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
- Advanced Research Projects Agency Energy ARPA-E: wires for wind generators, superconducting magnetic energy storage

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
LN₂/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

- 1T
- 77K
- 70K
- 60K
- 50K
- 35K

Field Orientation (deg)

High temperature, low field applications

1.2 μm Coil Wire

- 1T
- 77K
- 70K
- 60K
- 50K
- 35K

Field Orientation (deg)

Low temperature, perpendicular field applications

N. Strickland
Callaghan Innovation (previously IRL)
# Amperium Wire Architectures

Application specific mechanical packaging

<table>
<thead>
<tr>
<th>Wire Type</th>
<th>Architecture</th>
</tr>
</thead>
</table>
| **Standard Amperium Wires**  
See [www.AMSC.com](http://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 |

<table>
<thead>
<tr>
<th>Wire Type</th>
<th>Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Laminated 4.8</td>
<td>Single HTS, 3-layer 4.8 mm wide 50 µm thick copper</td>
</tr>
<tr>
<td>Copper Laminated 12</td>
<td>Single HTS, 3-layer 12 mm wide 50 µm thick copper</td>
</tr>
</tbody>
</table>
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))
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

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

✓ 68% improvement demonstrated in wire performance at wind generator operating condition of 30 K, 2.5 T
✓ Increase $I_c$ to over 1,500A (demo in mid 2014)
Thinner substrates offer improved current density while still providing strong mechanical support

- Current 2G HTS production material based on either 50 or 100 μm Hastelloy® C276 substrate
  - For standard Cu thickness of 40 μm total, the conductor thickness of current production 2G HTS conductor is ~ 0.095 mm.

- Thinner Hastelloy® C276 of 25, 30 and 38 μm thicknesses are being evaluated
  - For standard Cu thickness of 40 μm total on a 25 μm Hastelloy® C276 substrate, conductor thickness is reduced to ~70 μm
  - This implies a 36% increase in current density

- Available second half of 2014

Baseline is 40 micron thick copper stabilizer
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
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 manufacturing 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

Technology Transfer and Partnerships
Wireless Product Business
Cryogenic Cooler Business

2012 and Beyond

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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. 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

**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.

**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
DHS’ Resilient Electric Grid (REG) ConEd System

- 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

Commercialization requires a significant installation
Phase II Hydra Project Summary

- HTS 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 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

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

**Reactor (+CT/PT)**
- Installed by Central Hudson
- AMAT monitoring T3 (and T1 for reference)
10+ MW Wind Turbine Generator Team

AML’s Fully Superconducting Generator

EERE Wind Program Phase II:
Offshore Wind Turbine Advanced Drivetrain
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

- 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.

Engineered Nanoscale defects  
4x improved wire manufacturing  
High-power, efficient wind turbines
4x HTS conductor can enable commercial feasibility of devices

<table>
<thead>
<tr>
<th>Metric</th>
<th>Now</th>
<th>End of project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical current at 30 K, 2.5 T (A/12 mm) (device operating condition)</td>
<td>750</td>
<td>~3,000</td>
</tr>
<tr>
<td>Wire price at device operating condition ($/kA-m)</td>
<td>144</td>
<td>36</td>
</tr>
<tr>
<td>Estimated HTS wire required for a 10 MW generator (m)</td>
<td>65,000</td>
<td>16,250</td>
</tr>
<tr>
<td>Estimated HTS wire cost for a 10 MW generator ($ ,000)</td>
<td>7,020</td>
<td>1,755</td>
</tr>
</tbody>
</table>

Technical Approach
• Quadruple the critical current performance to **3,000 A** at 30 K, 2.5 T:
  – **Doubling the lift factor** \(\frac{I_c(T, H)}{I_c(77K, s.f.)}\) 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 superconducting films** while maintaining the efficacy of pinning by nanostructures.
Increased nanoscale defect density in high Zr content wires

- 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 $I_c$ 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
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

- 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.

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

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.

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

**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
TYRC’s HTS SMES project targets and progress

<table>
<thead>
<tr>
<th>SMES Target Design</th>
<th>$I_{op}$ (kA)</th>
<th>$B_{op}$ (T)</th>
<th>$E_{stored}$ (MJ)</th>
<th>$V_{discharge}$ (kV)</th>
<th>HTS cable type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-25</td>
<td>10-12</td>
<td>60/100/250</td>
<td>1-5</td>
<td>Al stabilized</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Industry</th>
<th>Energy (MJ)</th>
<th>Power (MW)</th>
<th>Weight (kg)</th>
<th>Volume (m$^3$)</th>
<th>Foot Print [Dia. x L] (m x m)</th>
<th>B-field (T)</th>
<th>Cost/kW-hr ($/kW-hr$)</th>
<th>Cost/kW ($/kW$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
<td>5</td>
<td>1,000</td>
<td>9.42</td>
<td>2 x 3</td>
<td>&gt; 12</td>
<td>3,000</td>
<td>1,000</td>
</tr>
</tbody>
</table>

TYRC’s HTS SMES current progress:
- Compaction tests completed
- Cable bend diameter completed
- Al conduit weld qualification in-progress
- Sub-scale prototype Q3 2015

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

DOE ARPA-E SMES project

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

*US Air Force*

**Brookhaven Lab (Li - PI)**

**Airborne SMES Model**

**SMES for Tactical Micro-grid**
(2014)

*US 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

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


Trociewitz et al. APL 99,202506 (2011)
The National High Magnetic Field Laboratory (NHMFL) at FSU is developing a 32T *User* magnet

**Specification**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>32 mm</td>
</tr>
<tr>
<td>Uniformity 1 cm DSV</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Total inductance</td>
<td>254 H</td>
</tr>
<tr>
<td>Stored energy</td>
<td>8.6 MJ</td>
</tr>
<tr>
<td>Ramp to 32 T</td>
<td>1 hour</td>
</tr>
<tr>
<td>Cycles</td>
<td>50,000</td>
</tr>
</tbody>
</table>

- 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
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)

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

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

Cryo-cooler Cools 30 m @ 77K 0.23 lb/m
DOE Energy Frontier Research Center: Center for Emergent Superconductivity (CES)

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

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

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
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
  $\sim 10^5$ A/cm$^2$ at 31T
Bi-2212 round wire for high field applications

Key requirements for material:
- 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

Challenges for Bi-2212 round wire
- 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

- 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 applications
- Wire is twistable and ac loss reduced
- 5x longer piece-length process under developing
- High strength wire development is funded
Advances including “Core Densification + Over-Pressure HT” led to $J_E > 600 \text{ A/mm}^2$ at 4.2 K, 20 T.
OST Bi-2212 round wire development in the near future

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:

<table>
<thead>
<tr>
<th>Conductor Property</th>
<th>Delivered value today</th>
<th>In 2 years</th>
<th>In 5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current density $J_E$ @ 4.2K, 20T</td>
<td>~ 500 A/mm$^2$</td>
<td>~ 700 A/mm$^2$</td>
<td>~ 700 A/mm$^2$</td>
</tr>
<tr>
<td>Length</td>
<td>200 – 1,000 m</td>
<td>400 – 1,000 m</td>
<td>&gt; 3,000 m</td>
</tr>
<tr>
<td>Strength</td>
<td>110 MPa</td>
<td>150 - 200 MPa</td>
<td>&gt; 200 MPa</td>
</tr>
<tr>
<td>Selling price range $/kA.m @ 4.2K, 20T</td>
<td>330 - 550</td>
<td>200 - 400</td>
<td>100 - 150</td>
</tr>
</tbody>
</table>
### Hyper Tech MgB₂ conductor strand designs - Different % SC and % Cu

<table>
<thead>
<tr>
<th>Product #</th>
<th># filaments</th>
<th>Fill factor (%)</th>
<th>Copper (%)</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-MS</td>
<td>18</td>
<td>8</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>24-NM</td>
<td>24</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>30-NM</td>
<td>30</td>
<td>20</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>36-CM</td>
<td>36</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Demonstrated multi-strand MgB₂ cable:

- 10° pitch angle
- 20° pitch angle
2nd generation MgB$_2$ under development at Hyper Tech

- 4 to 5 times improvement in J$_c$ over 1st gen MgB$_2$

- $J_c$ at 4.2K
- $J_c$ at 20K

2nd 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
Design a 5 MW MgB$_2$-based generator and developing a radiation treatment background magnet.

Generator design is expandable from 5-20 MW.

### Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>5.0</td>
</tr>
<tr>
<td>RPM</td>
<td>10</td>
</tr>
<tr>
<td>Configuration</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Voltage (kVrms)</td>
<td>1,350</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>24</td>
</tr>
<tr>
<td>Output Frequency (Hz)</td>
<td>2.0</td>
</tr>
<tr>
<td>Diameter (M)</td>
<td>4.87</td>
</tr>
<tr>
<td>Length (M)</td>
<td>1.74</td>
</tr>
<tr>
<td>Weight (Tons)</td>
<td>76.5</td>
</tr>
<tr>
<td>Superconductor</td>
<td>MgB$_2$</td>
</tr>
<tr>
<td>Rotor Coolant</td>
<td>LHe/GHe</td>
</tr>
<tr>
<td>Stator Conductor</td>
<td>Copper</td>
</tr>
<tr>
<td>Stator Coolant</td>
<td>Water or EGW</td>
</tr>
</tbody>
</table>

Image Guided Conduction Cooled Radiation Treatment Background Magnet

- Magnet structural supports (3)
- Gantry supporting 3 Co-60 treatment sources
- Gradient and RF send/receive coils
Current and projected $J_E$ and $$/kA.m$: based on 1 mm round wire, and volume orders of wire

<table>
<thead>
<tr>
<th>Property of importance</th>
<th>Delivered value today-1\textsuperscript{st} gen</th>
<th>In 3 years 2\textsuperscript{nd} gen</th>
<th>In 5 years 2\textsuperscript{nd} gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range</td>
<td>4-30K</td>
<td>4-30K</td>
<td>4-30K</td>
</tr>
<tr>
<td>Field range</td>
<td>6T-0T</td>
<td>8T-0T</td>
<td>8T-0T</td>
</tr>
<tr>
<td>Conductor current density ($J_E$) Based on temperature and field on wire</td>
<td>4K-1T-1400A/mm\textsuperscript{2}</td>
<td>4K-1T-2800A/mm\textsuperscript{2}</td>
<td>4K-1T-2800A/mm\textsuperscript{2}</td>
</tr>
<tr>
<td></td>
<td>4K-4T-400A/mm\textsuperscript{2}</td>
<td>4K-4T-1400A/mm\textsuperscript{2}</td>
<td>4K-4T-1400A/mm\textsuperscript{2}</td>
</tr>
<tr>
<td></td>
<td>4K-6T-200A/mm\textsuperscript{2}</td>
<td>4K-6T-800A/mm\textsuperscript{2}</td>
<td>4K-6T-800A/mm\textsuperscript{2}</td>
</tr>
<tr>
<td></td>
<td>20K-0T-2000A/mm\textsuperscript{2}</td>
<td>20K-0T-5000A/mm\textsuperscript{2}</td>
<td>20K-0T-5000A/mm\textsuperscript{2}</td>
</tr>
<tr>
<td></td>
<td>20K-1T-600A/mm\textsuperscript{2}</td>
<td>20K-1T-2000A/mm\textsuperscript{2}</td>
<td>20K-1T-2000A/mm\textsuperscript{2}</td>
</tr>
<tr>
<td></td>
<td>20K-2T-320A/mm\textsuperscript{2}</td>
<td>20K-2T-1200A/mm\textsuperscript{2}</td>
<td>20K-2T-1200A/mm\textsuperscript{2}</td>
</tr>
<tr>
<td></td>
<td>20K-3T-120A/mm\textsuperscript{2}</td>
<td>20K-3T-600A/mm\textsuperscript{2}</td>
<td>20K-3T-600A/mm\textsuperscript{2}</td>
</tr>
<tr>
<td>Conductor form</td>
<td>Round 0.25-2 mm</td>
<td>Can be custom size</td>
<td>Can be custom size</td>
</tr>
<tr>
<td>Conductor length</td>
<td>6-10km</td>
<td>40-60km</td>
<td>80km</td>
</tr>
<tr>
<td>Conductor shape</td>
<td>Round or rectangular</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delivered selling price range $$$/kA.m</td>
<td>4K-1T-$5/kAm</td>
<td>4K-1T-$0.5-$1.5/kAm</td>
<td>4K-1T-$0.4/kAm</td>
</tr>
<tr>
<td></td>
<td>4K-4T-$16/kAm</td>
<td>4K-4T-$1.5-4.5/kAm</td>
<td>4K-4T-$1.3/kAm</td>
</tr>
<tr>
<td></td>
<td>4K-6T-$30/kAm</td>
<td>4K-6T-$3.0-9.0/kAm</td>
<td>4K-6T-$2.5/kAm</td>
</tr>
<tr>
<td></td>
<td>20K-0T-$3.30/kAm</td>
<td>20K-0T-0.37/kAm</td>
<td>20K-0T-0.35</td>
</tr>
<tr>
<td></td>
<td>20K-1T-$10/kAm</td>
<td>20K-1T-$0.75-2/kAm</td>
<td>20K-1T-$0.70/kAm</td>
</tr>
<tr>
<td></td>
<td>20K-2T-$20/kAm</td>
<td>20K-2T-$1.5-5/kAm</td>
<td>20K-2T-$1.3/kAm</td>
</tr>
<tr>
<td></td>
<td>20K-3T-$50/kAm</td>
<td>20K-3T-$3-10/kAm</td>
<td>20K-3T-$2.5/kAm</td>
</tr>
<tr>
<td></td>
<td>Range is 2\textsuperscript{nd} gen (low value) vs 1\textsuperscript{st} gen wire (higher value).</td>
<td>Based on 2\textsuperscript{nd} gen wire</td>
<td></td>
</tr>
</tbody>
</table>

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 2\textsuperscript{nd} generation MgB\textsubscript{2} wire performance
Office of Electricity Delivery and Energy Reliability  [http://energy.gov/oe/]
US Department of Energy  [http://energy.gov/]

IEA HTS ExCo Meeting 2014

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