Ultra-Conducting Copper (UCC) (Keystone Project #2)

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Oak Ridge National Laboratory

2018 U.S. DOE Vehicle Technologies Office
Annual Merit Review

June 11, 2019 Project ID: ELT220

Overview

Timeline

- Start – FY19
- End – FY21
- 25% complete

Barriers

- Meeting DOE ELT 2025 power density & cost targets
- Increasing both the electrical & thermal conductivity of windings to increase efficiency of electric motors (EMs)

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY19: $150K

Partners

- Southwire, Magnekon, & Chasm
- ORNL team members: Tolga Aytug, Burak Ozpineci, Mina Yoon, Michael McGuire, Andrew Lupini, Tsarafidy Raminosoa, Chengyun Hua, Lydia Skolrood, and Kai Li

Any proposed future work is subject to change based on funding levels

Project Objective and Relevance

- **Overall Objective:**
  - Develop a new class of high performance copper (Cu) wires using carbon nanotubes (CNT) that are higher in electrical & thermal conductivity to increase the power density of electric motors while improving the overall efficiency

- **FY19 Objectives:**
  - Optimize processing protocols & identify the two most promising scalable approaches for the prototyping of carbon nanomaterial enabled UCC conductors
  - Integrate additional Cu/CNT stack(s) on the first Cu/CNT/Cu architecture & investigate their influence on the electrical performance
  - Utilize theoretical modelling to understand metal-nanocarbon interface properties for optimized electronic/thermal transport characteristics
  - Understand the impact of UCC winding conductivity on traction motors performance

Milestones

Date	Milestones and Go/No-Go Decision	Status
Dec. 2018	Milestone: Optimize processing protocols & produce prototype multilayer Cu/CNT/Cu composites	✔
April 2019	Milestone: Down-select at least one promising processing approach that provides reproducible CNT alignment & performance	✔
June 2019	Milestone: Establish roll-to-roll deposition capability of CNTs on Cu tapes using sonospray technique	**On track**
Sept. 2019	Go/No-Go decision: Integrate additional Cu/CNT stack(s) on the first Cu/CNT/Cu architecture and determine if these multilayer prototype UCC composites demonstrate improved electrical conductivity	**On track**

Approach/Strategy

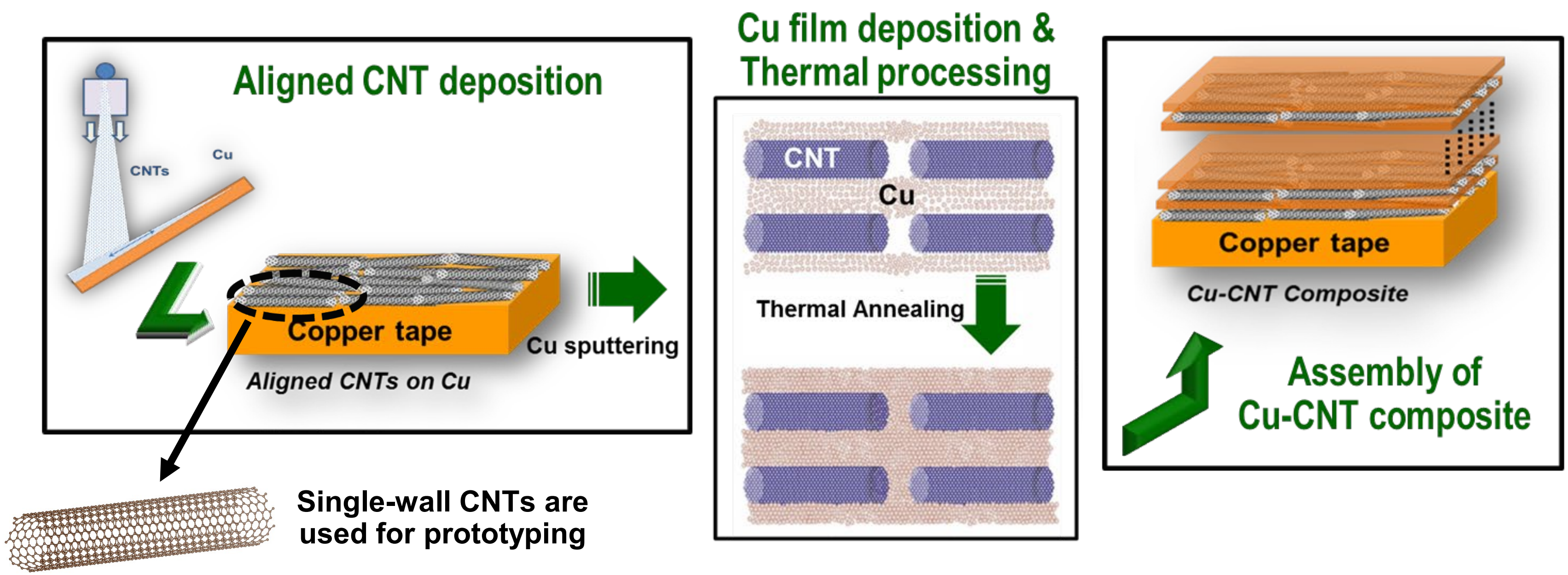
Design an advanced composite material consisting of carbon nanotubes embedded in Cu matrix – Ultra Conductive Copper (UCC)

A better conductor with reduced electrical loss enables:

- Volume/weight reductions ➡ improved power density and specific power
- Higher efficiency (i.e., lower conduction losses)

Process-flow for ORNL-UCCs:

1) CNT deposition; 2) Cu-film deposition/annealing; 3) Cu-CNT multilayer assembly



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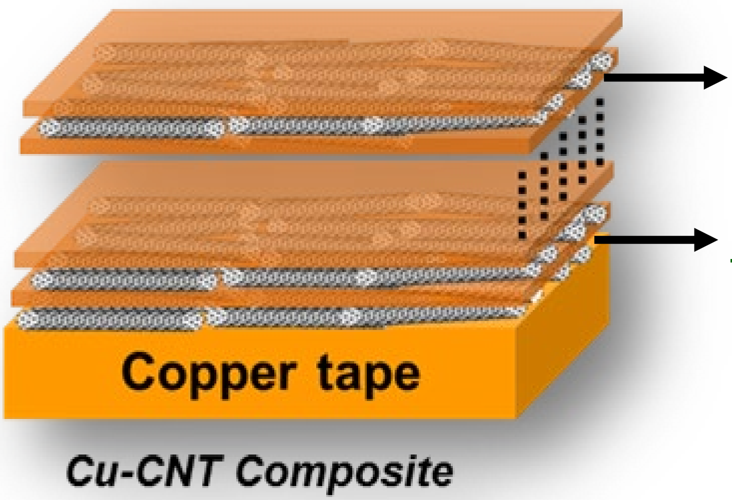
Approach/Strategy

CNTs provide extraordinary electrical, thermal, & mechanical properties compared to Cu

- ×1.7 higher electrical conductivity (along the tube axis)
- ×10 higher thermal conductivity (along the tube axis)
- ×100 current density

	Cu	CNT
Electrical Conductivity	59.6 MS/m	100 MS/m
Thermal Conductivity	400 W/m-K	4000 W/m-K
Current Density	10^6 A/cm^2	10^8 A/cm^2

ORNL UCC Multilayer Architecture



Process challenges:

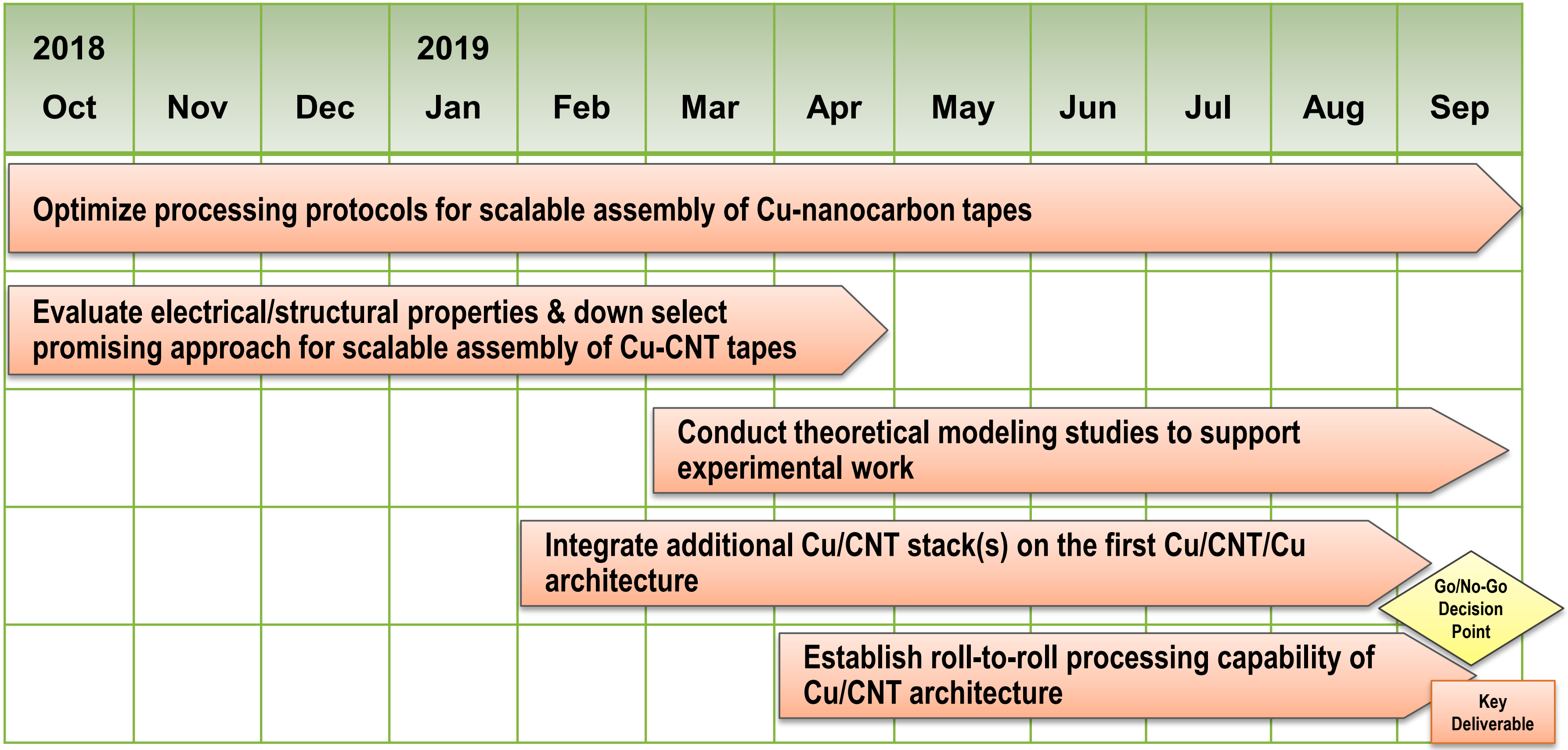
Cu-film (orange layers):

Any voids/porosity from the Cu/CNT matrix needs to be eliminated

CNT-layer:

- CNTs need to be aligned along the tape length (i.e, direction of current)
- Organic processing chemicals (solvent & surfactants) used during processing must be removed from the CNT matrix

Approach FY19 Timeline

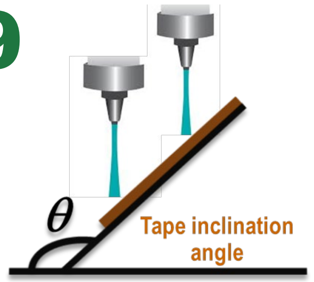


Go/No-Go Decision Point: Integrate additional Cu/CNT stack(s) on the first Cu/CNT/Cu architecture and determine if these multilayer prototype UCC composites demonstrate improved electrical conductivity

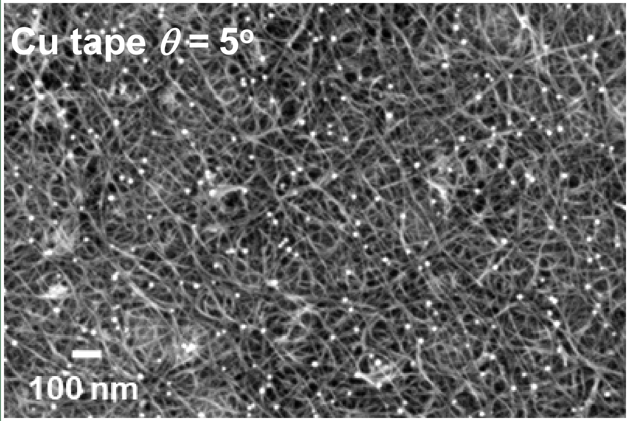
Key Deliverable: Sufficient number of Cu-CNT single-/multi- layer specimens for performance evaluation

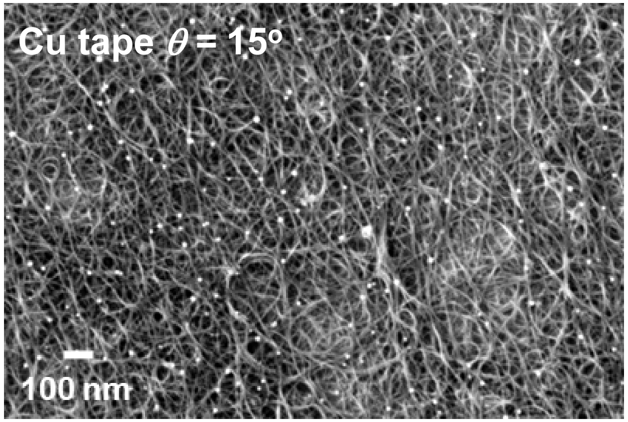
Any proposed future work is subject to change based on funding levels

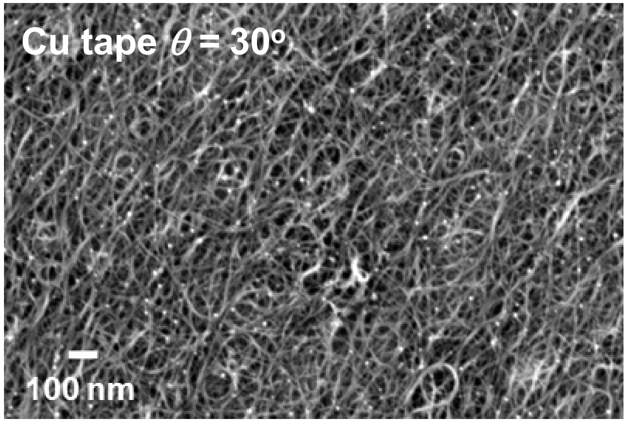
Technical Accomplishments – FY19

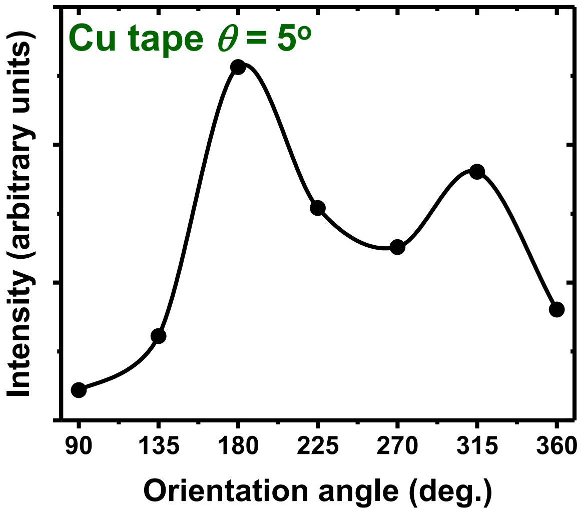


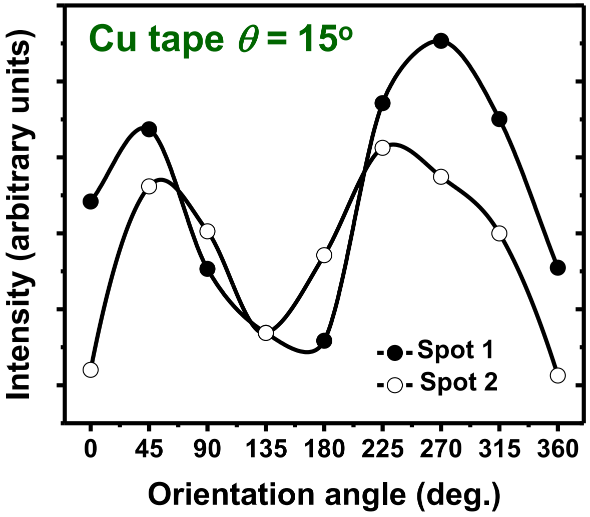
Optimize process: Using SEM & polarized Raman spectroscopy confirmed that shear induced alignment of CNTs can occur at all experimentally accessible Cu tape inclination angles during sonospray

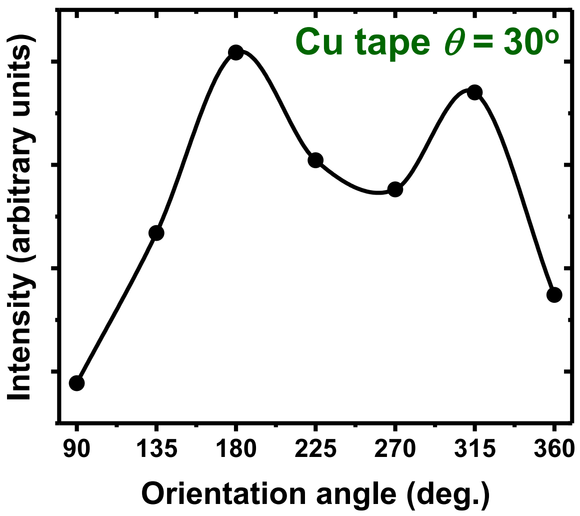






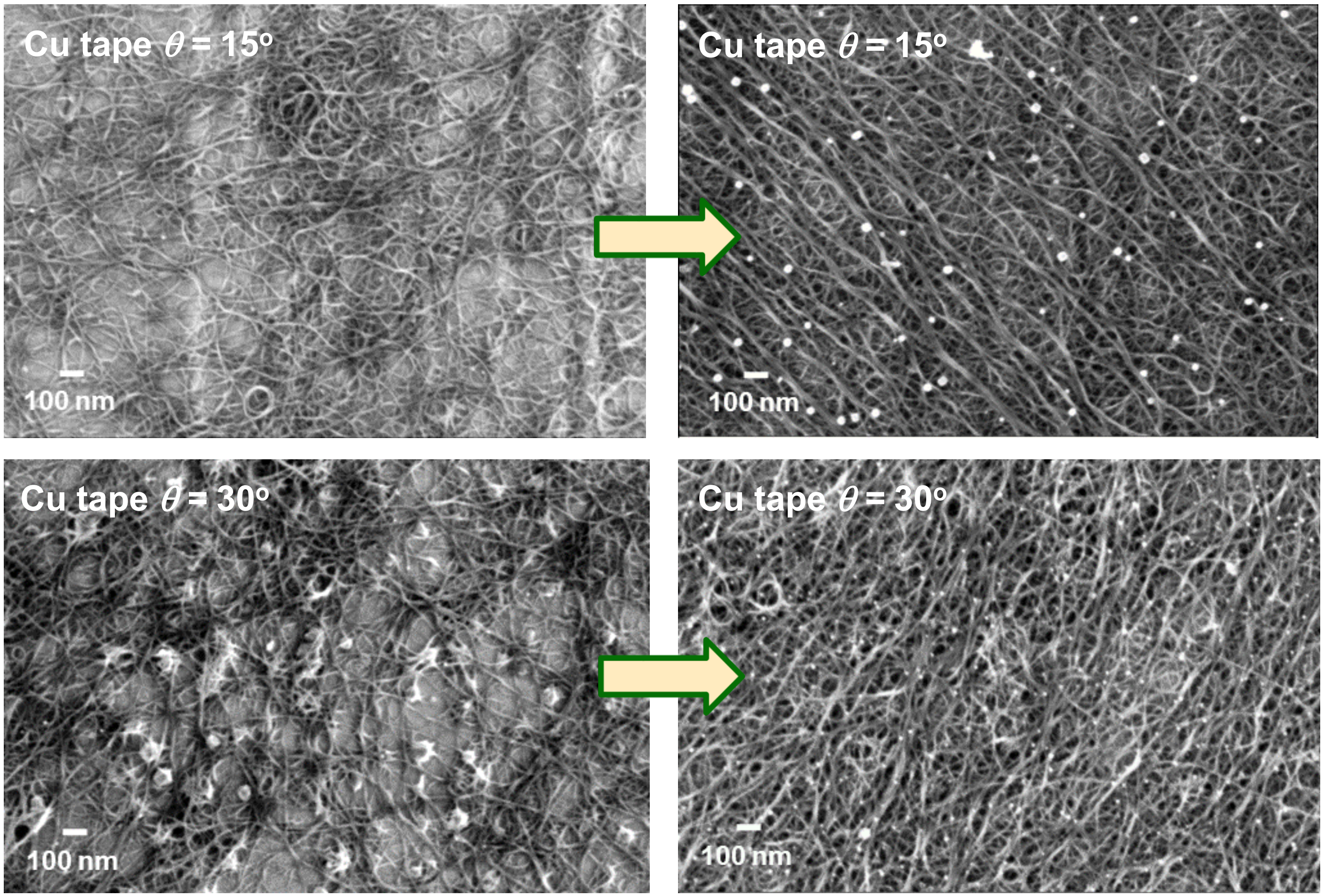






Technical Accomplishments – FY19

Optimize process: Established that preferential shear induced alignment along the tape length initiates with increase in CNT amount



Higher amount of CNT loading on the Cu surface increases shear for alignment parallel to flow-field direction

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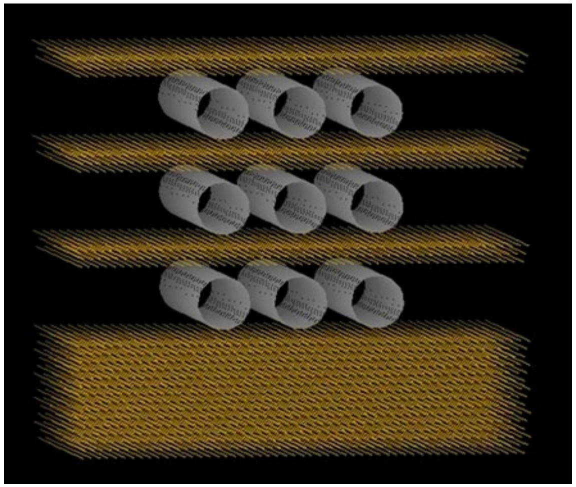
Technical Accomplishments – FY19

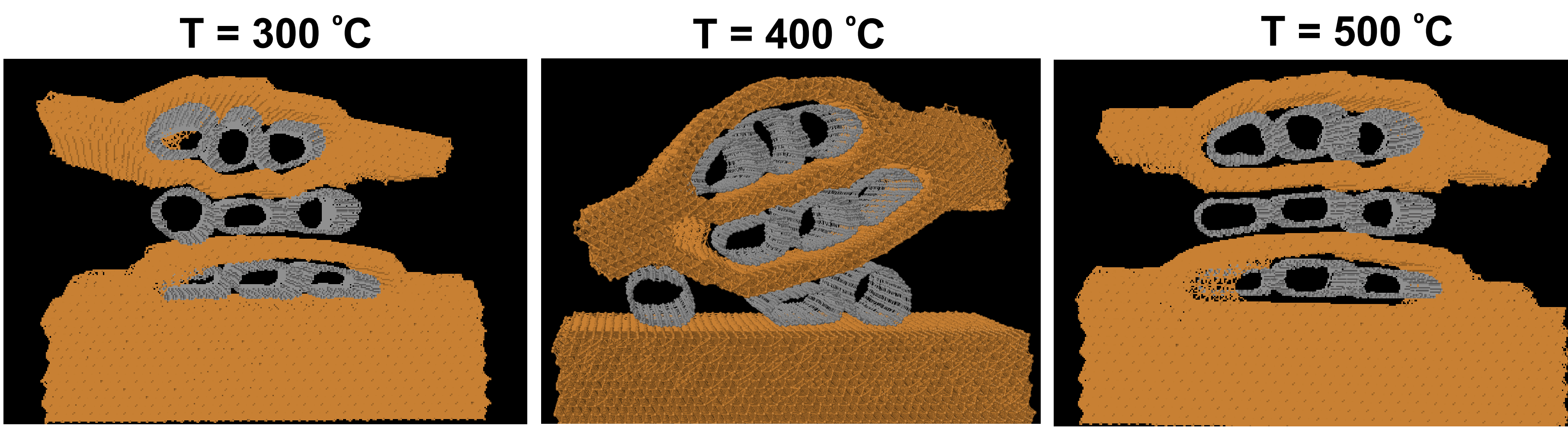
Used theoretical modeling & simulations to optimize materials & process parameters for multilayered UCC assembly

3 Cu/CNT/Cu layer composite



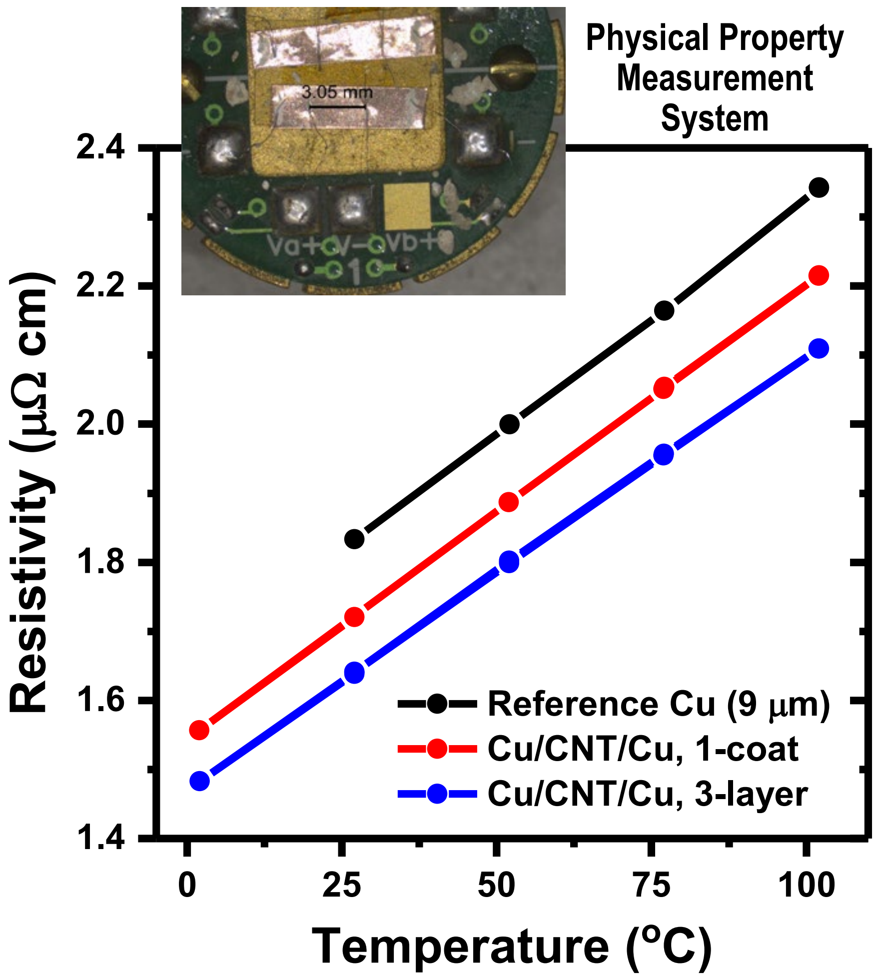
Classical molecular dynamics simulations based on empirical potentials performed to identify the optimum temperature to homogeneously coat CNTs with Cu layers; determined by the competition between diffusion of CNTs on Cu substrate & melting of Cu layers

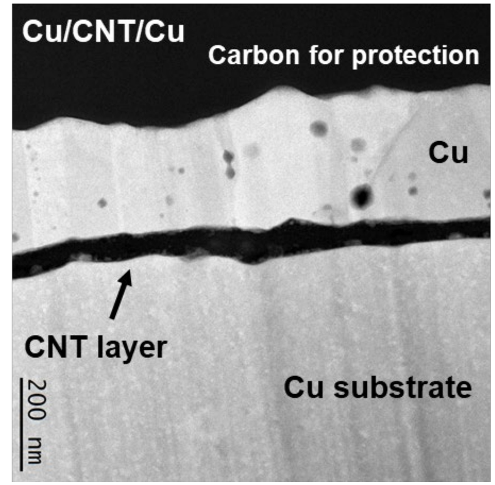
- Identified the range of critical temperature (400 °C) where the formation of homogeneously covered Cu/CNT assembly is favorable
- Simulations showed similar behavior for the 2-layer Cu/CNT/Cu composites

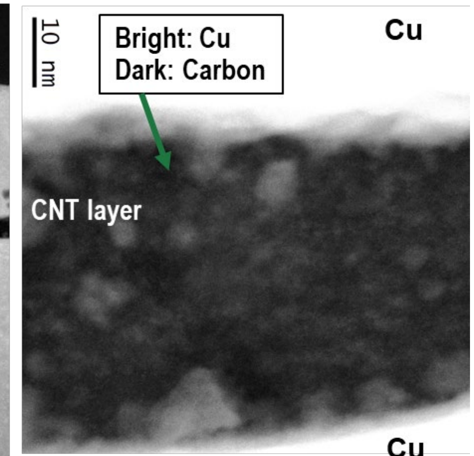


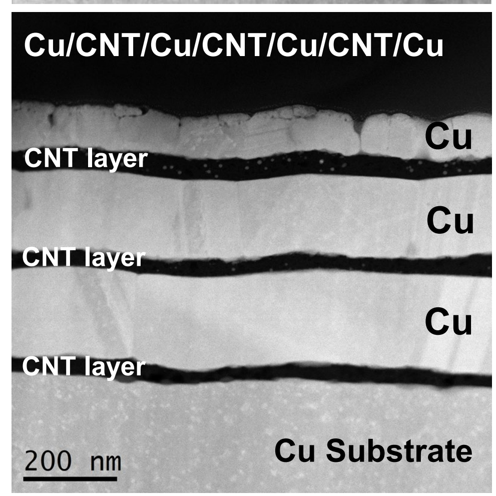
Technical Accomplishments – FY19

Integrated additional Cu/CNT stack(s) on the first Cu/CNT/Cu architecture & demonstrated improved conductivity over reference pure Cu for prototype multilayered UCC composites (sonospray samples)









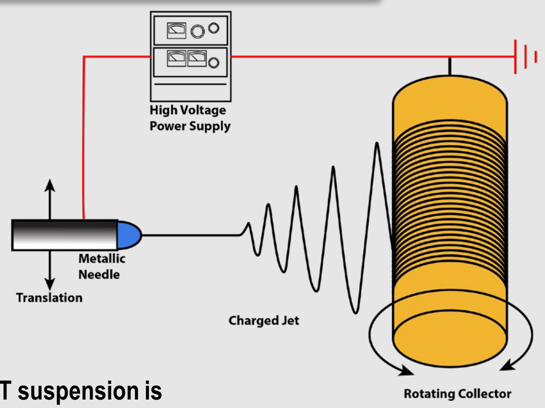
- Evidence of Cu inside the CNT layers
- Relatively homogeneous & dense Cu films on CNT layers
- Any current rendering defects (e.g., voids & pores) throughout the Cu/CNT matrix needs to be eliminated

Decreased resistivity > 10% for multilayer Cu/CNT/Cu (3-stacks) prototype, (T = 0 – 100°C)

Technical Accomplishments – FY19

Explored the viability of two new processing techniques & CNT dispersion formulations for deposition on Cu tapes: 1 – Electrospinning

Electrospin/Electrospray



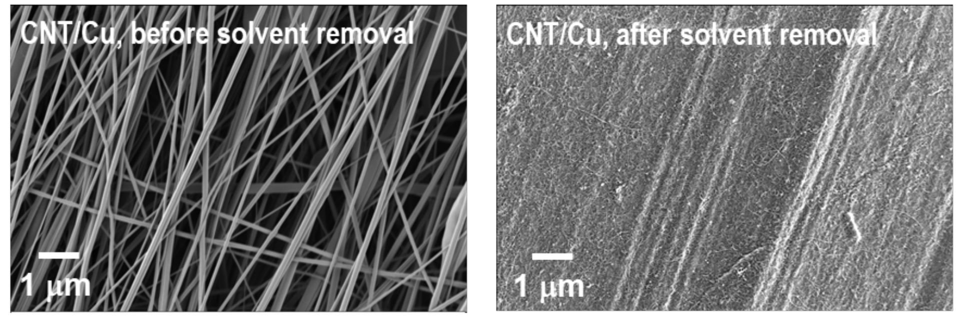
CNT suspension is extruded from the needle tip at a constant rate under high voltage

High voltage applied between the syringe & collector induce droplet elongation along deposition direction

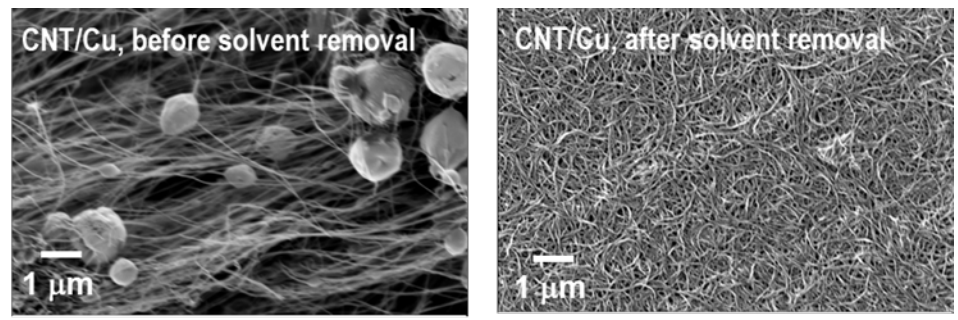
CNT/Cu

DMF + PVP solution:

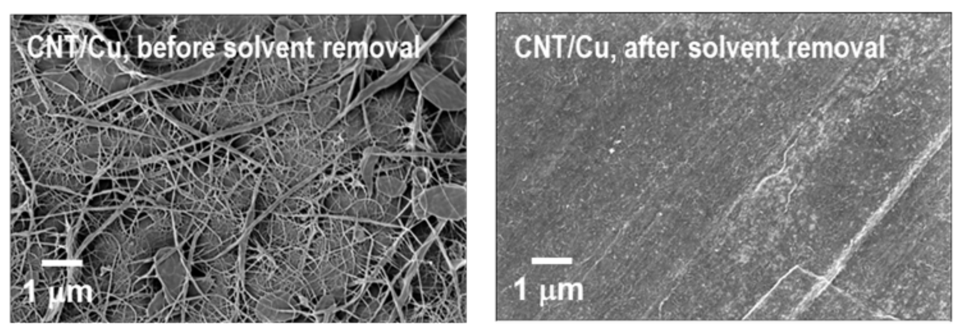
Aligned CNT fibers & uniform CNT coverage on Cu substrate



Solvent: Dimethylformamide (DMF) + polyvinyl pyrrolidone (PVP) ✓



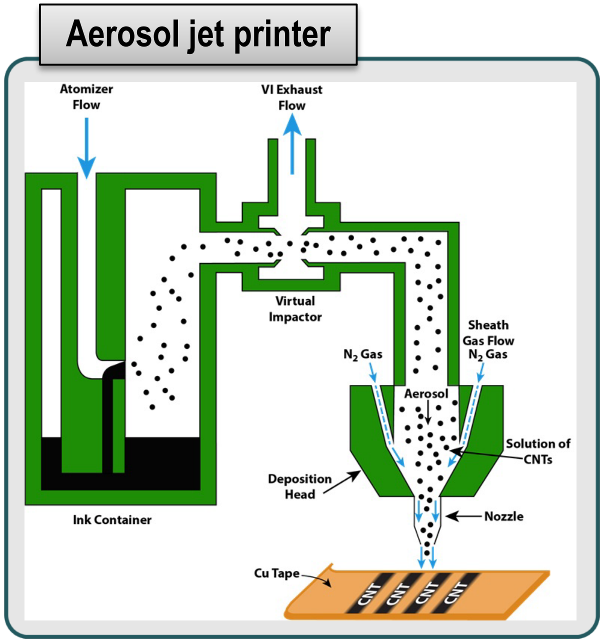
Solvent: PVP + ethanol + water ✗



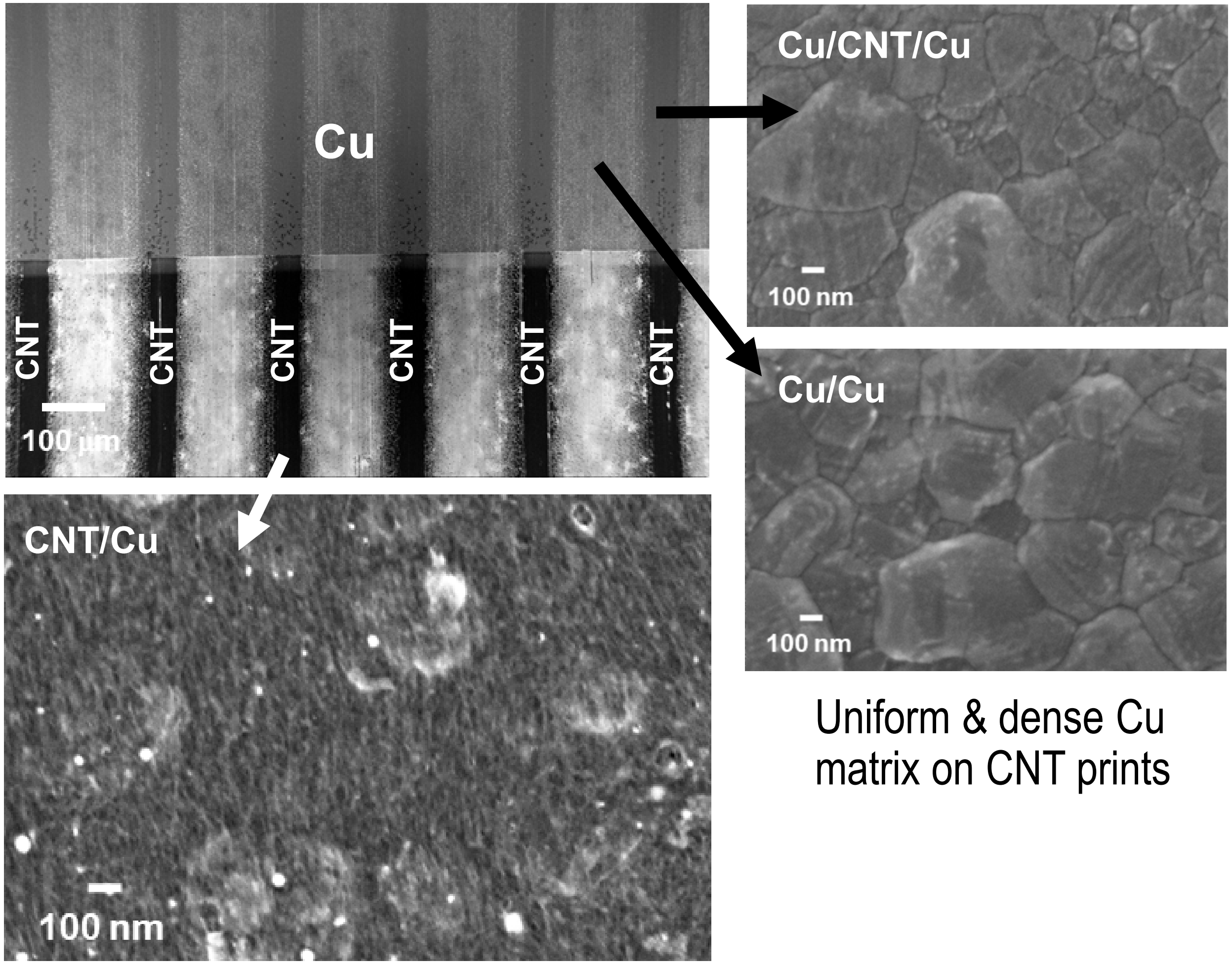
Solvent: DMF ✗

Technical Accomplishments – FY19

Explored the viability of two new processing techniques & CNT formulations for deposition on Cu tapes: 2 – Aerosol Jet Printing



Demonstrated preferential CNT alignment along the tape length with aerosol jet printer



Uniform & dense Cu matrix on CNT prints

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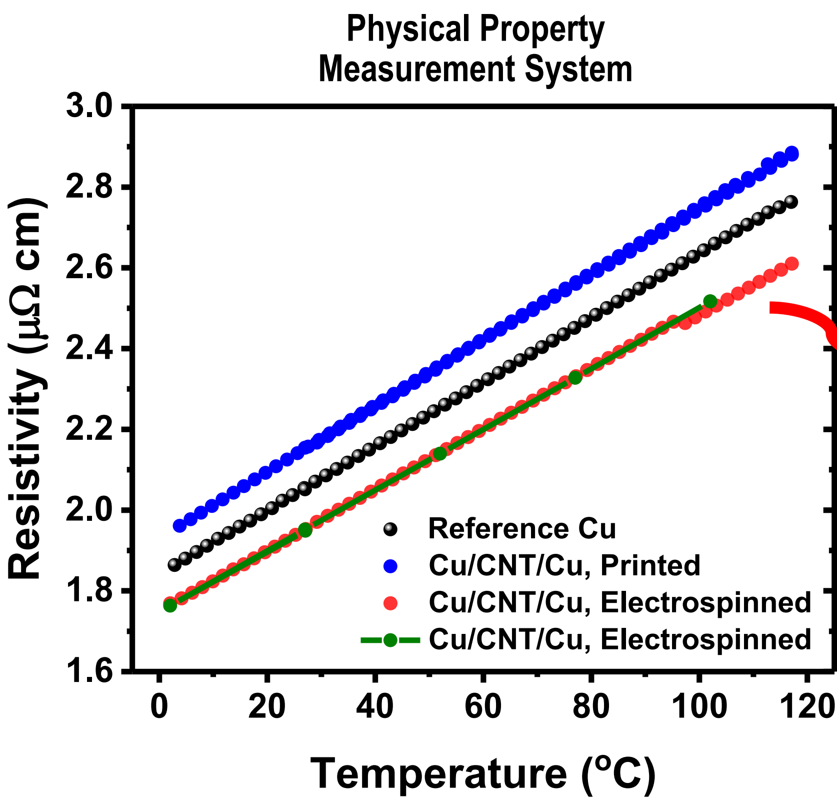
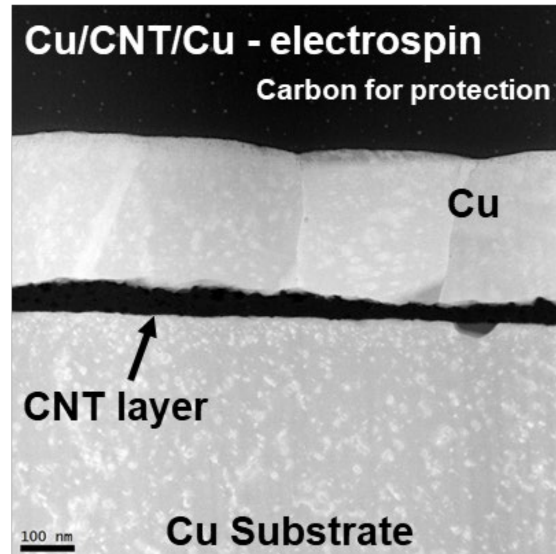
Technical Accomplishments – FY19

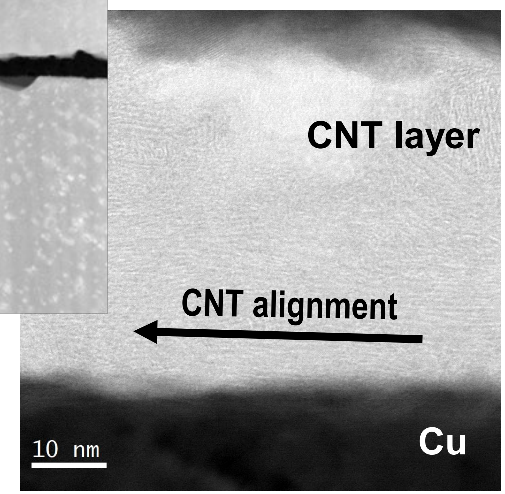
Demonstrated improved conductivity for electrospinned single CNT layer UCC prototypes over reference Cu, however conductivity is lower for printed samples



High-angle annular dark field image



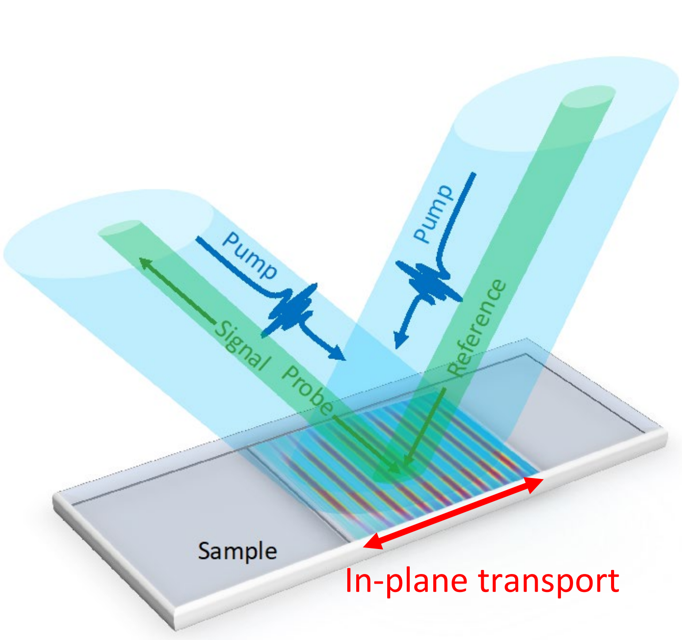
Bright field image

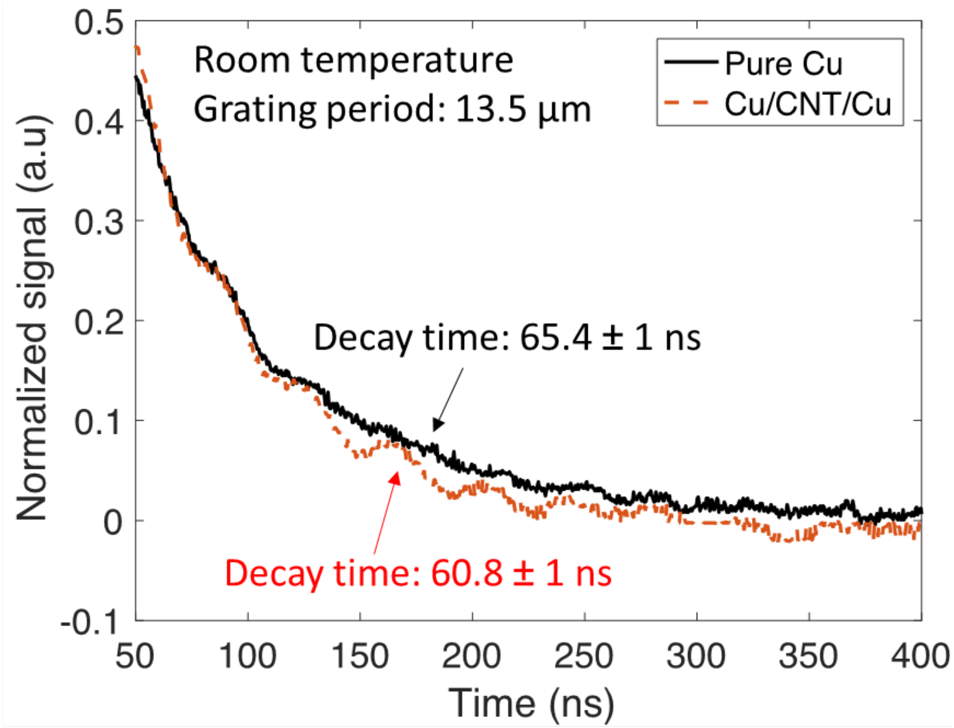


- **Decreased resistivity ~5 % for electrospinned Cu/CNT/Cu prototype samples has been realized**
- Higher resistivity for printed samples ➡ organic solvent & surfactant are not effectively removed
- Graphitic structure visible in the bright field image
  - ↪ supports alignment of CNTs parallel to the Cu surface
- Uniform & dense Cu matrix on electrospinned CNT layer

Technical Accomplishments – FY19

Established Transient Thermal Grating technique (TTG) & analyzed influence of CNT interface on the in-plane thermal transport properties





- TTG is a pump-probe technique that monitors the cooling of the material to a grating heating pattern on the surface of the sample. The change in optical properties is linearly related to the temperature changes of the surface
- Decrease in thermal decay time compared Cu reference indicates higher thermal conductivity in Cu/CNT/Cu
- Persisted oscillations in Cu/CNT/Cu sample suggests potential ballistic phonon transport in CNTs

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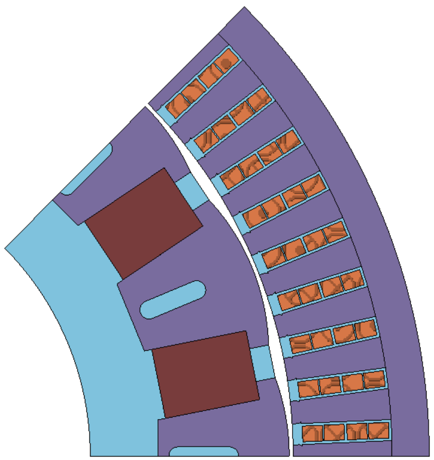
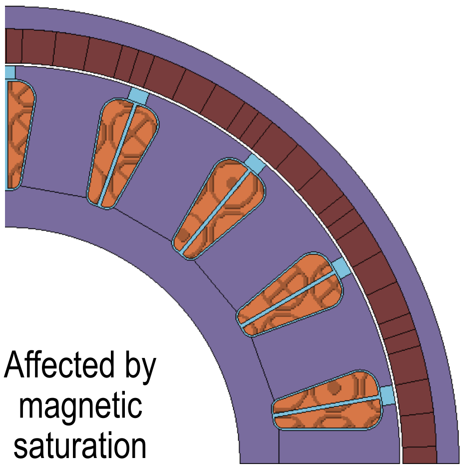
Technical Accomplishments – FY19

Analyzed impact of UCC winding conductivity on various traction motor topologies

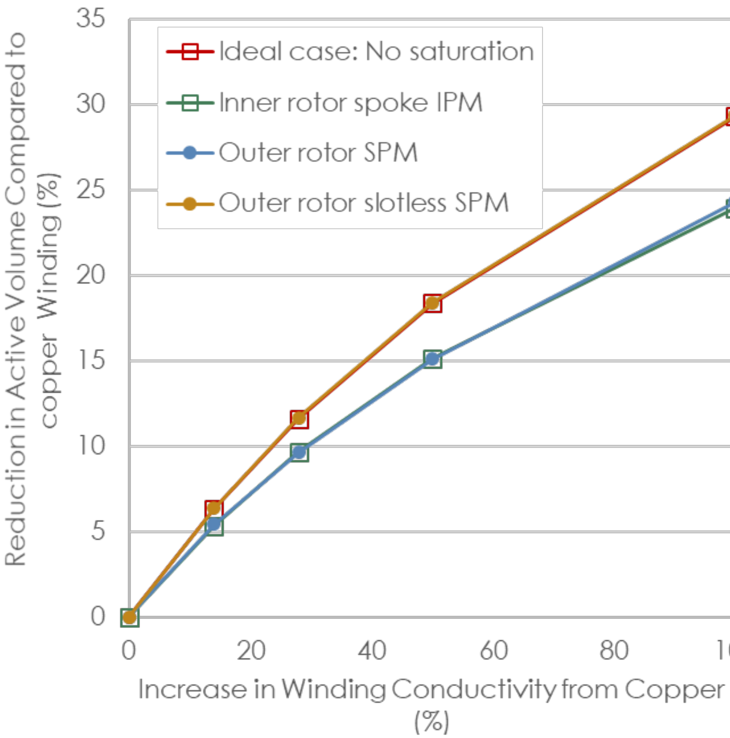
Inner-Rotor Spoke Internal PM motor



Outer-Rotor Surface PM motor



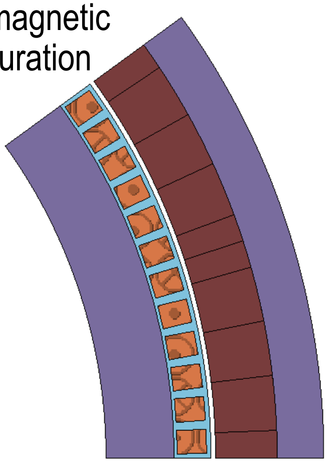
Affected by magnetic saturation



Calculations assumed:

- Three topologies of heavy rare-earth-free permanent magnet (PM) motors
- Same outer diameter of 242 mm & 100 kW peak power
- The conductivity of the winding is varied up to 2X of the Cu & the heat load in the slots are kept constant

No magnetic saturation



Outer-Rotor Slotless Surface PM motor

With 30% increase in conductivity:

- 10% reduction in volume for conventional motors
- 12% reduction for motors not affected by magnetic saturation (slotless)

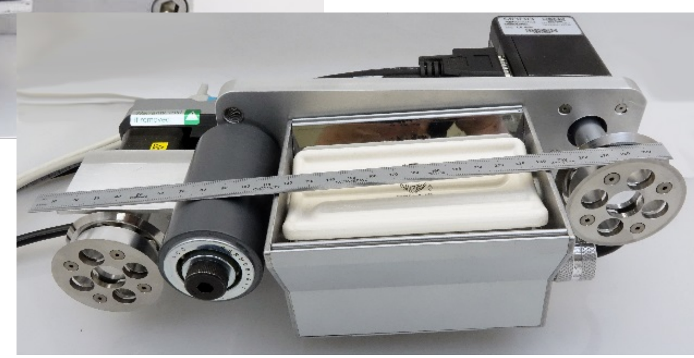
Please see:
Project ID: elt212
Non-Heavy Rare-Earth High-Speed Motor
T. Raminosoa, ORNL, June 11

Technical Accomplishments – FY19

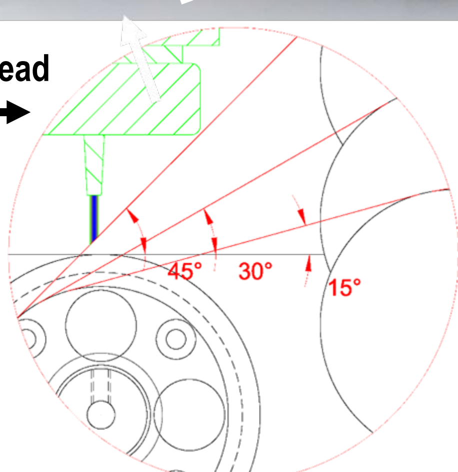
Designed & assembled a compact tape handler system for roll-to-roll multi-coat CNT deposition on 0.50" wide & up to 25' long Cu tape using sonospray

Long-length prototyping will begin in May

Top view



Spray head



- To facilitate CNT alignment, the spray angle can be varied by adjusting the idler spool
- The radiant heater continuously cures the CNT coating & enables multi-coat deposition
- The tape speed can be varied from 0.5 mm/sec to 100 mm/sec

Collaboration and Coordination with Other Institutions

Initiated discussions with Southwire, Magnekon, Magna International

CHASM™

Chasm Advanced Materials, Inc: Supplier of CNTs

Southwire®

Southwire: Discussions on performance evaluations & technology integration

magnekon®
A Viakable Brand

Magnekon: Discussions on performance evaluations & technology integration

Remaining Challenges and Barriers for FY19

- Achieving similar performance characteristics from double-wall & multi-wall CNTs compared to single-wall based Cu/CNT/Cu composites
- Effects of additional Cu/CNT layers on the electrical performance of the multilayered UCC prototypes
- Solution for large parameter space involved in producing UCC tapes
- Achieving similar performance on UCC prototypes using long-length deposition system

Proposed Future Work

Remainder of FY19:

- Continue process optimization efforts for the production of UCCs
- Continue integration & optimization of additional Cu/CNT stack(s) on the first Cu/CNT/Cu architecture.
- Analyze electrical & thermal impacts of additional Cu/CNT layers
- Produce prototypes using newly established long-length scalable CNT deposition capability

FY20:

- Continue processing, optimization, characterization efforts & fabricate prototypes
- Continue incorporating detailed theoretical modelling efforts to support/speed-up experimental work
- Perform comprehensive properties evaluation of samples produced by long-length CNT deposition system (alignment, morphology, electrical, thermal)

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:** Advanced materials with higher electrical conductivity are needed to increase power density & reduce cost while improving performance & reliability of electric motors
- **Approach:** Design an advanced conductor with reduced electrical loss by depositing CNTs on Cu tapes
- **Collaborations:** Chasm, Southwire, and Magnekon
- **Technical Accomplishments:**
  - Continued processing, optimization, characterization efforts & fabricate prototypes
  - Explored viability of two new scalable processing techniques for CNT deposition – electrospinning & aerosol jet printing
  - Conducted microstructural analyses to provide key insights into process optimization
  - Demonstrated that theoretical modeling can support experimental efforts
  - Analyzed influence of CNT interface on the in-plane thermal transport properties
  - Integrated additional Cu/CNT layers on the first Cu/CNT/Cu architecture, performed electrical characterizations, demonstrated improved conductivity over reference pure Cu
  - Analyzed the impact of UCC winding conductivity for various traction motor topologies
- **Future Work:** Continue processing, optimization, characterization efforts, & fabricate multilayered as well as long-length processed prototypes; incorporate detailed theoretical modelling efforts to support/speed-up experimental work; & analyze electrical & thermal impacts of additional Cu/CNT layers