Enabling Soft Magnetics for Power Conversion Applications

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Project Summary

- Background/problems being addressed:
  More efficient and flexible magnetic components are needed to keep pace with higher voltage/switching frequency devices for grid modernization, electrification, and shifts toward distributed generation resources.

- Overall objectives:
  Help develop loss- and size-optimized, high-frequency (kHz – MHz) compatible magnetic components through:
  - Application Relevant Characterization of Magnetic Cores and Insulation Materials
  - Development of Soft Magnetic Composites for High-Frequency Applications
  - Electromagnetic (EM) Field-Assisted Soft Magnetic Alloy Processing

The Numbers

- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- FUNDING OPPORTUNITY:
  N/A
- LOCATION:
  Pittsburgh, PA
- PROJECT TERM:
  07/01/2022 to 06/30/2024
- PROJECT STATUS:
  Ongoing
- AWARD AMOUNT (DOE CONTRIBUTION):
  $500,000
- AWARDEE CONTRIBUTION (COST SHARE):
  $0
- PARTNERS:
  University of Pittsburgh
  North Carolina State University

Disclaimer

Drivers for High-Frequency Magnetics: Higher Efficiency & Miniaturization

Background – Problem(s) Being Addressed

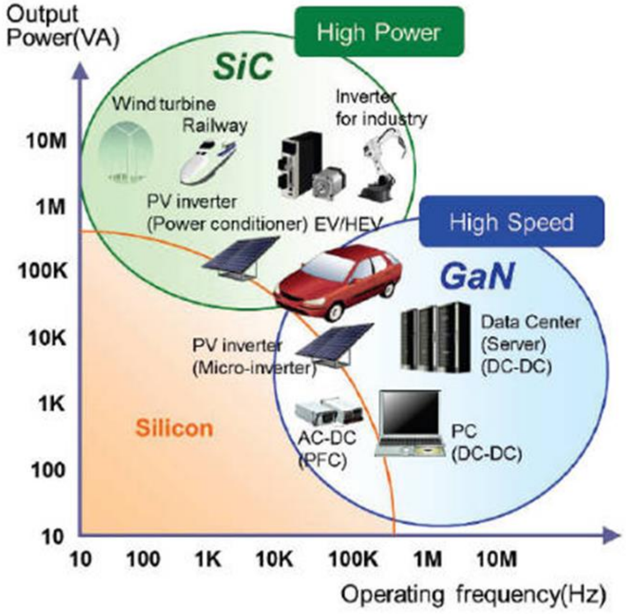
New Challenges

- Grid modernization, electrification, and shifts toward distributed generation resources

- Wide bandgap (SiC and GaN-based) and ultra-wide bandgap (AlN) devices with higher switching frequency, higher voltage, and higher temperature-capability

- Desire for higher efficiency and more flexible transformer technologies

- Miniaturization: Desire for smaller and lighter passives

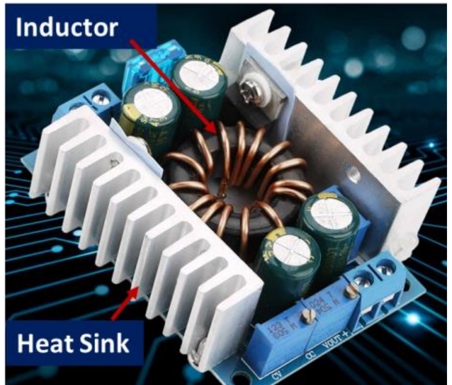


SiC for high power voltages (>1kV) with high current = niche market

GaN on Si for high frequency at midrange voltages (<1kV, up to 100A) = mass market

https://www.electronicsweekly.com

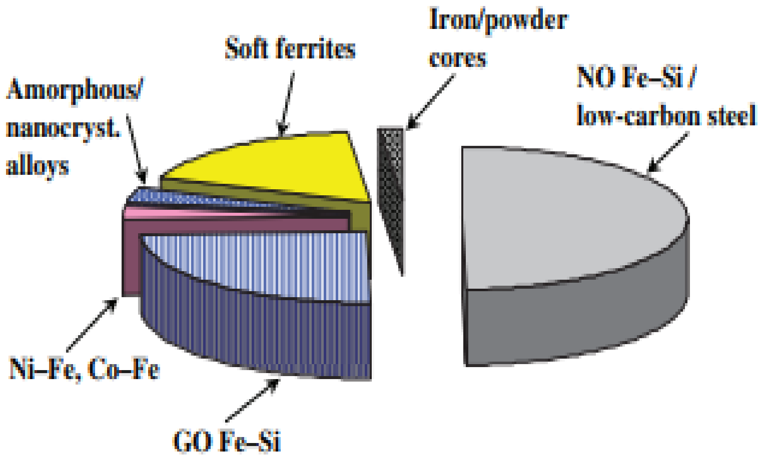
Borgaonkar (2015). DOI: 10.13140/RG.2.1.1491.1443



www.amazon.com

Current State-of-the-Art Magnetic Core Materials

Background – Problem(s) Being Addressed



Webster, et. al. "Soft Magnetic Materials," In Wiley Encyclopedia of Electrical and Electronics Engineering, J.G. Webster (Ed.). (2016)

	M_s(T)	Resistivity (μΩ-cm)	f_{upper} (Hz)	T_{upper} (C)	Mechanical Properties
Electrical Steels	1–2.5	~10	100	400–1000	Excellent
Soft Ferrites	0.2–0.4	>1000	1G	100–300	Brittle, Machinable
Amorphous Alloys (Fe-based)	0.5–1.6	~100–130	250k	150	Good
Commercial Metal Nanocrystalline (Fe-based)	1.3	~100–130	150k	150	Brittle

Desired Attributes of New Magnetic Components

- Minimize requirements for insulation materials
- Linearity at high DC bias fields
- Manufacturing scalability and cost
- Lower loss at higher switching frequencies
- Higher power ratings
- Improved thermal and mechanical performance

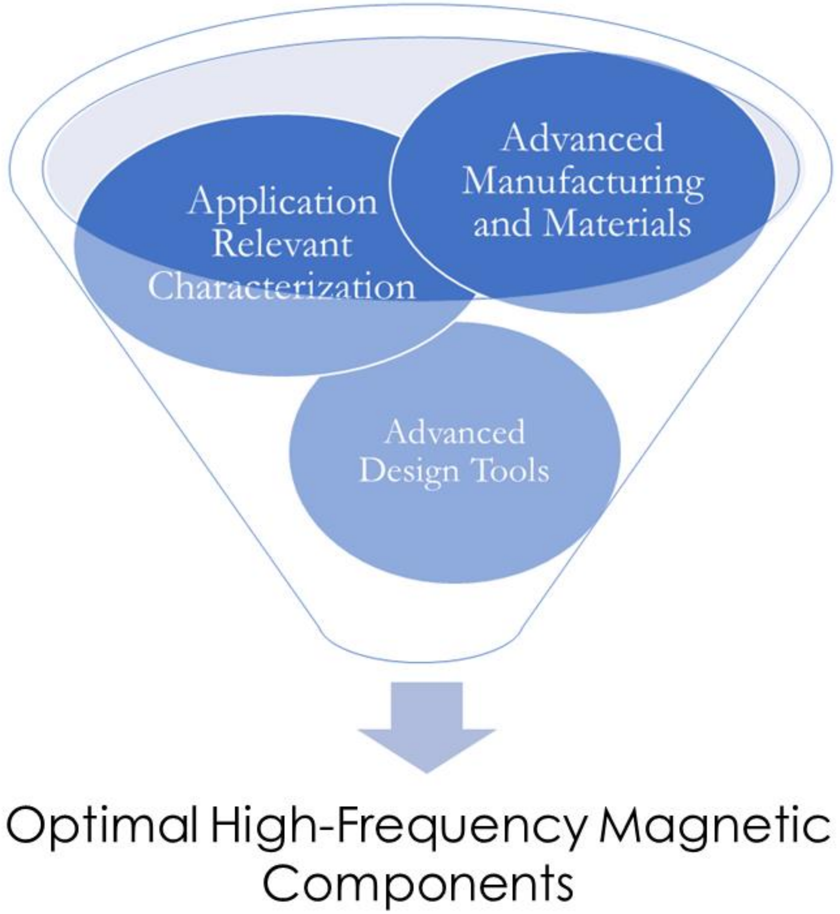
Technical Approach

Pathway for High Frequency Magnetic Components

- Application Relevant Characterization of Magnetic Cores and Insulation Materials
  - Capability development for application-relevant core and component characterization
  - Development of advanced data sheets

- Development of Soft Magnetic Composites for High-Frequency Applications
  - Investigation of metallic/oxide-based nanocomposite core materials
  - Scalable wet chemistry-based synthesis techniques

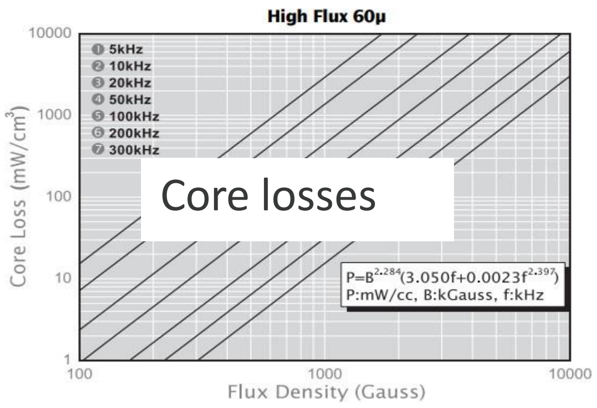
- Electromagnetic Field-Assisted Soft Magnetic Alloy Processing
  - Soft magnetic alloy manufacturing through laser processing

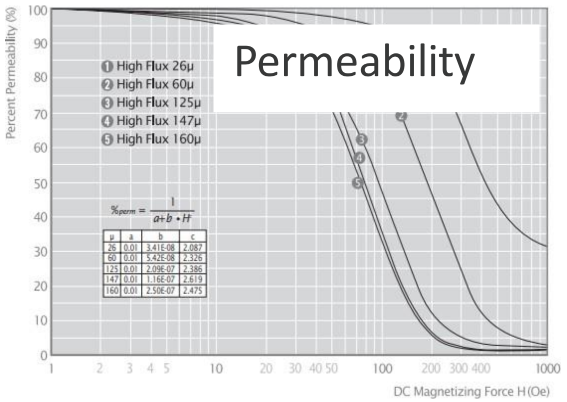


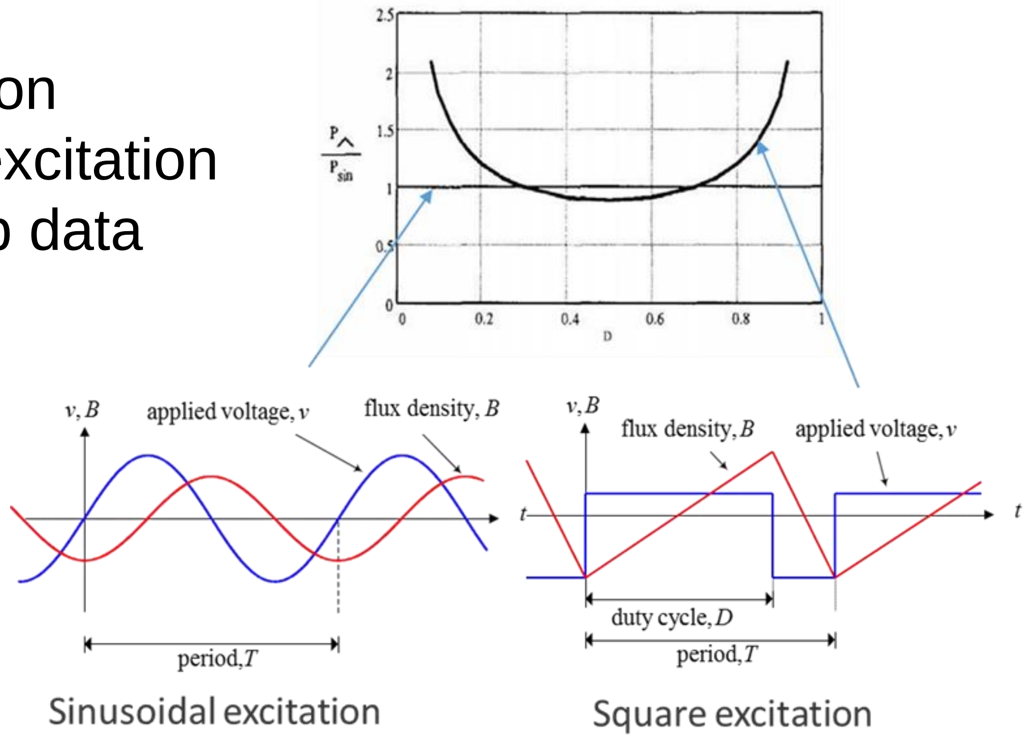
Technical Approach: Application Relevant Characterization

Background – Problem(s) Being Addressed

- Information from manufacturers' data sheets are:
  - Typically based on sinusoidal excitation that are less relevant
  - Difficult to extract and/or lacking detailed information
- Test magnetic cores and components under relevant excitation conditions at relevant scales and voltages and develop data sheets







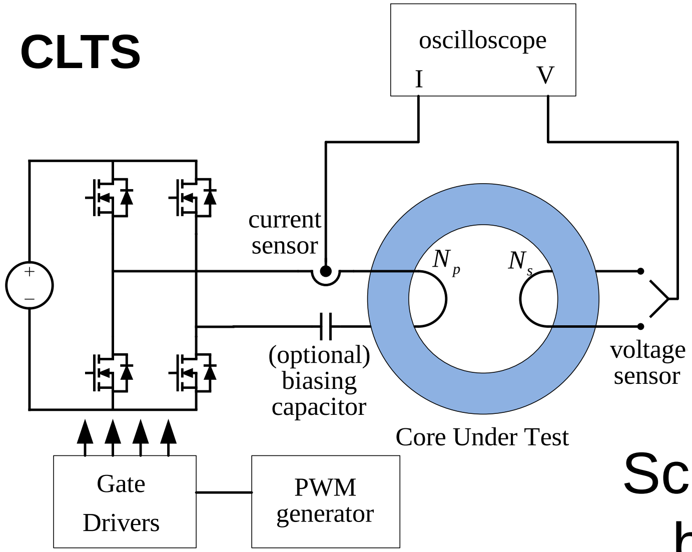
Manufacturer's Data Sheet
(http://www.mhw-intl.com/assets/CSC/CSC_Catalog.pdf)

Technical Approach: Application Relevant Characterization

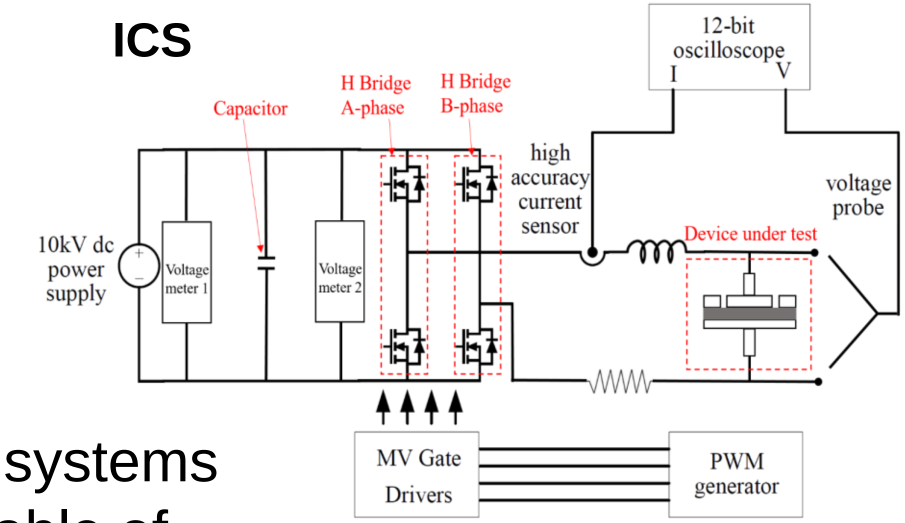
Innovation – Explanation of the Approach

- Establish the core loss testing systems (CLTS) and insulation characterization systems (ICS) for characterization of magnetic cores, insulation materials, and components under relevant excitation conditions at relevant scales and voltages
- Test magnetic cores, insulation materials, and components, and develop data sheets to supplement manufacturers' data sheets

CLTS



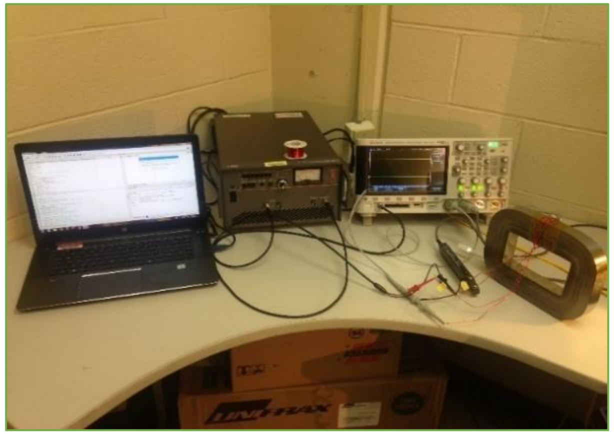
ICS



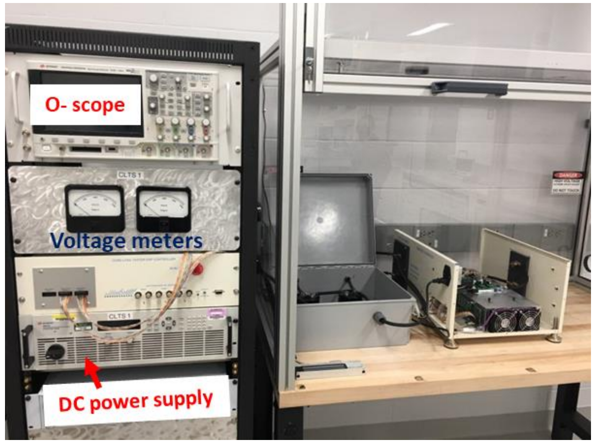
Schematics of 3kV+ testing systems built at NETL that are capable of exciting square waves

Technical Approach: Application Relevant Characterization

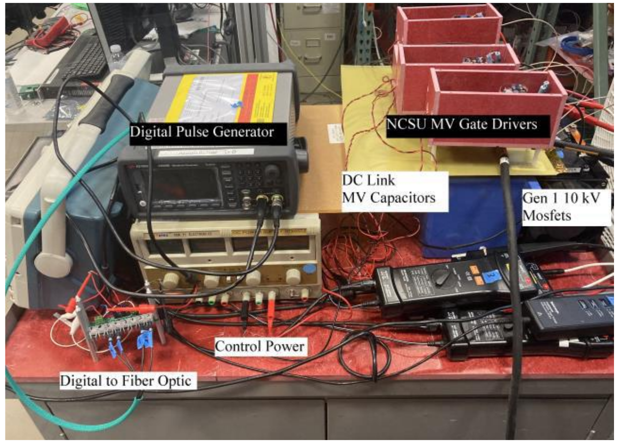
Execution & Productivity



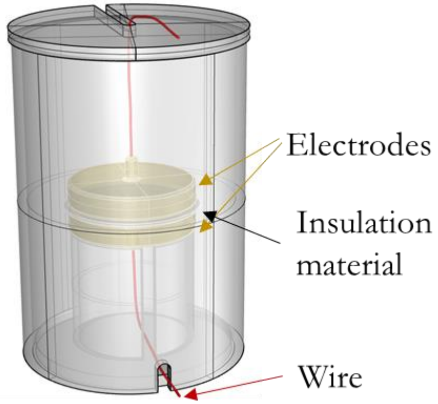
Extra Low Voltage
(ELV; <75V) CLTS



Low Voltage
(LV; 1.2kV) CLTS



Medium Voltage
(MV; 3 kV+) CLTS



Insulation Materials Test
Fixture

Multiple test systems have been built under the support of the TRAC Program and are being expanded for additional waveform excitations

Technical Approach: Application Relevant Characterization

Relevance – Data Sheets

- Data sheets of five core materials have been published previously to the public on NETL's website
- Data sheets of an additional core material, a transformer, and an insulation material are being published on NETL's website
- More data sheets on different materials are being generated
- Test systems are available to the community

MV Transformer

Date: September 25

Revision 0.1

Nano-Crystalline Core

Nanocrystalline materials are emerging soft magnetic materials that possess grain sizes on the order of a billionth of a meter and possess extremely useful magnetic properties. These materials fill the gap between amorphous materials (without any long-range order) and conventional (coarse-grained) materials. Nanocrystalline alloys are materials on the basis of Fe (iron), Si (silicon), and B (boron), with additions of Nb (niobium) and Cu (copper). Typically, they are produced through a rapid solidification process as a thin, ductile ribbon. Initially the ribbon is in the amorphous state, then crystallized in a subsequent heat treatment to promote nano-crystallization (~10-20 nanometers). Once nano-crystallized, they exhibit low core loss and magnetostriction, while maintaining high saturation induction and permeability. A variety of forms can be manufactured, including toroidal, rectangular, racetrack and block cores.

Fig. 1: Core under test (Nano-crystalline core)

Date: Feb 2023

Revision 0.1

Insulation Paper

Nomex 410

datasheet

Grid Asset Performance > Insulation Materials

NOMEX 410 is a family of insulation paper offering high inherent dielectric strength, mechanical toughness, flexibility and resilience. NOMEX 410 is the original form of NOMEX paper. Because it's unique combination of excellent electrical, thermal, and mechanical properties, Nomex 410 has been widely used by the electrical industry for use in Motors, Generators, and transformers.

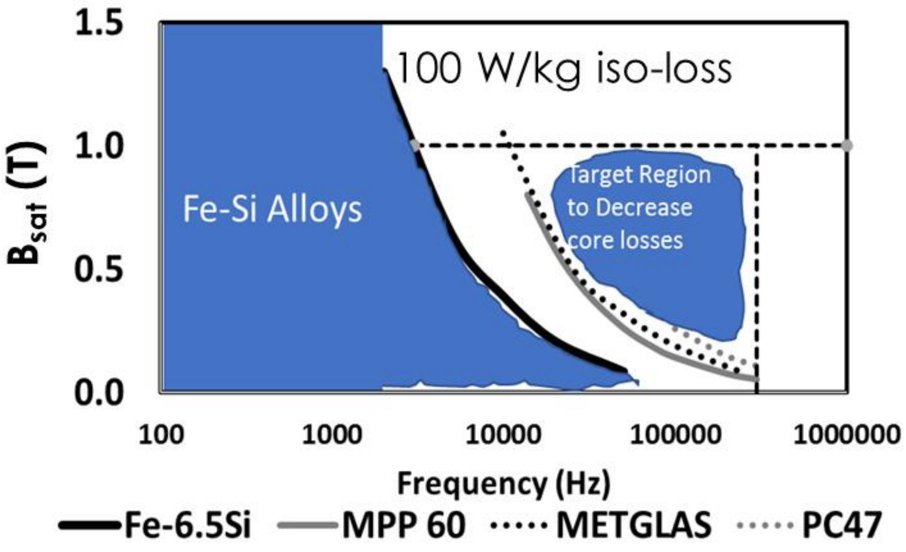
Fig. 1: Nomex 410 under test

Date: April 2022

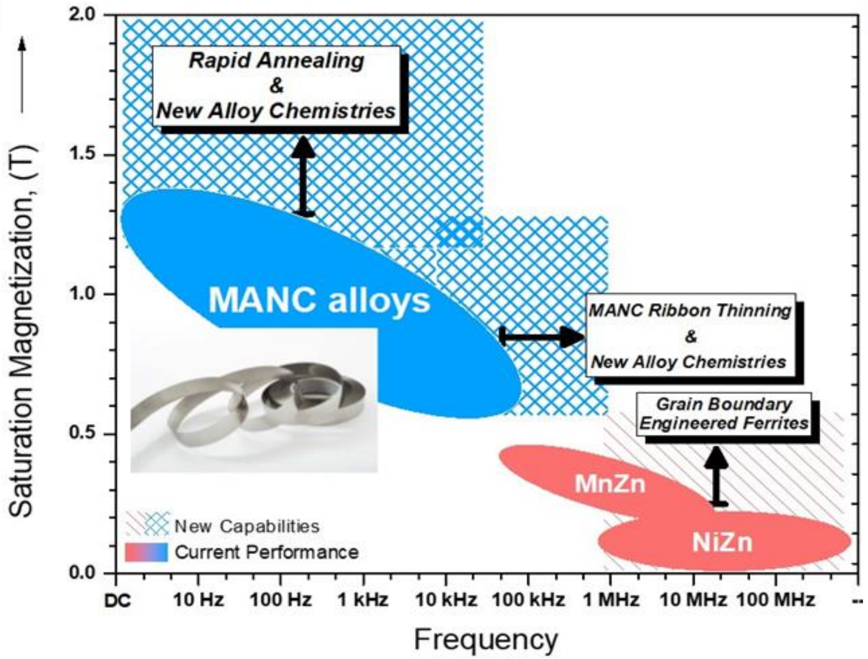
Revision 0.1

Technical Approach: Advanced Soft Magnetic Composites

Background – Problem(s) Being Addressed



Losses of popular soft magnetic materials
(MPP60 – molypermalloy and PC47 - MnZn ferrite)



Talaat, Suraj, Byerly, Wang, Wang, Lee, Ohodnicki,
J. Alloys Compd. **870**, 159500 (2021)

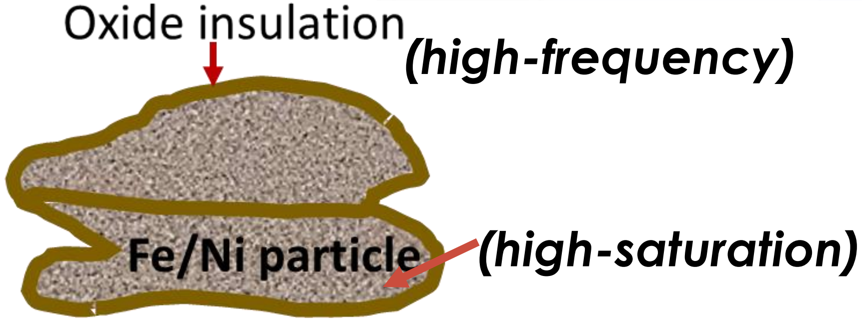
- State-of-the-art materials are not suitable for high-frequency and high-power applications
- Existing synthesis techniques lack the scalability for production of emerging materials with controlled microstructures

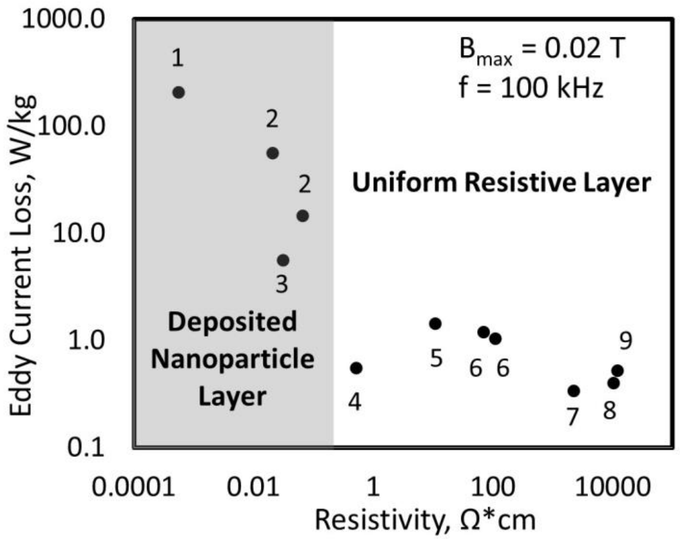
Technical Approach: Advanced Soft Magnetic Composites

Innovation – Explanation of the Approach

- New class of materials consisting metallic and oxide phases are emerging candidates:
  - Metallic Phase: Retain high saturation induction for high power applications
  - Insulating Oxide Phase: Improve high-frequency performance

- 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 for expensive ball-milling process

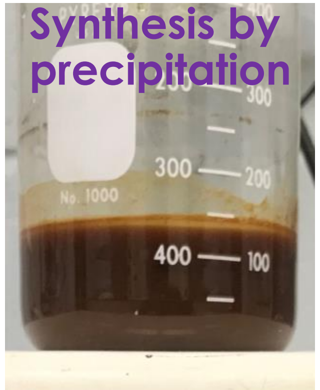


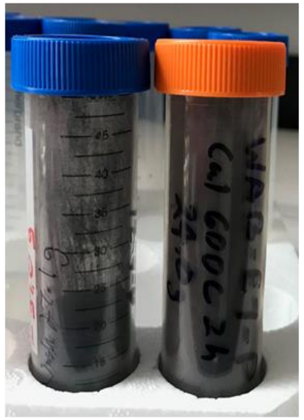


1, 4, 7: Choi et al., 2019
2: Lee et al., 2017
3: Wu et al., 2012
5: Lee et al., 2017
6, 8: Huang et al., 2015
9: Verma et al., 2006

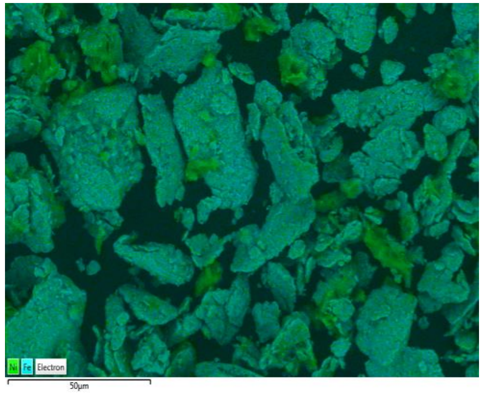
Technical Approach: Advanced Soft Magnetic Composites

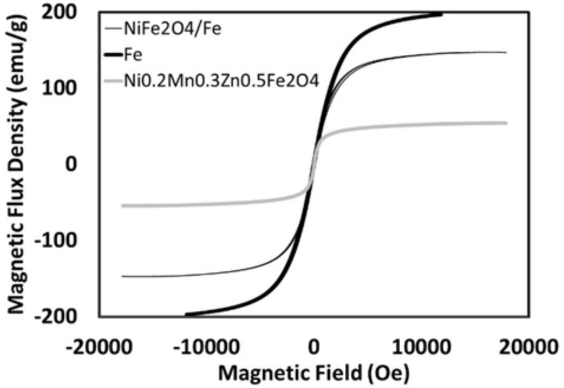
Execution & Productivity

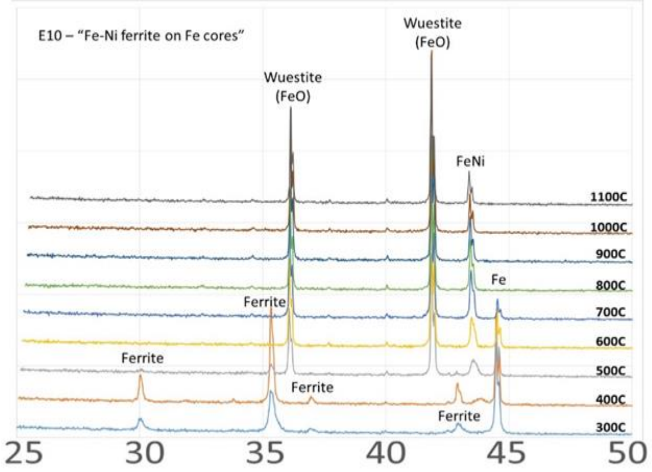


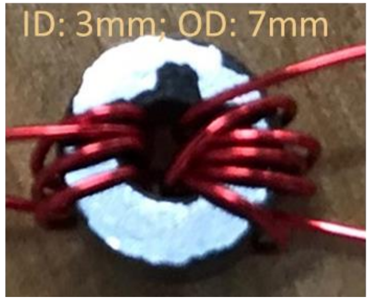


Synthesis at scale

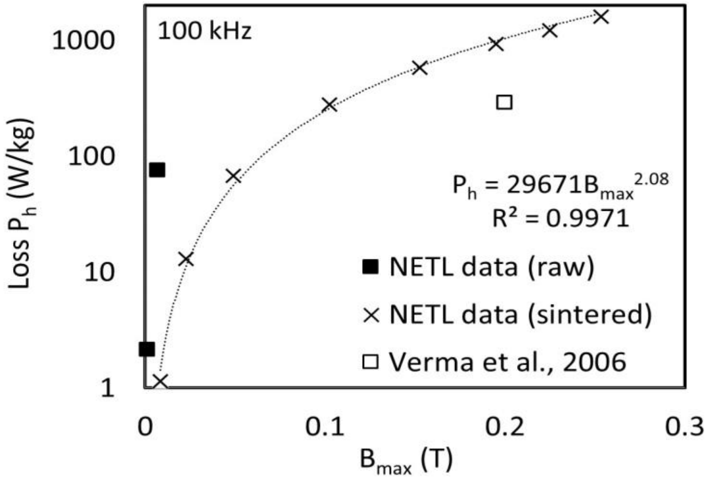








Characterization and compaction



<u>Optimization</u>

Materials composition
Synthesis procedure
Core fabrication
Post processing such as heat treatment

Loss evaluation and optimization

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Technical Approach: Advanced Soft Magnetic Composites

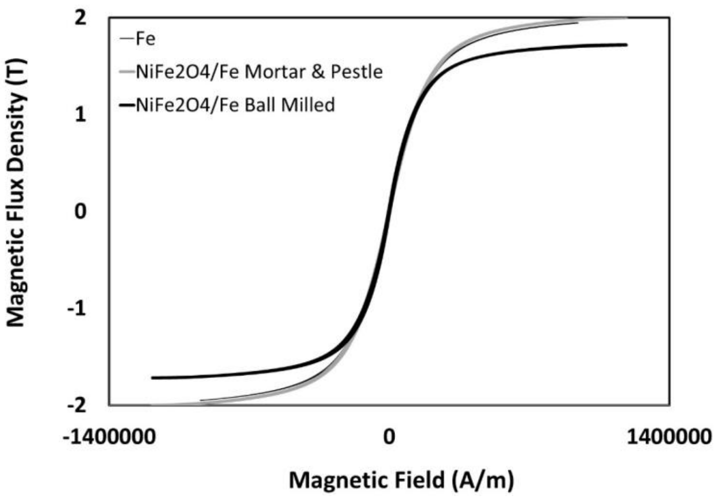
Relevance – Results

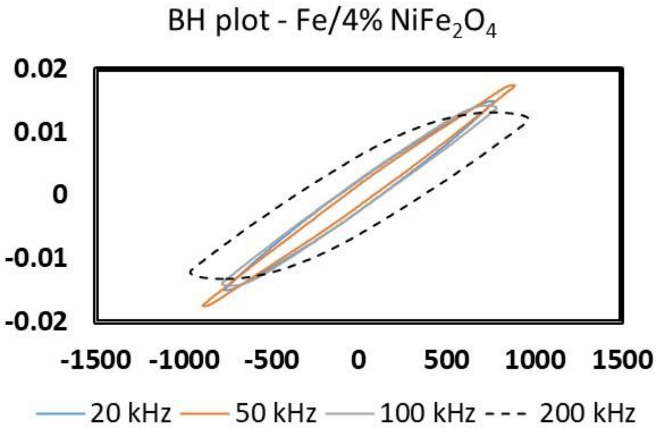
- Produced Fe/$NiFeO_4$ soft magnetic materials at scale by a wet chemistry-based method and characterized for structural and magnetic properties

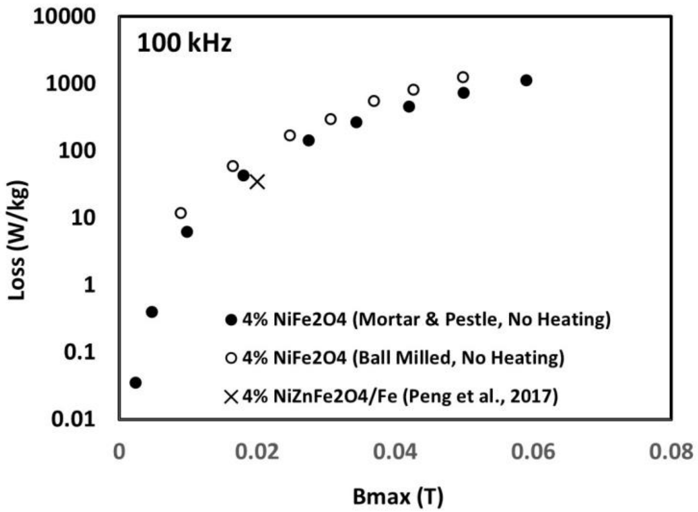
- Compacted the synthesized powder into a core and characterized for loss properties

- Results are equivalent to published data

- Optimization in the compositional and microstructural properties and processing methods are underway







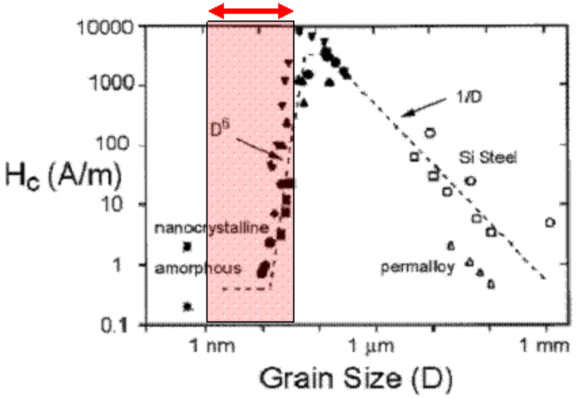
Technical Approach: EM Field-Assisted Soft Magnetic Alloy Processing

Background – Problem(s) Being Addressed

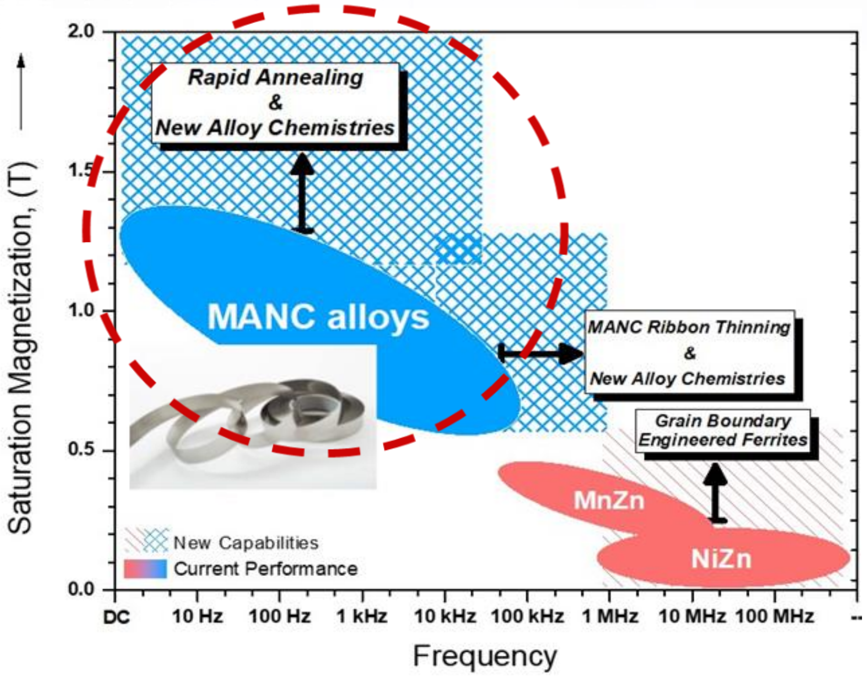
- Existing materials are lossy at high frequencies; an improvement is required
- A trade-off between saturation magnetization and losses at high switching frequencies is realized by tailoring chemistry, microstructure, short-range order, and atomic level defects

State-of-the-Art Soft Magnetic Materials

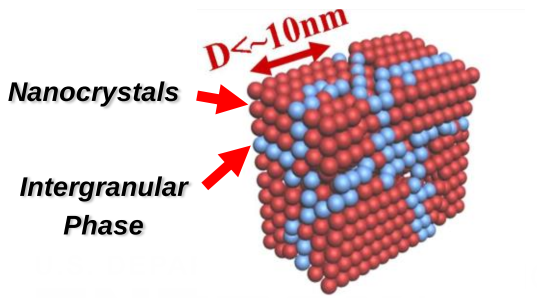
- **Nanocrystalline and Amorphous Nanocomposite Alloys**
- Spinel Ferrites
- Bulk Crystalline Alloys
- Amorphous Alloys



EM Field-Assisted Processing of Nanocrystalline Alloys



Talaat, Suraj, Byerly, Wang, Wang, Lee, Ohodnicki, J. Alloys Compd. **870**, 159500 (2021)

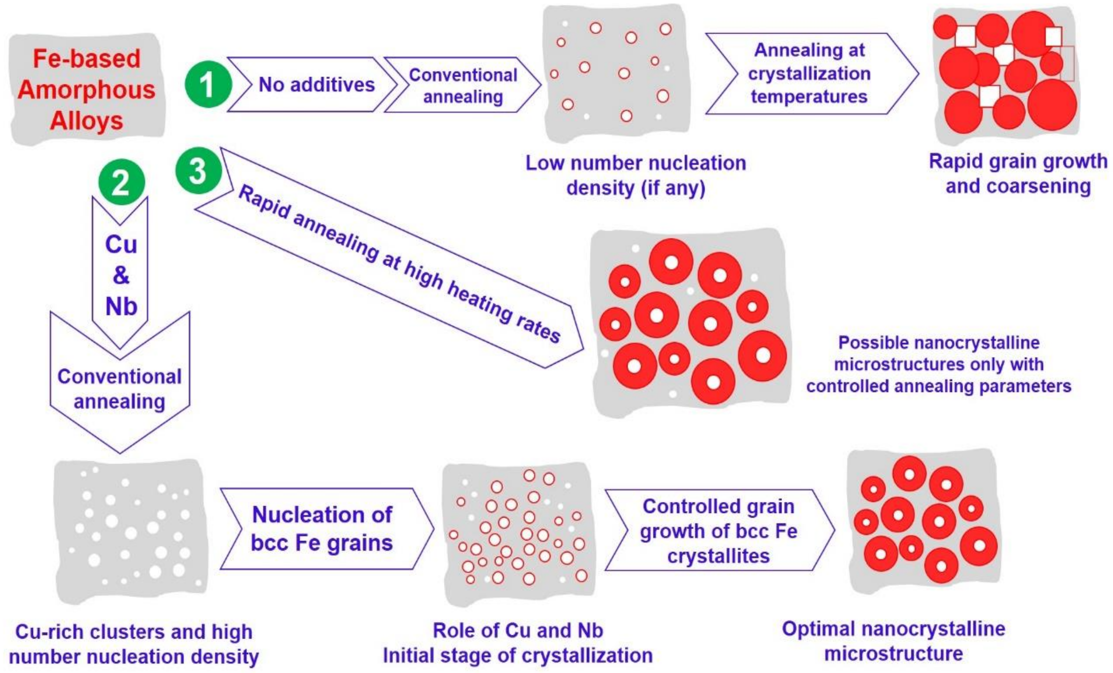


Technical Approach: EM Field-Assisted Soft Magnetic Alloy Processing

Innovation – Explanation of the Approach

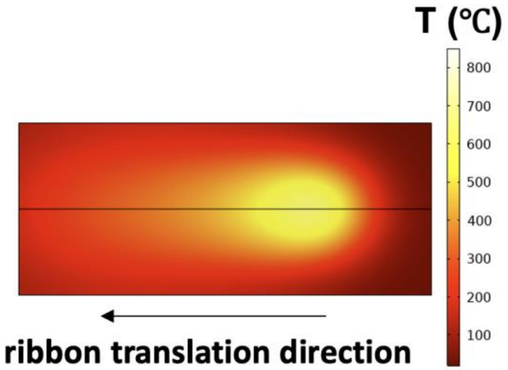
- Rapid thermal processing can refine grain size and improve soft magnetic properties
- Conventional techniques have limited scalability

- Proposed electromagnetic processing techniques enable unprecedented control (temporally and spatially)



Talaat, et al., J. Alloys and Compounds 854 (2021): 156480

Induction Heating



Laser Processing

(Finite Element Modeling)

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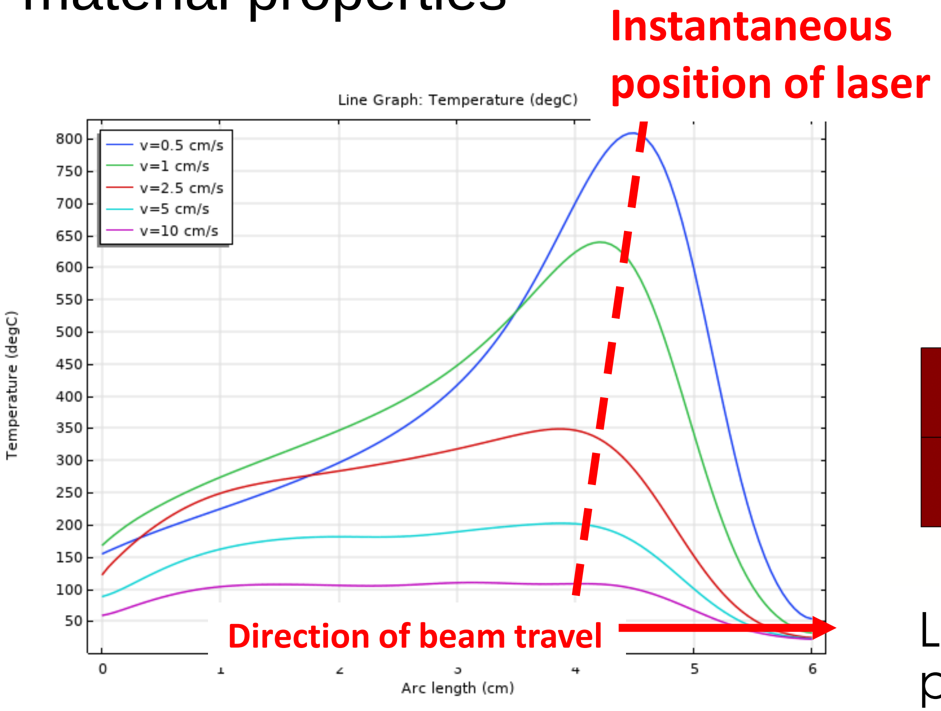
Technical Approach: EM Field-Assisted Soft Magnetic Alloy Processing

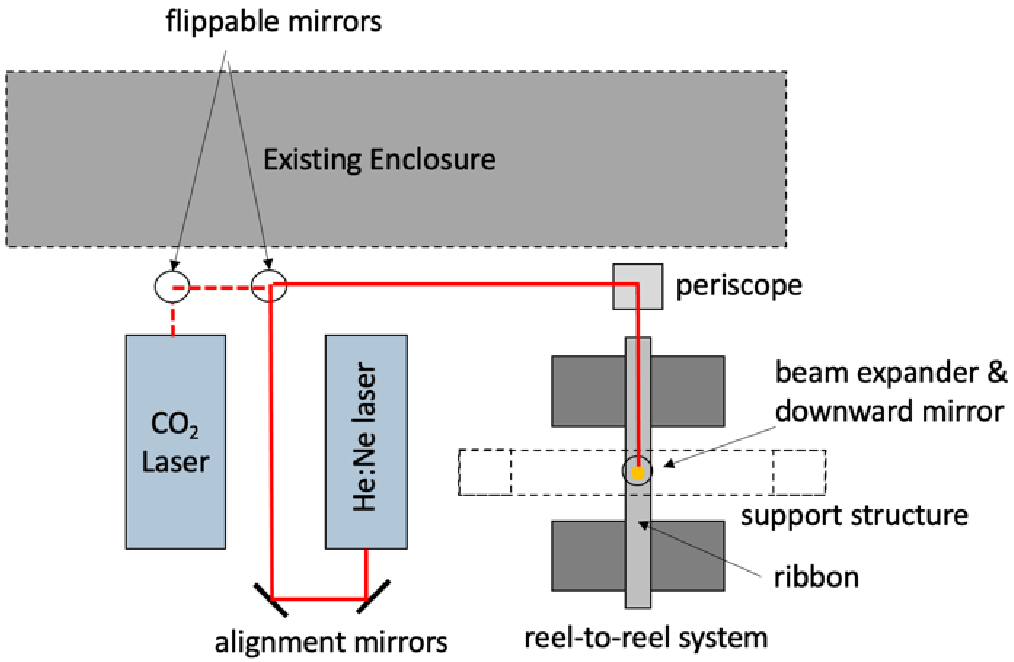
Execution & Productivity

Finite Element Model (in COMSOL) of laser processing capable of representing variation of laser power, laser travel velocity (shown left), and material properties



Laser processing

Proposed experiment design for laser processing of soft magnetic alloys



Accomplishments

- ✓ Developed an initial data sheet for a representative nanocrystalline magnetic core using the custom test system capable of exciting square waveforms and operating up to 1.2kV
- ✓ Characterized several custom-fabricated low-permeability powder cores under sinusoidal wave excitations up to 50V
- ✓ Synthesized a SMC consisting of 4% $NiFe_2O_4$/Fe using a wet chemistry-based scalable procedure and characterized for structural and magnetic properties
- ✓ Fabricated a core of wet chemistry-synthesized $NiFe_2O_4$/Fe SMC, measured the core loss properties, and compared with the available literature data
- ✓ Developed a model of laser processing capable of representing variation of laser power, laser travel velocity, and material properties
- ✓ Designed the experiment for laser processing of identified metallic alloys and began resourcing the components

Timeline

Milestone Update

Milestone	Planned Completion Date	Status
Test commercial or custom cores under square wave excitations using LV/MV CLTS and develop data sheet for review and feedback by DOE.	03/31/2023	**Completed**
Test custom printed and pressed powder cores using extra LV core loss testing system and analyze the power loss mechanism.	03/31/2023	**Completed**
Test commercially sourced insulation materials under square wave excitations using an existing LV/MV ICS and develop initial data sheet for review and feedback by DOE.	09/30/2023	On Schedule
Prepare and characterize soft magnetic composite-based magnetic cores using LV core loss testing system and analyze the power loss mechanism.	12/30/2023	On Schedule
Expand the existing LV or MV test systems for at least excitation of sinusoidal waves.	03/31/2024	On Schedule
Successful synthesis of at least one soft magnetic composite consisting of metallic and oxide phases (e.g., metallic alloy nanoparticles and magnetic oxide layers) and characterization for structural and magnetic properties.	12/31/2022	**Completed**
Preparation and characterization of a core based upon a new material and comparison with commercial core.	03/31/2023	**Completed**
Production of a scaled batch (>100 gram) of a soft magnetic composite and characterization for structural and magnetic properties.	09/30/2023	On Schedule
Post processing of a magnetic core (e.g., sintering) and core-loss characterization.	03/31/2024	On Schedule
Electromagnetic simulations of laser processing techniques for amorphous and nanocrystalline core materials.	03/31/2023	**Completed**
Perform a systematic set of laser annealing treatments for commercial Fe-based, Co-based, and FeNi-based alloys.	09/30/2023	On Schedule
Compare characteristics of laser processed ribbons with a ribbon processed by conventional annealing.	03/31/2024	On Schedule

Timeline

Risks and Mitigation Strategy

Risk	Risk Level	Mitigation Strategy
Difficulties in characterizing insulation materials beyond > 100V and developing reliable data sheet	Medium	Use available literature and manufacturers' data sheet as reference. Measure dielectric constants using standard methods under small signal analysis to create a baseline before testing at high voltages. Perform multiple tests using different setups and compare the data.
Characterization of low permeability powder cores under square wave excitation using the test system capable up to 1.2kV	Low	Review available literature and manufacturers' data sheet/procedure on similar materials. Use previously gained knowledge and practice during the testing of amorphous/nanocrystalline cores and develop the test procedure for low permeability cores.
Magnetic properties of new materials can be difficult to benchmark with existing materials	High	Well established capabilities in magnetic property measurements will be leveraged to compare and benchmark performance of new materials. Various compaction and post processing techniques will be explored.
Difficulties in controlling annealing conditions under the laser processing technique	Medium	Explore advanced thermometry to monitor temperature in real-time such as IR imaging methods and color changing paints. Focus initial efforts on well-known commercial alloys to understand impacts of advanced annealing methods at beginning.

Impact/Commercialization

- **Data sheets**
  - Data sheets of a MV transformer (up to 2.5kV), an insulation material (up to 100V), and a nanocrystalline core (up to 1.2 kV) are being published

- **Journal papers**
  - One research paper on induction processing is being developed, two published on induction and flash annealing techniques
  - One review article on wet chemistry-based synthesis of SMC is being developed

- **Conference papers/presentations**
  - Presentations at TMS Annual 2023, MMM/Intermag 2022, ANPA Conference 2022

- **Patent(s):**
  - IP on laser processing of amorphous and nanocrystalline alloys has been submitted
  - IP on wet-chemistry synthesis of soft magnetics is being considered

Future Work

- Expanding the capability of existing core loss testing systems for sinusoidal wave excitation
- Data sheet of insulation materials under application relevant conditions
- Benchmarking the magnetic properties of a metal/oxide soft magnetic composite with the existing materials
- Demonstrated capability for scalable processing using electromagnetic processing techniques for amorphous and nanocrystalline alloys
- Magnetic properties of a nanocrystalline material annealed using electromagnetic techniques and conventional techniques

Future Work

Milestone	Planned Completion Date
Test commercially sourced insulation materials under square wave excitations using an existing LV/MV ICS and develop initial data sheet for review and feedback by DOE.	09/30/2023
Prepare and characterize soft magnetic composite-based magnetic cores using LV core loss testing system and analyze the power loss mechanism.	12/30/2023
Expand the existing LV or MV test systems for at least excitation of sinusoidal waves.	03/31/2024
Production of a scaled batch (>100 gram) of a soft magnetic composite and characterization for structural and magnetic properties.	09/30/2023
Post processing of a magnetic core (e.g., sintering) and core-loss characterization.	03/31/2024
Perform a systematic set of laser annealing treatments for commercial Fe-based, Co-based, and FeNi-based alloys.	09/30/2023
Compare characteristics of laser processed ribbons with a ribbon processed by conventional annealing.	03/31/2024

Technical Team

NETL/NETL Support Contractor

- Jagannath Devkota
- Ward Burgess
- Richard Pingree

Previous Members

- Richard Beddingfield
- Qianqian Jiao

University of Pittsburgh

- Paul Ohodnicki
- Tyler Paplham

North Carolina State University

- Subhashish Bhattacharya
- Mark Nations
- Isaac Wong
- Shubham Dhiman

THANK YOU

This project is supported by the U.S. Department of Energy (DOE) Office of Electricity’s Transformer Resilience and Advanced Components (TRAC) program. It is led by Andre Pereira, TRAC Program Manager.

Acronyms

DC: Direct current

M_s: Saturation magnetization

f_{upper}: Upper limit of frequency

T_{upper}: Upper limit of temperature

GO: Grain-oriented

NO: Non-oriented

IR: Infra-red

NETL: National Energy Technology Laboratory

DOE: Department of Energy

TMS: The Minerals, Metals & Materials Society

MMM: Magnetism and Magnetic Materials

ANPA: Association of Nepali Physicists in America