Designing Soft Magnetic Materials

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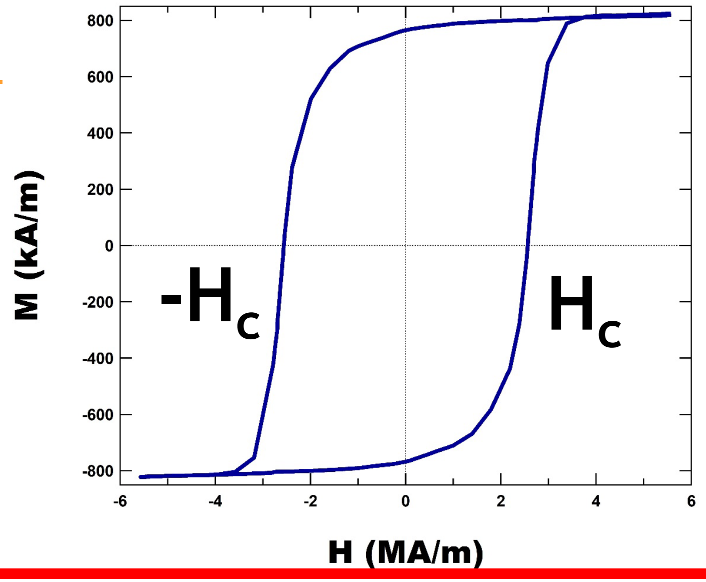
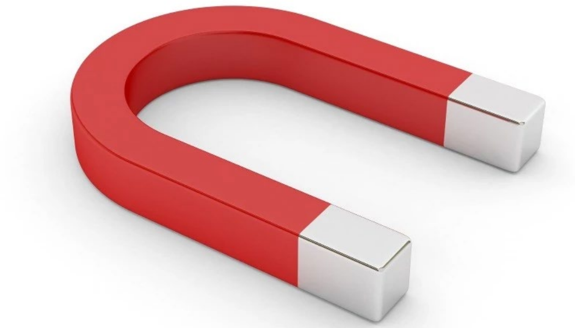
Hard vs. Soft Magnets

Hard (permanent) magnet

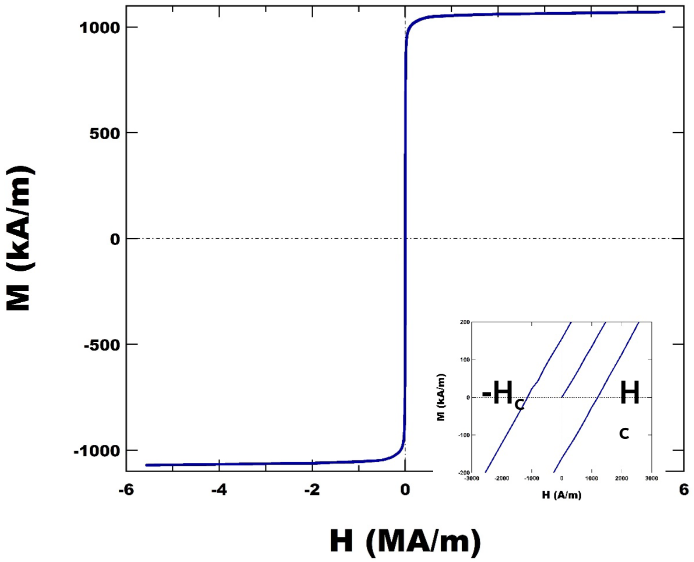
H_c > 1000 A/m

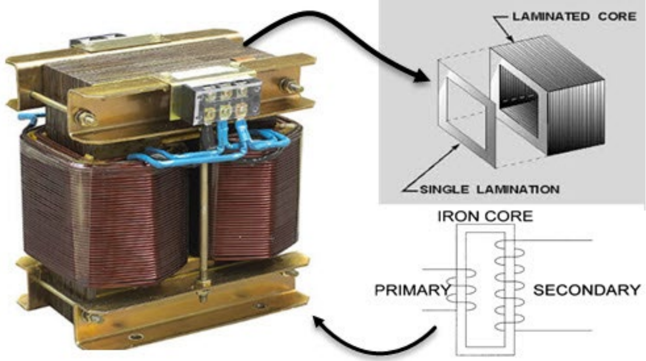


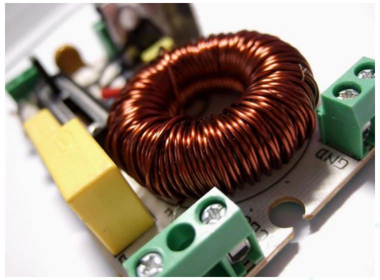


Soft magnet

H_c < 1000 A/m







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Desired Properties in Soft Magnetic Materials

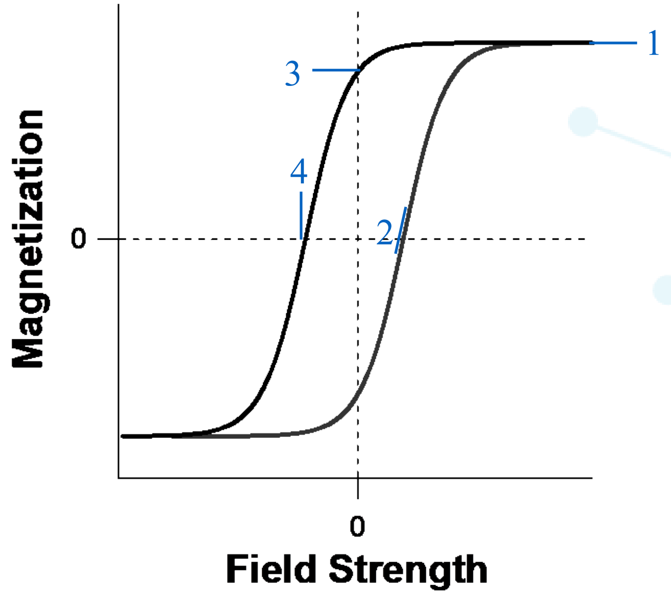
What matters:

Hysteretic losses caused by hysteresis loop

Eddy current losses caused by conduction in the magnetic material

High susceptibility/permeability

High saturation magnetization



1. Saturation magnetization
2. Susceptibility (permeability)
3. Remanence
4. Coercive Field

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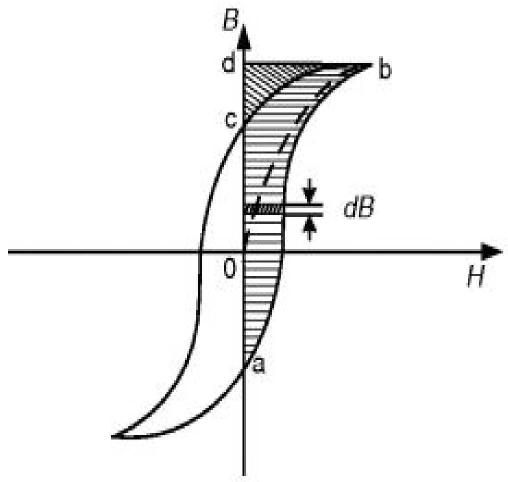
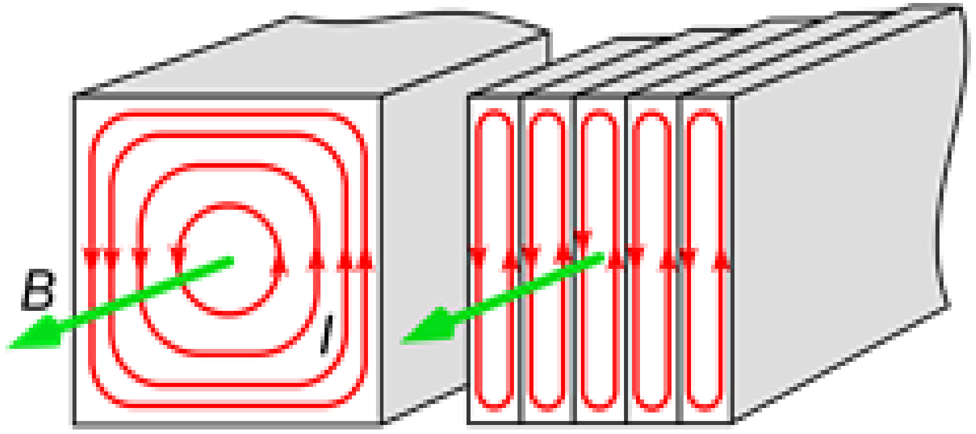
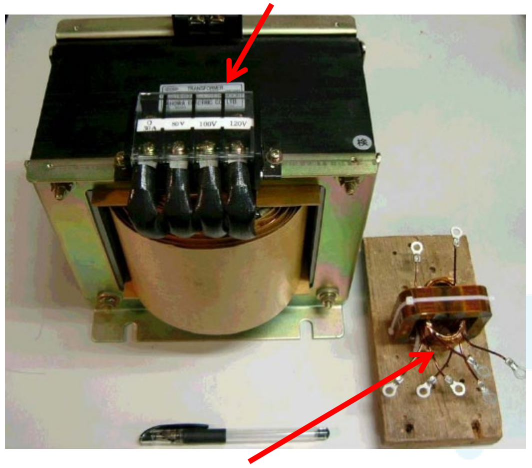
Magnetic Property Variation with Frequency





Line frequency (50 Hz) transformer



High frequency (20 kHz) transformer

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

Scale as f

Hysteretic losses

Scale as f^2

Eddy Currents

Less critical at high f

Susceptibility

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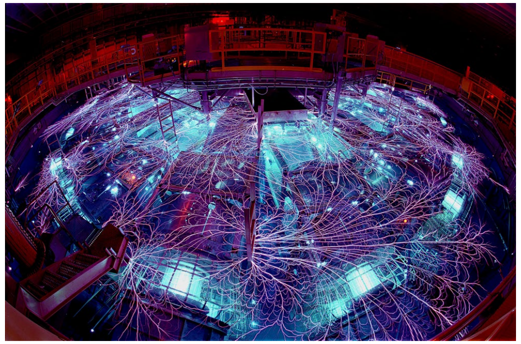
High Frequency Applications

Pulsed Power



Power Electronics / Solid State Transformers

Low hysteretic losses

Low eddy current losses

High susceptibility/permeability

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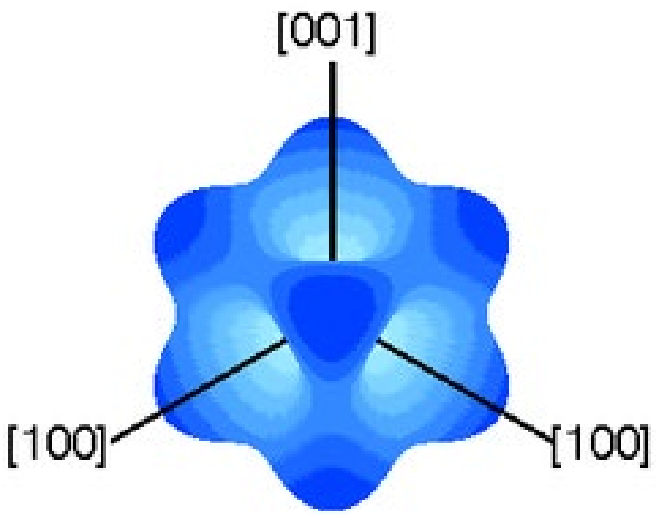
Properties are Coupled

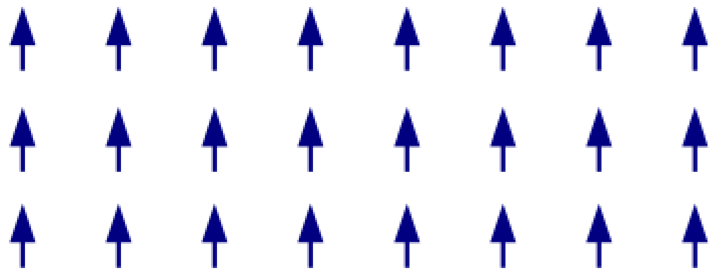
Crystallinity



Magnetocrystalline anisotropy is a major driver of hysteretic losses.

Crystallinity allows spins to align effectively leading to high magnetization.

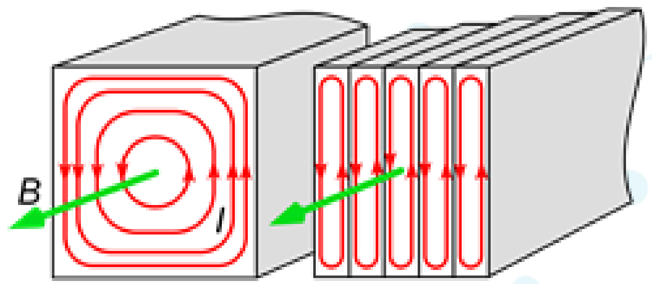
Unpaired electrons



Unpaired electrons populate the conduction band in metals.

Only unpaired electrons contribute to magnetism.

Physical size



Both hysteretic losses and eddy current losses can change with decreased physical size.

Gaps between magnetic material lower magnetization.

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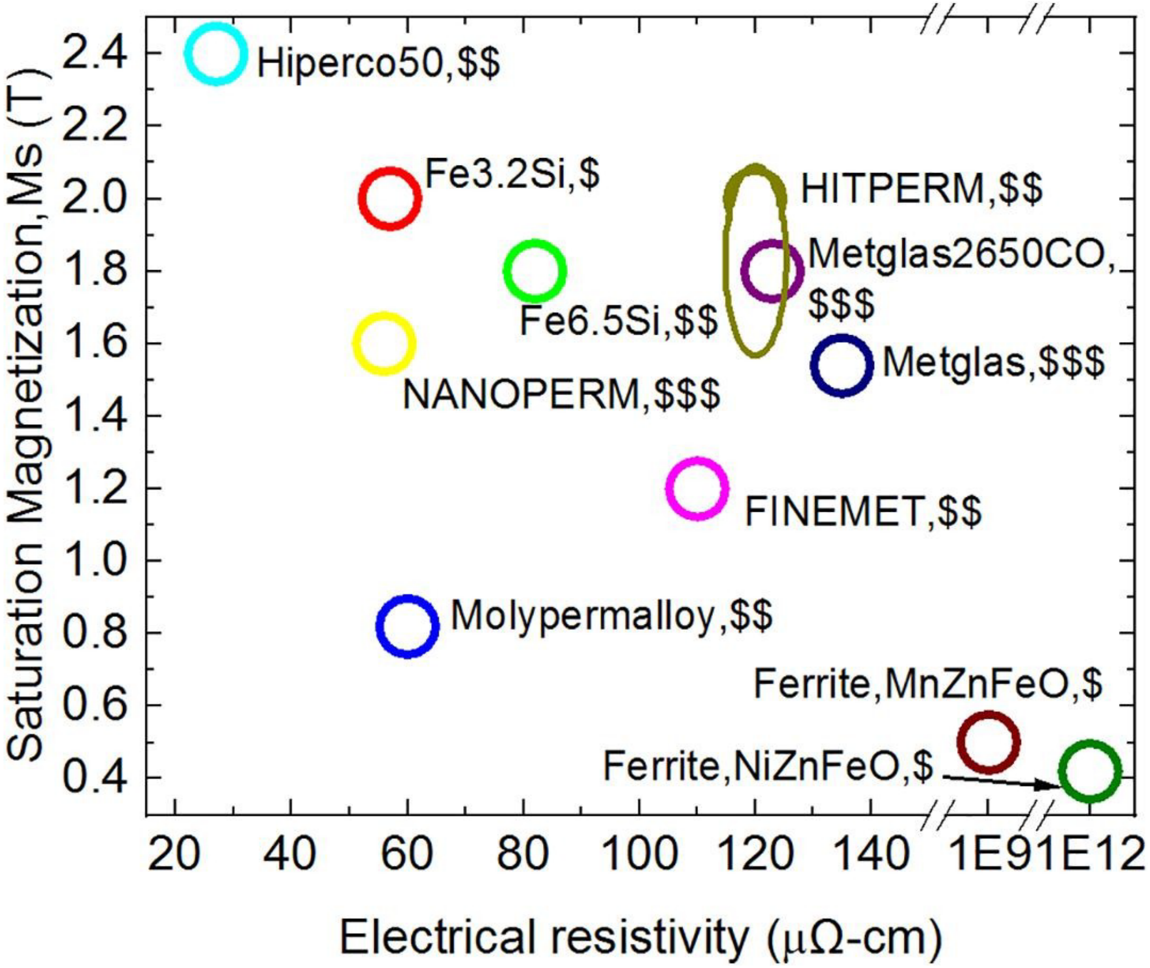
Magnetization vs. Resistivity



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.

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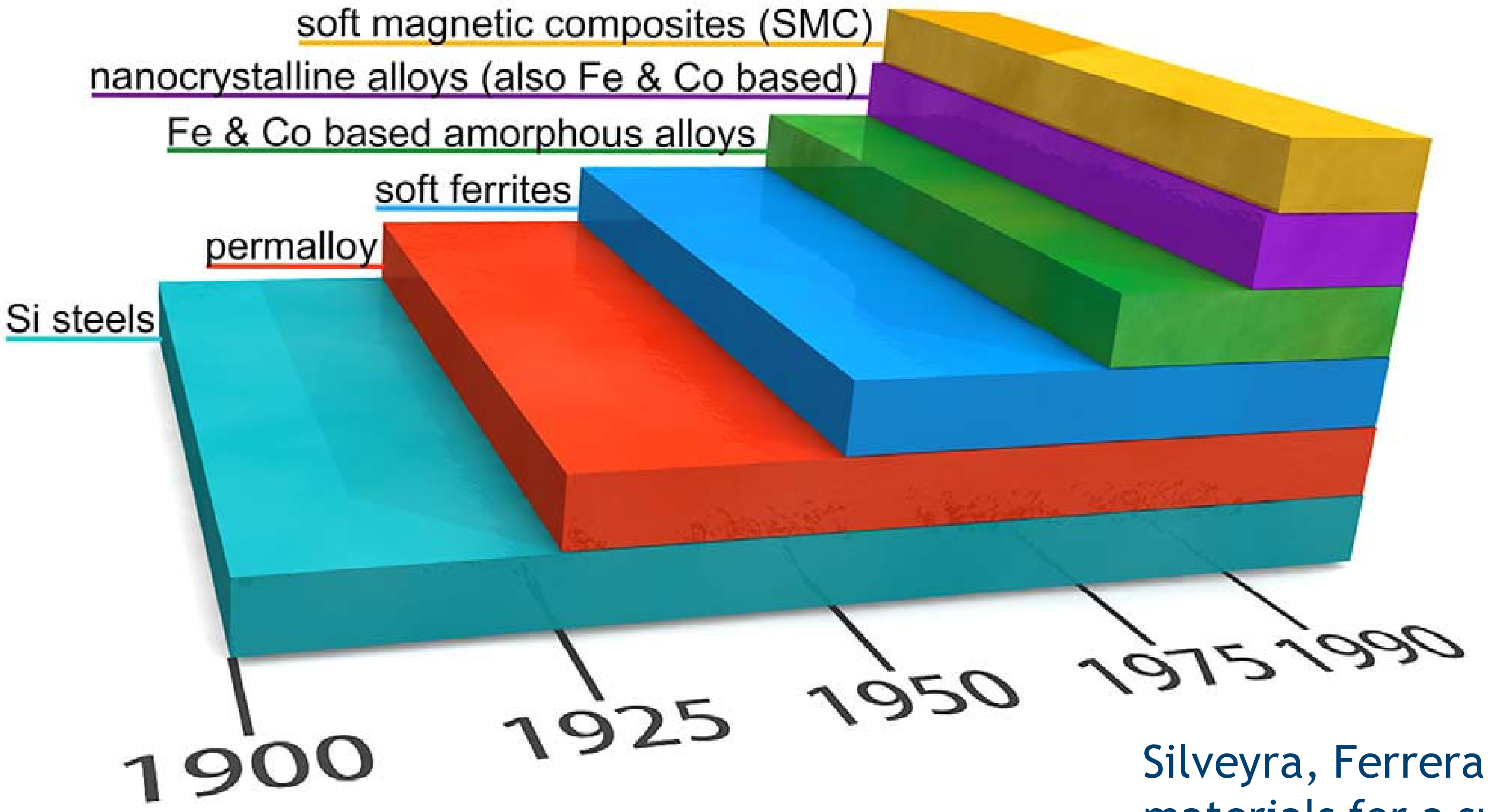
Soft Materials Development in the 20th Century



Silveyra, Ferrera, Huber, Monson (2018). "Soft magnetic materials for a sustainable and electrified world." Science 362(6413): eaao0195. DOI: 10.1126/science.aao0195.

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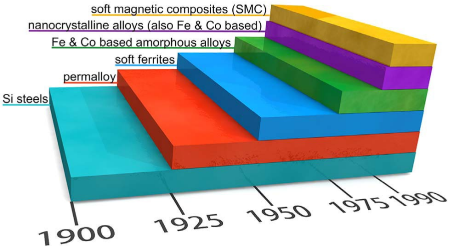
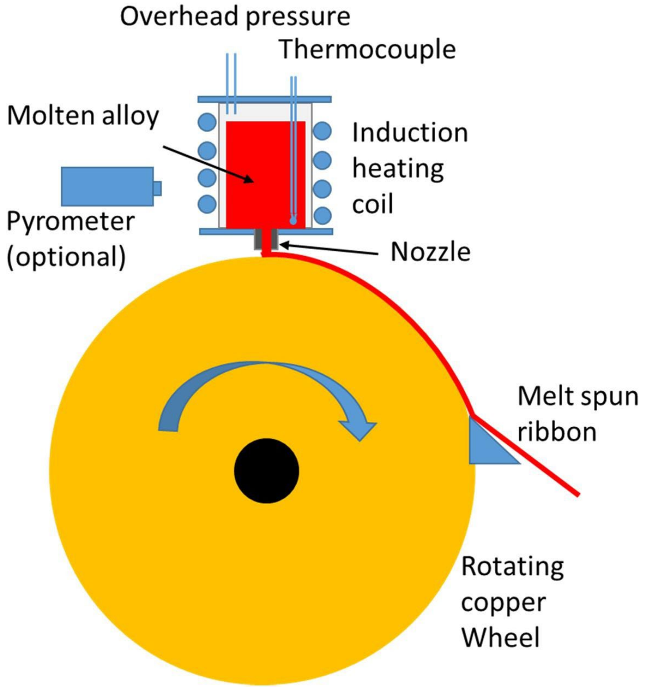
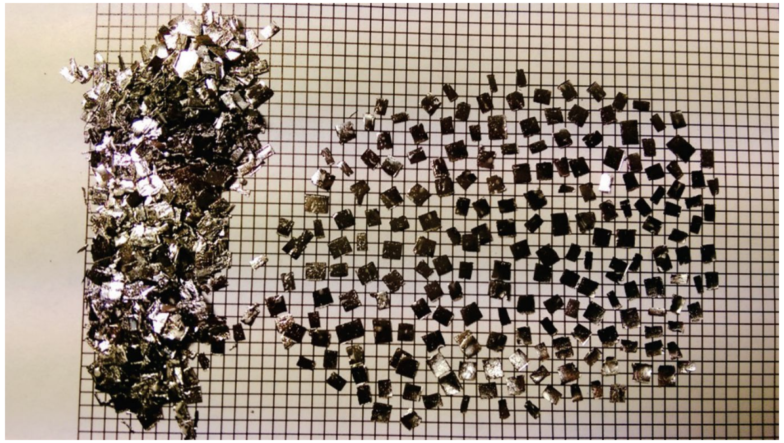
Advances in Silicon Steel: 6.5% Si Increases Resistance



Silicon Steel



- 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.

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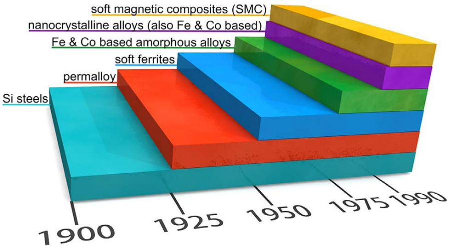
Permalloy, Supermalloy, Permendur, etc.



Permalloy

- Permalloy 80% Ni, 20% Fe
- Mu-metal 77% Ni, 16% Fe, 5% Cu, 2% Cr or Mo
  - *MuMETAL*, *Mumetall*, and *Mumetal2*
- Supermalloy 75% Ni, 20% Fe, 5% Mo
- Permendur 50% Co, 50% Fe
- Permendur 2V 48% Co, 49% Fe, 2% V
- Supermendur
- Hiperco (many types)
- Vicalloy …

Foreshadowed:

- Labradoodle, Goldendoodle, Yorkipoo, Pugapoo

SPS consolidated iron nitride (γ'-Fe_4N)

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 (Ferroxcube)	0.52	$5x10^6$	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).

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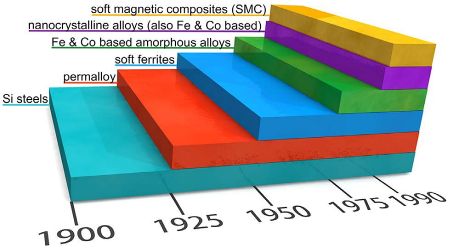
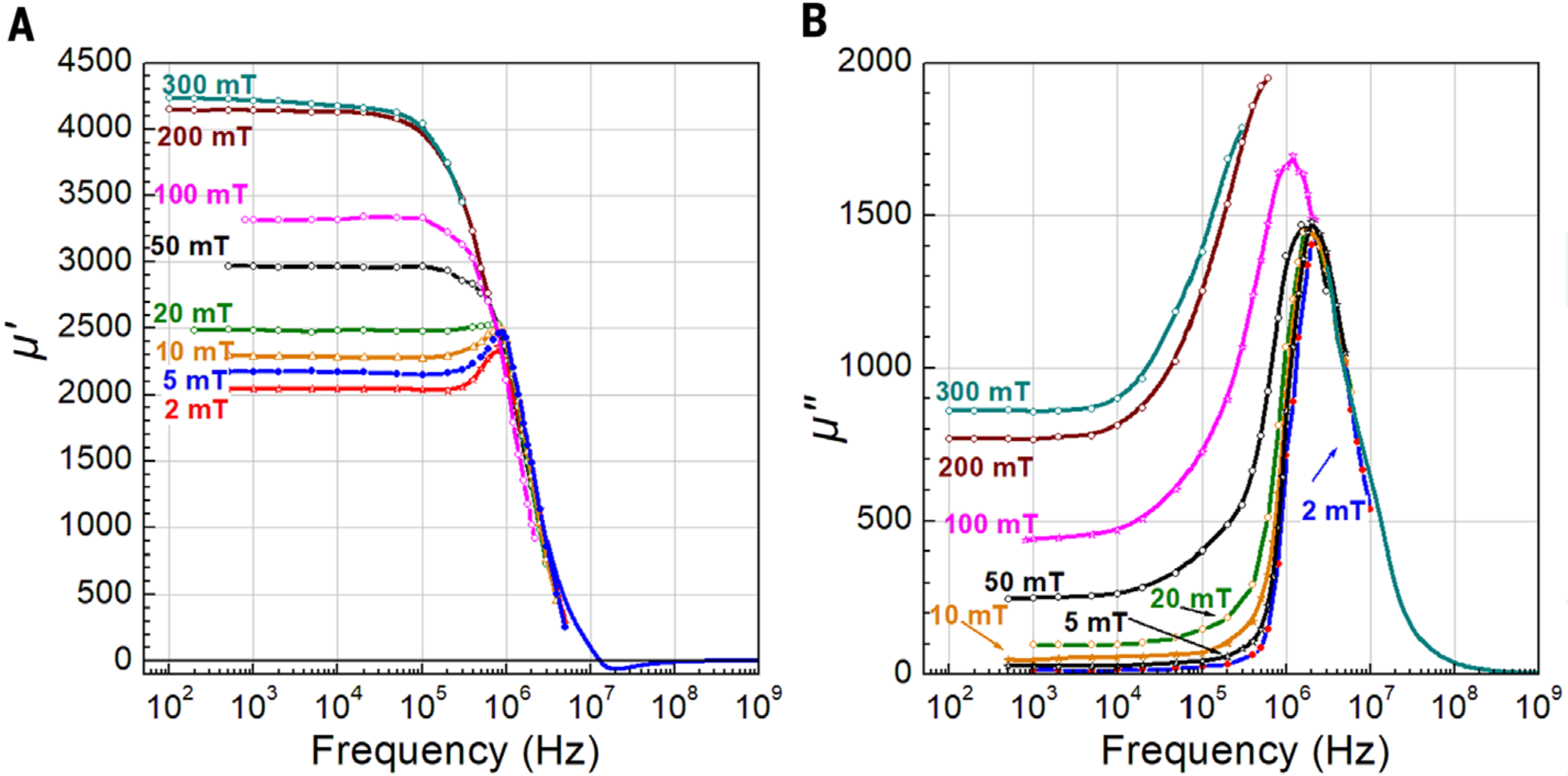
Ferrites



Soft Ferrites



Real and imaginary permeability of state-of-the-art Mn-Zn ferrite inductors

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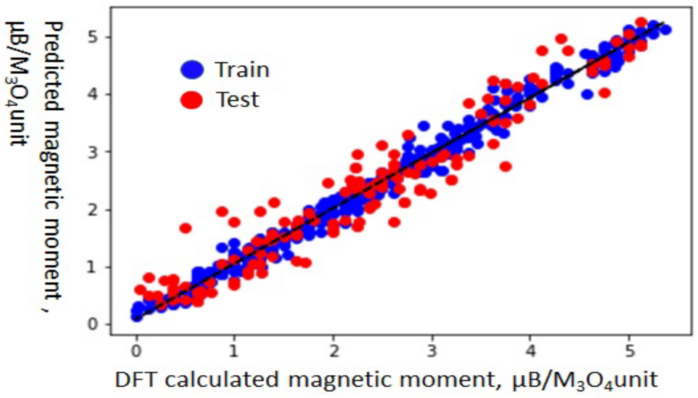
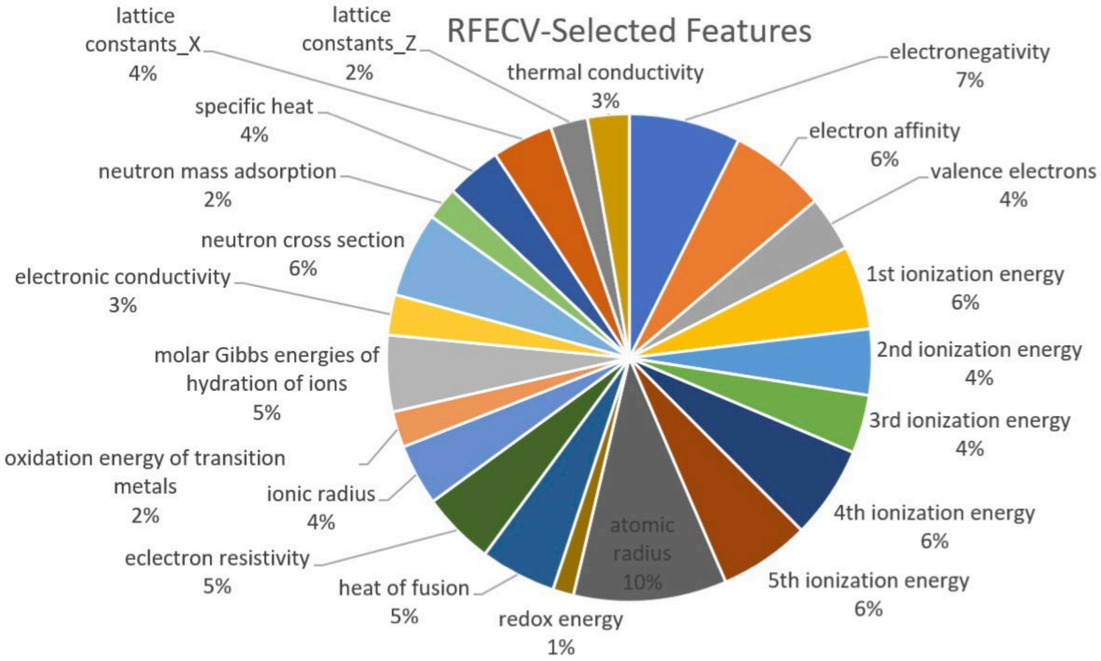
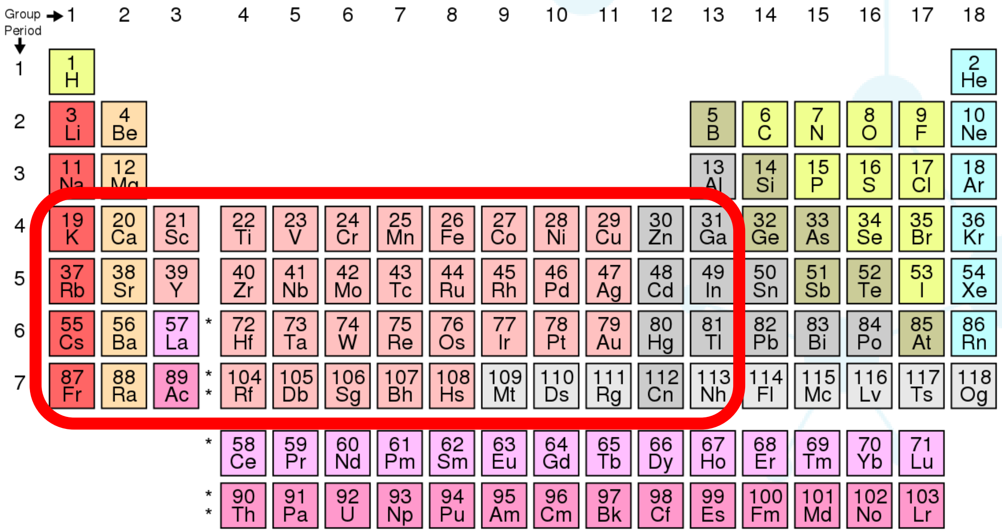
Simulations to Train Artificial Intelligence to Find New Ferrites







The most common ferrite components are the row 4 metals, but in principle any metal is a candidate for substitution.

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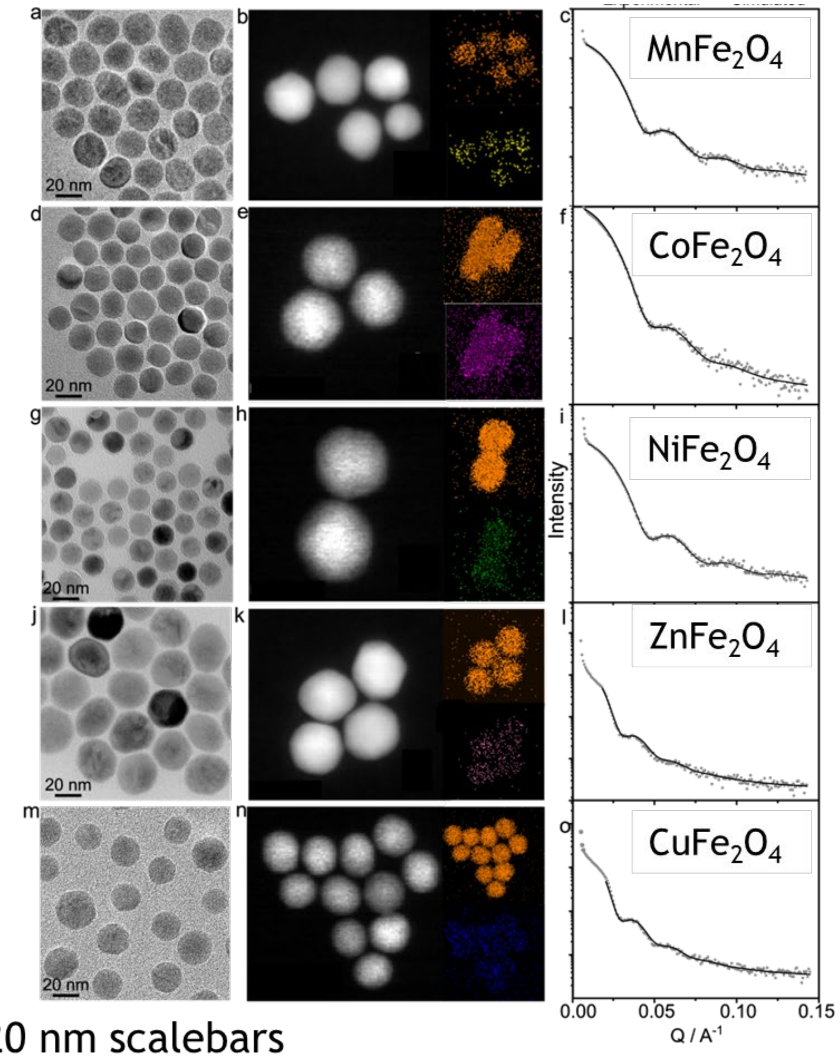
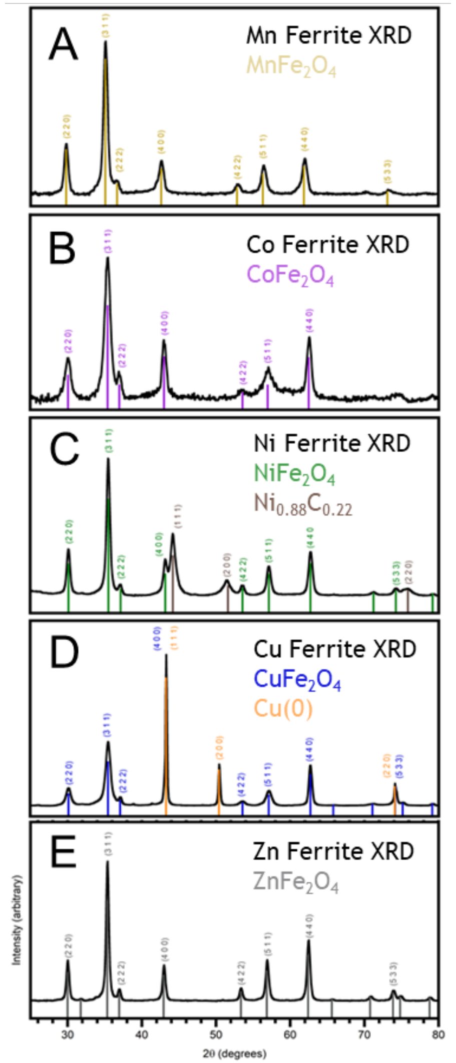
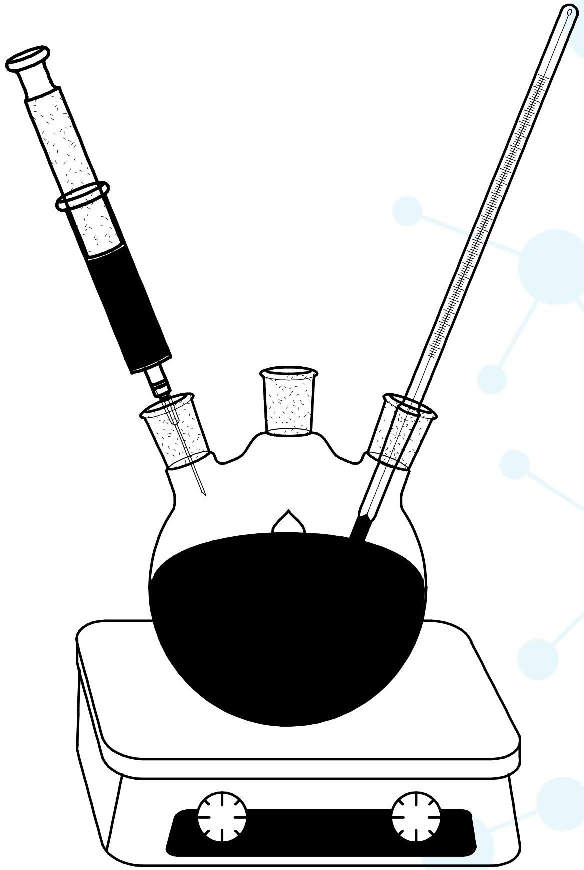
Universal Ferrite Synthesis



20 nm scalebars





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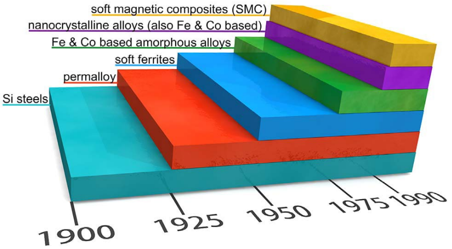
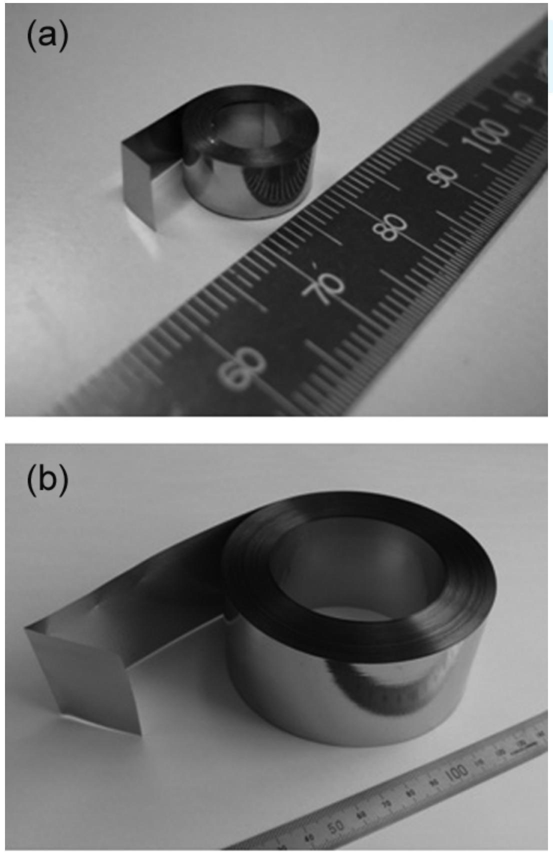
Metal Glasses



Amorphous 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

Very low magnetic anisotropy makes hysteresis losses low, while eddy current losses are minimized by the thin laminations. Not used extensively above 10s of kHz.

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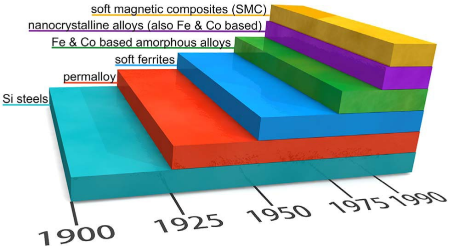
Nanocrystalline Alloys



Nanocrystalline Alloys

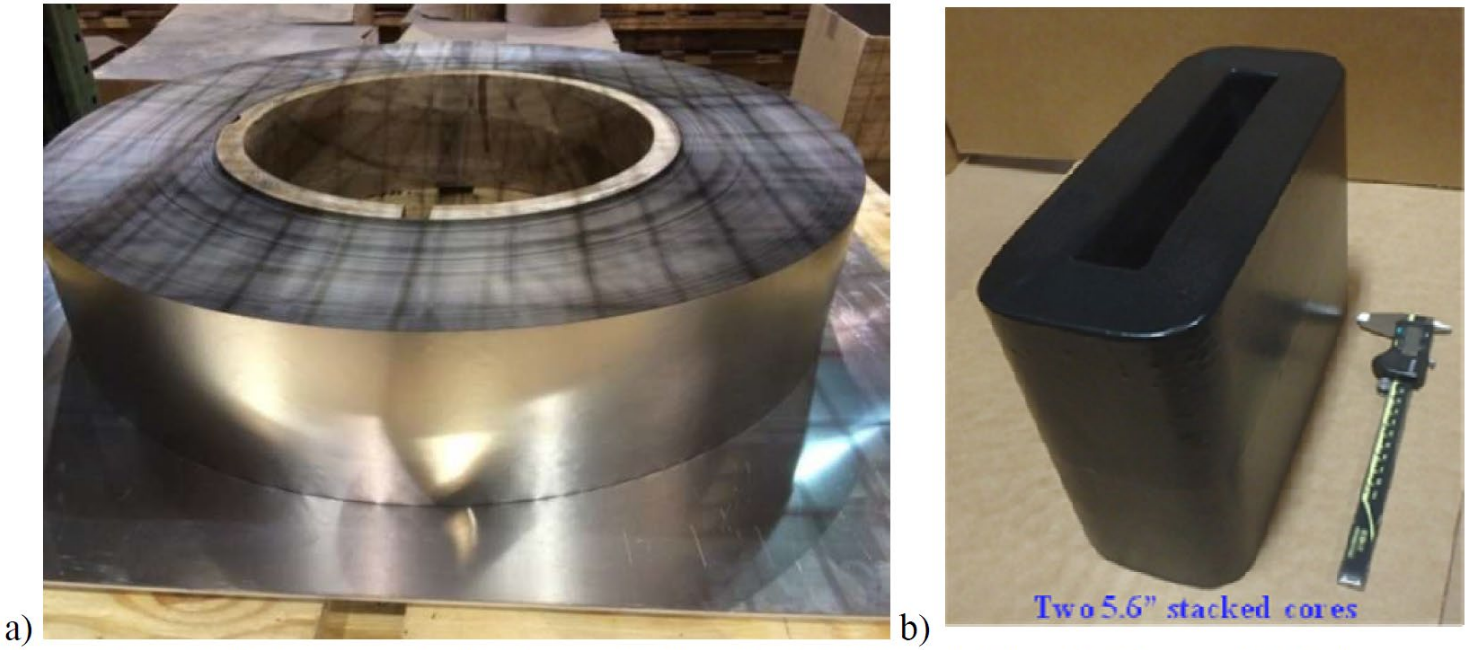


Figure 3: a) Full sized spool of 142mm (5.6") wide FT-3W weighing 500 kgs and b) Inductor core fabricated from the 142mm nanocrystalline FT-3W ribbon.

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

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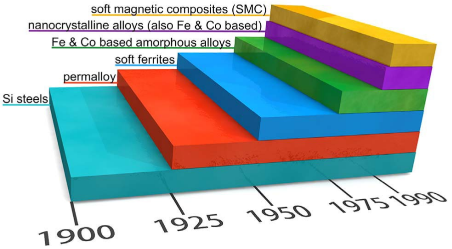
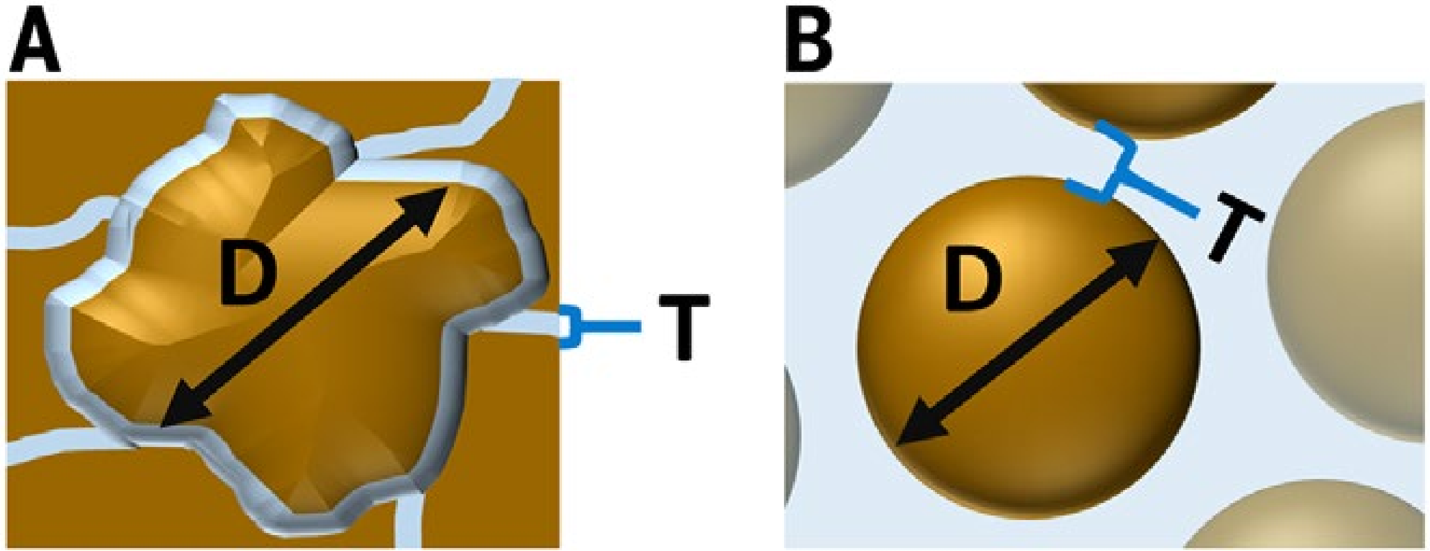
Soft Magnetic Composites



Soft Magnetic Composites



Micron-scale (A) and Nanoscale (B) soft magnetic composites

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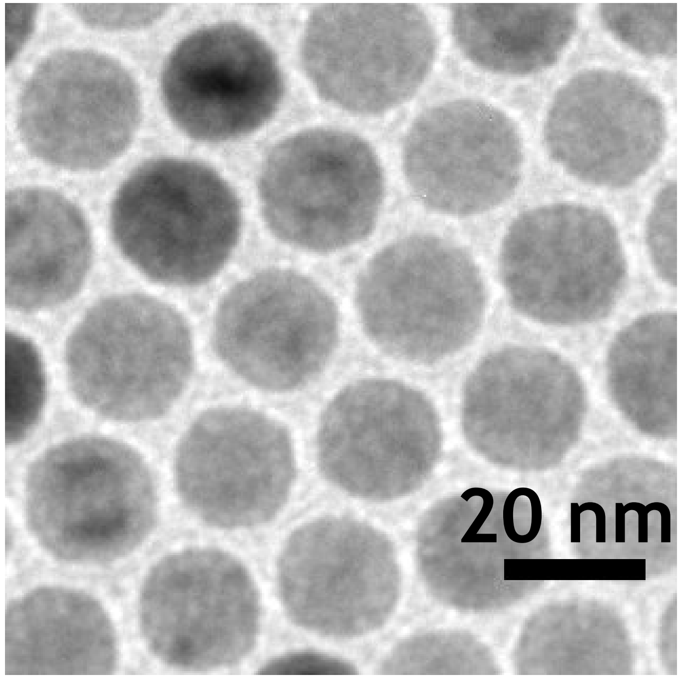
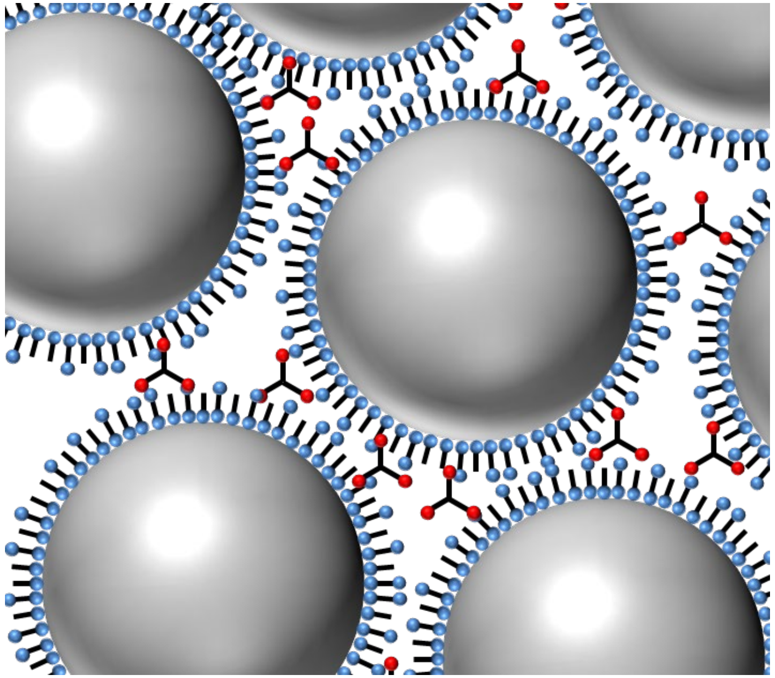
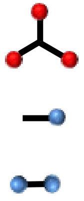
Magnetic Nanocomposites, Organic Matrix







- **Uniform particles**
- **Uniform, controlled spacing**
- **Insulating composite**
- **Can leverage superparamagnetic behavior (no hysteresis)**
- **Particles are too small to support eddy currents**
- **Tradeoff: reduced susceptibility**

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).

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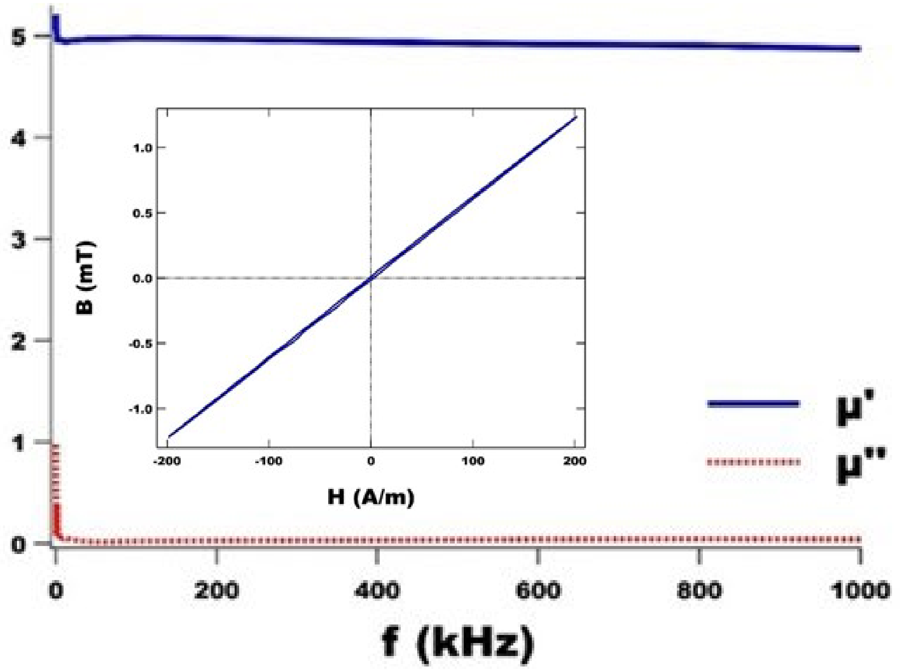
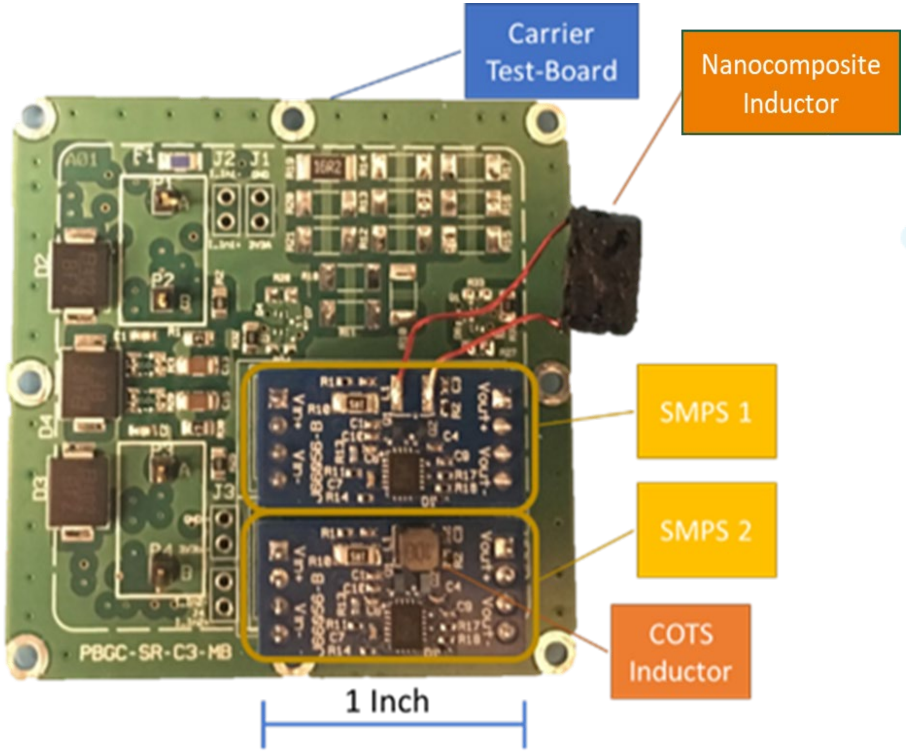
Real World Testing





In a real system, a 3.3V synchronous buck converter, we saw a 3% efficiency improvement over a state-of-the-art inductor.

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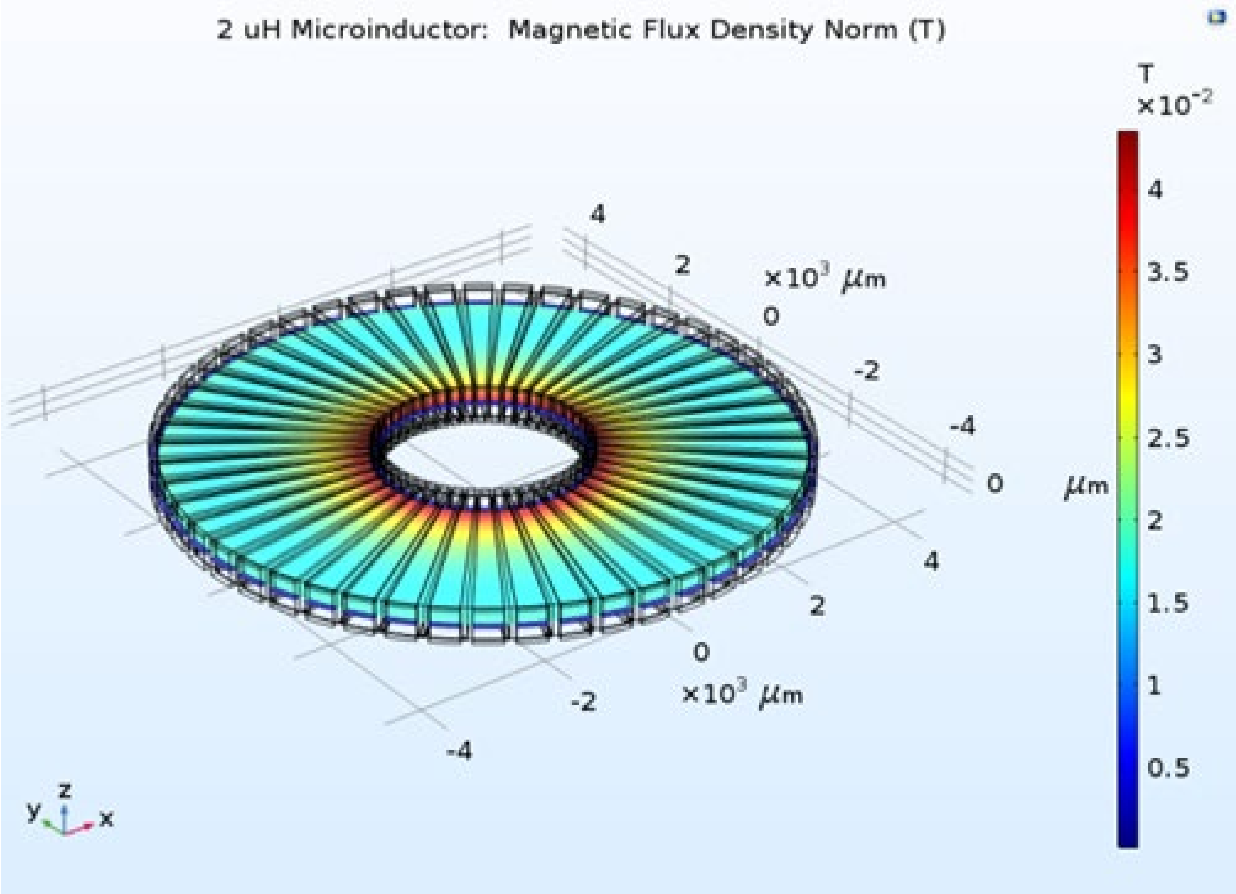
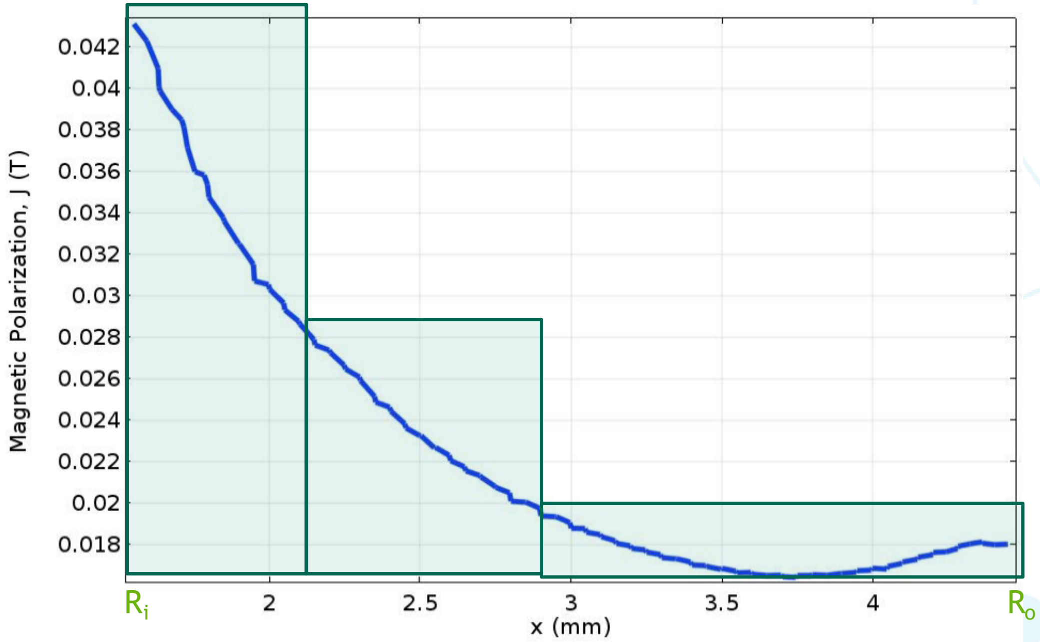
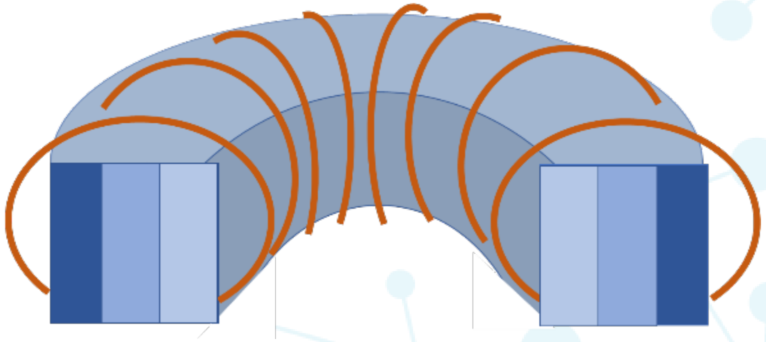
Hybrid Cores







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