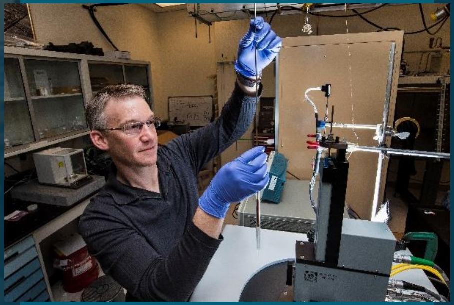
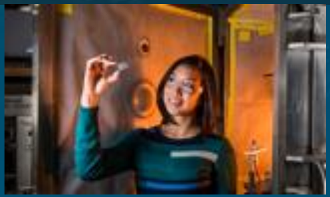
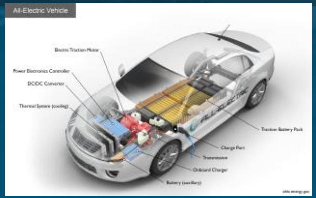
# Isotropic, Bottom-Up Soft Magnetic Composites for Rotating Machines








Todd C. Monson, PI, Electric Motors

Keystone 2: Electric Motors

Sandia National Laboratories

June 11, 2019

Project ID: elt216

# Overview

## Timeline

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

## Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY19: $125k

## Barriers

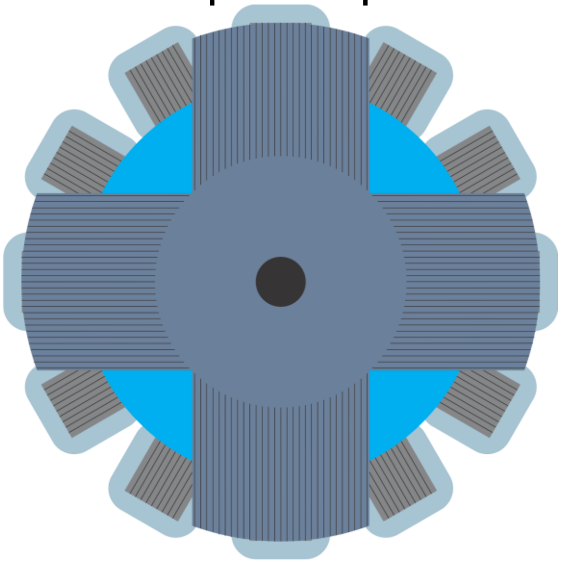
- Non-rare-earth electric motor performance
- Material property optimization (to lower cost and improve performance and reliability)
- Reliability: High temperature performance (150 ºC) over a long lifetime (300,000 miles)

## Partners

- ORNL, NREL, Ames Lab
- Purdue University, Illinois Institute of Technology (IIT)
- Project lead: Sandia Labs

# Relevance

- To meet 2025 goals for enhanced peak power (100 kW), specific power (50kW/L), and reduced cost (3.3 $/kW) in a motor that operates at > 20,000 rpm, improved soft magnetic materials must be developed
- Improved soft magnetic materials will enable high performance non-rare-earth motors
- Replacement of permanent magnets with soft magnet materials highlighted in Electrical and Electronics Technical Team (EETT) Roadmap as a potential R&D pathway for meeting 2025 targets



Homopolor motor design (courtesy of Scott Sudhoff at Purdue) that doesn't require permanent magnets

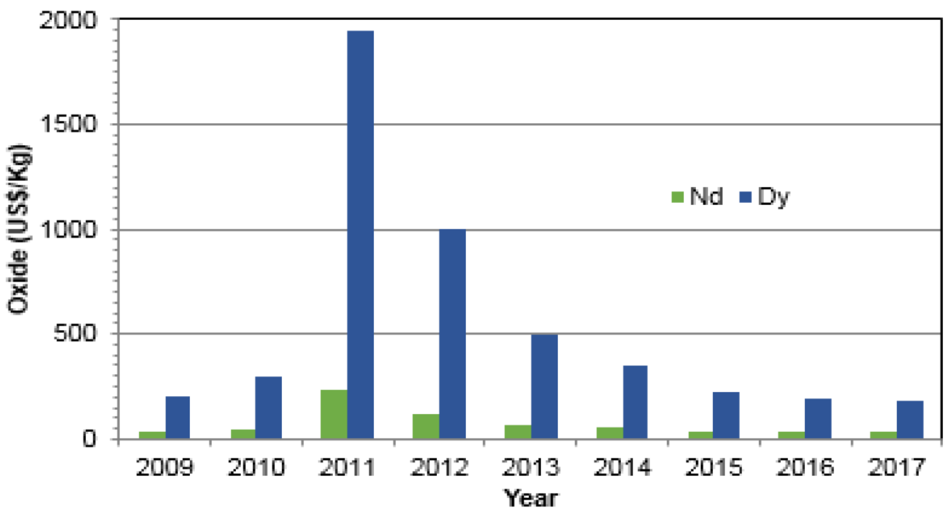



*Figure 9. Rare Earth Metal Prices Track Oxides Very Closely*
Source: Metal Pages courtesy of Critical Materials Institute

As seen in Oct. 2017 EETT Roadmap

# Milestones

| Milestone, Keystone 2 – Electric Motors | |
|---|---|
| 2.1 Demonstrate a composite magnetic stator, and evaluate saturation polarization ($J_s$) and eddy-current losses. | 9/30/2019 |

**Progress towards milestone to date:**

- Completed a survey of current state of the art in soft magnetic composites for electrical machine applications
- Developed process for converting mixed phase commercial $Fe_xN$ powder to phase pure γ’-$Fe_4N$
- Fabricated prototype $Fe_4N$ composite inductor and characterized its magnetic properties
- Selected epoxy chemistry and demonstrated the formation of an iron/epoxy composite toroid

# Approach

- Develop high magnetization, low loss iron nitride based soft magnetic composites for electrical machines
- Composite approach will lower losses even further and enable efficient operation at rotational speeds up to 20,000 rpm
- Epoxy based matrix (binder) capable of operating at elevated temperatures (up to 150 °C) over an extended lifetime (300,000 miles or 15 yrs.)
- $\gamma'$-$Fe_4N$ has a higher saturation polarization ($J_s$) and electrical resistivity than Si steel
- Use of abundant elements (Fe and N) will keep costs low

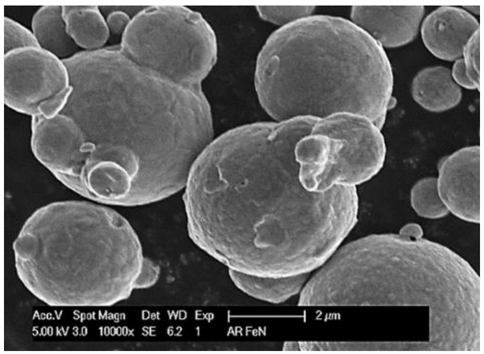
| Element | Mass fraction (ppm) |
|---|---|
| Hydrogen | 739,000 |
| Helium | 240,000 |
| Oxygen | 10,400 |
| Carbon | 4,600 |
| Neon | 1,340 |
| Iron | 1,090 |
| Nitrogen | 960 |
| Silicon | 650 |
| Magnesium | 580 |
| Sulfur | 440 |

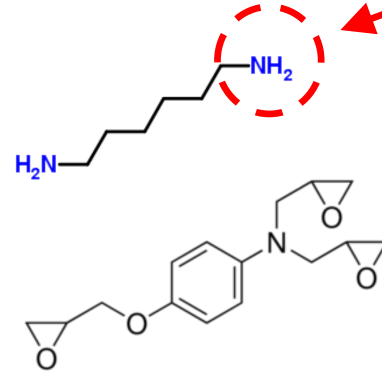
From Croswell, Ken (February 1996). Alchemy of the Heavens. Anchor. ISBN 0-385-47214-5.

# Approach

Diamines will bond directly to $Fe_4N$ surface and epoxy matrix for enhanced mechanical robustness and particle electrical isolation

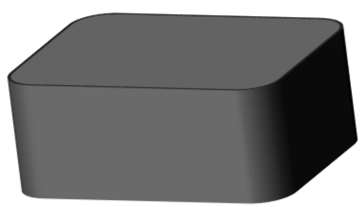
Convert commercial $Fe_xN$ powder to phase pure $Fe_4N$

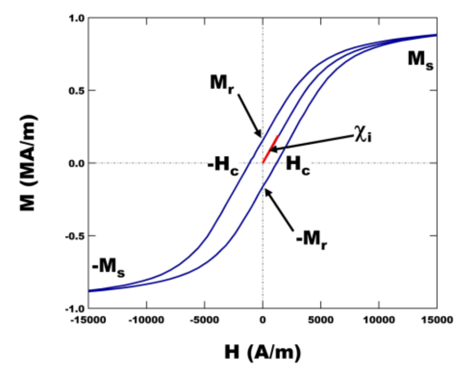



Coat $Fe_4N$ and mix with epoxy monomers

- Pour into 3D printed mold and cure into stator/rotor part
- Press if necessary to increase density and loading factor
- Results in a net-shaped part (no machining required)






Evaluate and test

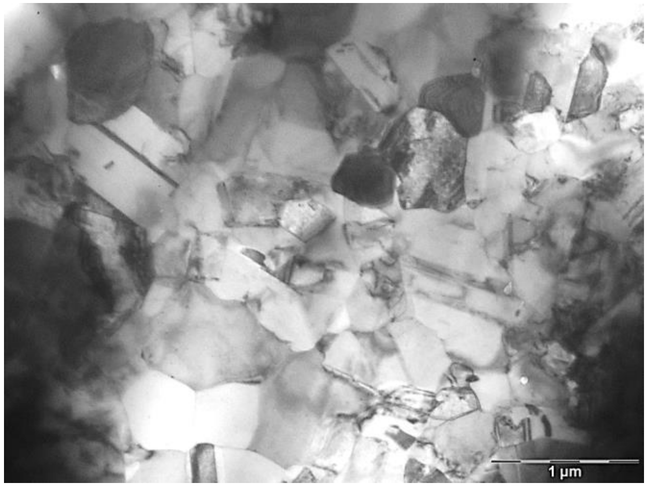
# Approach – Epoxy Robustness in Motors

- Possible to design epoxy systems with glass transition temperatures ($T_g$) much greater than 150 °C [1,2]
- Epoxies are already ubiquitous in electrical machine construction [2,3]
- Composites have already been successfully demonstrated in high speed motors [4] and even flywheels rotating up to 60,000 rpm [5]
- Selecting our own epoxy monomers allows us to design our composite from the ground up and tailor its properties
    - Curing protocol can be adjusted to further tune $T_g$ and mechanical properties
- Diamines will bond directly to $Fe_4N$ surface and epoxy matrix for enhanced mechanical robustness and particle electrical isolation


1. https://www.masterbond.com/techtips/how-optimizing-glass-transition-temperature-tg
2. https://magneticsmag.com/new-structural-adhesive-from-delo-for-magnet-bonding-has-high-temperature-stability/
3. http://www.crosslinktech.com/products-by-application/featured-electric-motor-products.html
4. A. Schoppa and P. Delarbre, "Soft Magnetic Powder Composites and Potential Applications in Modern Electric Machines and Devices," in IEEE Transactions on Magnetics, vol. 50, no. 4, pp. 1-4, April 2014, Art no. 2004304. DOI: 10.1109/TMAG.2013.2290135
5. Mason, Patrick & Atallah, K & Howe, D. (1999). Hard and soft magnetic composites in high speed flywheels. International Committee on Composite Materials, Paris

# Technical Accomplishments and Progress

## Fabrication of γ'-$Fe_4N$ components

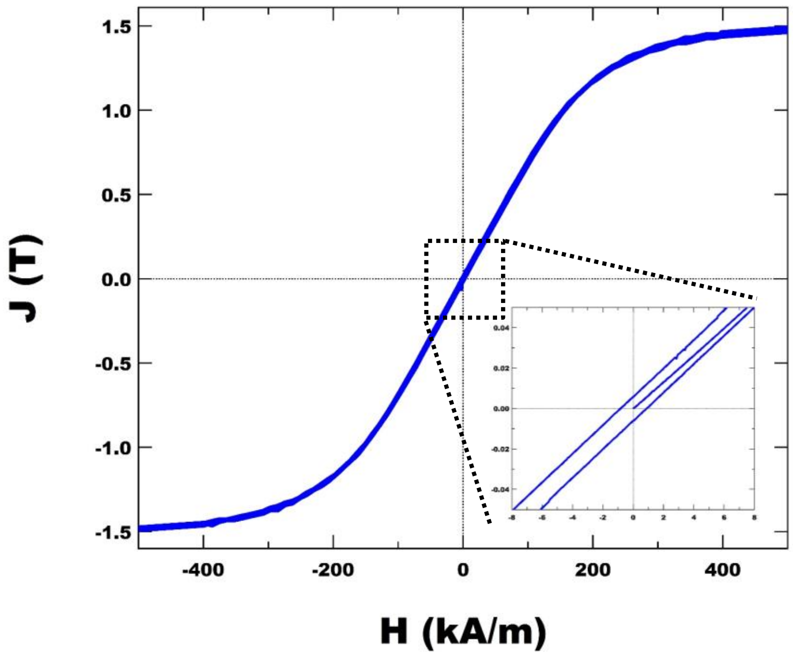


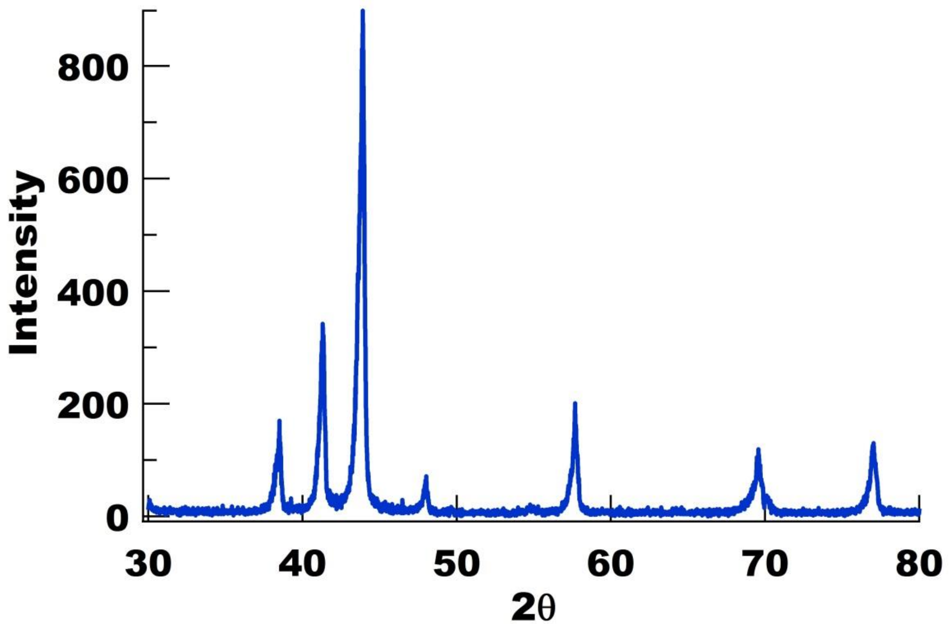

- First ever fabrication of bulk γ'-$Fe_4N$ parts
  - Spark plasma sintering (SPS) used for consolidation of bulk $Fe_4N$
- U.S. Patent #9,963,344

| Magnetic Material | $J_s$ (T) | ρ(μΩ·m) | Cost |
|---|---|---|---|
| Si steel | 1.87 | 0.05 | Low |
| γ'-$Fe_4N$ | 1.89 | ~200 | Low |

# Technical Accomplishments and Progress

## Current γ'-$Fe_4N$ properties

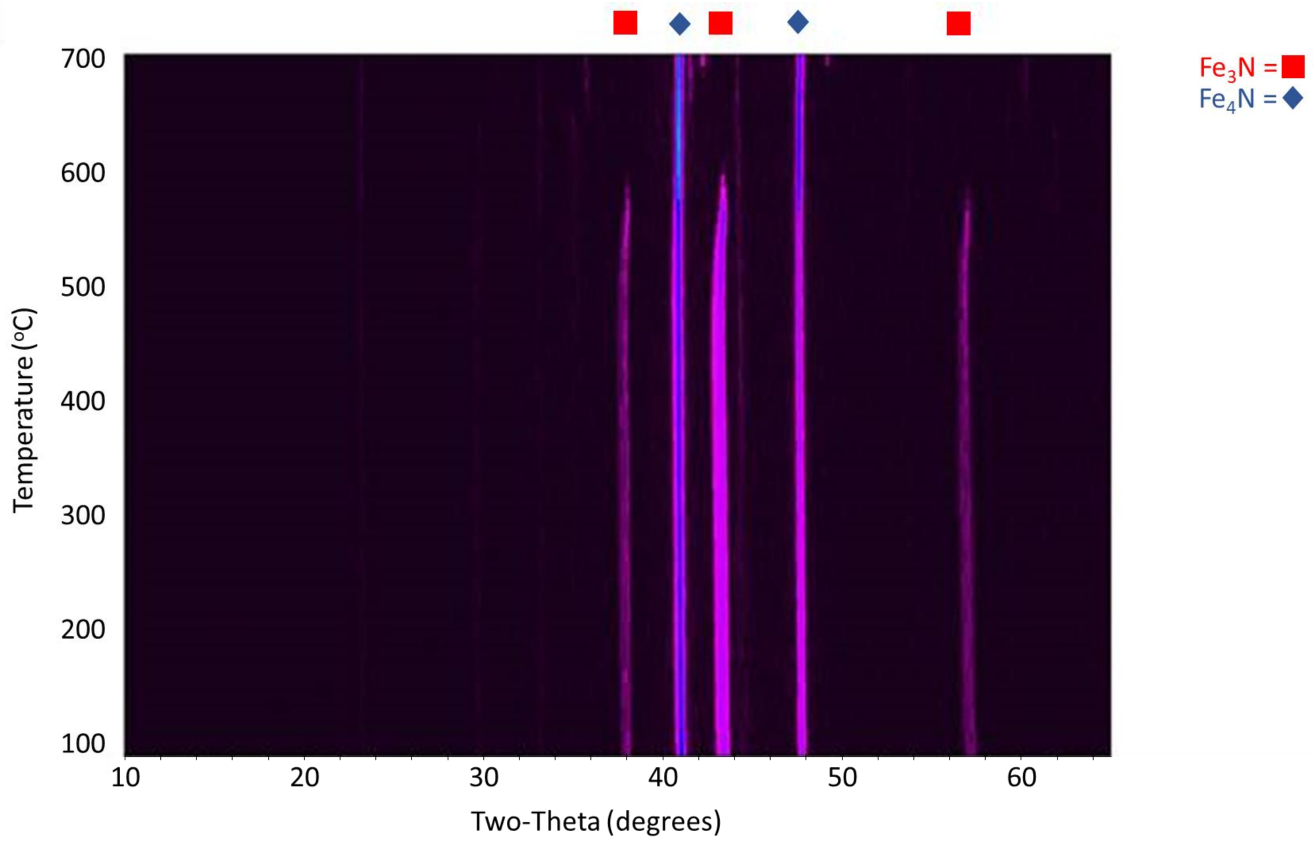



- $J_s$ = 1.62 T (Theoretical value is 1.89 T)
- > 80% γ'-$Fe_4N$
  - Secondary phases of $Fe_3N$ and Fe present
- We have developed a process to create phase pure material…

# Technical Accomplishments and Progress

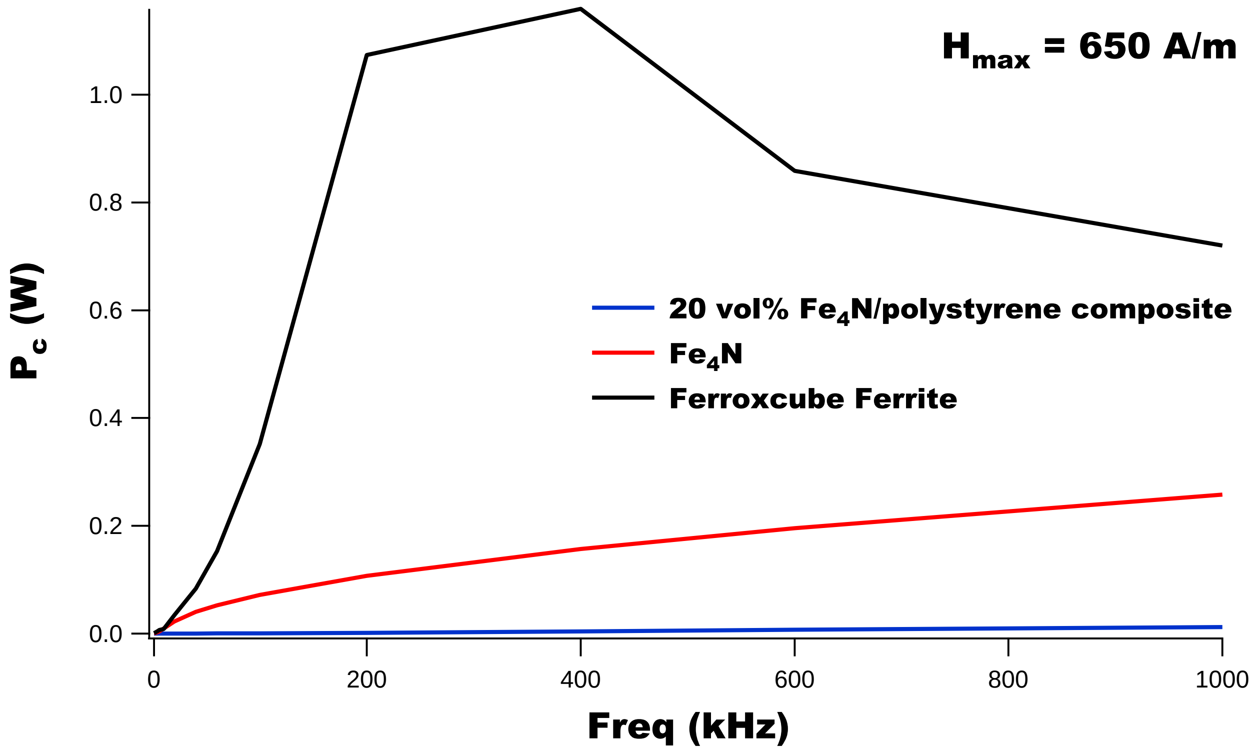
## Production of phase pure γ'-$Fe_4N$ powder




- Simple heat treatment converts mixed phase commercial powder
- Only phase pure γ'-$Fe_4N$ remains

# Technical Accomplishments and Progress

## Preliminary γ'-$Fe_4N$ composite results

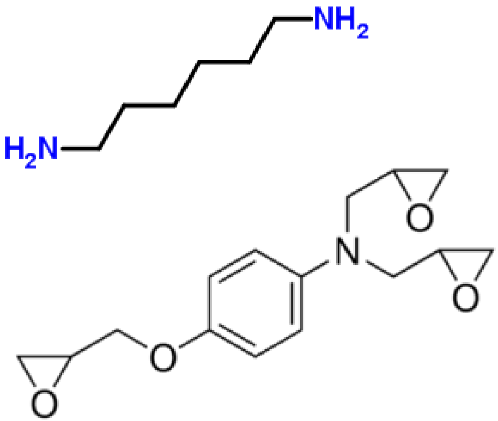



- Significantly lower core losses in $Fe_4N$ composites when compared to both bulk $Fe_4N$ and COTS ferrites
- Much higher volume loadings of $Fe_4N$ still possible
- Transitioning to epoxy matrix will exceed temperature and mechanical strength requirements

# Technical Accomplishments and Progress

## Epoxy chemistry demonstrated

- Epoxy based chemistry successfully demonstrated using iron particles
- Chemistry should proceed identically as we transition to $Fe_4N$ particles
- Smaller chain diamines available to decrease particle spacing and increase volume loading of $Fe_4N$ even further




Iron/epoxy 3D printed toroid

# Responses to Previous Year Reviewers' Comments

- N/A:  First year of project
  - Project not reviewed last year

# Collaboration

- Purdue University (Scott Sudoff) – Motor design, prototyping, and testing
- IIT – Design, construction, and dynamometer testing of 3 reduce power prototype machines
- ORNL – High-Fidelity Multiphysics Material Models for Electric Motors
- Ames – Additional expertise in magnetic material fabrication, processing, and characterization
- NREL – Advanced packaging, reliability, prognostics, thermal management

# Remaining Challenges and Barriers

- Ensuring epoxy $T_g$ > 150 °C
- Ensuring adequate mechanical strength for > 20,000 rpm motor operation
- Achieving sufficient magnetic particle volume loading for high performance in non-rare-earth electric motor designs

# Proposed Future Research

## Remaining FY19 Tasks

- Demonstrate epoxy composite approach with phase pure γ’-$Fe_4N$ particles
- Demonstrate a composite magnetic stator, and evaluate saturation polarization ($J_s$) and eddy-current losses (end of FY19 milestone)

## Research Beyond FY19

- Improve $Fe_4N$/epoxy composite based on evaluation of FY19 results (volume loading, eddy current loss, mechanical properties)
- Optimize epoxy properties
- Demonstrate $Fe_4N$/epoxy composite in prototype motor

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

# Summary

- Iron nitride (γ'-$Fe_4N$) properties ($J_s$, ρ) exceed those of Si steel
- Since Fe and N are the 6th and 7th most abundant elements, $Fe_4N$ will be a very low cost new soft magnetic material
- Net-shaped Fe4N/epoxy composites will increase efficiency through reductions of eddy current losses
  - Custom epoxy crosslinked directly to magnetic particles will have enhanced properties
  - Epoxy matrix will exceed 150 °C temperature requirements
  - $Fe_4N$/epoxy composite can achieve the required mechanical strength for motors operating at > 20,000 rpm

Sandia Labs Team Members: Jason Neely, Jack Flicker, Bob Kaplar, Tyler Stevens