Dual Phase Soft Magnetic Laminates for Low-cost, Non/Reduced-rare-earth Containing Electrical Machines

PR Subramanian – Principal Investigator
Min Zou – Project Leader, Presenter

GE Research

Annual Merit Review and Peer Evaluation
June 11, 2019

Project ID# elt090

Imagination at work.

Overview

Timeline

- Project start date:
  - October 2016
- Project end date:
  - September, 2019
- Percent complete: 83%

Budget

- Total project funding: $6,848,335
  - DOE: $4,999,285
  - Contractor: $1,849,050
- FY 2017 Funding: $2,557,127
- FY 2018 Funding: $2,226,115
- FY 2019 Funding: $2,065,093

Barriers

- Magnet cost and rare-earth element price volatility
- Non-rare-earth electric motor performance
- Material property optimization (soft magnetic materials)

Partners

- GE Global Research
  - Project Lead
  - Motor design & test
  - Materials & market development
- Oak Ridge National Laboratory
  - Fundamental metallurgy and processing
- Carpenter Technology Corporation
  - Alloy sheet production
- Applinetics Engineering
  - Prototype manufacturing

Relevance

Overall Objectives

- Advance dual phase soft magnetic material technology to Technology Readiness Level (TRL) 7
- Demonstrate the material in a 30 kW electric motor for electric vehicles capable of meeting EETT electric motor 2020 targets without using any permanent magnets

Objectives in the reviewed period (March 2018 – March 2019)

- Demonstrate manufacturability of the dual phase magnetic laminates by fabricating a subscale prototype
- Develop supply chain for dual phase magnetic laminates scaled-up production
- Demonstrate the tested performance matches calculated performance of the subscale prototype
- Complete full-scale prototype dual phase design and rotor fabrication

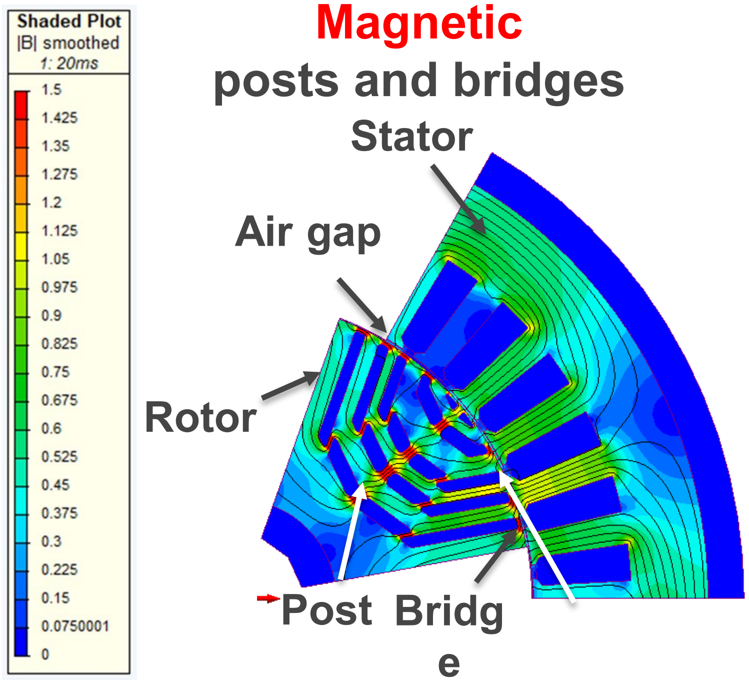
Impact & Relevance to VT Office

- Reduce the electric traction drive system cost by eliminating the use of permanent magnets in electric motors
- Enhance electric motor performance and efficiency
- Advance market penetration of electric vehicles into automotive market
- Mitigate reliance on critical materials, i.e. rare-earths

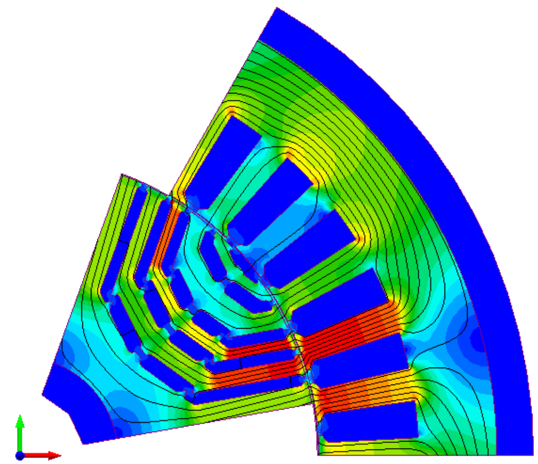
Approach: Strategy

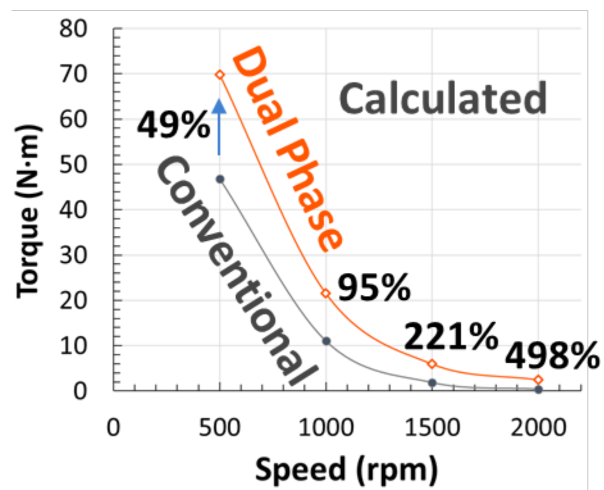
Locally control the magnetic and mechanical properties of motor laminates by material alloying and processing

Magnetic
posts and bridges



Non-magnetic
posts and bridges



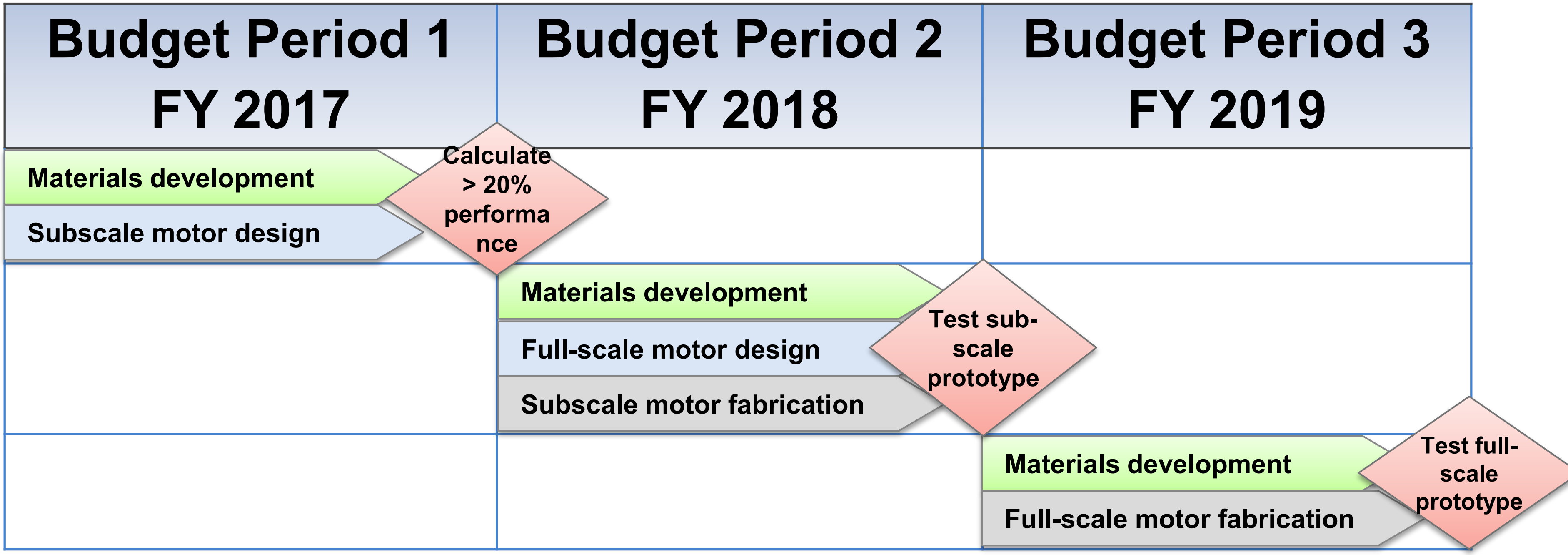


- Decrease magnetic flux leakage
- Enhance mechanical integrity
- Improve machine performance

Approach: Plan

- FY2017
  - Produce 1,000 lbs of custom dual phase alloy sheet
  - Measure material properties and calculate motor performance
- FY2018
  - Demonstrate manufacturability of dual phase laminates by fabricating a subscale prototype based on an off-the-shelf motor for quick turnaround
  - Demonstrate tested performance matches calculated performance. Target is not for performance optimization, which is limited by the configuration of the off-the-shelf motor, but for validating prediction.
- FY2019
  - Build 55 kW peak power, 30 kW continuous power dual phase SynRel prototype
  - Demonstrate dual phase SynRel motor constructed without permanent magnets can match or exceed performance of IPM motor

Approach: Milestones



Go/NoGo Decision Point

- Detailed subscale dual phase design shows 20% greater performance than conventional motor ✓
- Subscale prototype shows 3.7 kW ✓

Passed FY2017 & FY2018 Go/NoGo Decision Points

Approach: Milestones

Date	Budget Period 1 (FY2017)	Status
3/31/17	Produce 275 kg of 20.3 cm wide by 254 μm thick sheet	Complete
6/30/17	Report nitride kinetics study and residual stress analysis on 2.5 cm by 5.0 cm coupon	Complete
9/30/17	Complete initial market study	Complete
9/30/17	Detailed subscale dual phase design shows 20% greater performance than conventional rotor	Complete
Date	**Budget Period 2 (FY2018)**	**Status**
12/31/17	Nitride laminates for 13.9 cm dia. by 13.3 cm length subscale prototype	Complete
3/31/18	Stacked and bonded subscale rotor with 13.3 cm stack length	Complete
6/30/18	Report nitride kinetics study and residual stress analysis on 13.9 cm dia. subscale laminate	Complete
6/30/18	Complete subscale prototype testing up to 5,000 rpm and 100 A_{RMS}	Complete
9/30/18	Complete initial cost model	Complete
9/30/18	Subscale prototype shows 3.7 kW	Complete

FY2017 & FY2018 Deliverables Completed

Approach: Milestones

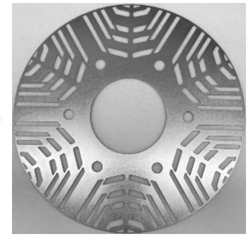
Date	Budget Period 3 (FY2019)	Status
12/31/18	Nitride laminates for 19.9 cm dia by 7.0 cm length full-scale prototype	Complete
3/31/19	Stack and bond 7.0 cm long rotor with 7.0 cm stack length	Complete
6/30/19	Report nitride kinetics study and residual stress analysis on 19.9 cm dia full-scale laminate	On track
6/30/19	Complete full-scale prototype fabrication	On track
9/30/19	Complete full-scale prototype testing up to 14,000 rpm and 400 A_{RMS}	On track
9/30/19	Produce market development plan	On track
9/30/19	Complete final cost model and marketing plan	On track

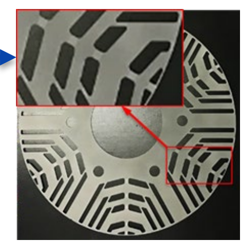
FY2019 Deliverables On Track

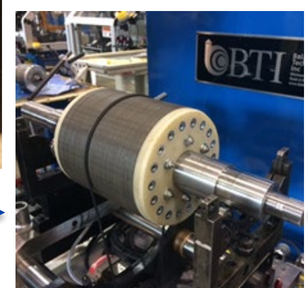
Technical Accomplishments & Progress

Demonstrated Dual Phase Laminates Manufacturability

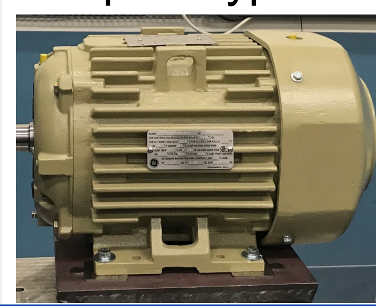
Cast and roll alloy sheet → Cut rotor laminates → Coat with ceramic mask → Nitrogenate laminates → Strip coating → Apply insulation → Stack and bond rotor → Assemble prototype







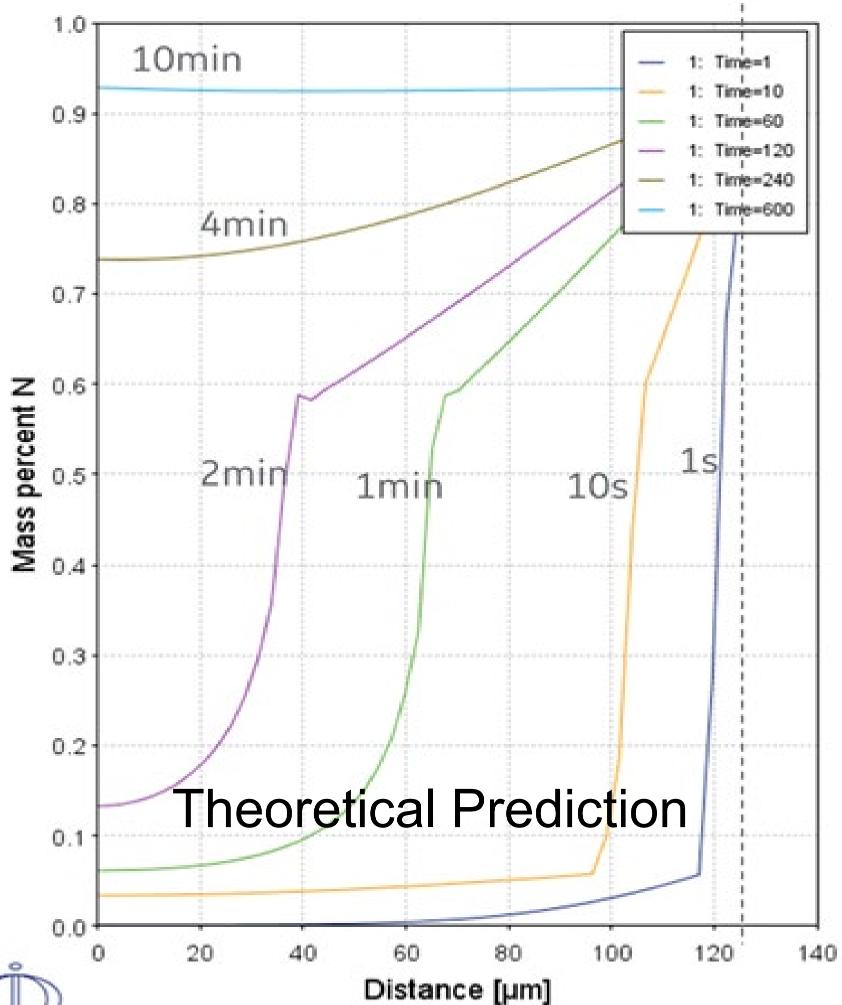
525 dual phase laminates installed in subscale motor prototype

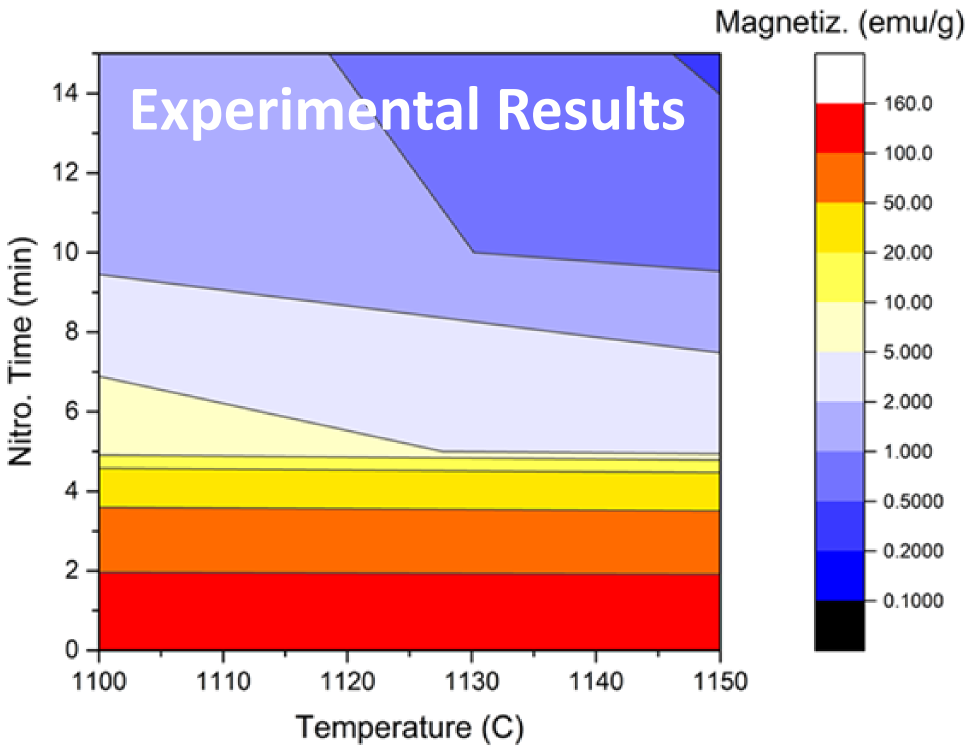


Dual Phase Laminates Manufacturability Established

Technical Accomplishments & Progress

Magnetic ↔ Non-Magnetic Reaction Kinetics Study
Improved Processing Conditions

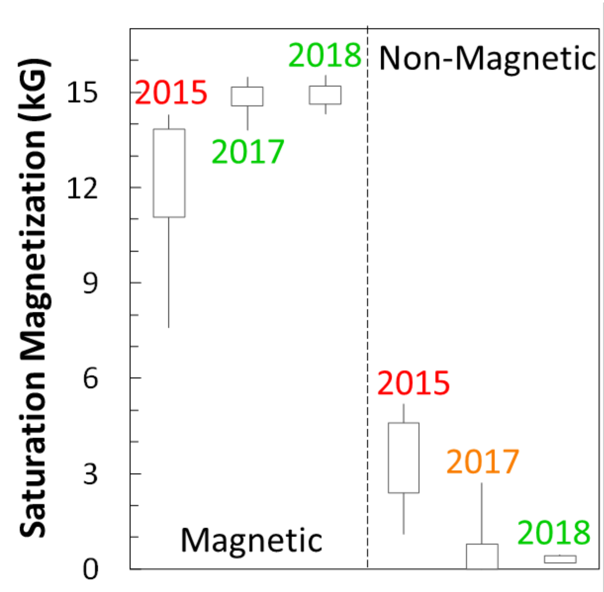


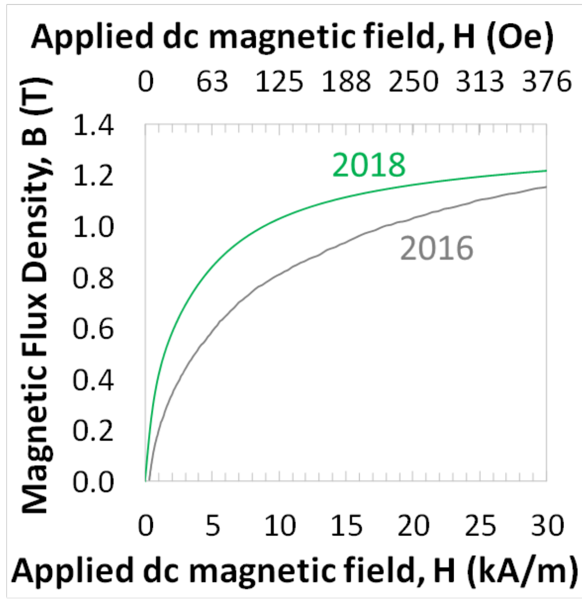


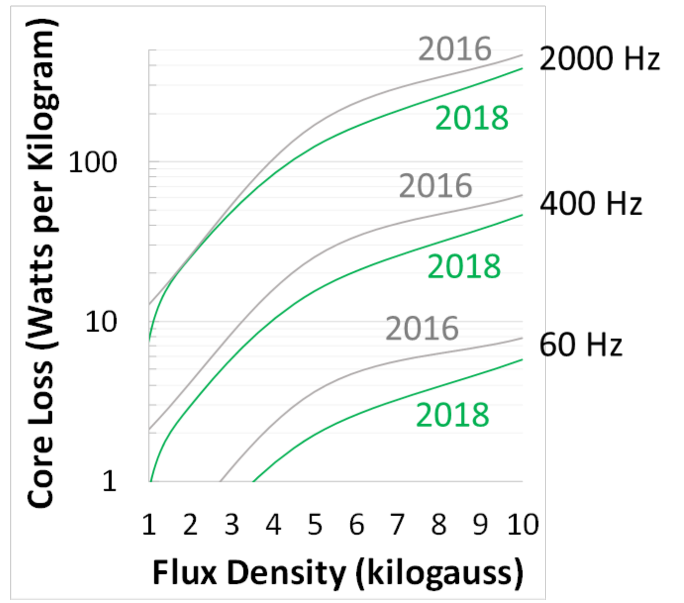
Excellent Agreement Between Predictions and Measurements

Technical Accomplishments & Progress

Improved Magnetic Properties by Improved Processing Conditions







Improved:

- Sheet quality
- Mask uniformity
- Heat treatment protocol

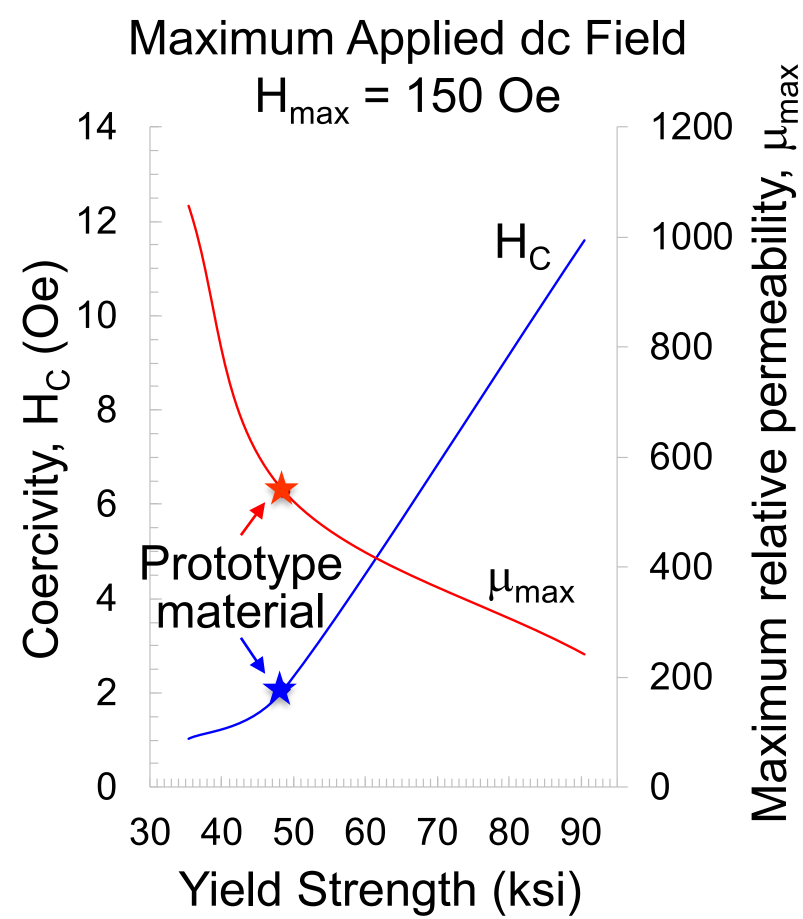
Desired:

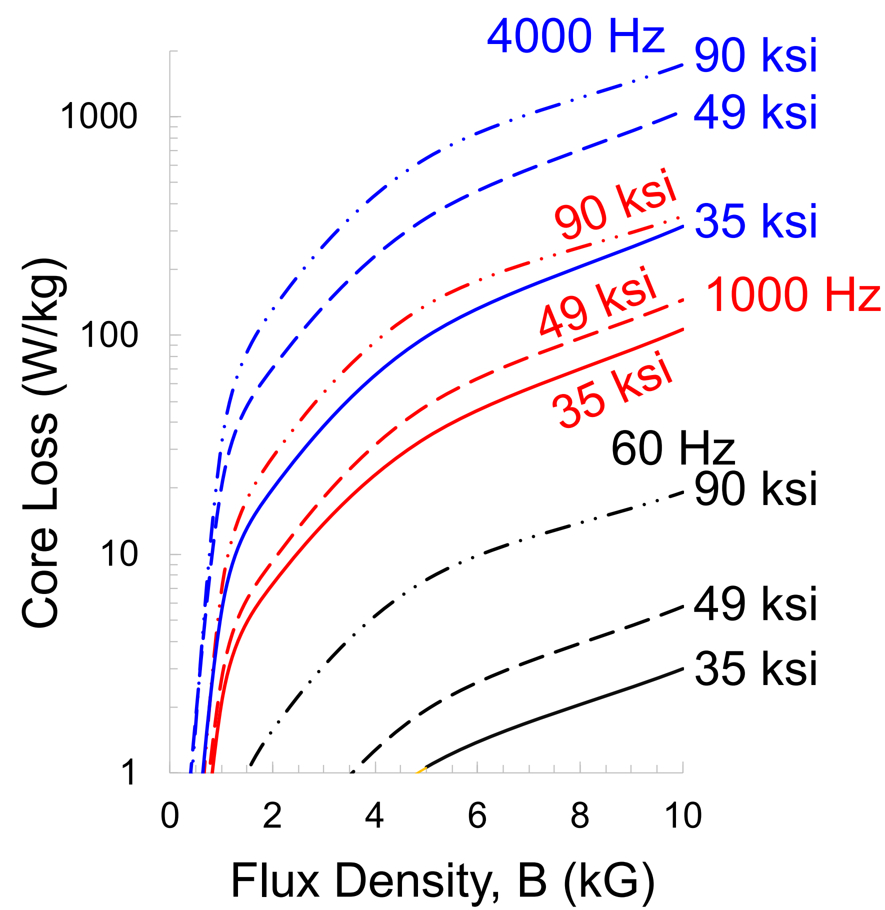
- Increased saturation magnetization in magnetic phase
- Decreased saturation magnetization in nonmagnetic phase
- Increased permeability in magnetic phase
- Decreased core loss in magnetic phase

Magnetic Performance Improved by Improved Processing

Technical Accomplishments & Progress

- Tunable mechanical and magnetic properties by heat treatment conditions
- Magnetic and mechanical properties meet the prototype design requirements





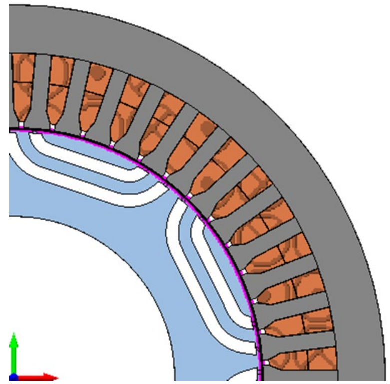
Tradeoff between Magnetic and Mechanical Properties Established

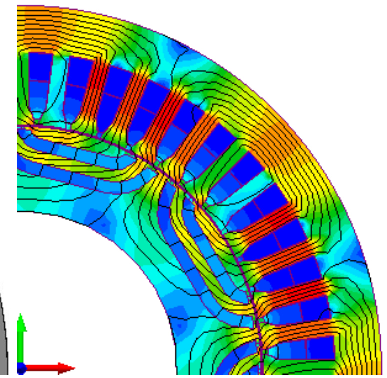
Technical Accomplishments & Progress

Dual Phase Laminates Motor Without Permanent Magnet Design

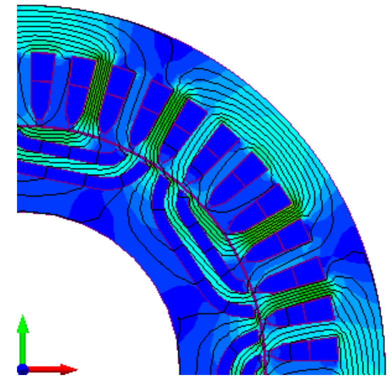
Design Requirements

Parameter	Value
Weight (kg)	≤ 35
DC Link voltage	200 to 450 V
Maximum Current	400 A
Max. Efficiency	95%

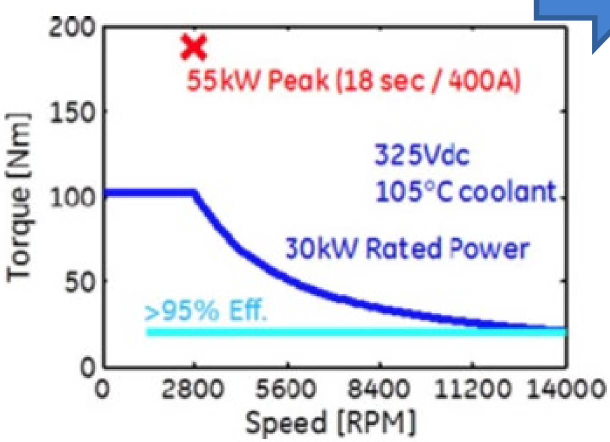




Peak Power 55 kW @ 2.8k RPM



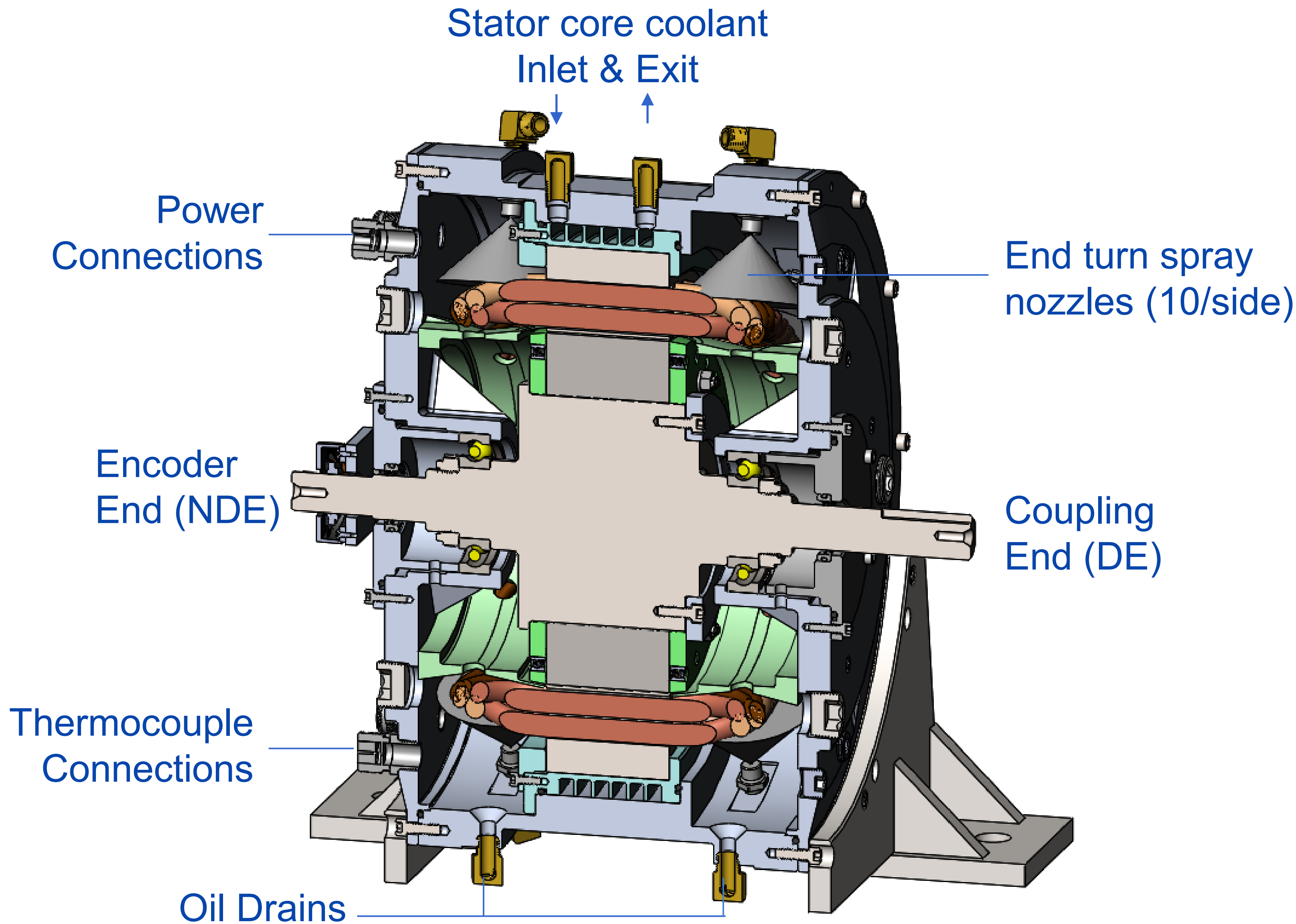
Max. Speed 30 kW @ 14k RPM



Parameter	Target	Calculated
Peak Power (kW)	≥55	**56.2**
Continuous Power (kW)	≥30	**34**
Specific Power (kW/kg)*	≥1.6	**1.93**
Power Density (kW/l)	≥5.7	**5.86**
Maximum Speed (rpm)	14,000	**14,000**
Maximum Efficiency (%)	≥95	**95.3**
Cost ($/kW)	<4.7	**TBD**

Design Meets 2020 EETT Traction Motor Performance Targets

Technical Accomplishments & Progress



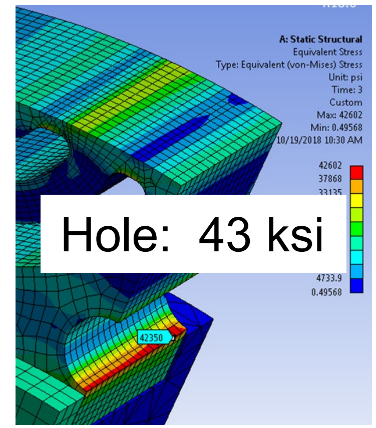
Dual Phase Laminates Motor Without Permanent Magnet Solid Model

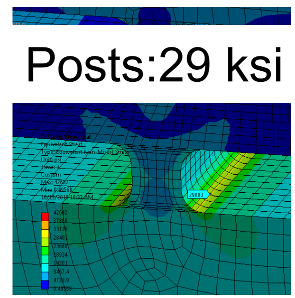
Technical Accomplishments & Progress

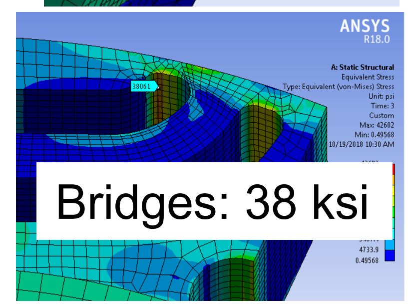
Mechanical Stress Analysis at Motor Operation Speeds Validated Dual Phase Laminates Applicability

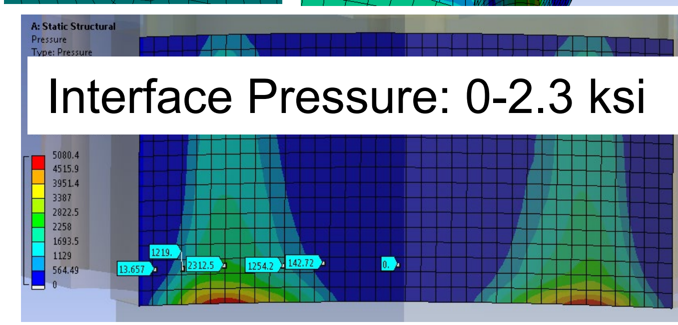
Location	Speed (rpm)	Calculated Stress (ksi)	Material Property: Yield Strength (ksi)	Material Property: Ultimate Tensile Strength (ksi)
Posts	0	< 10	83 ± 4	111 ± 2
	10,000	29		
Bridges	0	28		
	10,000	38		
Hole	0	37	49 ± 7	58 ± 5
	10,000	43		
Interface	0	1.3 – 2.5		
	10,000	0 – 2.3		

Speed: 10,000 rpm
Radial Interference: 0.0015”









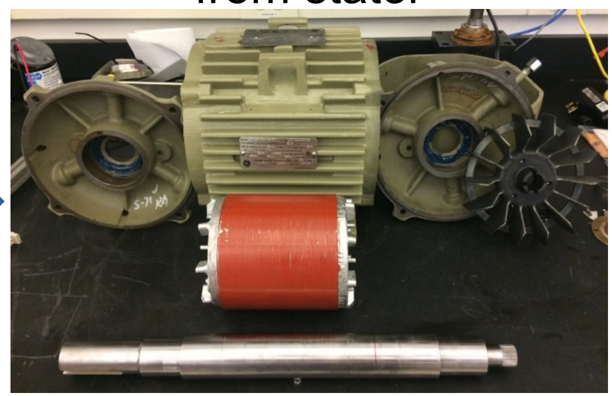
Material Mechanical Strengths are sufficient up to 10,000 rpm

Technical Accomplishments & Progress

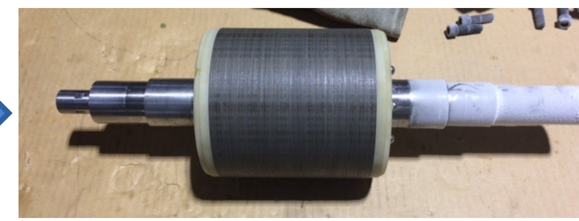
Subscale Dual Phase Laminates Prototype Fabricated For
- Demonstrate dual phase laminates manufacturability
- Compare calculated and tested prototype performance (design not targeted for optimal motor performance)

Purchased off-the-shelf motor

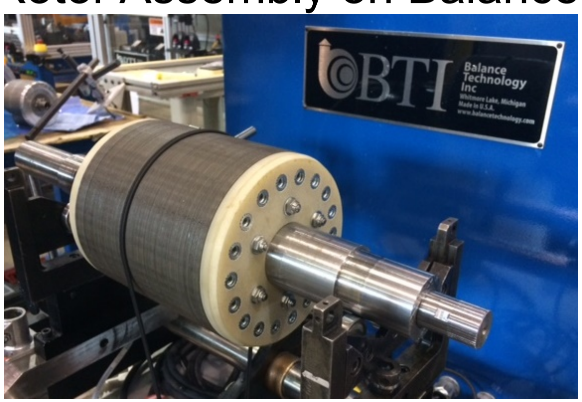
Removed rotor assembly from stator



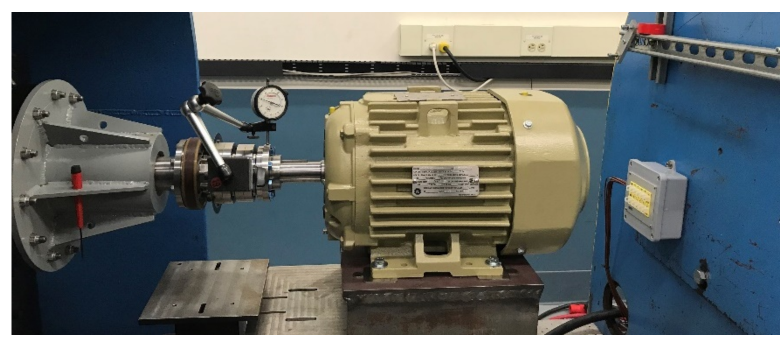
Shrink fitted Dual Phase Laminate Assembly on to shaft



Rotor Assembly on Balance



Motor on test stand



Technical Accomplishments & Progress

Subscale Dual Phase Laminates Motor Tested and Matched Calculated Performance

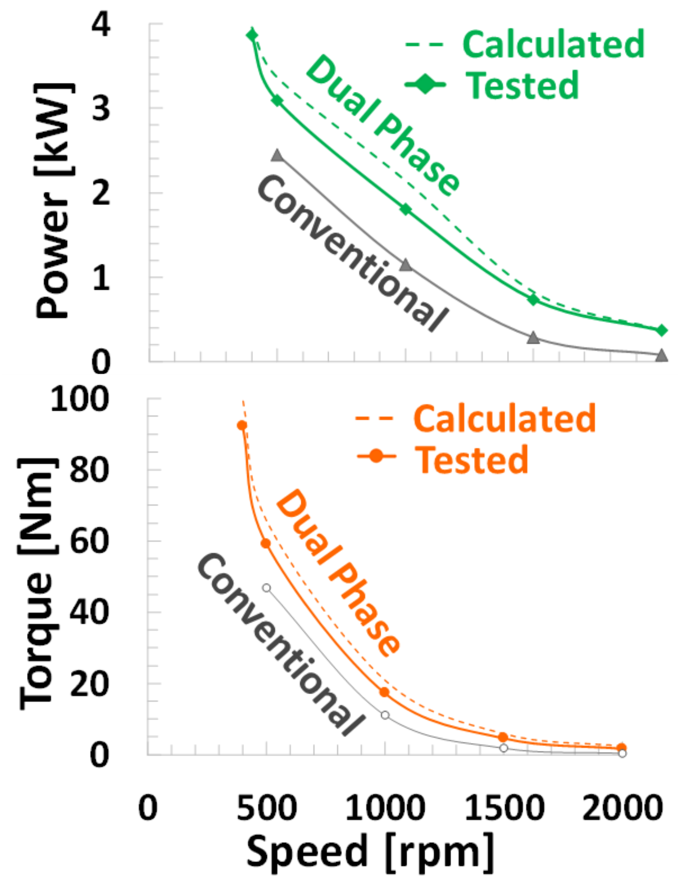
✓ FY2018 **Go/NoGo**: Subscale prototype shows 3.7 kW

Test method:

1. Power up the dyno (DC motor) to rotate in constant speed mode.
2. Apply the AC current excitation to the test motor (constant torque mode) and measure torque output from the torque meter.
3. Subtract measured end winding loss + rotor loss + no load loss from the simulated "air gap" torque to get shaft torque.

Results:

1. Prototype shows 3.9 kW at 400 rpm.
2. For high torque operation, variation between simulated and tested torque output are between 2% to 8%.



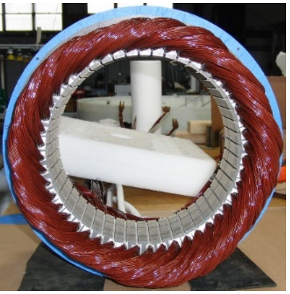
Good Agreement Between Predictions and Measurements

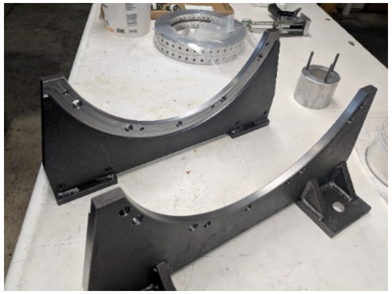
Technical Accomplishments & Progress

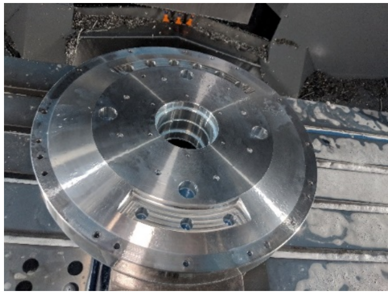
Full-Scale Dual Phase Laminates Prototype Fabrication Highlights

- Trial armature winding completed: Nov. 2018
- All drawings approved: Jan. 2019
- Dual phase rotor fabricated: Feb. 2019
- Custom tooling designed/built: March. 2019
- Bill of Materials completed: Apr. 2019
  - Off-the-shelf parts purchased
  - GE Supplied parts delivered
  - Custom and machined parts finished

Dual Phase
Rotor Laminates







Full-scale Prototype Fabrication and Testing On Track

Responses to previous year reviewers' comments

Comment #1: The reviewer asked if there has been any study carried out for long-term mechanical and magnetic characteristics change for this particular dual phase alloy (Reviewer 2)
Response #1: The dual phase alloy had been exposed at 180 °C for 5000 hours in air, the microstructures and magnetic properties of the alloy in the magnetic and non-magnetic phases remained unchanged. The phase boundary between the two phases grew from 100 μm to 200 μm, which is expected to have no significant impact on the applications. The microstructure images of the thermal stability sample are displayed in Slide #26 of the Technical Backup section.

Comment #2: The reviewer thought that one of the key barriers that needs to be addressed is the tradeoff between the mechanical and the magnetic properties. (Reviewer 1)
Response #2: The tradeoff between the mechanical and magnetic properties has been addressed in the current review period. The results are shown in Slide #12. Mechanical and electromagnetic analysis of the prototype indicates that the mechanical and magnetic properties of the dual phase magnetic laminates are sufficient for the motor prototype design to meet the motor performance targets.

Responses to previous year reviewers' comments

Comment #3: The reviewer posited that this dual phase alloy for synchronous reluctance motor looks unique and is an interesting approach, but it was not clear to the reviewer as to the specific motivations to go to a synchronous reluctance motor. The reviewer also suggested that a reasonable route to consider is a non-heavy RE interior permanent magnet (IPM) motor assisted by higher reluctance with this dual-phase alloy. Also, specific challenges and potential roadblock description are expected as key outputs. (Reviewer 2)

Response #3: The specific motivation to go to a synchronous reluctance motor is that the synchronous reluctance motor eliminates the use of permanent magnets, therefore, addressing the electric motor specific barriers of (1) Magnet cost and rare-earth element price volatility; (2) Non-rare-earth electric motor performance; and (3) Material property optimization, as stated in the EETT Roadmap. The goal of the project is to demonstrate a dual phase magnetic laminates synchronous reluctance motor without any permanent magnets, to match or exceed the performance of IPM motors using conventional magnetic laminate materials.

Regarding the non-RE and non-heavy RE assisted synchronous reluctance motor, an assessment of the motor performance has been conducted in this review period, results are shown in the slide #28 of the Reviewer Only Section,.

Collaboration & Co-ordination

Oak Ridge National Laboratory

- Expertise in nitriding/nitrogenation
- Measurement of nitrogenation kinetics
- X-Ray/Neutron residual stress distribution

CARPENTER®

- Produce custom alloy dual phase sheet to GE's specification

Applinetics Engineering LLC

McCleer Power, Inc.

- Build sub-scale and full-scale prototypes
- GE provides dual-phase rotors

SOLAR ATMOSPHERES

- Heat treatment in production scale furnaces

POLARIS LASER LAMINATIONS, LLC.

- Rotor and stator laminates cutting, insulating, stacking and bonding

GUYSON Corporation of USA

- Surface treatment, coating removal of heat treated laminates

Remaining Challenges & Barriers

- Finalizing the build and test of the 30 kW continuous power dual phase synchronous reluctance motor prototype
- Some technical risks regarding the rotor eccentricity and residual stress due to the dual phase rotor lamination deformation during heat treatment yet to be retired
- Conforming the predicted performance of the prototype
- Manufacturers for high volume production of dual phase magnetic laminates yet to be established due to the uniqueness of the technology

Proposed Future Research

FY2019

- Full-scale 55 kW peak power, 30 kW continuous power motor fabrication and testing to meet EETT 2020 target
- Residual stress measurement of stacked and bonded dual phase rotor by neutron diffraction
- Market development for high volume production

Motor Performance	**EETT Target**	
	2020	2025
Peak Power (kW)	≥55	≥100
Continuous Power (kW)	≥30	≥55
Specific Power (kW/kg)	≥1.6	≥5
Power Density (kW/l)	≥5.7	≥50
Maximum Speed (rpm)	≤14k	≤20k
Maximum Efficiency (%)	≥96	>97
Cost ($/kW)	≤4.7	≤3.3

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

Summary

Relevance

- Eliminate permanent magnets in electric motors
- Reduce electric traction drive system cost

Approach

- Control magnetic states and mechanical properties to reduce flux leakage
- Retire manufacturability risks
  - Material properties optimization
  - Subscale rotor fabrication
  - Subscale motor performance prediction and testing
- Demonstrate full-scale prototype performance
  - Detailed design
  - Motor fabrication and testing

Technical Accomplishments

- Subscale dual phase laminates motor tested and matched calculated performance: passed Go/NoGo
- Full-scale motor prototype design complete: met targets
- Key material properties tests complete: met requirements
- Full-scale motor prototype fabrication and testing on track

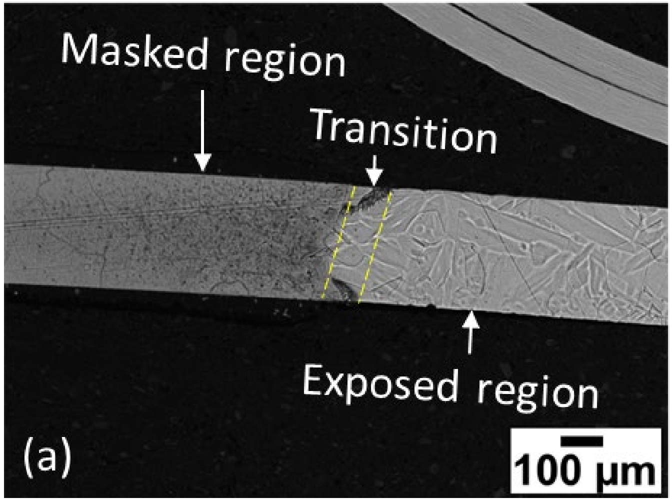
Future Work

- Full-scale motor fabrication and testing
- Residual stress measurement of stacked and bonded dual phase rotor by neutron diffraction
- High volume production market development

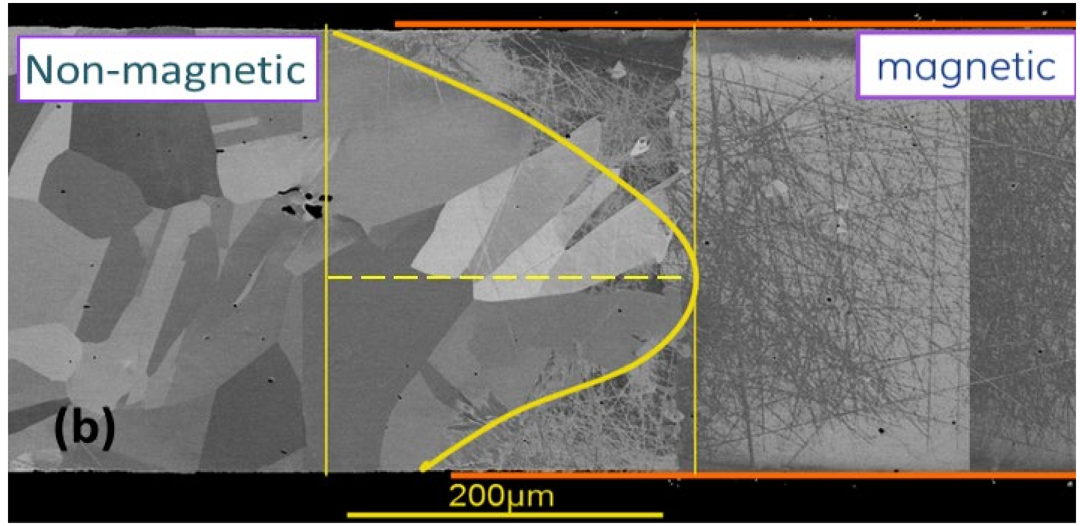
Technical Back-Up Slides

Thermal stability of dual phase material

(Completed on project DE-E0005573, “Alternative High-Performance Motors with Non-Rare Earth Materials”, 2012-2017)



As nitrogenated dual phase material



The same sample after 5000 hours of exposure to 180 °C in air

After having been exposed in air at 180 °C for 5,000 hours,

- magnetic and non-magnetic regions stayed in the same magnetic states as in their prior states
- Transition region between the magnetic and non-magnetic regions grew from 100 μm to 200 μm
- Transition region expansion is not expected to impact the application