Opportunities and Challenges in Magnetics for PV Systems

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Magnetics in power electronics

- Increasingly critical bottleneck
- Responsible for much of the
  - Size (volume and weight)
  - Power loss
  - Cost
  - Difficulty in design (long development cycles)

Solantro 350 W PV microinverter: Miniaturized control chips are great but passives are still huge.

Important for all PV power electronics

- Large inverters (100 kW to MW scale)
- Mid-size inverters (1~20 kW)
- Module-level (~200 W)
  - Micro-inverters
  - Optimizers
- Sub-module power electronics
  - Active balancing bypass diode replacement (e.g. Maxim VT80XX).
  - Cell-by-cell balancing.
  - Active combiner circuits for multi-junction cells.

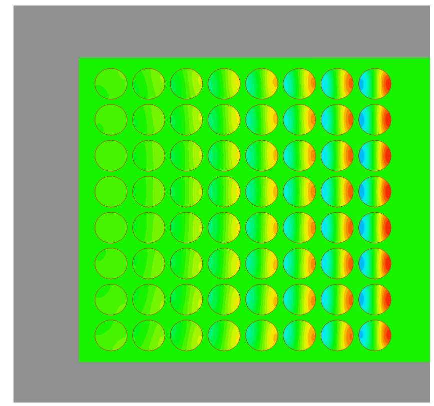
Magnetics Design Overview

- Component design:
  - Winding loss vs. core loss; size and shape.
  - Interaction with circuit design: choice of L, f, etc.,
  - Multi-function components: leakage xfrmer = coupled L; LC; etc.
- Winding design:
  - Linear materials precisely modeled by Maxwell's equations: can analyze and/or simulate accurately.
  - Complex design—opportunity to optimize.
  - Capacitance, voltage breakdown considerations.
- Core considerations:
  - Nonlinear; incomplete physical understanding of loss.
  - Semi-empirical models and material selection.
  - Geometric effects on flux distribution
- Measurements: challenges arising from Q, terminations, nonlinearity, high DC bias, etc.
- Fabrication and manufacturing issues: macro and micro.

High-frequency winding design

- It's all about proximity effect: interaction of field and conductors.
- Not just diameter < skin depth: need d << δ in a multilayer winding.
- How much improvement is possible with many thin layers vs. a single layer?
  - With a number of layers, p, can improve by $1/\sqrt{p}$
  - With a minimum thickness, t_{min}, can improve by $2 t_{min}/3\delta$
  - For 10X improvement: 100 layers, t ~= δ/7
  - **Need right combination—optimization is essential.**

R_{ac}/R_{dc} = 27.7 with d = 2δ



Litz wire

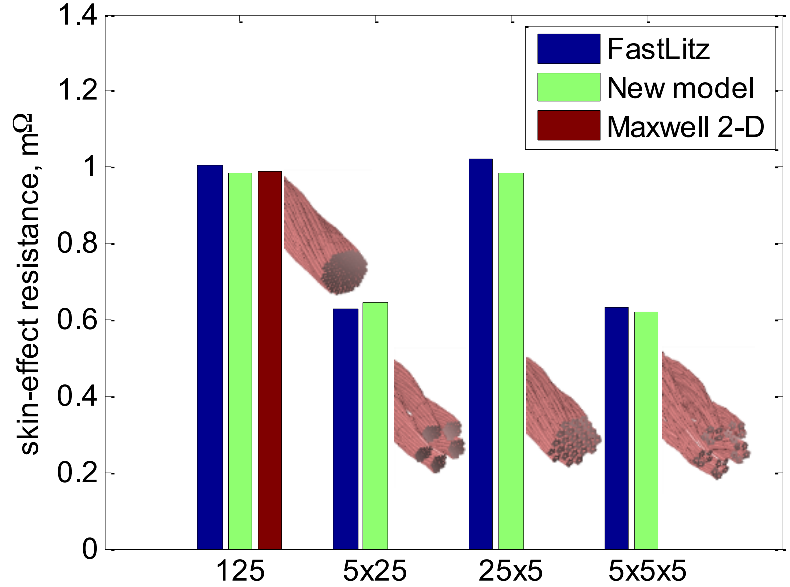
Image: Noah Technologies

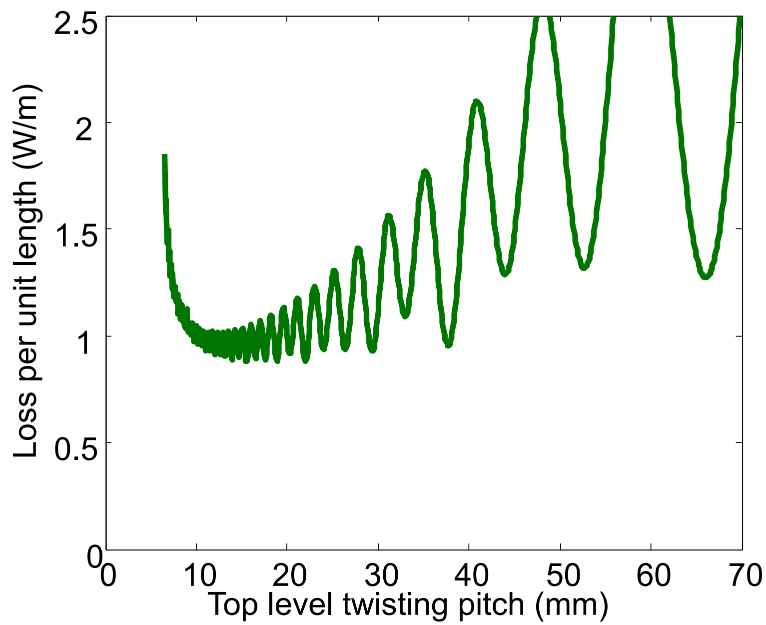
- Strands d << δ.
- Invention: 1888, Sebastian de Ferranti.
- Analysis 1917 Howe; 1926 Butterworth.
- Conventional design options:
  - Papers with lots of complex math.
  - Catalog guidelines … but these can lead to ***higher loss than with solid wire at much higher cost.***
- One solution: single-formula design. APEC 2014, http://bit.do/simplitz

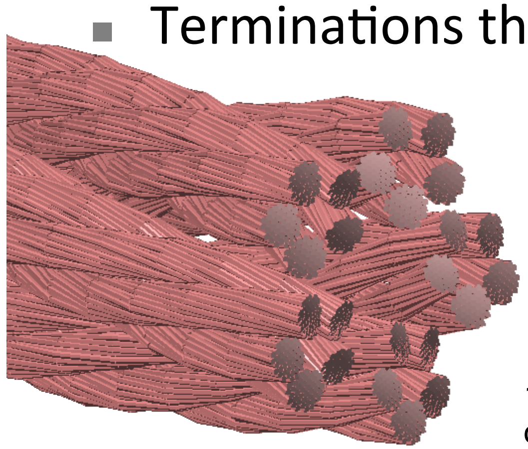
$$n_e = k \frac{\delta^2 b}{N_S}$$

Litz wire construction details and termination loss

- Important for large number of strands and/or small number of turns.
- Our recent research results:
  - Basic guidelines.
  - Detailed model.
- Research needs:
  - Optimization, verification and economics.
  - Terminations that preserve litz behavior.



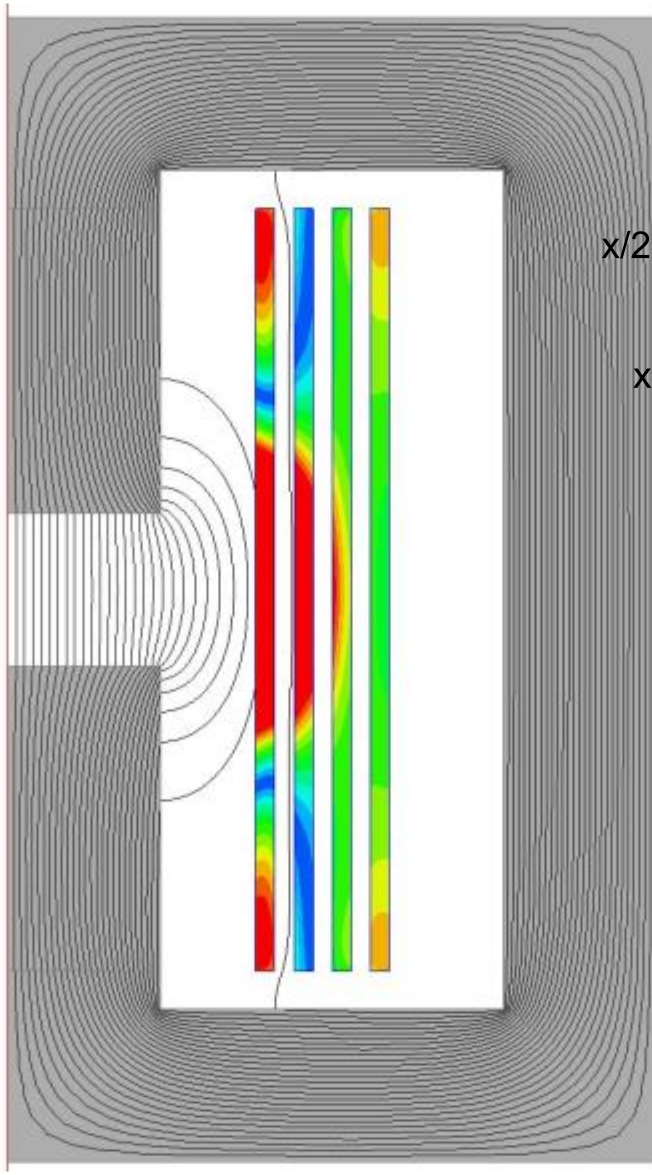


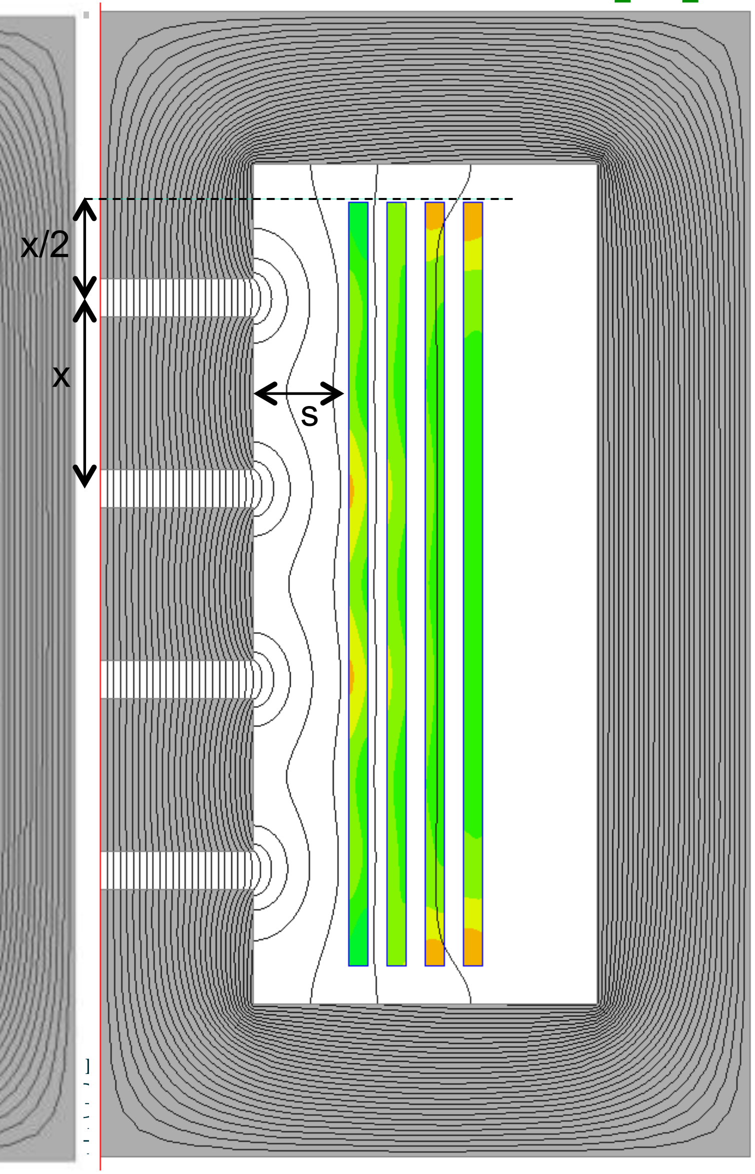


1050 strands of AWG 44, constructed as 5x5x42

Inductors

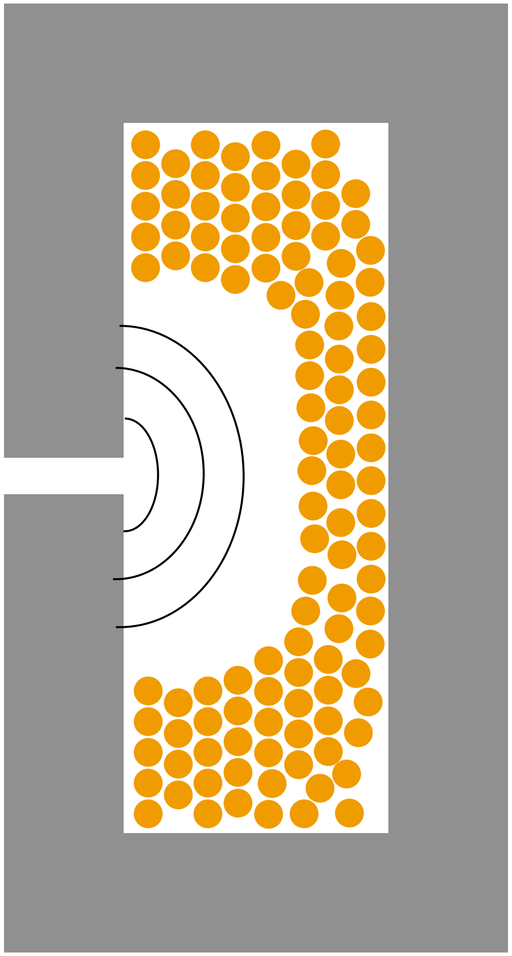
- Fringing field near gaps complicate design.
- Options to change:
  - Winding shape.
  - Gap configuration.





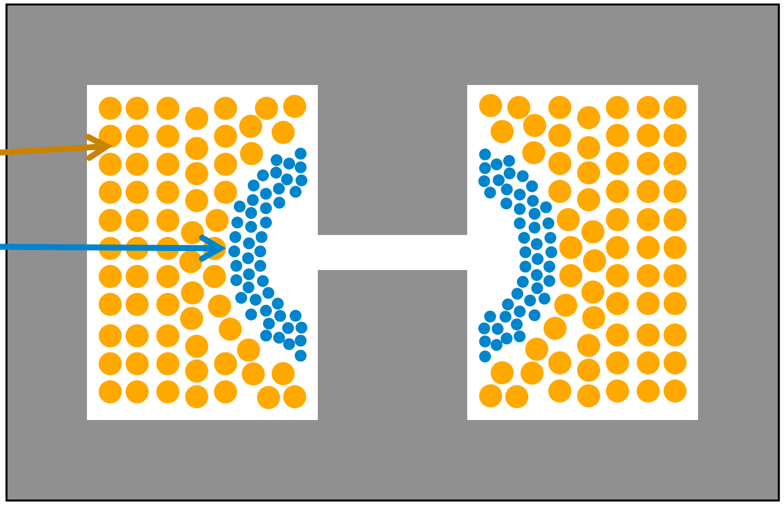
Winding shape optimization

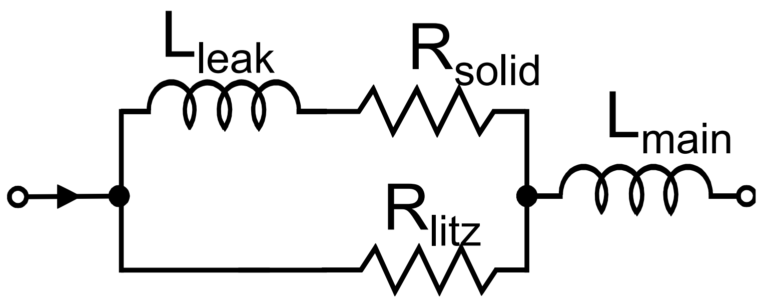
- Shape winding configuration to work ***with*** curved gap field.
- Applies to round wire and litz wire, not foil.
- Can actually work ***better*** than a distributed gap!
- Ad-hoc approach common, but full optimization is available.



Inductor for a dc-dc converter: DC current plus HF ripple

- Use a combination of a **solid-wire winding** and a **litz winding.**
- DC distributes to minimize loss (mostly in solid wire).
- Leakage inductance forces most HF current through the litz winding.
- Spacing from gap keeps wire out of intense field.



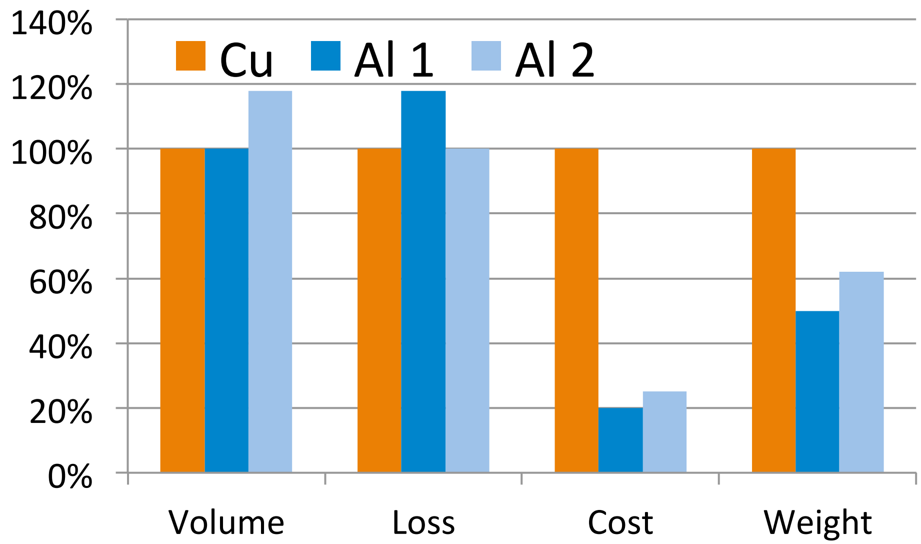


Costs: Cu vs. Al (as of 8 March 2016)

- Mass:
  \$5.00/kg vs. \$1.6/kg (wrong metric)
- Volume basis:
  4.42 ¢/cm^3 vs. 0.43 ¢/cm^3 10X
- Resistance basis:
  $7.67\ \frac{\$\mu\Omega}{m^2}$ vs. $1.22\ \frac{\$\mu\Omega}{m^2}$ 7.3X
- >7X more cost effective … dc or low frequency.
- What about high frequency?
  - Experiments and analysis show that the performance gap between Al and Cu is smaller at high frequency!

Real comparison of Al and Cu

- Fair comparison of good designs: Compare
  - a design optimized to use Al well, vs.
  - a design optimized to use Cu well.



Result: where to use Al:

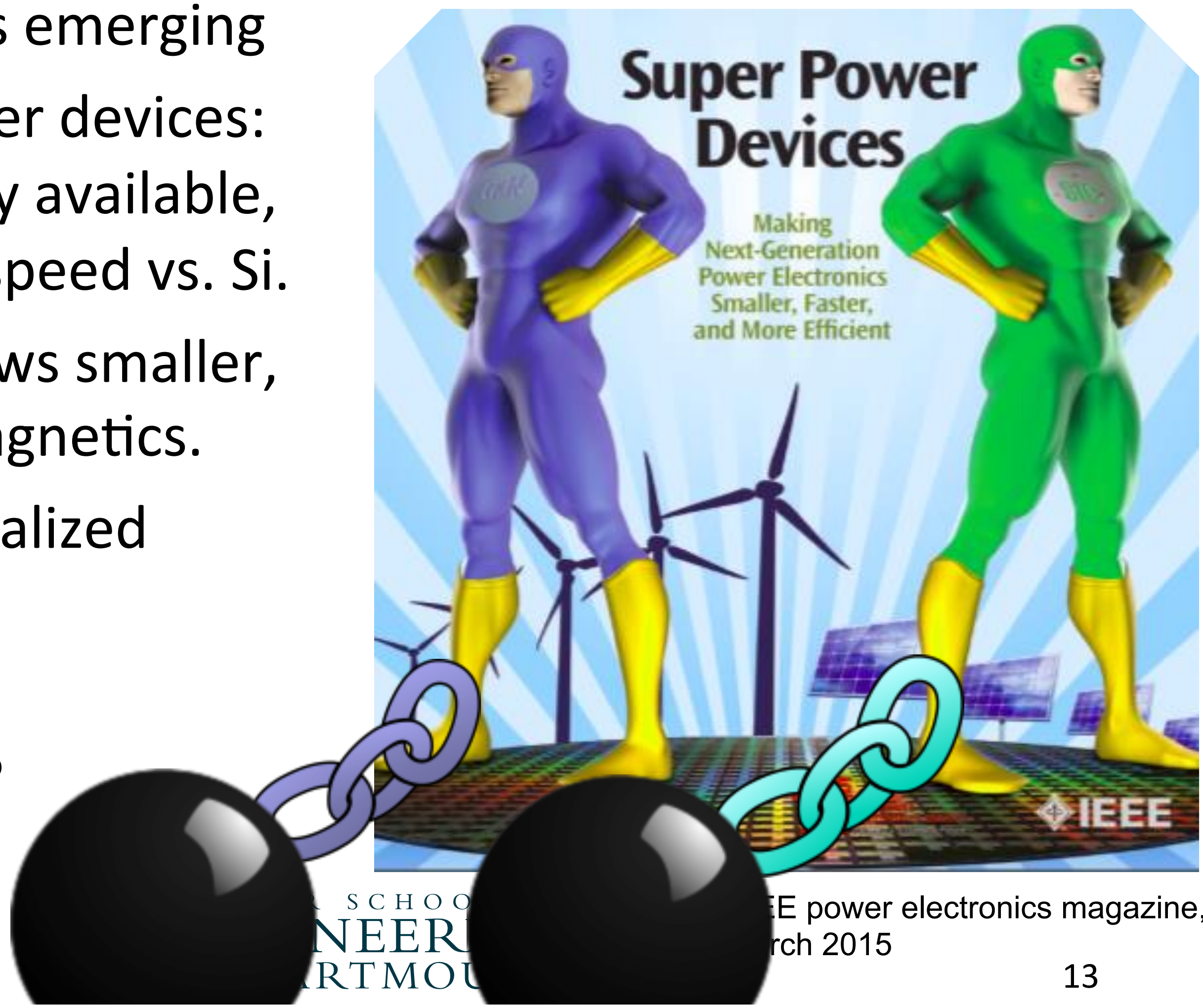
- Most situations!

Where to use Cu:

- Where compact size is more important than efficiency, cost, temperature or weight.
- If termination cost difference exceeds wire cost difference.

Miniaturization with MHz frequencies?

- We have good materials and design methods for 20 kHz to 300 kHz .
- New semiconductors emerging
  - GaN and SiC power devices: now commercially available, > 10X switching speed vs. Si.
  - Theoretically allows smaller, more efficient magnetics.
  - But can this be realized in practice?
    - Windings?
    - Core materials?

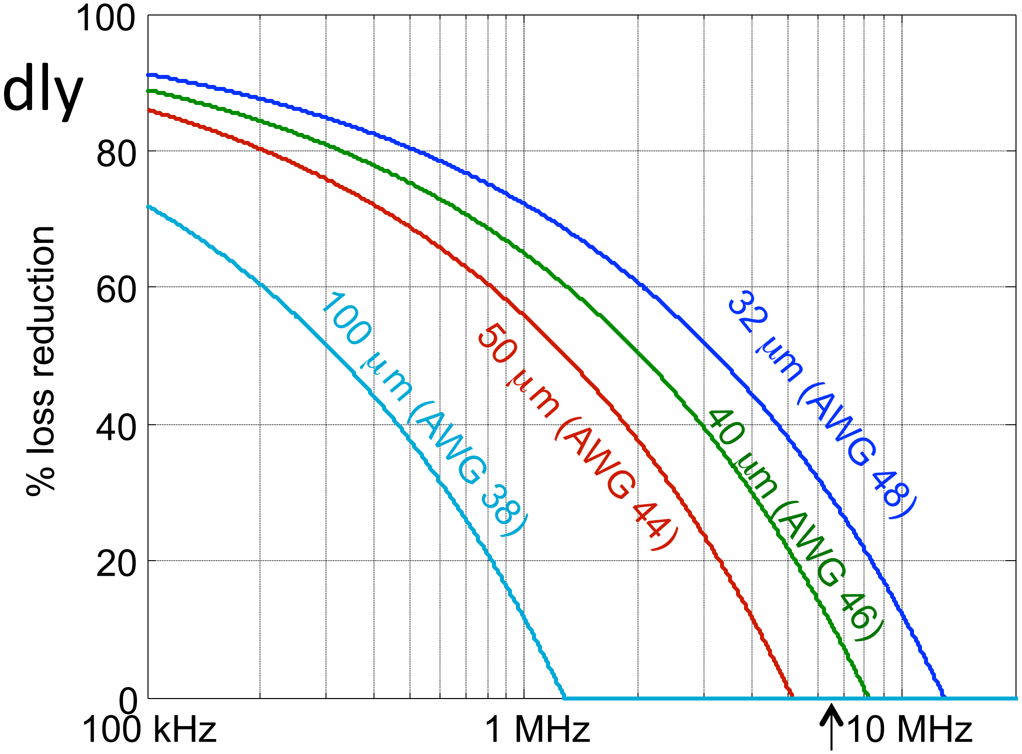


...E power electronics magazine, ...rch 2015

Credit to Jelena Popovic and Dragan Maksimovic for the ball and chain analogy

Windings at MHz frequencies … Litz?

- Litz benefits drop off rapidly in the MHz range.
  - Barely better than a solid-wire winding.



- Huge room for improvement in theory:
  - A single-layer winding only has current in one skin depth: At 10 MHz, 21 µm.
  - 0.2% of a 1 cm winding window (0.23% with litz).
    → 400X improvement theoretically available.

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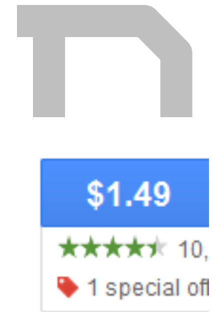
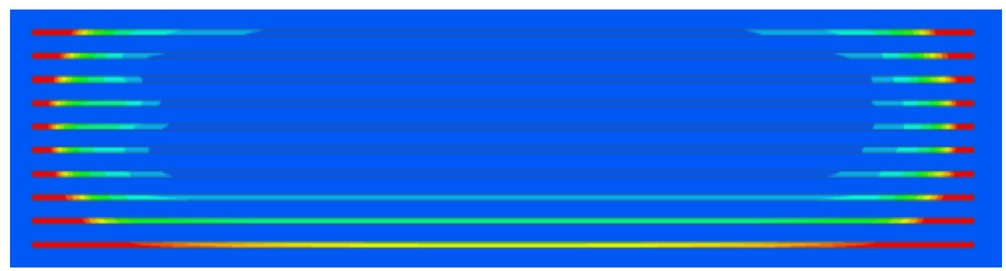
Foil: < 20 µm at low cost



- Easy to get thickness << skin depth.
  - Freestanding foil down to ~ 6 µm.
  - On plastic-film substrates for ease of handling from 35 µm to << 1 µm.
- Thin layers have high dc resistance—need many in parallel.



- Challenges:
  - Achieving uniform current density—laterally and among layers.
  - High capacitance between layers.
  - Terminations

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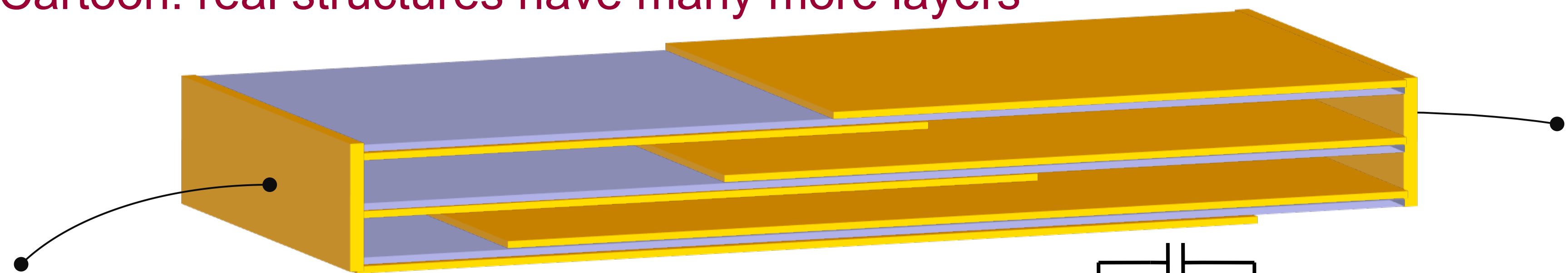
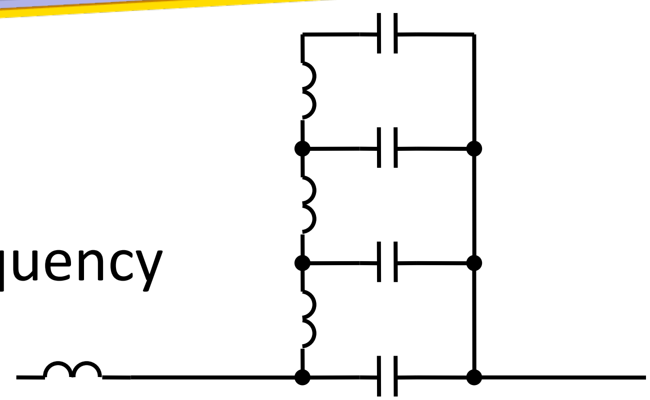
One example of our research on MHz foil windings: capacitive ballasting

- Use overlapping insulated layers to create a different tuned series capacitance for each layer.

Cartoon: real structures have many more layers



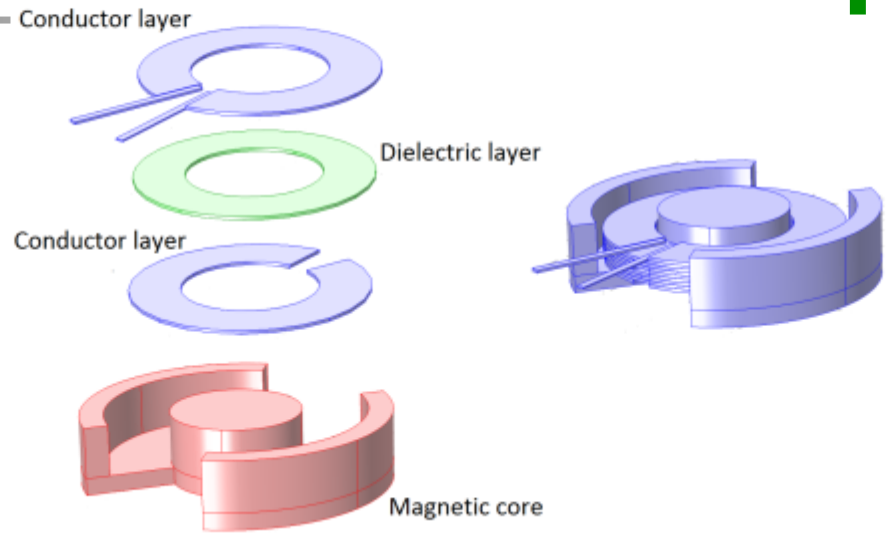
- Capacitance can be chosen for
  - Exact current sharing at one frequency
  - Approximate current sharing over a wider range by having Z_C dominate.

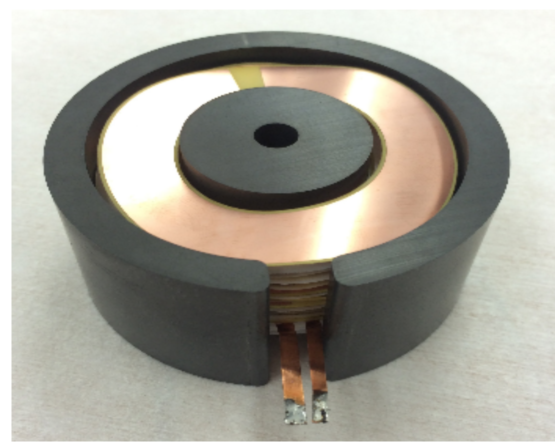


*patent pending

Resonant components for power conversion or wireless power

- Resonant capacitor = ballasting capacitors.
- Dual benefit from unavoidable capacitance between layers.
- High-Q resonance with a single component.
- Prototypes:
  - 9-12 µm Cu and Al
  - 12-50 µm PP or PTFE
- Experimental results for wireless power: > 5X improvement over state of the art (Q = 1030 in 2.6” diam. at 6.78 MHz).
- Now exploring similar structures for resonant power conversion, expected to have much higher Q.



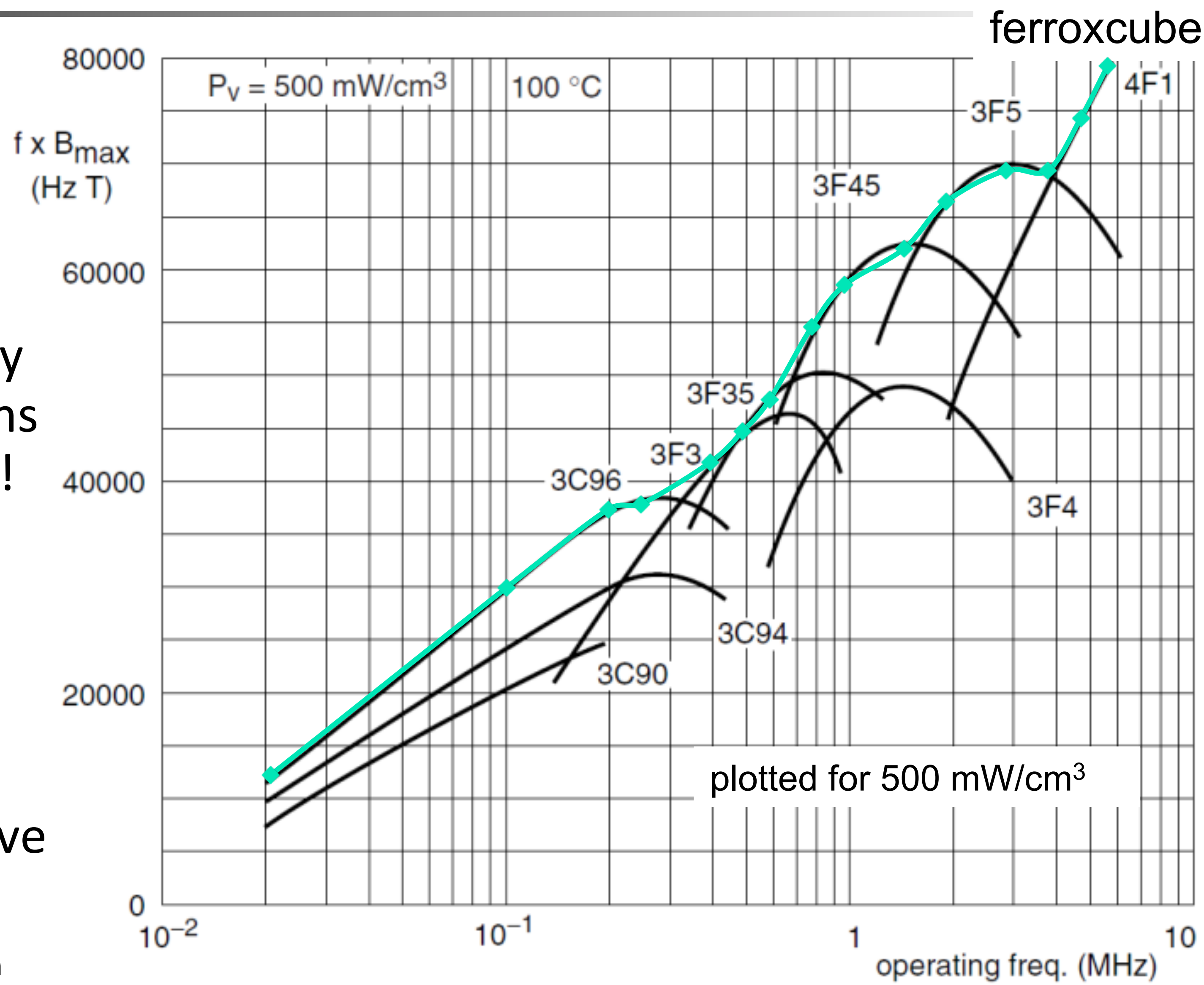


Also need core materials for MHz frequencies: are there good ones?

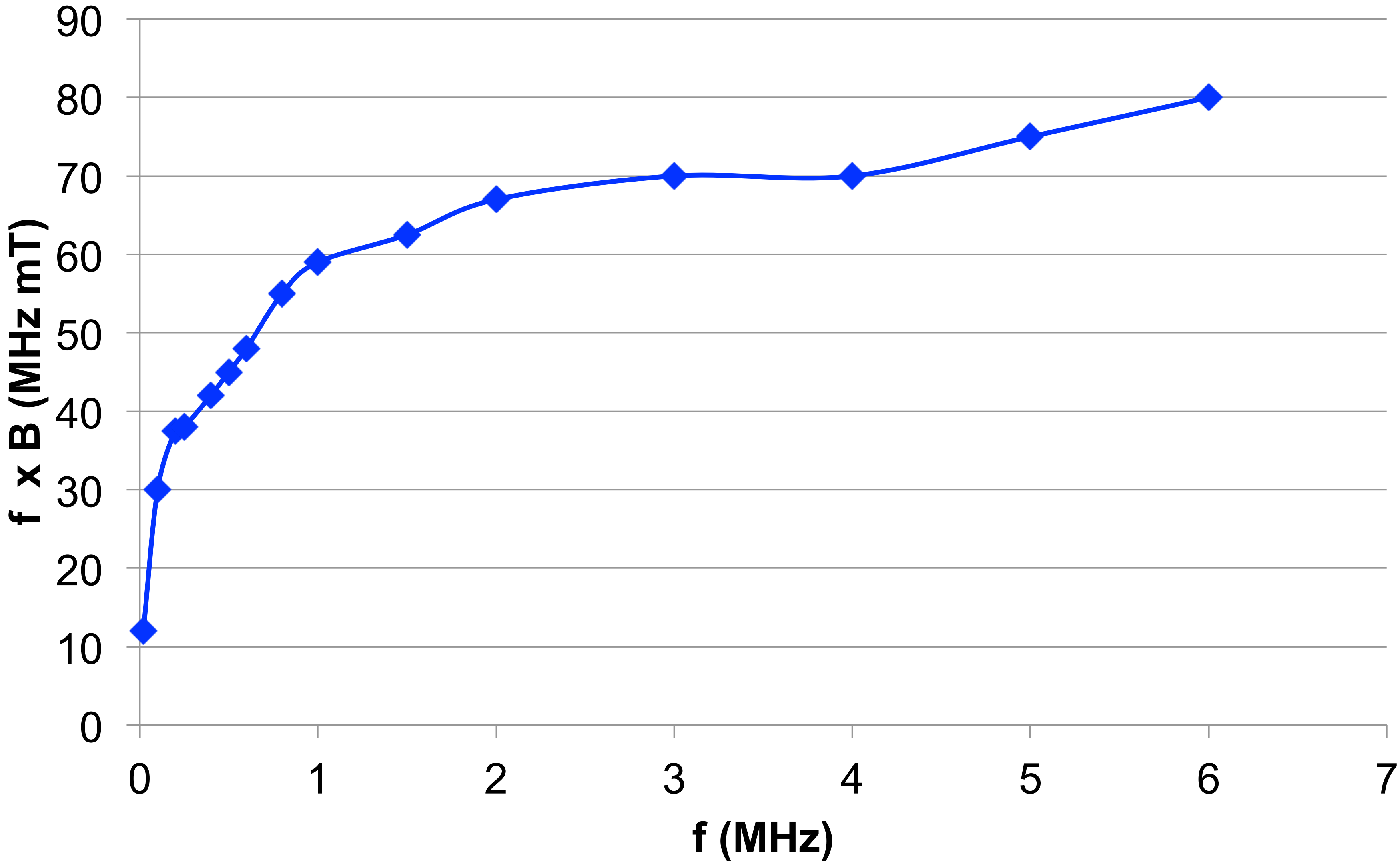
- A figure of merit helps us evaluate multiple materials.
- Standard figure of merit: "Performance factor" $B \cdot f$
  - For each frequency, f, choose flux density B based on maximum tolerable loss.
  - Voltage per turn of wire is proportional to dB/dt or $B \cdot f$
  - Current is fixed because it is determined by winding losses.
  - Power handling $\propto V \cdot I \propto B \cdot f$

“Performance factor” for MnZn power ferrites

- Curves of $B \cdot f$ product for constant power loss density.
- Looks like rapidly accelerating gains beyond 600 kHz!
- Looks like huge opportunity for GaN and SiC based power electronics with materials we have now.



Performance factor, linear scale



Some gain at high frequency—is it worth the pain?

- Other things get more difficult—board layout, skin effect and proximity effect in windings …
  - Can capture effect of high-frequency winding losses in a *modified performance factor.*

Modified performance factor

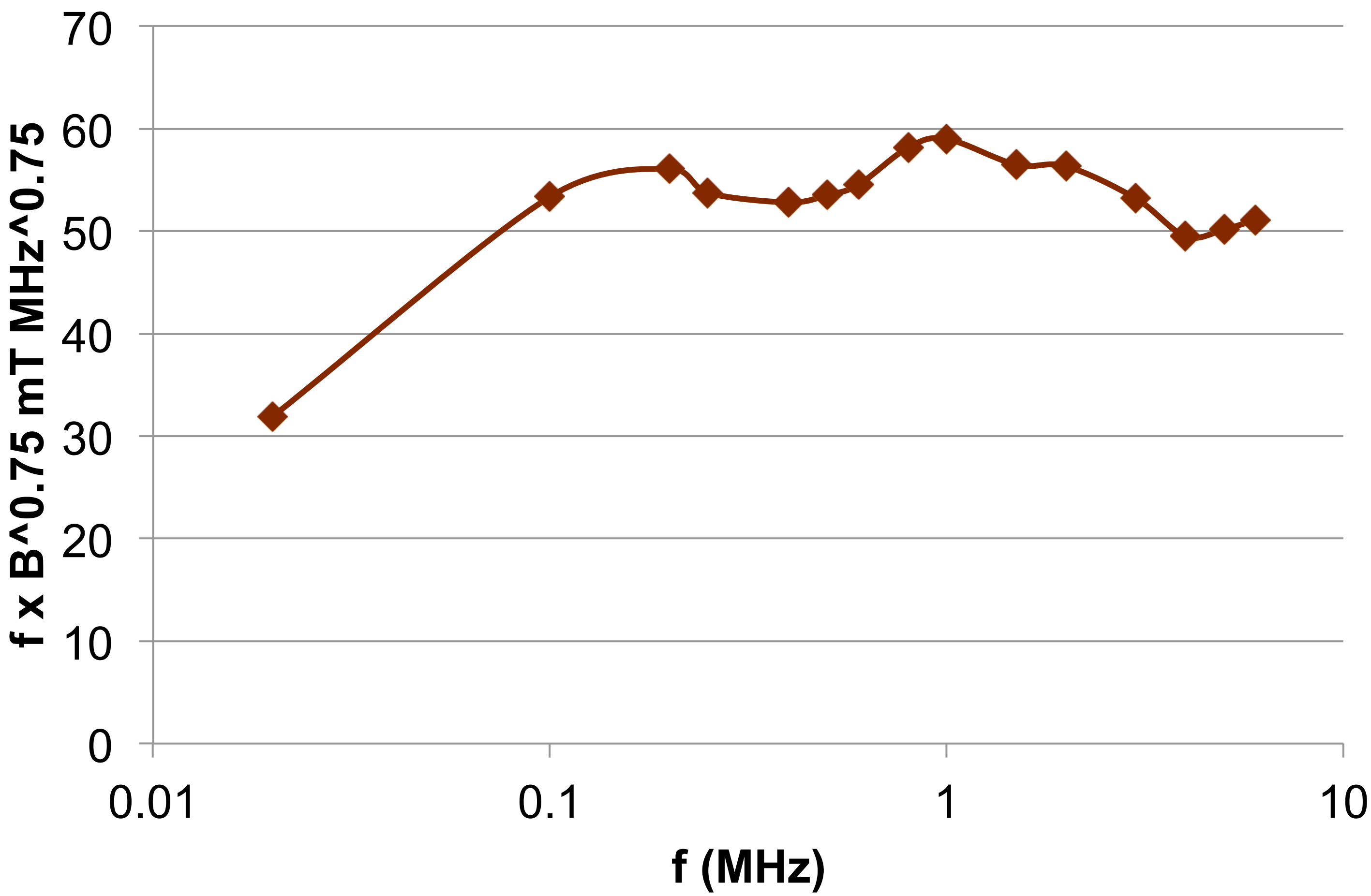
- Instead of fixing current, fix winding loss: $P_w = I^2 R_{ac}$
- Consider variation of R_{ac} with frequency.
  - Skin-effect limited $R_{ac} \propto f^{\,0.5}$
  - Current for constant P_w goes as $I \propto f^{\,-0.25}$
  - Modified performance factor PF = $Bf^{\,0.75}$
- Different assumptions about winding design lead to different exponents.

No significant ac resistance effects	PF = Bf
Fixed number of foil layers	PF = $Bf^{\,0.75}$
Fixed number of wire strands	PF = $Bf^{\,2/3}$
Fixed layer or strand thickness	PF = $Bf^{\,0.5}$

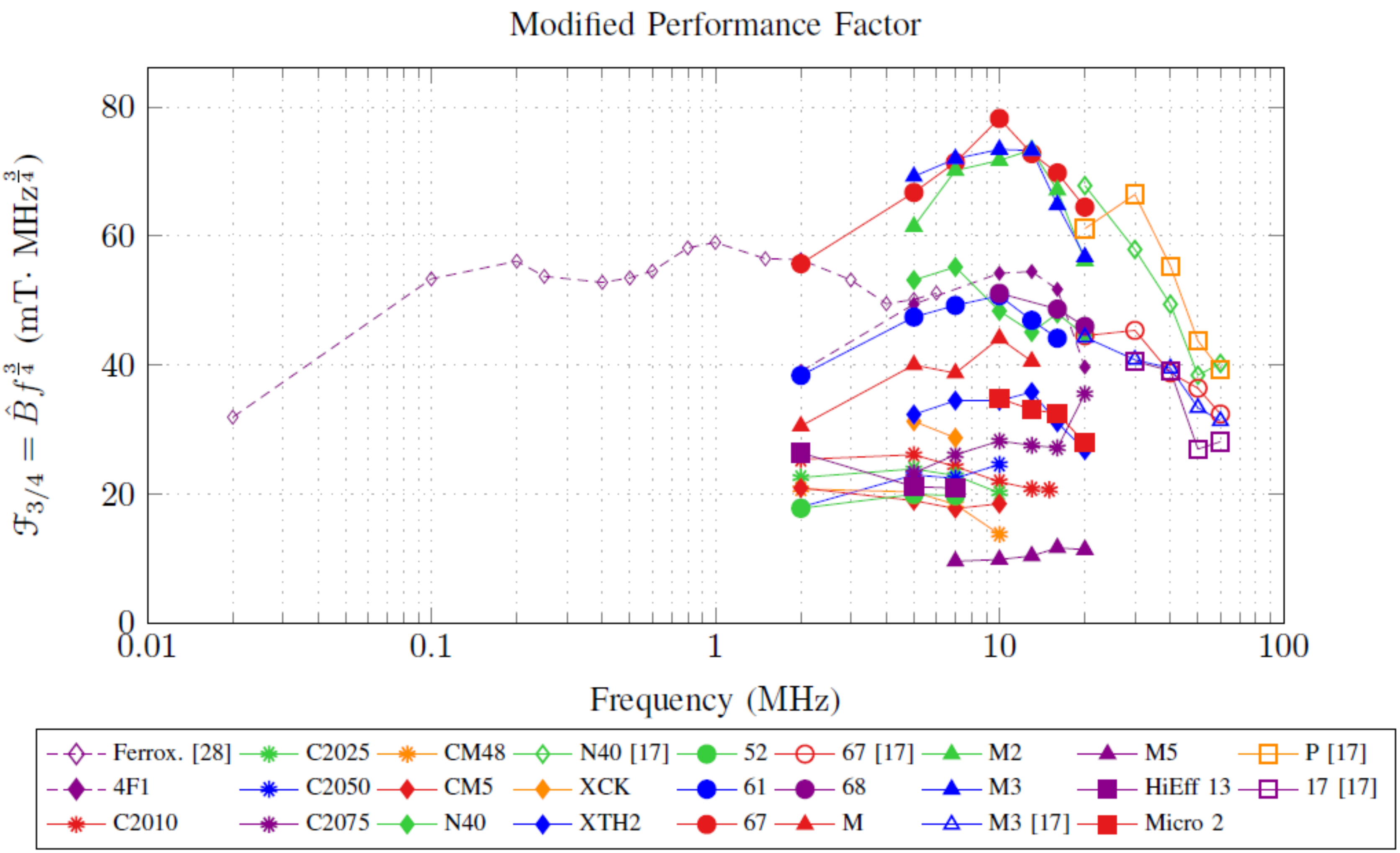
- Use PF = $Bf^{\,0.75}$ unless specific design scenario leads to a different choice.

Modified performance factor

- Based on considering skin effect in the winding
- $B \cdot f^{0.75}$

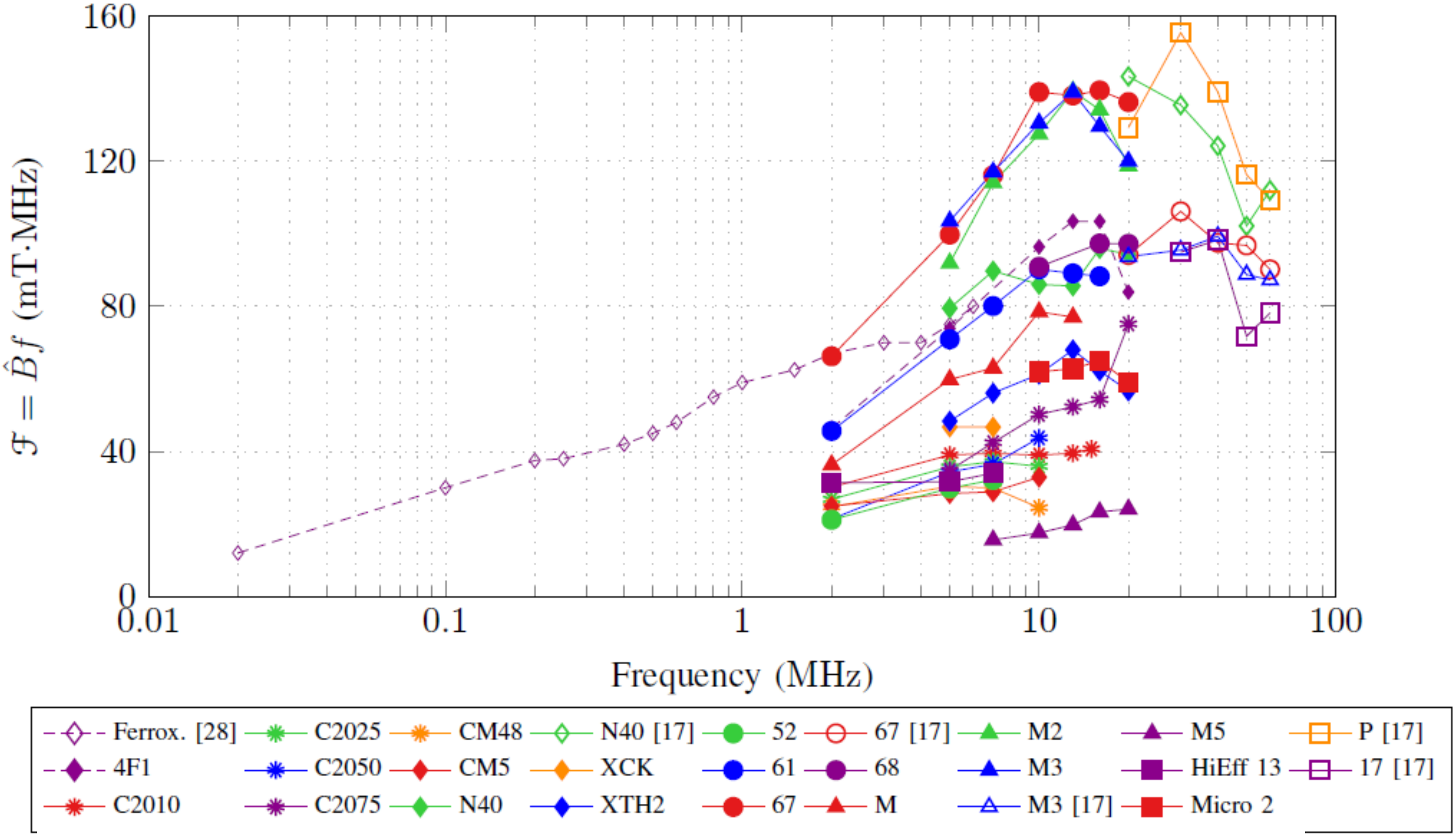


Adding data from more NiZn Ferrites



- Data from collaboration with Perreault group at MIT; Hansen et al., *IEEE Trans. Pow. El.,* early access.

Standard performance factor



- 4X improvement vs. 100 kHz ... If you have a winding technology that makes proximity effect negligible.

Conclusion on MHz magnetics

- Winding methods and core materials that offer high performance at MHz frequencies are available.
- Research opportunities on core materials and windings.
  - Core materials with low loss (high performance factor)
  - Windings that have low ac resistance without relying on litz.
- Other system benefits of MHz frequencies include:
  - EMI filter size/cost
  - Fast response
  - Capacitor size

Core loss models—all frequency ranges.

- Models are typically empirical approximations inspired by physics.
- All models have known limitations—room for improvement.
- Core manufacturers are considering offering more and better data—this could also help.

	Non-linear	Frequency dependent	Non-sinusoidal	DC Bias	Relaxation	Drops in simulation
Jiles-Atherton	✓		✓	✓		✓
Steinmetz	✓	✓-				
iGSE = composite wfrm	✓	✓-	✓			
Composite wfrm with square wave data	✓	✓+	✓			
i^2GSE	✓	✓-	✓		✓	
Complex impedance		✓	✓-			✓

Conclusions

- Proximity effect is the primary winding design consideration.
- Established winding loss reduction techniques include litz wire, interleaving, distributed gaps, quasi-distributed gaps, shaped windings, and parallel windings. Few designs use these to their maximum potential.
- Additional research needed on litz wire construction and termination.
- Aluminum wire can achieve lower loss than copper wire in cost-limited designs. This is an under-utilized opportunity.
- For MHz frequencies, litz strands are too big. We are developing ways to use thin foil effectively, particularly in resonant designs.
- Winding loss analysis methods are available if not always applied well; core loss modeling state of the art is less solid and new models are needed.
- New core materials are valuable if the have low enough loss to offer competitive performance factor at any frequency in the kHz or MHz range.

Appendices

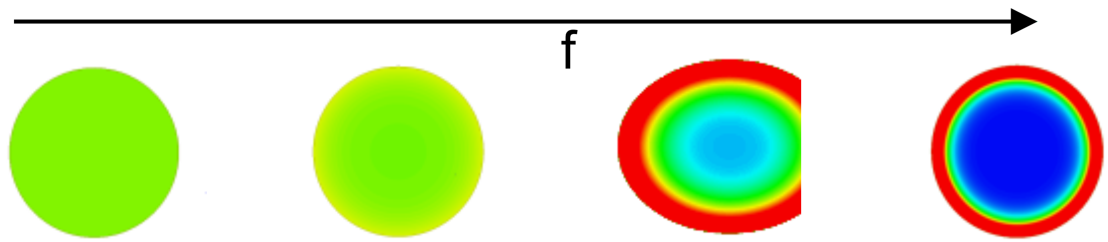
1. Extra slides not used.
2. References

Winding loss topics

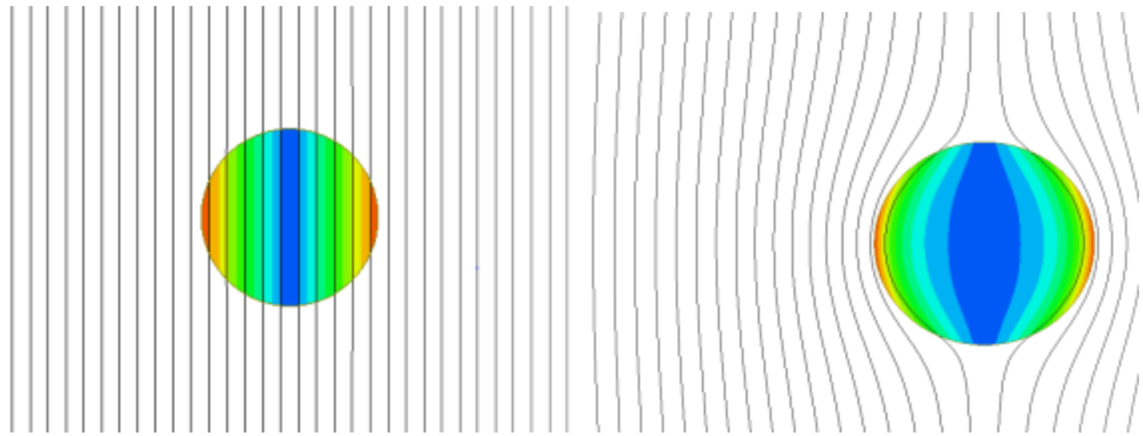
- Concepts:
  - Skin effect and proximity effect
  - Multilayer vs. single-layer windings
  - Understanding and estimating current and field distributions.
- Design Techniques and options:
  - Established, but not as well known/understood as they should be: litz wire, interleaving, distributed gaps, quasi-distributed gaps, shaped windings, parallel windings, and aluminum conductors.
  - Emerging: Effective utilization of very thin foil.
- Modeling and Analysis Techniques:
  - Proximity effect models: Dowell, Bessel, and approximations.
  - Interactions between transformer windings: resistance matrix.
  - 1-D, 2-D, and 3-D models.

Windings:
Two high-frequency effects

- Skin effect: Current near the surface in a skin depth $\delta = \sqrt{\frac{\rho}{\pi \mu f}}$

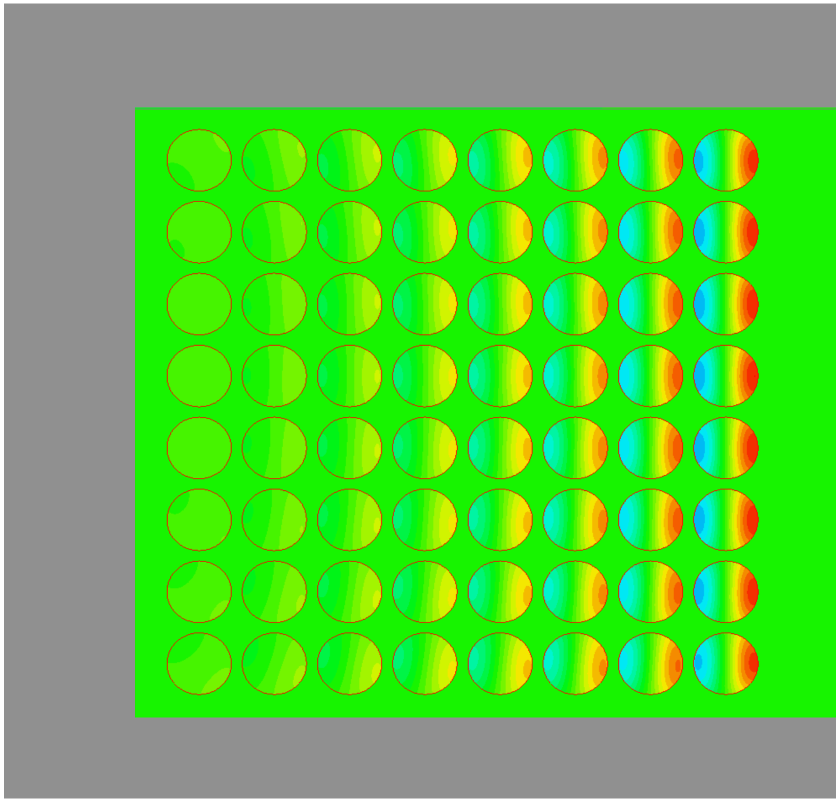


- Proximity effect: Fields from the winding and core induce losses in the winding.



d < 2δ => no significant skin effect

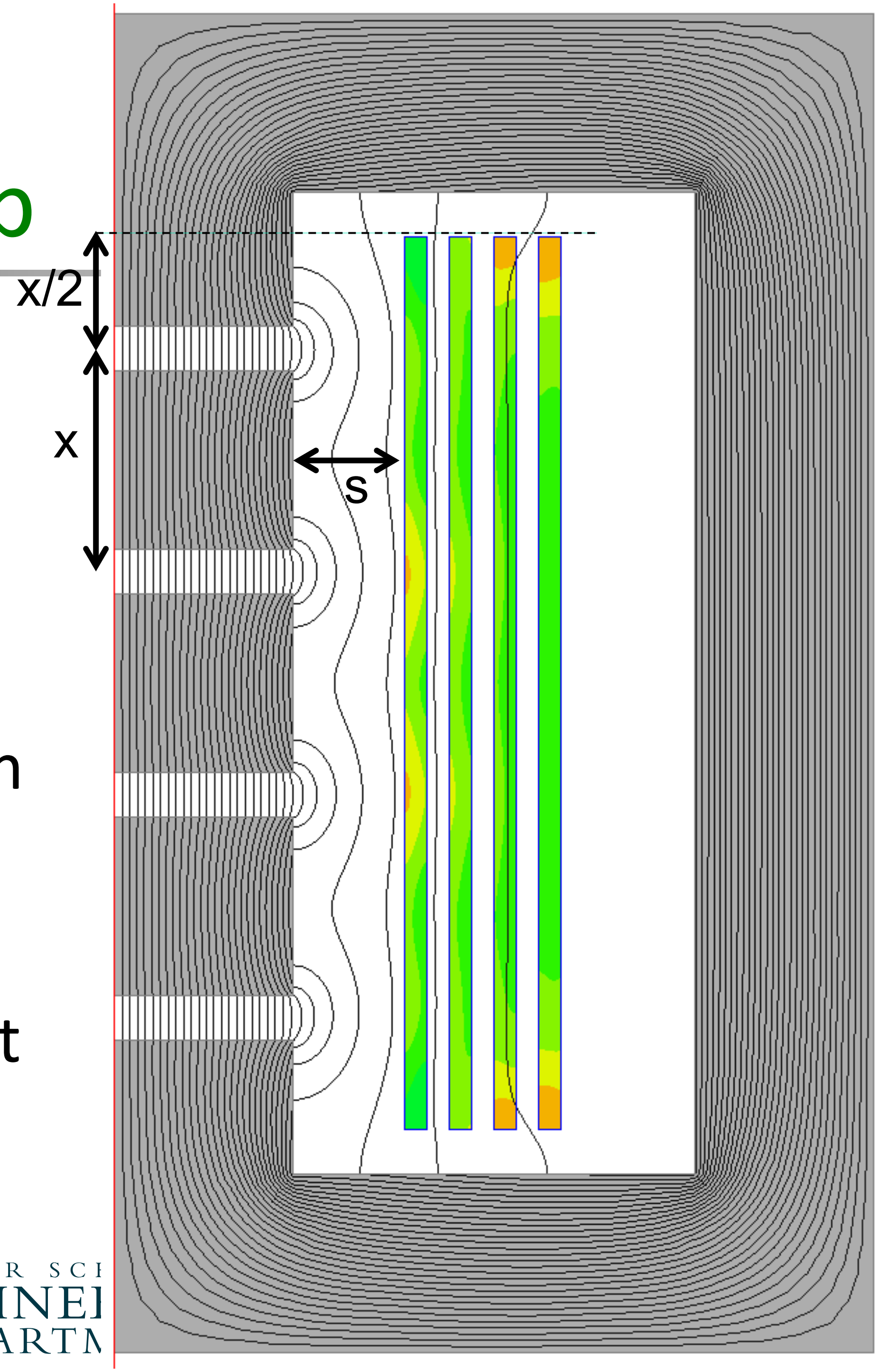
- Bessel-function skin-effect calculation: $R_{ac} = 1.02\ R_{dc}$
- In a multi-layer winding, proximity effect can still be severe: 27X worse than loss considering only skin effect in this example.



Rac/Rdc = 27.7

Quasi-distributed gap

- Approximate a distributed gap with multiple gaps.
- Design rule: s > x/4
- Common misconception: works by making gap length small.
- Actually ac resistance is approximately independent of gap length.



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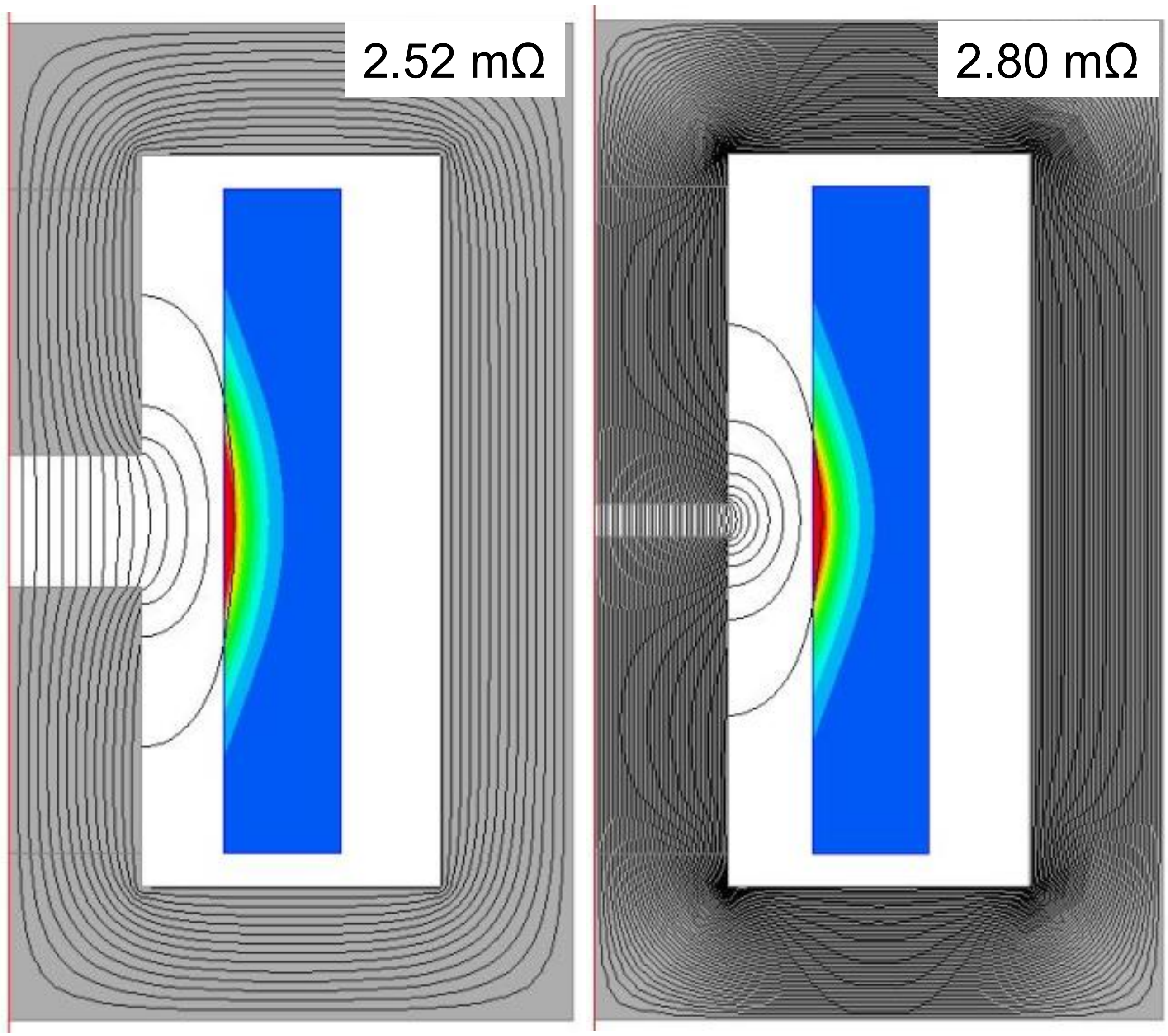
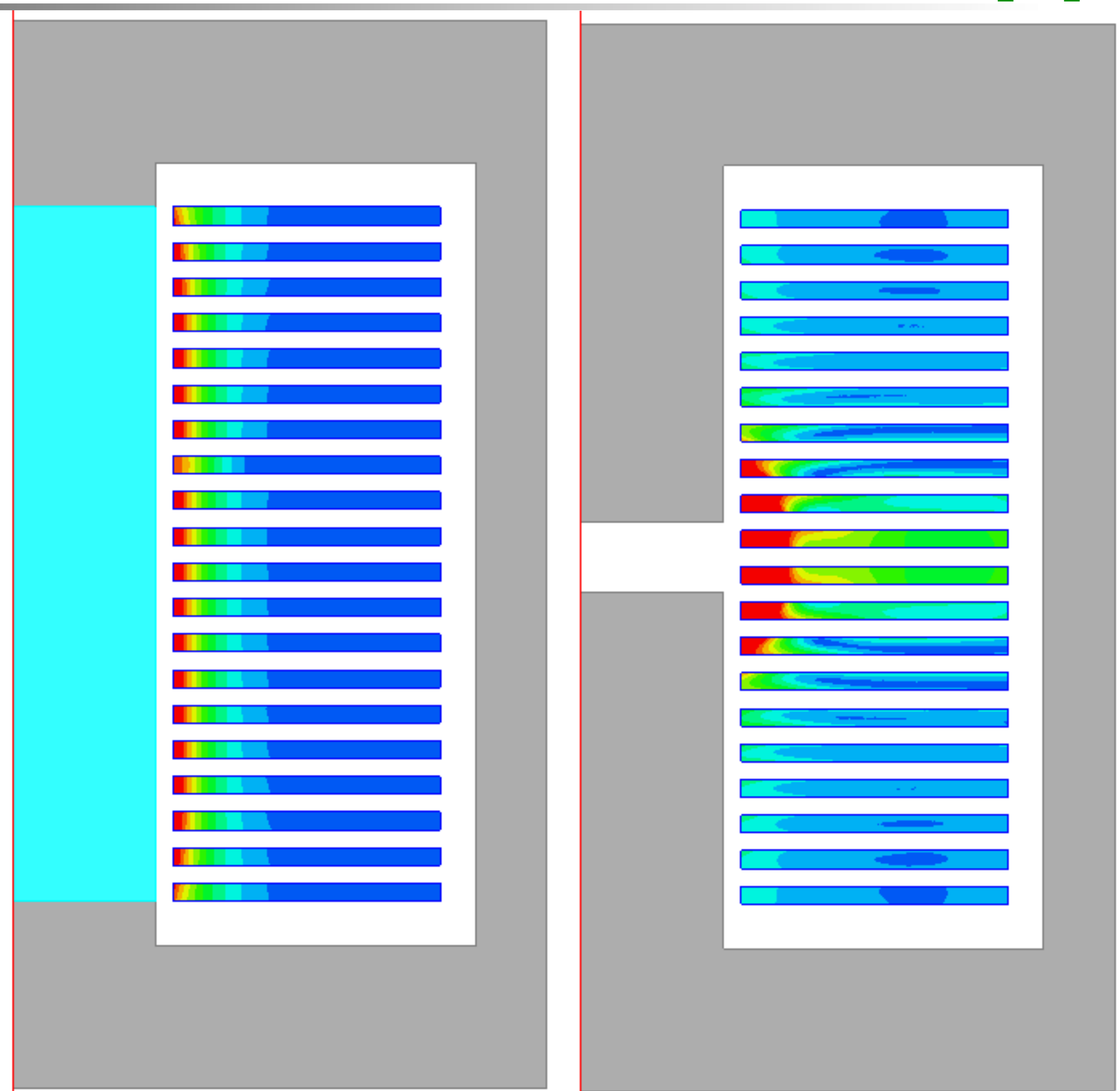
Gap length effect on R_{ac}:
When a small gap hurts.

- Same current.
- Field near gap is worse with smaller gap.
- Field far from gap is similar.
- Same MMF across gap.
- Far field depends on potential difference.



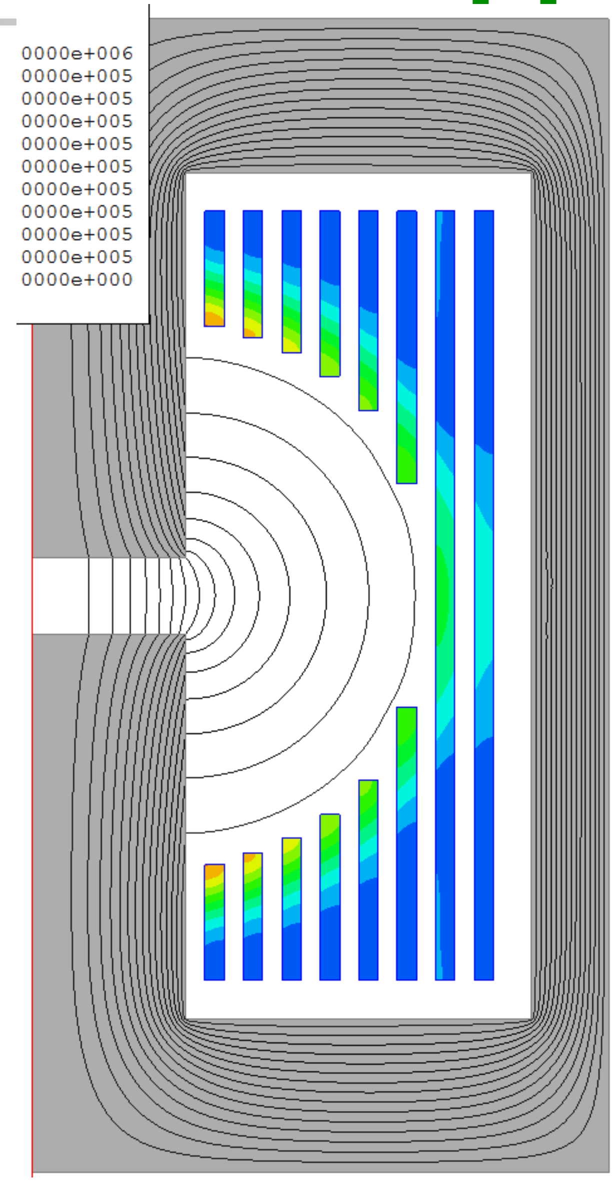
Helical = Edge-Wound Winding

- Single-layer.
- High-frequency resistance like a single-layer wire winding.
- Uses full window for dc current.
- Only works with distributed gap—lumped gap has 3.5X worse R_{ac}.

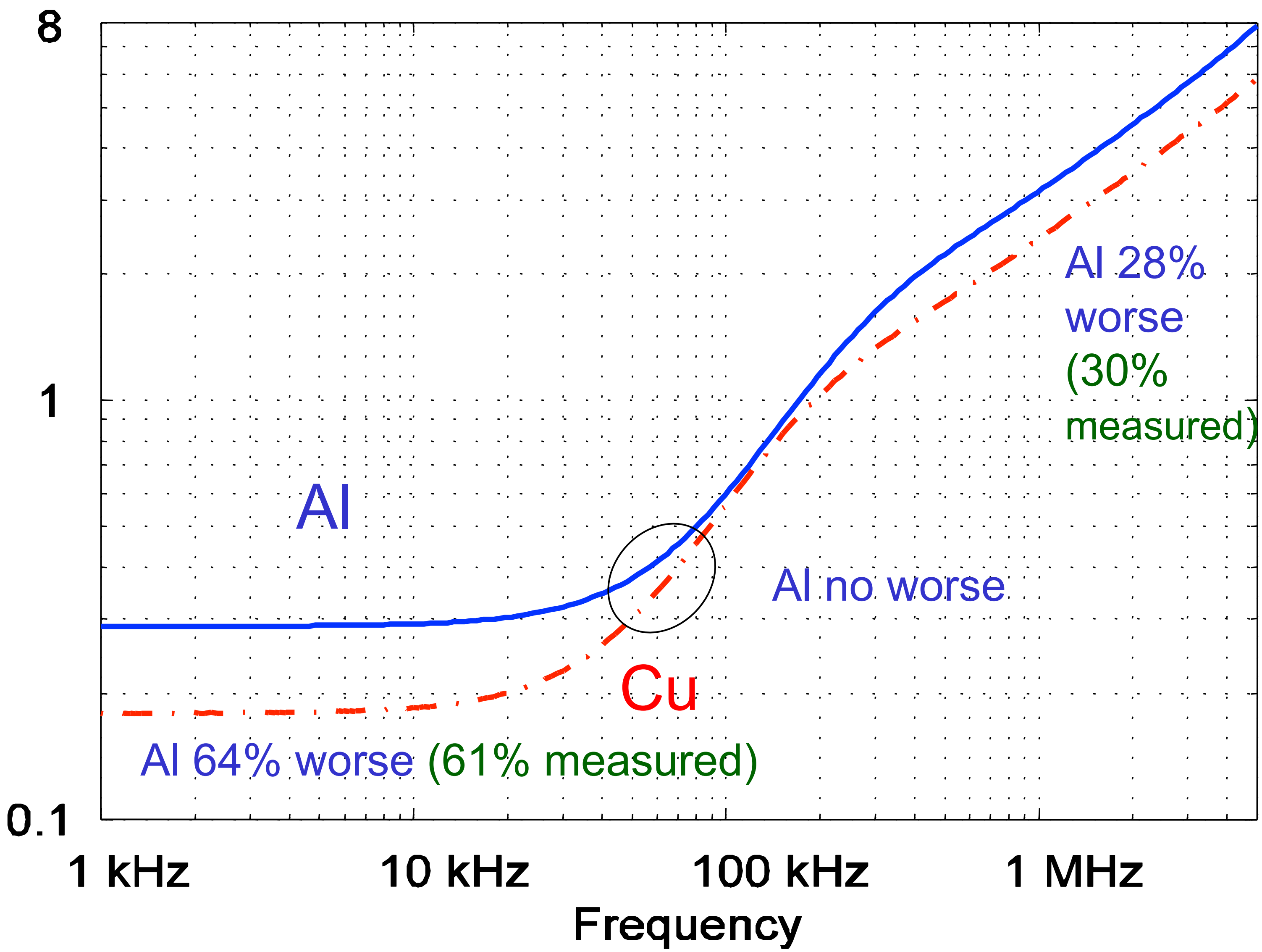


Shaped foil winding

- “Single layer” performance like helical winding—high-frequency current on tips on each turn.
- Size of cutout optimized for Rac vs. Rdc tradeoff.
- Expensive to build, but there’s a commercial proprietary configuration with similar performance that’s cheaper to build.



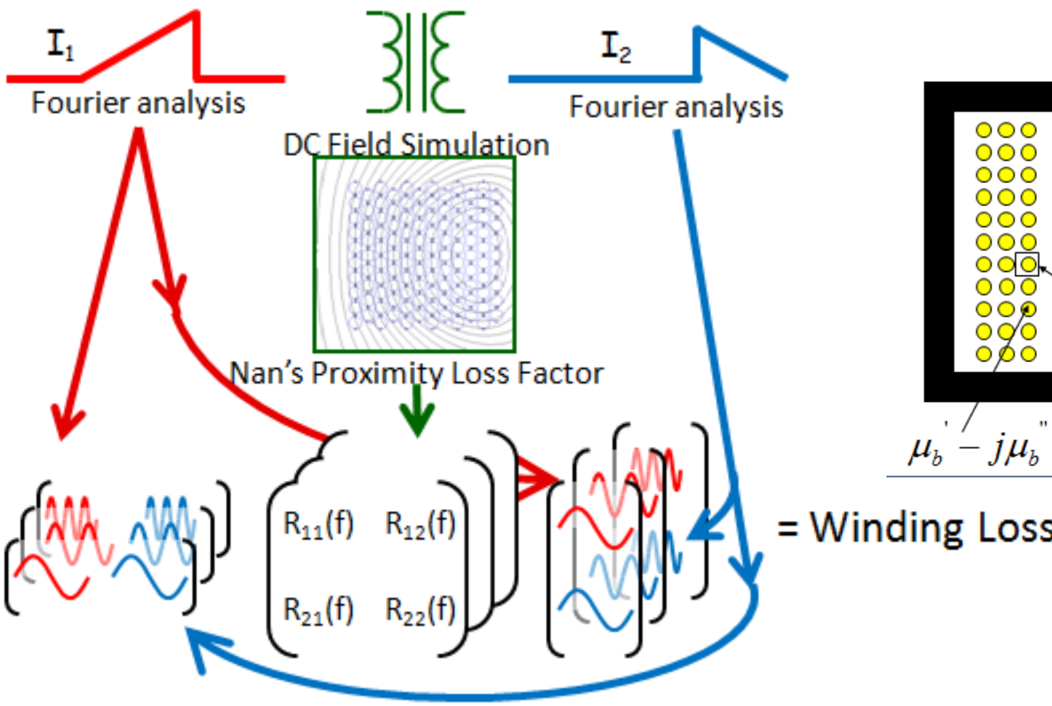
Measured transformer ac resistance

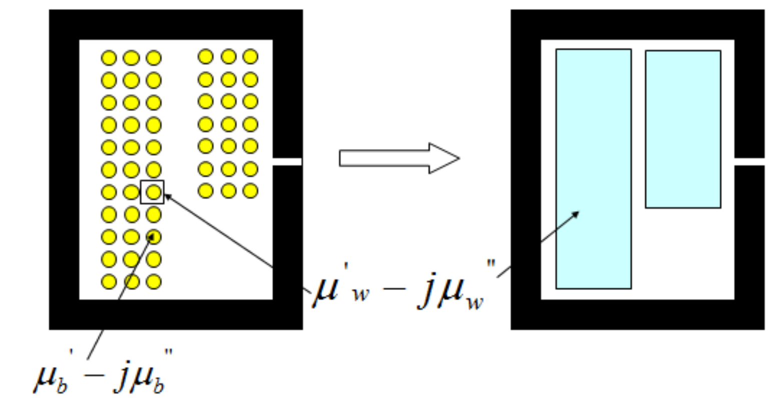


- 29 turns of 0.5 mm (AWG 24) wire.
- Two layers on EE19 core.

Multiple frequencies and 2D fields

- Hybridized Nan's method (Zimmanck, 2010)
- Homogenization with complex permeability (Nan 2009, Meeker, 2012)





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Description of key references

Key references in high-frequency power magnetics with an emphasis on publications from our group and a focus on discrete components rather than chip-scale microfabricated components; for our perspective on the latter see [1].

For windings, Zimmanck's method can efficiently generate frequency dependent winding loss matrices for any geometry, 1D, 2D, or 3D, and use them to predict loss for different nonsinusoidal waveforms in any number of [2]. This method applies very generally, including to coupled inductors, wireless power transfer coils, etc. References cited in [2] provide more detailed background, including [26,27]. See also [28]. A systematic approach to generating full models for loss and simulation for 1D geometry is provided in [3]. To use 2D models effectively for 3D geometries such as E-cores, the strategy in [25] can reduce the error involved by a factor of 5.

Although the Dowell model is reasonably accurate, see the appendix of [9] for a simple correction that can enhance the accuracy. Also useful in the appendix of [9] is a simple effective frequency approach to address winding loss with non-sinusoidal windings.

Strategies to reduce proximity effect loss, using multiple thin layers or avoiding multiple layers, are compared in [6, 7, 8], considering different types of optimization constraints. An overview of the most common implementation of thin layers to reduce proximity effect loss, litz wire, is provided in [9]. A practical guide to using it is provided in [10], and the most complete model including effects of details of twisting construction, is in [11]. Approaches for using thin foil layers beyond frequencies where litz is practical are discussed in [12]. An implementation of these concepts for a resonant coil for applications such as wireless power transfer is described in [13]. For other applications, thin foil layers can have capacitance issues; circuits designs that reduce the voltage swing on the windings (e.g., [14]) can help reduce the impact of the capacitance.

The impacts of gap fringing and the quasi-distributed gap technique for reducing these problems are discussed in [15]. This reference includes data showing that a small gap is not effective for reducing the impact of fringing. With round-wire or litz-wire windings, shaping the winding can allow excellent performance with a standard gap [16].

In inductors with substantial dc resistance, two windings in parallel can be a good choice for good dc and ac resistance[17]. It is possible to extend this approach to applications in which the inductor carries a combination of line frequency ac current and high-frequency switching ripple, using, if needed, a capacitor to prevent low-frequency current from flowing through the high-frequency winding [18]. A foil winding with a semi-circular cutout region near the gap [19, 20, 21] can also be used to achieve a favorable ac/dc resistance combination.

Although copper windings are most common, aluminum can offer advantages if cost or weight are important [22, 23].

Performance factor for magnetic materials is described and extended in [24], and data on performance factor is provided for many materials in the MHz range. For coreloss with non-sinusoidal waveforms, the iGSE model remains the standard method [4], although some of its limitations are now known, as discussed in [5].

References, p. 1 of 2

[1] C. R. Sullivan, D. Harburg, J. Qiu, C. G. Levey, and D. Yao, "Integrating magneticsfor on-chip power: A persepctive," *IEEE Trans. on Pow. Electr.*, 2013.

[2] D. R. Zimmanck and C. R. Sullivan, "Efficient calculation of winding loss resistance matrices for magnetic components," in *IEEE Workshop on Control and Modeling for Pow. Electr.*, 2010.

[3] M. Chen, M. Araghchini, K. K. Afridi, J. H. Lang, C. R. Sullivan, and D. J. Perreault, "A systematic approach to modeling impedances and current distribution in planar magnetics," *IEEE Trans. on Pow. Electr.,*, 31(1), pp. 560–580, Jan 2016.

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