Advanced Conductor Technologies LLC
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SuperPower Inc.
A Furukawa Company

Cost-effective Conductor, Cable, and Coils for High Field Rotating Electric Machines

Contract Number DE-EE0007872

Florida State University, Advanced Conductor Technologies, and SuperPower Inc.

June 2017 – June 2020

Professor Lance Cooley

Applied Superconductivity Center, Florida State University & FAMU-FSU College of Engineering, Tallahassee, Florida

The team:

Prof. Sastry Pamidi (PI) – Florida State University
Prof. David Larbalestier – Florida State University
Dr. Danko van der Laan – Advanced Conductor Technologies, LLC.
Mr. Drew Hazelton – SuperPower Inc.

U.S. DOE Advanced Manufacturing Office Program Review Meeting, Arlington, VA June 12, 2019

Overview

Project Title: Cost-effective Conductor, Cable, and Coils for High Field Rotating Electric Machines

Timeline:

Project Start Date: 06/01/2017

Budget Period End Date: 04/30/2019

Project End Date: 05/31/2020

Barriers and Challenges:

- 2G HTS conductors contain occasional flaws that reduce current-carrying capacity; transfer of current around flaws is not possible for insulated motor windings, so flaws can cause winding burnout.
- Conductor on round core (CORC®) cables facilitate current transfer around flaws and mitigate burnout risk.
- Project seeks to understand best conditions for current transfer and how to reliably utilize less expensive, higher yield run-of-the-mill conductor grades in electric machines.

AMO MYPP Connection:

- 3.3: Advanced Manufacturing for Energy Systems
  - 3.3.1 Advanced Manufacturing to Enable Modernization of Electric Power Systems
    - Next generation electric machines and other advanced power electronic devices

Project Budget and Costs:

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall Budget	$1,000,000	$250,000	$1,250,000	20%
Approved Budget (BP-1&2)	$378,742	$110,218	$488,960	22.5%
Costs as of 3/31/19	$337,964	$105,544	$443,508	23.7%

Project Team and Roles:

- **Florida State University** is the lead institution
  - *Center for Advanced Power Systems* (CAPS – Prof. Sastry Pamidi) provides management and high-current testing
  - *Applied Superconductivity Center* (ASC – Prof. Lance Cooley and Prof. David Larbalestier) provides management and conductor-level investigations (includes student and post-doctoral investigators)
- **SuperPower, Inc.** (SP – Mr. Drew Hazelton) is a subcontractor that manufactures the conductor used in this program and provides QC data
- **Advanced Conductor Technologies LLC** (ACT – Dr. Danko Van der Laan and Dr. Jeremy Weiss) is a subcontractor that manufactures conductor on round core (CORC®) cables and performs high-current testing

Project Objective

- AMO Targets for Next Generation Electric Machines:
  - Increase efficiency by 2-3 % (reduction of losses by 28-75%)
- Superconductors could reduce or remove I^2R losses
  - Field coils in MW-class rotating machines, armatures if AC loss challenges can be overcome
- Flaws in 2G-HTS conductor can cause burnout of windings. Cost of flawless 2G-HTS conductor is too high and its manufacturing yield is too low to realize AMO targets at the present time.
- **Objective:** Mitigate burnout risk to permit use of lower cost, higher yield variable-Ic 2G-HTS conductors
  - Approach: Multi-conductor cables facilitate transfer of current around flaws if the contact resistance is suitable.
  - Target: Increase yield by 2x for same ampere-turns in comparison to 500 m full-Ic conductor with 5 splices.

Technical Innovation

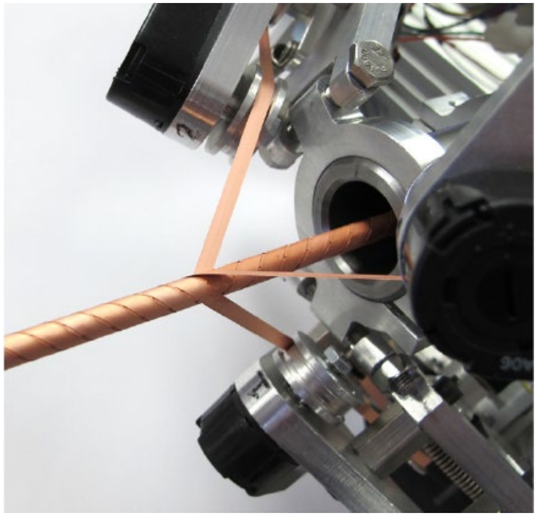
- Prototype electric machines uses 2G-HTS windings with high current density and high stored energy ½ $L\ I^2$
  - This energy will *rapidly* transfer to heat at a flaw; *uncontrolled local temperature rise* can result in loss of the entire winding
- **Limitations**:
  - Low current density is not cost effective for 2G-HTS electric machines
  - Active counter-measures: complex and too slow
  - Unrealistic to avoid flaws: Some flaws are a by-product of present manufacturing methods, others form during operation (fatigue)
- **Proposed approach**: Develop multi-conductor windings that tolerate conductors with variable Ic and build in *passive* burnout protection
- Conductor on round core (CORC®) cables maintain ready-to-wind flexibility and provide a matrix of transfer points around flaws
  - Critical Innovations: (1) Tunable contact resistance; (2) Narrow and thin 2G-HTS conductors with high critical current Ic; (3) Scalable fabrication

(Cost-effective Conductor, Cable, and Coils for High Field Rotating Electric Machines)

Technical Innovation

- Multiple layers create many parallel transfer points where tapes overlap
  - Current transfer length L at dissipation Ec can be tailored to frequency of flaws by tuning contact resistance Rc and cable design parameters
- Innovate 2G-HTS and CORC® production processes
  - Thin and narrow conductors tolerate small diameter bend at same bending strain
    - **2 mm wide, 46 μm overall thickness**
    - **CORC® cable < 3 mm diameter**
  - 2G-HTS innovations for pinning are added
- Parallel winding of shorter pieces: higher yield for same ampere-turns
  - Cost and delivery time for short-length variable-Ic pieces is significantly less than that for long-length full-Ic pieces
    - Yield gain more than offsets geometric winding factor

$$L = \sqrt{\frac{I_{tr} R_c p}{2 A_x N_{tapes} E_c}}$$



D C van der Laan *et al.*, *Supercond. Sci. Technol.* **28** (2015) 124001

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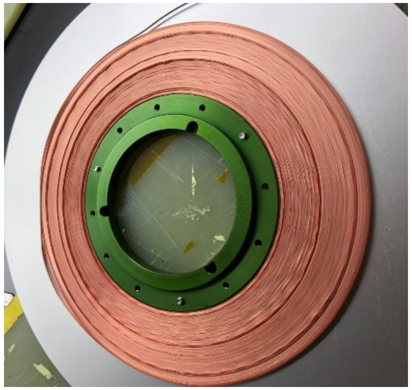
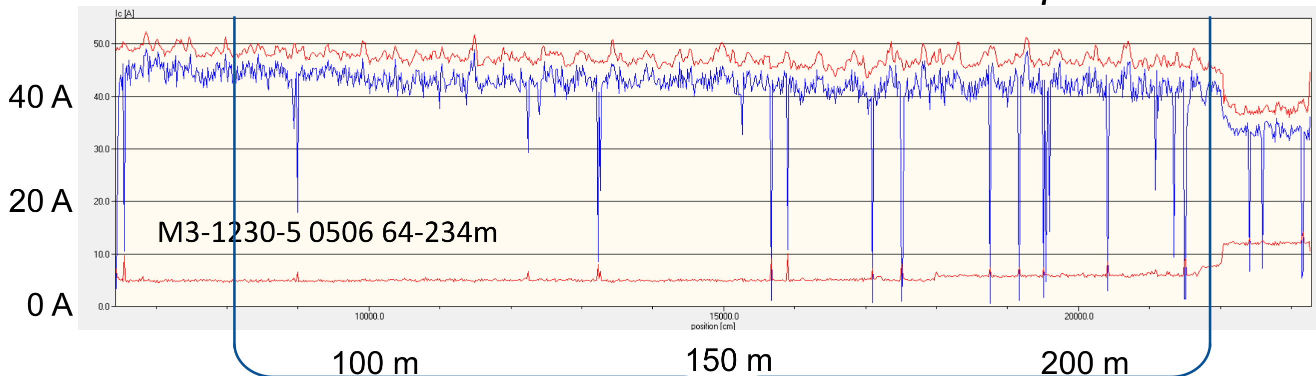
Technical Approach

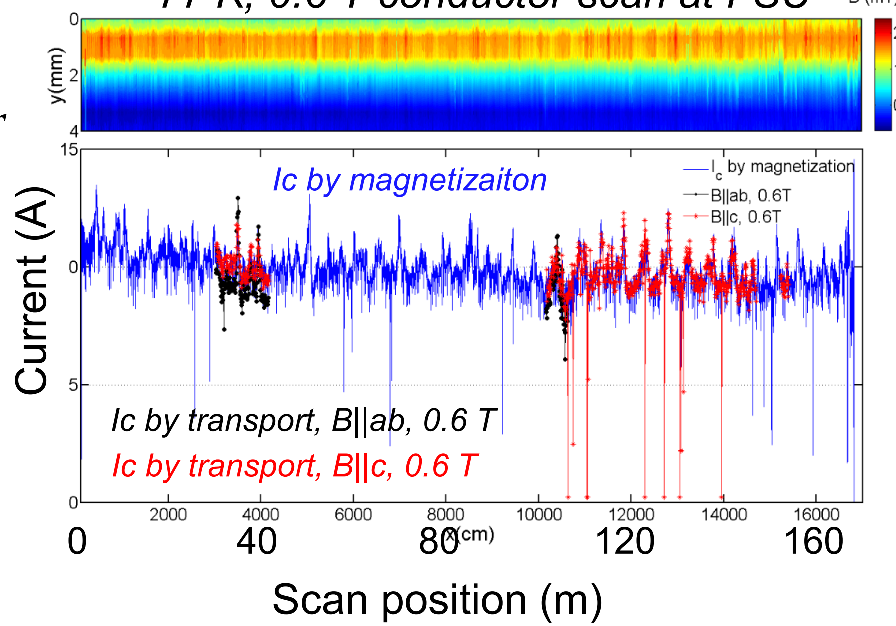


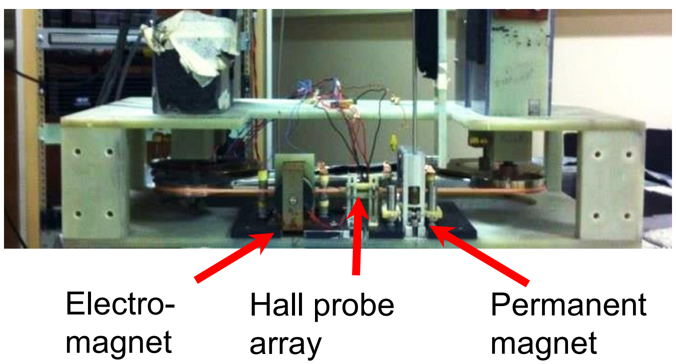
77 K s.f. Variable Ic conductor scan from SuperPower



Above: delivered 2G-HTS on spool
At right: Scans of variable-Ic conductor by SP and FSU get mapped to conductor selection and cable layout at ACT

77 K, 0.6 T conductor scan at FSU

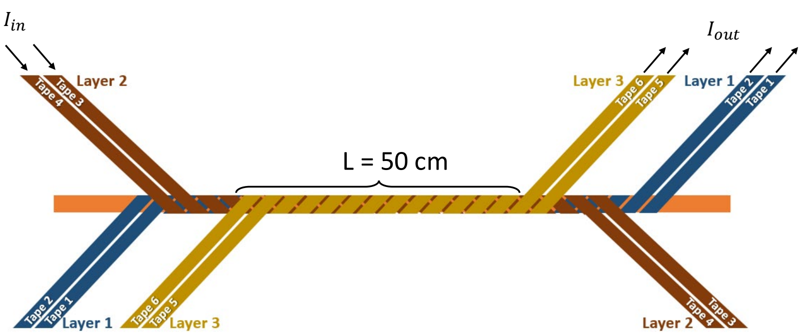




Technical Approach

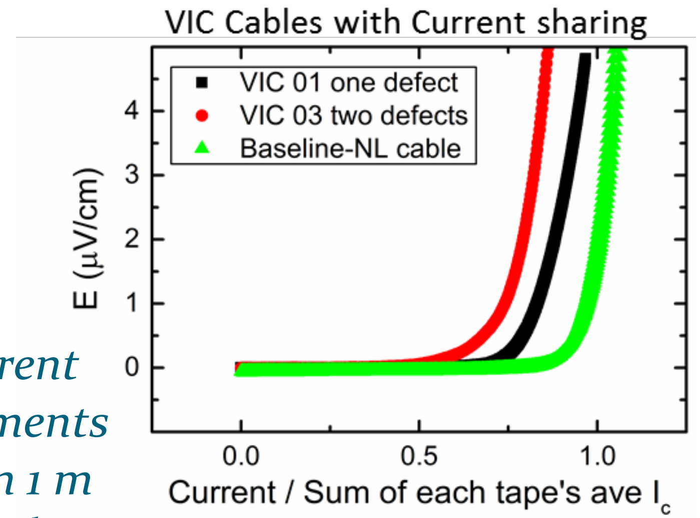
Design	Rc (μΩ-cm²)	L100%
Standard	800	2.1 m
High tension	1500	2.8 m
No lubricant	150	0.9 m
HC lubricant	70	0.3 m
(Soldered)*	0.1	< 1 cm

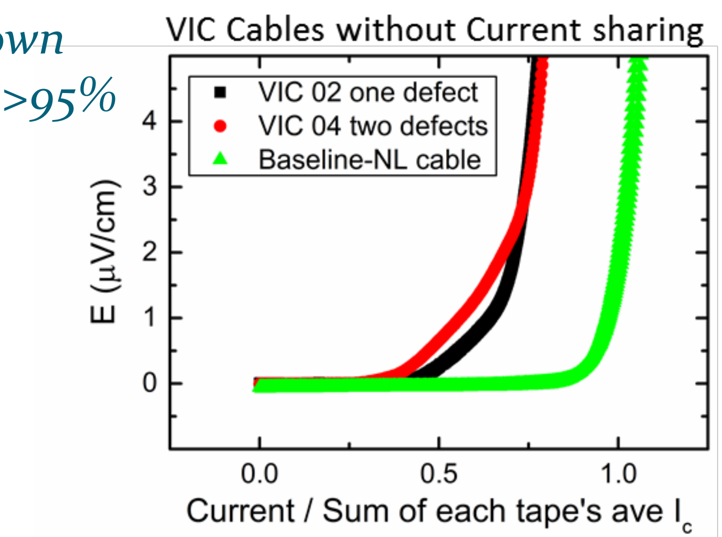
* Literature data for soldered 2G-HTS
L100% is the length (m) required to transfer 100% of current at 1 μV/cm and full-Ic capacity of 70 A.



Isolated conductor measurements at FSU

High-current measurements at ACT on 1 m cables made with known flaws at >95% Ic loss





Results and Accomplishments

- Over 2 km of conductor delivered by SuperPower
- Over 16 m of full-Ic cable and 8 m of variable-Ic cable produced by ACT, with up to 30 conductors
- Current sharing has been confirmed in multiple high-current and isolated-strand measurements
- Current transfer lengths are known for present manufacturing options

- Higher dissipation levels need to be explored to understand what is tolerable in an electric machine. So far the project has kept electric fields to conservative levels to protect cables from burnout.
- Longer cables and lower contact resistance ranges need to be probed.
- The most severe variable-Ic conditions have been explored without burnout. Broader variable-Ic conditions are now ready to explore.

- Next award budget period is under negotiation

Transition beyond DOE assistance

- Magnets have historically been the primary application pull for development of superconductors
  - Other agencies (e.g. DOE-HEP, Fusion) are actively using CORC® technology
  - Field coils in electric machines have not been extensively explored at 1 MW scale
    - Wind turbines: 3 MW and up, Ship propulsion: 36 MW
- TRL 5-6 expected by project end
  - Cold test of two 100 m CORC® cables (one with full-Ic conductor and one with variable-Ic conductor) in a field coil configuration