Non-Heavy Rare-Earth High-Speed Motors (Keystone Project #2)

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Oak Ridge National Laboratory

2020 DOE Vehicle Technologies Office Annual Merit Review

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Overview

Timeline

- Start: FY19
- End: FY24
- 30% complete

Barriers

- Magnet cost and heavy rare-earth element price volatility
- Non-heavy rare-earth electric motor performance
- Meeting DOE ELT 2025 targets for non-heavy rare-earth electric motor: $3.30/kW cost; 50kW/L power density and 300,000-mile lifetime

Budget

- Total project funding
  - DOE share – 100%
    - Funding for FY19: $400K

Partners

- National Renewable Energy Laboratory
- Ames Laboratory
- ORNL team members: Tsarafidy Raminosoa, Randy Wiles, Jason Pries, and Burak Ozpineci

Relevance - Project Objectives

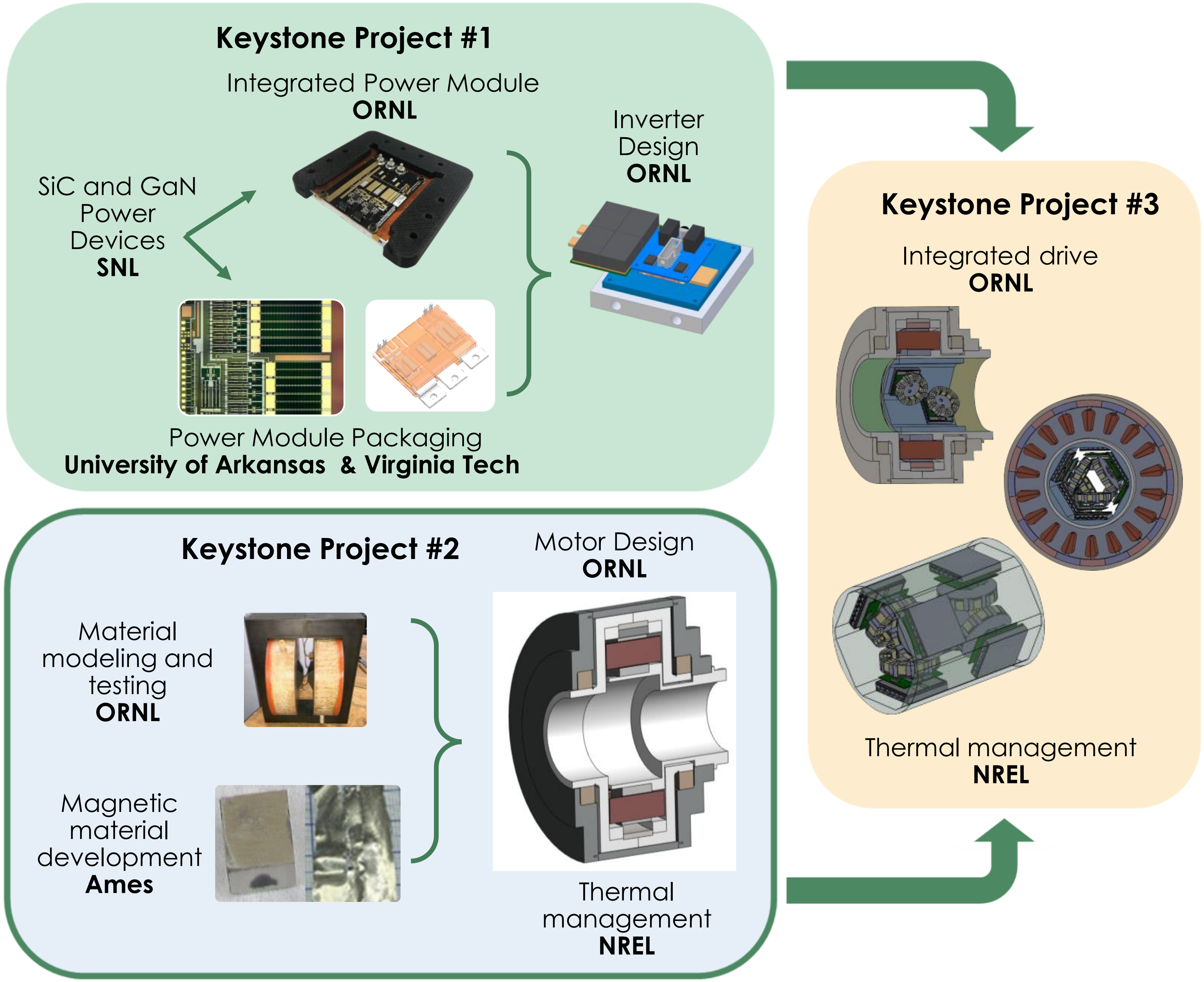
Overall Objective

- Enable the adoption of high-speed and high-power density non-heavy rare-earth (HRE) traction motors
- Analyze the impact of new advanced materials for non-heavy rare-earth electric motors

FY20 Objective

- Design a dual three phase non-heavy rare-earth permanent magnet high speed traction motor to meet the DOE ELT 2025 specifications.
- Design the thermal management system and the mechanical assembly of the motor.

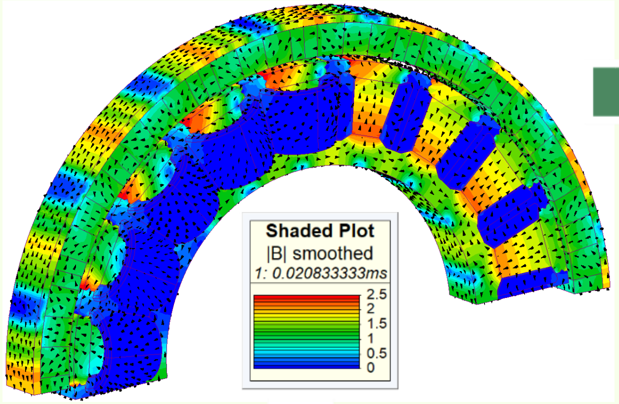
Project Scope within ELT Consortium



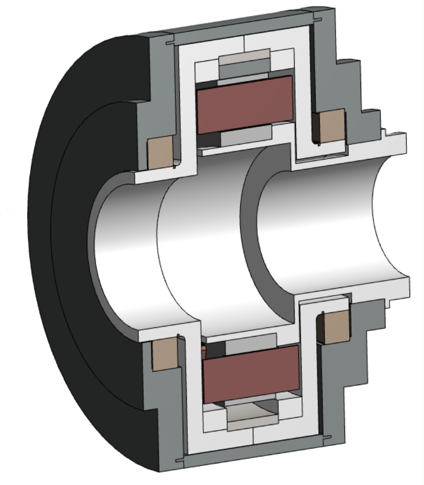
Relevance - Project Objectives

ELT212 ORNL

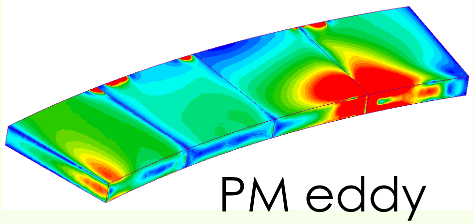
Electromagnetic design



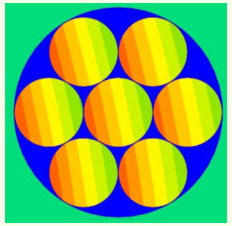
Mechanical assembly design



Loss evaluation



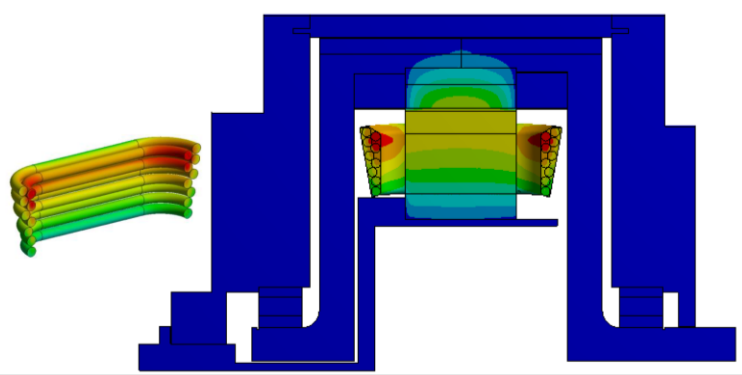
PM eddy current loss



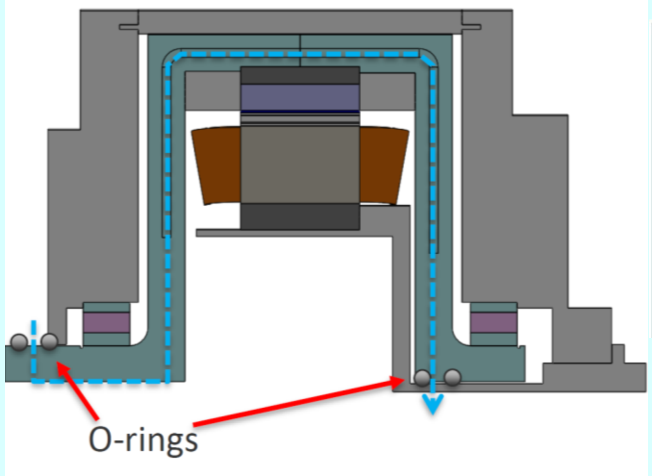
AC loss in Litz wire winding

ELT214 NREL

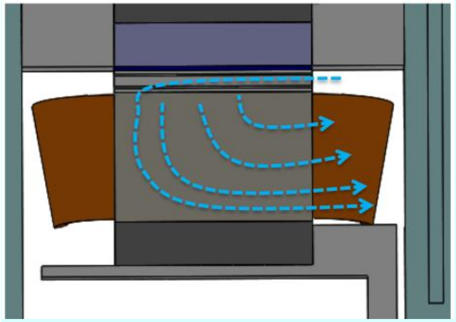
Thermal modeling



Cooling design



Rotor cooling



Slot heat exchanger

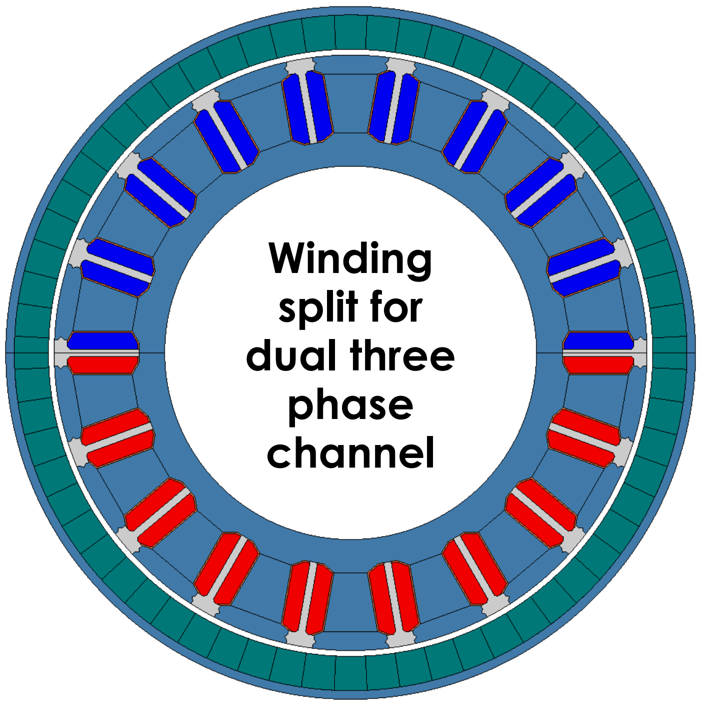
FY20-21 Milestones

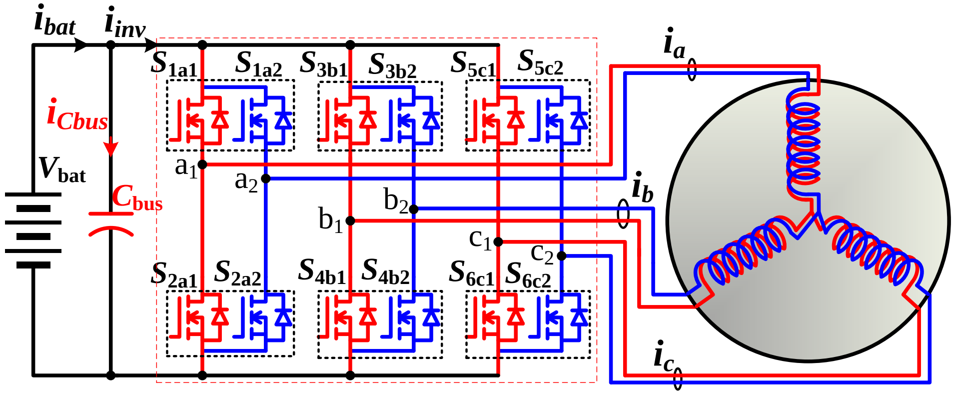
Date	Milestones and Go/No-Go Decision	Status
Dec 2019	Milestone: Complete electromagnetic design of a multiphase outer rotor surface PM motor.	Completed
Mar 2020	Go/No-Go Decision: If a high-speed motor candidate can yield a significant improvement in performance and power density, refine the cooling and thermal design of this motor.	Completed
Jun 2020	Milestone: Design the 100kW outer rotor motor structure for power electronics integration.	On track
Sep 2020	Milestone: Finalize cooling and mechanical design of the selected motor candidate.	On track
Dec 2020	Milestone: Build a mock-up prototype for verification of mechanical robustness.	On track
Mar 2021	Milestone: Generate final drawings for full prototype fabrication.	On track
Jun 2021	Milestone: Construct full prototype.	On track
Sep 2021	Milestone: Document test results and submit final report.	On track

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

Approach/Strategy

- ✓ Permanent magnet traction motors using non-HRE magnet materials are evaluated.
- ✓ Dual channel three phase winding configuration is proposed. This way, the motor can be powered by:
  - A conventional three phase drive with the two channels connected in parallel;
  - Or a dual three phase segmented drive (separate inverter for each channel) developed at ORNL (Refer to ELT209) to reduce current ripple and the DC Link capacitor.
- ✓ Dual channel configuration also reduces the back-EMF on each set of winding by half. This eases the voltage limitation constraint at high speed and eliminates uncontrolled regeneration.
- ✓ Dual channel configuration features fault tolerance which improves reliability.



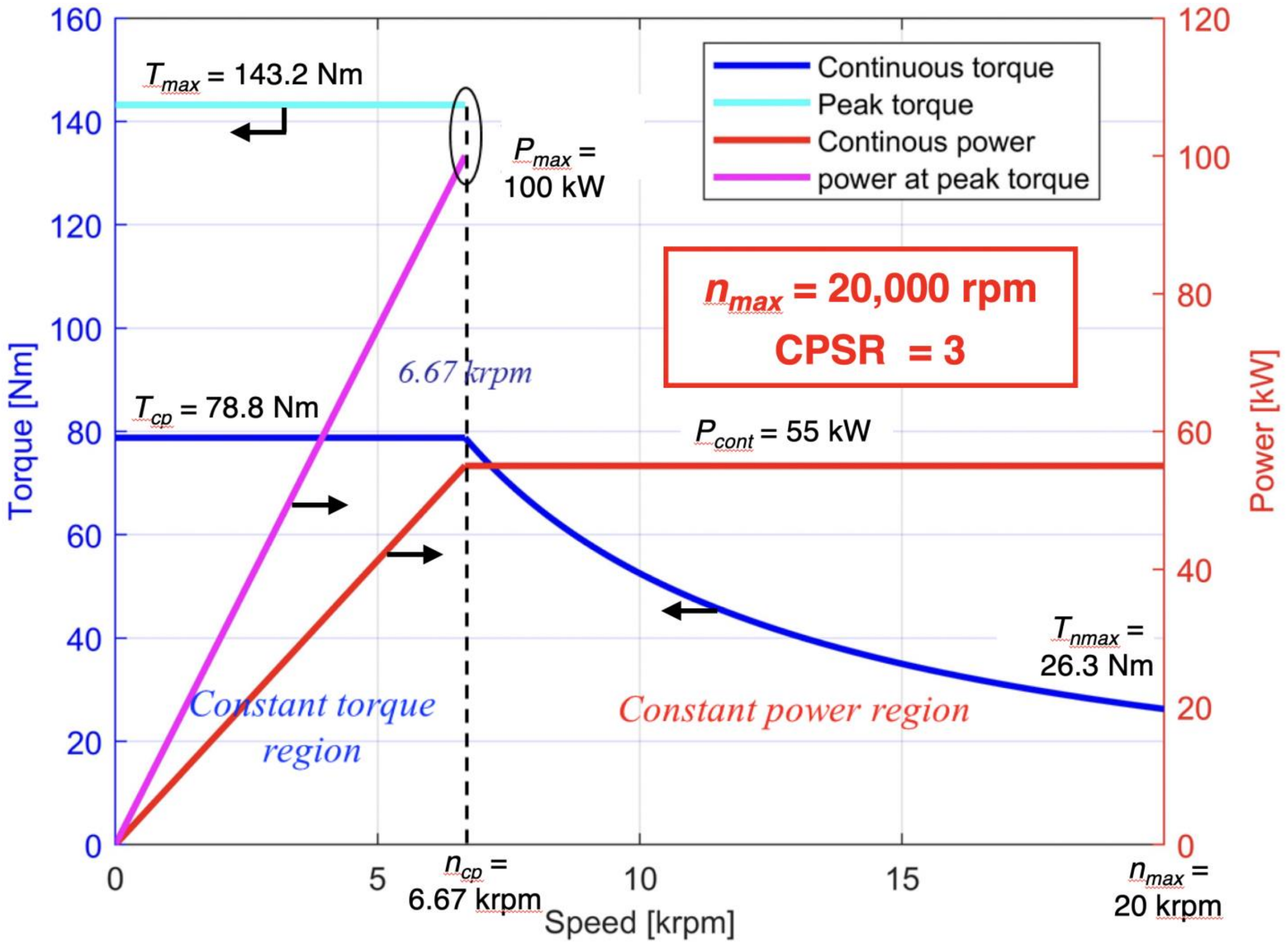


Segmented 3-phase inverter

Reduction of capacitor ripple current with interleaved switching
Refer to ELT209 by Gui-Jia Su

Technical Accomplishments – FY20

Completed Electromagnetic Design of Heavy Rare-Earth-Free Dual Three-Phase Outer Rotor Permanent Magnet Traction Motor



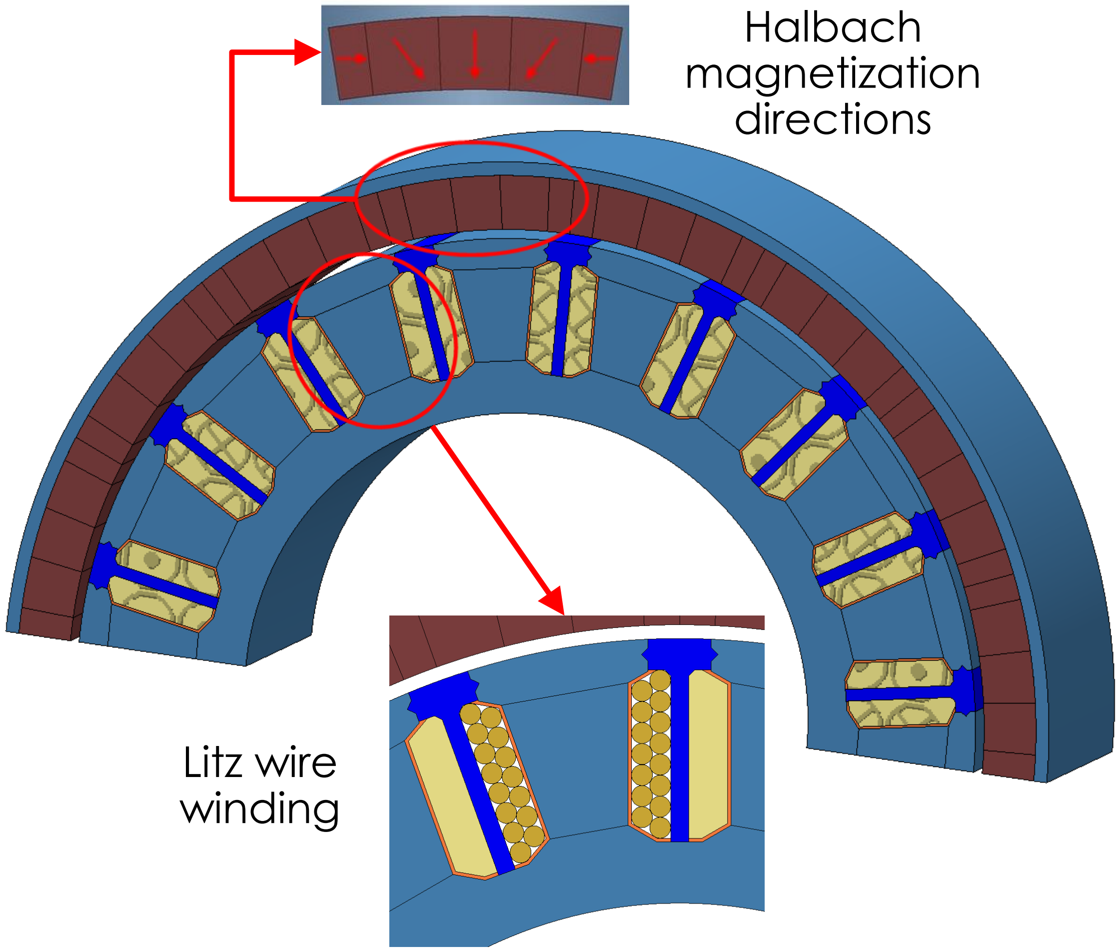
Source: University of Wisconsin-Madison

Peak power (kW)	100
Continuous power (kW)	55
Maximum speed (rpm)	≤20,000
Battery operating voltage (Vdc)	650
Power factor	> 0.8
Maximum current (A)	600
Maximum efficiency (%)	> 97
Torque ripple (%)	5
Volume (@50 kW/l)	2L
Mass (@5kW/kg)	20kg

Summary of Specifications

Technical Accomplishments – FY20

Completed Electromagnetic Design of Heavy Rare-Earth-Free Dual Three-Phase Outer Rotor Permanent Magnet Traction Motor



Why Outer Rotor SPM?

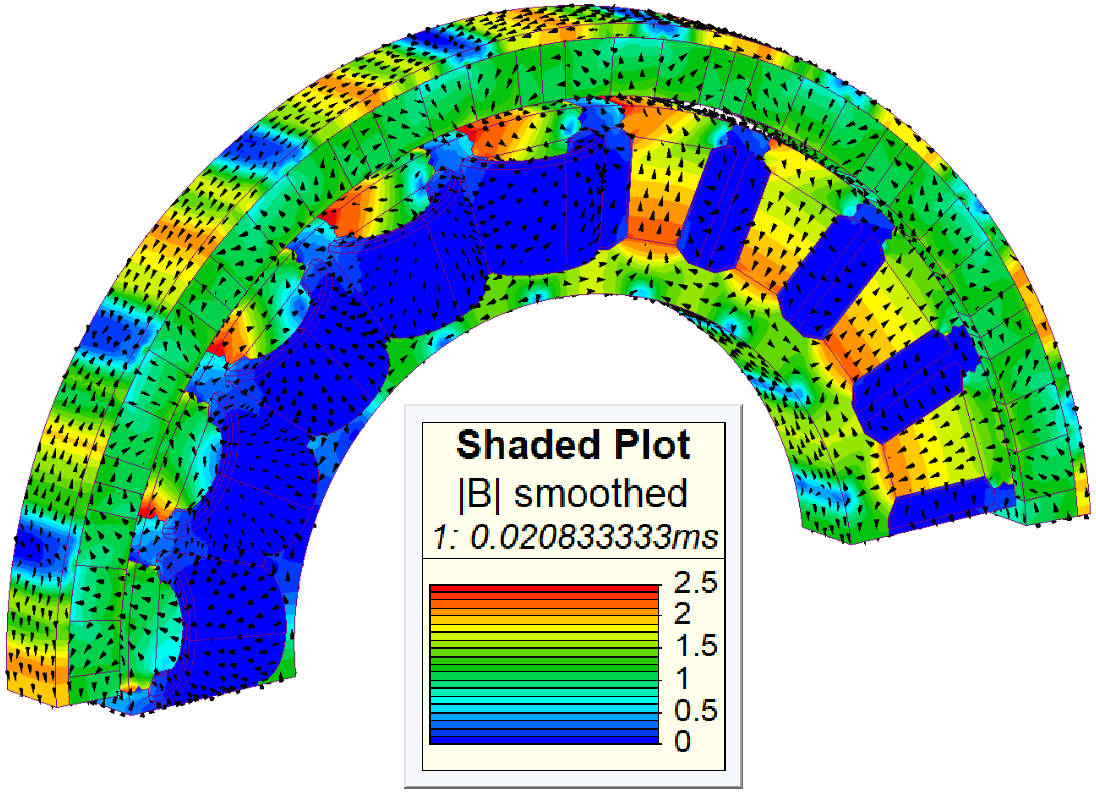
- Opportunity for integrating power electronics in the inner hollow volume.
- Robust continuous rotor construction (as opposed to segmented rotor construction for Spoke IPM). Magnet retention against centrifugal force naturally provided by rotor laminations and rotor support structure.
- Ability to provide the required power up to 20,000 rpm.
- Has the highest power density among the candidates analyzed.

With design margin for demagnetization and 3D effect

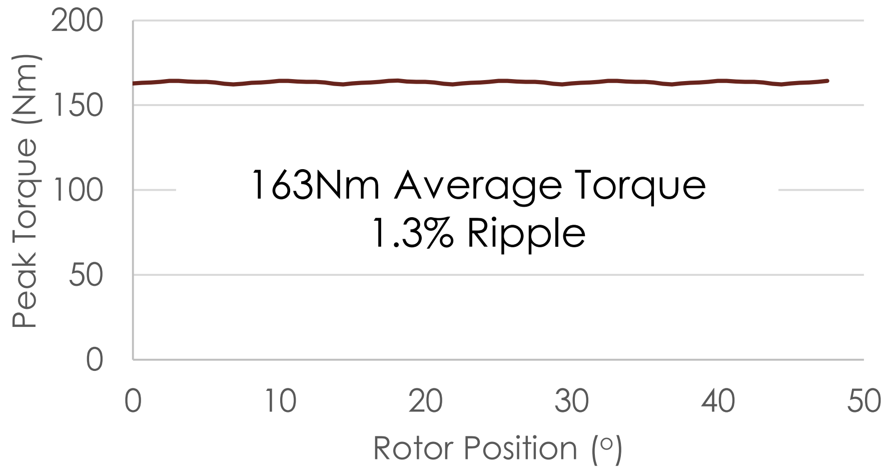
Technical Accomplishments – FY20

Completed Electromagnetic Design of Heavy Rare-Earth-Free Dual Three-Phase Outer Rotor Permanent Magnet Traction Motor

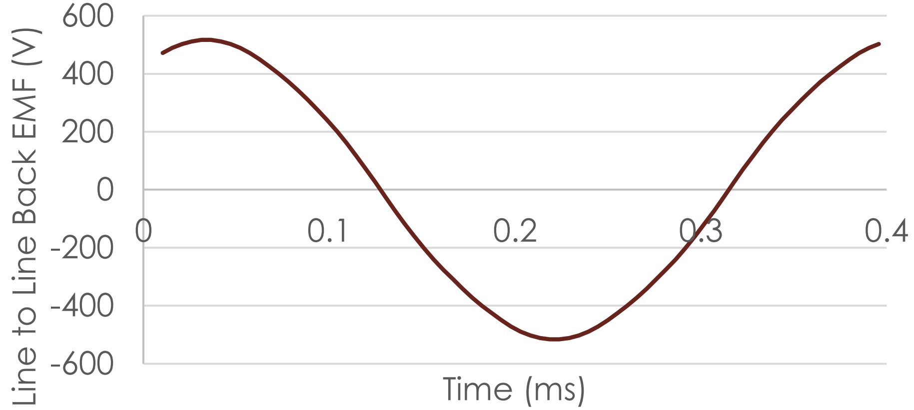
Flux Density Map at Peak Torque Condition



Peak Torque Waveform



Line to Line Back EMF at 20,000rpm

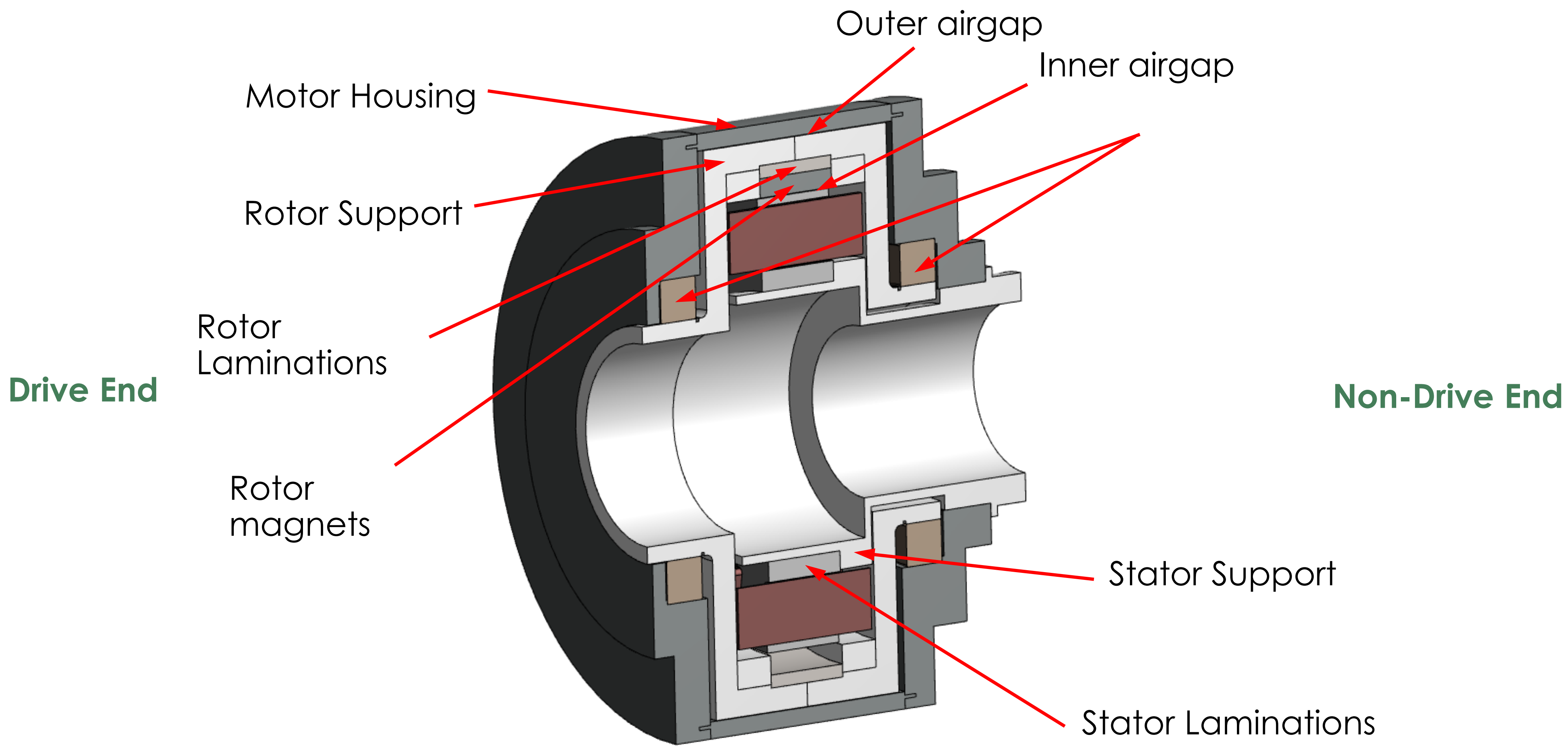


517V Peak to peak line back EMF at 20,000rpm < DC Bus Voltage

- Meets peak power and torque ripple requirement
- Avoids uncontrolled regeneration

Technical Accomplishments – FY20

Completed Assembly Design and Mechanical Stress Analysis

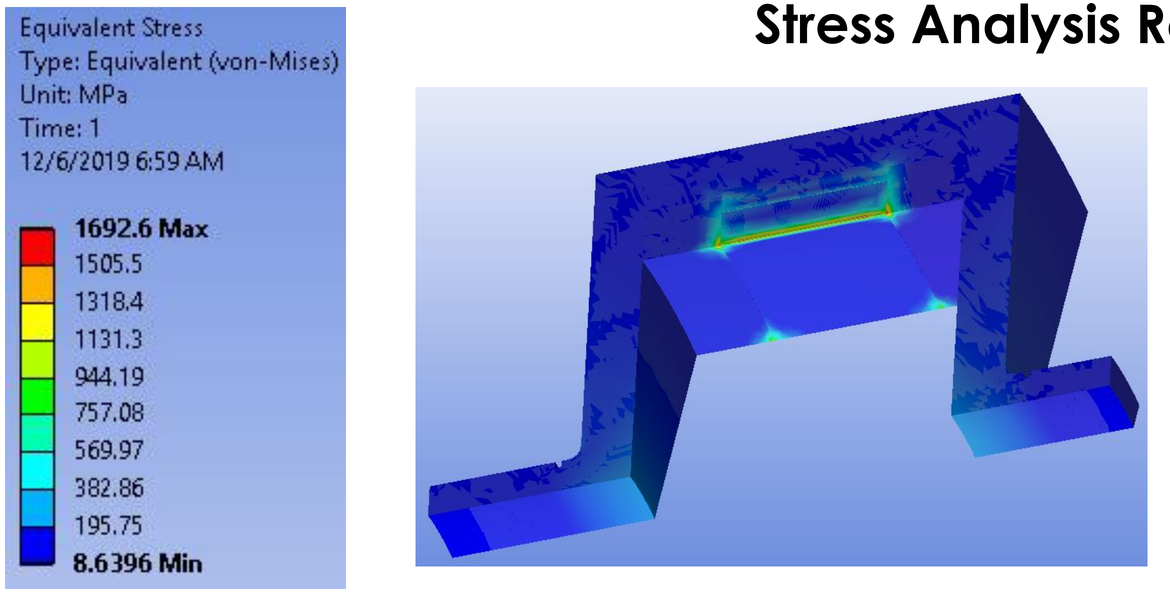


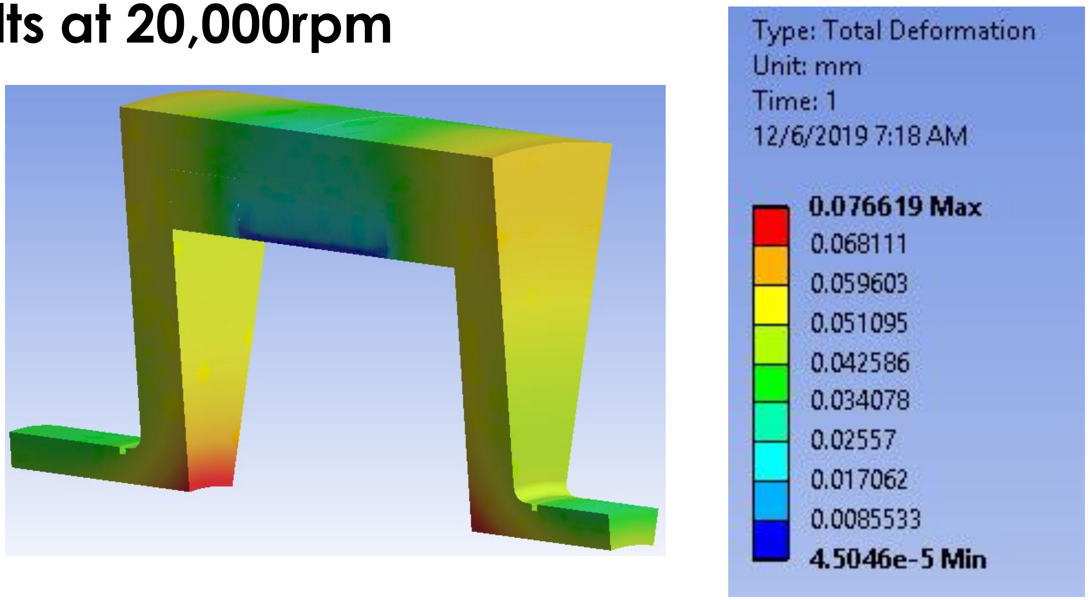
Large diameter bearing able to operate at 19,000 rpm identified

Technical Accomplishments – FY20

Completed Assembly Design and Mechanical Stress Analysis

Stress Analysis Results at 20,000rpm





410 Atlas Stainless Steel

Tempering Temperature (°C)	Tensile Strength (MPa)	Yield Strength 0.2% Proof (MPa)	Elongation (% in 50mm)
Annealed *	480 min	275 min	16 min
204	1310	1000	16
316	1240	960	14
427	1405	950	16
538	985	730	16
593	870	675	20
650	755	575	23

Source: Atlas Steels

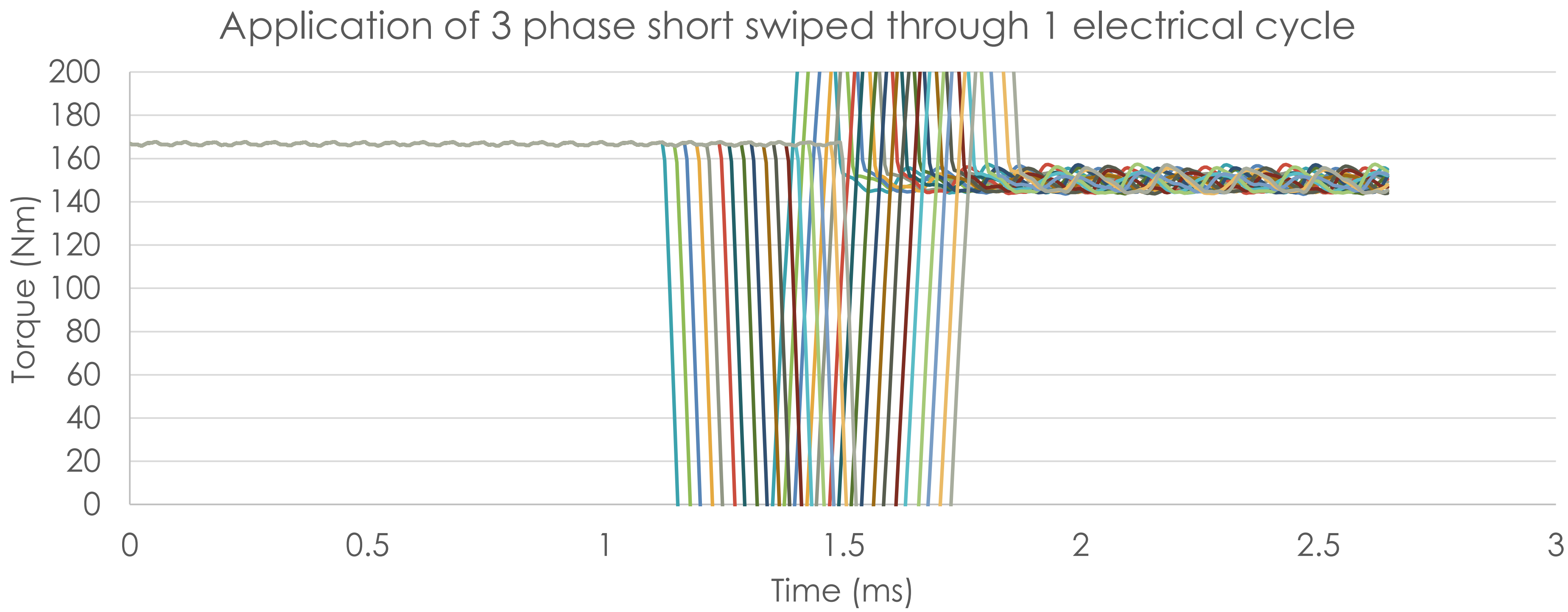
- Stress below 760MPa
- Max displacement is 0.077mm (3mils)

Viability of the rotor concept at 20,000rpm is validated

Technical Accomplishments – FY20

Evaluated Motor's Resistance to Demagnetization Under Worst Case Scenarios

Starting from peak torque operation at 20,000 rpm, three phase short circuit fault applied at various time instants

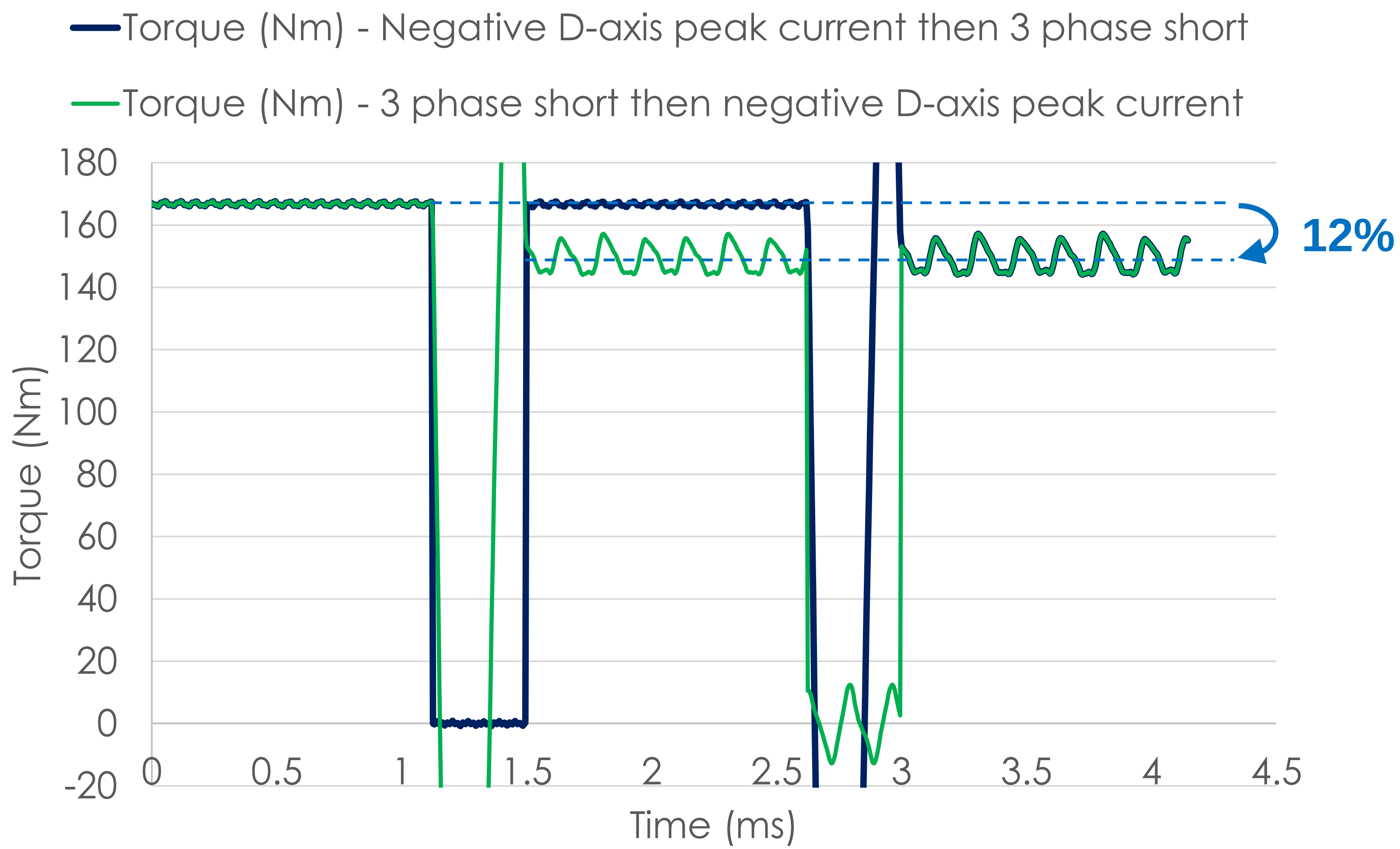


- 12% torque reduction due to three phase short circuit
- The timing of the fault does not affect the reduction in torque

Technical Accomplishments – FY20

Evaluated Motor's Resistance to Demagnetization Under Worst Case Scenarios

Effect of successive purely negative d-axis peak current and three phase short circuit faults



- Three phase short circuit fault at 20,000rpm is more severe
- The order of faults' occurrence does not affect the final torque reduction

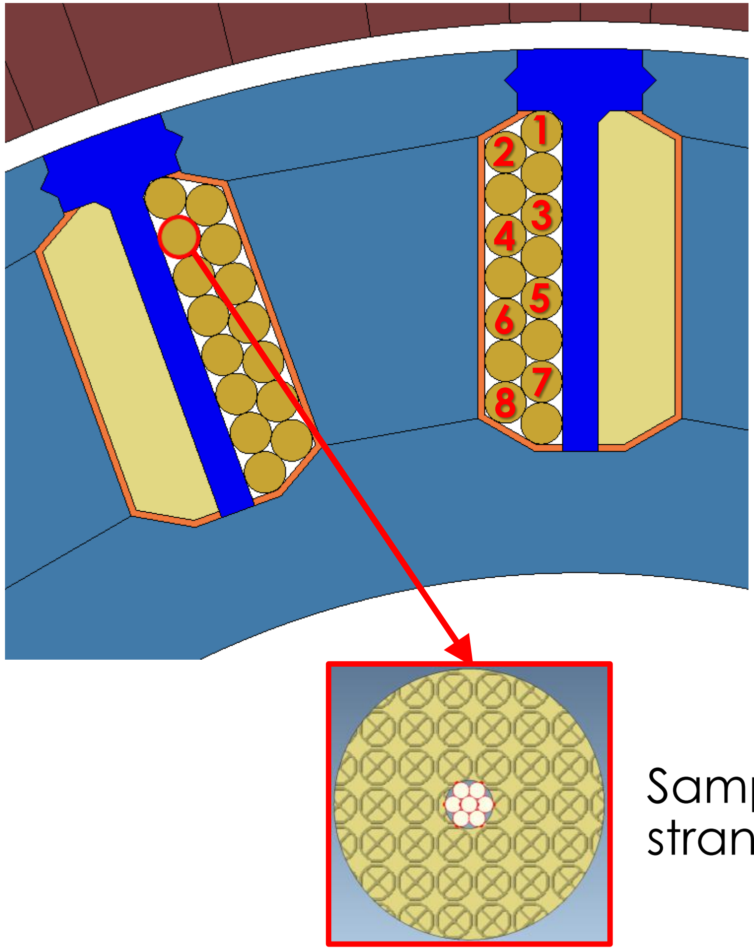
12% design margin for demagnetization risks

Technical Accomplishments – FY20

Evaluated Electromagnetic Loss Components as Input for Thermal Analysis

AC Loss Calculation

Positions of Litz wire bundles



Sample strands

- The sample strands are modeled
  (a) as a stranded conductor i.e. no eddy currents allowed and current density across the cross section is uniform, and
  (b) as a solid conductor i.e. accounting for induced eddy current.
- The two 2D analyses are carried out for a given current at 20,000 rpm.
- The difference in copper loss between case (b) and (a) is the AC loss. This AC component of the loss can be scaled with speed squared.
- The ratio of the losses in cases (b) and (a) is the AC loss factor.
- The AC loss factor is calculated for representative locations of the sample strands and the average is used as the overall AC loss factor for the considered speed.

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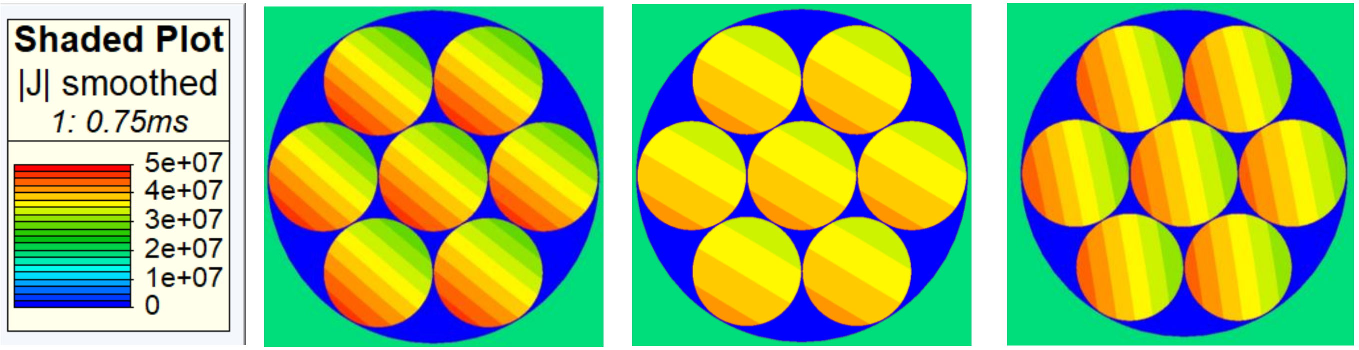
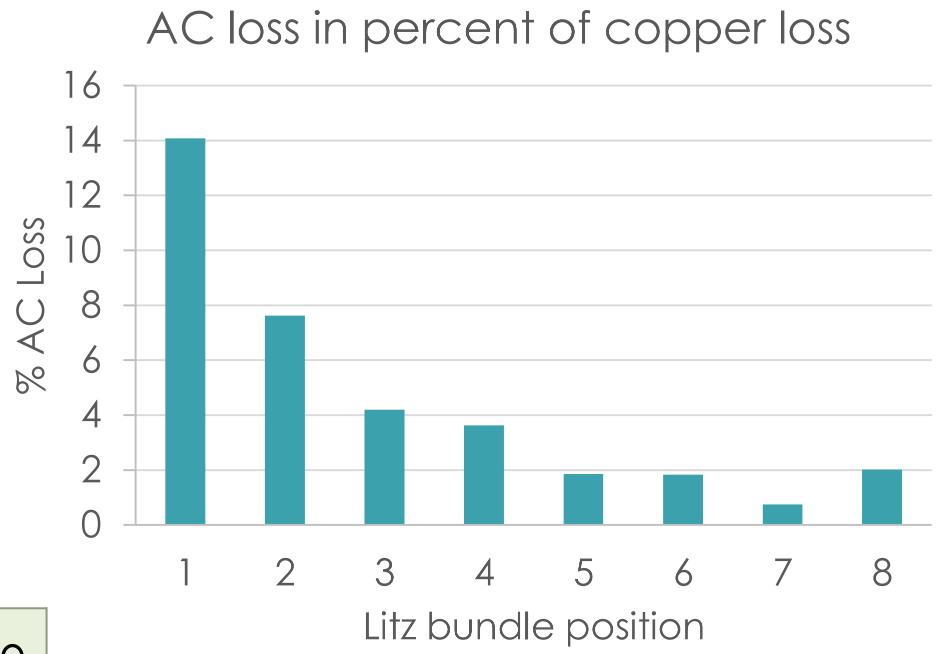
Technical Accomplishments – FY20

Evaluated Electromagnetic Loss Components as Input for Thermal Analysis

AC Loss Calculation for 600Arms at 20,000rpm

Position 1 (Slot opening) | Position 5 (Middle of slot) | Position 8 (Slot bottom)





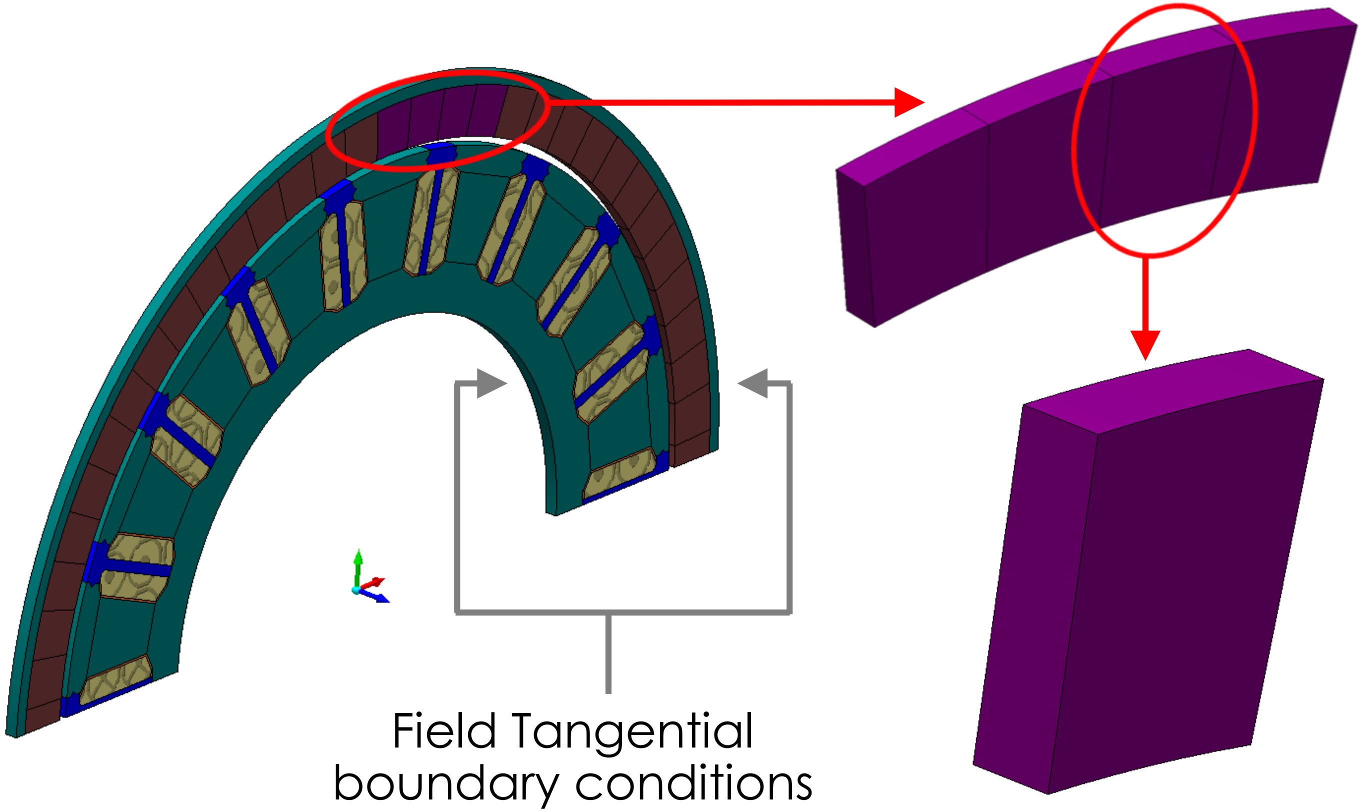
Speed (rpm)	6667	10000	12500	15000	17500	20000
Frequency (Hz)	889	1333	1667	2000	2333	2667
(AC+DC)/DC loss factor	**1.005**	**1.011**	**1.018**	**1.025**	**1.034**	**1.045**

AC loss < 5% of copper loss at top speed
Litz wire selection validated

Technical Accomplishments – FY20

Evaluated Electromagnetic Loss Components as Input for Thermal Analysis

PM Eddy Current Loss Calculation



Field Tangential boundary conditions on each faces of the model

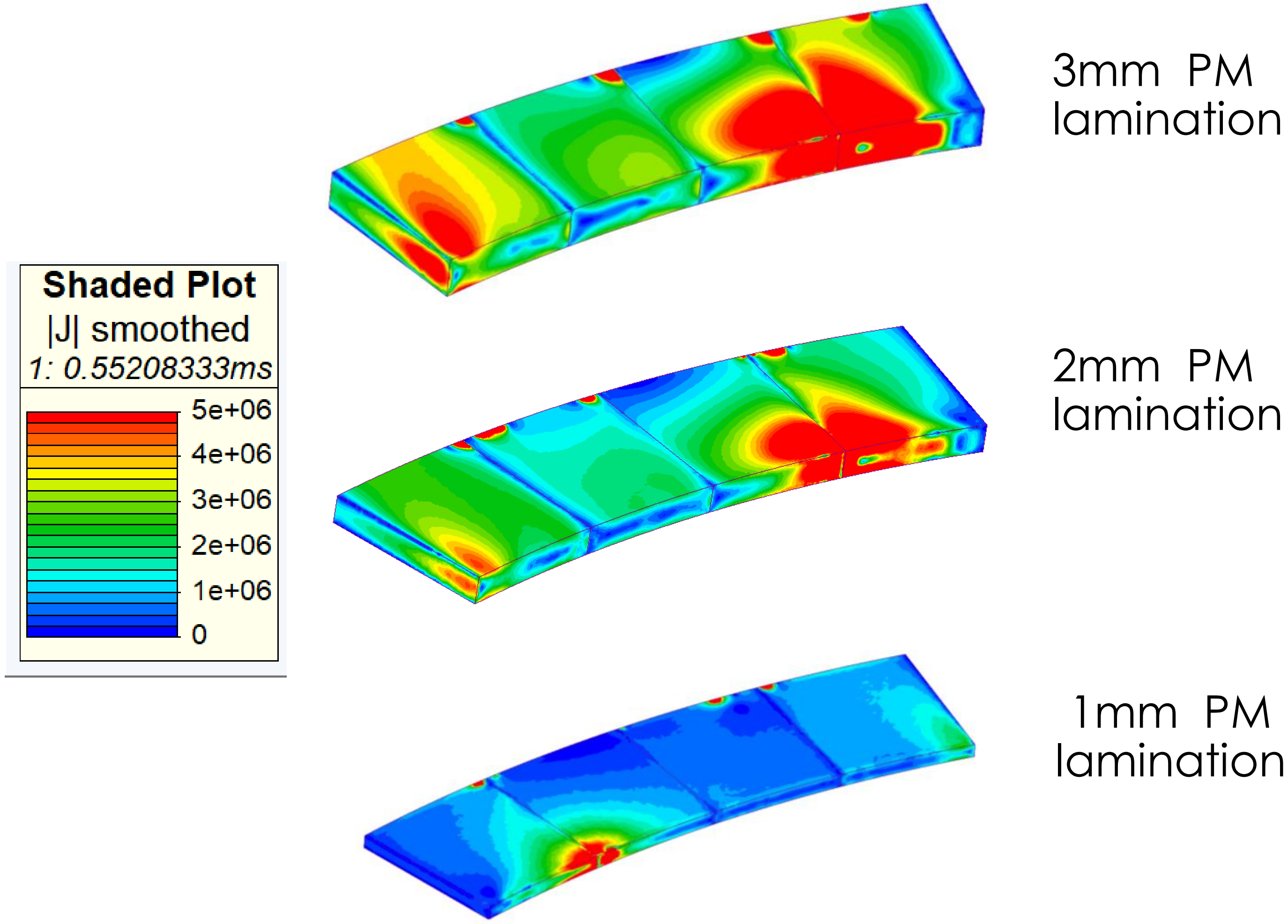
Perfect Electric Insulator boundary conditions on all faces of a magnet segment

- 3D Finite Element model with an axial length equal to the thickness of a PM lamination (Eddy currents are allowed to follow a 3D path).
- Feasible PM lamination of thicknesses of 1, 2 and 3mm were analyzed
- Eddy current losses in PMs are calculated for one operating point (600 Arms at 20,000rpm).
- For other operating points, the losses are scaled with the current squared and speed squared.

Technical Accomplishments – FY20

Evaluated Electromagnetic Loss Components as Input for Thermal Analysis

PM Loss Results at 20,000 rpm and 600 Arms



PM Lamination thickness (mm)	Total Eddy Current Losses in Permanent Magnets (W)
1	736
2	2562
3	4976

PM lamination thickness of 1mm chosen

Responses to Previous Year Reviewers' Comments

- *Comment*: The machine topologies investigated are not novel and it is hard to see how any of them will lead to the significant required increase in power density.

➢ *Response*: It was necessary to evaluate various machine topologies to understand their potential to meet the required power density and identify the most promising ones. Based on the results of the comparison study, the outer rotor surface PM topology was selected in consultation with the EETT Tech team. Although the topology is not new, there are novelties in the thermal management and the integration of the drive and motor.

- *Comment*: The results presented focused on electromagnetic performance. There are still significant mechanical and thermal challenges to be addressed and a detailed mechanical and thermal analysis is needed. Also, alternating current (AC) effects and losses are not accounted for, and hence the presented efficiency values are too high.

➢ *Response*: AC loss, thermal and mechanical challenges were addressed during FY20. Litz wire winding is used to address the AC loss at high frequency. Permanent magnets are laminated to address eddy current losses. The viability of the mechanical assembly design was confirmed by mechanical stress analysis. Thermal analysis and design were performed by NREL and presented in project ELT214.

- *Comment: The roles of NREL and AMES are not very clear.*

➢ *Response*: In FY20, NREL was performing the thermal analysis and providing thermal management solution presented in the project ELT214. Ames provided measured characteristics on their new magnetic materials for use in project ELT213 to develop accurate material and loss models in support of the present project.

Collaboration and Coordination with Other Institutions

Organization	Role
NREL NATIONAL RENEWABLE ENERGY LABORATORY	Investigates cooling methods for the selected advanced non-heavy rare-earth electric motors
AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY	Provides ORNL with the magnetic, electrical and mechanical properties of newly developed magnetic materials for traction motor design

Remaining Challenges and Barriers for FY20

- Implementation of the thermal management system:
  - *Challenge:* Coolant channels, manifolds and spray nozzles will take spaces within the motor and can complicate the mechanical assembly.
  - *Mitigation:* Rapid prototyping and trials on key subassemblies will be carried out to evaluate manufacturability.
- Containment of permanent magnets:
  - *Challenge:* Permanent magnets are subject to crack. They need to be contained and kept the in place in case of crack.
  - *Mitigation:* Identify high strength non-conductive and non-magnetic composite materials to be used as inner bore sleeve for the rotor.

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

Proposed Future Research

- **Remainder of FY20**
  - Complete refined cooling design of the selected motor candidate. Collaborate with NREL on the design of the thermal management system.
  - Complete refined mechanical design of the selected motor candidate including the mechanical integration of then thermal management system into the motor housing.
- **FY21**
  - Experimentally verify the robustness of the mechanical assembly by performing high speed spin test on a dummy motor prototype (without winding and replacing magnets with parts having the same mass density).
  - Build an actual prototype of the selected non-heavy rare-earth motor and validate its performance experimentally.

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

Summary

- **Relevance:** Non-heavy rare-earth high-speed traction motors have potential to meet the DOE ELT 2025 targets of 50kW/L, $6/kW, and 300,000-mile lifetime
- **Approach:**
  - Non-Heavy Rare Earth PMs for high power density and reduced cost electric motors
  - PM motor technology resistant to demagnetization
  - Outer rotor motor topology or power electronic integration and electric drive power density improvement
  - Dual-channel three phase winding for use with the segmented drive to reduce current ripple and DC link capacitor.
- **Collaboration:**
  - **NREL:** Exploring cooling methods for advanced non-heavy rare-earth electric motors
  - **AMES:** Providing magnetic, electrical and mechanical properties of newly developed magnetic materials
- **Technical accomplishment:**
  - Completed electromagnetic design of a non-heavy rare-earth outer rotor PM motor that meet most of the DOE ELT targets
  - Validated resistance to demagnetization of the motor design
  - Completed mechanical assembly design and confirmed mechanical viability at high speed
  - Completed loss evaluation including AC losses and eddy current losses in permanent magnets for thermal analysis.
- **Future work:**
  - Validate the performance of the selected non-heavy rare-earth motor experimentally

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