DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

PROJECT SUMMARY

Enabling Soft Magnetics for Power Conversion Applications

- *Task #1*: Establishment of a Medium-Voltage (MV) Core Loss Test System (CLTS) and Application-Relevant Characterization of MV Dielectric and Insulation Materials
- *Task #2:* Development of High Saturation Soft Magnetic Materials for High-Frequency and High-Power Applications
- *Task #3:* Soft Magnetic Alloy Advanced Manufacturing Through In-Line RF Processing
- *Goal:* Enabling improved operation of Wide Band Gap (WBG)-based converters and creating pathway for Ultra-WBG adoption through advanced magnetics

PRINCIPAL INVESTIGATORS
Dr. Jagannath Devkota, Research Scientist, NETL
Darryl Shockley, Supervisory General Engineer, NETL

WEBSITE
www.netl.doe.gov

The Numbers

DOE PROGRAM OFFICE:
OE – Transformer Resilience and Advanced Components (TRAC)

FUNDING OPPORTUNITY:
N/A

LOCATION:
Pittsburgh, PA

PROJECT TERM:
04/01/2020 to 03/31/2022

PROJECT STATUS:
Active

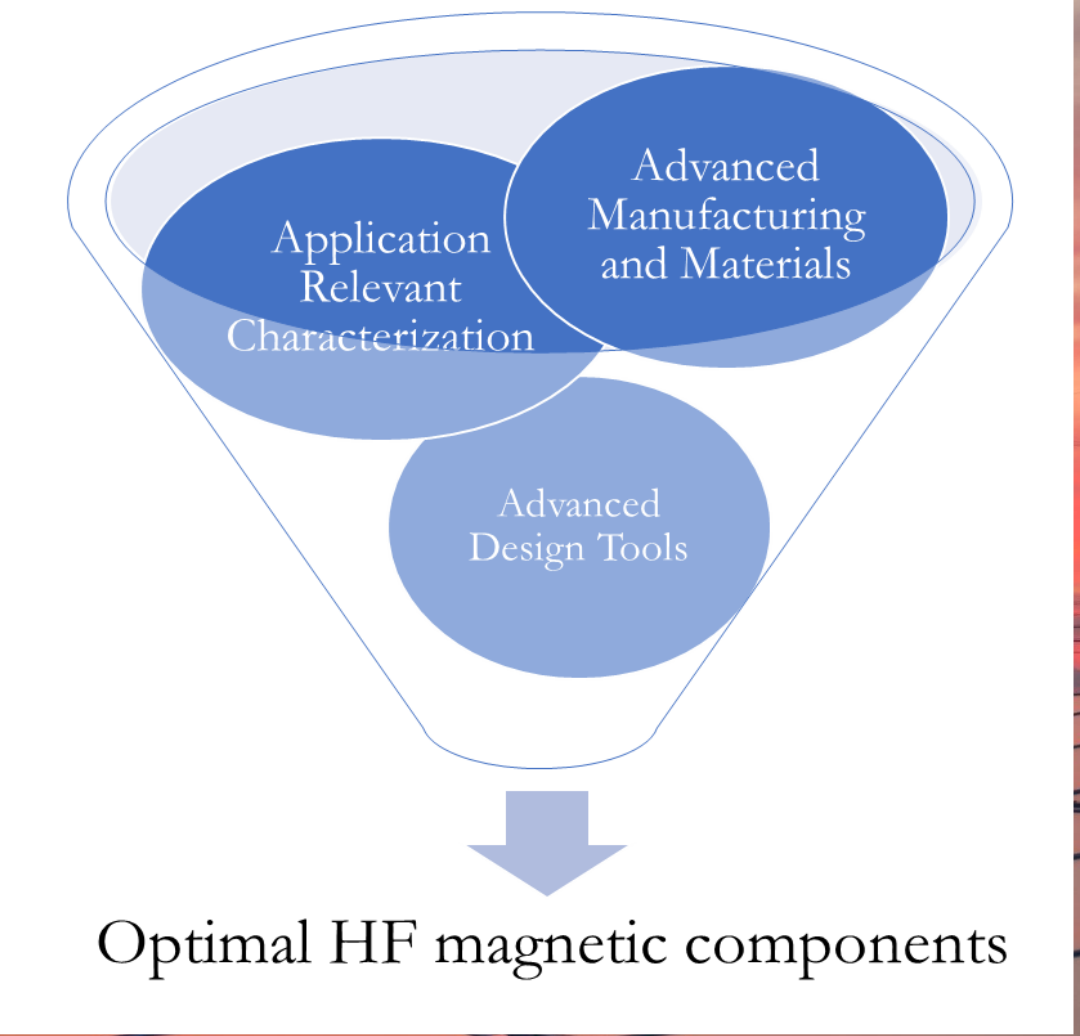
AWARD AMOUNT (DOE CONTRIBUTION):
$1,019,029

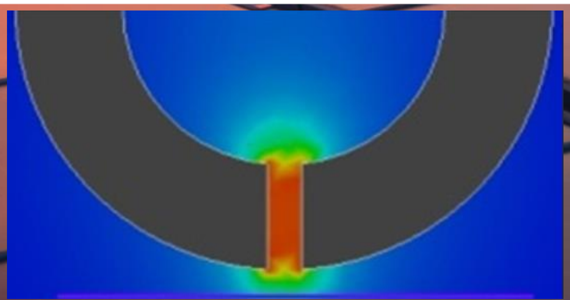
AWARDEE CONTRIBUTION (COST SHARE):
$000,000

Primary Innovation

To help keep pace with WBG switching devices, develop high frequency (kHz – MHz) capable & loss and size optimized magnetic components through

- **Materials Chemistry and Processing Methods**
  - New magnetic materials with high saturation and permeability
  - Chemical synthesis methods
  - In-line processing of the state-of-the-art materials
- **Application Relevant Core / Component Characterization**
  - Publication of data sheets based on application relevant excitations
  - Enable better materials informed designs and material utilization
- **Advanced Design Tools**
  - Multi-objective optimization and co-simulation methods
  - Process optimization through modeling





Engineer the material properties to eliminate the need of the gaps!

Impact/Commercialization

- **Datasheets for five core materials**
  - Available to public at https://netl.doe.gov/TRS and https://netl.doe.gov/node/8081
  - Conference publication: “Soft Magnetic Materials Characterization for Power Electronics Applications and Advanced Data Sheets”, 2019 IEEE ECCE Conference
  - More data are being generated for MV components

- **Journal paper and design toolbox**
  - Nacsimento et al., “Multiobjective Optimization Paradigm for Toroidal Inductors With Spatially Tuned Permeability,” IEEE Transactions of Power Electronics, 36, 2021, 2510
  - A release version of the toroidal inductor optimization toolbox as active content is available to the paper cited above

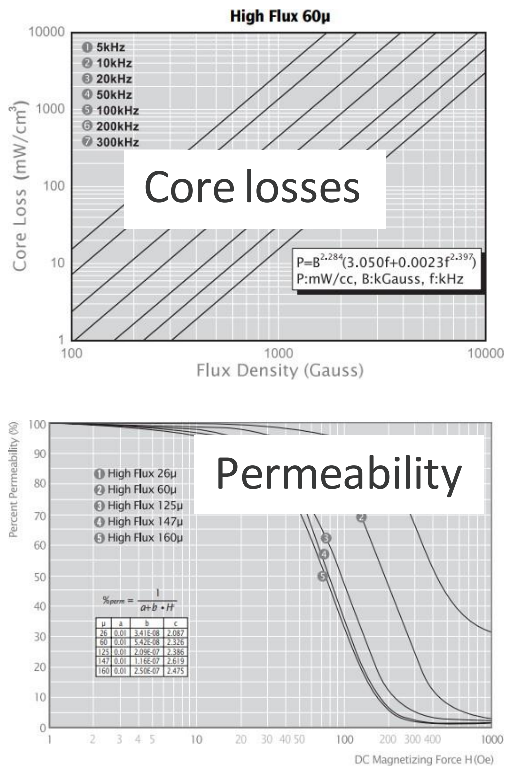
- **Three conference papers/presentations**

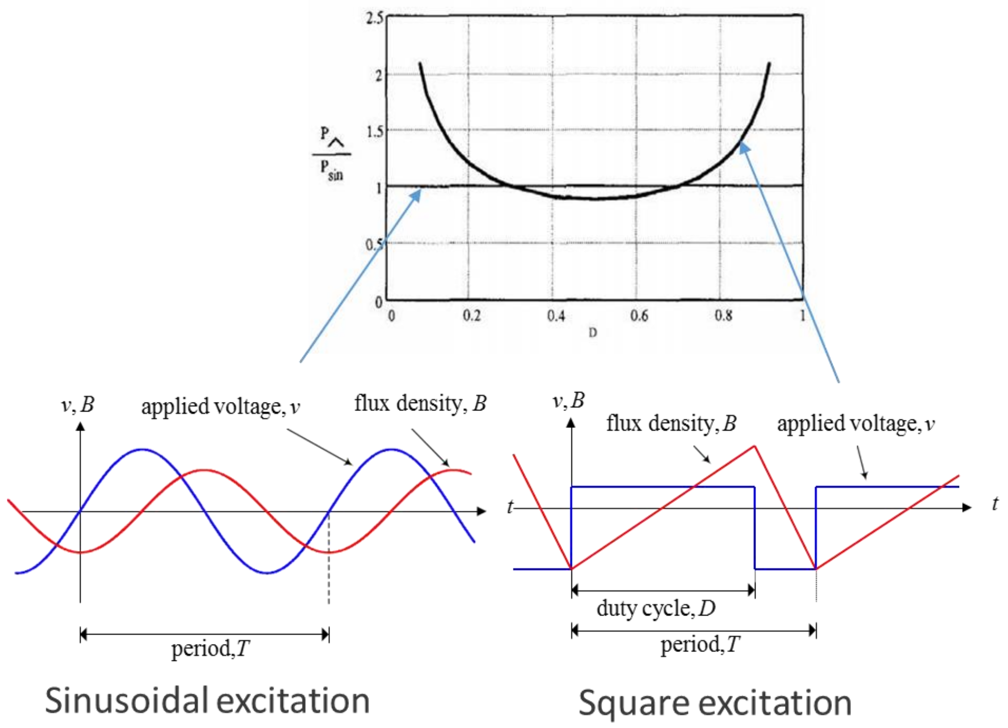
- **Patent(s):**
  - Two IPs have been issued on thermal/in-line microwave processing of alloys

1. MV CLTS and Application-Relevant Characterization

Significance and Impact

- In power electronics applications, various square and other more complex excitation waveforms are prevalent.
- Information from manufacturers' data sheets are
  - the core characteristics are typically based on sinusoidal excitation that are less relevant.
  - difficult to extract and/or lacking detailed information
- Magnetic cores and components must be tested under relevant excitation conditions at relevant scales and voltages.





Manufacturer's datasheet
(http://www.mhw-intl.com/assets/CSC/CSC_Catalog.pdf)

Publish the datasheet based on the power electronics relevant measurements as a resource.

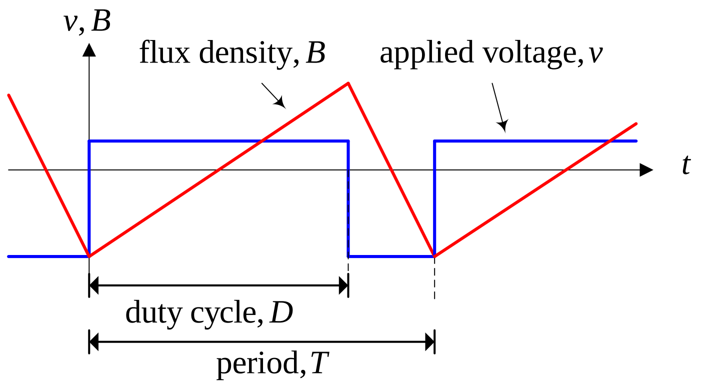
Make the power electronics relevant core loss testing facility available to the community.

1. MV CLTS and Application-Relevant Characterization

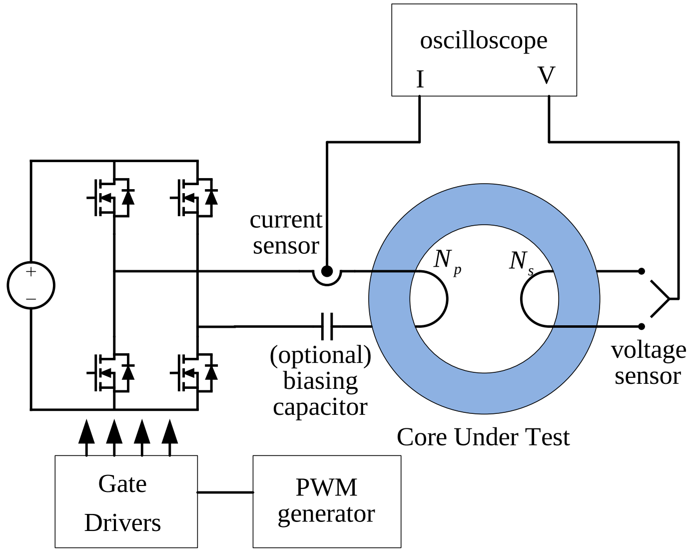
Approach and Execution

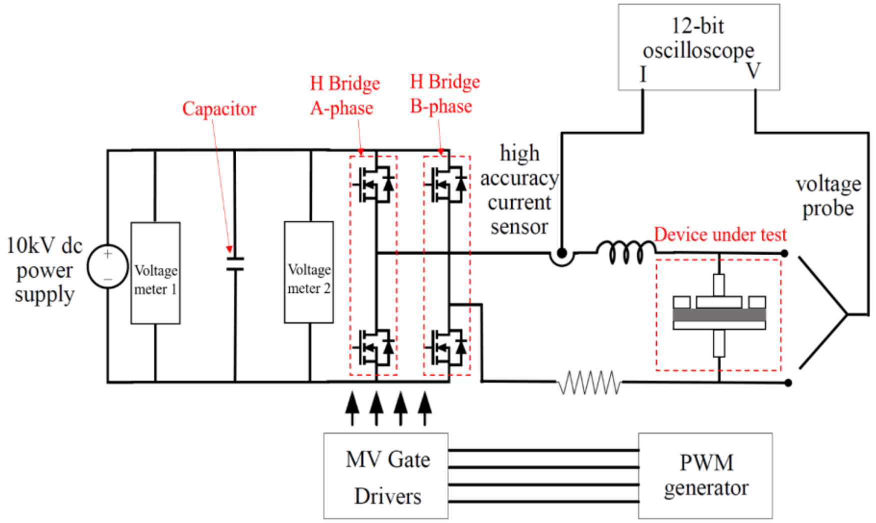
- Core Loss Test Systems (CLTS) and Insulator Characterization Systems (ICS) are developed to perform core characterization.

- To supplement manufacturers' data sheets, power electronics relevant square waveform CLTS are utilized to characterize soft magnetic materials on fabricated cores at scale.

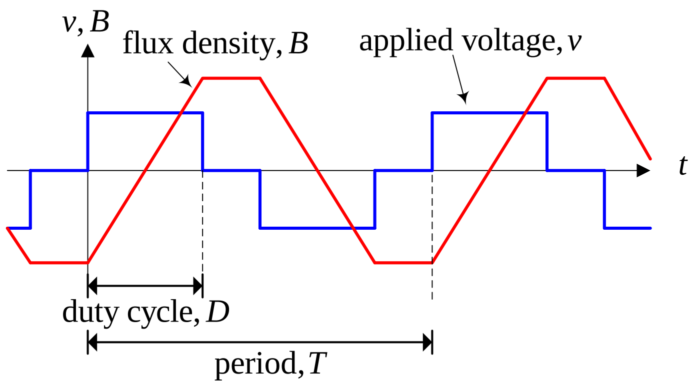


Asymmetrical square voltage excitation with triangular magnetizing current





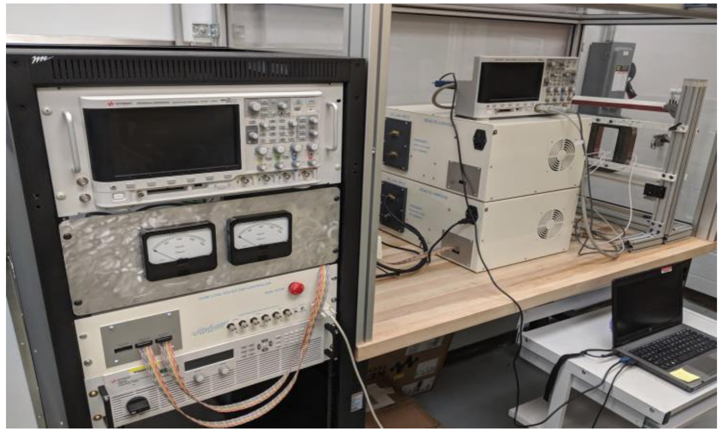
Schematics of the proposed MV CLTS and ICS capable for square wave excitation



Symmetrical square voltage excitation with trapezoidal magnetizing current

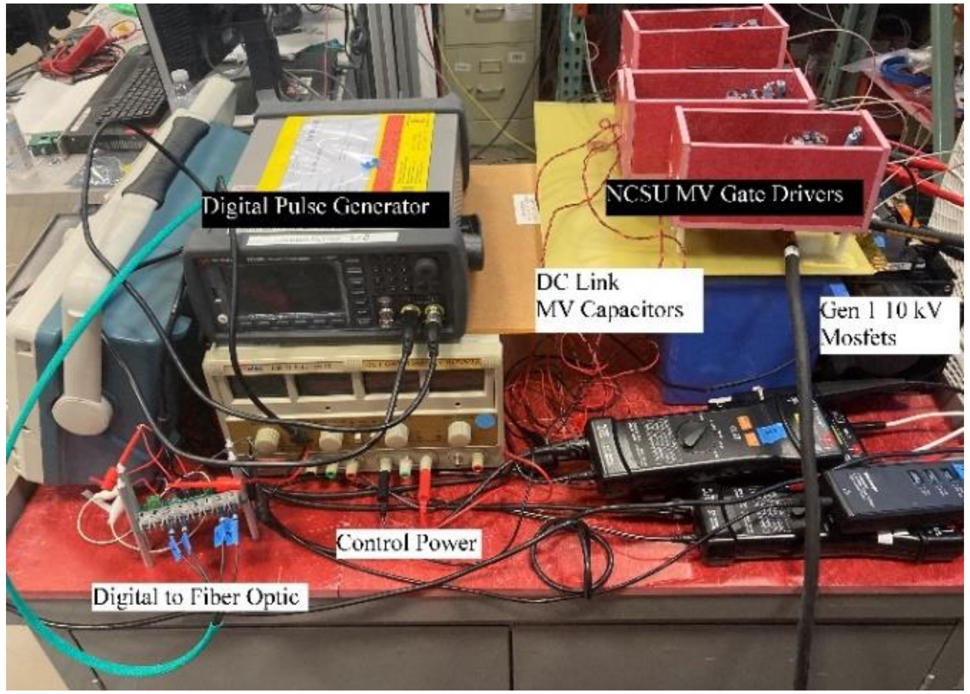
1. MV CLTS and Application-Relevant Characterization

Technical Productivity and Quality

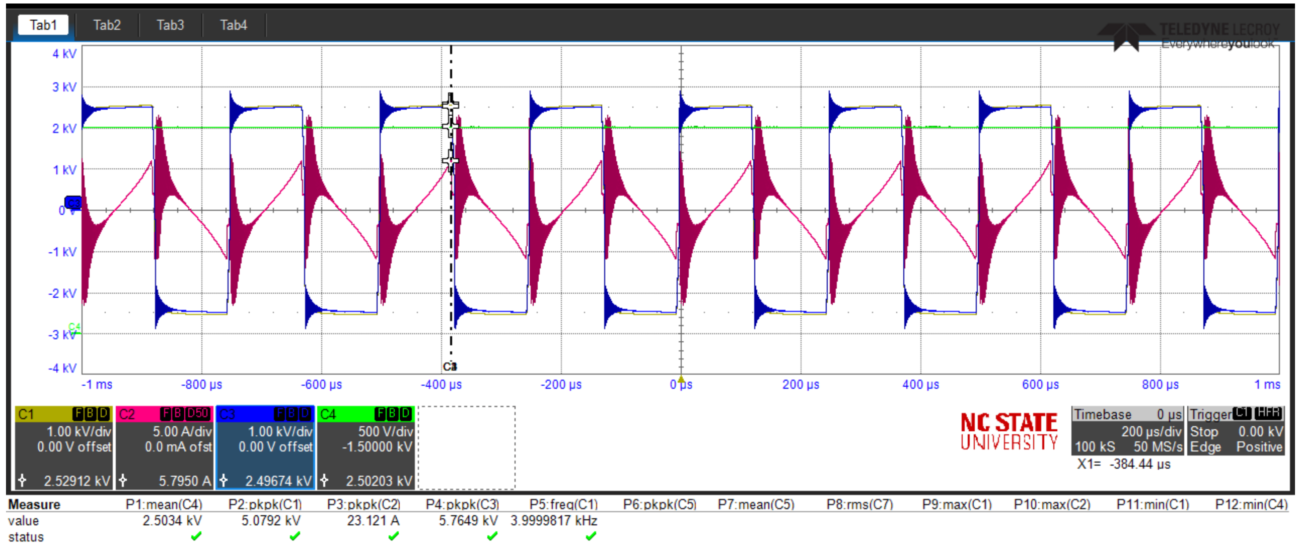


LV (<1.2kV) CLTS built under the support of TRAC program

- ➢DC supply from NCSU is 3kV/100 A Chroma
- ➢Testing
  - Open Circuit: 5 kV, 20 kHz
  - MV Transformer: 2.5 kV 40 kW, 10 kHz



MV CLTS built under the support of TRAC program



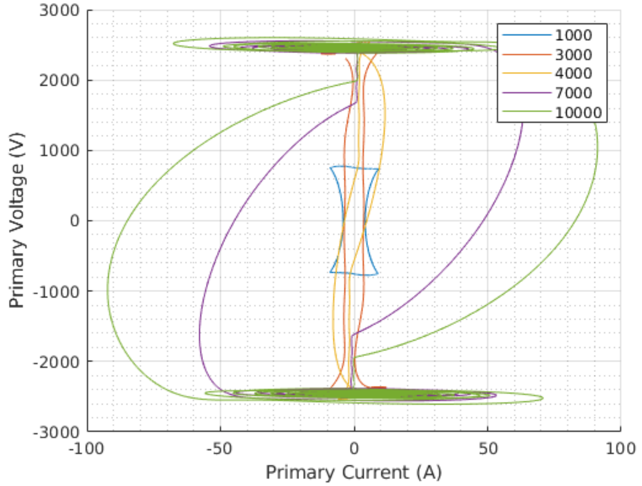
MV (3 kV+) CLTS and ICS have been Built and Tested for a Representative Component (Transformer)

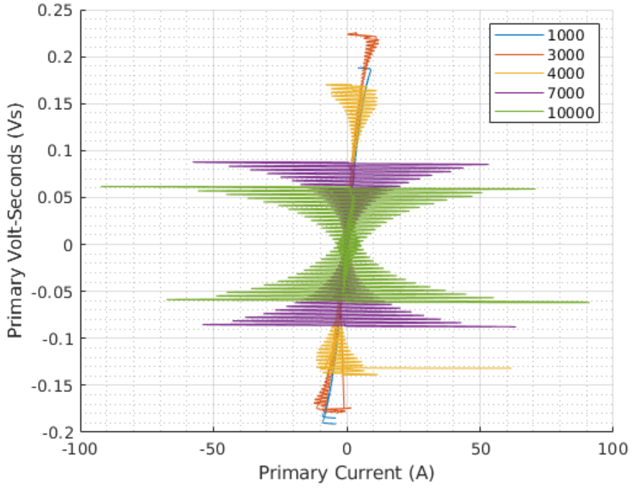
1. MV CLTS and Application-Relevant Characterization

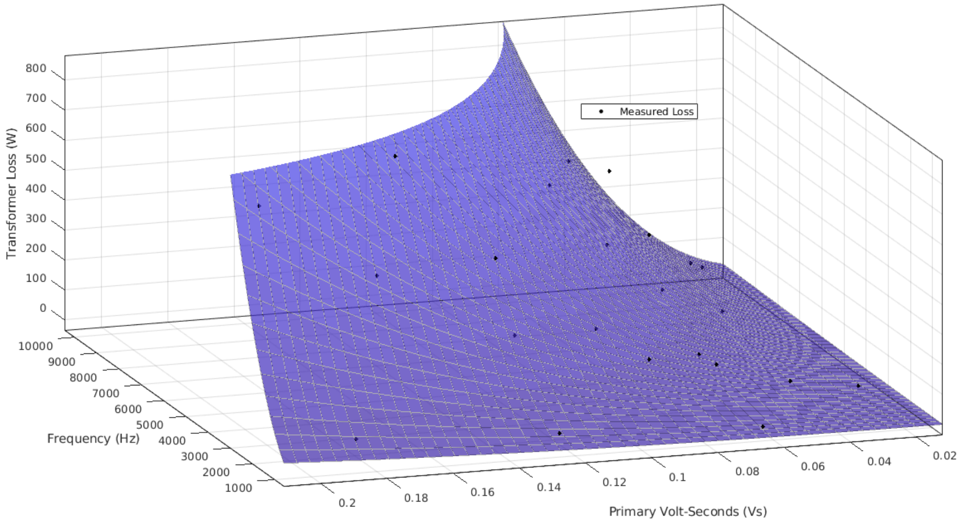
Relevance and Alignment – Development of Dataset

- Representative MV Transformer provided by NCSU
  - 40 kVA, 20 kHz, 3495 V_{pk} : 3495 V_{pk} rated
  - The university requested maximum 2.5 kV excitation
- Transformer construction unknown
  - Must develop VS loops which enables application relevant design
  - Steinmetz ‘like’ VS factors:

    k_{TX} = 0.206; α_{TX} = 1.774; β_{TX} – 2.263





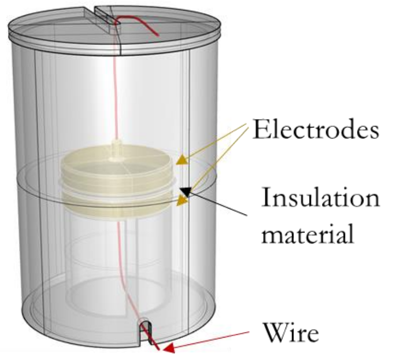


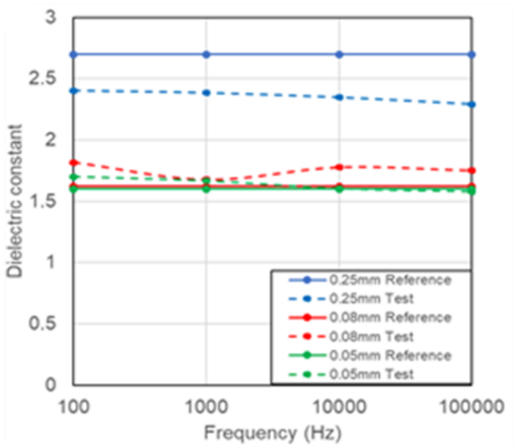
Initial Datasheet of an MV Component have been Developed for Review

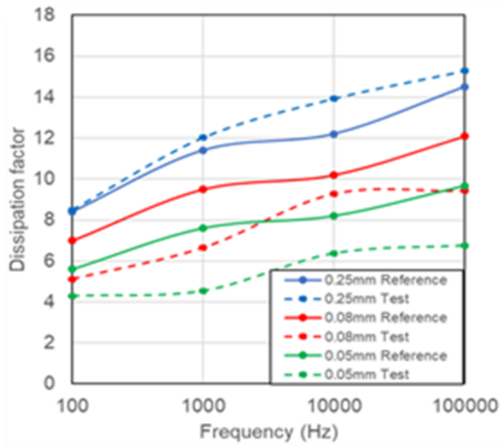
1. MV CLTS and Application-Relevant Characterization

Summary and Future Work

- MV Component Characterization and Datasheets
  - Work with partners, e.g, Industry, NETL sponsors, and AMPED Consortium for more MV components
  - Characterization as a 'service'
- MV Dielectric Testing
  - Apply MV CLTS
  - Apply material characterization before and after MV excitation
    - XRD etc
    - See if aging effects can be measured
  - Develop initial dielectric datasheets for review







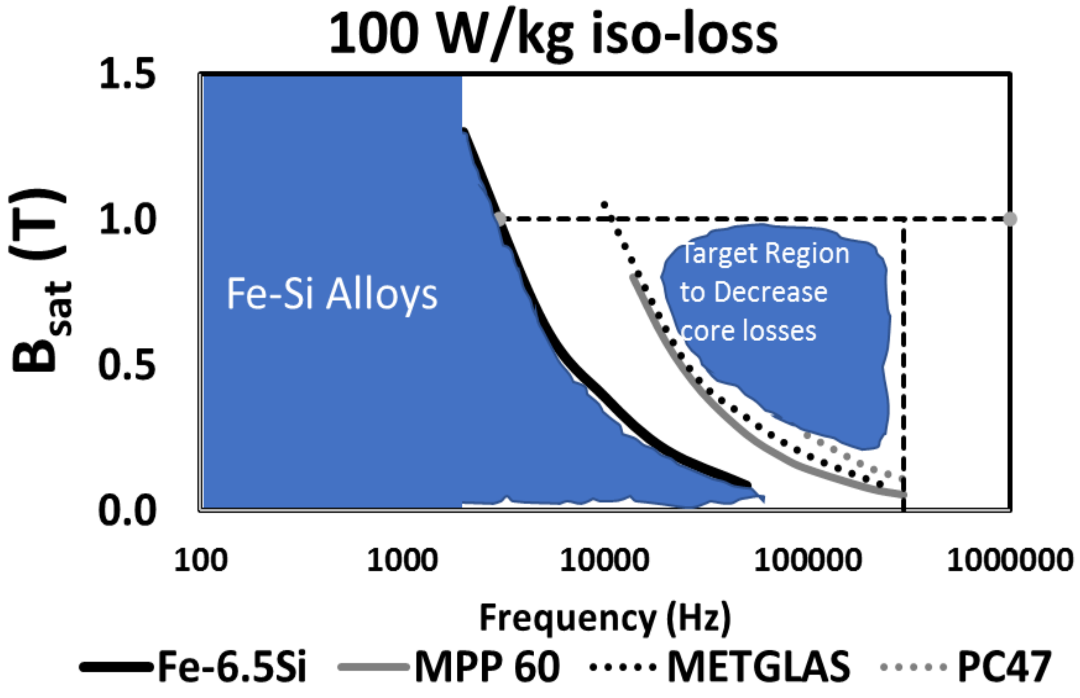
Dielectric properties of NOMEX 410 measured by an impedance analyzer

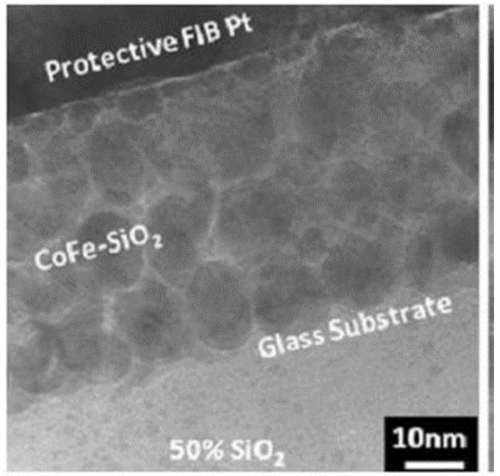
Establishment of MV Test System and Development of Initial Datasheet for a MV Component is Complete.

Initial datasheet development for a representative Insulation Material is in Progress.

2. Development of High Saturation Soft Magnetic Materials

Significance and Impact



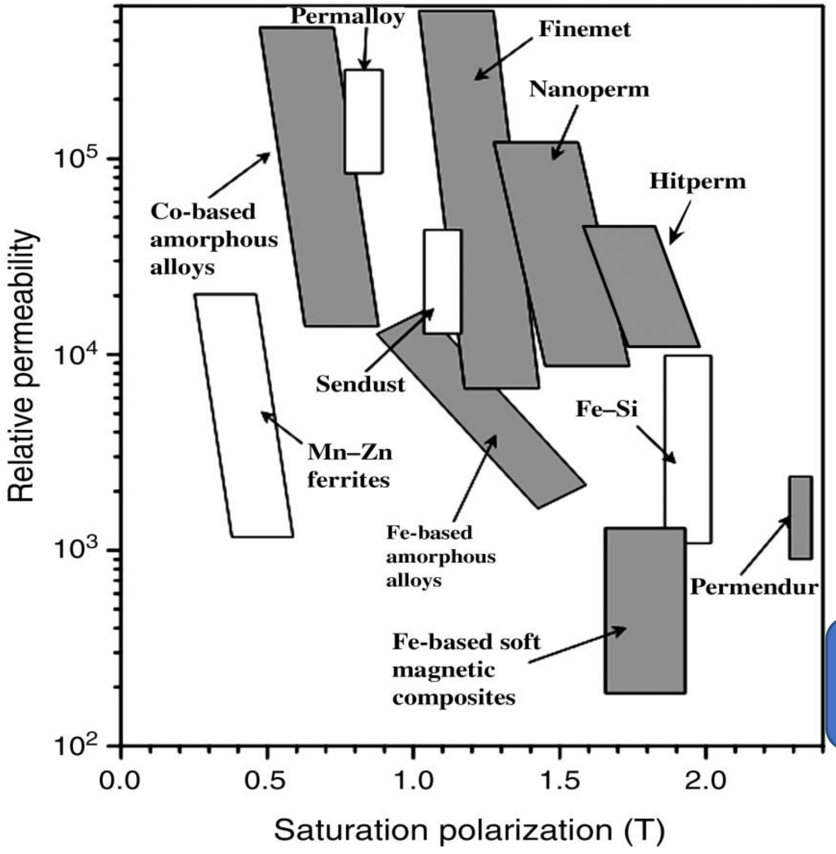


- State-of-the-arts materials are not suitable for high frequency and high-power applications.
- Existing synthesis techniques lack the scalability for production of emerging materials with controlled microstructures.
- New bottom-up synthesis technique would
  - produce soft magnetic composites (SMCs) at scale and low cost
  - provide greater flexibility to control the microstructures and materials chemistry
  - eliminate the need of expensive ball-milling process
- New core materials would be relevant for WBG semiconductors and applications and pave a path for ultra-WBG semiconductor applications

2. Development of High Saturation Soft Magnetic Materials

Approach and Execution

- Identify and implement a bottom-up method to synthesize SMCs comprising of candidate nickel-iron and silicon-iron alloy systems coated with nanoparticles (NPs).
- Measure magnetic properties as a function of structure/property/processing relationships and scale-up the synthesis.
- Fabricate representative cores for magnetic property testing and benchmarking.



Webster et al., 'Soft Magnetic Materials', (2016)
DOI:10.1002/047134608X.W4504.pub2

Material Design/Selection

Bottom-Up synthesis of powder and scaling up

↓

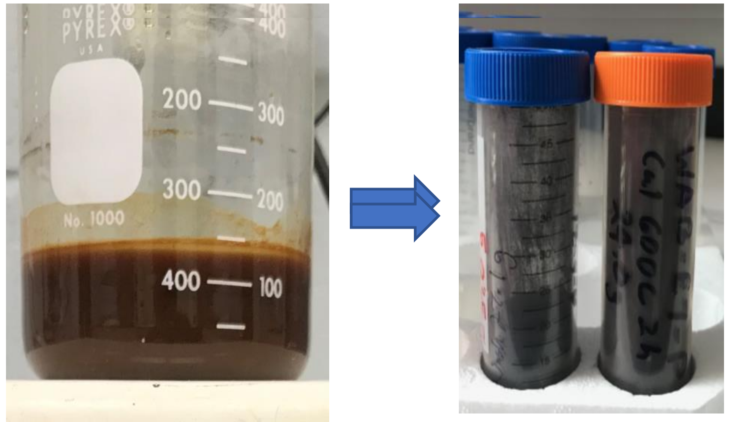
Structural and magnetic characterization

↓

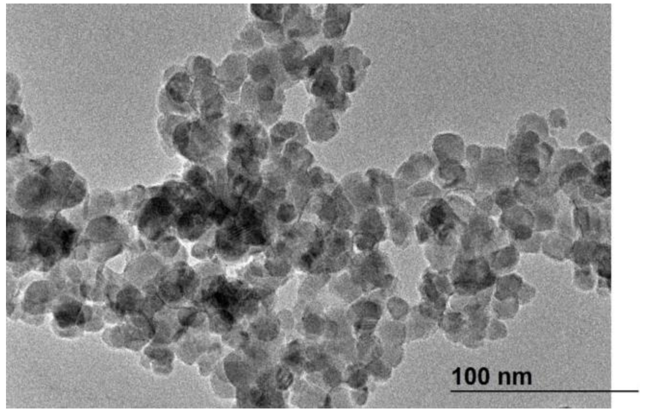
Core fabrication and benchmarking

2. Development of High Saturation Soft Magnetic Materials

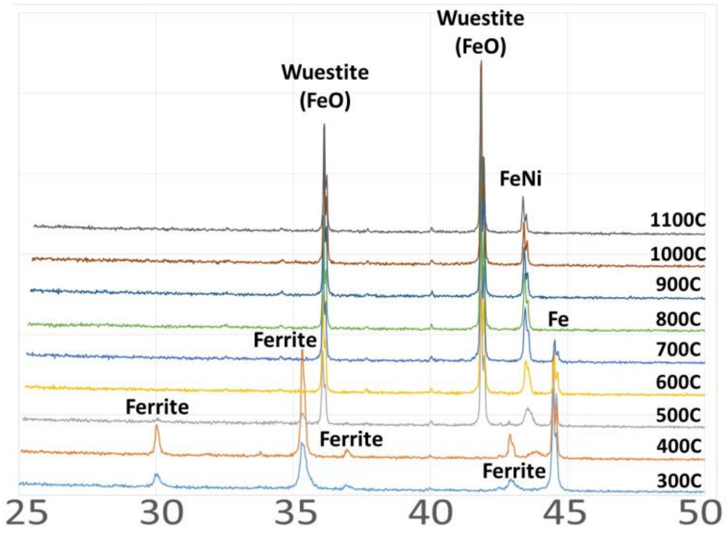
Technical Productivity and Quality



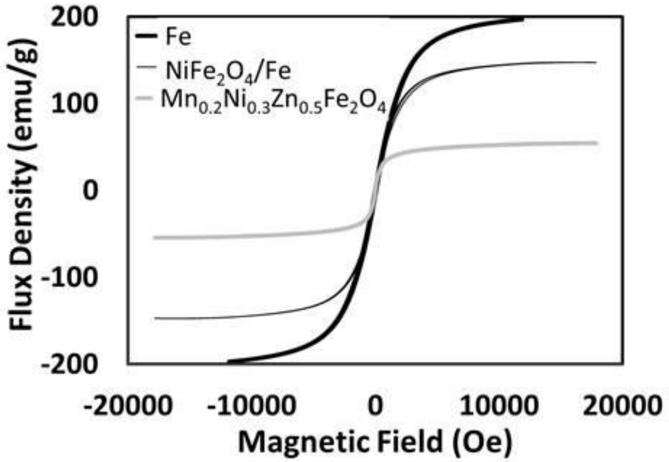
Wet chemistry-based synthesis of soft magnetic composites



TEM Image



XRD Spectra



Magnetic Hysteresis Loops

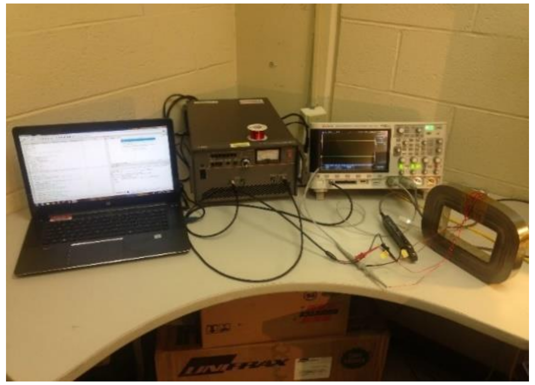
- Structural and magnetic properties comparable to those of existing powder martials
- Synthesized SMCs with various compositions using wet-chemistry based precipitation reactions.
- Produced 21g $NiFe_2O_4$ nanoparticles in 180mL volume and projected a production of 350g ferrite if scaled up to 3L volume.

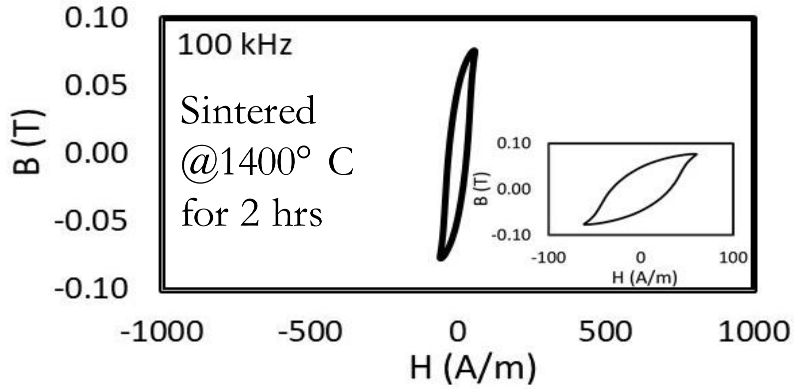
Formula	M_r (emu/g)	M_s (emu/g)	H_c (Oe)	Source
$Mn_{0.2}Ni_{0.3}Zn_{0.5}Fe_2O_4$ (25 C, 20 h, 24 g)	0.2	54.3	1.6	This work
15% $NiFe_2O_4$/Fe	4	147	47	This work
4% $Ni_{0.5}Zn_{0.5}Fe_2O_4$/Fe	~10	178.8	----	Ref. [1]
$NiFe_2O_4$ (<1 – 10 μm)	19.84	43.16	221.35	Ref. [2]
Fe microparticles (Fisher)	*~3.5*	*196.8*	*45*	This work
Fe (25-347 nm)	~10	212.6	109.5	Ref. [3]

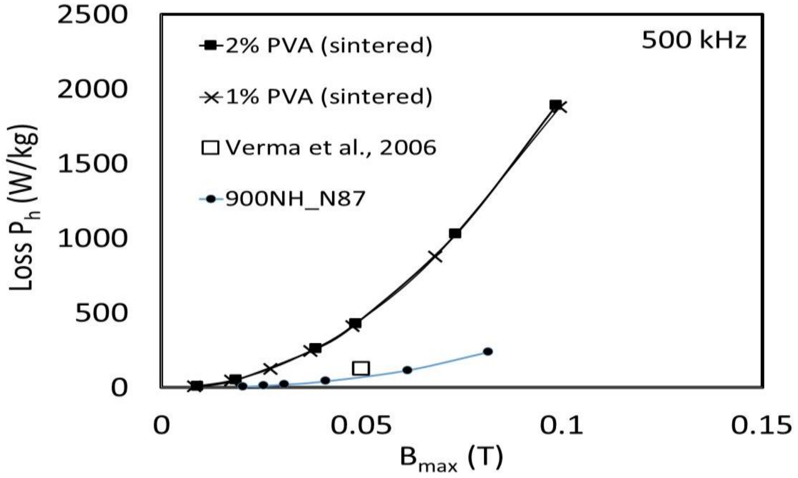
[1] Y. Peng, et al., J. Magn. Magn. Mater. 2017, 428, 148-153.
[2] V. Dhole *et al.*, *IJESRT* **2016**, *5(11)*, 1-4.
[3] M. Choi *et al.*, *J. Magn. Magn. Mater.* **2019**, *480*, 33-39

2. Development of High Saturation Soft Magnetic Materials

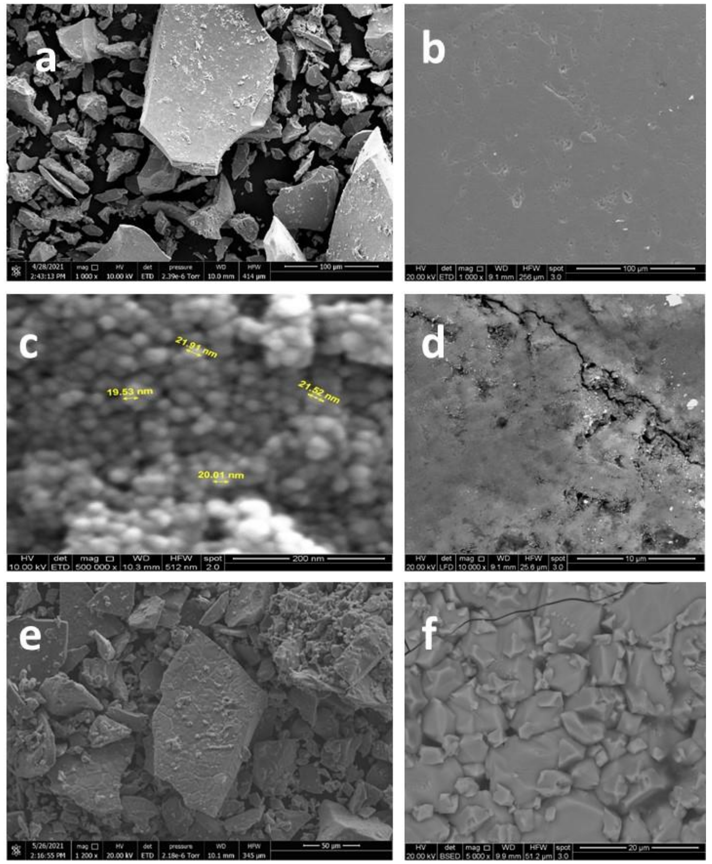
Relevance and Alignment







Representative toroidal core and test results



SEM images of the powder and compacts

Production of soft magnetic materials at scale is possible by wet chemistry-based methods.

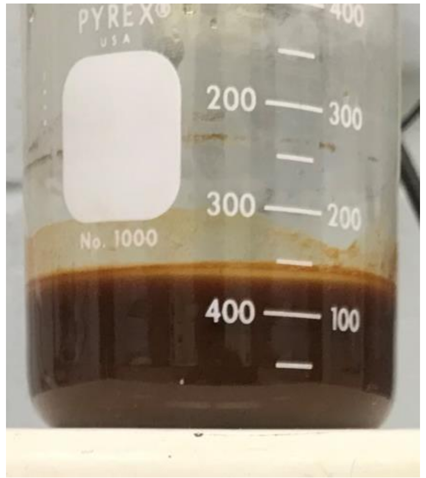
Optimization in the structural/compositional properties as well as processing methods is necessary to improve the performance.

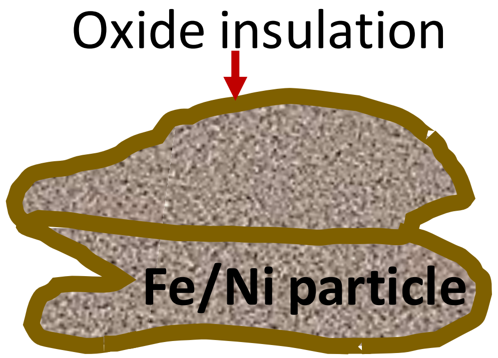
2. Development of High Saturation Soft Magnetic Materials

Summary and Future Work

- Successfully synthesized scaled-up batches of two representative soft magnetic composites ($Mn_{0.2}Ni_{0.3}Zn_{0.5}Fe_2O_4$ and $NiFe_2O_4$) using wet chemistry-based method. Synthesis >300g is possible.
- Characterized the magnetic composites for structural and magnetic properties, and compacted into cores, sintered at 1400 C, and analyzed for core loss properties.
- Optimization in composition, structural properties as well as the synthesis procedure, compaction, and post processing to improve the performance.
- Investigation of new materials consisting of consisting of metal/oxide phases for magnetic core applications.

  Metallic phase to retain high saturation (high power density) and insulation phase for better resistivity (high frequency)





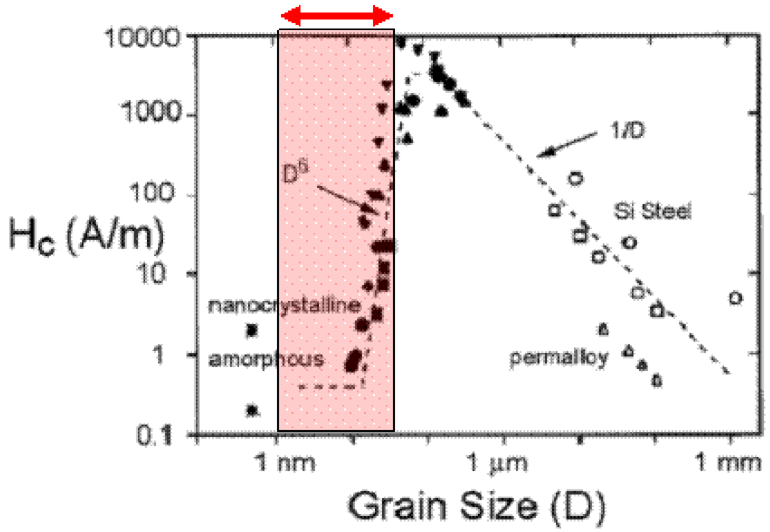
Wet-chemistry based methods could produce large scale soft magnetic composites with a greater flexibility to engineer their properties for high frequency and high-power applications.

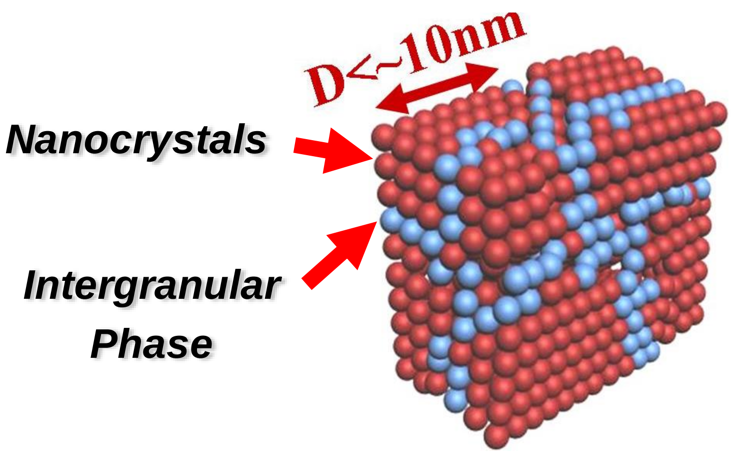
3. SMA Manufacturing through In-Line RF Processing

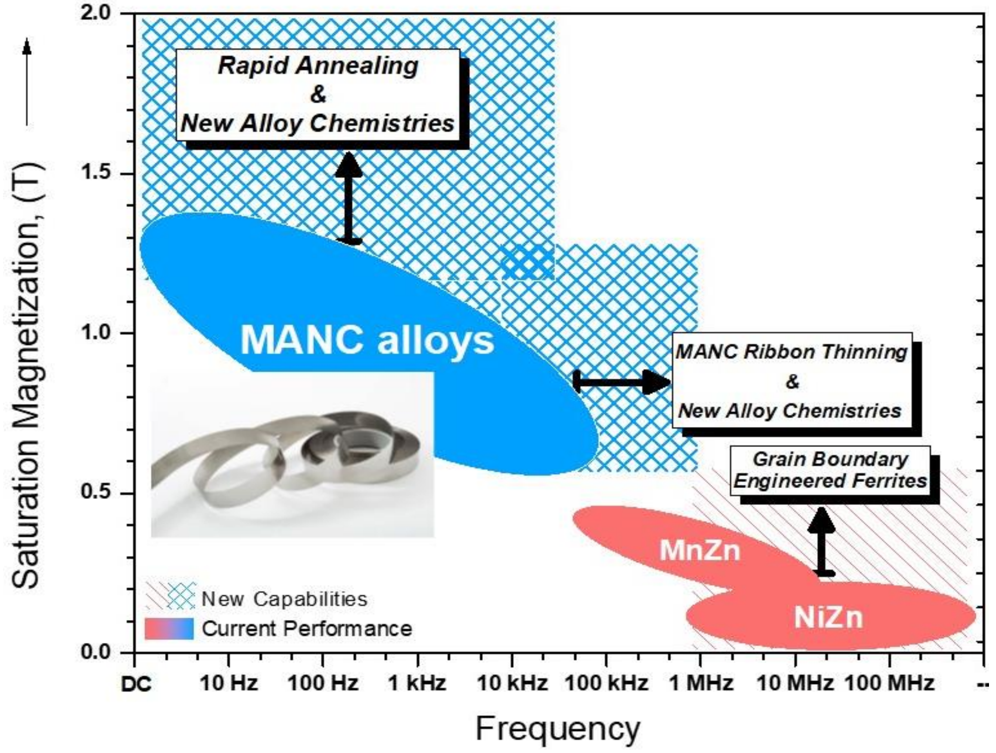
Significance and Impact

State of Art Soft Magnetic Materials

- Spinel Ferrites
- Bulk Crystalline Alloys
- Amorphous Alloys
- Nanocrystalline and Amorphous Nanocomposite Alloys







A. Talaat, M. V. Suraj, K. Byerly, A. Wang, Y. Wang, J. K. Lee, and P. R. Ohodnicki, *Review on Soft Magnetic Metal and Inorganic Oxide Nanocomposites for Power Applications*, J. Alloys Compd. **870**, 159500 (2021)

By **Tailoring Chemistry**, **Microstructure**, **Short Range Order**, and **Atomic Level Defects**, a Tradeoff Between Saturation Magnetization and Losses at High Switching Frequencies is Realized…

3. SMA Manufacturing through In-Line RF Processing

Approach:

Approach and Execution

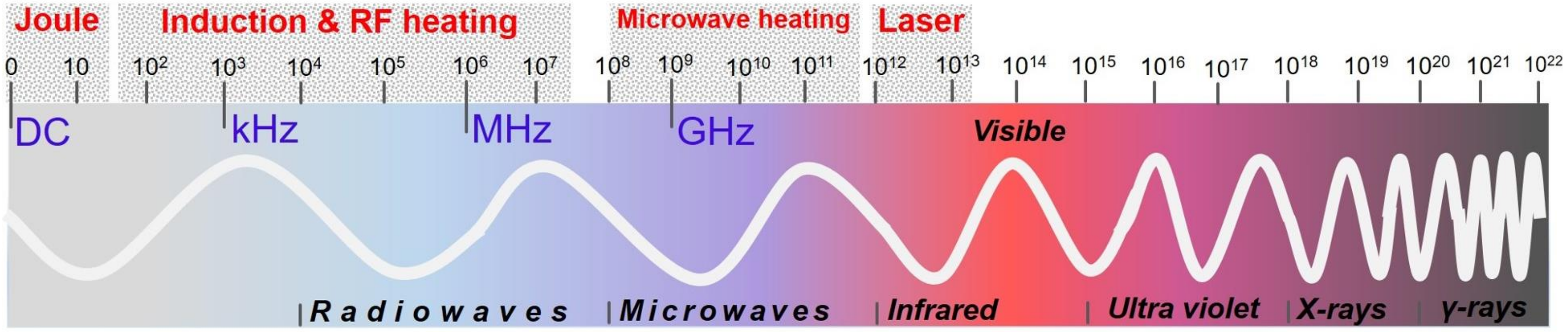
1) Utilize rapid thermal processing with alloy chemistries having reduced glass formers to increase saturation flux density.

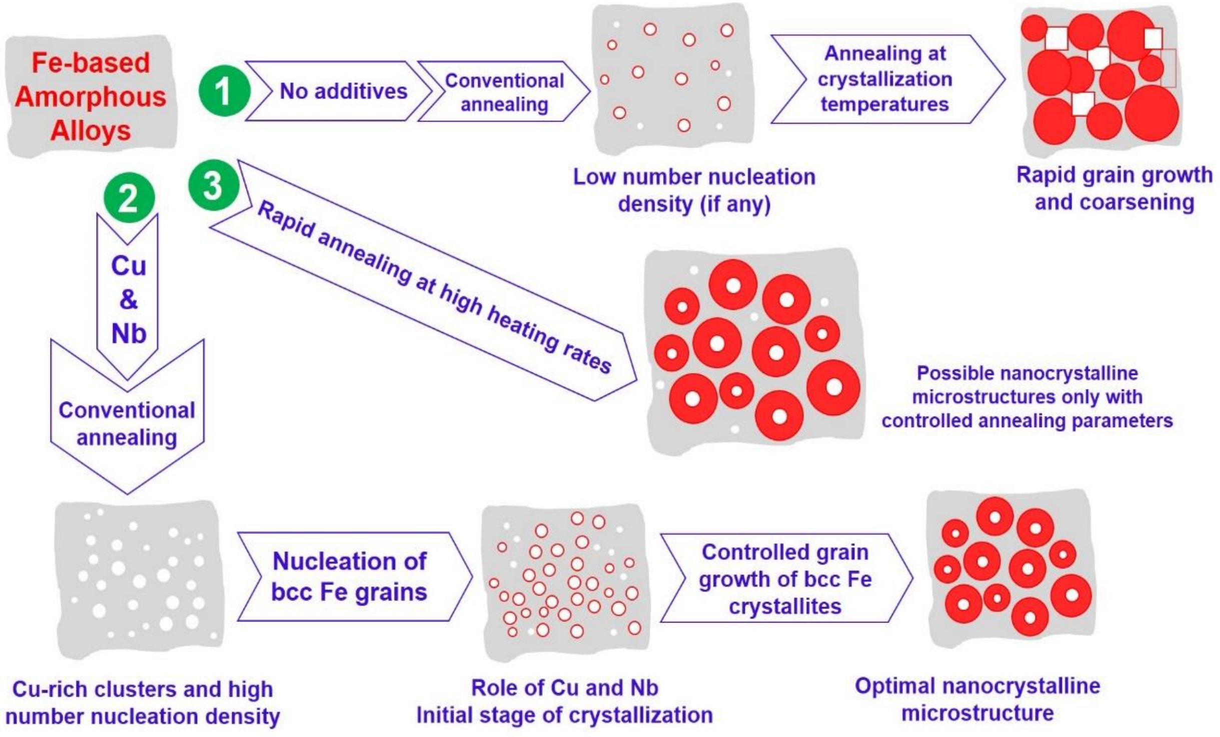
2) Leverage electromagnetic field processing methods, particularly RF induction coil-based processing techniques.

$$\delta \propto \sqrt{\frac{\rho}{f \mu_r}}$$

ρ is the electrical resistivity,
f is the frequency,
μ_r is the relative magnetic permeability

Degree to Which Electromagnetic Waves Penetrate is Dictated By the Frequency, Resistivity, and Permeability (Skin Depth)





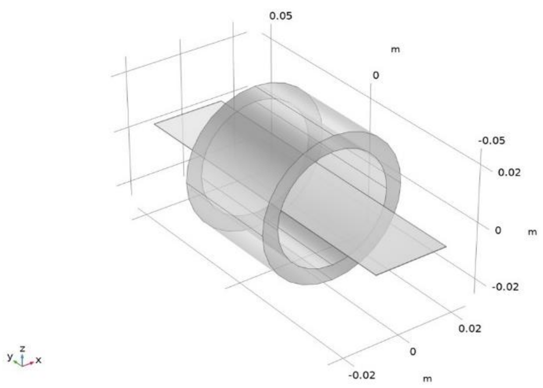
Alloy Chemistry and Thermal Processing Dictates Microstructure and Properties

A. Talaat, D. W. Greve, M. V. Suraj, P. R. Ohodnicki, Jr., “Electromagnetic assisted thermal processing of amorphous and nanocrystalline soft magnetic alloys: Fundamentals and advances”, Journal of Alloys and Compounds 854 (2021) 156480.

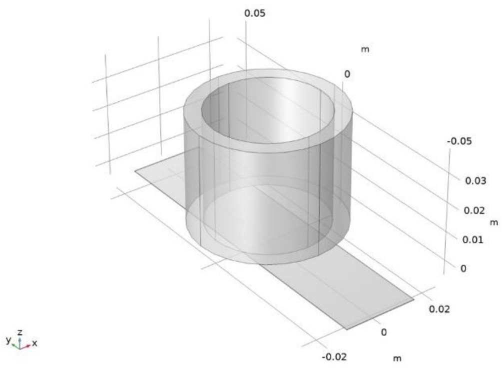
3. SMA Manufacturing through In-Line RF Processing

Technical Productivity and Quality

Induction Heating

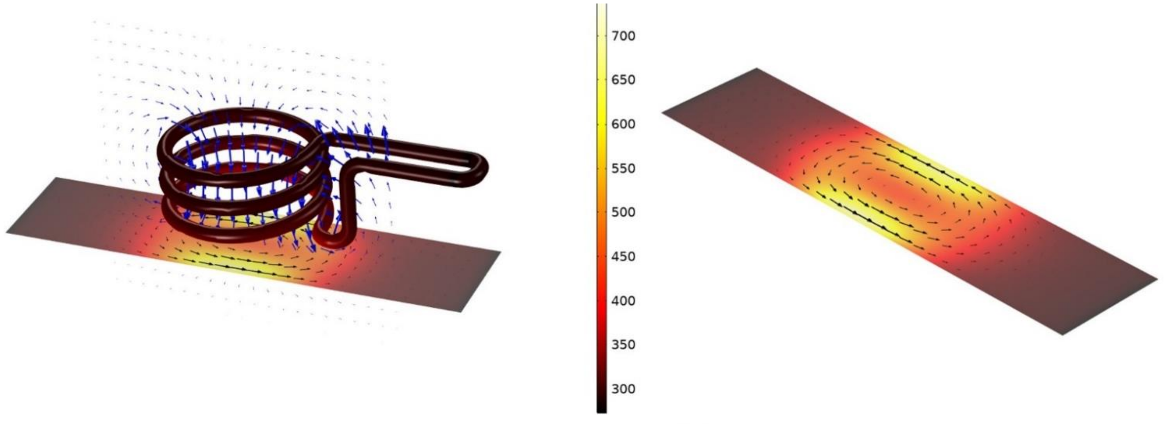


Longitudinal Flux Heating: ribbon is parallel to coil axis

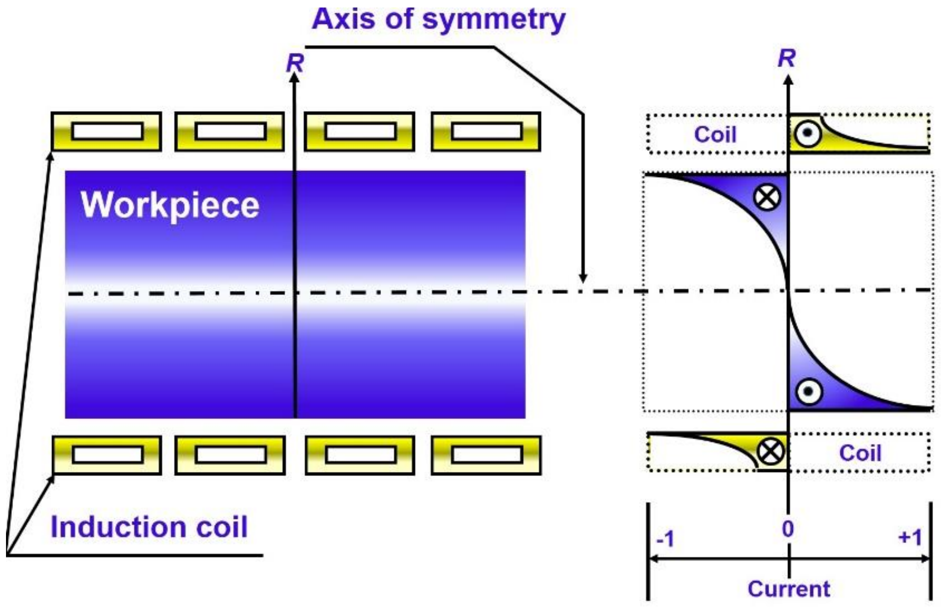


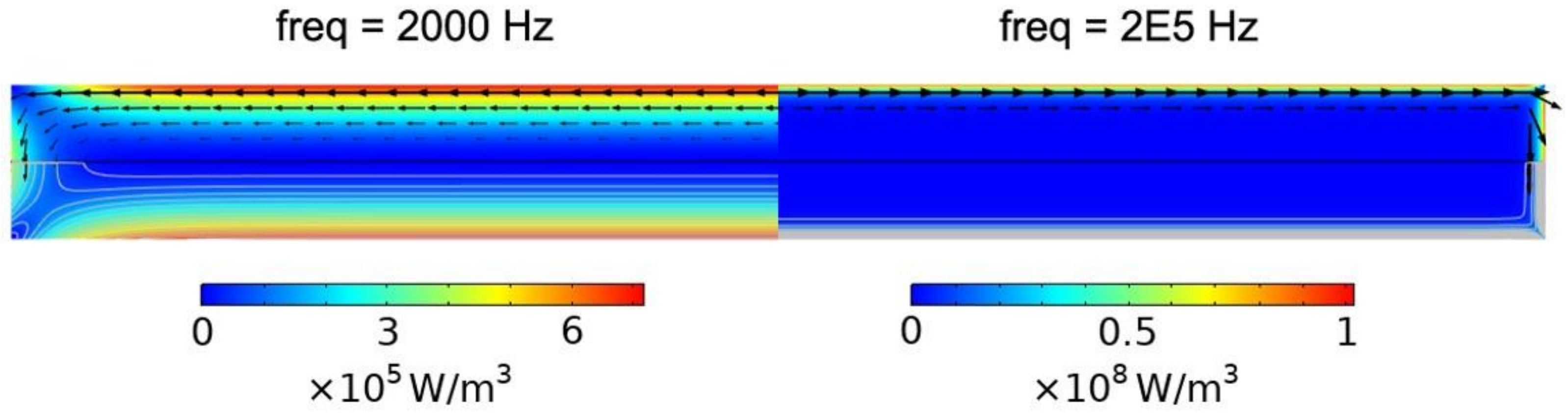
Transverse Flux Heating: ribbon is perpendicular to coil axis

Transverse Flux Heating: Finite Element Simulation Results



Longitudinal Flux Heating: Induced Eddy Current Distribution





Simulated longitudinal induction heating effect illustrating eddy currents distribution (black arrows) and heat power density (colored scale) in a magnetic slab; Permeability = 120, resistivity = 178 x 10^{-6} S/m, f= 2kHz, f = 200 kHz for assumed thickness of 1 mm

3. SMA Manufacturing through In-Line RF Processing

Relevance and Alignment: Results

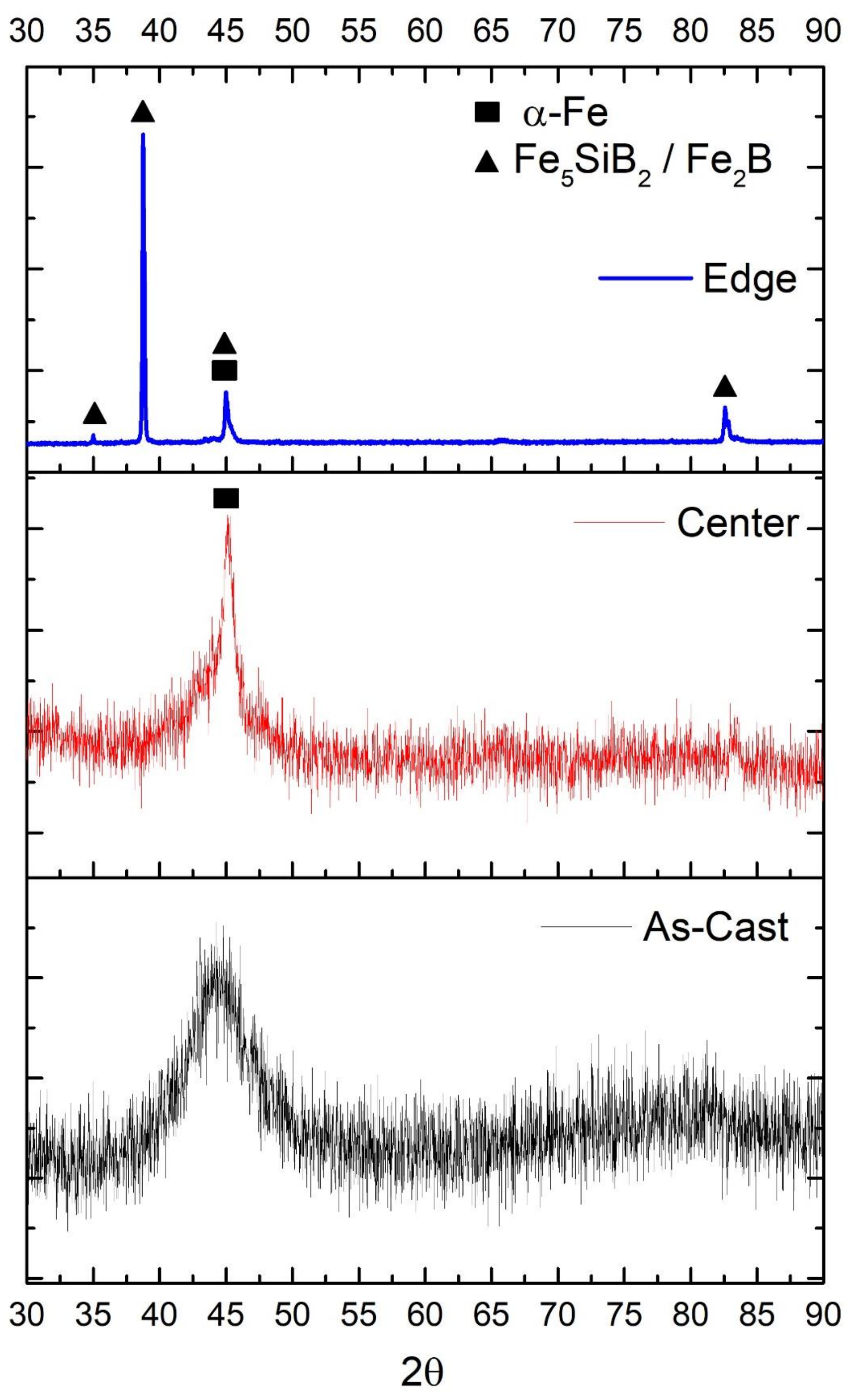
Fe-Based Nanocrystalline (i.e. Finemet) Alloys:

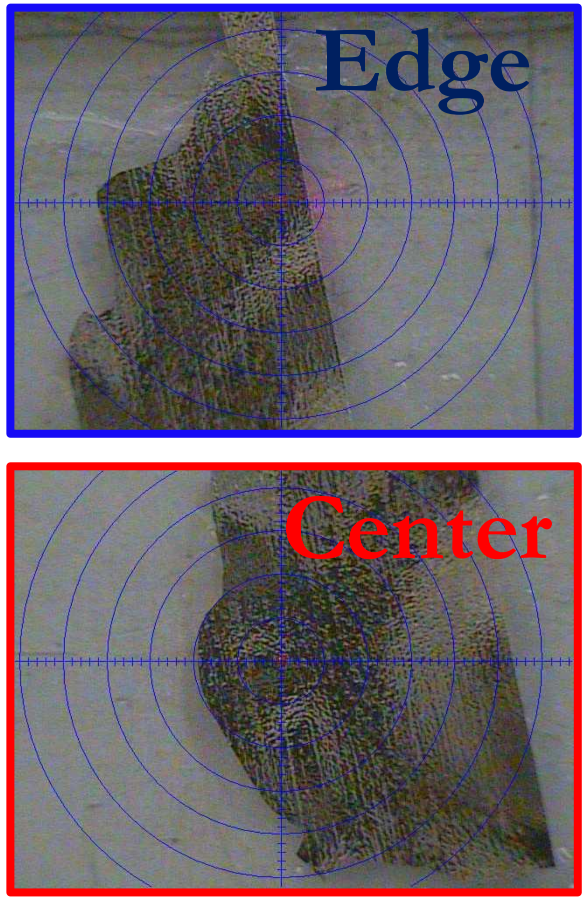
Edge:

Completely devitrified area with **34.2 nm bcc α—Fe** crystallites and boride phases near the edge

Center:

Nanocrystalline microstructure consisting of **15.6 nm bcc α—Fe** crystallites in the center of the ribbon

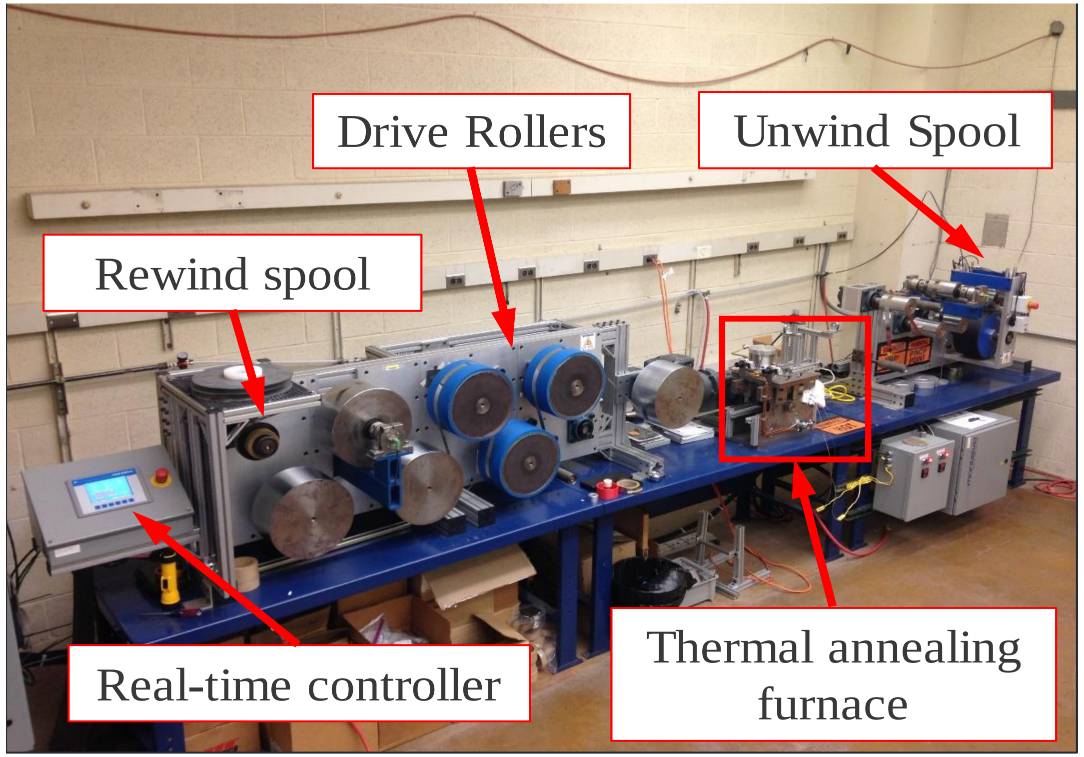




3. SMA Manufacturing through In-Line RF Processing

Summary and Future Work

- Electromagnetic heating can result in unique physical phenomena due to the detailed mechanism of electromagnetic energy absorption.
- Refined microstructures & novel magnetic properties can be achieved due to the enhanced phase transformation and nano-crystallization kinetics.
- Rapid heating rates are attainable, with additional capabilities for spatial and temporal control in processing techniques such as RF induction annealing.
- New alloy chemistries with suppressed non-magnetic additives allow for higher saturation induction than traditional alloy systems.
- In contrast with traditional "flash annealing", electromagnetic heating techniques are scalable, manufacturable, and compatible with in-line process.



Technical Team Bios

University of Pittsburgh

NC STATE UNIVERSITY

NATIONAL ENERGY TECHNOLOGY LABORATORY

Ahmed Talaat, Ph.D.
Research Assistant Professor, Materials Science
10+ years of experience in soft magnetic materials R&D

Richard B. Beddingfield, Ph.D.
Postdoc, Electrical Engineering
10+ years of experience in power electronics/ magnetics

Ms. Qianqian Jiao
Staff Scientist, NETL - Leidos
Power Electronics/Magnetics

Ward Burgess, Ph.D.
Staff Scientist, NETL - Leidos
10+ years of experience in materials synthesis and characterization

Paul Ohodnicki, Ph.D.
Associate Professor, Materials Science and Mech. Eng.
15+ years of experience in soft magnetic materials R&D

Subhashish Bhattarcharya, Ph.D.
Duke Energy Distinguished Professor
Founding Faculty Member of FREEDM Systems Center and Power America at NCSU

Jagan Devkota, Ph.D.
Staff Scientist, NETL - Leidos
10+ years of experience in applied electromagnetics R &D

AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

Consortium (Collaborator)

Acronyms

MV: Medium-Voltage
CLTS: Core Loss Test System
RF: Radio Frequency
WBG: Wide Band Gap
HF: High Frequency
ICS: Insulator Characterization Systems
LV: Low Voltage
SMC: Soft Magnetic Composite
NP: Nanoparticle
XRD: X-Ray Diffraction
SEM: Scanning Electron Microscope

NCSU: North Carolina State University
AMPED: Advanced Magnetics for Power & Energy Development

THANK YOU