Power Magnetics:
Emerging Technologies and Research Needs

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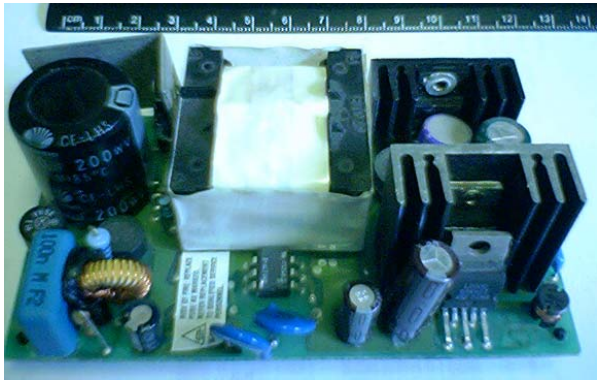
Why Magnetics?

- Magnetics (inductors and transformers) are required for most power conversion circuits, but are responsible for much of the
  - Size (volume and weight)
  - Power loss
  - Cost
  - Difficulty in design (long development cycles)



- Advances depend on magnetics:
  - High frequency circuits for miniaturization.
  - Resonant circuit designs.

Directions

not mutually exclusive

Miniaturization:
Very high frequency, integrated, thin-film, small, and (eventually) low cost.

Ultra-high efficiency:
Efficiencies in the high 90's without increasing size or cost.

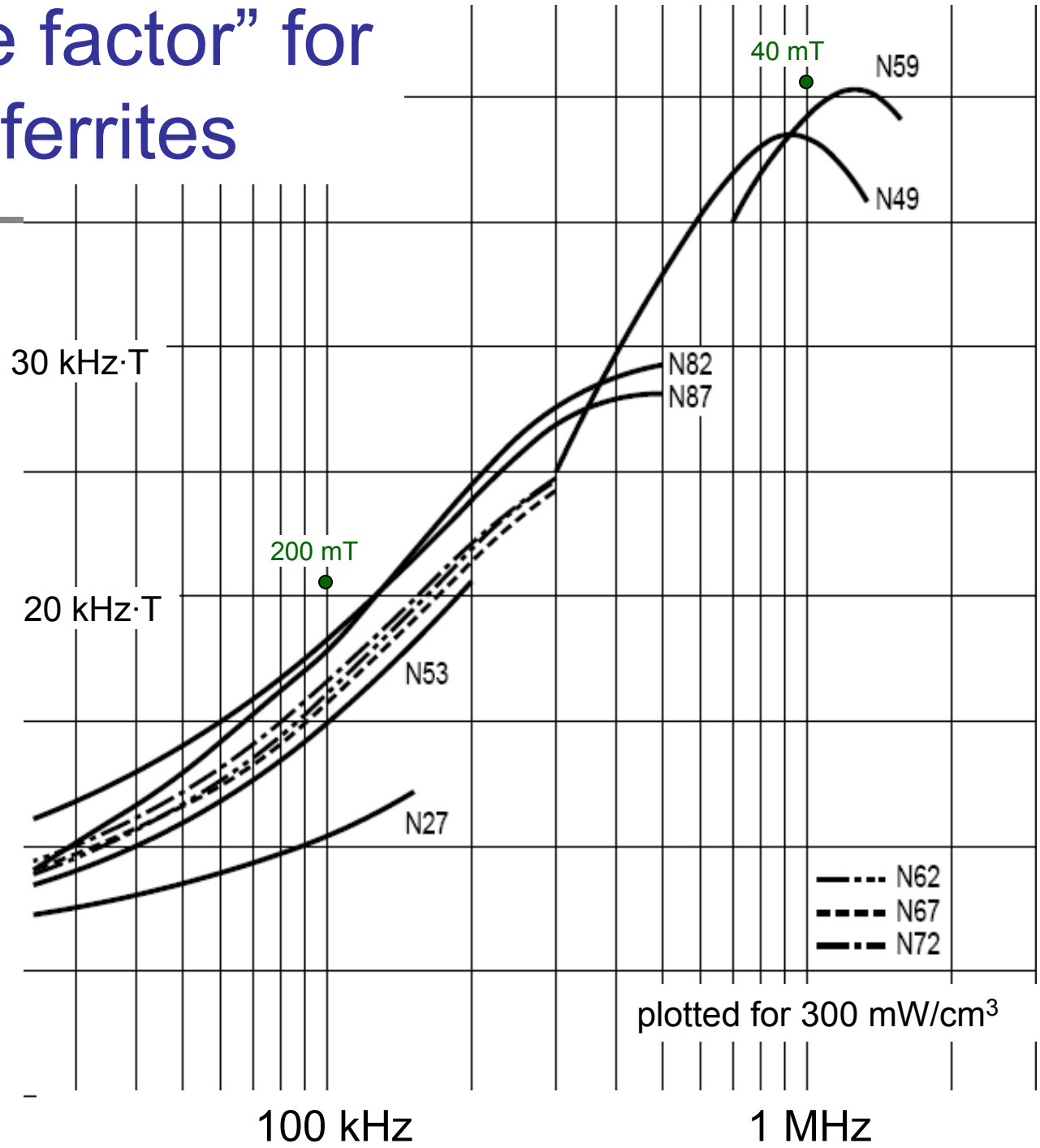
High-power
High-frequency, high-efficiency at multi-MW scale.

Minaturization

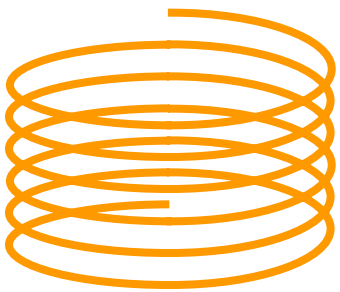
- General idea: for given impedance $Z = j\omega L$, the inductance needed goes down with frequency.
  - Similar scaling for transformers.
- Actual scaling depends on material properties (with a magnetic core).
  - Examine "performance factor" $B \cdot f$…..

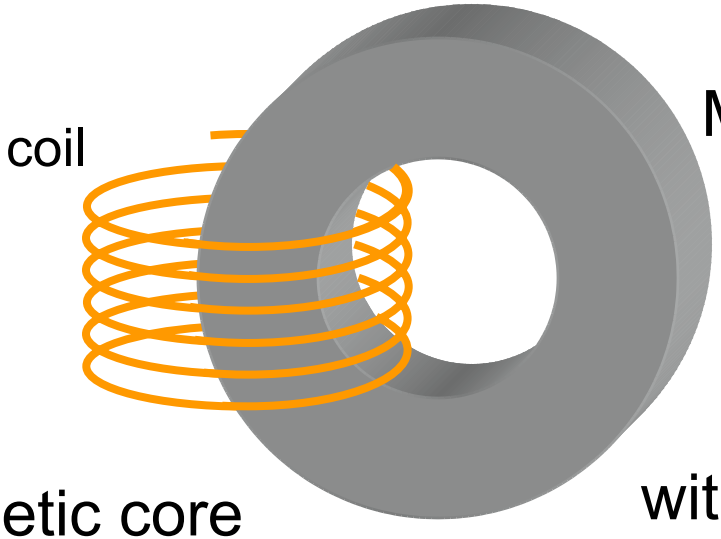
“Performance factor” for MnZn power ferrites

- Curves of *B·f* product for constant power loss density…
- No benefit from *f* > ~ 1 MHz.
- Need different materials for higher frequency.



Air-core vs. magnetic core





Magnetic Core: soft magnetic material with relative permeability $\mu_r >> 1$

- "Air core" is really any non-magnetic, dielectric material.
- Magnetic core increases L (inductance) by a factor μ_r, typ. 4 ~10,000
- Allows smaller volume, fewer turns for same *L*

$(B = \mu_r \cdot \mu_0 \cdot H)$

The case for air-core

- At very high frequencies (e.g. VHF = 30 MHz to 300 MHz), the inductance value is small and readily achievable without magnetic materials.
- Always gets better at higher frequency:

  At constant η (constant *Q*): Volume proportional to $f^{-3/2}$

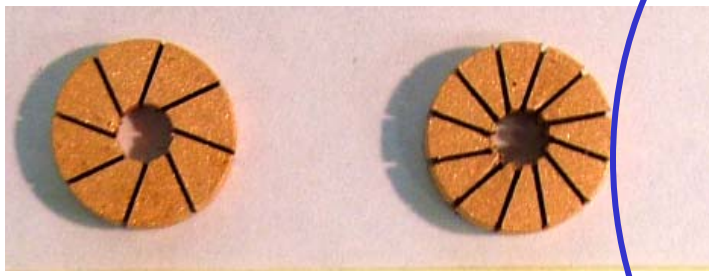
  At constant heat flux: Volume proportional to $f^{-1/2}$

  with *Q* improving as $f^{1/3}$
- Avoid magnetic material disadvantages:
  - Power losses due to hysteresis and eddy currents.
  - Frequency limitations: any material gets too lossy above some frequency, often only a few MHz.
  - Not available in standard IC or packaging processes.

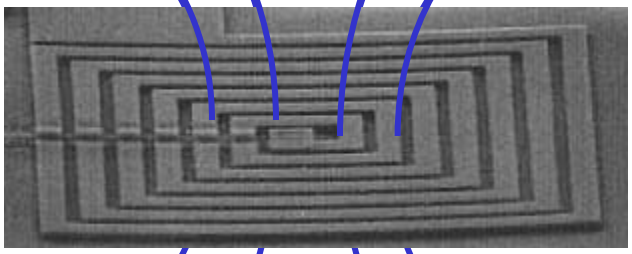
Air-core challenges

- Low permeability leads to low flux density, which requires substantial volume for sufficient flux.
- Requires more turns → more winding loss.
- Flux is not contained by a core; external flux can cause EMI problems and eddy-current loss in nearby conductors.
- Requires significant air volume.

Air-core geometries



Our work



C.P. Yue, CMU

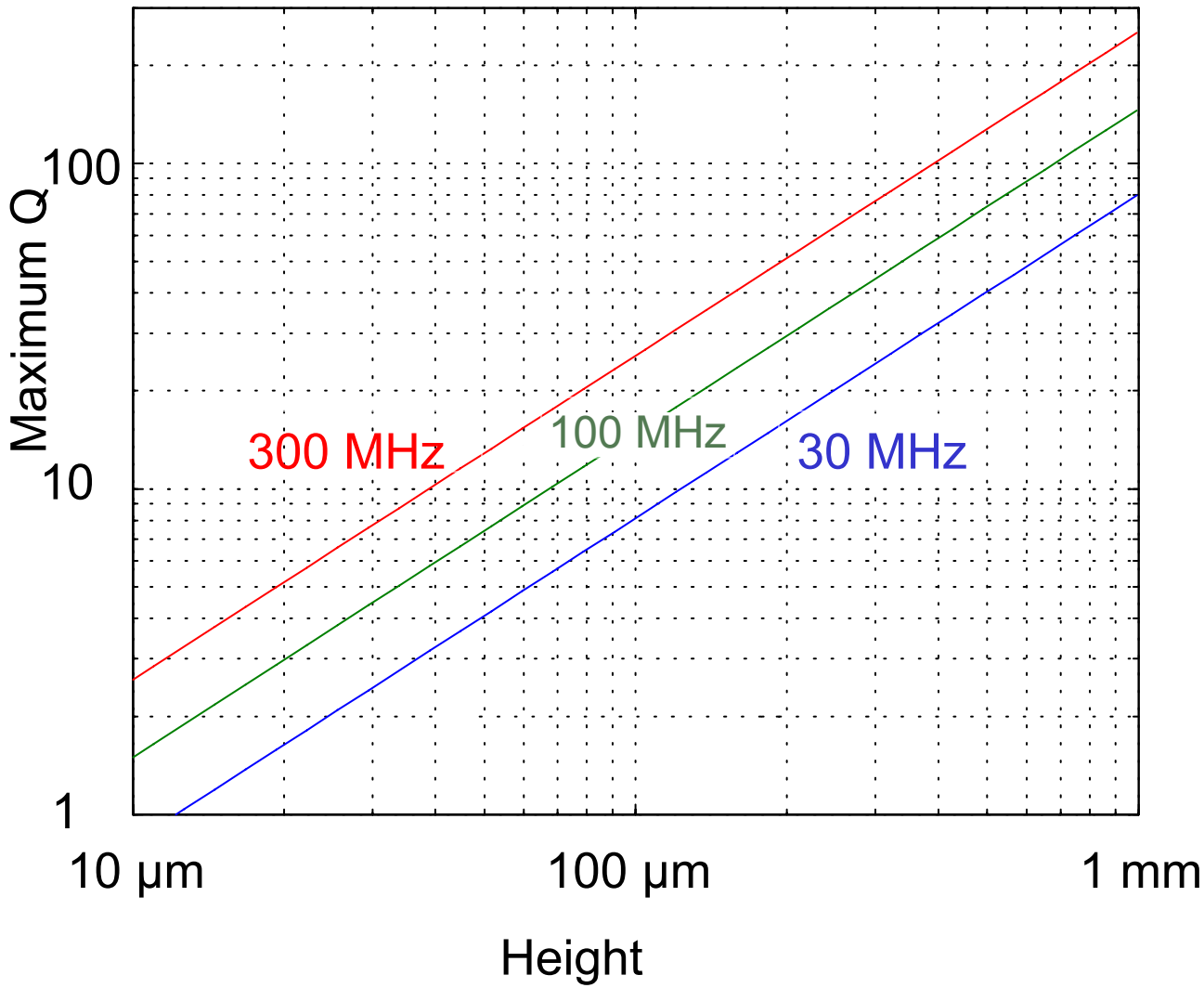
Toroid

- No external flux problem.
- Field is parallel to conductor: low eddy currents.
- Harder to make.
- Q: can be > 100

Planar spiral

- Flux in substrate, surroundings.
- Field perpendicular to conductor: high eddy currents.
- Easy to make.
- Typical Q:
  < 10 for 1 GHz
  < 4 for 100 MHz

Air-core performance limits



- Field between two layers of copper (e.g. large-footprint toroid)

- Can do better with multilayer copper (in theory): improve by a factor $\sqrt{p}$ where p is number of copper layers.
- Requires height for flux path!
- Packaging layer vs. on-chip.

Magnetic material options

- MnZn Ferrites: M_S = 0.45 T, but losses limit B_{AC} to 50 mT at f ~1 MHz
- RF materials: NiZn, powdered iron: 10's of MHz, but still only 10's of mT: need thick cores for power.
- Many thin-film materials:
  M_S = 1~2 T, can operate with full flux swing, up to 10's of MHz to 1 GHz.
  - Power density ~ $B \cdot f \Rightarrow 10^3$ to 10^4 X improvement.

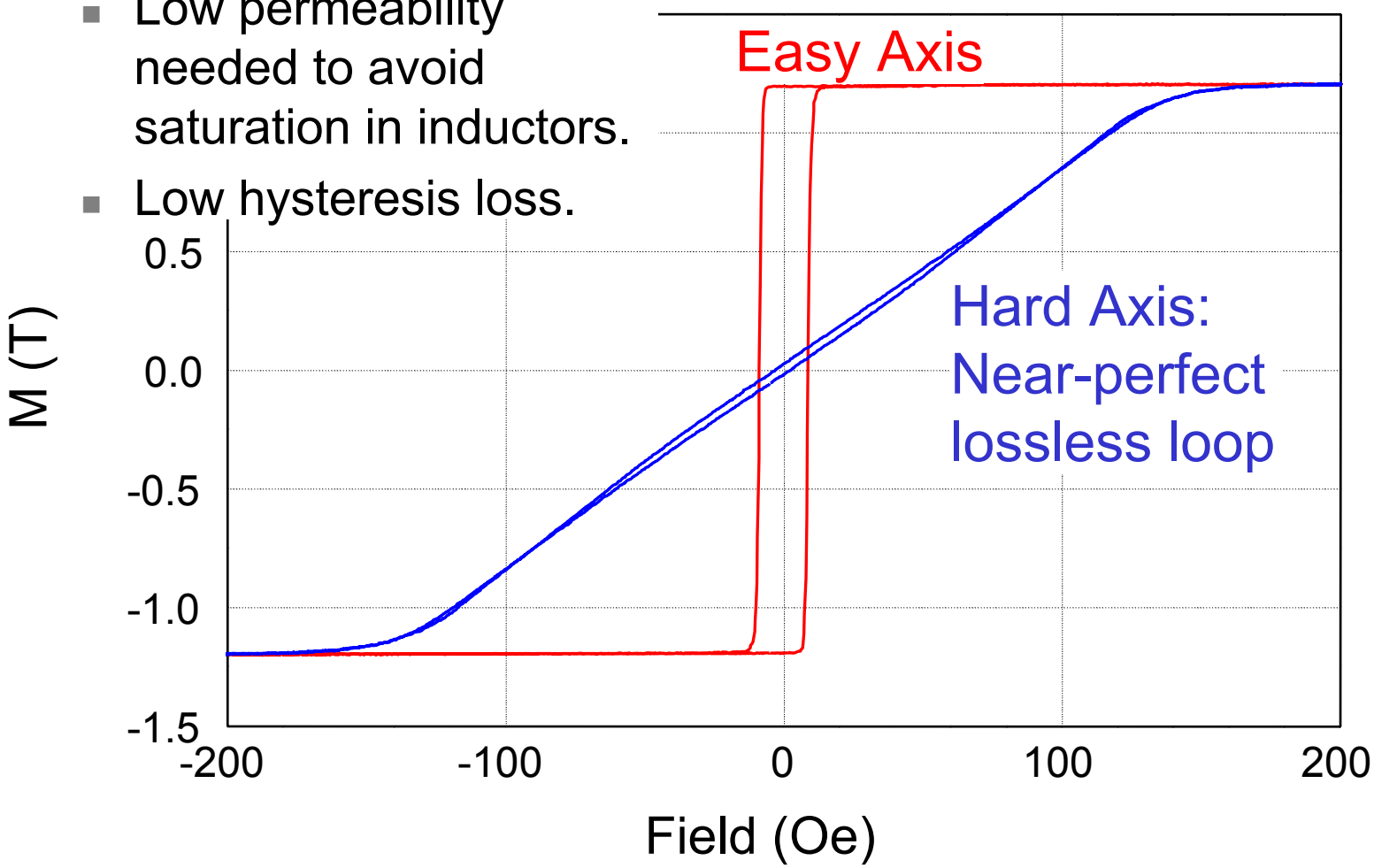
Option for aggressive miniaturization

Thin-film magnetic materials

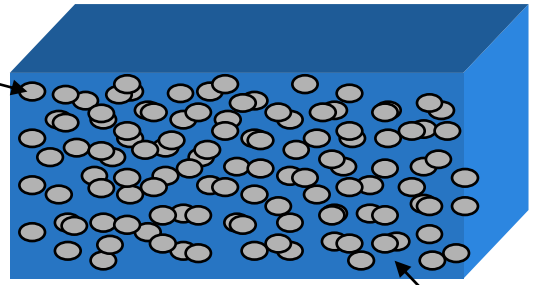
- Typically alloys with Fe, Co and or Ni.
- Sputtered or electroplated.
- Relative permeability μ_r in the 100's or 1000's.
- Resistivity ~ 20 – 600 μΩ·cm;
  - High end preferred for low eddy-current loss
  - May still need laminations.
- Hysteresis loss?

Magnetic anisotropy

- Hard axis loop provides:
  - Low permeability needed to avoid saturation in inductors.
  - Low hysteresis loss.



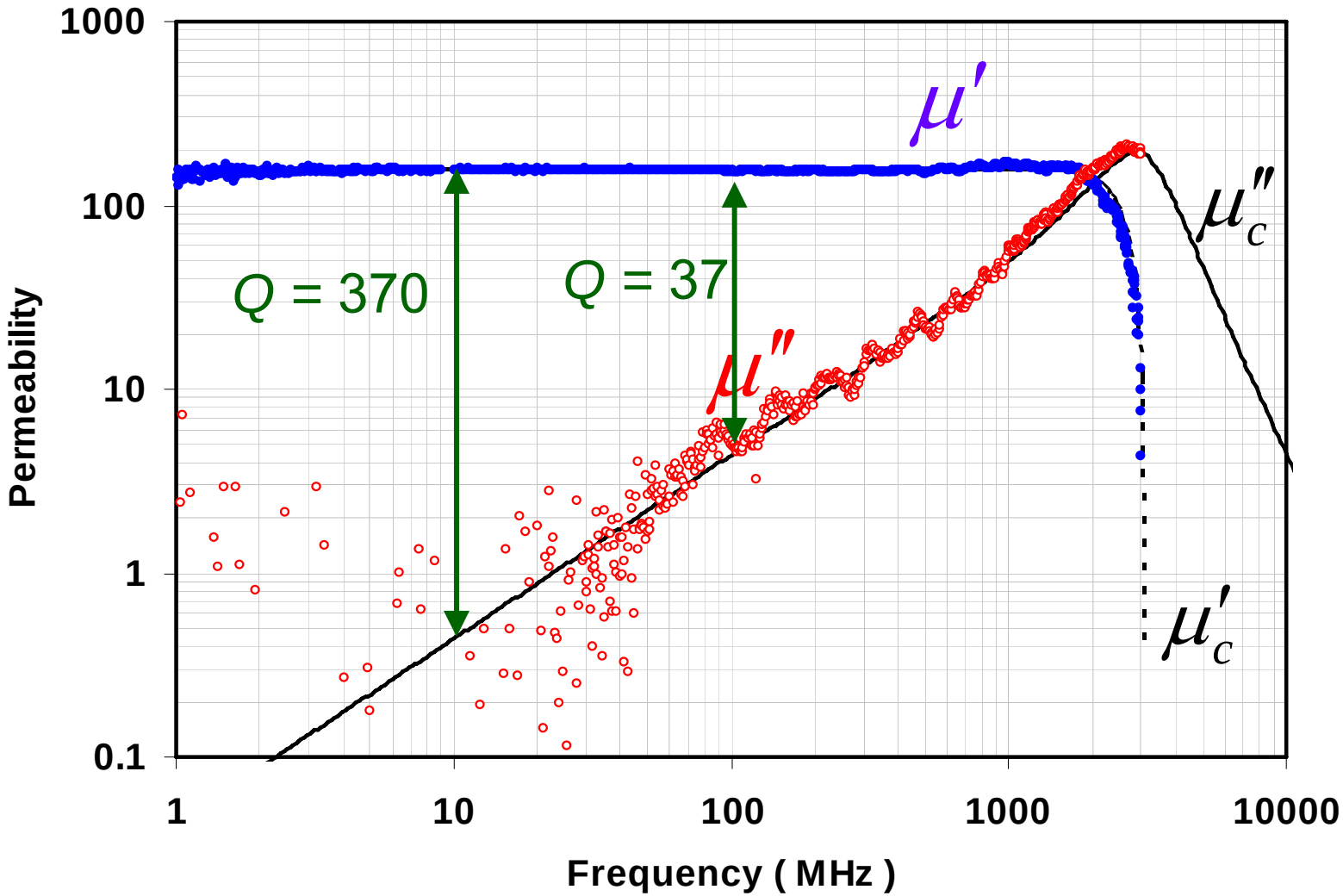
Nano-composite magnetic materials



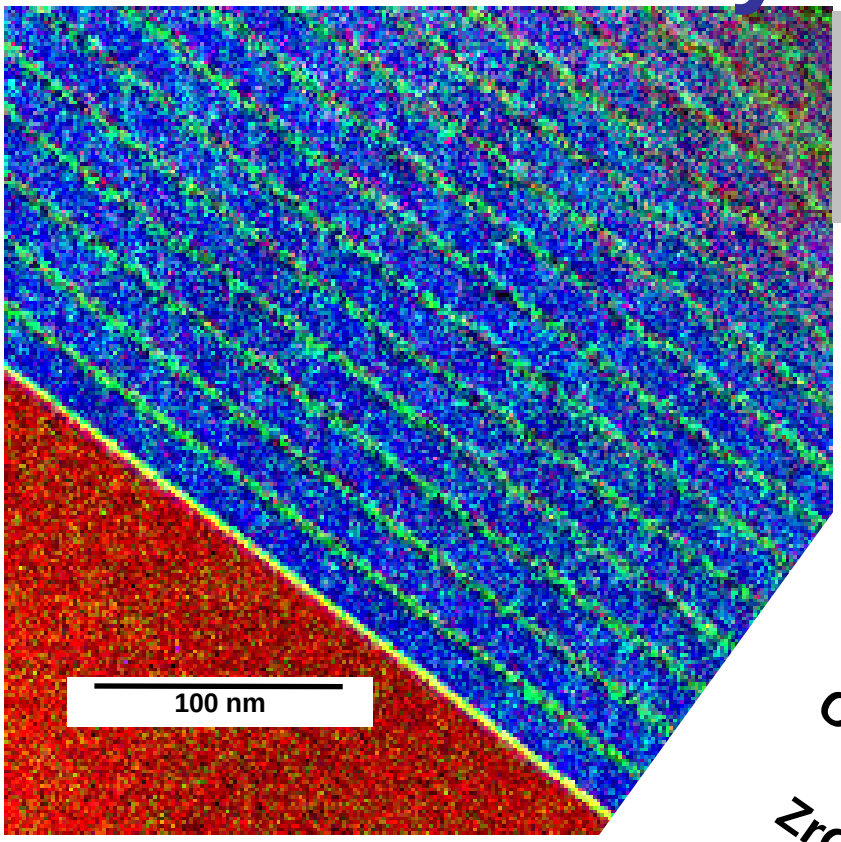
Advantages:

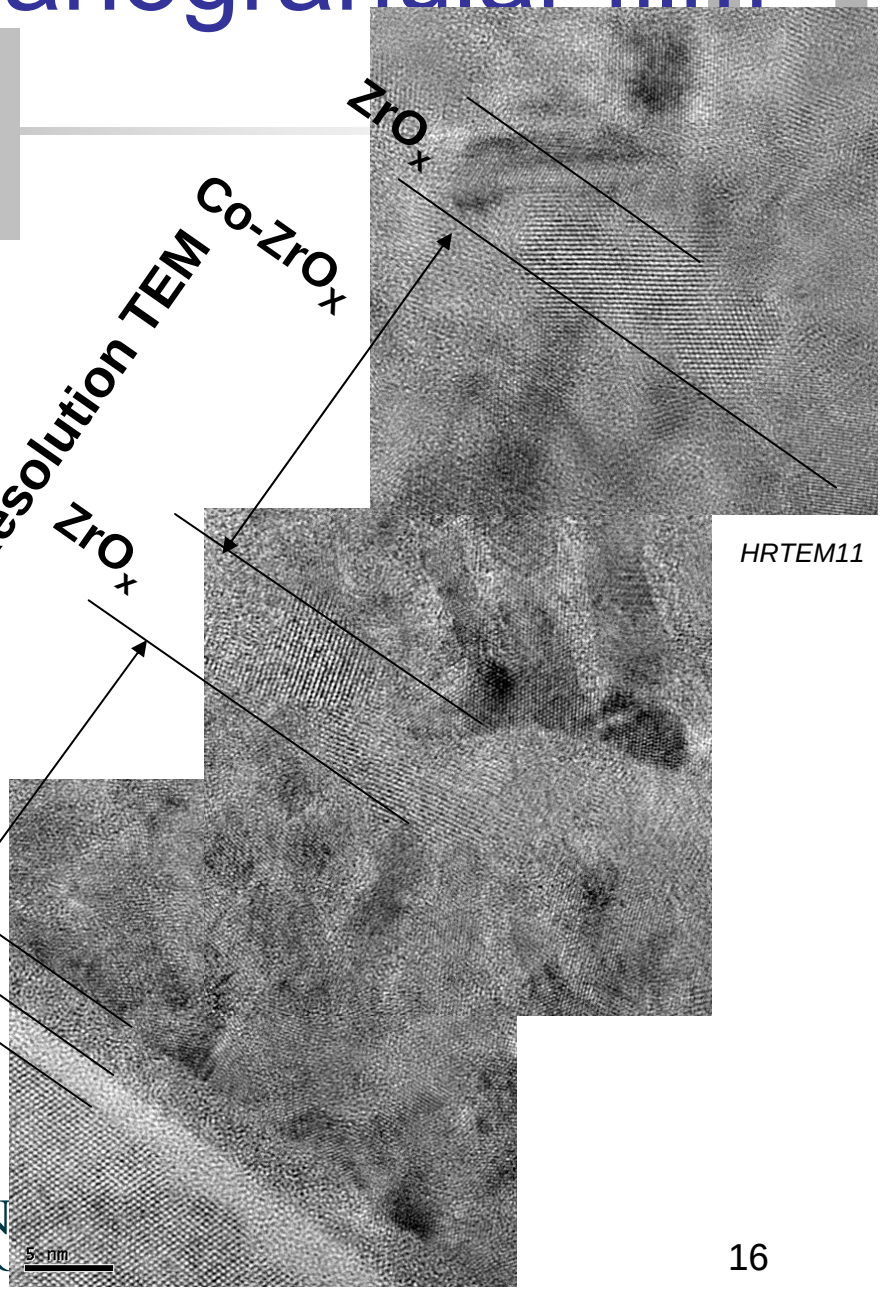
- Ferromagnetic (coupled particles)
- High resistivity (300 ~ 600 μΩ·cm) controls eddy-current loss independent of flux direction.
- Some have strong anisotropy for low permeability and low hysteresis loss.

Permeabilty vs. frequency

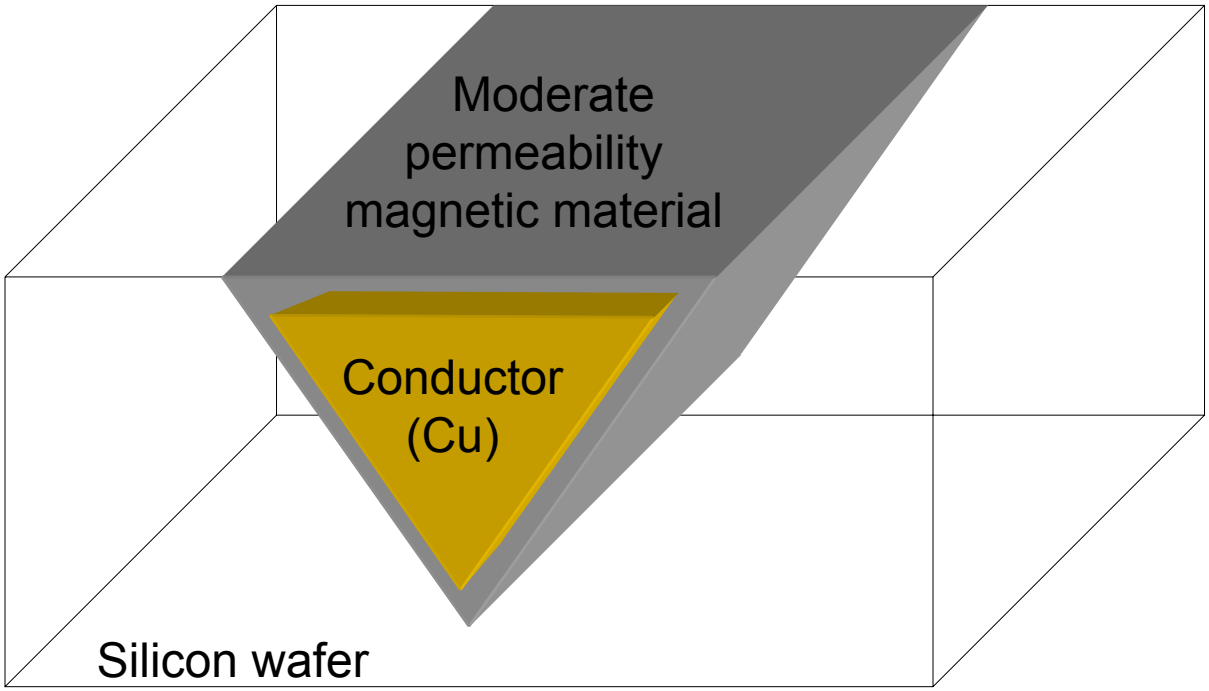


TEM of **multilayer** nanogranular film



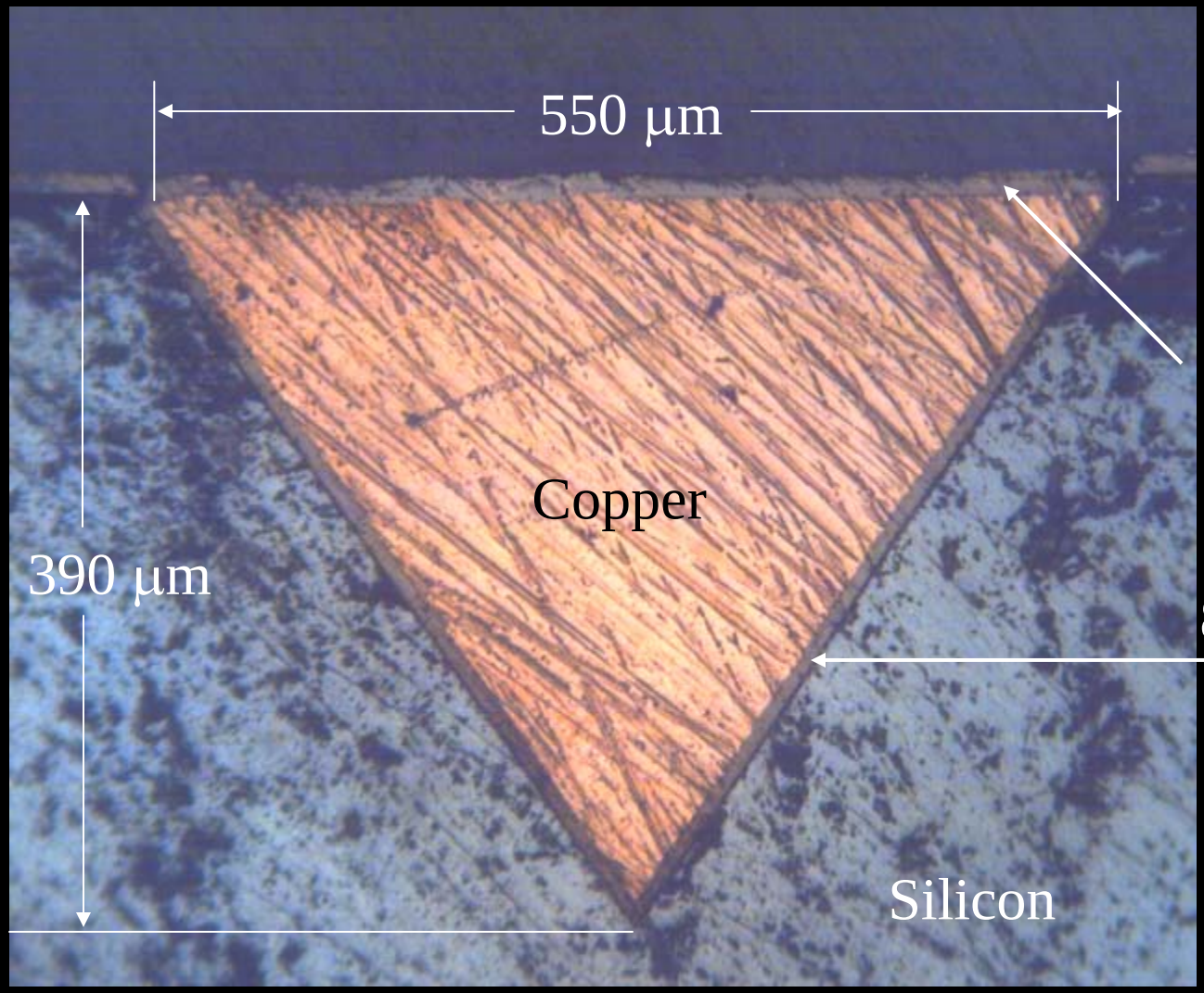


V-Groove Inductor Design



- One-turn inductor for high-current low-voltage microprocessor power supply.
- Easy fabrication process

Cross-Section of V-Groove Inductors



10-μm-thick Co-Zr-O

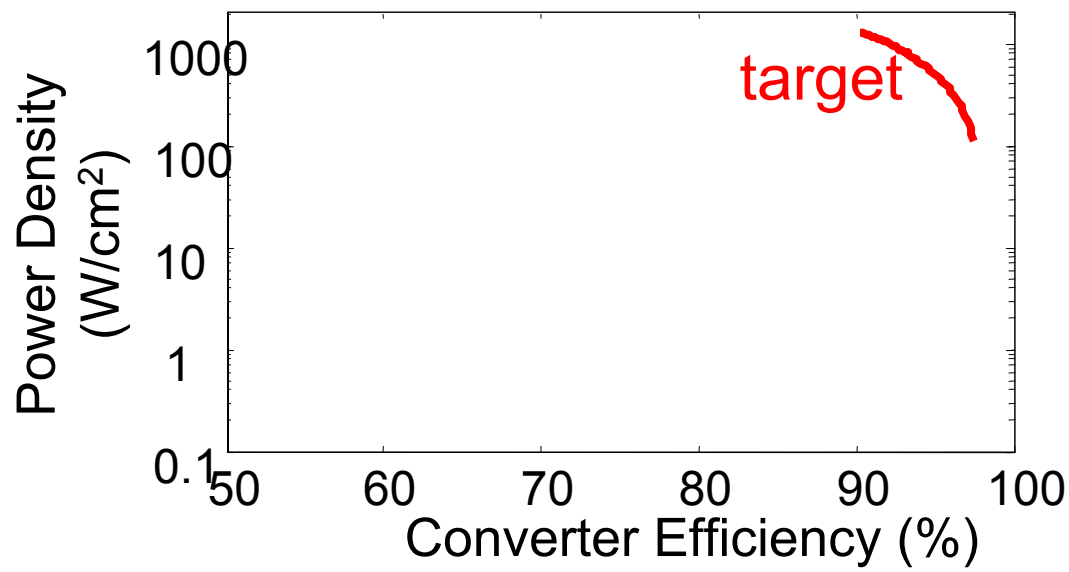
8-μm-thick Co-Zr-O

Miniaturization research needs

- Magnetic materials development.
- Understand, measure, and model power losses in materials.
- Fabrication processes for miniaturized inductors and transformers.
- Electromagnetic design for low losses.
  - High-frequency windings, application of anisotropic magnetic materials…
- Co-design of circuits and magnetic components.

Performance metrics for miniaturized magnetic-core inductors

- Q is an incomplete metric:
  - Doesn't reflect saturation limits.
  - DC resistance can be more important than AC resistance (used in calculating Q)
  - Core loss is nonlinear; Q can vary with drive level.
- Better metrics: efficiency and power density.



Ultra-high efficiency

Miniaturization:
Very high frequency, integrated, thin-film, small, and (eventually) low cost.

Ultra-high efficiency:
Efficiencies in the high 90's without increasing size or cost.

High-power
High-frequency, high-efficiency at multi-MW scale.

Ultra-high efficiency

- Accurate loss models are essential:
  - Understand all sources of loss.
  - Optimize to get ultra-high efficiency without high cost.
- Co-design with circuits.
- Materials
  - Better MnZn ferrite materials?
  - Bulk nanocomposite materials?

Loss models for ultra-high efficiency

- Core loss:
  - Effect of non-sinusoidal waveforms on loss in ferrites.
  - Effect of dc bias on loss in ferrites.
- Winding loss:
  - Tradeoff between ac and dc winding loss.
  - Practical models for complex winding approaches.

High Power

Miniaturization:
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High-frequency, high-efficiency at multi-MW scale.

High-power characteristics

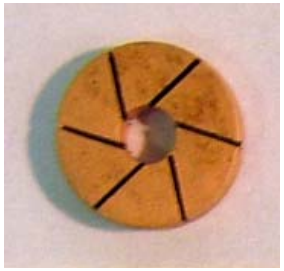
- Large size makes two particular challenges severe:
  - Overall winding size is large compared to skin depth. 10 cm scale at 10 kHz has the same ratio (150) as mm scale for 100 MHz.
  - Thermal management—low surface-area to volume ratio.
- Magnetic Materials: Amorphous, nanocrystalline, steel.

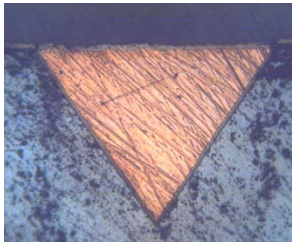
High-power research needs

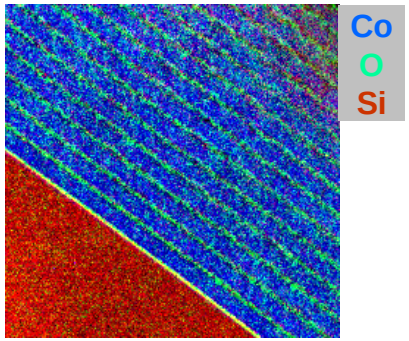
- Magnetic material improvements (amorphous, nanocrystalline, steel).
- Core loss modeling with nonsinusoidal waveforms.
- Winding designs:
  - For severe size-to-skin-depth ratios.
  - For mixed-frequency currents.
- Co-design of magnetics and circuits

Highlights

- Common Themes:
  - Magnetic material development.
  - Loss modeling and electromagnetic design.
  - Co-design of circuit and magnetics.
- Miniaturization:
  - Air core and magnetic core.
  - Nano-granular magnetic materials.
- Ultra-high efficiency:
  - Loss modeling and design optimization.
- High power:
  - Large size to skin-depth ratio.
  - Thermal design essential.







Selected references

This recent tutorial/overview paper on integrating magnetics for on-chip power converters has 66 references including many I'd like to list here, plus more extensive discussion of air-core and magnetic-core miniaturized power magnetics:

- C.R. Sullivan, "Integrating Magnetics for On-Chip Power: Challenges and Opportunities," Invited paper. IEEE Custom Integrated Circuits Conference, Sept. 2009.

This includes advanced modeling of losses in multilayer thin-film materials, and also introduces a modified performance factor for magnetic materials that is more appropriate for high-frequency designs:

- Di Yao and C.R. Sullivan, "Effect of Capacitance on Eddy-Current Loss in Multi-Layer Magnetic Films for MHz Magnetic Components," IEEE Energy Conversion Conference and Exposition, Sept. 2009.

This forthcoming paper has measurements of losses in ferrites with non-sinusoidal waveforms that show phenomena not expected based on existing models:

- C.R. Sullivan, J.H. Harris, E. Herbert "Core Loss Predictions for General PWM Waveforms from a Simplified Set of Measured Data," IEEE Applied Power Electronics Conference, Feb. 25, 2010.

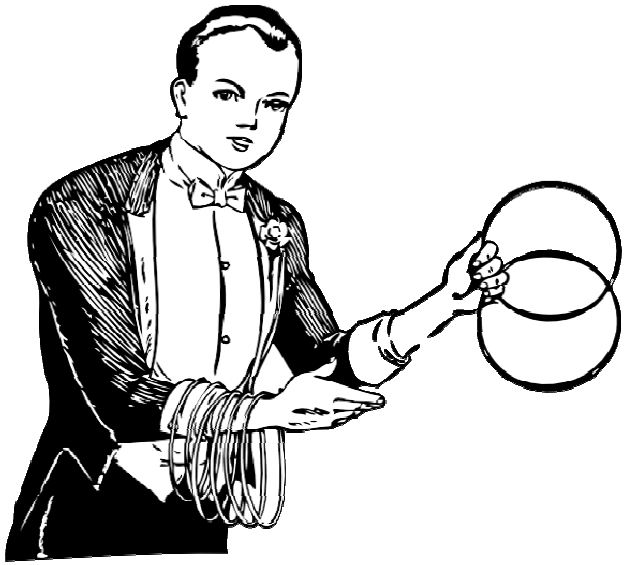
This paper contains a high-level theoretical overview of the potential for reducing winding loss through advanced winding design, without reference to particular practical designs:

- M.E. Dale and C.R. Sullivan. "Comparison of Single-Layer and Multi-Layer Windings with Physical Constraints or Strong Harmonics." IEEE International Symposium on Industrial Electronics, July 2006.

Additional Slides

Thin-film inductor designs

- Fundamental requirement: link core and coil.
- Requires at least three deposition steps:
  - Magnetic, Conductor, Magnetic (MCM), or
  - Conductor, Magnetic, Conductor (CMC)
- Or a magic trick….

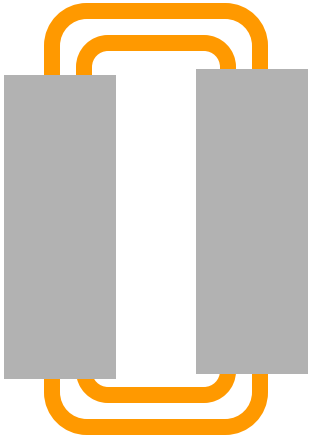


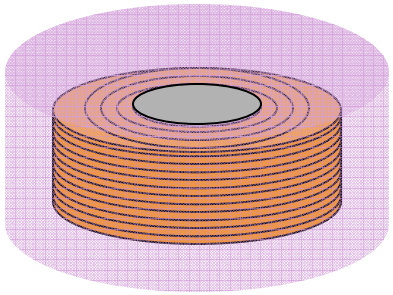
Designs linking core and coil

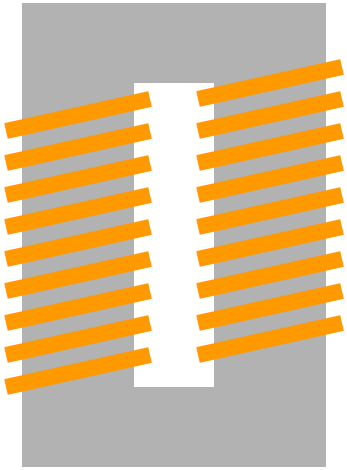
MCM "pot-core"

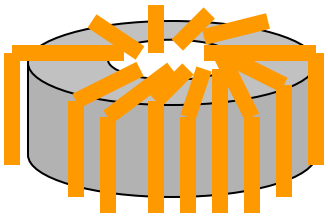
CMC "toroidal"

Plan









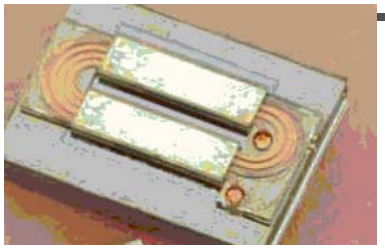
Steps:

Mag., Cond., Mag.

Cond., Mag., Cond

Cross-section

MCM vs. CMC

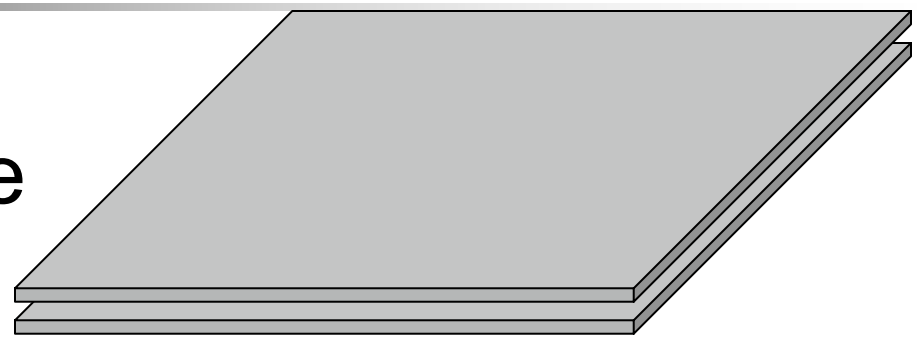


Tyndall

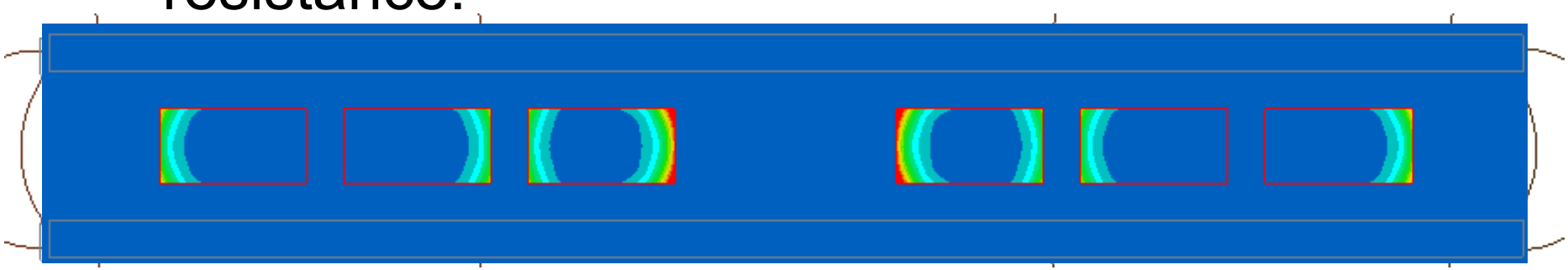
- Same efficiency
- 2X higher power density (see ref [48,51])
- More expensive (less than 2X) ***if*** magnetic deposition is more expensive than copper depostion.

- Lower power density (same copper thickness, same magnetic thickness.)
- Need good via resistance.
- Anisotropy orientation problem at ends
  - Lossy, or
  - Two magnetic deposition steps.

The sandwich inductor



- Straightforward concept to improve planar spiral.
- Multiple problems:
  - Air gap (in magnetic path) positioned wrong for ac resistance:



  - Flux direction in anisotropic core.