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Status of 2G HTS Wire Development & Production in the US, plus an Overview of the SFCL Transformer and 2G SMES Programs

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SuperPower Inc.

U.S. DOE 2G HTS wire development program has enabled significant progress

- Successful integration of national lab technologies with industry and with university support
- Industrial-scale HTS production techniques developed
- Multiple world records established and maintained for 2G HTS wire performance in long lengths
- Still the world's only demonstration of 1,000+ m long 2G wire
- World's first 2G HTS wire device inserted in the power grid - 2006
- U.S. is still the leading source of 'pre-commercial' 2G wire
  - Many hundreds of kilometers shipped around the world
  - Substantial price reduction in last three years, even before onset of a commercial market!

Wire price-performance is the key factor for commercialization

- Today's 2G wire: 100 A performance at 77 K, zero applied magnetic field
  Baseline price: $ 40/m = $ 400/kA-m
- At this price
  - Cost of wire for a typical device project (other than cable) is >$1M (more than the typical cost of the device itself)
  - Cost of wire for a 500 km cable project = $20M (about equal to the cost of cable project itself !)

Metric	Today	Customer requirement	
Price	$ 400/kA-m	< $ 100/kA-m*	For commercial market entry (small market)
		< $ 50/kA-m*	For medium commercial market
		< $ 25/kA-m*	For large commercial market

***at operating field and temperature**

4-15 X improvement in wire price-performance is needed !

2G HTS wire production in the U.S.

- American Superconductor (AMSC) – Devens, MA
- Superconductor Technologies Inc. (STI) – Santa Barbara, CA
- SuperPower Inc. – Schenectady, NY and Houston, TX

- With support from the DOE National Labs
  - LANL, ORNL, ANL, NREL, …
- and universities
  - TcSUH, FSU, Ohio State …

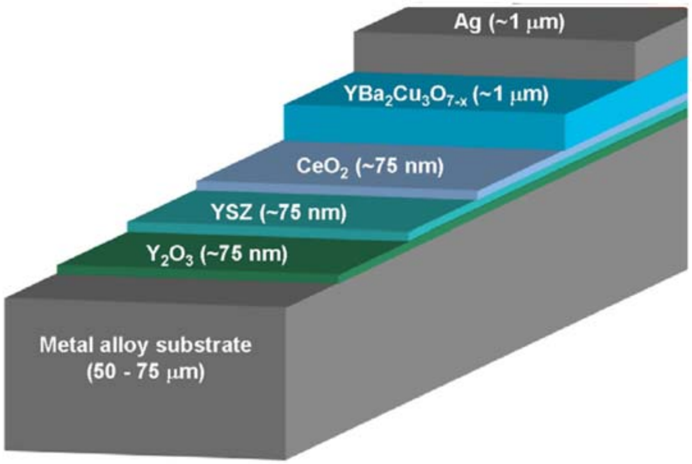
AMSC HTS Wire

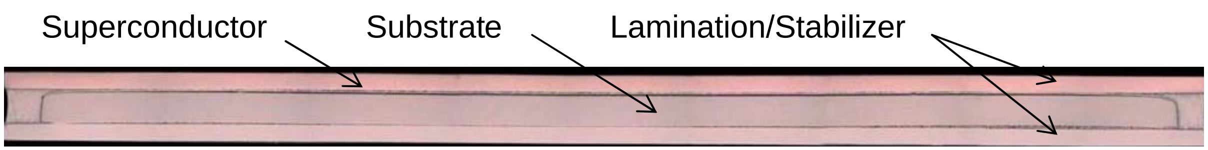
Low-cost high performance HTS insert

Wide strips: 4cm to 10cm, slit to industry standard 4mm, or custom 10mm

Customized for the application by a low cost lamination process:

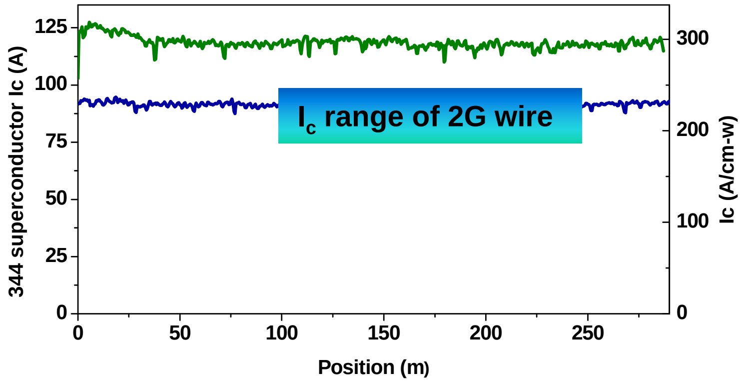
Electrical/Mechanical/Thermal





344 superconductors enable key industry applications

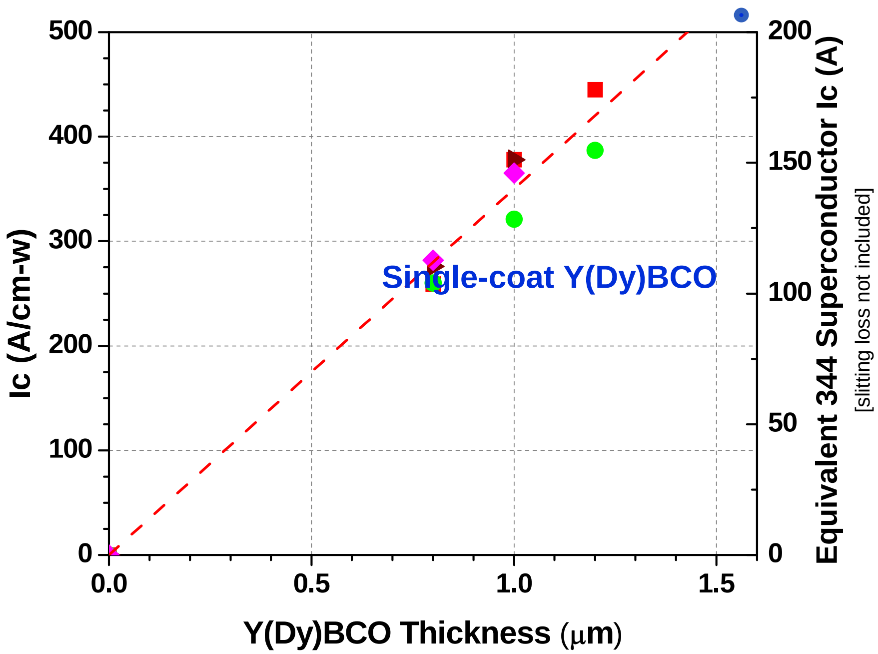
- 344B – Brass: Power Cable
- 344C – Copper, Coils (Motors and Generators)
- 344S – Stainless Steel, Fault Current Limiters



Current efforts focus on Performance, Cost/Capacity and Yield

- Performance:
  - *Low-loss RABiTS Template*.
  - *High I_c*
  - *Enhanced Pinning*
- Cost/Capacity
  - Wide web (100 mm) processing
  - *Innovative Materials*
  - *Simplified architectures*
  - *Rates*
- Yield
  - *Across web uniformity*
  - *Wire-to-wire uniformity*

Recent Record single-coat I_c 457 A/cm-w



I_c in single-coat films increases linearly with YBCO thickness

Superconductor Technologies Inc. - Overview

- Founded in 1987 to commercialize High Temperature Superconductors (HTS)
- Global leader in HTS thin film deposition, a novel process with order-of-magnitude cost advantage over other HTS processes
- Demonstrated success with commercially available HTS system
- Over $150 million in HTS sales to date with over 6,000 systems deployed worldwide
- Partnered with industry leaders leveraging extensive IP Portfolio and manufacturing experience to develop 2G HTS wire for large emerging markets

Wind Turbine (Generator)

Superconducting Fault Current Limiter

High Power Transmission Cables (AC)

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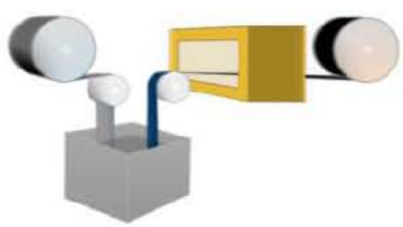
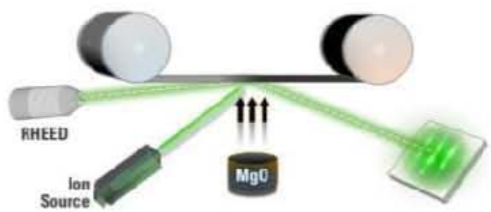
SUPERCONDUCTOR TECHNOLOGIES INC.

Engineered for High Performance and Low Cost





SDP | **IBAD/epi MgO** | **RCE-CDR**

Solution Deposition Planarization (SDP)

Ion Beam Assisted Deposition (IBAD)

Reactive Coevaporation – Cyclic Deposition and Reaction (RCE-CDR)

We believe that STI's 2G HTS wire will have a clear cost and performance advantage for the following reasons:

» Inexpensive substrate material
» Reduced number of template buffer layers – simple and repeatable
» Lower direct cost on raw materials
» Reduced number of deposition process steps – reduced runtime, higher yield
» High throughput, large HTS deposition area
» Lower capital expenditure cost than alternative methods

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STI SUPERCONDUCTOR TECHNOLOGIES INC.

STI 2G HTS Wire Key Development Milestones

Milestone	Date
Demonstrate 1m length of 2G HTS wire	Q2 2010 (Completed)
Produce customer samples of 2G HTS wire for 3 target market applications: High Power Transmission Cable (AC) Superconducting Fault Current Limiter Wind Turbine (Generator)	End 2010
Equipment operational capable of producing 50 meter 2G HTS wire lengths	Q2 2011
Demonstrate 1000 meter 2G HTS wire lengths	Late 2012
First manufacturing machine operational with annual production capacity of 750 kilometers of 2G HTS wire	Late 2012
Scale commercial manufacturing capacity from 750 km to 1500 km	2013

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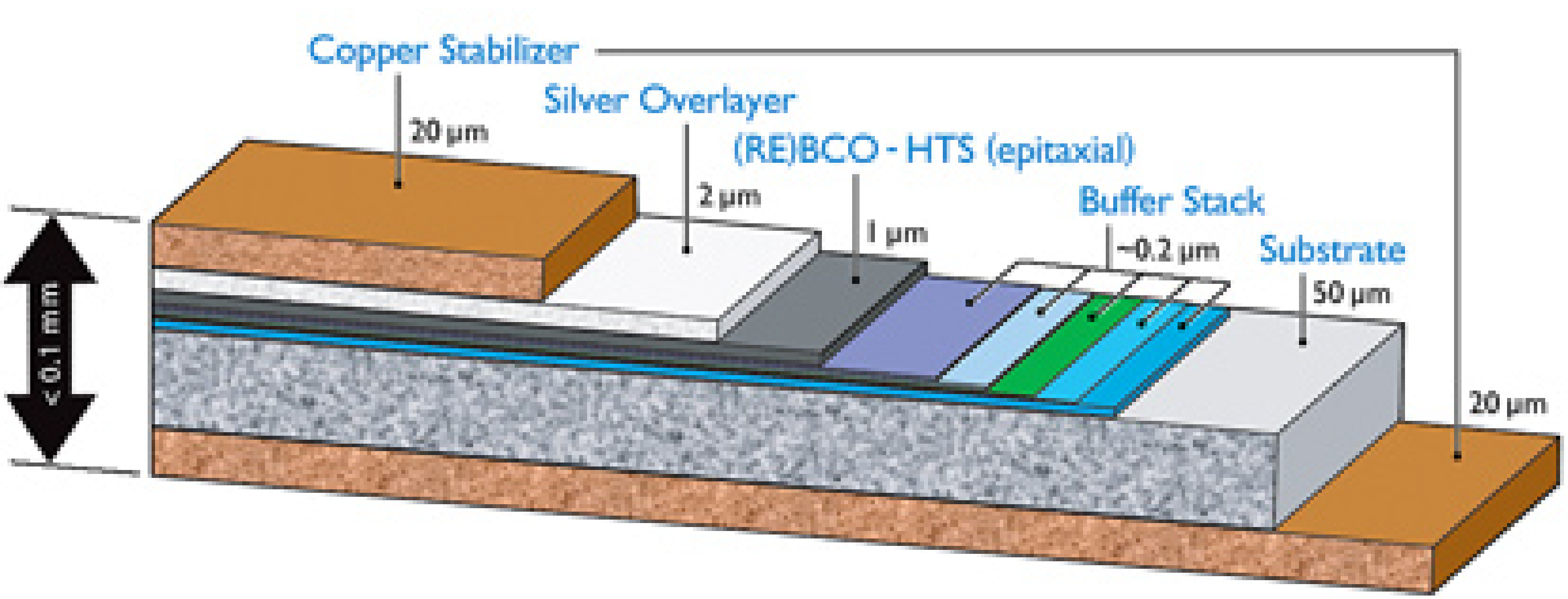
SuperPower Inc. - 2G HTS wire focus

- Development effort began late 1990s; company established 2000
- Based on high throughput processes (IBAD MgO and MOCVD) and superior substrate (high strength, low ac loss, high engineering current density)



SuperPower 2G wire program strategy

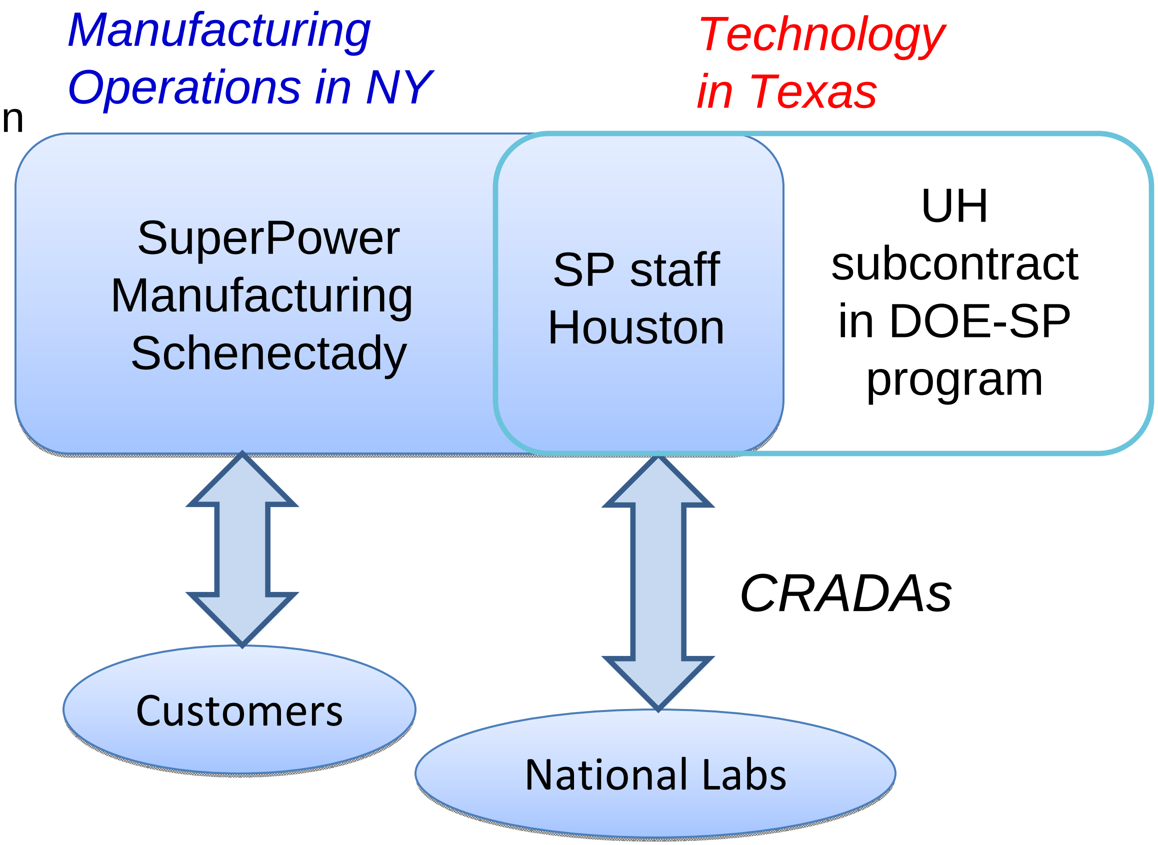
- Technology development operations consolidated in Houston in 2009 to enable total focus on manufacturing in Schenectady.

Manufacturing objectives

- High yield, high volume operation
- On-time delivery of high-quality wire
- Incorporate new technology advancements

Technology objectives

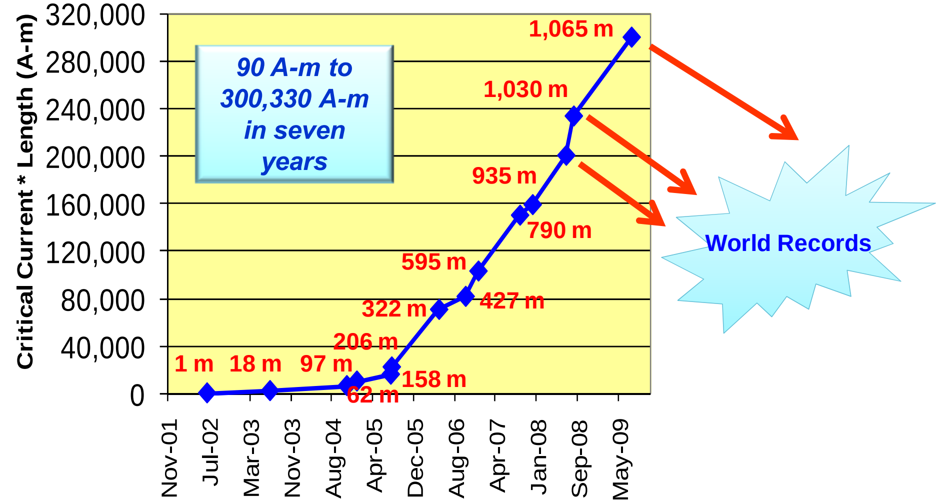
- High performance wires
- Highly efficient, lower cost processes
- Advanced wire architectures
- Successful transition to manufacturing

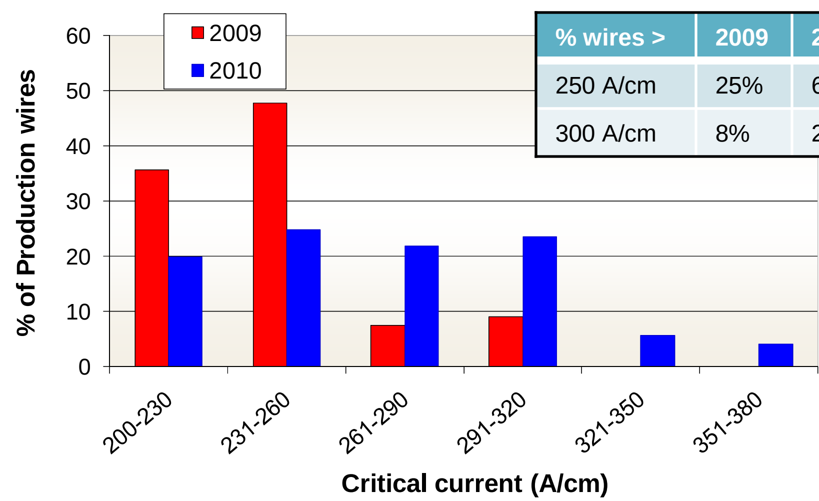


Best of both worlds:
strong and concentrated emphasis on both technology development & manufacturing

SuperPower manufacturing objectives

- 2009: **long length, high performance demonstrations**
  - Kilometer-long 2G wires with minimum critical current of 282 A/cm
  - Multiple world records (best: 300,000 A-m); still holding
- 2010: Focused on **high-yield manufacturing** (higher throughput/lower cost)
  - Enhanced on-line QC tools
  - Routine manufacture of Zr-doped ‘Advanced Pinning’ (AP) wire: new product offering
  - Reduce cost; improve price-performance metrics

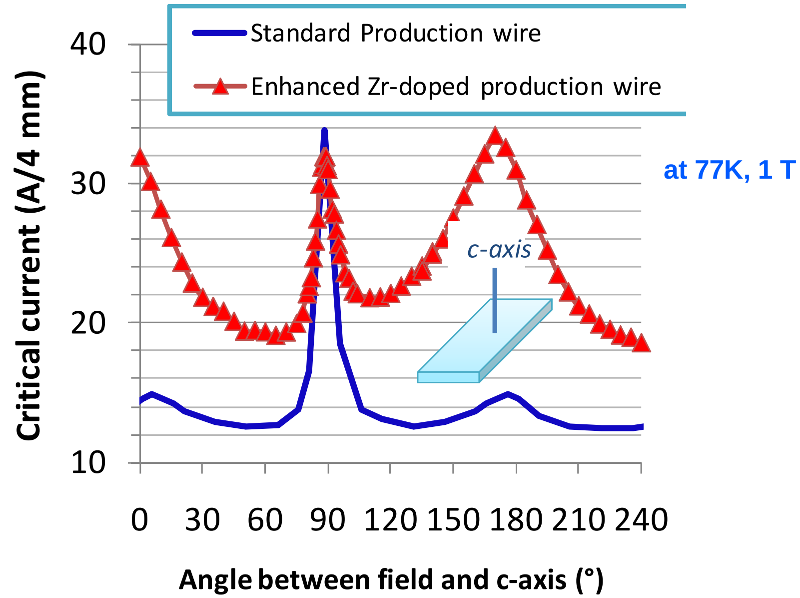


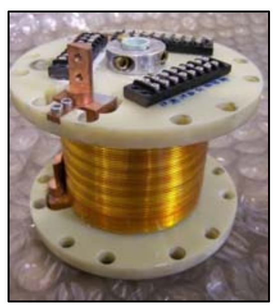


% wires >	2009	2010
250 A/cm	25%	60%
300 A/cm	8%	22%

SuperPower technology enhancements

- Improved pinning by doping of MOCVD HTS wires
  - Systematic study of improved pinning by Zr addition in MOCVD films at UH
  - Process know-how transitioned to SuperPower
- 2X improvement of in-field performance achieved!
  - Process for improved in-field performance successfully transferred to manufacturing
- Benefits of AP wire realized in coil performance
  - Same level of high-field coil performance can be achieved with AP wire, with lower zero-field 77K Ic, less wire, and larger bore





Coil properties	With AP wire	With standard (non-AP) wire
Coil ID	21 mm (clear)	12.7 mm (clear)
Winding ID	28.6 mm	19. 1 mm
# turns	2688	3696
2G wire used	~ 480 m	~ 600 m
Wire I_c	90 to 101 A	120 to 180 A
Field generated at 65 K	2.5 T	2.49 T

Advancing HTS adoption by enhancing value to the customer

- True measure of value to end customer is best represented by:
  $/kA-m @ field and temperature of application
- Key drivers to improve this measure:
  - Reduction of cost/price ($/m)
    - ~10% Average Selling Price reduction year over year
      - Pricing is more market-driven than cost-driven
      - Reduction of costs thru improved yield, improved productivity
  - Increase of global Ic at self field and 77K
    - 15 - 25% average improvement (80A to ~100A)
      - Integration of R&D efforts regarding MOCVD
      - Enhanced QA – in situ measurements
  - Increase of Ic at application field and temperature, utilizing AP techniques
    - Up to 100% increase of I_c at application field and temperature

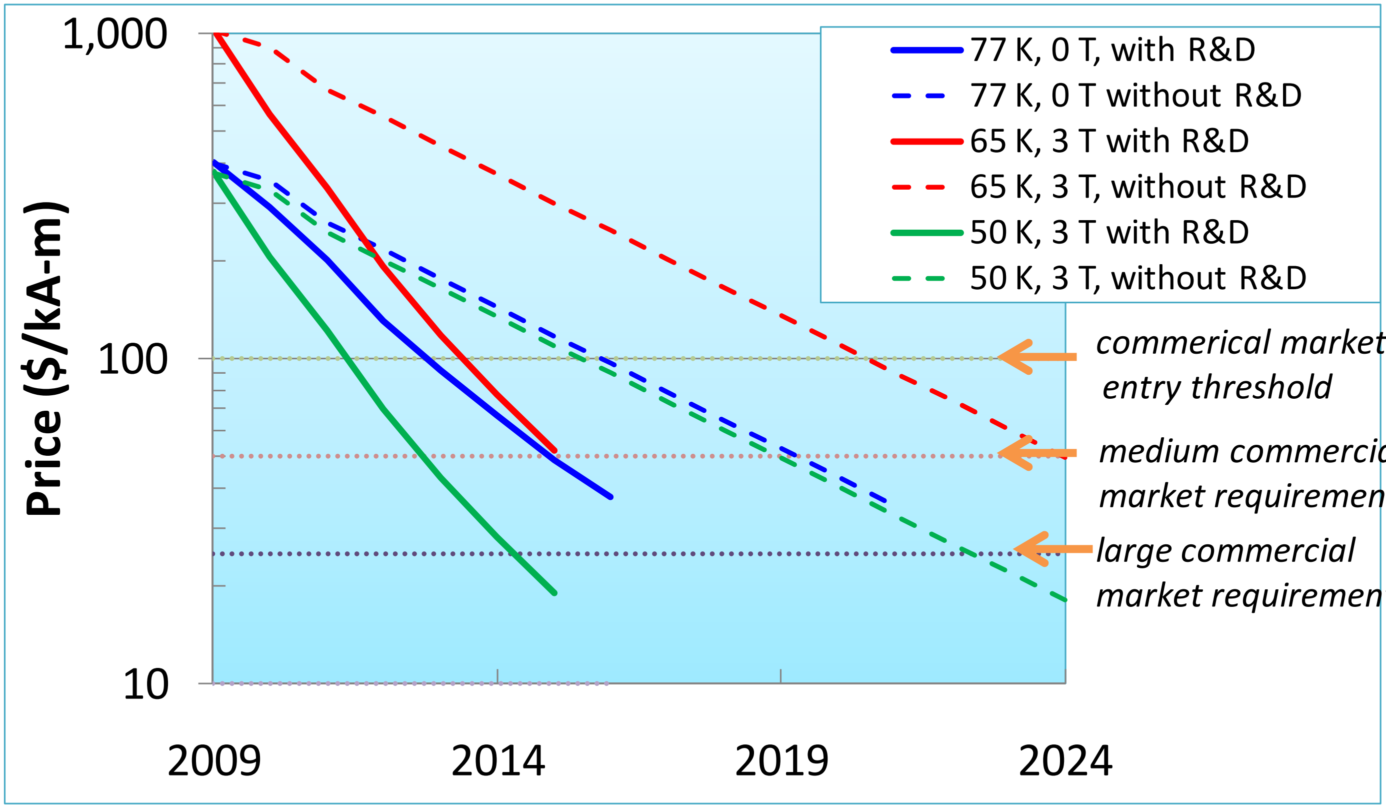
Operating Condition (Field ⊥ wire)	I_c-non AP* (A/4mm)	I_c-with AP* (A/4mm)	Improvement
60 K, 2 T	53.7	72.5	35%
30 K, 2T	124	254	105%

Value enhancement summary

Application	Temperature (K)	Field (T)	2009 $/kA-m (@ temp and field)	2010 $/kA-m (@ temp and field)	Improvement 2010 vs. 2009
Cable	77	0.01	513	368	36%*
Coils	60	2	838	494	70%
Rotating machinery, etc.	30	2	302	105	188%

* Improvement derived from cost and self-field I_c gains only

Commitment to HTS wire R&D will enable achievement of price-performance requirements of commercial market



Commercial market requirements could be reached 5-10 years sooner with R&D - DOE support for HTS program is critical to maintain National Lab & University support

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U.S. DoE Smart Grid Demonstration Program: SFCL Transformer

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Advantages of HTS Transformer

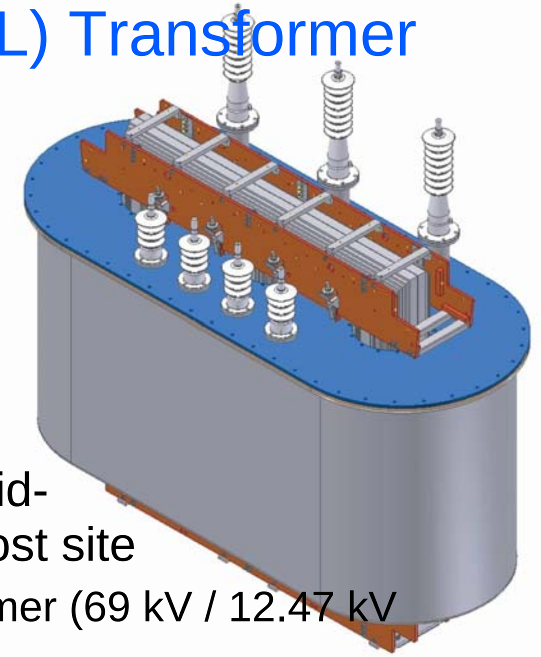
- Greater efficiency
- Smaller, lighter, potentially quieter
- Safety – no oil for cooling
- Can run indefinitely above rated power without affecting device life

- Add FCL feature …
  - Compatibility with Smart Grid requirements
    - Incorporation of FCL feature into transformer to rapidly detect and limit surges at high power levels that can be handled by downstream equipment
      - 30-50% reduction of prospective fault current

HTS transformer projects in the US

	1G HTS XFR	1G HTS XFR	SFCL XFR
Time	1994-1998	1996-2004	2010-2015
Partners	WES - system SP – wire, coils ORNL – HV, cryo RG&E – host utility	WES - system SP – wire, coils, cryo ORNL – HV, cryo Energy East - utility	WES-system, coil SP/UH - wire ORNL- HV, cryo SCE – host utility
Rating	1 MVA	5/10 MVA (normal/overload)	28/40 MVA (normal/overload)
Funding	DOE-SPI	DOE-SPI	DOE Smart Grid Demonstration

U. S. DoE Smart Grid Demonstration Program
Superconducting Fault Current Limiter (SFCL) Transformer



- Funding:
  - $21.5M overall project cost
  - $10.7M DoE Smart Grid funding
- Project objective:
  - 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 class)
    - 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 HTS wire
- Relevance:
  - Occupies smaller footprint than conventional transformers, enabling existing substations to increase distribution capability without expanding into limited or expensive real estate

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ARPA-E GRIDS Program: Superconducting Magnetic Energy Storage (SMES)

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SMES history in the U.S.

- 1976-1981: Bonneville Power Administration / Superconductivity, Inc.[1] / LANL
  - 30 MJ, 10 MW – Tacoma substation
  - Installed and ran for a short time at the end of 1981
- 1990-2000: Superconductivity Inc./AMSC (ASD, PQDC, D-SMES)
  - 1-3 MJ, power outputs up to 2.5 MW – including:
    - Iowa Public Service Co, Sioux City, Iowa
    - Georgia-Pacific Corporation, Bellingham, WA
    - Pacific Gas & Electric Co, San Ramon, CA
    - Cyanco Corp, Winnemucca, NV (in operation 4 years)
    - Ntl. Synchrotron Light Source at Brookhaven, Upton, NY (still operating in 2000)
    - US Air Force, Tinker AFB, Oklahoma City, OK
    - Central Hudson Gas & Electric (1 MW, 0.75 MJ, IBM-NY)
- 1994-1997: U.S. Air Force, Tyndal AFB / Intermagnetics
  - 6 MJ, 590 kW, 5 sec - continuous power conditioning, transportable container
- 1996-2000: Babcock & Wilcox for Anchorage Municipal Light & Power
  - Proof-of-concept 100 MJ-class connected to FACTS device, 24 kV

[1]SI acquired by AMSC in 1997

Why SMES?

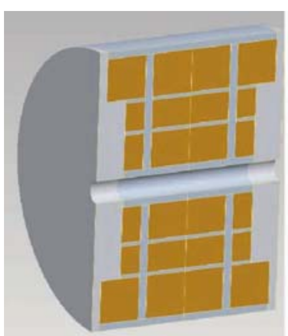
- Power quality requirements of industry and digital economy
  - Rapid response for either charge or discharge
- Grid stability challenges posed by renewable energy sources (changing conditions)
  - Power is available when needed, not only when generated
- High round trip efficiency vs. other storage technologies
  - Minimal resistive energy losses in the superconducting coil and solid state power conditioning
- The time is right with recent improvements in HTS materials
  - Superior performance characteristics
    - Ability to go to high fields – allow high energy density
    - High hoop strength of 2G HTS
  - Continued price improvements
- Clean and Green
  - Safe - no chemical reactions, no toxins produced

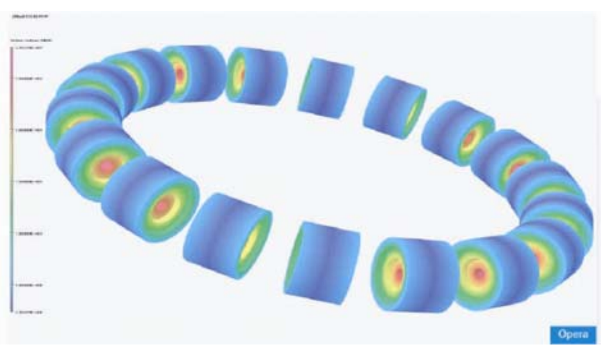
U. S. DoE ARPA-E GRIDS Program

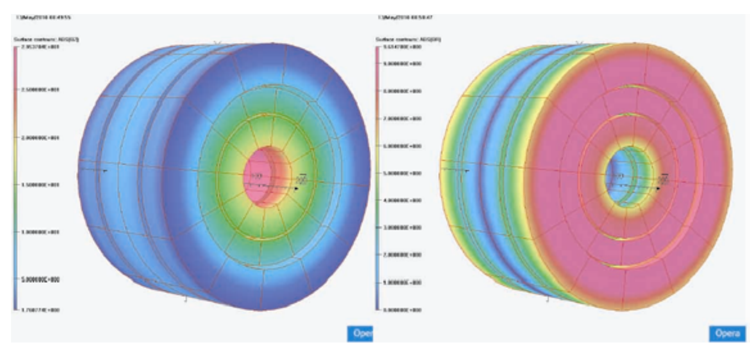
- ARPA-E (Advanced Research Projects Agency – Energy) is modeled after the successful Defense Advanced Research Projects Agency (DARPA)
- Agency within DOE that provides R&D funding for transformational new energy technologies and systems
- Objectives:
  - bring freshness, excitement, and sense of mission to energy research to attract best and brightest minds in the US
  - focus on creative “out-of-the-box” transformational energy research that industry by itself cannot or will not support due to high risk, but where success would provide dramatic benefits for the nation
  - create a new tool to bridge the gap between basic energy research and development/industrial innovation
- GRIDS: Grid-Scale Rampable Intermittent Dispatchable Storage

Superconducting Magnetic Energy Storage (SMES) with direct power electronics interface

- Project selected for funding in July 2010, contracted in August 2010
- Partners:
  - ABB, Inc.: project lead, grid-interface power converter, system integration, lab demo
  - Brookhaven National Lab: design & development of SMES coil
  - SuperPower Inc.: 2G HTS wire, assist BNL with coil development
  - University of Houston, TcSUH: 2G HTS manufacturing improvements for wire cost reductions







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Program overview

- Funding: Total program cost $ 5.25 Million
  - $4.2Million from DoE Advanced Research Projects Agency-Energy (ARPA-E)
- Program Duration: 36 months (2011-2013)
- Objective: Develop the proof of concept of a modular, scalable SMES system by integrating an advanced power conversion concept with a superconducting magnet coil
    - 20 kW ultra-high field SMES device with capacity of up to 3.4 MJ
    - Field of up to 30 T at 4.2K
    - 2G HTS wire with high critical currents (~ 800 A) to drive down price/performance
  - Capable of flexible connection to medium voltage distribution networks at 15-36 kV
- Relevance:
  - High power and high energy storage in a compact device with cost advantages in material and system costs
  - Modular units to address both long term (hours) and short term (seconds) storage requirements to help load leveling on the grid being fed by variable renewable sources such as solar and wind

Conclusion

- Good progress made, more to be done
- Wire manufacturing established
  - Ongoing efforts address production improvements needed to improve price, performance, capacity and quality
- Technology development continues
  - Supporting manufacturing and performance improvements
    - Will enable price-performance improvements
  - To address further applications requirements, new architectures
- Device demonstrations expand to areas addressing need for clean, green and smart grid
- Funding outlook unclear
  - Traditional sources may be discontinued
  - New approaches required
    - Include wire development as part of demonstration projects
  - Critical to keep technology moving forward

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- Colleagues at SuperPower

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Thank you for your attention!

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