Cost Effective 6.5% Silicon Steel Laminate for Electric Machines

Jun Cui[1], George Hadjipanayis[2], Jagadeesh Tangudu[3]

[1] Iowa State University

[2] University of Delaware

[3] United Technology Research Center

June 11, 2019

Project ID: elt091

IOWA STATE UNIVERSITY

UNIVERSITY OF DELAWARE

United Technologies Research Center

Overview

Timeline

- Start: October 1, 2016
- Finish: September 30, 2019
- Percent complete: 80%

Budget

- Total project funding
  - $3,835K (Federal)
  - $433K (Cost share)
- Funding for FY 2017: $1,489K
- Funding for FY 2018: $1,428K
- Funding for FY 2017: $1,351K

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

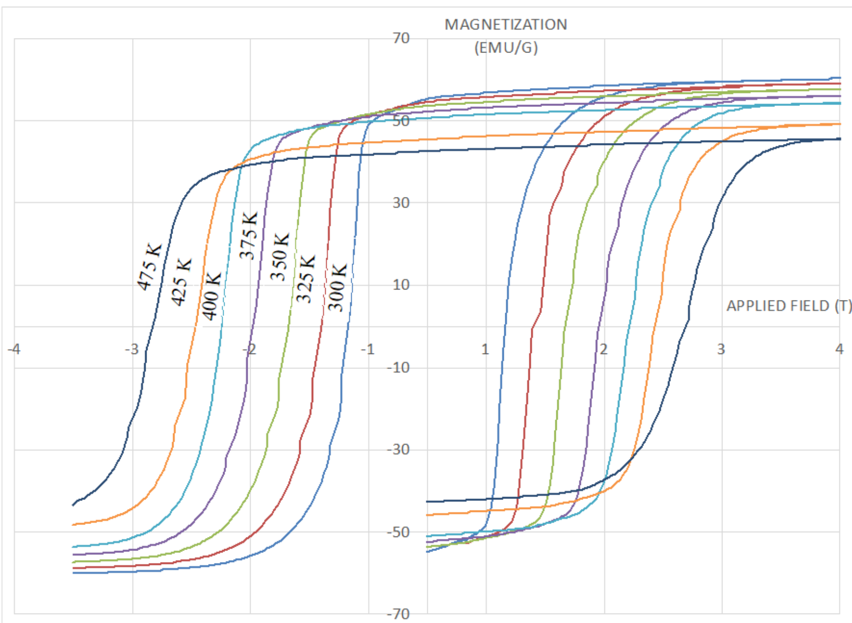
Milestones

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					✓	✓	✓	✓	✓	✓4		
3.3	Motor evaluation									X	X		

Challenges (MnBi)

Advantages of MnBi

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



Experimental M-H-T data showing increasing coercivity with increasing temperature

Challenges of MnBi

- Mn precipitation is inevitable, difficult to maintain high purity and high magnetization, which is limited at ~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
- Need to magnetically separate each grain in order to maintain magnetic coercivity

Approach (MnBi)

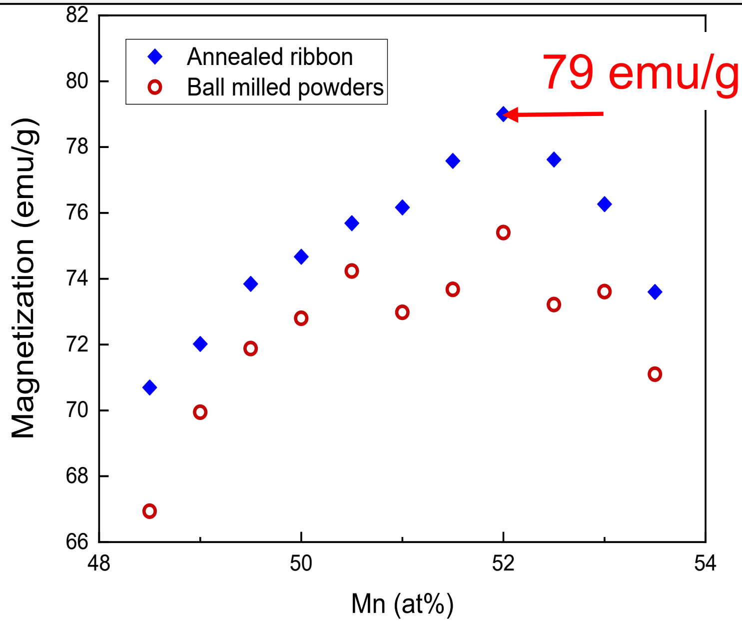
- Refine existing powder synthesis and magnet fabrication process, eliminate MnO formation
- Consistently produce bulk magnet with 8 MGOe
- Use amorphous feedstock to reduce Mn precipitation and improve energy product from 8.5 to 10 MGOe

	End results and annual go/no-goes
Yr 1	1. Produced 8 MGOe MnBi magnet (5 gram) 2. Produced 5 gram MnBi with 90% amorphous
Yr 2	1. Fabricated one 100 gram/pcs 8 MGOe MnBi magnet 2. Fabricate one small 10 MGOe MnBi (>2 gram)
Yr 3	1. Deliver 300 pieces of 8 MGOe MnBi magnet (10 gram each) machined to the desired dimension and coated

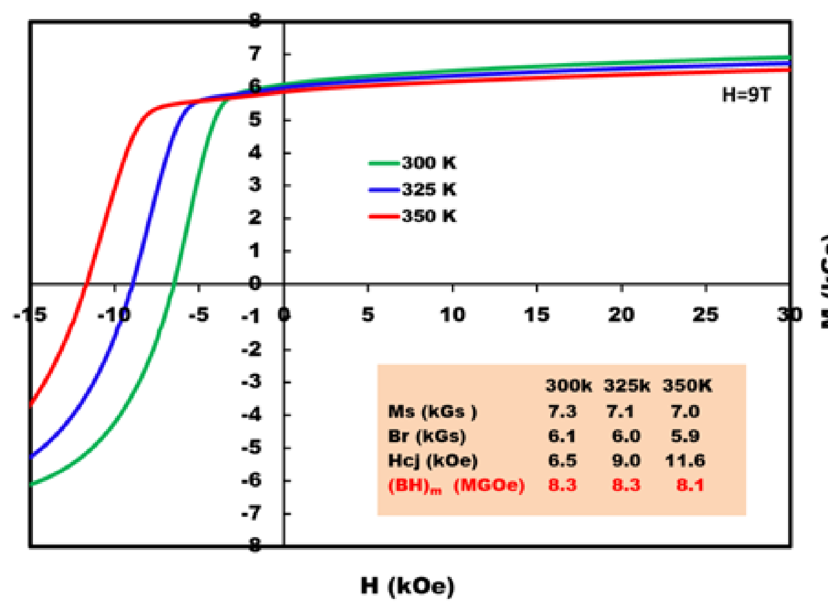
Table of year end results and go/no-goes

Technical Accomplishments (MnBi)

- Achieved a new record of saturation magnetization of 79 emu/g (theoretical limit is 82 emu/g)
- Milestone 8.5 MGOe is closely met (8.3 MGOe demonstrated)
- Cost-effective Cold-Iso-Press (CIP)-sintering process was developed
- The CIP bulk magnet exhibited excellent temperature stability: $(BH)_{max}$ drops 2% at 350K (15% for NdFeB)



Measured magnetization of alloys with different amount of manganese

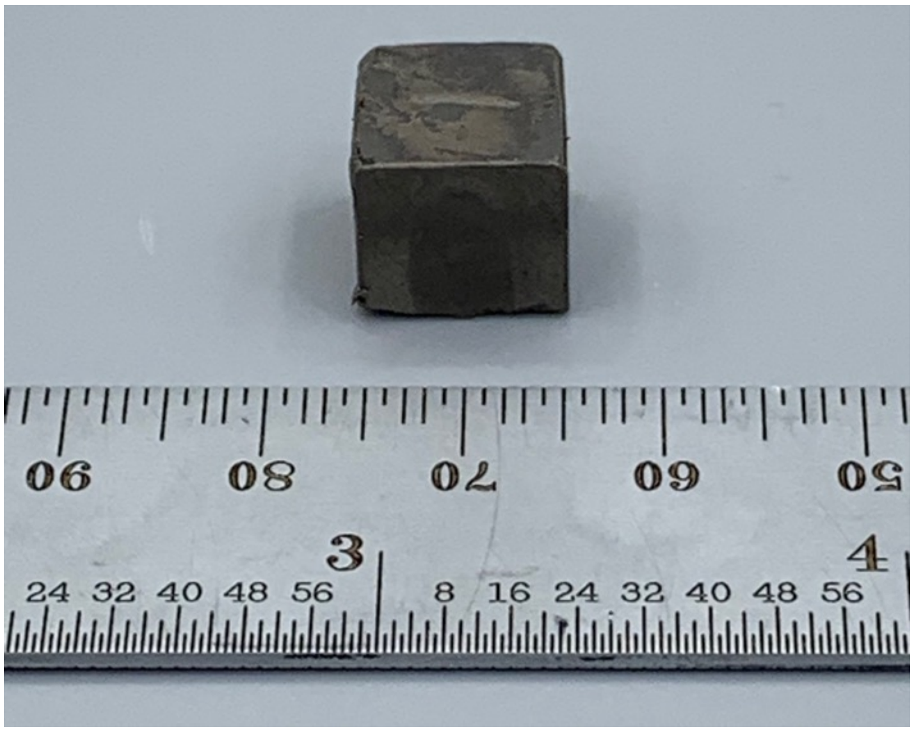


	300k	325k	350K
Ms (kGs)	7.3	7.1	7.0
Br (kGs)	6.1	6.0	5.9
Hcj (kOe)	6.5	9.0	11.6
$(BH)_m$ (MGOe)	8.3	8.3	8.1

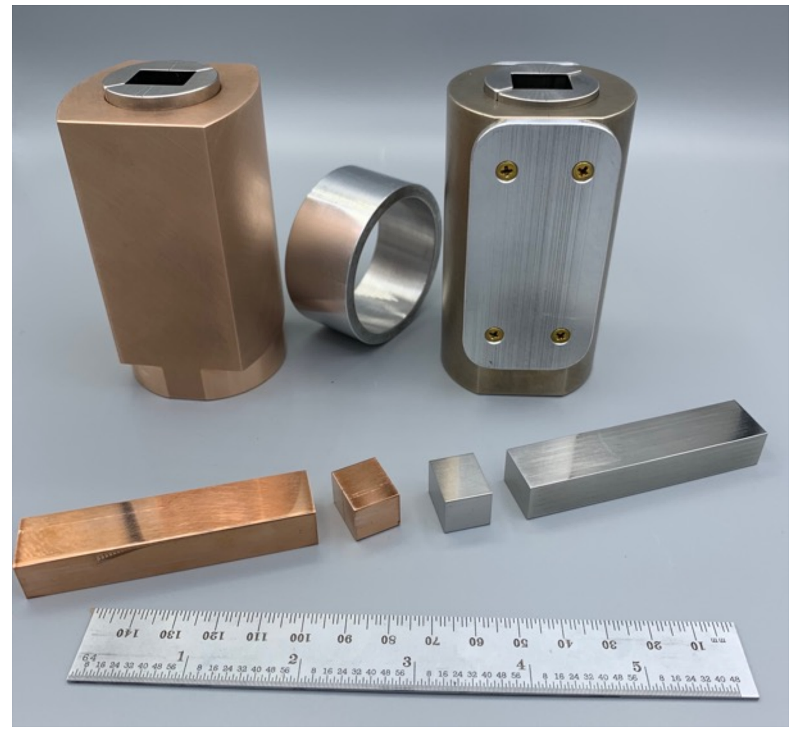
M-H curves of the MnBi bulk magnet at 300, 325 and 350 K

Technical Accomplishments (MnBi)

- Processes and facility for producing 300 magnets are setup.



Picture of a bulk MnBi magnet. It is the first of the 300 bulk MnBi magnets needed by the prototype motor



Picture of fabrication die set used to fabricate bulk magnet

Challenge (6.5% Si Steel)

Advantages of 6.5% Si Steel

Table of physical properties of various soft magnetic materials

Type	Materials	Bs (T)	Hc (A/m)	$10^3\mu_r$ 1 kHz	R ($\mu\Omega$-cm)	λ (ppm)	$W_{1.5/50}$ (W/kg)	$W_{10/400}$ (W/kg)	Ref
Crystalline	Electrical Steel, 0.2mm, NGO, 3.2% Si	2	26	15	57	8	0.7-1.2	11	[1,5]
	Electrical Steel, 0.2mm, NGO, 6.5% Si	1.6	45	19	82	0.01	0.6	8.1	[1,2]
	Molypermalloy, 0.5mm, Ni78Fe17Mo5	0.65-0.82	0.25-0.64	100-800	60	2-3	0.07	0.3	[3,4]
	Hiperco 50, Fe49Co49V2	2.4	16-400	5-50	27	60	4	10	[4]
Nano-crystalline	FINEMET, $Fe_{73.5}Si_{13.5}Nb_3B_6Cu_1$	1.2	0.5-1.4	80	110	0-2	–	1.1	[4-6]
	NANOPERM, $Fe_{88}B_4Zr_7Cu_1$	1.5-1.6	2.4-4.5	48	56	~0	–	3	[4-6]
	HITPERM, $(FeCo)_{44}Zr_7B_4Cu_1$	1.6-2.0	80-200	1-10	120	36	–	20	[4-6]
Amor-phous	Metglas, Fe78Si9B13	1.54	3	2.1	135	27	0.7	2-5	[7]
	Metglas 2650CO, $Fe_{67}Co_{18}B_{14}Si_1$	1.8	3.5	50	123	35	0.3	3	[4,8]
Ferrite	Ferrite, MnZnFeO	0.36-0.5	10-100	0.5-10	10^7-10^8	5	–	–	[4]
	Ferrite, NiZnFeO	0.25-0.42	14-1600	0.01-1	10^{11}	-20	–	–	[4]

Challenges of 6.5% Si Steel

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

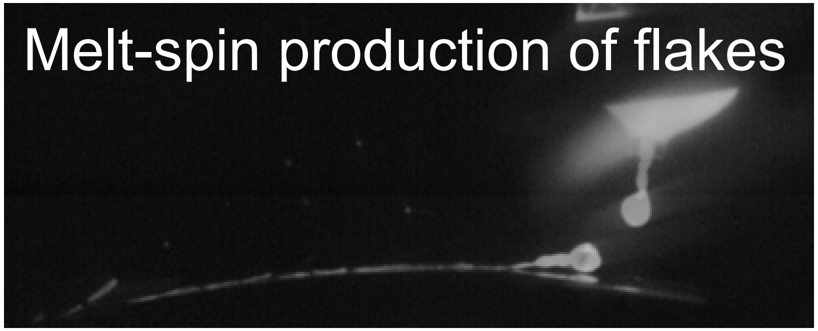
Approach (6.5%Si Steel)

- 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 mm 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. Deliver 8" OD stator laminate with W10/400<6 W/kg 2. Project manufacturing cost for small scale mass production

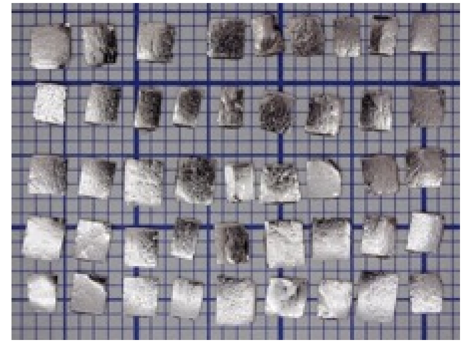
Table of year end results and go/no-goes

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 installed



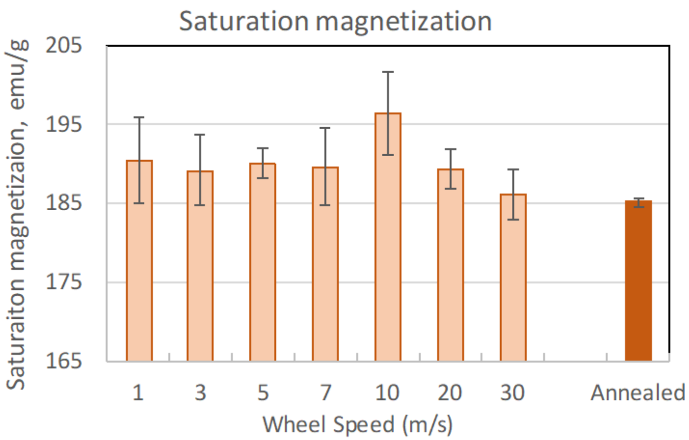
<u>2017 (1st year)</u>
Flakes with desired size produced in 5 gram quantity

<u>2018 (2rd year)</u>
Flakes with desired size produced in 150 gram quantity

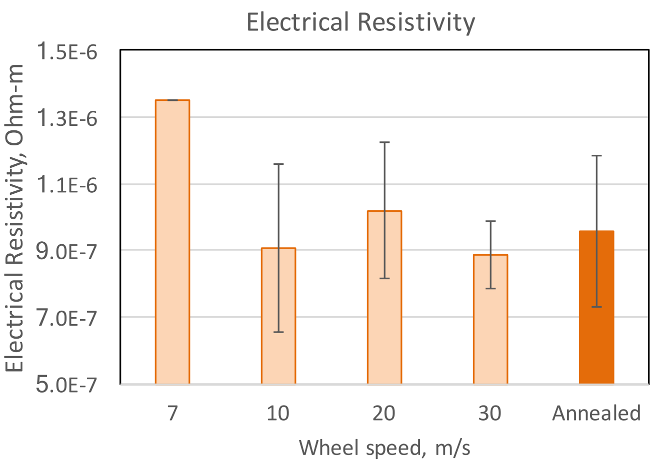
<u>2019 (3rd year)</u>
Flakes coating process was developed

Technical Accomplishments (6.5%Si Steel)

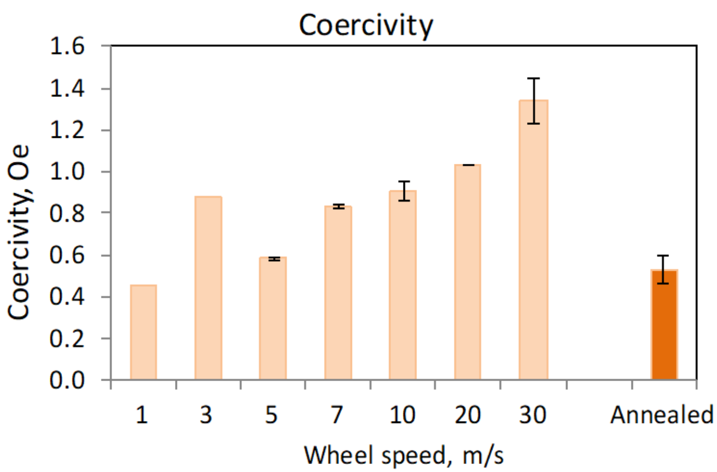
Relationship between wheel speed and physical properties established



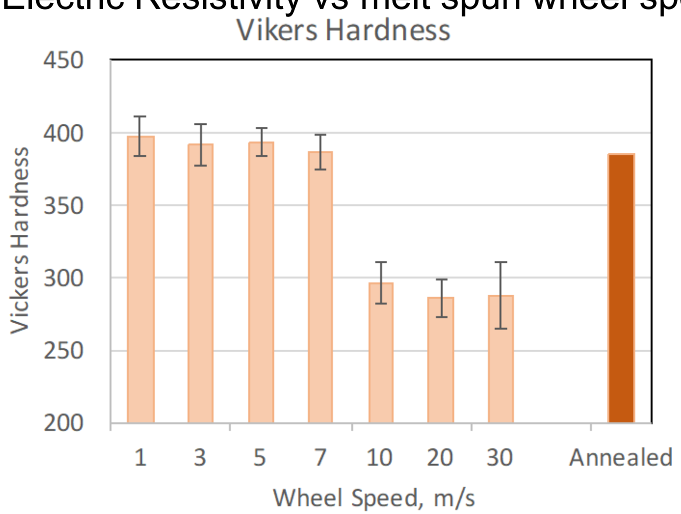
Saturation magnetization vs melt spun wheel speed



Electric Resistivity vs melt spun wheel speed



Coercivity vs melt spun wheel speed

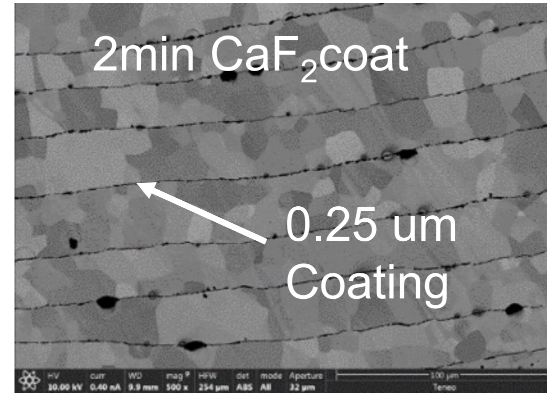


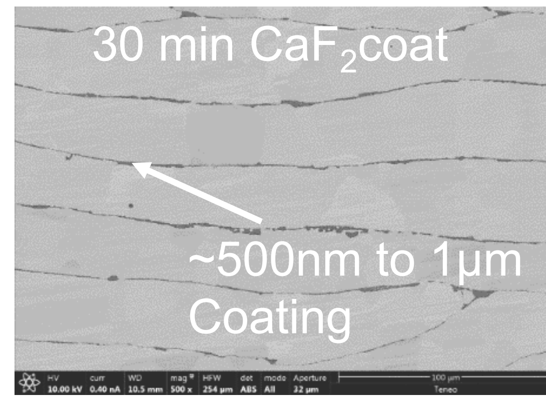
Hardness vs melt spun wheel speed

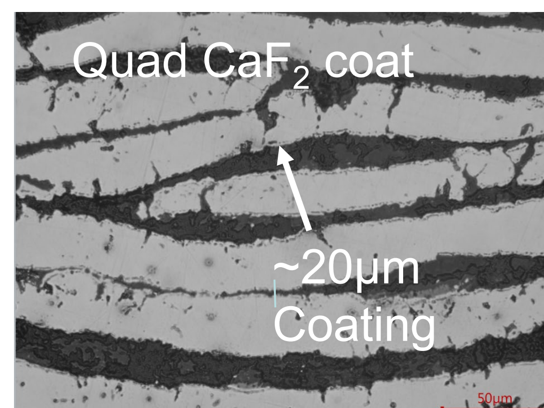
Technical Accomplishments (6.5%Si Steel)

- Coating thicknesses (0.25-20 μm) has been investigated.
- Mg_2SiO_4 effectively increased the resistivity up to 800 times.

Coating	Density g/cc	Densification	Resistivity μΩ-cm
None	7.48	100%	81.36; 84.29
CaF_2, 2min	7.35	98.3%	108.2, 93.5
CaF_2, 30min	7.32	97.8%	139.1; 115.4
CaF_2, 2h	6.85	91.6%	322.5; 294.5
CaF_2, quad coat	5.99	80.1%	339.5; 228.8
10% MgO, 30s dip	6.86	91.7%	510.1; 259.2
50% MgO, 30s dip	4.70	62.8%	66k; 22k
50% MgO anneal	6.34	84.8%	1111.5; 688.9





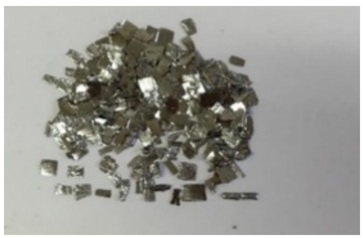


Figures on the right show consolidated Fe-Si flakes coated with different amount of CaF2

Technical Accomplishments (6.5%Si Steel)

Coreloss performance met/exceeded the expectation

- 0.2mm sample achieved record low iron loss at 400 and 1000Hz.
- 0.1mm sample has W10/400 of 6.1W/kg


Melt-spun flakes

Hot press →


Consolidated flakes

→ 1100°C x 2h annealing + Slice →


A ring sliced from the consolidated flakes

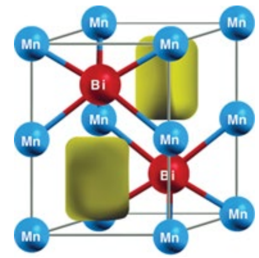
		Ameslab GO2P23	**NO Si steel**	**Ameslab GO2P23**	**JNHF**	**Ameslab GO2P23**	**JNEX**
		Fe-6.5Si	Fe-3.2Si	Fe-6.5Si	Gradient Fe-6.5Si	Fe-6.5Si	Fe-6.5Si
thickness	(mm)	0.33	0.35	0.2	0.2	0.1	0.1
W10/400	(W/kg)	10.8	14.4	7.2	14.5	6.1	5.7
W10/1k	(W/kg)	45.7	62.0	27.3	29.1	20.2	18.7
DC,μMax		28.7k	18.0k	28.4k	3.9K	25.8k	23.0k

UTRC Project Deliverables

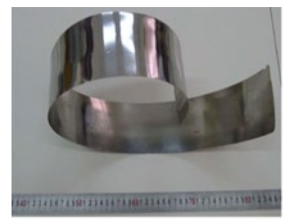
Task 1: *Preliminary Design:*
– **End of Sept 2017** **- Completed**

Task 2: *Detailed Design & Motor Build:*
– **End of Sept 2018** **– Design Completed – Motor Build Delayed. In-progress**

Task 3: *Experimental Validation, Re-build & Re-test:*
– **End of Sept 2019 – Delayed start due to delay in materials**



Non Rare Earth Magnets
Manganese Bismuth (8-10 MGOe)



Low Loss Density Steel
6.5% Si Steel with improved ductility

High Frequency Motor

Electric machine at low cost & improved performance (power density & efficiency)

		Year-1				Year-2				Year-3			
	Task Description	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	Preliminary Design												
Task 2	Detailed Design and Motor Build												
Task 3	Experimental Validation, rebuld & retest												
Task 4	Project Management												

Today

Performance Metrics & Materials Considered

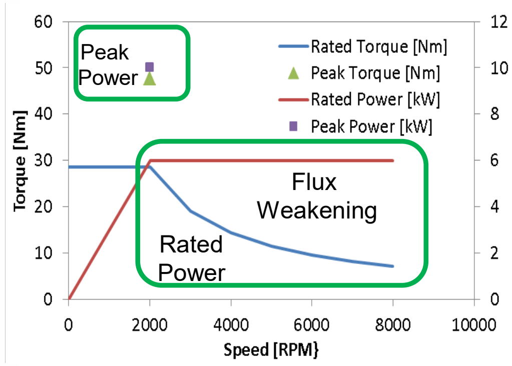
Machine Performance Specifications for 10 kW Peak, 6 kW Rated Power

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

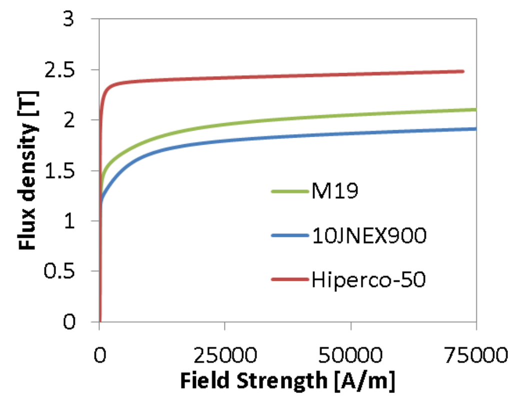
Target Motor Specifications

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

Torque/Power vs. Speed



Soft Magnetic Properties



Hard Magnet Properties

Material	Remnant Flux Density [T]	Coercive Force [kA/m]	Energy Product [MGOe]	Cost [$/kg]
NdFeB48	1.39	1060	46.2	80
MnBi	0.6	405.8	8.4	10
Ferrite	0.45	33.5	4.9	5

Modeling Approach: Electromagnetics

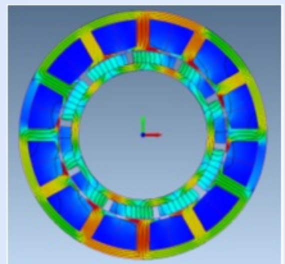
Suitable modeling methods to capture physics appropriately

GA Optimization – 2d Static

Change geometry

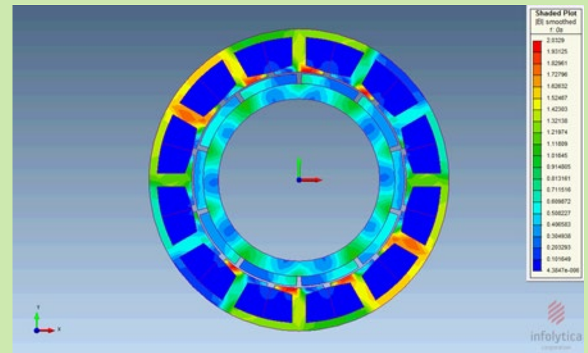
Evaluation

2D FE Analysis



Objective Function: Weight
Constraint: Torque

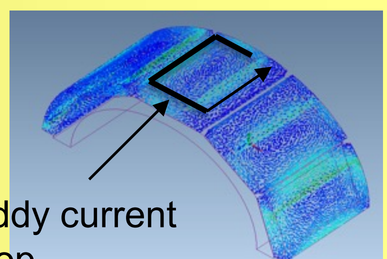
Core Losses - Transient 2D w Motion



Steinmetz's equations: $P = K_h f^{\alpha} B^{\beta} + K_e (fB)^2$

Magnet Losses - 3D Transient w Motion

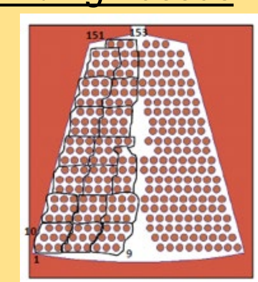
Capture the Eddy current loops in the magnet



Eddy current loop

Analytical Formulation – AC Winding Losses

Compute skin depth and then use the wave equations to capture the AC copper losses in the conductors



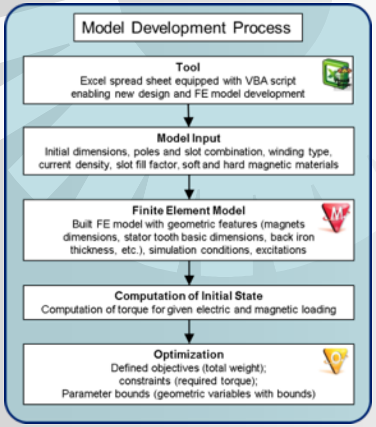
Stator slot view

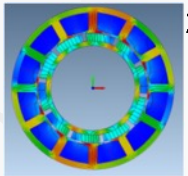
$$R_{ac} = \frac{d}{h}\left[\frac{\sinh\left(\frac{2d}{h}\right)+\sin\left(\frac{2d}{h}\right)}{\cosh\left(\frac{2d}{h}\right)-\cos\left(\frac{2d}{h}\right)}\right] R_{dc}[1]$$

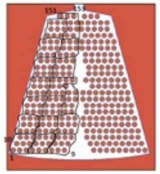
Source: [1] T. A. Lipo, *Introduction to AC Machine Design*, Wisconsin Power Electronics Research Center, Wisconsin, 2004

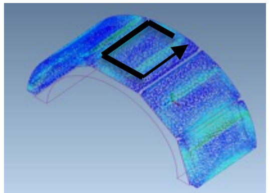
Modeling Approach: Multi-Physics

Multi-physics modeling to address some of the key risks identified




2D FE Analysis


Stator slot view


Capture the Eddy current loops in the magnet

Electromagnetics

2d Static – For initial Optimization
3d Transient – For losses
Analytical – AC Winding Losses

Structural

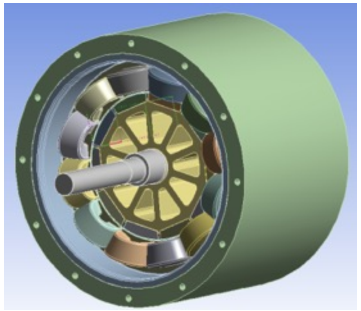
1d Closed form – Prelim Sizing
2d Plain strain –Detailed Design

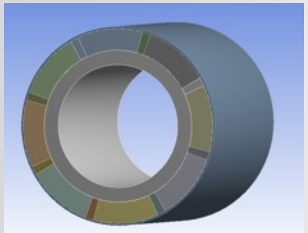
Detailed Design

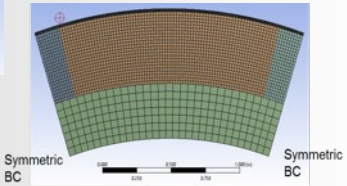
Thermal

1d Models – Prelim Sizing
2d Models – Down-Select
3d Models – Detailed Design

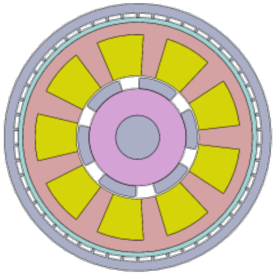
3d Model with End Winding







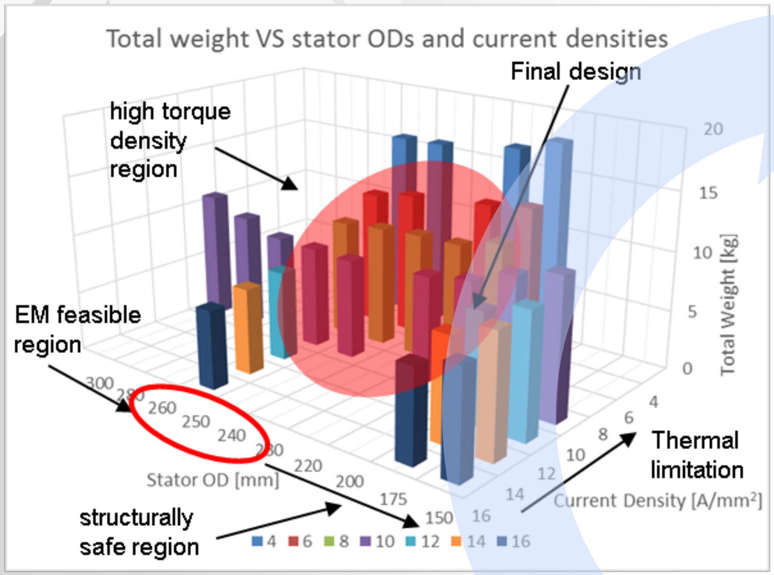

End fan


2d Model cross section

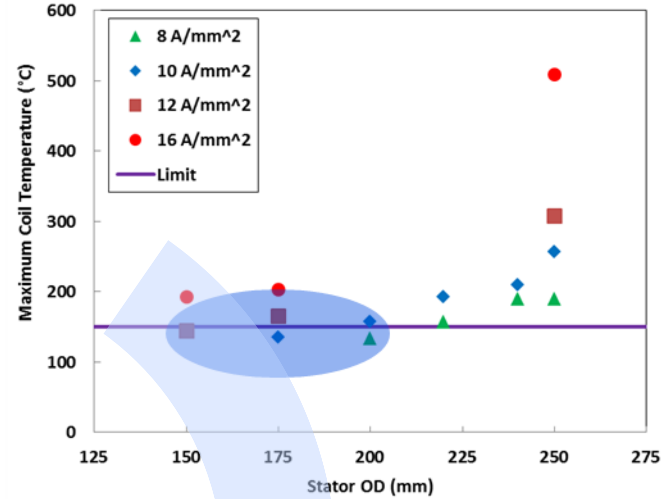
Design Iteration & Down Select

Design down select with multi-physics modeling and constraints

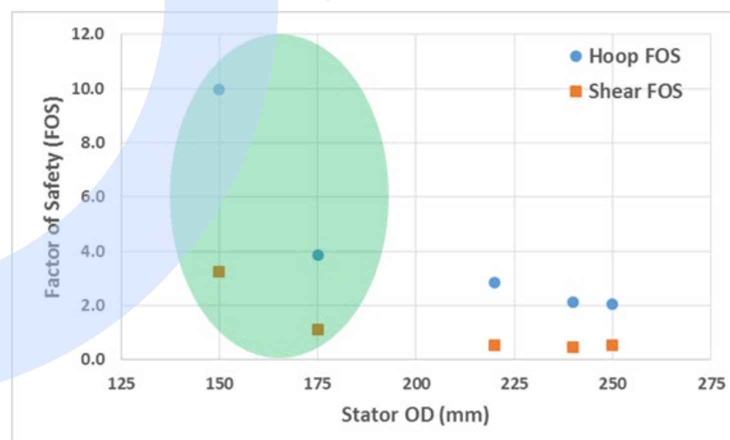
Electromagnetics



Thermal: max coil temp vs stator OD



Structural: safety factor vs stator OD



Down Selected Designs

Stator OD	Rotor OD	Stack length	Total weight	Current density	Max Tempearture	FOS Hoop	FOS Shear
[mm]	[mm]	[mm]	[kg]	[A/mm^2]	[ºC]		
150	96	126.4	10.32	12	145	3.29	1.19
175	101.5	89.3	11.24	10	135	9.93	2.04
175	122.5	83.4	9.2	12	148	4.5	1.3
200	128	59.8	9.44	10	158	3.51	0.99

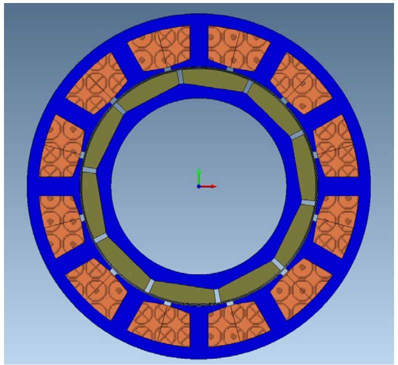
Design Parameters

Final prototype design key parameters

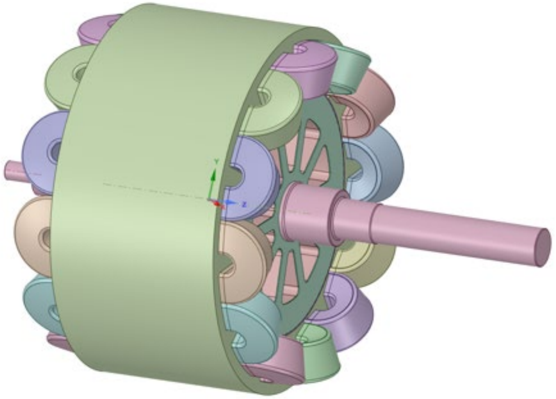
Key Dimensions

Number of slots	12
Number of poles	10
Number of phases	3
Slot per pole per phase	2/5
Stator outer diameter [mm]	180
Magnet thickness [mm]	7.0
Rotor OD [mm]	108.5
Air gap [mm]	1.135
Turns per coil	26
Turns per phase in series	104
Copper mass [kg]	3.4
Lamination mass [kg]	4.9
Magnet mass [kg]	1.8
Total mass [kg]	10.1
Power density [kW/kg]	0.99

2d Cross Section



3d Model with End Winding



Design Parameters

Parameter	Units	Values	
D-Axis Inductance	mH	2.15 Unsaturated	2.11 Saturated
Q-Axis Inductance	mH	2.29 Saturated	1.55 Saturated
Resistance:	Ohms	0.114	
Back EMF Constant	Vrms/kRPM	43.92	
Torque Constant	Nm/Arms	1.2	

Conclusions & Next Steps

Teams Recommendation: Go with First Motor Prototype Build

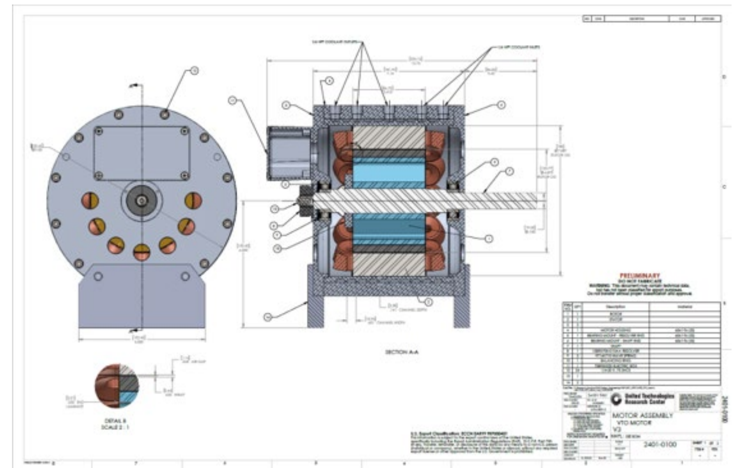
Phase-II

- Detailed Design – Due End of Sept 2018
- Tasks completed till date
  - Completed design down-select and detailed design
  - Motor build in progress. Delayed by 6 months due to material arrival from Japan and custom magnets to match with MnBi properties
  - Current status: Final stage of assembly and testing in progress

Next Steps – Phase-III – Delayed start due to Materials

  - Experimental validation
  - Refine design for MnBi and ISU steel
  - Build second prototype and experimental validation

Prototype Drawings



Rotor & Stator Laminations

Stator with Winding

Rotor with Magnets

Responses to Previous Year Reviewers' Comments

Q1-Reviewer 2

It was not clear to the reviewer that MnBi magnets can provide a realistic path to replace RE NdFeB magnets while achieving the required performance metrics. Even though the PI mentioned that one of the key enablers is to go to high frequency/speed, the 400 Hertz (Hz) targeted frequency is fairly low compared to current traction motors.

The 6.5% silicon steel can lead to higher efficiency, but it was not clear to the reviewer how this can enable non-RE designs. Also, this material can be used with RE designs as well. In general, the reviewer stated that the project seems to be pursuing two or three technical areas that do not seem to be tied together and it was not clear how they can end up providing a comprehensive solution for the RE challenge.

Q1-Review 3

Reviewer expected a description of specific challenges and potential roadblock as expected as key outputs.

Q1-Reviewer 4

The increase in relative permeability of 6.5% SiFe with respect to 3.2% SiFe alone does not seem enough to make up the gap in remanence for the MnBi to RE materials.

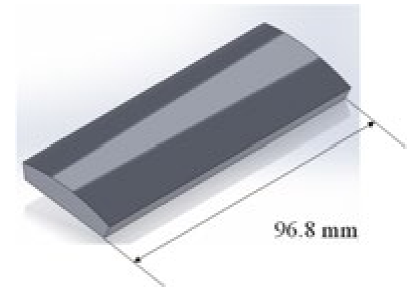
Responses to Previous Year Reviewers' Comments

Reviewer comments	Reply
It was not clear MnBi magnets can provide a realistic path to replace NdFeB magnets while achieving the required performance. The 6.5%Si steel can lead to higher efficiency, but it was not clear how this can enable non-RE designs.	Non-RE motor will always have less power density than RE motor. MnBi will not replace RE magnet. But, it is possible for MnBi based motor to achieve 5.7 kW/L power density.
Progress made on addressing the brittleness of the 6.5% silicon steel is good but scalability needs to be proven.	Agree, mass production of thin sheet ductile 6.5%Si steel needs to be demonstrated
A disconnect between the team at Iowa State and UTRC, who are almost independently working on this project.	Separate objectives for each sub-team allow the project to proceed without inter-dependency. But at the end, only ISU team can deliver the MnBi bulk magnets for the final prototype
The research team re-visit the approach and confirm that the developed materials will really enable a feasible RE free design	Motor is designed to use a permanent magnet with 6 kG remanent magnetization and 6 kOe coercivity, a property unique to MnBi magnet

Collaboration and Coordination

Ames Laboratory	Melt-spin flakes production; Bulk magnet production
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

Remaining Challenges and Barriers



- MnBi:
  - Scale up
  - Increase energy product to 10 MGOe
- 6.5% Si steel:
  - Scale up
- Motor
  - Improve power density from 4.5 kW/L to 5.7 kW/L

Proposed Future Research

- MnBi

  Milestone: 300 bulk MnBi magnet with 8 MGOe

  – Improve energy product to 10 MGOe
  – Quality control of mass production of bulk magnet (300+ magnets)

- 6.5% Si steel

  Milestone: sectional stator fabrication

  – Optimize flake coating thickness and laminate architecture
  – Fabricate 8' OD stator with sectional approach

- Non-Re motor

  Milestone: Construct 400 Hz non-Re PM motor.

  – Execute the motor design and coordinate with vendors

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

Summary

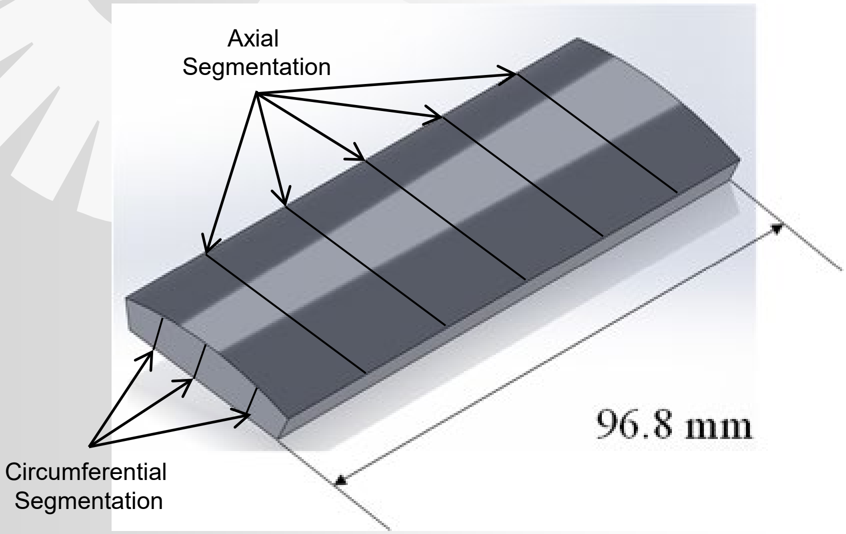
- MnBi
  - Powder quality was improved from 70 emu/g to 79 emu/g
  - Cost effective bulk magnet fabrication method was developed
  - Process of mass production bulk magnet has been initiated.
- 6.5% Si steel
  - Relationship between physical properties and cooling rate was established
  - Flake production method and capacity were established
  - Laminate inner structure was optimized and fabrication method was established
- Motor
  - 10 kW 400 Hz motor was designed.
  - Construction of the 1st prototype will be finished by May 2019

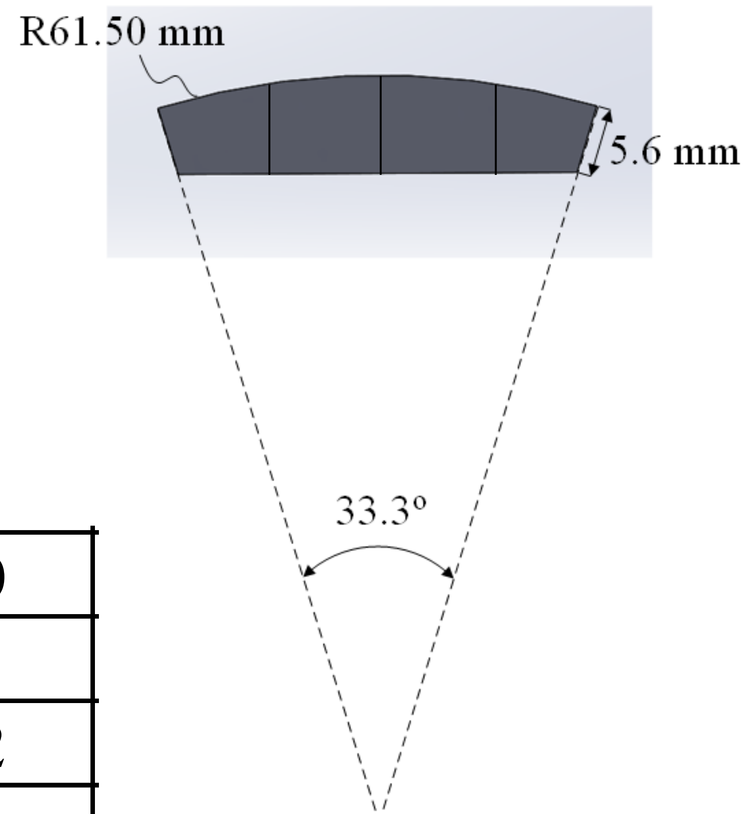
Technical Backup Slides

Magnets used in this project

	Axial	Circumferential
Number of segments	4	5-10

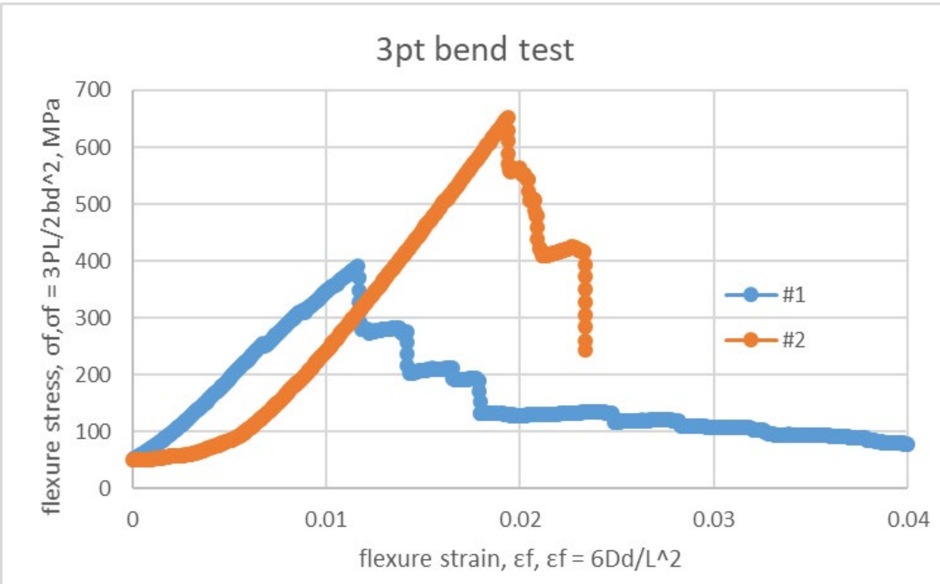
Mn-Bi magnet geometry



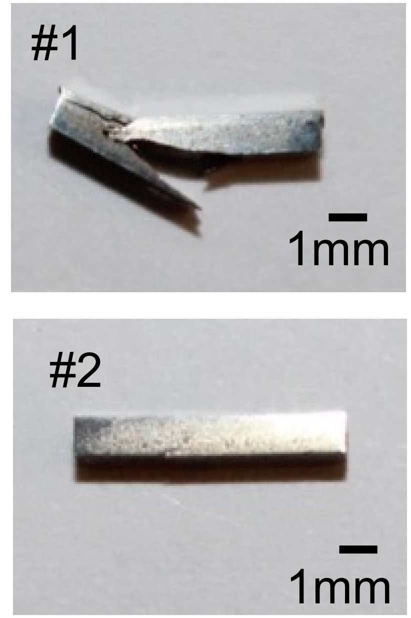


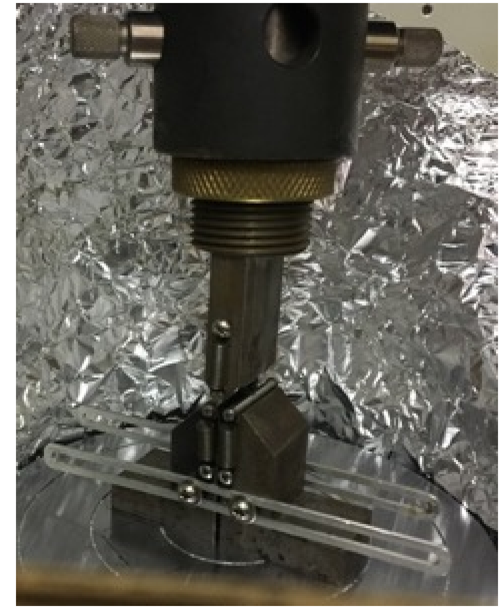
Br [kG]	6.0
Hc [kOe]	5.1
Hci [kOe]	6.2
Bhmax [MGOe]	8.4

Mechanical Properties



3pt bending test of flake-consolidated FeSi sample





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.