Process Innovations for High Temperature Superconducting (HTS) Wire Manufacturing

DE-EE0007871
Superconductor Technologies Inc. , TECO-Westinghouse, & M.I.T.
Start Date: 6/1/2017 – End Date: 9/30/2020

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This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- 3yr/$4.5M award kickoff June 2017
- End date Sept 2020 (extended)
- Fiscal Year#1 High Temp. Superconductor composition & motor design, ends Sept 2018.
- FY#2 Produce enhanced HTS wire meeting goals.
- FY#3 Build & test motor coil with enhanced HTS.

Budget

	Year 1	Year 2	Year 3	Total Project
DOE Funding	$ 2,188,352	$ 1,618,800	$ 689,963	$ 4,497,115
Cost Share	$ 547,088	$ 404,700	$ 172,491	$ 1,124,279
Total	**$ 2,735,440**	**$ 2,023,500**	**$ 862,454**	**$ 5,621,394**

Total Actual (as of 5/31/2018)	
DOE Funded	$ 1,202,174
Cost Share	$ 300,544
Total	**$ 1,502,718**

Barriers

- In-situ, vacuum, 800°C film composition sensing at ±1% atomic accuracy.
- Gd/Ba/Cu elements
- Lack of available OEM solutions affected equipment spending.

Partners

- Superconductor Technologies Inc. (prime) focused on enhancements in 2G Superconductor film growth, metrology, testing.
- TECO-Westinghouse (sub) focused on 2G Superconductors applied to motor design.
- M.I.T. (sub) focused on 2G Superconductor testing and electromagnetics/cryogenics integration.

Project Objectives

- **Annual USA energy savings >6,000 GWh**

  High Temperature Superconductor wires used in large motors and generators has the potential to reduce U.S. annual electricity consumption by 0.2% with >96% motor efficiency

(3)-Year Program OBJECTIVES:

#1: *Improve 2G High Temperature Superconducting (HTS) wires*

Start: <480A/cm-width (77K, s.f.) → Goal: 1440A/cm-width Ic_{Min} at 65K/1.5Tesla

Use renewable Liquid Nitrogen as 65K cryo-coolant.

#2: *Reduce manufacturing costs of 2G HTS wires*

Cost/performance EQUAL to -or- BETTER than copper magnet wire.

Doubling yields @200-meter lengths, and/or reducing components costs by 50%

#3: *Demonstrate progress in a >500HP motor coil @ 1.5T/65K*

- **Challenge Areas:**

  Thin film stack: Exploring & measuring each ReBCO HTS process type w/ optimization(s)

  Measurements: Techniques to control growth & measure long high-performance HTS tapes.

  Demonstration Project: Multiple competencies required to build/test Lg. motor coil

  {Electrical, Mechanical, Magnetic, Thermal/Cryogenics, Software}

Year #1	Year #2	Year #3
Explore & measure HTS process variations. Design Motor for specs.	Select best-in-class process, Scale-up, build yield measurement capability	Wind & Test 5000HP rotor coil & test 2G HTS in cryostat @ 65K/1.5 Tesla

Technical Innovation

- Previous 'record performance measurements' of 2G HTS have been accomplished with various dopants. (RE, Zr, Hf, Sn, Ag, etc..) in addition to HTS $RE_1Ba_2Cu_3O_{7-d}$ formula.
- With DOE Funding, STI upgraded our RCE1km System with new electron beam sources and control systems to enable (4) unique superconductor film growth cases in (1) deposition tool.

(4) In-Field Optimization Deposition Types;

1. HTS Thickness w/ Intrinsic-Pinning
2. HTS Extrinsic-Pinning w/ Dopants
3. HTS w/ Superlattice
4. Combinatorial (best-of-of above)

- Measure performance & yield of each HTS growth type in same flexible reactor.

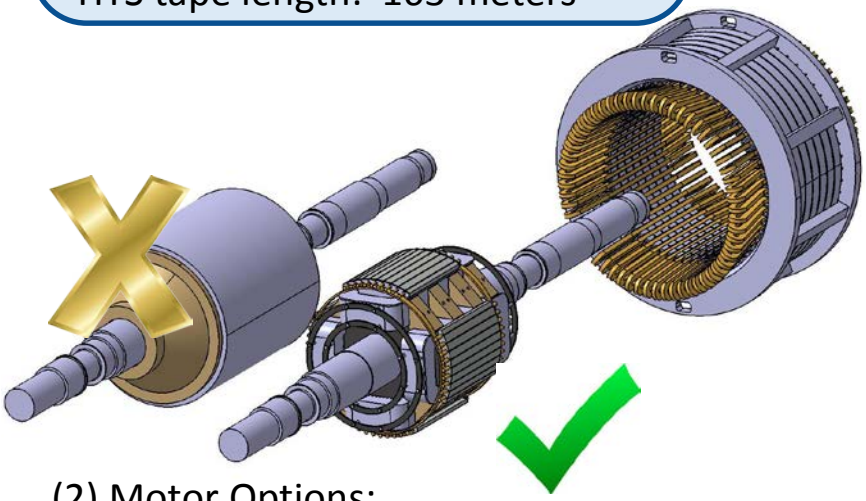
Added Electron Beam Sources, Power Supplies, 480VAC Power, Quartz Crystal flux monitors, & control software, Jan 2018

Unloading Finished 2G HTS Tape from Drum

Technical Innovation

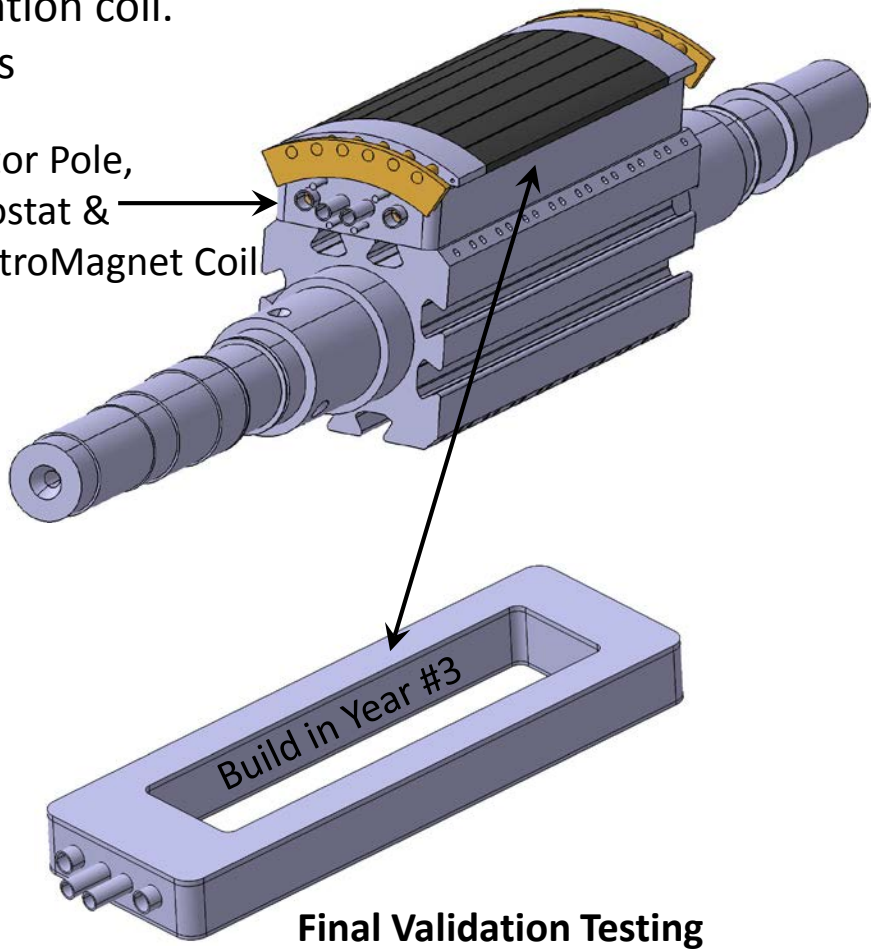
- TECO-Westinghouse Motors Corp. chose a 5000HP 4-Pole (3423AA) design vs. smaller 500HP for this HTS demonstration coil.
- Approved by D.O.E. as meeting objectives
- M.I.T. assisting with Design & Analysis

Core length: 30" (762mm)
HTS operating current: 500 Amps
Flux Density: 1.5 Tesla
Temperature: 65K
# of HTS tape turns: 74
HTS tape length: 163 meters



(2) Motor Options:
Enclosed vs. Modular Cryostats

Motor Pole,
Cryostat &
ElectroMagnet Coil



Final Validation Testing of coil in cryostat assembly

Results & Accomplishments

- Upgraded hardware in Jan 2018 with this DOE funding
- STI's RCE1km deposition system is the *most flexible*, large-batch (100's meters), high-performance 2G HTS film growth reactor in the world.
- As of mid-June 2018 completed (18x) process runs of Intrinsic, Extrinsic, & Superlattice types to quantify HTS film performance.

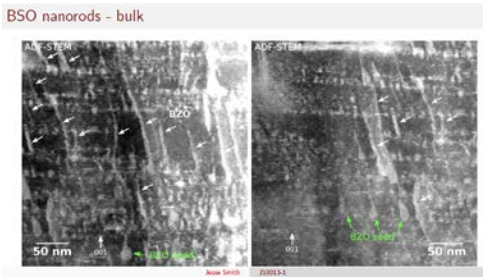
Run ID	Date	SOPO Task	Ic (A) 77K / s.f.	Dopant	Thk (µm)
J17029	9/14/17	3.10	800+	Intrinsic	6+
J17036	11/2/17	3.30	300	CeO_2 Superlattice	6+
J17038	11/16/17	3.10	600-800	Intrinsic	6+
RCE	1km	E-Beam	Hardware	Upgrade	
J18009	3/19/18	3.20	200-300	ZrO_2	1.8
J18010	3/26/18	3.20	50	ZrO_2	1.8
J18011	4/2/18	3.20	40 – 170	Zr	1.8
J18012	4/9/18	3.20	20 – 180	Zr	1.8
J18013	4/17/18	3.20	60 – 290	Sn	1.8
J18014	4/23/18	3.20	60 – 340	Sn	3.6
J18015	4/27/18	3.20	90 – 290	Sn	3.6
J18016	5/3/18	3.20	100 – 810	Ag	3.6
J18017	5/9/18	3.20	200-500	Ag	3.6
J18018	5/15/18	3.20	625-950	Ag	4.5
J18019	5/22/18	3.20	<100 FAILED E-beam	Ag	5.2
J18020	5/29/18	3.20	400-790	Ag	5.2
J18021	6/4/18	3.30	400-625	ReBCO Superlattice	3+
J18023	6/15/18	3.20	400+	Sn	6+
J18024	6/22/18	3.20	tbd	Sn	6+

(18) Process Runs w/ results

Red Text identifies 'Best-In-Class' runs

Results & Accomplishments

- Discovered high-performance HTS film combinations;
  - (1.5X) Critical Current Electrical Performance: >1000Amps/12mm
    - Raised 77K/self-field Ic by increasing ReBCO thickness to >6+μm
  - (2X) Increase@ 1.5 Tesla In-Field Magnetic Performance
    - Multiple Flux Pinning Techniques & Dopants. SEM/TEM Analyses
    - Pinning Engineering & Quantitative Metrology to lower Ic_{Max}/Ic_{Min} variation
  - Verfied Mechanical Performance:
    - Found Ic vs. ReBCO film thickness mech. limits.
    - Optimized stresses (ΔCTE) in thin-film stack
  - Improved Thermal Performance:
    - Increase ΔIc/ΔTemp. Tighter composition range →mfg. yield targets

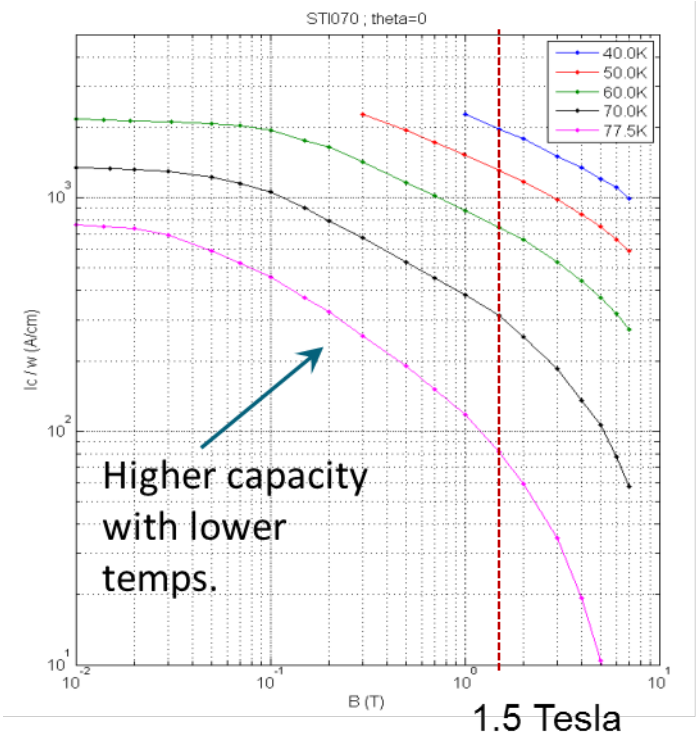


- Grateful to contributing organizations which have made our 1st year successful;

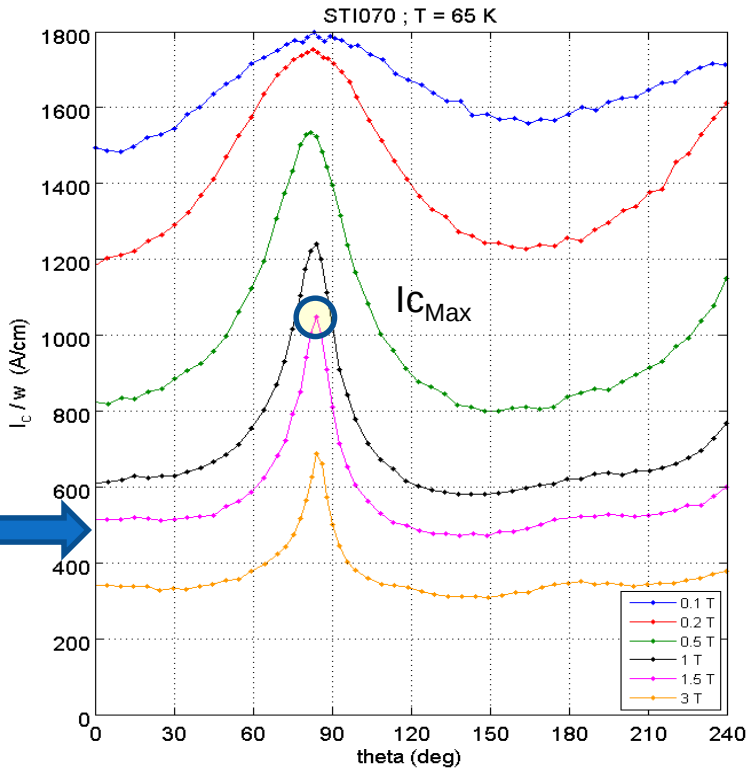
Robinson Research Institute
VICTORIA UNIVERSITY OF WELLINGTON
UNT UNIVERSITY OF NORTH TEXAS
Ceriumlabs BRINGING THE ELEMENTS TOGETHER

(Commercial Partners
Not D.O.E. Funded)

Results and Accomplishments



1.5T Target Field



Consistent Temperature dependence

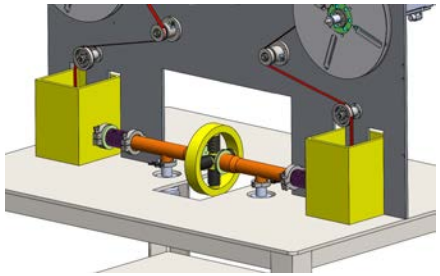
Excellent Angular Scan In-Field Performance

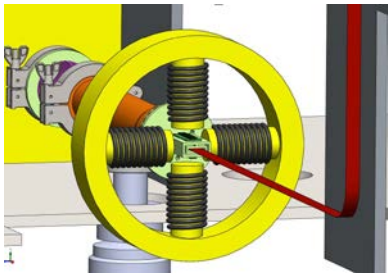
- 65 K 1.5 Tesla $\mathbf{Ic_{Max}}$ >1000 A/cm

Milestone	SOPO	# Runs	Dopant
Thickness Intrinsic	3.10	2	RE
Extrinsic	3.20	14	Zr, Sn, Ag
Superlattice	3.30	2	CeO_2, REBCO

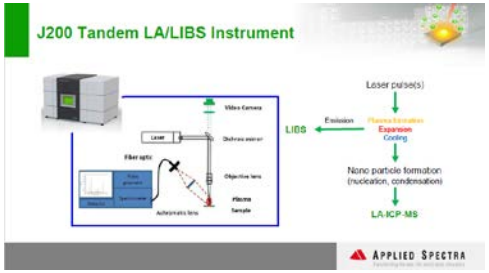
Transition

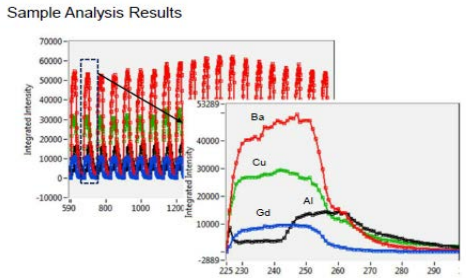
- 3rd Party performance measurements. D.O.E./Office of Naval Research
  Submission of (5x) 4mm unique samples for measurement & performance comparison
- VOLUME: D.O.E. program runs are completed with 100+ meter lengths on STI's Manufacturing Tool, so scale-up to commercial lengths will be proven.
- QUALITY: Developing 1km roll-to-roll Measurement System – maintain quality & high-performance levels {65K/1.5T/All-Angles} Not OEM Available.

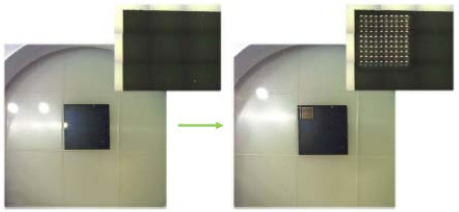




- YIELD: Focused on LIBS (Laser induced breakdown spectroscopy) for in-situ composition monitoring with Applied Spectra. SOPO 6.40. ↑Yields







Questions?