Non-Rare Earth Motor Development

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U.S. DOE Vehicle Technologies Office
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Project ID: EDT062

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start – FY14
- End – FY17
- ~38% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY14: $ 1,175K
- Funding for FY15: $ 1,516 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/BREM
- ORNL Team members
  - Curt Ayers
  - Radhakrishnan Balasubramaniam
  - Randy Wiles
  - Andy Wereszczak
  - Zheng Gai
  - Chad Parish
  - 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.

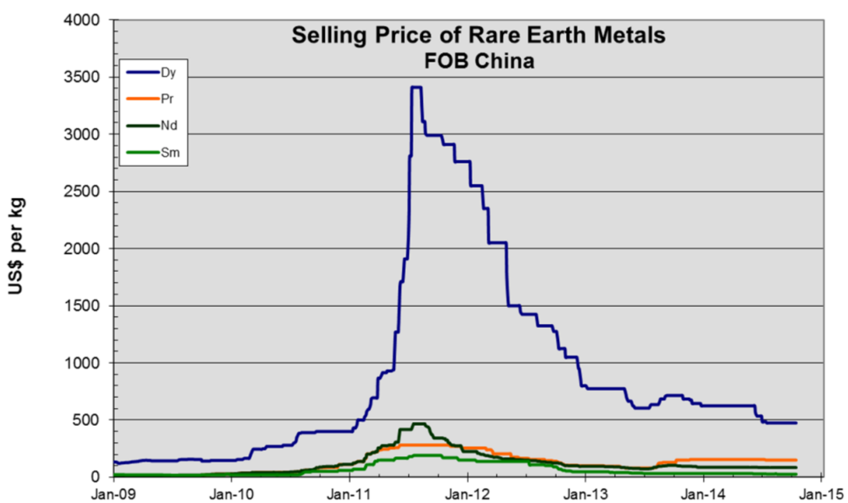
- **FY15 Objectives:**
  - Conduct proof-of-principle prototype testing to aid with modeling activities.
  - Develop/implement methods to facilitate the use of high efficiency steel.
  - Continue fundamental electromagnetic material studies and experiments to identify impacts of residual stress upon magnetic properties in electrical steel.
  - Utilize micro-magnetics software code to aid with magnetic domain evolution theory, and complement residual stress studies.
  - Perform detailed modeling of down-selected motor designs based on basic simulations that indicate promising results with respect to DOE targets.

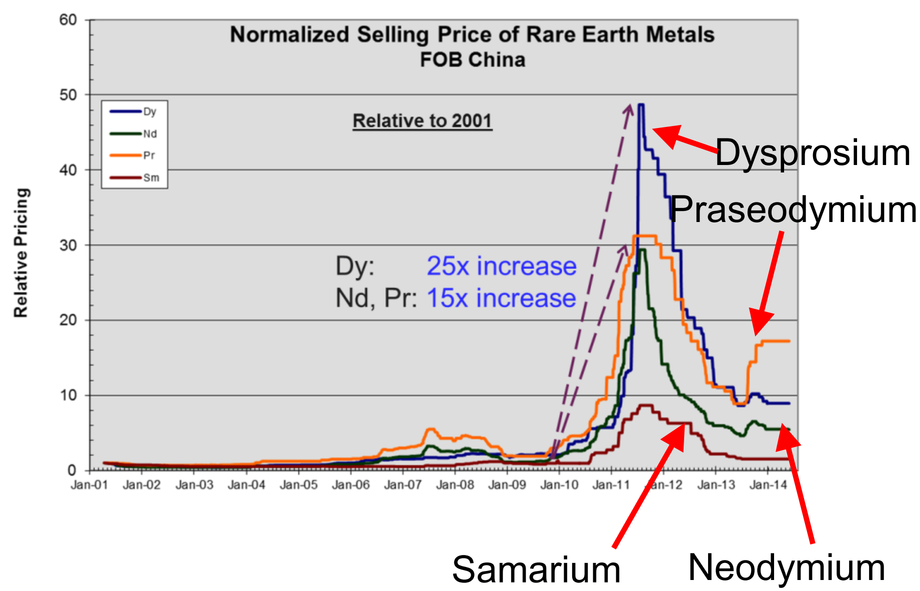
Milestones

Date	Milestones and Go/No-Go Decisions	Status
March 2015	Milestone: Characterize various materials including lamination steel and other magnetic materials.	Complete.
May 2015	Milestone Complete preliminary non-rare earth motor prototype design with simulation results that meet DOE EDT 2020 motor targets.	On track.
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.	On track.
September 2015	Milestone: Summary report with findings from materials research and development and motor testing.	On track.

Problem to be Addressed

- 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 2020 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

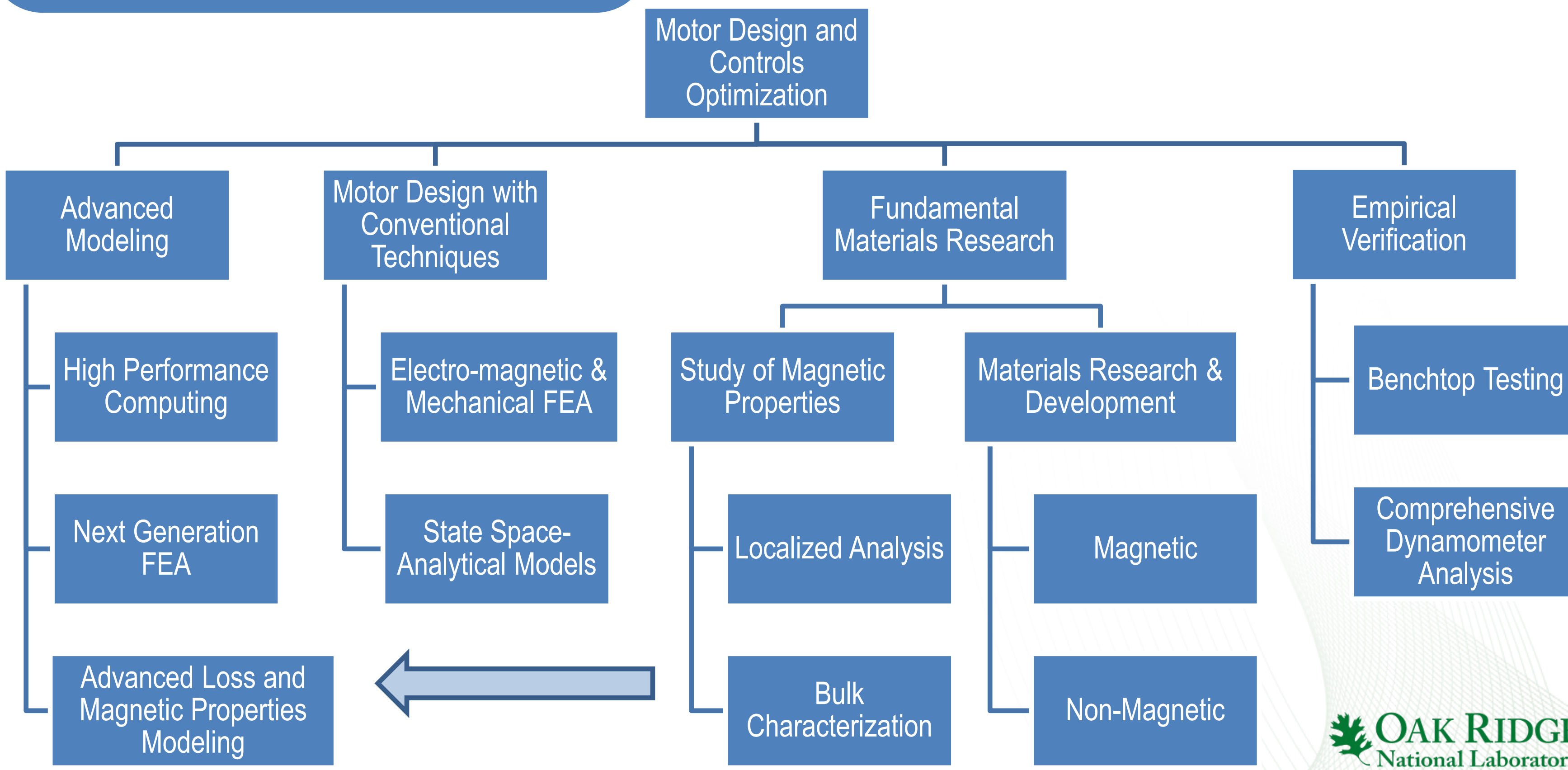
Approach/Strategy

- 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



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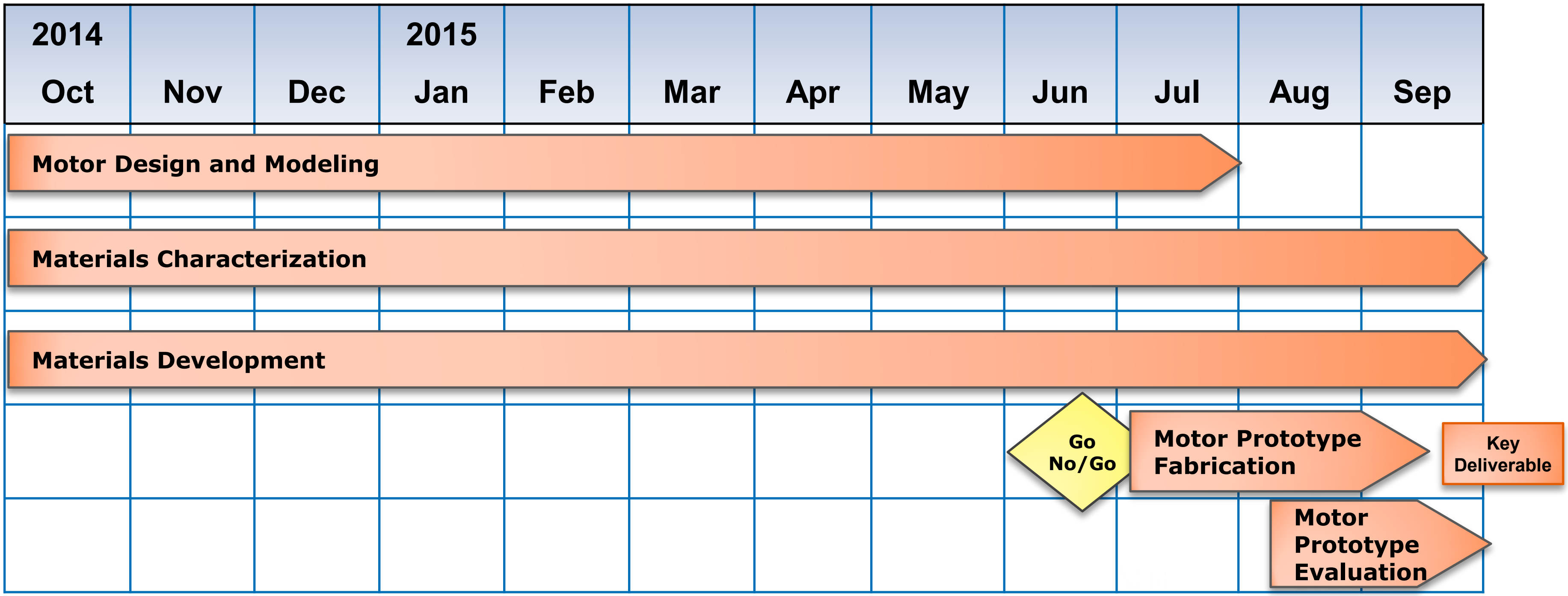
FY15 Tasks to Achieve Key Deliverable



Go No/Go Decision Point: If non-rare earth motor design simulation results indicate that the design will meet EDT 2020 motor targets, then fabricate motor prototype.

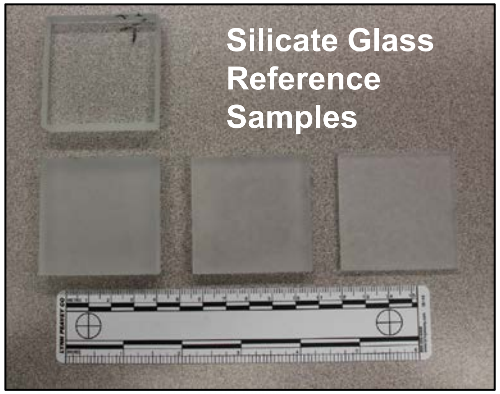
Key Deliverable: Non-rare earth motor prototype.

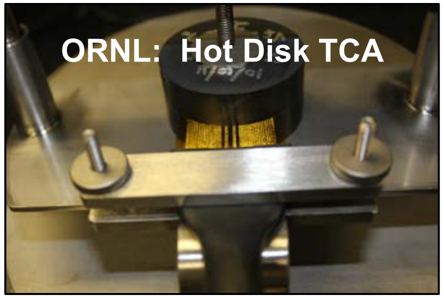
FY14/FY15 Accomplishments

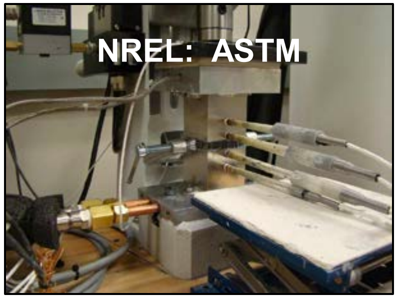
Collaboration with NREL's Electric Motor Thermal Management Project

- Prepared/supplied motor winding samples for thermal conductivity (TC) measurements
  - Various factors under consideration
    - Wire size
    - Type of varnish
    - Insulation voltage and temperature rating
  - Two TC measurement methods
    - Hot disk
    - ASTM measurement
- Developing methods and utilizing new materials to
  - Improve heat transfer from end-windings
  - Enhance winding integrity/longevity
  - Increase power density/specific power due to improved cooling
  - Reduce cooling system costs

Sato, *et al*., SAE International, 2011-01-0350





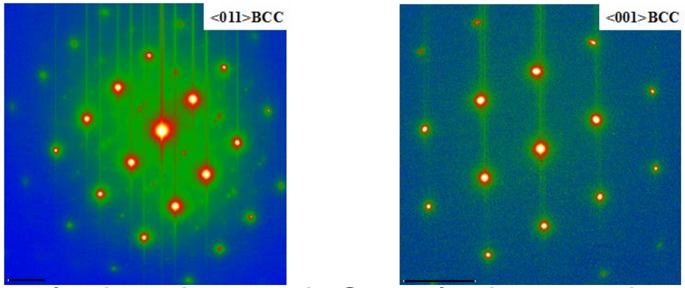


FY13/FY14/FY15 Accomplishments

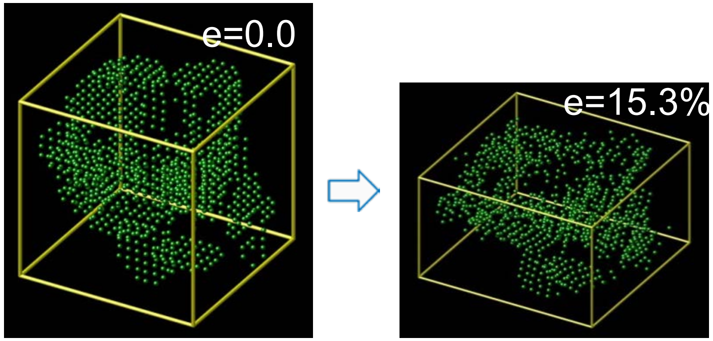
Process development for high efficiency electrical steel

- 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.

Confirmation of Improved Workability with Base Material

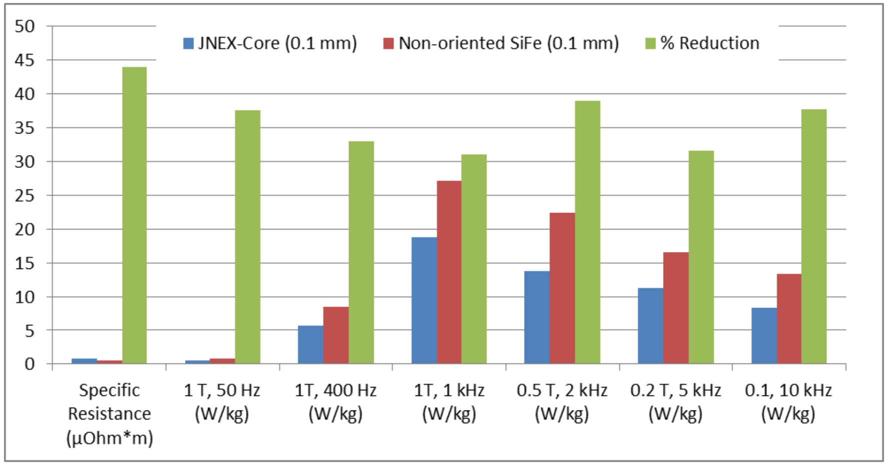


Superlattice observed   Superlattice not observed



Improved molecular dynamic simulation environment to establish fundamental understanding of deformation induced elimination of B2 phase in Fe-Si. After a compressive strain of 15.3%, the Si atoms loose their body center coordination get become disordered. This illustrates the work-softening phenomenon.

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

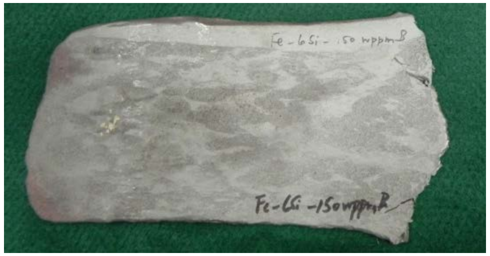


Data Source: JFE Super Core Catalog

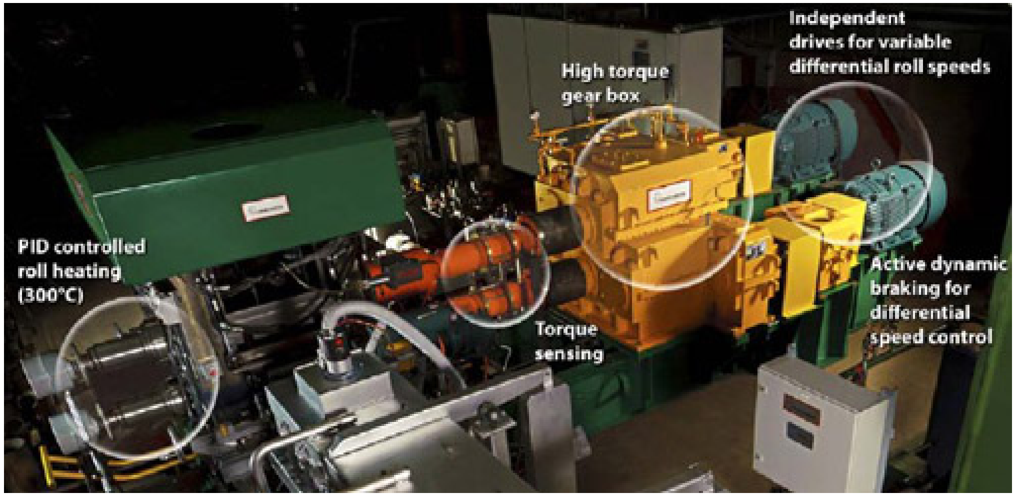
FY14/FY15 Accomplishments

Warm Rolling of Various High Efficiency Steel Specimen to Guide Process Development

- Fe-6%Si-150 ppm B and Fe-6%Si-250 ppm B alloys were warm rolled to about 86% reduction in thickness without serious issues
- Initial tensile tests following rolling have been completed at room temperature (hardness values indicated below)
- Will ultimately perform magnetization and loss testing on exemplar material
- Fe-6.5Si-500ppm B alloy cast successfully for further processing



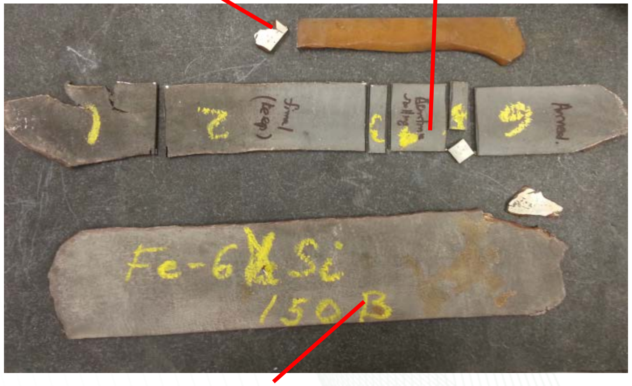
Plates trimmed and prepared for warm rolling



ORNL's Isothermal Shear Rolling Mill

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

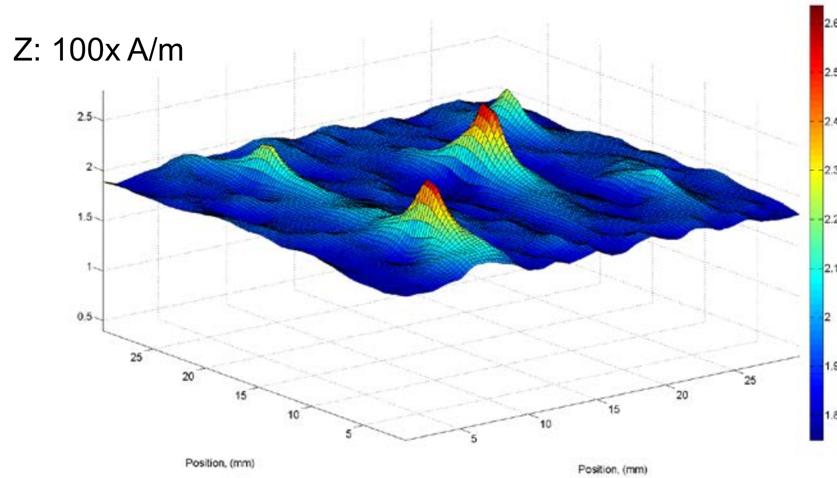
Jointly funded by D.O.E. VTO's Electric Drive Technologies and Propulsion Materials Programs

FY14/FY15 Accomplishments

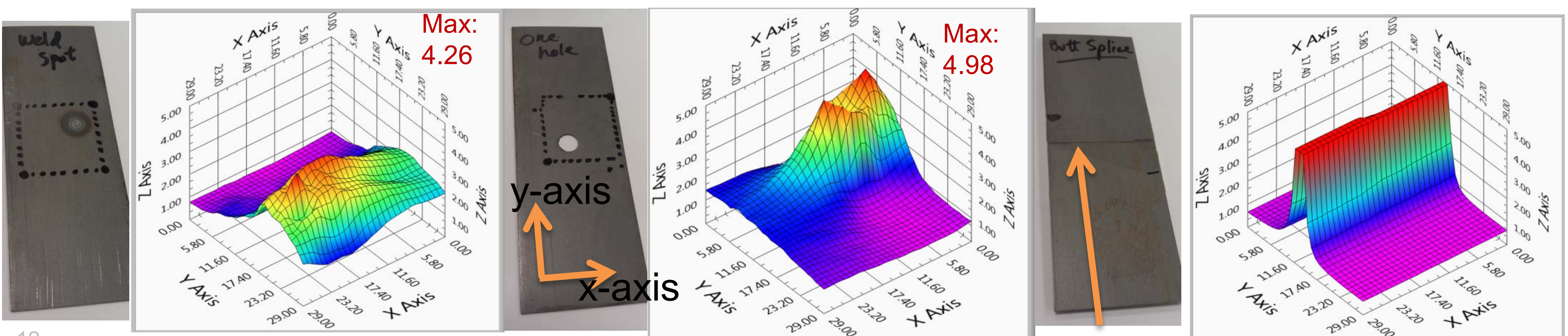
Localized Characterization of Silicon Steel

- 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)



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.)

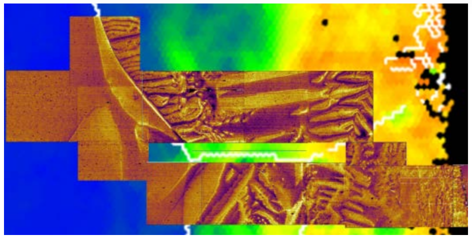
Splice joint here

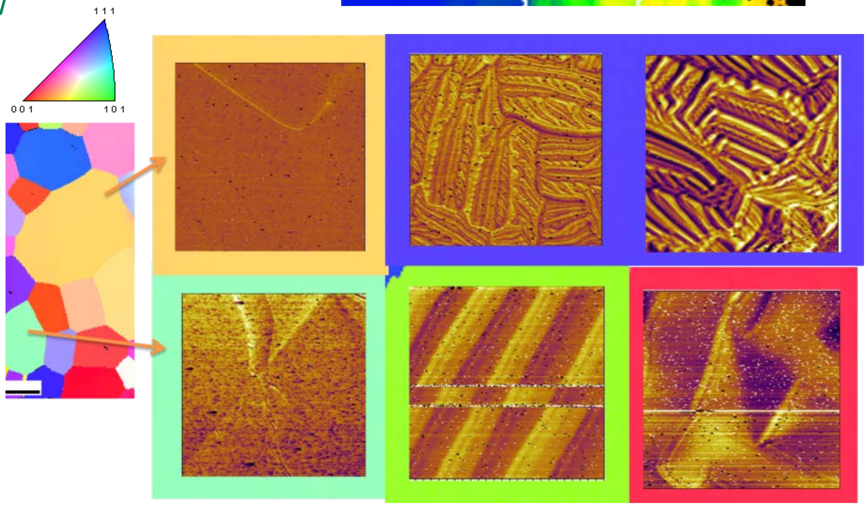
FY14/FY15 Accomplishments

Magnetic Domain Observation

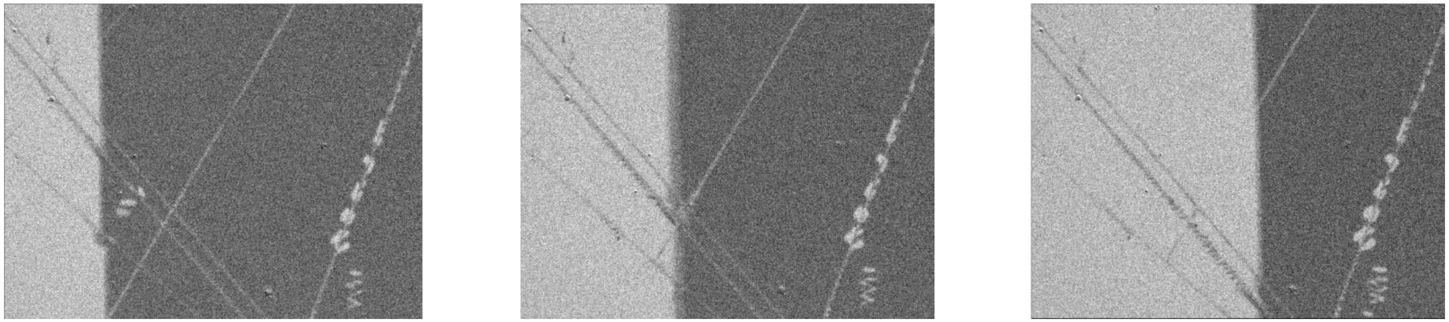
- Atomic force microscopy (AFM) analysis of magnetic domains near deformation zone.
- Microscopy with quadratic electro-optic effect used for in-situ observation during application of AC and other transient fields.
- Resolution is not as high as AFM, but AFM lacks capability to easily obtain characteristics related to transient excitations.
- Impacts of pinning, residual stress, etc. upon domain wall movement is being empirically observed.
- These phenomenon have significant impact upon magnetization and hysteresis losses.

Magnetic domains near deformation zone





Magnetic domain patterns for various lattice angles



Domain wall movement with applied AC field

FY15 Accomplishments

Advanced Modeling of Magnetic Properties

- Micromagnetics code/simulation space has been expanded to a larger scale to include multiple domains.
- HPC with 1024 processors, and growing.
- Compliments experimental domain wall observation.
- Includes consideration of various externally applied fields and stress/strain.
- Code will ultimately generate theoretical magnetization and loss properties with the consideration of various parameters.

(Due to external field, H)

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

(magneto-crystalline anisotropy)

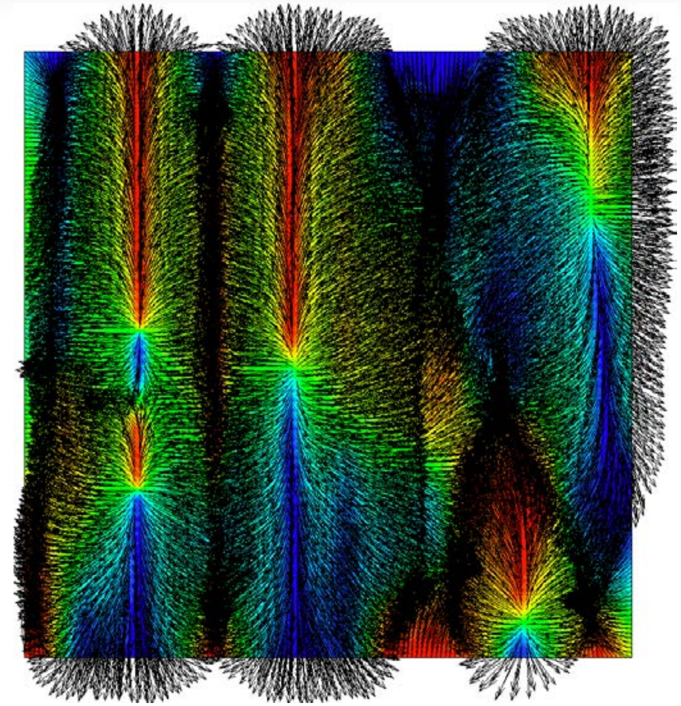
$$E_{an} = K_1\left(a_1^2 a_2^2 + a_2^2 a_3^2 + a_3^2 a_1^2\right) + K_2 a_1^2 a_2^2 a_3^2$$

(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)

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



Simulation cell showing multiple domains

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

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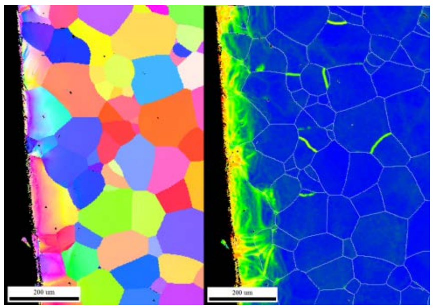
FY15 Accomplishments

Development of Advanced FEA Modeling Method With Detailed Magnetization/Loss

Stress Distribution

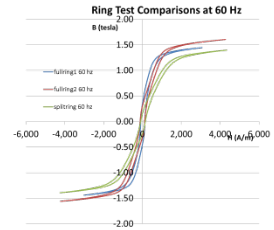
- Function of cutting/stamping method
- Influenced by mechanical fastening
- Impacted by rotation and other forces



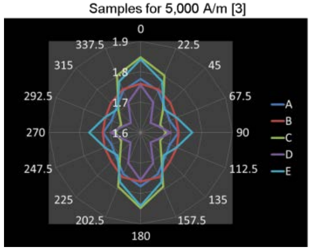
Advanced FEA Modeling Tool

Bulk Characterization

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

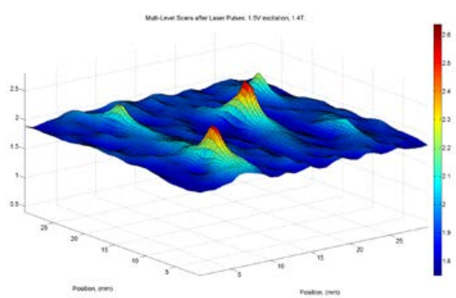


Flux Density (T) in Various 3% Si Steel Samples for 5,000 A/m [3]



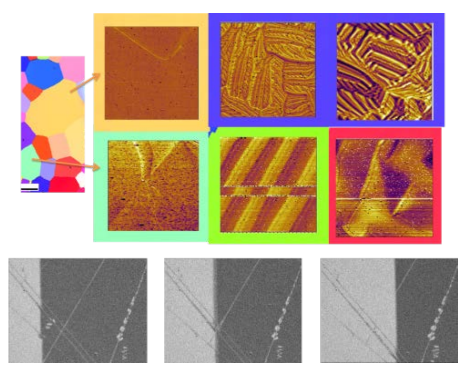
Localized Magnetic Properties

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



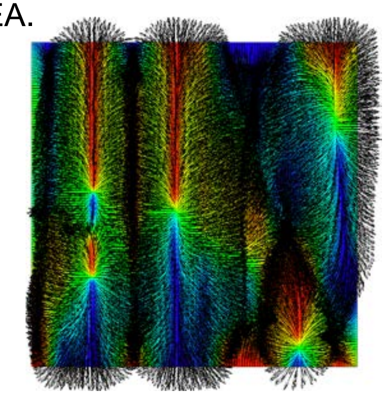
Empirical Magnetic Domain Analysis

- 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.



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

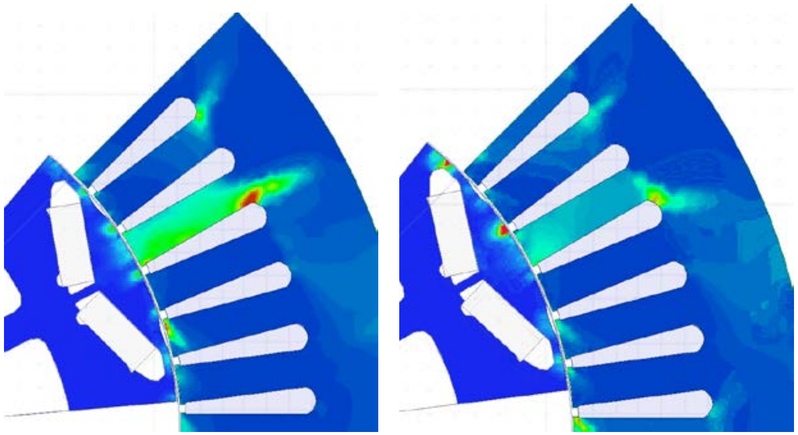
Build and test motor prototype and optimized control technique

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

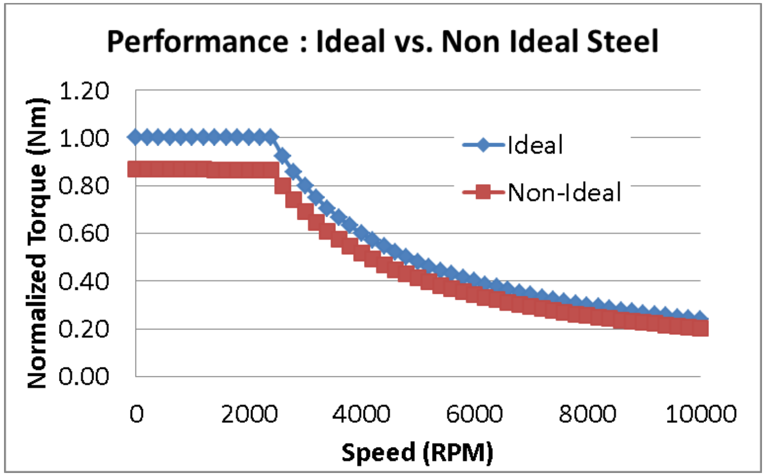
FY15 Accomplishments

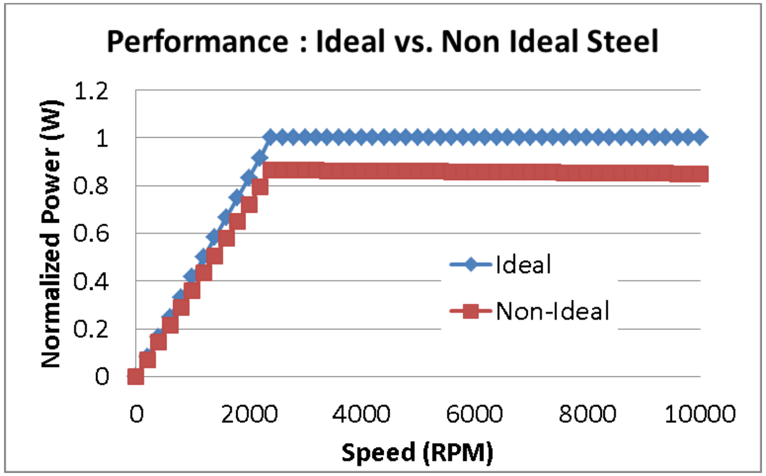
Initial Comparison of Motor Performance Characteristics (Ideal vs Non-Ideal Material)

- Magnetization degradation has direct impact on torque production.
- Increased hysteresis losses have indirect impact on performance.
- Core losses are typically higher near lamination edges even with ideal material model, and are further increased after stamping/deformation.
- Initial comparisons of motor performance with ideal versus non-ideal Silicon Iron indicate a discrepancy of about 15-20%, and this is comparable to discrepancies observed during pasts experiments.



Plot of core losses from FEA simulation shows increasingly more core losses near edge of lamination.

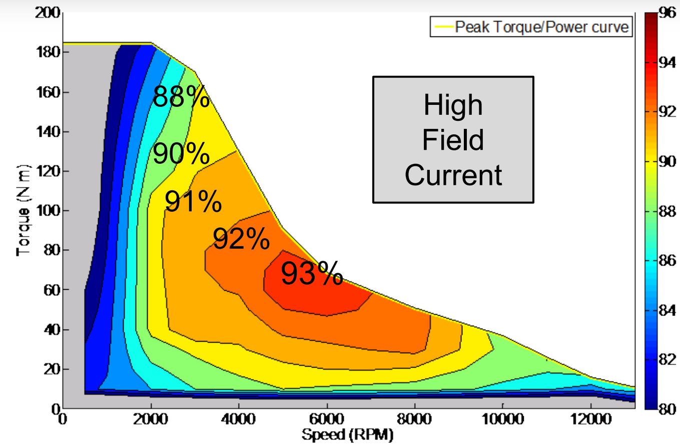


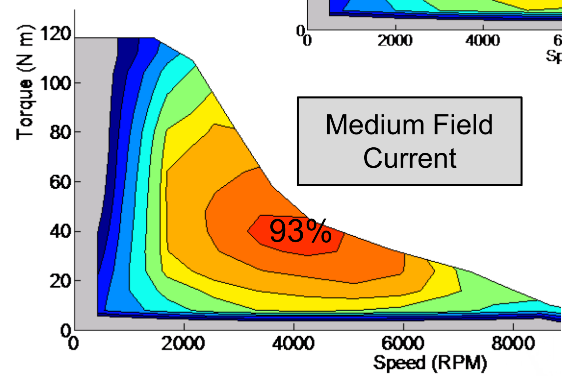


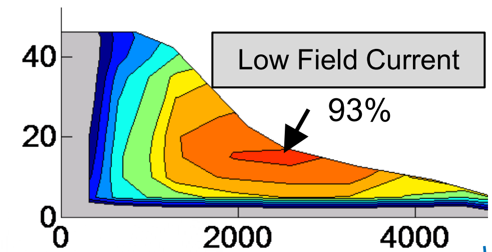
FY15 Accomplishments

Simulated Motor Performance and Efficiency

- FEA results are similar to analytical model results.
- With adjustable field designs, the peak efficiency operation region shifts such that efficiency can be optimized with respect to field current.
- Torque comparisons reflect that the BFE reaches saturation more quickly.
- Simulations indicate that both non-RE designs have a high potential to reach DOE EDT 2020 motor targets, and have similar performance to PM motor.

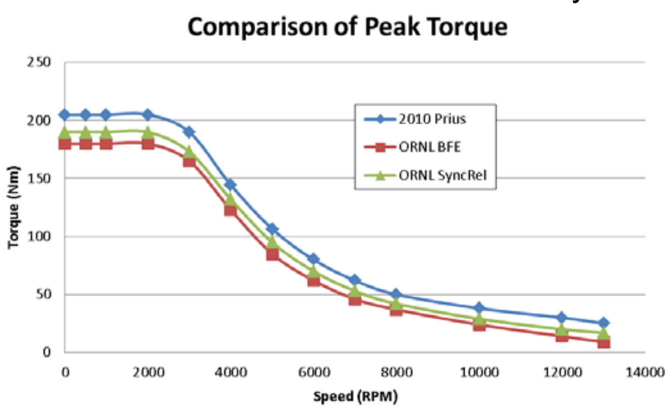


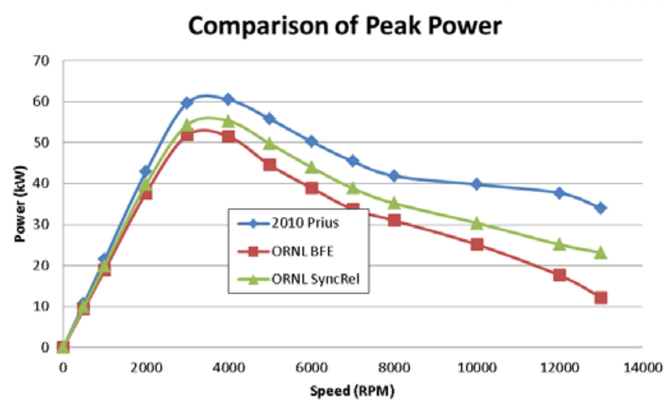




Although operation region reduces with decreasing secondary field, the peak efficiency operation region shifts such that efficiency can be optimized with respect to field current.

Performance for ORNL BFE and SyncRel electric motors same size as 2010 Prius





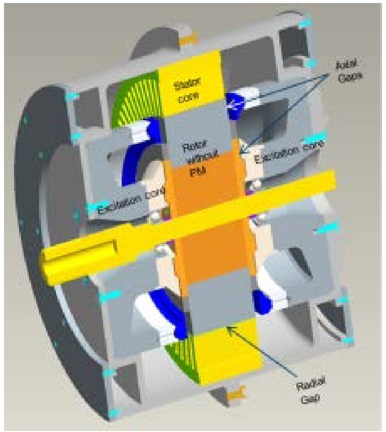
FY14/FY15 Accomplishments

Motor Design and Controls Optimization and Down-Selection

- Originated and designed more than 10 new motor designs and developed analytical models for controls optimization.
- Identifed next generation synchronous reluctance and second generation brushless field excitation motors as leading candidates for intensive design optimization.

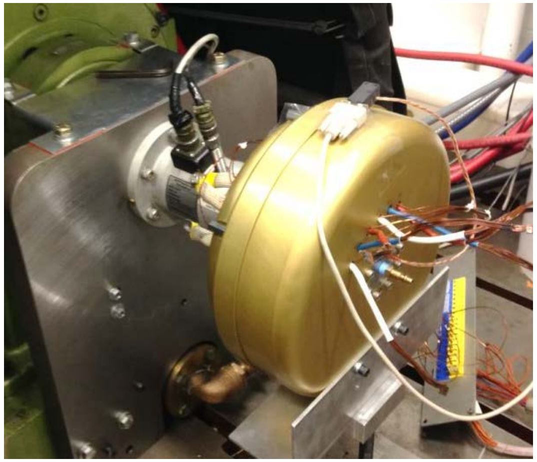
Expanding in the area of high performance computing (HPC) and parallel processing.

- From PC/workstations to computational clusters and ultimately large scale supercomputing resources.
- Developing highly parallelized electromagnetic FEA code.



First Generation BFE

Proof-of-Principal Novel Synchronous Reluctance



Proof-of-Principal Synchronous Reluctance Motor on ORNL Dynamometer

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.

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 FY15
  - Utilize results from basic testing and materials research to design, build, and test first-stage prototype.
- FY16
  - Incorporate detailed theoretical and experimental findings using advanced FEA modeling method.
  - Scale FEA to large HPC system.
  - Perform intermediate design optimization and build/test second-stage prototype.
- FY17
  - 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 two promising motor technologies, custom characterization tools have been developed to conduct magnetic materials research, and advanced model developments are underway.
- **Future work:**
  - FY15: Utilize results from basic testing and materials research to design, build, and test first-stage prototype.
  - FY16: Perform intermediate design optimization and build/test second-stage prototype.
  - FY17: Perform final design optimization and build/test final prototype.