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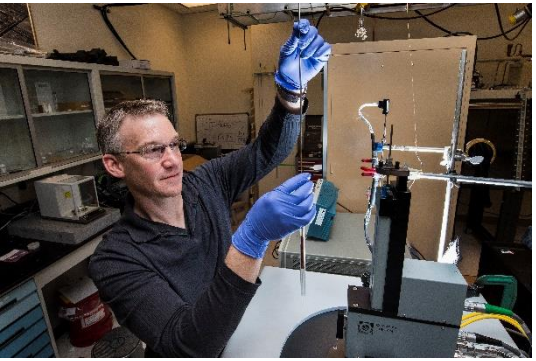
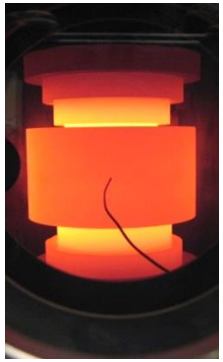
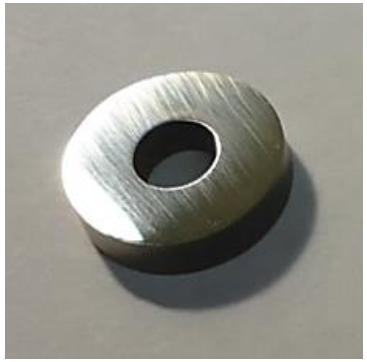


High Frequency Link Converters Using Advanced Magnetics

September 27, 2016

Todd Monson

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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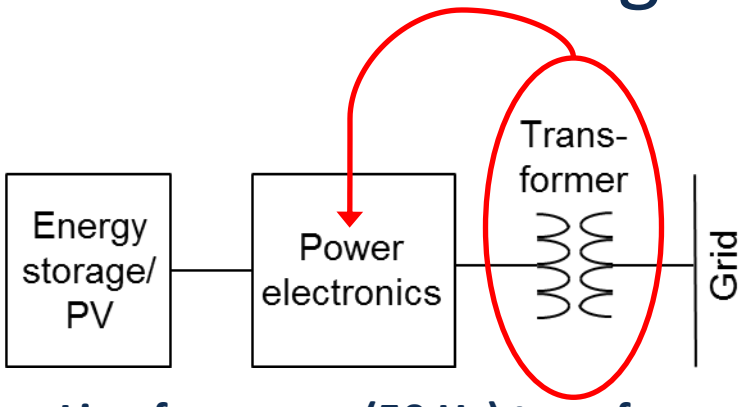
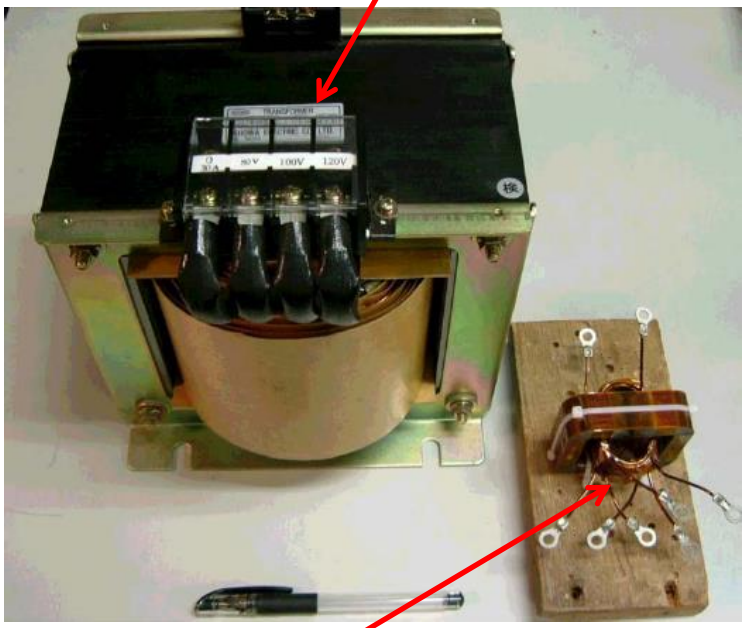
Benefits of a High Frequency Transformer



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 in 10-200 kHz frequency range**
- **High permeability (low coercivity)**
- **High saturation magnetizations**
- **High temperature performance**
- **Scalable & Affordable**
- **Overall increased reliability and performance**

Transportable Energy Storage and Power Conversion Systems (PCS)

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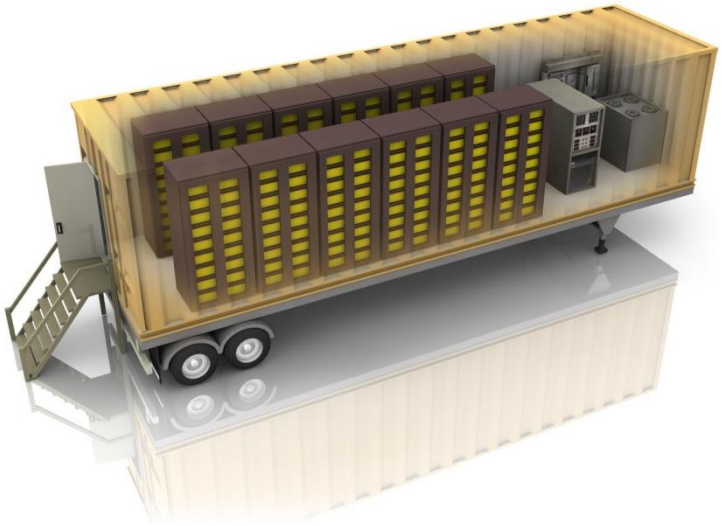
Benefits of Energy Storage:

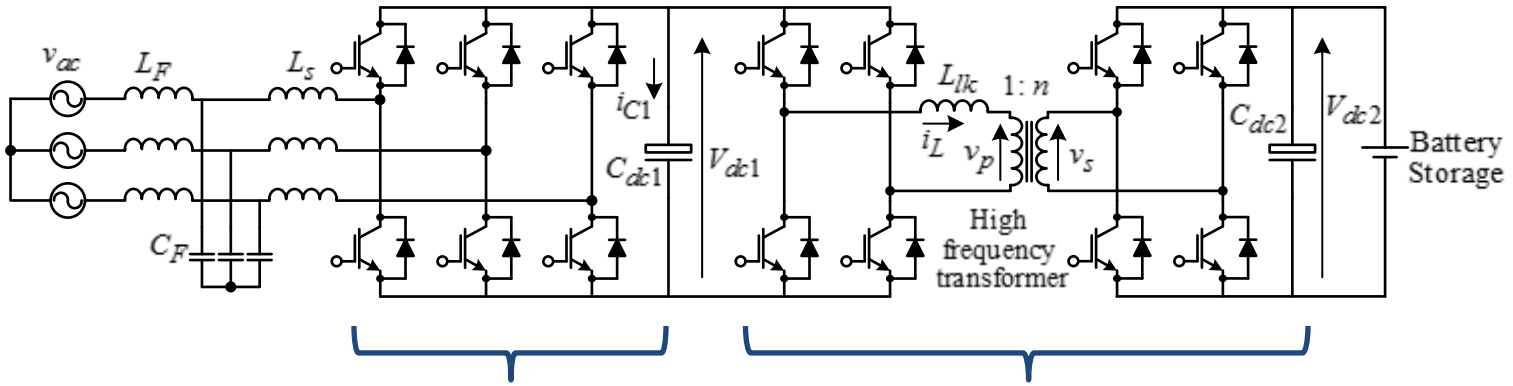
- **Maintain power quality and reliability**
  - **Improve stability and defer upgrades**
  - **Enhanced agility and control (load leveling, power factor control, frequency and voltage regulation)**
- **Increase deployment of renewable energy**



Benefits of Transportable Systems:

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

High Frequency Link Power Conversion System



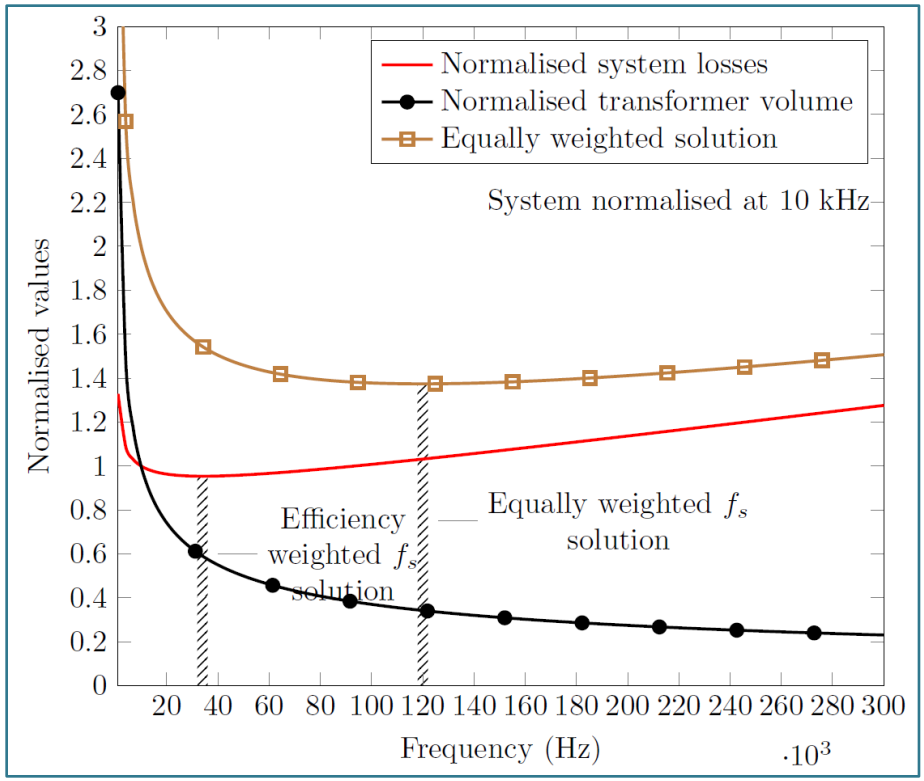
- **Optimal switching frequency based on the losses at this stage**

Volume occupied by heat sinks and non-magnetic components were not considered !!

- **Optimal switching frequency based on:**
- **Switching and conduction losses in the switch**
- **Volume of the transformer**
- **Losses in the transformer**
  - **Copper losses in transformer windings**
  - **Core losses of the transformer**

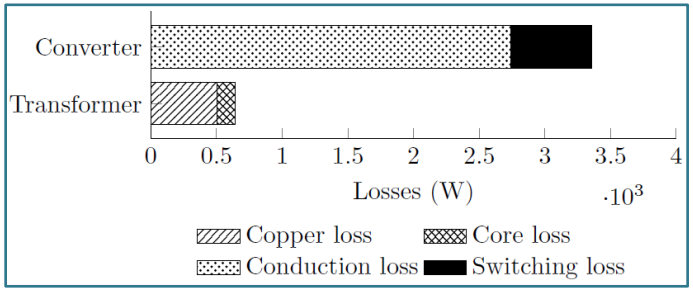
S. Kulasekaran, R. Ayyanar, Analysis, Design, and Experimental Results of the Semidual-Active-Bridge Converter, IEEE Transactions on Power Electronics, 29 (2014).

Optimum Frequency with SiC MOSFETs



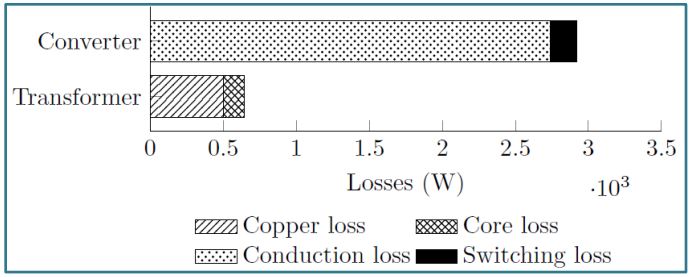
Equally weighted solution:

The converter has optimal solution at a frequency of **120 kHz** with equal weights on volume and losses



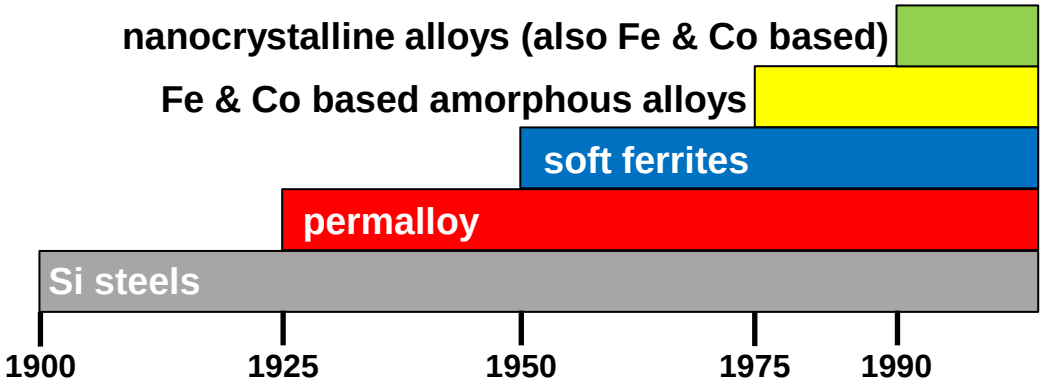
Efficiency driven solution:

The optimal solution for minimum loss condition is **35 kHz**

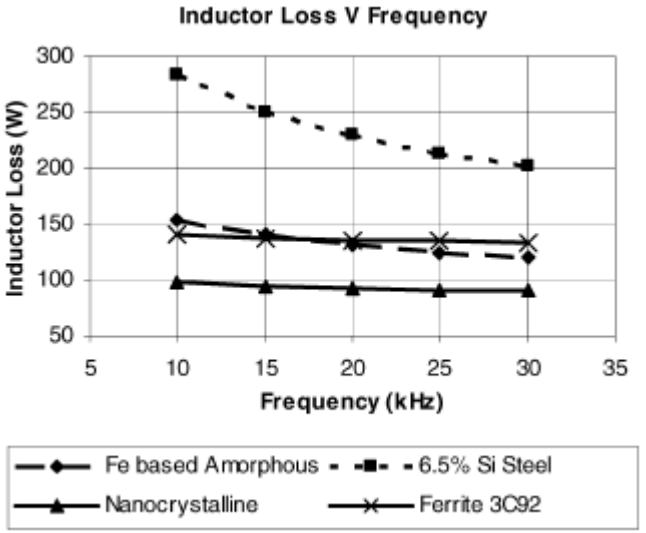


S. Kulasekaran, R. Ayyanar, Analysis, Design, and Experimental Results of the Semidual-Active-Bridge Converter, IEEE Transactions on Power Electronics, 29 (2014).

Soft Magnetic Material Development



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).

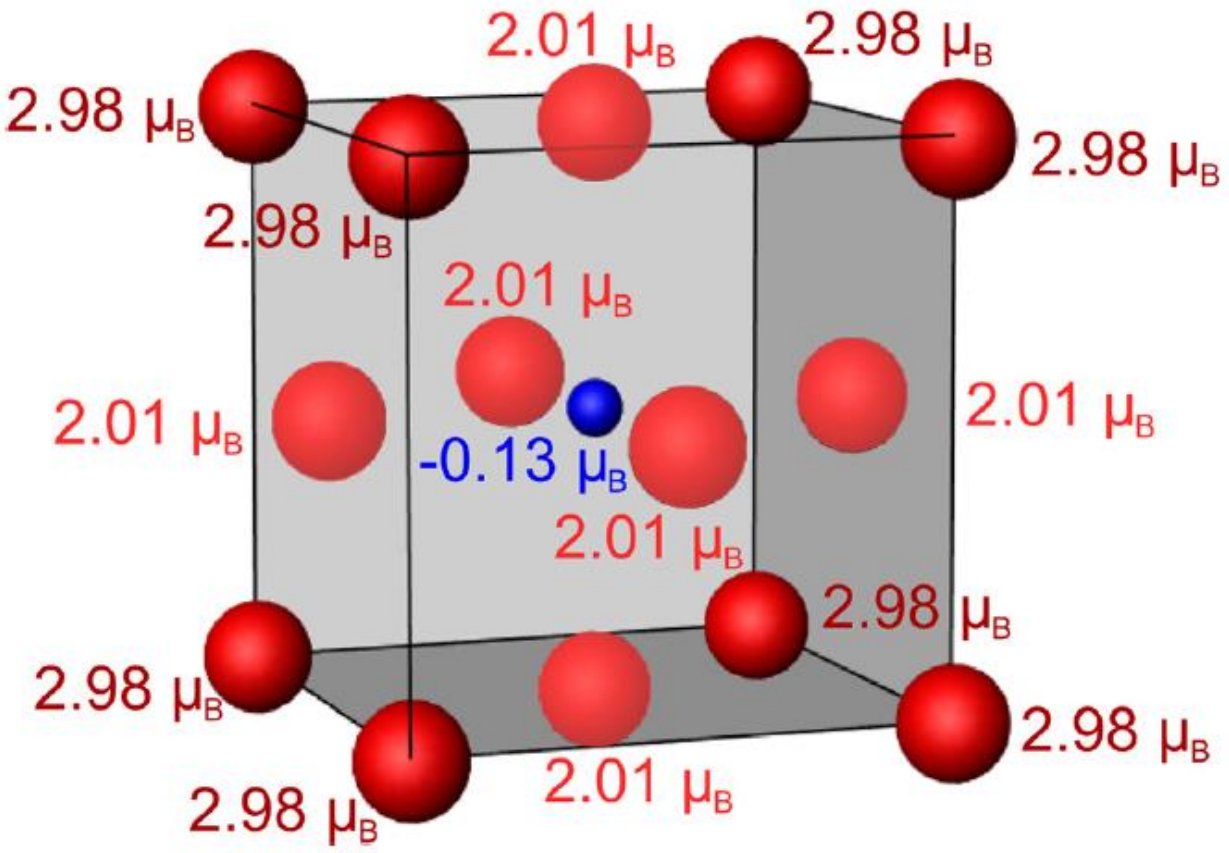


B.J. Lyons, J.G. Hayes, M.G. Egan, Magnetic Material Comparisons for High-Current Inductors in Low-Medium Frequency DC-DC Converters, IEEE, 71 (2007).

Magnetic Material	J_s (T)	$\rho(\mu\Omega\cdot m)$	Cost
VITROPERM (Vacuumschmelze)	1.20	1.15	High
Metglas 2605SC	1.60	1.37	High
Ferrite (Fexxocube)	0.52	$5x10^6$	Low
Si steel	1.87	0.05	Low
γ'-Fe_4N	1.89	~200	Low

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

γ'-Fe_4N Unit Cell



fcc γFe structure stabilized by interstitial nitrogen in the body center

G. Scheunert, et al., A review of high magnetic moment thin films for microscale and nanotechnology Applications, Appl. Phys. Rev., 3, 011301 (2016).
J.M.D. Coey, *Magnetism and Magnetic Materials* (Cambridge University Press, Cambridge, UK, 2012).

γ'-Fe_4N Synthesis and Processing

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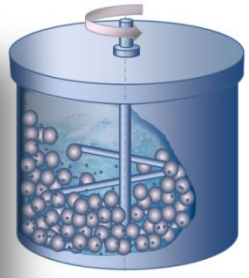
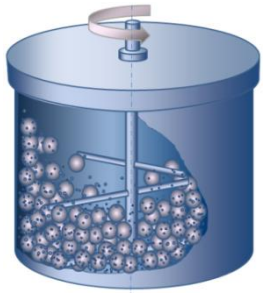
U.S. Patent Filed January 2016 (#15/002,220)

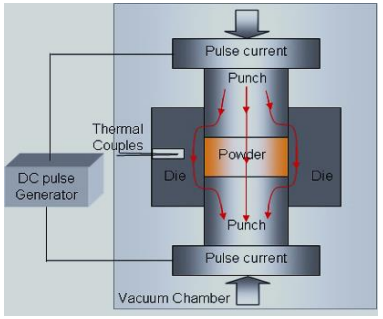
Synthesis of dense nanocrystalline iron nitrides using a two-step reactive milling and high pressure spark plasma sintering (SPS).



Liquid N_2



NH_3



Spark Plasma Sintering (SPS)

- **Cryomilling creates nanocrystalline Fe powder with large amounts of vacancies, grain boundaries, and dislocations**
- **Defects serve as fast diffusion pathways for nitrogen atoms from NH_3**
- **SPS quickly consolidates raw powders with a low sintering temperature**
  - **Excellent control over grain growth**
  - **Result: Improved magnetic properties**

Large scale manufacturing via SPS

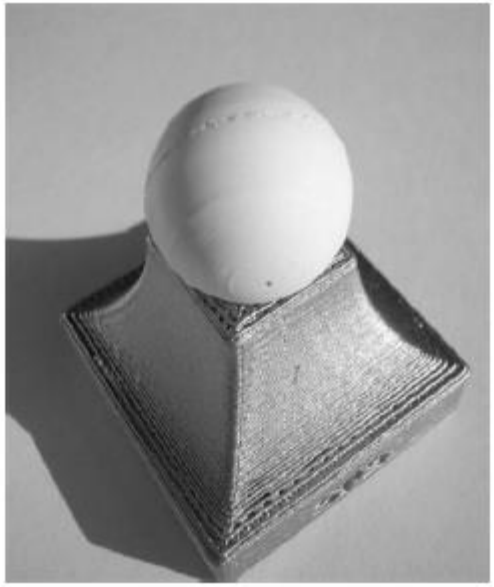


Fig. 9. Al_2O_3 sphere obtained in one single step by SPS.[63]

J. Galy, Private Communication, 2007.

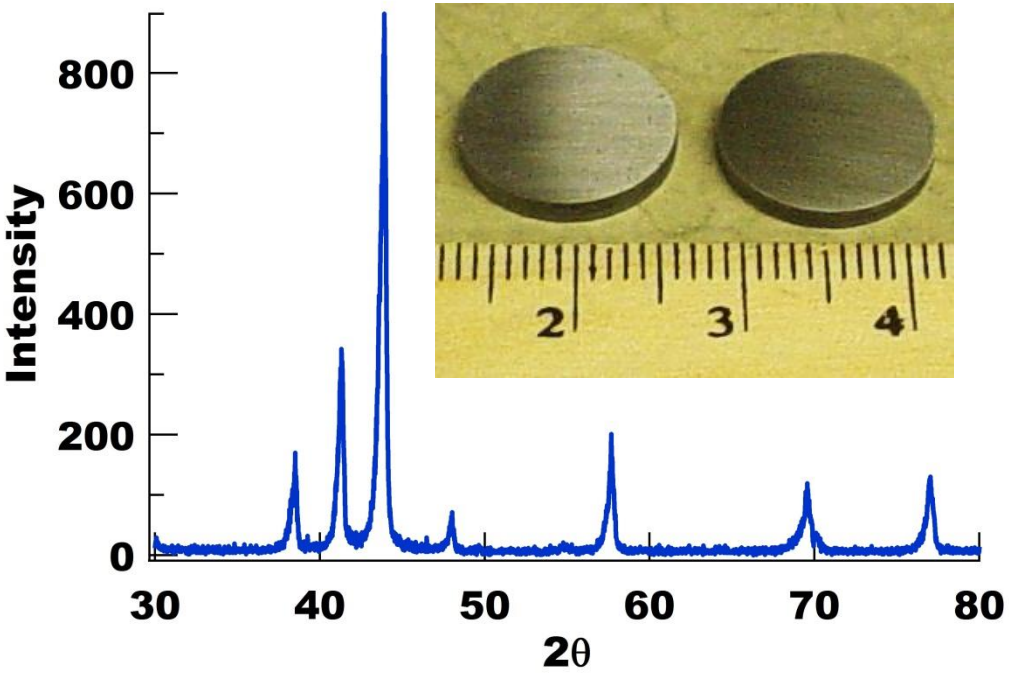
Hungría et. al., Adv. Eng. Mater. Vol. 11 (2009) 616; DOI: 10.1002/adem.200900052

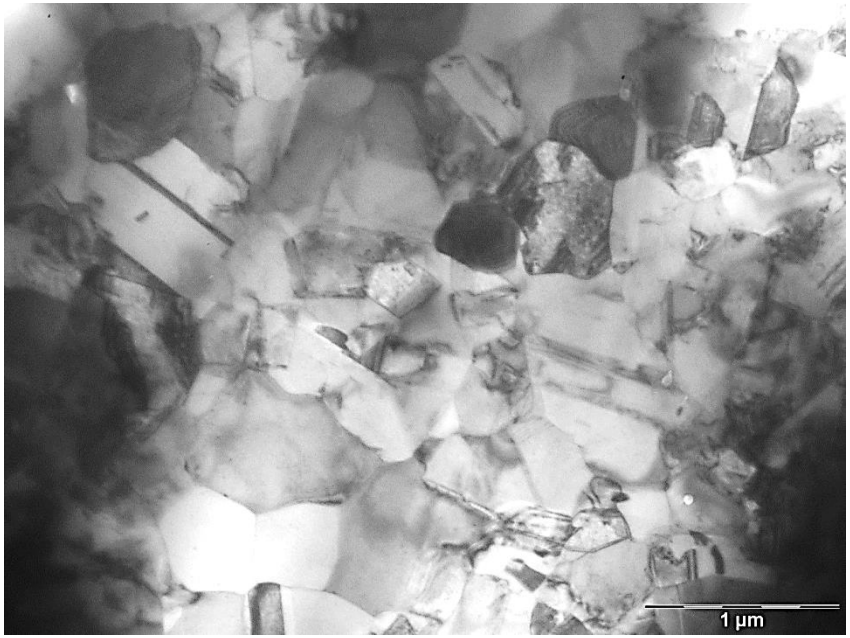
SPS System Manufacturers:

- Fuji Electronic Industrial Co. (Japan)
- FCT Systeme GmbH (Germany)
  - Can make components up to 500 mm (~20”) in diameter
- Thermal Technology LLC (Santa Rosa, CA)

- Size of equipment increasing to accommodate commercial needs
- Technology for continuous SPS under development
- A large number of companies have acquired SPS but often request this info to not be made public to maintain a competitive advantage

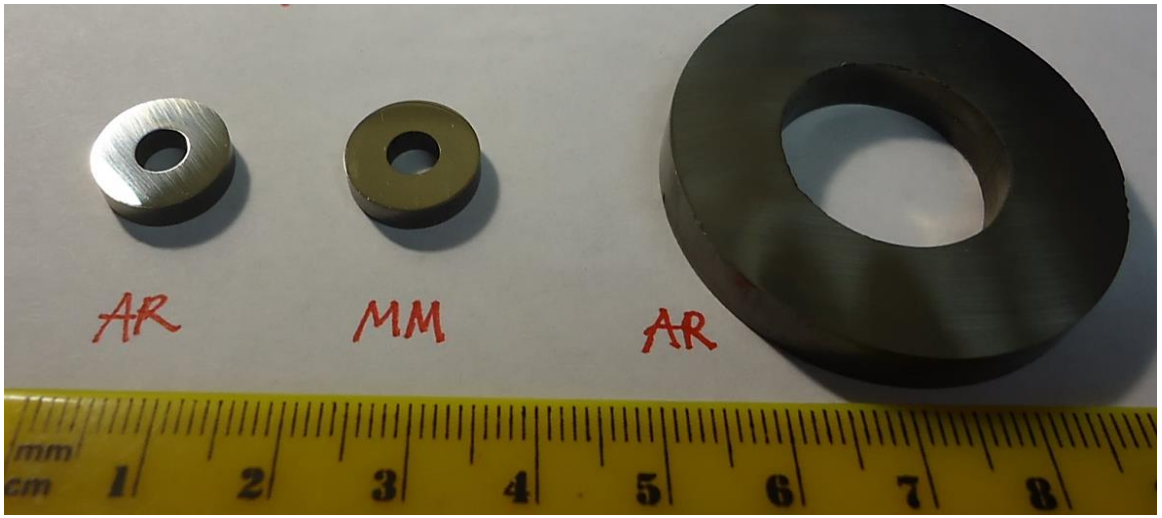
World's first bulk γ'-Fe_4N!





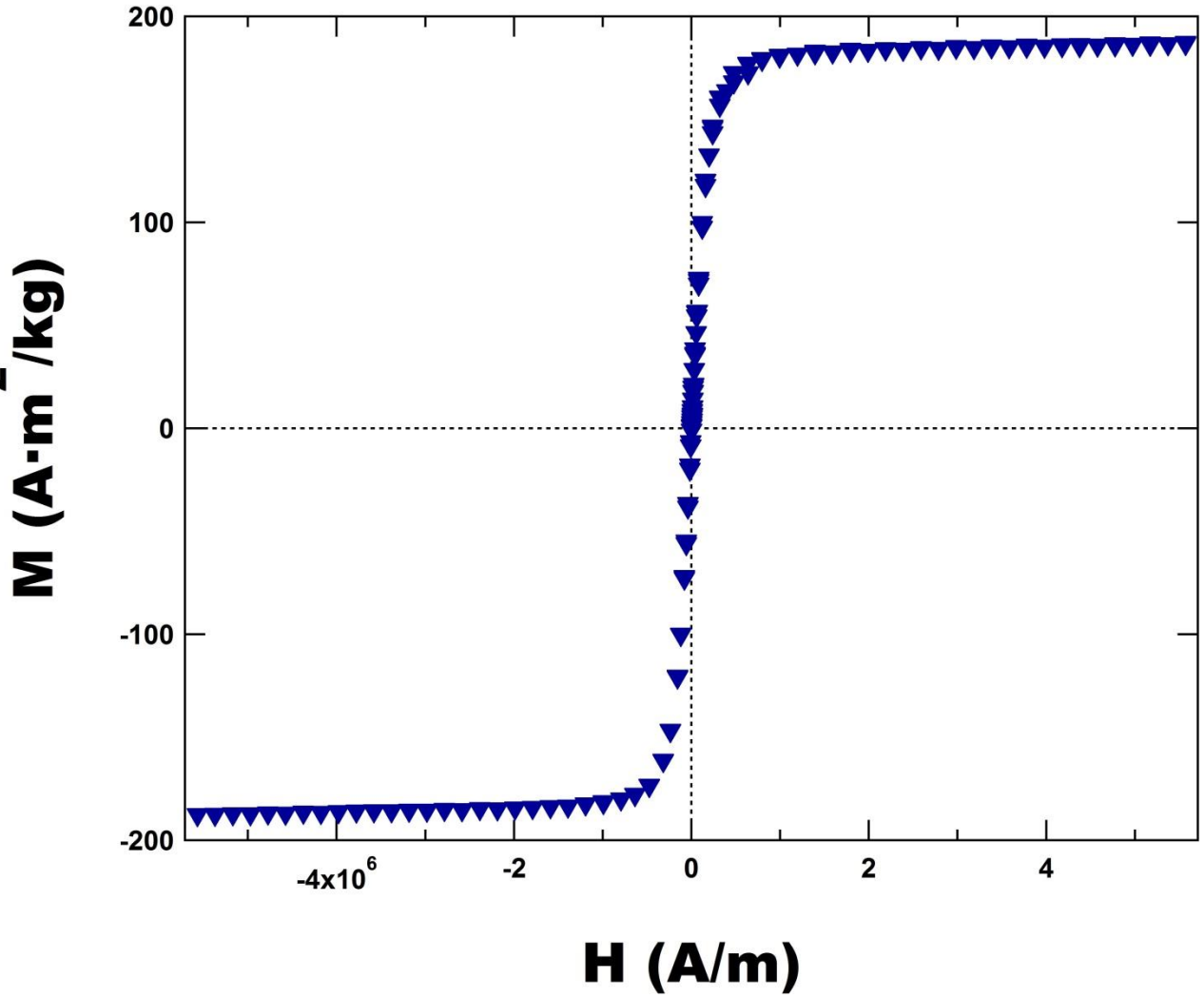
- Fe nitride powders well consolidated with little porosity
- Grain sizes 200 nm – 1 µm → fine grain size = low loss
- γ'-Fe_4N primary phase
- Fe_3N secondary phase from mixed phase starting material

Net-Shaping of Transformer Cores



- Can sinter toroids and other shapes directly (net-shaping)
- Eliminates the need for any machining

Magnetic Characterization



- Fe_4N SPSed at 550°C and 100 MPa achieved an M_{sat} of 188 $A \cdot m^2/kg$.
- Predicted M_{sat} of bulk γ'-Fe_4N is 209 $A \cdot m^2/kg$ (Fe is 217 $A \cdot m^2/kg$)
- Negligible coercivity

Summary/Conclusions

- **γ'-Fe_4N has the potential to serve as a new low cost, high performance transformer core material**
  - **M_{sat} > Si steel**
  - **Increased field and current (and therefore power) carrying capability**
  - **Resistivity 200X greater than nanocrystalline and amorphous alloys**
  - **Only requires low cost and abundant elements (Fe & N)**
  - **High temperature (T) operation complementing Sandia development of high T capacitors and WBG semiconductors**

Patents:

T. C. Monson, K. Waldrip, "Electrochemical Solution Growth of Magnetic Nitrides," U.S. Patent Application # 14/531,075.

T. C. Monson, E. J. Lavernia, B. Zheng, Y. Zhou, "Method to Synthesize Nanocrystalline Iron Nitride," U.S. Patent Application # 15/002,220

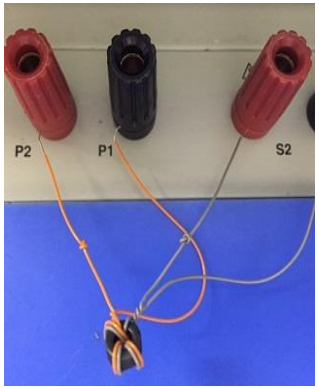
Presentations:

MMM-Intermag, Advances in Magnetics, Magnetics 2015, IECON 2014

Manuscript in review at IEEE Magnetics Letters

Future Tasks

- SPS processing parameters are being modified to improve phase purity, grain structure, and magnetic performance
- Parallel development of improved synthesis route to pure nanocrystalline γ'-Fe_4N raw powders
- Evaluation and comparison of transformers at high frequency and elevated temperatures



Acknowledgements

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

Questions?

Principal Investigator Contact Information:

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Extra Slides

Magnetic Devices Impact Power System Volume and Weight

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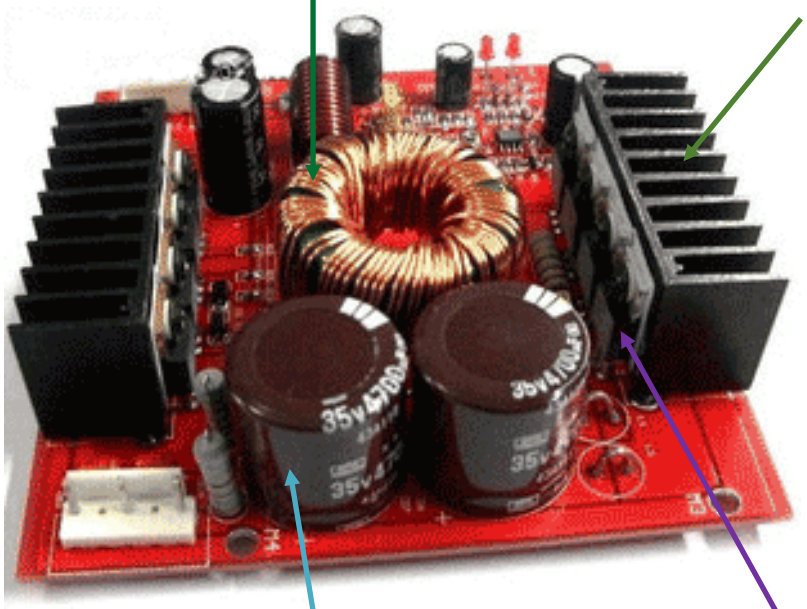
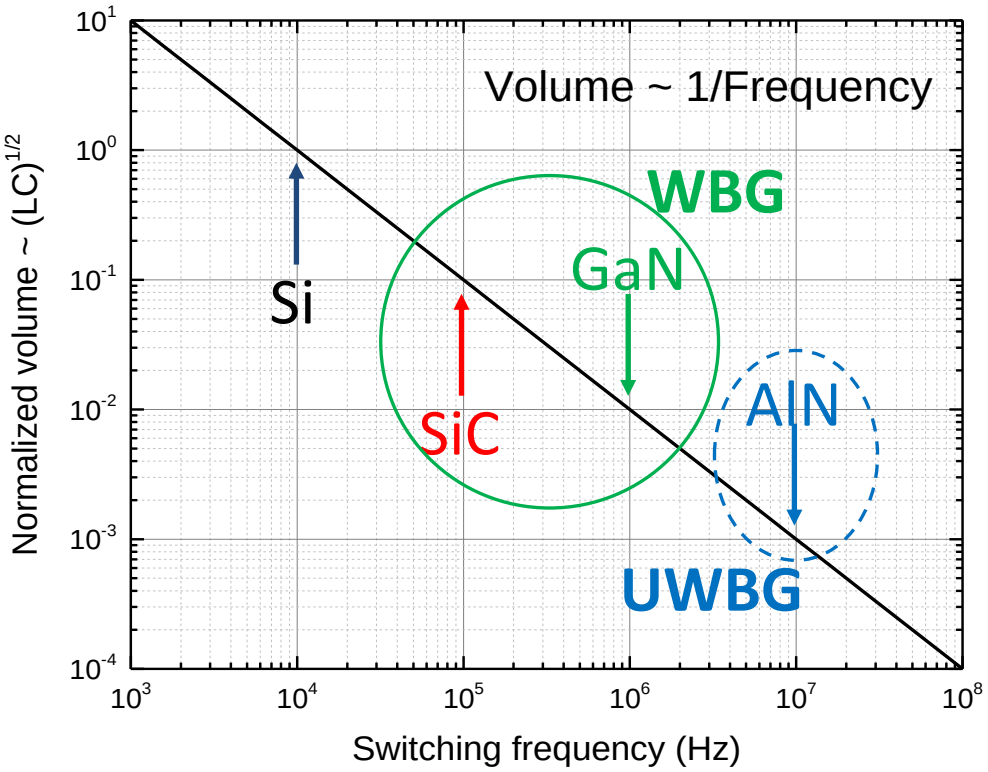
Passive elements and thermal management comprise the bulk of the volume and mass of a power converter

WBG/UWBG materials enable higher switching frequency and better thermal management



J. Neely, J. Flicker, B. Kaplar (SNL)

Higher Frequencies Decrease Inductance Requirements, However…



- **Higher switching frequency is enabled by scaling properties of WBG/UWBG materials**
- **Ideal 1/f SWaP dependence (true dependence likely weaker $1/f^n$ with $n < 1$ due to nonidealities)**
- **Other benefits exist, e.g. higher voltage without series stacking of devices, and higher temperature operation**
- ***UWBGs may be required for specialized applications such as pulsed power***

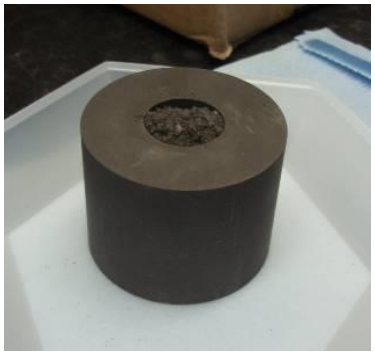
Inductive core materials have essentially been an afterthought and new magnetic materials are needed

Adapted from Bob Kaplar (SNL)

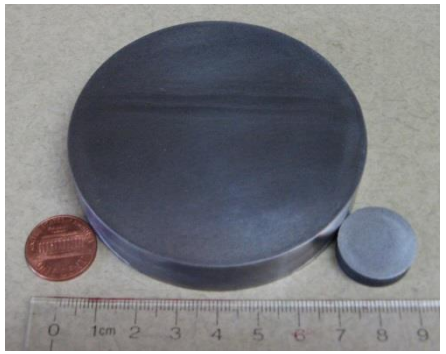
Spark Plasma Sintering (SPS)

Sandia National Laboratories

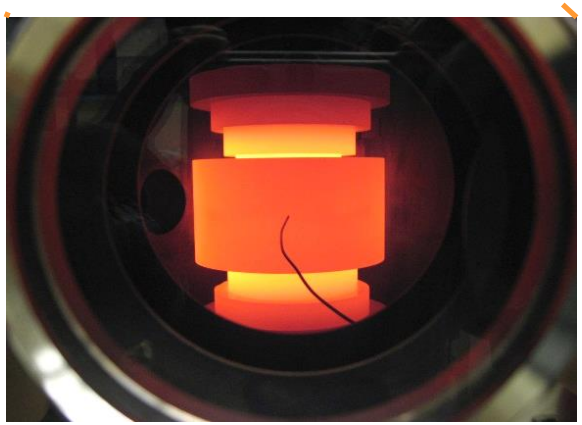
SPS Model: SPS-825S Dr. Sinter® at UCD



Starting Powder in Die



End Product



SPS Chamber