1467-1561 Amorphous and Nanocomposite Magnets for High Efficiency, High Speed Motor Designs

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Carnegie Mellon University/NETL/North Carolina State University

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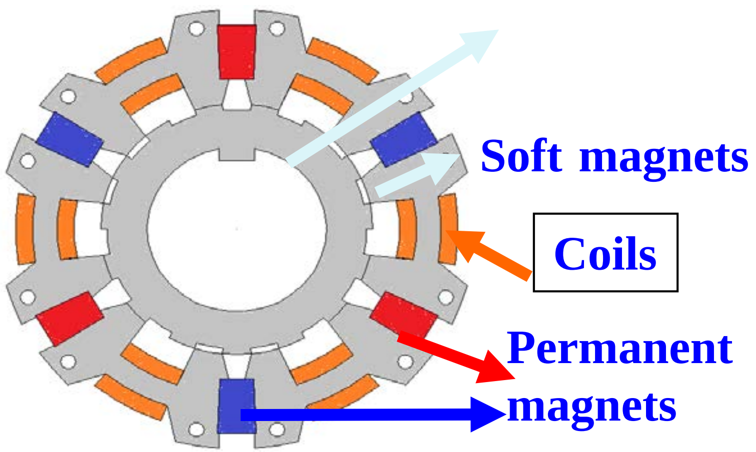
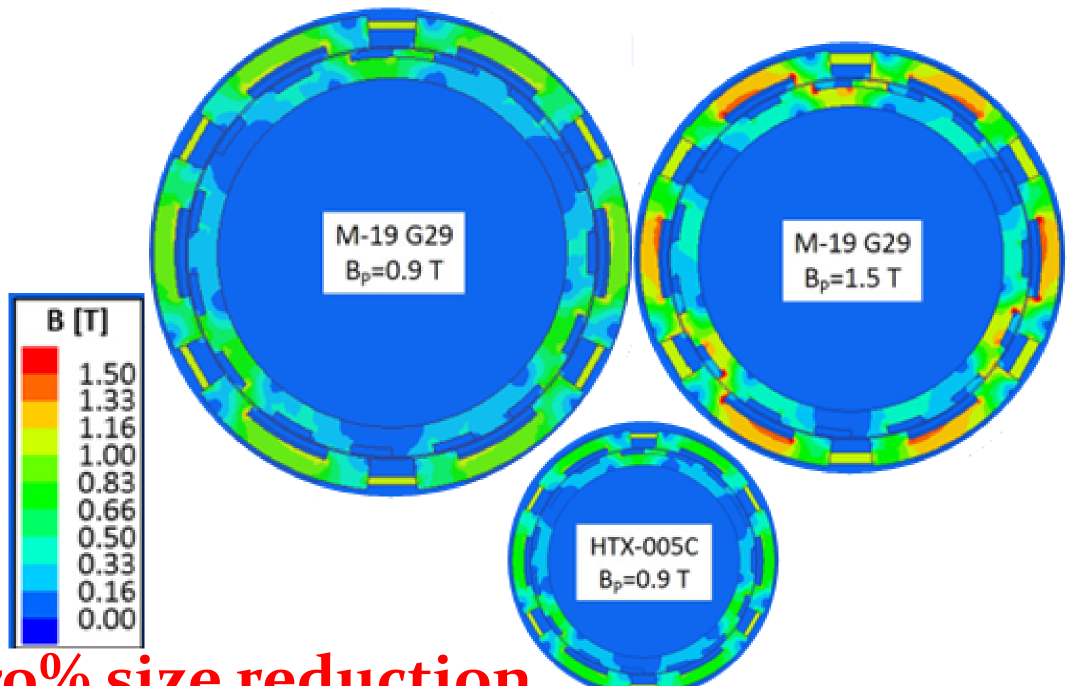
Project Objective

- CMU team will develop metal amorphous nanocomposite (**MANC**) soft magnet materials (**SMMs**) for a rare earth (RE)-free, 2.5 kW motor with 4% efficiency increase portioned between a) controller; (b) Cu-; (c) Fe-; & (d) windage-losses. We will model RE-free motors and address supply chain steps:
  - (a) metal to alloy processing & magnet core production;
  - (b) soft magnetic laminate & core post- processing; and
  - (c) demo a 2.5 kW motor. Transfer **MANC** casting technology to domestic production of high power density motor materials.
- Conventional Si-steels do not have combined resistivity and thickness required for tolerable losses at magnetic switching frequencies > 1 kHz targeted for the project.
- This new materials technology for motors and requires new topologies and processes to leverage MANC SMMs in motors.
- Mechanical properties must be investigated for high motor speed.

Technical Innovation – MANC SMMs

- Current practice for several kW motors use Si-steels which are limited by losses to switching f < 1 kHz. New MANC technology adoption is hindered by: (a) limited US manufacturing; (b) materials limits for high frequency switching and (c) mechanical property constraints for certain motor applications;
- **Prior simulation:** P = Torque x speed. Outrunner motor





- **PPMT technology**
- **M-19 = Si-steel grade**
- **HTX-005 = MANC yields 70% size reduction**

Technical Metrics Enabling Applications: Power Losses.

$$P_{tot} = P_h + P_e + P_a$$

Hysteresis Losses

$$P_h = afB^2$$

Random crystal anisotropy

(MANC H_c < 40 A/m)

Eddy Current Losses

$$P_e = bf^2B^2$$

$$b = \frac{(\pi \cdot t)^2}{6 \cdot \rho}$$

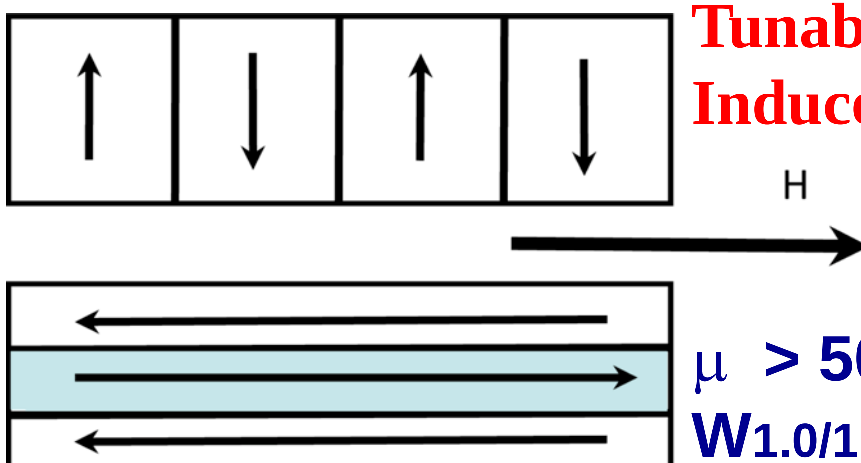
Resistivity, Thickness

ρ > 100 μΩ-cm

t < 25 μm

Anomalous Losses

$$\boxed{P_a = e(f \cdot B)^{1.5}}$$



Tunable (graded) Induced Anisotropy

μ > 5000,

$W_{1.0/1kHz}$ < 10 W/kg

Technical Approach

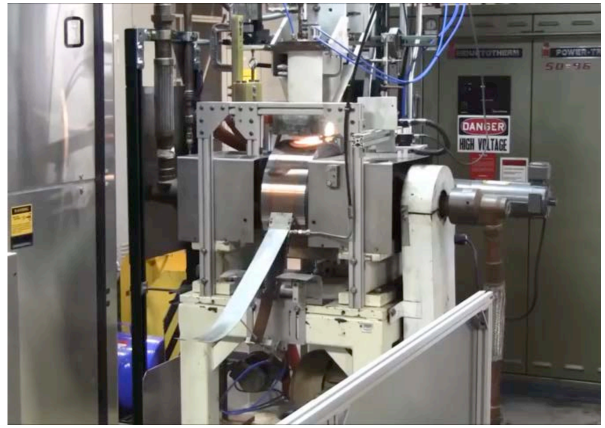
- Technical Approach:
  - *Identify prototype FEA motor design for MANCs (CMU/NETL);*
  - *Lab scale rapid solidification (RSP) & post-processing to tune magnetic permeability in cores (CMU);*
  - *Post processing into rotor/stator components (CMU, NETL);*
  - *Winding techniques for use in new topologies (NETL),*
  - *Incorporate state of the art motor controllers (NCSU).*
  - *Measure loss partitioning between controller, copper, iron, & windage in 2.5 kW motor (CMU, NCSU).*

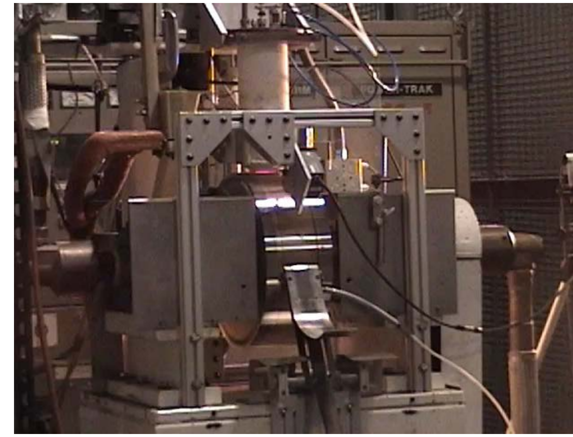
Project Risks:

- Cutting/shaping technologies, Mechanical Properties.

Unique Advantages:

- Commercial scale caster & US owned company, state of the art ribbon processing for permeability tuning, Patented alloys.

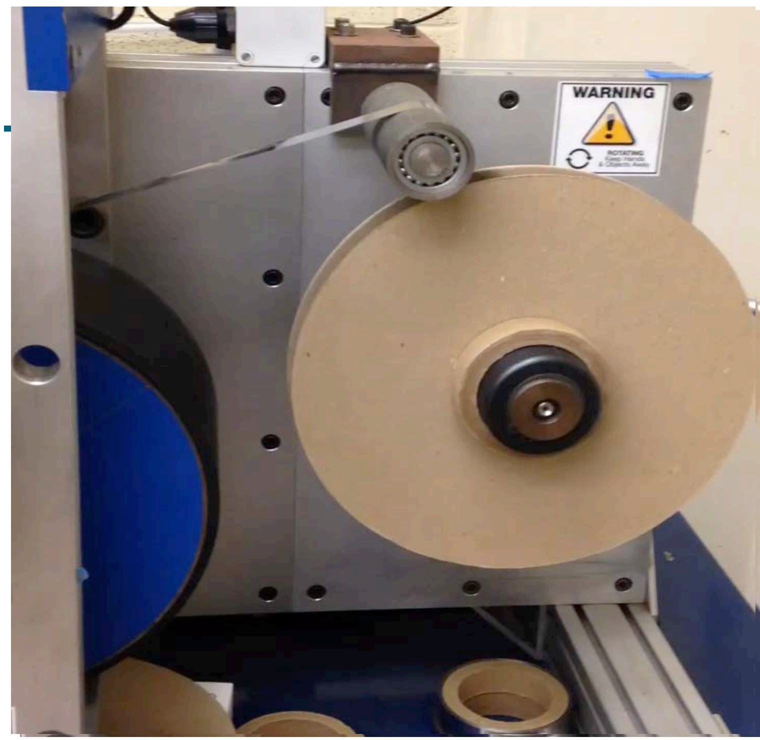


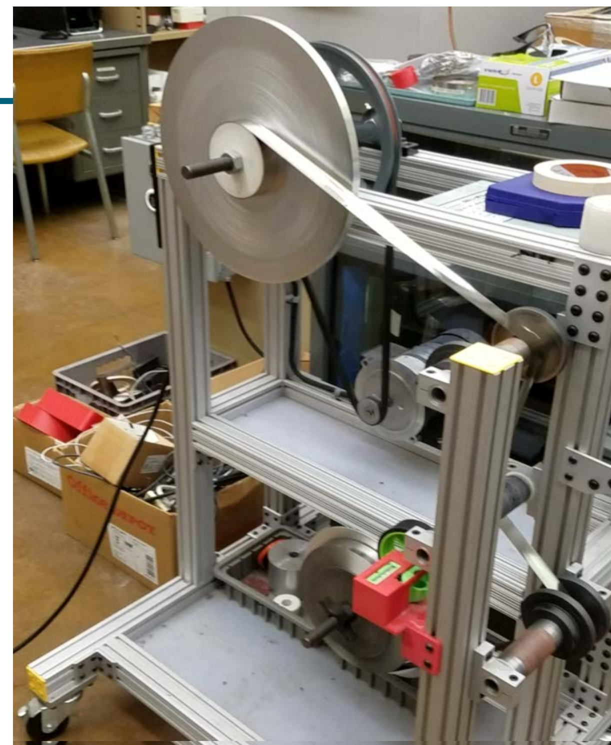


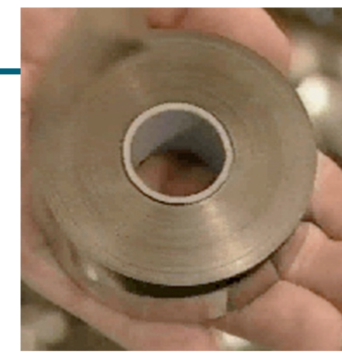
Lab Scale CMU (5-10 g)

Lab Scale (3-5 kG,1-2”) NASA

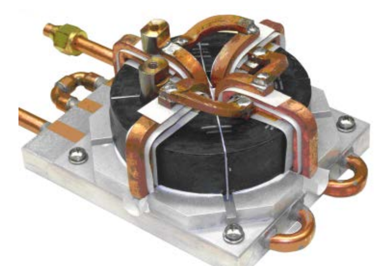
Commercial Scale Casting - Fort Wayne Metals (40 kG,2-4”)







Wound Ribbon,
Converter- CMU,ARL



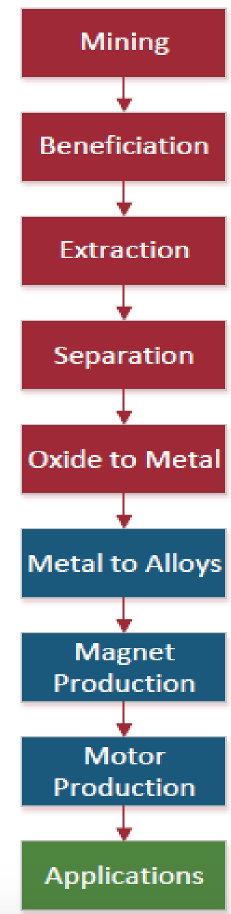
Strain Annealing Line at CMU

Core Winding Machine (CMU)

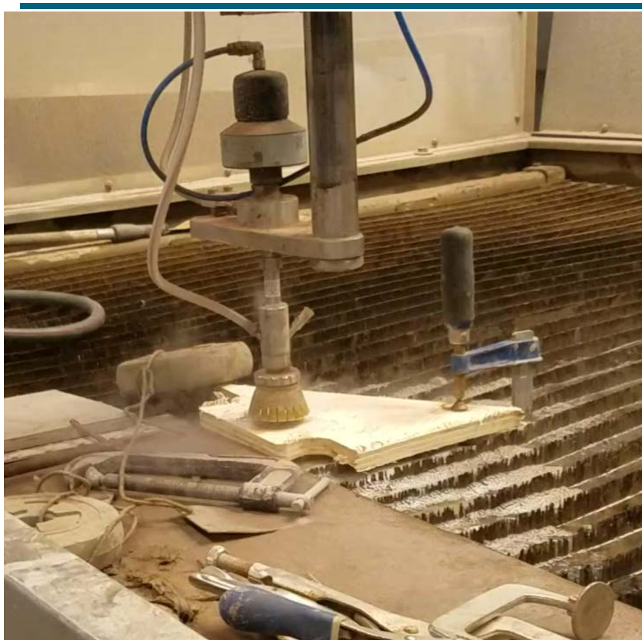
Transition (beyond DOE assistance)

- Project seeks to demonstrate efficiencies in high speed motors that will open new markets for MANC ribbon.
- FWM will be the end user of casting technologies.

  A > 50 kg capacity VIM melting & planar flow cast facility is leased to FWM by CMU positioning them as a sole US MANC materials manufacturer.
- Commercialization approach:
  - Technology transfer of Casting technology to FWM
  - Scaling, control system development for strain anneal.
  - 2.5 kg Motor Demo
- This technology impacts materials criticality issues in magnet production in supply chain steps: Metals to Alloys; Magnet Production; Motors.



Transition (beyond DOE assistance) - II

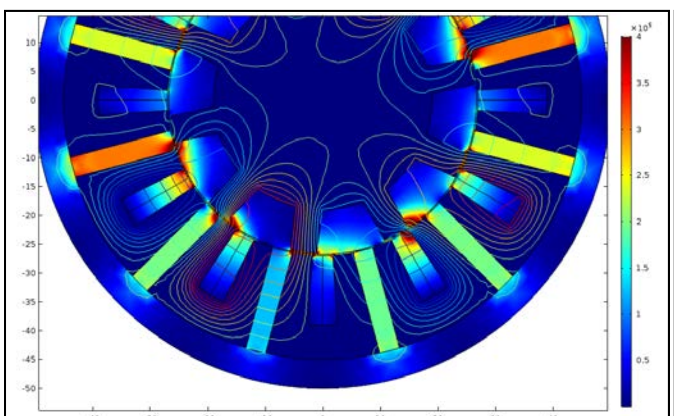


Waterjet Cutting
Nanocomposites

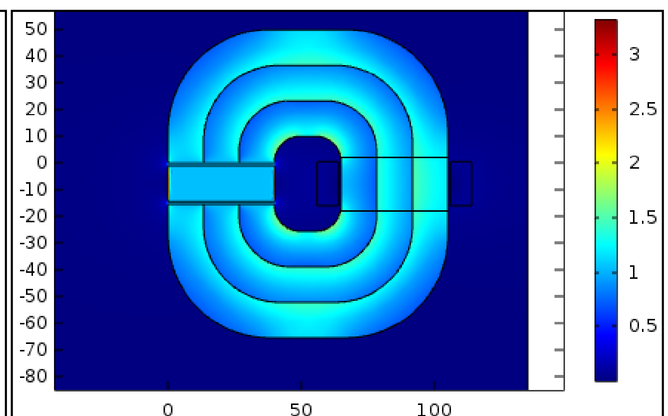
Training scale waterjet cutting available at TechShop, located in Pittsburgh's Bakery Square. CMU has a formal structure in place for student projects at TechShop.
NETL has a 5-axis waterjet available in its WV facility.

CMU offered a new course on Power Magnetics in S'2017.
P. Ohodnicki, NETL and M.E. McHenry, Instructors, M.S. and Ph.d student participants presented Comsol FEA power electronic simulations including motor topologies leveraging MANC materials. Promising designs are being optimized.

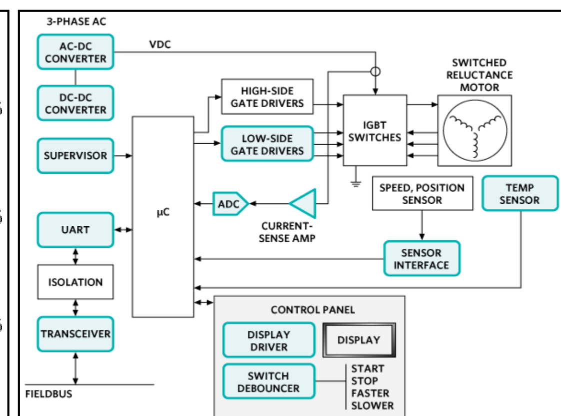
NCSU will design motor controller for new motor topologies.
NCSU sub-contract has just been executed.



Flux Switching Motor
IEEE 2005.



Cross-section of axial switched reluctance motor

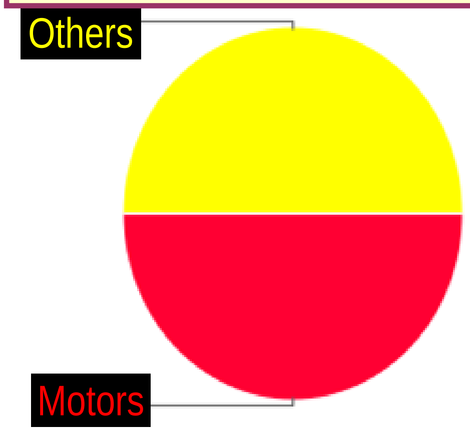


Motor controller (source: Maxim Integrated)

Measure of Success

- **GO/NO-GO DECISION 1:** Demonstrate metrics: Bs > 1.0 T, peak μ > 5000, ρ > 100 **μΩ-cm**, and W10/1 k (Power loss at 1 T and 1000 Hz) < 15 W/kg FEA motor model with energy losses 50-60% that of (0.35 mm laminated) non-oriented Si steels, enabling 4% motor efficiency increase, to an overall 96% metric.
- Potential for energy/economic impact:

US Electric Energy Consumption (2010)



Source: Moyer, Univ. Chicago, 2010

At the Project end we will be able to estimate size/weight reduction possible at higher frequencies to show where MANC motors will outperform other high speed motors (HSMs). This will provide a basis for future increases in motor power densities and extensions to other HSM and ultra-HSM motors

Project Management & Budget

- 3 years
- Project task and key milestone schedule
  - Project Budget Period 1 (ends 02/28/18): will staff project, purchase computers, software M&S. Research includes: (1) Comsol Finite Element Analysis (FEA) to determine a motor design, (2) alloy characterization to identify compositions for subsequent lab caster runs and materials properties for models, (3) Identify practices for cutting, lamination bonding, and basemark switching losses.

Total Project Budget (3 Yr)	
DOE Investment	$1,110,000
Cost Share	$230,566
Project Total	$1,340,566

Milestones – Completed and Go/No-Go

- Milestones – Budget Period 1
- **Task 1.0:** Q1 Staff & train project personnel: **Complete**

Dr. Satoru Simizu, Senior Scientist; Dr. Mst. Nazmunhar, Scientist; Mr. Yuval Krimer, M.S. Student, complete list appended. **Summary:** Comsol and RSP training: **Complete.**

- **Task 2.0:** Q1 Purchase software licenses, components, expendables for alloy studies. **Complete**

Milestone 1: Q1 Staff and Equip Project. Report Project staff list to DOE AMO (list Appendix I). Complete

GO/NO-GO DECISION 1: Demonstrate metrics: Bs > 1.0 T, peak μ > 5000, ρ > 100 **μΩ-cm**, and W10/1 k (Power loss at 1 T and 1000 Hz) < 10 W/kG FEA motor model with energy losses 50-60% that of (0.35 mm laminated) non-oriented Si steels, enabling 4% motor efficiency increase, to an overall 96% efficiency metric.

Results and Accomplishments

- Y1Q1 will finish 06/30/17
- **Milestone 1: Q1 Staff and Equip Project. Staff list list appended. Complete. Milestone 2: Report FEA topology for gearless motors suitable for > 1 kHz operation enabling 4% efficiency increase benchmarked with 0.35 mm non-oriented 3% Silicon steel, to reach 96% overall efficiency to DOE AMO. In Progress.**
- **Results**: Promising compositions met: Bs > 1.0 T, in H < 40 A/m, peak μ > 5000, ρ > 100 mΩ-cm, W10/1 k (Power loss at 1 T and 1000 Hz) < 10 W/kG. **In press (tabulated in Appendix I):**

N. Aronhime, V. DeGeorge, V. Keylin, P. Ohodnicki, and M. E. McHenry, " The Effects of Strain-Annealing on Tuning Permeability and Lowering Losses in Fe-Ni based Metal Amorphous Nanocomposites. " J. Materials; in press, (2017).

- Work to be completed in Budget Period 1:
  - FEA Motor models (2-d and 3-d).
  - Identify cutting and forming techniques.