IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation PL-5 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

Application Driven Superconducting Wires Development and Future Prospects in US

Qiang Li

Advanced Energy Materials Group

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Plenary talk at 1st Asian ICMC – CSSJ50, Kanazawa, Japan, Nov 10, 2016)

Department of Energy

- OE (Office of Electricity): Smart Grid HTS-FCL transformer
- EERE (Office of Energy Efficiency and Renewable Energy) : Offshore wind generator, Next generation electric machines: enabling technologies* (2016 FOA – AMO)
- ARPA-E (Advanced Research Projects Agency Energy): wires for wind generators and grids, superconducting magnetic energy storage
- Office of Science: High Energy Physics HEP, Fusion Energy Sciences FES, Small Business Innovative Research SBIR: wires and magnets

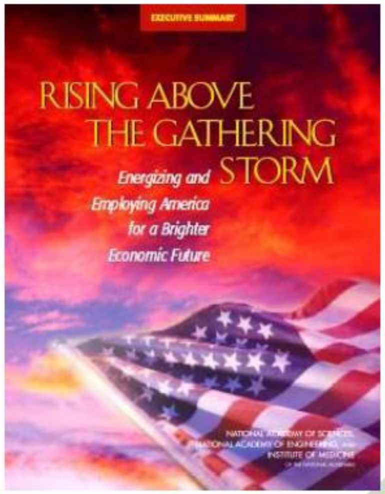
Other Federal Agencies

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

State Agencies

- NYSERDA et al

ARPA-E: Applying The ARPA Model To Energy



2006
Rising Above the Gathering Storm
(National Academies)

2007
America COMPETES Act

American Recovery and Reinvestment Act of 2009 (Recovery Act)

$400M appropriated for ARPA-E
President Obama launches ARPA-E in a speech at NAS on April 27, 2009

ARPA-E's Distinct Culture

- Excellence
- Openness
- Integrity
- Speed
- Metrics Driven
- Flat and Nimble

ARPA-E Funded Superconductor Programs

Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)

Developing 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.

Dr. Mark Johnson
Former ARPA-E Program Director,
Now Director of DOE Office of
Advanced Manufacturing (AMO)

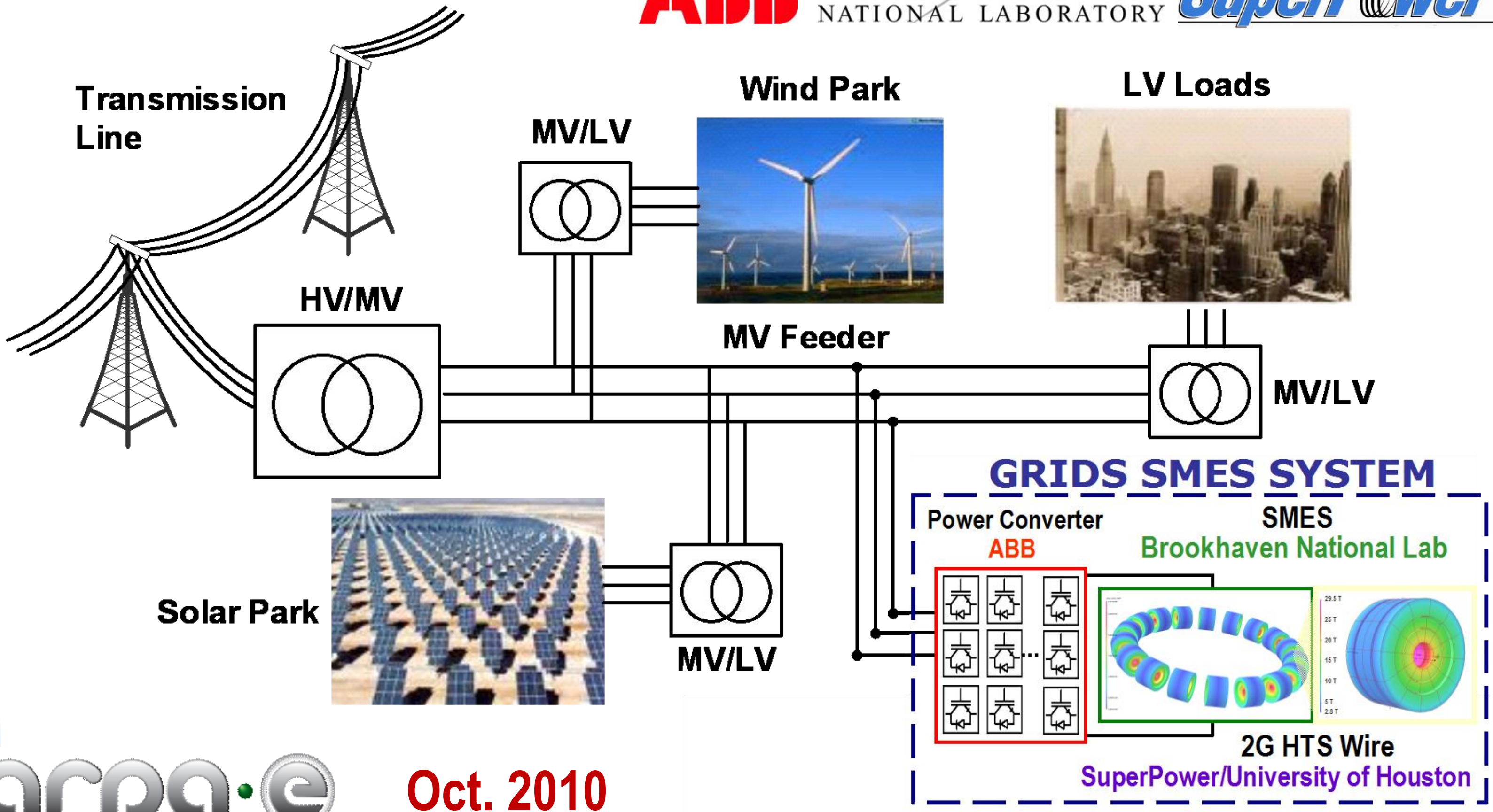
- **ABB (lead)/BNL/SuperPower/UH**

  – **Superconducting Magnetic Energy Storage (SMES) for grid applications**

12 Projects

Superconducting Magnet Energy Storage (SMES) System with Direct Power Electronics Interface for GRIDS

ABB BROOKHAVEN NATIONAL LABORATORY SuperPower Inc.



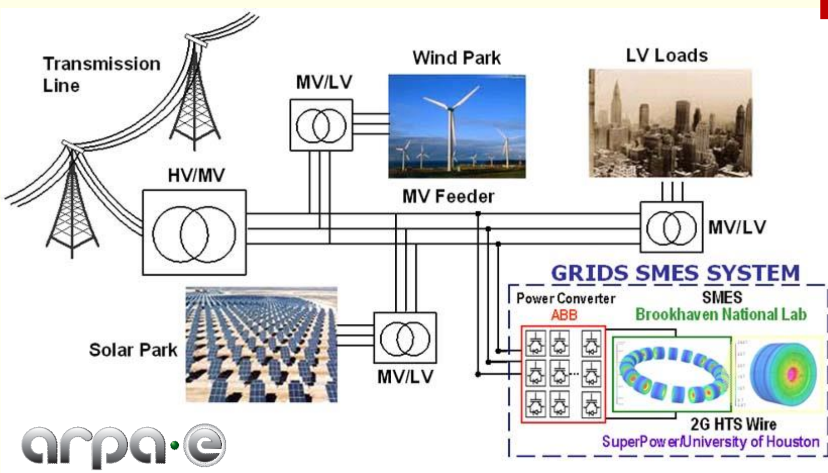
arpa·e **Oct. 2010**

Team: ABB (V. Ramanan), Brookhaven Lab (Q. Li), SuperPower, Inc. (D. Hazelton)/U of Houston (Selva)

SMES – Civilian to Military Applications

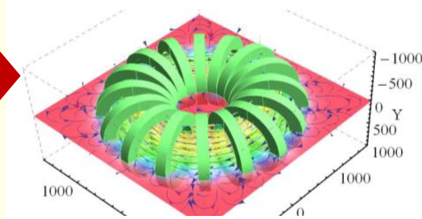
DOE ARPA-E funded project (2010)

Superconducting Magnet Energy Storage (SMES) System with Direct Power Electronics Interface for Grids



Team: ABB (V. Ramanan), Brookhaven Lab (Q. Li),
SuperPower, Inc. (D. Hazelton)/U of Houston (Selva)

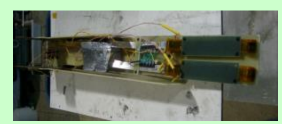
Numerical Model of SMES for Air and Space Applications (June 2011)



Airborne SMES Model

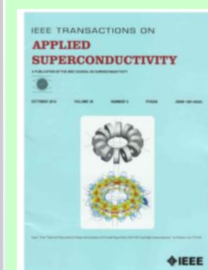
U.S. AIR FORCE

Brookhaven Lab (Li - PI)



2015 R&D 100 Award – aFCL, Ref. "Fast HTS switch for high current applications

Solovyov, QL, App. Phys. Lett. (2013)



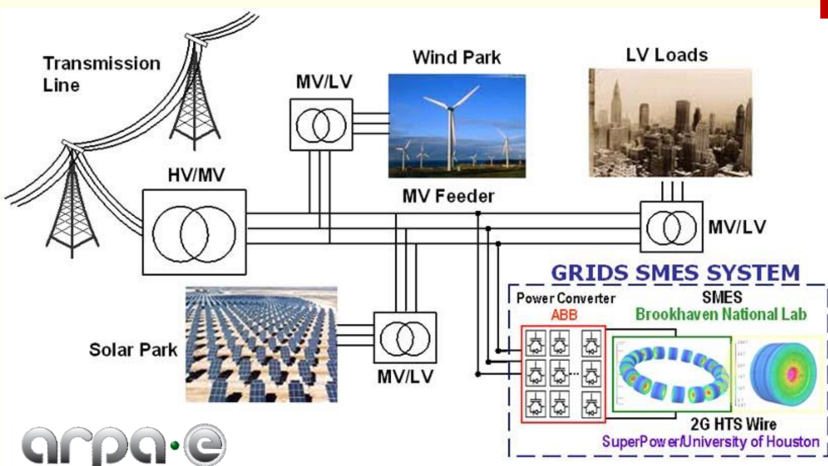
Dimitrov, QL, et al IEEE, Oct. 2015

Slowa Solovyov/Brookhaven Technology Group

SMES – Civilian to Military Applications

DOE ARPA-E funded project (2010)

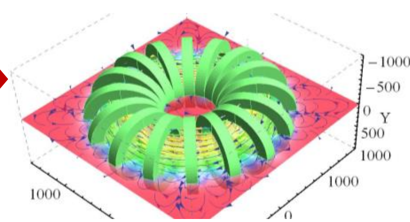
Superconducting Magnet Energy Storage (SMES) System with Direct Power Electronics Interface for Grids



Team: ABB (V. Ramanan), Brookhaven Lab (Qiang Li), SuperPower, Inc. (D. Hazelton)/U of Houston (Selva)

Program manager: Mark Johnson (ARPA-E)

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

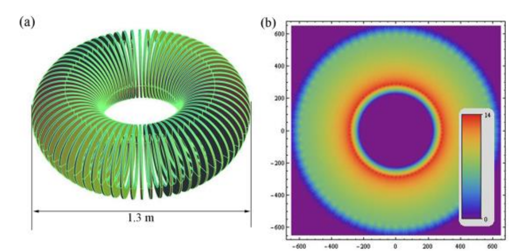


Airborne SMES Model

U.S. AIR FORCE

Brookhaven Lab

SMES for Tactical Micro-grid



U.S.ARMY

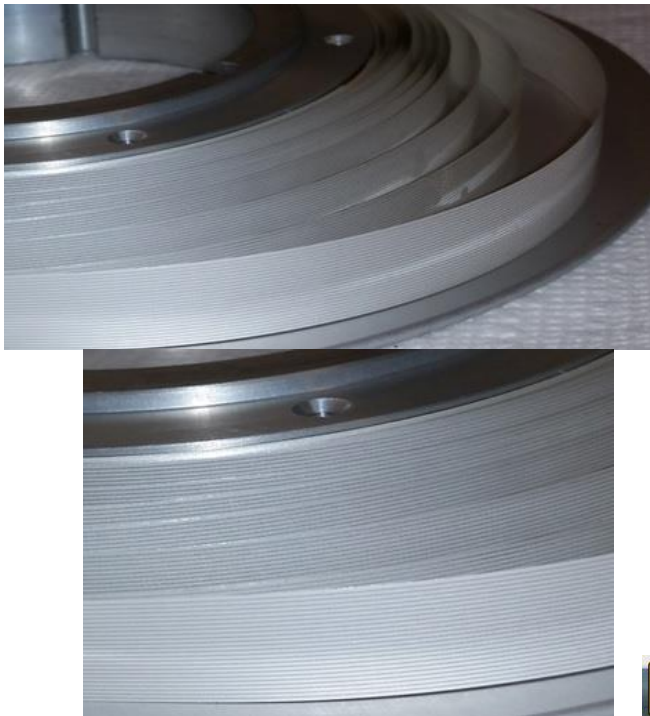
Courtesy of Dr. Rong, Charles C CIV USARMY RDECOM ARL (US)

HTS high-field magnetic energy storage using 24 Tesla HTS magnet designed by BNL is under development for a complete 1.7MJ SMES system

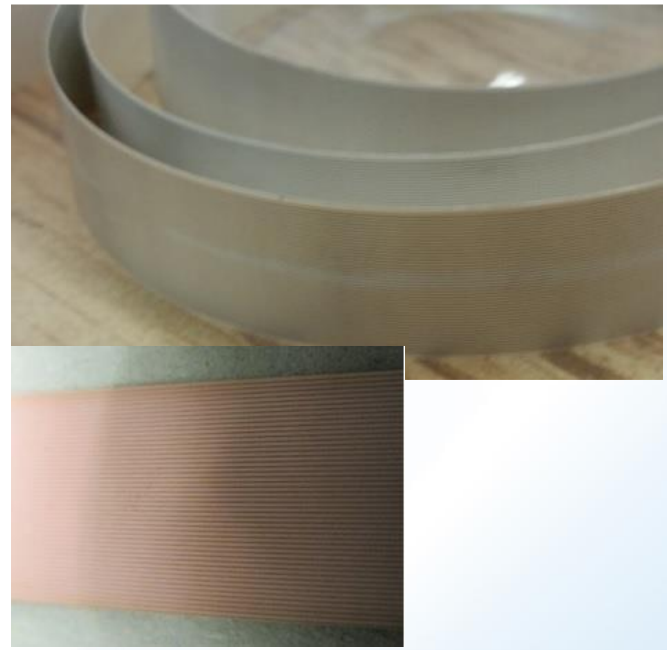
Courtesy of Dr. Rong, Charles C CIV USARMY RDECOM ARL (US)

Higher Filament Count Coated Conductors

24-filament conductor



48-filament conductor



1

Energy to Power Solutions

HTS SMES R&D at e2P

Specific Opportunity for Energy Storage in Military (3-10 y) and In-Grid (> 10 y) Applications:

- AFRL STTR: 75 -150 kJ HTS storage unit
- 2014-2017 ARPA-E, 3-year effort to develop HTS SMES technology using CICC

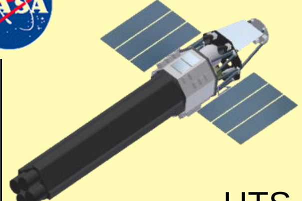
Courtesy of Dr. Chris Rey
President, 10/31/2016

Energy to Power Solutions

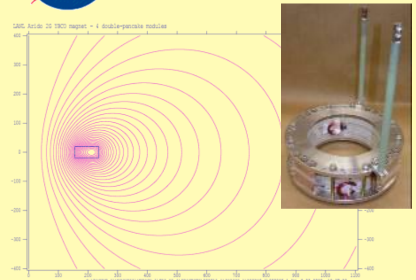
Courtesy of Dr. Chris Rey, President, 10/31/2016

Energy to Power Solutions (e2P)

HTS degaussing for Navy ships



HTS current leads for space flight systems

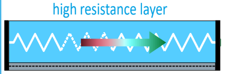
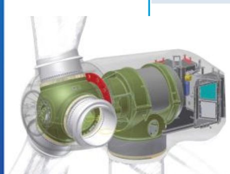


HTS magnets for space and military applications

Dr. Chris Rey
President
10/31/2016

Key Power Applications and Requirements

Courtesy of Dr. Martin Rupich, marty.rupich@amsc.com, 978-842-3217, October 31, 2016

	Typical Requirements	Comment
Power Cables		
 Low AC losses - Nonmagnetic substrate	$<10^{-8}$ J/mA^2	at 60% of Ic
High current density per unit width	>350 A/cm	
Cabling strain tolerance	Helix	
REG		
 Controlled current capacity for limiting	<10% Ic variation	
Stability for transient currents	200% for ~100ms-1 sec	Through faults
Tailored Impedance	~3-7 $\mu\Omega$cm 77K	Site dependent
Stand-alone FCL		
 High current density per unit width SF 77K	>300 A/cm x 2	
High sheet resistance	~7.6 $\mu\Omega$cm 90K (23 300K)	typical
Stability for transient currents	200% for ~100ms-1 sec	through faults
Electric Power Generators		
 High current density at 2-4 T and 40K	>400 A/cm	Power Density
Mechanically robust	~100 MPa	EM loading
Centrifugal loading	>0.1% strain in all directions	150 m/sec
Stress tolerance associated with impregnation	>20 MPa C axis tension	

Resilient Electric Grid Solutions

Courtesy of Dr. Martin Rupich,
marty.rupich@amsc.com

Resilient Electric Grids (REG) are Distribution Voltage, HTS Cable Systems designed to be inherently Fault Current Limiting and are applied in Urban Areas to improve system Reliability and Load Serving capability.

Key Applications:

- ***Distribution Interconnecting:*** *Allow the Interconnecting of Urban Distribution Grids to increase reliability and load serving capability while managing fault currents.*
- ***Small urban substations:*** *Allow the installation of small, cost effective urban substations that consist of a distribution bus only; bulk power is transported in at distribution voltages*

REG Systems Key Characteristics:

Power Density: Transmission Power at Distribution Voltages

Ease of Siting: 3-Phases in One Cable and Thermal Isolation make siting easier

Fault Current Limiting: FCL capability allows for approaches not available with any other technology.

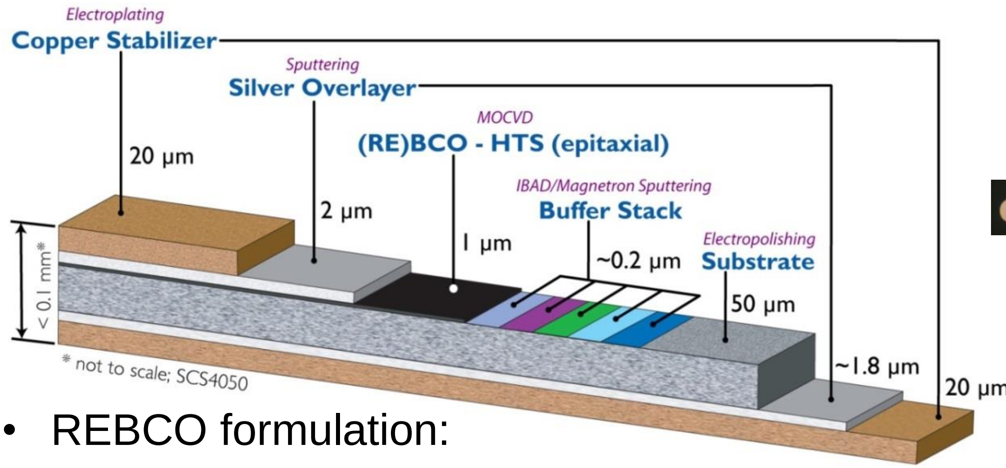
Photos courtesy of Nexans

SuperPower Inc. A Furukawa Company

Courtesy of Drew Hazelton (SuperPower)

2G HTS wire production at SuperPower

IBAD-MOCVD based REBCO wire on Hastelloy substrate

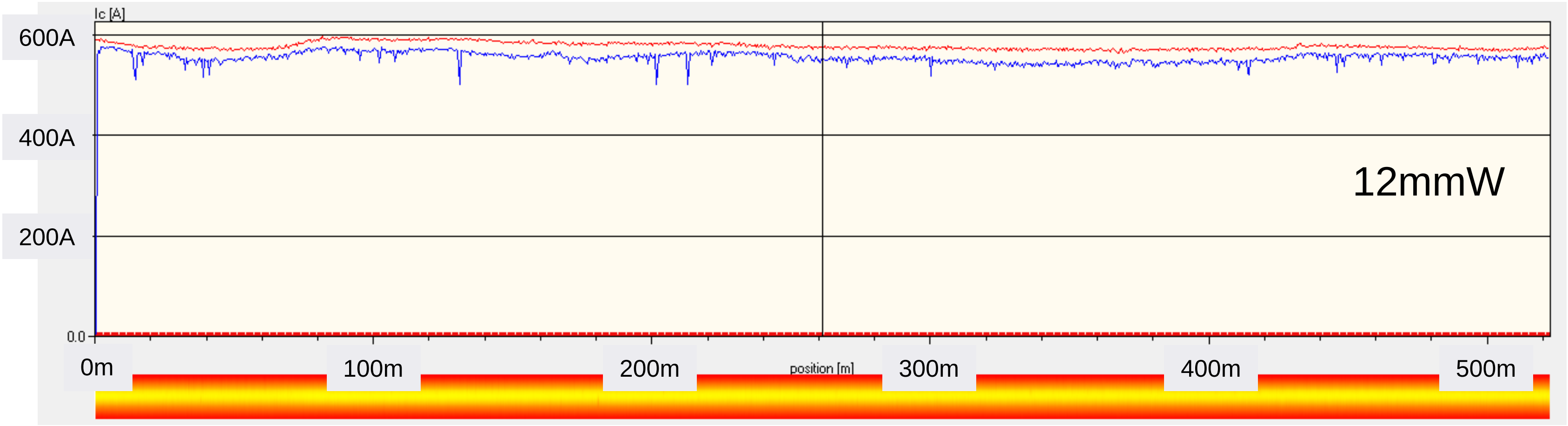


Cross-sectional image of a Cu-plated wire

- REBCO formulation:
  - **AP** (Advanced Pinning) – with enhanced in-field performance for B//c, targeting at coil applications such as high-field magnets, SMES, motors/generators
  - **CF** (Cable Formulation) – for cables, transformers, FCL
- I_c(77K, s.f.)/12mm = 400-600A, piece length = up to 500m.
- Variations in width (2-12mm), substrate thickness (30, 50 or 100µm) Ag thickness (1-5µm), Cu thickness (10-115µm), and insulation
- Bonding conductors : 2x2mm, 2x4mm, 2x12mm (face to face / back to back)
- Product lineup is expanding

Courtesy of Drew Hazelton (SuperPower)

Ic performance of Enhanced A.P wire at 77K/s.f

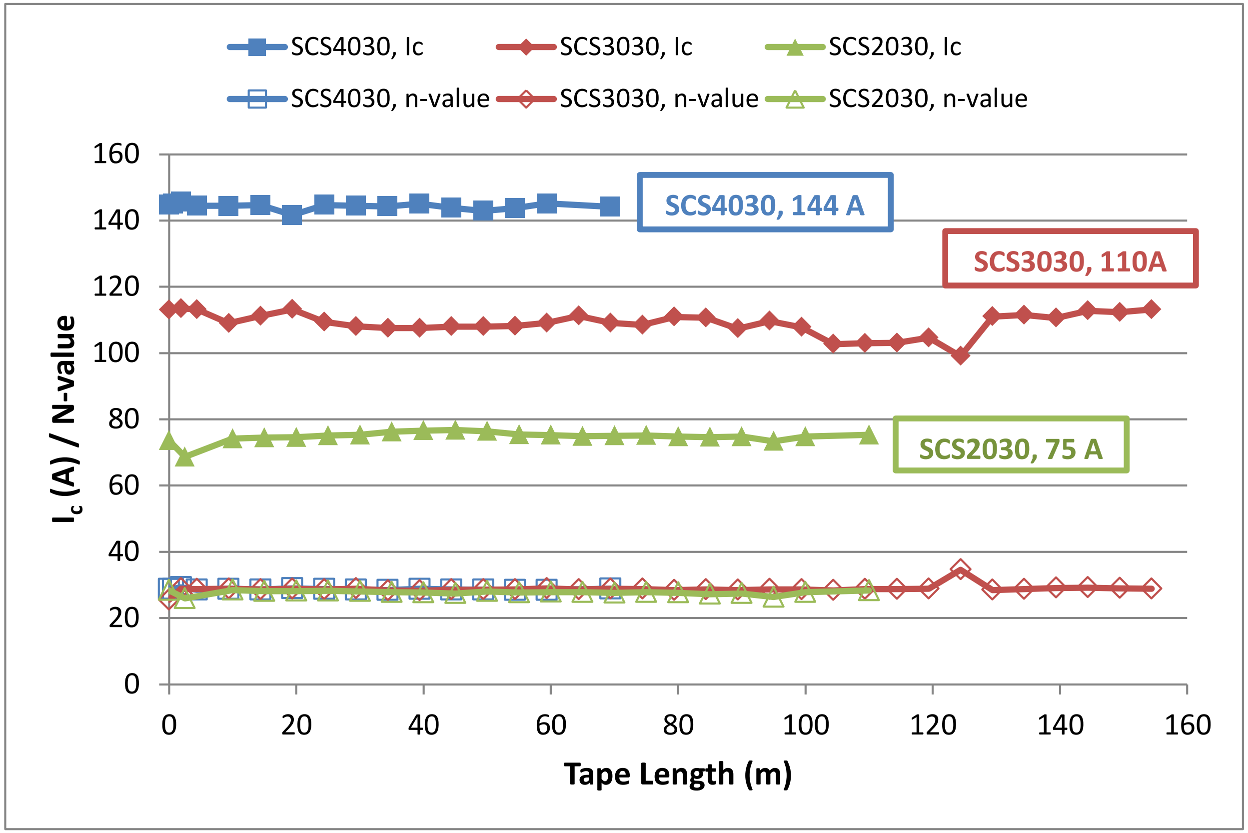


- Magnetic, non-contact measurement
- High special resolution, high speed, reel-to-reel
- Monitoring I_c at multiple production points after MOCVD
- Capable of quantitative 2D uniformity inspection

SuperPower Inc. A Furukawa Company

Courtesy of Drew Hazelton (SuperPower)

Development progress of 30µm substrate



- Base performance of 30µm substrates are comparable to 50µm.

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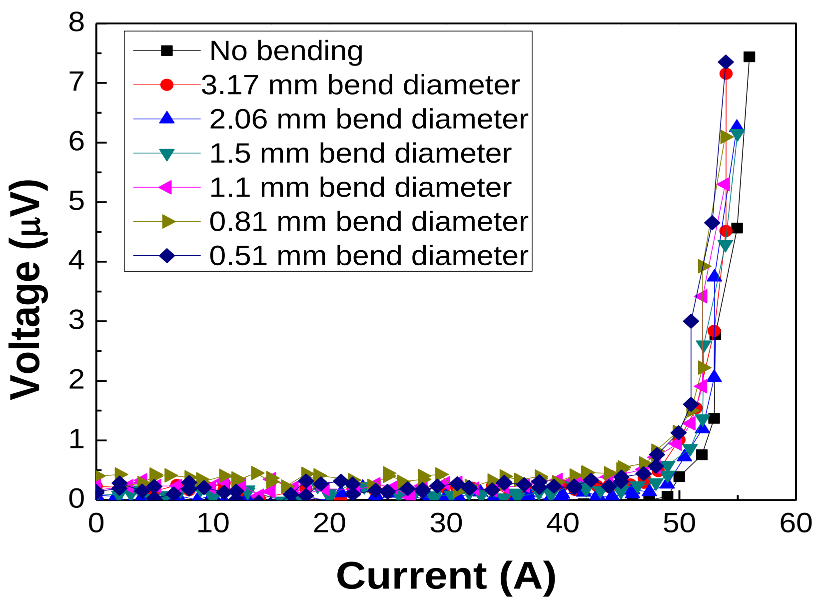
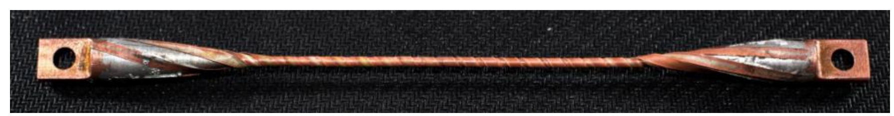
Additional improvements in J_e with thinner tapes

- 3x J_e improvement with 25% Zr addition
- Additional 2X J_e improvement with 2X thicker film → J_e ~ **1700 A/mm² at 4.2 K, 20 T**
- Yet another 2X J_e improvement with ½ thick tapes → 25 µm total tape thickness! (45 µm with Cu stabilizer) → J_e of **3000 A/mm² at 4.2 K, 20 T** feasible!





Ultrathin REBCO tapes enable ultra-small diameter REBCO wires.

1.6 mm diameter wire wound on 0.8 mm diameter core, with I_c of 283 A

*Ultrathin REBCO tapes can be wound on **0.51 mm diameter** without Ic degradation!*

TcSUH

Courtesy of Selva (UH)

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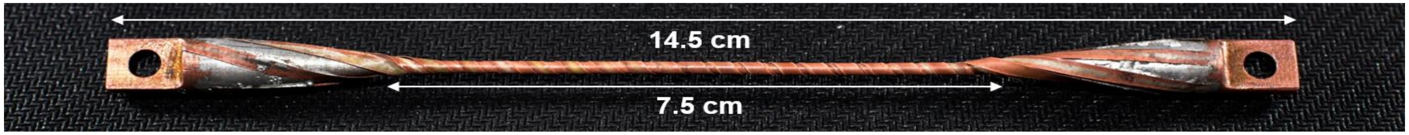
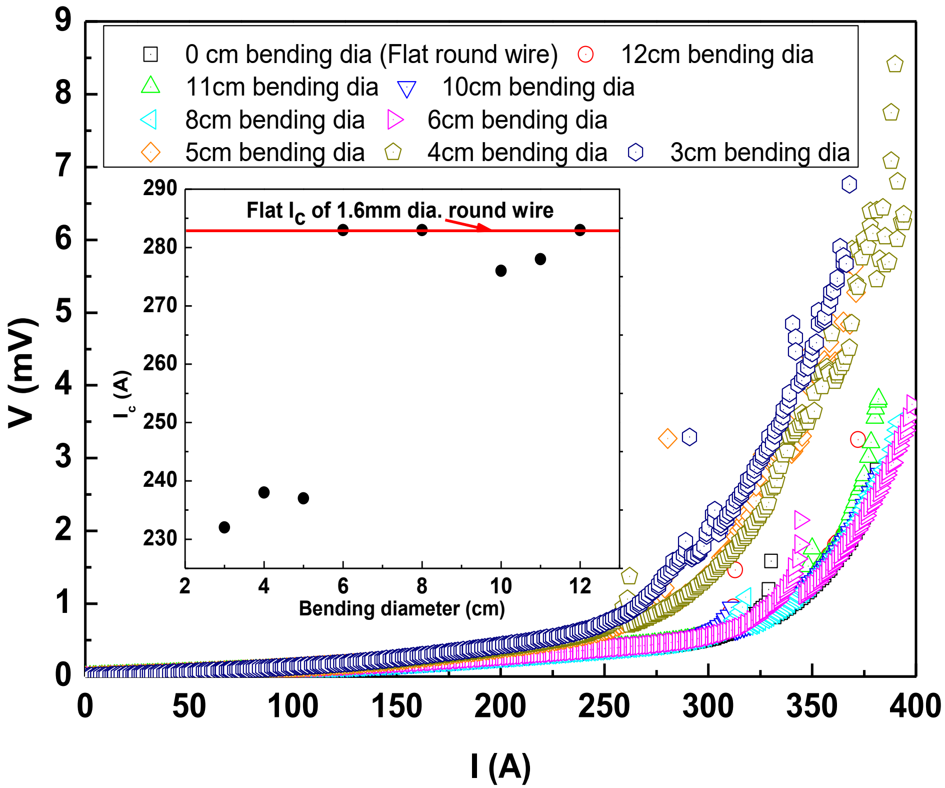
Excellent mechanical properties of round ultra-small diameter REBCO wire



3 cm bending diameter



TcSUH

Courtesy of Selva (UH)

arpa·e
CHANGING WHAT'S POSSIBLE

ARPA-E: The First Seven Years

A Sampling of Project Outcomes

CHANGING WHAT'S POSSIBLE

The report can be downloaded here: http://go.usa.gov/x2V3T

ARPA-E funded 475 projects the first seven years. ~36 projects made to this list of impact sheet, Two from SC projects

arpa·e
CHANGING WHAT'S POSSIBLE

QUADRUPLING CRITICAL CURRENT IN HIGH TEMPERATURE SUPERCONDUCTOR WIRES

Updated: June 20, 2016

PROJECT TITLE:	Superconducting Wires for Direct-Drive Wind Generators	High Performance, Low Cost Superconducting Wires and Coils for High Power Wind Generators
PROGRAM:	Rare Earth Alternatives to Critical Materials (REACT)	
AWARD:	$3,298,424	$5,131,458
PROJECT TEAMS:	Brookhaven National Lab & American Superconductors	University of Houston, SuperPower, Energy2Power & Teco-Westinghouse
PROJECT TERMS:	January 2012 – March 2016	January 2012 – June 2015
PRINCIPAL INVESTIGATOR (PI):	Dr. Qiang Li	Prof. Venkat Selvamanickam

TECHNICAL CHALLENGE

High performance electric machines, such as motors in electric vehicles or generators in wind turbines, require rare earth elements, particularly Neodymium (Nd) and Dysprosium (Dy) for the electric machines' magnetic components. In wind generators, the need for rare earths is quite large (a generator in a wind turbine contains approximately 100 kg of rare earth materials for every MW of rated power) and is still growing, as both the total amount of installed wind capacity and the average size of each individual wind turbine continue to increase. Price fluctuations over the past decade have shown that rare earth materials are sensitive to supply disruptions, and alternative technologies to mitigate or eliminate the dependence of this energy technology on critical rare earth materials would offer risk mitigation for the continued growth of wind power against potential market risks in the future.

TECHNICAL OPPORTUNITY

Using high temperature superconductor (HTS) magnets in wind turbines could dramatically reduce the rare earth requirement compared with traditional permanent magnet (PM) generators (from ~100 kg of Nd and Dy MW in a PM generator to ~100 grams of rare earths per MW in an HTS generator). In addition, HTS generators offer better performance and lower weight for large turbines (see Fig. 1)[24] with corresponding lower operational and capital costs. However, historically the highest performance commercially available HTS wire (Rare earth Element Barium Copper Oxide – (RE)BCO) ranged in cost from $200/kA-m upwards. To be competitive with PM generators, the cost of the HTS conductor must be reduced ~4x, which in turn requires a dramatic increase in the critical current (I_c, the maximum current that a superconductor can sustain)[25]. Advances in materials design and fabrication techniques make it possible to address this challenge by engineering specific defects, known as flux pinning centers, into HTS wires.

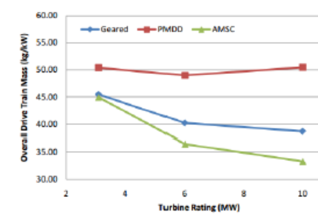


Figure 1. Comparison of overall drivetrain mass for permanent magnet (PM) geared, PM direct drive, and HTS (designed by AMSC) turbines

[24] "Comparative Assessment of Direct Drive High Temperature Superconducting Generators in Multi-Megawatt Class Wind Turbines" B. Maples, M. Hand and W. Musial NREL/TP-5000-49086 www.nrel.gov/docs/fy11osti/49086.pdf (2010)

[25] "Design and Analysis of a 12 MW Superconducting Wind Power Generator", M. Park, International Workshop on Coated conductors for Application 2014, Dec 1 – Dec 3, Jeju, South Korea. (http://www.cca2014.org/)

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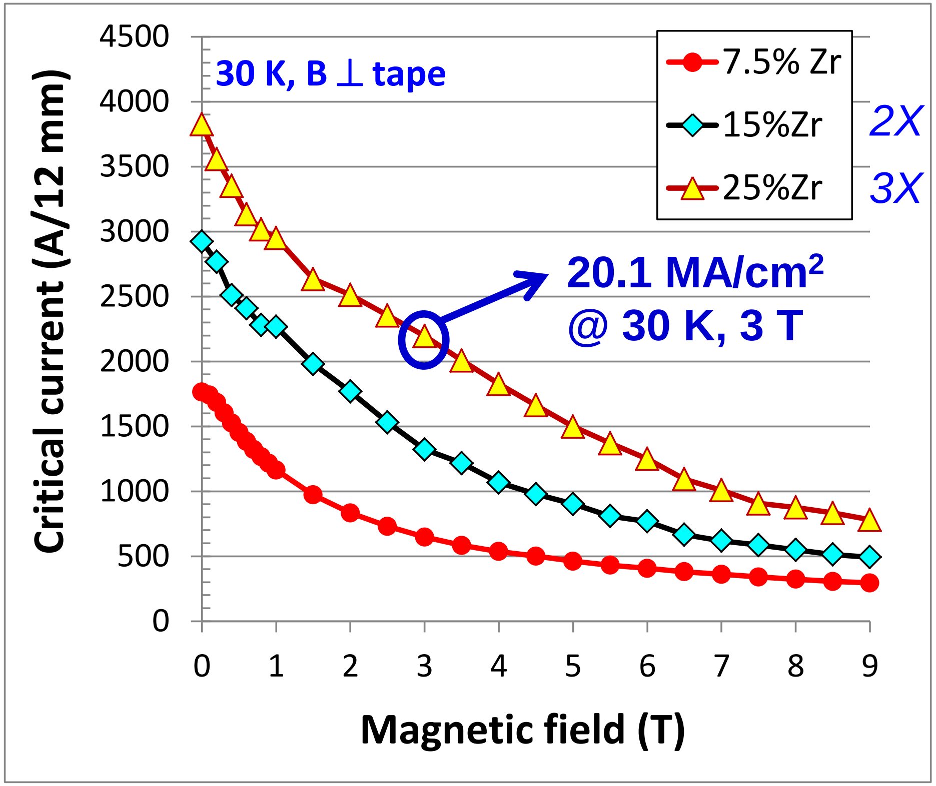
3X improvement in in-field performance in the with increasing Zr content



- *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!)***

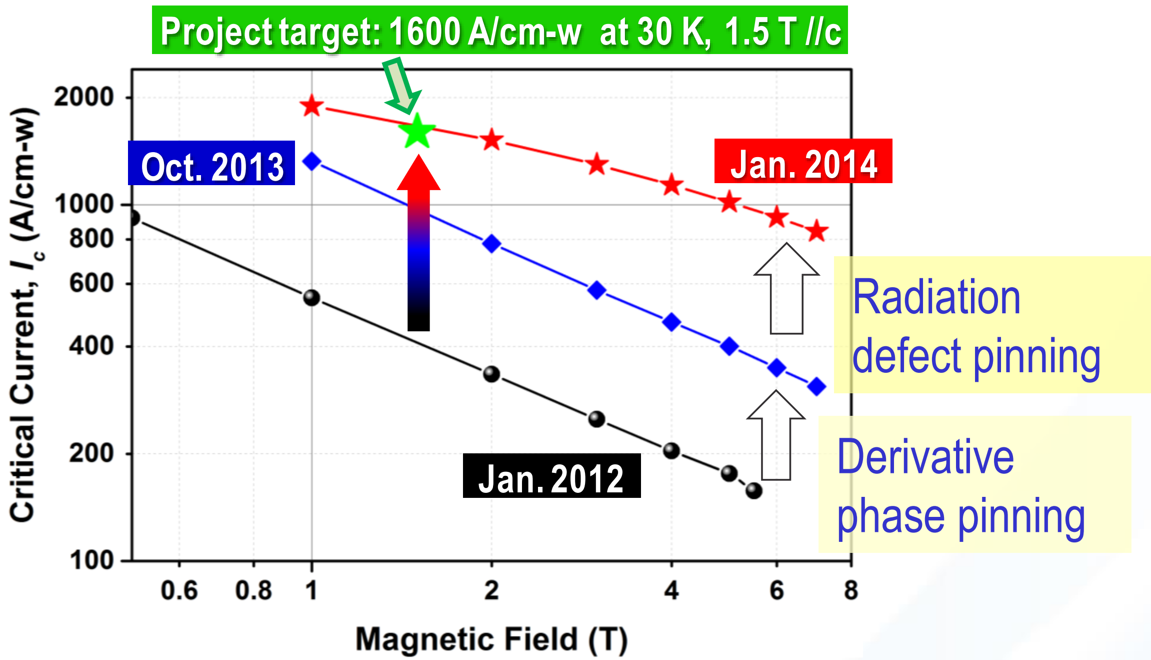
- Enabled by engineering a high density of nanoscale defects while maintaining high crystalline quality of the superconductor films

TcSUH

Courtesy of Selva (UH)

Superconducting Wires for Direct-Drive Wind Generators

Brookhaven National Lab (Qiang Li – PI)



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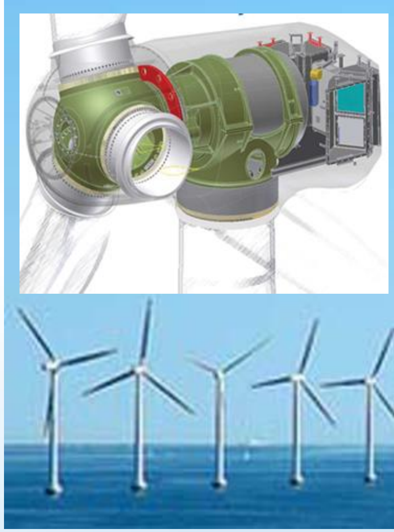
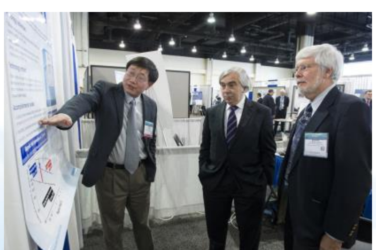
Superconducting Direct Drive Wind Generator (10MW+)



Project kick-off in Jan. 2012

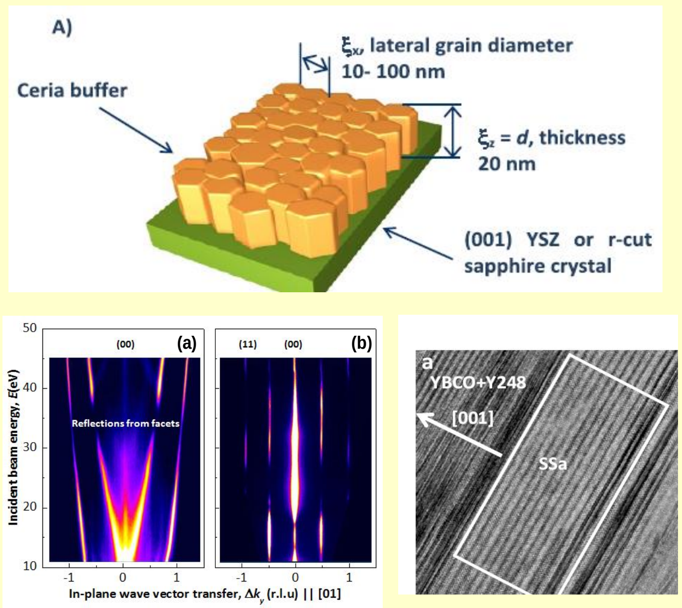


ARPA-E Energy Summit Feb. 24 2014

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

Advanced HTS Wires for Energy Applications

“Solid state catalyst” CeO_2 buffer*



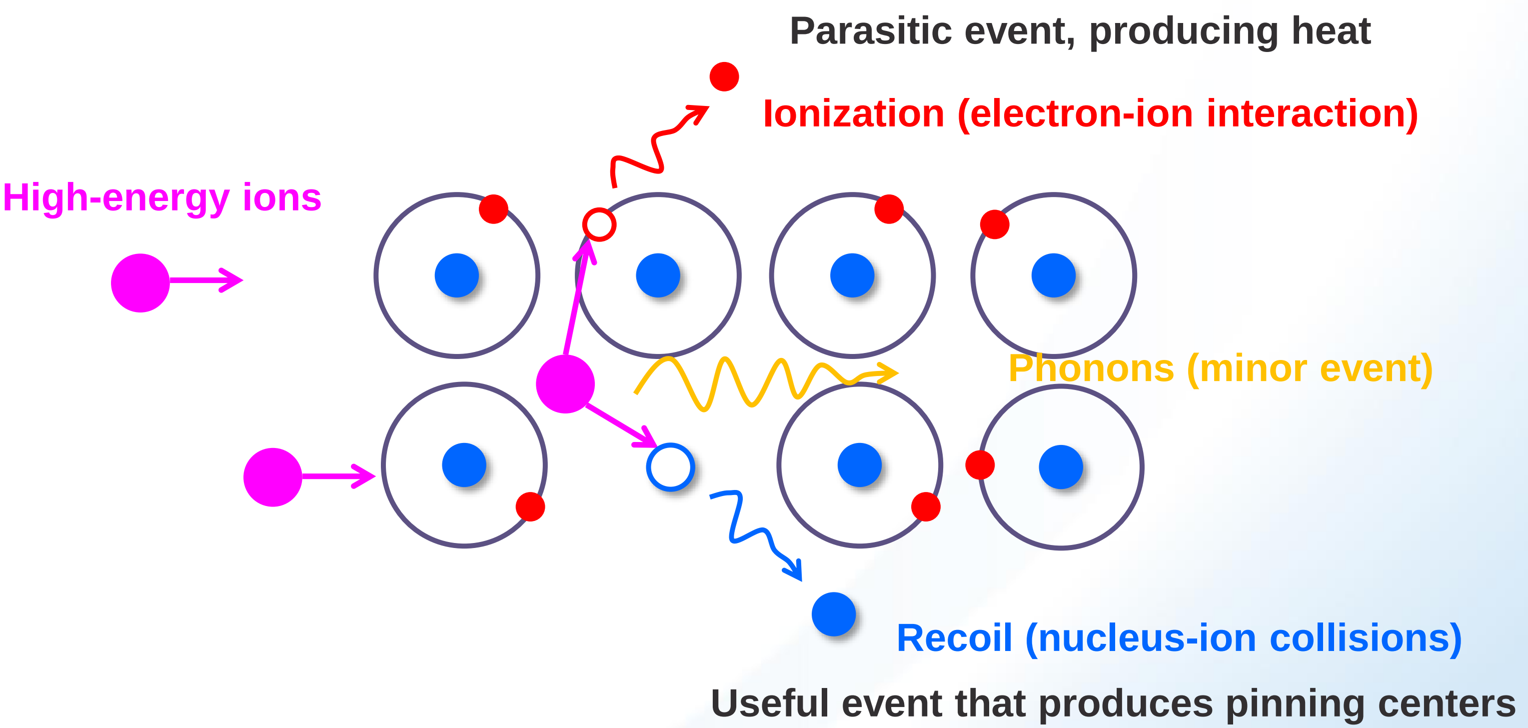
Accomplishments :

- Analytical probes developed at BNL providing guidance for improving I_c
  (Micro-LEEM, a CFN instrument at NSLS)
  **Nature Communications (2013), Scientific Report (2014, Nature)*
- 200% I_c gain by derivative phase pinning
- 200% I_c gain by R2R ion irradiation

Significance and Impact:

- High performance & lower cost wire
- Application of superconductors for magnets, motors, generators, etc

Effect of ion irradiation on matters



It is desirable to maximize the recoil cross-section

Consideration of irradiation facility for 2G wire:

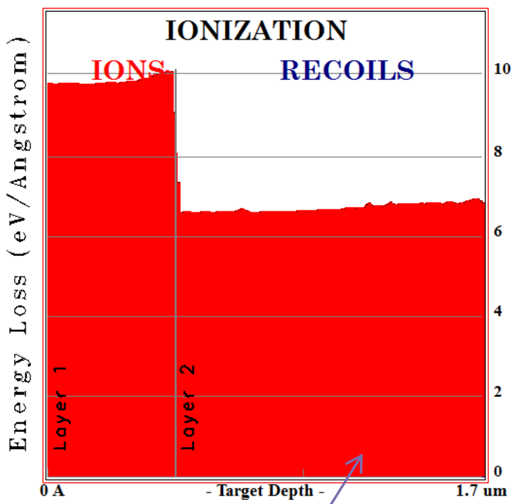
1) Effectiveness
2) Low energy
3) Low dosage
4) Low heat load (beam heating)

Importance of keeping irradiation energy as low as possible

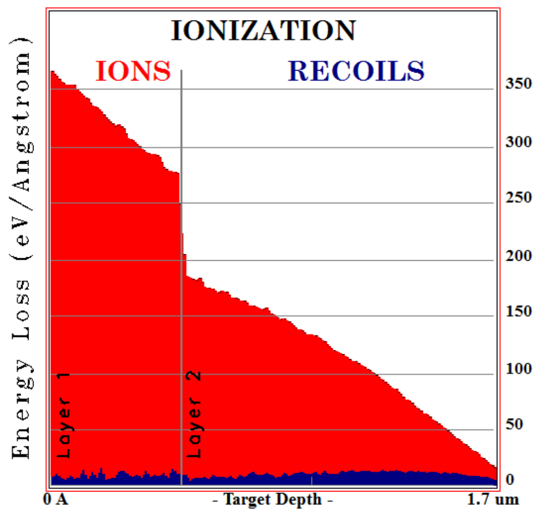
- Lower capital cost
- Required dose is $\sim 1/E^2$, i.e. reducing energy by a factor of 10, we increase irradiation rate by 100
- Heat load on the sample is $\sim E$

Advantage of heavy ions

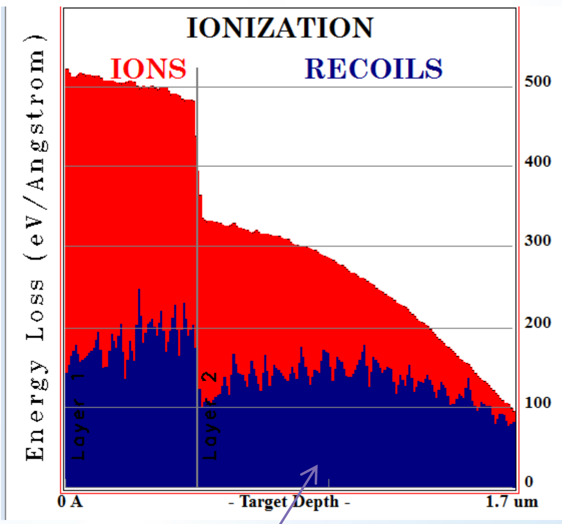
1 MeV H^+
Recoil loss: 0.03 eV/Å•ion



3.5 MeV Ar^+
Recoil loss: 40 eV/Å•ion



3.0 MeV Au^{4+}
Recoil loss: 300 eV/Å•ion

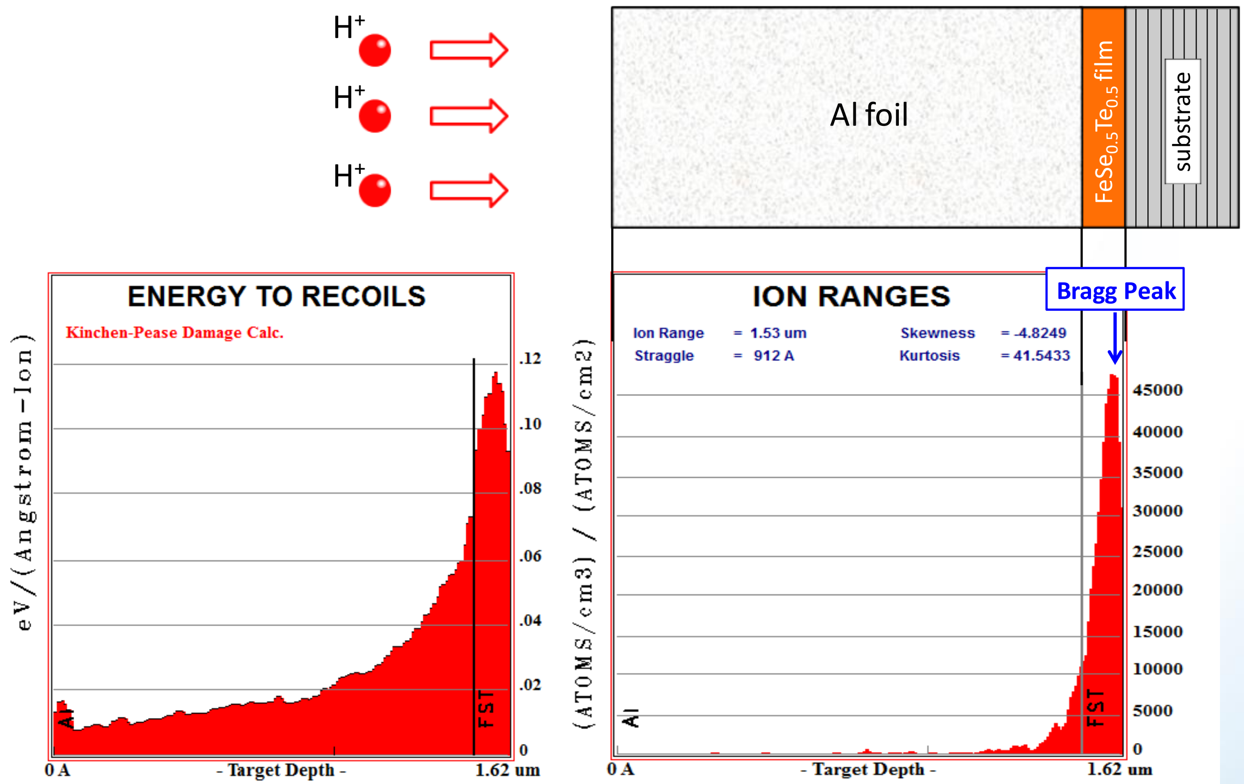


Ionization loss (heating)

Recoil loss (defect generation)

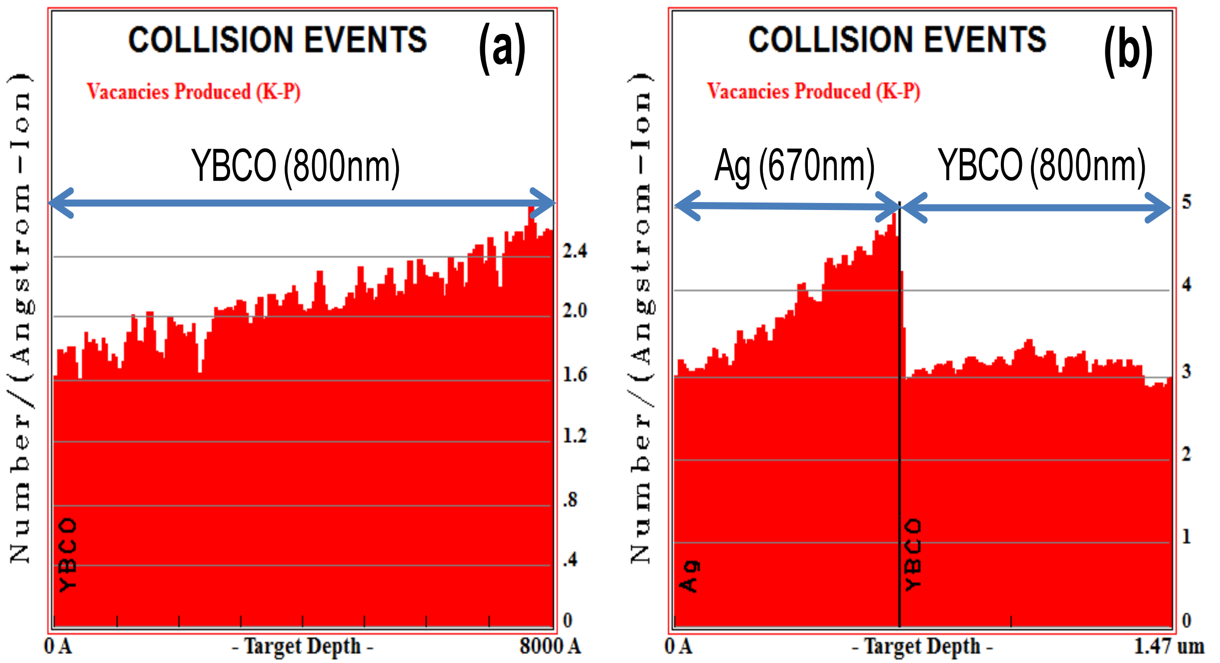
- ✓ Heavier ions offer potentially more efficient defect generation
- ✓ Lower doses can reduce the beam heating issues
- ✓ For Ar and Au the ion energy is set at the lowest level: the Bragg peak at YBCO-substrate interface

Ion irradiations



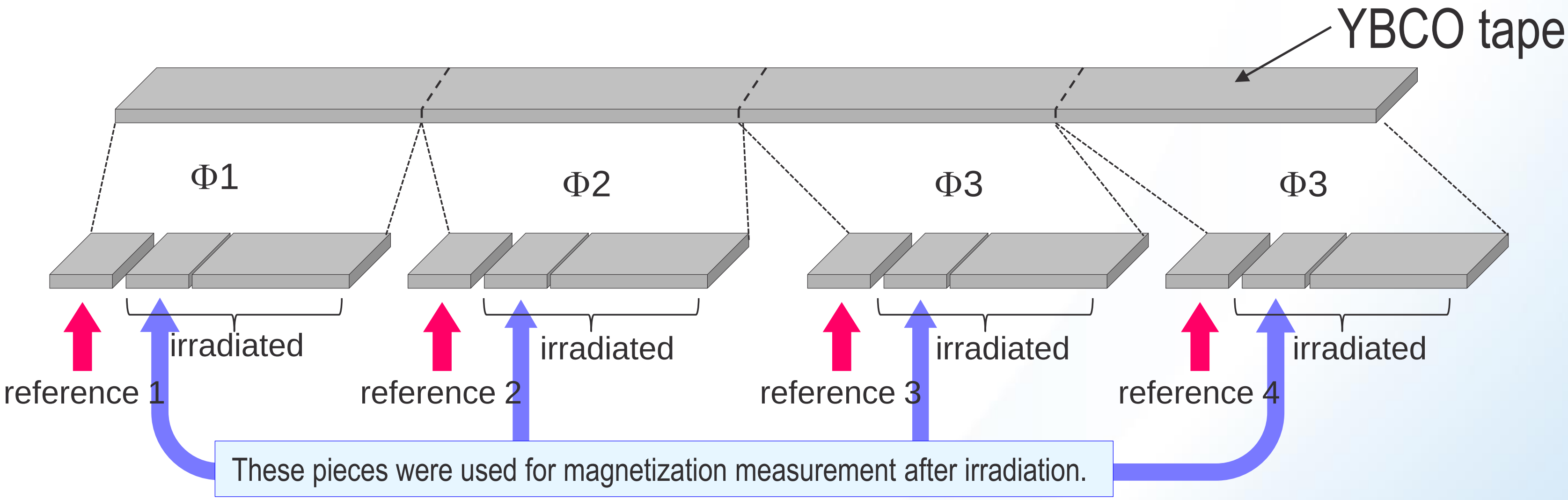
Energy to recoils and ion ranges of 190 KeV in FST films (120 nm) covered by Al foil (1.5 μm) simulated by SRIM 2008.

Ion irradiations



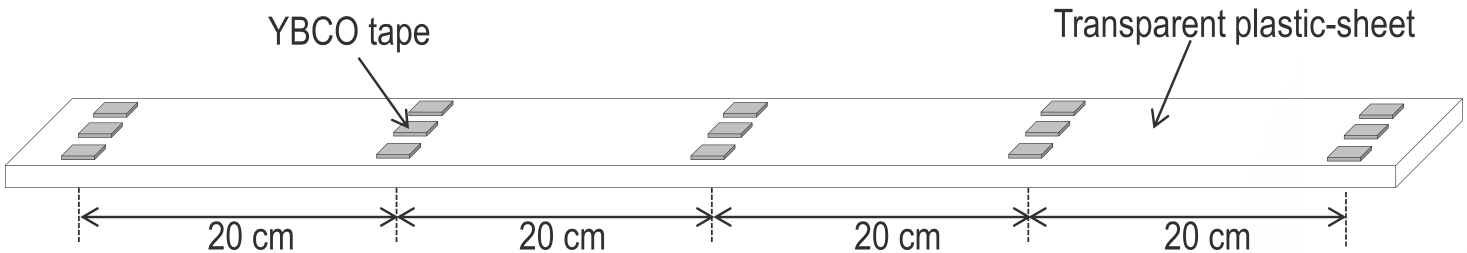
Recoil collision events as a function of target depth inside 800 nm thick YBCO film (a), and a stack of 670 nm Ag on top of 800 nm thick YBCO film irradiated by 12 Mev Ag^{4+} irons, calculated with 10,000 incident ions. (Ozaki and Li, unpublished)

Optimizing the dosage for 2G YBCO tape

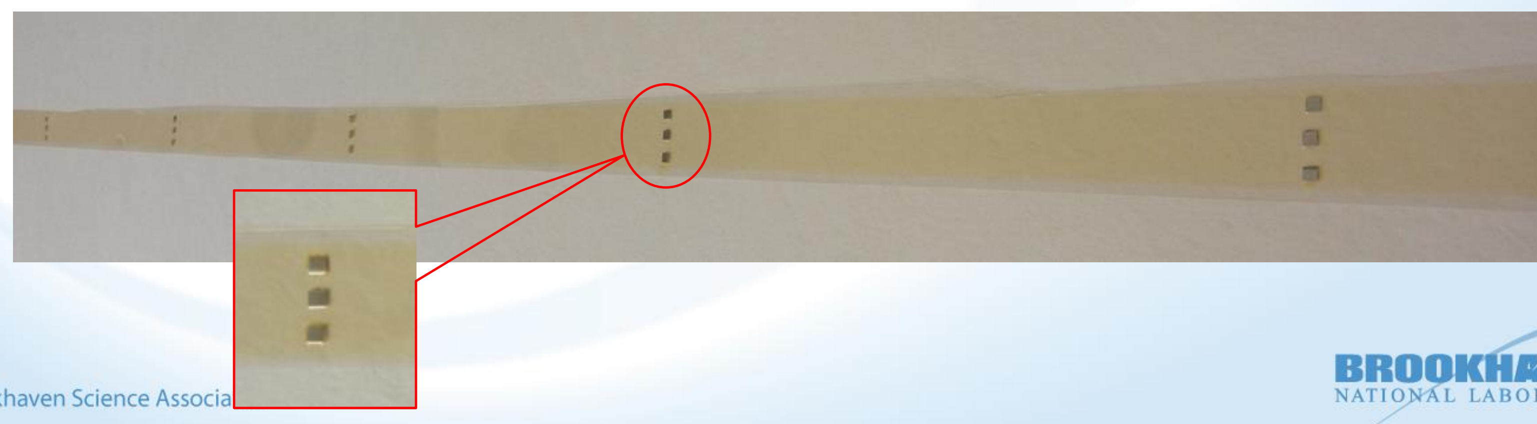


IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation PL-5 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

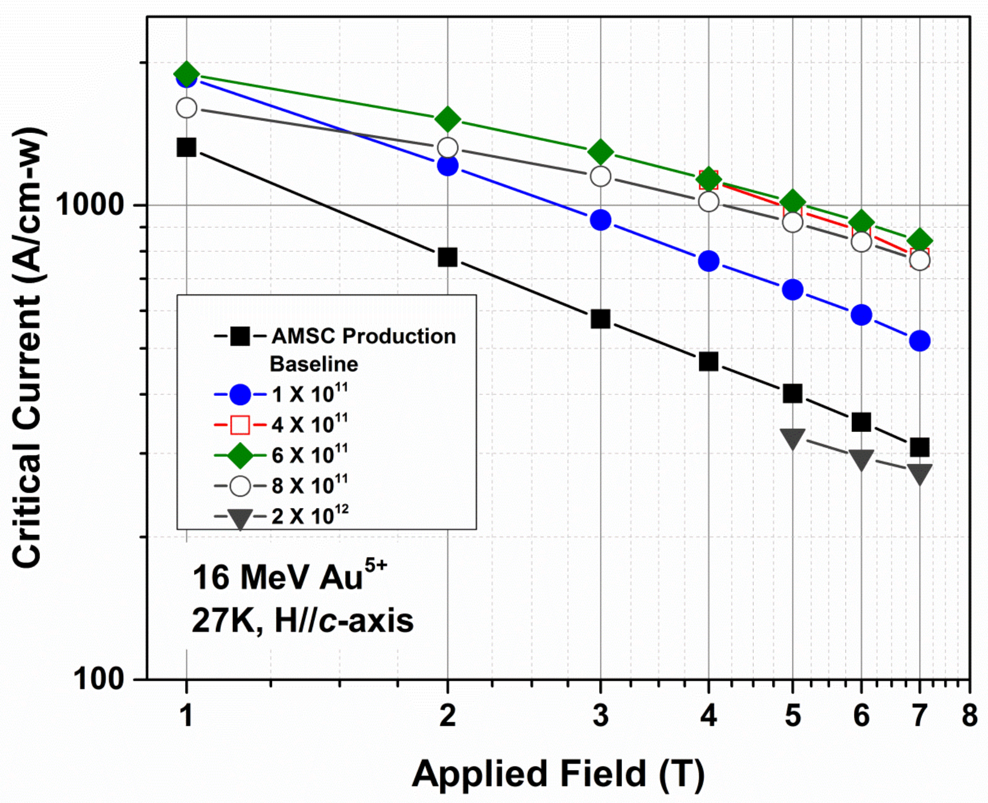
Uniformity of irradiation for 2G YBCO tape



The irradiated area on the clear plastic tape shows light brown color after exposed to irradiation (Au^{5+}, 18 MeV, 5x10^{11} ion/cm^2). The whole tape was optically scanned to check the irradiation uniformity. Small pieces of 2G tapes had been cut and placed at various places to check J_c.



Au Ion Irradiation of Production Line Coated Conductors

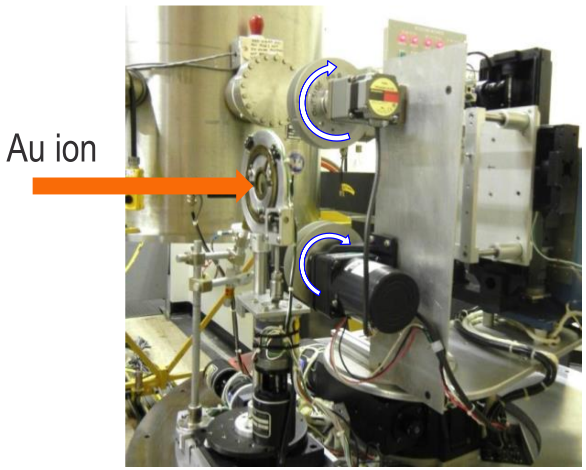


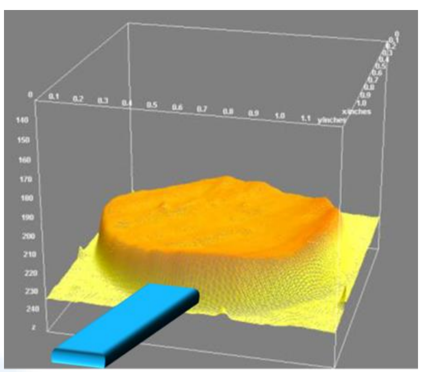
Tandem Van de Graaff accelerator at Brookhaven National Laboratory

Sample chamber

- ➢Optimal dose ~ $6x10^{11}$ Au ions/cm^2
- ➢Effective band width ± 30%

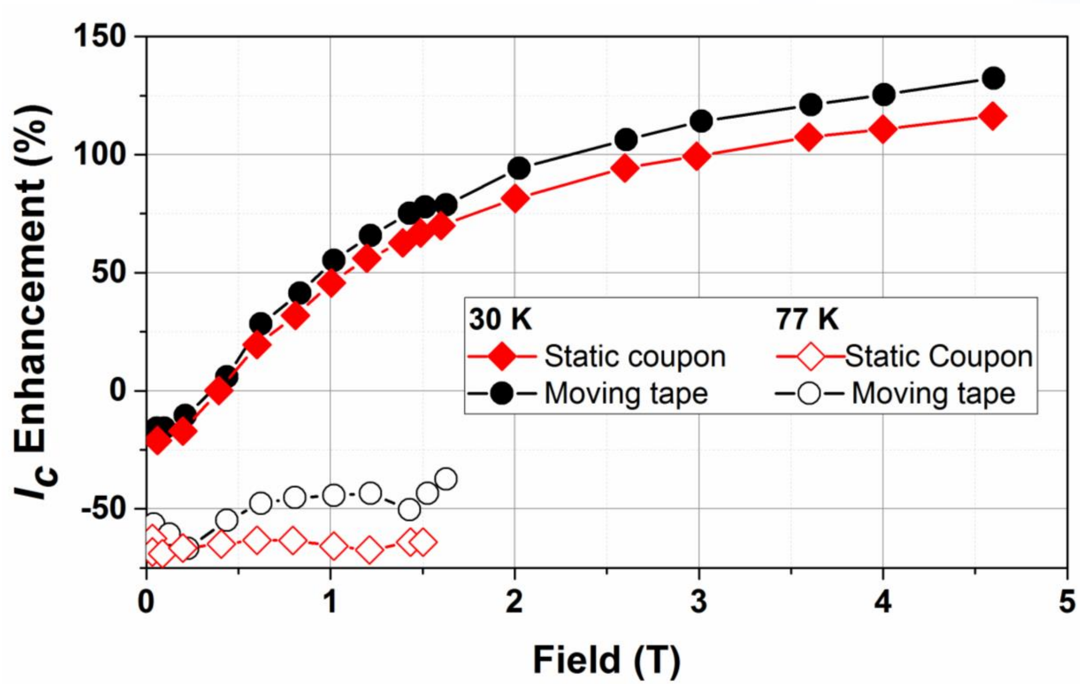
Static vs Roll-to-Roll Irradiation



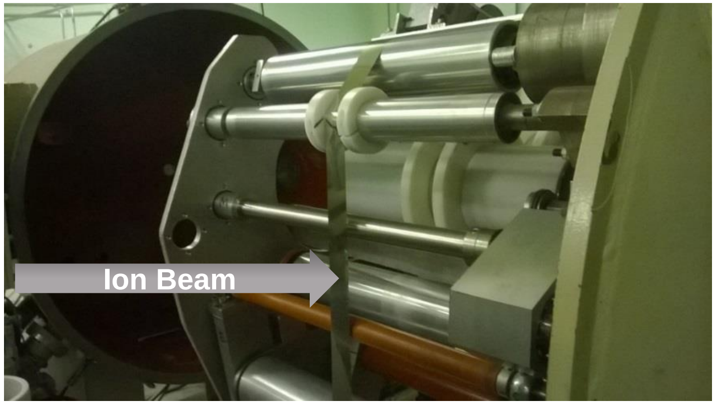


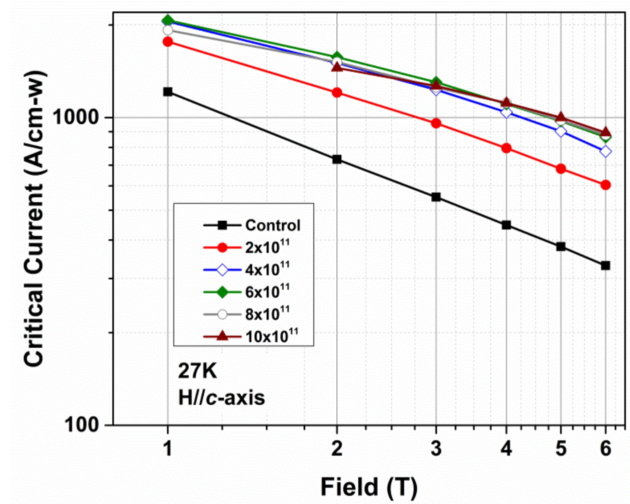
Static Sample (1 x 2cm) Irradiation

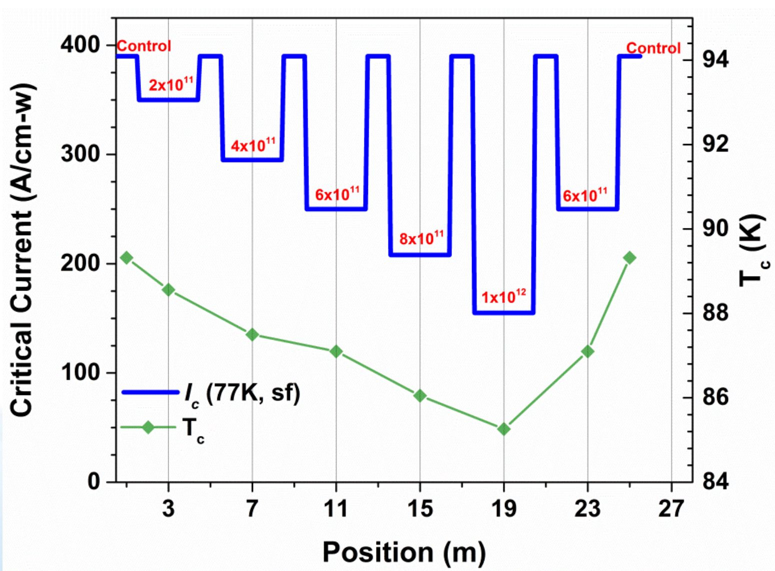
Moving Sample (1m x 1cm) Irradiation

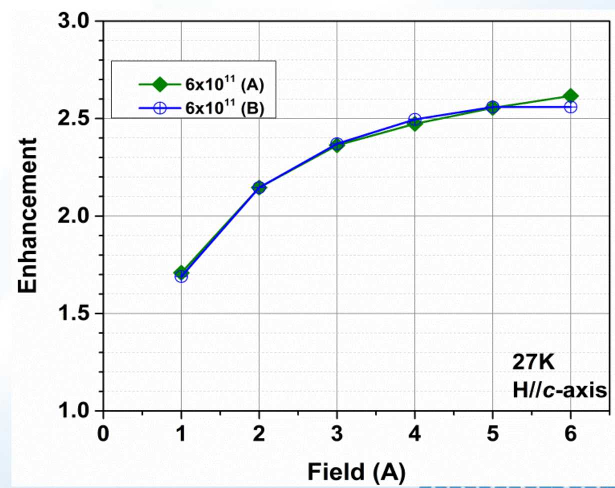


R2R Au Irradiation Optimization in 46 mm Wide Production Strip

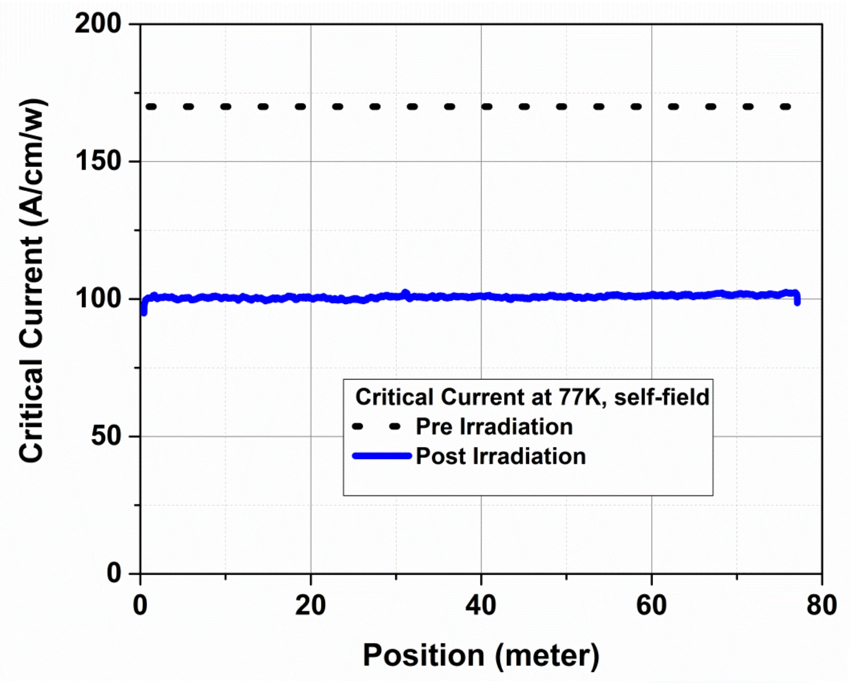








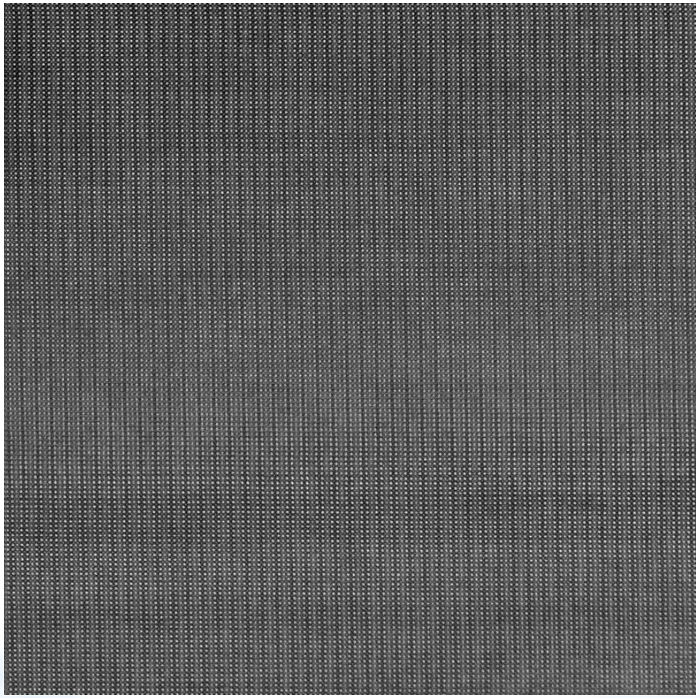
R&D Demonstration to "Production Length" Wire



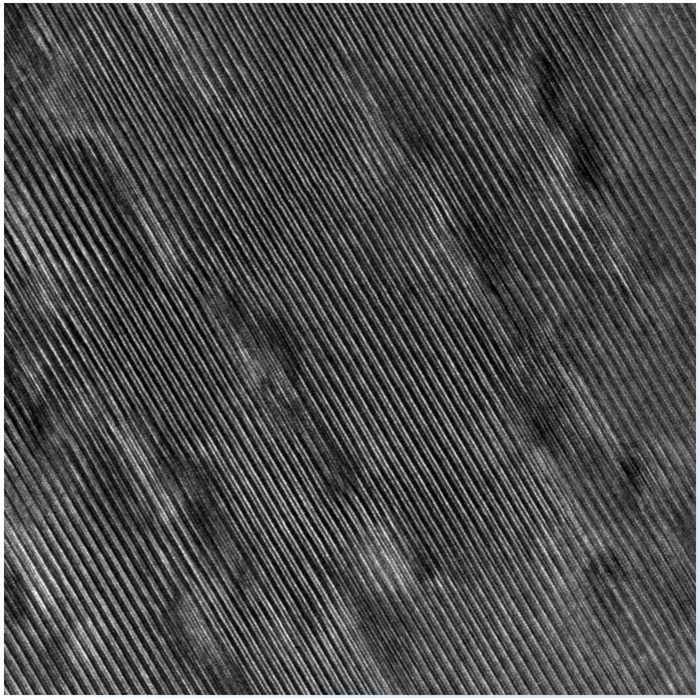
Consistent change in I_c at 77K, sf confirms that irradiation dose and pinning is constant along length of wire

Microscopic investigation of irradiation-induced pinning defects: TEM study (Wu & Li/DOE-BES)

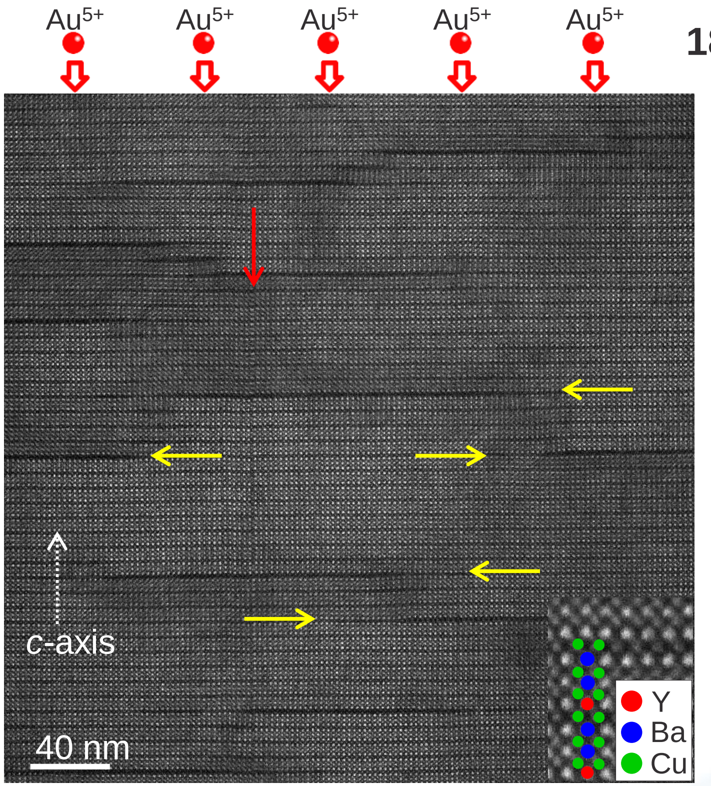
Before Irradiation



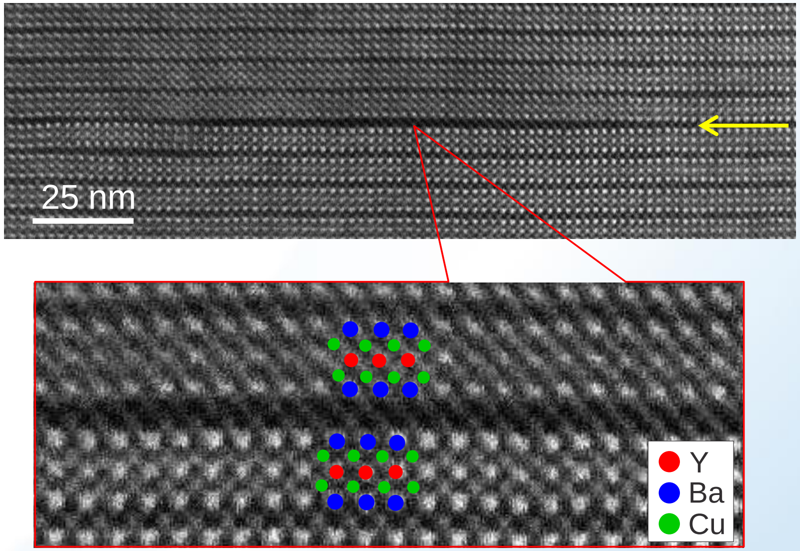
After 18 MeV, Au^{5+} irradiation at 6×10^{11} ion/cm^2



Microscopic investigation of irradiation-induced pinning defects: TEM study (Wu & Li/DOE-BES)

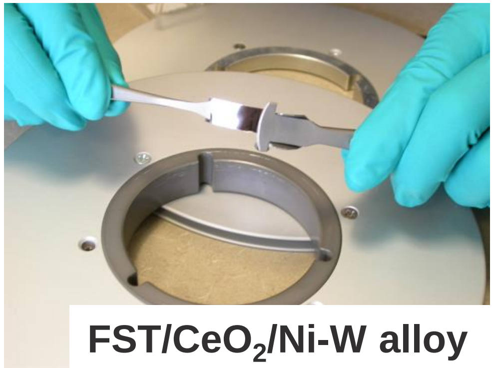


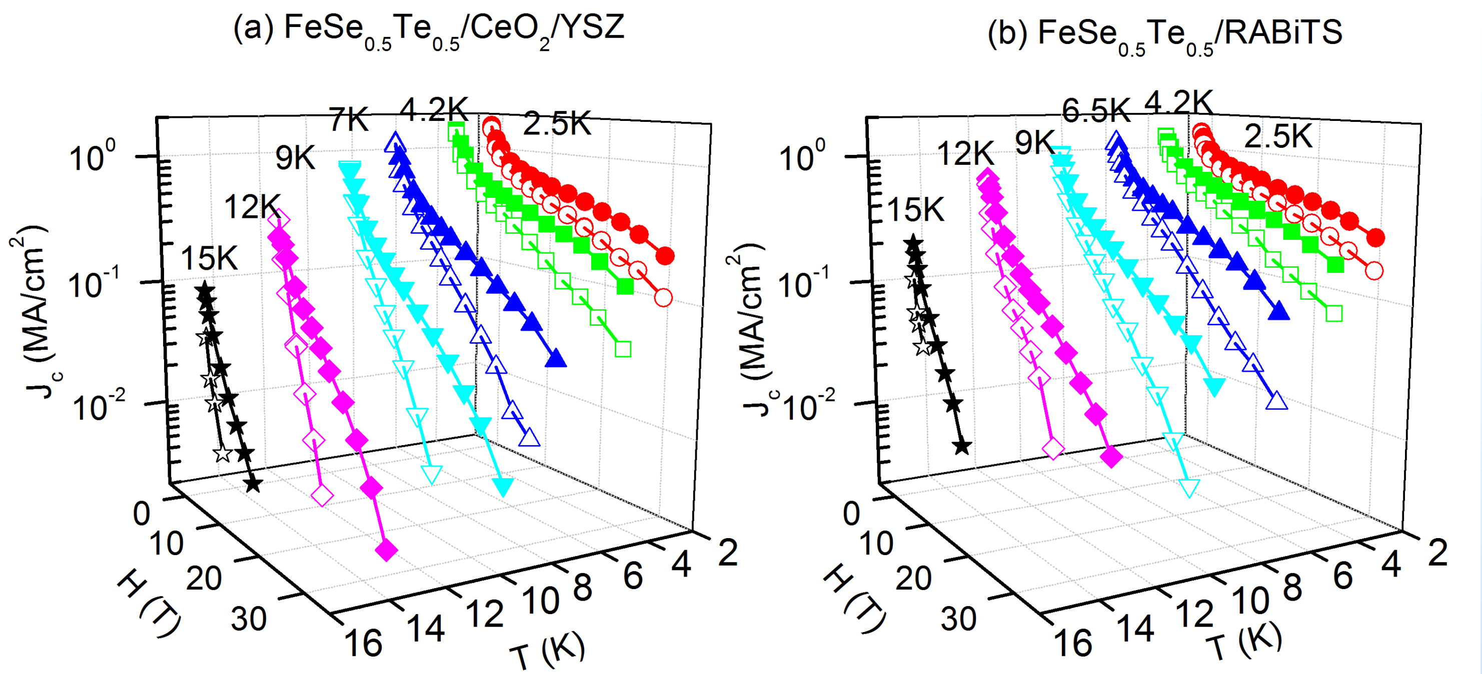
18 MeV, Au^{5+} irradiated YBCO tape, 6×10^{11} ion/cm^2



- ✓ The ripples (indicated by yellow arrows) are present between BaO-BaO layers
- ✓ Incident ions direction is indicated by red arrow

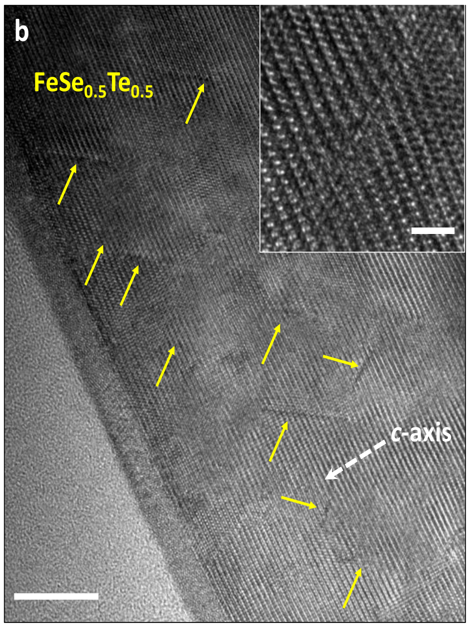
$FeSe_{0.5}Te_{0.5}$ coated conductors

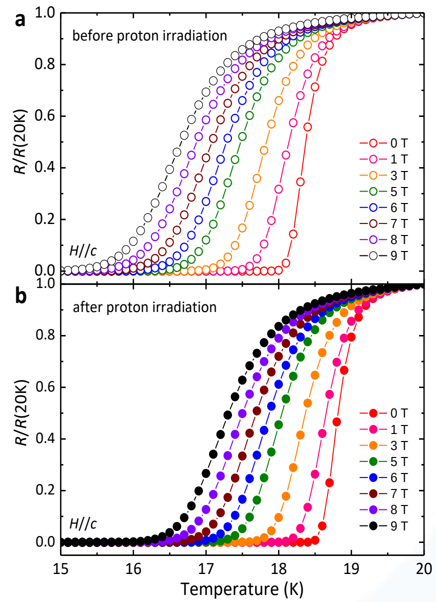


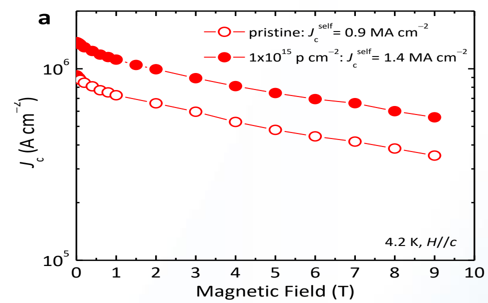


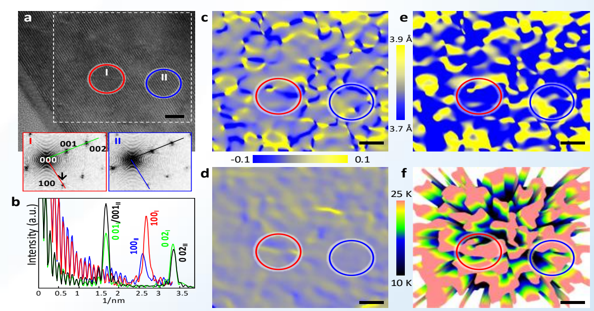
Si, QL, et al Nature Communications **4**, 1347 (2013)

Simultaneous increase of T_c and J_c in $FeSe_{0.5}Te_{0.5}$ superconducting films by 190 KeV proton irradiations









T. Ozaki, QL, et al Nature Communications, doi:10.1038/ncomms13036 (2016)

Challenges for Cuprate HTS wires and cables

No wire fits all

H

20 T

1.5 T

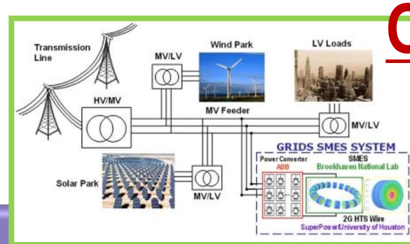
SMES
4.2-20K

Rotary Machines
30K, 1.5-2T

Transmission

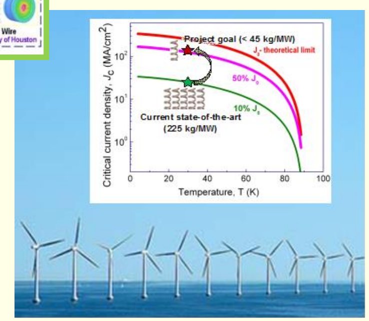
T

4.2K 30K 77K



Oct. 2010 arpa·e

ABB BROOKHAVEN NATIONAL LABORATORY SuperPower Inc.



Jan. 2012

arpa·e

BROOKHAVEN NATIONAL LABORATORY amsc

June 2008

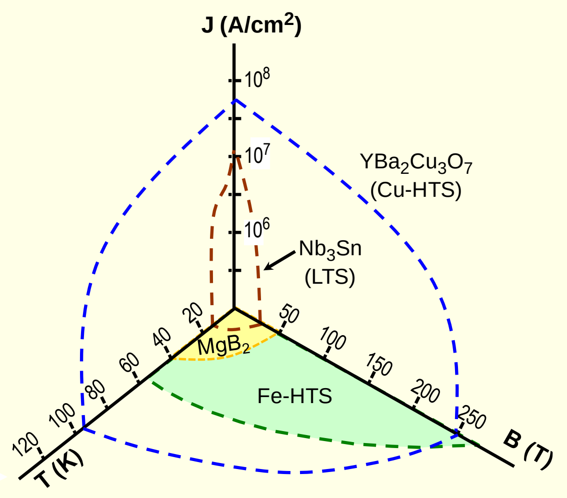
LIPA-Holbrook (1G, 2G at 77K), **DOE EERE**

Summary

- Superconductivity, as a powerful energy carrier, can be used to provide many transformative solutions to the key challenges in renewable energy
- Doubling in-field critical current in cuprate HTS coated conductors is demonstrated by a roll-to-roll ion irradiation process
- Significant progress has been made for 2G wires and cables. No one wire fits all yet --- whether it is desirable is another question.

***T_c, H_{c2}, J_c*, and anisotropy are limiting factors for large-scale application of superconductors**

Q. Li et al - Rep. Prog. Phys. **74** (2011) 124510



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