Advanced Electric Motor Research

Tim Burress

Email: burressta@ornl.gov

Phone: 865-946-1216

Oak Ridge National Laboratory

2016 U.S. DOE Vehicle Technologies Office Review

June 7, 2016

Project ID: EDT062

ORNL is managed by UT-Battelle for the US Department of Energy

OAK RIDGE National Laboratory

Overview

Timeline

- Start – FY14
- End – FY16
- ~38% complete (June/36)

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY15: $ 1,516 K
- Funding for FY16: $ 1,400 K

Barriers

- Even without using rare earth PM material, DOE EDT 2020 cost targets are challenging.
- PD and SP targets will be difficult to meet with alternative technologies
  - Field excitation
  - Synchronous reluctance
  - Switched reluctance
  - Non-RE PM
  - Induction machine

Partners

- UQM
- NREL
- AMES/DREaM
- University of Wisconsin, Madison
- ORNL Team members
  - Radhakrishnan Balasubramaniam
  - Jason Pries
  - Randy Wiles
  - Andy Wereszczak
  - Amit Shyam
  - G. Muralidharan

Project Objectives and Relevance

- **Overall Objective:** Develop low cost non-rare earth motor solutions while maintaining high power density, specific power, and efficiency.
  - Develop or utilize new materials.
  - Perform fundamental research to improve motor modeling accuracy.
    - Evaluate impacts of factory stamping upon magnetic properties and motor performance.
    - Develop advanced modeling algorithms.
  - Employ high performance computational tools and resources.
  - Design unconventional motor technologies that address DOE EDT 2020 motor targets.

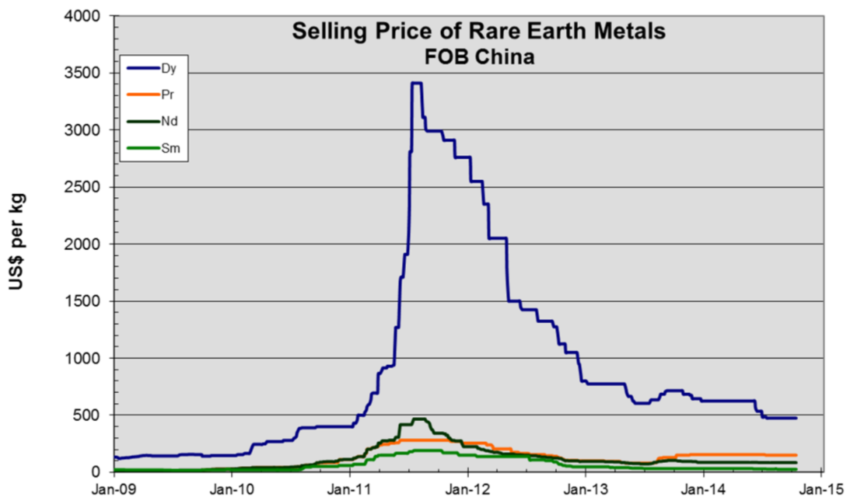
- **FY16 Objectives:**
  - Conduct proof-of-principle prototype testing to aid with modeling activities.
  - Develop/implement methods to facilitate the use of high efficiency steel.
  - Continue fundamental electromagnetic material studies and experiments to identify impacts of residual stress upon magnetic properties in electrical steel.
  - Utilize micro-magnetics software code to aid with magnetic domain evolution theory, and complement residual stress studies.
  - Perform initial optimization of down-selected motor designs based on basic simulations that indicate promising results with respect to DOE targets.

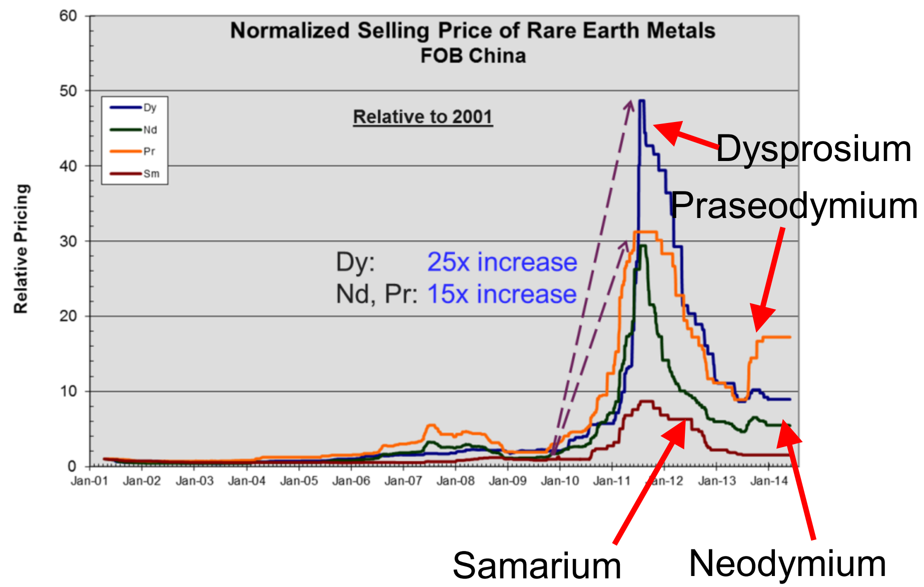
Milestones

Date	Milestones and Go/No-Go Decisions	Status
July 2015	Go/No-Go decision: If non-rare earth motor design simulation results indicate that the design will meet DOE EDT 2020 motor targets, then fabricate motor prototype.	Complete.
September 2015	Milestone: Summary report with findings from materials research and development and motor testing.	Complete.
March 2016	Milestone: Fabricate and test high efficiency electrical steel.	Complete.
June 2016	Go/No-Go decision: If non-rare earth or reduced rare-earth motor design simulation results indicate that the design will meet DOE EDT 2022 motor targets, then fabricate motor prototype.	On track.
September 2016	Milestone: Complete dynamometer testing of prototype selected in Q3 Go/No Go Decision Point.	On track.

Approach/Strategy

- Rare earth (RE) permanent magnet (PM) motors that dominate the EV/HEV motor market are not cost effective.
  - RE elements in PMs contribute up to 78% of the total DOE EDT 2022 electric motor cost target
    - Currently 30-50% of actual cost
  - Uncertainty in RE material availability and the likelihood that metallurgical separation processes for heavy RE mean that pricing will remain high over the near term and longer





Source: Steve Constantinides, Arnold Magnetics

Approach/Strategy

- Design alternative motors that do not use rare-earth permanent magnets.
- Develop or utilize processes/materials that yield:
  - High efficiency
  - Improved heat transfer (in collaboration with NREL)
  - Increased power density and specific power
- This project has the potential to impact industry, academia, and the scientific community in many ways:
  - Fundamental research and new modeling techniques in the area of soft magnetic material (electrical steel).
  - Materials research and development is not specific to ORNL's motor designs.
  - Commercialization of innovative motor designs.

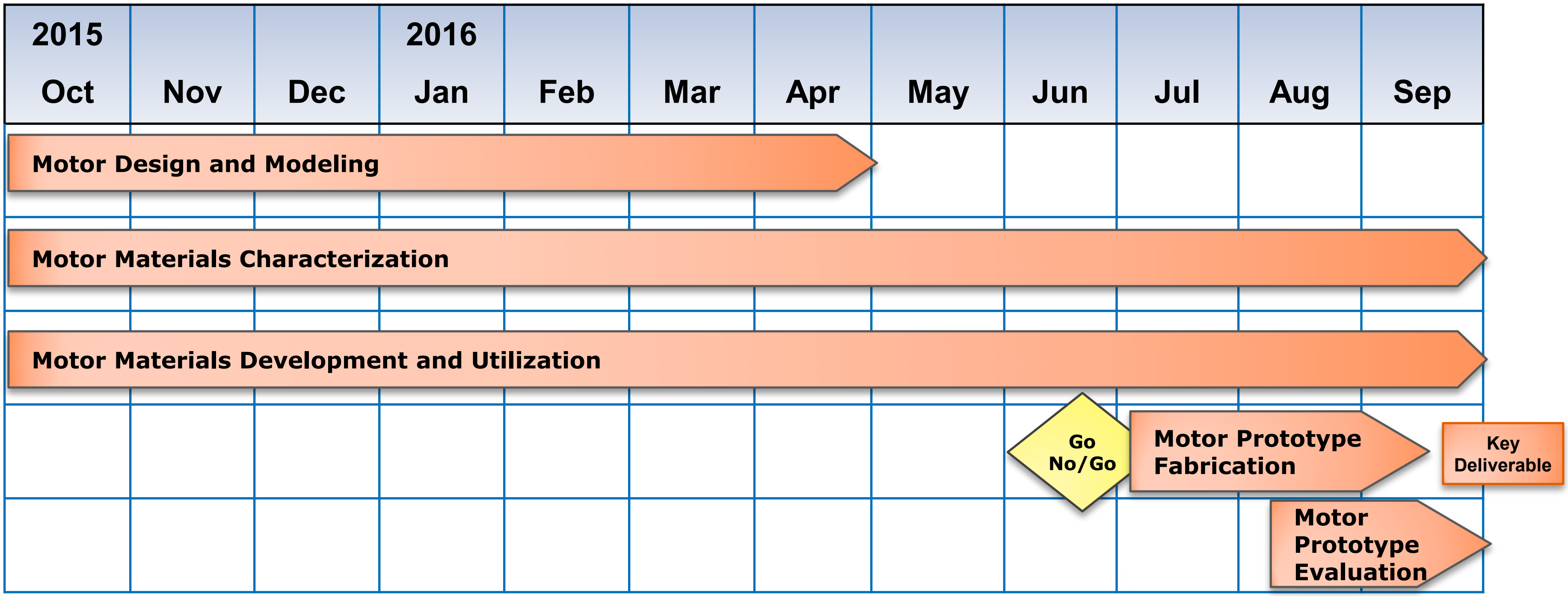
Approach/Strategy

Use advanced modeling and simulation techniques to perform design and control optimization for various electric motor types

- Brushless Field Excitation (BFE)
- Synchronous reluctance
- Non-RE Permanent magnet
- Switched reluctance
- Combination of two or more of the above

- Motor Design and Controls Optimization
  - Advanced Modeling
    - High Performance Computing
    - Next Generation FEA
    - Advanced Loss and Magnetic Properties Modeling
  - Motor Design with Conventional Techniques
    - Electro-magnetic & Mechanical FEA
    - State Space-Analytical Models
  - Fundamental Materials Research
    - Study of Magnetic Properties
      - Localized Analysis
      - Bulk Characterization
    - Materials Research & Development
      - Magnetic
      - Non-Magnetic
  - Empirical Verification
    - Benchtop Testing
    - Comprehensive Dynamometer Analysis

Approach FY16 Timeline



Go No/Go Decision Point: If non-rare earth or reduced rare-earth motor design simulation results indicate that the design will meet DOE EDT 2022 motor targets, then fabricate motor prototype.

Key Deliverable: Non-rare earth motor prototype.

FY14/FY15 Accomplishments

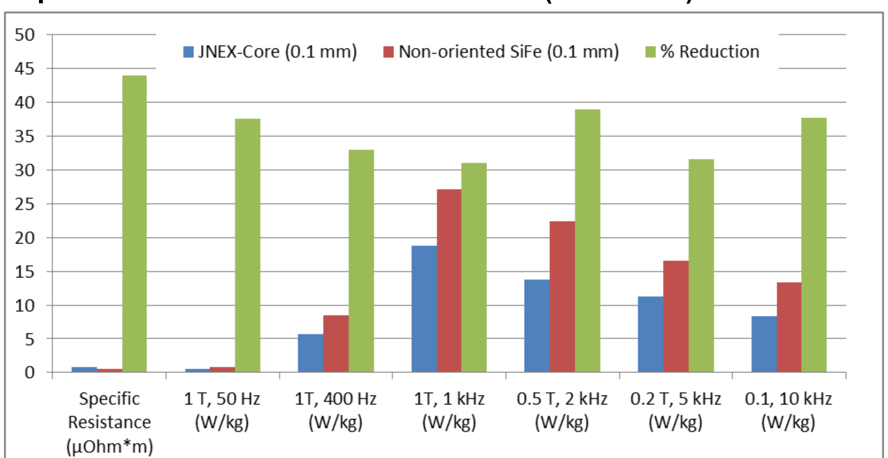
- Advanced Modeling
  - Developed simulation environment on supercomputer for modeling magnetic domains (at or near atomistic level) and domain wall propagation.
  - Began developing highly parallelized electromagnetic FEA code for use on high performance computing resources at ORNL.
    - The ultimate goal is to have an open platform supercomputer optimization tool for industry, national laboratories, universities, and other outside parties to optimize motor designs.
- Fundamental Materials Research
  - Process development for high efficiency electrical steel
    - Modeled, fabricated, and tested various high efficiency steel specimen for softening processes
  - Initiated first principles approach to loss modeling
  - Developed custom characterization systems for measuring non-homogeneous properties of electrical steel
  - Collaborated with NREL on motor thermal management research
    - See Andy Wereszczak's PM054 and Kevin Bennion's EDT064 2016 DOE AMR presentations.
- Motor Design and Testing
  - Developed 10 different motor technologies and down-selected to two promising motor technologies.
  - Prototyped and performed benchtop testing to confirm simulated torque performance.

FY16 Accomplishments

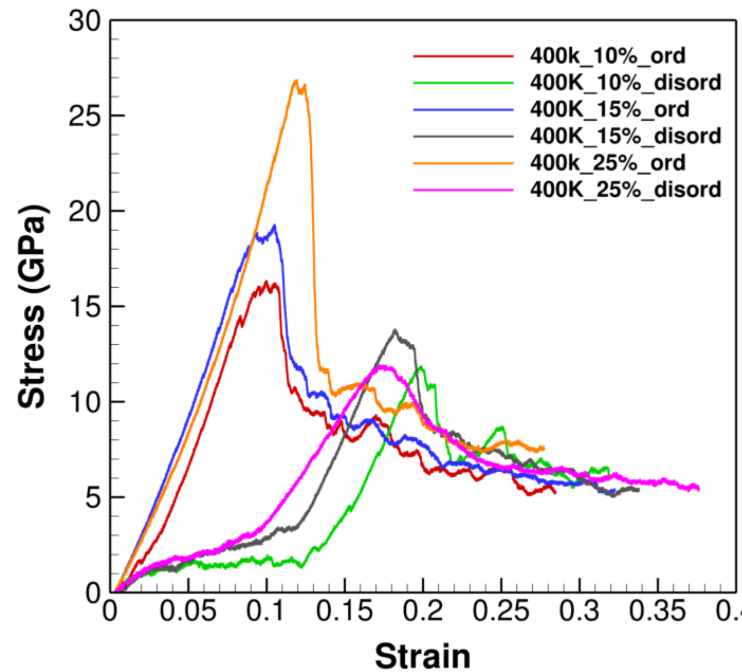
Modeling, Fabrication, and Testing for Process Development of High Efficiency Steel

- Currently, steel laminations with high Silicon content are 10-20x cost conventional steel laminations.
- New processes developed
  - May lead to costs comparable to conventional steel, with up to 40% reduction in losses.
  - Addresses difficulty with brittleness/workability of existing material and conventional processes.
  - Facilitates rolling of 6.5%Si Steel
  - Enhancement for cutting/stamping - improves tool lifetime.
  - Currently evaluating feasibility of techniques.

Comparison of Core Losses: 6.5% Silicon (JFE JNEX) vs 3% Silicon



Data Source: JFE Super Core Catalog



- Atomic scale simulations show the embrittling effect of Si during mechanical working of high silicon steels.
- Work focused on developing novel processing route to eliminate the embrittlement.

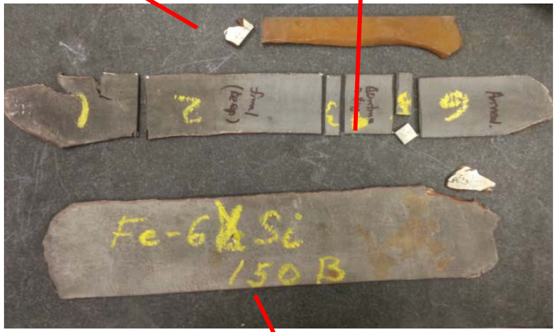
FY16 Accomplishments

Modeling, Fabrication, and Testing for Process Development of High Efficiency Steel

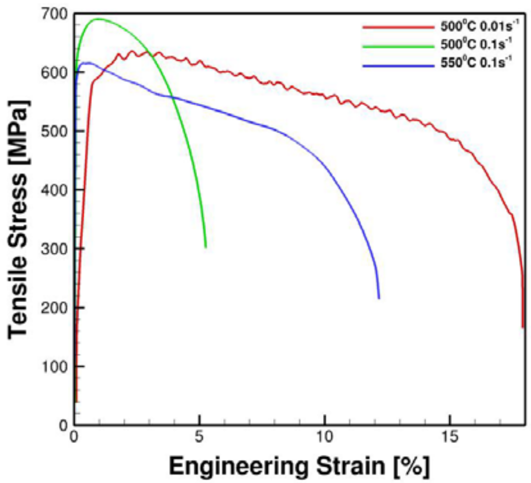
- Fe-6.5%Si-500ppm B alloy cast and rolled successfully to a thickness of 1 mm
- Exploited softening during warm deformation to perform initial rolling trials at room temperature.
- Current effort focused on optimizing warm rolling parameters for maximum RT ductility
- Controlled tension tests show clear indication of strain softening during warm deformation.

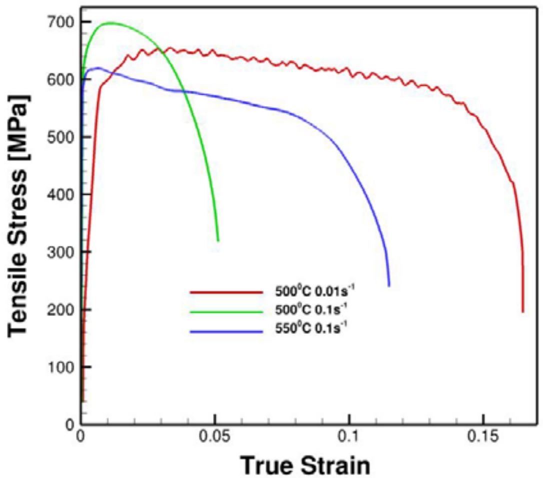
Fe-6Si+250wppm B
Hot rolled
HRC: 26.1

Fe-6Si+250wppm B
Warm rolled 53% ε
HRC: 39.6



Fe-6Si+150wppm B
Warm rolled 64% ε
HRC: 39





Measurements demonstrate softening during warm deformation tension testing at 500C during

Jointly funded by D.O.E. VTO's Electric Drive Technologies and Propulsion Materials Programs

FY16 Accomplishments

Advanced Modeling of FeSi Magnetic Properties

- Magnetic domain research provides deeper insight into factors that impact magnetization and loss properties, thereby facilitating improved modeling accuracy and material development efforts.
- Micromagnetics code/simulation space has been expanded to a larger scale to include multiple domains using unique scaling techniques and high performance computing.
- Complements experimental domain wall observation.
- Includes consideration of various interaction energies at the atomic scale, externally applied fields and elastic strains.

(Due to external field, H)

$$E_{ext} = -H.M$$

(magneto-crystalline anisotropy)

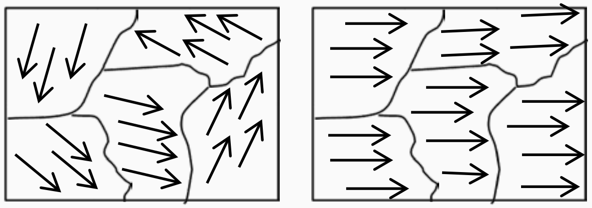
$$E_{an} = K_1\left(a_1^2 a_2^2 + a_2^2 a_3^2 + a_3^2 a_1^2\right) + K_2 a_1^2 a_2^2 a_3^2$$

(spin exchange energy)

$$E_{exch} = \sum_i \left(J_1 \sum_{n1=1}^{8} a_i a_{n1} + J_2 \sum_{n2=1}^{6} a_i a_{n2} + J_3 \sum_{n3=1}^{12} a_i a_{n3} + J_4 \sum_{n4=1}^{6} a_i a_{n4} \right)$$

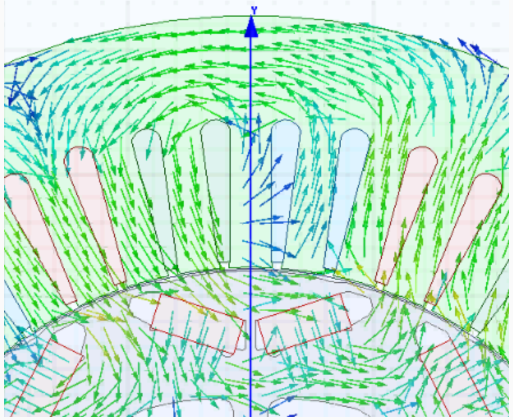
(dipole-dipole interaction energy)

$$E_{dip} = \sum_{j=1}^{n} \sum_{k \neq j}^{n} \frac{\left(a_j . a_k - 3\left(a_j e_{jk}\right)\left(a_k e_{jk}\right)\right)}{4\pi\mu_0 r^3}$$



FeSi Without Applied Field

FeSi With Applied Field



Example with varying magnetization vectors in an electric motor

α – direction cosines of the magnetic moment vector

K_1 and K_2 – anisotropy constants for iron

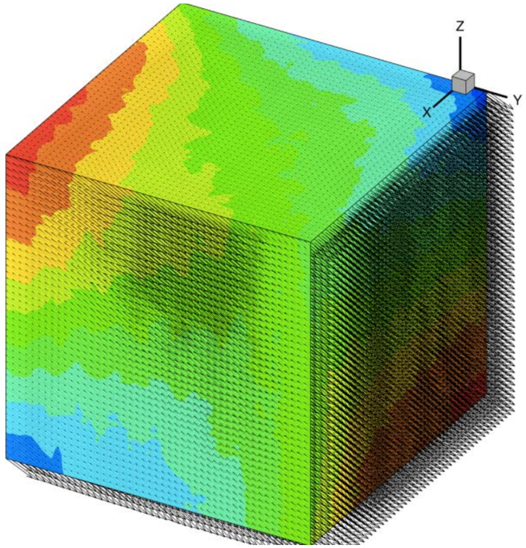
J_1 to J_4 - Exchange parameters for BCC iron

μ_0 – magnetic permeability

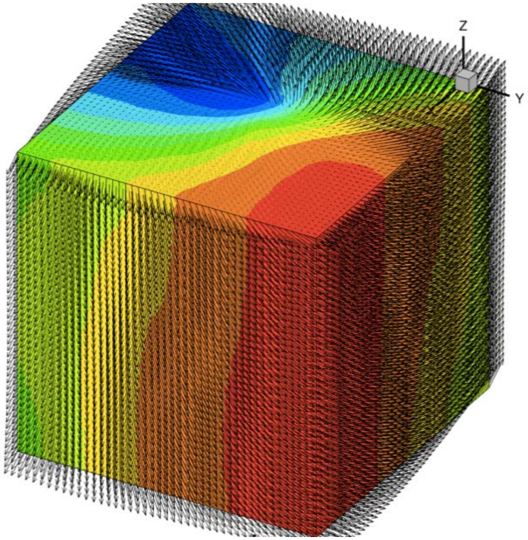
e_{jk} - unit vector along the direction connecting atoms at j and k

FY16 Accomplishments

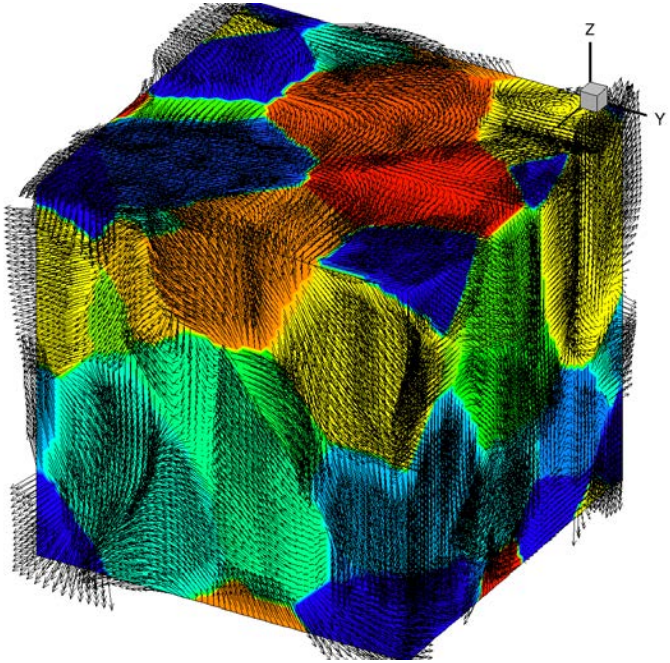
Advanced Modeling of FeSi Magnetic Properties



Simulations with 190 million atoms do not show the formation of domains.



Domains appear when simulation size reaches 2.2 billion atoms. This is accomplished by using unique scaling techniques and HPC.

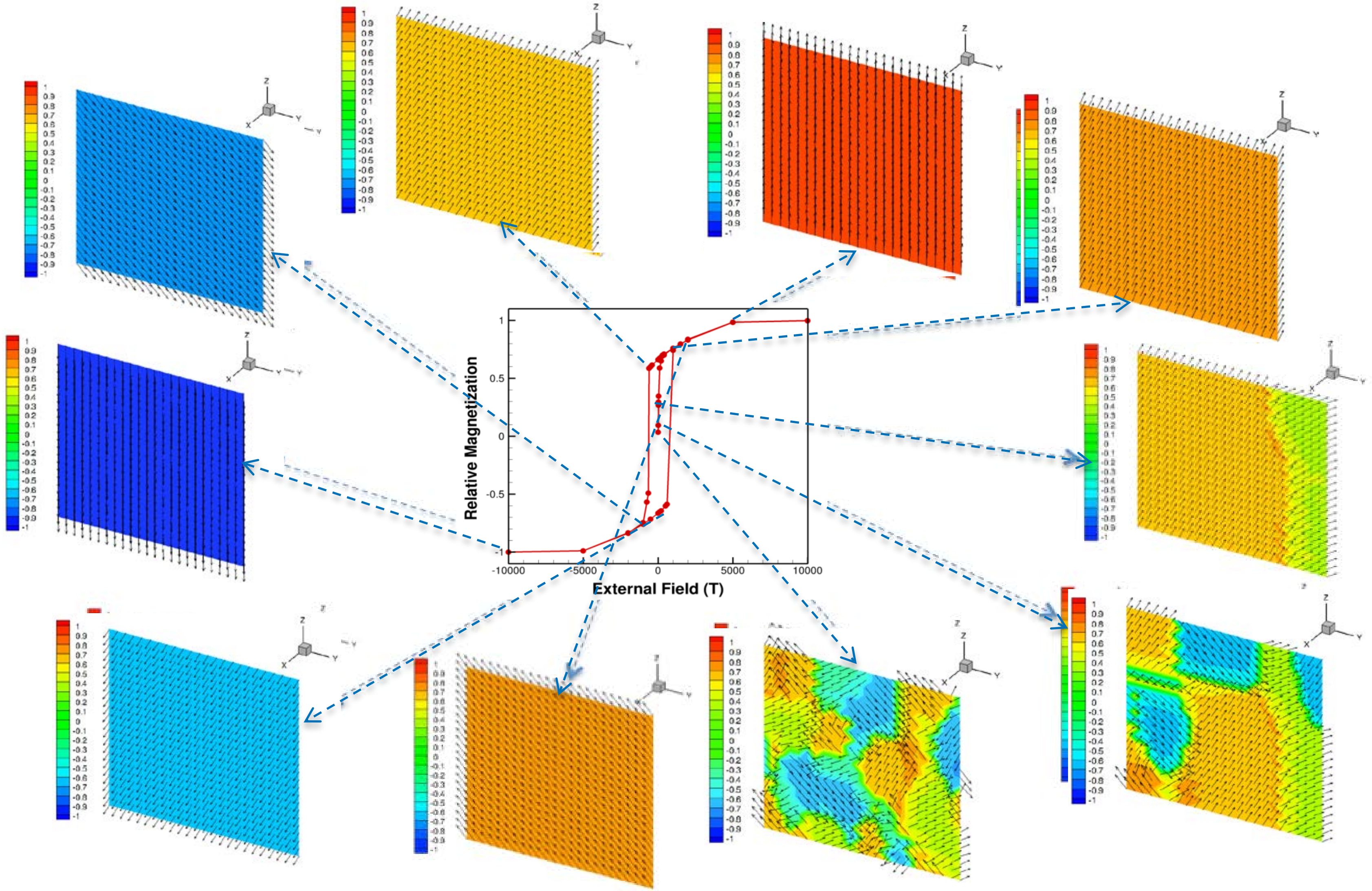


Simulation with grain structure and about 700 billion atoms

- Formation of domains inside individual grains clearly seen
- Tendency to form domains increases with scaling

FY16 Accomplishments

Advanced Modeling of FeSi Magnetic Properties

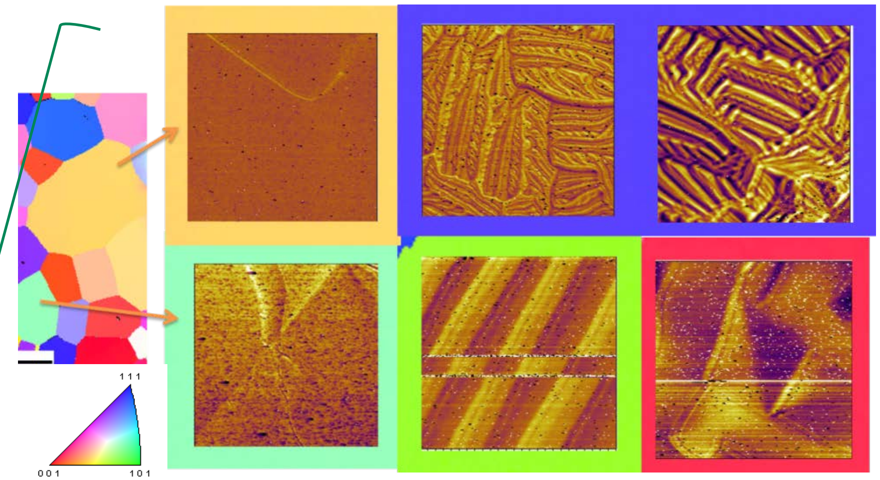


B-H curve/Hysteresis Loop using First Principles - Monte Carlo atomistic modeling

FY16 Accomplishments

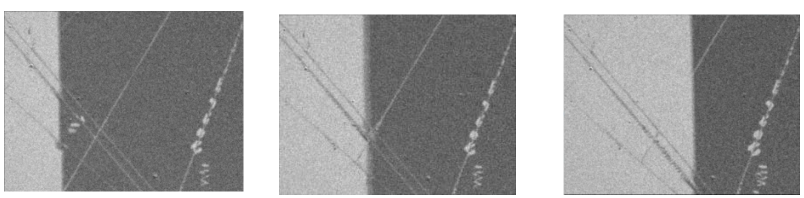
Magnetic Domain Observation

- Atomic force microscopy (AFM) analysis of magnetic domains near deformation zone.
- Impacts of pinning, residual stress, etc. upon domain wall movement are being characterized.
- Provides experimental input for validation of detailed domain simulations and their evolution during magnetization (B-H curve).
- Scanning on the order of 200μm x 200μm per day.

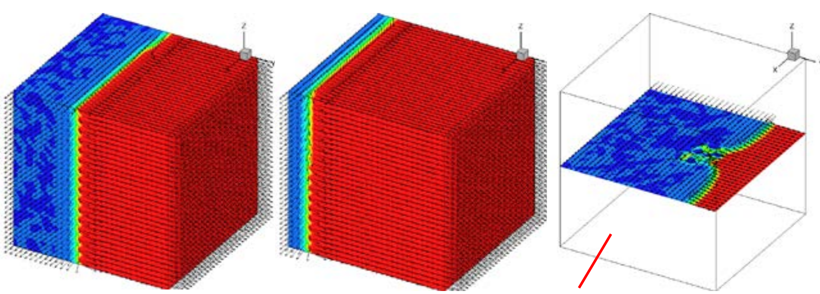


Magnetic domain patterns for various lattice angles

Domain wall movement with applied AC field

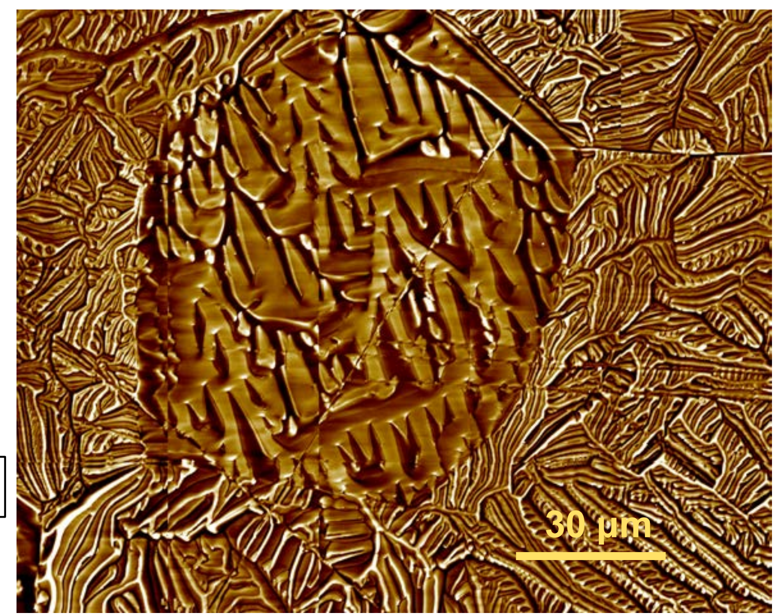


Observed



Simulated

Domain wall pinning by non-magnetic obstacle



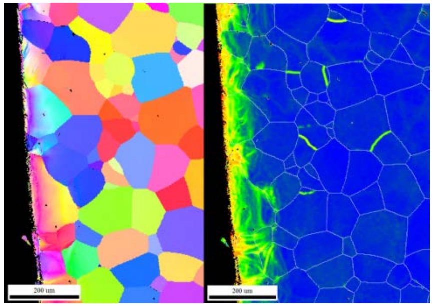
Misoriented magnetic domains – Large Scan Area

FY16 Accomplishments

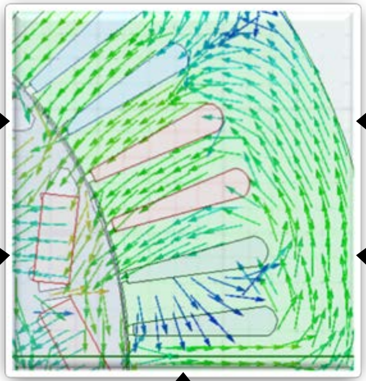
Development of Advanced FEA Modeling Method With Detailed Magnetization/Loss

Stress Distribution

- Function of cutting/stamping method
- Influenced by mechanical fastening
- Impacted by rotation and other forces

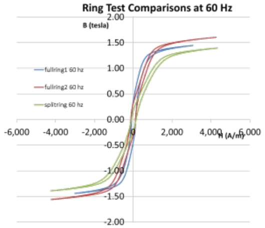


Advanced FEA Modeling Tool

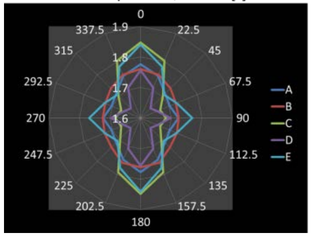


Bulk Characterization

- Traditional Epstein and ring specimen testing at various temperatures
- Custom analysis of rotational losses, anisotropic magnetization/loss, PWM, etc.

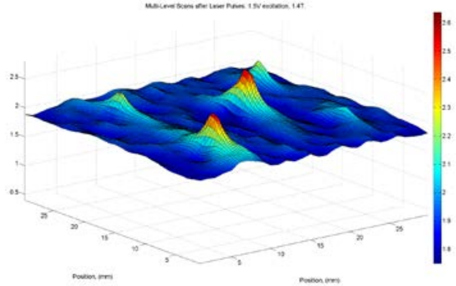


Flux Density (T) in Various 3% Si Steel Samples for 5,000 A/m [3]



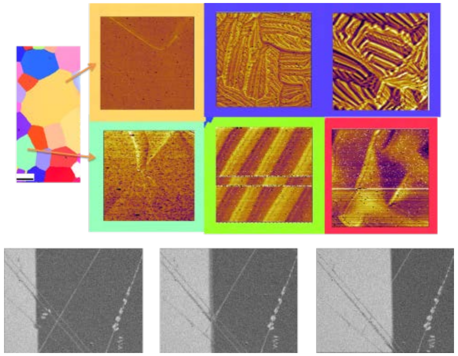
Localized Magnetic Properties

- Function of stress distribution
- Magnetization and loss characteristics are not homogeneous



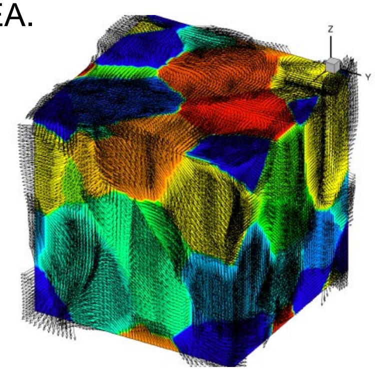
Empirical Magnetic Domain Analysis

- Traditional Epstein and ring specimen testing
- Impacts of stress, pinning, etc. upon domain wall movement, and ultimately magnetization/loss properties.



Theoretical Magnetic Domain Analysis

- Fundamental theory to confirm and supplement empirical findings.
- Indirect link to FEA - too computationally intensive for direct use in FEA.



FY16 Accomplishments

Motor design approach

Select leading designs from preliminary simulations

- Analyze basic feasibility of various novel motor designs
- Conduct finite element analysis (FEA) and dynamic modeling to obtain motor characteristics
- Choose preferred designs based on preliminary cost assessments, FEA, and dynamic simulation results

Perform detailed design and simulation of high potential candidates

- Implement advanced design optimization routines
- Refine control algorithms to optimize operation
- Conduct basic structural and thermal modeling and adjust design approach as necessary

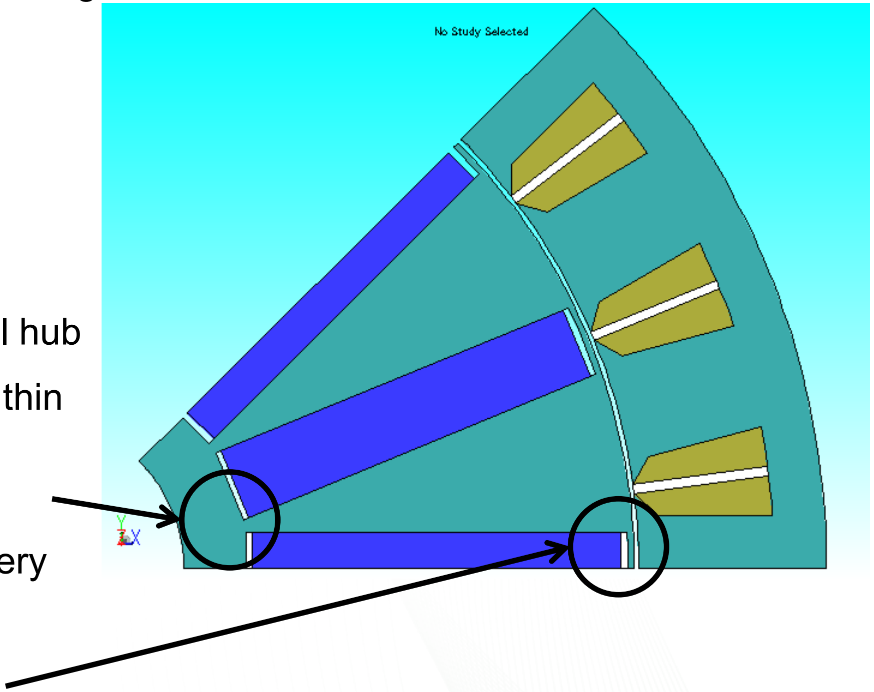
Build and test motor prototype and optimized control technique

- Verify model accuracy and forecasted operational characteristics
- Determine power density, specific power, and cost based on results from dynamometer tests

FY16 Accomplishments

Concentrated Winding Ferrite (CWF) Motor

- Concentrated winding benefits
  - Large slots with high pole count facilitates manufacturing process.
  - Short end-turns yield reduced resistance and inductance, and therefore efficiency/power factor improvements.
- Mechanical challenges with rotor design
  - Requires long magnets → large rotor OD and small hub
  - Mechanical forces must be transfer to hub through thin bridges and stress grows cubically with Rotor OD ($\sigma \sim \omega^2 r^3$)
  - Leakage flux: ~5mm magnet length required for every 1mm of bridge thickness
  - Long magnet experiences significant compressive forces on small face.
- Concentrated windings have lower reluctance torque, which limits overall power capability.
- High open circuit back-EMF fault condition is also a challenge for this design

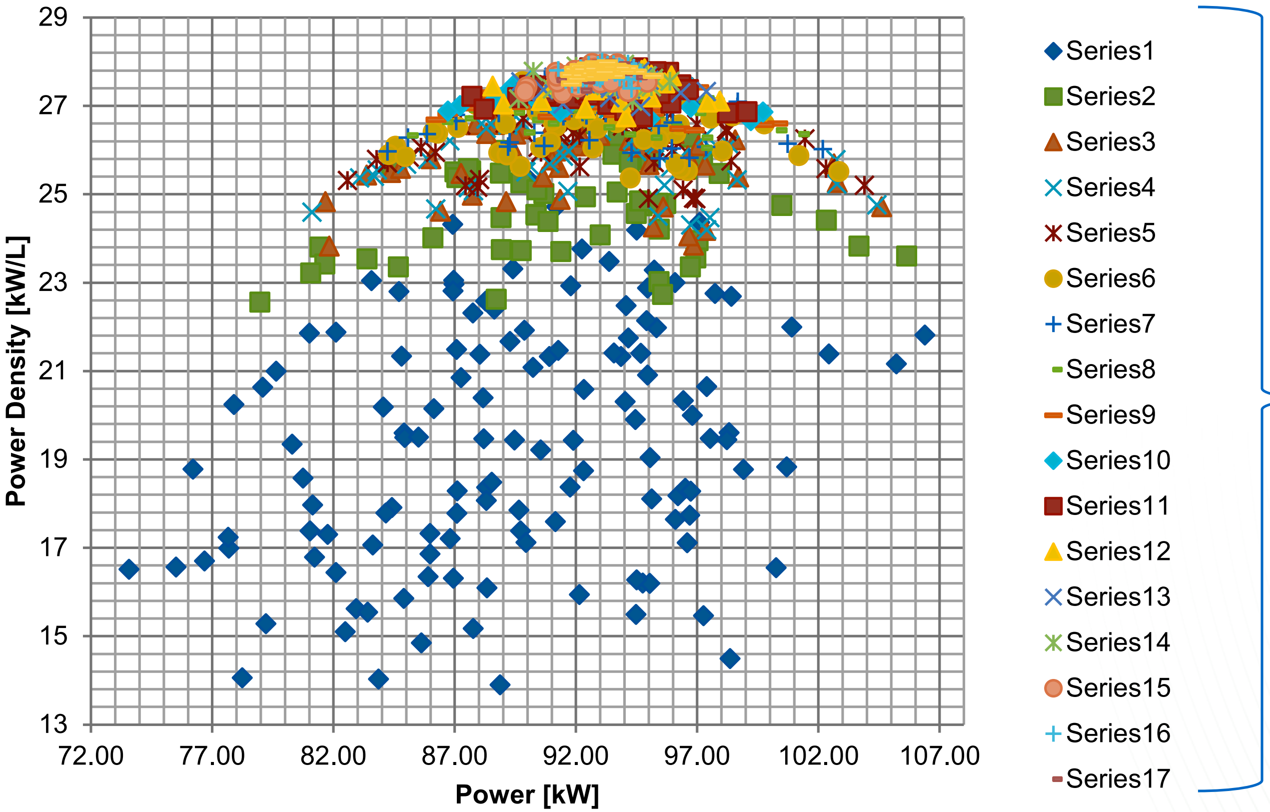


OAK RIDGE National Laboratory

FY16 Accomplishments

Distributed Winding Ferrite (DWF) Motor Design Optimization

- Various ferrite rotor topologies were investigated with distributed windings to allow greater reluctance torque and sufficient room for sizeable magnets.
- Comprehensive mechanical model included as a part of the optimization process



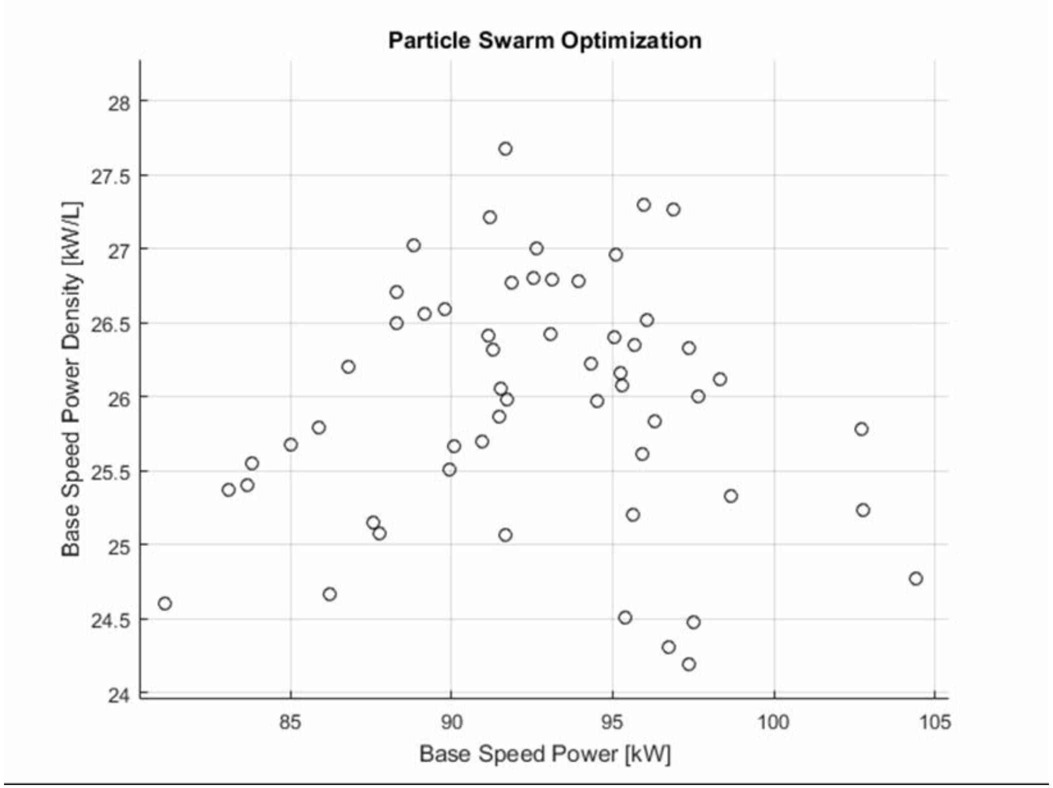
Multidimensional optimization includes variations of many parameters including

- Stator tooth width, length, shape, and back-iron thickness.
- Magnet thicknesses, widths, and angles.
- Rotor feature widths, angles, etc.
- Bridge shape and thickness.

Oak Ridge National Laboratory

FY16 Accomplishments

Distributed Winding Ferrite (DW_Ferrite) Motor Design Optimization



Animation of particle swarm optimization process

FY16 Accomplishments

Motor Performance Comparison

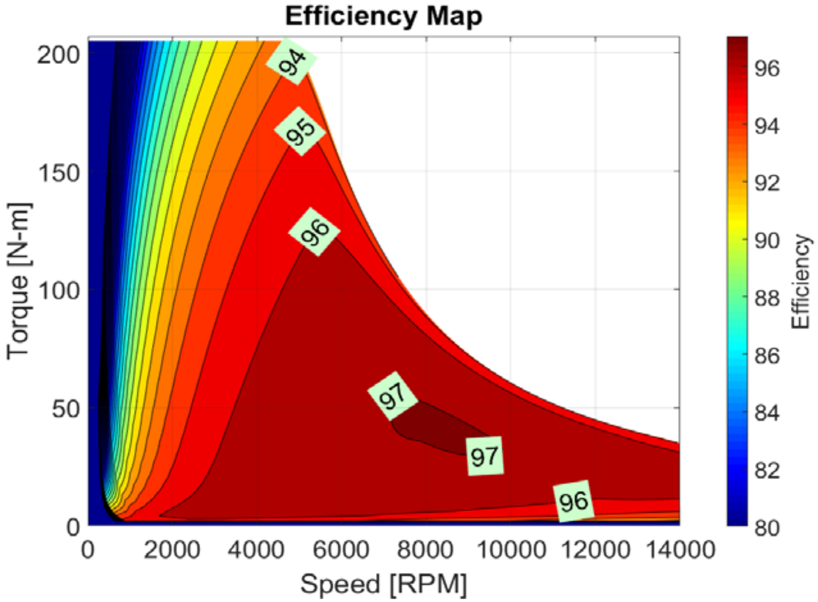
	ORNL DWF[3] (6.5 L)	ORNL DWF[3] (6.8 L)	2010 Toyota Prius (6.7 L)
Volume • Active • With End Turns[1]	 • 2.9 L • 6.5 L	 • 3.2 L • 6.8 L	 • 2.8 L • 6.7 L
Lamination Mass	15.4 kg	17.0 kg	14.7 kg
Copper Mass[1]	3.6 kg	4.0 kg	4.9 kg
Magnet Mass	1.8 kg	2.0 kg	0.8 kg
Shaft Mass	2.1 kg	2.3 kg	1.6 kg
Total Mass	22.9 kg	25.3 kg	22.0 kg
Maximum Torque	205 N-m	225 N-m	200 N-m
Torque Density[2]	32 N-m / L	33 N-m / L	30 N-m / L
Specific Torque[2]	8.9 N-m / kg	8.9 N-m / kg	9.1 N-m / kg
Power[2] • Peak • At Max. Speed	 105 kW 51 kW	 105 kW 48 kW	 60 kW 40 kW
Power Density[2] • Peak • At Max. Speed	 **16.2 kW/L** 7.8 kW/L	 **15.4 kW/L** 7.1 kW/L	 9.0 kW/L 6.0 kW/L
Specific Power[2] • Peak • At Max. Speed	 **4.5 kW/kg** 2.2 kW/kg	 **4.1 kW/kg** 1.9 kW/kg	 2.7 kW/kg 1.8 kW/kg

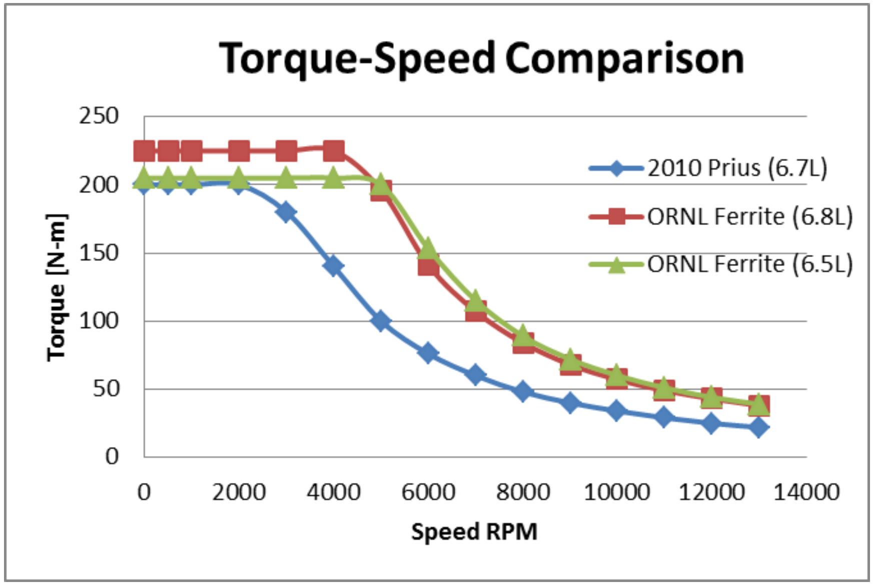
[1]ORNL values estimated based on typical distributed winding end turn dimensions
[2]Based on volume including end turn length estimate
[3]Simulations performed at magnet temperature of 100C

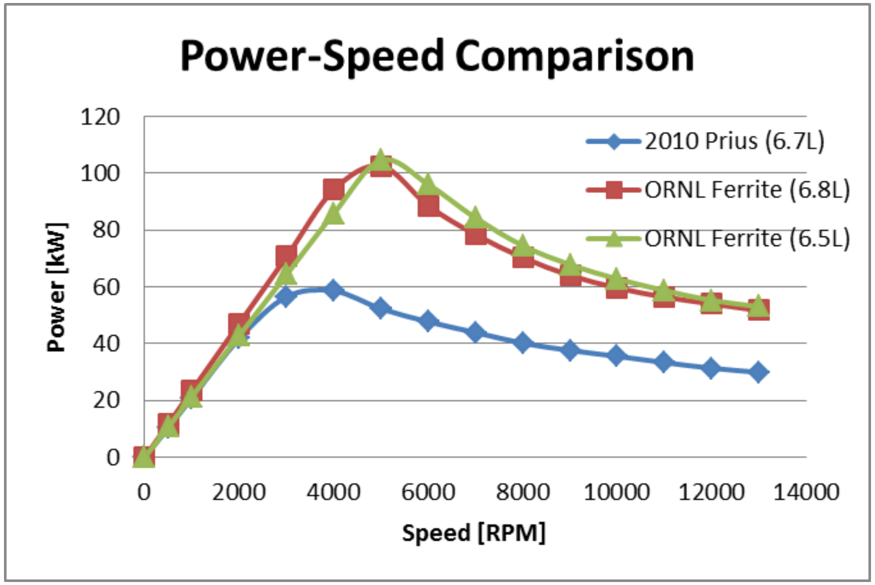
FY16 Accomplishments

Motor Performance and Efficiency Summary

- Simulations indicate that several of ORNL's designs will reach DOE EDT 2022 motor targets, and have similar performance to a rare-earth PM motor.
- Two ORNL designs have been developed with a similar volume to the 2015 Prius (6.7L):
  - Design 1 (6.8 L): torque is increased by 10% and power at maximum speed is increased by 20%.
  - Design 2 (6.5 L): torque is the same and power at maximum speed is increased by 27%.







Responses to Previous Year Reviewers' Comments

Reviewer comment: "A reviewer cautioned that the residual stress generated upon material cutting/stamping was also a matter of concern affecting the magnetization and permeability. The reviewer asked whether a low-temperature stress relief treatment would be considered to address this problem."

Response/Action: Yes, the primary motivation for investigating residual stress is in regards to cutting/stamping, among other cutting methods. Depending on the supplier, low-temperature stress relief can yield some improvement, but long-term high temperature annealing is likely required to completely restore properties. Many suppliers avoid this due to the high cost. The current focus of our efforts is to quantify the impact of these stresses, and we may focus on low-cost methods to reduce residual stress later in the project.

Reviewer comment: "A reviewer explained that the presentation was focused more on magnetic materials and analysis tools. The reviewer wondered why the non-RE material selection and improvements were not presented. The commenter also suggested that it would have been nice to see the details about the trade study results of machine types."

Response/Action: The magnetic materials characterization and analysis tools are supporting tasks to improve modeling accuracy. We have extensive parametric optimization of several designs, and we will be publishing details after patent applications are finalized and submitted.

Partners/Collaborators

Logo	Organization	Role
	UQM	ORNL, NREL, and UQM are collaborating on the use of injection molded potting compounds for improved reliability, heat transfer, and overall power density and specific power.
	University of Wisconsin - Madison	Collaborating on motor design and FEA studies.
	NREL	ORNL will provide heat generation map throughout motor for NREL to develop and provide feedback on integrated cooling techniques.
	AMES	ORNL is attending BREM/DREAM review meetings, workshops, and WebEx updates to keep up to date on non-RE PM alternative development, and keeping design options available for use of new PM developments from AMES.

Remaining Challenges and Barriers

- Maintaining consistency of mechanical and magnetic properties for small prototype batches of high efficiency steel desirably to be used in prototype motor.
- Implementation of material processing developments on a massive scale.

Proposed Future Work

- Remainder of FY16
  - Utilize results from basic testing and materials research to design, build, and test full scale prototype.
- FY17
  - Continue incorporating detailed theoretical and experimental findings using advanced FEA modeling method.
  - Scale FEA to large HPC system.
  - Perform final design optimization and build/test final prototype.

Summary

- **Relevance:** The objective is to develop low cost non-rare earth motor solutions while maintaining high power density, specific power, and efficiency to meet DOE targets.
- **Approach:** Use advanced modeling and simulation techniques and develop/research materials to help optimize performance of various electric motor types.
- **Collaborations:** Interactions are ongoing with other national laboratories, industry, and other government agencies.
- **Technical Accomplishments:** Design and modeling efforts have produced several promising motor technologies, custom characterization tools have been developed to conduct magnetic materials research, and advanced model developments are underway. Update this based on summary in motor design slides: meet and beat Prius.
- **Future work:**
  - FY16: Utilize results from basic testing and materials research to design, build, and test prototype.

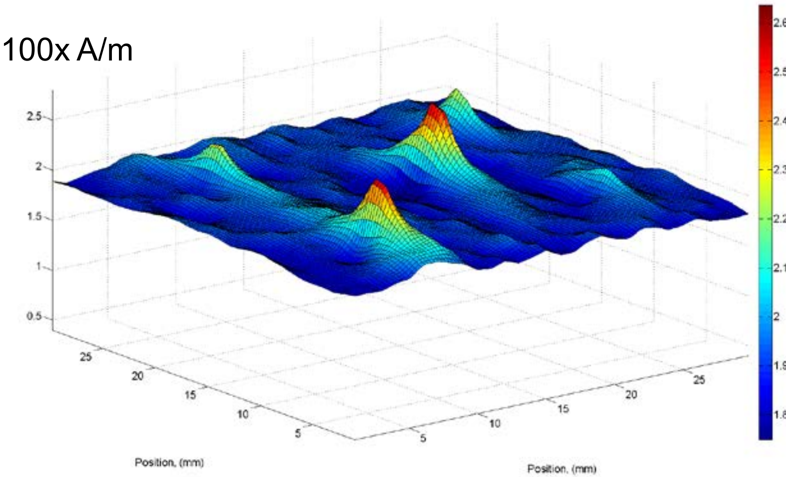
Back-up slides

Localized Characterization of Silicon Steel

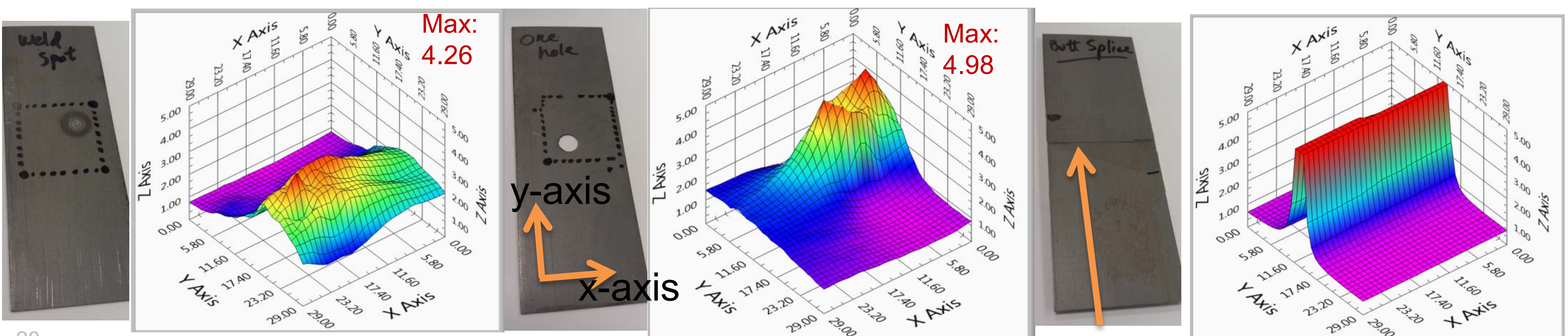
- Designed and implemented advanced characterization system to analyze impact of residual stress/strain (primarily due to cutting/stamping during manufacturing) upon magnetization and loss characteristics in electrical steel.
- Surface magnetic field measurements made on single-sheets of M19 with various deformations applied.
- Quantitative technique was developed and implemented in FY15.
- Even slight residual stress has significant impact on the magnetic properties of the material.

Scans at Multiple Flux Levels (1.4 T case)

Z: 100x A/m



Scan of steel sheet with 5 mild laser pulses (the pulses did not cut or even visibly modify the samples)



X,Y (mm), Z(A/m p.u.)

Splice joint here