Materials Paradigm as Applied to New and Evolving Power Magnetic Materials.

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Outline

I. Introduction: Materials Paradigm for Power Magnetic Materials: Metal Amorphous Nanocomposites (MANCs)

II. New Metal Amorphous Nanocomposite (MANC) Soft Magnetic Materials: Synthesis → Structure → Properties Relationships

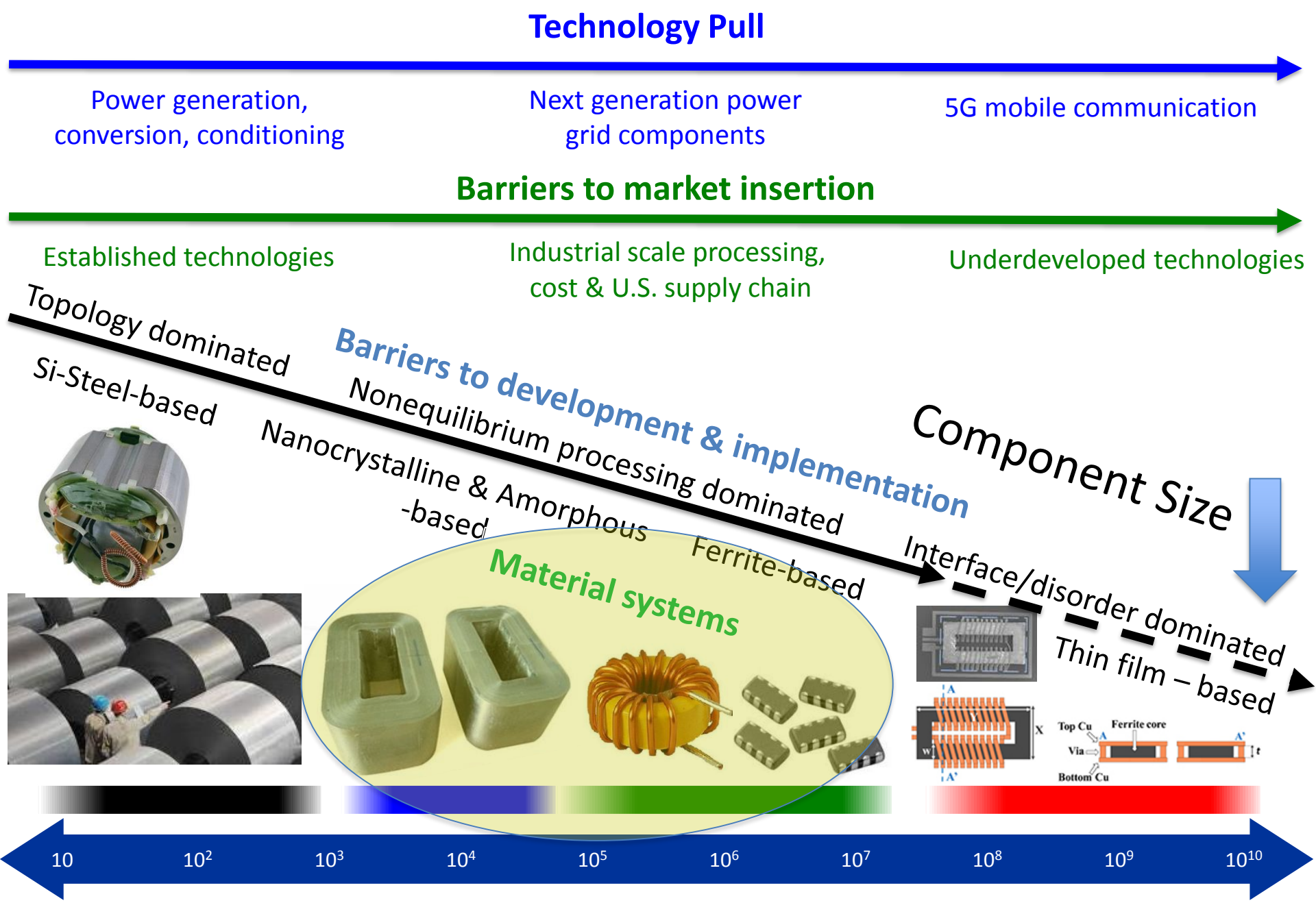
II.1 Co-based MANC Materials for Permeability Engineering.

II.2 FeNi-based MANC Materials.

III. Conclusions.

Support from DOE EERE AMO, DOE SUNLAMP, Eaton

Collaborators: S. Simizu, Mst. Nazumunnahar, S. Greene & Y.Krimer, CMU
P. Ohodnicki, K. Byerly, NETL; S. Bhattacharya; NCSU
A. Leary, R. Noebe, R. Bowman, NASA GRC;
N. Aronhime and S. Kernion Cartech


Technology Pull
Power generation, conversion, conditioning
Next generation power grid components
5G mobile communication
Barriers to market insertion
Established technologies
Industrial scale processing, cost & U.S. supply chain
Underdeveloped technologies
Topology dominated
Si-Steel-based
Barriers to development & implementation
Nonequilibrium processing dominated
Nanocrystalline & Amorphous -based
Ferrite-based
Component Size
Interface/disorder dominated
Thin film – based
Material systems
Top Cu
Ferrite core
Via
Bottom Cu
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
Frequency, Hz

History of Soft Magnetic Metals

Time

Bulk (1880's – 1940's)

- Fe (Abundant, Cheap)
- Fe-Si (Resistivity)
- Fe-Co (High B_S High T_C)
- Fe-Ni (High μ)

Amorphous Magnetic Ribbon (AMR) (1960's – 1980's)

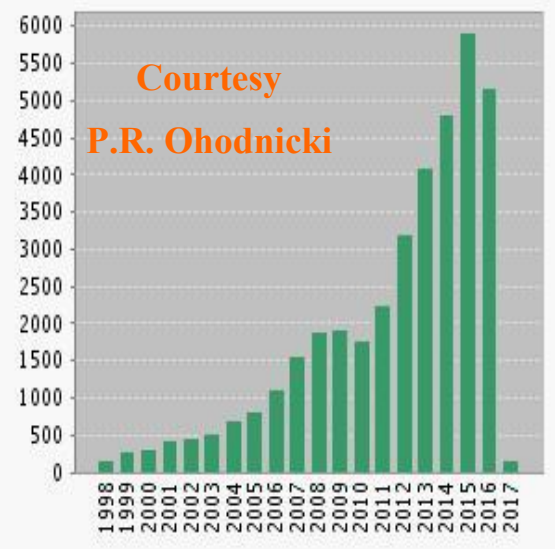
- Fe based
- Co based
- Ni based

Metal Amorphous Nanocomposite (MANCs) (1980's – Present)

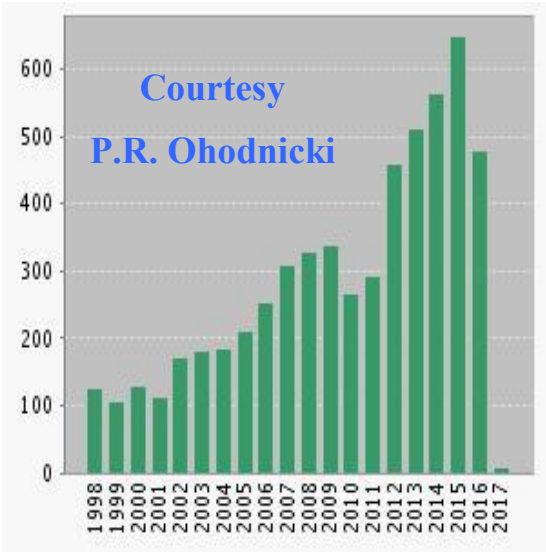
- Fe-Si based (FINEMET)
- Fe-based (NANOPERM)
- Fe-Co based (HITPERM)
- Co-based Fe(Ni)-based

Y. Yoshizawa, S. Oguma, and K. Yamauchi, J. Appl. Phys. 64, 6044 (1988).
M.E. McHenry, M.A. Willard, and D.E. Laughlin, Prog. Mater. Sci. 44, 291 (1999)

Power Transformation

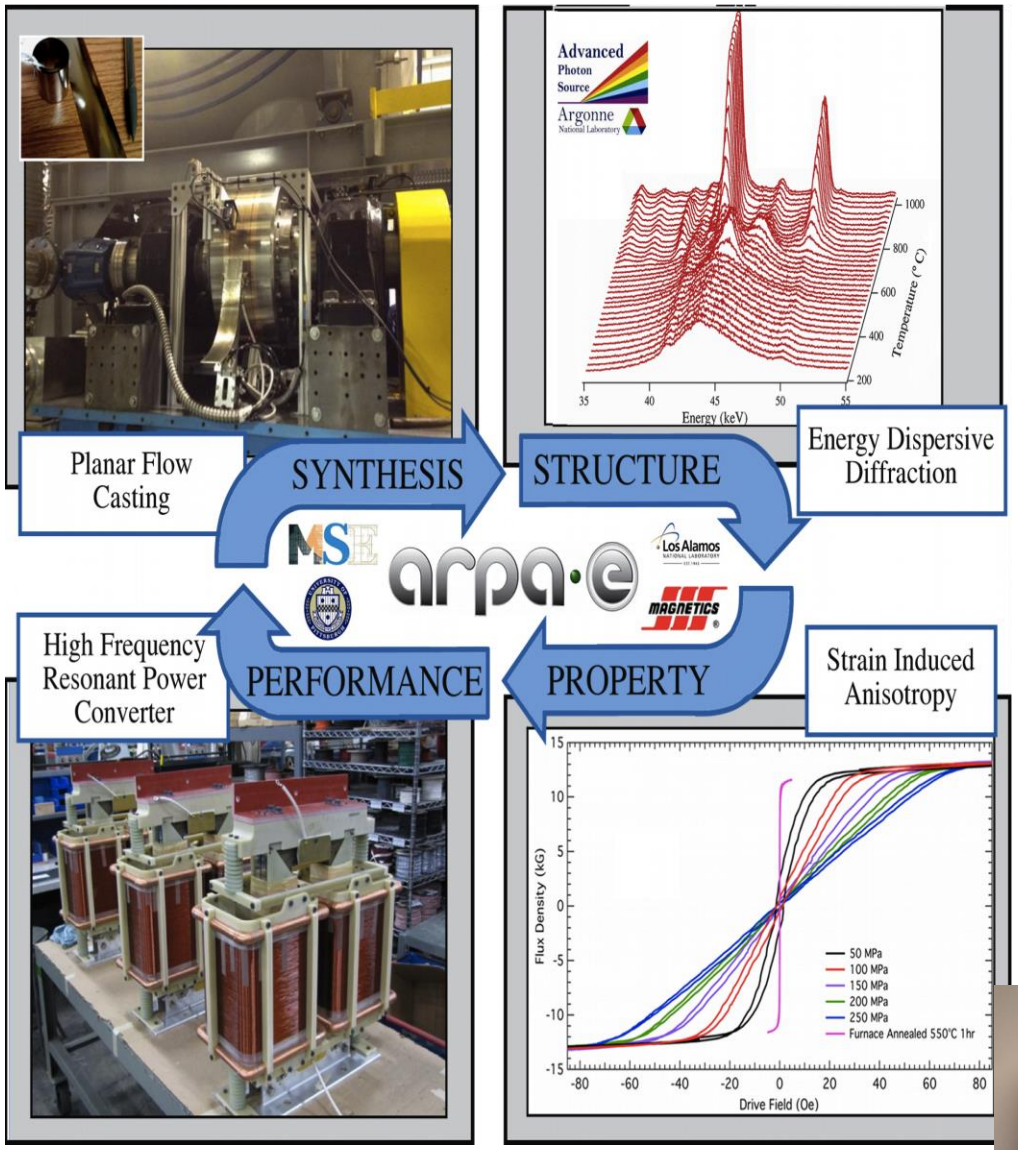


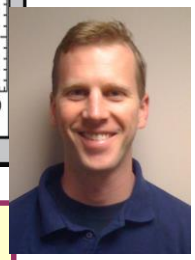
High Freq. Transformer Citations



High Frequency Transformer Pubs

Materials Paradigm for MANC Power Transformation

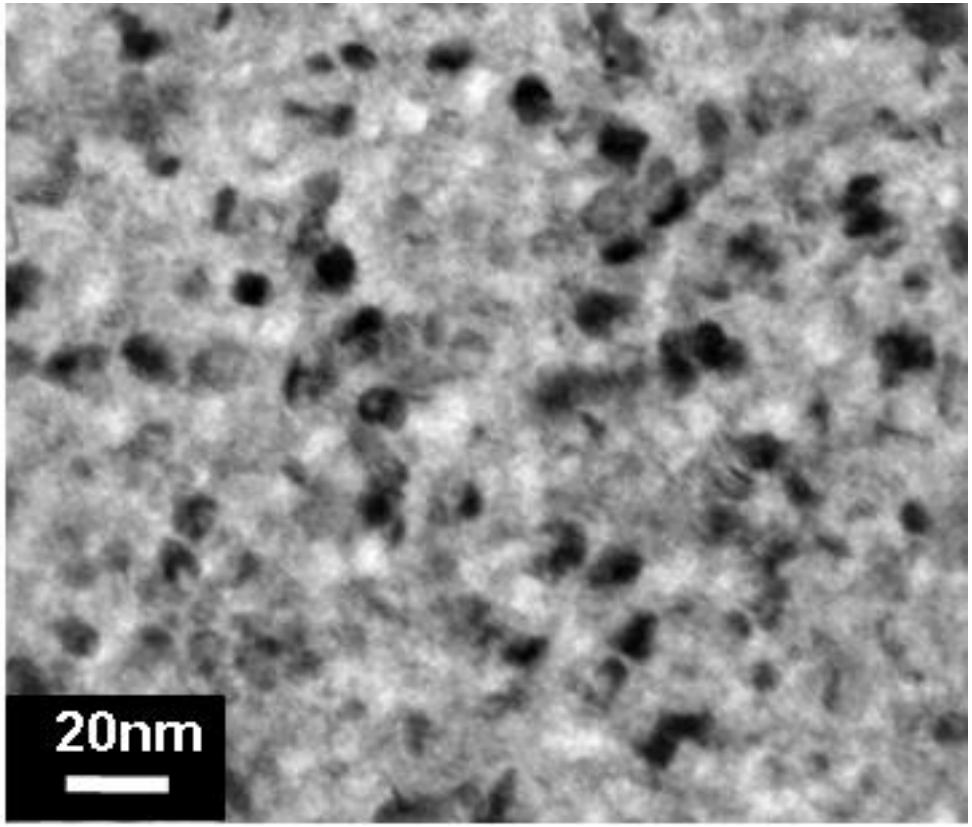


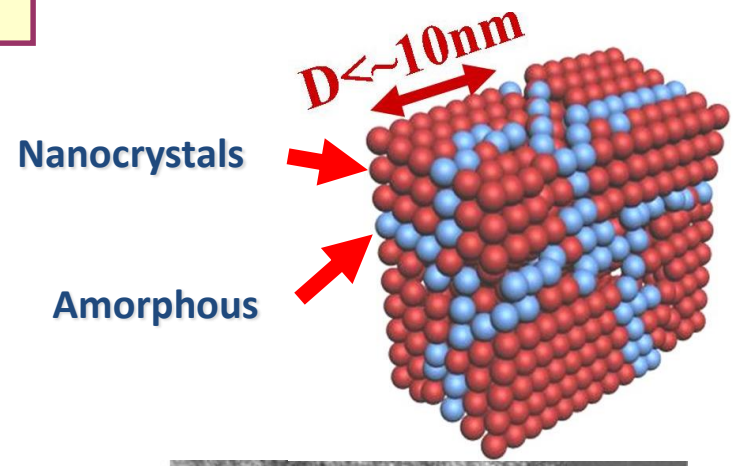


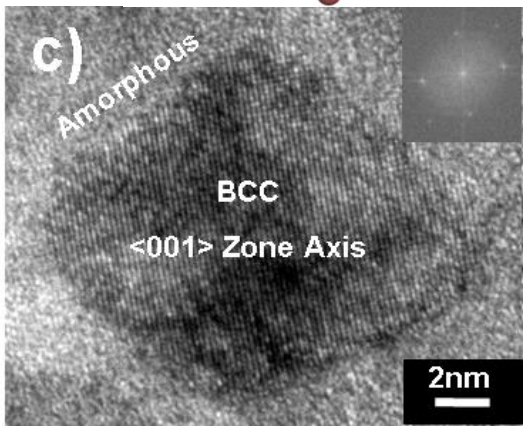
Similar trends in SS power transformers.

Intro: What are Nanocomposites?

Courtesy of J. Long

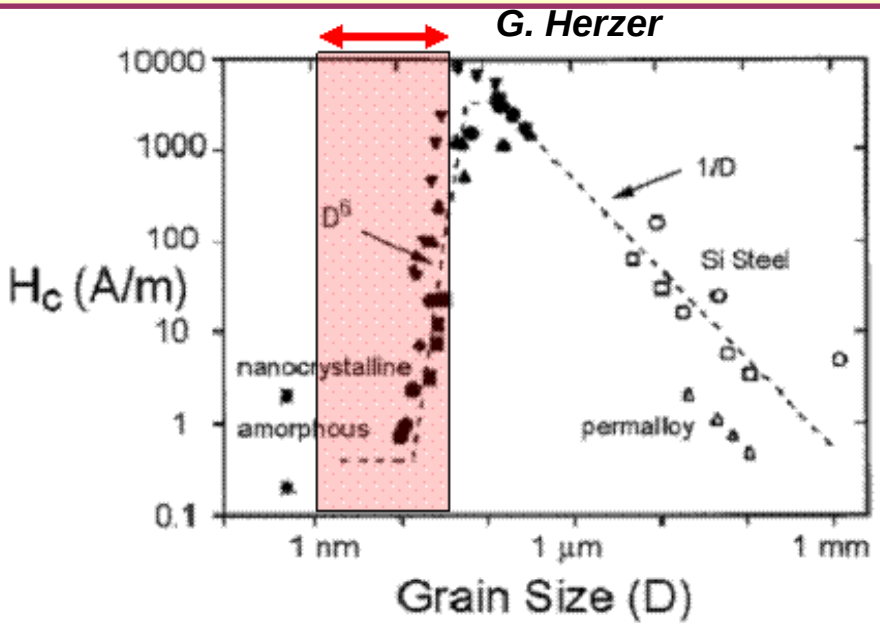


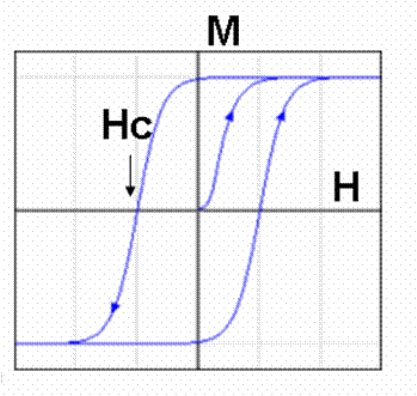


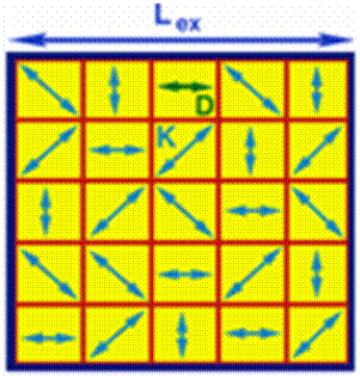


Ferromagnetic Nanocrystals Embedded in an Amorphous Matrix:
Nanocrystals → High Induction
Amorphous Phase → Small Grain Size and Large Resistivity
Composite → Low Losses

Why are Nanocomposite Magnets so "Soft"?







$$\langle K \rangle = \frac{K_1}{\sqrt{N}} \quad L_{ex} = \sqrt{\frac{A}{\langle K \rangle}} \quad N = \left(\frac{L_{ex}}{D}\right)^3$$

$$H_C \propto \langle K \rangle \, \mathbf{D^6}$$

Energy loss upon cycling a magnetic material = Area of the hysteresis loop

Nanocrystalline Grains

→ Strong Intergranular Exchange Interactions

→ Dramatic Reduction in Energy Losses

High Resistivity of Nanocomposites Also Reduces Losses at High Frequency

Amorphous and Nanocrystalline Materials for Applications as Soft Magnets. **M. E. McHenry**, M. A. Willard and D. E. Laughlin; *Prog. Mat. Sci.*, **44**, 291-433, (1999).

Technical Metrics Enabling Applications: Power Losses.

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

Hysteresis Losses

$$P_h = a f B^2$$

Random crystal anisotropy
(MANC H_c < 40 A/m)

Eddy Current Losses

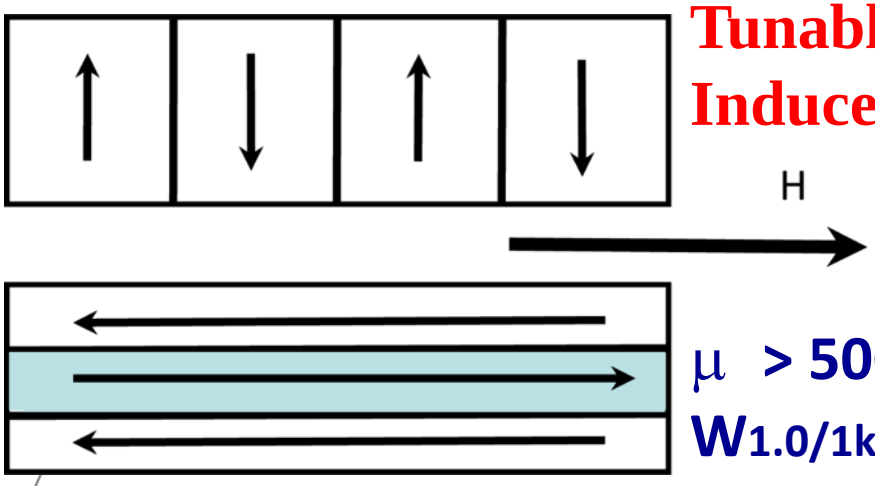
$$P_e = b f^2 B^2$$

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

Resistivity, Thickness
ρ > 100 μΩ-cm
t < 25 μm

Anomalous Losses

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



Tunable (graded)
Induced Anisotropy

μ > 5000,
$W_{1.0/1kHz}$ < 10 W/kg

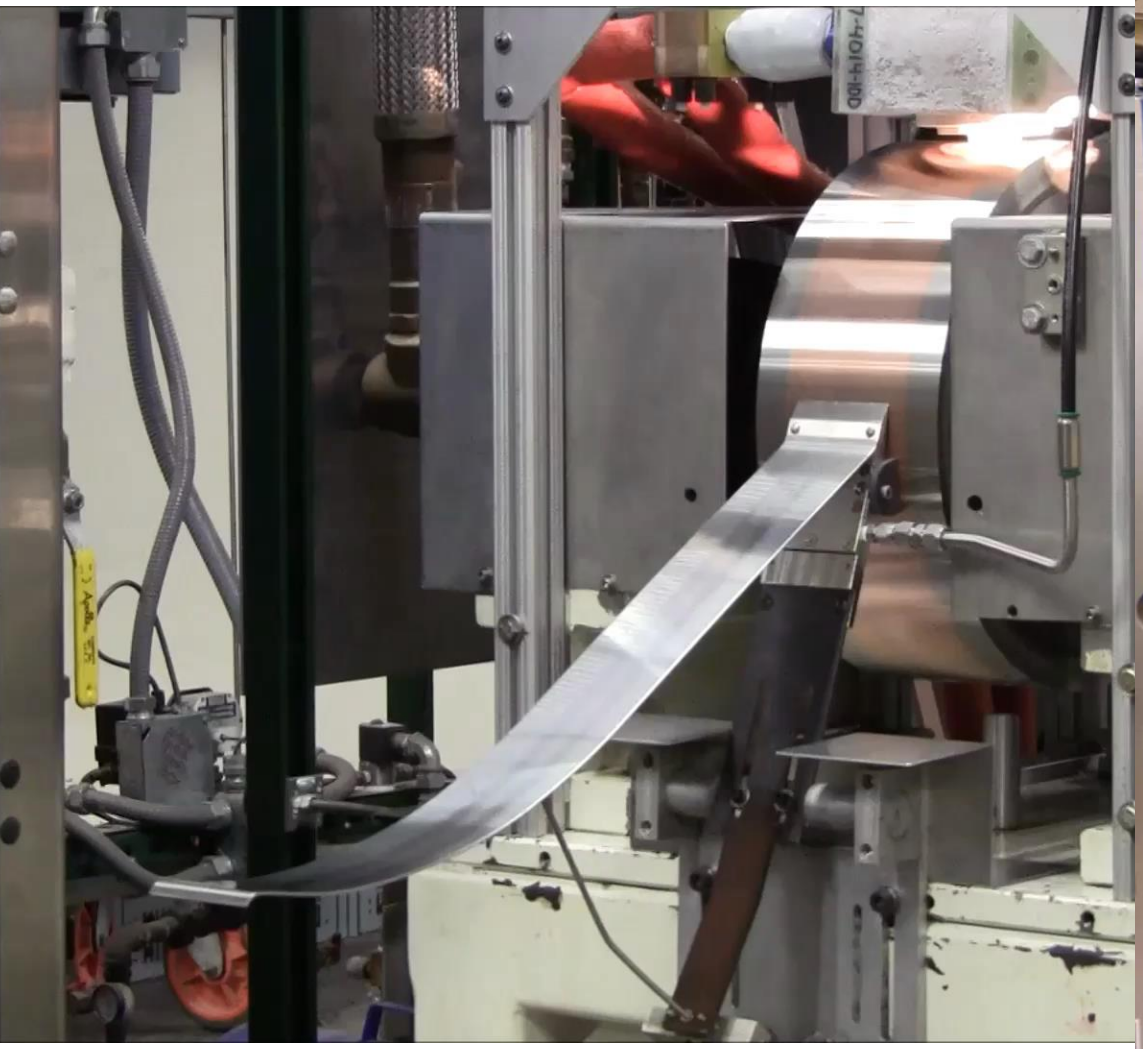
II. New Metal Amorphous Nanocomposite (MANC) Soft Magnetic Materials: Synthesis → Structure → Properties Relationships

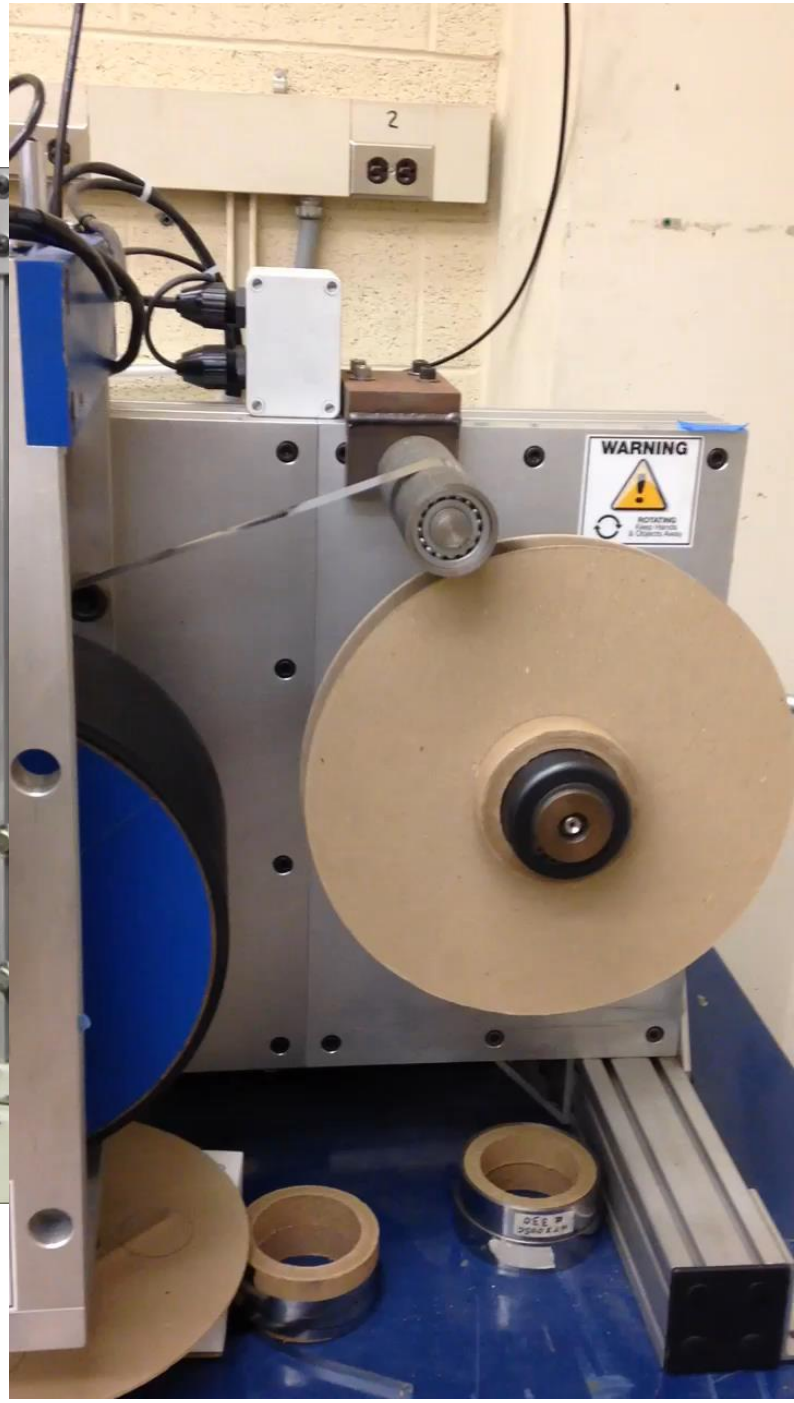
II.1 Co-base MANC Materials and Permeability Engineering.

II.2 FeNi-based MANC Materials.

MANC Manufacturing

Caster NASA GRC

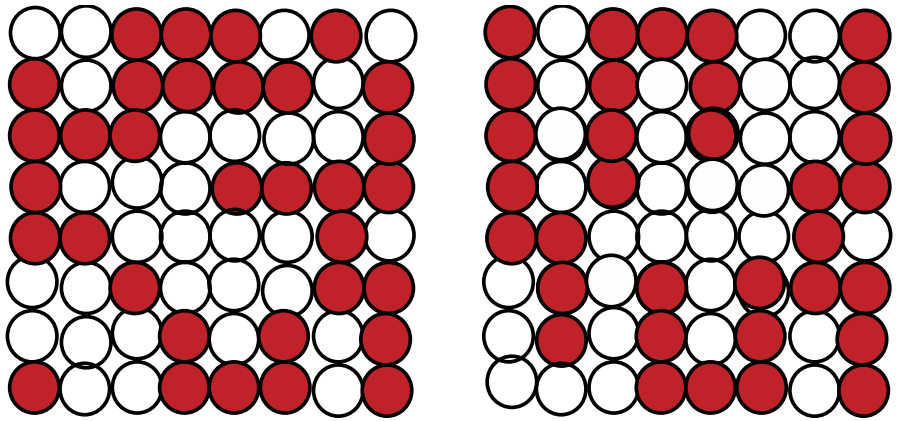




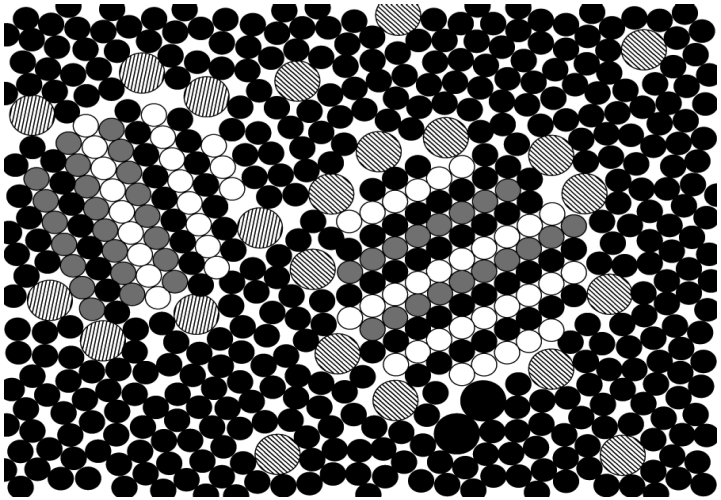
Strain Annealing Line at CMU

A.1 Co-rich Alloys with Multiple Nanocrystalline Phases: Resistivity Tuning and Permeability Engineering by Strain Annealing (SA)

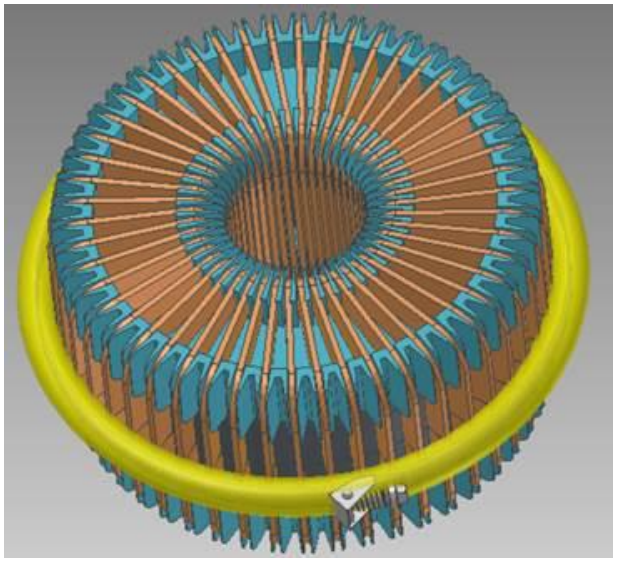
TMF



SA



Filter Inductor Applications



Tuning Permeabilty Eliminates Gapping, Reduced Stray Fields:

1) **Reduced Electromagnetic Interference**
2) **Reduced Proximity Losses in Windings**

EATON Powering Business Worldwide

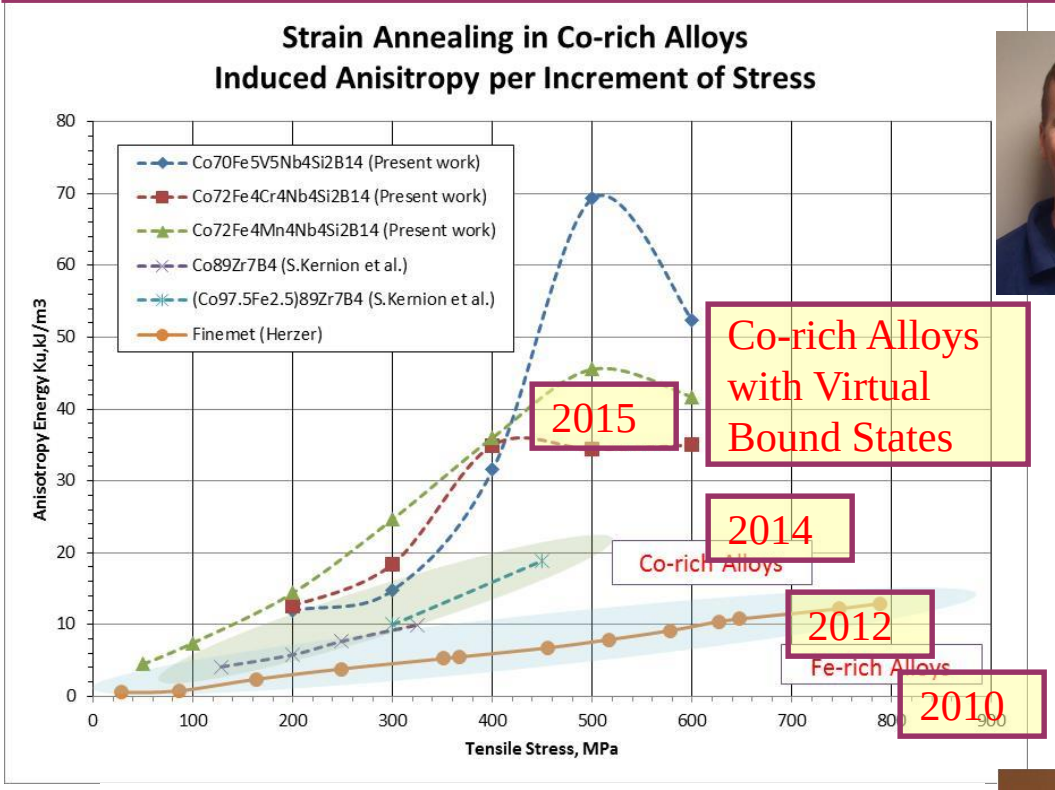
NC STATE UNIVERSITY

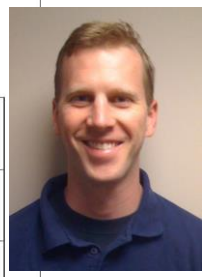
NASA

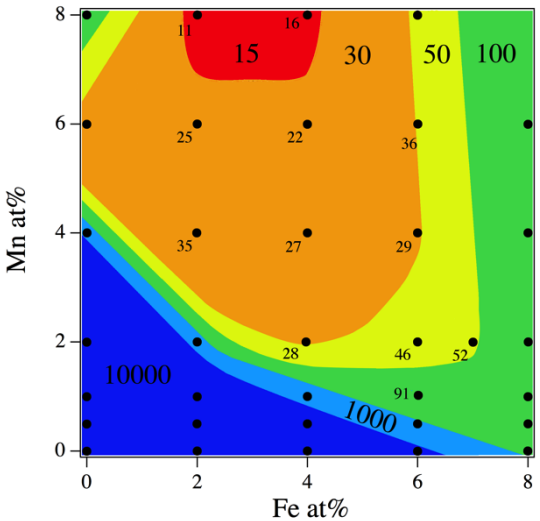
NATIONAL ENERGY TECHNOLOGY LABORATORY

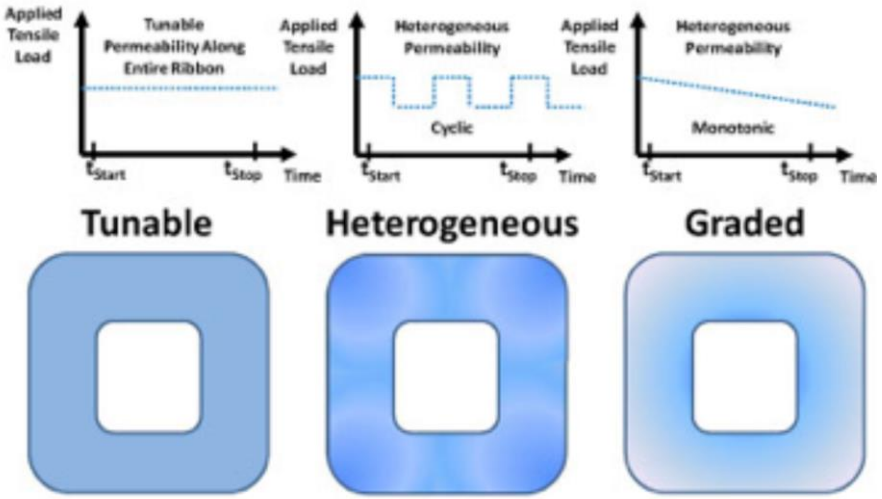
Carnegie Mellon University

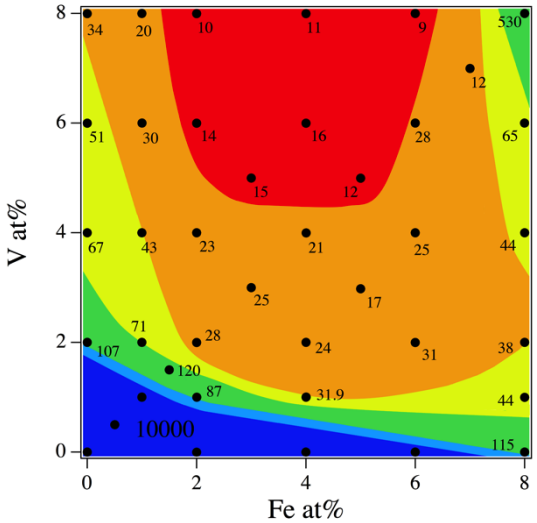
Induced Anisotropy – Tunable Permeability





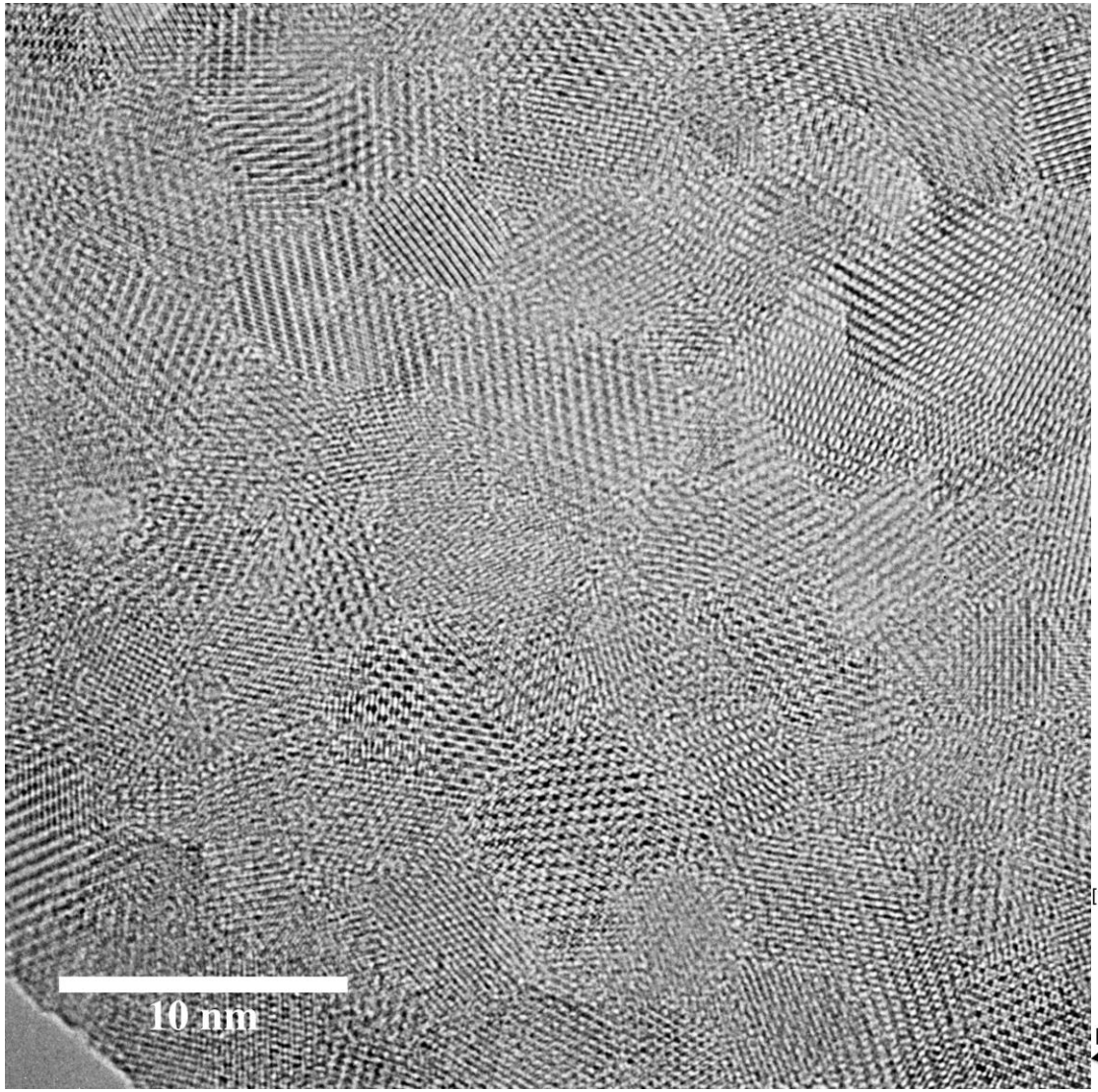


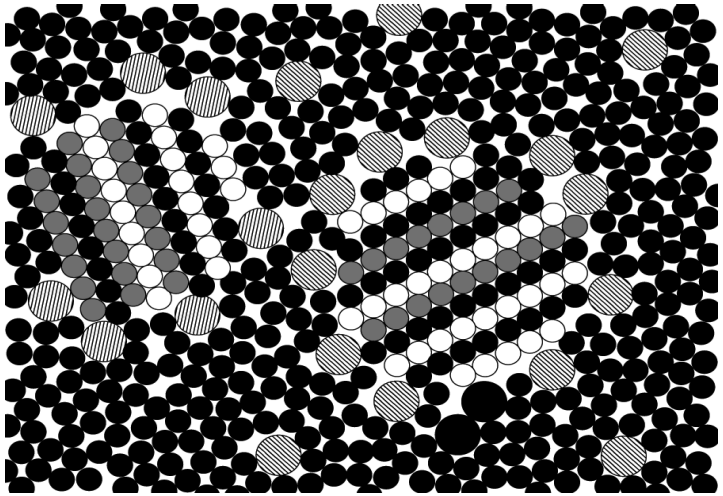


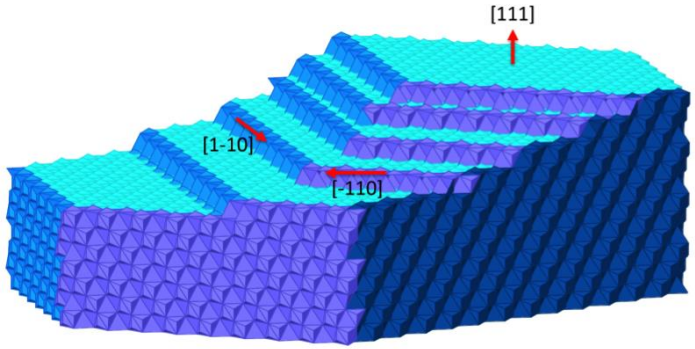


μ ~ 3 – 10, 000

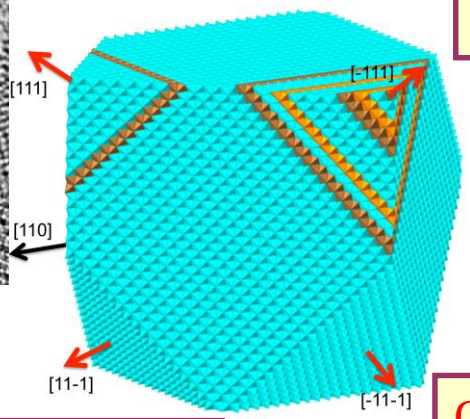
Nanostucture







Growth Faults



Orientations

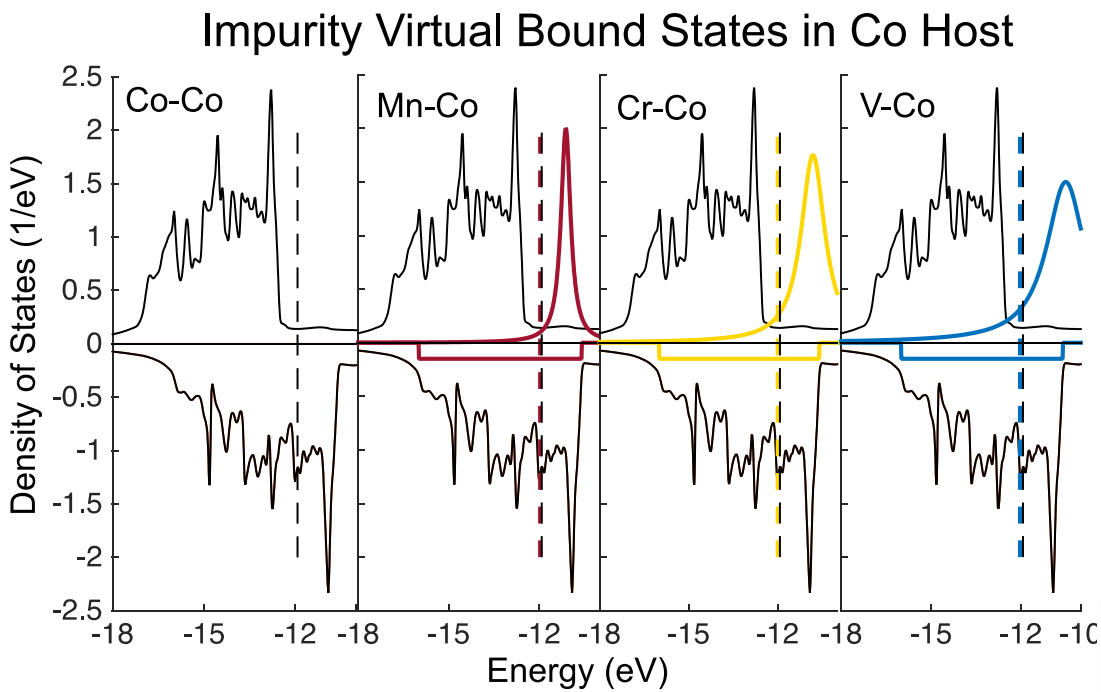
Deformation Faults

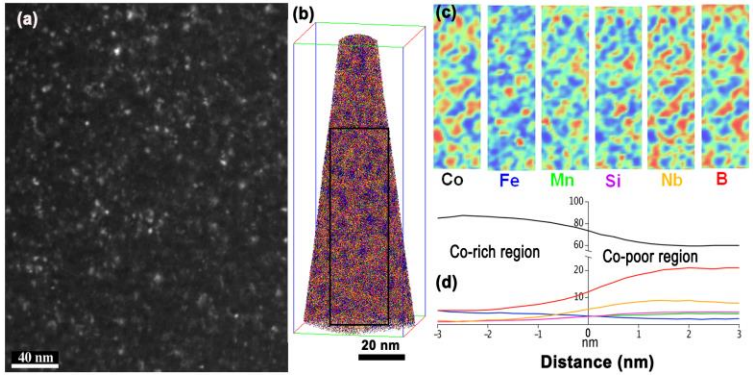
A. Leary, V. Keylin, A. Devaraj, V. DeGeorge, and P. Ohodnicki & M. E. McHenry;· "Stress Induced Anisotropy in Co-rich Magnetic Nanocomposites for Inductive Applications." J. Mat. Res. 31 (20), 3089-3107, (2016) Editor's Feature.

Virtual Bound States - Friedel

$$g(e) = \frac{5}{p}\frac{D}{(e - e_d)^2 + D^2}$$

$$D = \frac{2p}{\hbar |V_{sd}|^2} g_{Al}(e_d)$$

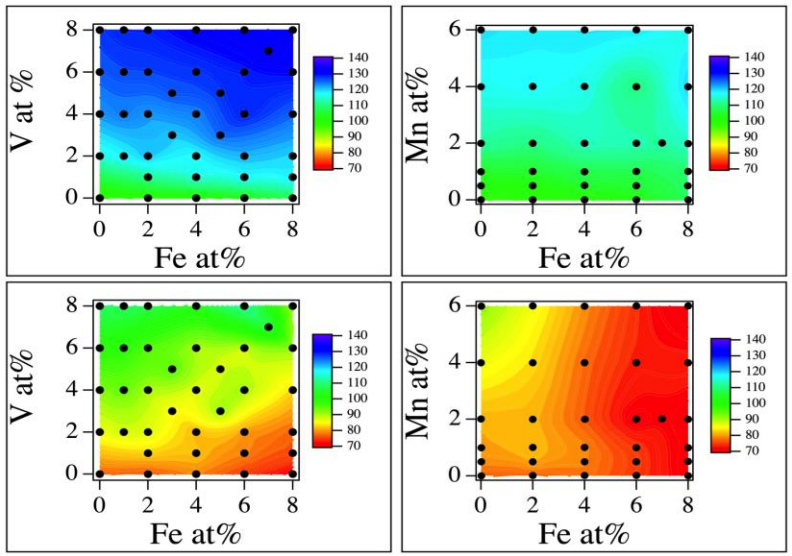




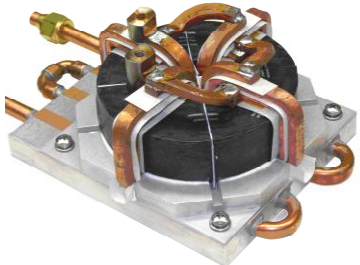
Virtual Bound States:

1. **Magnetization reduction (price we must pay)**
2. **Resonant scattering → Resistivity.**
3. **Change stacking faults (hcp vs. fcc) → Induced anisotropy**

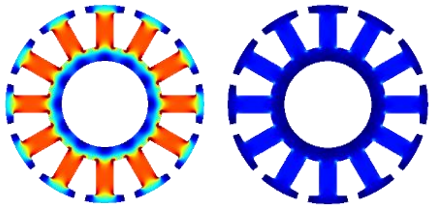
Resistivity (μΩ–cm)



Converter



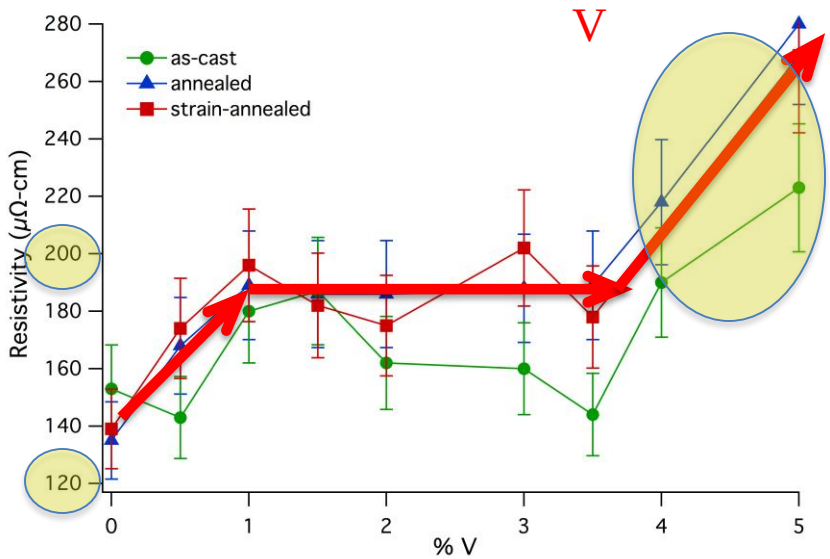
Motor (Si-steel, MANC)

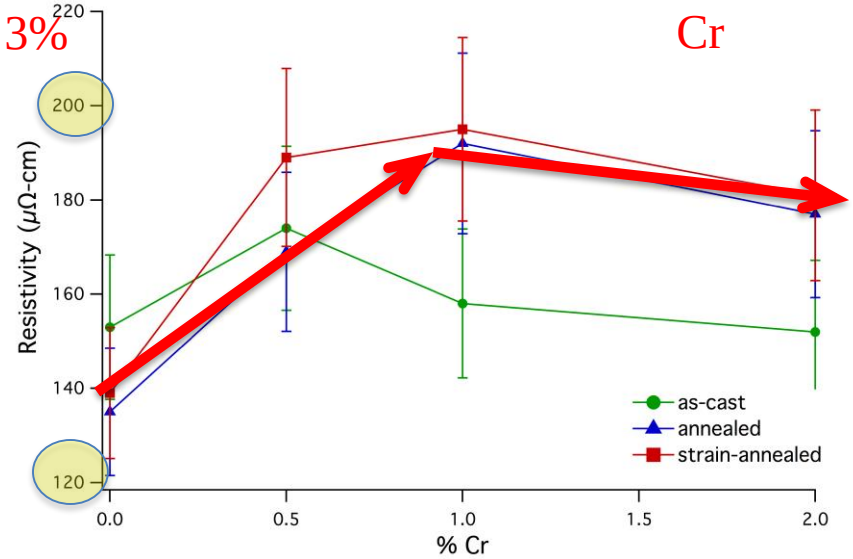


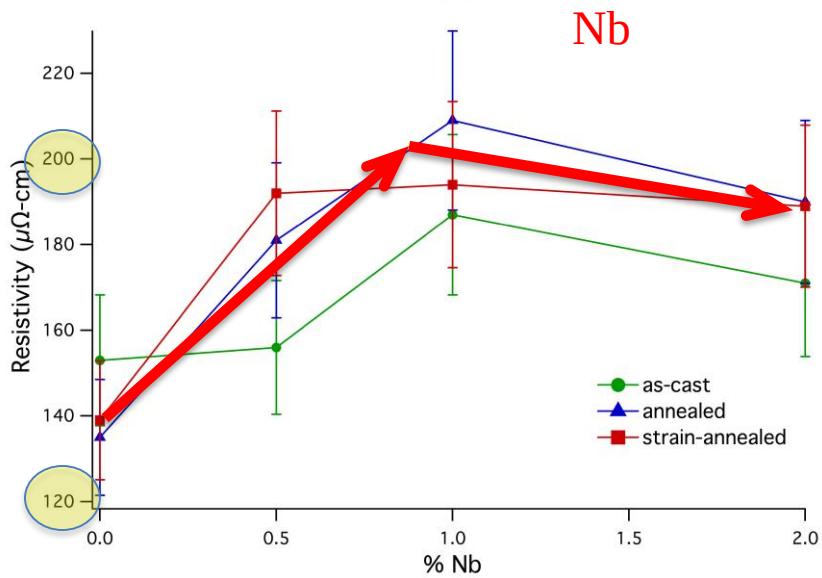
Resistivities

25 -35% Increase in resistivity As large as 200 μΩ-cm

V, Cr, Nb → Plateau at ~ 1 at% Mo at ~2.5-3%







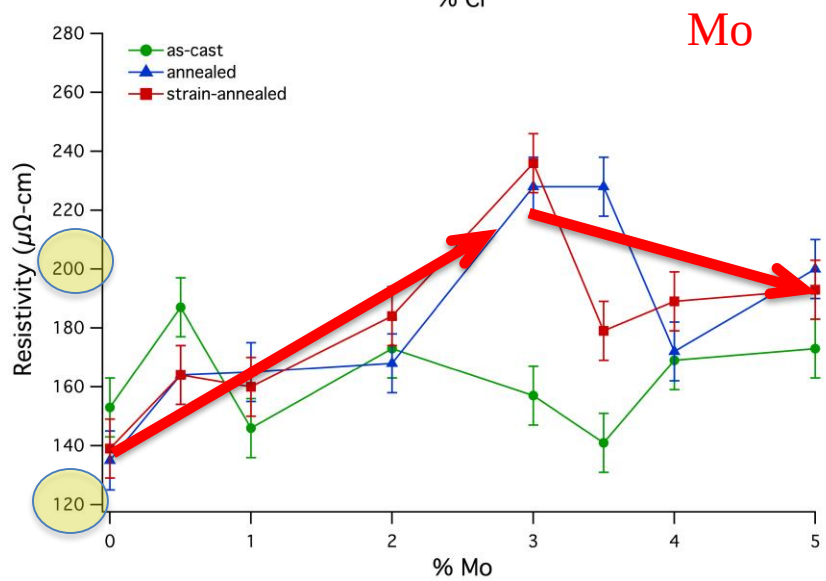


Figure 1: Resistivity of V, Cr, Nb, and Mo series.

Induced Anisotropy: SA vs. TMF

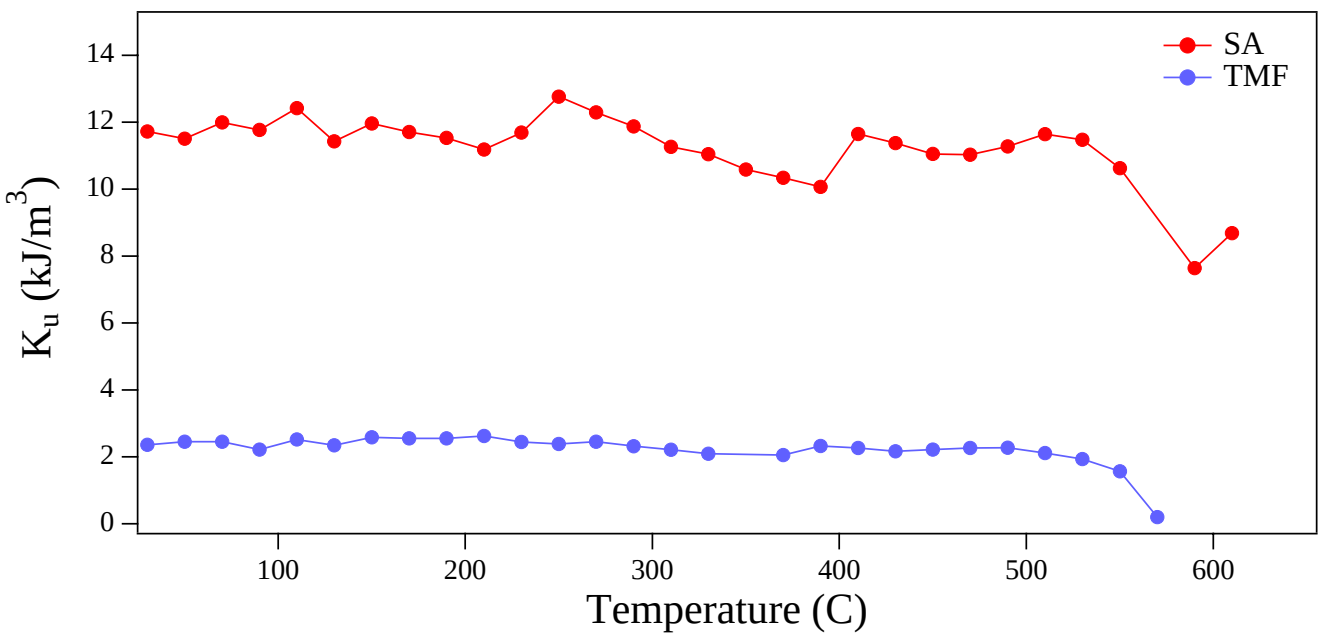
$$K = K_{magnetocrystalline} + K_{induced}(\theta, H) + K_{shape}(H, \tfrac{c}{a})$$

$$\frac{1}{\chi_{hard}} - \frac{1}{\chi_{easy}} = \frac{1}{M_s}(H_{hard} - H_{easy})$$

with uniaxial anisotropy Ku=MH/2….

$$\Delta K_u = \frac{\mu_0 M_s^2}{2}\left(\frac{1}{\chi_{hard}} - \frac{1}{\chi_{easy}}\right)$$

$$\Delta K_u = K_{induced}(0,0) - K_{induced}(\tfrac{\pi}{2}, 0)$$



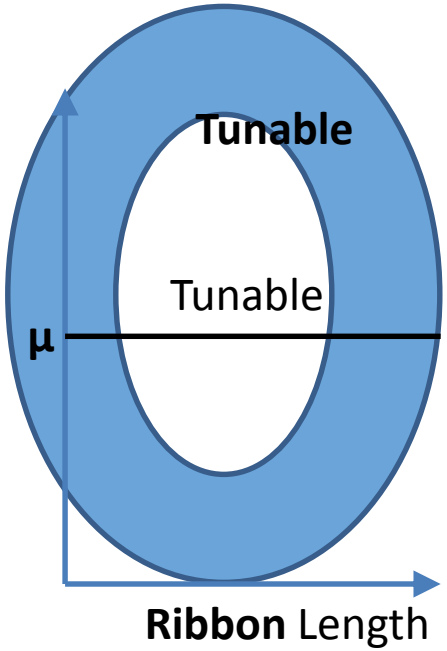
K_u = 11.5 kJ/m^3
μ_r = 34.6

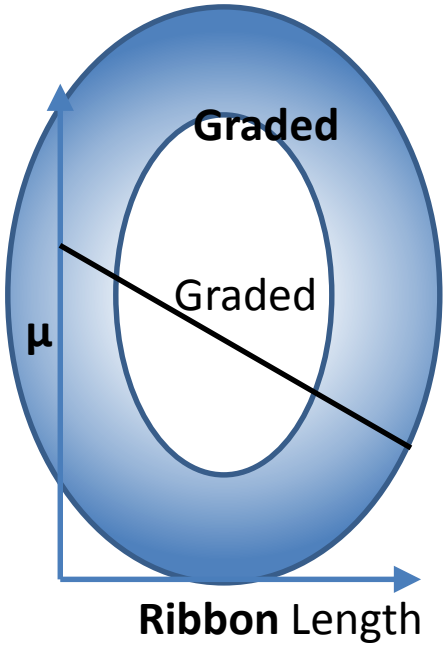
Samples annealed at 560 C

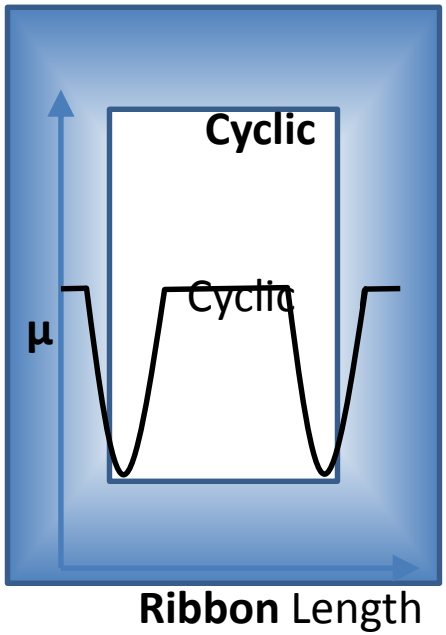
K_u = 2 kJ/m^3
μ_r = 199

Strain Annealing Modes

- Three modes of controlling stress during strain annealing:
  - "Tunable" or constant stress
  - "Graded" or ramped stress
  - "Cyclic" or oscillating stress
- Real-time control and monitoring of applied stress is necessary.

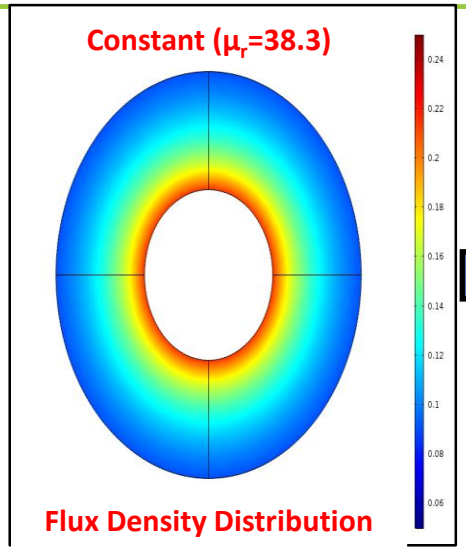


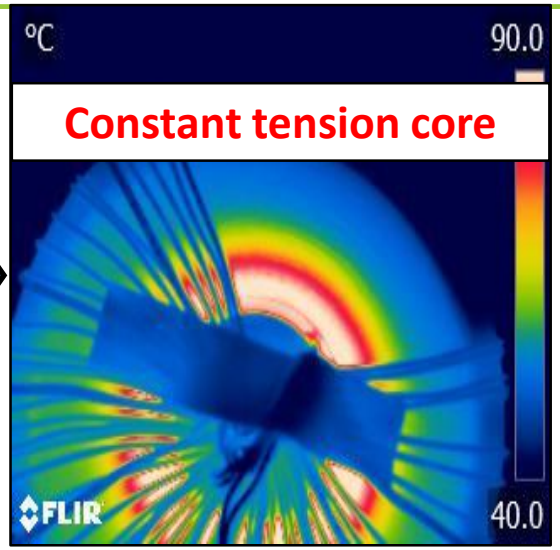


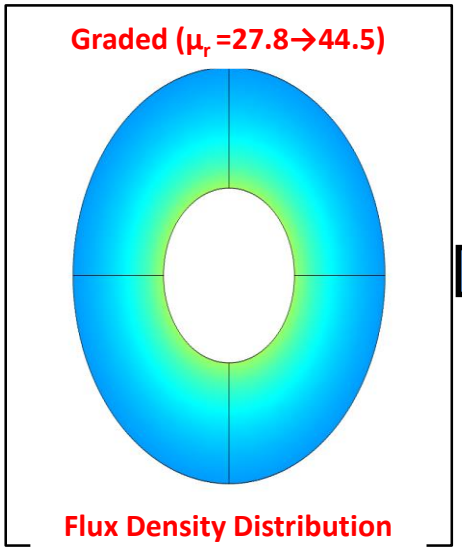


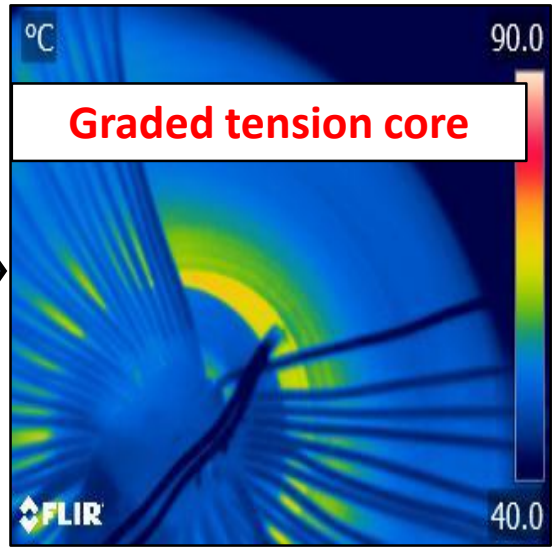
K. Byerly, S. R. Moon, P. R. Ohodnicki, M. E. McHenry, S. Simizu, A. M. Leary, V. Keylin, R. Noebe, R. Bowman, R. Beddingfield, S. Bhattacharya; Metal Amorphous Nanocomposite Alloy Cores with Spatially Tuned Permeability for Advanced Power Magnetics Applications. JOM, (2018), Invited submission.

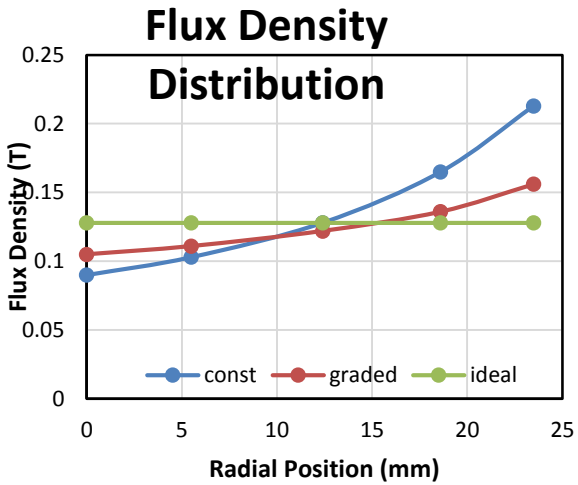
Comsol FEA Modeling and Thermal Characterization

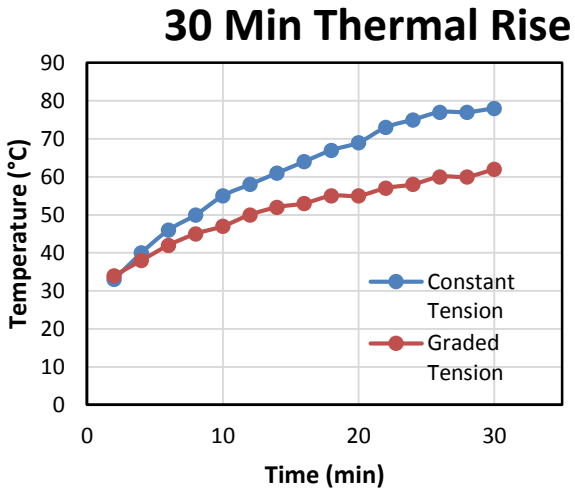








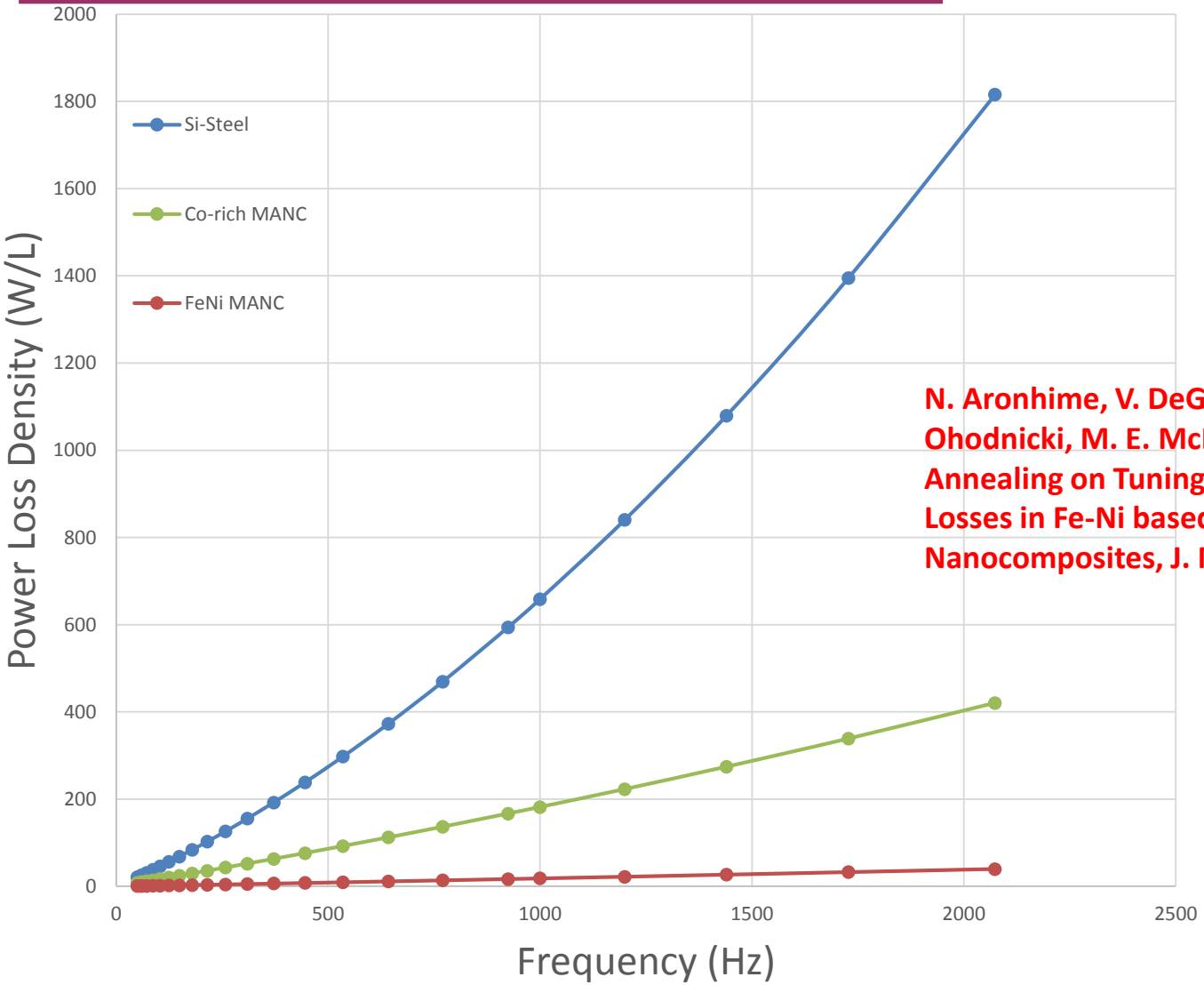




P. Lu, K. Byerly, M. Buric, P. Zandhuis, C. Sun, M.E. McHenry, R. Beddengfield, A. Leary & P.R. Ohodnicki; Distributed Fiber-optic Sensor for Real-time Monitoring of Energized Transformer Cores. Proc. SPIE: Computational Imaging 10194, 101941S, (2017). doi:10.1117/12.2263387.

A.2: FeNi-based MANC Materials

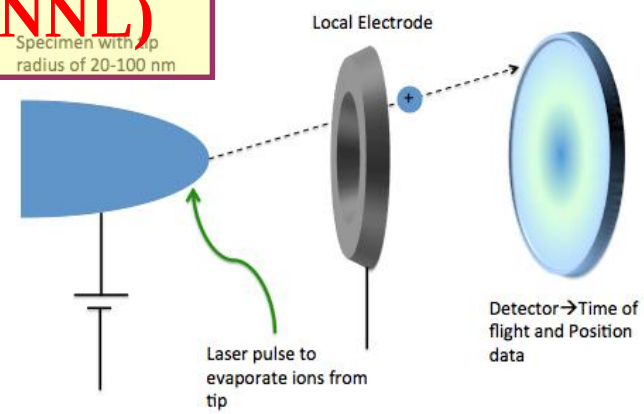
Low Core Loss at High Frequency (B = 1 T)



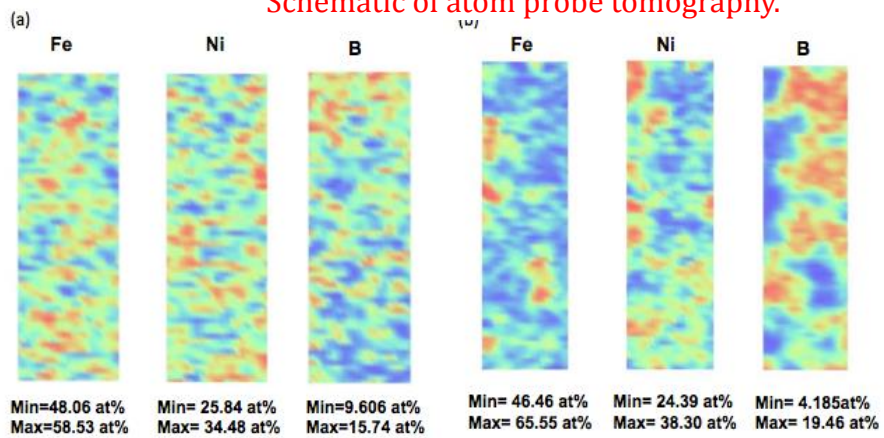
N. Aronhime, V. DeGeorge, V. Keylin, P. Ohodnicki, M. E. McHenry, "The Effects of Strain-Annealing on Tuning Permeability and Lowering Losses in Fe-Ni based Metal Amorphous Nanocomposites, J. Materials, (2017)

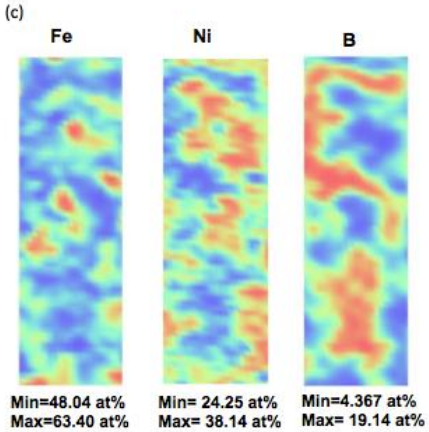
Atom Probe Tomography (A. Devaraj, PNNL)

- Clear B partitioning after annealing
- Residual amorphous is close to 23:6 composition
- Fe:Ni maintain parent alloy ratio



Schematic of atom probe tomography.





Atom probe tomography 2D contour maps for Fe, Ni and B in (a) as-cast ribbon, (b) annealed ribbon, and (c) strain-annealed ribbon.

NC FeNi-based MANCs Magnetization and Tc Trends

- B_S decreases with increasing Ni (μ_{Fe}=2.2 μ_B, μ_{Ni}=0.6 μ_B)
- a-T_C peaks at ~30% Ni

In patented compositions we can induce longitudinal anisotropy enabling increasing as-cast permeability of ~1000 To > 16, 000.

High permeability is desirable for motor applications.

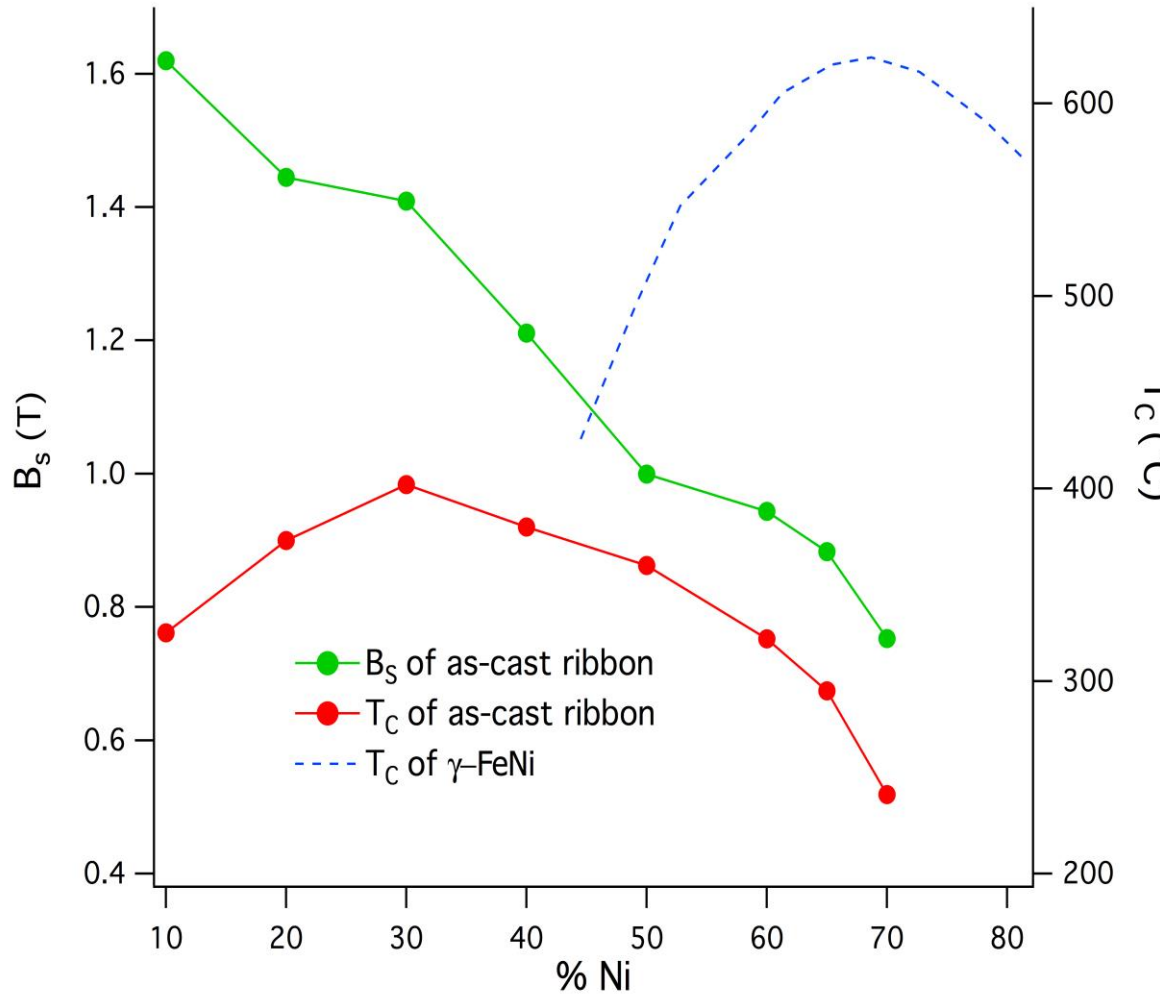


Figure 5.4: Saturation induction and Curie temperature for as-cast ribbon. Curie temperature for γ-FeNi is in blue.

[17],[77],[99]

Benchmarking : nc FeNi-based NC Baseline

Table I: Coercivity, saturation induction, thickness, losses at 1 T and 400 Hz, and losses at 1 T and 1 kHz for nanocrystalline $(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{15}$, nanocrystalline $Fe_{85}B_{13}Ni_2$, Fe-based Metglas 2605SA1, and non-oriented 3% Si-steel and 6.5% Si-steel. *H_c measured at 60 Hz and 1 T induction.

	H_c (A/m)	B_s (T)	t (μm)	$W_{1.0/400}$ (W/kg)	$W_{1.0/1k}$ (W/kg)
nc-$(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{15}$	7.0*	1.3	20	0.9	2.3
nc-$Fe_{85}B_{13}Ni_2$[38]	4.6	1.9	13.4	2.3	6.3
nc-$Fe_{89}Hf_7B_4$[39]	5.6	1.59	17	0.61	1.7
Fe-based amorphous[38]	2.4	1.56	23.9	1.6	4.7
3% Si-Steel[39,40]	55	2.05	100	8.5	27.1
6.5% Si-Steel[40]	18.5	1.85	100	5.7	17.2

Summary: 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.

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; on-line (2017).

MANC Mechanical Properties

Videos showing brittleness of FINEMET-type alloy:

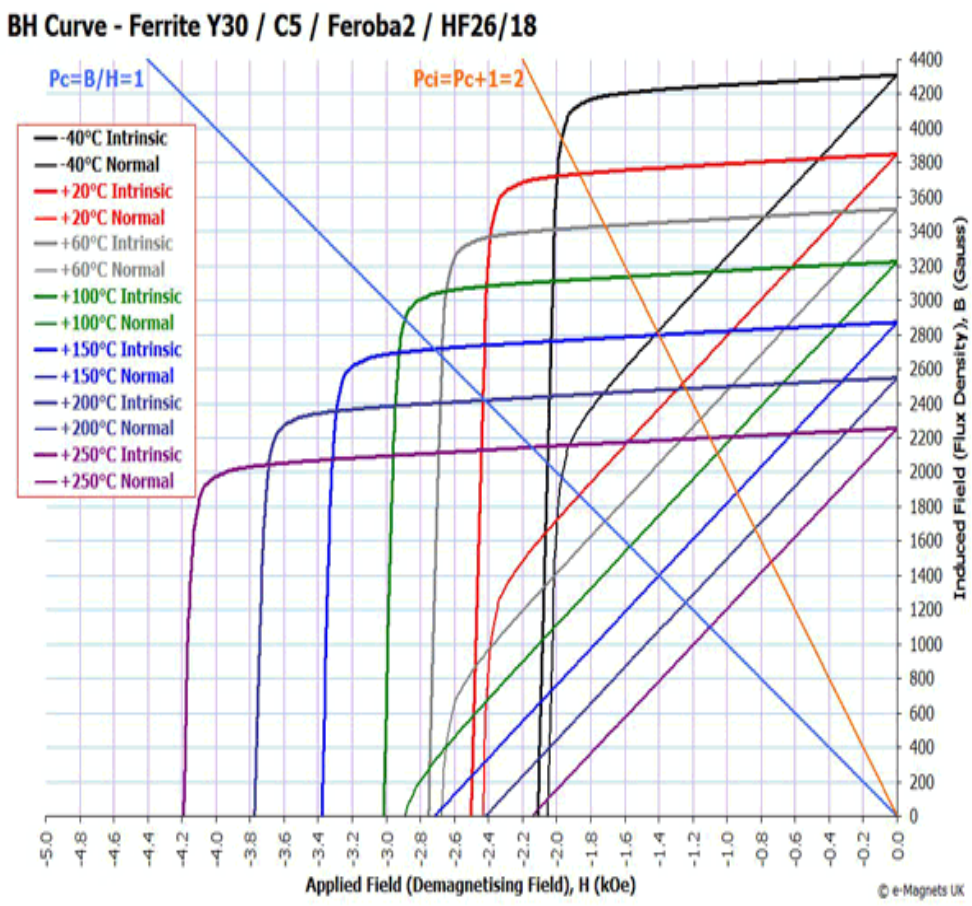
Ductility of Strain annealed FeNi- MANC

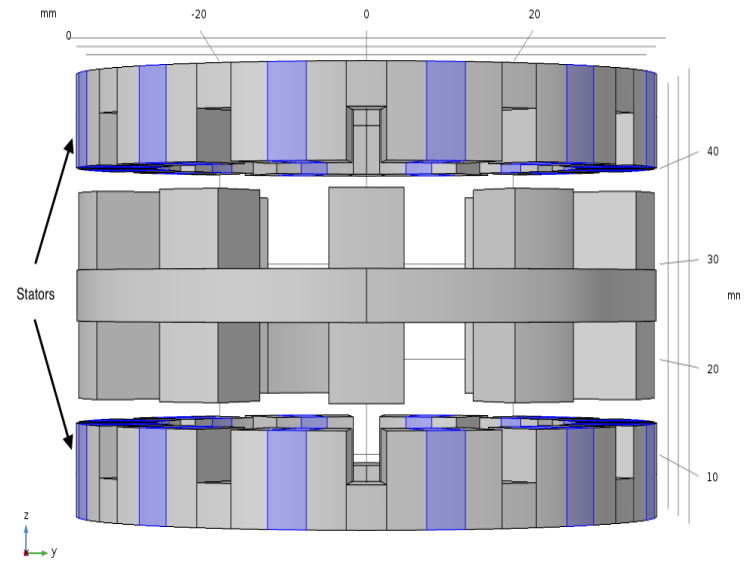
VS.

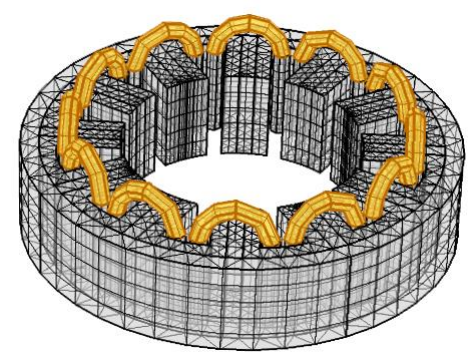
Commercial Ferrite PMs (Br ~ 0.4T) In FSWPM High Flux Density Results (1 T) from Flux Focusing of MANC

Power Density ~ #poles & angular speed

Axial Motor Design with MANC Rotors



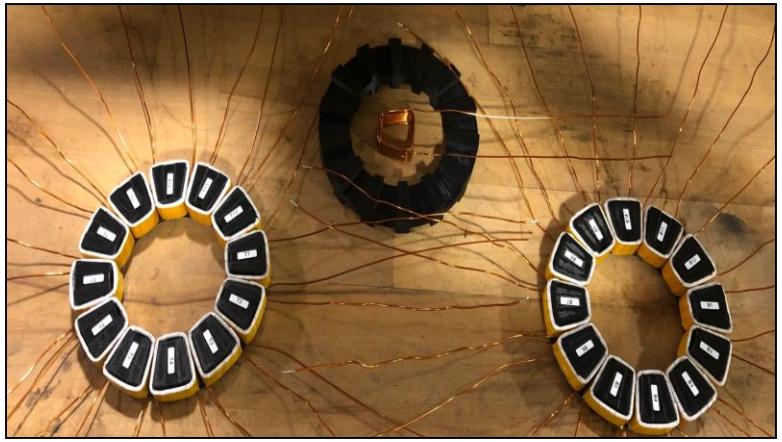


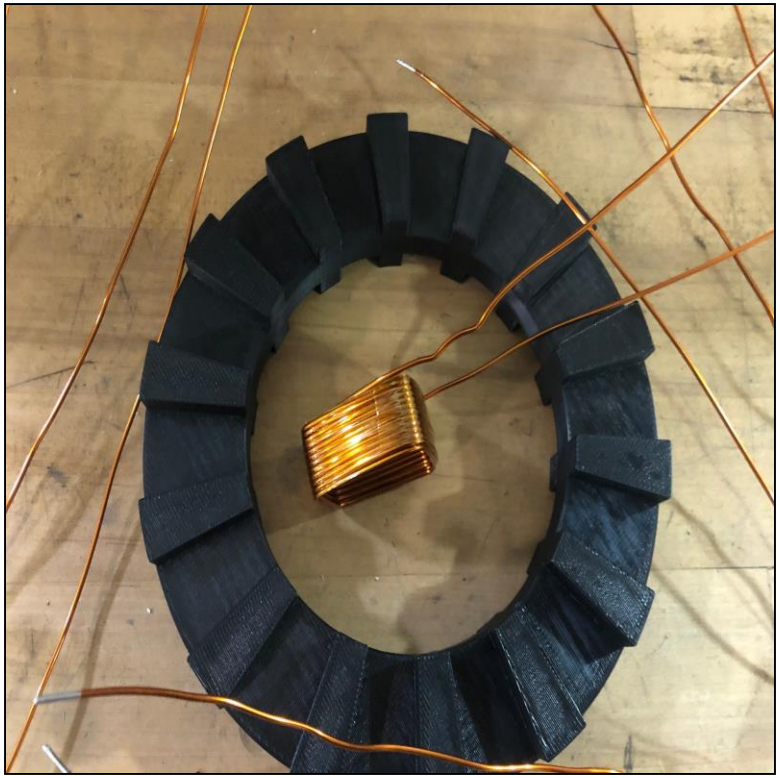


S. Simizu, P. R. Ohodnicki and M. E. McHenry, "Metal Amorphous Nanocomposite Soft Magnetic Material-Enabled High Power Density, Rare Earth Free Rotational Machines," *IEEE Trans. Mag*. 99, 1-5. doi: 10.1109/TMAG.2018.2794390. Also presented at MMM 2017, Pittsburgh, PA

Stators with coils and rotor

(3-d printed mock-up, > 50% wire fill factor)





rotor

Conclusions.

- A Variety of Emerging Trends Drive the Need for Innovations in Soft Magnetics for Power Electronics and Power Conversion Applications:
  - Electricity Grid Infrastructure
  - Large-Scale Electrical Machinery
  - “Electrification” of the Transportation Fleet
- Metl Amorphous Nanocomposites (MANCs) in Novel Topologies Show Promise for a Range of Applications Spanning Various Application Areas
- Inductor Applications:
  - Engineered Permeability Through Field and Strain Annealing
  - Temperature Stability and Performance Under DC-Bias Conditions
- Transformer Applications:
  - Temperature Stability Even Under “Ambient” Conditions
  - Losses Under Application Relevant Excitation
  - High Frequency Transformer Technology Can Be Cost Effective
- Motor Applications are being demonstrated in DOE Advanced Manufacturing Program.
  - Higher rotational speeds yield higher power densities.
  - Potential for operating at speeds unreachable by steels.
  - New MANC compositions of matter.
- We Are Always Looking for Partners to Collaborate

M. E. McHenry Biosketch.

Michael E. McHenry is Professor of Materials Science and Eng. (MSE), with an appointment in Physics and Biomedical Engineering at Carnegie Mellon. He graduated with a B.S. in Metallurgical Eng. and Materials Science from Case Western Reserve in 1980. From 1980 to 1983 he was employed as Process Engineer at the U.S. Steel Lorain Works. In 1988 he earned a Ph.D in Materials Science and Eng. from MIT. He was a Director's Funded Post-doctoral Fellow at Los Alamos Lab from 1988 to 1989. He has expertise in the area of nanocrystalline magnetic materials including soft magnetic nanocomposites, faceted ferrite nanoparticles and materials for power conversion, biomedical, energy and data storage applications. His research involves rapid solidification processing, plasma and solution synthesis of nanoparticles, magnetic field of processing materials, structural characterization by x-rays and electron microscopy and magnetic properties characterization as a function of field, temperature and frequency. He directed a Multidisciplinary University Research Initiative (MURI) on high temperature magnetic materials for aircraft power applications and led an ARPA-E program in magnetic materials for power electronics. He served as Technical Evaluator for the NATO AVT-231 Specialists Meeting on "Scarcity of Rare Earth Materials for Electrical Power Systems". Brussels, Belgium, (Oc. 13-15, 2014) and continues with a NATO team considering implications Rare Earth Element scarcity for NATO countries. He has served as proceeding Editor, Publication Chair and a member of the Program Committee for the Magnetism and Magnetic Materials (MMM) and Intermag Conferences. He has published over 350 papers and owns two patents in the field. He has co-authored, with Marc DeGraef, the textbook “Structure of Materials”, Cambridge University Press, 2007 with a second edition in 2012.