Windings for High Frequency

Charles R. Sullivan
chrs@dartmouth.edu

Dartmouth Magnetics and Power Electronics Research Group

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

http://power.engineering.dartmouth.edu

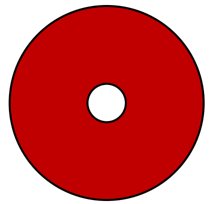
The Issue

- The best-available technology for low-loss windings up to ~ 3 MHz is litz wire.
- At higher frequencies, litz wire has little benefit.

This Talk:

- What limits litz wire above 3 MHz?
- What else can be done above 3 MHz?
- Litz wire and other approaches for < 3 MHz

Naïve idea to overcome skin effect

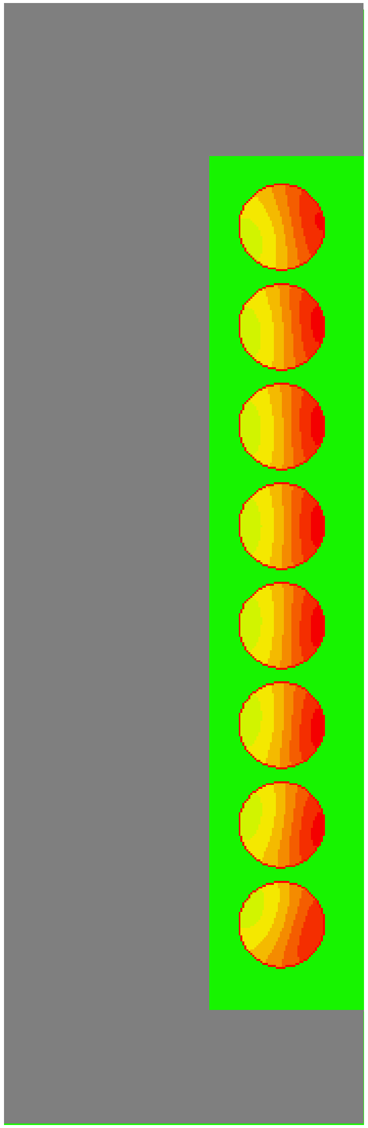


- Use diameter no bigger than ~2 skin depths…

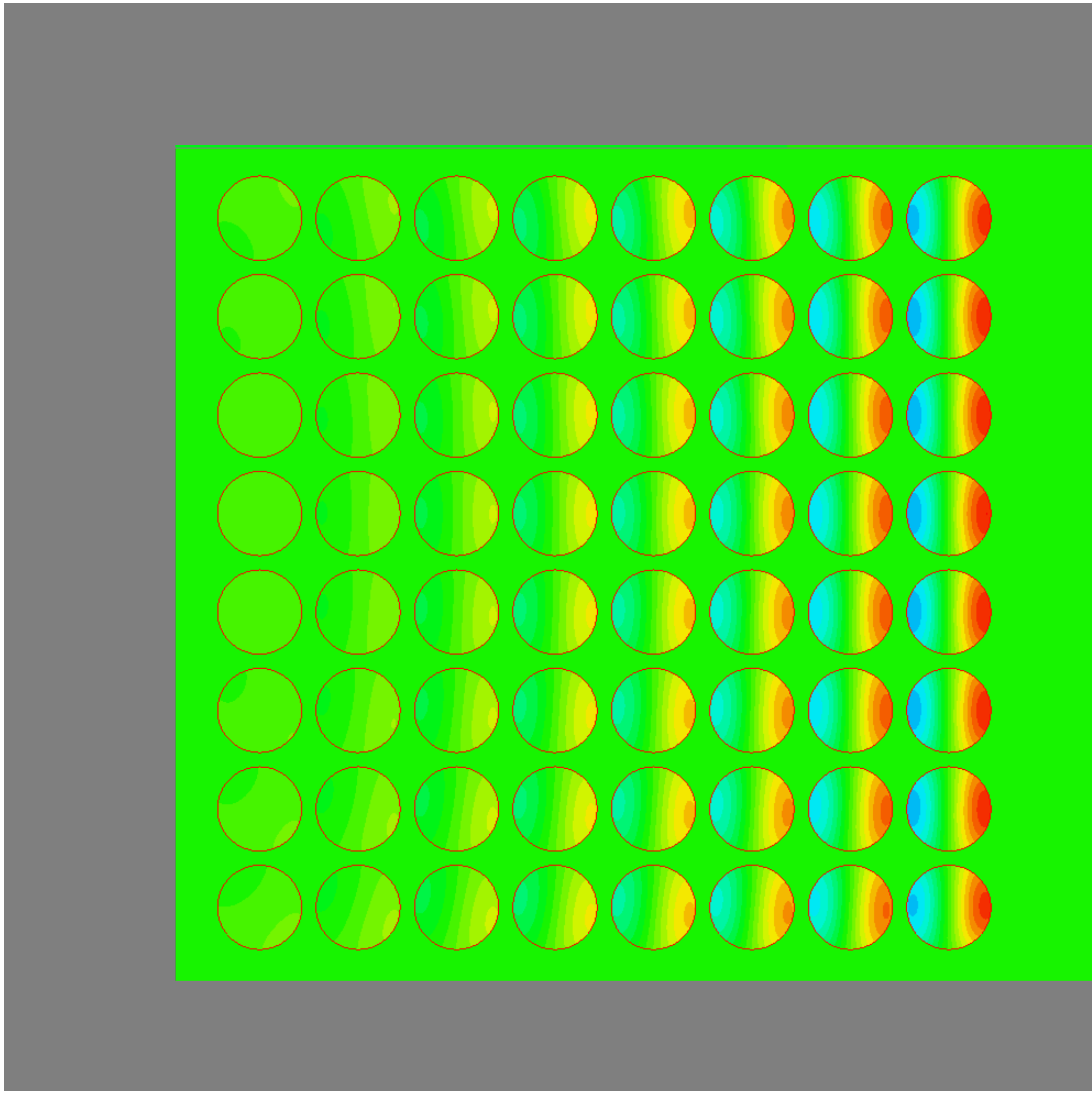
f	60 Hz	20 kHz	200 kHz	1 MHz	10 MHz
δ	8.5 mm	0.467 mm	0.148 mm	66 μm	21 μm
	AWG 0	AWG 24	AWG 35	AWG 42	AWG 51
2δ	17 mm	0.93 mm	0.30 mm	132 μm	42 μm
	AWG 7/0	AWG 18	AWG 29	AWG 36	AWG 45

Diameter = 2 skin depths

200 kHz
d = 0.3 mm

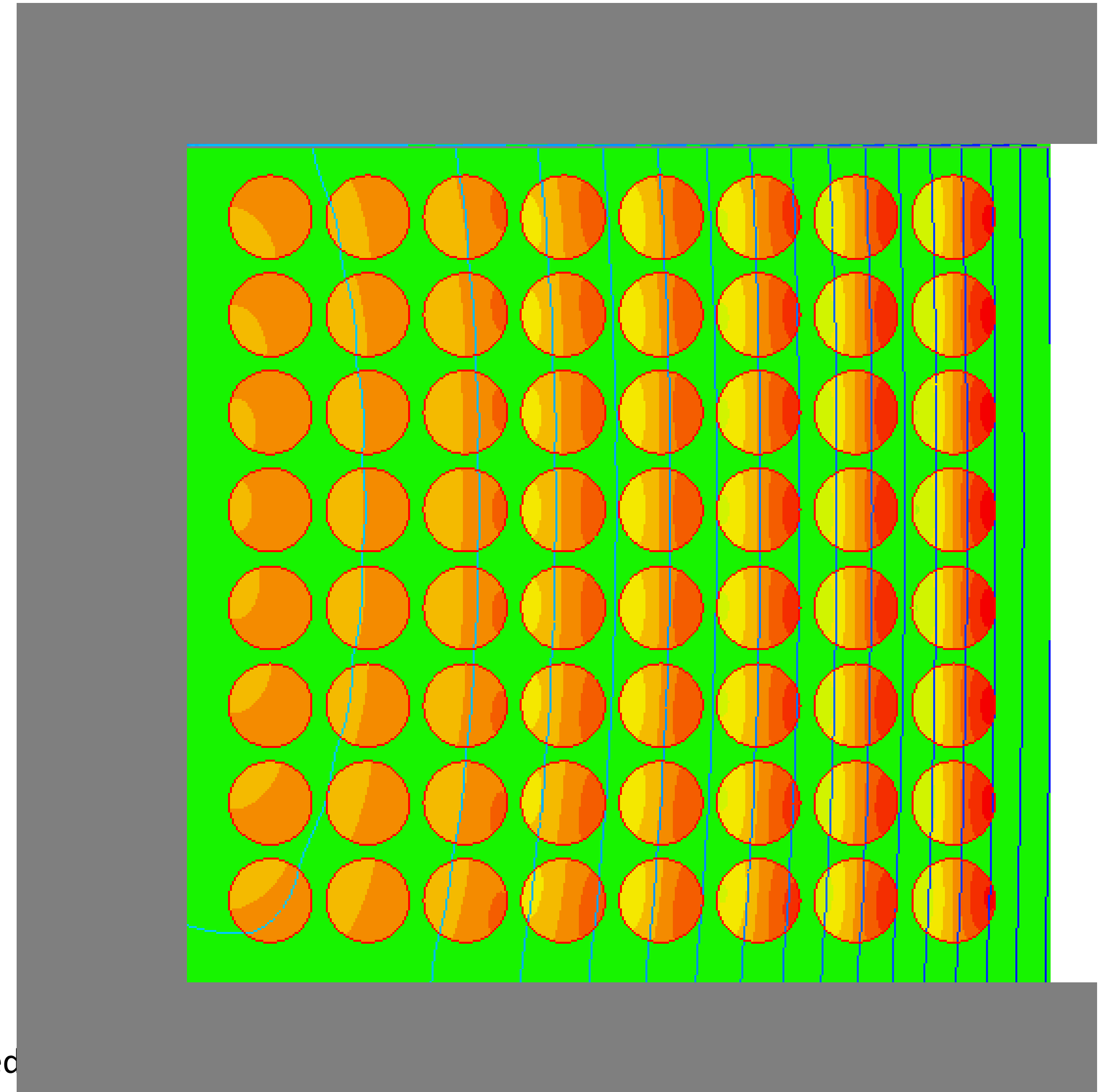


Rac/Rdc = 1.36



Rac/Rdc = 27.7

Issue: Proximity Effect (field impinging on wire)



Design Criterion with Proximity Effect

- Effect of using many layers. (Simplified 1-D analysis)
  - For p layers, the layer thickness for minimum ac resistance is $t = 1.3\delta / \sqrt{p}$
  - Achievable ac resistance is proportional to $1/\sqrt{p}$
- We'd like wire diameter of $\delta/10$, for example, but at 1 MHz, $\delta/10$ = 6.6 µm, about ¼ the smallest available.
- Consider the case of constrained wire diameter.

Litz > 1 MHz

- Available improvement vs. single-layer solid wire: $$\frac{P_{litz}}{P_{solid}} \approx 0.58 \frac{d}{\delta}$$

		f	300 kHz	1 MHz	3 MHz	10 MHz
		δ	0.148 µm	66 µm	38 µm	21 µm
Strand size			Loss reduction			
AWG44	51 µm		80%	55%	22%	None
AWG46	40 µm		84%	65%	39%	None
AWG48	32 µm		87%	72.7%	51%	11%

- For 3 MHz and higher need d << 32 µm

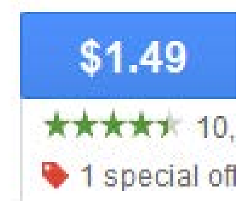
Low AC resistance > 3 MHz

Options:

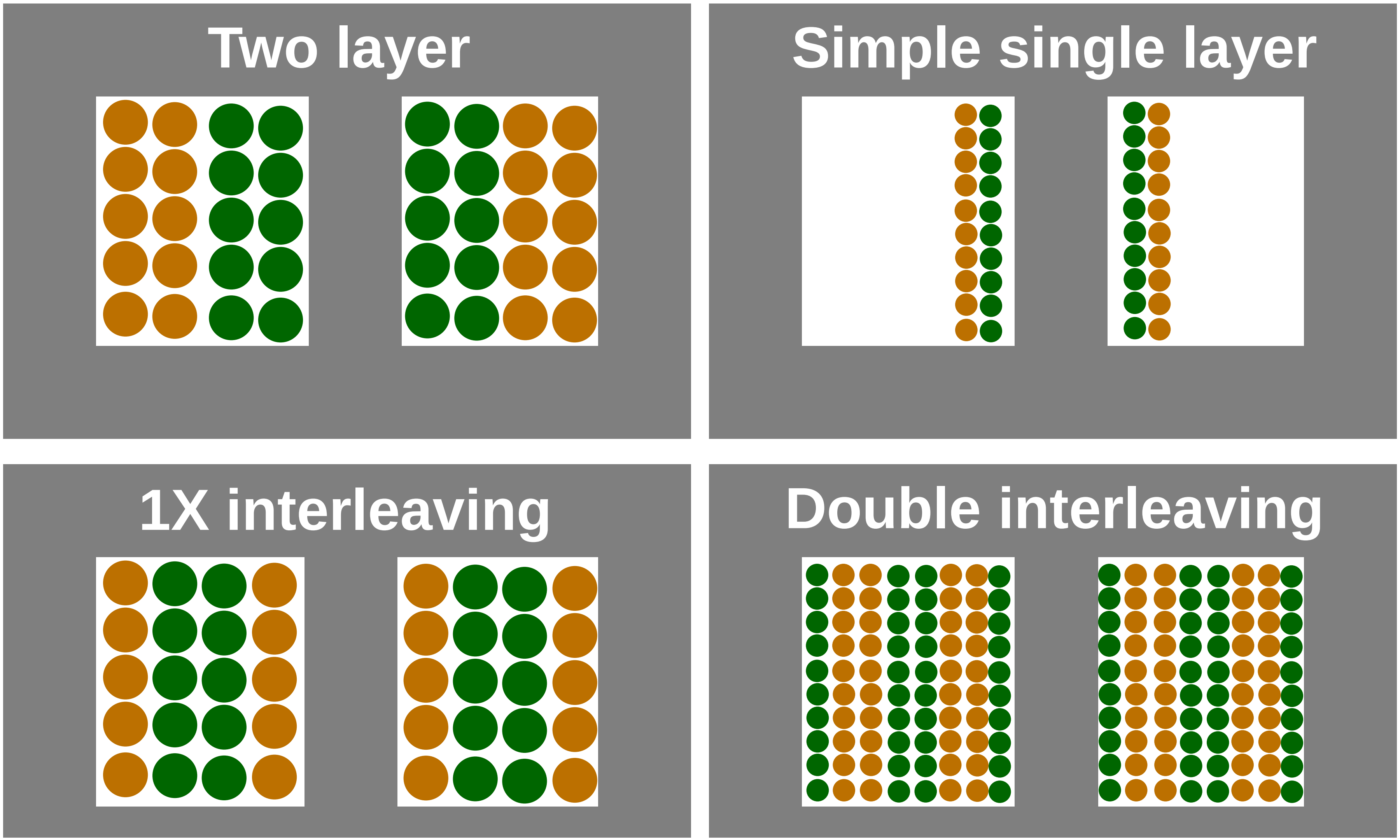
- Single-layer windings

  OR

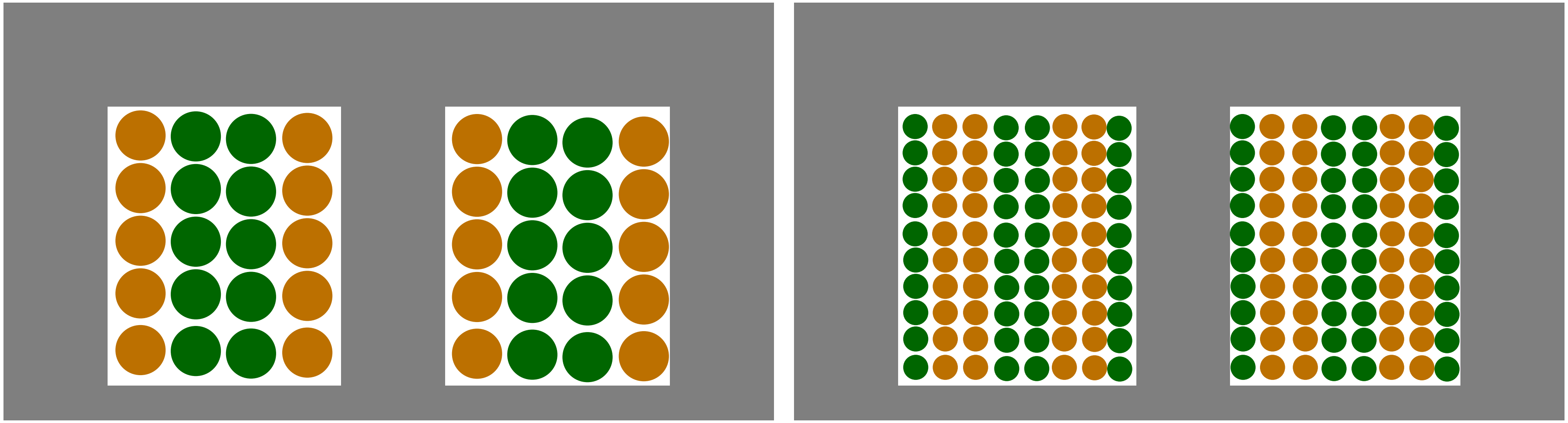
- Winding dimensions < 20 µm
  - Wire is too expensive.
  - Foil is cheap.
  - Microfabrication with photolithography also an option.



Single-layer transformer designs

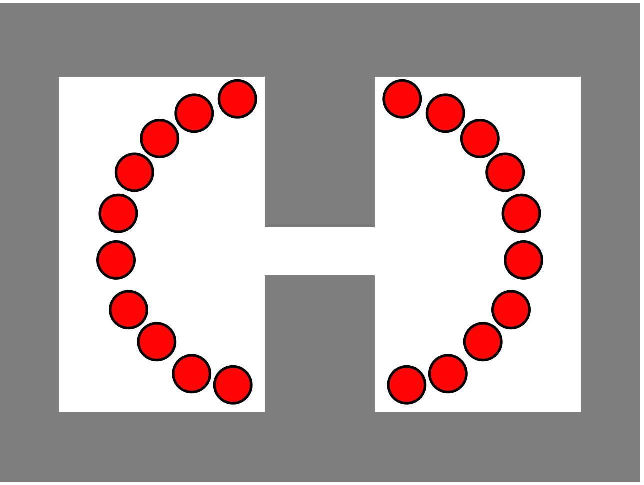


Interleaving limitations



- Each level of interleaving adds capacitance.
- Also adds fabrication complexity.
- Not possible with inductors.

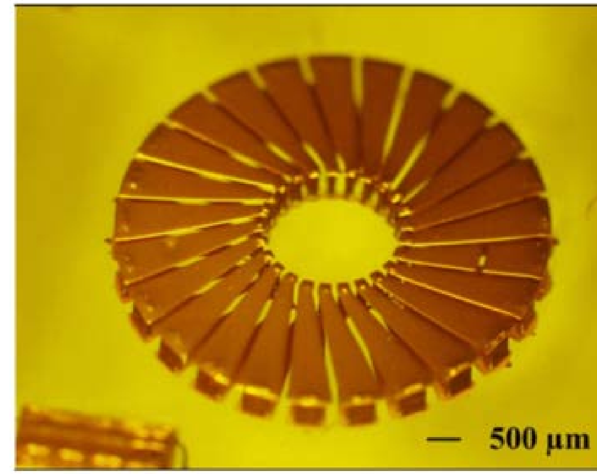
Single-layer inductors



Gapped high-perm

Techtrans.co.tw

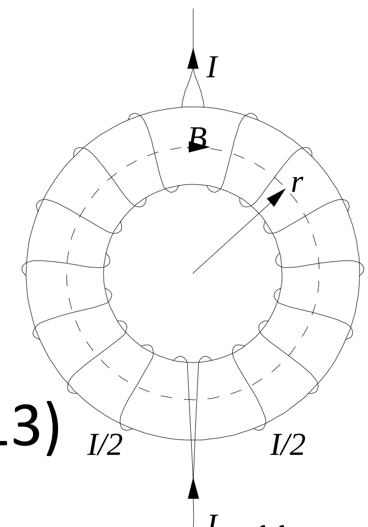
Low-perm core



Kim, Herrault, Allen et al Georgia Tech

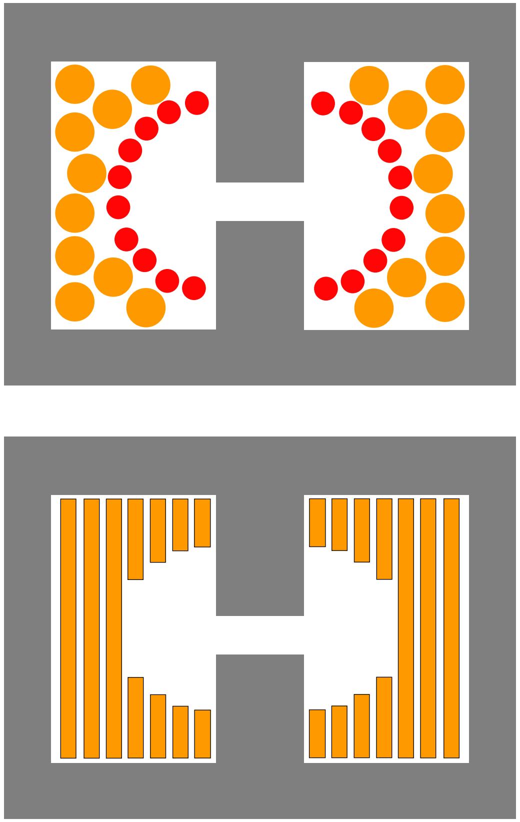
Air core

- All have low window utilization.
    - Toroids: can reduce end-to-end capacitance with split winding (Qiu, Hanson and Sullivan COMPEL 2013)



Improving window utilization in inductors

- If there's substantial dc current, add a parallel winding to reduce Rdc.
- Simpler construction for the same net effect: Shaped foil windings. (available from West Coast Magnetics)
- Improving Rac further requires a multilayer winding.

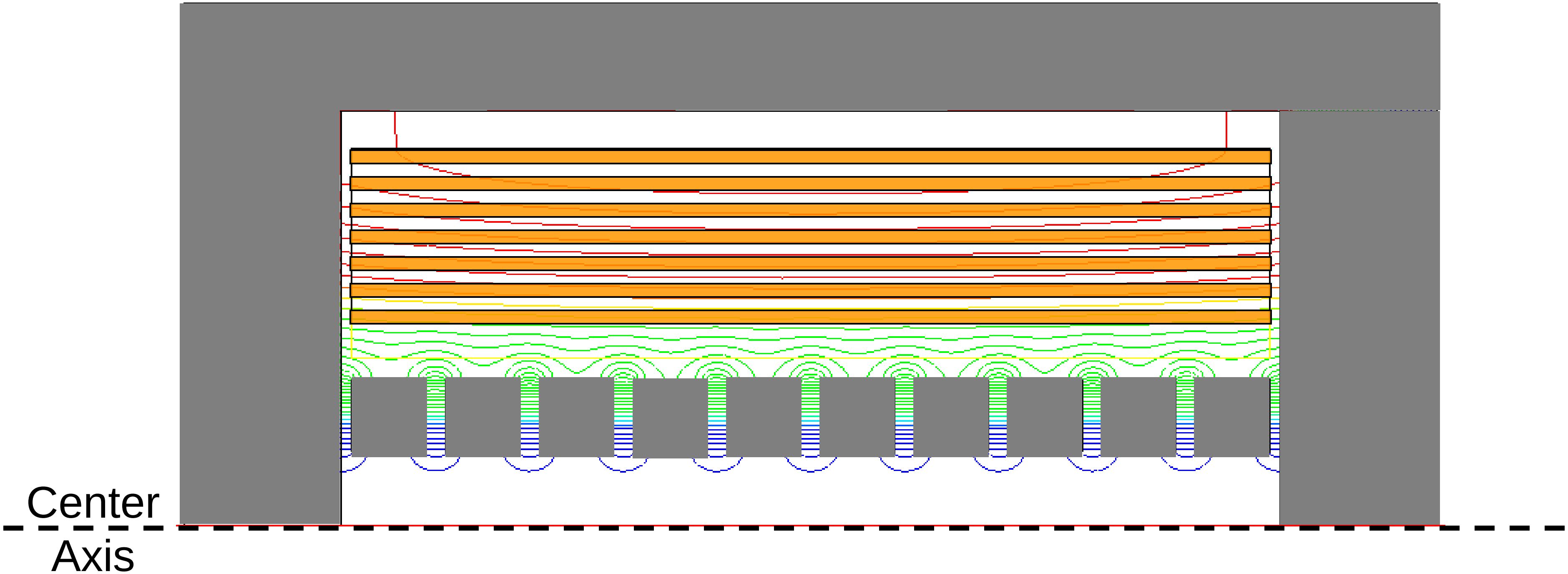


Multi-layer foil windings: $N = p$

- Compared to single-layer winding, AC resistance ideally reduced by $1/\sqrt{p}$ for *p* layers, if the layer thickness is $t = 1.3\delta/\sqrt{p}$
- Simplest option: barrel-wound foil where the number of turns *N* is equal to the number of layers *p*.
- Two challenges:
  - Keeping the field parallel to the foil (esp. in gapped L)
  - Terminations

Michael Timmis, Grabcad.com

Solutions for multilayer foil inductors:
I. Field Parallel to Foil

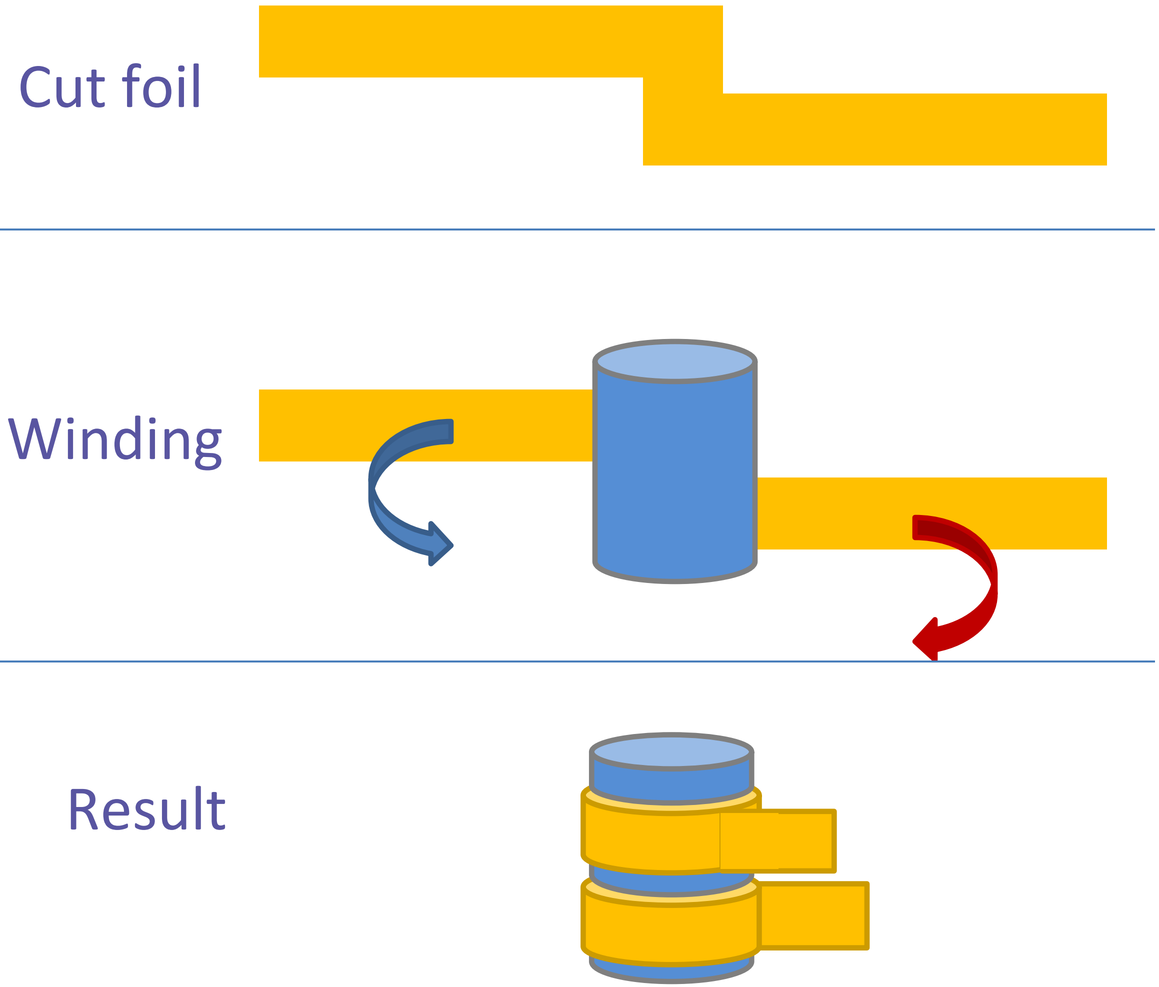


- Quasi-distributed gap, designed right, produces parallel field in winding region.
  - Sullivan et. al., “Inductor Design for Low Loss with Dual Foil,” ECCE 2013

Solutions for multilayer foil inductors: II. Terminations

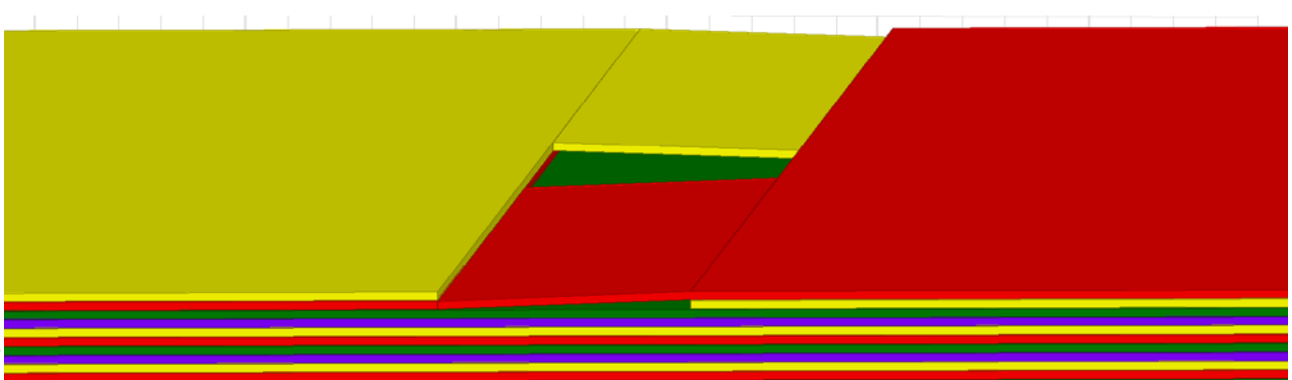
- Counter-wound Z-foil keeps terminations away from inner high-field region.

Same reference:
Sullivan et. al., "Inductor Design for Low Loss with Dual Foil," ECCE 2013



Paralleling foil layers

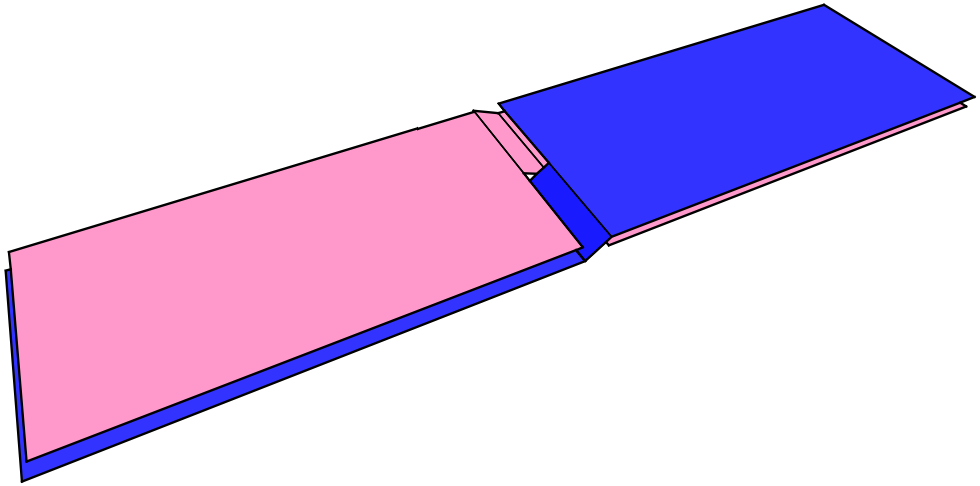
- Simple paralleling has little benefit.
  Current flows in surface layer(s).
- One solution: interchange layers to achieve equal flux linkage.
  - Option 1: use many regularly spaced interchanges (like litz); hope for flux to average out.
  - Option 2: Calculate positions of interchanges needed to equalize flux linkage; use minimum number of interchanges.
    (Pollock, Sullivan, and Lundquist, "The Design of Barrel-Wound..", APEC 2011).



Options for Making Foil Winding Interchanges

- Vias in PCB technology
  - E.g., paper 16.3 yesterday,
    Lope, Carretero, Acero, et al.
- Folding
  - E.g., Glaser and de Rooij, PESC 2006

- Interlinked slits



Options for Making Foil Winding Interchanges: **Side View**

- Vias in PCB technology
  - E.g., paper 16.3 yesterday, Lope, Carretero, Acero, et al.
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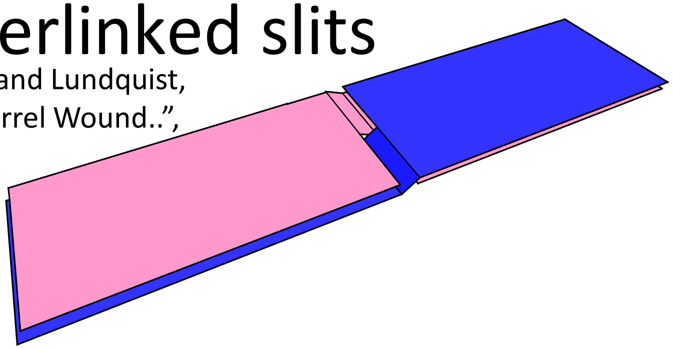
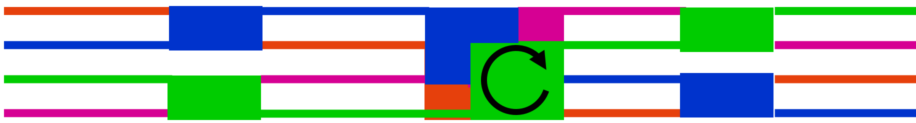
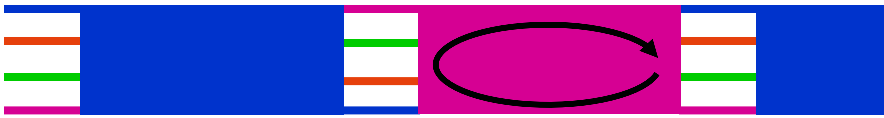


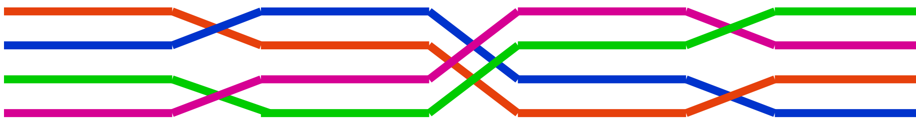
Flux into page induces eddy currents



2nd best performance



Lowest performance

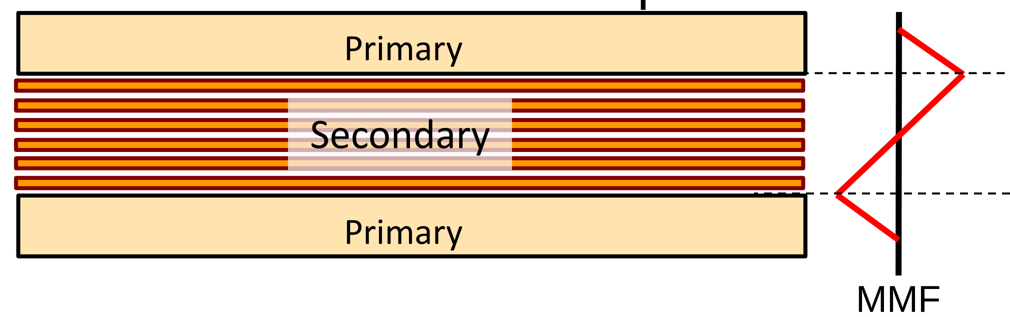


Highest performance

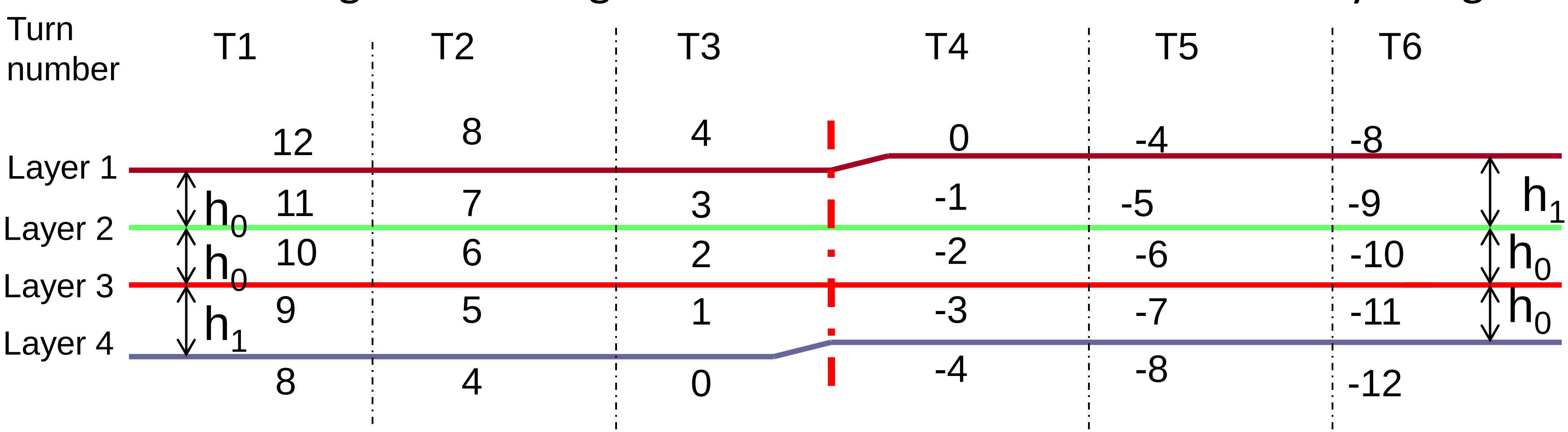
Current sharing between layers without interchanges: I. Spacing*

- With balanced MMF, it is possible to achieve balanced flux linkage just by adjusting spacing between layers.

Balanced MMF example



- "Unwound" diagram showing relative flux densities in each inter-layer region.

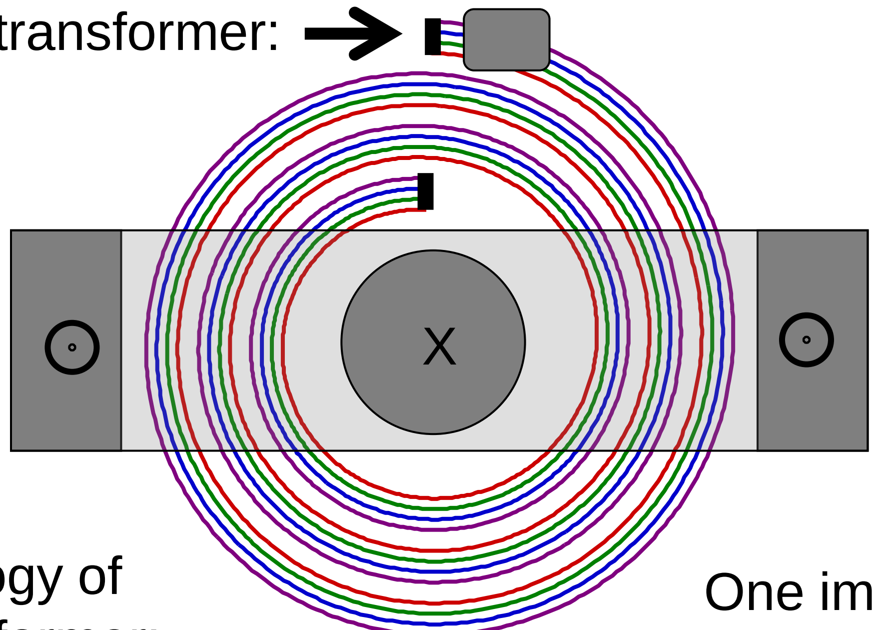


- In this case, with equal turn lengths, the net flux between any two layers is zero when $h_1 = 1.4\ h_0$

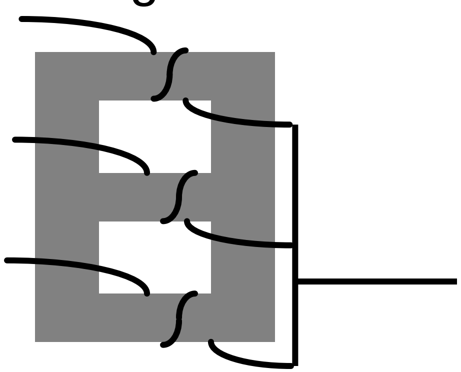
*patent pending

Current sharing without interchanges:
II. Current balancing transformer*

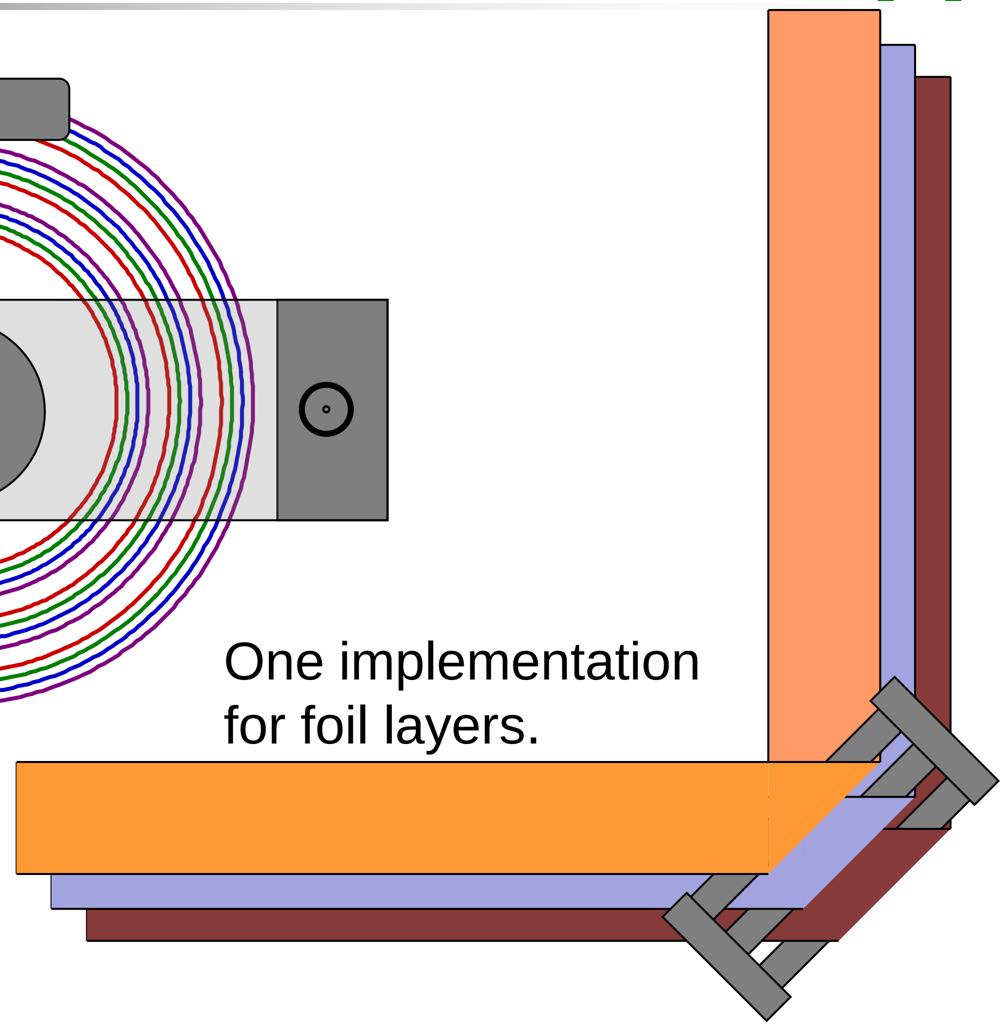
Overall concept:
add balancing transformer:



Magnetic topology of
balancing transformer:



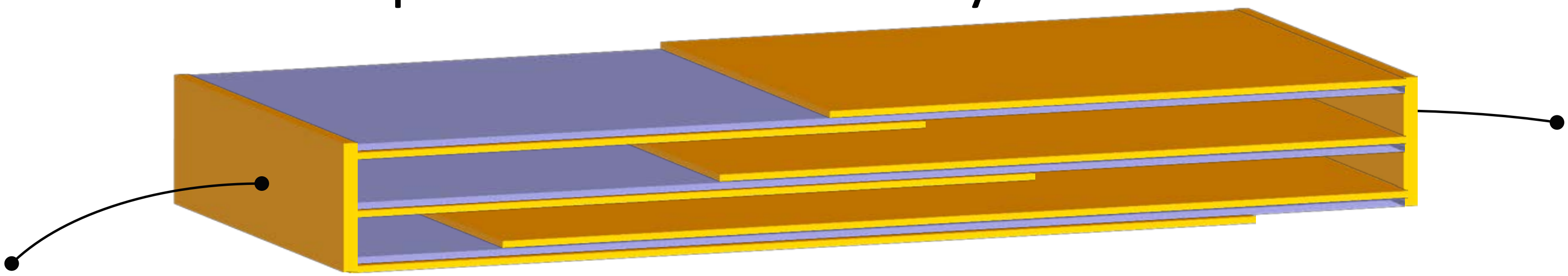
One implementation
for foil layers.



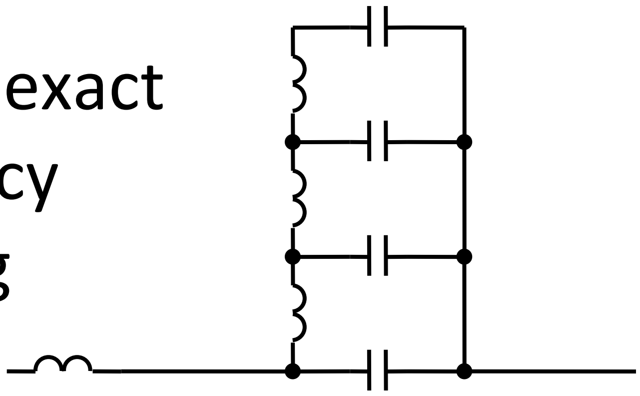
Current sharing without interchanges:

III. Capacitive ballasting*

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



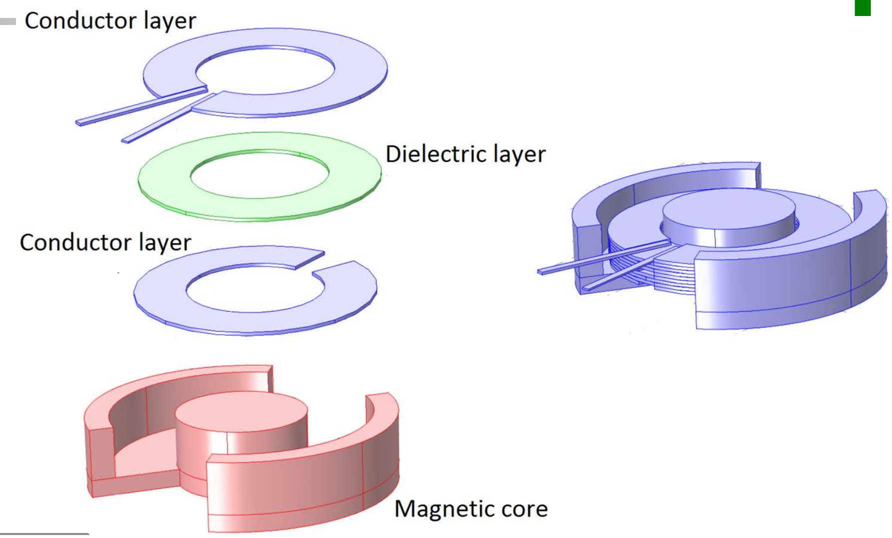
- Capacitance can be chosen for exact current sharing at one frequency or approximate current sharing over a wider range.

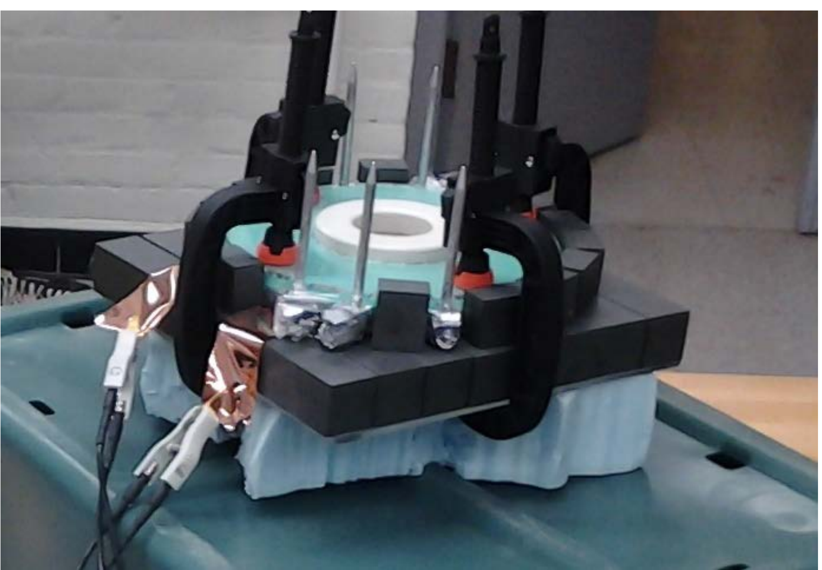


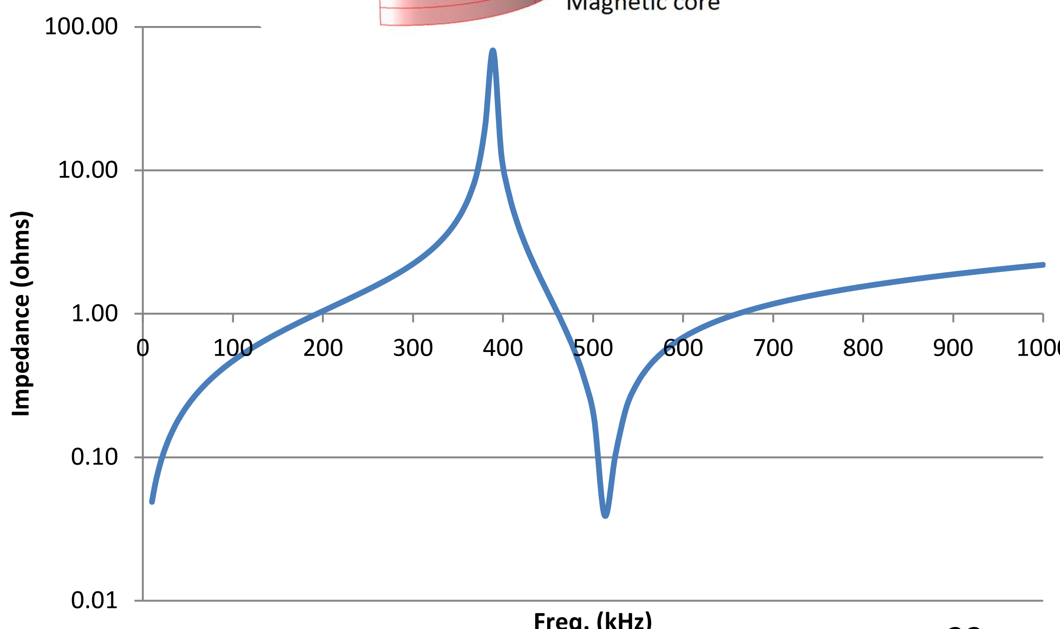
*patent pending

One application/implementation of current sharing by capacitive ballasting

- Resonant coil for wireless power or nanoparticle cancer treatment.
- Resonant capacitor = ballasting capacitors
  for hundreds of layers
  of 12 µm foil.





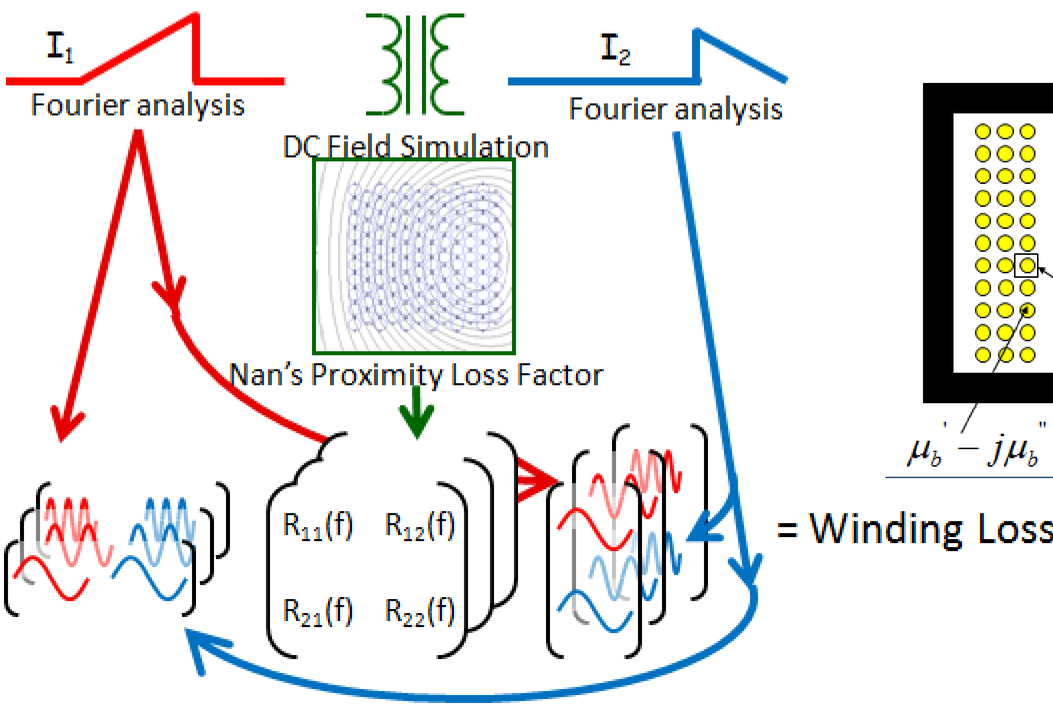


Below 3 MHz

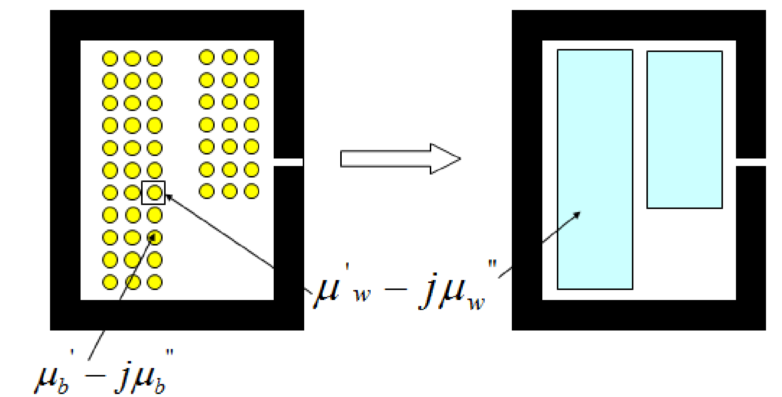
- Foil options are still attractive for low cost and high packing factor. Al foil is especially economical.
- Litz wire also viable.
  - Essential to do careful design—otherwise can have higher loss than a single-layer winding and much higher cost.
  - Simple and accurate method: Poster D10.11: Sullivan and Zhang "Simplified Design Method for Litz Wire".
  - LitzOpt online or MATLAB:
    - Updated/upgraded this year.
    - But not commercial software—no support.

Winding loss analysis: methods for wide frequency range and 2D shapes

- Hybridized Nan's method (Zimmanck, 2010)



- Homogenization with complex permeability (Nan 2009, Meeker, 2012)



Summary and Conclusions

- For lowest loss: need dimensions not just smaller than a skin depth but much smaller.
- Wire fine enough to help much at > 3 MHz is not economical, but foil down ~ 6 μm is inexpensive.
- The challenge with foil is getting current to share equally with many layers…but there are many possible ways to do this.
- There may be no "silver bullet" magnetic material…but there's a lot that can be done to make better windings.
  - Better windings -> can use more turns -> lower flux density -> lower core loss.

References and notes for simple round-wire loss formulas

The simplest formulations are valid for wire diameter smaller than about two skin depths. Good designs will use wire that small, except when the winding is optimized primarily for one frequency and you are interested in analyzing loss at a higher frequency.

1. E. C. Snelling, *Soft ferrites, properties and applications*, second ed. London U.K.: Butterworths, 1988. *Includes loss formulas equivalent the ones discussed here, and discusses optimization for round wire (not litz wire).*
2. C.R. Sullivan "Computationally Efficient Winding Loss Calculation with Multiple Windings, Arbitrary Waveforms, and Two- or Three-Dimensional Field Geometry." *IEEE Transactions on Power Electronics* 16(1), January 2001, pp. 142 -150. (link)
   The "SFD" method. Includes a derivation of the loss formula written in terms of dB/dt.
3. C.R. Sullivan. "Optimal Choice for Number of Strands in a Litz-Wire Transformer Winding." *IEEE Transactions on Power Electronics,* 14(2), March 1999, pp. 283-291. *Lots of background on litz wire and optimization not considering cost.* (link)
4. C.R. Sullivan. "Cost-Constrained Selection of Strand Size and Number in a Litz-Wire Transformer Winding." *IEEE Transactions on Power Electronics,* 16(2), March 2001, pp. 281-288. *The optimization in reference 3. leads to expensive designs. This work includes costs considerations and shows how to find Pareto-optimal designs for cost and loss.* (link)
5. C.R. Sullivan and R.Y. Zhang, "Simplified Design Method for Litz Wire." APEC 2014. Simplified application of reference 4, plus guidance on litz wire construction. More of a practical how-to article than a theory article.

References for windings with multiple frequencies

6. Spreen, J.H.; , "Electrical terminal representation of conductor loss in transformers," Power Electronics, IEEE Transactions on , vol.5, no.4, pp.424-429, Oct 1990. doi: 10.1109/63.60685.
7. Xi Nan and C. R. Sullivan, "Simplified High-Accuracy Calculation of Eddy-Current Losses in Round-Wire Windings." IEEE Power Electronics Specialists Conference, June 2004, pp. 873 - 879.
8. Christopher Schaef and C.R. Sullivan, "Inductor Design for Low Loss with Complex Waveforms," IEEE Applied Power Electronics Conference, Feb. 2012.
9. C.R. Sullivan, Hamza Bouayad and Yue Song, "Inductor Design for Low Loss with Dual Foil Windings and Quasi-Distributed Gap" ECCE 2013.
10. 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.
11. M.E. Dale and C.R. Sullivan "Comparison of Loss in Single-Layer and Multi-Layer Windings with a DC Component." IEEE Industry Applications Society Annual Meeting, Oct. 2006.

References for windings with multiple frequencies and 2D fields

12. D. R. Zimmanck and C.R. Sullivan, “Efficient Calculation of Winding Loss Resistance Matrices for Magnetic Components,” Twelfth IEEE Workshop on Control and Modeling for Power Electronics (COMPEL), June, 2010. *In some cases this is slightly less accurate than the following two, but the FEA computation is dramatically less: rather than using one FEA simulation at each frequency of interest, it uses one dc (static) simulation and can then predict losses for any frequency.*
13. Xi Nan and C. R. Sullivan "An Equivalent Complex Permeability Model for Litz-Wire Windings." *IEEE Transactions on Industry Applications*. 45(2), March-April 2009, pp. 854–860.
14. Meeker, D.C., “An improved continuum skin and proximity effect model for hexagonally packed wires,” *J. of Computational and Appl. Mathematics,* 236(18), 2012, pp. 4635–4644.
15. A.F. Hoke and C.R. Sullivan. “An Improved Two-Dimensional Numerical Modeling Method for E-Core Transformers.” IEEE Applied Power Electronics Conference, Dallas, March 2002. *Two key useful things in this are 1) a formula for fringing for more precise inductance calculation with a gap, and 2) a method for simulating an E-core structure accurately with 2-D simulations only.*
16. C. R. Sullivan, T. Abdallah, T. Fujiwara, “Optimization of a Flyback Transformer Winding Considering Two-Dimensional Field Effects, Cost and Loss”, *IEEE Applied Power Electronics Conference*, pp. 142–150, Mar. 2001. *The methods above specifically apply to flyback transformers.*

More References:

- C. R. Sullivan, "Aluminum Windings and Other Strategies for High-Frequency Magnetics Design in an Era of High Copper and Energy Costs", *IEEE Transactions on Power Electronics*, vol. 23, no. 4, pp. 2044–2051, 2008.
- Sullivan, Charles R; Beghou, Lotfi; "Design methodology for a high-Q self-resonant coil for medical and wireless-power applications," IEEE 14th Workshop on Control and Modeling for Power Electronics (COMPEL), 2013. http://dx.doi.org/10.1109/COMPEL.2013.6626460
- Jiankun Hu, C. R. Sullivan, "Optimization of Shapes for Round Wire, High Frequency Gapped Inductor Windings", *IEEE Industry Applications Society Annual Meeting*, pp. 907–911, Oct. 1998. See also http://engineering.dartmouth.edu/inductor/shapeopt.shtml
- J. D. Pollock, C. R. Sullivan, "Loss Models for Shaped Foil Windings on Low-Permeability Cores", *IEEE Power Electronics Specialists Conference*, pp. 3122–3128, June 2008.