

High-Frequency Magnetics Design: Overview and Winding Loss

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Magnetics Design Objectives

- Efficiency
- Cost
- Size
- Reliability
- Weight
- Time to market

Three paths to improvement:

- Model losses accurately
- Reduce losses (with similar cost)
- Reduce cost (with similar efficiency)
- Fungible benefits:
reduced loss can be translated to reduced cost and
reduced cost can be translated to reduced loss.
- Loss impacts reliability.

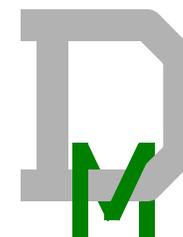




Magnetics Design Overview

- 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.
- Measurements: challenges arising from Q , terminations, and nonlinearity.
- Fabrication: macro and micro.

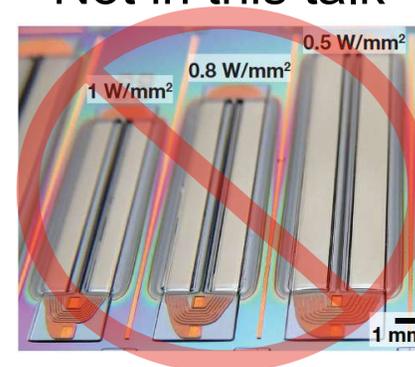




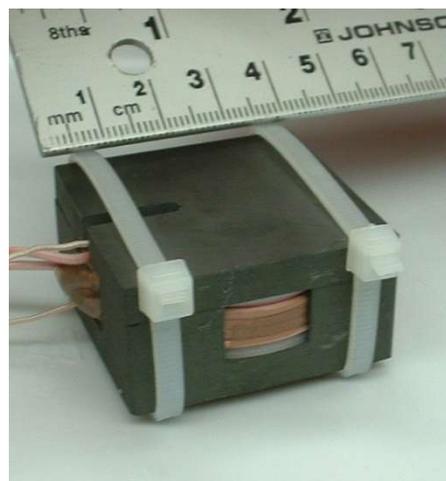
Agenda for this talk

- Macro magnetics, not micro magnetics
- Winding Loss:
 - Techniques for high performance
 - Models
- Brief notes on core loss

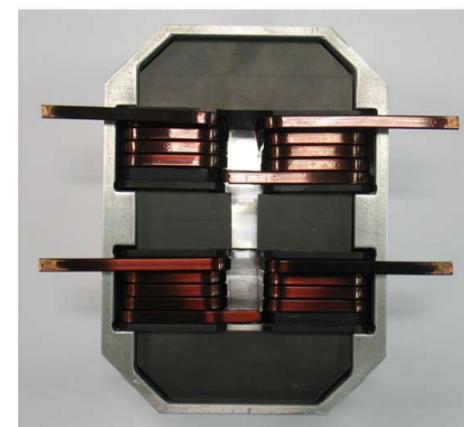
Our other work,
Not in this talk



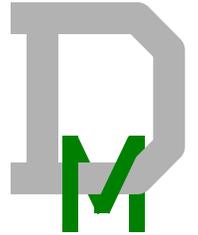
72 W, Volterra



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72 kW, UC Cork 4



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.





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 - [Emerging: Effective utilization of very thin foil.](#) [See COMPEL 2014 paper](#)
- Modeling and Analysis Techniques:
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*Read Lloyd Dixon's
TI/Unitrode app notes*

See COMPEL 2014 paper

More from Jenna Pollock later today

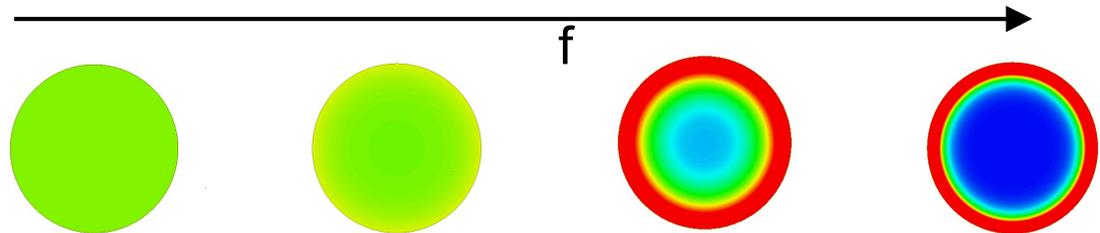


Windings: Two high-frequency effects

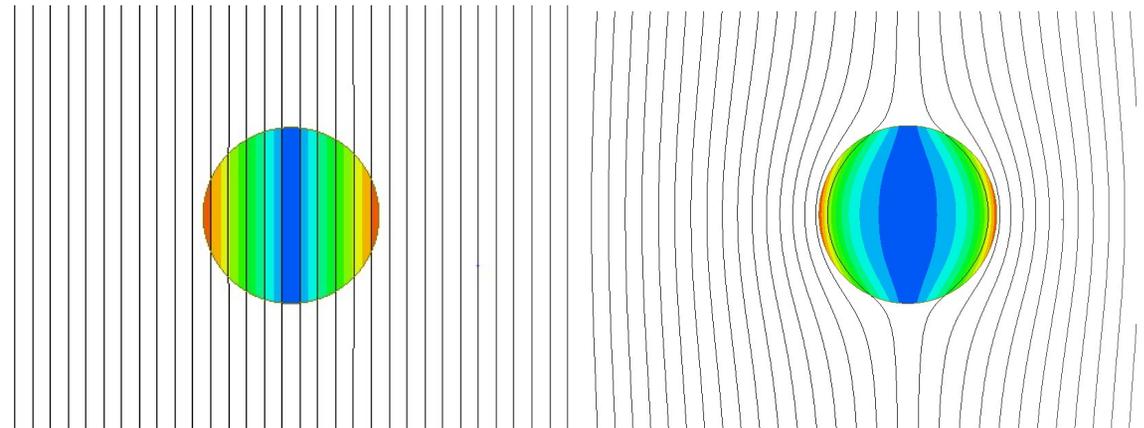


- Skin effect:
Current near the surface in a skin depth

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$



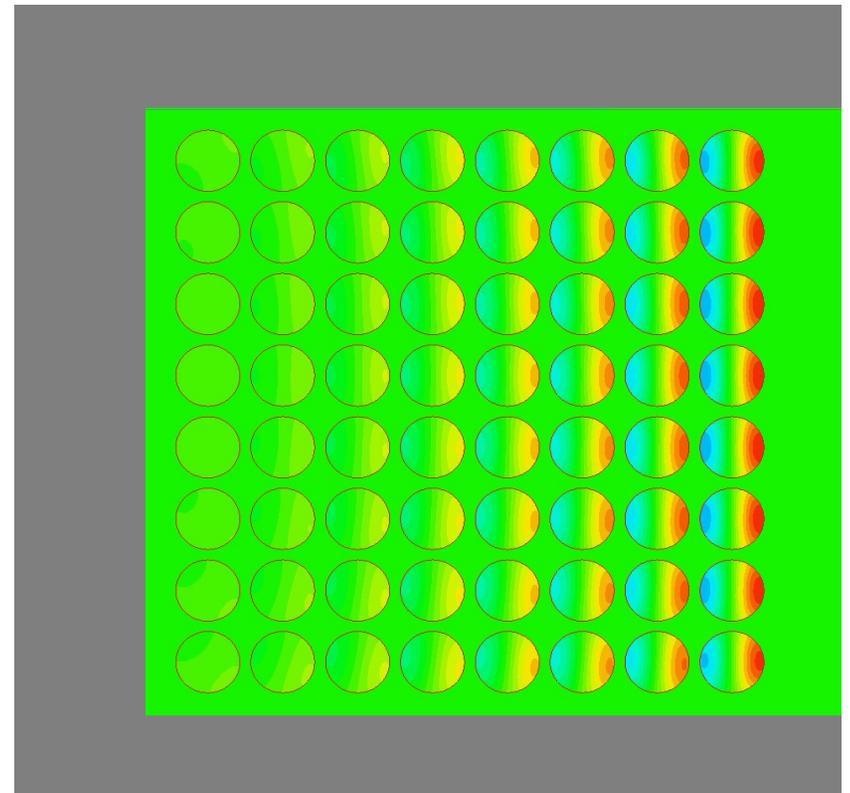
- Proximity effect:
Fields from the winding and core induce losses in the winding.



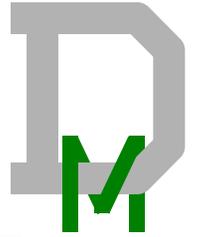


$d < 2\delta \Rightarrow$ no significant skin effect

- 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.



$R_{ac}/R_{dc} = 27.7$



High-frequency winding design

- It's all about proximity effect.
- Not just diameter $<$ skin depth— need $d \ll \delta$ 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 $\frac{2t_{min}}{3\delta}$
 - For 10X improvement: 100 layers, $t \approx \delta/7$
 - Need right combination—optimization is essential.

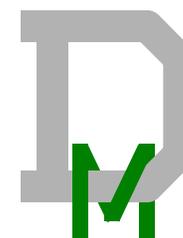
Litz wire



Image: Noah Technologies

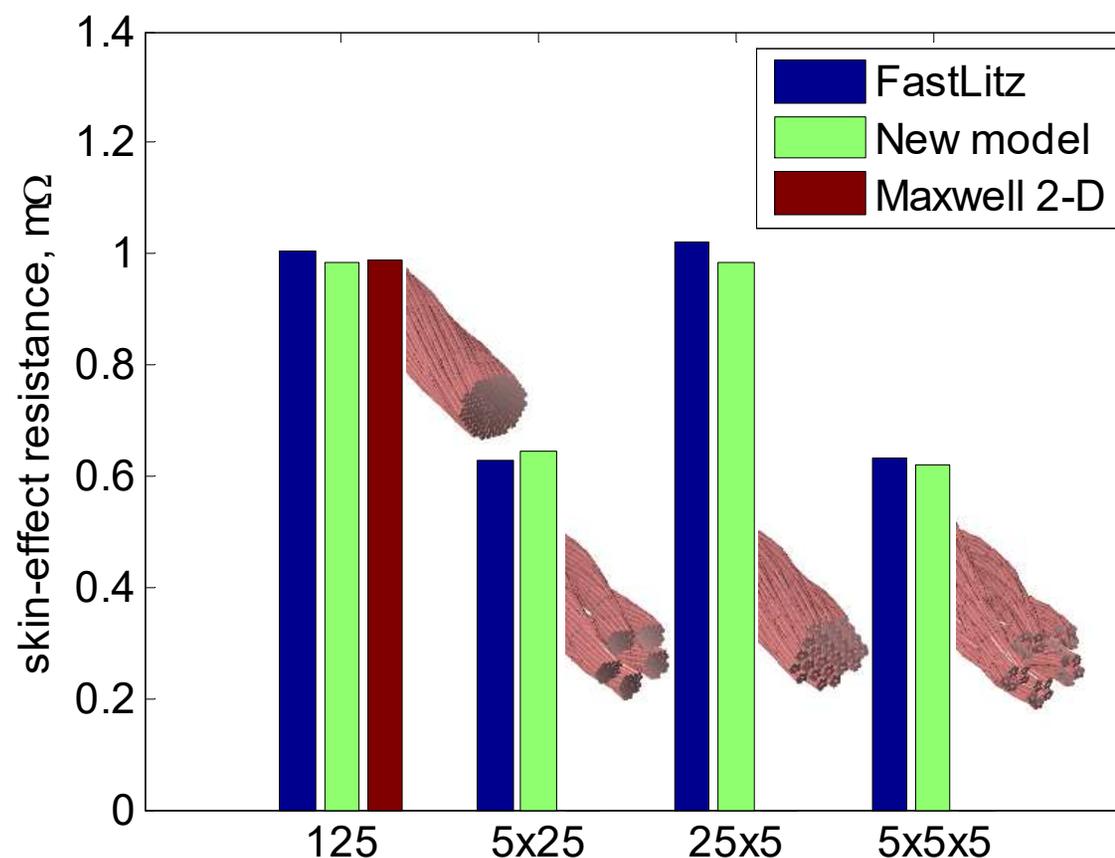
- Strands $d \ll \delta$.
- Invention: 1888, Sebastian de Ferranti.
- Analysis 1917 Howe; 1926 Butterworth.
- Conventional design options:
 - Papers with lots of complex math.
 - Catalog guidelines ... but these can lead to **higher loss than with solid wire at much higher cost.**
- One solution: single-formula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

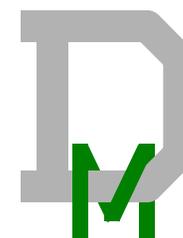
$$n_e = k \frac{\delta^2 b}{N_s}$$



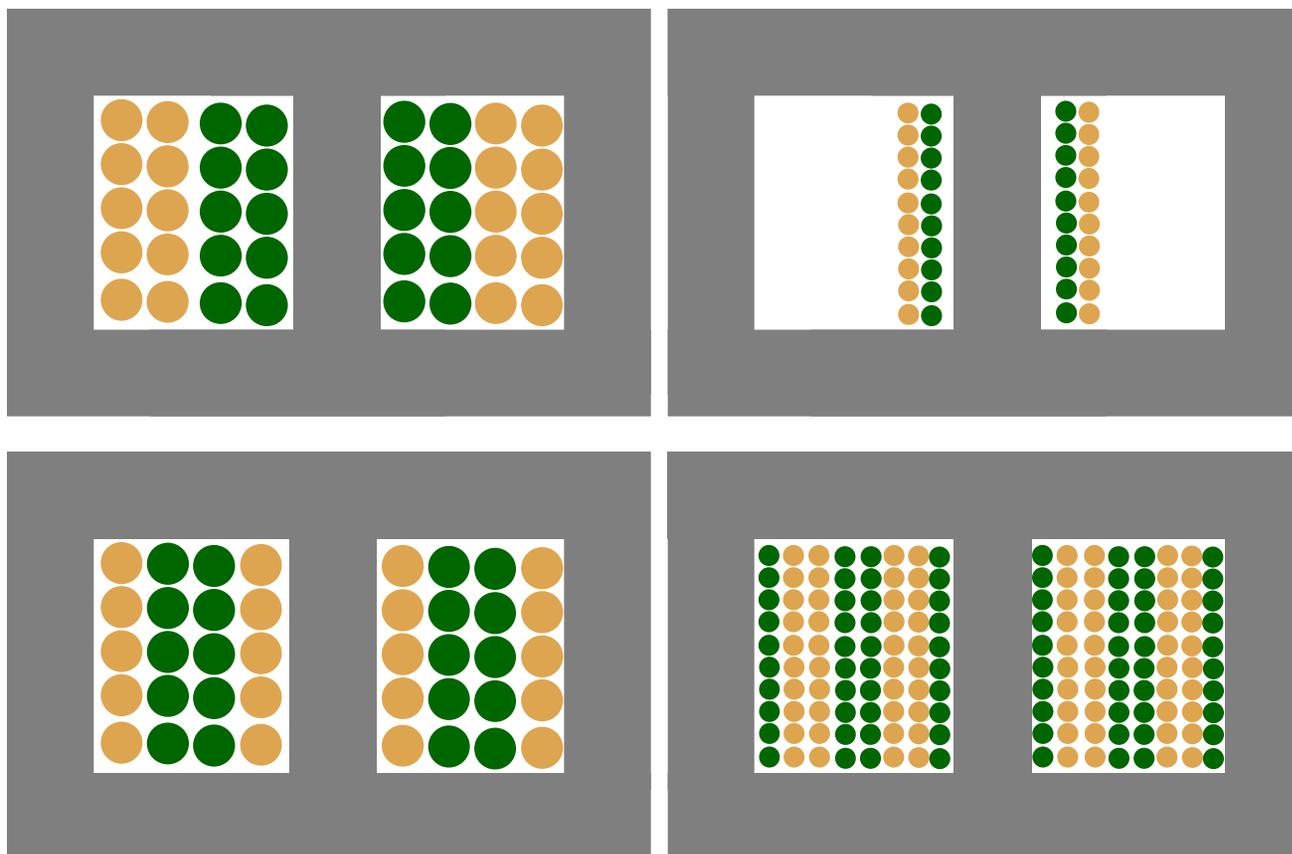
Litz wire construction details

- Full model now available to predict effect of construction.
- Simple rules to avoid problems are in the 2014 simple litz paper.





Layers and Interleaving



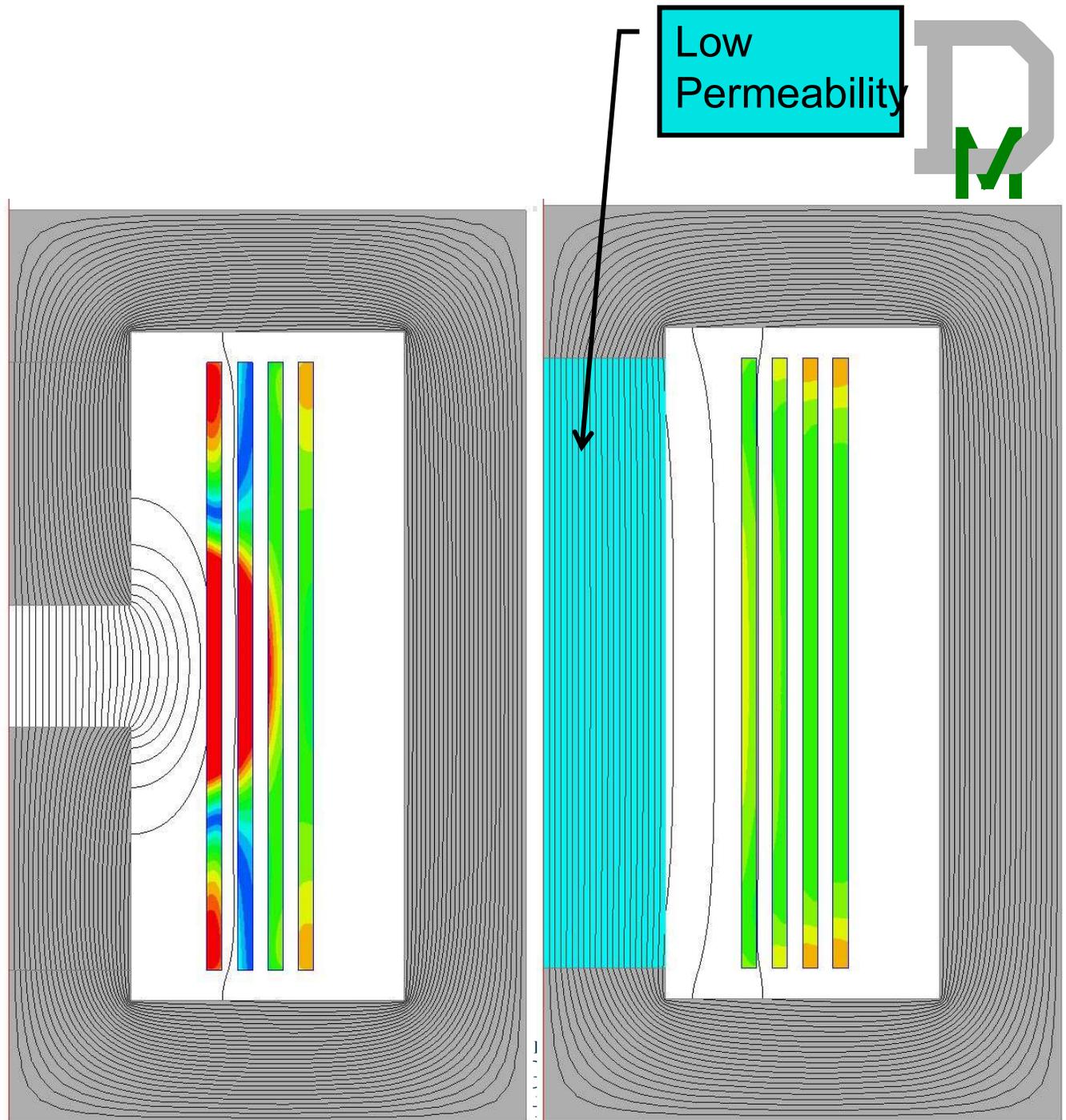
Drastic reduction in proximity effect

Limits:

- Capacitance
- Complexity

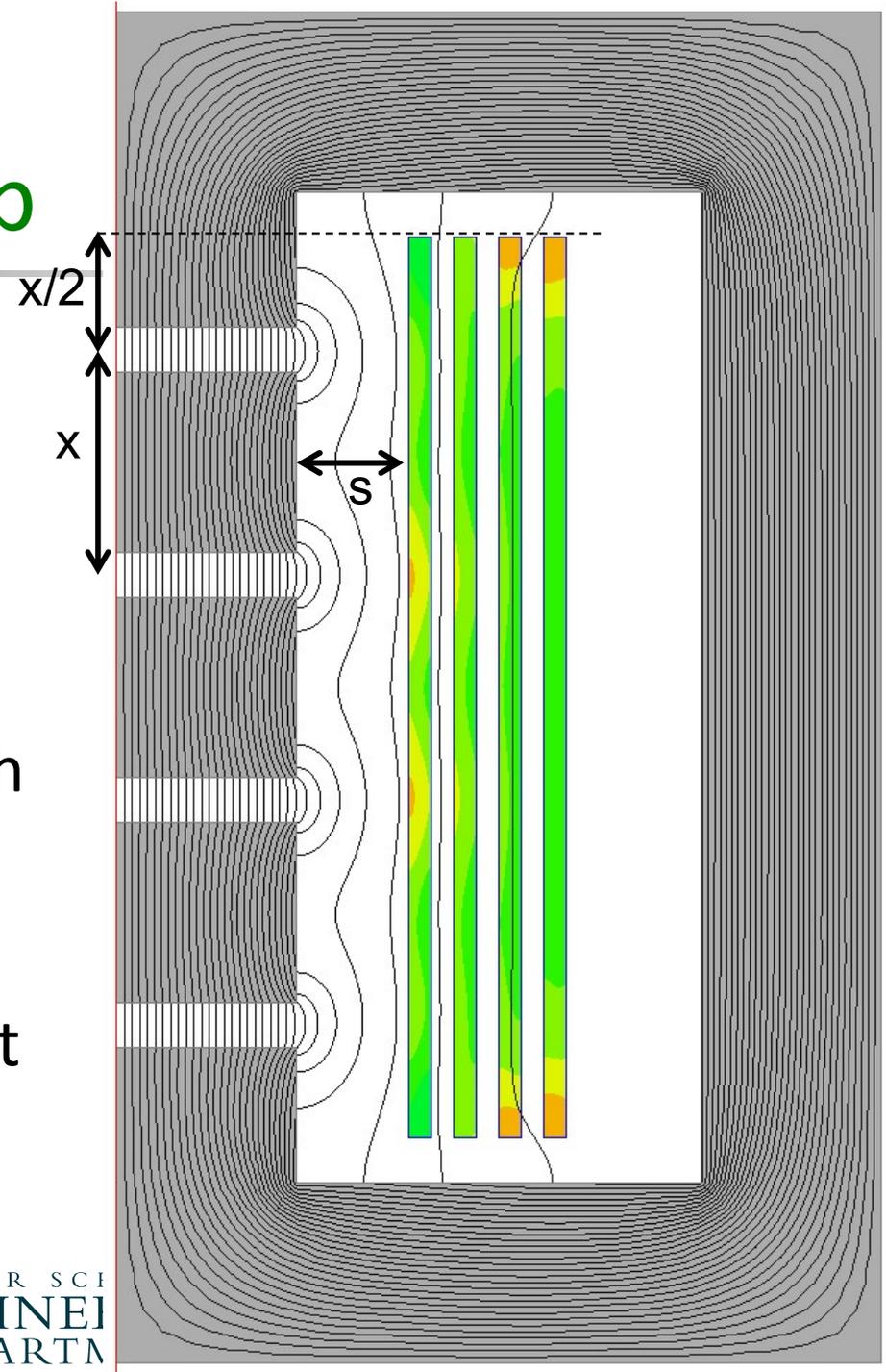
Inductors

- Interleaving is not an option.
- Fringing field near gaps.
- Distributed gap makes field $\sim 1D$



Quasi-distributed gap

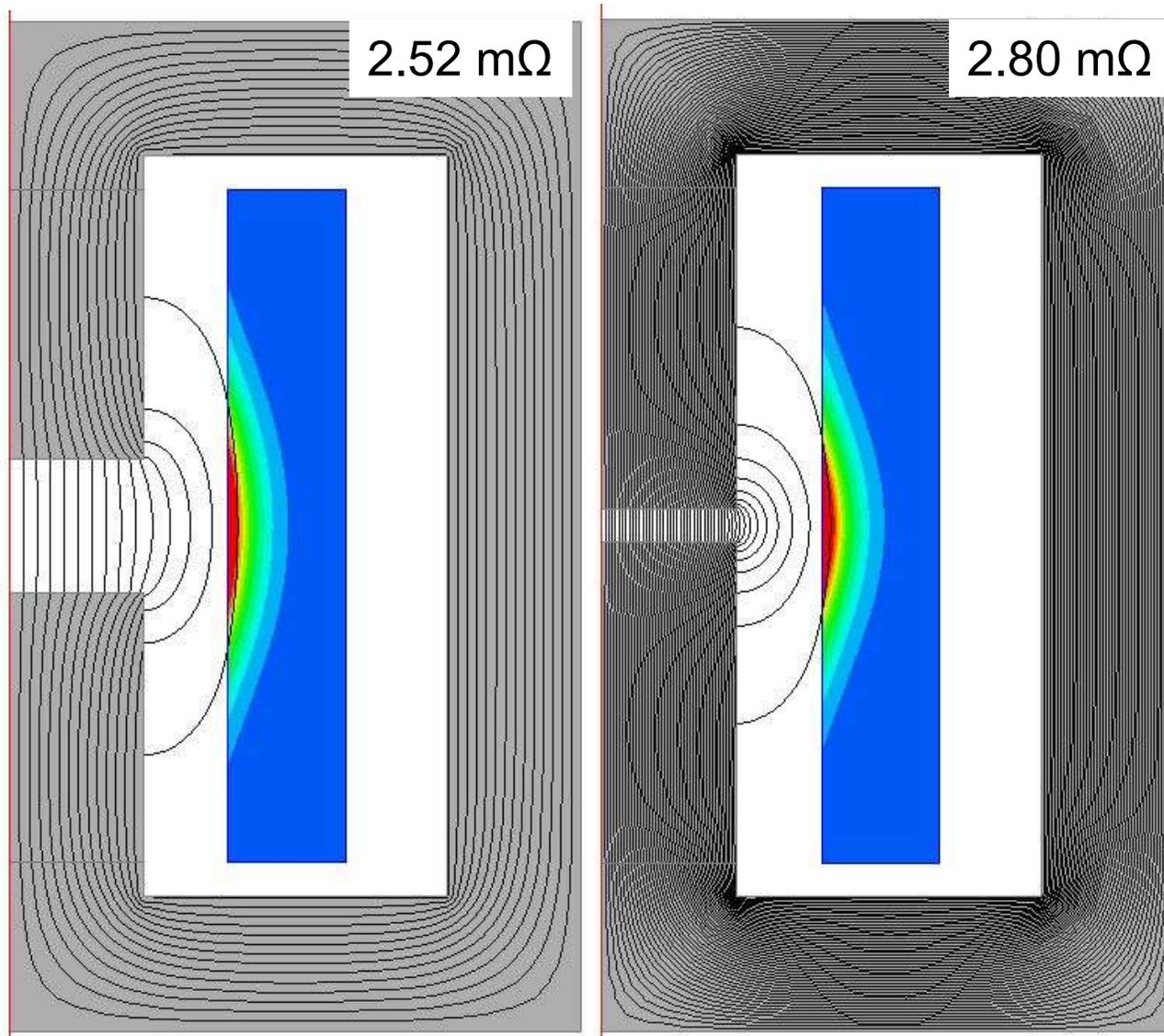
- Approximate a distributed gap with multiple gaps.
- Design rule: $s > x/4$
- Common misconception: works by making gap length small.
- Actually ac resistance is approximately independent of gap length.





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.



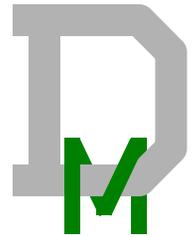


“But I’ve been designing inductors for 25 years and I’ve always had less fringing loss with a small gap”

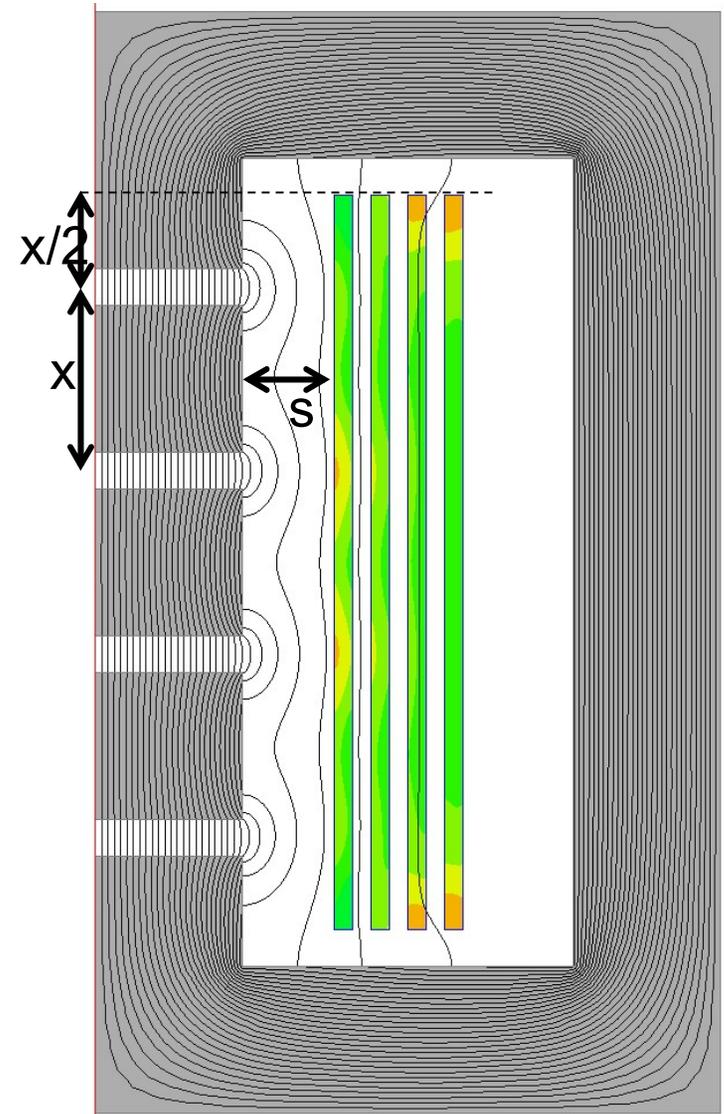
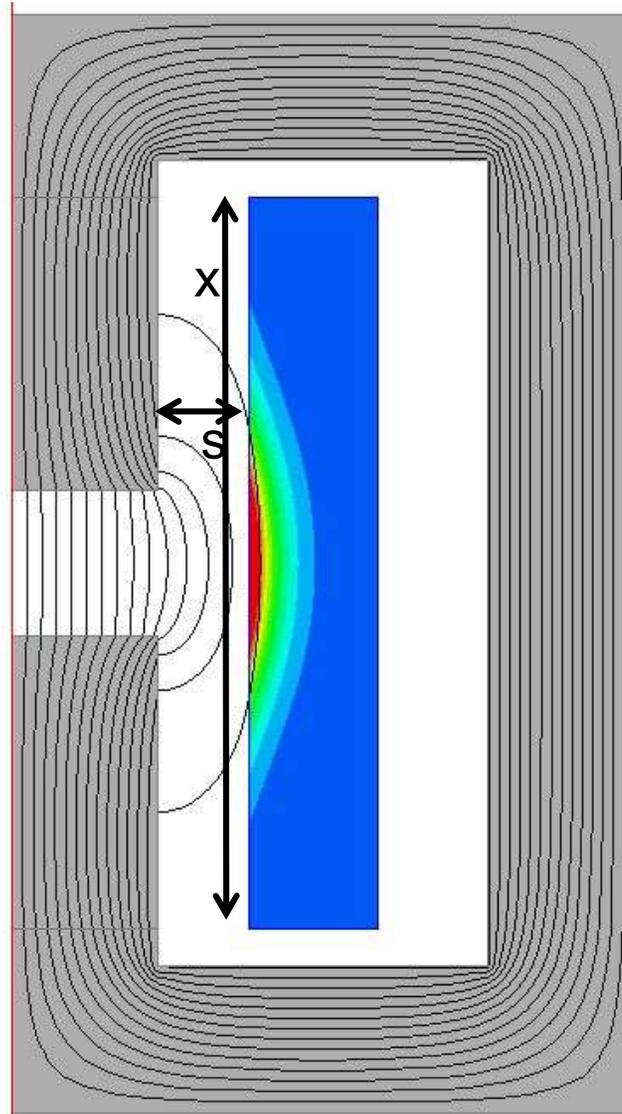
- When a small gap makes fringing loss lower:
 - With N fixed and a smaller gap, L goes up. Higher L means less ripple, so $I_{ac}^2 R_{ac}$ is reduced, but it’s because I_{ac} is reduced. R_{ac} is worse, and saturation is worse.
 - With N reduced to keep L constant. *All* winding losses go down. $F_r = R_{ac}/R_{dc}$ is still bad, but R_{dc} goes down. Losses are shifted to core loss.
 - With core area increased and N adjusted for the same flux density. Again, all winding losses go down and both cost and loss are shifted from the winding to the core.
- All the above are valid design strategies, but they are ways to live with high F_r , not ways to reduce F_r .
- One way a small gap can reduce F_r : use a low-permeability core with small or no gap.



Correct design consideration to minimize effect of gap on $F_r = R_{ac}/R_{dc}$

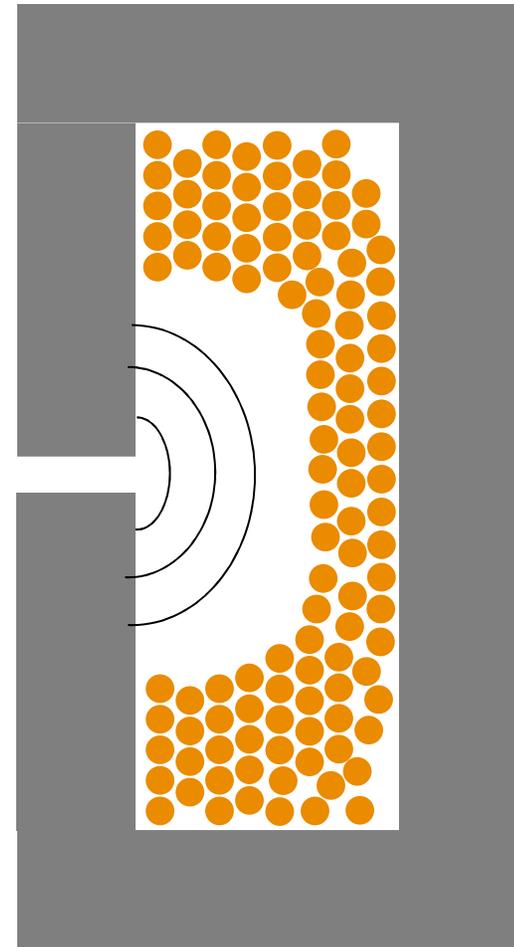


- $x > s/4$
(better $> s/2$)



Winding shape optimization

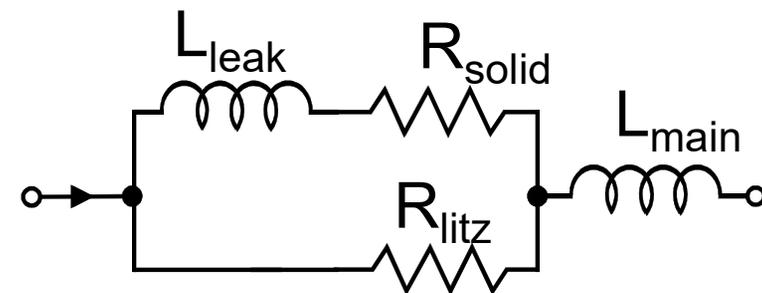
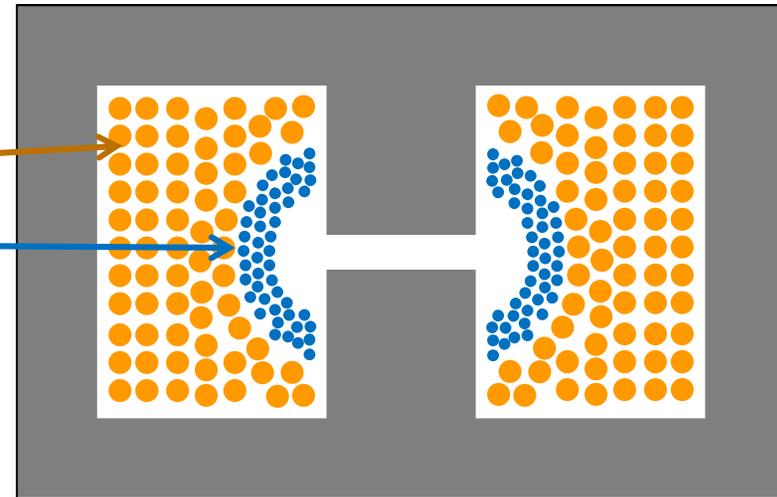
- Shape winding configuration to work **with** curved gap field.
- Applies to round wire and litz wire, not foil.
- Can actually work **better** than a distributed gap!
- Ad-hoc approach common, but full optimization is available.



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

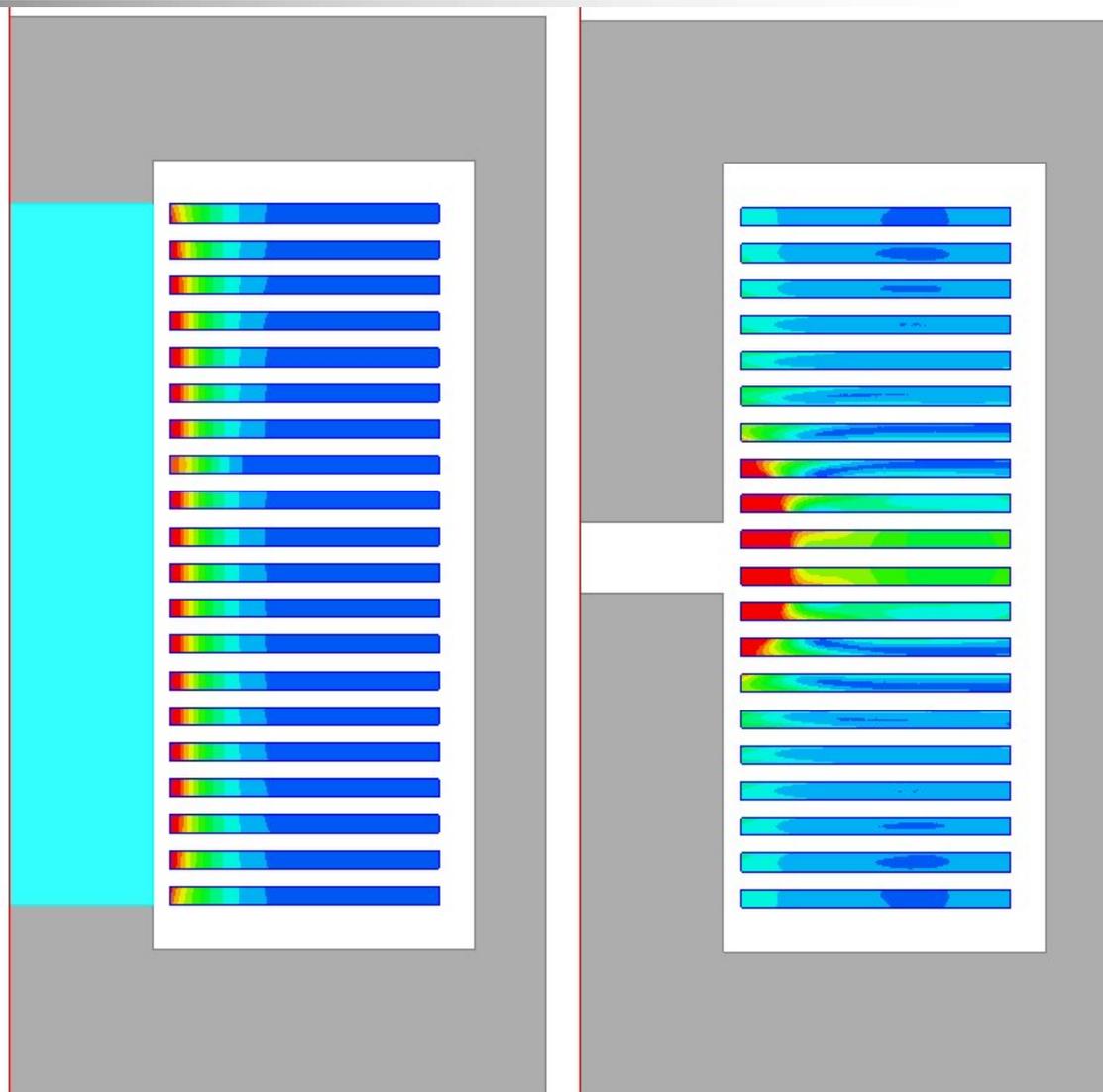


- Use a combination of a **solid-wire winding** and a **litz winding**.
- DC distributes to minimize loss (mostly in solid wire).
- Leakage inductance forces most HF current through the litz winding.
- Spacing from gap keeps wire out of intense field.

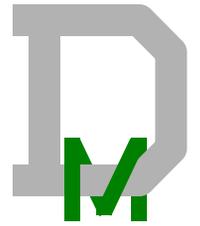


Helical = Edge-Wound Winding

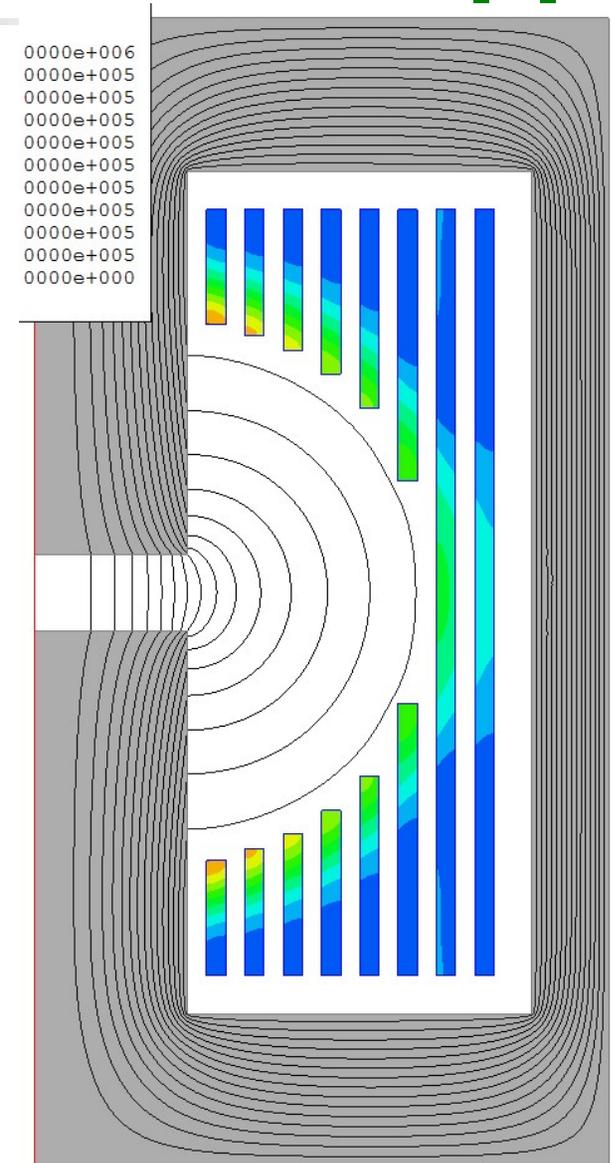
- Single-layer.
- High-frequency resistance like a single-layer wire winding.
- Uses full window for dc current.
- Only works with distributed gap—lumped gap has 3.5X worse R_{ac} .



Shaped foil winding



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

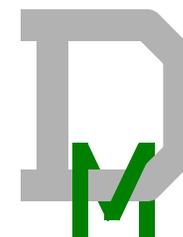




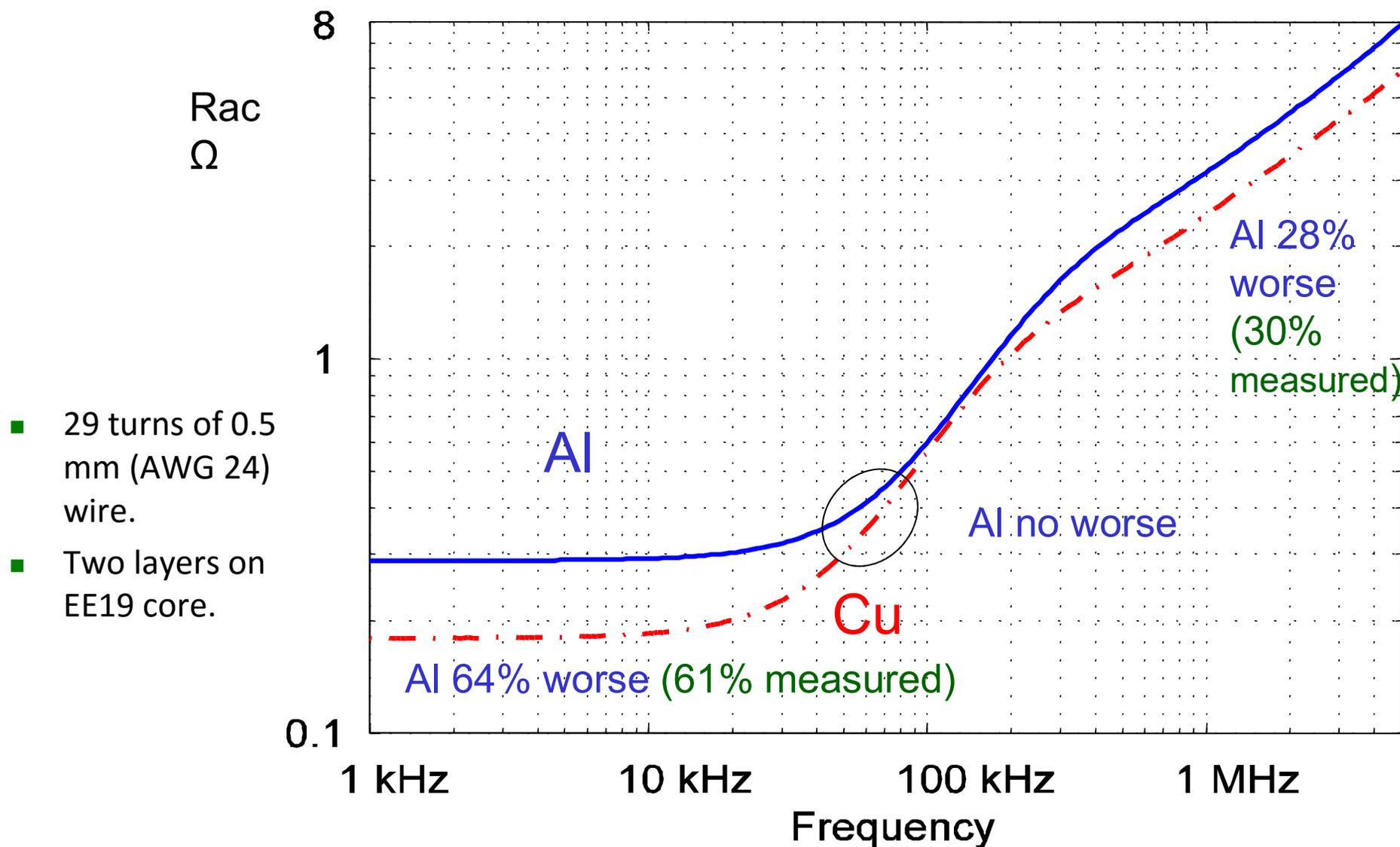
Costs: Cu vs. Al (as of 8 March 2016)

- Mass:
\$5.00/kg vs. \$1.6/kg (wrong metric)
- Volume basis:
4.42 ¢/cm³ vs. 0.43 ¢/cm³ 10X
- Resistance basis:
 $7.67 \frac{\$ \mu \Omega}{\text{m}^2}$ vs. $1.22 \frac{\$ \mu \Omega}{\text{m}^2}$ 7.3X
- >7X more cost effective ... dc or low frequency.
- What about high frequency?





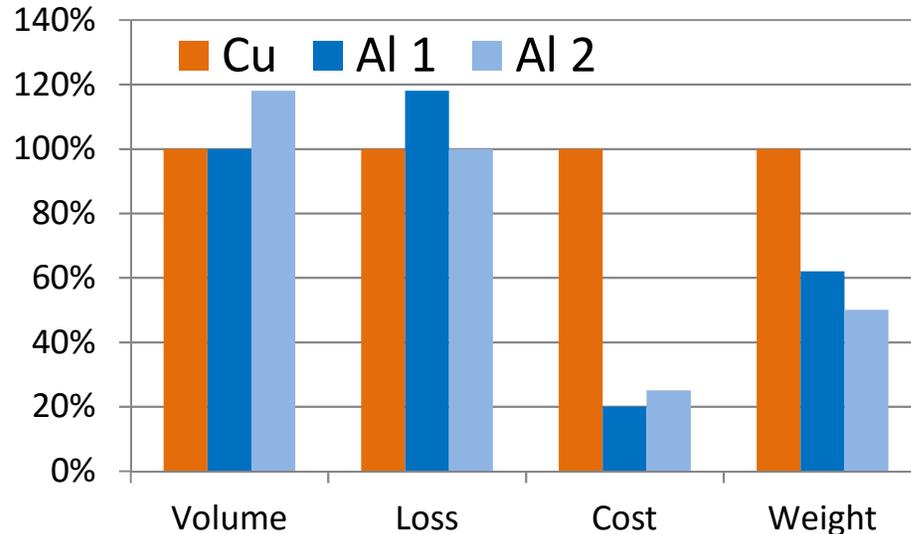
Measured transformer ac resistance





Real comparison of Al and Cu

- Comparison without design work is only useful if you don't plan to do good design work.
- Compare a design optimized to use Al well to a design optimized to use Cu well.



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?

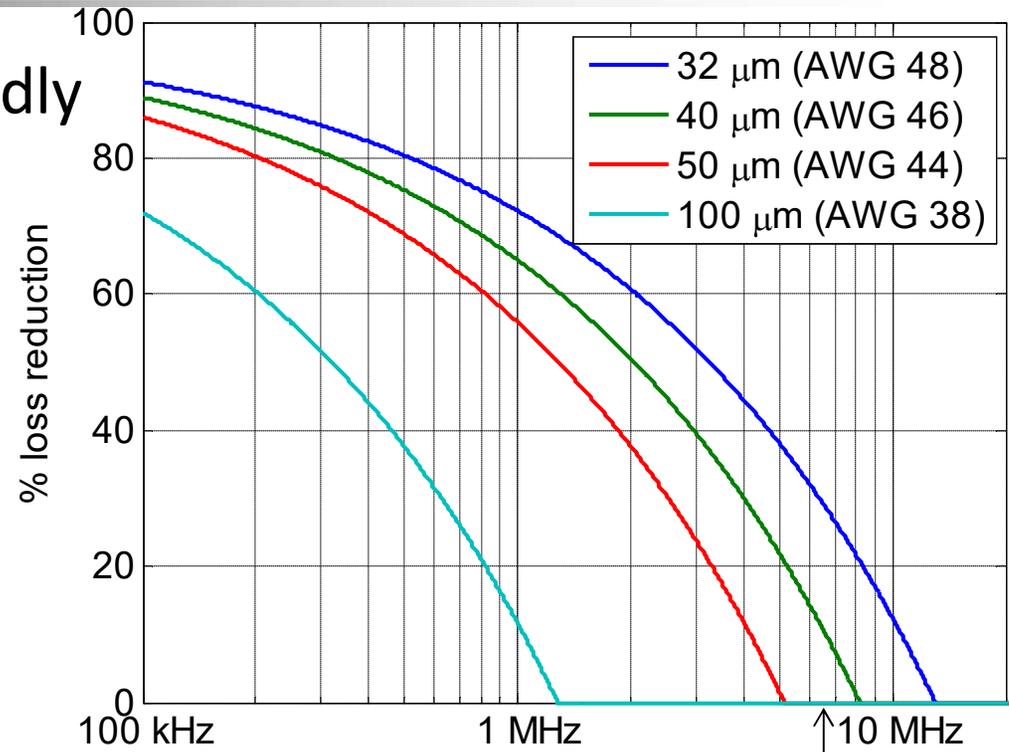
- We have good materials and design methods for 20 kHz to 300 kHz .
- New semiconductors emerging
 - GaN and SiC power devices: now commercially available, > 10X switching speed vs. Si.
 - Theoretically allows smaller, more efficient magnetics.
 - But can this be realized in practice?
 - Windings?
 -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



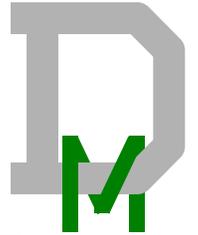


Windings at MHz frequencies ... Litz?

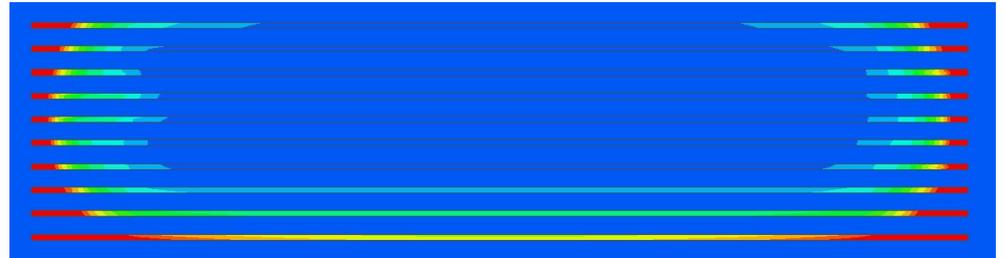
- Litz benefits drop off rapidly in the MHz range.
 - Barely better than a solid-wire winding.
- Huge room for improvement in theory:
 - A single-layer winding only has current in one skin depth: At 10 MHz, 21 μm .
 - 0.2% of a 1 cm winding window (0.23% with litz).
→ **400X improvement theoretically available.**



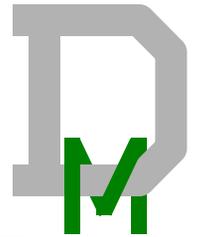
Foil: $< 10 \mu\text{m}$ at low cost



- Easy to get thickness \ll skin depth.
- Thin layers have high dc resistance—need many in parallel.
- Challenges:
 - Achieving uniform current density—laterally and among layers.
 - High capacitance between layers.
- Solutions:
 - Shape the field to be parallel to the layers.
 - Four approaches to balance current in COMPEL 2014 paper... one highlighted here.

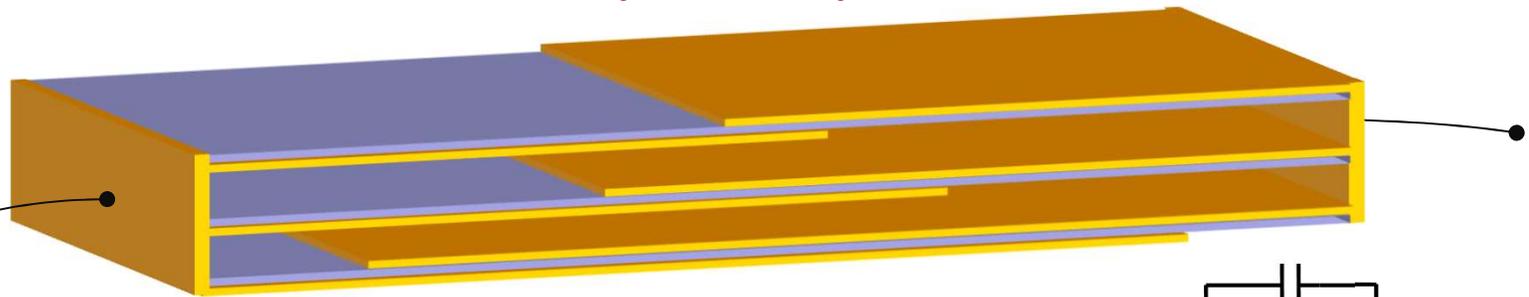


Current sharing with capacitive ballasting

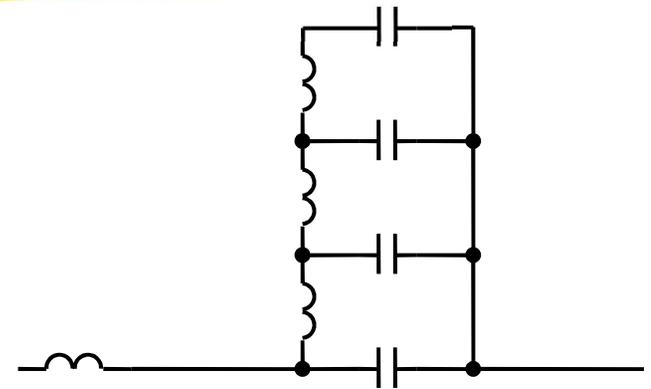


- Use overlapping insulated layers to create a different tuned series capacitance for each layer.

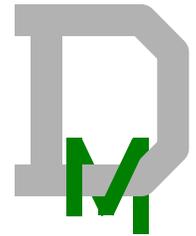
Cartoon: real structures have many more layers



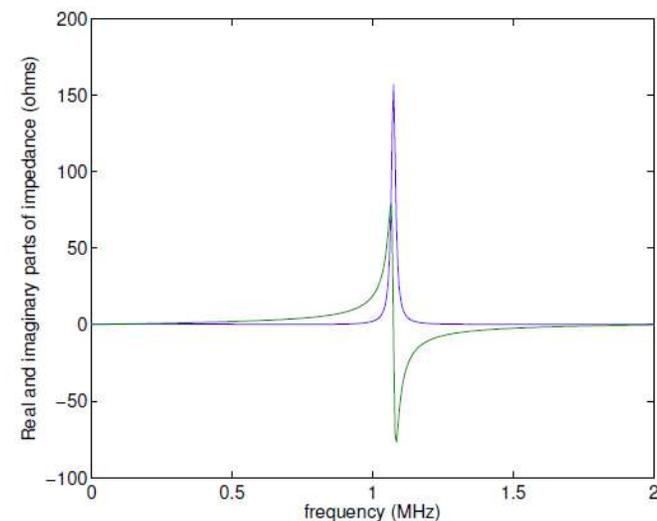
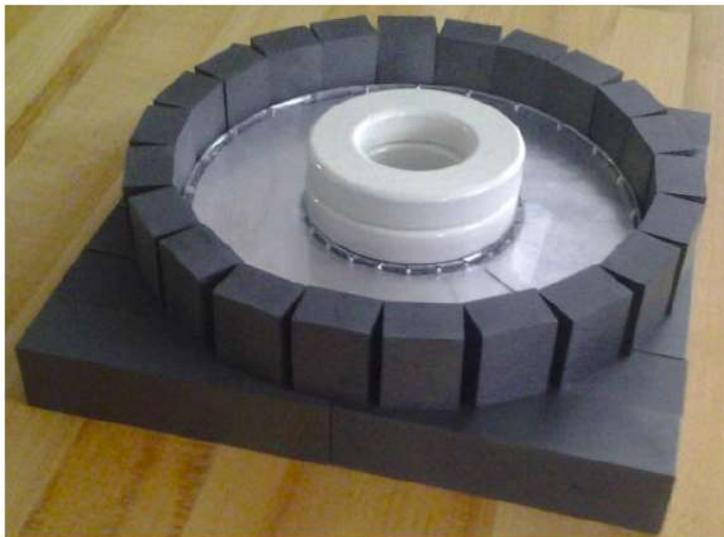
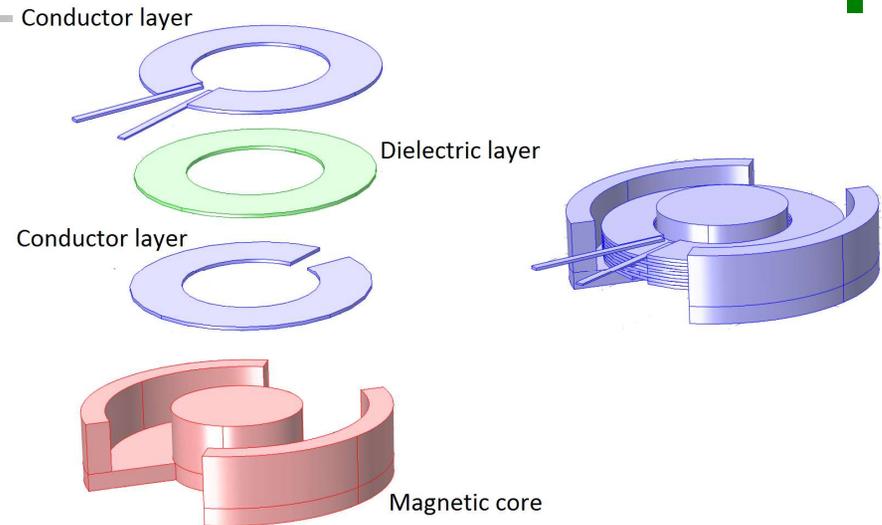
- Capacitance can be chosen for exact current sharing at one frequency or approximate current sharing over a wider range.
- Other current-sharing approaches under development.



Resonant components for power conversion or wireless power

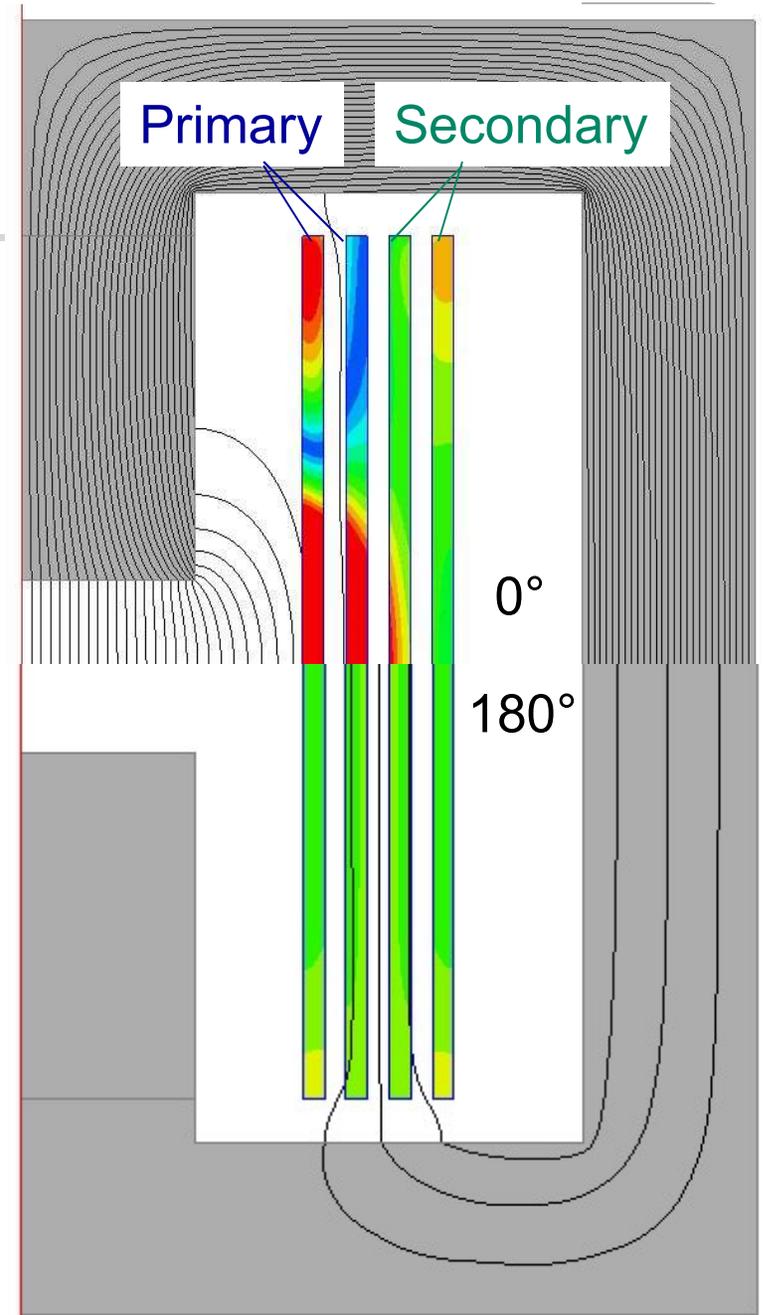


- Resonant capacitor = ballasting capacitors.
- Dual benefit from unavoidable capacitance between layers.
- High-Q resonance with a single component.
- Prototype: 12 μm Al and PP.



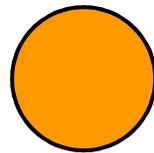
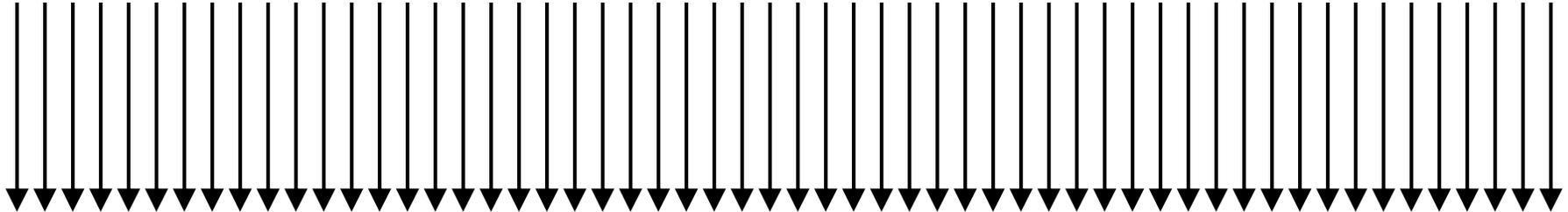
Modeling: need for resistance matrix

- Conventional, incorrect, model for transformer winding loss (assume sine waves for now).
 - $P_{\text{winding}} = I_1^2 R_1 + I_2^2 R_2$
 - Problem: Loss varies drastically depending on relative phase/polarity.
 - Factor of 4 error in this case.
- Correct model options:
 - R_1 and R_2 that are only for specific phase relationship.
 - Resistance matrix.





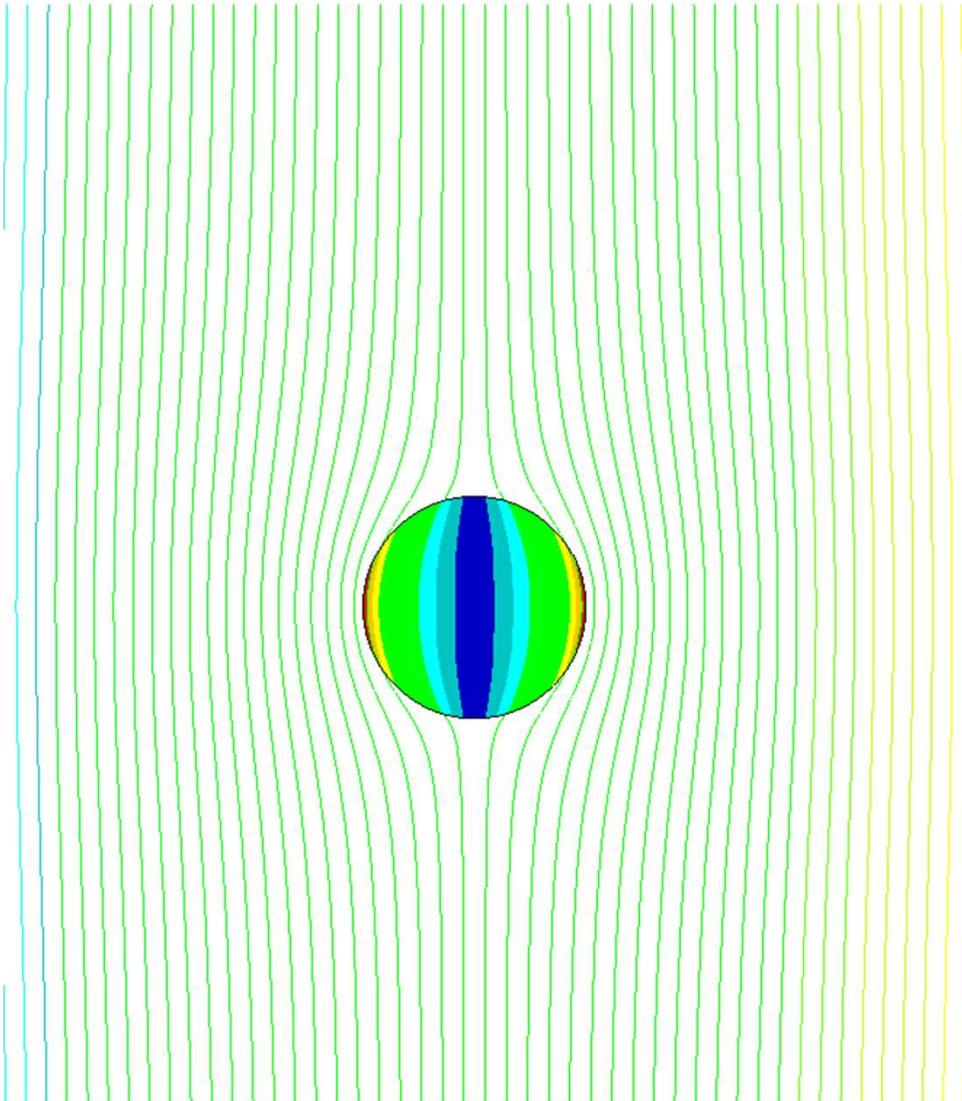
Loss analysis: Textbook problem



- Cylinder subjected to uniform field
- Dowell's model is a crude approximation.



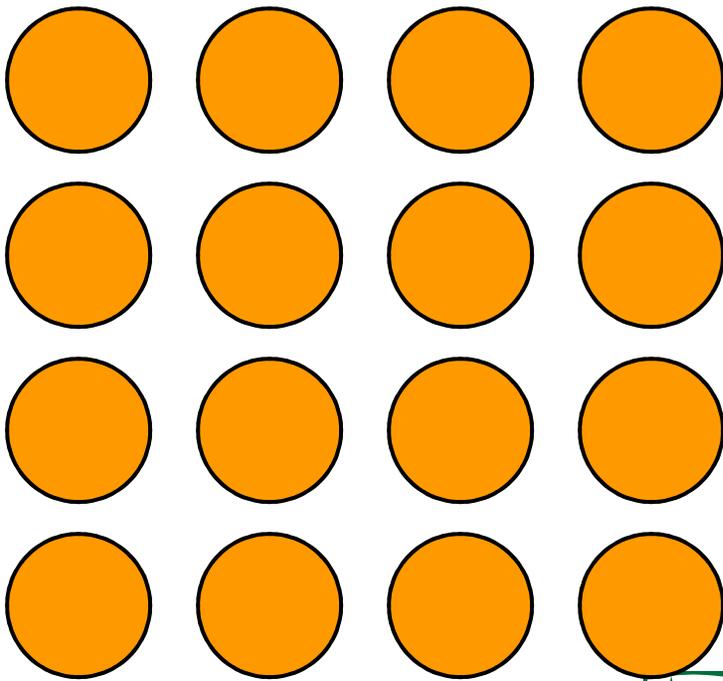
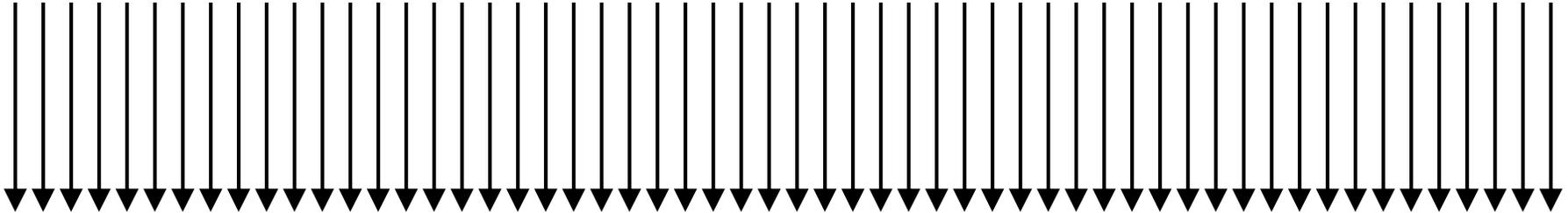
Textbook solution



- Exact solution, described by Bessel functions.
- Use for winding loss analysis pioneered by Ferreira.



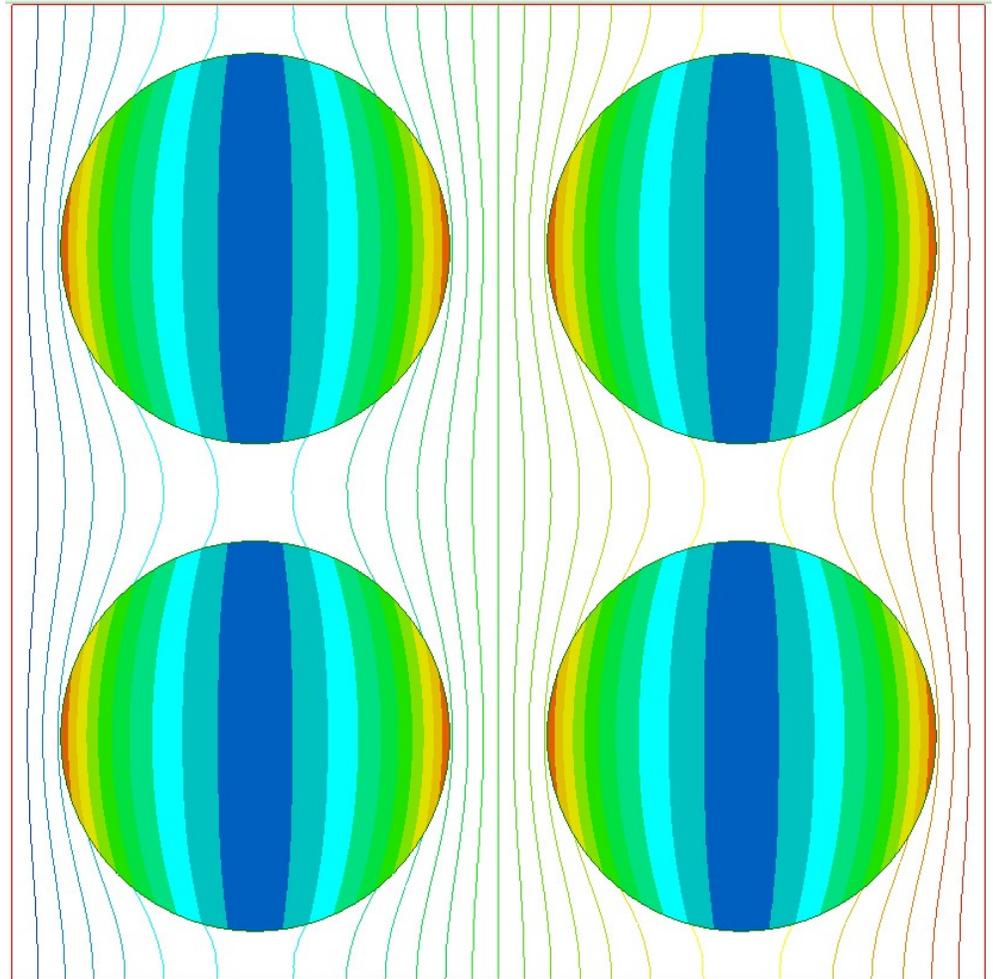
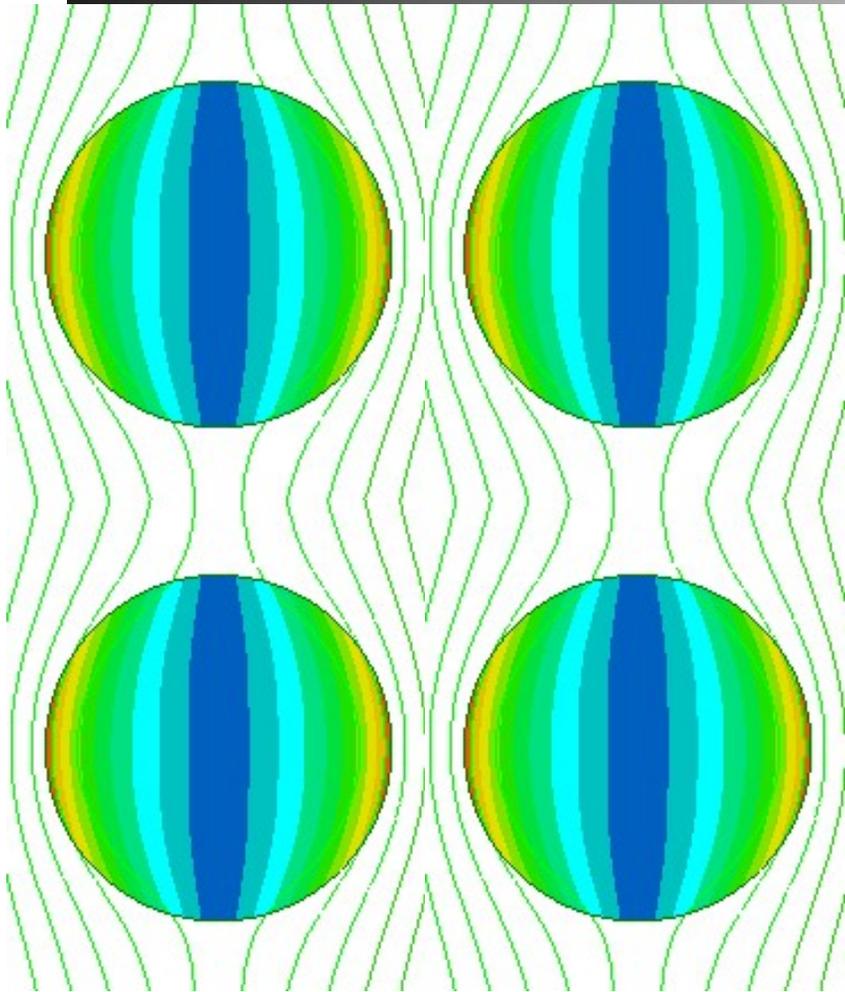
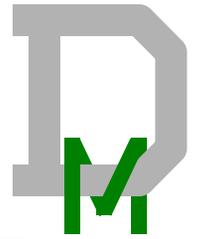
Actual problem



- *Array of* cylinders subjected to uniform field
- (This is a cartoon—actual problem must be more precisely defined.)



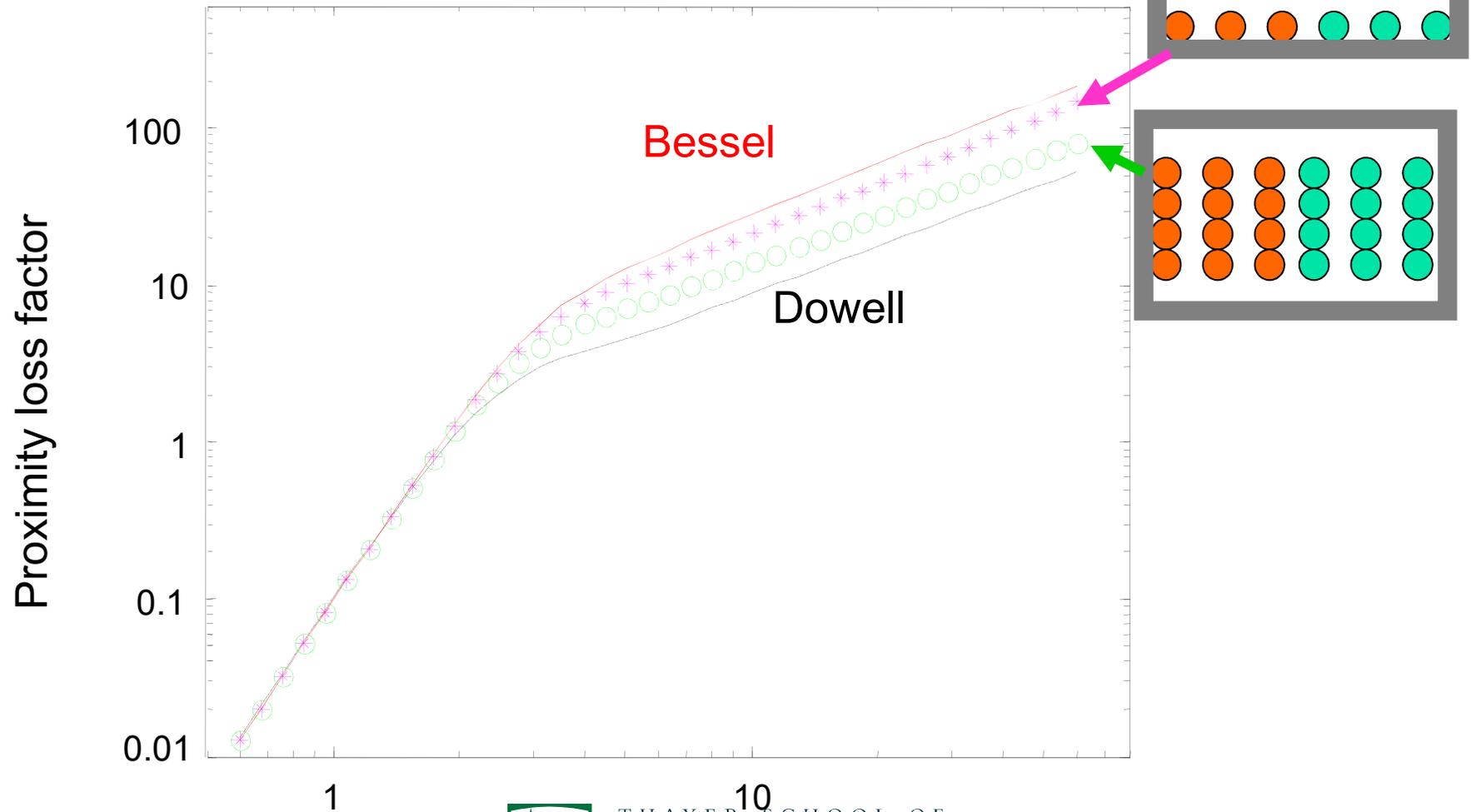
Using the Bessel solution for the real problem



Not a valid solution!

Real Solution (FEA)

Simulation Results

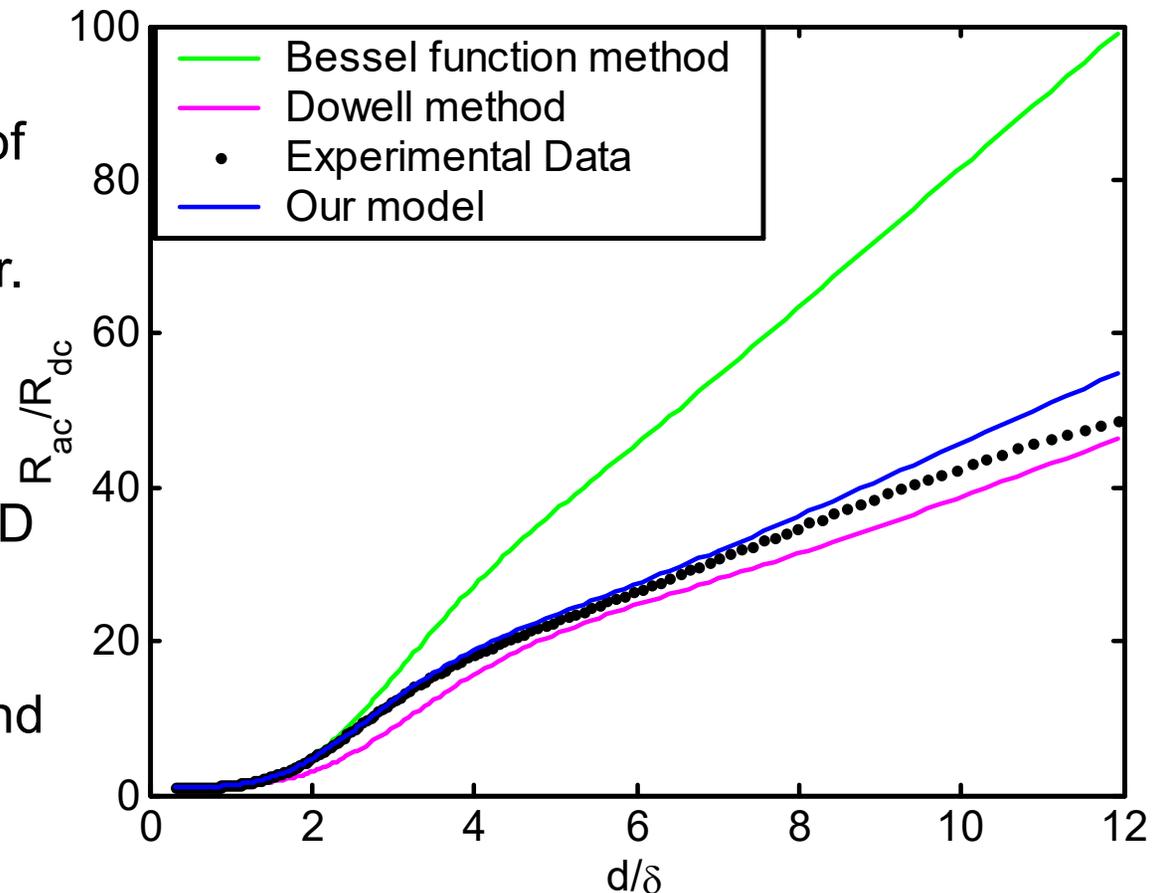




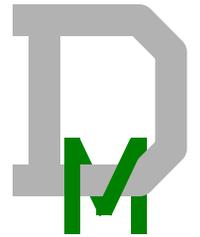
Experimental Measurements

Xi Nan's model:

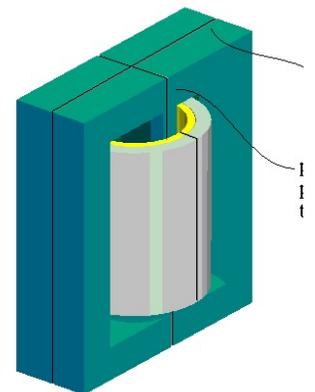
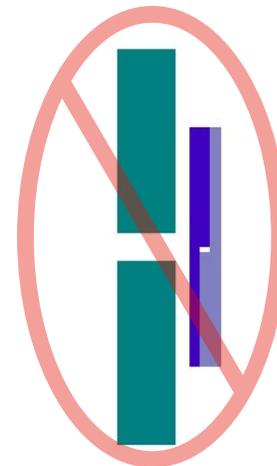
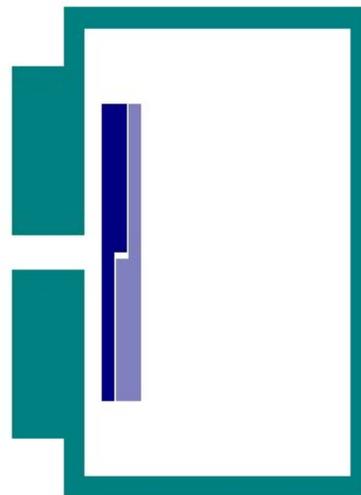
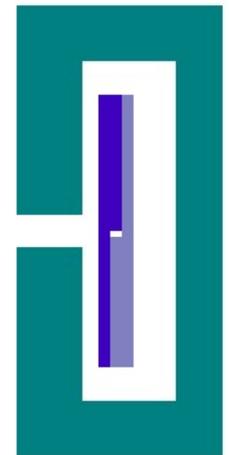
- Weighted average of Dowell-like and Bessel-like behavior.
- Fits experimental results better than Dowell or Bessel.
- Can be applied to 2D or 3D field configurations with multiple windings and arbitrary waveforms—see Zimmanck.

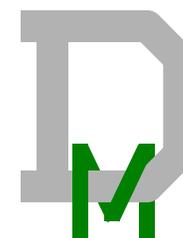


1D, 2D and 3D modeling approaches



- 1D: can use analytical models.
 - For Xfrmers and good (quasi-) distributed gap Ls.
 - Dowell isn't precise but we know how to do better.
- 2D: Fast, easy, low-cost simulations.
 - Naïve sections for E-cores can be misleading.
 - Mimic return path for to reduce error 5X.
- 3D: Use for verification, not design.



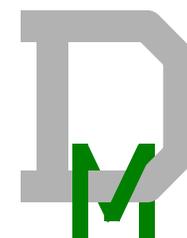


Core loss models & metrics

- Models:

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

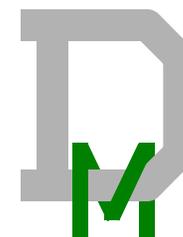
- Metrics: performance factor and modified performance factor.



Conclusions

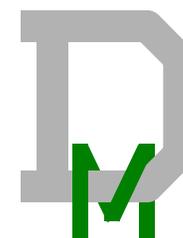
- Proximity effect is the primary winding design consideration.
- Reduce proximity effect using a single layer or many layers much thinner than a skin depth ($R_{ac} \propto \frac{1}{\sqrt{p}}$) with optimum thickness.
- Established winding loss reduction techniques include litz wire, interleaving, distributed gaps, quasi-distributed gaps, shaped windings, and parallel windings.
- For MHz frequencies, litz strands are too big
 - Very thin foil is available. Need to balance current in parallel layers.
 - Four techniques under consideration; capacitive ballasting discussed here.
- Winding loss analysis methods are available; core loss harder.





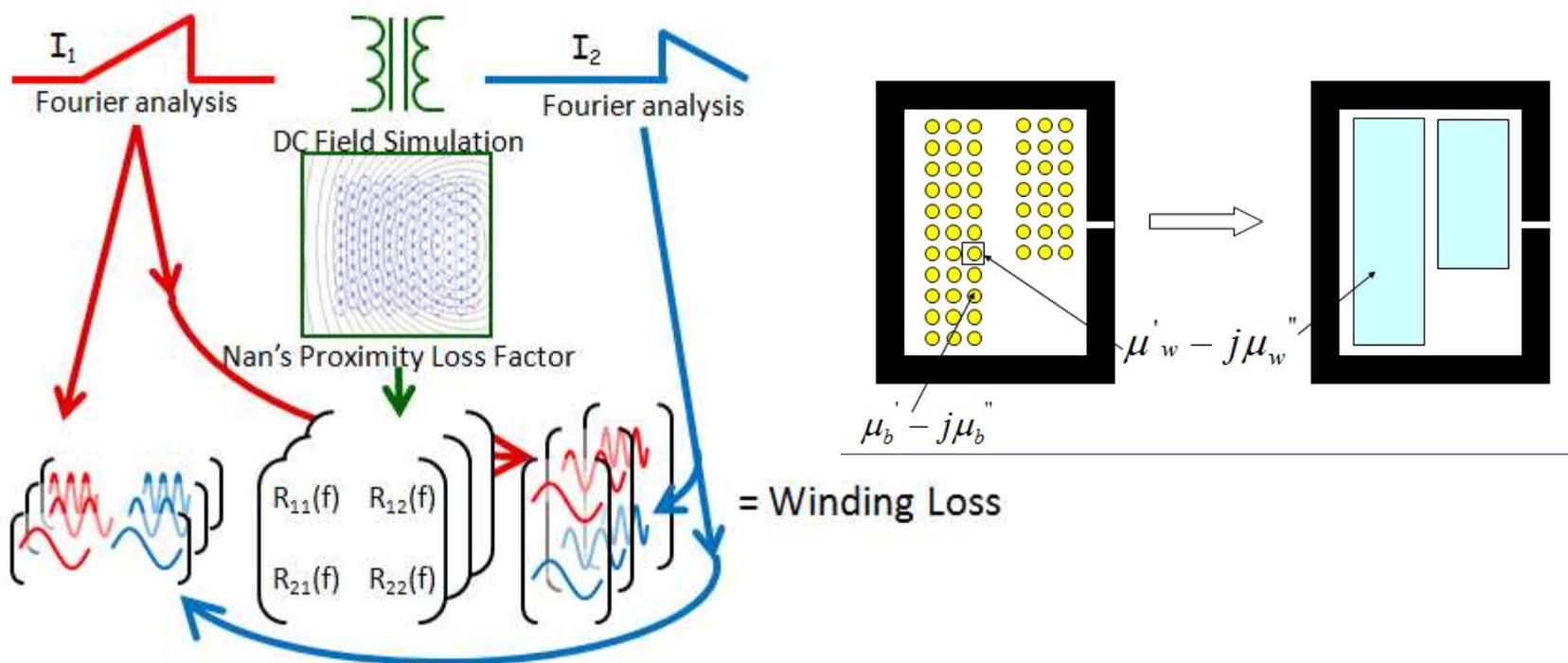
APPENDIX





Multiple frequencies and 2D fields

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



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].

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