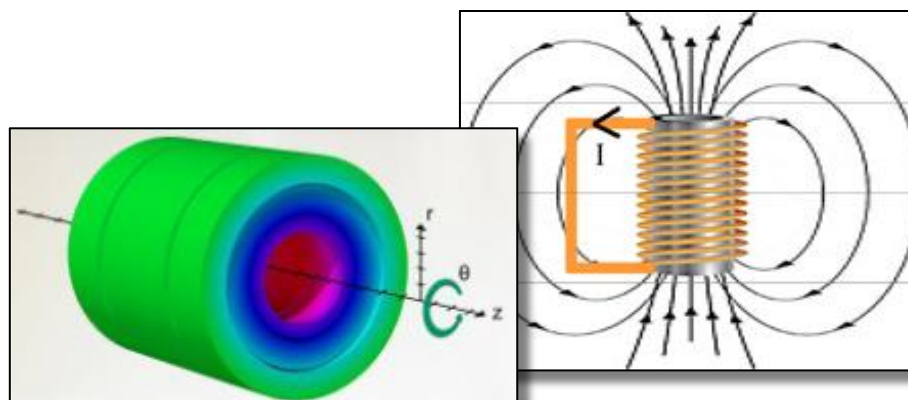
HTS SMES stores energy just like a battery (chemical) or capacitor (electric field) but in magnetic field.

Advantages:

- Ultra High power density (>1-100 MW)
- > 95 % round-trip efficiency
- > 100 k charge/discharge cycle, no degradation, very safe

Disadvantages:

- Low energy density (30-100 W-hr/kg),
- higher costs per W-hr/kg



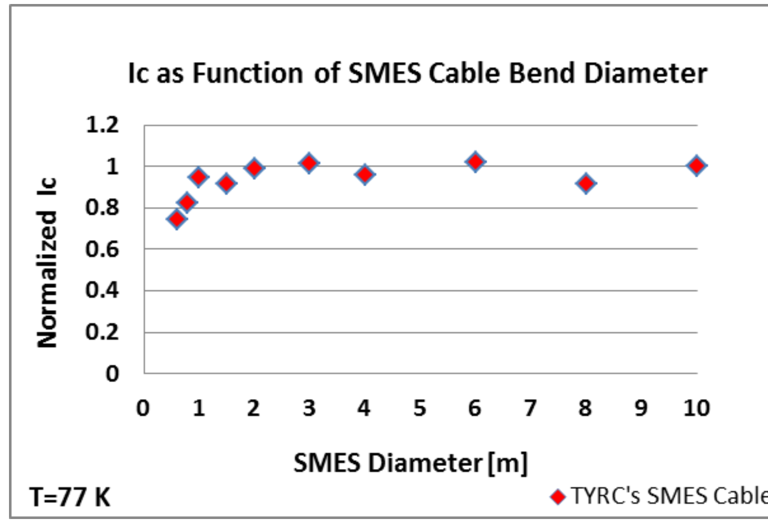
TYRC's HTS SMES project targets and progress

SMES Target Design	I_{op} (kA)	B_{0p} (T)	E_{stored} (MJ)	$V_{discharge}$ (kV)	HTS cable type
	10-25	10-12	60/100/250	1-5	Al stabilized

Industry	Energy (MJ)	Power (MW)	Weight (kg)	Volume (m^3)	Foot Print [Dia. x L] (m x m)	B-field (T)	Cost/kW-hr ($/kW-hr)	Cost/kW ($/kW)
	60	5	1,000	9.42	2 x 3	> 12	3,000	1,000

TYRC's HTS SMES current progress:

- ✓ Compaction tests — completed
- ✓ Cable bend diameter — completed
- • Al conduit weld qualification — in-progress
- • Sub-scale prototype — Q3 2015



U.S. AIR FORCE

Air Force STTR: TYRC is also performing 1MJ SMES design study for high energy laser ($ 750K USD, 2 years)

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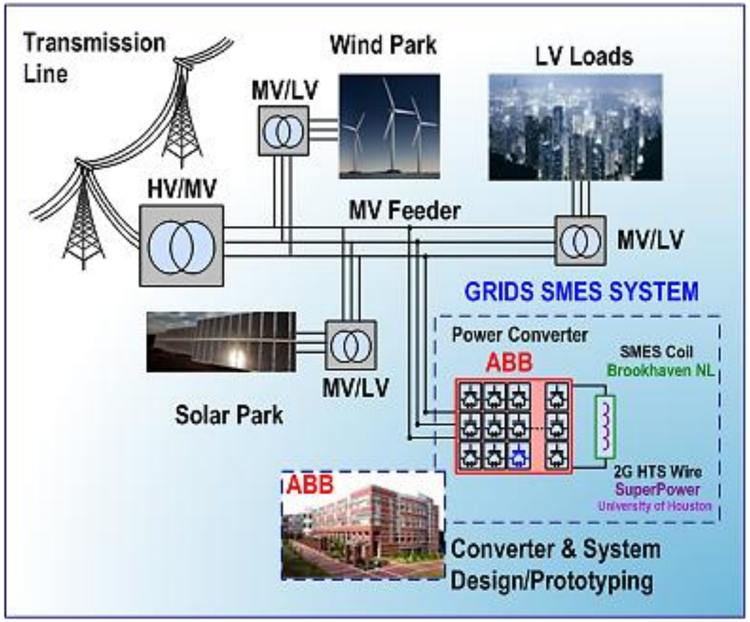
Superconducting Magnet Energy Storage System with Direct Power Electronics Interface

Goal: Develop a competitive, fast response, grid-scale MWh SMES system by demonstrating a small scale 1.7 MJ prototype with direct connection Si-based power electronics converter.

Program: ARPA-E GRIDS
Award: $ 4.6 Million USD
Duration: Oct '10 – June '14
Lead: ABB
Dr. VR V. Ramanan
vr.v.ramanan@us.abb.com
Partners: Brookhaven NL, SuperPower, Univ. Houston



SMES system advantages:

- Energy storage & dynamic compensation;
- Fast dynamic response & nearly infinite cycling capability of HTS coil;
- No moving parts or reacting chemicals;
- Solid state operation; Very long lifetimes and environmentally benign.

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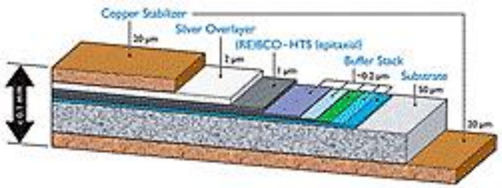
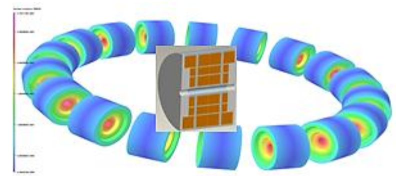
BROOKHAVEN NATIONAL LABORATORY SuperPower Inc. A Furukawa Company TcSUH ABB arpa·e

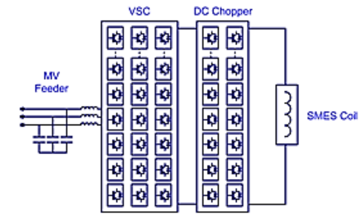
SMES system components and status



Wire: 2G wire with high Ic.



Magnet: 20 kW, 1.7 MJ SMES demonstrator (ultra-high field at 4.2 K).



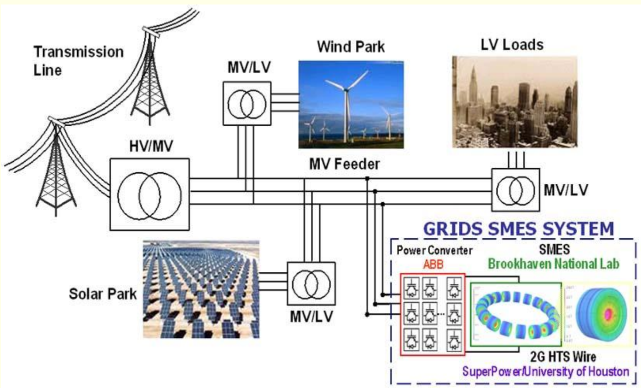
Converter: Modular, scalable direct medium voltage grid connection concept.

- ✓ 9.2 km of 12 mm-wide 2G HTS conductor delivered
- ✓ Novel bypass switch built and successfully tested
- ✓ Advanced quench protection system built and successfully tested
- ✓ Power electronics converters built and successfully tested
- Coils for magnet built; final tests under way
- Full system integration tests in June

SMES: From civilian to dual use applications

BROOKHAVEN NATIONAL LABORATORY

DOE ARPA-E SMES project



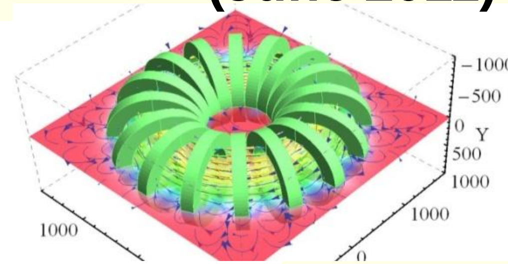
arpa·e

Numerical Model of SMES for Air and Space Applications (June 2011)

US Air Force

U.S. AIR FORCE

Brookhaven Lab (Li - PI)

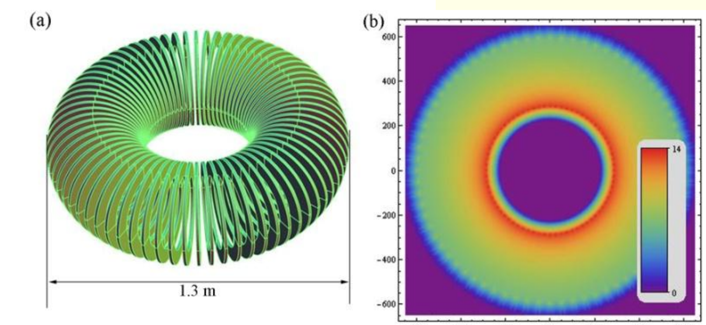


Airborne SMES Model

SMES for Tactical Micro-grid (2014)

US Army

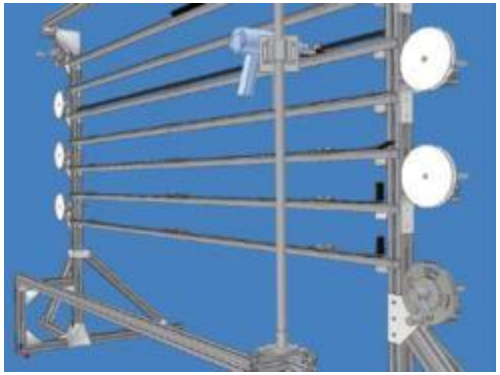
U.S.ARMY



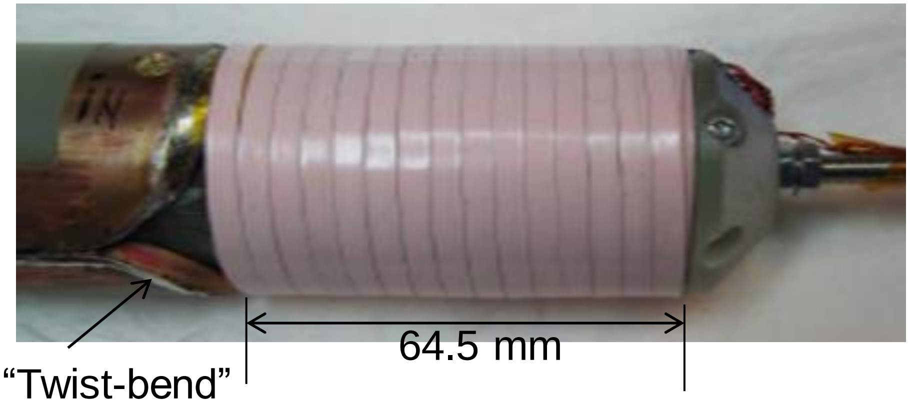
SuperPower. Inc (Hazelton - PI), BNL, and M-Tech

REBCO layer wound high field coil delivers World record 35.4 T field

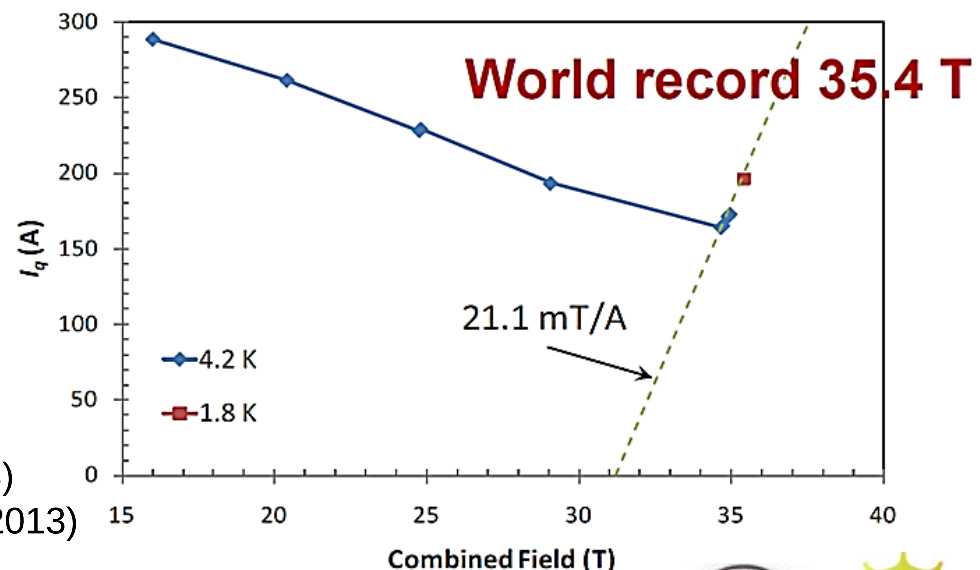
Conductor insulation facility



Whittington *et al.* Patent disclosed (2013)



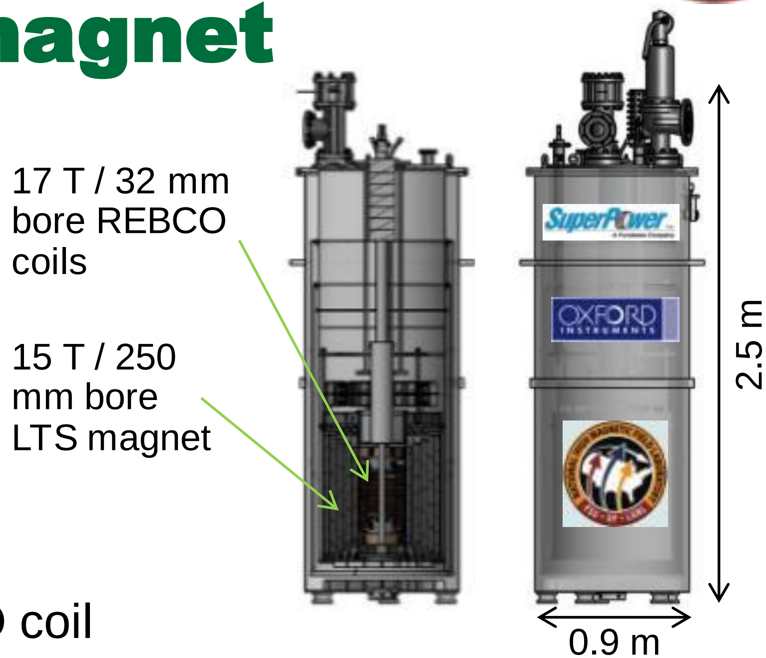
- Wet layer-wound, epoxy filled
- No splices
- Thin walled polyester heat- shrink tube insulated conductor (patent)



Trociewitz *et al.* APL 99 ,202506 (2011)
Patent Hilton *et al.* on insulation US 8,530,390 B2 (2013)
Patent Trociewitz *et al.* on terminals US 8,588,876 B1 (2013)

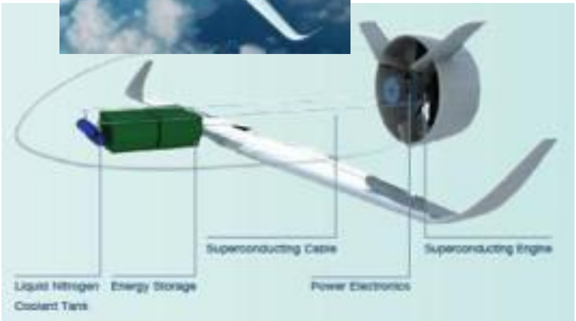
The National High Magnetic Field Laboratory (NHMFL) at FSU is developing a 32T *User* magnet

Specification	
Bore	32 mm
Uniformity 1 cm DSV	5×10^{-4}
Total inductance	254 H
Stored energy	8.6 MJ
Ramp to 32 T	1 hour
Cycles	50,000



- ✓ Have developed and continue to refine REBCO coil technology for 32 T high-field all-SC magnets
- ✓ Developed unique REBCO conductor specification, partly at 4.2 K. Delivery nearly complete (~90% of 12.3 km)
- ✓ Specified and ordered LTS outer magnet + cryostat. Expect delivery in 2014
- ✓ Tested full-featured prototype Inner REBCO coil
- ✓ Initial design of Quench Protection system for 32 T
- Full-featured prototype Outer REBCO coil Feb 2014 . Construction of final REBCO coils 2014-2015. Testing of real REBCO coils 3Q 2015. Full field 4Q 2015.

US Air Force is evaluating HTS components for EV aircraft

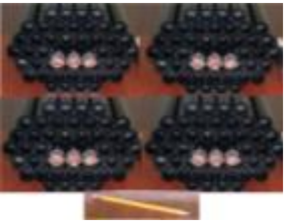


SC Motor

- VoltAir's two next-gen lithium-air batteries would power **two highly efficient superconducting motor**…
- The **necessary cooling** of these engines to reach superconducting temperature can be realised with low-cost and **environmentally friendly liquid nitrogen**.

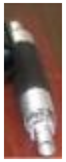
MV-Class Power Transmission Cables

- 2.3 MW DC co-axial cable at 76K (~20 MW @ 20K)



Cu Wire MCM 750 Gauge Cable @ 60° C 1,429 lb/m

YBCO @ 20K 0.97 lb/m



CryoflexTubing Heat Loss @ 20-77K ~ 0.5 W/m 1 lb/m

	Cu wire @ 60C (x322)	YBCO cable @ 20K	Improve factor
Weight	1,585 lbs/m	~3 lbs/m	**530x**
Heat loss	7,000 W/m	3.8 W/m (cryo cool + LN2)	**1,840x**
X-section area	2,170 cm2	5 cm2	**230x**

Cryo-cooler Cools 30 m @ 77K 0.23 lb/m

U.S. DEPARTMENT OF ENERGY

IEA HTS ExCo Meeting 2014

U.S. AIR FORCE

DOE Energy Frontier Research Center:
Center for Emergent Superconductivity (CES)

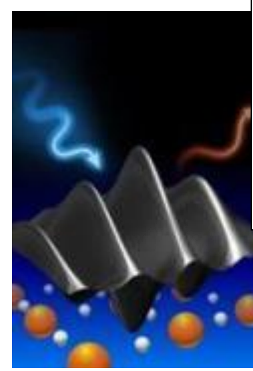
BROOKHAVEN NATIONAL LABORATORY
Center for Emergent Superconductivity

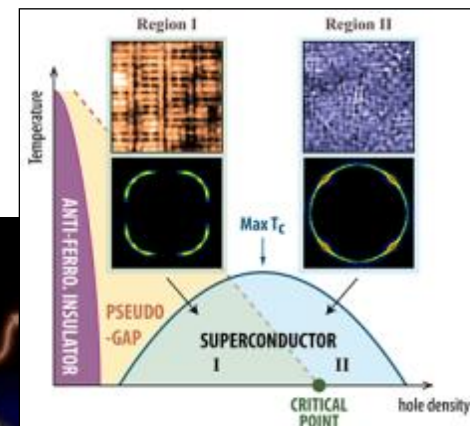
Mission: To discover new high-temperature superconductors and improve the performance of known superconductors by understanding the fundamental physics of superconductivity.

Program:	DOE EFRC
Award:	$ 22.5 Million USD
Duration:	Aug '09 – Aug '14
Director:	Dr. J. C. Seamus Davis
Lead:	Brookhaven NL
Partners:	Argonne NL, U. Illinois U-C

Examples of Recent Achievements:

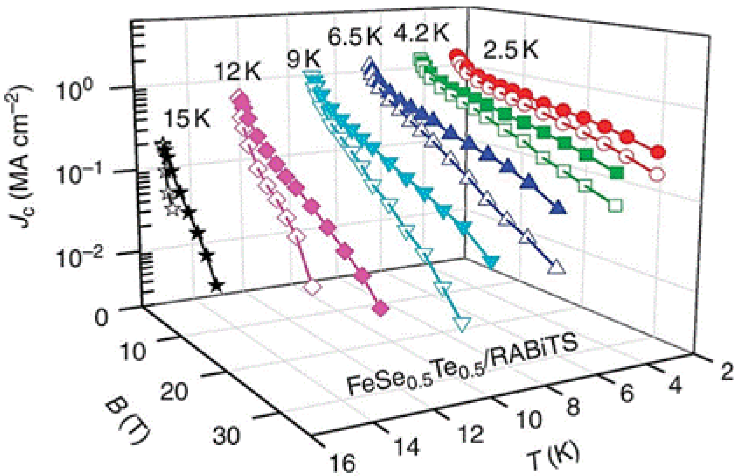
- A Grand Unified Theory of Exotic Superconductivity
- Scientists Discover Hidden Magnetic Waves in HTS
- Scientists Chart the Emergence of HTS
- Superconducting Magnet Researchers Develop Exciting New HTS Technology
- Key Advance in Understanding 'Pseudogap' Phase in HTS





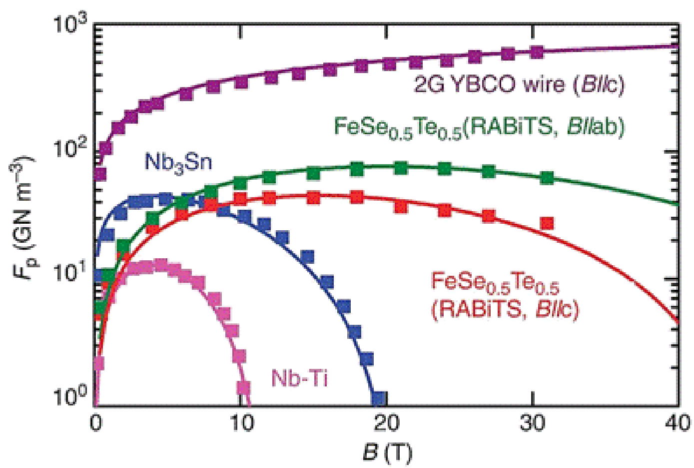
Record performance in iron-based HTS coated conductor

New fabrication method could advance technologies ranging from grid-scale energy storage to medical imaging devices.



Major findings:

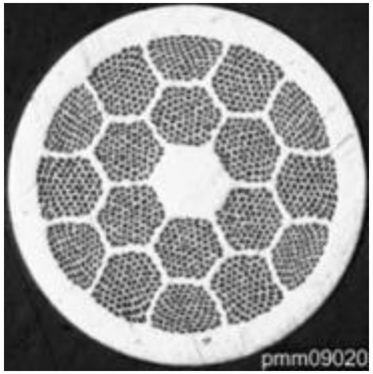
- Layered structure – "CeO_2 Cap Layer" gives higher T_c & J_c
- Lower processing temp – PLD at 400°C
- Same J_c on CeO_2/YSZ single crystals and RABiTS
- J_c > 1 MA/cm^2 at 4.2K self field
  ~ 10^5 A/cm^2 at 31T



Bi-2212 round wire for high field applications

<u>Key requirements for material</u>:

- High current under ultra high field
- High strength and strain limit
- *Ability to twist, cable and transpose*
- Resistance to quench, compatible insulation
- Long piece-length to wind coils
- Cost

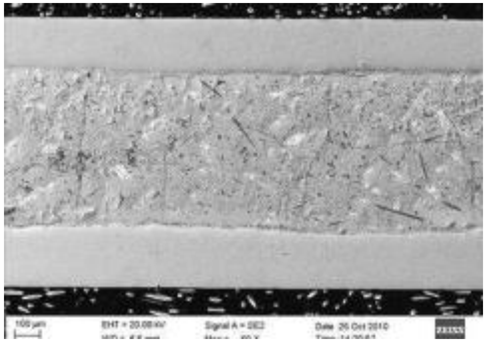


<u>Challenges for Bi-2212 round wire</u>

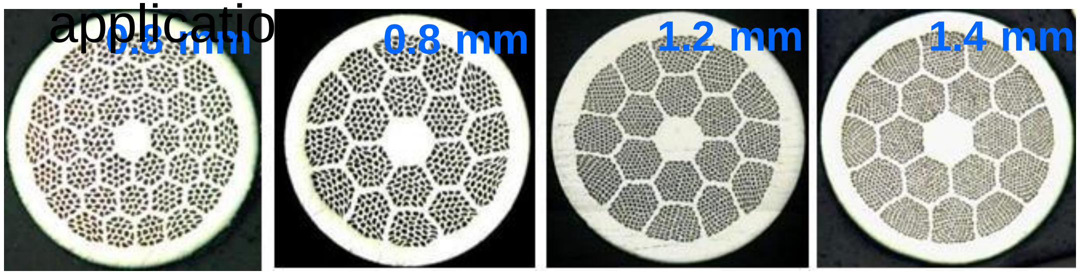
- Achieving short sample J_E in long lengths
- Increasing wire piece-length
- Enhancing wire strength
- Reducing cost

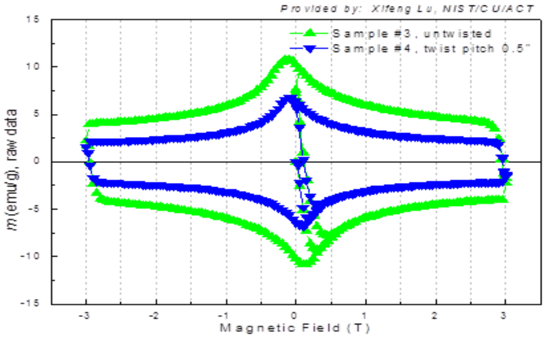
OST Bi-2212 round wire development under DOE support

OXFORD INSTRUMENTS

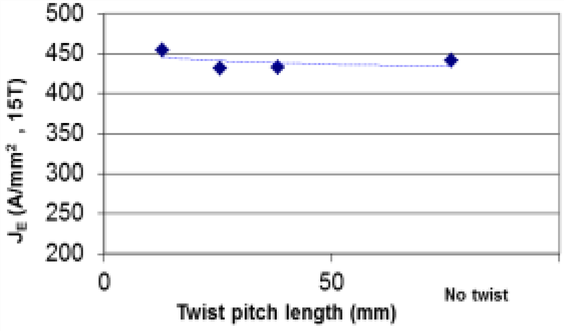


- ✓ Established Bi-2212 round wire process by the Powder-in-tube method and easy to scale up.
- ✓ Established reliable Bi-2212 powder sources
- ✓ Various wire configurations to fit different applicatio



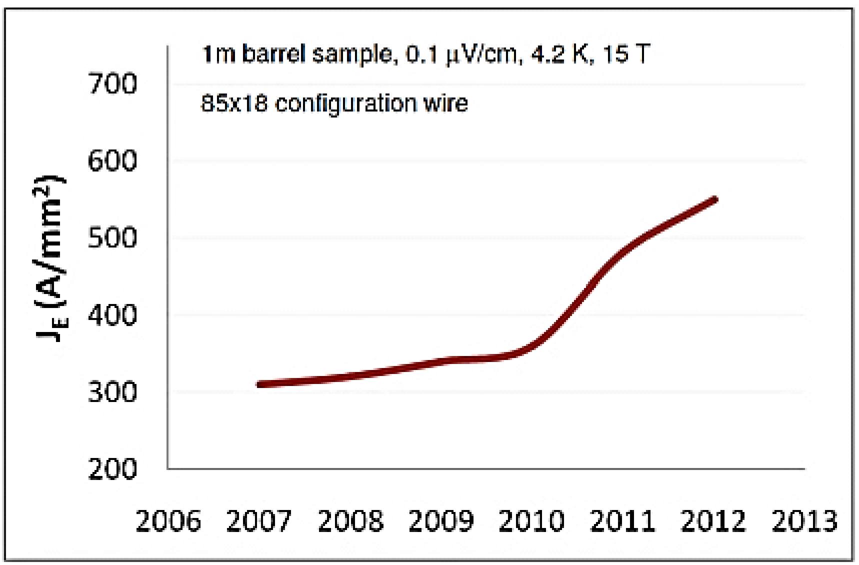


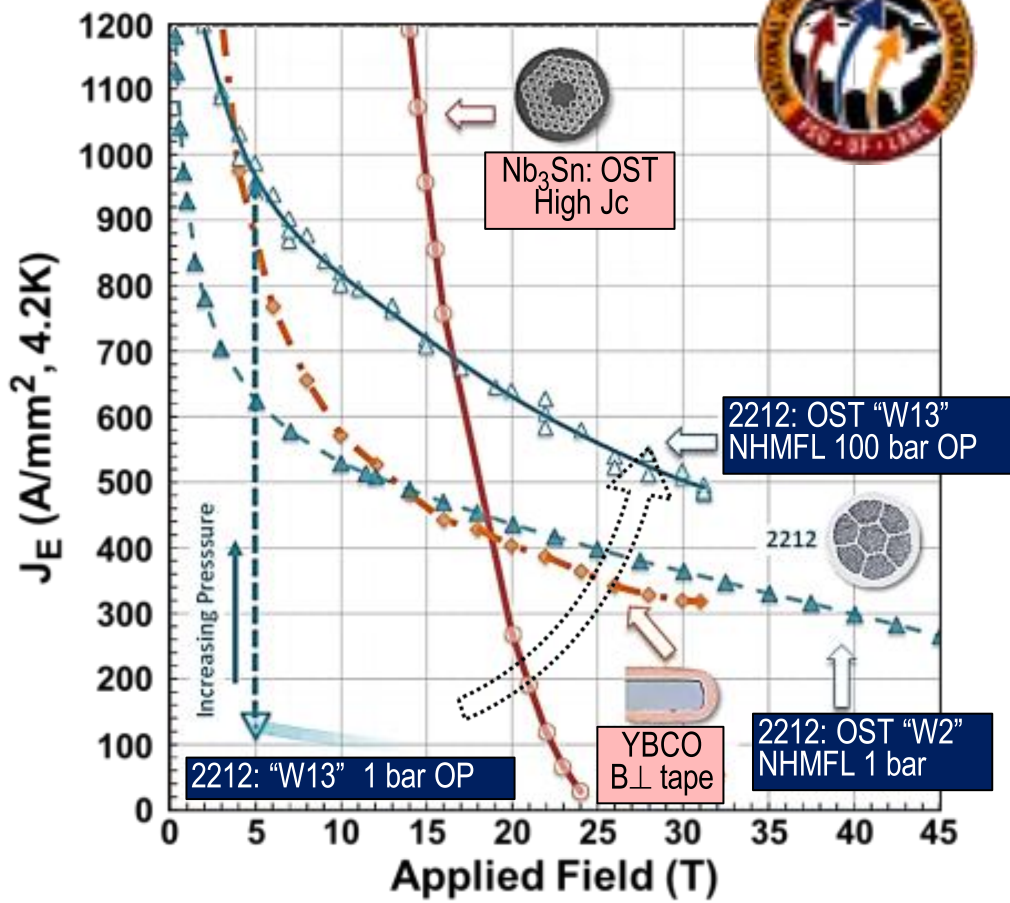
- ✓ Wire is twistable and ac loss reduced
- ✓ 5x longer piece-length process under developing
- ✓ High strength wire development is funded



Continuous improvement through process modifications

- ✓ Advances including "Core Densification + Over-Pressure HT" led to $J_E > 600\ A/mm^2$ at 4.2 K, 20 T.





OST Bi-2212 round wire development in the near future

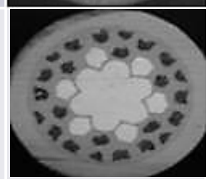
OXFORD INSTRUMENTS

For Bi-2212 round wires, > 0.5mm diameter, operating between 4.2 to 20 K, in 20 to 50 T field, with silver stabilizer and isotropic performance:

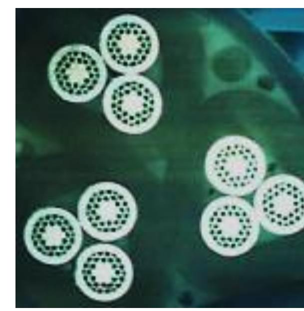
Conductor Property	Delivered value today	In 2 years	In 5 years
Current density J_E @ 4,2K, 20T	~ 500 A/mm^2	~ 700 A/mm^2	~ 700 A/mm^2
Length	200 – 1,000 m	400 – 1,000 m	> 3,000 m
Strength	110 MPa	150 - 200 MPa	> 200 MPa
Selling price range $/kA.m @ 4.2K, 20T	330 - 550	200 - 400	100 - 150

Hyper Tech MgB_2 conductor strand designs- Different % SC and % Cu

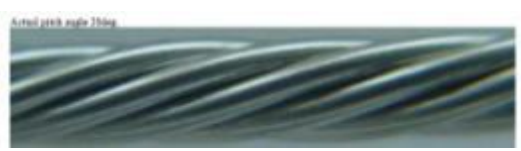
Hyper Tech

Product #	# filaments	Fill factor (%)	Copper (%)	Cross section
18-MS	18	8	32	
24-NM	24	17	16	
30-NM	30	20	12	
36-CM	36	15	15	

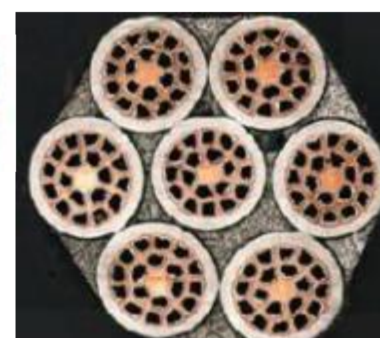
Demonstrated multi-strand MgB_2 cable:



10° pitch angle

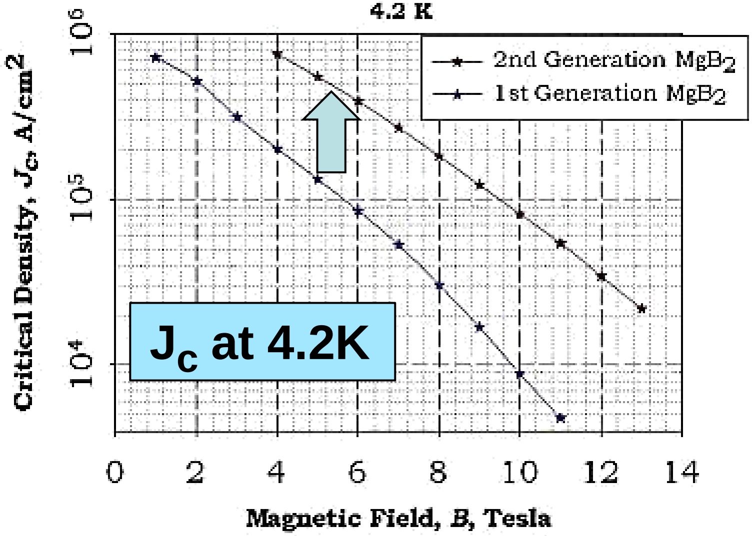


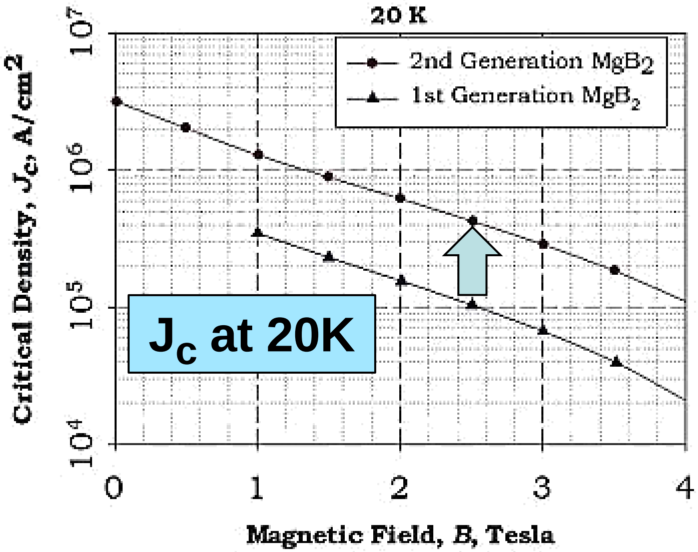
20° pitch angle



2^{nd} generation MgB_2 under development at Hyper Tech

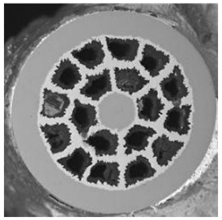
Hyper Tech

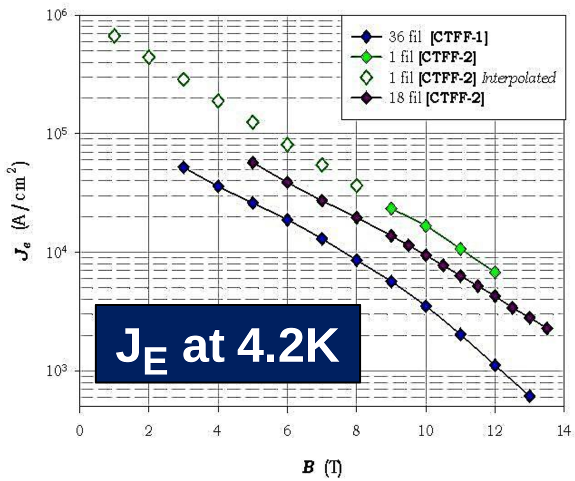




✓ 4 to 5 times improvement in J_c over 1^{st} gen MgB_2

2^{nd} Gen: 18% SC





Engineering Current Density J_E at 4.2K, 5 T:

CTFF-1 (best of class 36 filament)-
26,000 A/cm^2

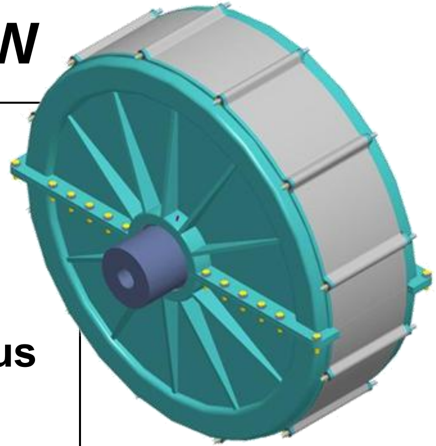
CTFF-2 (18 filament)-
58,000 A/cm^2 ***2.2x increase***

CTFF-2 (monofilament, extrapolated)-
122,000 A/cm^2 ***4.7x increase***

Designed a 5 MW MgB_2-based generator and developing a radiation treatment background magnet

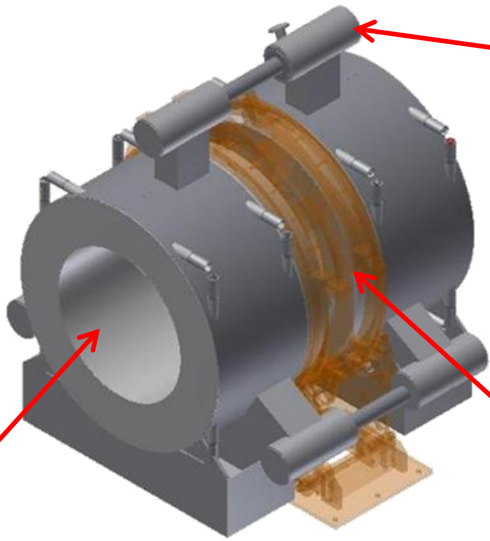
Hyper Tech

Generator design is expandable from 5-20 MW



Specifications	
Power (MW) …………………….	5.0
RPM ……………………………….	10
Configuration …….	Synchronous
Voltage (kVrms) ………….	1,350
Number of Poles ……………..	24
Output Frequency (Hz) …….	2.0
Diameter (M) ………………..	4.87
Length (M) ………………….	1.74
Weight (Tons) ………………	76.5
Superconductor ……………	MgB_2
Rotor Coolant …	LHe/GHe
Stator Conductor ……….	Copper
Stator Coolant …	Water or EGW

Image Guided Conduction Cooled Radiation Treatment Background Magnet



Current and projected J_E and $ / kA.m: based on 1 mm round wire, and volume orders of wire

Hyper Tech

Property of importance	Delivered value today-1st gen	In 3 years 2nd gen	In 5 years 2nd gen
Temperature range	4-30K	4-30K	4-30K
Field range	6T-0T	8T-0T	8T-0T
Conductor current density (Je) Based on temperature and field on wire	4K-1T-1400A/mm2 4K-4T-400A/mm2 4K-6T-200A/mm2 20K-0T-2000A/mm2 20K-1T-600A/mm2 20K-2T-320A/mm2 20K-3T-120A/mm2	4K-1T-2800A/mm2 4K-4T-1400A/mm2 4K-6T-800A/mm2 20K-0T-5000A/mm2 20K-1T-2000A/mm2 20K-2T-1200A/mm2 20K-3T-600A/mm2	4K-1T-2800A/mm2 4K-4T-1400A/mm2 4K-6T-800A/mm2 20K-0T-5000A/mm2 20K-1T-2000A/mm2 20K-2T-1200A/mm2 20K-3T-600A/mm2
Conductor form	Round 0.25-2 mm	Can be custom size	Can be custom size
Conductor length	6-10km	40-60km	80km
Conductor shape	Round or rectangular		
Delivered selling price range $/kAm Varies based on diameter, temperature and field on wire some examples For 1 mm round wire	4K-1T-$5/kAm 4K-4T-$16/kAm 4K-6T-$30/kAm 20K-0T-$3.30/kAm 20K-1T-$10/kAm 20K-2T-$20/kAm 20K-3T-$50/kAm	4K-1T-$0.5-$1.5/kAm 4K-4T-$1.5-4.5/kAm 4K-6T-$3.0-9.0/kAm 20K-0T-0.37/kAm 20K-1T-$0.75-2/kAm 20K-2T-$1.5-5/kAm 20K-3T-$3-10/kAm Range is 2nd gen (low value) vs 1st gen wire (higher value).	4K-1T-$0.4/kAm 4K-4T-$1.3/kAm 4K-6T-$2.5/kAm 20K-0T-0.35 20K-1T-$0.70/kAm 20K-2T-$1.3/kAm 20K-3T-$2.5/kAm Based on 2nd gen wire

Price decreases coming from :

1) **Improvement in Hyper Tech's manufacturing speed (CTFF)**
2) **Lower material costs due to increased manufacturing volume**
3) **Commercialization of 2nd generation MgB_2 wire performance**

Office of Electricity Delivery and Energy Reliability [**http://energy.gov/oe/**](http://energy.gov/oe/)

US Department of Energy [**http://energy.gov/**](http://energy.gov/)