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Advanced Magnetics for High Frequency Link Converters

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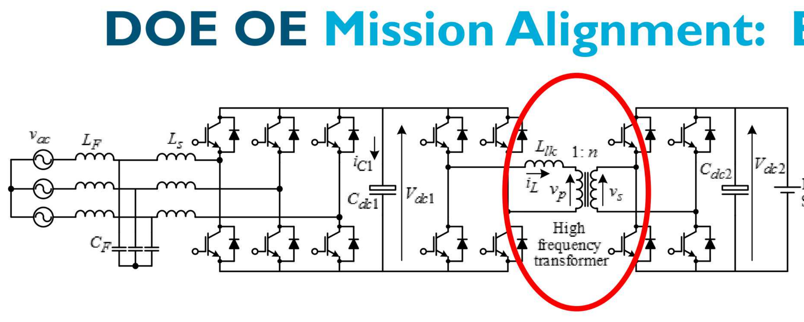
Project Objective

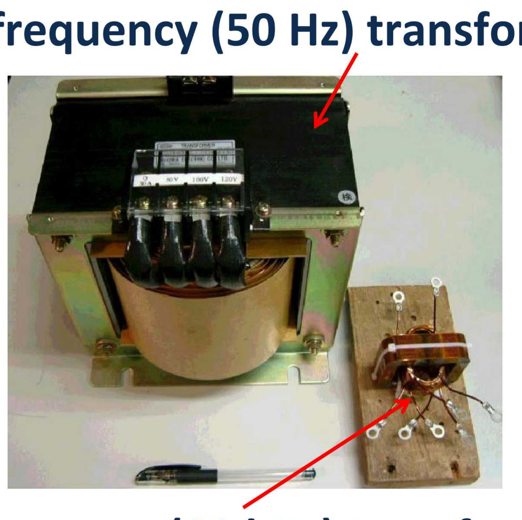
Advanced magnetic materials will enable compact and efficient high frequency DC links and their implementation in transportable energy storage and power conversion systems. Compact and agile systems, able to fit inside a single semi-trailer, will significantly decrease both installation cost and time for solar, wind, and geothermal energy systems in even extremely remote locations. Innovative magnetic core materials suitable for high frequency link converters that can perform without active cooling are being fabricated. Fe_4N, manufactured into magnetic components for the first time ever, will lead to lighter, smaller, more affordable, and higher efficiency transformers required for transportable energy storage systems and the widespread adoption of renewable energy.

DOE OE Mission Alignment: Benefits of a High Frequency Transformer



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

Line frequency (50 Hz) transformer



High frequency (20 kHz) transformer

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

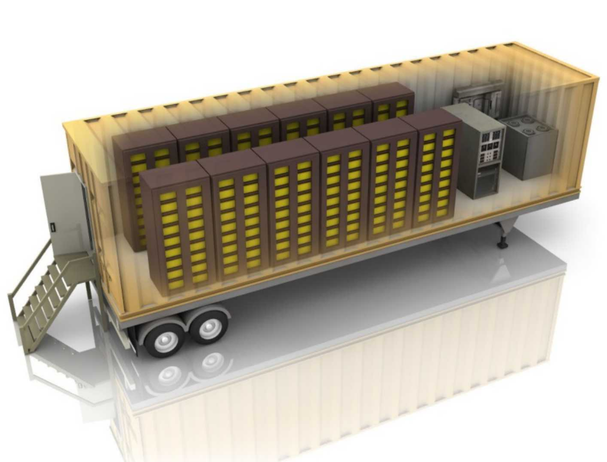
Objectives:

- Integrate output transformer within power conversion electronics
- Leverage high switching speed, voltage, and temperature performance of WBG semiconductors

Benefits:

- Enable solid state transformer (SST) designs
- Bidirectional power flow enabled through use of dual active bridge (DAB) topologies
- High temperature performance (reduced cooling requirements)
- Decreased size and weight of transformer and power conversion system (PCS)
- Improved reliability, resiliency, and flexibility

DOE OE Mission Alignment: Transportable Energy Storage and Power Conversion Systems (PCS)



Benefits of Energy Storage:

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

Benefits of Transportable Systems:

- Lower cost and increased flexibility
- Modular design reduces assembly and validation time
- Faster installation at renewable energy generation sites

Previous Work in the Field

Magnetic Material	J_s (T)	ρ (μΩ·m)	Cost
VITROPERM (Vacuumschmelze)	1.20	1.15	High
Metglas 2605SC	1.60	1.37	High
Ferrite (Ferroxcube)	0.52	5x10[6]	Low
Si steel	1.87	0.05	Low
γ'-Fe_4N	1.89	> 200	Low

- No existing magnetic material meets all requirements for SSTs
- γ'-Fe_4N can meet all demands of high frequency transformers
- Note: $J = \mu_0 \cdot M$

Methodology

Hypothesis:

- γ'-Fe_4N can meet all requirements of high frequency transformers

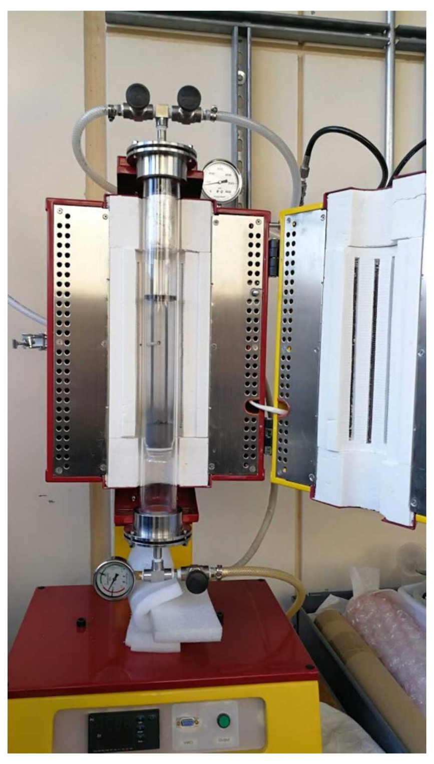
Methods:

- Develop pathways for high quality γ'-Fe_4N raw powder synthesis
- Fabricate novel iron nitride and iron nitride based composite magnetic cores
- Test new magnetic cores in relevant environments
- Demonstrate improved performance over state of the art

Innovation/Risk:

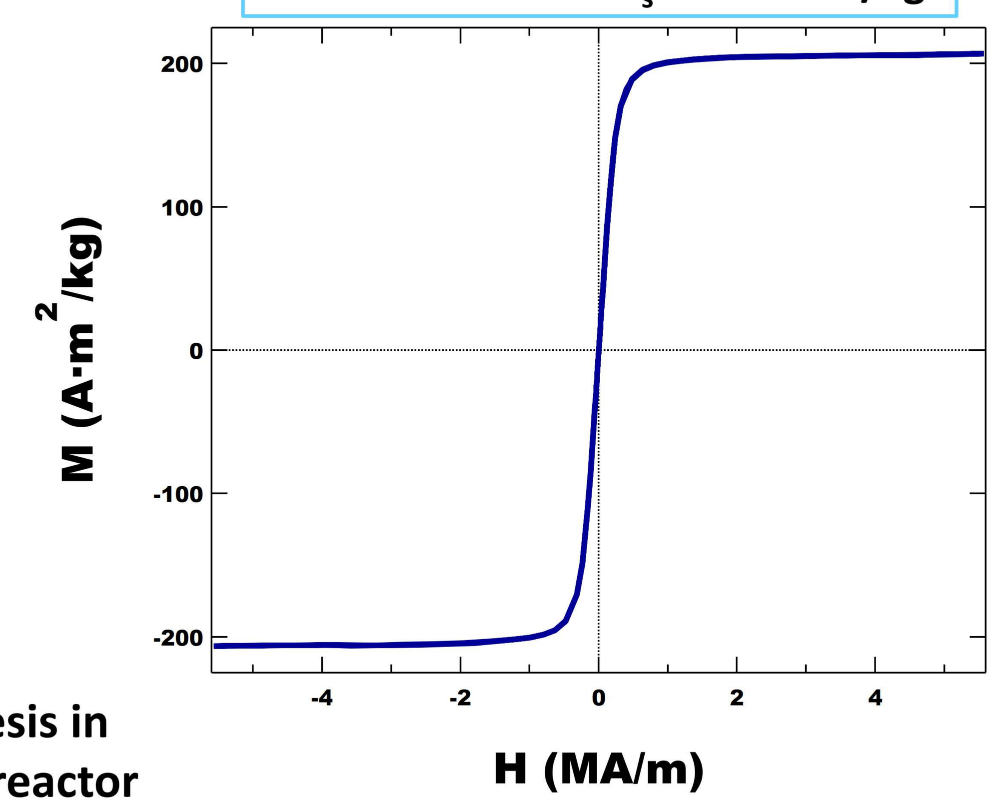
- γ'-Fe_4N not fabricated as a bulk material or demonstrated in any device prior to this work

Results: γ'-Fe_4N raw powder synthesis



γ'-Fe_4N synthesis in fluidized bed reactor

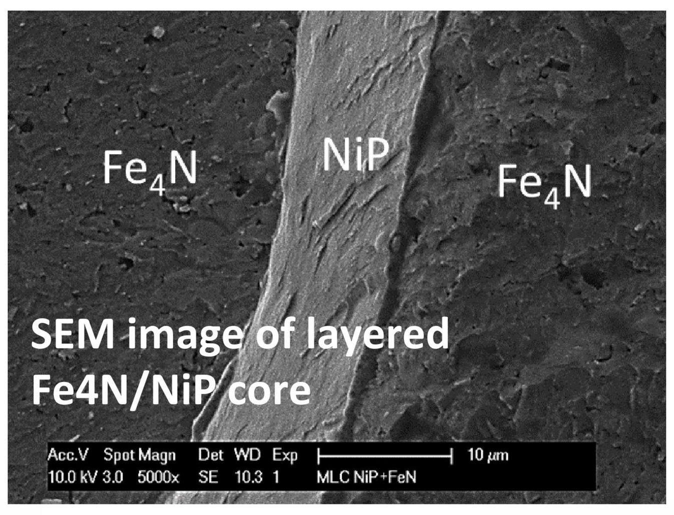
M_s = 207 Am^2/kg
Theoretical value M_s = 209 Am^2/kg

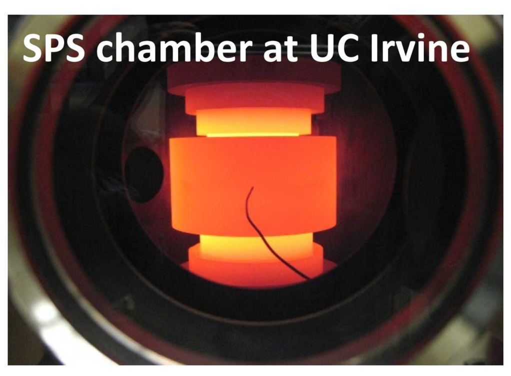


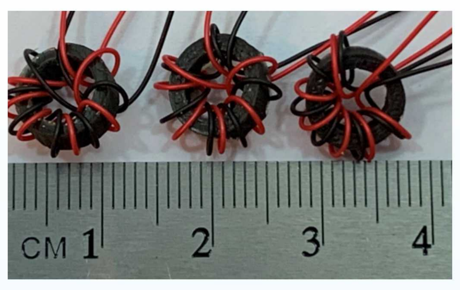
*M_s is magnetic saturation (per mass)

Results: Magnetic core fabrication and testing

Spark Plasma Sintering (SPS) of layered Fe_4N/NiP toroids

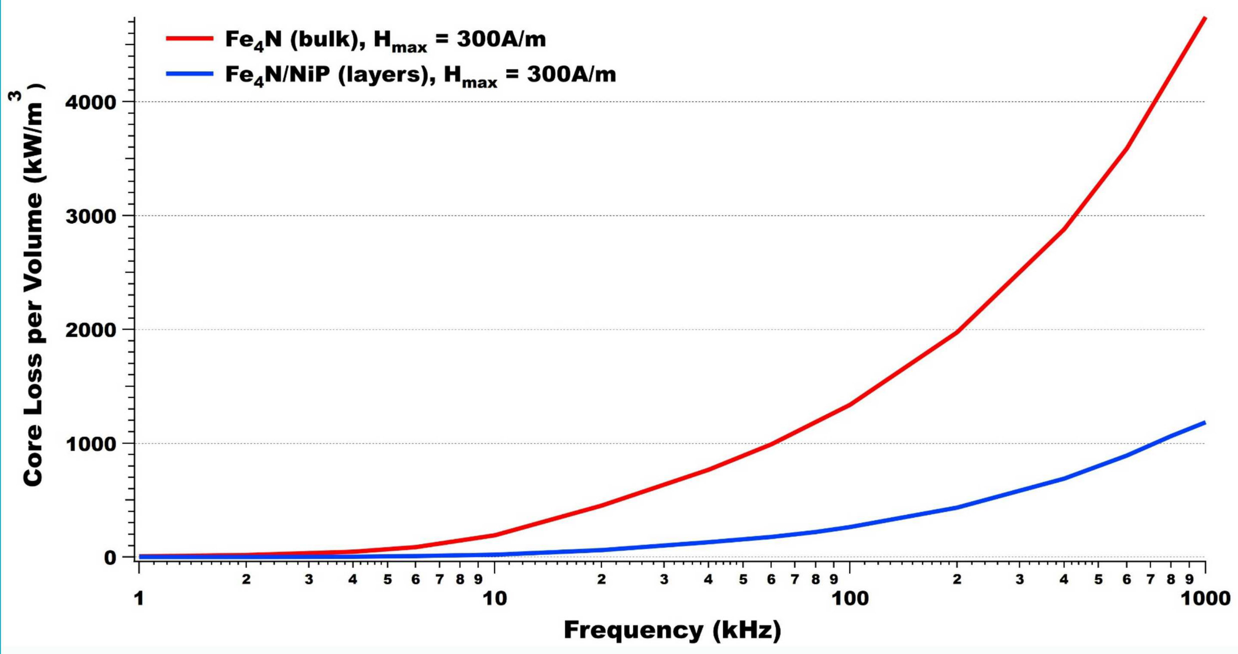




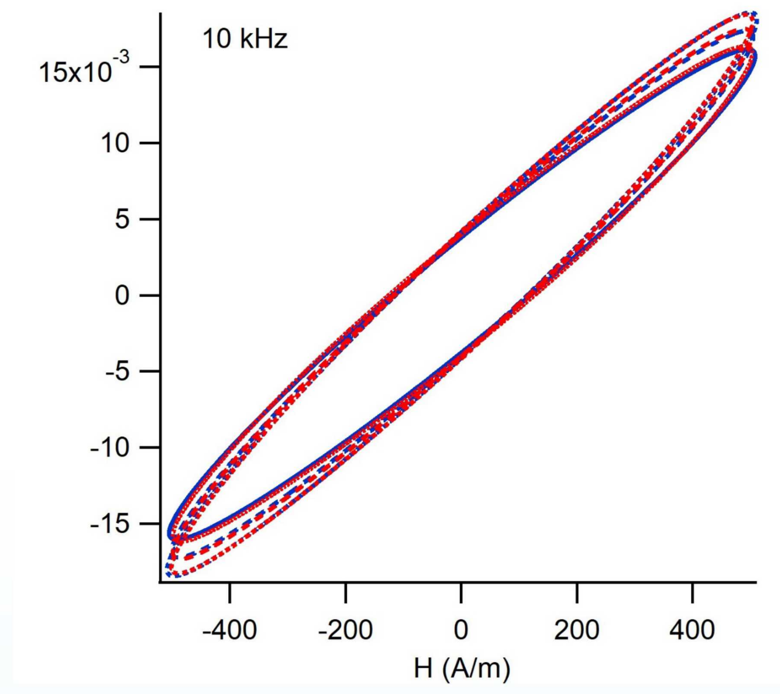


Characterization of toroidal cores in Iwatsu B-H analyzer

Results: Decreased core loss in Fe_4N/NiP layered cores



Results: Improved performance at elevated temperatures



Results: FY20 Publications & Patent Applications

- E. Langlois, J. Watt, D. Huber, M. McDonough, T. C. Monson and J. Neely, "Design and Evaluation of Nano-Composite Core Inductors for Efficiency Improvement in High-Frequency Power Converters" 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), June 2020, https://doi.org/10.1109/APEC39645.2020.9123995
- Z. Fu, B. E. MacDonald, A. D. Dupuy, X. Wang, T. C. Monson, R. E. Delaney, C. J. Pearce, K. Hu, Z. Jiang, J. M. Schoenung, W. Chen, E. J. Lavernia "Exceptional combination of soft magnetic and mechanical properties in a heterostructured high-entropy composite" Applied Materials Today, June 2019, Vol. 15; 590-598, https://doi.org/10.1016/j.apmt.2019.04.014
- B. Zheng, Y. Zhou, E. J. Lavernia, T. C. Monson "Isostatic Pressure Spark Plasma Sintering (IP-SPS) Net Shaping of Components Using Nanostructured Materials" Provisional Patent Application No. 62/985,223, Date: March 4, 2020

Acknowledgements

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