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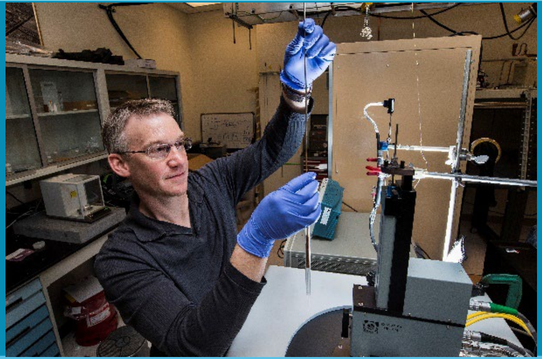
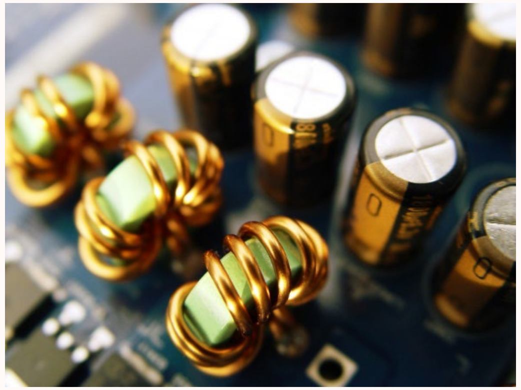


Design and Circuit Evaluation of Advanced Iron Nitride Magnetics



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Presentation ID: 803

SAND2023-11150C

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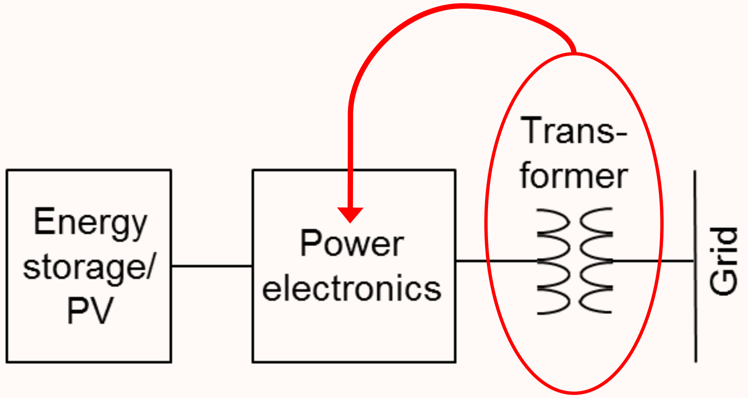
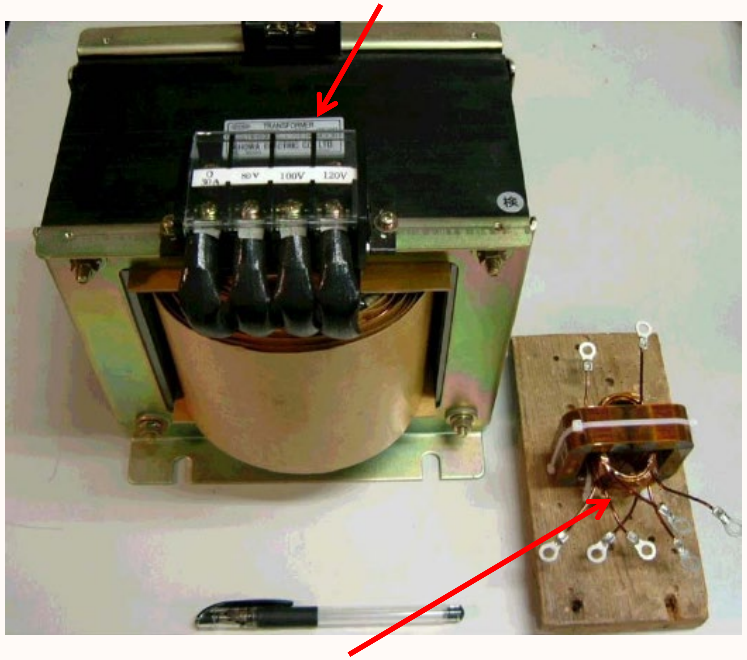
OVERVIEW: Magnetics for High Frequency Power Conversion



Line frequency (50 Hz) transformer



High frequency (20 kHz) transformer

S. Krishnamurthy, Half Bridge AC-AC Electronic Transformer, IEEE, 1414 (2012).

- Integrate output transformer within power conversion electronics
- Leverage high switching speed, voltage, and temperature performance of WBG semiconductors
- Core materials for high frequency transformers have been an afterthought (no current material meets all needs)

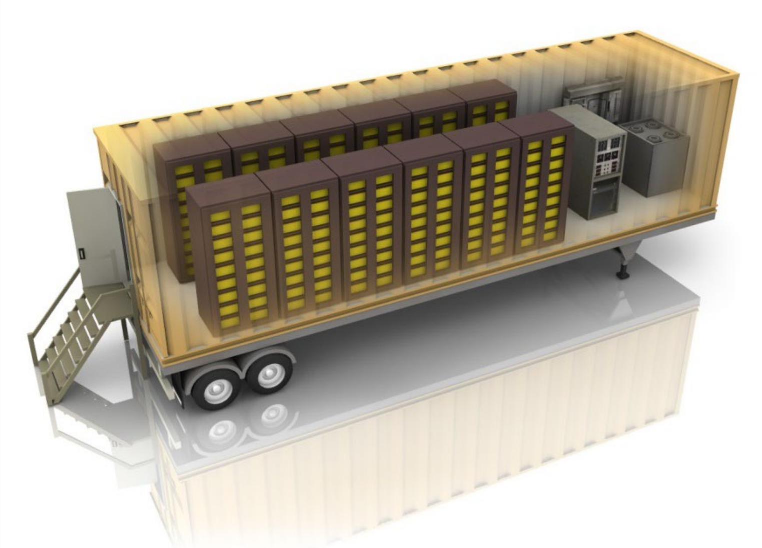
Material requirements:

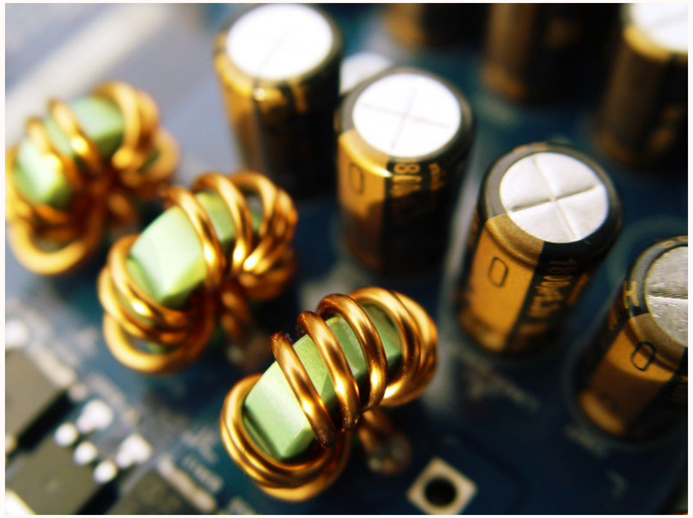
- Low loss over 10-200 kHz frequency range
  - low coercivity, high ρ
- High $J_s \rightarrow$ high power density
- High temperature performance
- Scalable & Affordable
- Increased resiliency, reliability, and better SWaP

OVERVIEW: Transportable Energy Storage and Power Conversion Systems (PCS) for Grid Modernization

Benefits of Energy Storage:

- Improve flexibility, resiliency and reliability
  - Improve power quality, stability and defer upgrades
  - Enhanced agility (flexibility) and control (load leveling, power factor control, frequency and voltage regulation)
- Increase deployment of renewable energy

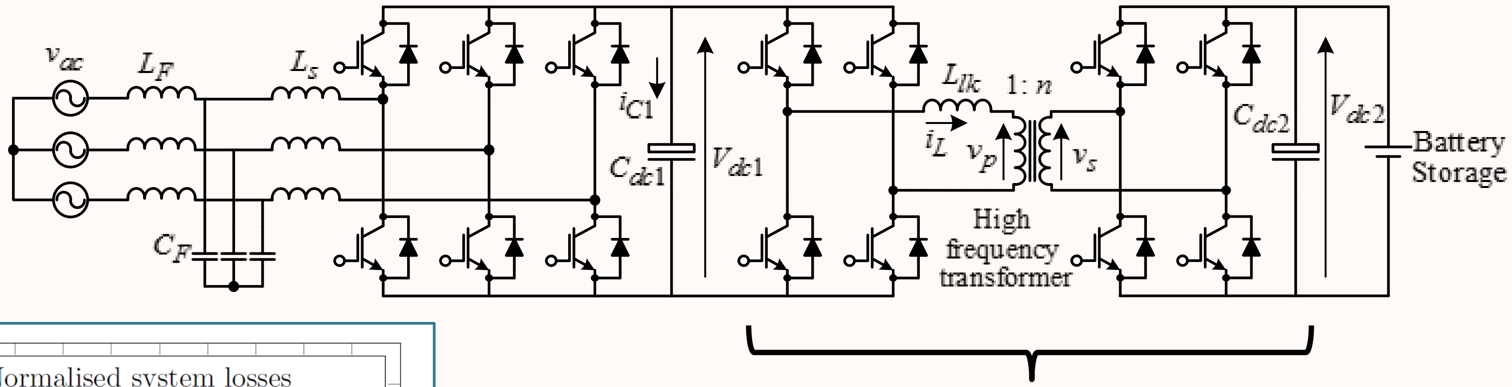


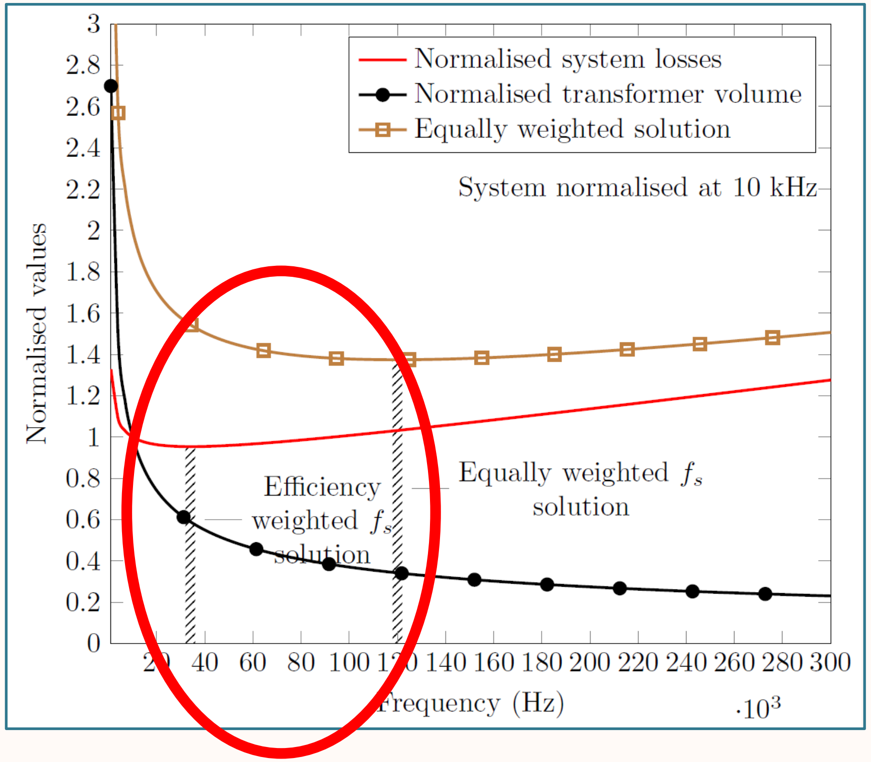


Benefits of Transportable Systems:

- Lower cost
- Modular design reduces assembly and validation time
- Faster installation at renewable energy generation sites
- Greater flexibility, resiliency and reliability

OVERVIEW: High Frequency Link PCS





Optimal frequency based on:

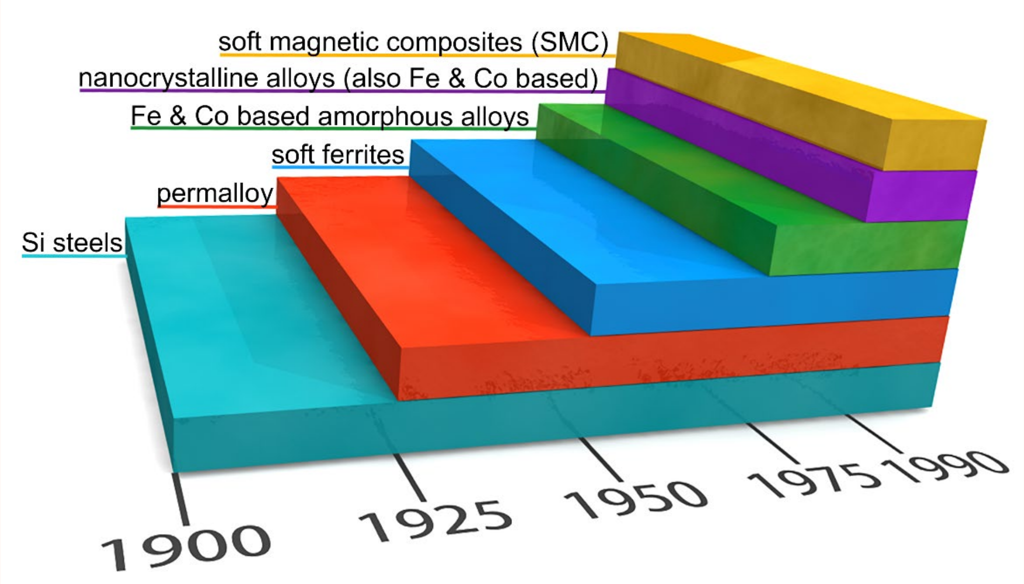
- **Switching and conduction losses in semiconductors**
- **Volume of the transformer**
- **Losses in the transformer**
  - **Winding (copper) losses**
  - **Core losses**

S. Kulasekaran, R. Ayyanar, Analysis, Design, and Experimental Results of the Semidual-Active-Bridge Converter, IEEE Transactions on Power Electronics, 29 (2014).

OBJECTIVES AND PREVIOUS WORK IN THE FIELD

- **Develop advanced core materials for high frequency power conversion systems**
  - **High frequency link converters will increase power density and performance**
  - **Enable transportable energy storage and PCS → Greater flexibility, resiliency and reliability**
- **Existing soft magnetic materials do not meet all the requirements for high frequency PCS**

Previous work in the field:



adapted from: L.A. Dobrzański, M. Drak, B. Ziębowicz, Materials with specific magnetic properties, Journal of Achievements in Materials and Manufacturing Eng., 17, 37 (2006).

Magnetic Material	J_s (T)	ρ(μΩ·m)	Cost
Nanocrystalline alloys	1.2	1.2	High
Amorphous alloys	1.6	1.4	High
Soft ferrites	0.5	10^6	Low
SMCs	~1	0.1 - 1200	Low
Si steel	1.9	0.5	Low
γ'-Fe_4N	1.9	≥ 1.6	Low

- **γ'-Fe_4N can meet all requirements of high frequency power electronics**

PREVIOUS WORK IN THE FIELD

- Prior to OE investment Fe_4N had only been produced as a thin film
  - No bulk material was available
  - Impossible to fabricate magnetic cores for any application
  - High risk endeavor to fabricate bulk iron nitride soft magnetic components

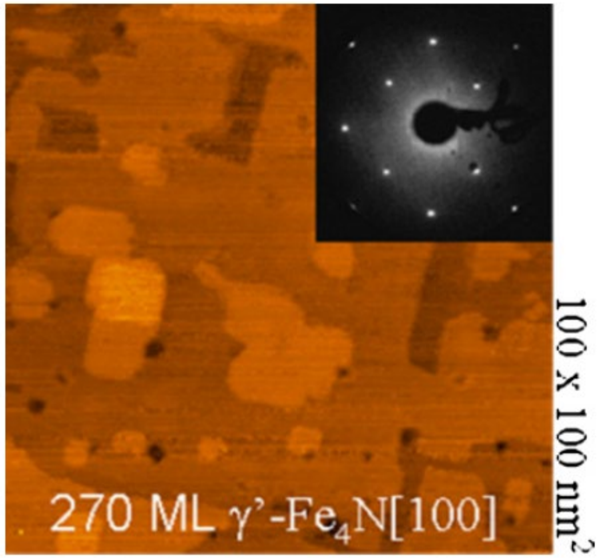
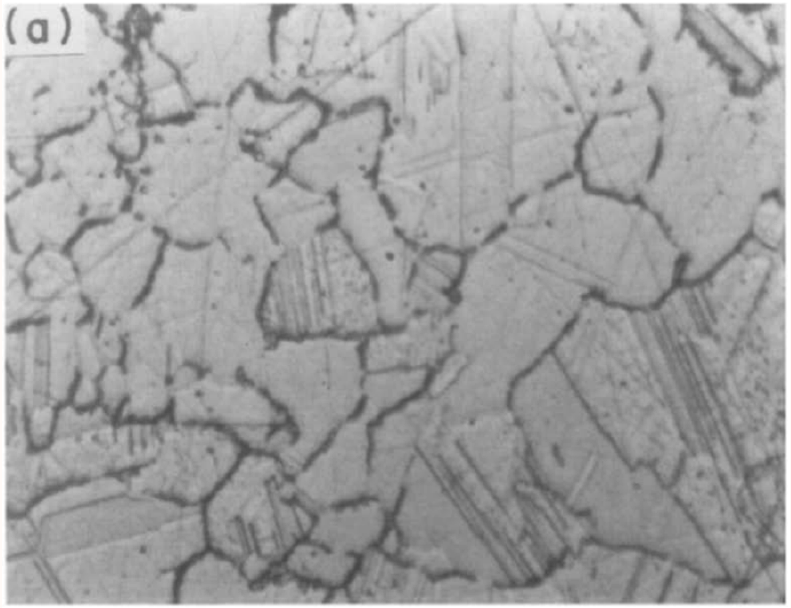


Fig. 1. STM image of a 270 monolayers (ML) thick γ′-Fe_4N film grown on Cu(1 0 0). The inset shows the corresponding LEED pattern (110 eV).

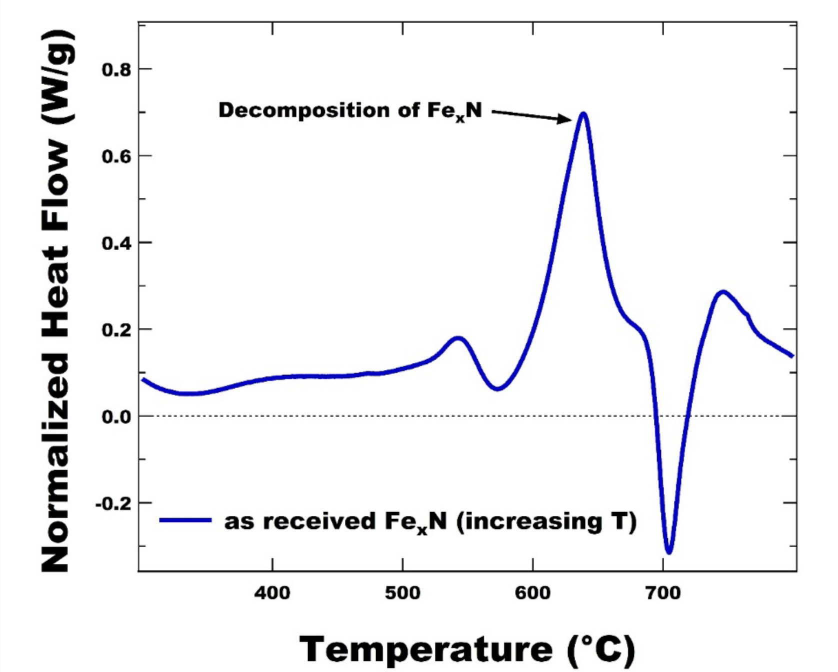


D. Ecija, et. al., "Magnetization reversal of epitaxial films of γ'-Fe_4N on Cu(100)", J. Magn. Mag. Mat., 316, 321 (2007).

S.K. Chen, et. al., "Synthesis and magnetic properties of Fe_4N and (Fe, Ni)$_4$N sheets", J. Magn. Mag. Mat., 110, 65 (1991).

METHODOLOGY

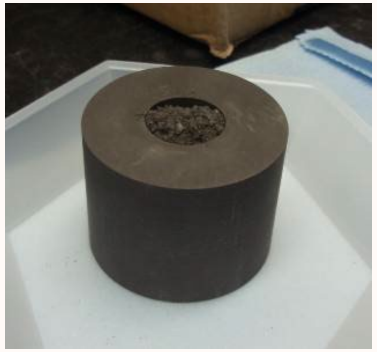
Challenge:



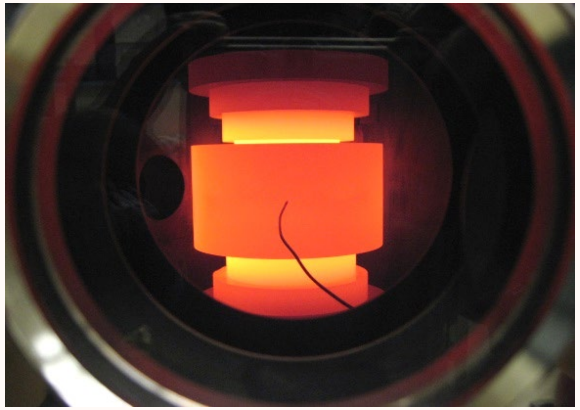
Relatively low thermal decomposition limits consolidation/fabrication methods

Hypothesis: It will be possible to fabricate bulk γ'-Fe_4N using the lower temperatures, higher pressures, and rapid consolidation of spark plasma sintering (SPS)

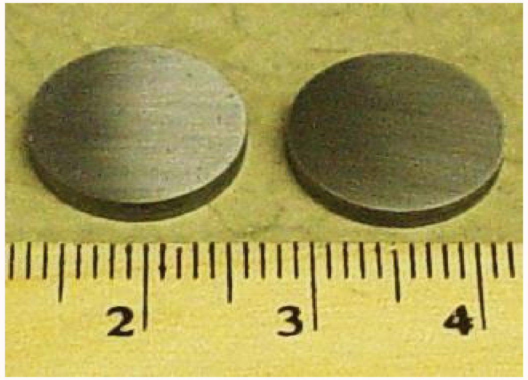
Innovation: Fabrication of γ'-Fe_4N magnetic cores using SPS



Starting powder in die

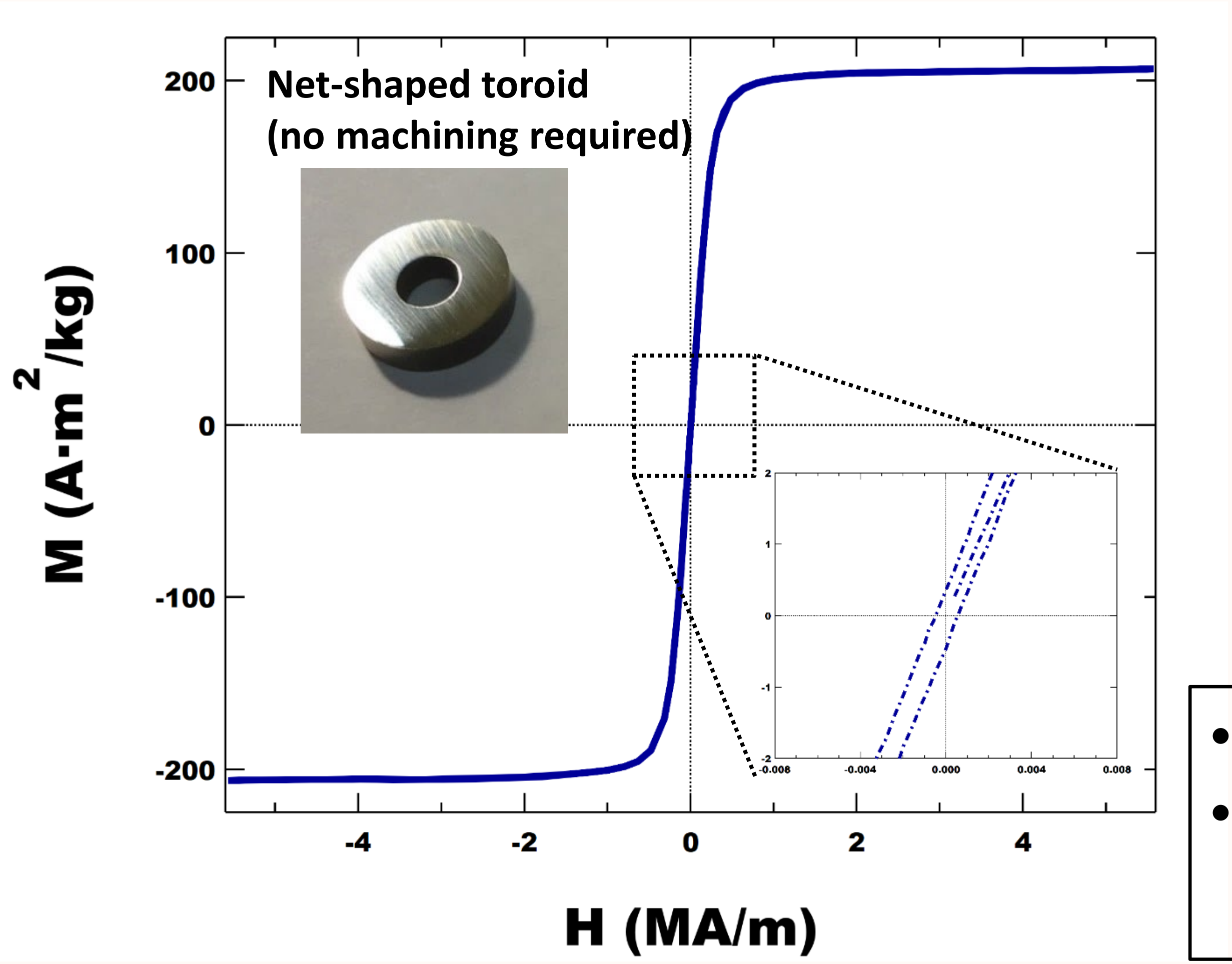


SPS chamber



End Product

RESULTS: SPSed γ'-Fe_4N



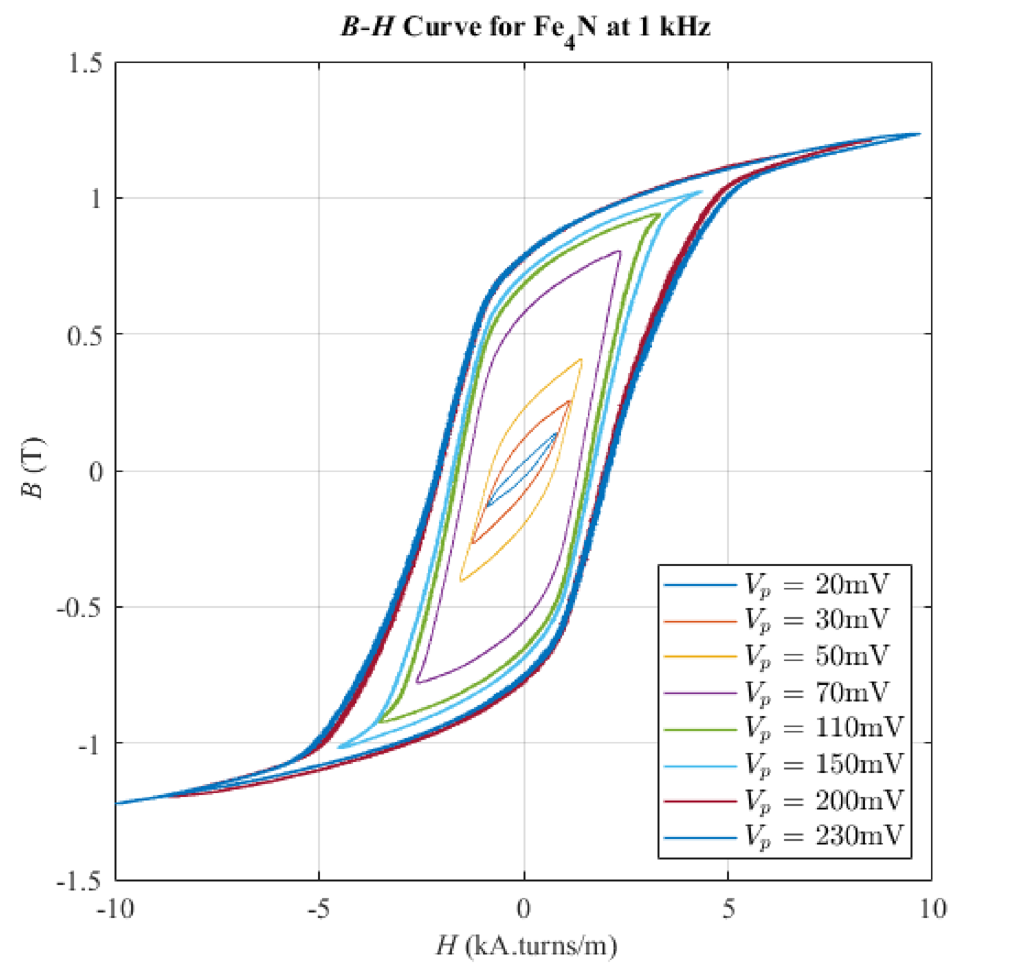
- SPSed at 530°C and 200 MPa
- M_s = 207 Am^2/kg
- Theoretical M_s = 209 Am^2/kg
  - α-Fe M_s = 217 Am^2/kg @ room temp.
- H_c < 500 A/m
  - H_c can be reduced further through reductions in grain size and/or annealing steps

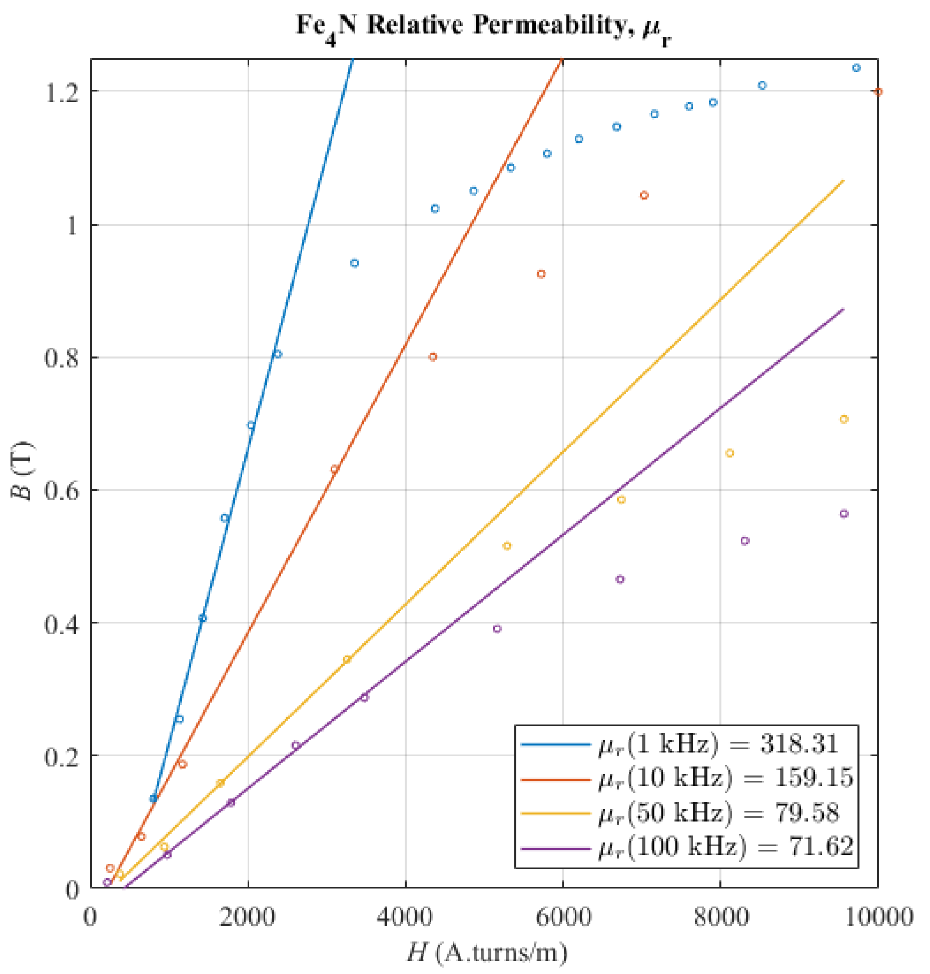
- U.S. Patent #9,963,344
- 2022 R&D 100 Award winner in the Process/Prototyping category

T. C. Monson, B. Zheng, R. E. Delany, C. J. Pearce, E. D. Langlois, S. M. Lepkowski, T. E. Stevens, Y. Zhou, S. Atcitty, E. J. Lavernia, "Soft magnetic multi-layered FeSiCrB-Fe_xN metallic glass composites fabricated via spark plasma sintering," IEEE Magnetics Letters **10**, 1-5 (2019).

RESULTS: Evaluation at Advanced Power Electronic Conversion Systems (APEX) Lab

Luciano Rodriguez, Jake Mueller



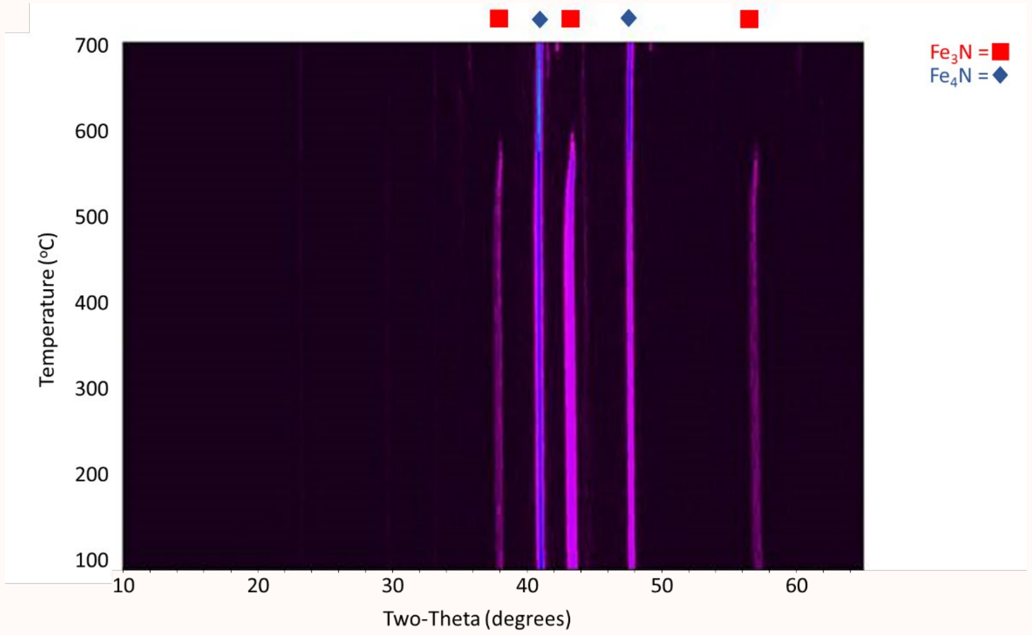


- **APEX allows us to evaluate magnetic behavior across a wider range of fields**
  - **Much higher currents (fields) than bench top B-H analysis**
  - **Explores circuit behavior as we utilize broader range of magnetic hysteresis**

RESULTS: Scaling to Larger Part Size

Methodology:

- Obtain ≥ kg quantities of iron nitride powders
  - Purify ≥ kg quantities of iron nitride powder
- SPS cores ≥ 40 mm O.D.
  - Work with commercial SPS provider
  - Small scale SPS conducted at Sandia
- Evaluate cores
- Optimize cores for high frequency power conversion
  - Powder size & morphology, SPS parameters, innovative core design



- Simple heat treatment converts mixed phase iron nitride powders
- Only phase pure γ'-Fe_4N remains

Fuji Dr. Sinter Lab Jr. SPS at Sandia Labs

RESULTS: Scaling to Larger Part Sizes

- Partnering with California Nanotechnologies (Calnano)
  - Facilities for milling 100s to 1000s of kg of powder/week
  - SPS equipment for fabrication of parts up to 6” diameter
- Larger cores are evaluated at APEX (Luciano Rodriguez)

calnano

9 mm O.D. Fe_4N toroid

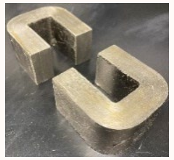
41 mm O.D. Fe_4N toroid

Large scale SPS system at Calnano capable of manufacturing parts up to 6” in diameter

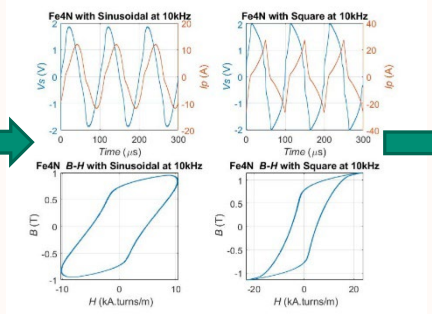
RESULTS: Circuit Informed Design of High Frequency Magnetics for Utility Scale Power Conversion Systems

Fe_4N toroid

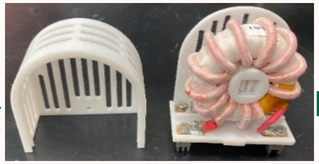
N87 ferrite toroid



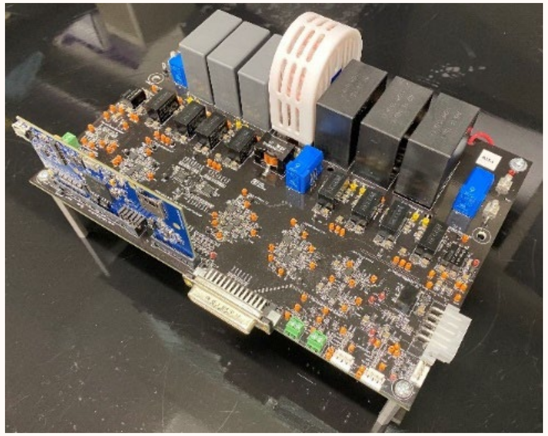
Amorphous
C-core



Characterization performed at APEX

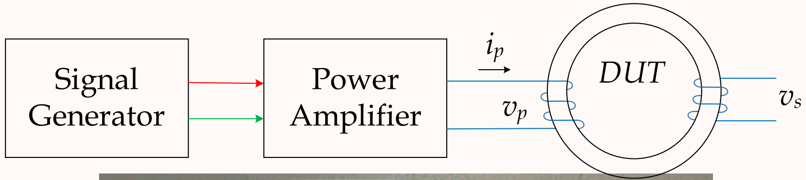


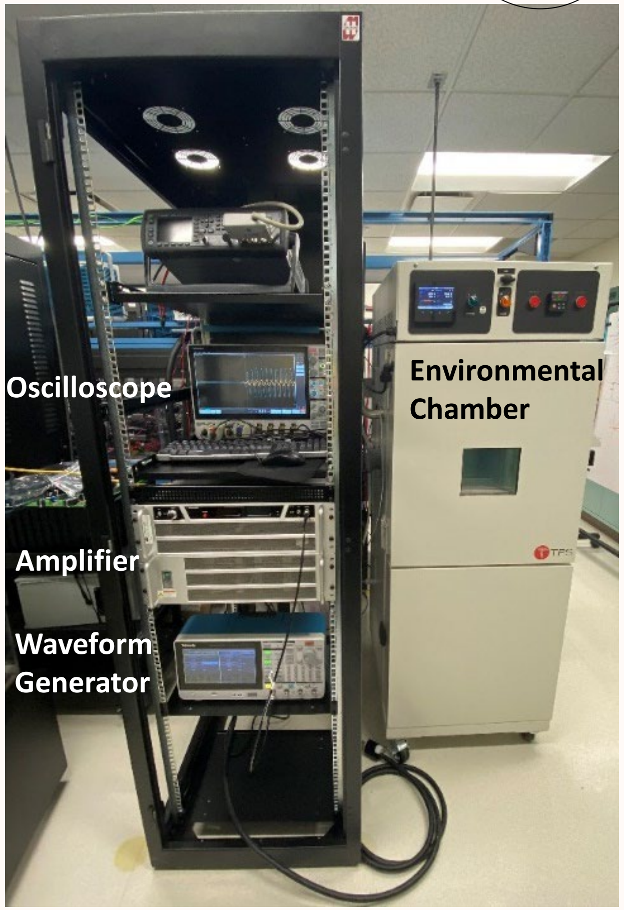
Transformer is built for required system specifications



System level performance is evaluated in a power electronics converter (Dual Active Bridge or DAB)

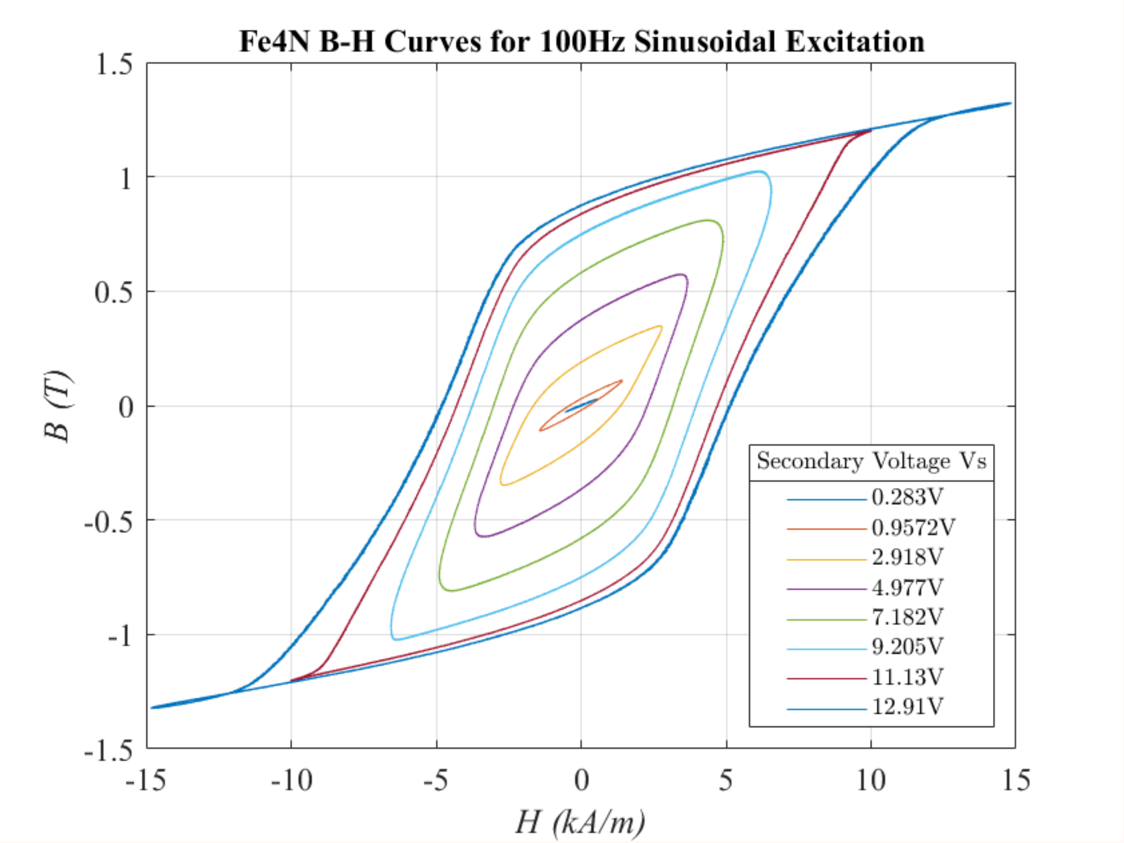
APEX Magnetic Characterization Setup

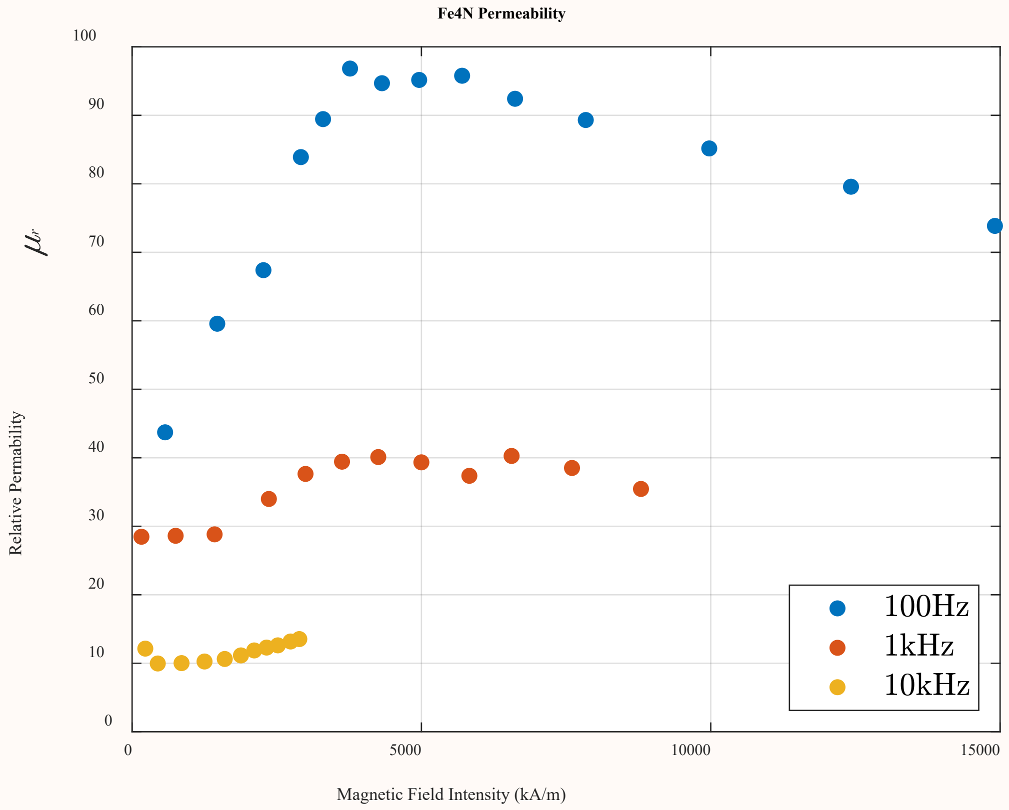




- Hardware based validation of high voltage and high frequency magnetic designs for emerging power conversion applications
- Design high frequency transformers for modular cascaded storage system
- Building the capabilities needed to prototype and assess novel magnetic materials, conductors, and insulators

RESULTS: Evaluation of > 4 cm O.D. Toroids



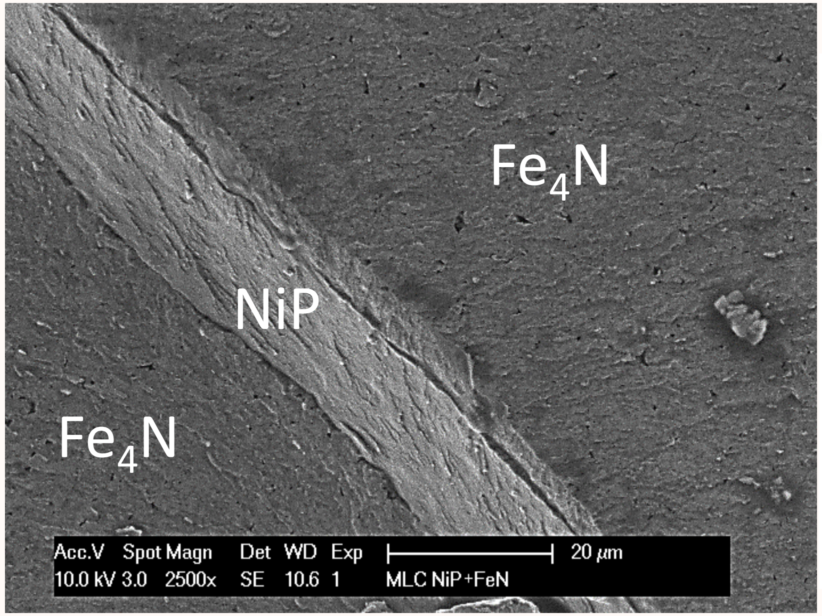


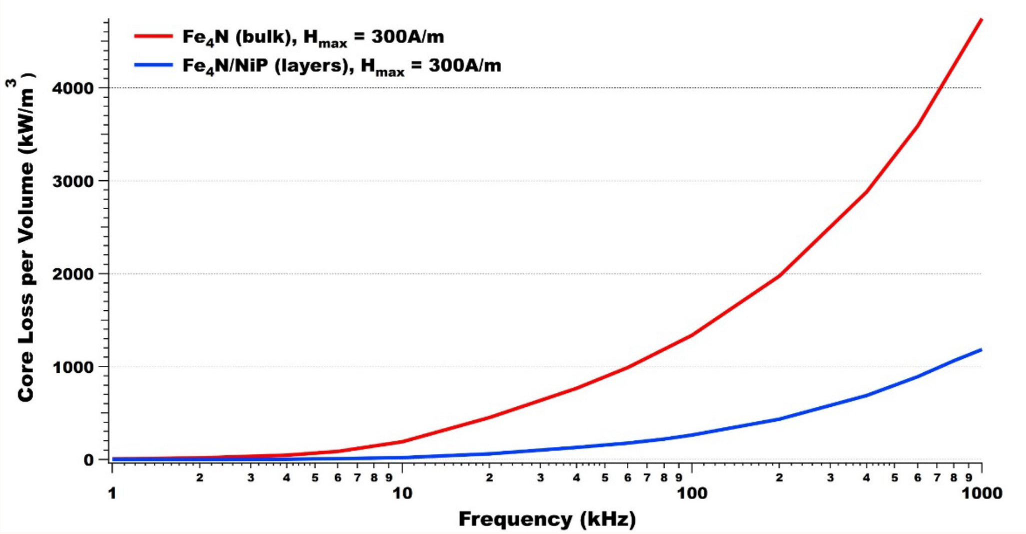
- **Full evaluation of toroids in excess of 2 cm O.D. not possible with our Iwatsu B-H analyzer**
  - **APEX setup allows for testing of cores at higher power levels (and magnetic fields)**
- **Plans to address μ_r and core loss in upcoming year (see next slide)**

LOOKING FORWARD

Future Work

- Fabricate Fe_4N cores using finer grained starting material (to increase μ_r)
- Investigate additional Fe_4N/composite concepts (lamination analogs)
  - Will reduce core loss and further increase μ_r
- Continued evaluation of cores in DAB setup (at APEX)
  - Continued circuit informed design of high frequency magnetics for utility scale power conversion systems





Demonstration of laminated Fe_4N based composite with reduced core losses

QUESTIONS / ACKNOWLEDGEMENTS

We thank Dr. Imre Gyuk and the Energy Storage Program in the Office of Electricity (OE) at the US Department of Energy for supporting this work