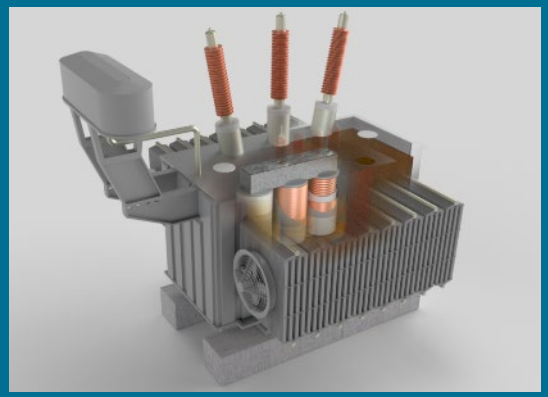
Multiphysics Optimization of Iron Nitride Based Transformers

DOE OE TRAC Peer Review, September 2026







PRESENTED BY

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Purdue University: Scott Sudhoff, Tino Mwarunzika

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Project Overview

Project Description:

Multiphysics Optimization of Iron Nitride Based Transformers will use multi-objective optimization to design, build, and demonstrate the world's first soft magnetic iron nitride line frequency transformer. Iron nitride transformers will address supply chain issues associated with electrical steel, increase transformer performance (decreased losses & reduced volume), and reduce transformer cost by 2X.

Period of Performance:

10/1/2025 – 9/30/2027 (2 Years)

Technology Area: Transformer Materials

Alignment: Grow

Prime:

Sandia National Laboratories

Funding Profile & Cost Share:

Federal Funding $750k

Purdue Cost Share $83.3k

Total $83.3k

Sandia: $400k

Purdue: $350k

Cal Nano (Spark Plasma Sintering or SPS vendor): $25k

Problem Statement

Key challenges for resilient US transformer assets

- Aging infrastructure
- Supply chain dependencies
- Transformer size, weight, and efficiency
- Transformer resiliency

Iron nitride (Fe_4N) has emerged as a promising material for use in transformers, primarily due to its superior magnetic properties and domestically abundant elements.

Spark Plasma Sintering (SPS) and abundant, low cost raw materials (iron & nitrogen) ensures domestic fabrication and robust supply chain.

Demonstration of Fe_4N in a transformer prototype is the next step towards adoption on the U.S. grid

Increasing the technology readiness level (TRL) of SPSed iron nitride will provide solutions for other critical soft magnetic applications.

Element	Mass fraction (ppm)
Hydrogen	739,000
Helium	240,000
Oxygen	10,400
Carbon	4,600
Neon	1,340
Iron	1,090
Nitrogen	960
Silicon	650
Magnesium	580
Sulfur	440

From Croswell, Ken (February 1996). Alchemy of the Heavens. Anchor. ISBN 0-385-47214-5.

Technical Approach / Innovations
Project Objectives

A soft magnetic material (**iron nitride**) that offers an alternative to GOES with improved magnetic properties and an equivalent or reduced cost.

A Fe_4N magnetic core that can be manufactured at scale for the same cost or less than a Si steel core of an equivalent power rating.

A path toward **50% reduction in core energy losses** for line frequency transformers compared to Si steel (at equivalent or greater flux densities).

Multiphysics multi-objective optimization will be used to design the world's first soft magnetic iron nitride line frequency transformer which will then be built and demonstrated.

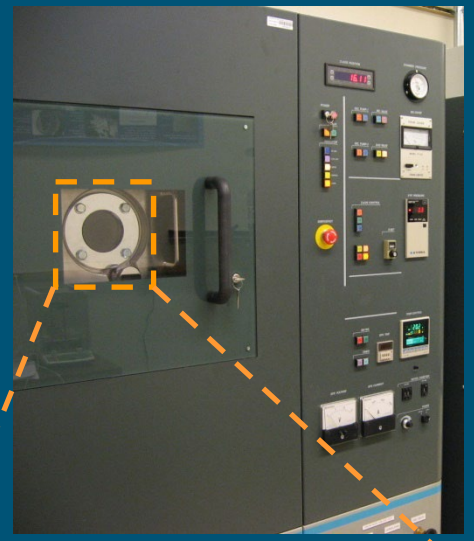
A path to replace GOES in transformers of almost all sizes and other devices such as motors and generators.

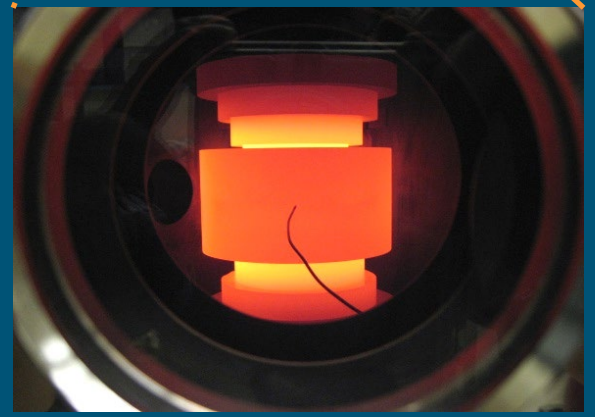
Magnetic Material	J_s (T)	$\rho(\mu\Omega\cdot m)$	Net-shapeable	Cost
Amorphous alloys	1.6	1.4	No	High
Si steel	1.9	0.5	No	Low
γ'-Fe_4N	1.9	1.6 - 200	Yes	Low

Long term, Fe_4N properties will result in a reduction in eddy current losses, transformer size, and transformer cost

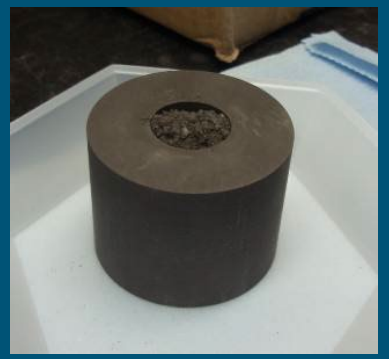
Materials development & characterization @ Sandia Labs
Spark Plasma Sintering (SPS)

Fuji SPS-825S Dr. Sinter®





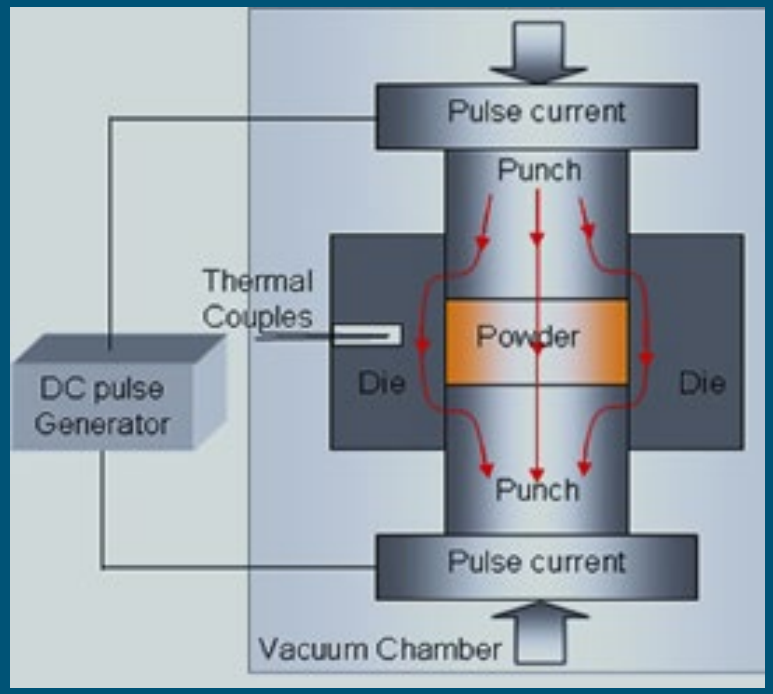
SPS Chamber



Starting Powder in Die

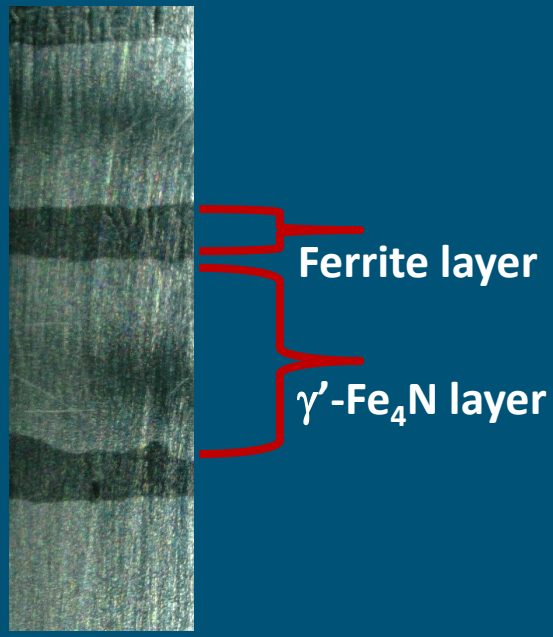


End Product



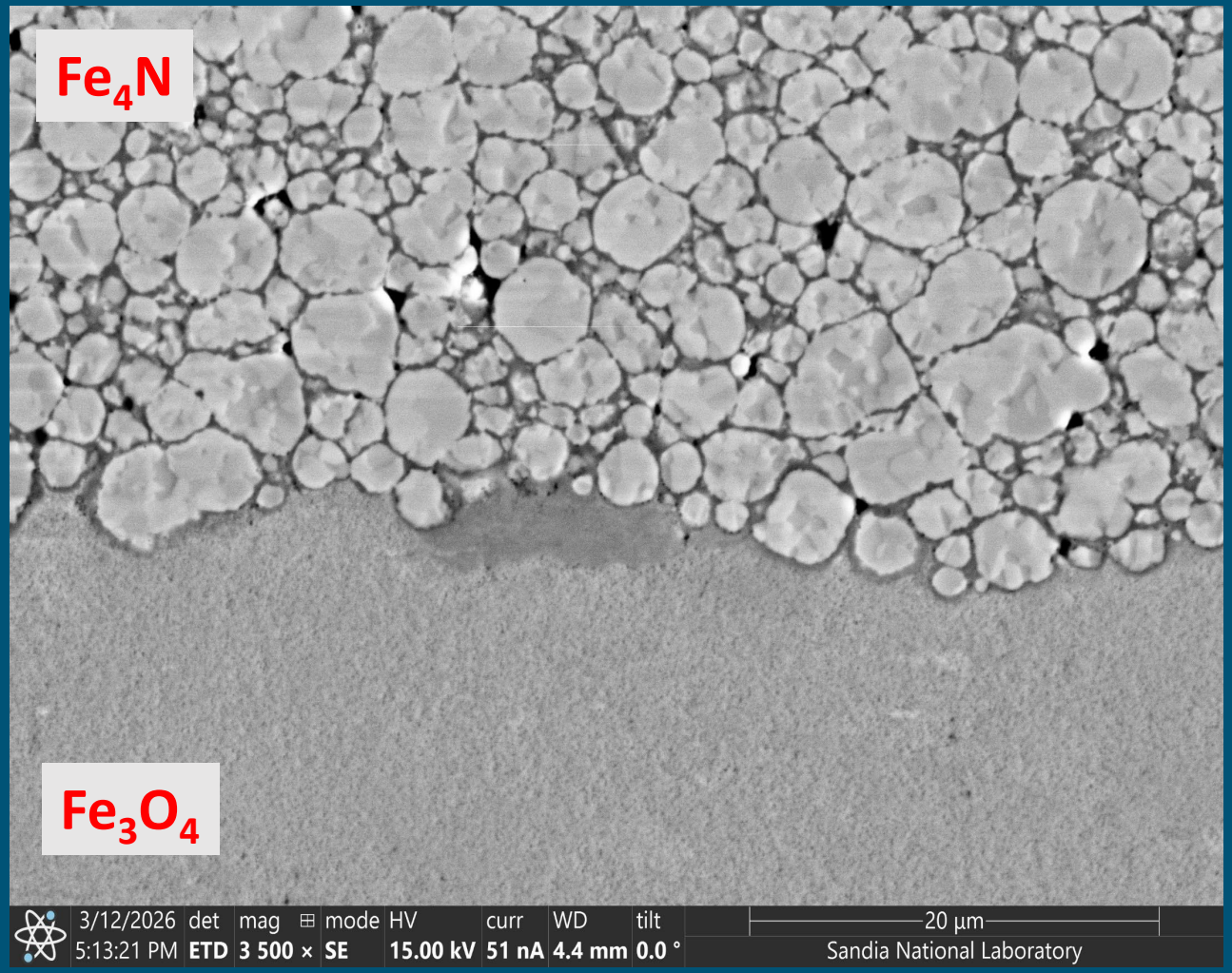
Materials development & characterization @ Sandia Labs
Spark Plasma Sintering (SPS)



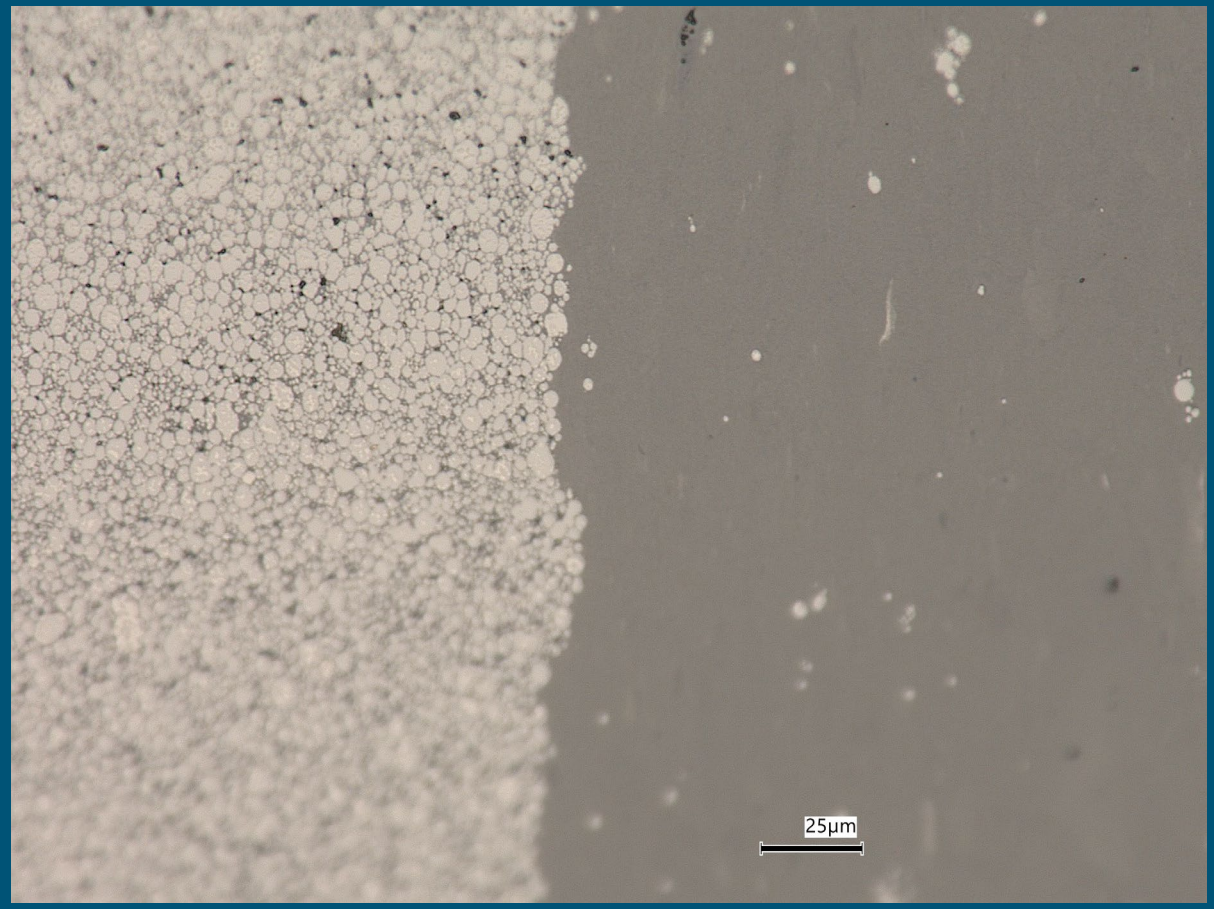


- Fe_4N toroid manufactured for magnetic characterization
  - Toroid uses ferrite (Fe_3O_4) lamination analogs to decrease eddy current losses
  - Multiple toroids shipped to Purdue for characterization
- We are also investigating the implementation of laminations with a thin epoxy or kapton insulating layer rather than ferrite.

Materials development & characterization @ Sandia Labs
Microscopy of laminated (layered) iron nitride



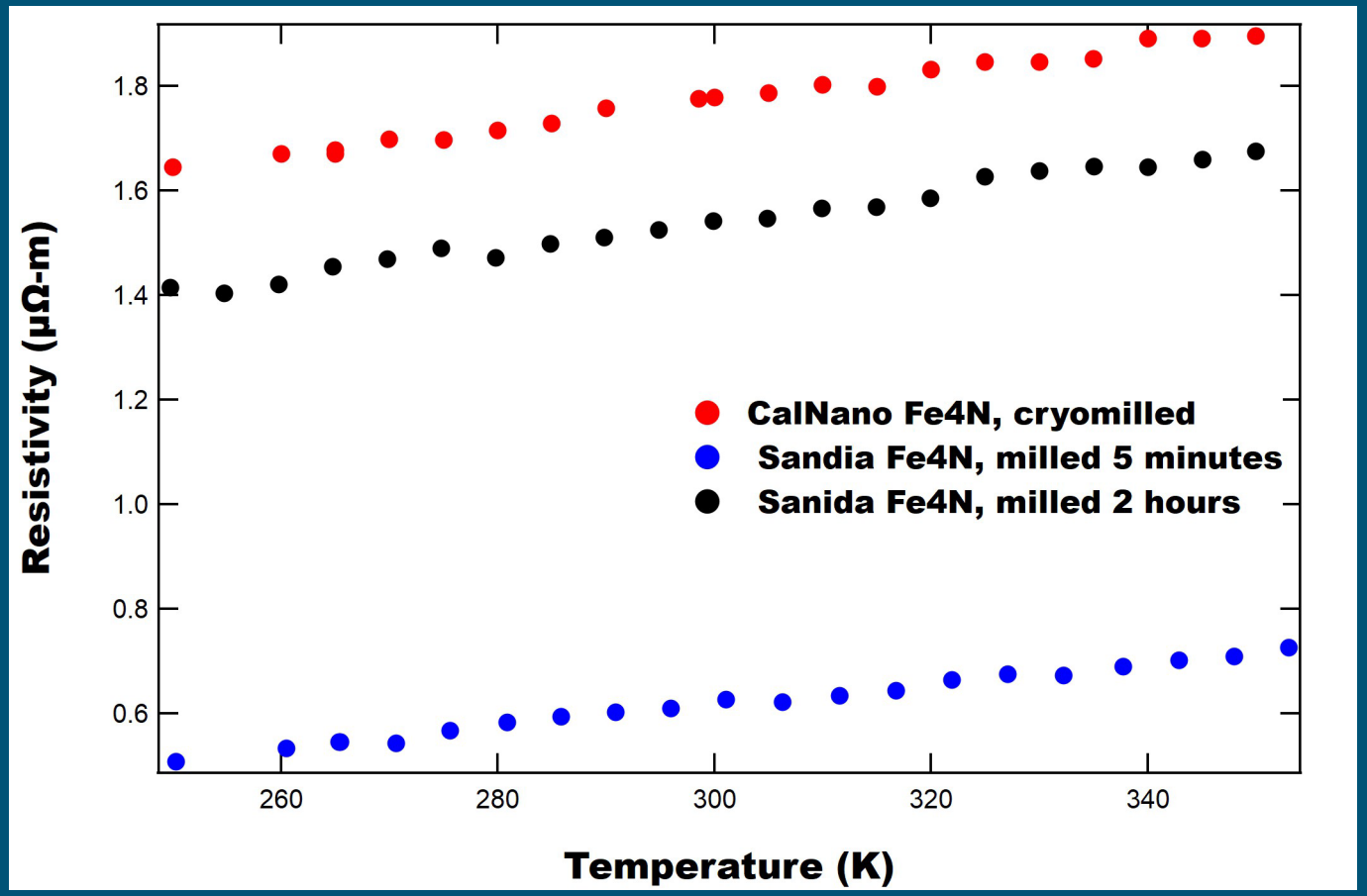
Scanning Electron Micrograph (SEM)



Optical

Materials development & characterization @ Sandia Labs
Electrical resistivity measurements in PPMS

- Values are roughly consistent with literature predictions.
- Since resistivities are ± 1.6 μΩ·m this will mean decreased eddy current losses in comparison with Si steel.
- Linear increase in resistivity with temperature will also prove advantageous as transformer will spend most of the time significantly above room temp.
- It appears possible to increase ρ through milling & decreasing grain size.



*Also measured thermal conductivity of the same samples to provide input for multiphysics optimization and transformer design.

Materials development & characterization @ Sandia Labs
Shaping and machining practices

- A combination of near net shaping via spark plasma sintering (SPS) and wire electrical discharge machining (EDM) will allow us to fabricate and shape magnetic core parts for transformer fabrication.
- Fabrication of near net shaped parts and wire EDM have been performed both at Sandia and by our proposed corporate manufacturing partner, California Nanotechnologies (Cal Nano).

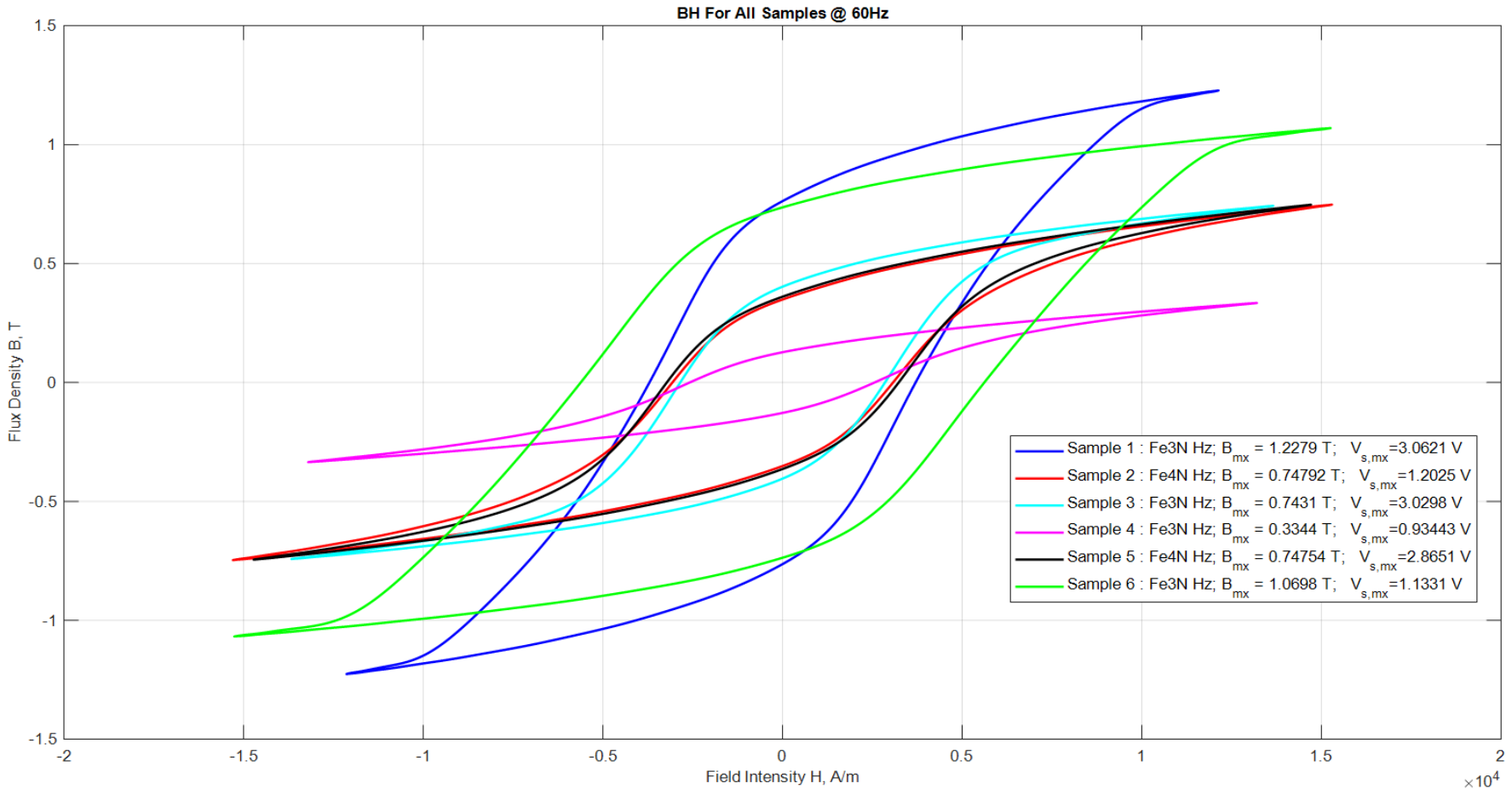


Transformer design @ Purdue University
Toroid characterization

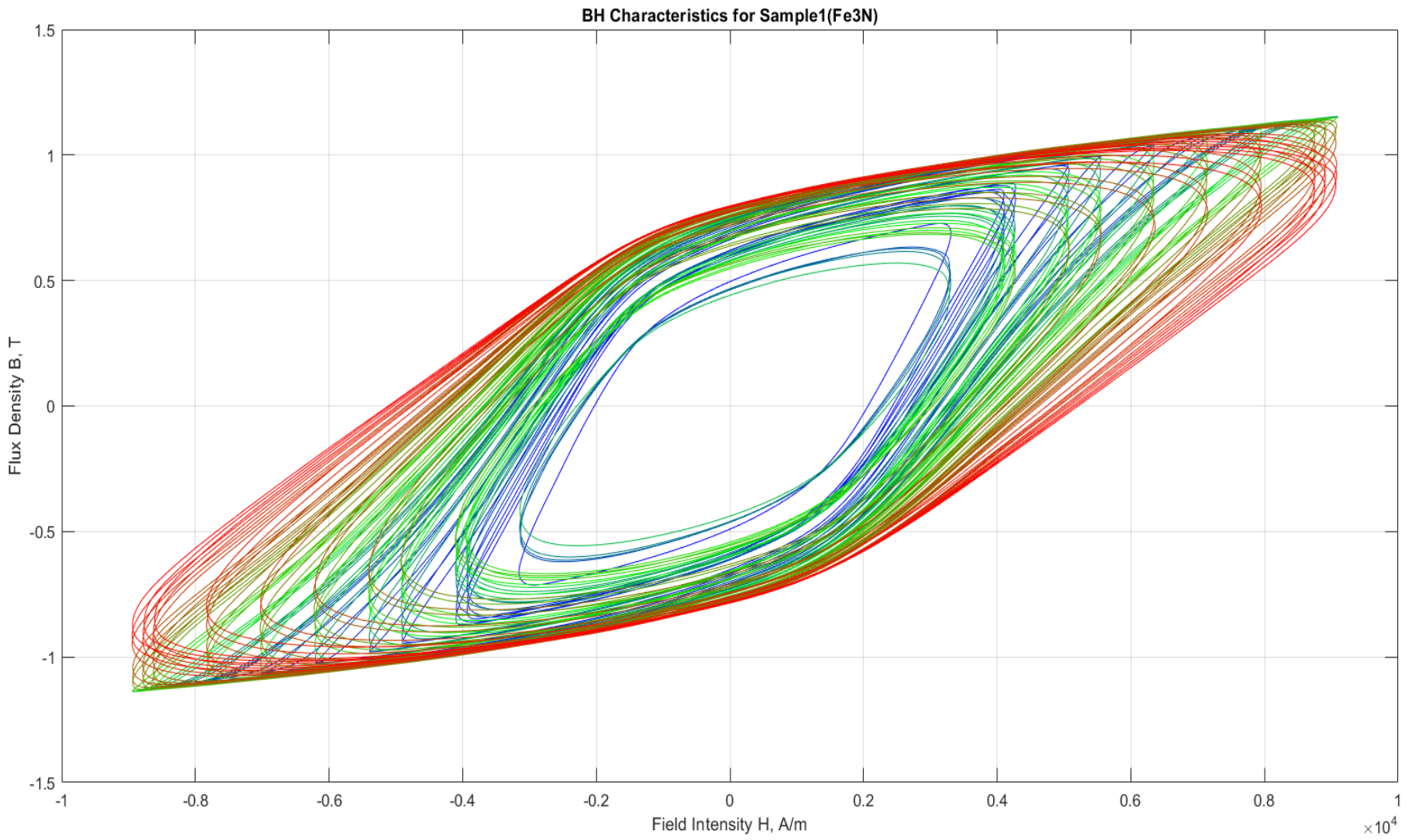


- Purdue University toroidal tester
- Measures anhysteretic *B-H* characteristics and the parameters of the series modified Steinmetz model
  - Includes both eddy and hysteretic loss components
- Outer winding is the primary and used to excite the coil
  - Exaggerated distance between the winding and the core results in a **very regular field pattern within the sample**.
- The secondary winding measures the flux through the sample.
- By characterizing losses as a function of excitation frequency, amplitude, and excitation waveshape, an optimization-based curve fitting process is used to determine the series modified Steinmetz model parameters.

Transformer design @ Purdue University
Toroid characterization



Transformer design @ Purdue University
Toroid characterization



Sample1 (Fe_3N)

Transformer design @ Purdue University
Toroid characterization – MSE parameters

α	0.72665	0.65485
β	2.9509	3.0983
k_h ***(J/l)***	245.9454	-303.0517
k_e ***(Js/l)***	0.0010927	
Maximum error in loss density (%)	5.67	
Mean error in loss density (%)	1.41	

$$p = \frac{f}{f_b} k_h \left(\frac{f_{eq}}{f_b} \right)^{\alpha-1} \left(\frac{\Delta B}{2B_b} \right)^{\beta} + k_e f \int_0^{1/f} \left(\frac{dB}{dt} \right)^2 dt$$

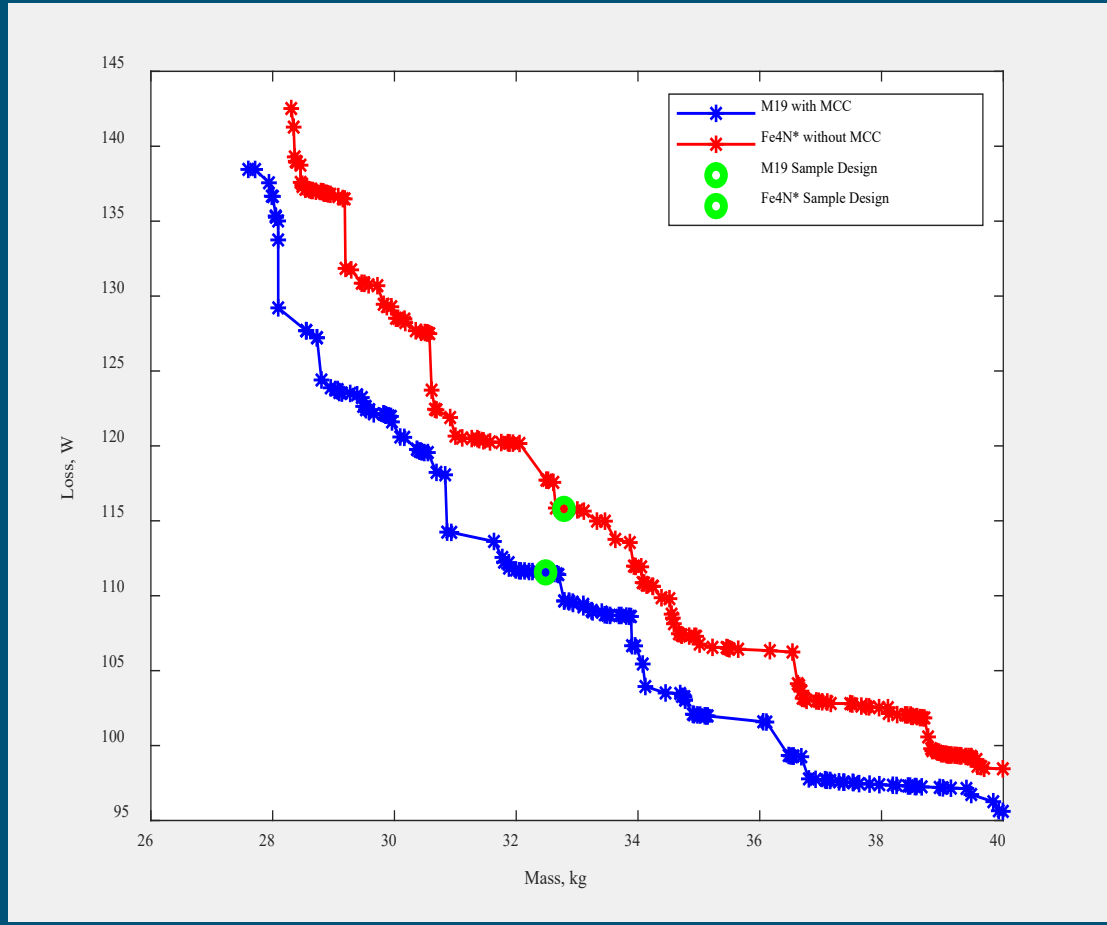
$$f_{eq} = \frac{2}{\Delta B^2 \pi^2} \int_0^{1/f} \left(\frac{dB}{dt} \right)^2$$

$$f_b = 1 \text{ Hz}$$

$$B_b = 1 \text{ T}$$

*MSE is the Modified Steinmetz Equation

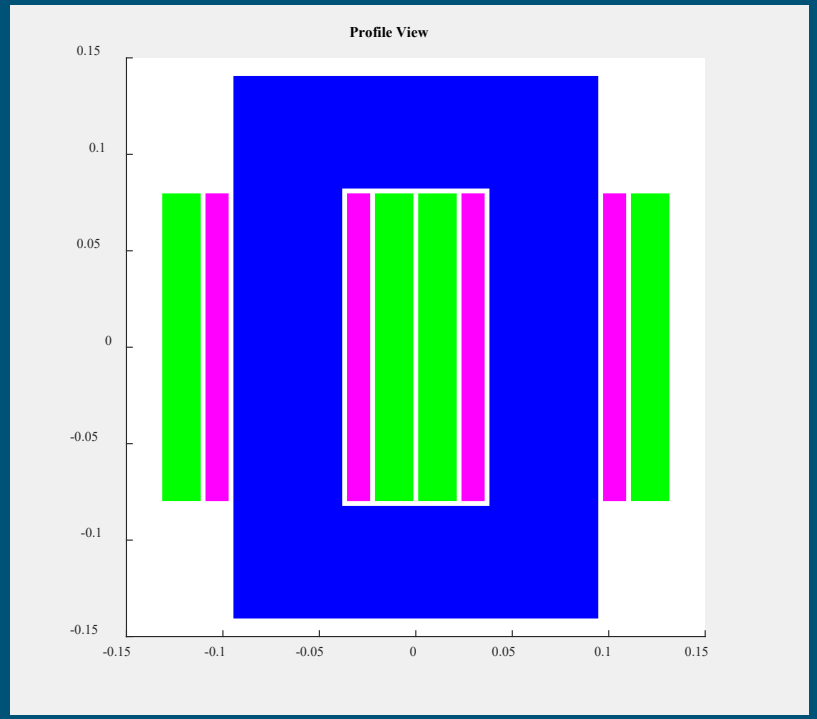
Transformer design @ Purdue University (Review)
Preliminary transformer design, Pareto optimal front



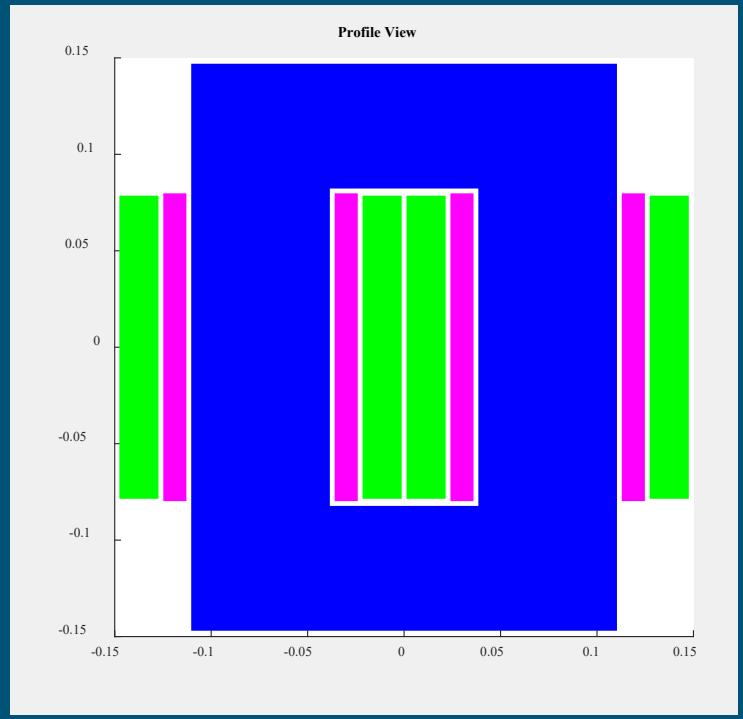
- Although Fe_4N μ_r is currently relatively low (~300) compared to M19 the Pareto optimal fronts are quite close.
- Initial result is very encouraging
- Note: MCC is Magnetizing Current Constraint

Transformer design @ Purdue University (Review)
Preliminary transformer design, profile view of transformer designs

M19 with MCC



Fe_4N without MCC



- Fe_4N relatively low μ_r (~300) does lead to a difference in magnetizing current, particularly at no-load.
- However, possible to add some shunt capacitance to address this issue
  - This is commonly done to make up for load power factor anyway

Conclusion / Impact

Multiphysics optimization and SPS can be used to design & fabricate a Fe_4N line frequency transformer

- Fe_4N transformer will be fabricated from domestically abundant, non-critical elements

Impact:

Improved size, weight, and power density of line frequency transformers

Advanced manufacturing techniques: Utilizing SPS enables the fabrication of near net-shaped parts and tailored properties. **Enabling thicker laminations improves thermal conductivity, also promoting improved power density.**

Domestic manufacturing and cost-effectiveness. Iron nitride's **abundant raw materials** will ensure a **robust supply chain**. This effort will also set the stage to utilize iron nitride as a low cost replacement to GOES in other applications, such as electric machines

Future Directions / Next Steps

Prototype 5 kVA transformer will be completed, tested, and demonstrated

- Fe_4N core will be sintered/fabricated at Cal Nano
- Core will be wound and tested at Purdue University

Acknowledgements

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