Advanced Conductor Technologies LLC
www.advancedconductor.com

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

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FAMU-FSU College of Engineering, Tallahassee, Florida

The team:

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Mr. Drew Hazelton	–	SuperPower Inc.

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

Overview

Timeline

- Part of the NGEM program
- Awarded in June 2017
- Projected end date May 30, 2020
- Project 30% complete (BP1 ends on August 30, 2018)

Partners

(Approximately equal funding)

- Florida State University (Prime)
  - Conductor and cable characterization
- Advanced Conductor Technologies, LLC. (Sub)
  - Cable manufacturer
- SuperPower Inc. (Sub)
  - Conductor manufacturer

Scope

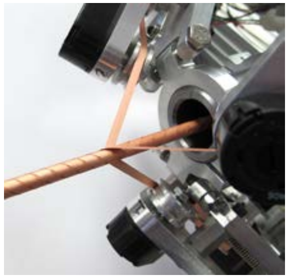
- Understand how conductor on round core "CORC®" cables enable sharing of current to permit bypass of 2GHTS conductor defects to increase reliability of superconducting motor windings
- Design optimized CORC® cables to utilize much more "unsorted" conductor to reduce cost

Budget

	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	–	$378,000	$622,000
Project Cost Share	–	$110,000	$220,000

Project Objectives

- **Increase the reliability** of HTS-based motors and other devices by **building in intrinsic protection** for field coils
  - Currently, coils are wound using single strand conductor. Insulated single strand conductors cannot share current around defects in conductors, often leading to local burning and coil failure. Active protection of field coils is not available in rotating machine technology.
  - **Conductor on Round Core (CORC®) cables** could replace single strand conductors to mitigate risk of coil failure.



- **Reduce high cost** of Second Generation High Temperature Superconductors (2G HTS) for commercial applications by **mitigating factors that reduce manufacturing yield**
  - The intrinsic current-sharing mechanism of CORC® cables should permit increased utilization of run-of-the-mill conductor from the manufacturer.
  - Otherwise, long spans of defect-free conductors would be required to address reliability concerns above, with few splices allowed
- **Demonstrate** an **optimized CORC® cable** with run-of-the-mill conductor having operational properties suitable for motors

Challenges for single-conductor electric machines

- Manufactured 2G HTS conductor is run through quality controls at 77 K, zero field to identify and isolate sellable sections.
  - Often, this involves cutting out regions with low critical current
- Present yield is low for the long (~500 m) piece lengths needed for coils. **Price of long pieces is high** to compensate.
  - Present methods of coil construction therefore use several splices between short pieces; **each splice adds risk and cost**
- Quality controls miss some defects that manifest in operating conditions with high magnetic field, such as 65 K, 1.5 T
  - In particular, **variation of the engineered flux-pinning centers** results in regions with local variation of the field dependence of critical current
- Recent test coils reveal dire consequences of defects when used in single-conductor coils
  - **Defects can trigger quench**, sometimes leading to **coil burnout**
  - **Lack of quench tolerance** is a primary **detriment to reliability** of superconducting motors and other coil-based HTS applications

Fundamental Knowledge to be Gained

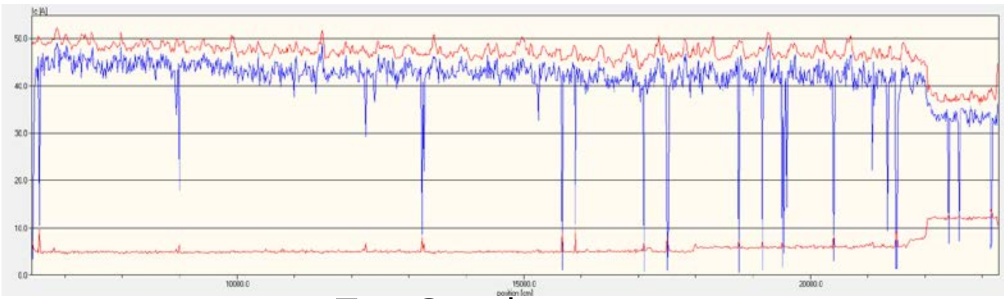
- Understand the implications and opportunities for using **bundled conductor cables** to make HTS motor coils
  - Bundled conductors and cables provide **alternative current pathways around quench zones**, which limits temperature rise even without external protections
    - How do parameters such as contact resistance, contact area, number of layers and contacts, contact pressure (from winding tension and other sources), field and temperature affect the flow of current?
    - How do different cable designs affect current flow?
  - **Quench-tolerance** becomes an **intrinsic property of the conductor**; coil reliability increases
- Understanding of the possibilities to increase manufacturing yield and reduce cost of HTS conductor
  - Does building in of quench tolerance remove reliance on cut-outs and splices and **permit use of run-of-the-mill conductor**?

Technical Innovation

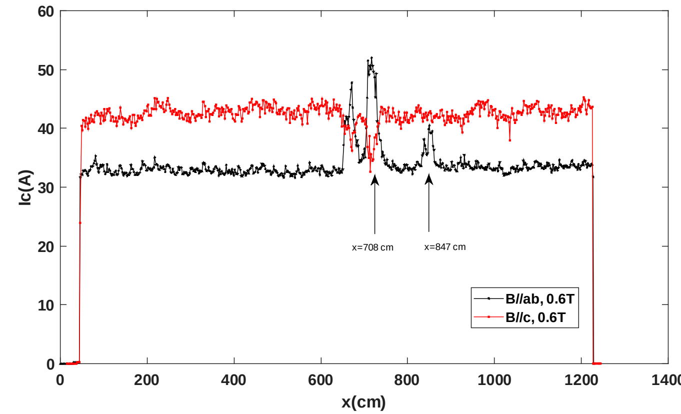
- We characterize the manufactured conductors using a specialized tool "YateStar" to **map the density and distribution of defects in field**
  - We presently use 77 K, 0.6 T where critical current is lower to mitigate conductor burnout risks
  - Reliable scaling to 65 K, 1.5 T was determined
- YateStar is also able to re-assess conductors after tests, even when such tests result in burnout or creation of new defects
  - Direct feedback to cable design from test results
  - Re-use conductor to change conditions for known defects
- We fabricate and test CORC® cables with the thoroughly characterized conductor to **compare the performance of cables** made with the best conductor to that of cables made from run-of-the-mill conductor
- We also **isolate certain defects for focused study** of their behavior
- Observations will lead to optimization of cable design

Technical Innovation

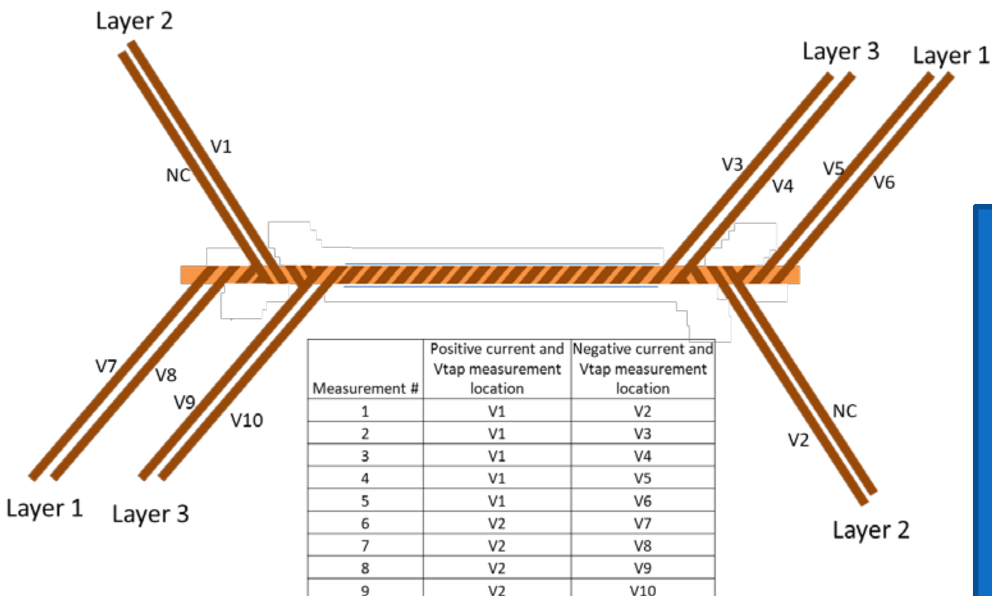
Characterizations identified defects in manufactured 2G HTS conductor cause sharp I_c dropouts



TapeStar data



YateStar data



Measurement #	Positive current and Vtap measurement location	Negative current and Vtap measurement location
1	V1	V2
2	V1	V3
3	V1	V4
4	V1	V5
5	V1	V6
6	V2	V7
7	V2	V8
8	V2	V9
9	V2	V10

Cable layout to understand and engineer current sharing

Several model cables were fabricated and multiple cable design parameters are being studied to identify useful parameters that will enhance current sharing (winding parameters, conductive lubricants)

Technical Approach

- Collaborative approach
  - SuperPower - HTS conductor manufacturer
  - Advanced Conductor Technologies - CORC® cable manufacturer
  - Florida State University – Advanced HTS characterization, coil and cable characterization capabilities at variable temperatures and magnetic fields

1. SuperPower provides HTS conductor batches in long lengths and shares information on defects in manufactured conductor
2. Florida State University characterizes the conductor using "YateStar" to map the density and distribution of defects at 77 K, 0.6 T in two orthogonal field orientations to reveal variations in flux pinning (variations are a type of defect)
3. Advanced Conductor Technologies fabricates CORC® cables with varying cable designs and winding parameters
4. Florida State University tests the cables and ultimately test coils with CORC® cables at 65 K

- Iterations of the process will yield knowledge about:
  - Correlations between defects and performance
  - Relative performance of cables with run-of-the-mill vs those with best conductor
  - Optimum design and winding parameters for motor applications

Results and Accomplishments

- The advanced characterization tool “YateStar” was redesigned to accommodate up to 500 m conductor batches
- The design modifications included safe handling of thin, 2 mm wide conductor
- 2 km of HTS conductor from many different batches has been procured
- Several CORC® cables fabricated to study winding parameters that would help in engineer current sharing
- Measurements on cables are in progress
- All BP1 milestones will be completed by August 30, 2018 (a no-cost extension till August 30 was granted)

Measure of Success

- Successful demonstration of CORC® cables fabricated with "unsorted" conductor will lower the cost and increase **reliability of HTS machines**
- This project will be a success if we demonstrate the **current sharing in CORC® cables** that will enhance the reliability of HTS motors and other coil based applications
- Success will be measured by the **reduction in cost of HTS** conductors obtained through higher yield
- HTS adoption in industrial motors will significantly increase the **energy efficiency of industrial motors** – Positive economic and environmental impact

Project Management & Budget

- Duration of the Project: 3 years
- BP1 will end on August 30, 2018
- Requested to have BP2 start on September 1, 2018

Total Project Budget (for 3 years)	
DOE Investment	$1,000,000
Cost Share	$250,000
Project Total	$1,250,000

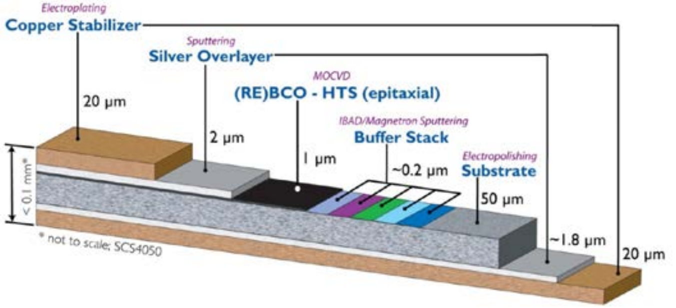
Transition and Deployment
(outside the scope of the DOE funded effort)

- Original Equipment Manufacturers are waiting for inexpensive HTS conductor and reliable motor designs
- Success in this project will pave the way to **low cost** HTS cables suitable for **reliable** industrial motor applications
- Successful demonstration of CORC® cables for motor applications will lead to commercial transition of the technology
  - The HTS conductor and cable manufacturers have strong partnership
  - Both companies have strong collaborations and joint projects with the University partner other than the NGEM program
  - CORC® cable technology is rapidly developing with the support from DOE High Energy Physics, DOE Fusion Sciences, and US Navy

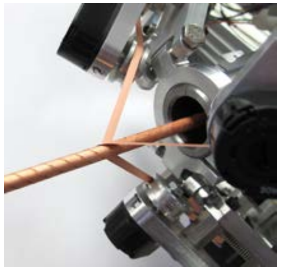
Technical Strengths of Project Partners

- Florida State has generated the highest field (45.5 T, 14.5 T REBCO in 31 T resistive) test magnets and is presently commissioning the first >30 T all superconducting magnet (15 T LTS + 17 T REBCO)

- SuperPower provided the coated conductor for both the magnets above



- ACT has contracts for coated conductor cable from 5 customers and has provided the only macroscopically isotropic REBCO conductor made to date, with the highest current density of any HTS cable (344 A/mm² at 4.2 K and 20 T)



Questions?