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Recent Advances in High Temperature Superconductors and Potential Applications

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http://www2.egr.uh.edu/~vselvama/

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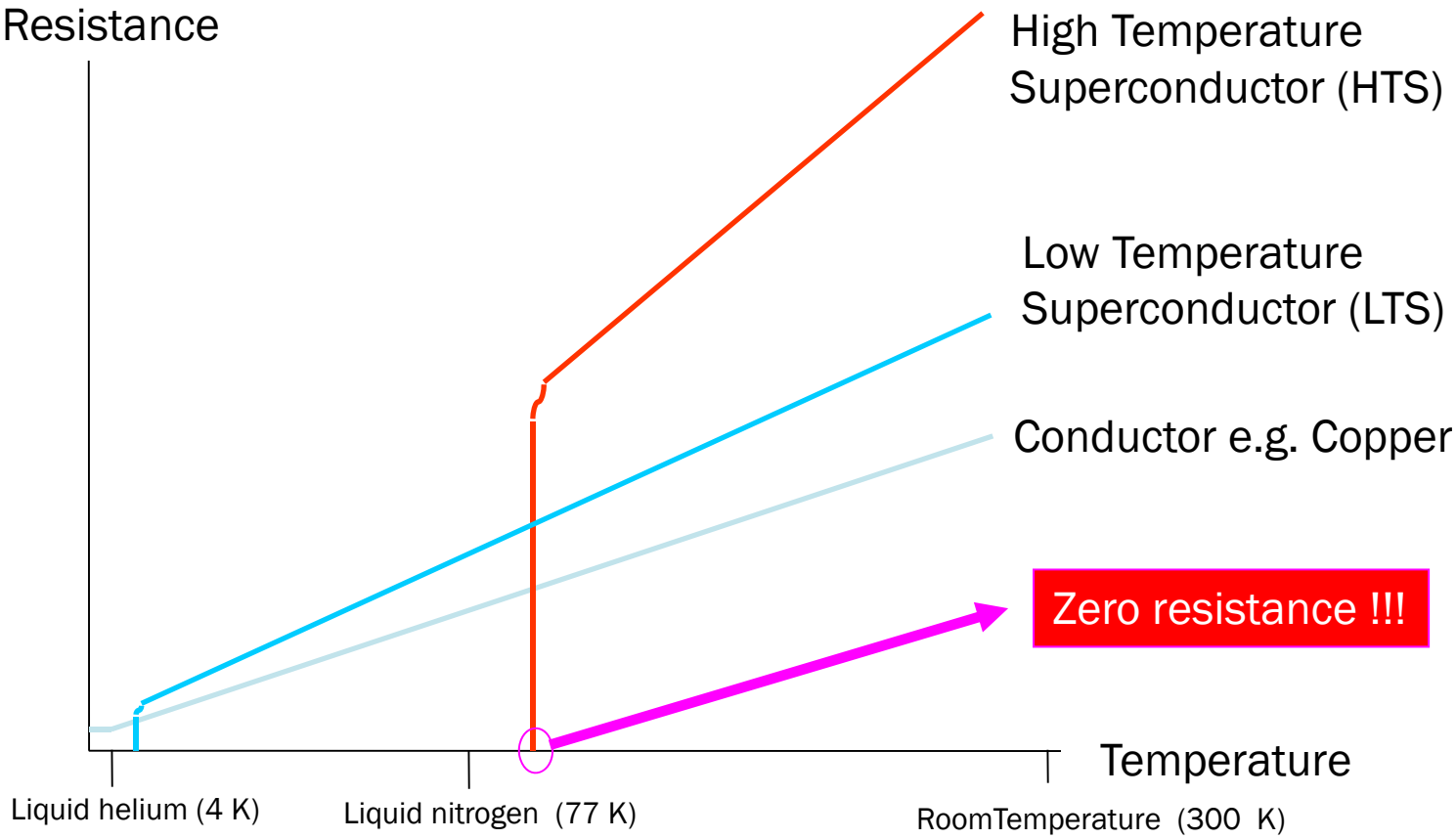
Outline

- Superconductor Applications
- High Temperature Superconductor wire manufacturing
- Recent advances at UH on high-performance superconducting wires

Superconductivity and its applications

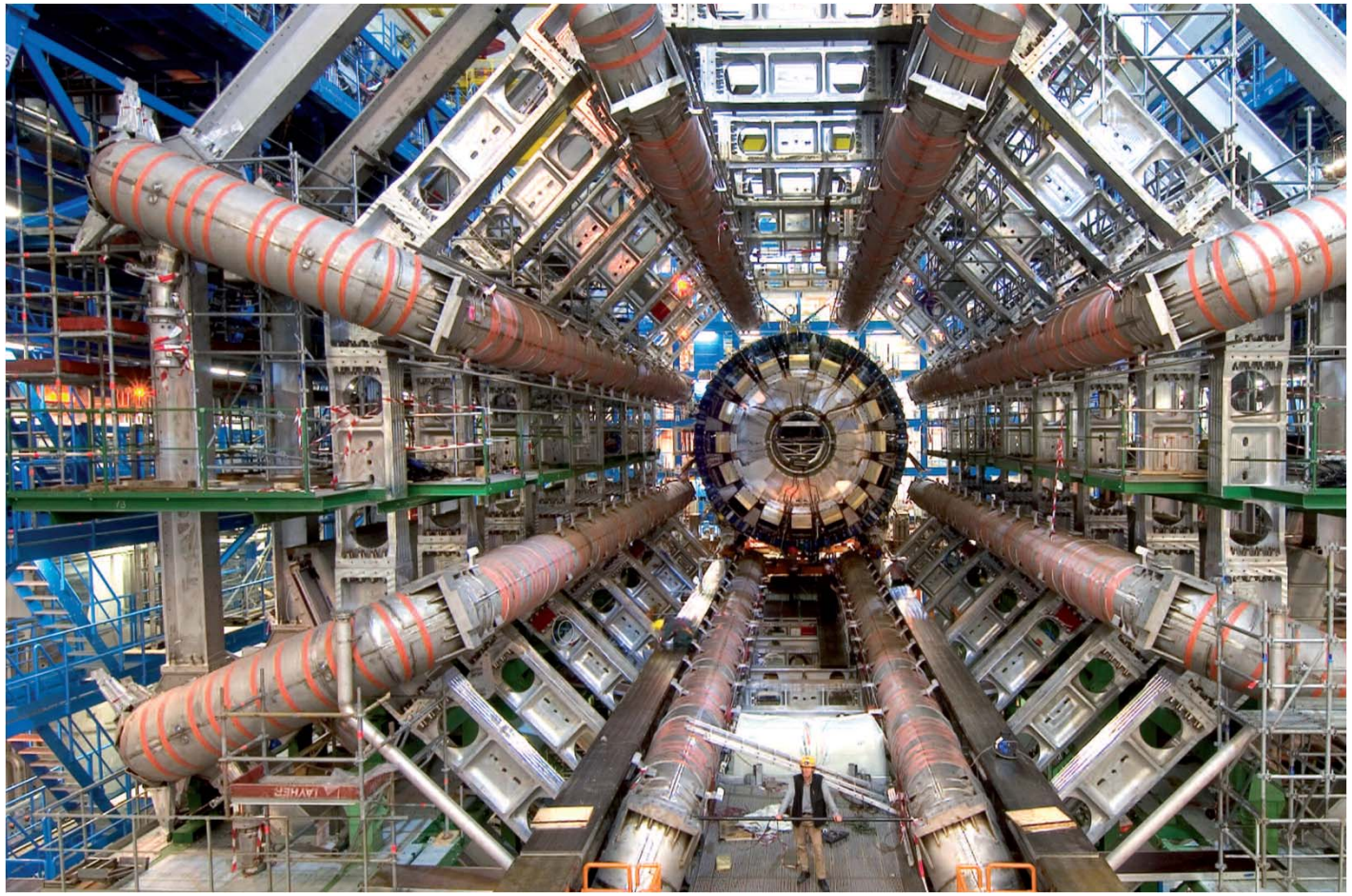
High temperature superconductors : Unique materials with great potential



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

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

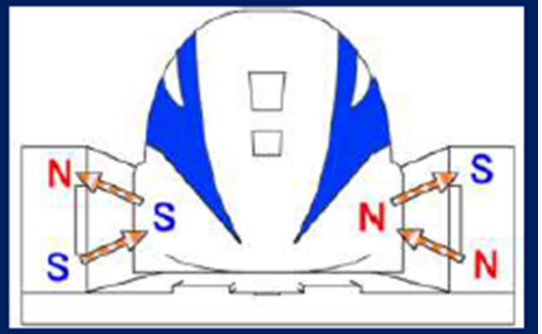
Low Temperature Superconductors enable High Energy Physics Research



- 14 TeV Large Hadron Collider with more than **9000** superconducting magnets for beam bending, focusing, correction and detection

Low Temperature Superconductors enable Maglev transportation

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



Courtesy of Herman ten Kate

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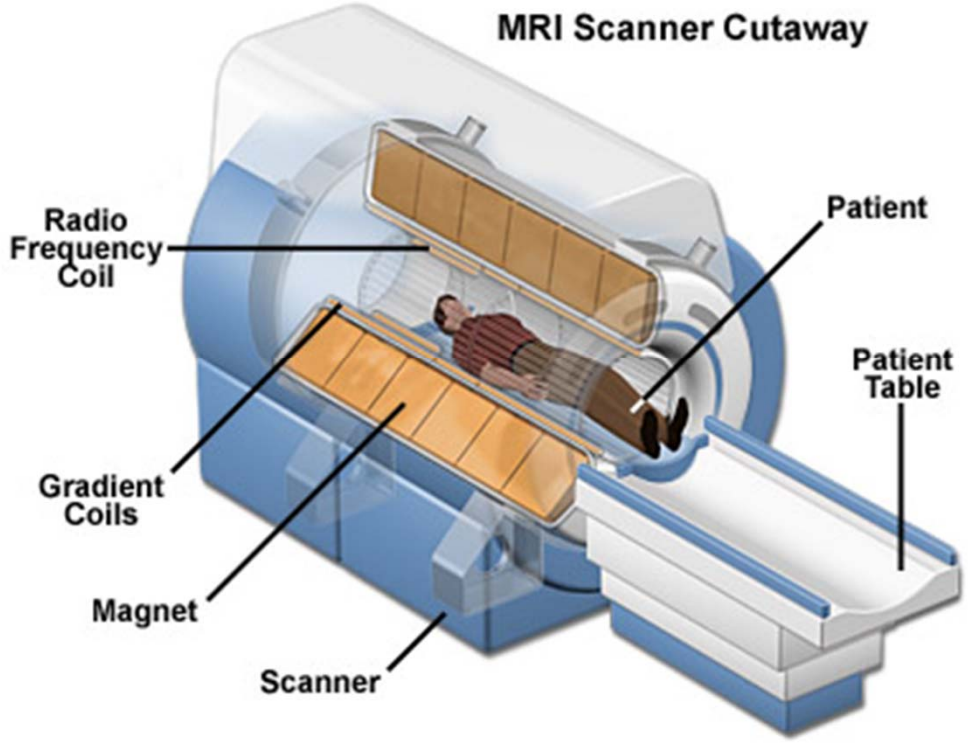
Low Temperature Superconductors are widely used in medical applications

Medical Devices: MRI

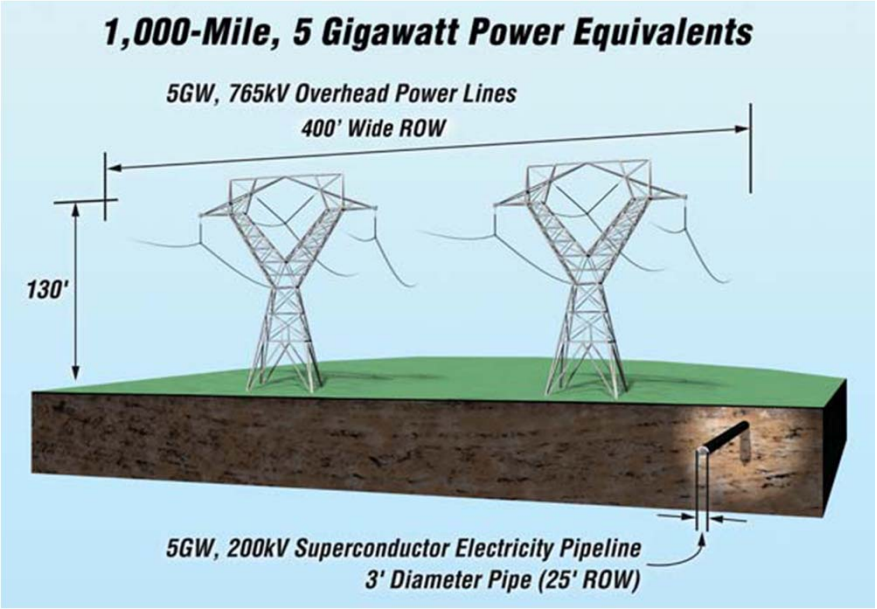


http://www.magnet.fsu.edu/education/tutorials/magnetacademy/mri/index.htm

MRI is a $ 3B industry enabled by superconductors.

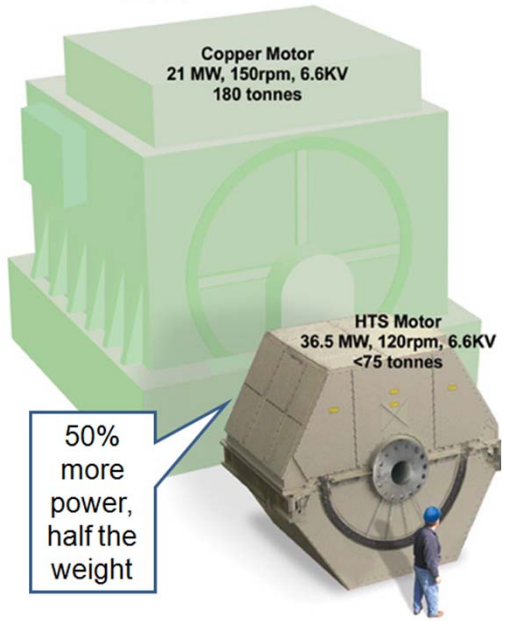
High Temperature Superconductors can greatly benefit energy applications

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

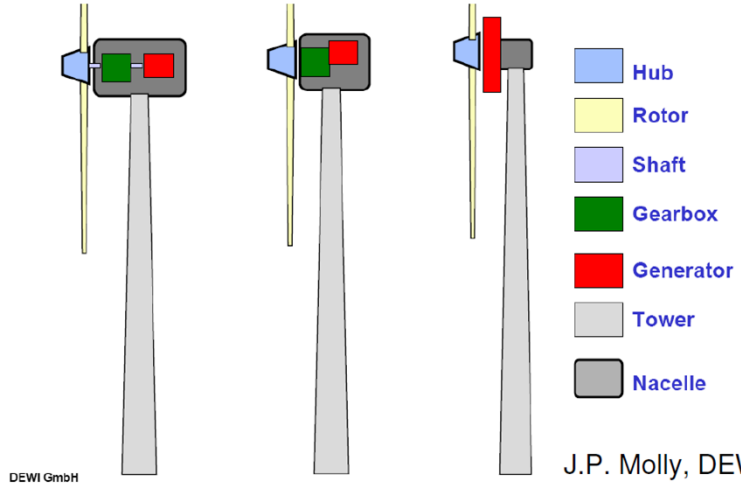


Significant benefits of HTS in energy applications

- Liquid nitrogen coolant is also dielectric medium (no oil)
  - *eliminates the possibility of oil fires and related environmental hazards*
- Superconducting generators, motors & transformers are less than 50% the size and weight of conventional equipment
  - *High power wind turbines & off shore platforms.*
  - *Direct drive wind turbines – less maintenance*
- More efficient electrical equipment
  - *Less energy lost*



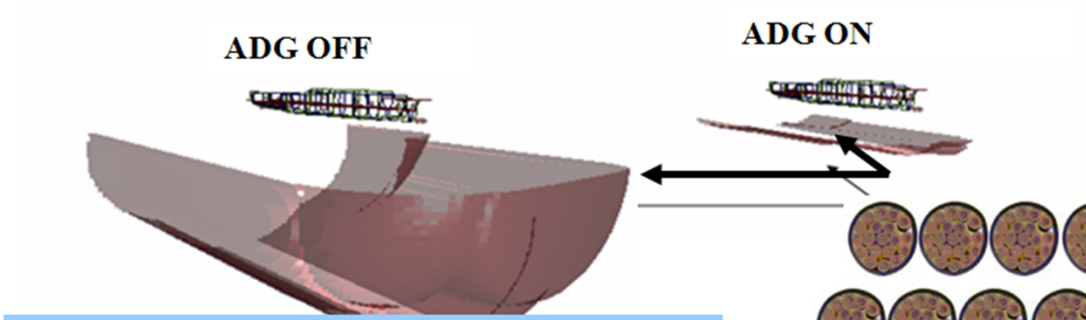
- **Conventional :** **15 RPM → 1:100 gearbox → 1500 RPM gen.**
- **Hybrid:** **15 RPM → 1:6 gearbox → 90 RPM gen.**
- **Multi-pole:** **15 RPM direct drive**



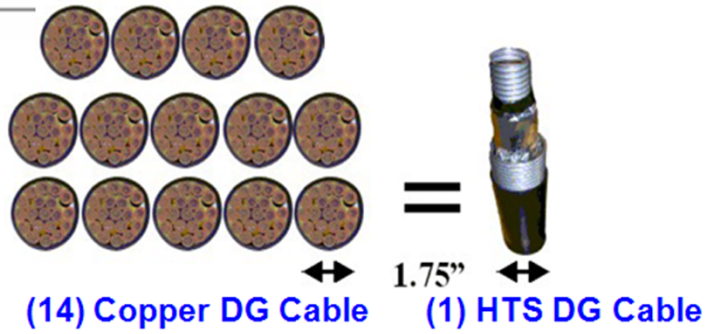
J.P. Molly, DEWI 2007

Superconductor cables in the Navy

- Superconducting Degaussing system to reduce magnetic signature of ships.
- Form-fit replacement to copper cabling with benefits of reduced weight and cost.
- Being deployed in USS Higgins DDG76



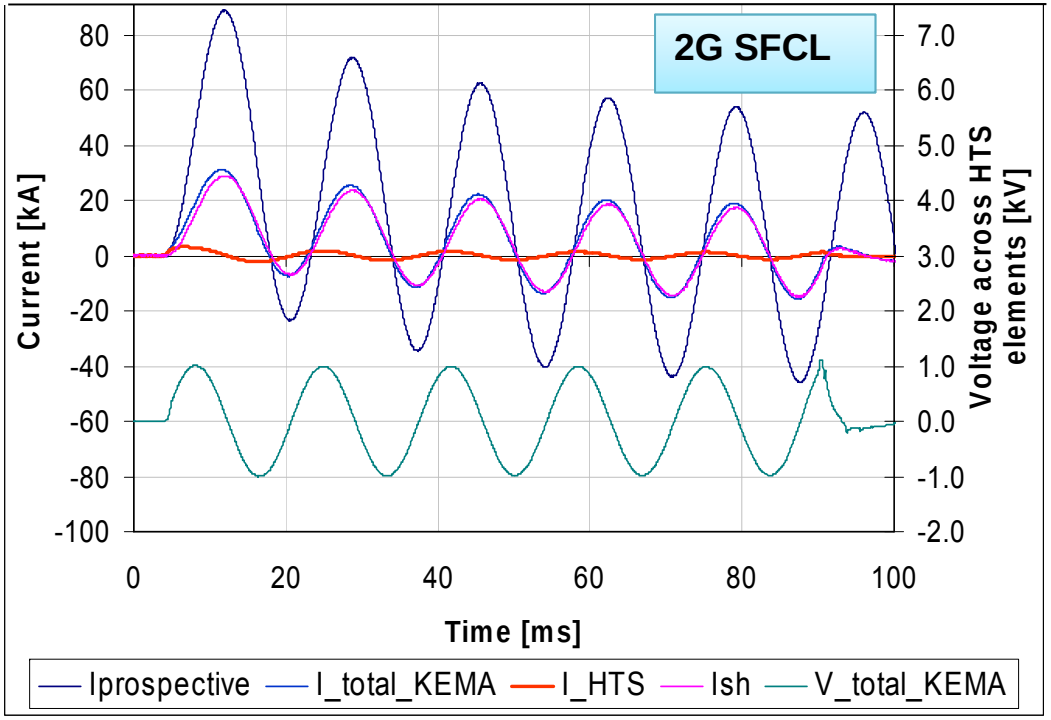
ADG Significantly reduces ships magnetic signature



HTS is a form fit replacement with the less "cable"

Fault current limiting feature : a bonus with superconducting devices

- Fault-current limiter successfully demonstrated → "Power valve" to rapidly detect and limit surges at high power levels without interrupting power or having to manually reset breaker
- Prototypes tested by SuperPower/Nexans, Nexans and Zenergy.



High-power SFCL test	2G FCL
Prospective current	90 kA*
Limited current	32 kA
Current through element	3 kA
Response time	< 1 ms

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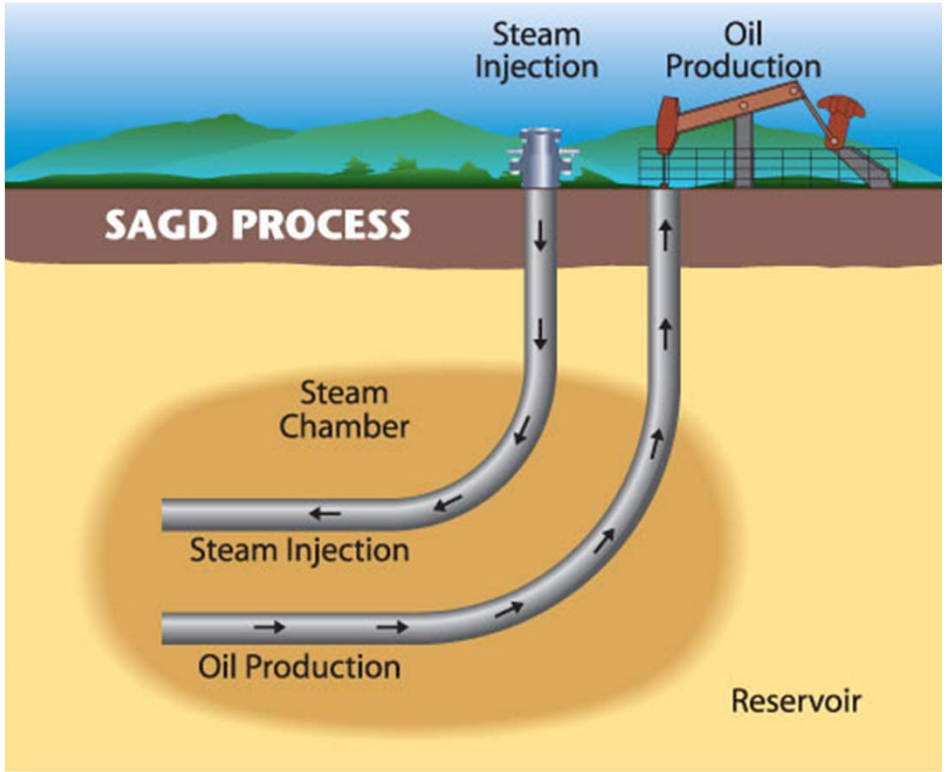
HTS power cables can benefit SAGD Operations

Electric Heaters to supplement SAGD!
Present Electric Heaters down hole challenged by Power density!



Source: Canadian Centre for Energy Information

~900 Existing Operational Wells

Producing 800,000 Barrels Per Day

Concept developed in I-CORPS program in collaboration with ARPA-E

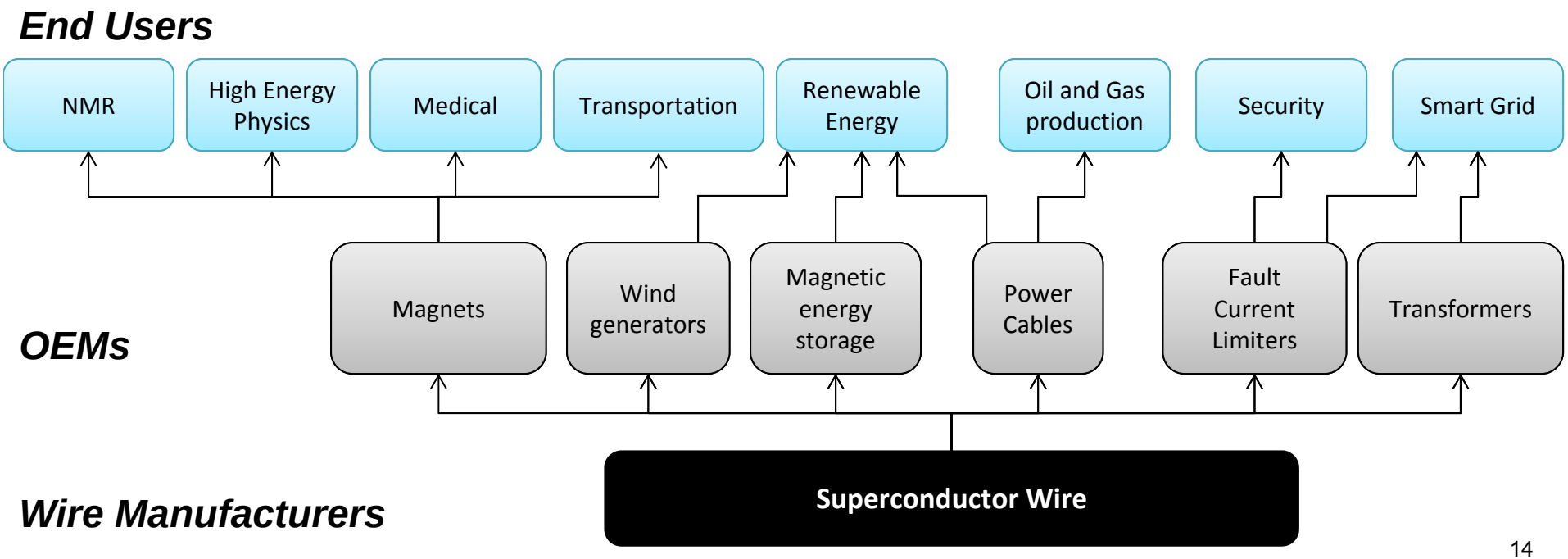
Significant benefits of HTS in high magnetic field applications

Generation of high magnetic fields at temperatures of 4.2 K to 65 K (single stage cooling above 40 K) . ***Compact magnets that use less power.***

- High-field magnets 25 Tesla and beyond
- Superconducting Magnetic Energy Storage
- Magnetic Resonance Imaging
- NMR spectroscopy
- Magnetic separation
- Plasma confinement for space rocket propulsion
- Magnetic heating for induction heaters

Multi-pronged impact of Superconductors can be realized in a variety of applications

- Enhanced energy efficiency
- High power density
- Less CO_2 emission
- Better power quality
- Better security of electric power grid
- Medical Imaging
- High Speed Transportation
- Pharmaceutical – drug discovery
- Defense



Superconductor wire impacts a broad range of industries; meets national needs

Energy

Cables
Transformers
Generators
Energy Storage
Grid Protection

Medical

MRI
Proton Beam Therapy

Defense

Airborne generators
All-electric ship
Degaussing cables
Rail Gun

Superconductor Wire

Industry

NMR
Fault Current Limiters
Motors
Induction heaters
Magnetic Separation
Crystal Growth

Transportation

Maglev trains
Rocket propulsion

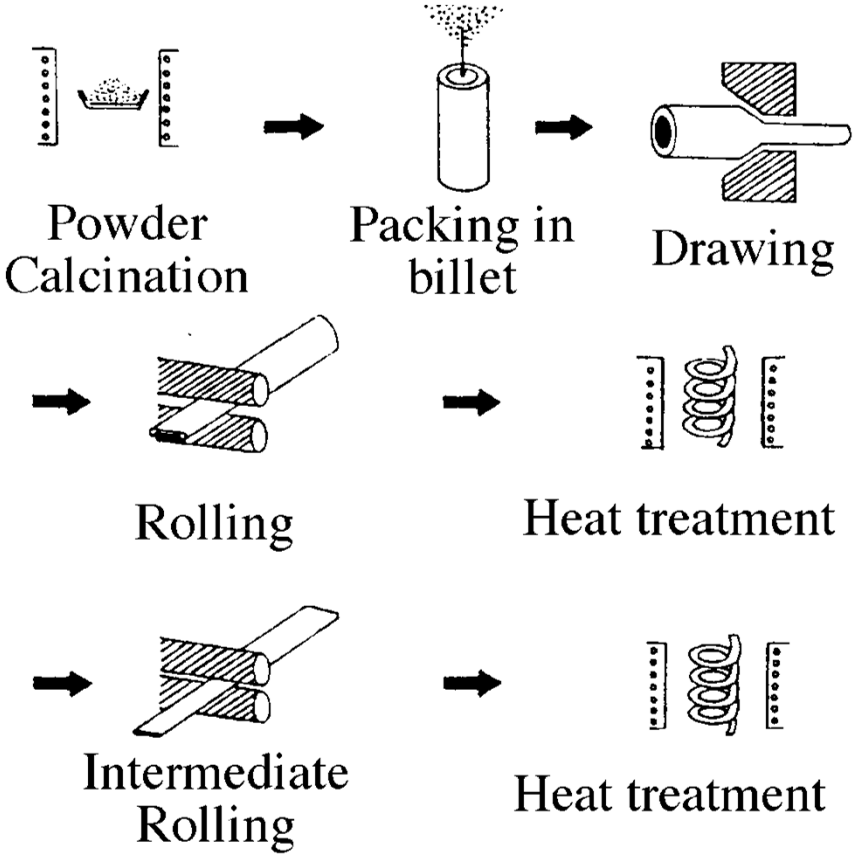
Research

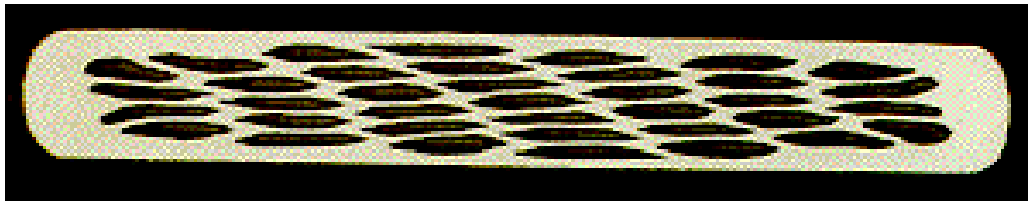
High-field magnets
High Energy Physics
Fusion reactors

High Temperature Superconductor Wire Manufacturing

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

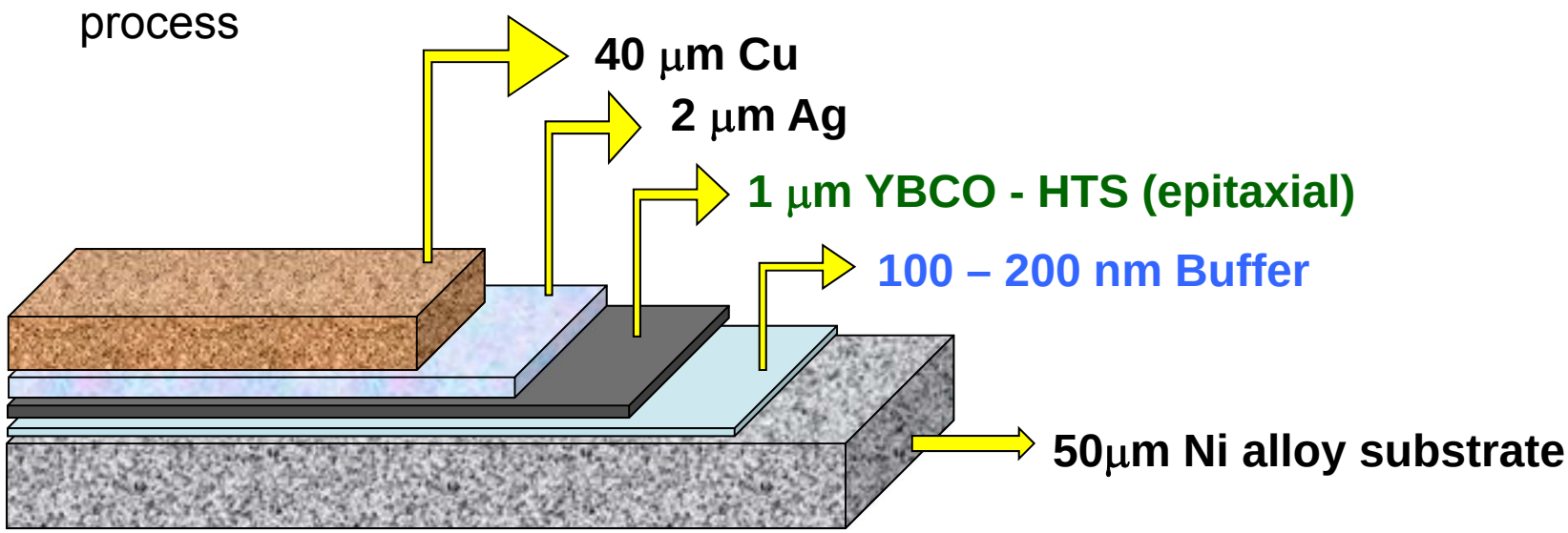
- High-temperature superconductors are ceramic materials and are inherently brittle. Challenge is to produce them in a flexible wire form in lengths of kilometers
- Two approaches to produce HTS in flexible tape form:
  - First-generation (1G) HTS - HTS is encapsulated as filaments in a silver sheath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





Thin film (2G) HTS wire manufacturing approach

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

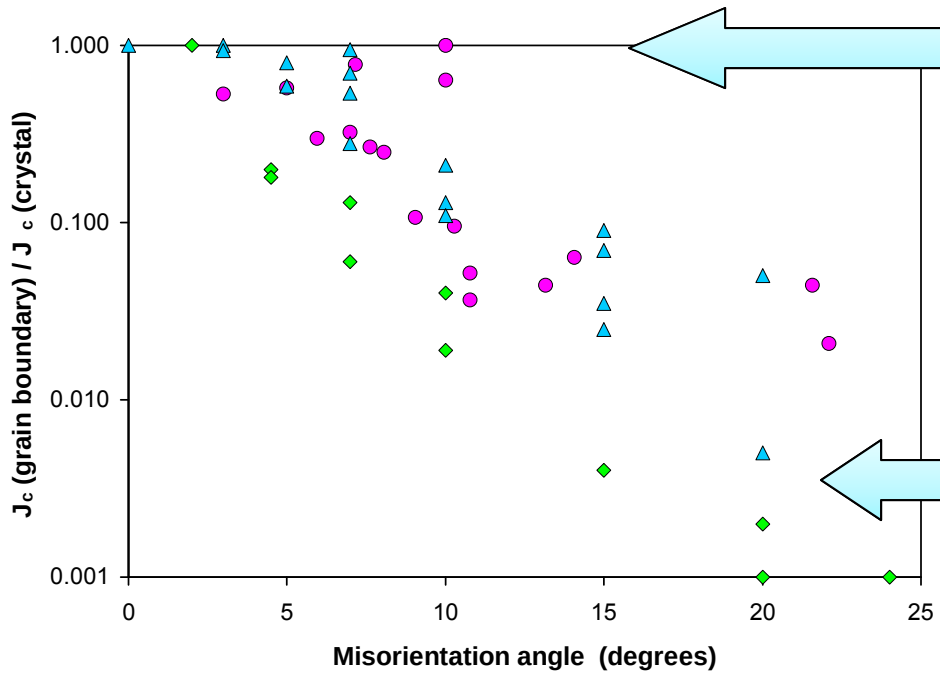


Fundamental challenge in thin film HTS tapes

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

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

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



Single crystal film current density

- D. Dimos, *et al.*, Phys. Rev. B **41**, 4038 (1990).
- N.F. Heinig, *et al.*, Appl. Phys. Lett. **69**, 577 (1996).
- D. T. Verebelyi, *et al.*, Appl. Phys. Lett. **76**, 1755 (2000).

Typical current density of HTS film on polycrystalline substrate

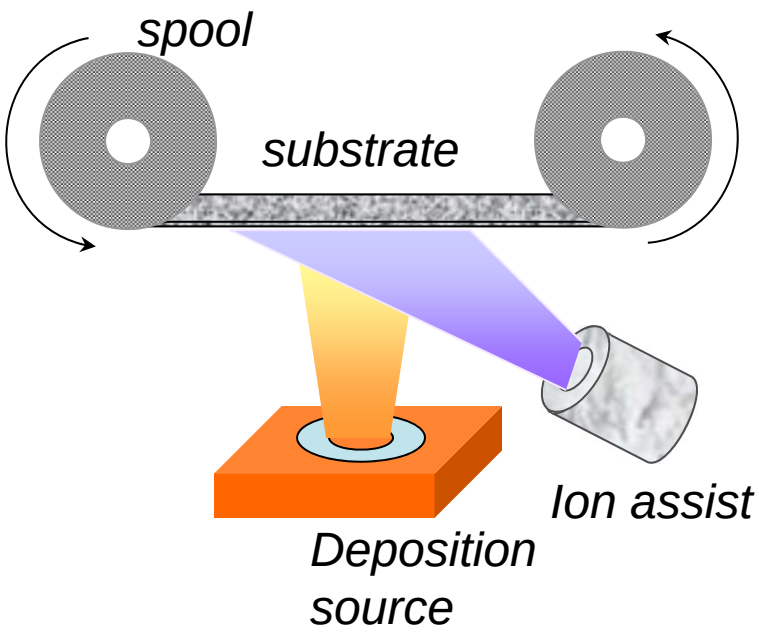
(data complied by S. Foltyn, LANL)

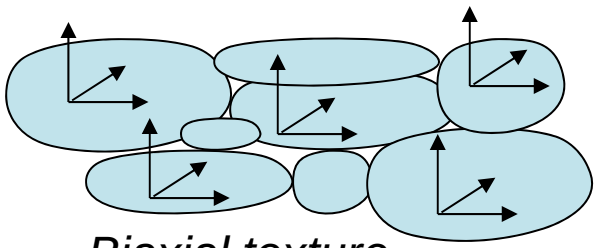
Cannot make kilometer lengths of HTS thin film wire on single crystal substrates.

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

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

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



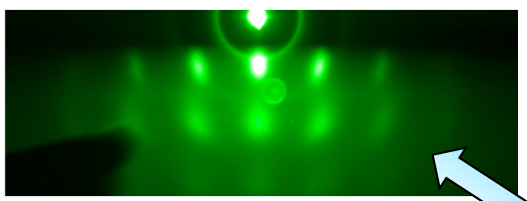


Biaxial texture

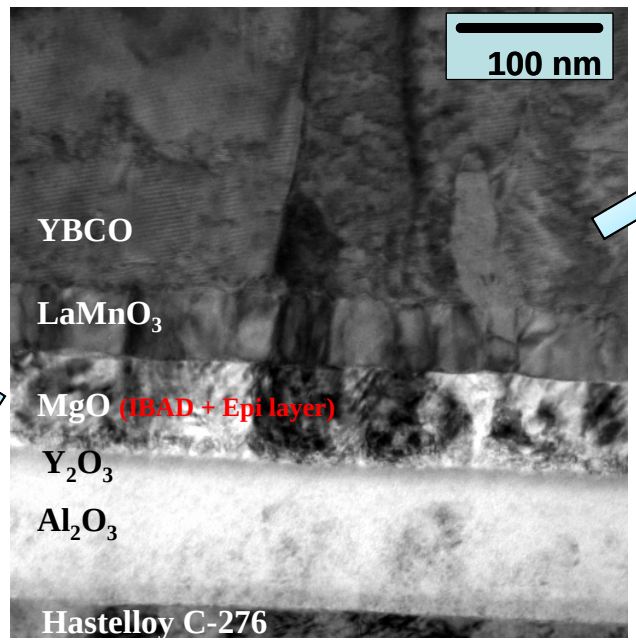
Grains in the IBAD film are arranged in a 3-dimensional aligned structure with grain-to-grain misorientation in any axis less than 5 degrees – essentially a near-single crystalline structure

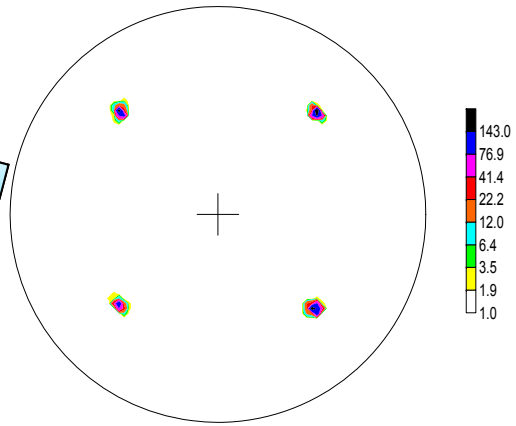
Epitaxial single crystalline-like films on polycrystalline or amorphous substrates based on IBAD

- 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

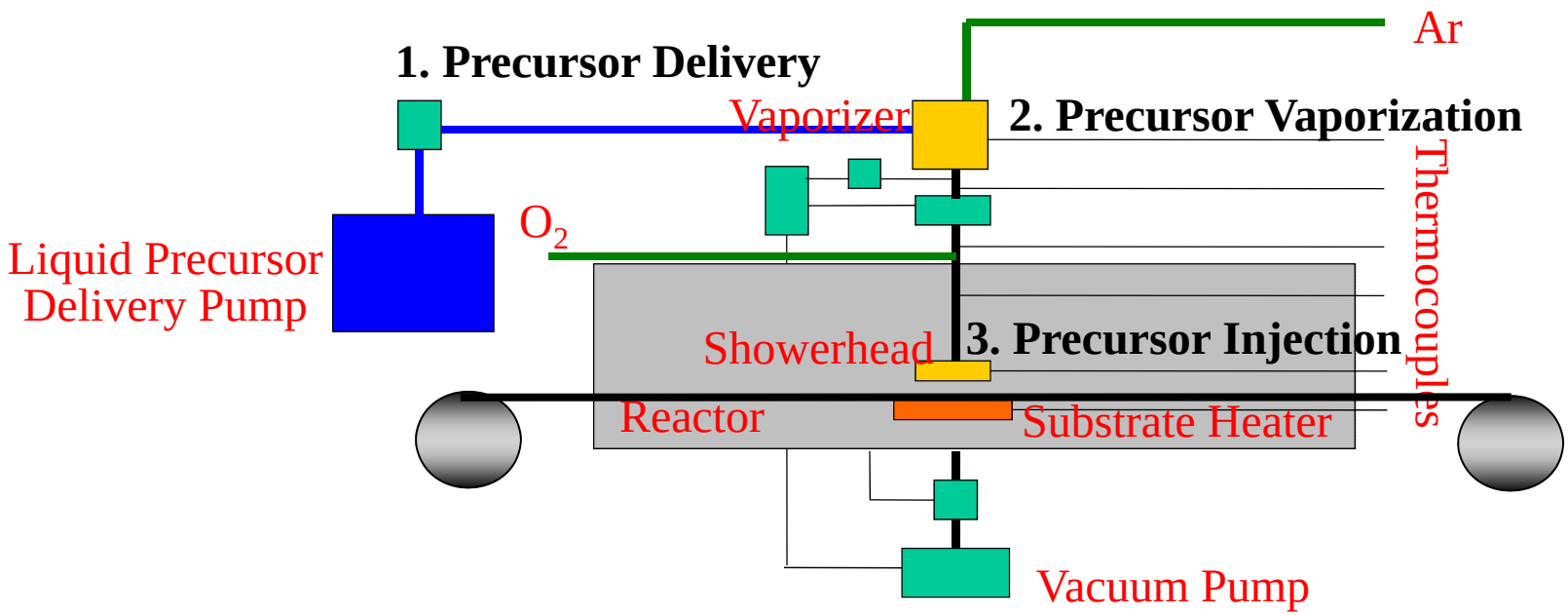




YBCO(113)

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)



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

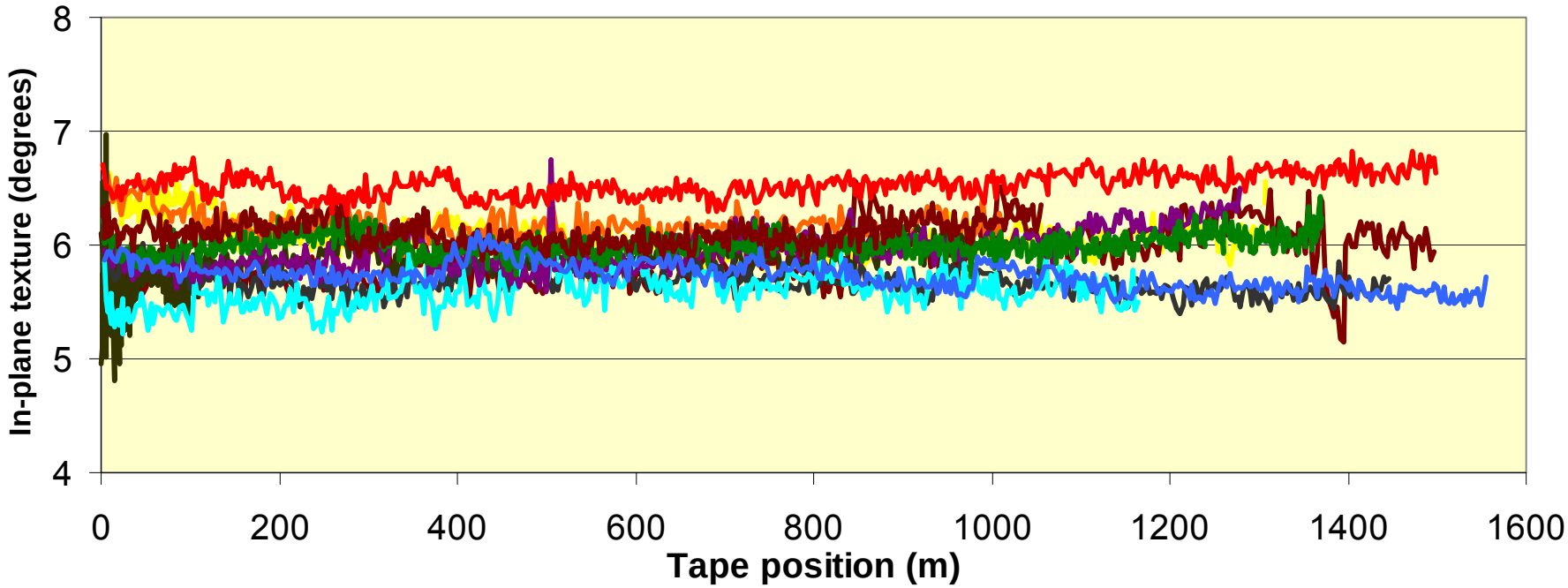
thd = (2,2,6,6-tetramethyl-3,5-heptanedionate) = $OCC(CH_3)_3CHCOC(CH_3)_3$

Immense challenge in scaling up 2G HTS wire 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

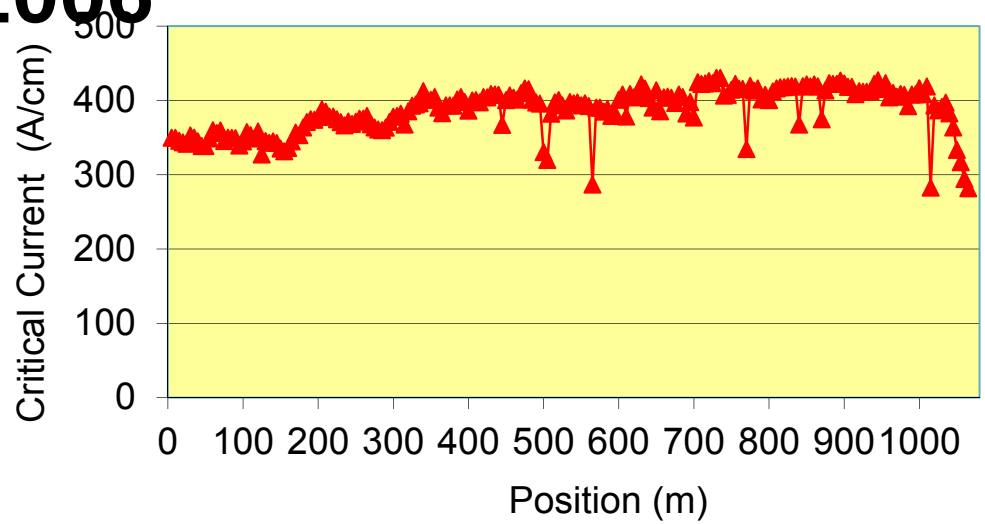
Numerous advances in materials science, processing, and equipment engineering were needed for scaling up to kilometers

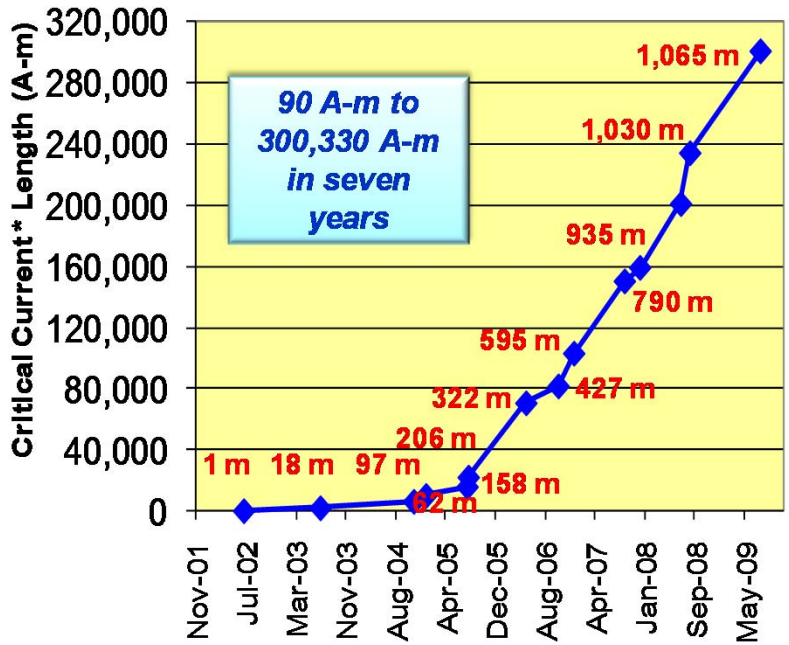
Routine manufacturing of kilometer lengths of full 5-layer IBAD buffered tape



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%

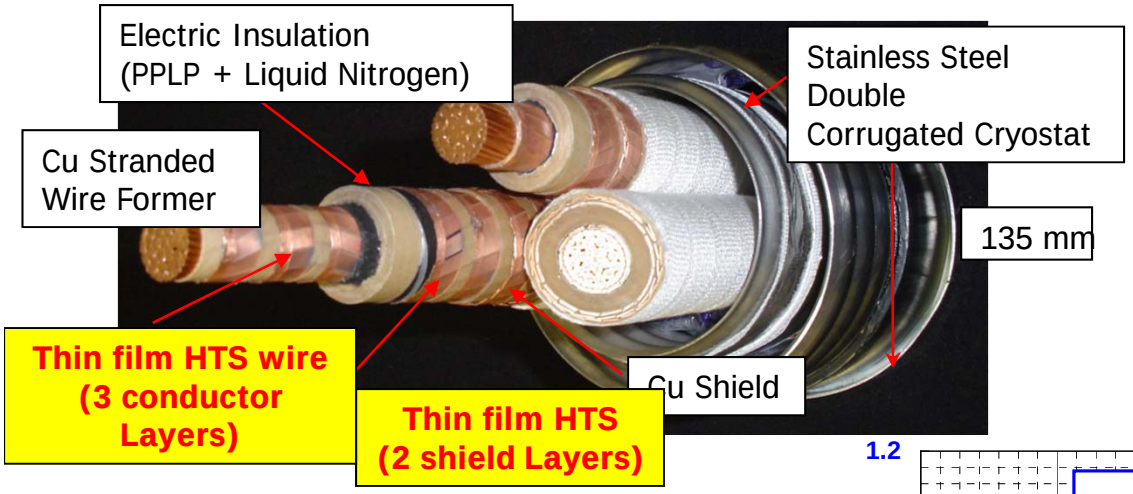
2G HTS wire was scaled to pilot manufacturing in 2006

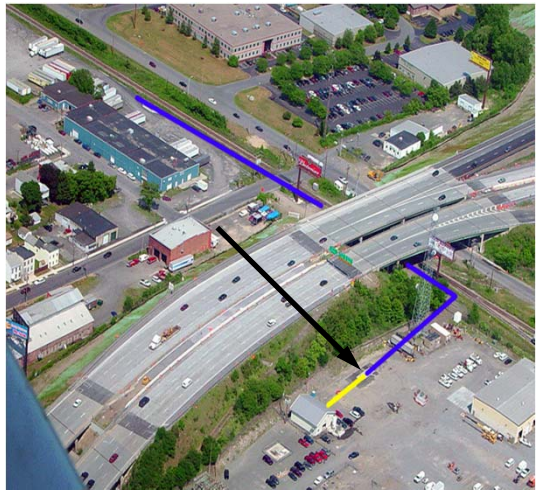


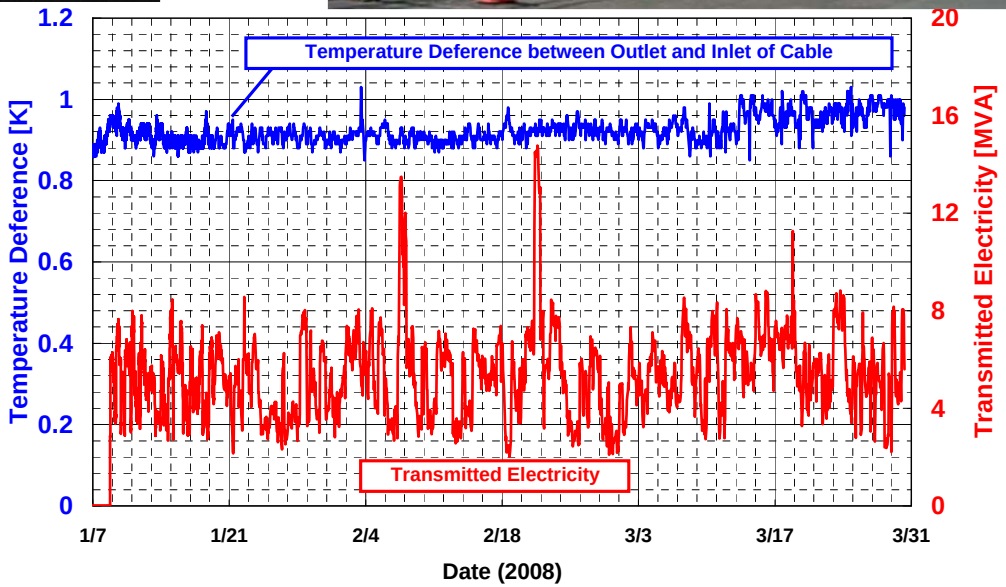


2G HTS wire is now routinely produced up to **kilometer lengths** with **300 times** the current carrying capacity of copper wire

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





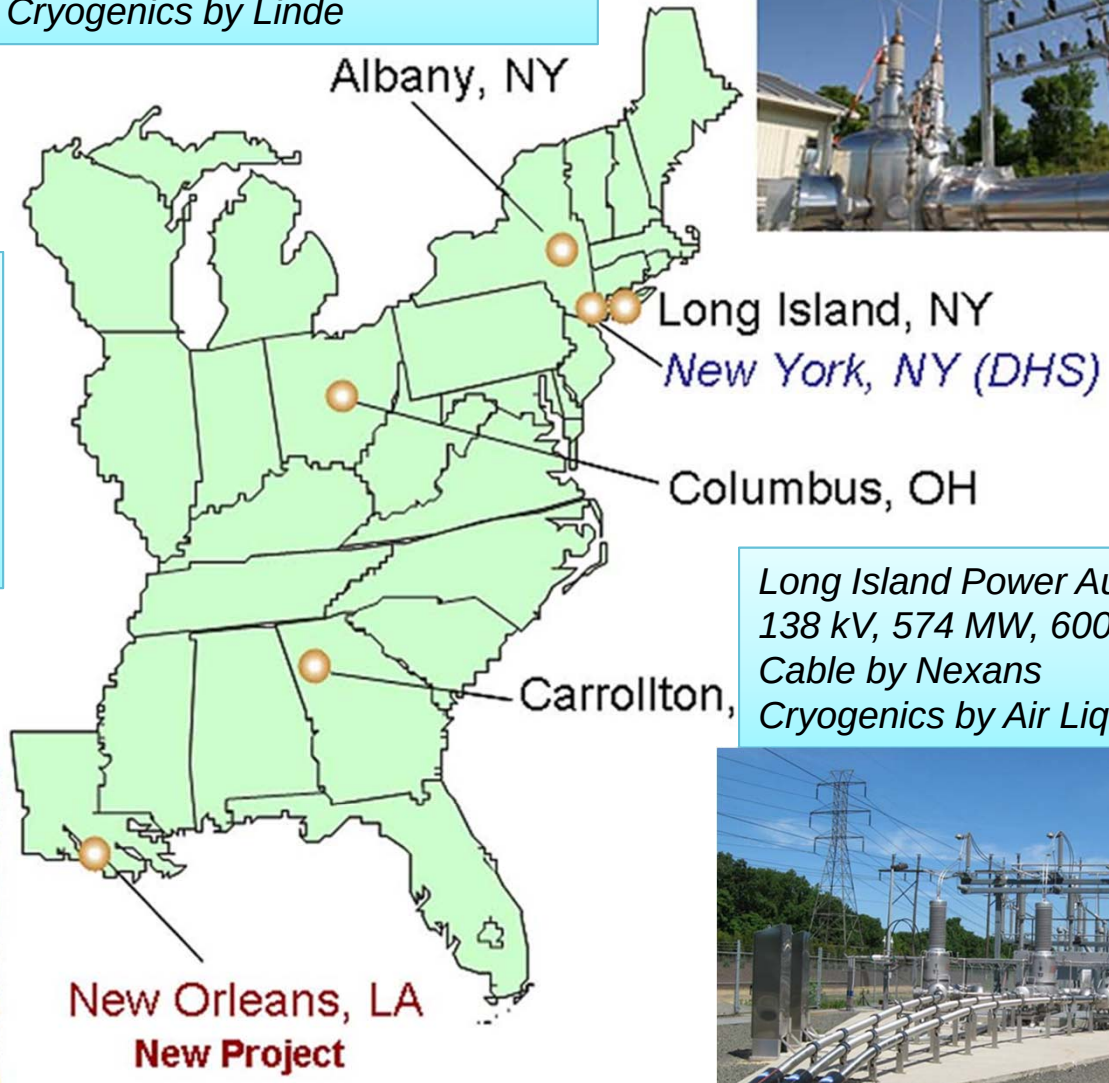


350 m cable made with 30 m segment of 2G HTS thin film wire was energized in the grid in January 2008 & supplied power to 25,000 households in Albany, NY

U.S. HTS Cable Installations

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

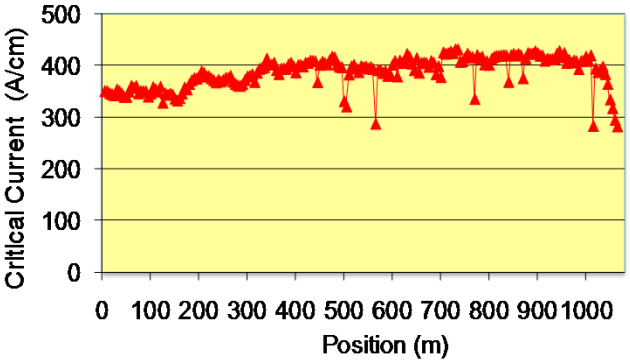
Bixby station, American Electric Power, Columbus
13.2 kV, 3000 A, 69 MVA, 200 m
Cable by Southwire & NKT cables
Cryogenics by Praxair



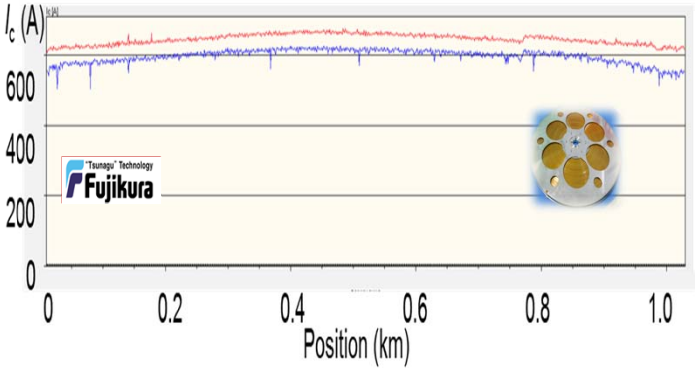
Long Island Power Authority
138 kV, 574 MW, 600 m
Cable by Nexans
Cryogenics by Air Liquide

2014: At least 5 companies producing 500 – 1000 m lengths of 2G HTS wires

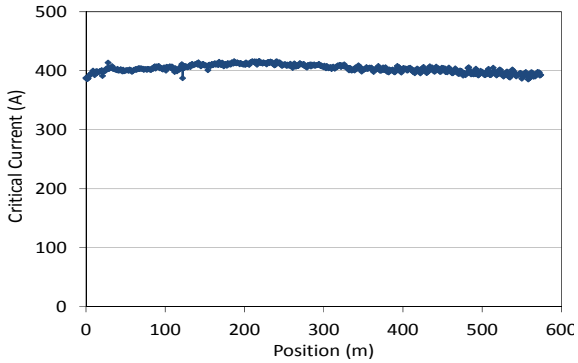
SuperPower



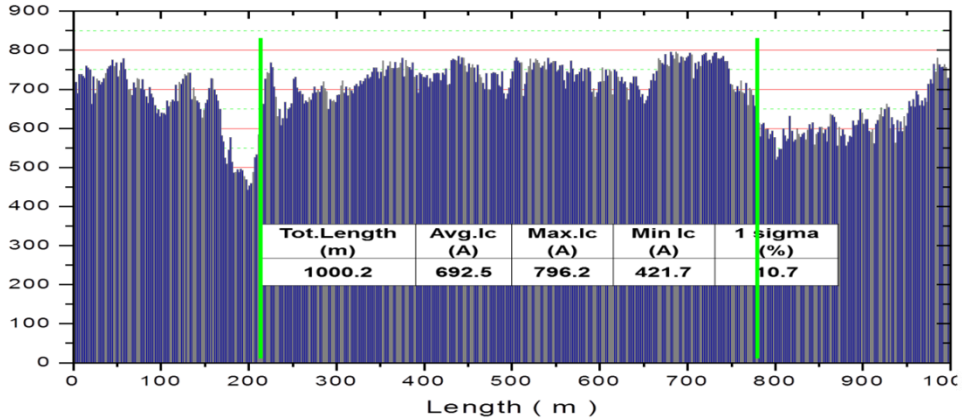
Fujikura



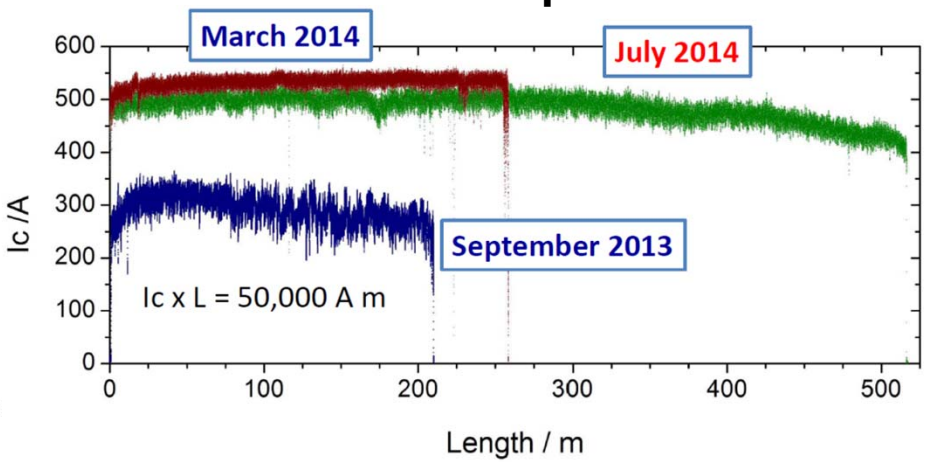
AMSC



SuNAM



SuperOx



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Several major organizations driving superconductors in energy/power applications

Wire Manufacturer	***OEM***	***Utility/System Integrator***
SuperPower	Southwire[1]	American Electric Power
American Superconductor	Sumitomo Electric[1]	Long Island Power Authority
	Nexans[1,2]	Southern California Edison
Fujikura	Waukesha Electric System[3]	Con Edison
SuNAM	Applied Materials/Varian[2]	Southern Company
	General Electric[4]	Northrup Grumman (US Navy)
Bruker	Baldor Electric[5]	Lockheed Martin (US Air Force)
STI	TECO-Westinghouse[4]	Doosan Heavy Industries
Sumitomo Electric	Naval Surface Warfare Center[1]	Korean Electric Power Company
	Siemens[2,4]	Chubu Electric
	ABB[3,6]	Tokyo Electric Power Company
BASF	Oswald[5]	Furukawa Electric
Theva	L.S. Cable[1]	Shanghai Electric Power
MetOx	LS Industrial Systems[2]	Toshiba
	Toshiba[2]	Nuon
	IHI Heavy Industries[5]	
	NKT[1]	
	InnoPower[1,2]	

[1]Cable [2]Fault Current Limiter [3]Transformer [4]Generator [5]Motor [6]SMES

Recent advances at UH on high-performance superconducting wires

2G HTS wire 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

Current research on HTS at UH

- 2G HTS wire price now is about $ 300 to $ 400/kA-m, about 6 to 8 times that of copper.
- Price will decrease with volume over time but we are working towards innovative ways for drastic cost/performance improvement even without high volume.
  - 3x improvement in critical current performance
  - Additional 3x improvement in critical current performance in a magnetic field.
  - Simplify tape architecture of tape to reduce cost
- Improving superconductor deposition efficiency to increase throughput
- Multifilamentary architectures for low ac losses
- Device demonstration with enhanced wire and testing at operating conditions
- Power systems integration

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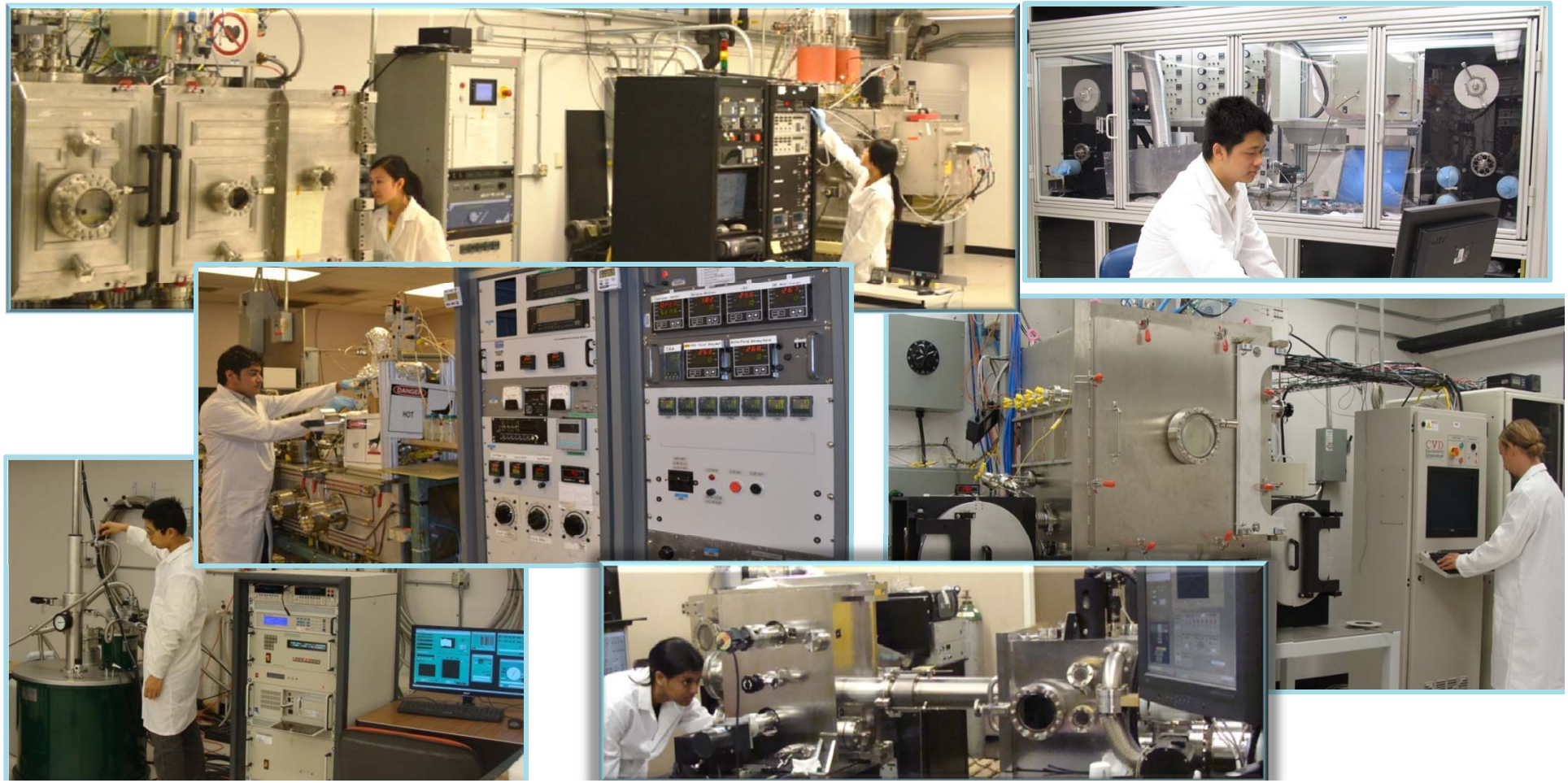
HTS Wire R&D program at Univ. Houston

- 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



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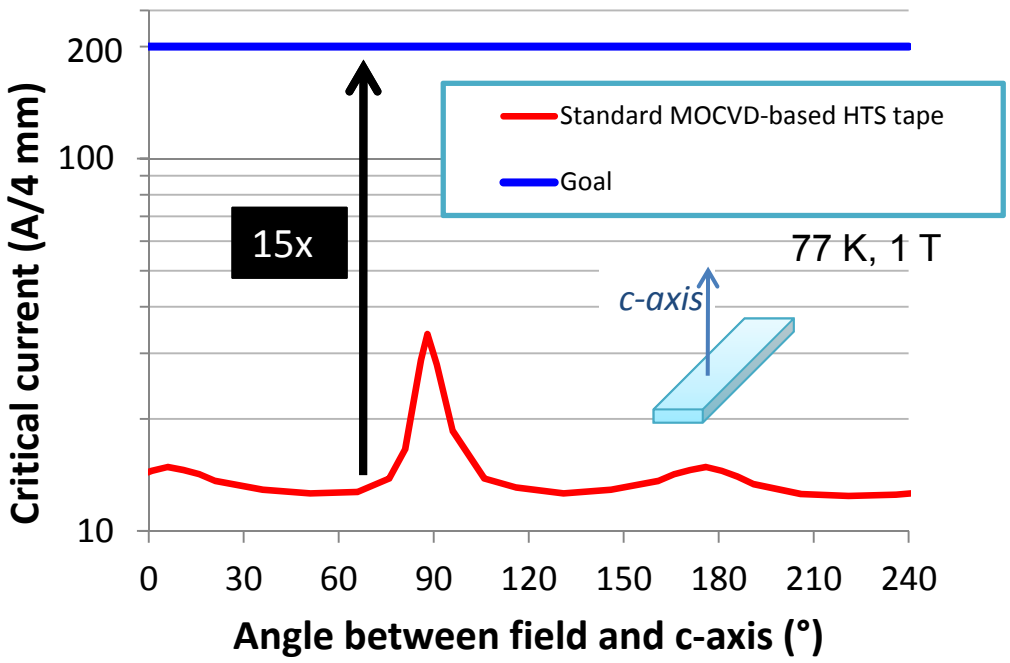
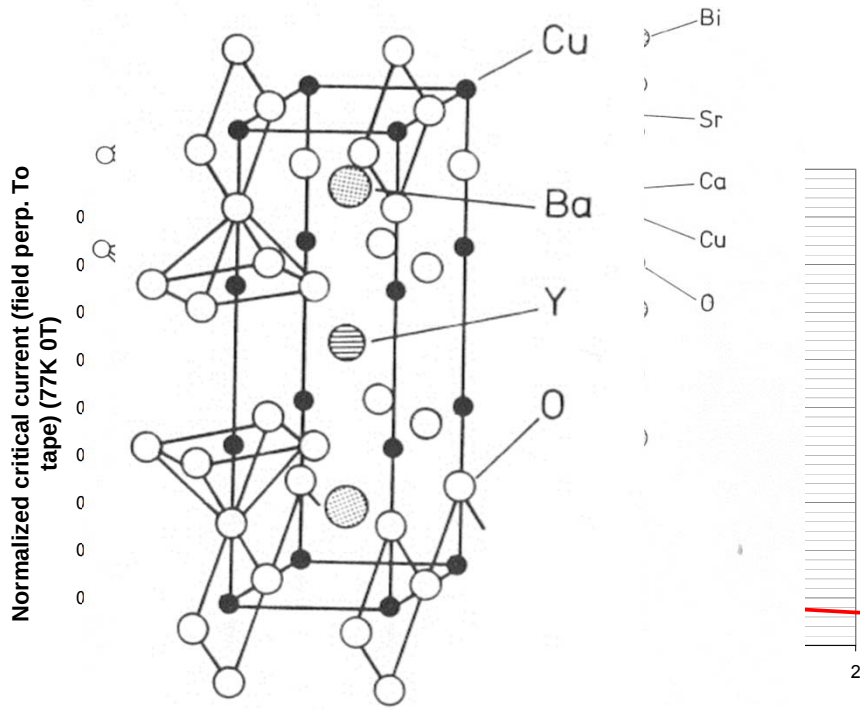
In-field I_c improvements in thin film HTS

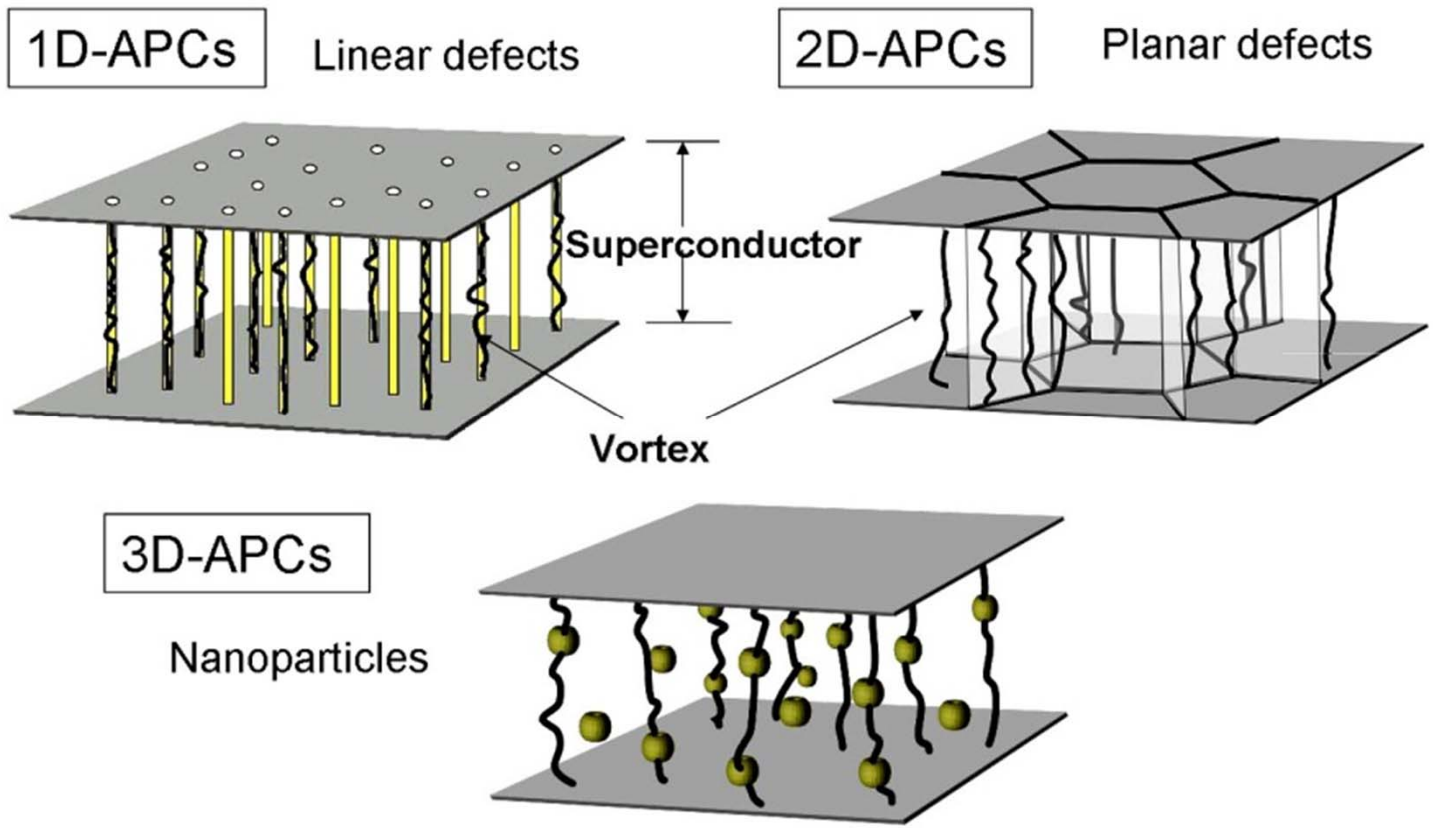
- Even though HTS tapes have good critical current properties at zero field, their performance reduces rapidly in an applied magnetic field at higher temperatures.
- Critical current of HTS tapes are very anisotropic and the minimum current value limits use.





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

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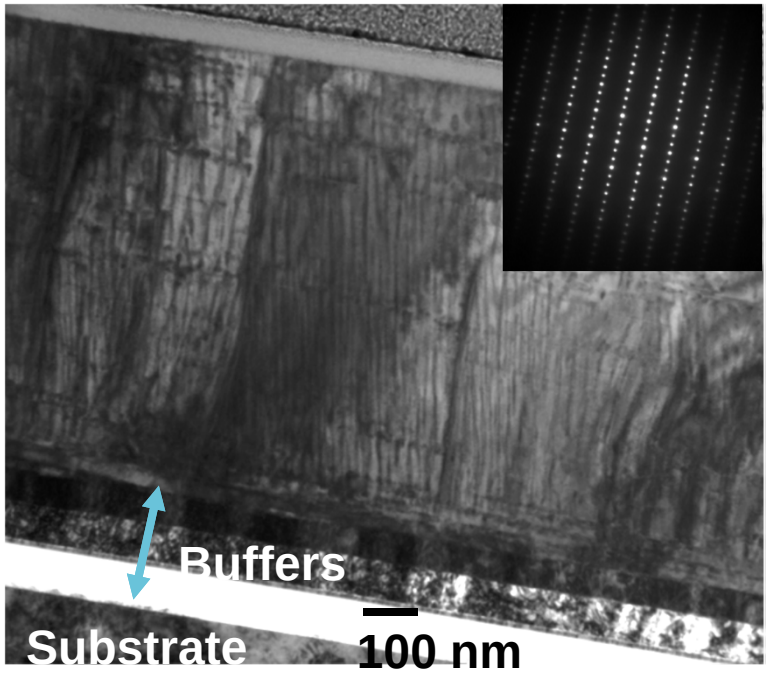
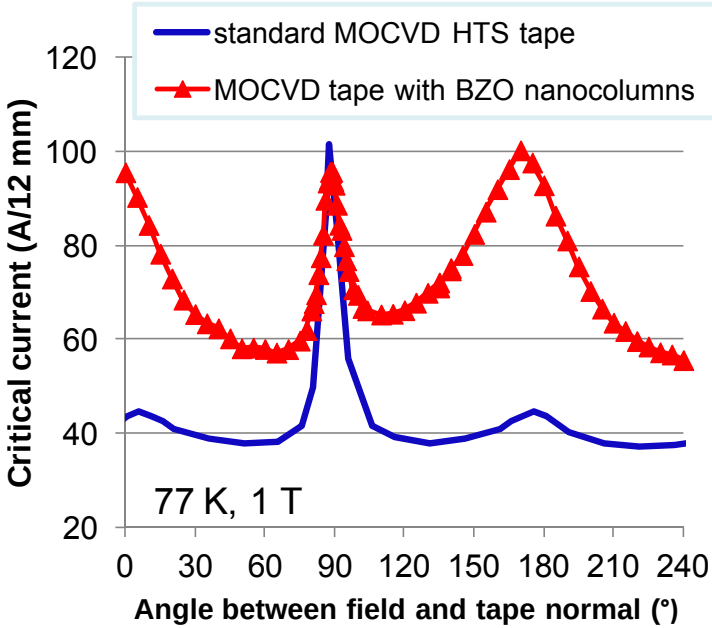
Improved pinning by Zr doping of MOCVD HTS conductors

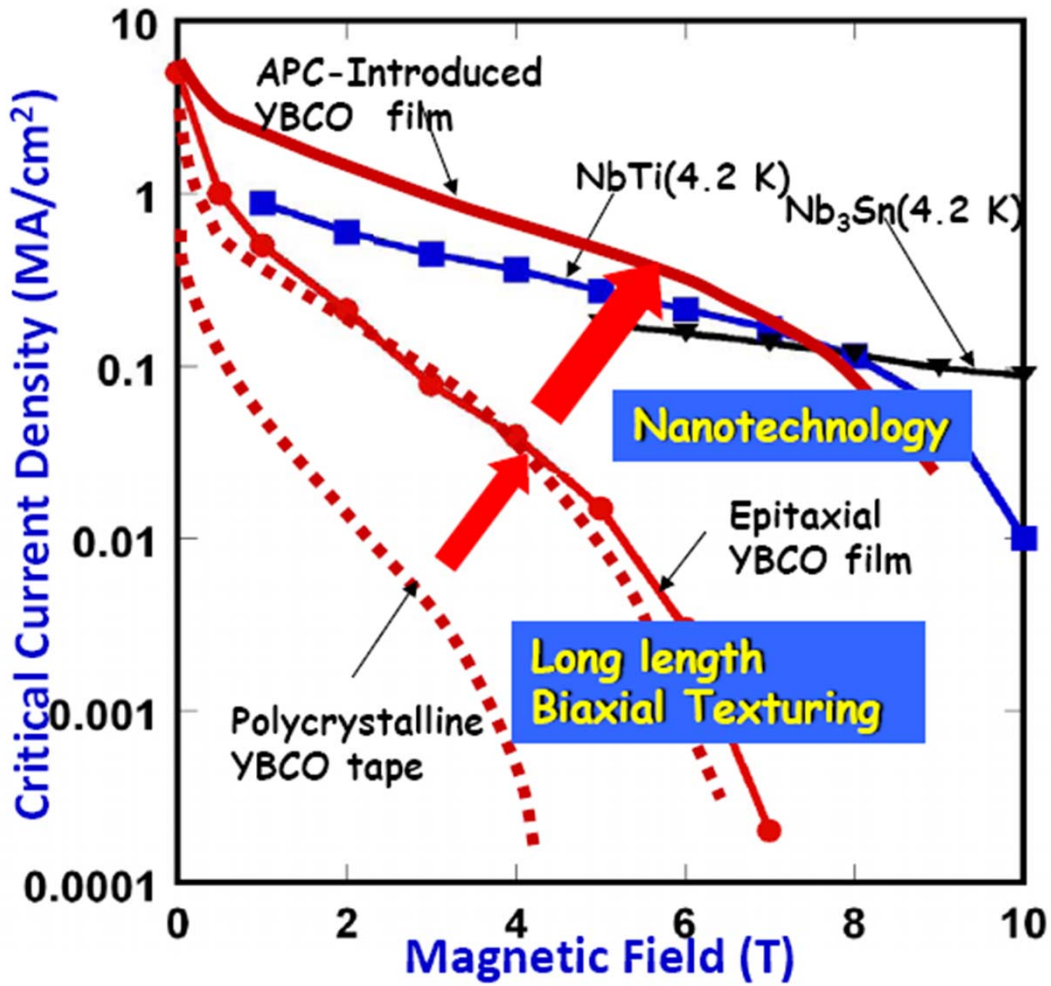
- *5 nm sized, few hundred nanometer long $BaZrO_3$ (BZO) nanocolumns with ~ 35 nm spacing created during in situ MOCVD process with 7.5% Zr*
- Two-fold improvement in critical current at 77 K, 1 T achieved by **7.5%** Zr addition in MOCVD films





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

Nanotechnology enabled improved critical current density in HTS tapes



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

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SuperPower Inc. A Furukawa Company

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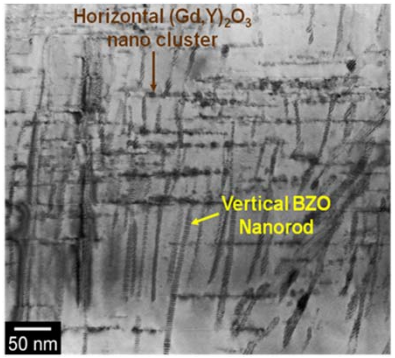
High Performance, Low Cost Superconducting Wires and Coils for High Power Wind Generators

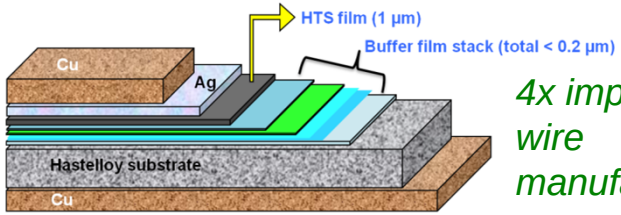
- University of Houston-led ARPA-E REACT program with SuperPower, TECO-Westinghouse, Tai-Yang Research and NREL targeted on 10 MW wind generator using advanced HTS wire



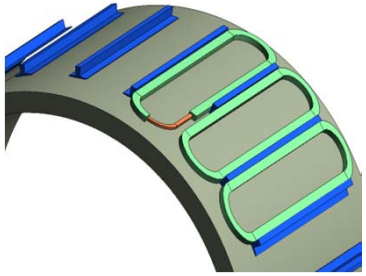
Technology Impact

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



Lower cost Generator coils

High-power, Efficient Wind Turbines

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

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SuperPower Inc. A Furukawa Company

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.

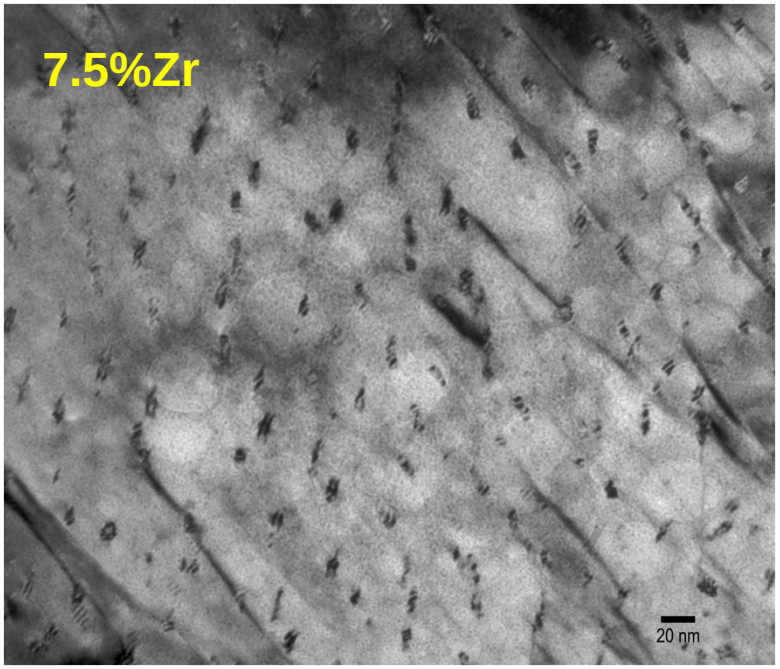
Tai-Yang Research

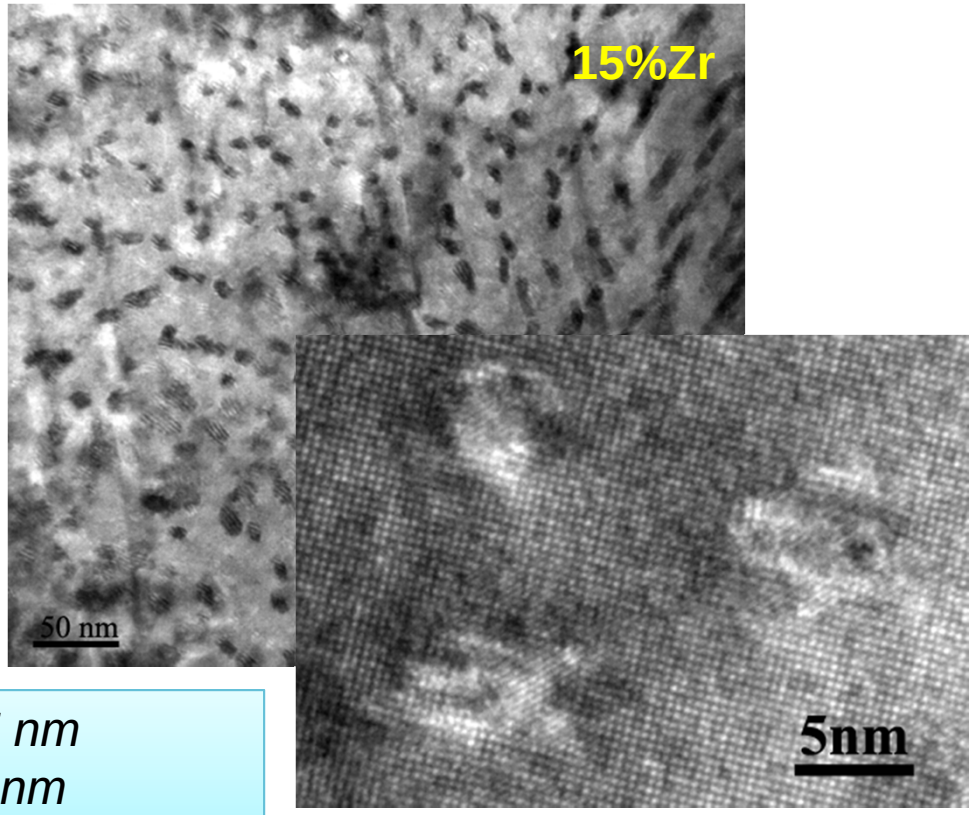
TECO Westinghouse

NREL NATIONAL RENEWABLE ENERGY LABORATORY

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

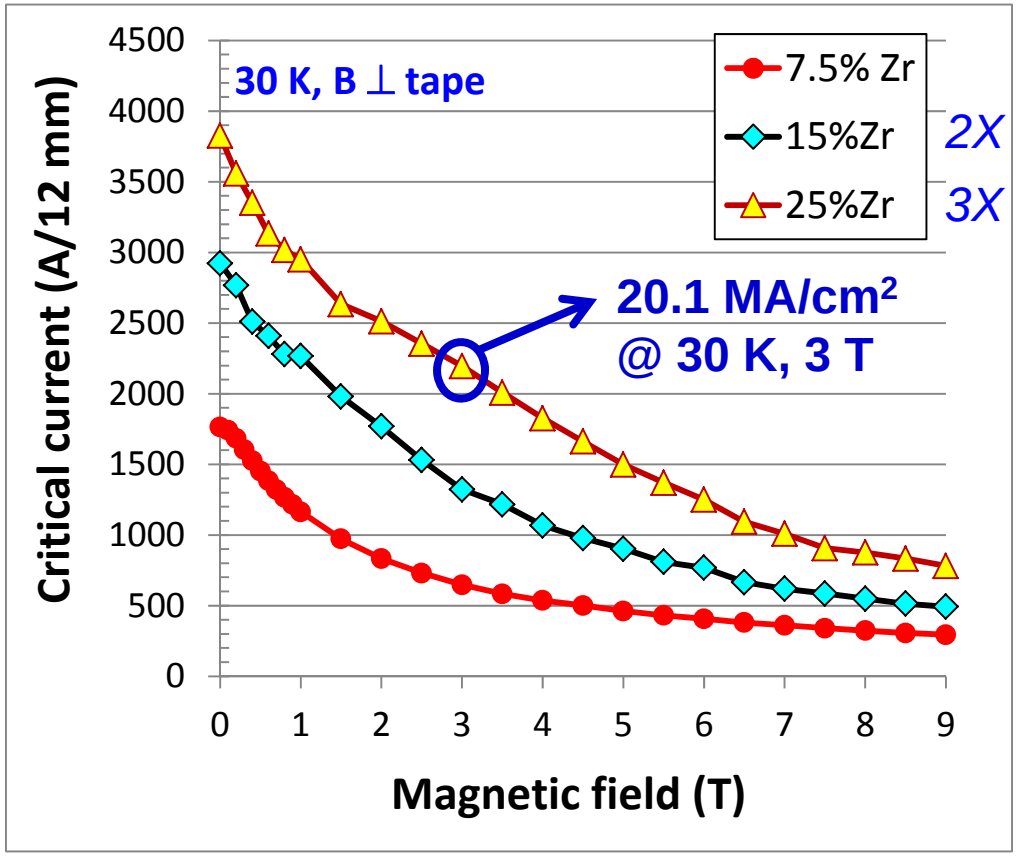
- All good Ic results reported so far with PLD, MOD and MOCVD films have been with less than 10 mol.% of second phase addition





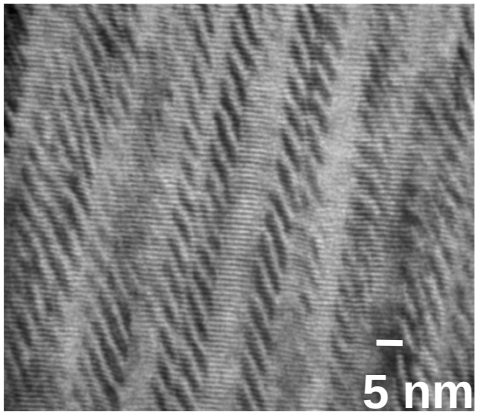
BZO spacing in 7.5%Zr sample : 35 nm
BZO spacing in 15%Zr sample : 17 nm
Average size of BZO ~ 5 nm in both

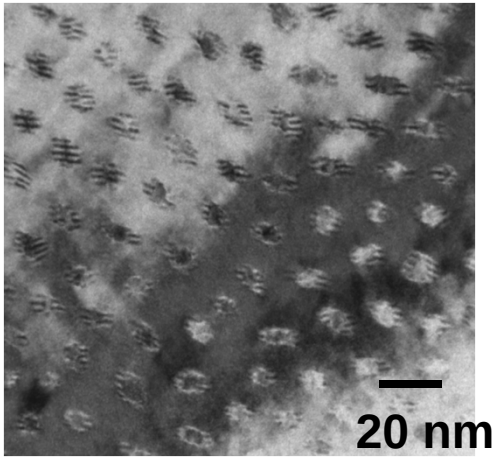
3X improvement in in-field performance in the last 2 years



2X improvement

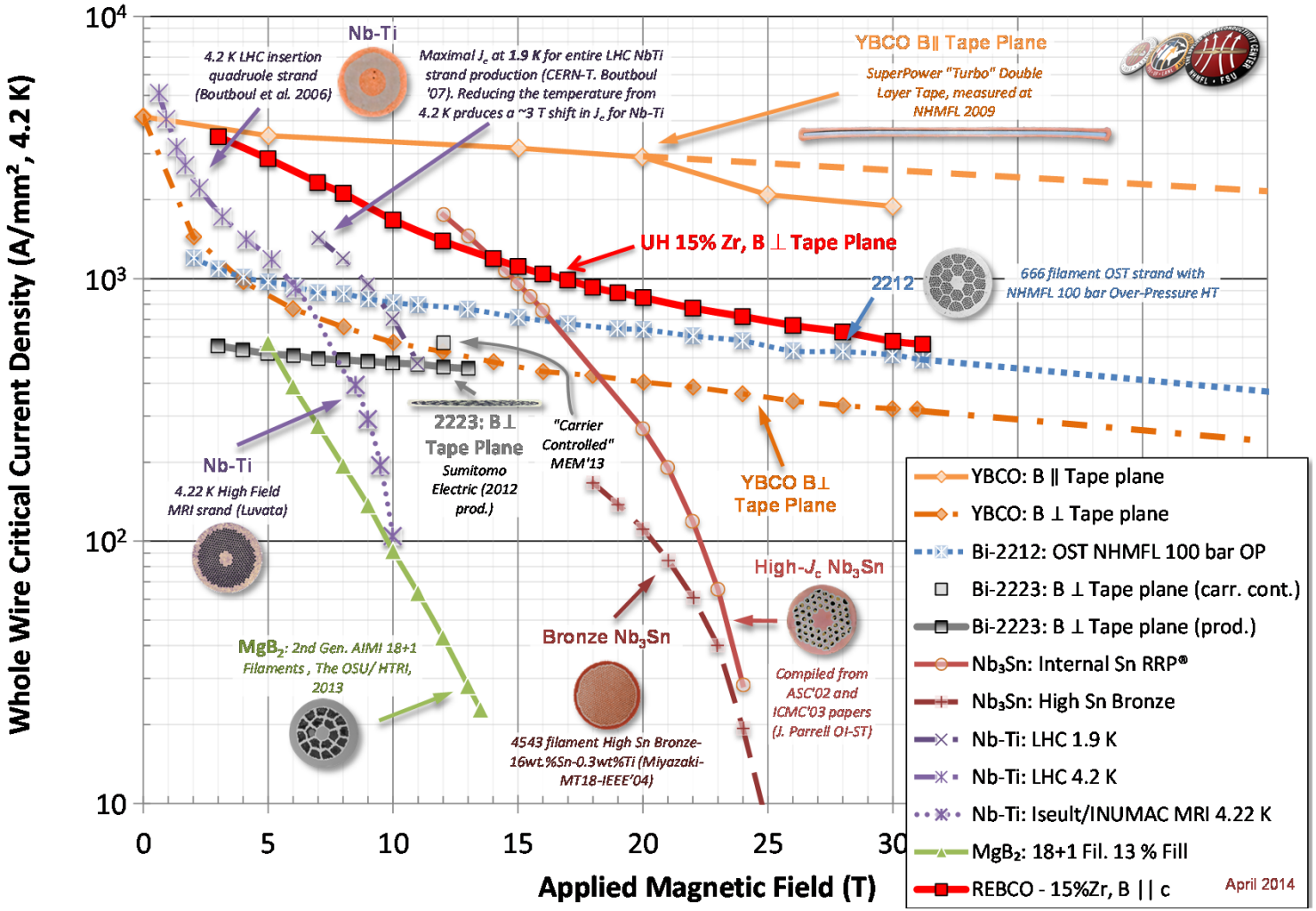
3X improvement





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

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



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)

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SuperPower Inc.

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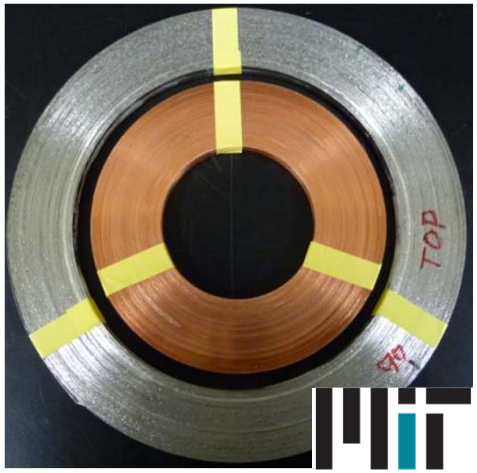
Multiple coil applications using Thin Film HTS wires

3.6 T gantry magnet for **Particle Beam Therapy**. Four racetrack coils and 14 bent coils. 2,500 m with min I_c of 115 A/4 mm.

Linear Induction Motor using 3 mm wide conductor to reduce ac losses

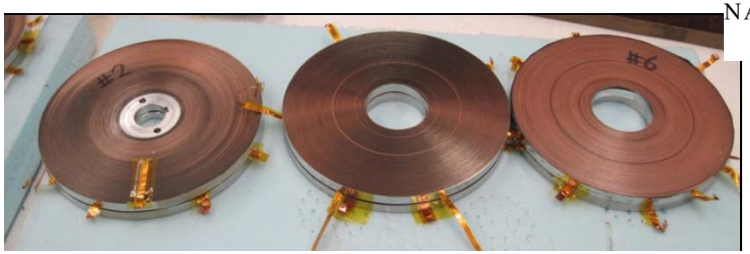
Race track coils for **generator**



Massachusetts Institute of Technology

1.3 GHz NMR Magnet
8.34 T contribution from coated conductor coil

BROOKHAVEN NATIONAL LABORATORY



20+T HTS **solenoid for muon collider**

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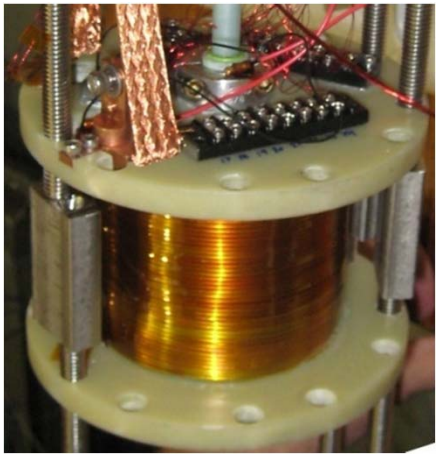
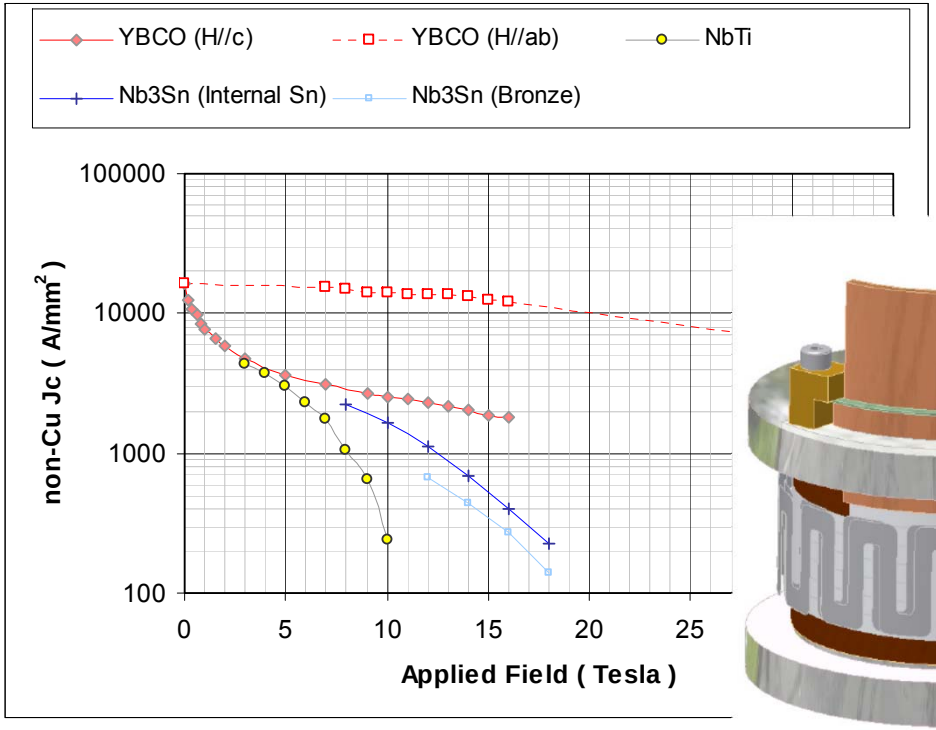
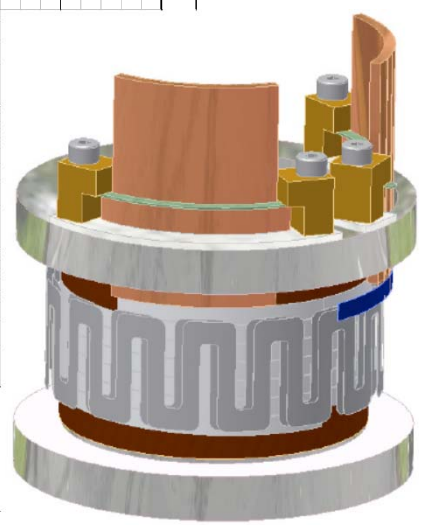
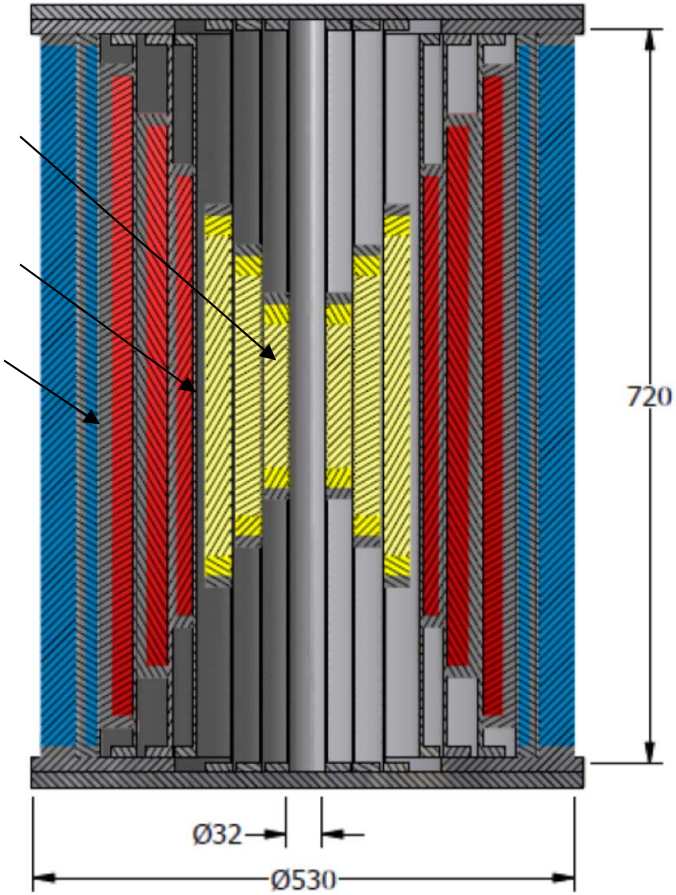
High Magnetic Field Systems

- 2G HTS wire enables very high magnetic field systems at far less operating power than copper.
- 27 T hybrid superconducting magnet demonstrated with 2G HTS wire
- 32 T all-superconducting magnet being constructed by NHMFL.



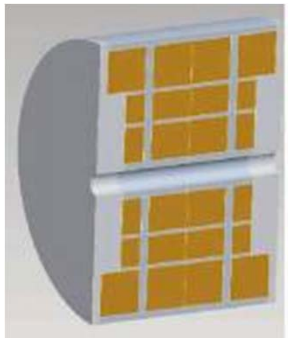


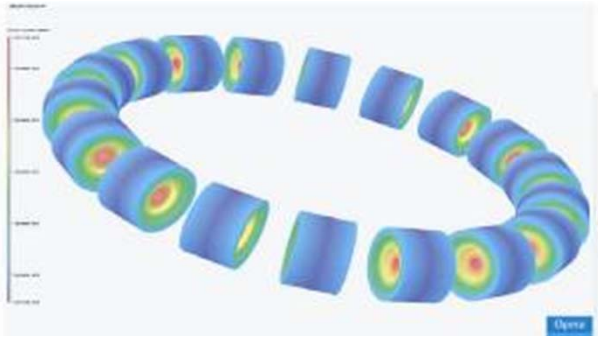


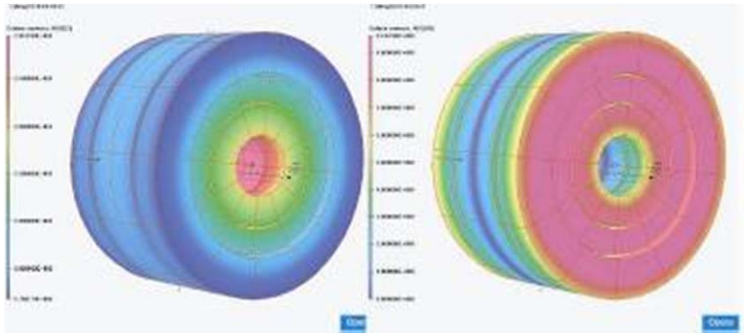


Superconducting Magnetic Energy Storage (SMES) using high-field HTS coils

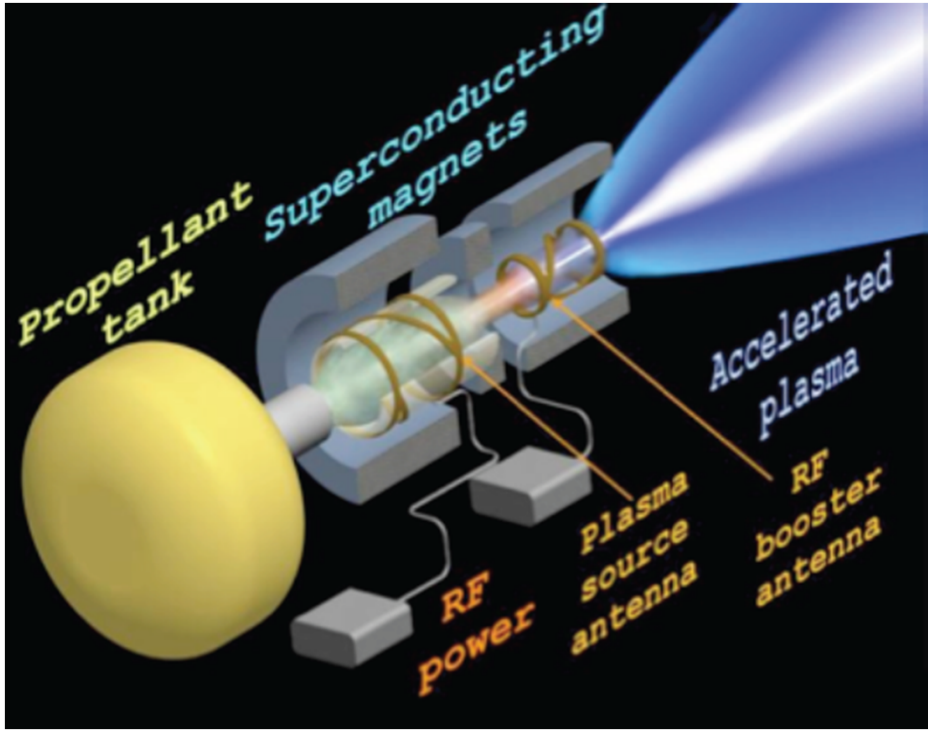
- Energy storage with greater than 97% efficiency.
- Provides rapid response for either charge or discharge – amount of energy available is independent of discharge rating – charge and discharge sequence can repeat infinitely without degradation of magnet
- 2G HTS-based SMES being developed by ABB, SuperPower, UH and BNL through $ 5.2M program funded by ARPA-E (GRIDS: Grid-Scale Rampable Intermittent Dispatchable Storage)
- 20 kW ultra-high field SMES device with capacity of up to 3.4 MJ based on HTS coils operating at magnetic fields of up to 30 Tesla at 4.2K

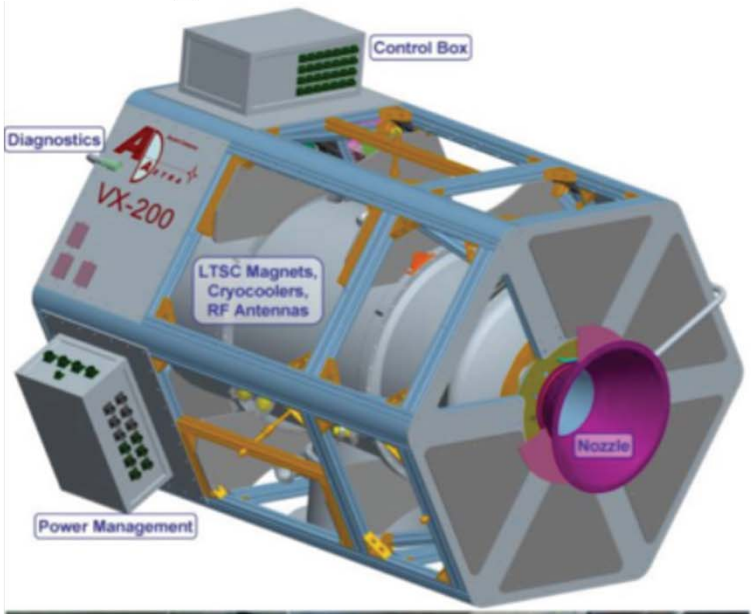


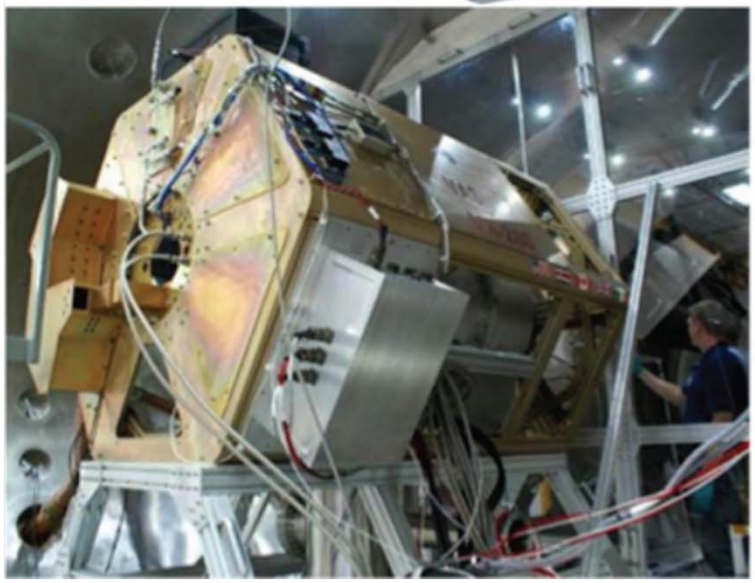




High-field, low-weight capability of HTS coils for space applications



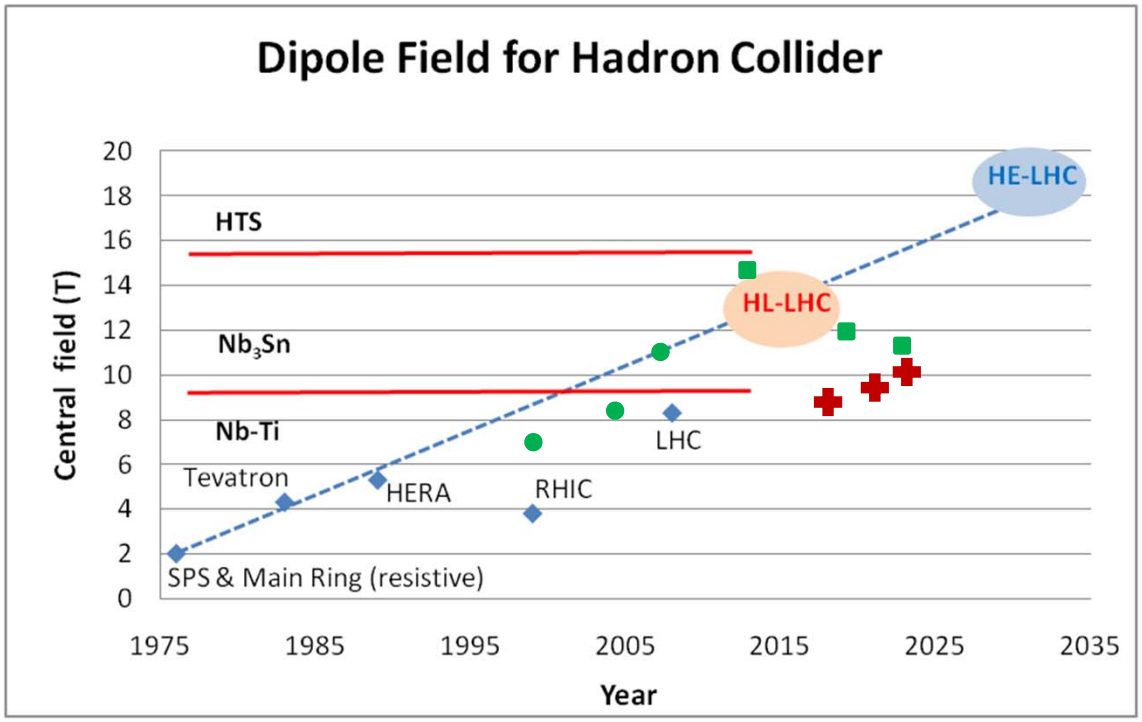


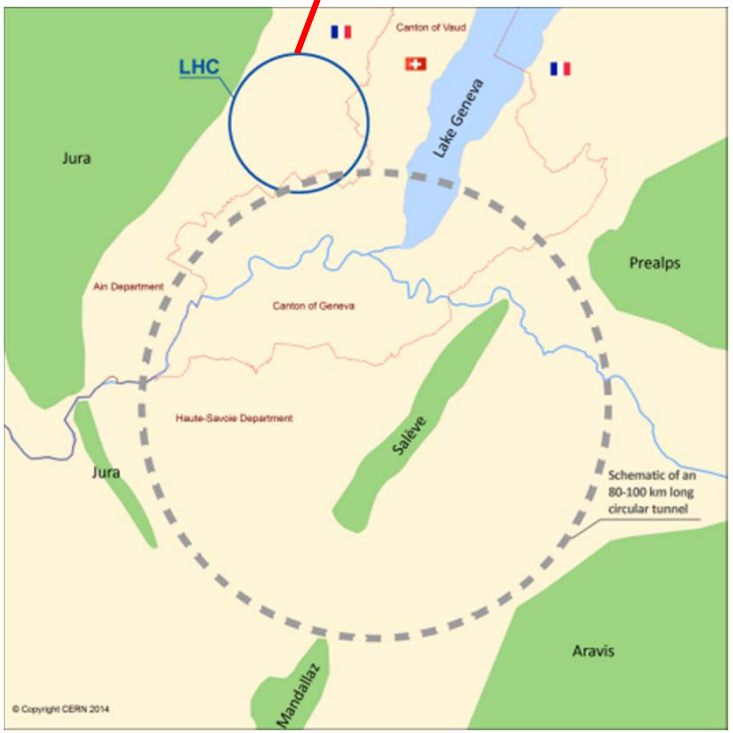


- Ad Astra's Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) enabled by HTS

High Energy LHC could be enabled by HTS

HE-LHC :33 TeV with 20T magnets





- ◇ Nb-Ti operating dipoles;
- ● Nb3Sn cosϑ test dipoles
- ■ Nb3Sn block test dipoles
- ✚ Nb3Sn cosϑ LARP QUADs

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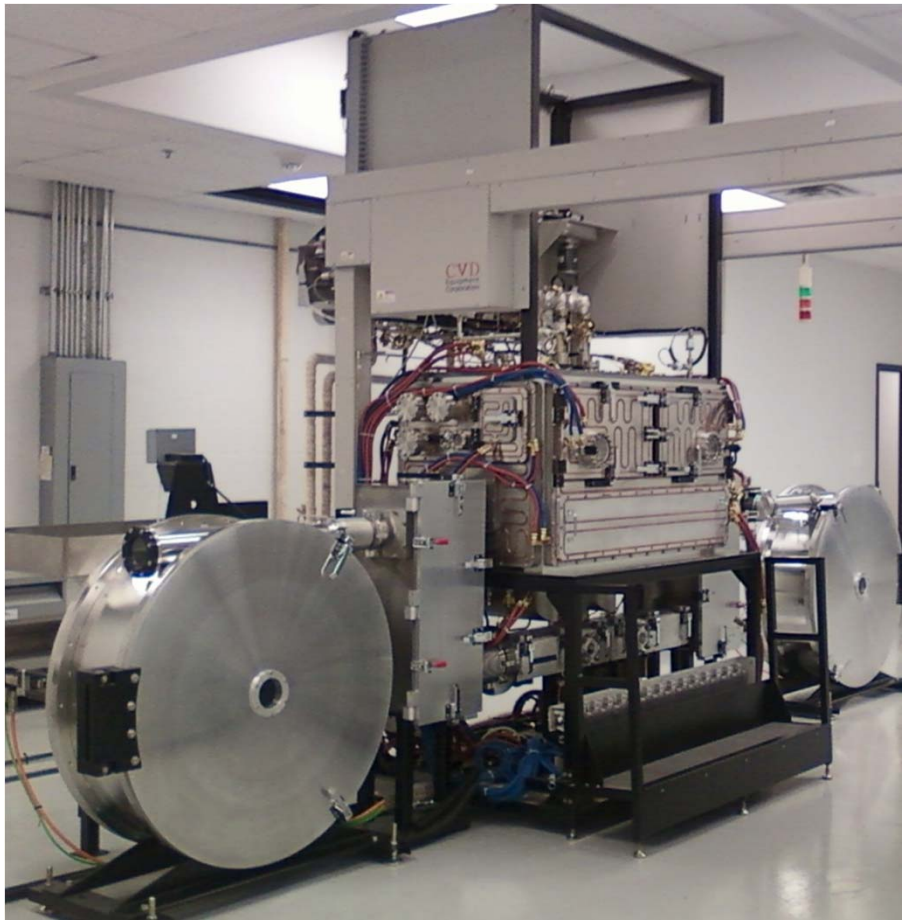
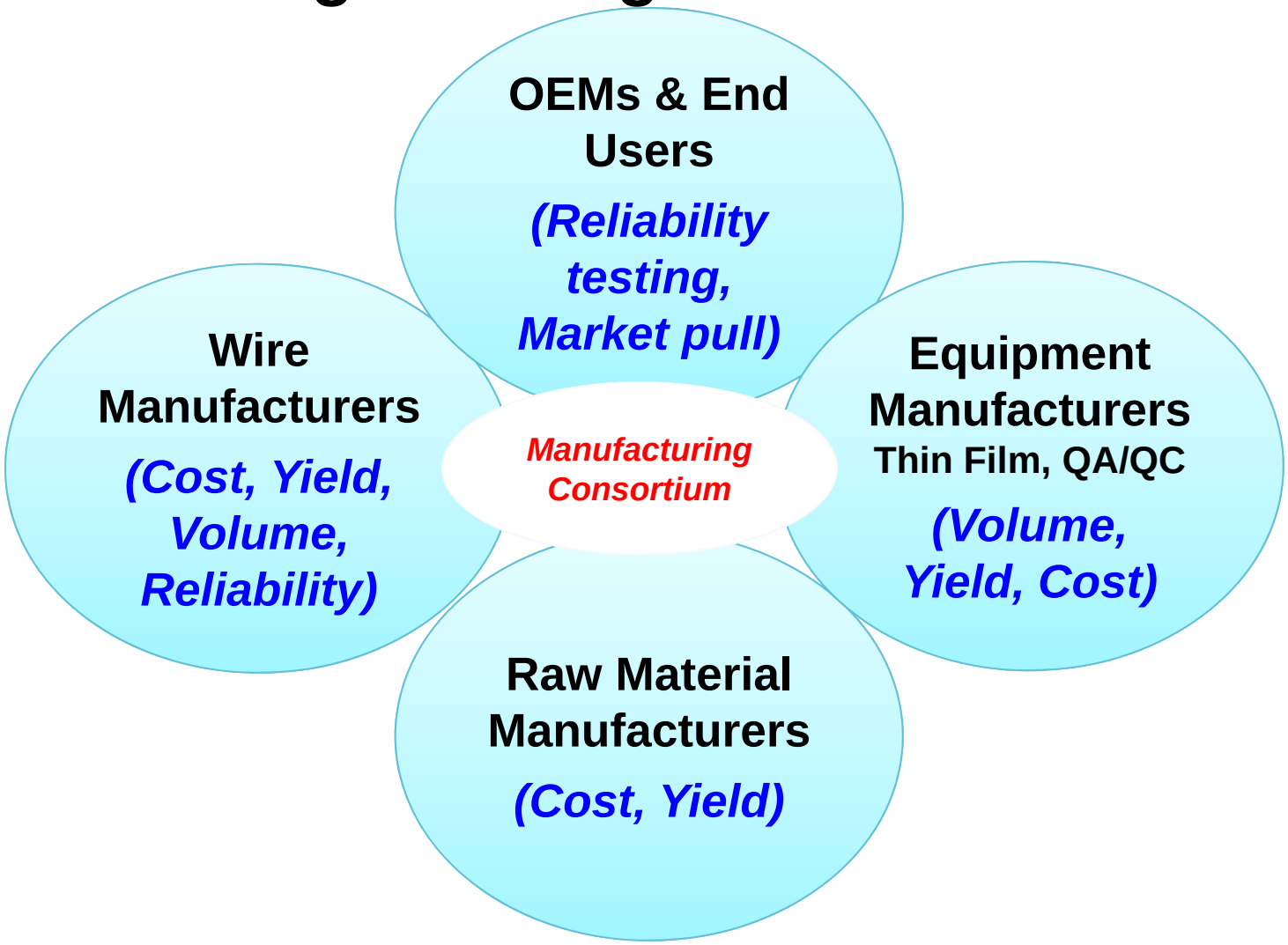
UH Energy Research Park operation to accelerate technology transfer and manufacturing innovation

- 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 (~ 100 m) with the latest advances

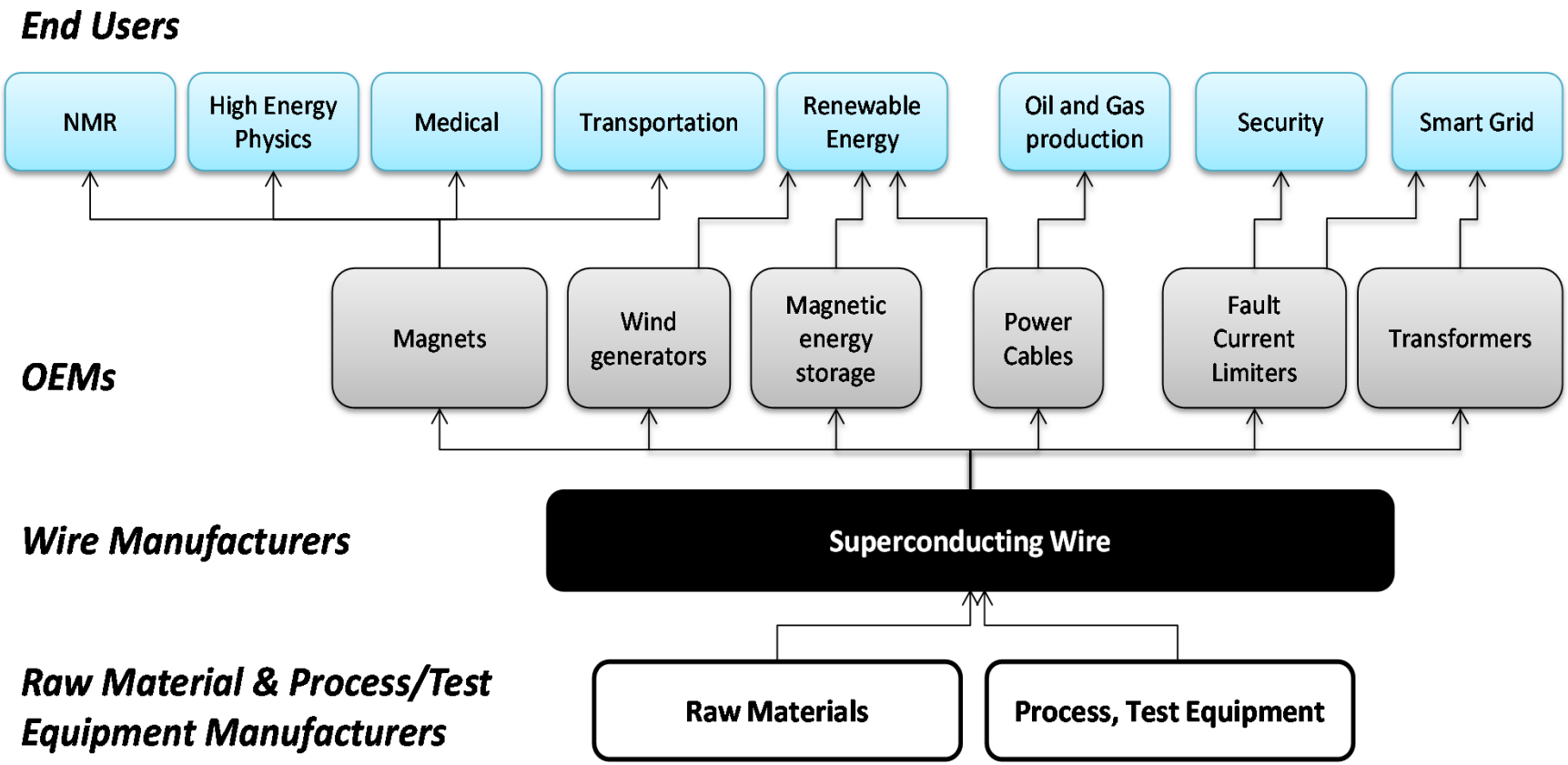


Rapid transfer of technology advances to manufacturing to accelerate commercialization of HTS for energy and other applications

Consortium being formed to bring industry together to comprehensively address manufacturing challenges in HTS wires



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



For more information contact

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