Cost Effective 6.5% Silicon Steel Laminate for Electric Machines

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June 20, 2018

Project ID: elt091

Overview

Timeline

- October 1, 2016
- September 30, 2019
- Percent complete: 45%

Budget

- Total project funding
  - $3,835K (Federal)
  - $433K (Cost share)
- Funding for FY 2017: $1,489K
- Funding for FY 2018: $1,428K

Barriers and targets

- Magnet cost and rare-earth element price volatility
- Non-rare-earth electric motor performance
- 2020 DOE EDT cost target of $4.7/kW and power density target of 5.7 kW/L.

Partners

- Iowa State University (Lead)
- Ames Laboratory
- United Tech. Research Center
- University of Delaware

Relevance

- MnBi based non-rare earth magnet:
  - Objective: Scale up and enable MnBi magnet for motor application
  - Impact: The price of MnBi bulk magnet is estimated at $26/kg (NdFeB-Dy Grade N42HS, was $69/kg in March 2016).
- Electrical steel with 6.5%Si:
  - Objective: Solve the brittleness problem and enable 6.5%Si steel for motor application
  - Impact: Reduces iron loss at higher frequency, improve motor power density and efficiency
- Non-rare earth motor
  - Objective: Demonstrate motor with MnBi as permanent magnet and 6.5%Si steel as the soft magnetics
  - Impact: Improve non-rare earth motor power density

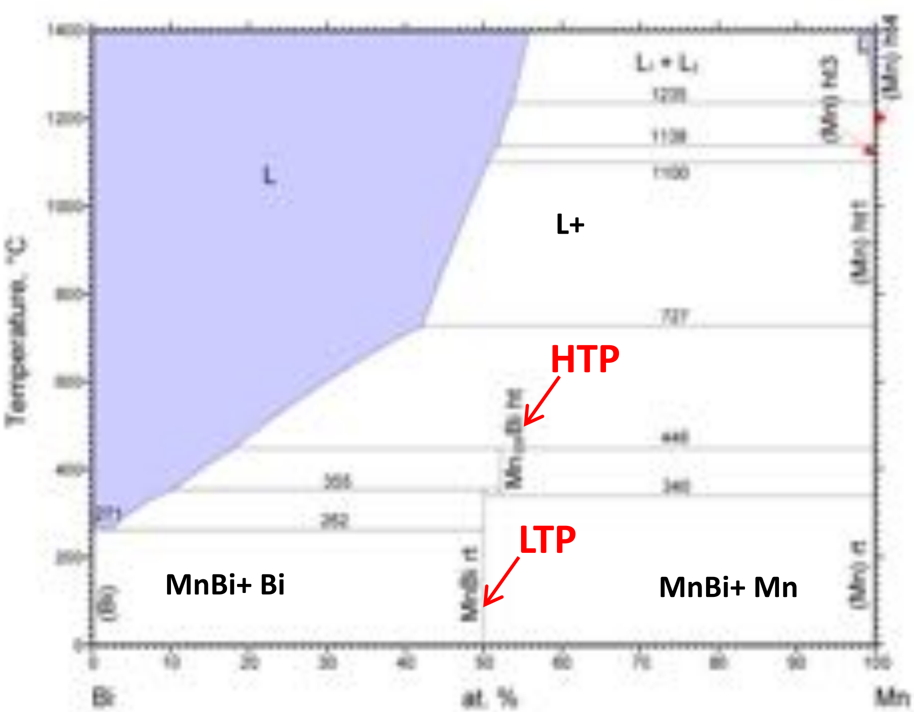
Milestones

Tasks #	Description	2017				2018				2019			
1	MnBi magnet (UDEL and ISU)	1	2	3	4	1	2	3	4	1	2	3	4
1.1	Fabricate 8.5 MGOe (ISU)	■	■	■	■	■	■	■	■	■	■	■	■
1.1.1	Small scale 8.5 MGOe magnet demonstration (5 gram)	■	■										
1.1.2	Design/construction of large warm-compaction setup		■	■	■	■	■						
1.1.3	Large 8.5 MGOe MnBi magnet fabrication					■	■	■	■	■	■	■	■
1.2	Develop 10 MGOe MnBi magnet (UDEL)	■	■	■	■	■	■	■	■	■	■	■	■
1.2.1	Setup high speed melt-spinning system	■	■										
1.2.2	Produce 90% amorphous MnBi flakes (UDEL)			■	■								
1.2.3	Develop field annealing method (UDEL)					■	■	■	■				
1.2.4	Scale up 10 MGOe magnet process (ISU)									■	■	■	■
2	Fe-6.5%Si stator (ISU)	1	2	3	4	1	2	3	4	1	2	3	4
2.1	Investigation ductility of melt-spin Fe-6.5%Si	■	■	■	■								
2.2	Melt-spun flake production	■	■	■	■								
2.3	Flake compact and sintering					■	■	■	■				
2.4	Stator thickness optimization							■	■	■	■		
2.5	Scale-up cross section											■	■
3	Task 3: 400 Hz PM motor (UTRC)	1	2	3	4	1	2	3	4	1	2	3	4
3.1	Motor design	■	■	■	■								
3.2	Construction with dummy magnetics					■	■	■	■				
3.3	Motor evaluation									■	■	■	■
3.4	Retrofit with MnBi and ISU stator and evaluation											■	■

Challenges (MnBi)

Advantages of MnBi

- Large coercivity that is increasing with temperature.
- Theoretical energy product $(BH)_{max}$ 20 MGOe



Challenges of MnBi

- Peritectic reaction at 355°C, Mn precipitation is inevitable, making it difficult to maintain high purity
- LTP magnetization is limited (~90 kG), any impurity will reduce the energy product
- At 340°C LTP-MnBi decomposes to HTP-$Mn_{1.08}Bi$ and liquid Bi, making it difficult to fabricate bulk magnet using the conventional sintering or warm compaction method

Approach (MnBi)

- Refine the previously developed powder preparation and bulk magnet fabrication process
- Scale up 5 gram magnet to 100 gram
- Use amorphous feedstock to reduce Mn precipitation and improve energy product from 8.5 to 10 MGOe

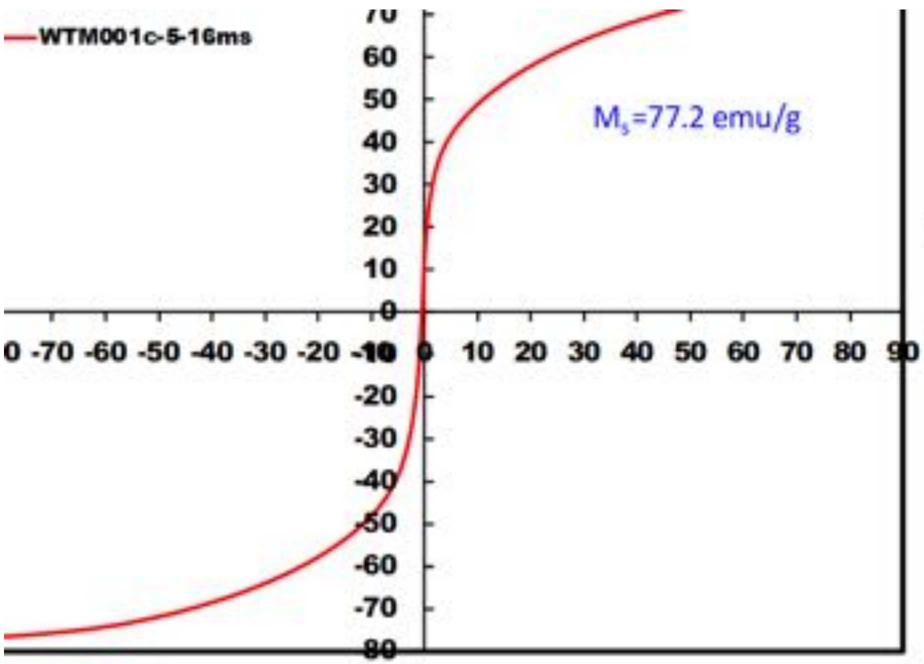
	End results and annual go/no-goes
Yr 1	1. Produced 8 MGOe MnBi magnet (5 gram) 2. Finished a large warm-compaction system capable of (200 gram/pcs) 3. Produced 5 gram MnBi with 90% amorphous
Yr 2	1. Fabricated one 100 gram/pcs 8.5 MGOe MnBi magnet 2. Fabricate one small 10 MGOe MnBi (>2 gram)
Yr 3	1. Delivered 50 pieces of 8.5 MGOe MnBi magnet (100 gram each) machined to the desired dimension and coated.

Technical Accomplishments (MnBi)

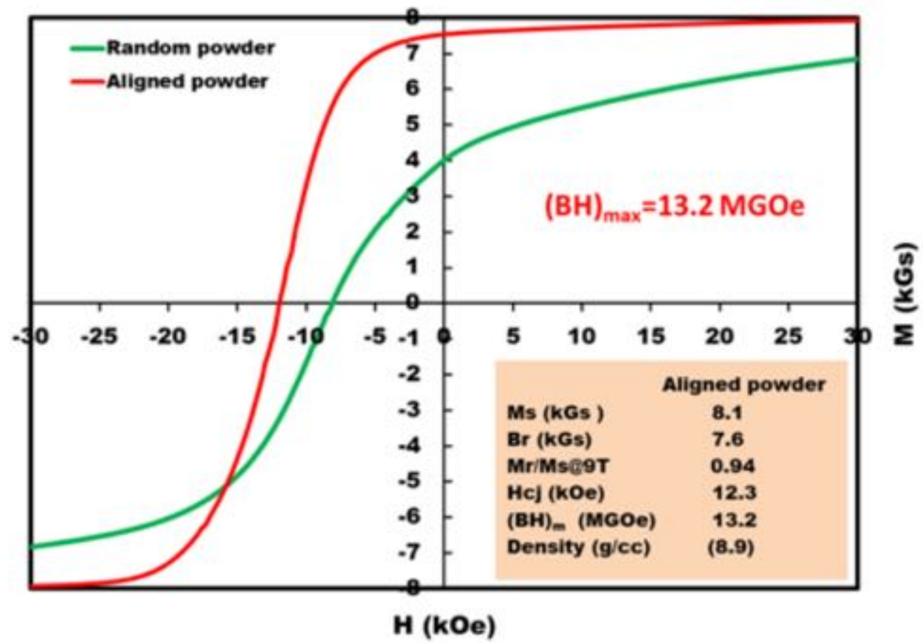
New records were established for feedstock powder preparation

M_S 77.2 emu/g, $(BH)_{max}$~13.2 MGOe

Previous records were M_S 74.5 emu/g, $(BH)_{max}$~12 MGOe



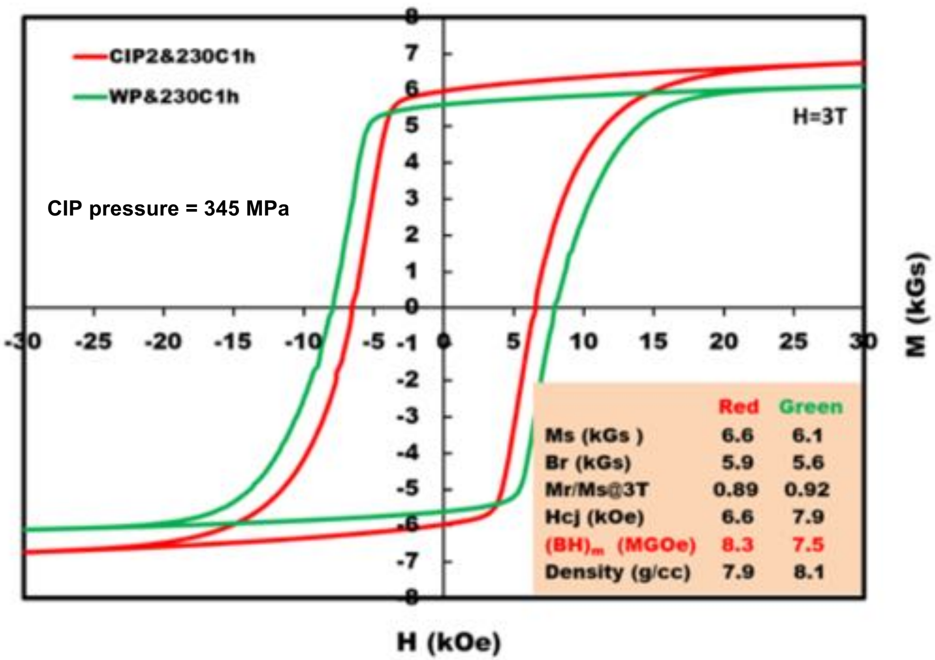
M-H of coarse powder



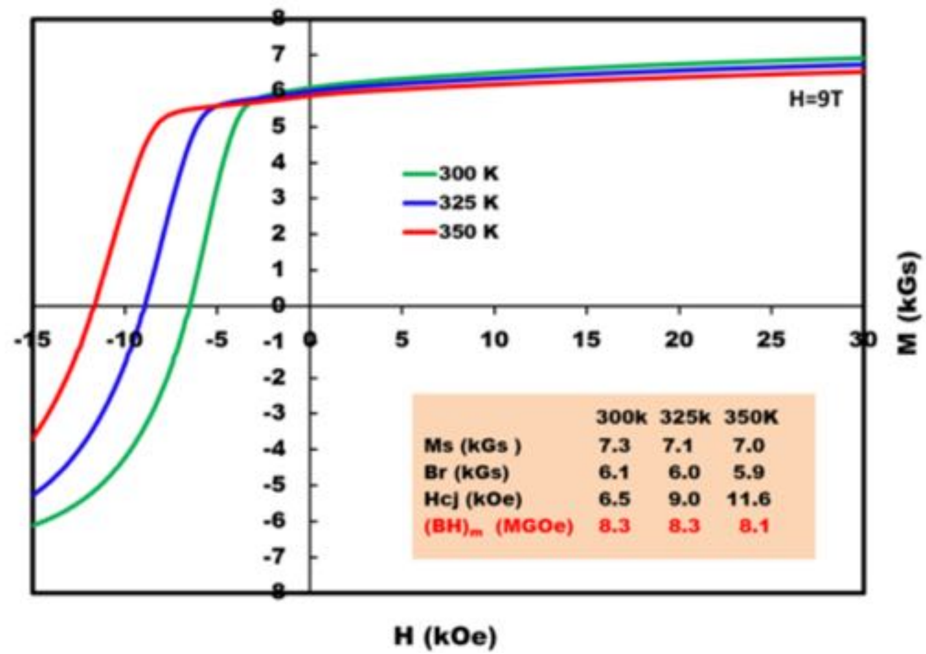
M-H of ball-milled powder

Technical Accomplishments (MnBi)

- Milestone 8.5 MGOe is closely met (8.3 MGOe demonstrated)
- Optimized the cost-effective Cold-Iso-Press (CIP) and sintering process to replace the expensive warm-compaction (WP) method
- The CIP bulk magnet exhibited excellent temperature stability: $(BH)_{max}$ drops 2% at 350K (15% for NdFeB)



M-H loops of CIP & WP samples



Demag curves at 300/325/350 K

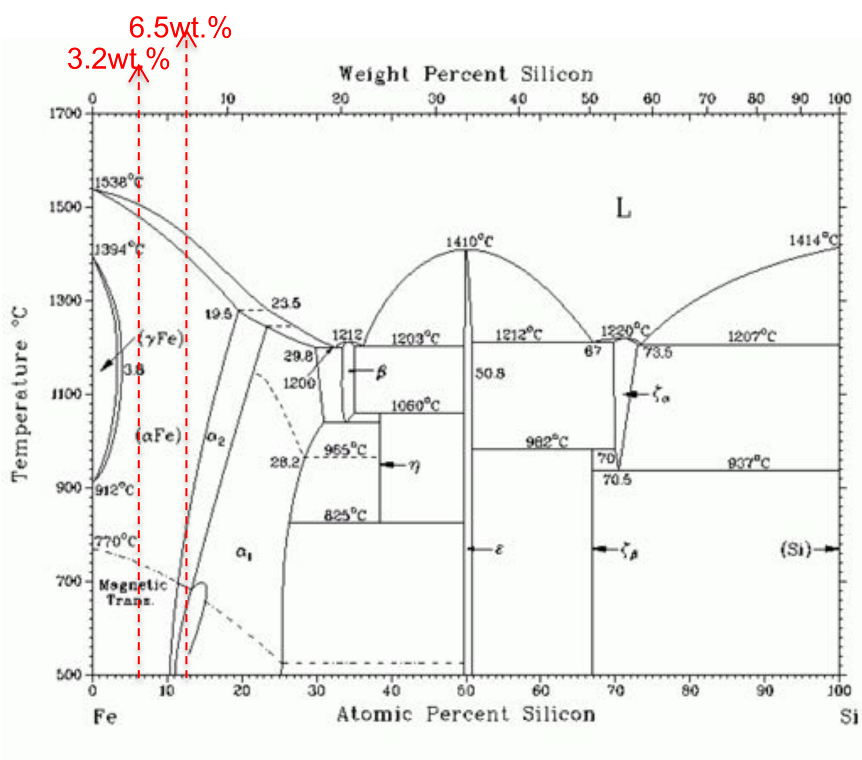
Challenge (6.5% Si Steel)

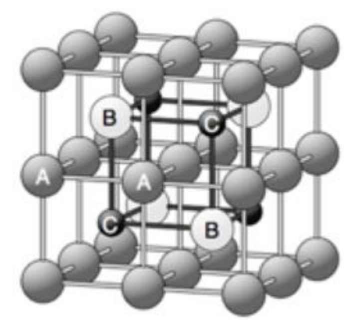
Advantages of 6.5% Si Steel

FeSi steels	Ms (T)	DC relative permeability	Electric resistivity (μΩ-cm)	Magneto striction (ppm)	Core loss $W_{10/400}$ (W/kg)
3.2% Si	1.96	18,000	52	7.8	14.4
6.5% Si	1.8	23,000	82	0.1	5.7

Challenges of 6.5% Si Steel

- Too brittle to be manufactured using cost effective cast/hot-roll/cold-roll process





Fe (A) Fe (B) Si (C)

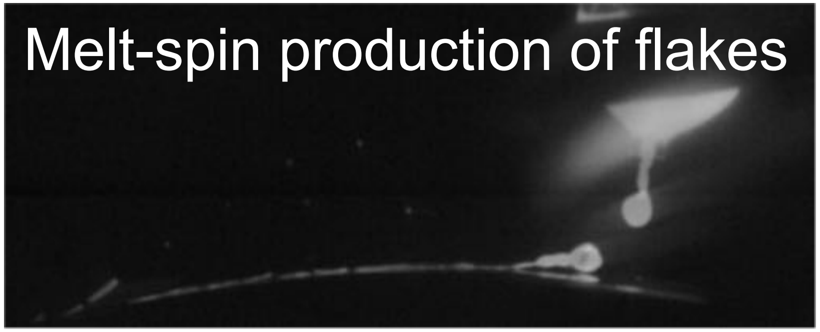
α- FeSi	A2	All sites are randomly occupied by Fe or Si
α_2- FeSi	B2	C, B sites are randomly occupied by Fe or Si
α_1- FeSi	$D0_3$	C sites are randomly occupied by Fe or Si

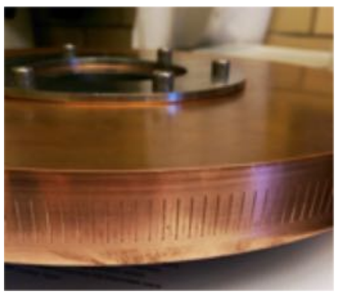
Approach (6.5%Si Steel)

- Use rapid solidification to suppress the deleterious ordering phase and produce ductile thin flakes.
- Dip-coat flakes with thin CaF_2 layer for insulation.
- Consolidate ductile flakes into near-net-shape part with laminated internal structure.

	End results and annual go/no-goes
Yr 1	1. Delivered 10 gram of ductile Fe-6.5%Si flakes (30 μm thick, 1x1 mm^2, 180º bending no crack)
Yr 2	1. Delivered Fe-6.5%Si rings with 0.1, 0.4, 1, and 4 mm thickness (OD: 1.5”, ID: 1.25”, 98% dense, various levels of oxidization) 2. Validated power loss $W_{10/400}$<6 W/kg for the ring with 0.4 mm thickness.
Yr 3	1. Delivered 8” OD stator laminate with W10/400<6 W/kg 2. Project manufacturing cost for small scale mass production

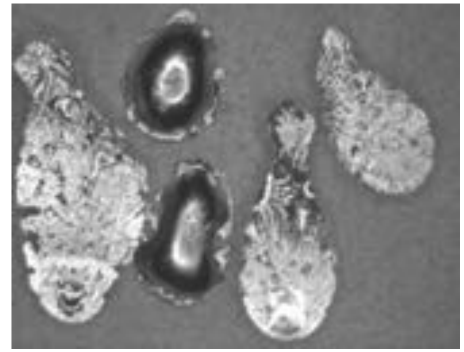
Technical Accomplishments (6.5%Si Steel)



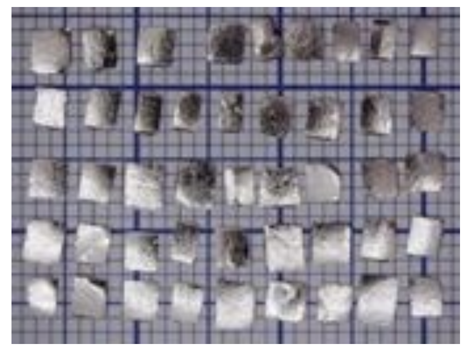


Grooved wheel breaking continuous ribbon to flakes

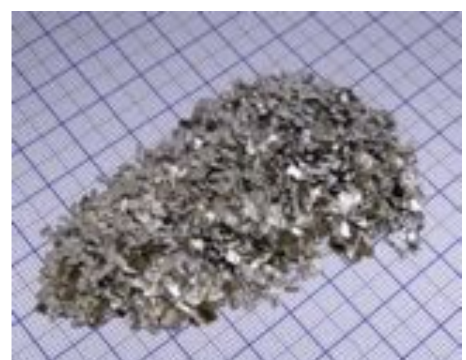
- Developed the process for producing flakes (2x2x0.1 mm^3)
- Approximately 75% yield of the flakes with the desired size
- System capable of 500 gram per batch was acquired/installed



Early stage: Melt didn't stick to wheel properly



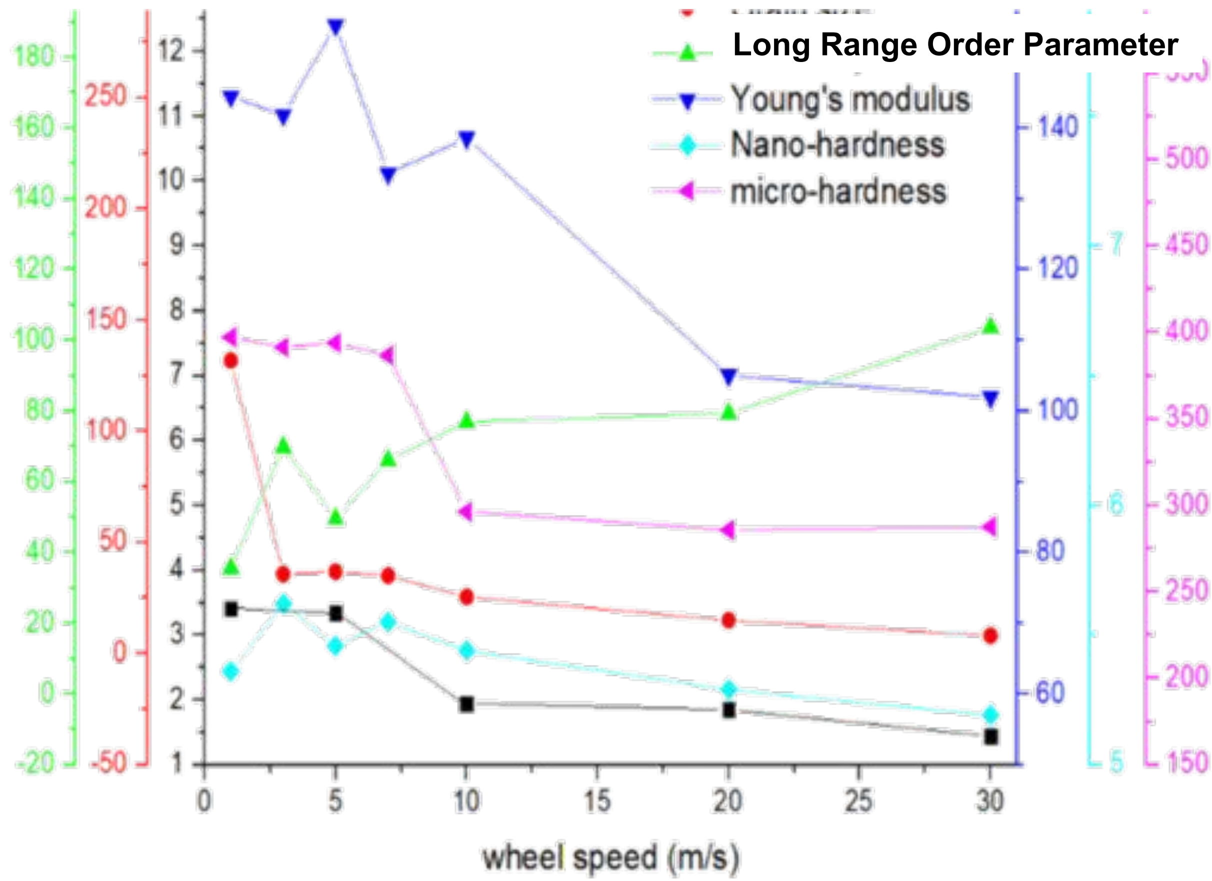
2017 (1st year) Flakes with desired size produced in 5 gram quantity

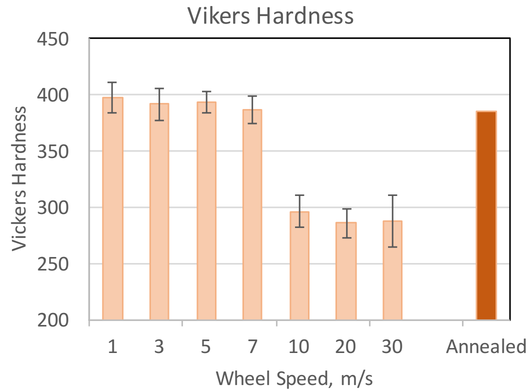


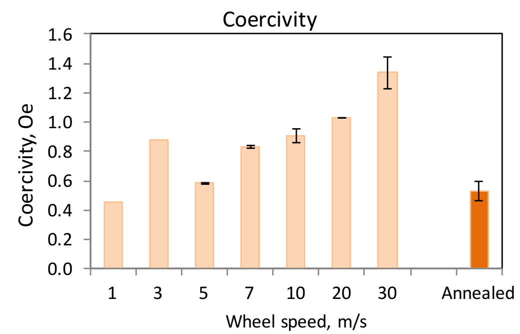
2018 (2rd year) Flakes with desired size produced in 150 gram quantity

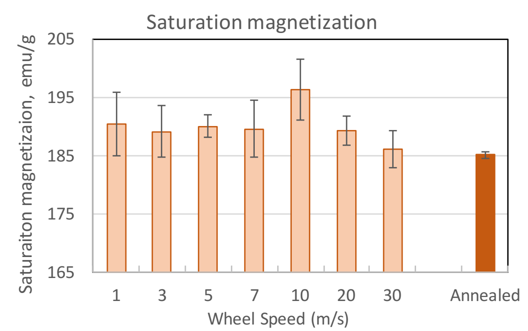
Technical Accomplishments (6.5%Si Steel)

Relationship between wheel speed and physical properties established





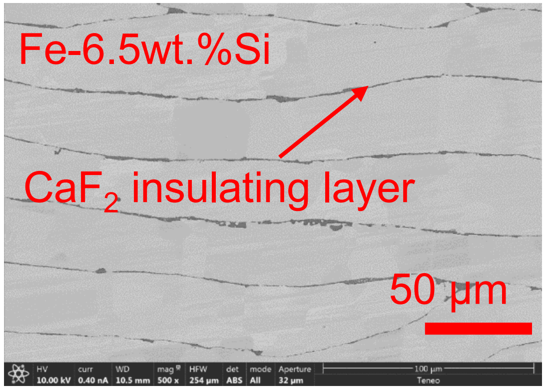




With increasing wheel speed:
Grain size (↓); Young's Modula (↓); Hardness (↓); Magnetization (↓); Coercivity (↑); Electrical resistivity (~flat)

Technical Accomplishments (6.5%Si Steel)

- Rings with OD~1" and 0.4, 2, 5mm thickness were fabricated.
- Process for OD~2" is being developed
- The rings comes with various levels of inter flake coatings
- Power loss $W_{10/400}$ 15.1 W/kg was demonstrated with 0.4mm ring with coating-free flake before heat treatment.

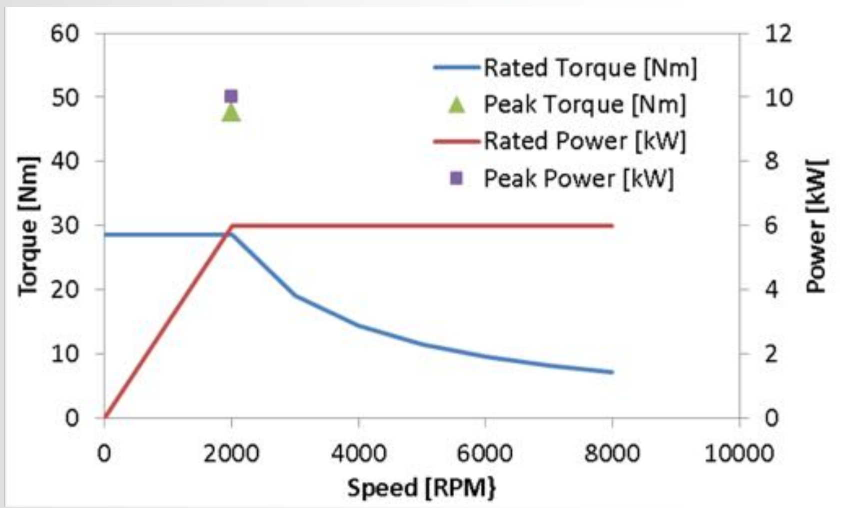


Material	composition	thickness (mm)	B Max (T)	Br (T)	Hc (A/m)	µMax	B8 (T)	B25 (T)	W10/400 (W/kg)
Ameslab Hp142	Fe-6.5Si	2	1.74	0.88	39.02	8470	1.19	1.32	66.1
JNEX-core	Fe-6.5Si	0.1	1.8			23000	1.29	1.4	5.7
JNHF-core	Gradient Fe-6.5Si	0.2	1.94			3900	1.09	1.47	14.5

Challenges (Non-RE Motor)

Machine Performance Specifications for 10 kW Peak, 6 kW Rated Power

Technical Targets		
Cost	Specific Power	Power Density
≤$4.7/kW	≥1.3 kW/kg	≥5.7 kW/Liter



Target Specifications Table

Specifications	Units	Values
Peak Power	kW	10
Continuous Power	kW	6
Max Speed	RPM	8000
Min Frequency	Hz	300
Voltage	V	325
Max per Phase Current	A rms	35
Characteristics Current	A rms	< 35
Weight	kg	7.69
Volume	l	2.2
Unit Material Cost	$	47
Max Efficiency @ 1/2 Speed & 1/2 Torque	%	95%
Based Speed	RPM	2000
Peak Torque @ Rated Speed	Nm	47.75
Rated Torque @ Rated Speed	Nm	28.65
Max Speed	RPM	8000
Torque @ Max Speed	Nm	7.16

Approach (Non-RE Motor)

Model development to automate and minimize iterative enhancements

Model Development Process

Tool
Excel spread sheet equipped with VBA script enabling new design and FE model development

↓

Model Input
Initial dimensions, poles and slot combination, winding type, current density, slot fill factor, soft and hard magnetic materials

↓

Finite Element Model
Built FE model with geometric features (magnets dimensions, stator tooth basic dimensions, back iron thickness, etc.), simulation conditions, excitations

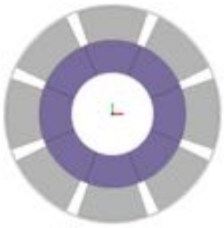
↓

Computation of Initial State
Computation of torque for given electric and magnetic loading

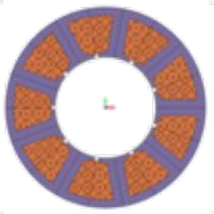
↓

Optimization
Defined objectives (total weight);
constraints (required torque);
Parameter bounds (geometric variables with bounds)

Configurations Under Consideration

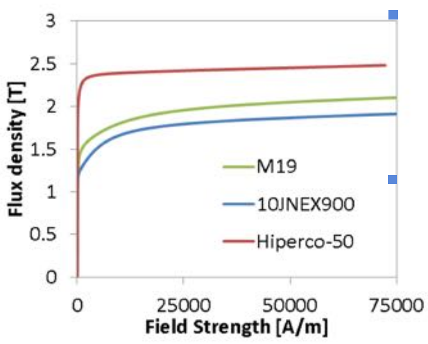


Surface PM



Fractional Slot Concentrated Winding

Material Properties

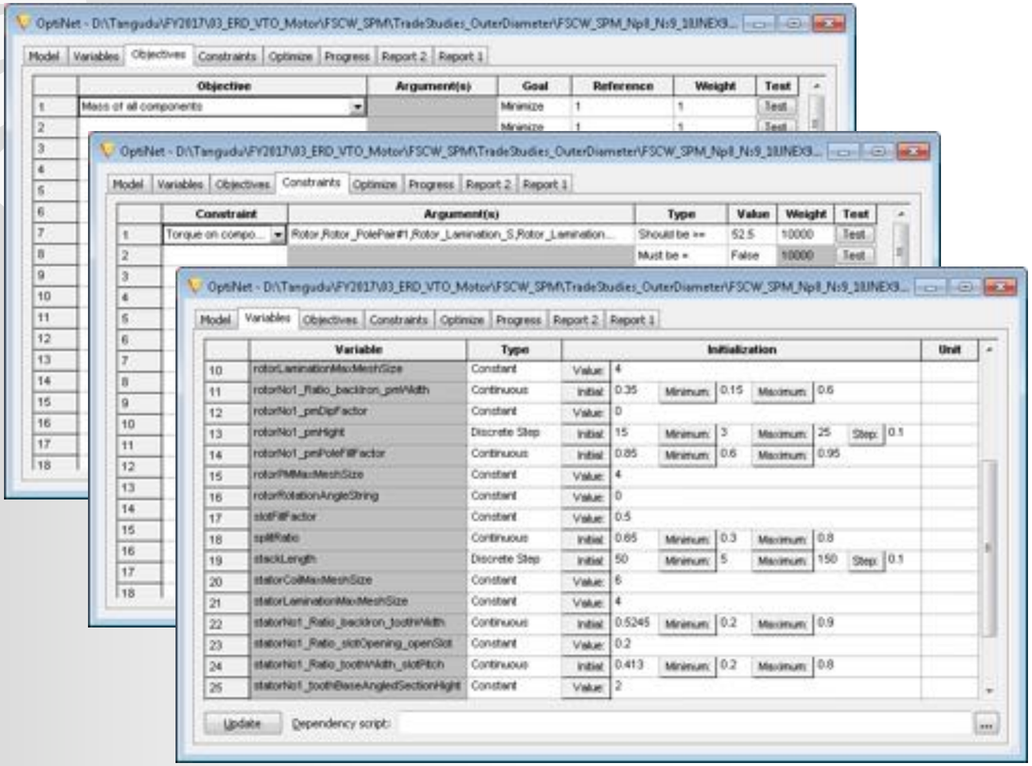


- Lamination materials
  - HIPERCO (6 mils)
  - M19 - 3.5 Si (14 mils)
  - 10JNEX900 - 6.5% Si (4 mils)
- Magnet Material
  - NdFeB48
  - MnBi
  - Ferrite

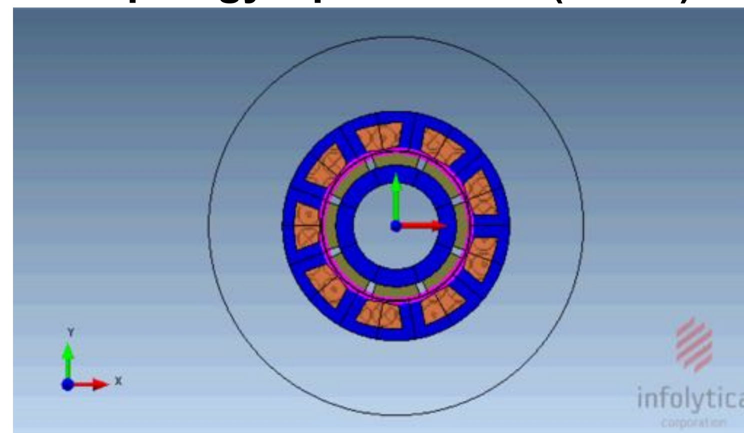
Material	Remnant Flux Density [T]	Coercive Force [kA/m]	Energy Product [MGOe]
NdFeB48	1.39	1060	46.2
MnBi	0.6	405.8	8.4
Ferrite	0.45	33.5	4.9

Technical Accomplishments (Non-RE Motor)

Topology optimization: Genetic algorithm based 2d optimization for reduced weight and cost

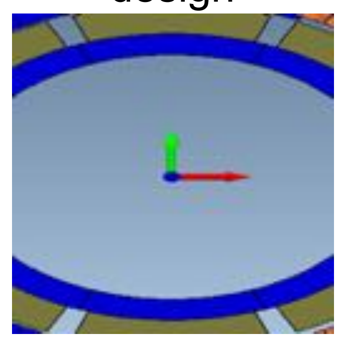


Topology Optimization (Video)

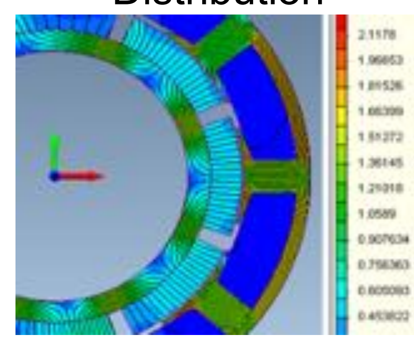


- 2d model design/topology optimization
- Objective: Minimize weight
- Constraints: Torque > 52.5 Nm (10% higher than peak torque)

Optimized design



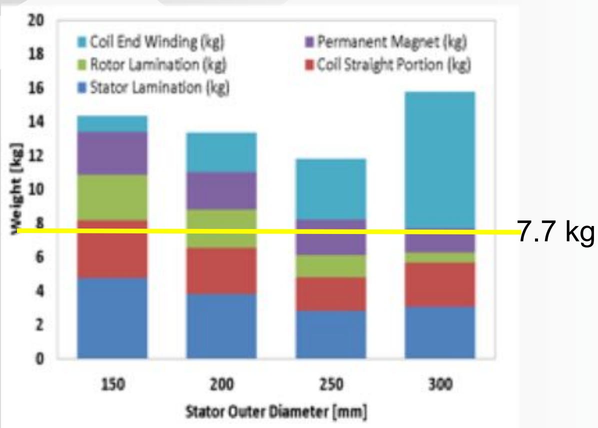
Magnetic Field Distribution



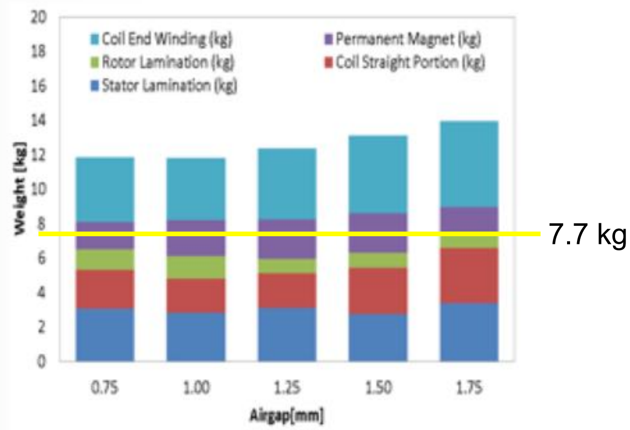
Technical Accomplishments (Non-RE Motor)

End winding contribution to total weight is significant for smaller power

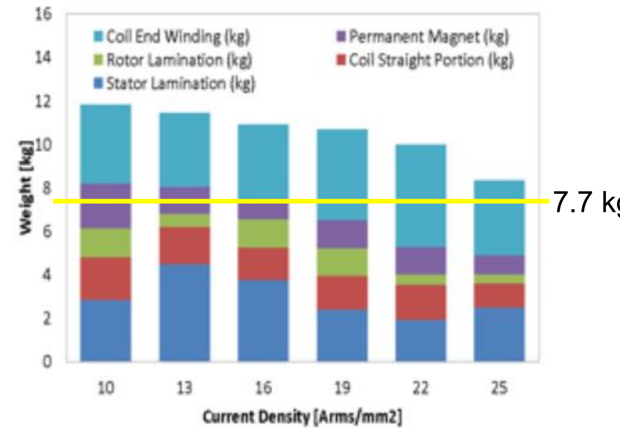
Trade Studies: Outer Diameter



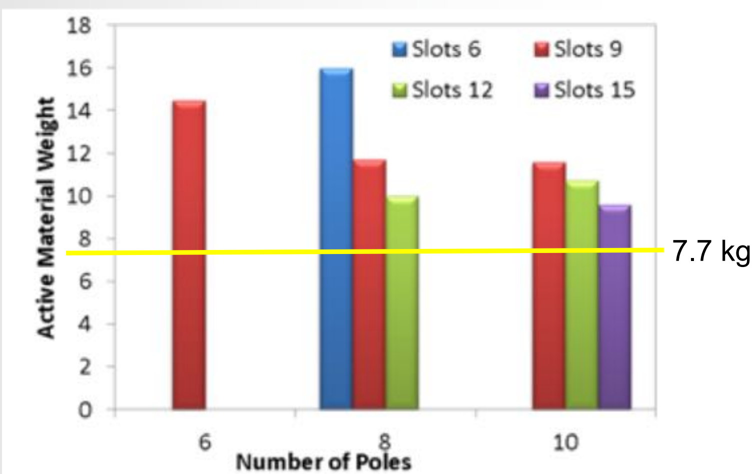
Trade Studies: Airgap



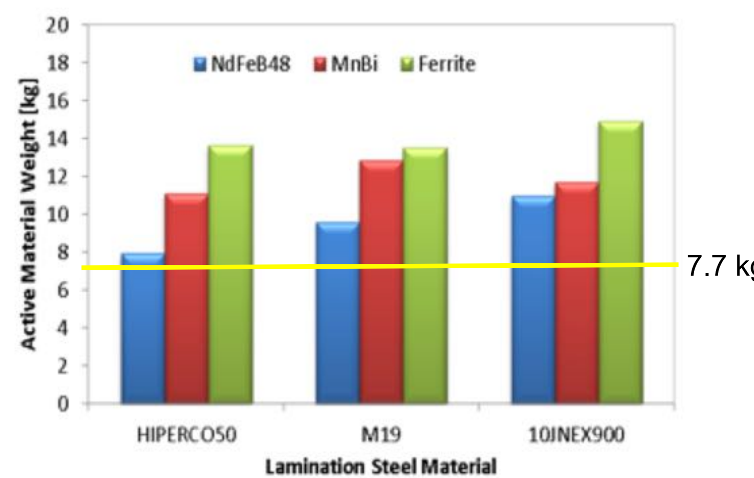
Trade Studies: Current Density



Trade Studies: Slot Pole Combination



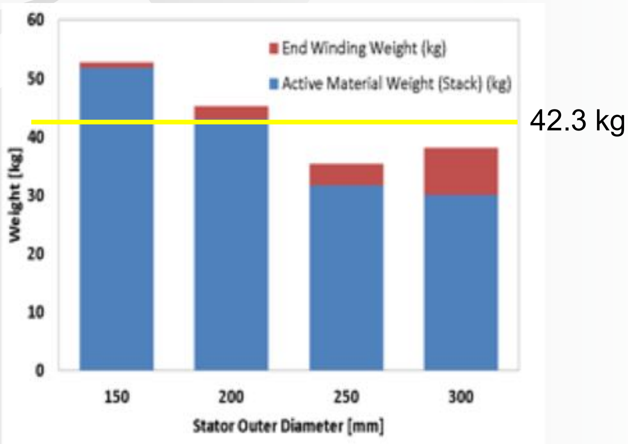
Trade Studies: Materials



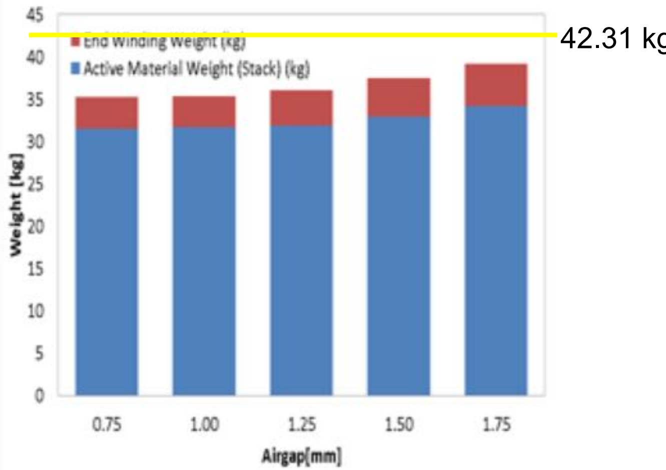
Technical Accomplishments (Non-RE Motor)

Scalability studies show that proposed design meets target power density

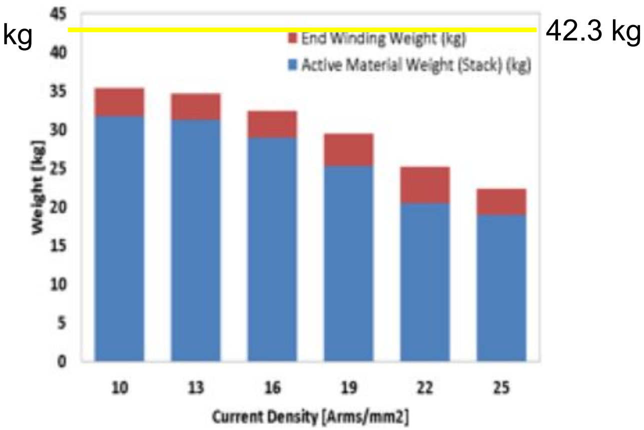
Trade Studies: Outer Diameter



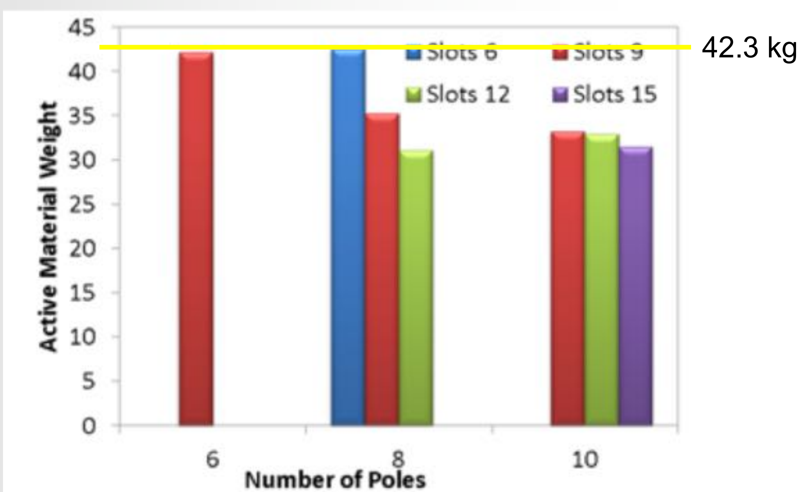
Trade Studies: Airgap



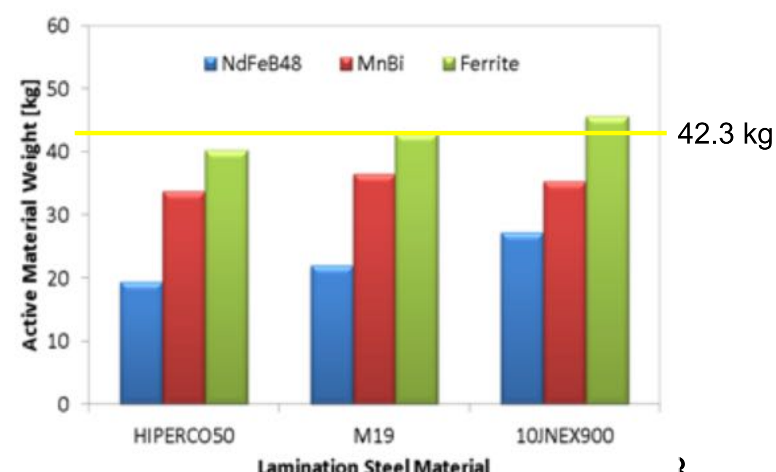
Trade Studies: Current Density



Trade Studies: Slot Pole Combination



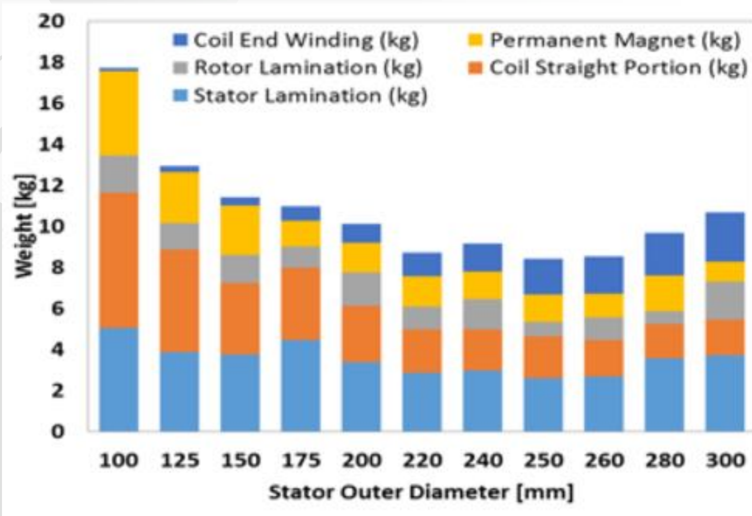
Trade Studies: Materials



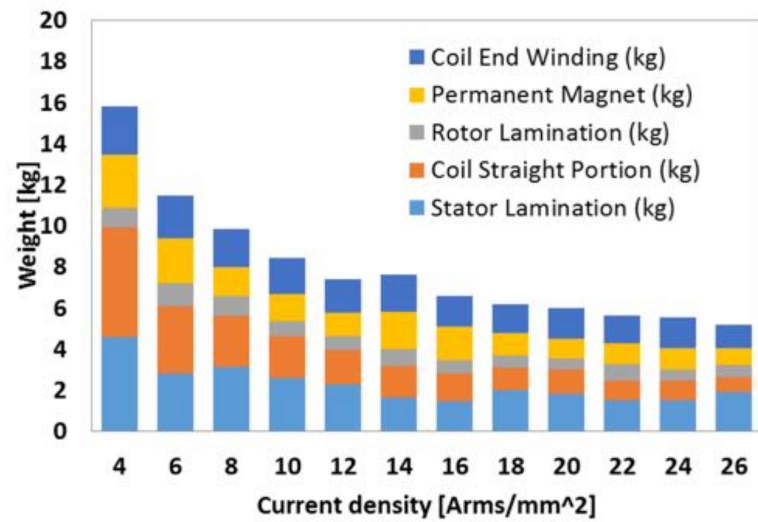
Technical Accomplishments (Non-RE Motor)

Detailed design with key design parameters (Power density & efficiency)

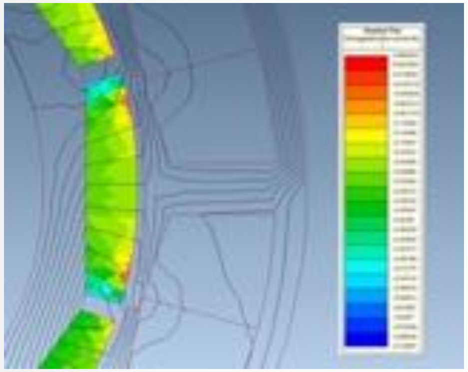
Finer Outer Diameter Sensitivity



Finer Current Density Sensitivity



Demagnetization

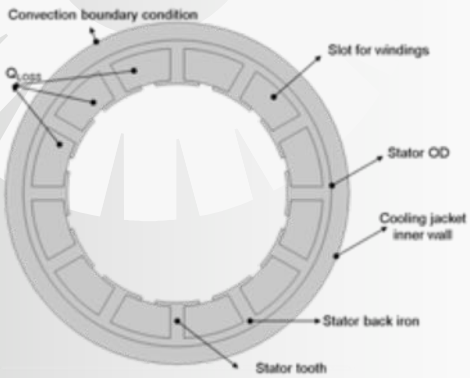


- Design space exploration to identify optimal design parameters
- Preliminary design performed using magnetic (B airgap) and electric loading (Ampere Turns)

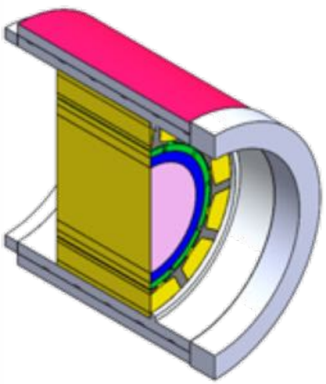
Technical Accomplishments (Non-RE Motor)

2D/3D Thermal models to capture temperature distribution in the motor

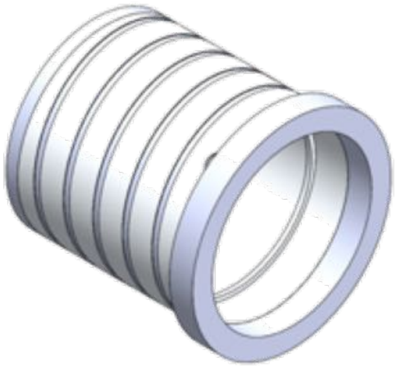
2D Thermal Model



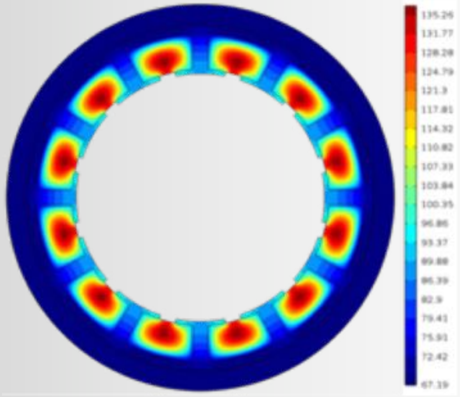
3D CAD Model – Cut View



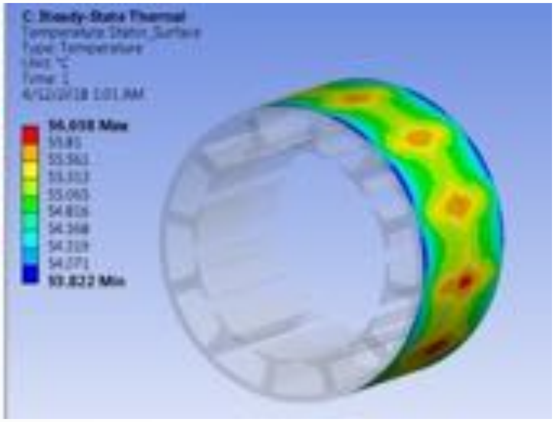
Spiral Cooling Jacket



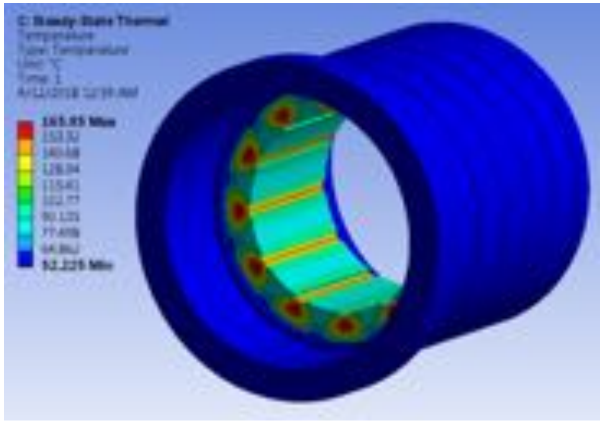
2D Temperature Distribution



3D Temperature Distribution



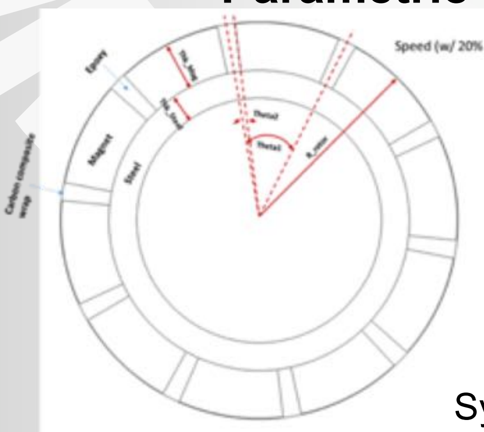
Distribution for Complete Model



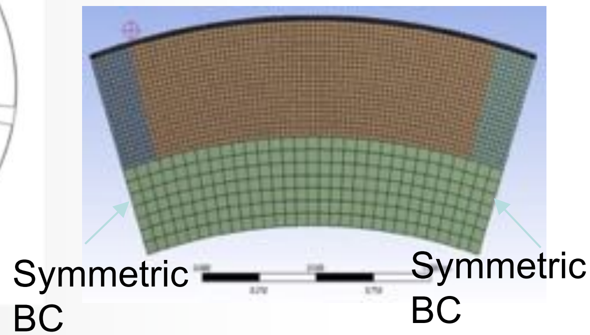
Technical Accomplishments (Non-RE Motor)

Structural modeling to design the carbon fiber composite thickness

Parametric Geometry



2D Model



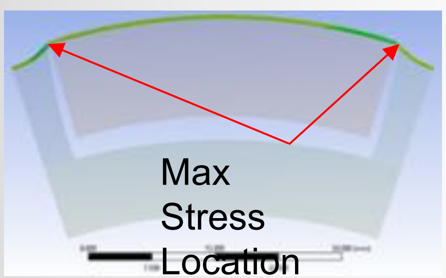
FE Models

2D (plane strain) sector models used for analysis

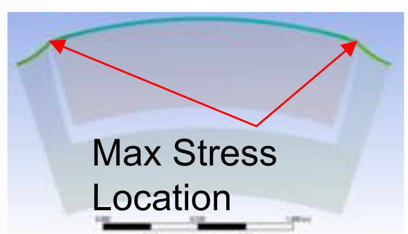
Contacts:

- Magnet is only bonded to composite wrap
- Adhesive bonded to the steel rotor and composite wrap

Interlaminar Shear Stress (SXY)



Hoop Stress (SY)



Angular Velocity: 8000 RPM
20% Over speed: 9600 RPM

Composite wrap thickness: 0.5mm

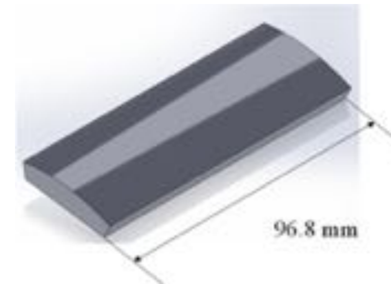
Responses to Previous Year Reviewers' Comments

- N/A (this is the first first review).

Collaboration and Coordination

Ames Laboratory	500 gram flakes production; 100 gram magnet fabrication
United Technology Research Center	Motor design and testing
University of Delaware	Amorphous MnBi flakes production
Electron Energy Corp.	Dummy magnet simulating the performance of MnBi magnet
JFE Steel Corp.	Commercial 6.5 Si% steel sheet (0.1 mm)
Leppert-Nutmeg Inc.	Motor construction
Oak Ridge National Laboratory	Additive manufacturing of motors

Remaining Challenges and Barriers



- MnBi:
  - Magnet shape
  - Scale up
  - Increase energy product to 10 MGOe
- 6.5% Si steel:
  - Retain the lambda texture to further reduce the core loss
  - Increase OD to 7 inch
- Motor
  - Improve power density to 5.7 kW/L

Proposed Future Research

- MnBi

Milestone: one 100 gram 8.5 MGOe MnBi magnet; and one 2 gram 10 MGOe MnBi

  - Improve fabrication process (better alignment and minimum oxidization)
  - Mass produce high purity MnBi powder (5 kg, 72 emu/g)

- 6.5% Si steel

Milestone: $W_{10/400}$<6 W/kg for the ring with 0.4 mm thickness

  - Optimize flake coating thickness and laminate architecture

- Non-Re motor

Milestone: Construct 400 Hz PM motor with dummy magnet and stator.

  - Execute the motor design and coordinate with vendors

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

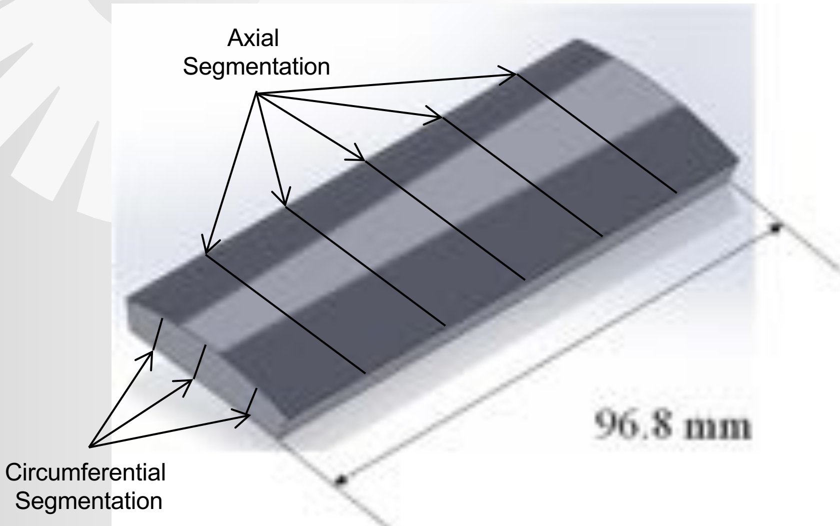
Summary

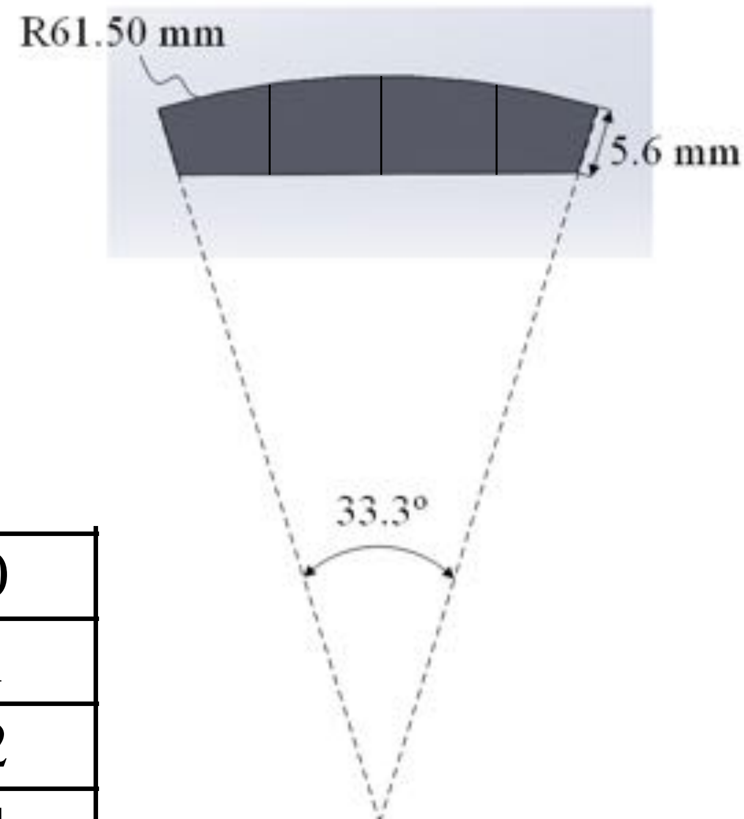
- MnBi
  - Powder quality was improved from 65 emu/g to 70 emu/g
  - Cost effective bulk magnet fabrication method was developed
  - A 100 gram bulk magnet with 6.5 MGOe was fabricated
- 6.5% Si steel
  - Relationship between physical properties and cooling rate was established
  - Flake production method and capacity were established
  - Laminate inner structure was optimized and fabrication method was established
- Motor
  - 10 kW 400 Hz motor was designed
  - Vendors for constructing the motor were contracted.

Technical Backup Slides

Magnets used in this project

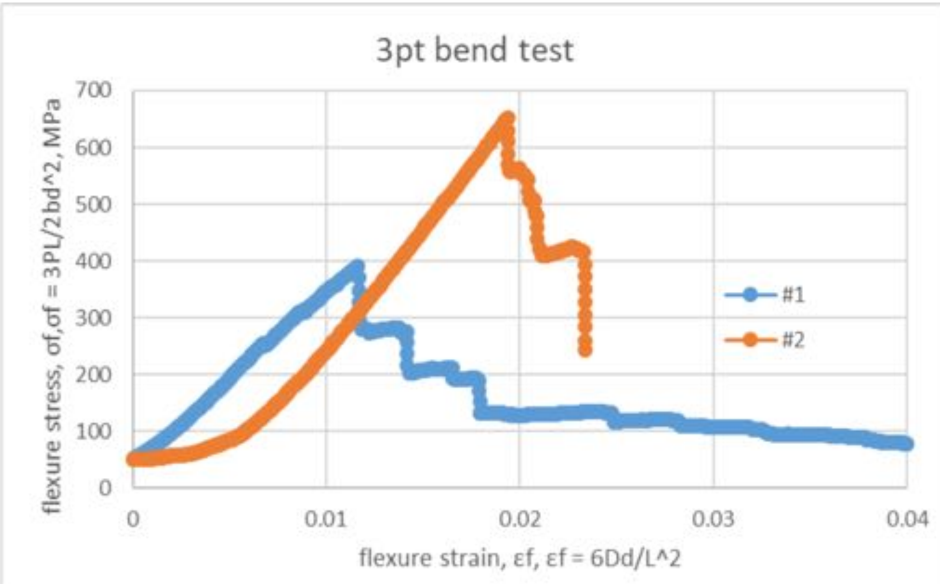
	Axial	Circumferential
Number of segments	4	5-10

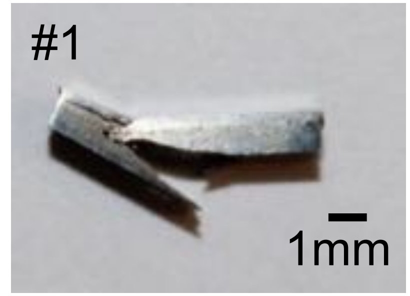


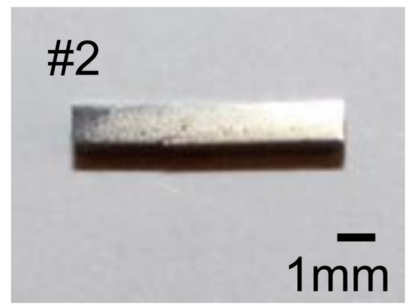


Br [kG]	6.0
Hc [kOe]	5.1
Hci [kOe]	6.2
Bhmax [MGOe]	8.4

Mechanical Properties







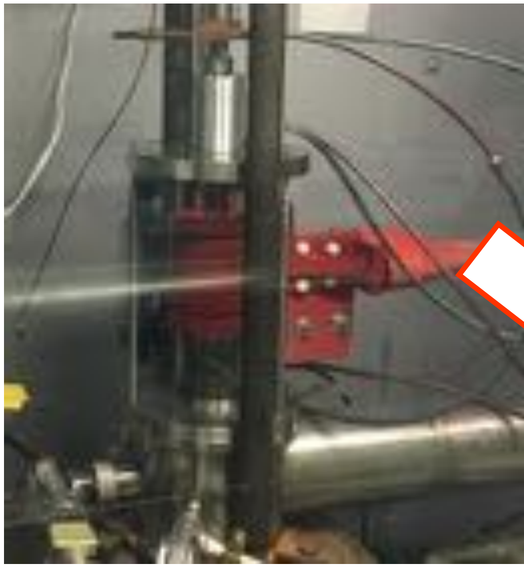
Sample #1 has pre-existing crack

The mechanical properties of the CaF_2 coated is remarkable

- High bending strength (650MPa)
- CaF_2 interlayer bonding prevented the sample from catastrophic failure on breakage.

Current Effort To Scale Up

2’’ diameter



3’’ diameter

7’’ diameter