# Alternative High-Performance Motors with Non-Rare Earth Materials

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DOE Peer Review Presentation


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# Team and stakeholders

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### Motor Development

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### Material Development

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### Thermal Management

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**Mr. Kevin Bennion**
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NREL

### Motor Controls

**Dr. Kum-Kang Huh**
GE Global Research

### Prototype Manufacturing

**Dr. Patrick McCleer**
McCleer Power

# Overview

## Timeline

- Start: October 1, 2011 (official kickoff with DoE February 7, 2012)
- End: January 31, 2016
- 55% complete (Kickoff meeting Feb. 7, 2012)

## Budget

- $ ~12M total budget
- $ ~6M DOE share
- $ ~6M GE cost share

•Funding received from the DoE to date: $ 3,643,568

## Barriers

Very challenging set of specs

- High efficiency over a wide speed and load ranges
- High power density and high coolant inlet temperature
- Low cost targets based on 100,000 units/year
- High speed poses mechanical challenges
- No rare-earth permanent magnets

## Partners

- GE Global Research (lead)
- GE Power Conversion/GE Licensing
- University of Wisconsin-Madison
- North Carolina State University
- University of Akron
- ORNL
- NREL
- McCleer Power
- Ames National Lab
- Arnold Magnetics

# The Problem

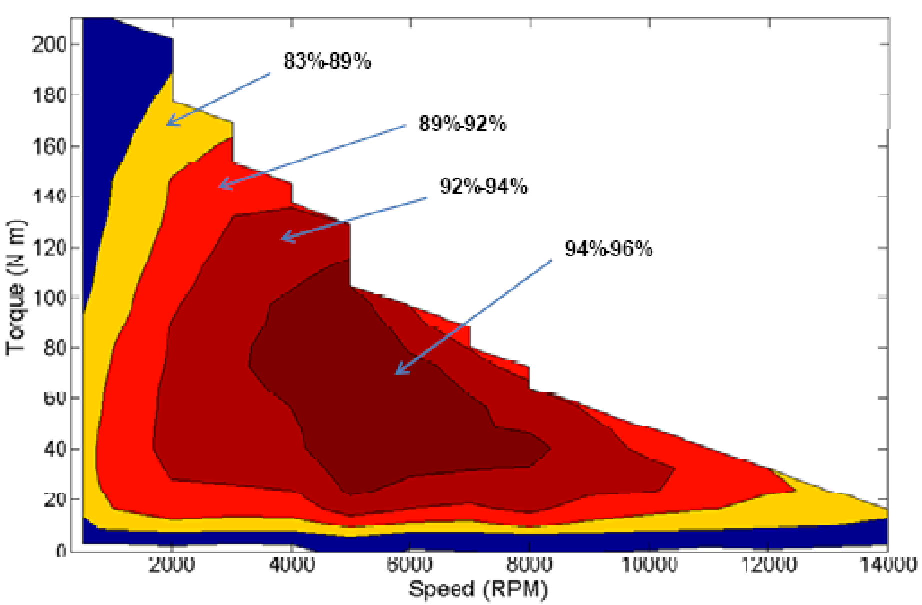
- The specifications for hybrid vehicle motors are challenging in terms of power density, efficiency and cost. This requires a comprehensive approach to advance the state of the art, including novel concepts to push past barriers.
- High speed is key to high power density
- High speed leads to higher electrical frequency
- Higher stator core and rotor losses
- On top of all these challenges, eliminating rare-earth permanent magnets makes the problem an order of magnitude more challenging

# Project Objective (FY14/FY15)

| Items | Specification |
|---|---|
| **Max. Speed** | 14,000rpm |
| **Peak Power** | 55kW @ 20% speed for 18sec |
| **Maximum Current** | 400Arms |
| **Cont. Power** | 30kW @ 20~100% speed @ Vdc=325 |
| **Efficiency** | Refer to target efficiency map |
| **Operating Voltage** | 200~450V (325V nominal) |
| **Back EMF** | <600Vpk line-to-line @ 100% speed |
| **Torque Pulsation** | <5% of Peak Torque @ any speed |
| **Characteristic Current** | < Maximum Current |
| **Weight** | ≤35kg |
| **Volume** | ≤9.7L |
| **Cost @100k** | ≤$275 |
| **Ambient (outside housing) Operating Temperature** | -40~140°C |
| **Coolant inlet** | 105°C, <10LPM, 2psi drop, <20psi inlet |
| **Minimum isolation impedance-phase terminal to GND** | 1Mohm |

- Finish build and testing of the down-selected 3 motor prototypes
- Down-select and build/test final 55kWpk non-rare earth motor to meet DOE specifications

**Figure 1. Motor Efficiency Targets**



# Relevance

Developing a low-cost, high-performance advanced traction motor is a key enabler to meeting the 2020 technical targets for the electric traction system. Elimination of rare-earth permanent magnets is very strategic in terms of eliminating the uncertainty regarding sustainability of rare-earth magnets

*Table 1. Technical Targets for Electric Traction System*

| | 2010[a] | 2015[b] | 2020[b] |
|---|---|---|---|
| **Cost, $/kW** | <19 | <12 | <8 |
| **Specific power, kW/kg** | >1.06 | >1.2 | >1.4 |
| **Power density, kW/L** | >2.6 | >3.5 | >4.0 |
| **Efficiency (10%-100% speed at 20% rated torque)** | >90% | >93% | >94% |

[a] Based on a coolant with a maximum temperature of 90°C.

[b] Based on air or a coolant with a maximum temperature of 105°C.

[c] A cost target for an on-board charger will be developed and is expected to be available in 2010.

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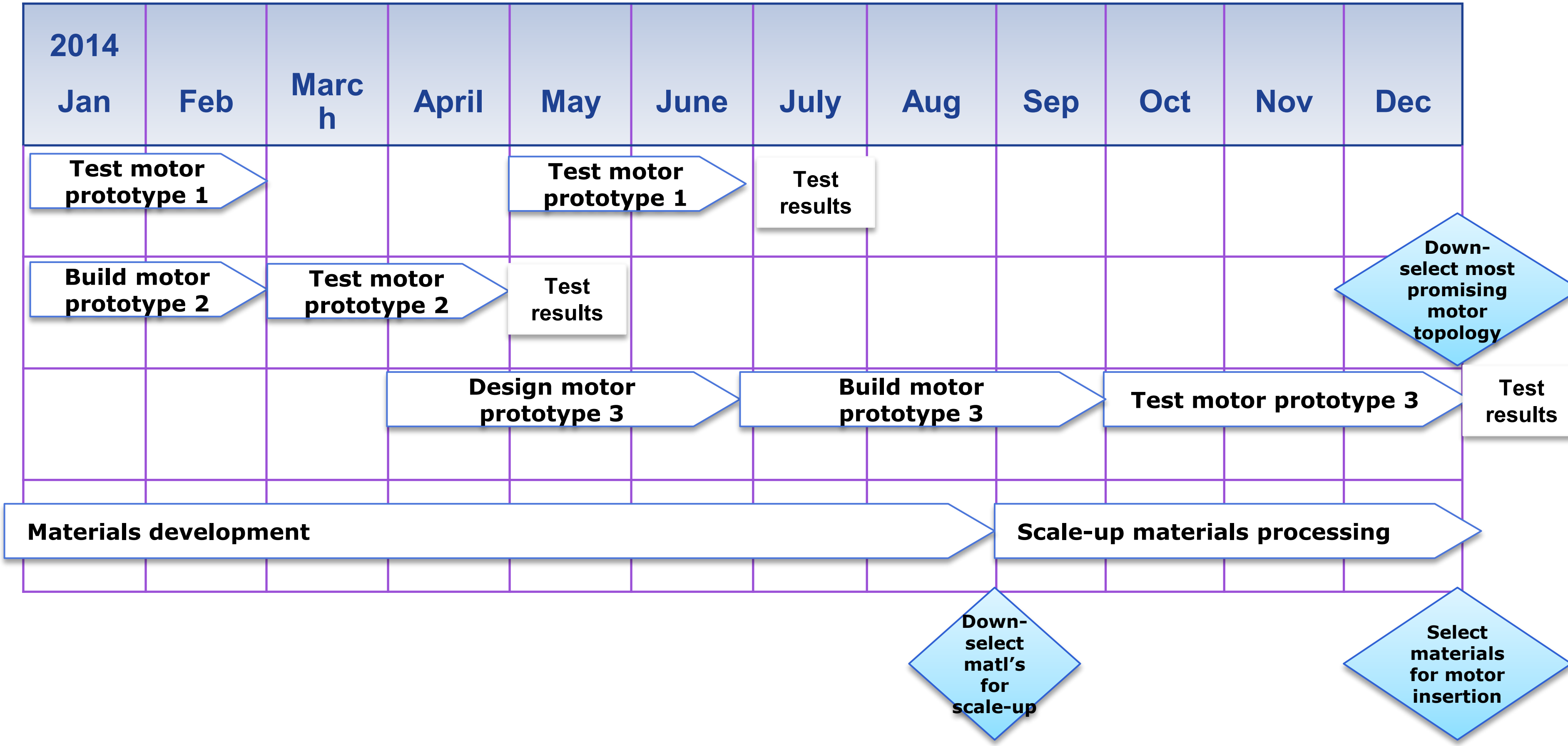
# Project Uniqueness and Impacts

- The project proposes a very comprehensive approach in terms of identifying the technologies that will meet the required performance
- The project will explore various motor topologies; some include no magnets at all and some include non-rare earth magnets
- Some of the motor topologies use only conventional materials while others will be enabled by advanced materials that will be developed under the project
- Advanced materials including magnetic as well as electrical insulating materials will be developed to enable the motors to meet the required set of specifications
- Advanced motor controls and thermal management techniques will also be developed.
- By evaluating the wide range of motor topologies and advanced materials, down-selected topologies/materials are expected to meet the required set of specifications

# Approach

- Perform tradeoff study of various motor topologies (≈10 topologies: some use conventional materials while others will be enabled by new materials)
- Identify promising scalable materials and produce coupons showing the expected properties (1 hard magnetic, 2 soft magnetic, 1 dielectric)
- Down-select promising topologies/materials
- Design/build/test 2-3 proof-of-principle motors
- Down-select final motor topology
- Design/build/test 3 identical motors as the key project deliverable(s)
- Develop cost model for the final motor

# FY14/15 Approach and Milestones




**Go No/Go Decision Point:** The key go no/go decision point will be after the 3 down-selected motor prototypes are built and tested to determine based on test results how do they compare to the baseline IPM with rare-earth magnets.

**Challenges/Barriers:** The set of specifications is very challenging and eliminating rare-earth permanent magnets is a big hit in terms of torque density and efficiency

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# Accomplishments to Date

## 9 patent applications with several others pending

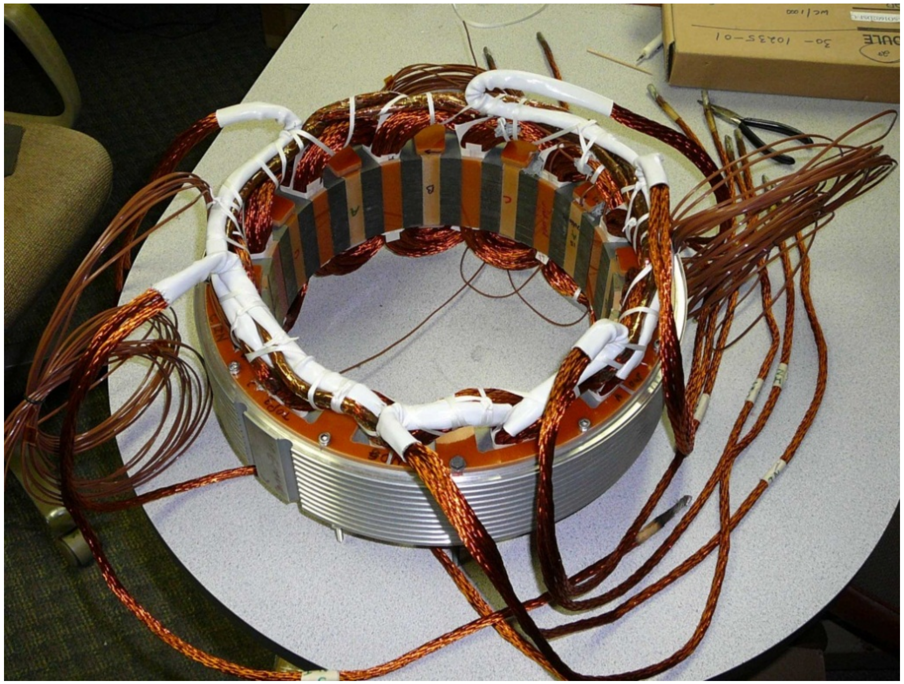
# Motor accomplishments:

- Continue to evaluate more motor topologies (more than 10 evaluated so far)
- Down-selected the first 2 topologies while the third is still under evaluation:
  - First prototype has reduced rare-earth content (built and currently being tested)
  - Second has non-rare earth magnets (built and currently being tested)
  - Third prototype has no magnets (down-select topology, build and test in FY14)
- Identified the theoretical properties for the advanced materials to be developed and quantified their impact on some of the motor topologies

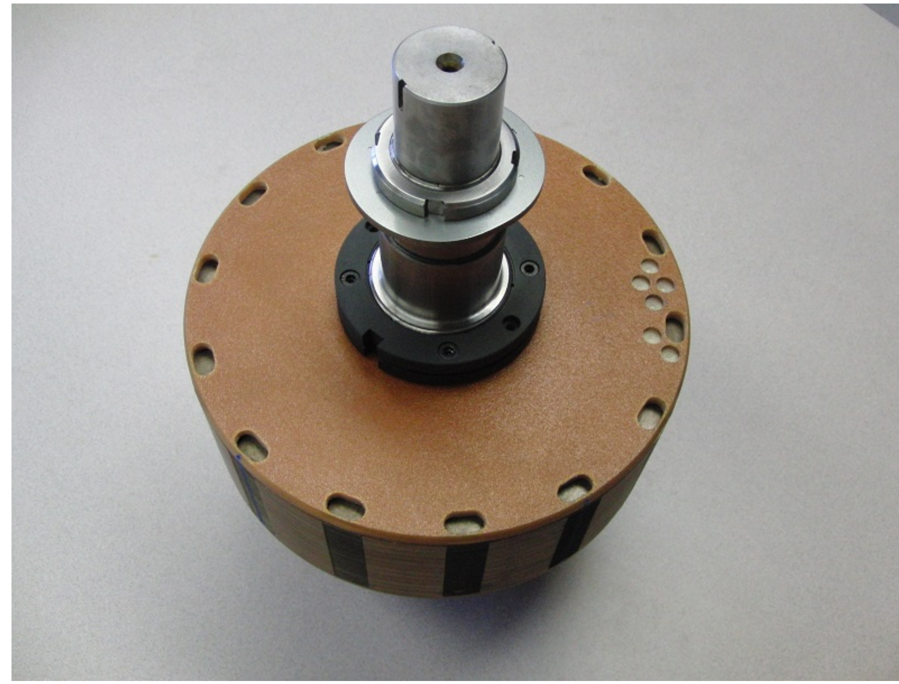
# Materials accomplishments:

- High temperature (>250 °C ) slot-liner insulation ready for scale-up
- Demonstrated GE-synthesized non-rare-earth permanent magnets with Hci > 2.0 kOe
- Developed method for locally patterning non-magnetic regions on motor lams with < 100 µm interface widths that are stable > 5000 hours at 180 °C
- Discontinued efforts to develop higher-strength silicon steel laminates due to high core loss
- Performed initial studies on scalability of new materials for sub-scale prototype motor builds.

# First Motor Prototype (Dy-free magnets)



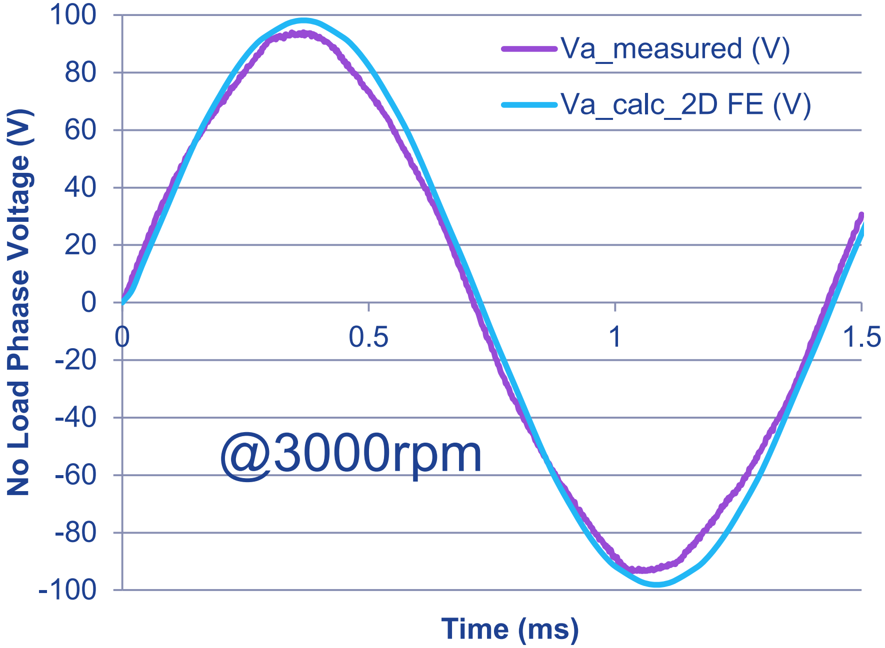
Stator

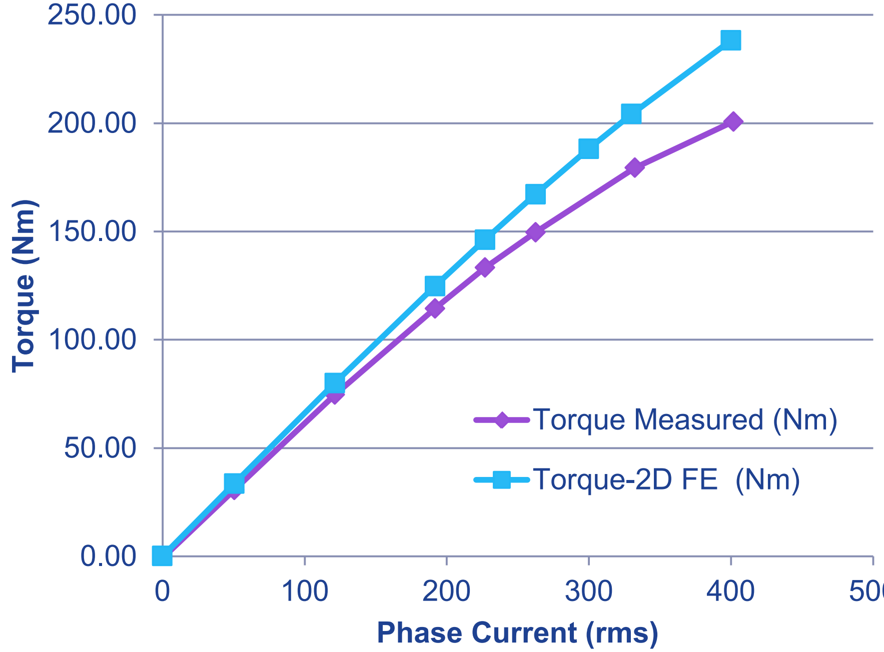


Rotor

***Prototype build finished and testing is underway***

# Tested Machine Performance

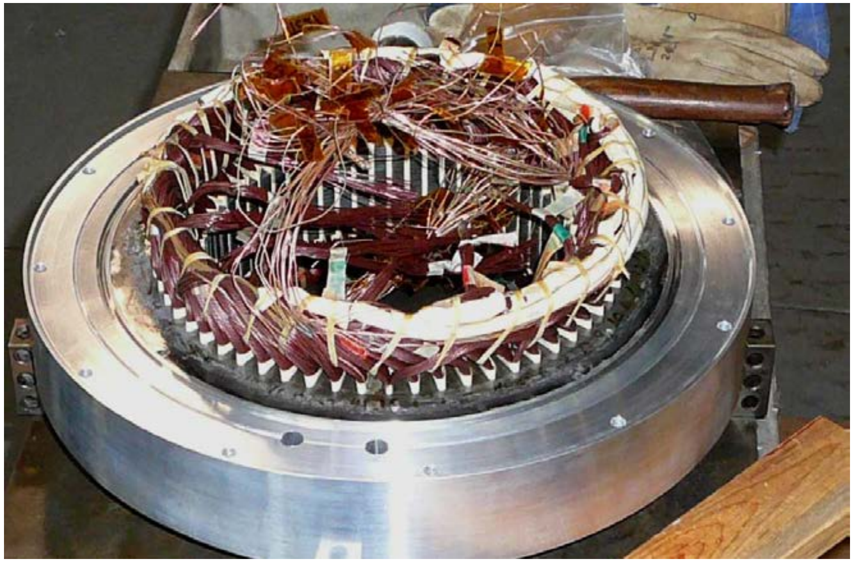



Discrepancy due to 3D effect (accounted for in design stage to achieve required torque)
Machine able to provide 200Nm Peak Torque at Max Current (requirement is 187.6Nm)

| Speed [RPM] | Irms Ref. | Gamma Ref. | Speed [RPM] | Torque [N-m] | Pm [kW] | Pmot [kW] | Eff [%] | Vph [Vrms] | Vll [Vrms] | Iph [Arms] | PF | Loss [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2800** | 224.7 | 10.00 | 2800 | **131.9** | **38.67** | 40.89 | **94.6** | 71.4 | 123.7 | 230.7 | 0.828 | 2.22 |
| **5600** | 108.2 | 2.00 | 5600 | **61.8** | **36.23** | 38.76 | **93.5** | 116.4 | 201.5 | 111.8 | 0.993 | 2.53 |

# Second Motor Prototype (Ferrite magnets)

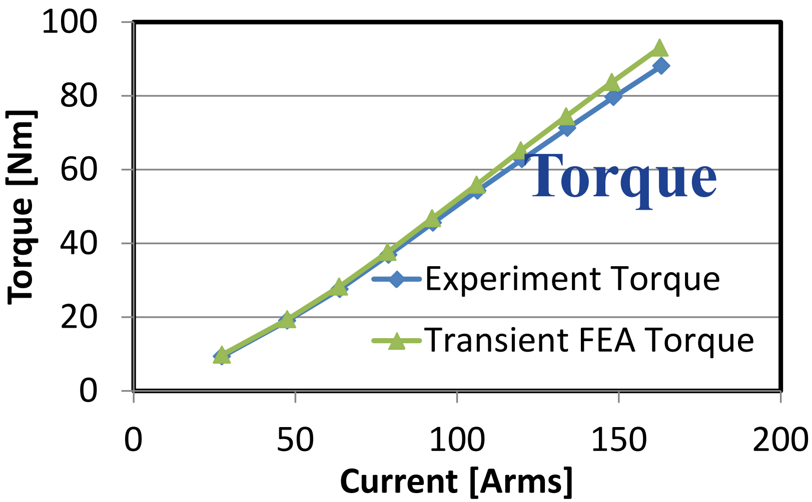


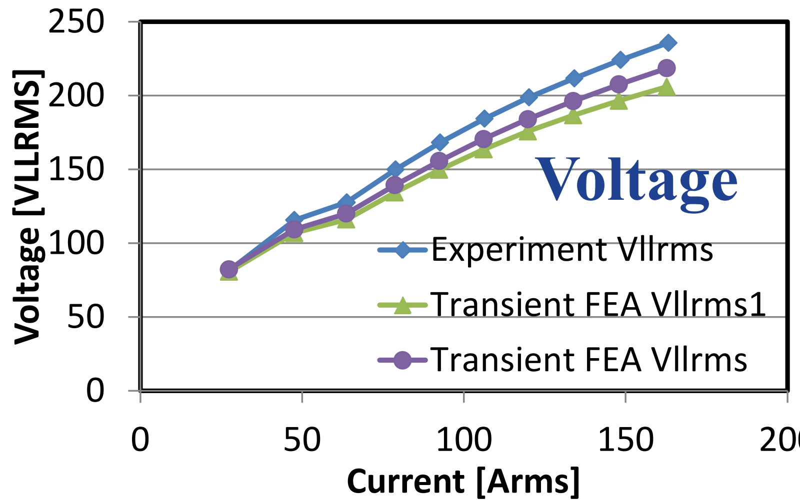
Stator

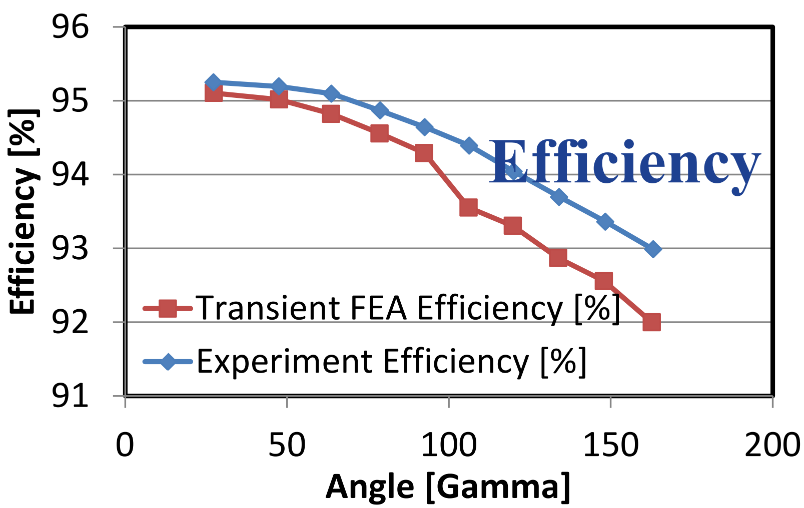

Rotor

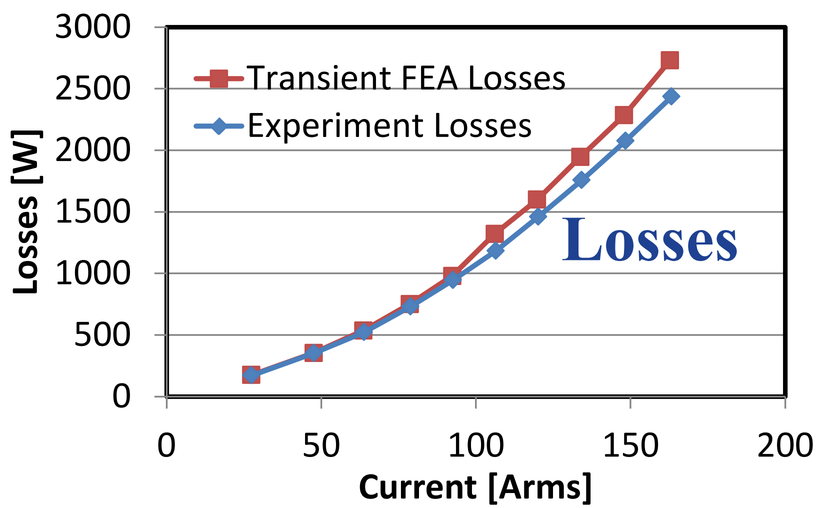
***Prototype build finished and testing is underway***

# Sample Measured Performance at 3500 rpm



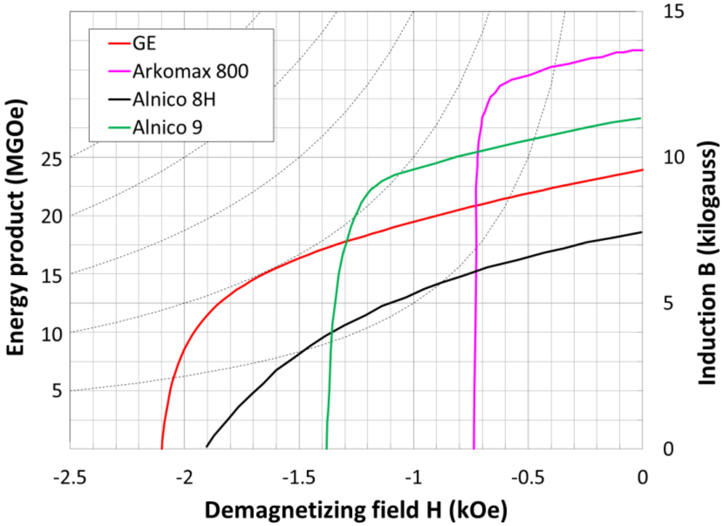



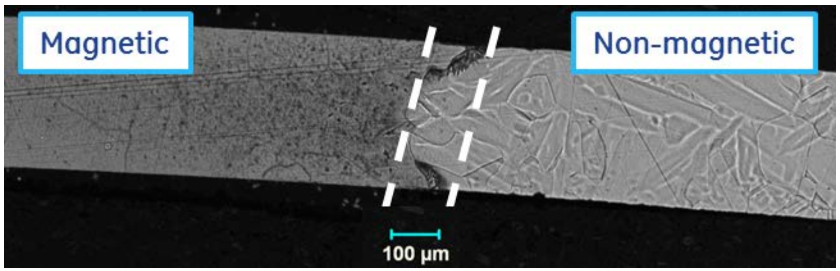



# Materials accomplishments

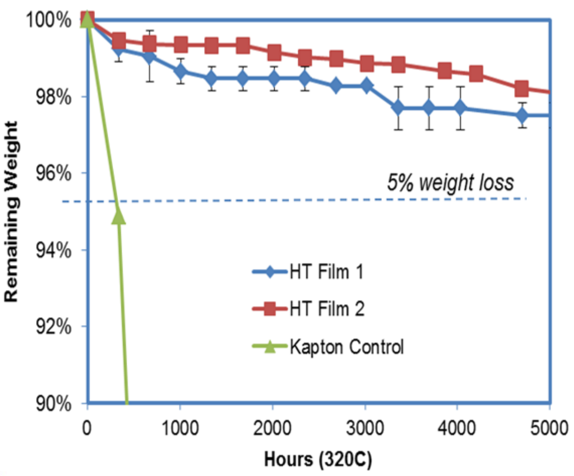
Advanced processing of non-rare-earth permanent magnets

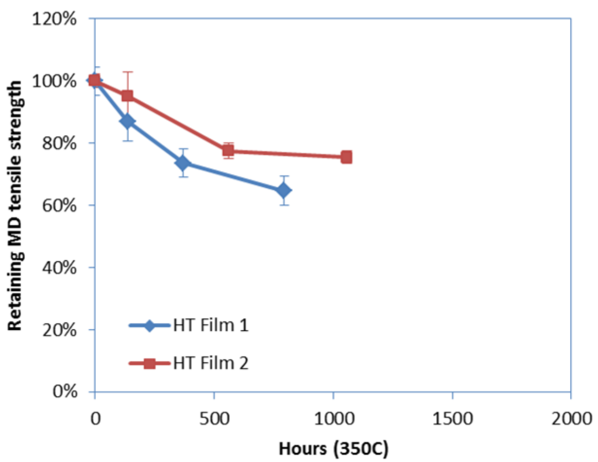



Dual-phase motor laminates with locally patterned low μ regions for flux path control




High temperature slot-liner insulation

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# Remaining Challenges and Barriers

- Successful testing of the 3 motor prototypes in 2014 and confirming that their performance is close to predictions
- This will guide the down-selection of the final motor concept
- Developing the advanced materials with the required properties
- Being able to scale the materials up in time for the final motor build and test

# Collaborations

## Motor Development:

- North Carolina State University: Evaluation of motor topologies
- University of Akron: Evaluation of motor topologies
- University of Wisconsin: Evaluation of motor topologies
- NREL: Evaluation of thermal management schemes
- ORNL: Evaluation of motor topologies and materials

## Materials Development:

- Ames Laboratory: High resolution microscopy of magnetic materials
- Arnold Magnetic Technologies: Specialized magnetic material processing and characterization

# Proposed Work Beyond FY13

FY14

- Finish test proof-of-principle motors/materials
- Final selection of motor topology/materials based on test results of proof-of-principle motors
- Scaled manufacturing of selected materials

FY15

- Down-select, build and test final motor
- Scaled manufacturing of selected materials

# Summary

- Significant progress made since last year
- More than 10 motor topologies fully evaluated
- 9 filed patent applications with several others pending
- First motor prototype using Dy-free magnets built and currently being tested
- Second motor prototype using ferrite magnets built and currently being tested
- 3 topologies with no magnets are currently under evaluation to down-select the third motor prototype that will be built and tested in 2014
- Test coupons of advanced motor materials have been manufactured and characterized
- Scalable manufacturing methods for advanced materials have been identified
- Improved performance has been quantified in soft magnetic laminates and high temperature insulation

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