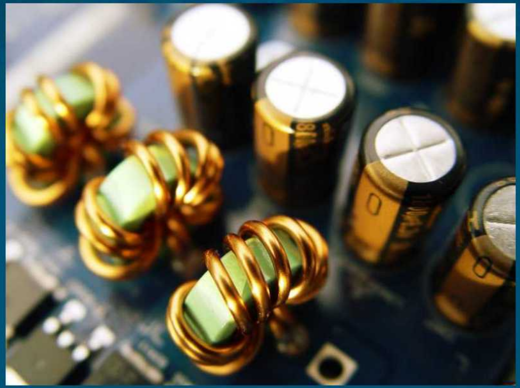
SAND2020-2650C

Advancements in soft magnetic materials for future energy needs



PRESENTED BY

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GERA: Towards realizing the energy future

2020 APS March Meeting

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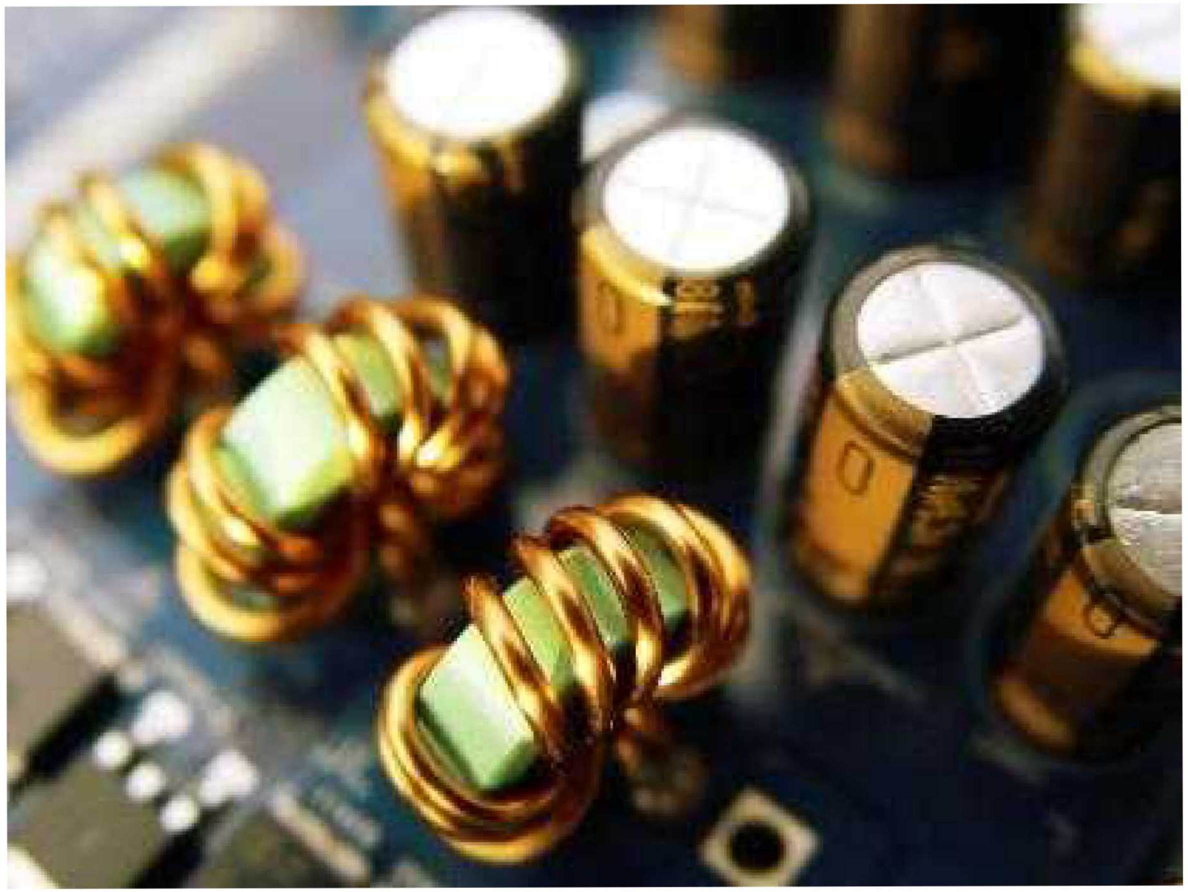
Outline

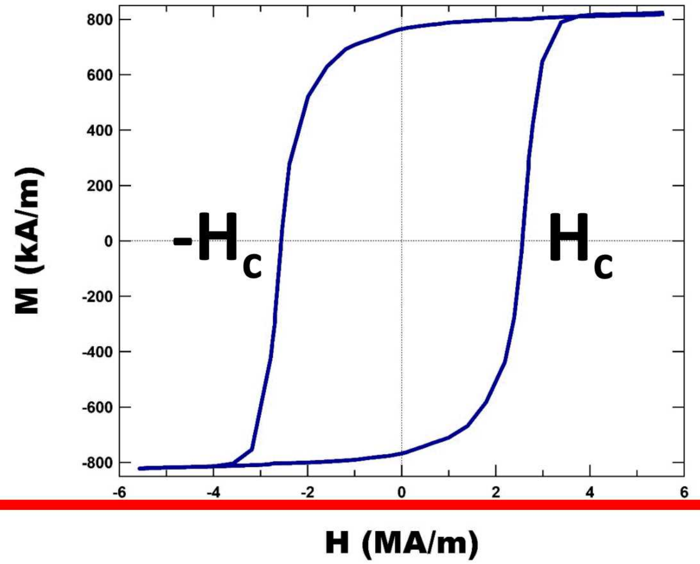
- Introduction
- Soft Magnetic Materials
  - Applications/needs
  - History
  - Current state of the art
  - Challenges
  - Opportunities

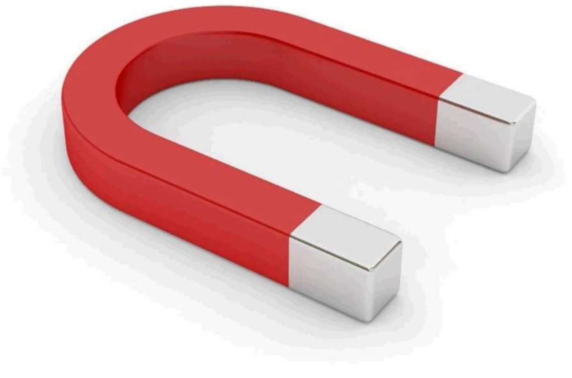


Hard vs. Soft Magnets

Hard (permanent) magnet

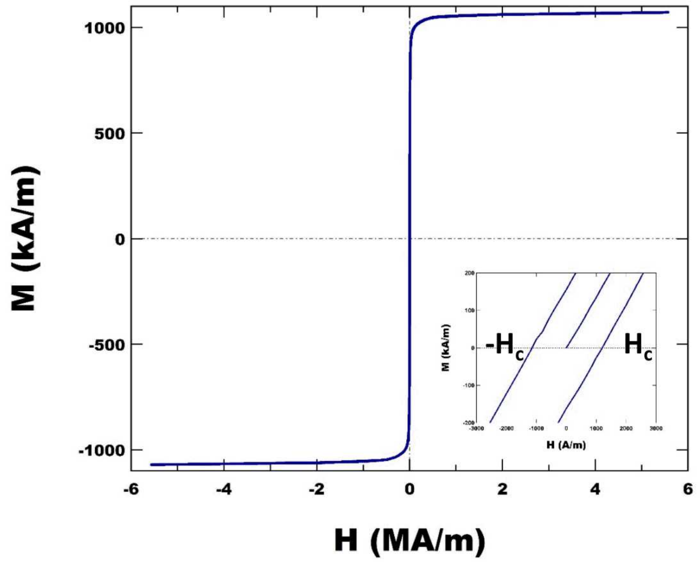
H_c > 1000 A/m

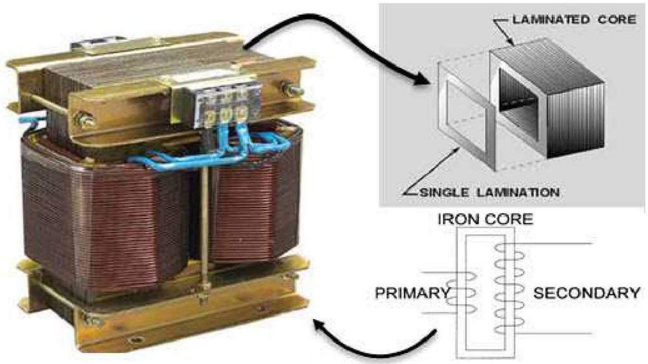


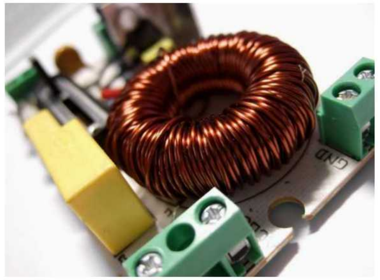


Soft magnet

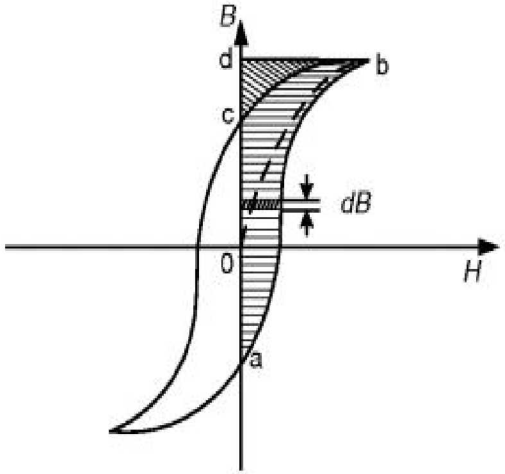
H_c < 1000 A/m

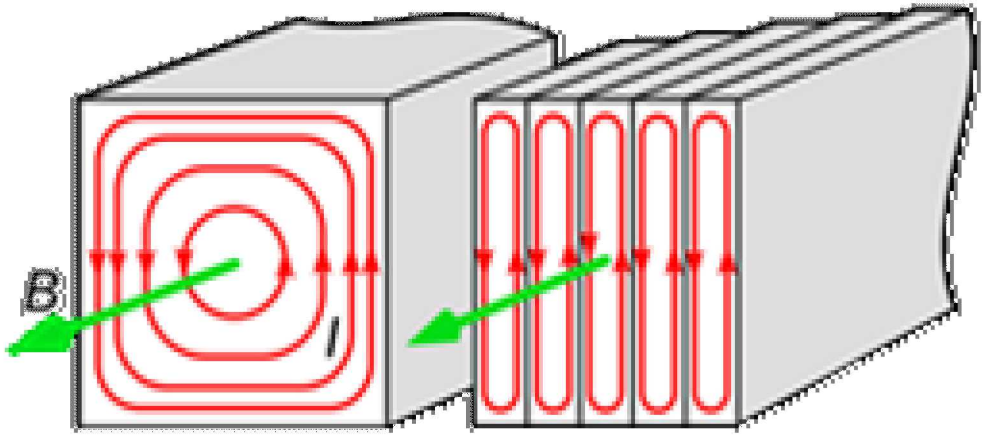




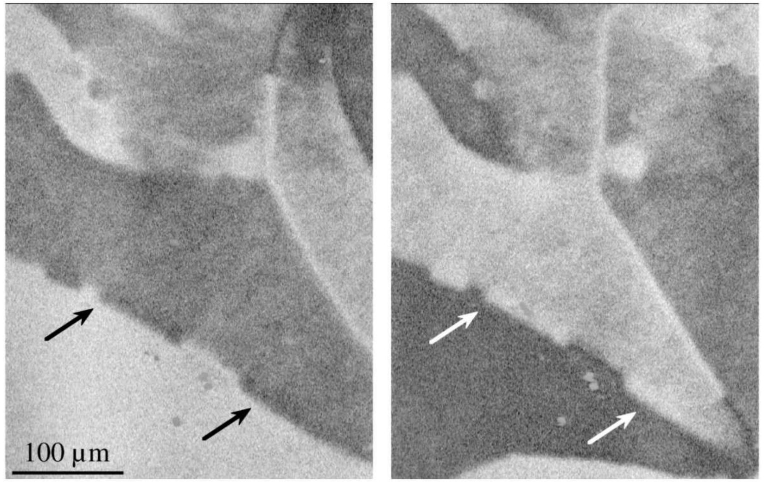


Magnetic Losses





R. Schaefer and G. Herzer, "Continuous magnetization patterns in amorphous ribbons," IEEE Transactions on Magnetics, vol. 37, pp. 2245-2247, 2001.



$$\frac{P_{hys}}{V} = \oint H(t)dB$$

$$\frac{P_{eddy}}{V} = \frac{\omega B^2 A}{48\rho}$$

Hysteresis

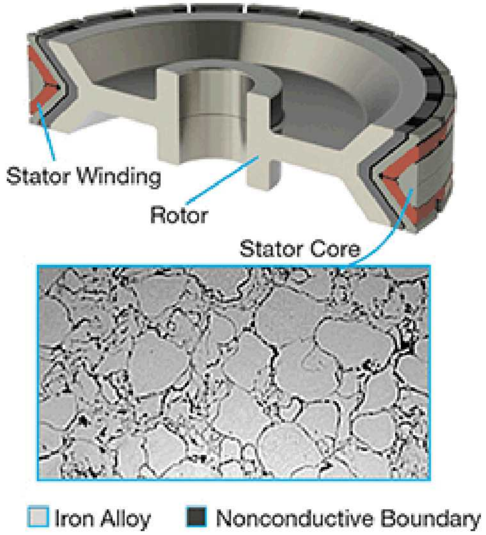
Eddy Currents

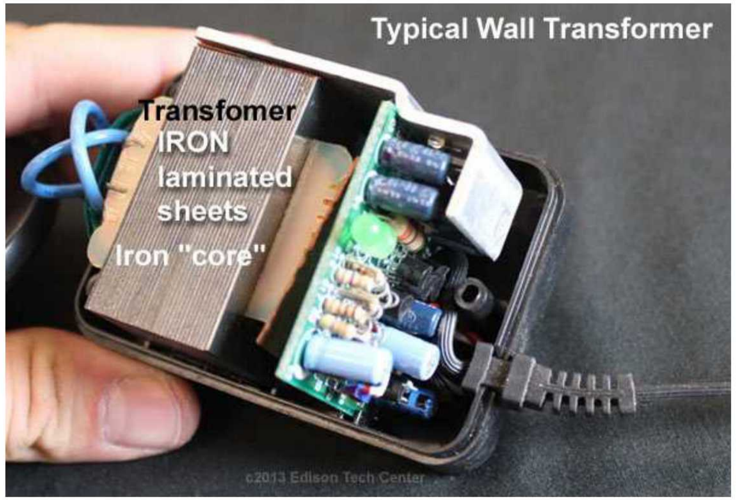
Domain Wall Motion

Soft Magnet Energy Related Applications

Inductor cores

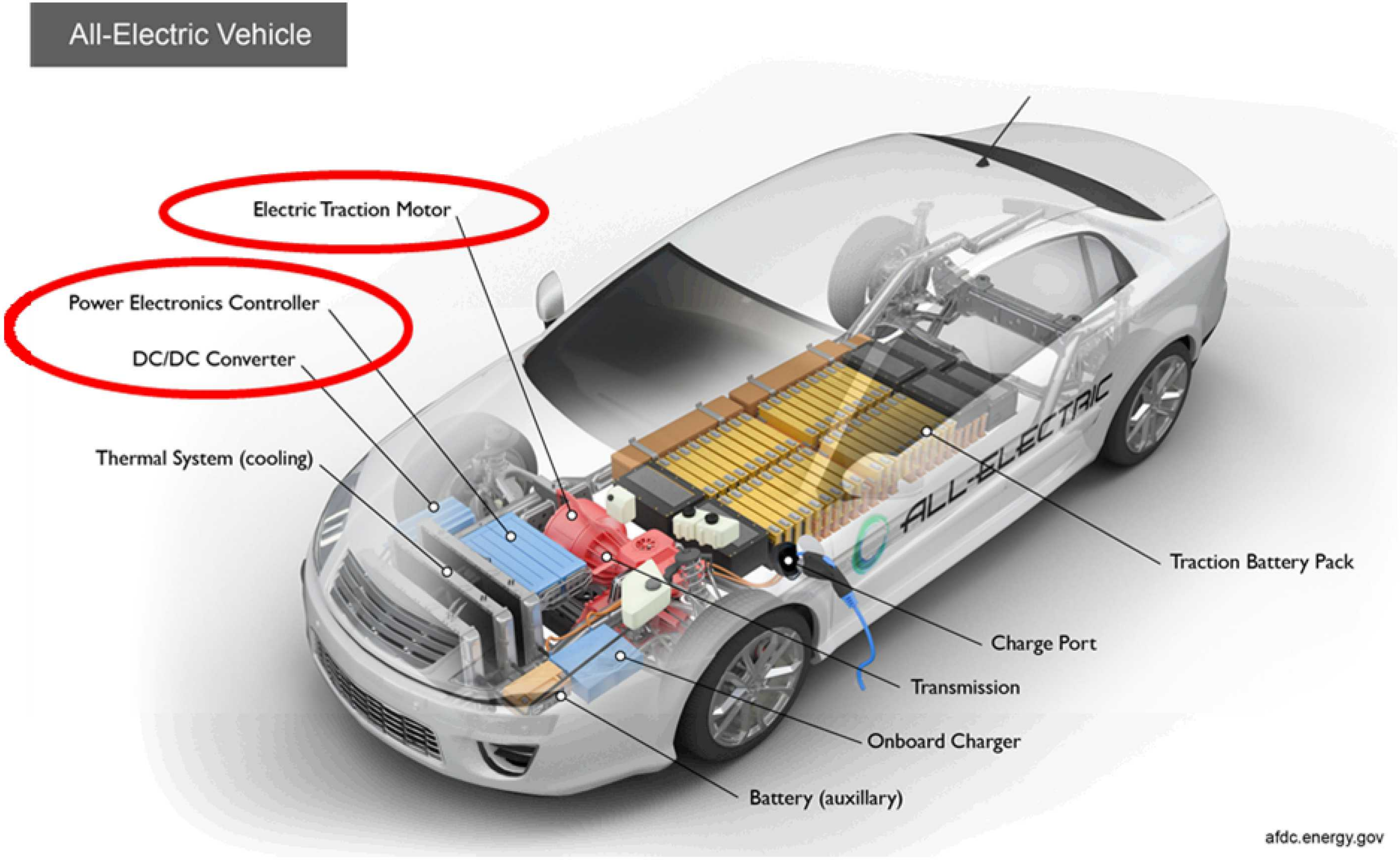
Transformer cores





Electrical machines (motors & generators)

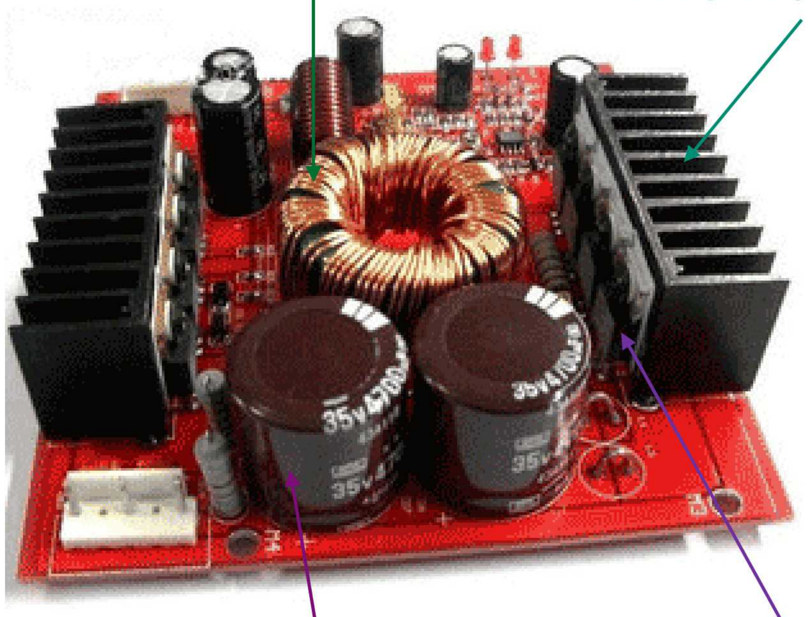
Electric Vehicles



Magnetics Impact Power Conversion Volume and Weight

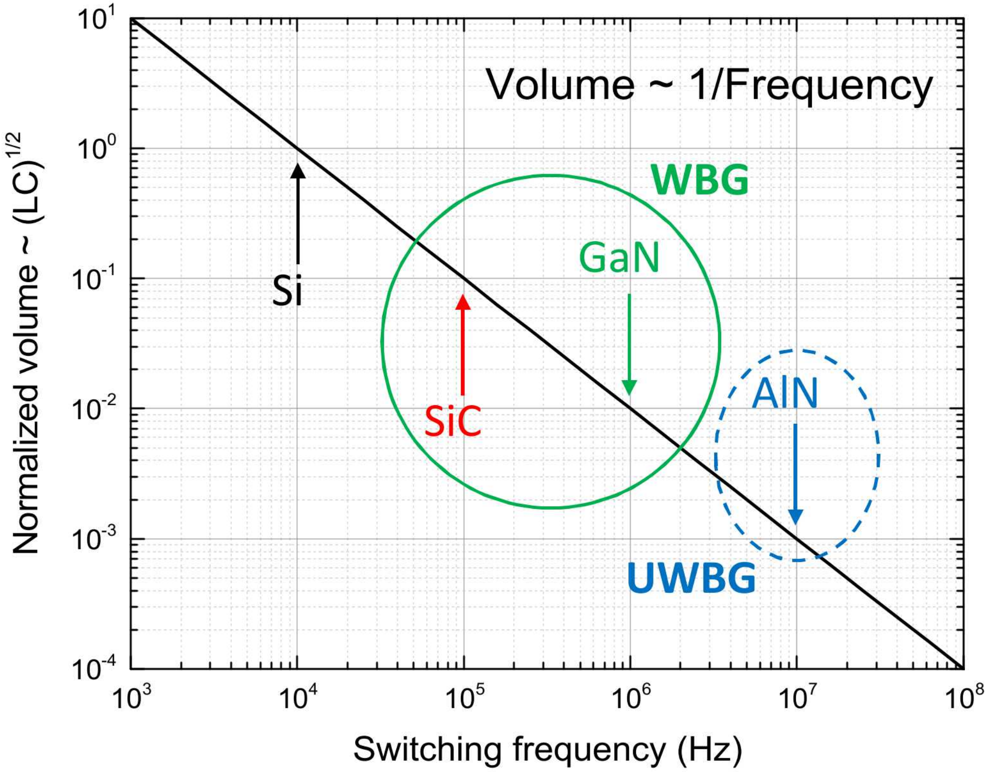
Passive elements and thermal management comprise the bulk of the volume and mass of a power converter

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



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

Higher Frequencies Decrease Inductance Requirements, However…

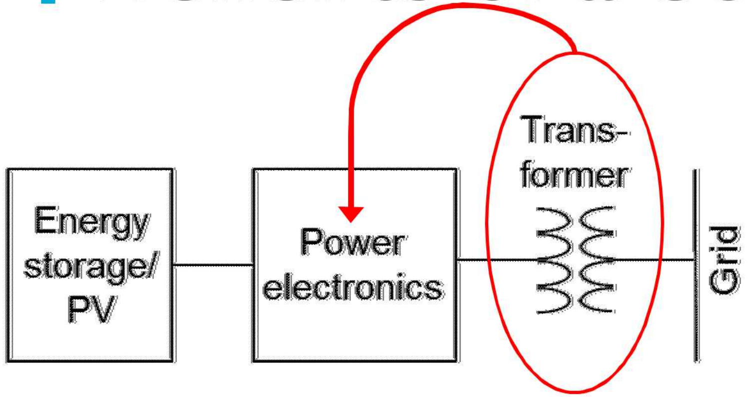


- **Higher switching frequency is enabled by scaling properties of WBG/UWBG materials**
- **Ideal 1/f SWaP dependence (true dependence likely weaker $1/f^n$ with $n < 1$ due to nonidealities)**
- **Other benefits exist, e.g. higher voltage without series stacking of devices, and higher temperature operation**

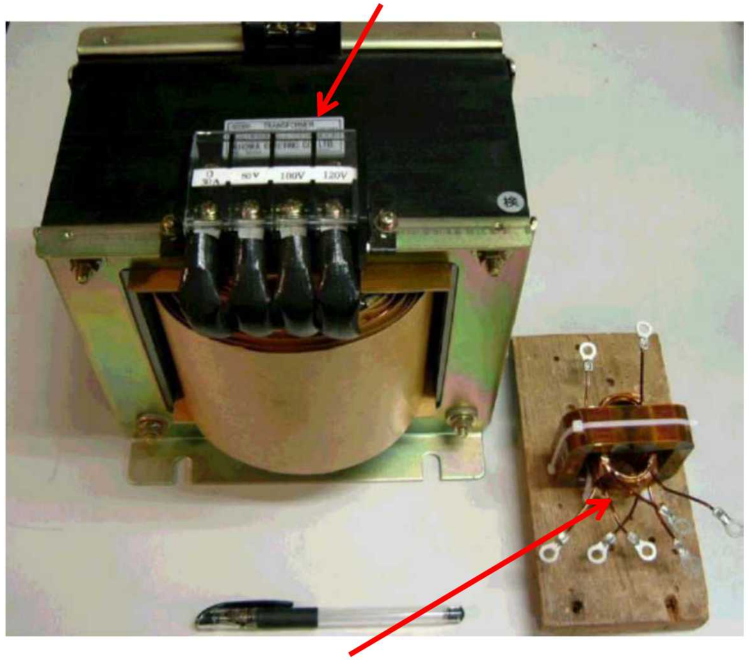
Inductive core materials have essentially been an afterthought and new magnetic materials are needed

Adapted from Bob Kaplar (SNL)

Benefits of a Solid State Transformer



Line frequency (50 Hz) transformer



High frequency (20 kHz) transformer

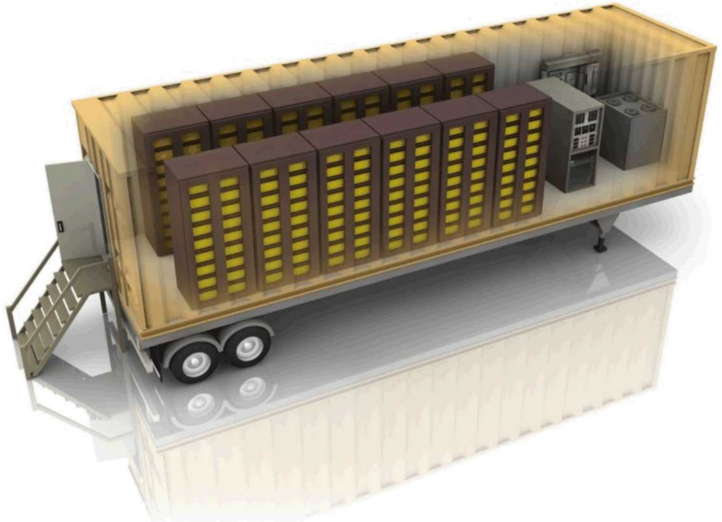
S. Krishnamurthy, Half Bridge AC-AC Electronic Transformer, IEEE, 1414 (2012).

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

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 reliability and better SWaP**

Transportable Energy Storage and Power Conversion Systems (PCS)



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**

Microinverters for PV

Improved soft magnetic materials improve performance and decrease size of all inverters

Central Inverter
(1 per solar *system*)

or

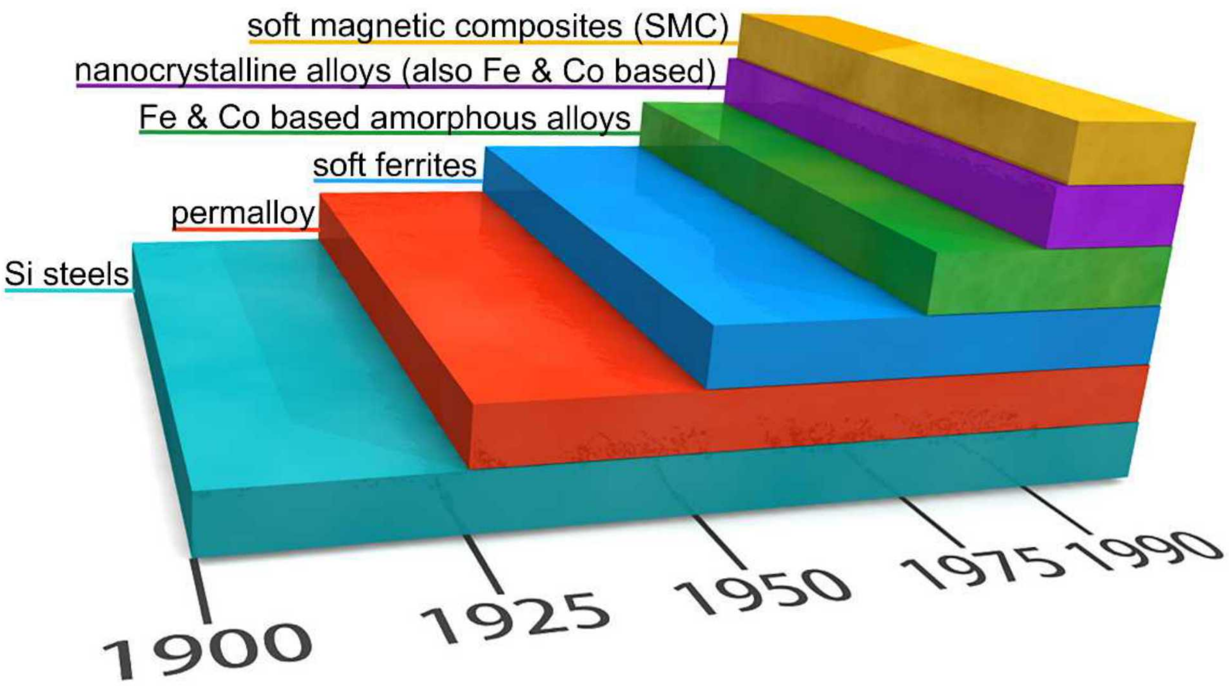
Micro-inverter
(1 per solar *panel*)

Can increase overall system efficiency by accommodating:

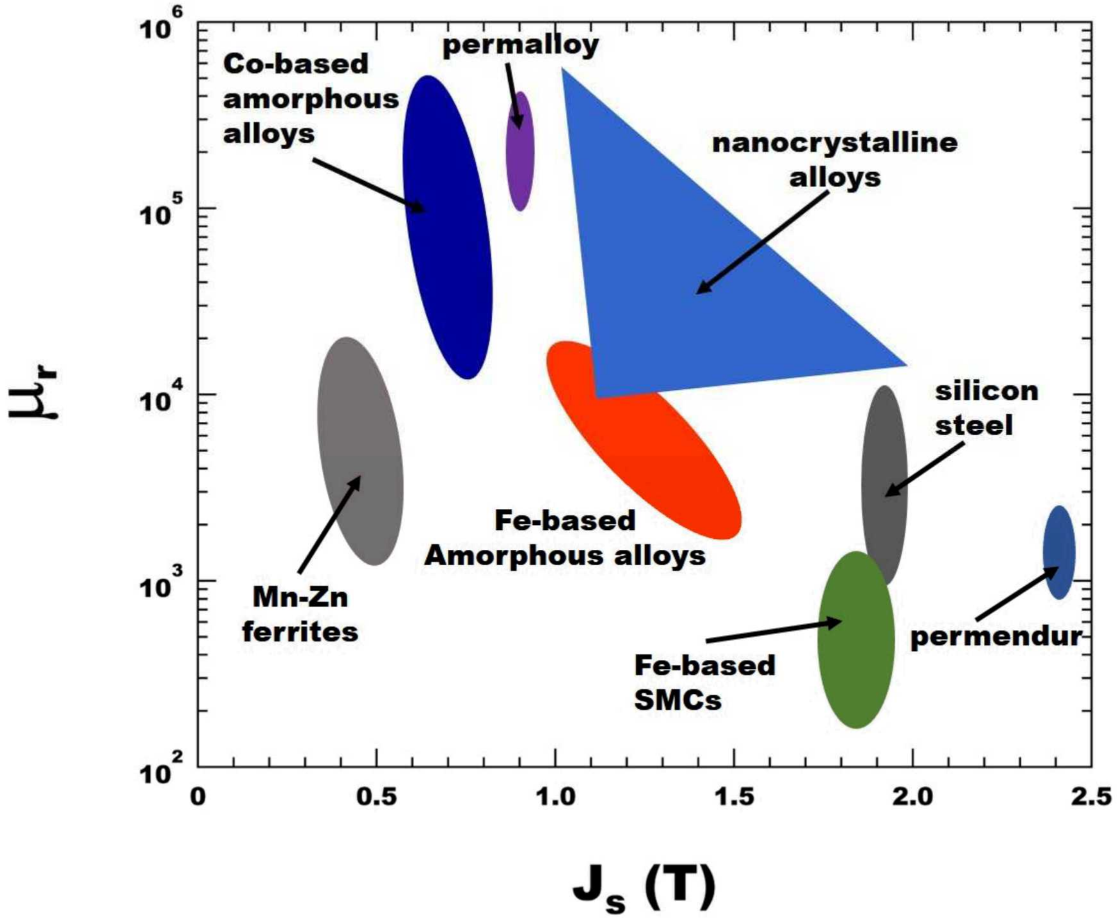
- Solar panel mismatch
- Panel orientation
- Shading

Less loss → Less waste heat → Less failures

Soft Magnetic Materials



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).

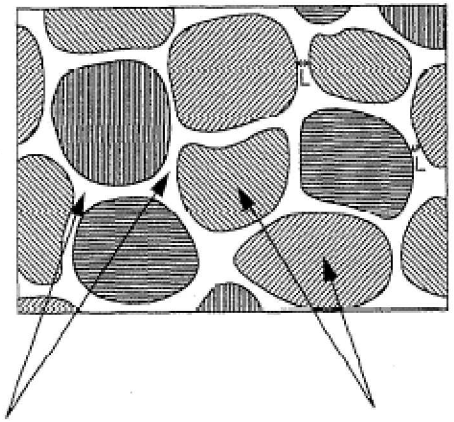


Adapted from: F. Fiorillo, G. Bertotti, C. Appino, M. Pasquale, and J. G. Webster, "Soft Magnetic Materials," in *Wiley Encyclopedia of Electrical and Electronics Engineering*: John Wiley & Sons, Inc., 1999.

$$P_{max} \propto J_s^2$$

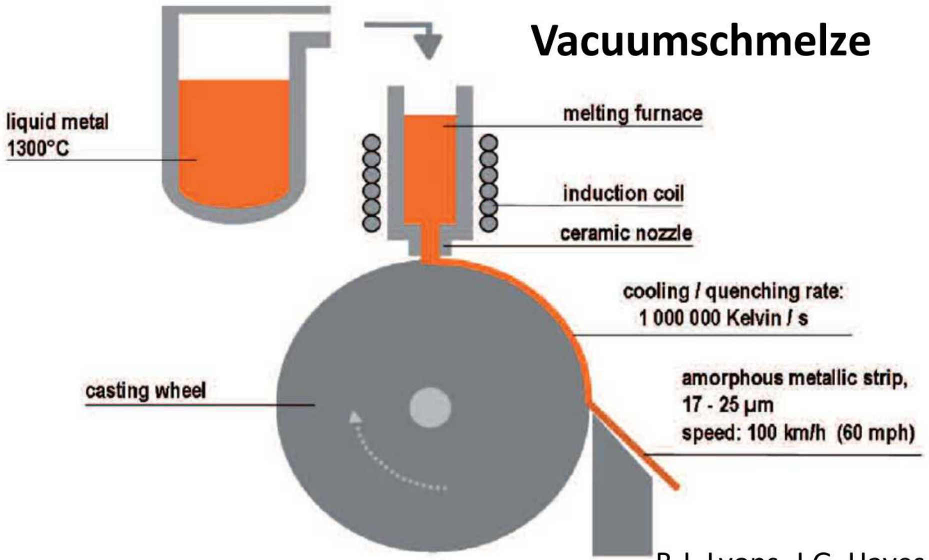
Amorphous & Nanocrystalline Alloy Manufacturing

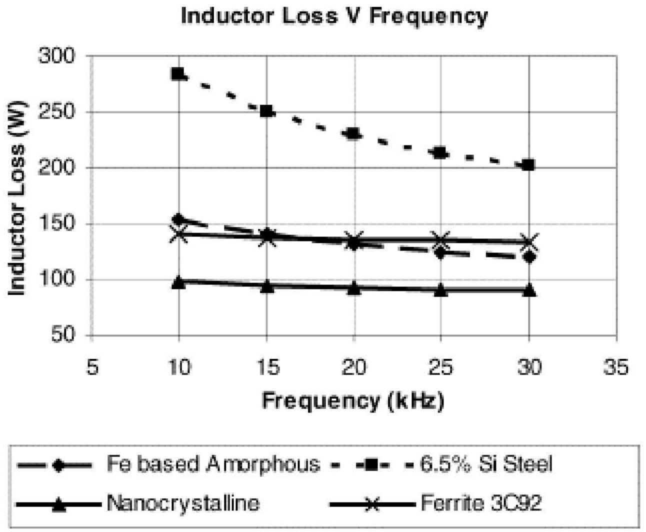
"NANOPERM"



A. Makino, et. al., Nanocrystalline Soft Magnetic Fe-M-B (M = Zr, Hf, Nb) alloys and their applications, Mat. Sci, and Eng., A226-228, 594 (1997).

Vacuumschmelze





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).

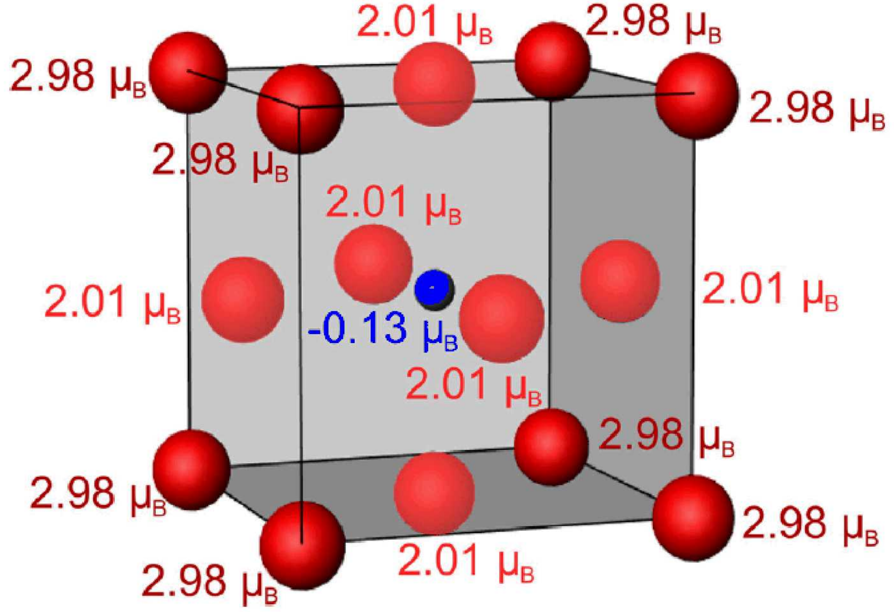
- Complex stoichiometries including Fe and/or Co
  - Many other non-magnetic elements such as B, Zr, Hf, Nb, Cu, Mo, Si, C
- Material produced in tapes 5 – 20 µm thick
- Up to several cm wide
- Can be difficult to stamp into shapes

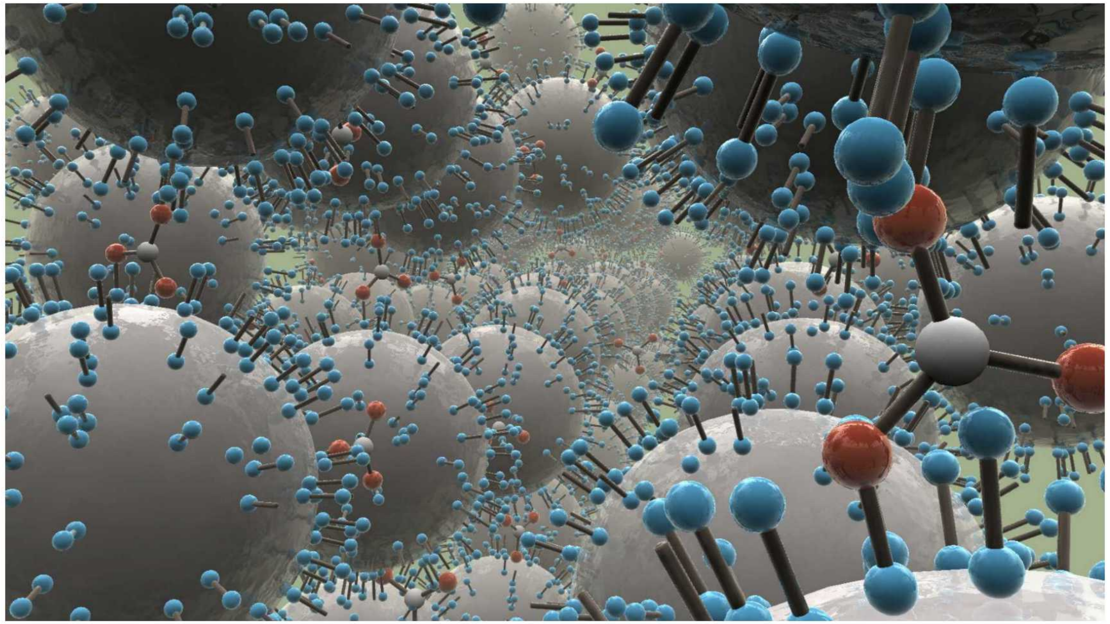
J. M. Silveyra, E. Ferrara, D. L. Huber, T. C. Monson, "Soft magnetic materials for a sustainable and electrified world," Science 362, 418 (2018).

Opportunities

- Improve existing materials
  - 3% → 6.5% Si (electrical) steel
  - Increasing M_s and tape width in amorphous and nanocrystalline alloys
  - Grain boundary engineering in ferrites
- Invent new materials
  - Nitrides
  - New composite (SMC) approaches
  - Ideas no one has thought of?
- Better control over crystallinity and grain size
- Better control over domain wall motion

γ’-Fe_4N unit cell

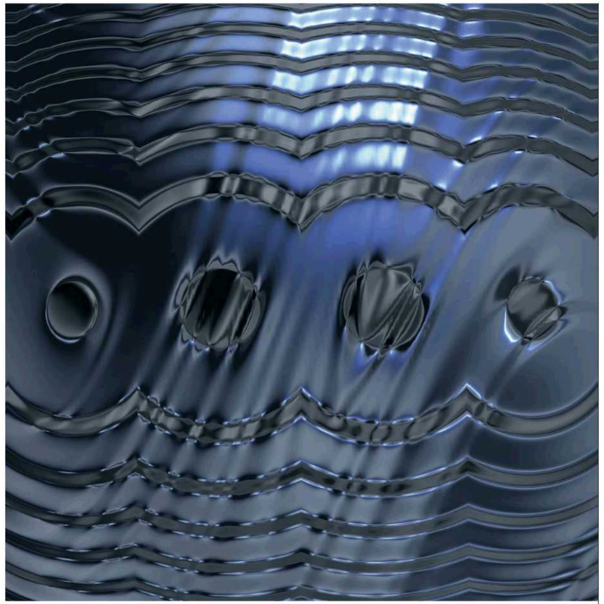




Fe nanoparticle nanocomposite

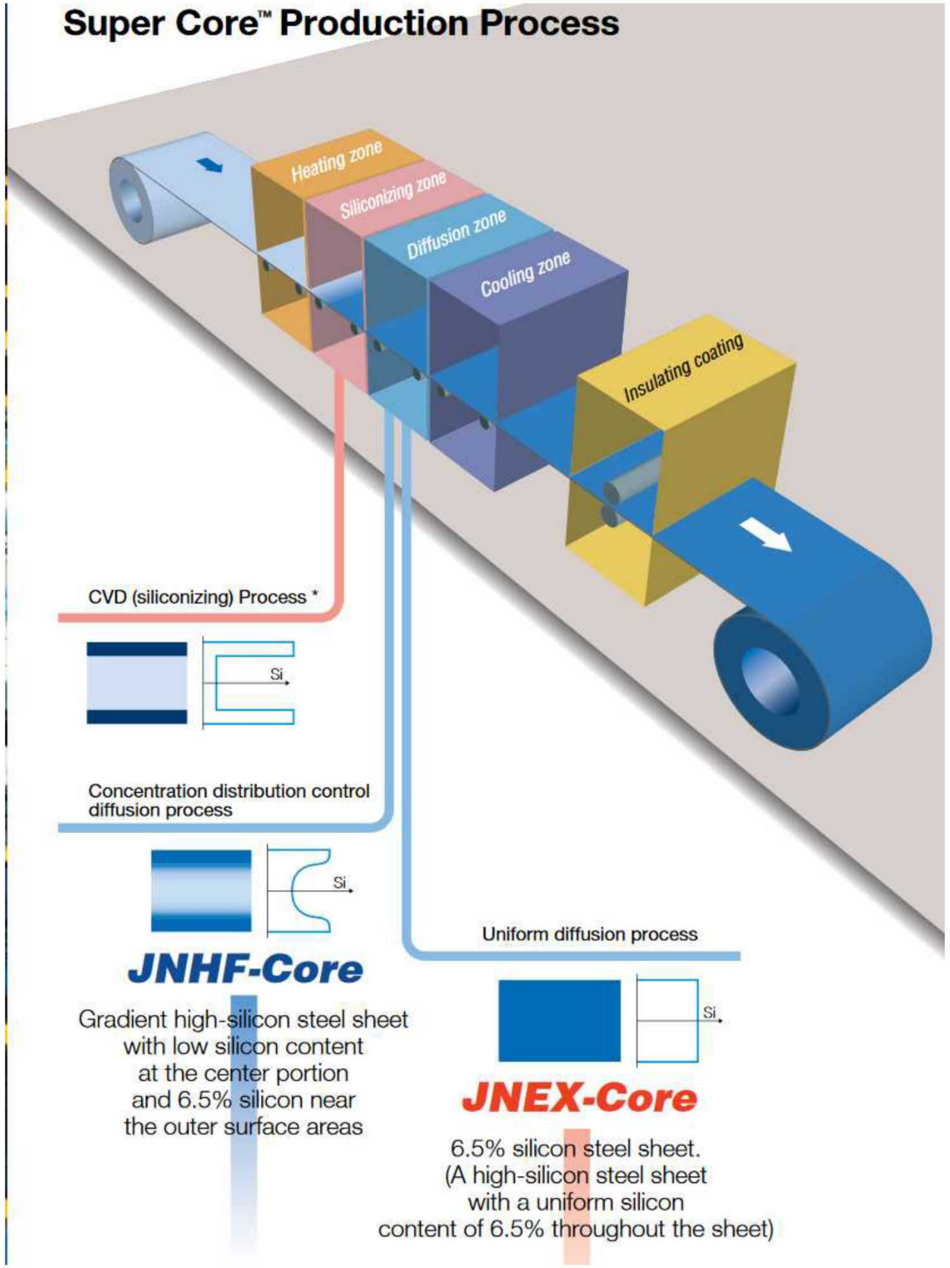
6.5% Si Steel, CVD Process

$$SiCl_4 + 5Fe \rightarrow Fe_3Si + 2FeCl_2$$

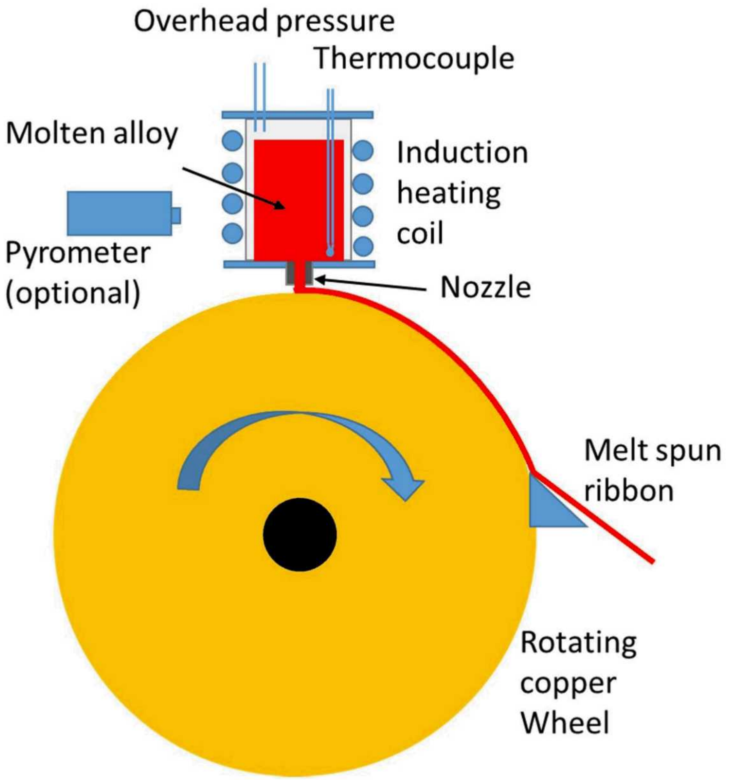


JFE Steel Corporation

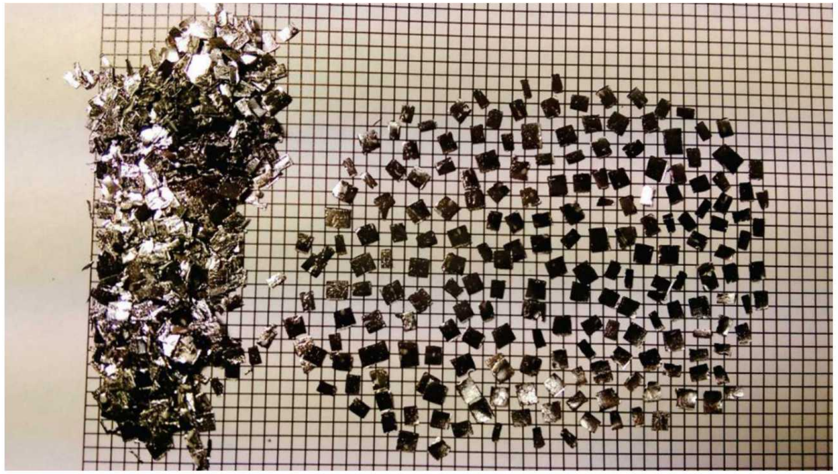
Material	Thickness (mm)	Specific resistance (μΩ·m)	DC max relative permeability	Saturation magnetization (T)	Magnetic flux density B_8(T)	Magnetic flux density B_{25}(T)	Magnetostriction λ10/400 (×10⁻⁶)
JNEX-Core	0.10	0.82	23,000	1.80	1.29	1.40	0.1
Grain-oriented silicon steel	0.05 0.10 0.23 0.35	0.48	– 24,000 92,000 94,000	2.03	1.75 1.84 1.92 1.92	– 1.91 1.96 1.96	−0.8
Non-oriented silicon steel	0.10 0.20 0.35	0.57	12,500 15,000 18,000	2.05 2.03 1.96	1.58 1.44 1.45	– 1.53 1.56	7.8
Fe-based amorphous	0.025	1.30	300,000	1.50	1.38	–	27.0
Ferrite	Bulk	–	3,500	–	0.37	–	21.0



6.5% Si Steel, Melt Spinning



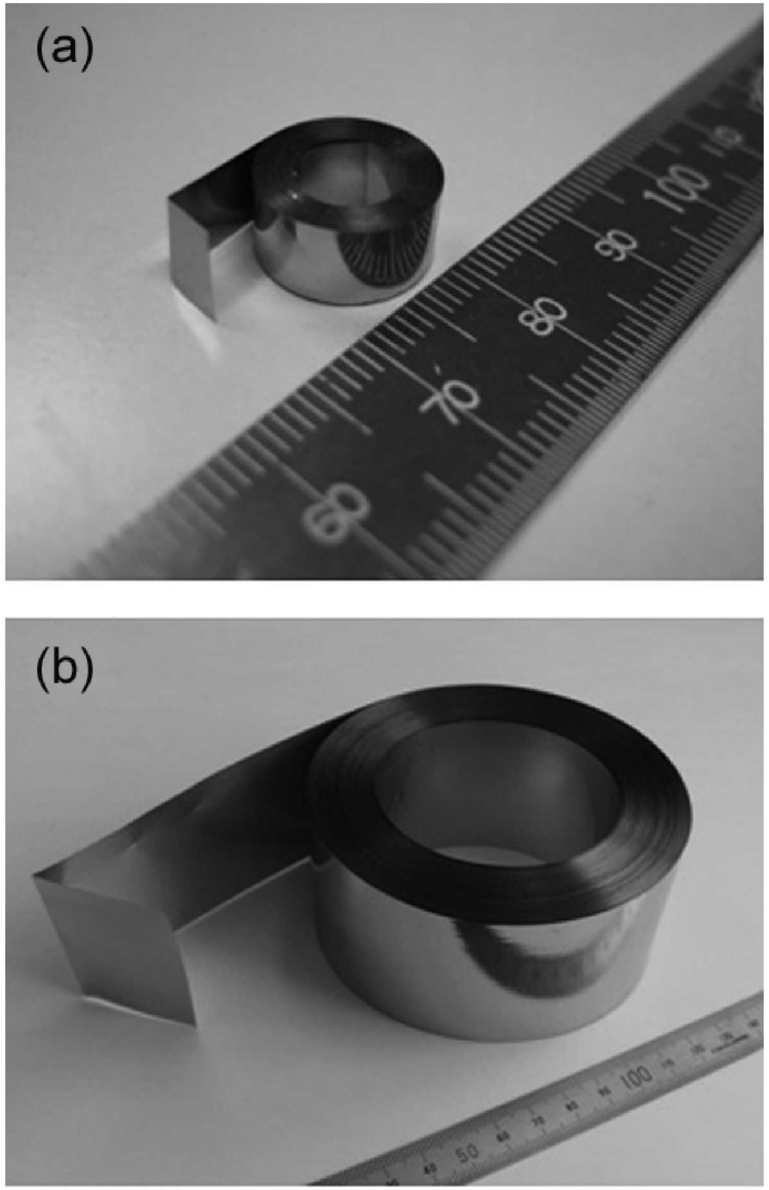
- Limited range of thickness (0.03 – 0.1 mm)
- Limited widths (< 300 mm)
- Currently used in laboratories to produce small batches (< 1 kg)



Cui, Jun, "Cost Effective 6.5% Silicon Steel Laminate for Electric Machines," Electrification 2018 Annual Progress Report, Vehicle Technologies Office, U.S. DOE

Ouyang, Gaoyuan & Chen, Xi & Liang, Yongfeng & Macziewski, Chad & Cui, Jun. (2019). Review of Fe-6.5 wt% Si high silicon steel—A promising soft magnetic material for sub-kHz application. Journal of Magnetism and Magnetic Materials. 481. 10.1016/j.jmmm.2019.02.089.

Improving Amorphous and Nanocrystalline Alloys



Theisen, E. (2017). Development of New Amorphous and Nanocrystalline Magnetic Materials for Use in Energy-Efficient Devices. *MRS Advances, 2*(56), 3409-3414. doi:10.1557/adv.2017.552

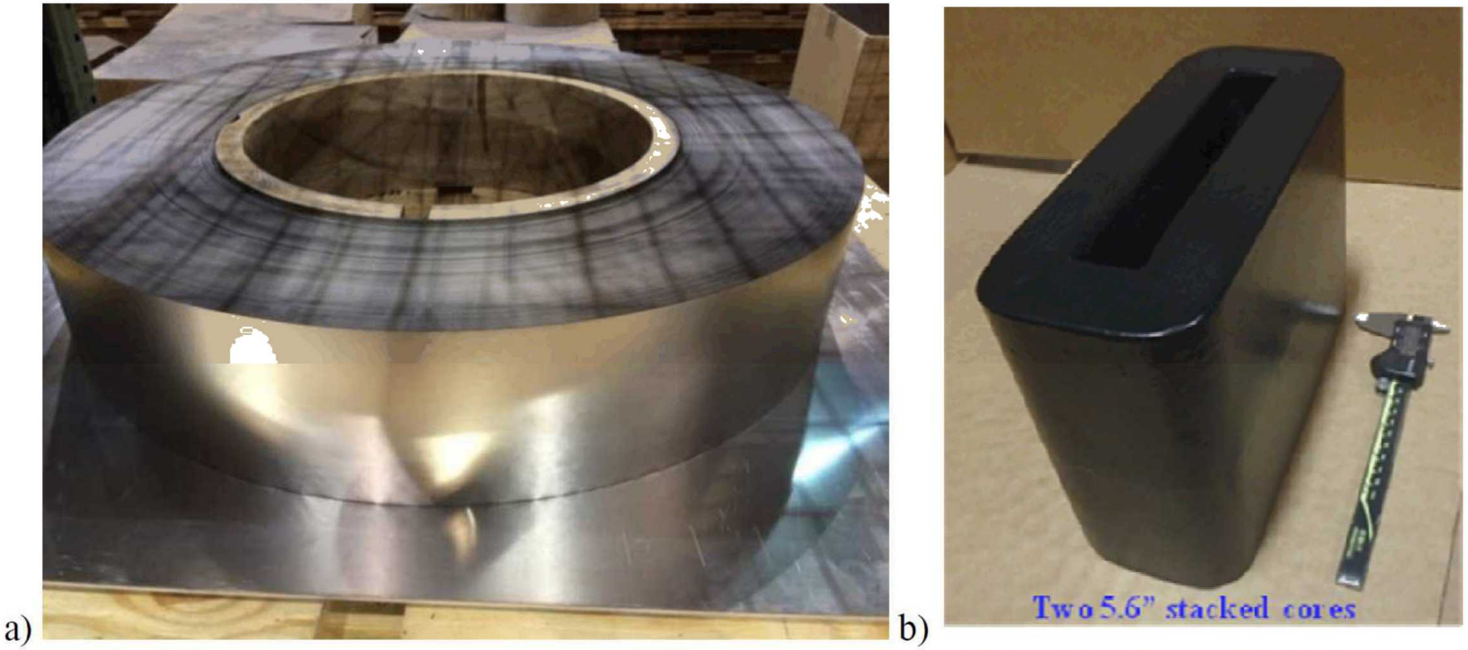
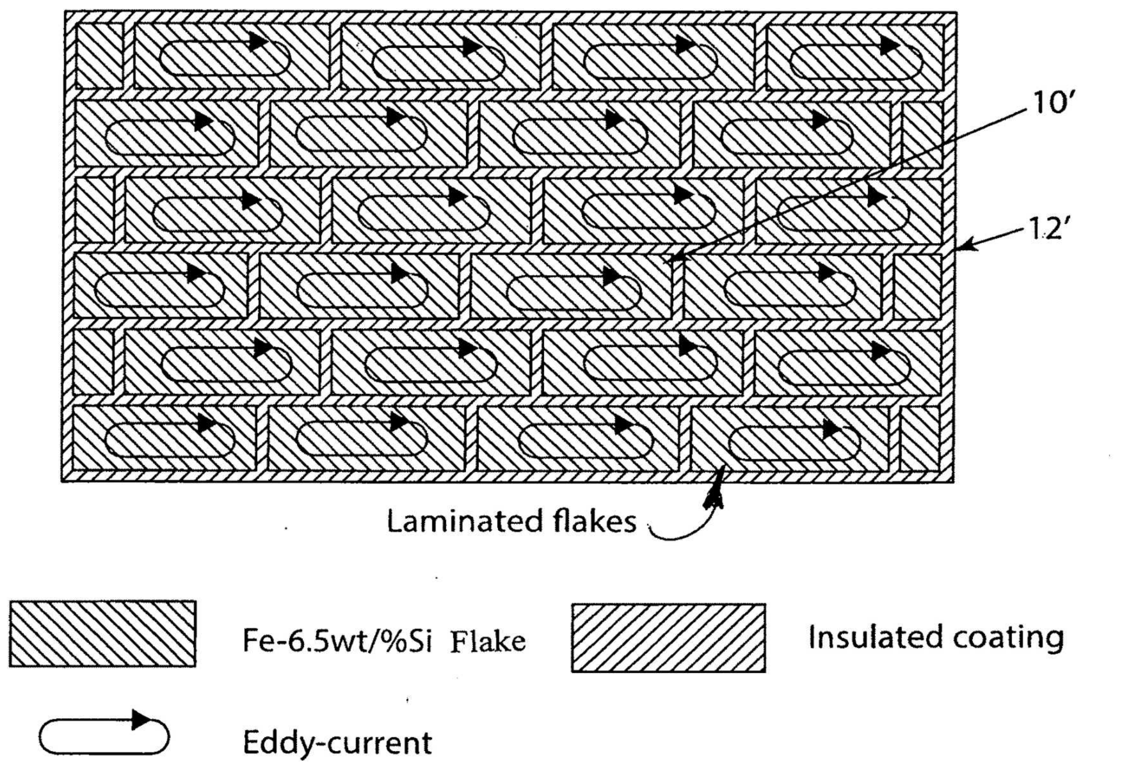
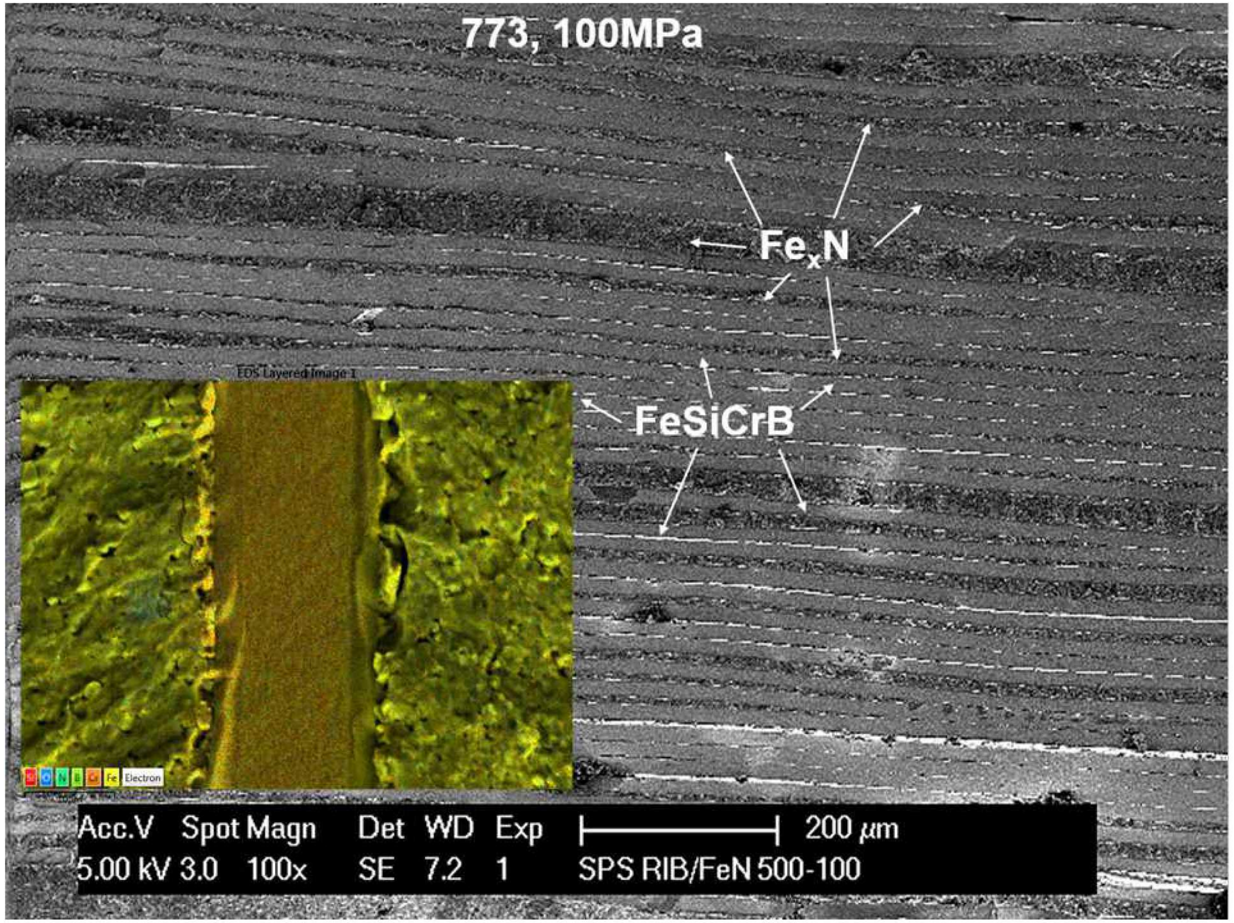


Figure 3: a) Full sized spool of 142mm (5.6") wide FT-3W weighing 500 kgs and b) Inductor core fabricated from the 142mm nanocrystalline FT-3W ribbon.

A. Makino, "Nanocrystalline Soft Magnetic Fe-Si-B-P-Cu Alloys With High B of 1.8–1.9T Contributable to Energy Saving," in *IEEE Transactions on Magnetics*, vol. 48, no. 4, pp. 1331-1335, April 2012. doi: 10.1109/TMAG.2011.2175210

Inorganic Magnetic Composites





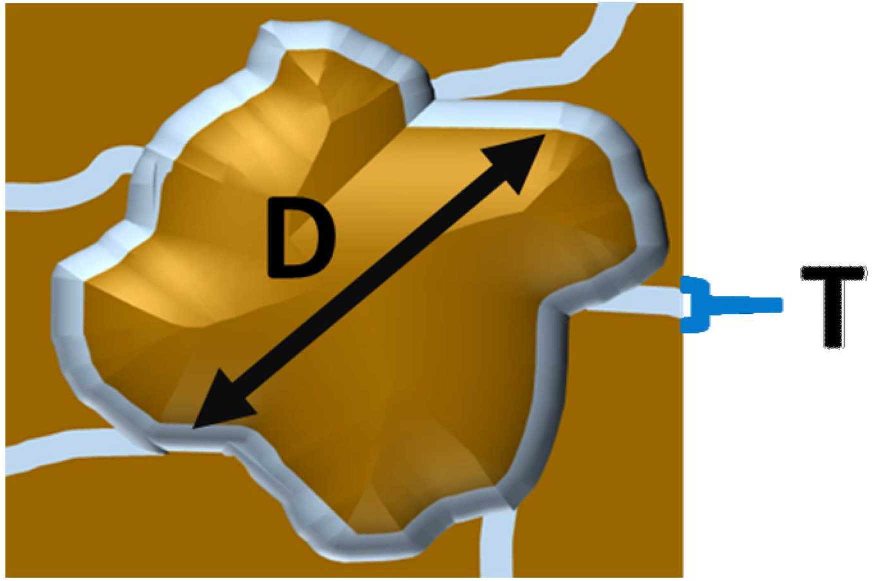
Cui, Jun, et al. "Near net shape bulk laminated silicon iron electric steel for improved electrical resistance and low high frequency loss." U.S. Patent Application No. 16/501,332.

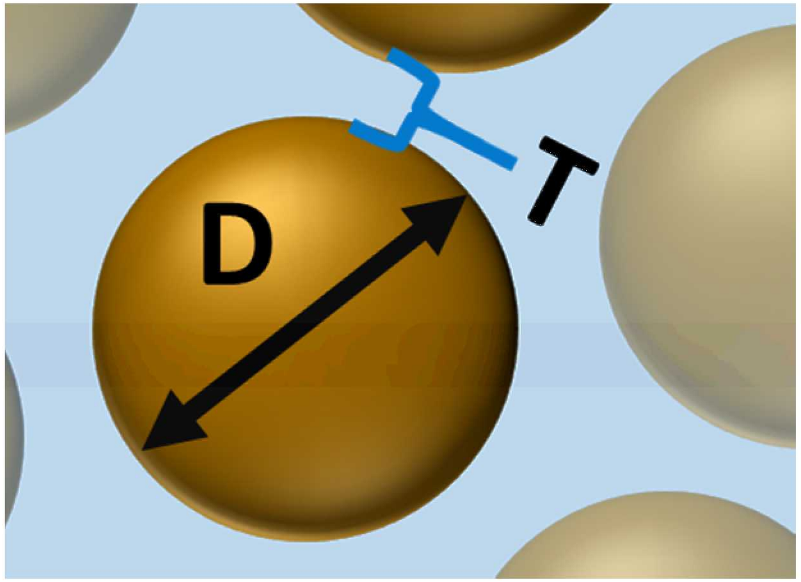
T. C. Monson, B. Zheng, R. E. Delany, C. J. Pearce, E. D. Langlois, S. M. Lepkowski, T. E. Stevens, Y. Zhou, S. Atcitty, E. J. Lavernia, “Soft magnetic multi-layered FeSiCrB-Fe$_x$N metallic glass composites fabricated via spark plasma sintering,” IEEE Magnetics Letters 10, 1-5 (2019).

Bottom-up Magnetic Composites, Organic Matrix

Current SMCs

New possibility



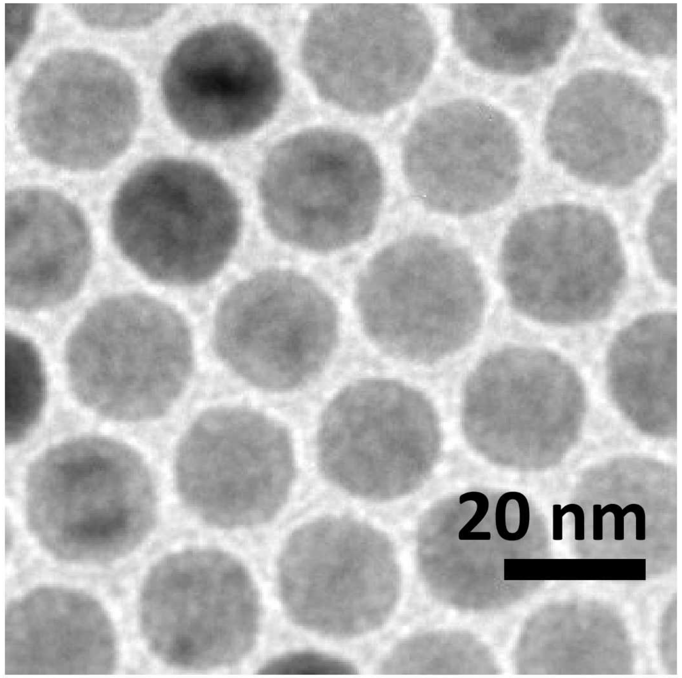


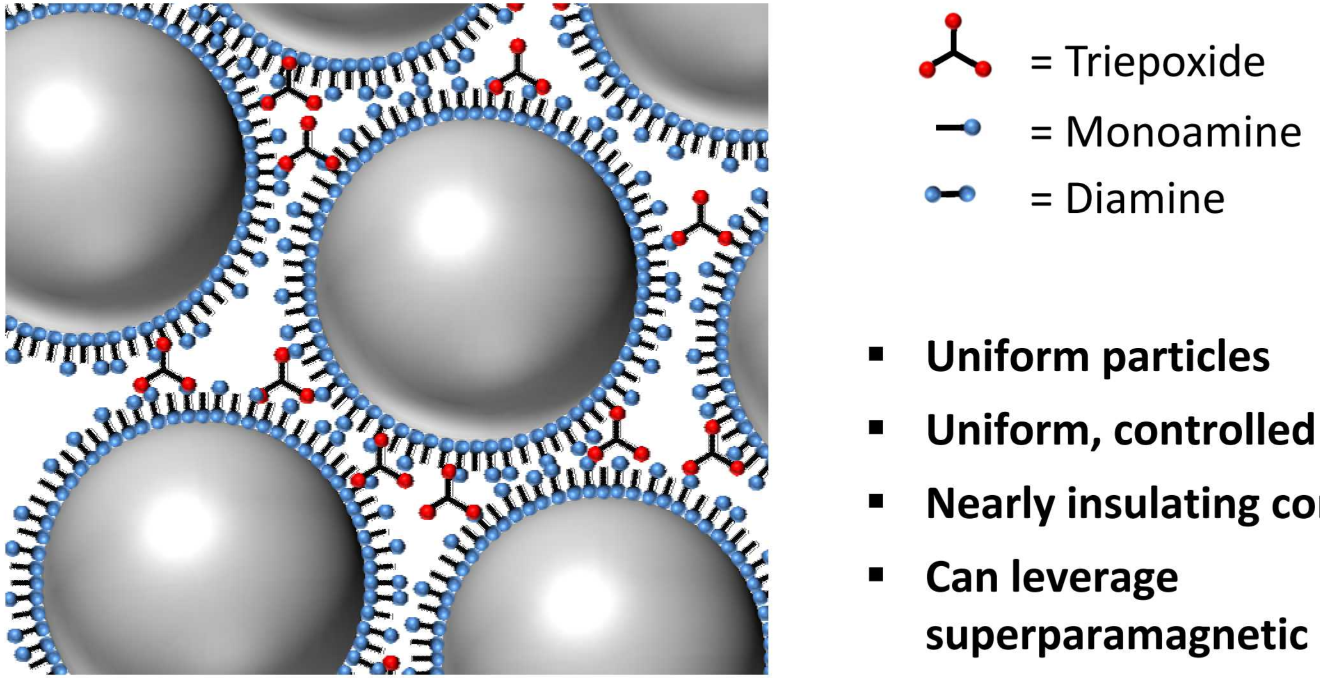
- **Irregular shape increases anisotropy**
  - **Further limits μ**
- **Particles still touch throughout composite**
  - **Multiple conductive pathways**

- **Tailored shapes to minimize anisotropy**
  - **Increased μ**
- **Better control over particle dispersion**
  - **True insulating composite**

J. M. Silveyra, E. Ferrara, D. L. Huber, T. C. Monson, “Soft magnetic materials for a sustainable and electrified world,” Science 362, 418 (2018).

Magnetic Nanocomposites, Organic Matrix



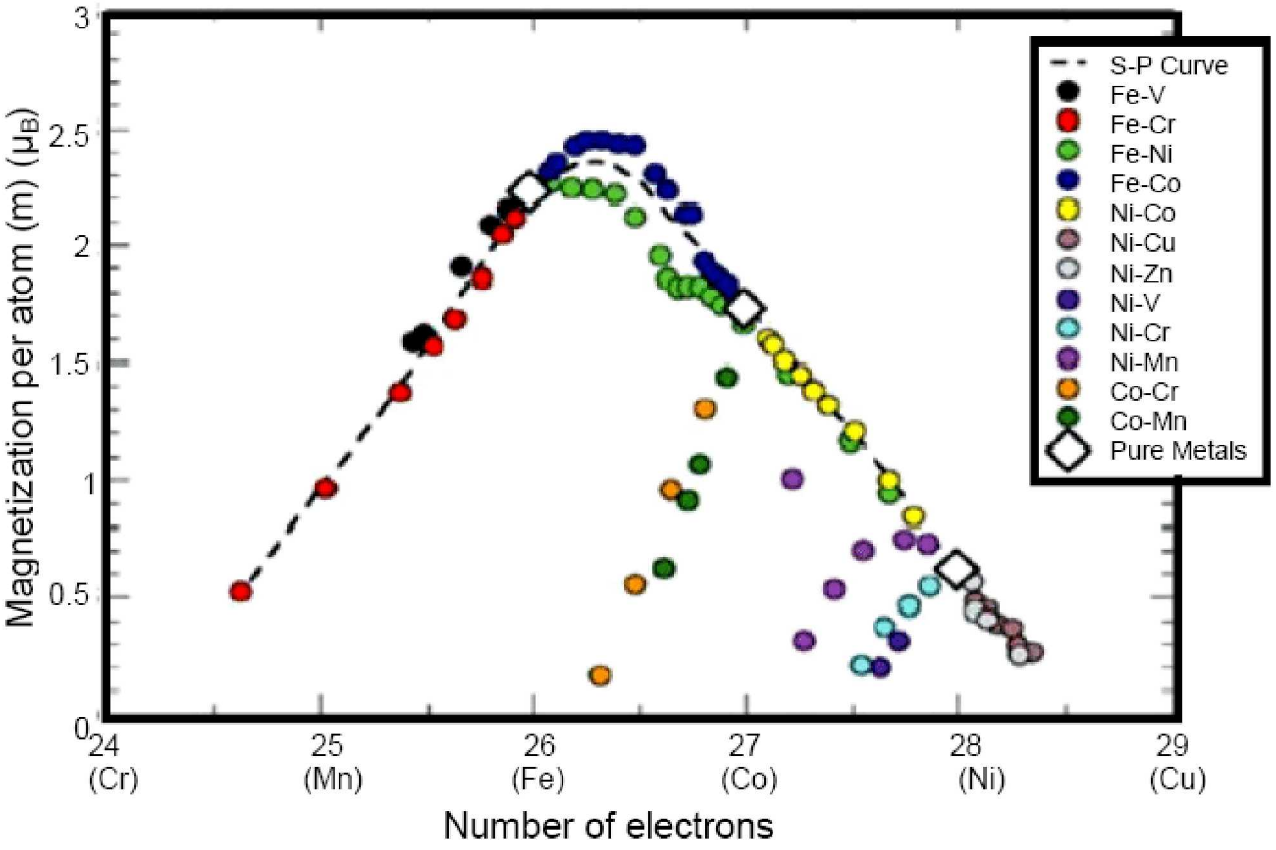


- **Uniform particles**
- **Uniform, controlled spacing**
- **Nearly insulating composite**
- **Can leverage superparamagnetic behavior**

J. Watt, G. C. Bleier, Z. W. Romero, B. G. Hance, J. A. Bierner, T. C. Monson, D. L. Huber, "Gram scale synthesis of Fe/Fe_xO_y core-shell nanoparticles and their incorporation into matrix-free superparamagnetic nanocomposites," Journal of Materials Research **33**, 2156-2167 (2018).

New Magnetic Materials

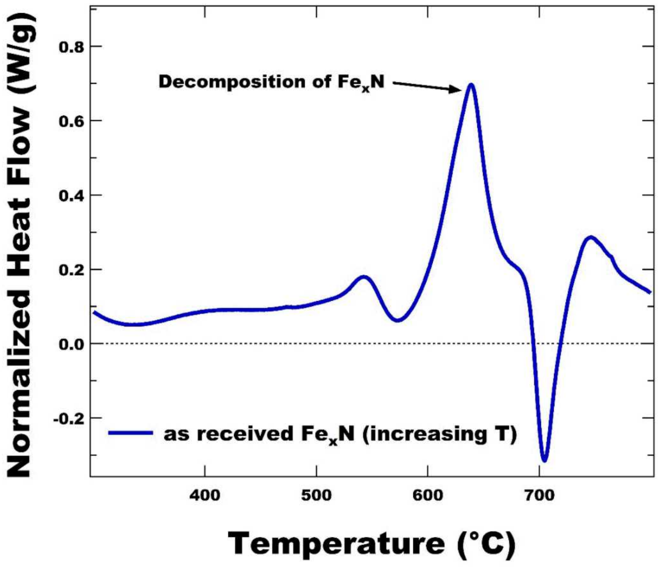
Slater – Pauling Curve



Roy, Rajat & Panda, Ashis & Mitra, Amitava. (2015). Alloy Development through Rapid Solidification for Soft Magnetic Application. 10.5772/60772.

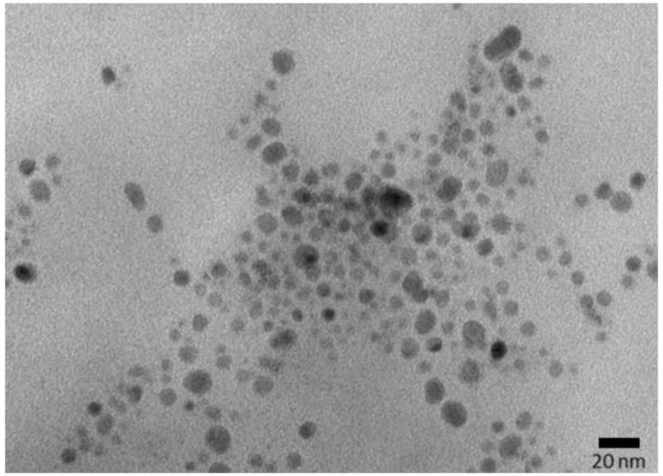
- Alloying alters spacing between atoms
- Tunes exchange coupling and therefore magnetization
- There are other ways to tune the spacing between atoms

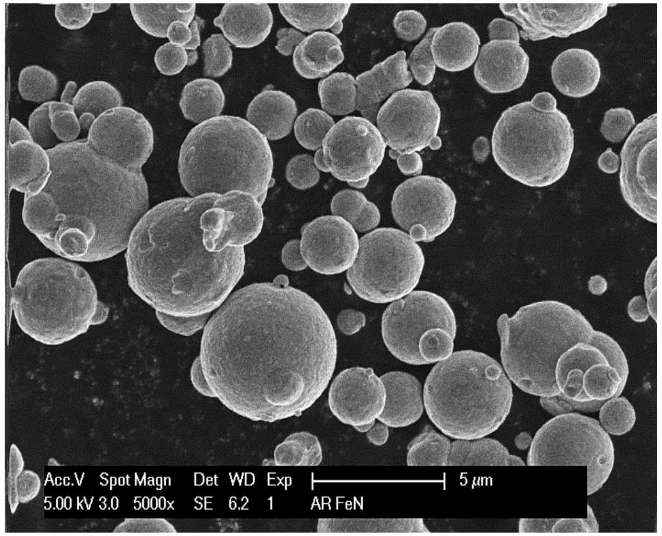
SPS consolidated iron nitride (γ'-Fe_4N)



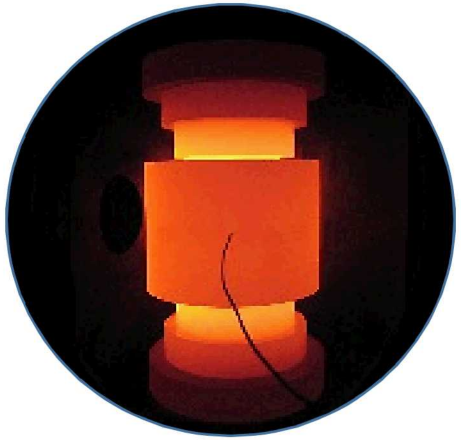
Relatively low thermal decomposition limits consolidation & fabrication methods

$$FeCl_2 + Li_3N \xrightarrow[\text{oleylamine, -LiCl}]{350\ °C} Fe_3N$$





SPS Consolidation

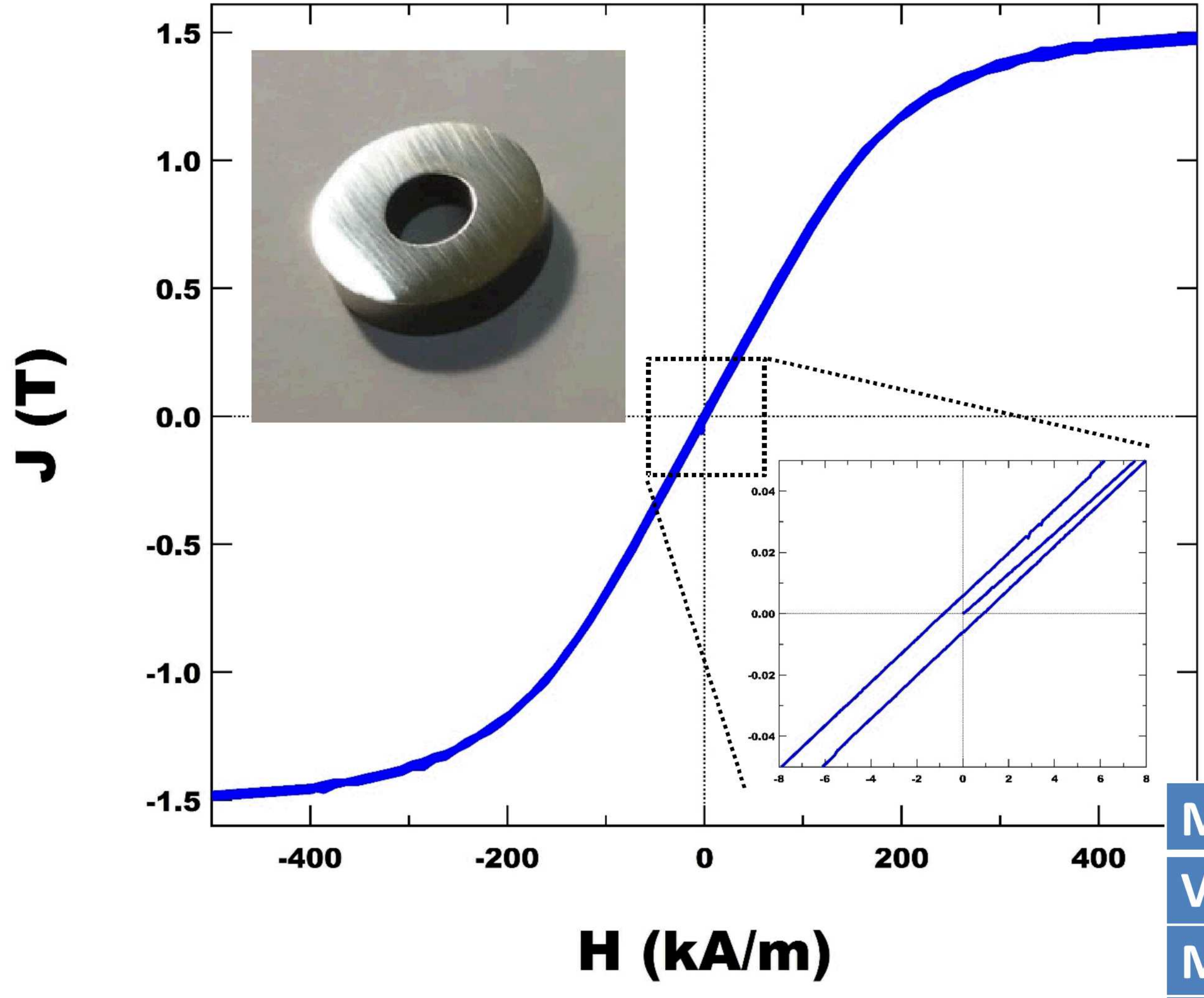


Spark Plasma Sintering

Fast sintering

- **Pressure and pulsed current assisted sintering process**
- **Precision control over heat, pressure, and time**
- **Restrain grain growth**
- **Full densification**

SPS consolidated iron nitride (γ'-Fe_4N)



First ever bulk γ’-Fe_4N!

U.S. Patent #9,963,344

- **SPSed at 550°C and 100 MPa**
- **J_s = 1.62 T**
- **Theoretical J_s = 1.89 T (SiFe is 1.87 T)**
- **H_c < 1000 A/m**

Magnetic Material	J_s (T)	ρ($\mu\Omega\cdot$m)	Cost
VITROPERM (Vacuumschmelze)	1.20	1.15	High
Metglas 2605SC	1.60	1.37	High
Ferrite (Ferroxcube)	0.52	5×10^6	Low
Si steel	1.87	0.05	Low
γ'-Fe_4N	1.89	> 200	Low

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).

Grain Size, Domain Wall Motion, and Coercivity

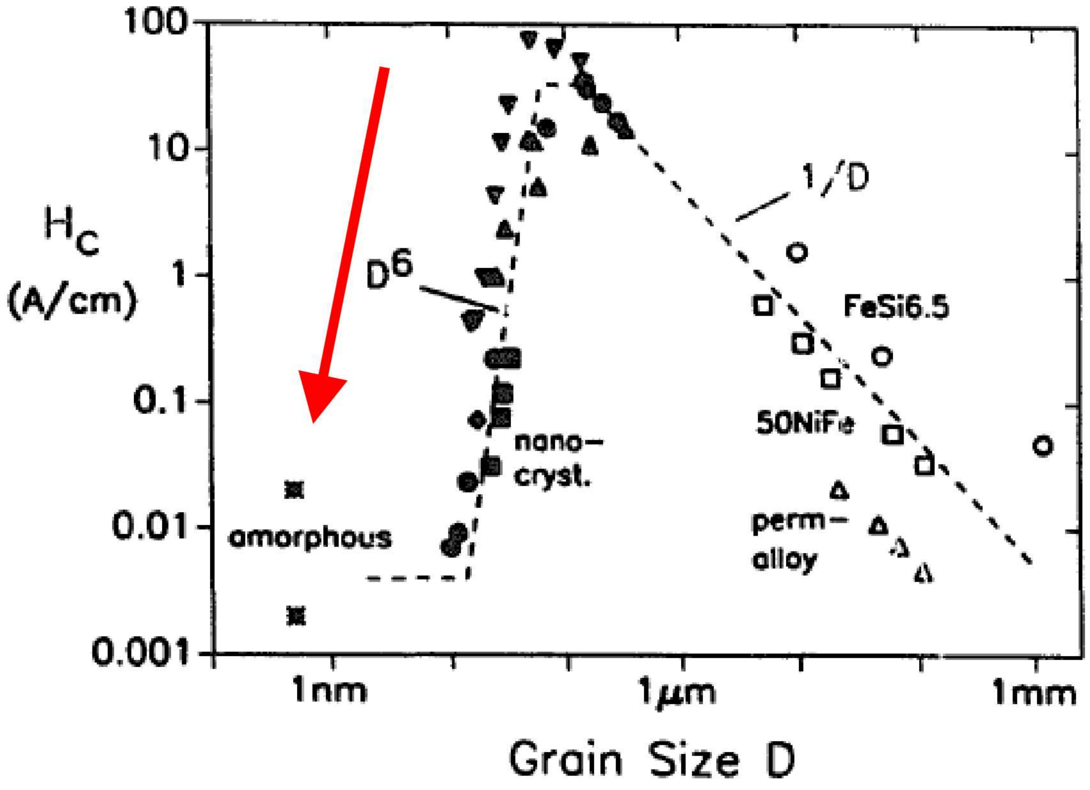
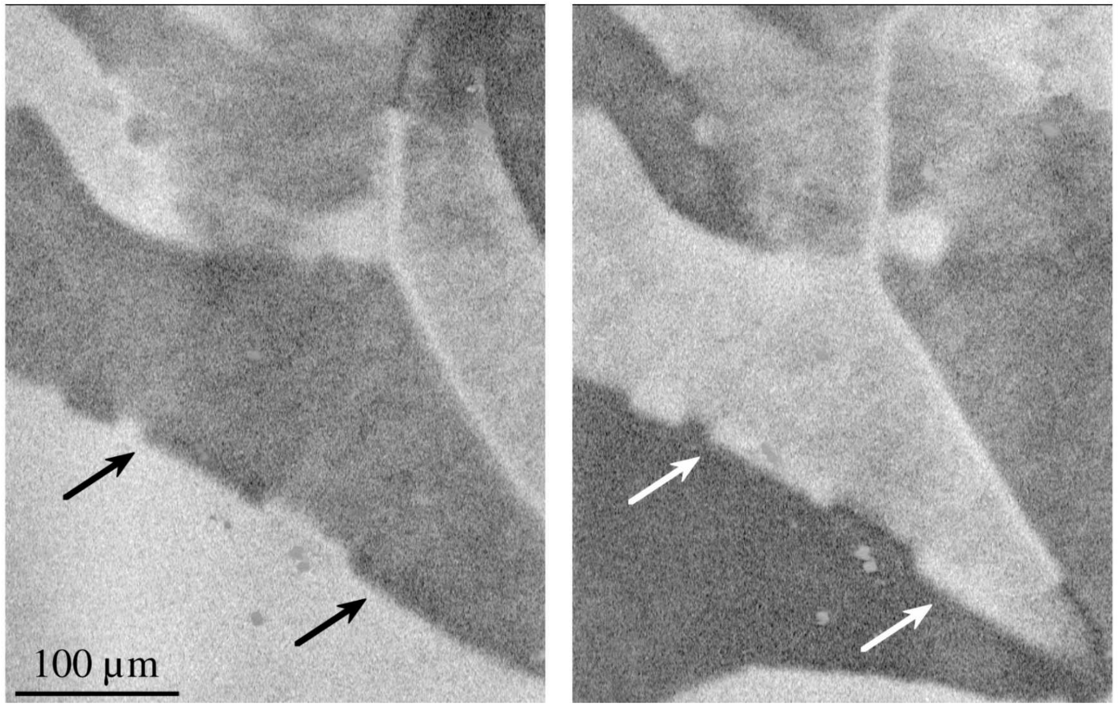


Fig. 2. Coercivity H_c vs. grain size for various soft magnetic metallic alloys. The data of the nanocrystalline material refer to (▲) FeNbSiB and (●) FeCuNbSiB [14], (◆) FeCuVSiB [15], (■) FeZrB [4] and (▼) FeCoZr [16].

G. Herzer, Nanocrystalline Soft Magnetic Materials, J. Magn. Mag. Mat., 112, 258 (1992).



R. Schaefer and G. Herzer, "Continuous magnetization patterns in amorphous ribbons," IEEE Transactions on Magnetics, vol. 37, pp. 2245-2247, 2001.

Conclusions

- Soft magnetic materials are ubiquitous and will only become more important as our energy supply and distribution modernizes
- Tradeoffs between magnetization, electrical losses, cost, and suitability for a particular application must always be considered
- No single magnetic material can meet all current and future needs
- Opportunities exist for both incremental and revolutionary improvements

Acknowledgements

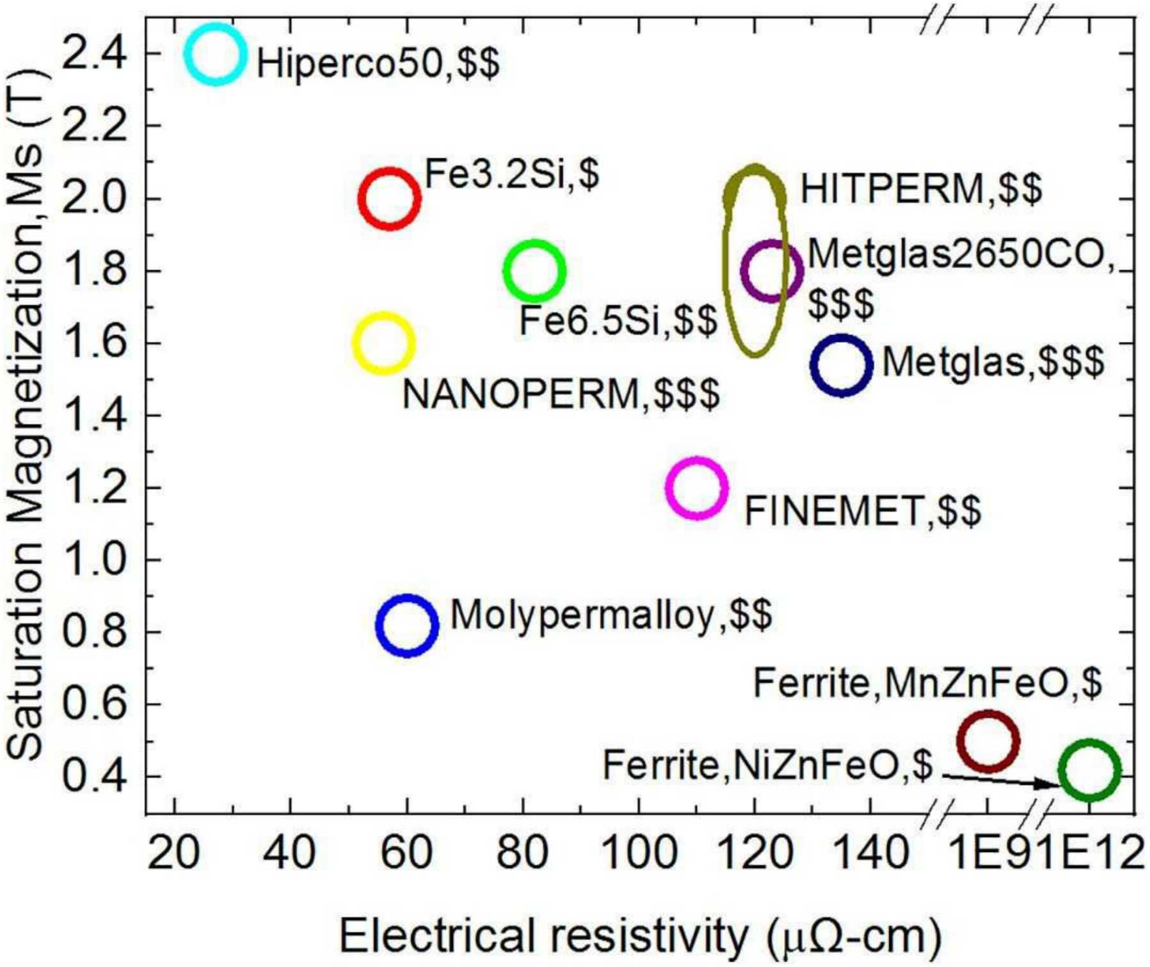
- DOE/OE, VTO, ARPA-E, Sandia National Labs LDRD
- CJ Pearce, Melinda Hoyt, Tyler Stevens, Robert Delany, Emily Johnson, and many others…

Questions?

tmonson@sandia.gov

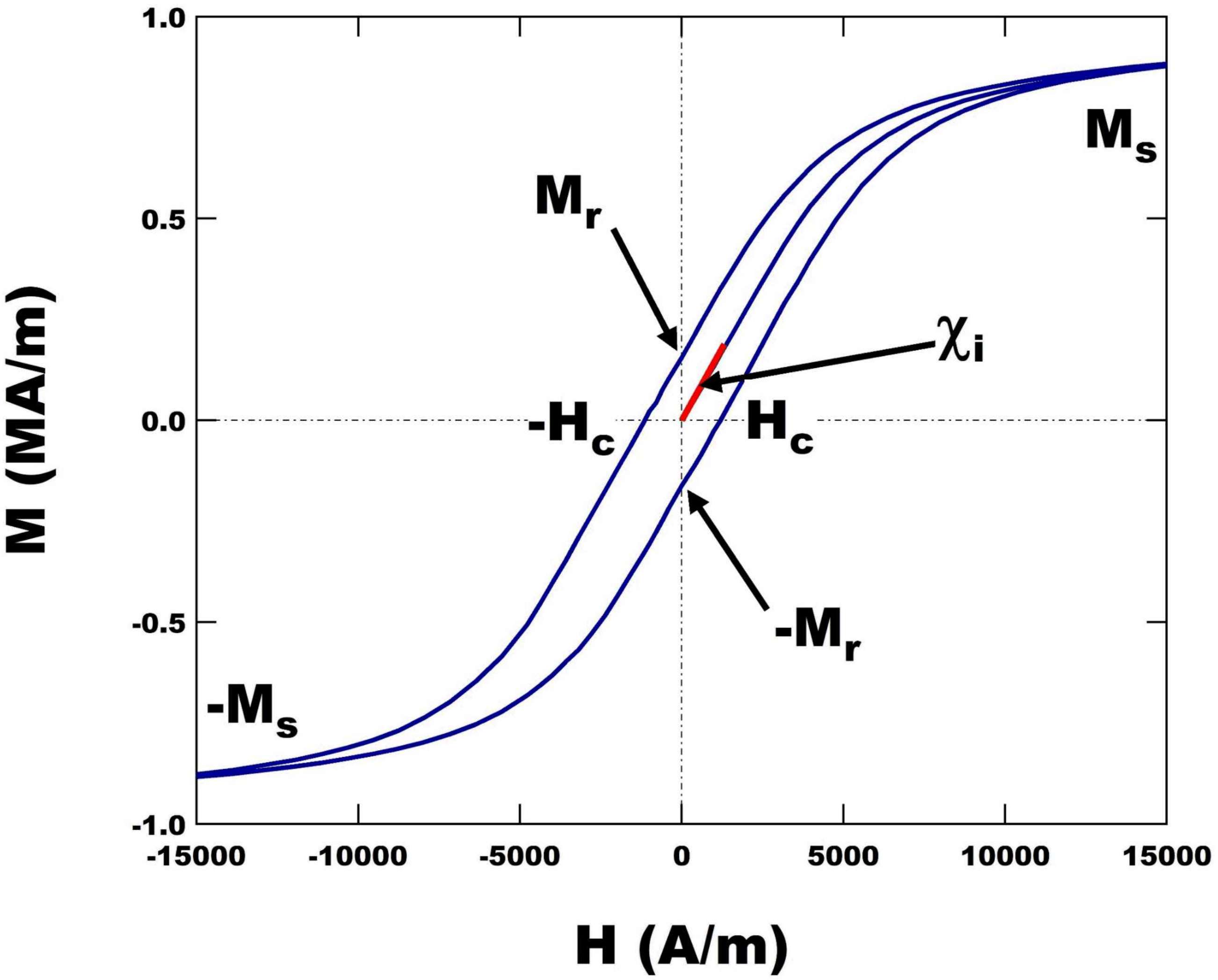
Backup Slides

Magnetization vs. Resistivity



Ouyang, Gaoyuan & Chen, Xi & Liang, Yongfeng & Macziewski, Chad & Cui, Jun. (2019). Review of Fe-6.5 wt% Si high silicon steel—A promising soft magnetic material for sub-kHz application. Journal of Magnetism and Magnetic Materials. 481. 10.1016/j.jmmm.2019.02.089.

Magnetic Properties



M_s = saturation magnetization

M_r = magnetic remnance

H_c = coercivity

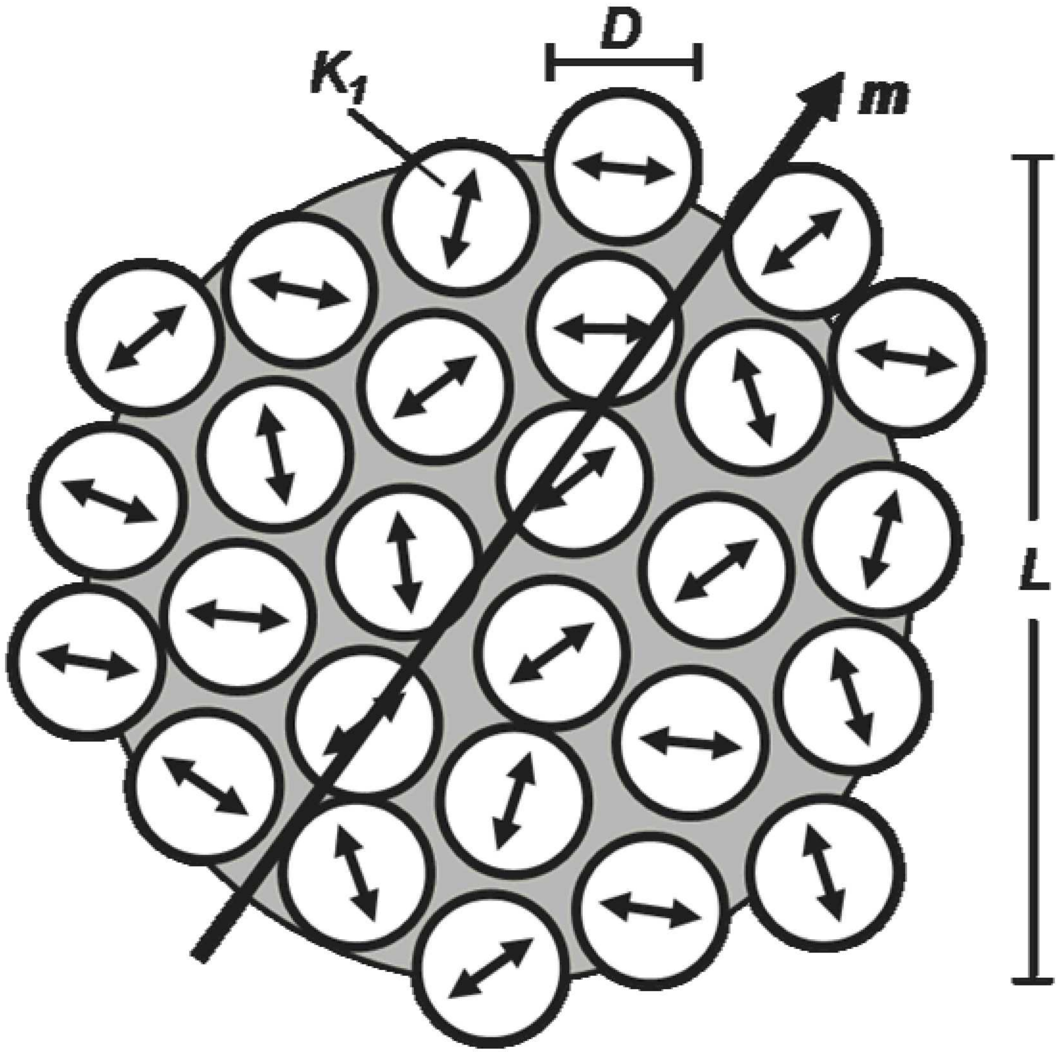
χ_i = initial susceptibility

μ = permeability

μ_r = permeability

$\mu_r = \mu/\mu_0 = 1 + \chi$

Random Anisotropy Model



- Magnetic correlation length (L) is longer than structural correlation length (D)
- Effective anisotropy becomes negligible

K_1 = Randomly oriented uniaxial anisotropy

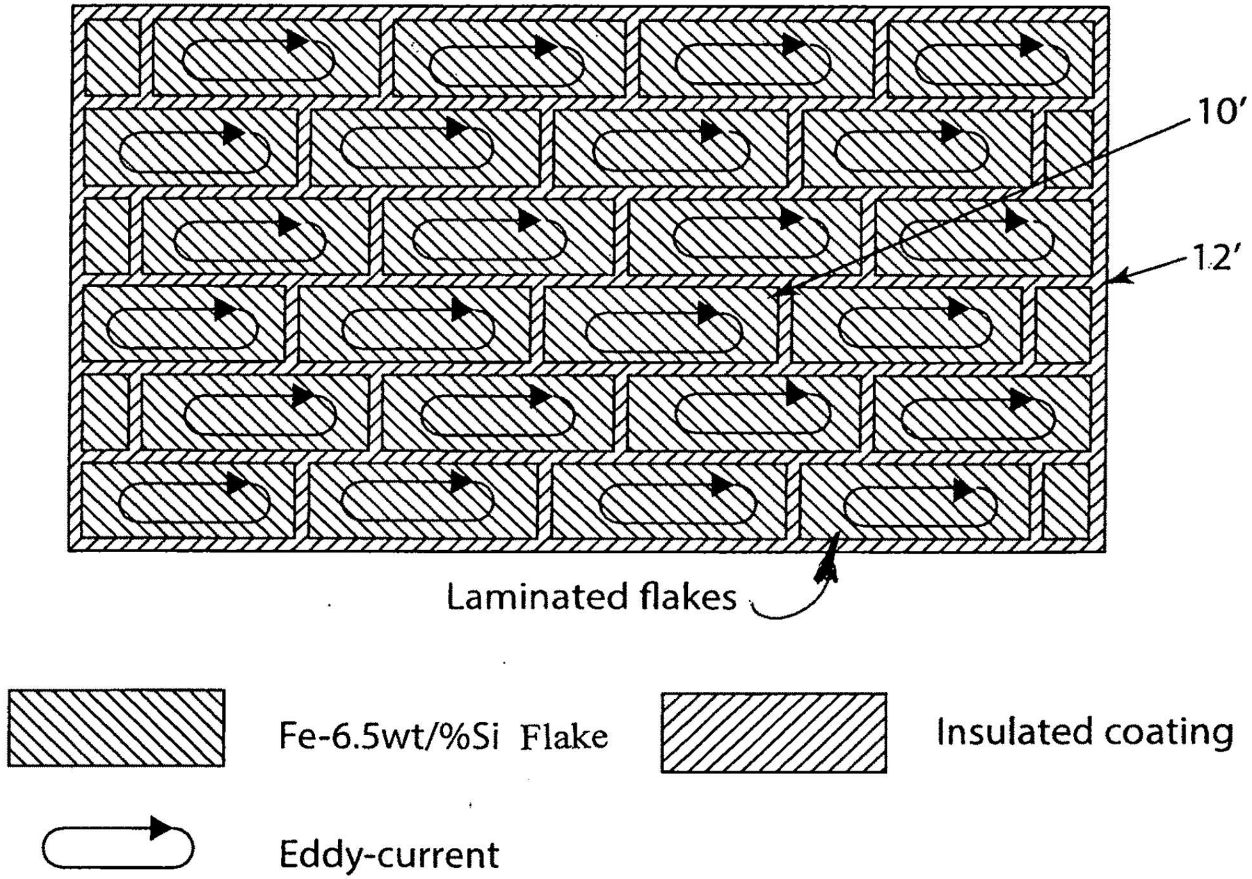
D = Structural correlation length (grain size)

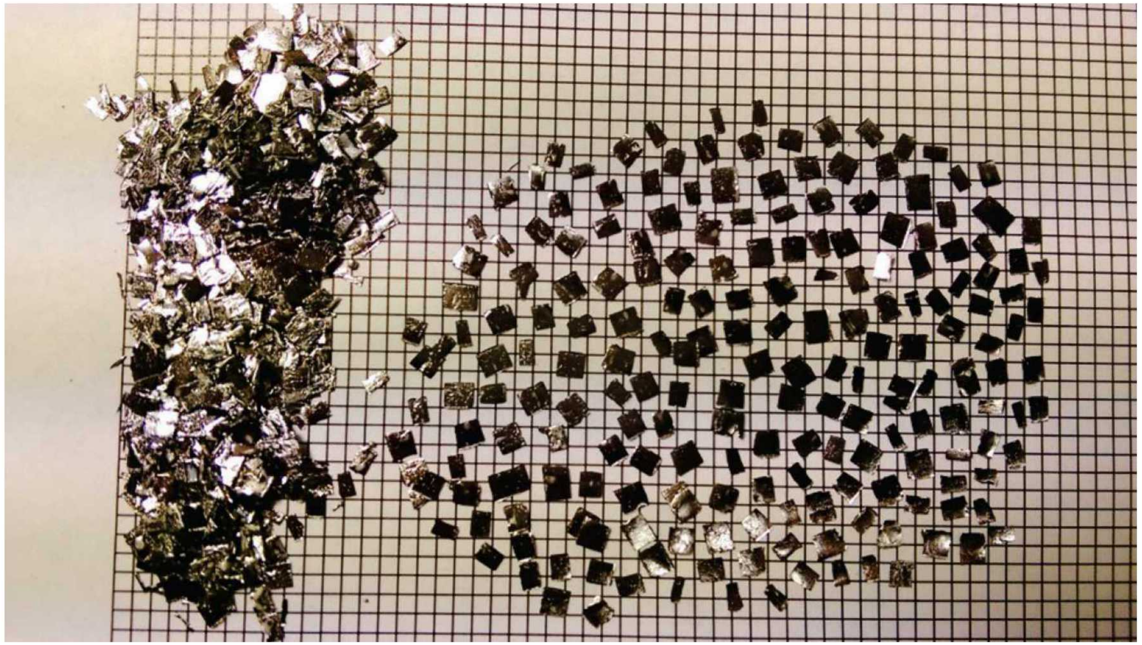
m = Magnetization

L = Magnetic correlation length

J. M. Silveyra, E. Ferrara, D. L. Huber, T. C. Monson, "Soft magnetic materials for a sustainable and electrified world," Science 362, 418 (2018).

Inorganic Magnetic Composites



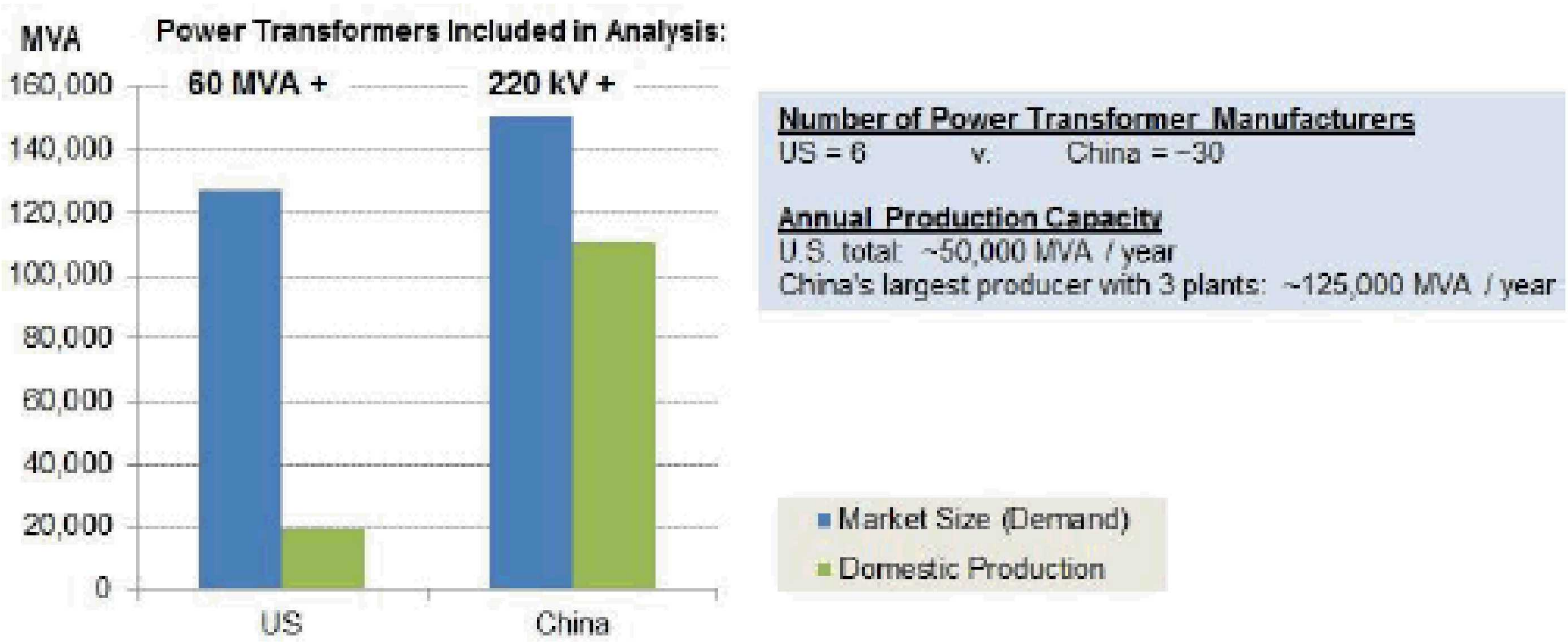


Cui, Jun, "Cost Effective 6.5% Silicon Steel Laminate for Electric Machines," Electrification 2018 Annual Progress Report, Vehicle Technologies Office, U.S. DOE

Cui, Jun, et al. "Near net shape bulk laminated silicon iron electric steel for improved electrical resistance and low high frequency loss." U.S. Patent Application No. 16/501,332.

Power Transformer Market Analysis

Figure 12. Estimated Power Transformer Markets: United States v. China in 2010

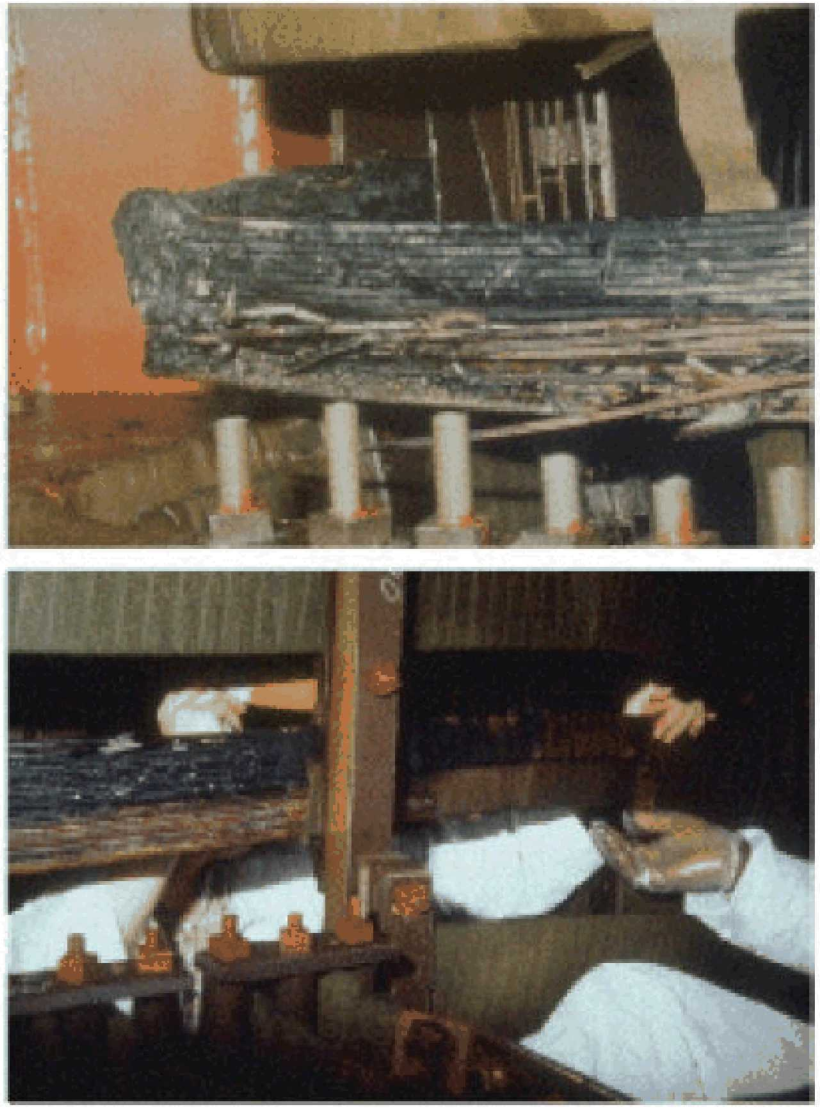


Note: Different criteria used for the United States and China. For the United States, power transformers with capacity greater than or equal to 60 MVA are included in the data; for China, power transformers with capacity greater than or equal to 220 kV are included in the data.

Sources: USITC, 2011; China Transformer Net, 2010; China's Power Transformer Industry Report, Reuters, 2011.

"Large Power Transformers and the U.S. Electric Grid", Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy, June 2012.

Transformer EMP Vulnerability



- **Geomagnetic storms couple very efficiently to long transmission lines**
- **Transformer can be driven to saturation, creating harmonics and reactive power**
- **Enough heat generated to melt copper windings**
- **Transformers the grid component that is hardest to replace**

Permanent damage to the Salem New Jersey Nuclear Plant GSU Transformer caused by the March 13, 1989 geomagnetic storm. Photos courtesy of PSE&G.

Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, Critical National Infrastructures, April 2008

Applications of High Frequency Transformers

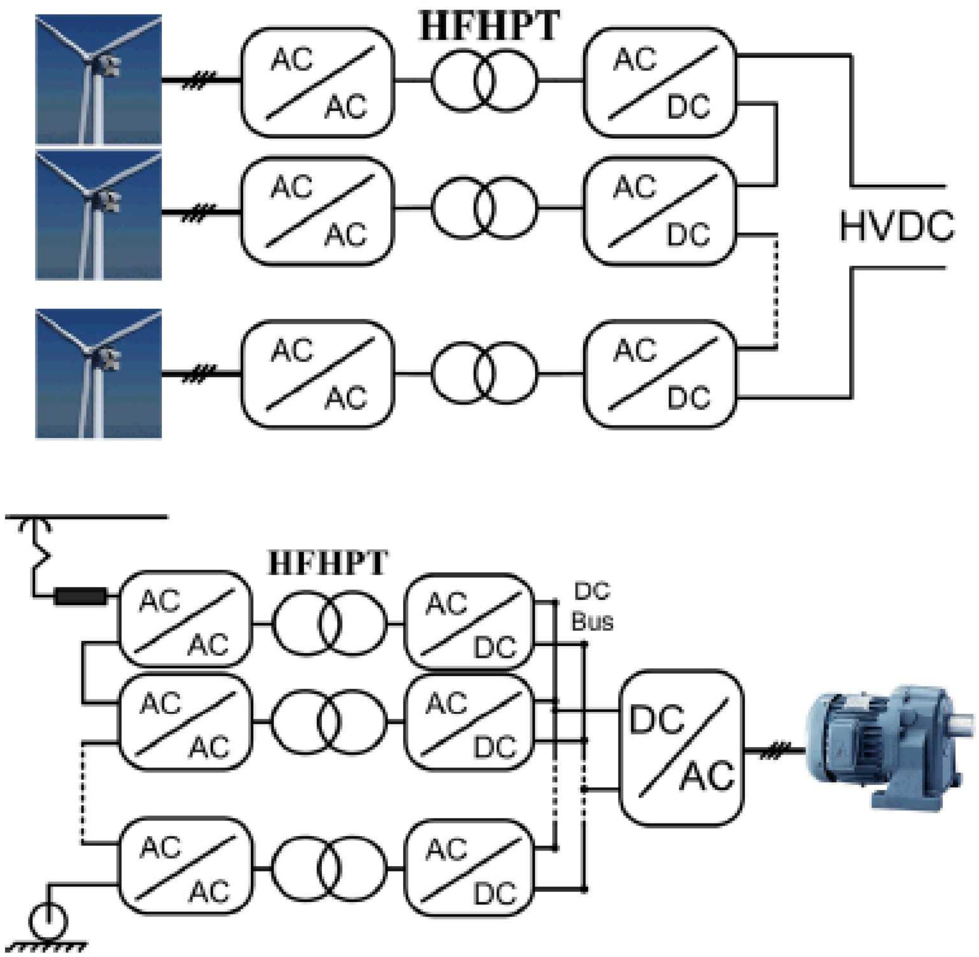
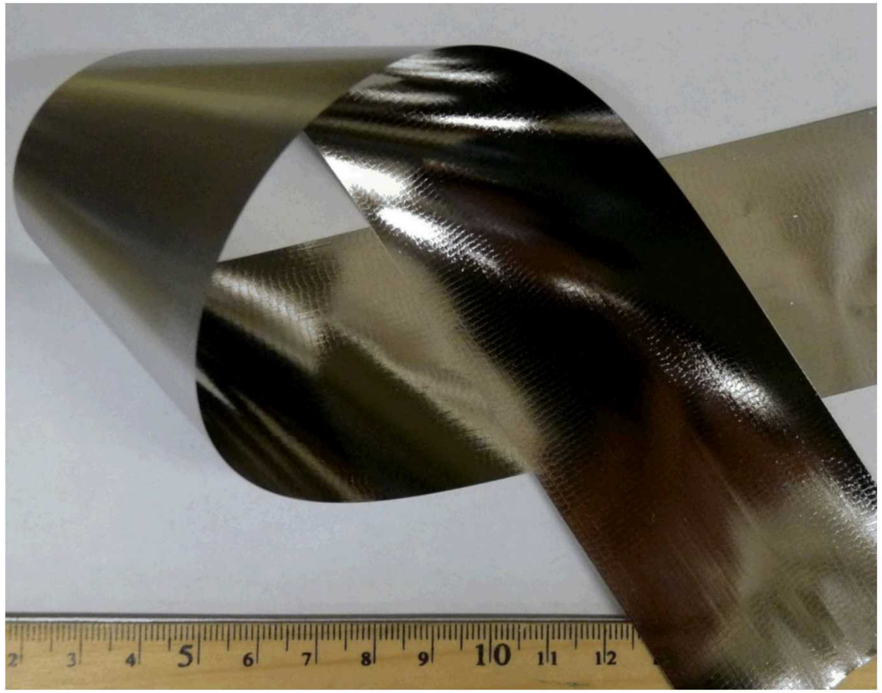


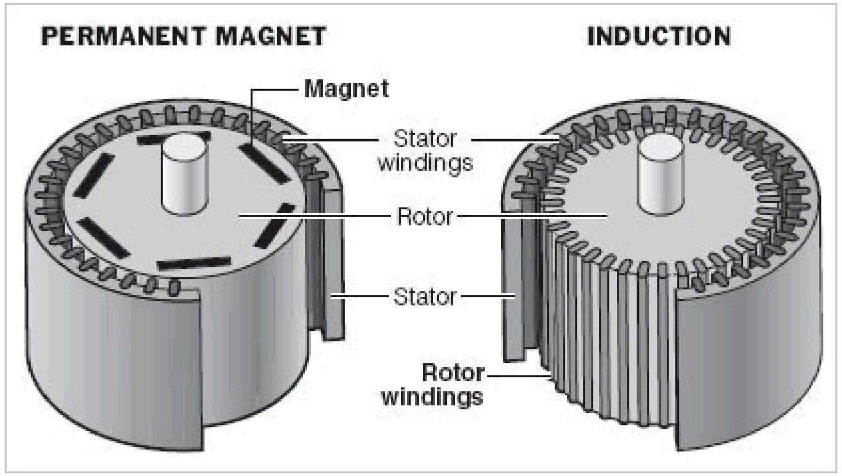
FIG. 1. Two main applications of high power converters with HFHPTs, (top) offshore wind farm and (bottom) traction converter.

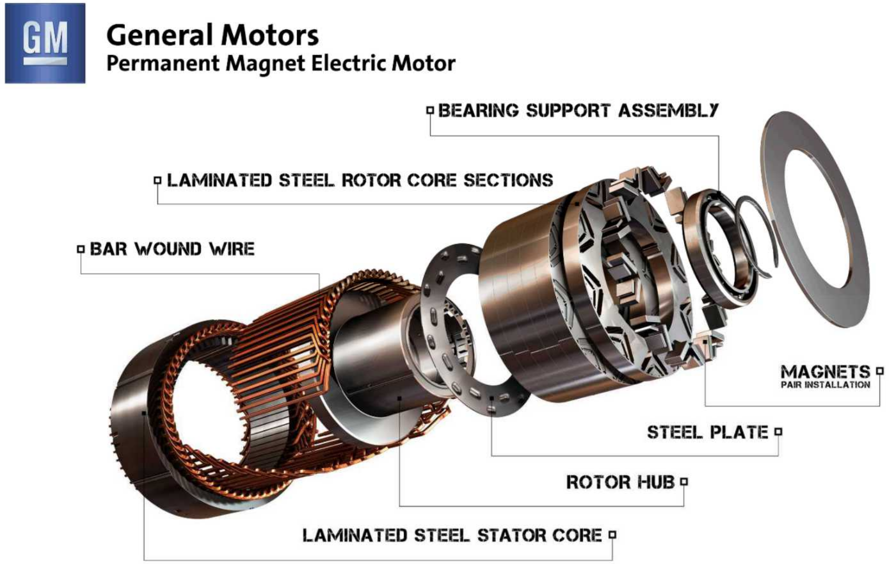
E. Agheb, et. al., Core loss behavior in high frequency high power transformers-II: Arbitrary excitation, J. of Renewable and Sustainable Energy, 4, 033113 (2012).

Metglas Ribbon and Laminated Motor Parts

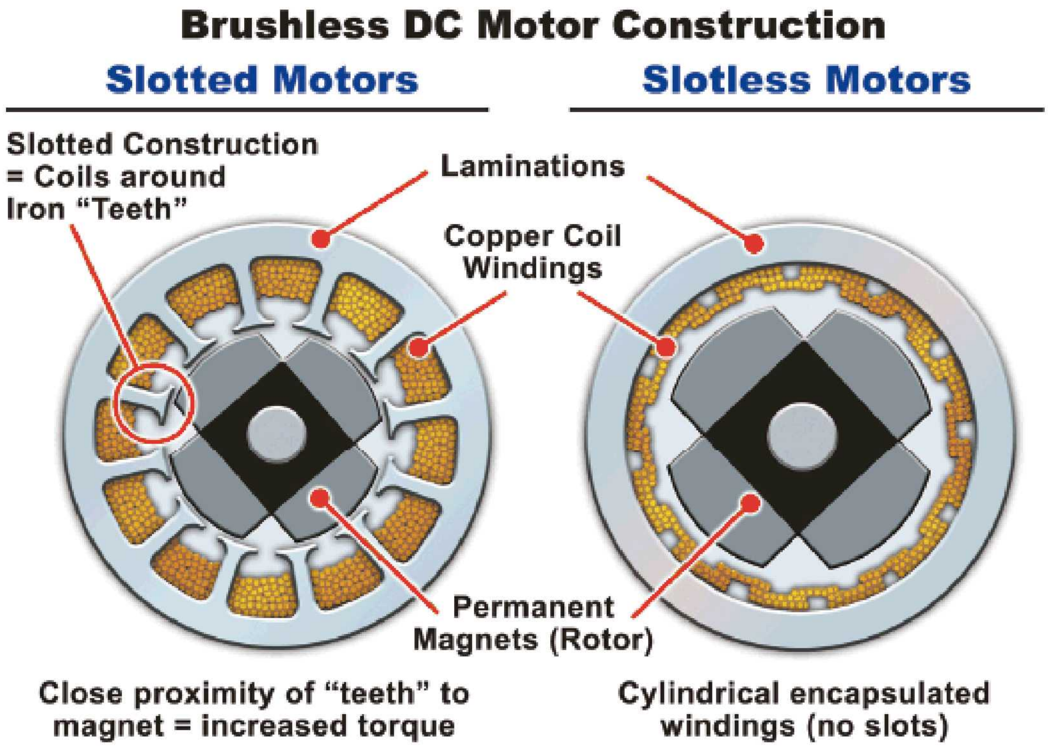


Motors

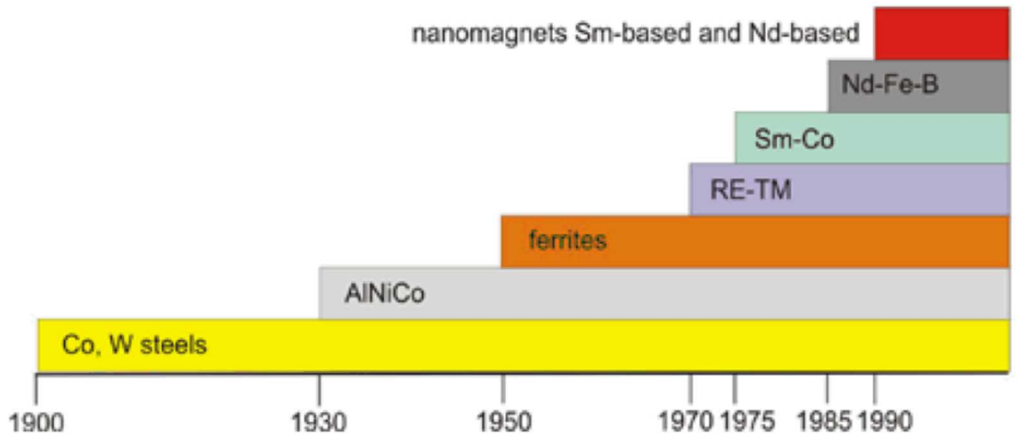

PERMANENT MAGNET
INDUCTION
Magnet
Stator windings
Rotor
Stator
Rotor windings


General Motors
Permanent Magnet Electric Motor
BEARING SUPPORT ASSEMBLY
LAMINATED STEEL ROTOR CORE SECTIONS
BAR WOUND WIRE
MAGNETS
PAIR INSTALLATION
STEEL PLATE
ROTOR HUB
LAMINATED STEEL STATOR CORE

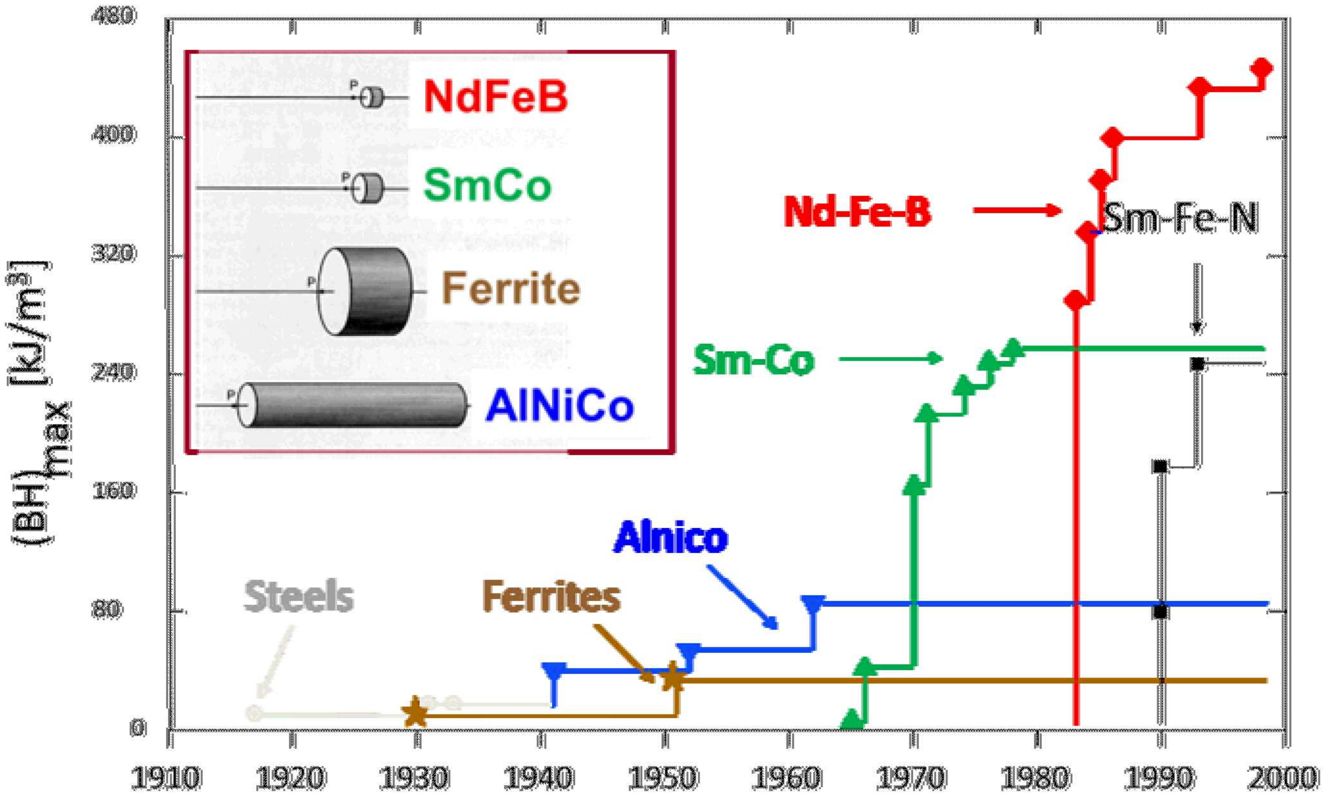
Slotted vs. Slottless Motors



Hard Magnetic Materials



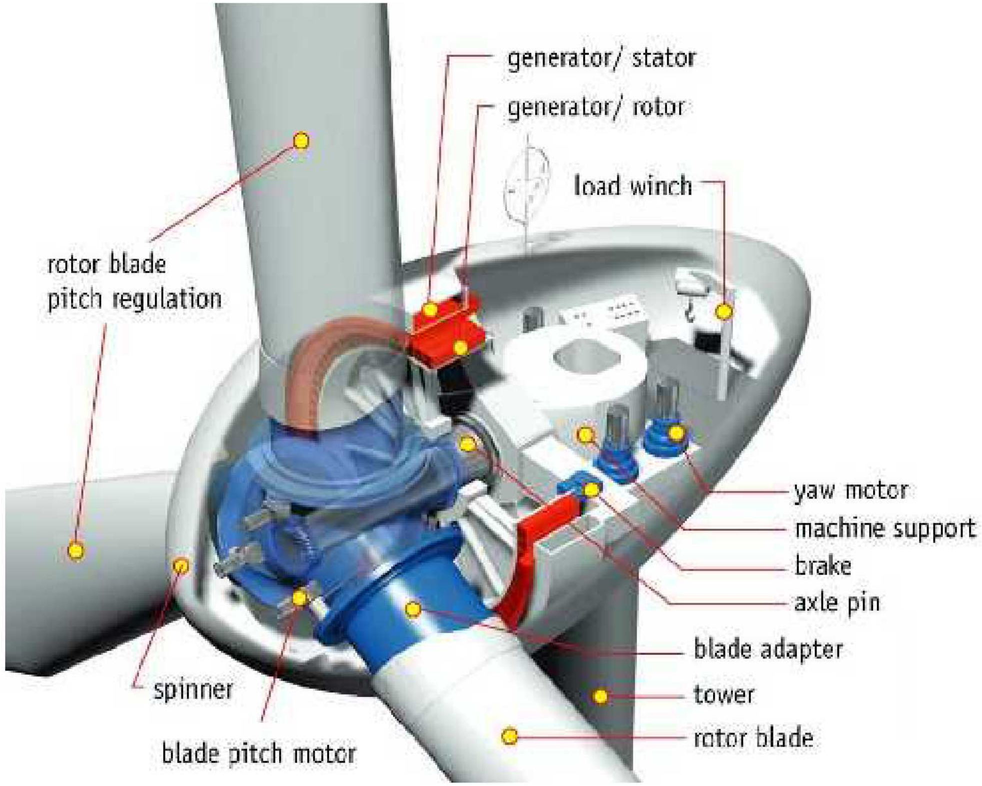
L.A. Dobrzański, M. Drak, B. Ziębowicz, Materials with specific magnetic properties, Journal of Achievements in Materials and Manufacturing Eng., 17, 37 (2006).



TU Darmstadt Functional Materials

Permanent (Hard) Magnet Applications

Electrical Machines (Generators & Motors)



H. Polinder, J. Abraham Ferreira, B. Bech Jensen, A. Abrahamsen, K. Atallah, and R. McMahon, *Trends in Wind Turbine Generator Systems* vol. 1, 2013.

General Motors
Permanent Magnet Electric Motor