

# Electrical Parameter Integration

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Dartmouth Magnetics  
and Power Electronics  
Research Group



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ENGINEERING  
AT DARTMOUTH

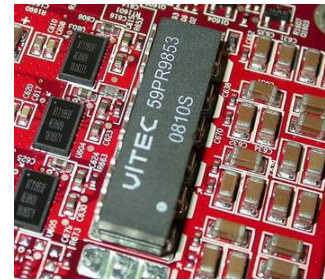
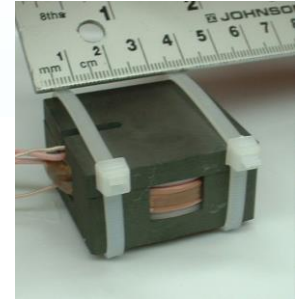
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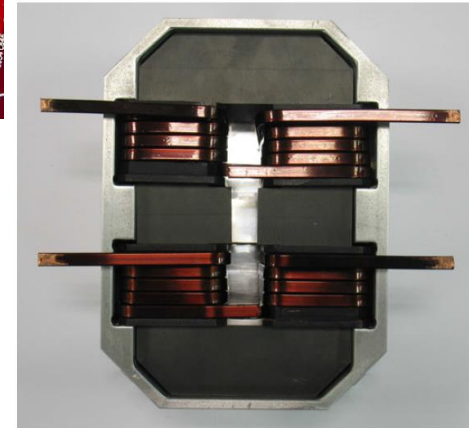
# Types of Integration



- Multiple functions from one component.
  - Transformer “parasitic” inductances used for circuit operation, reducing component count
  - Coupled inductors to enhance circuit and magnetics performance
  - Combine L and C functions
- Integration of multiple objectives and constraints in a design process.

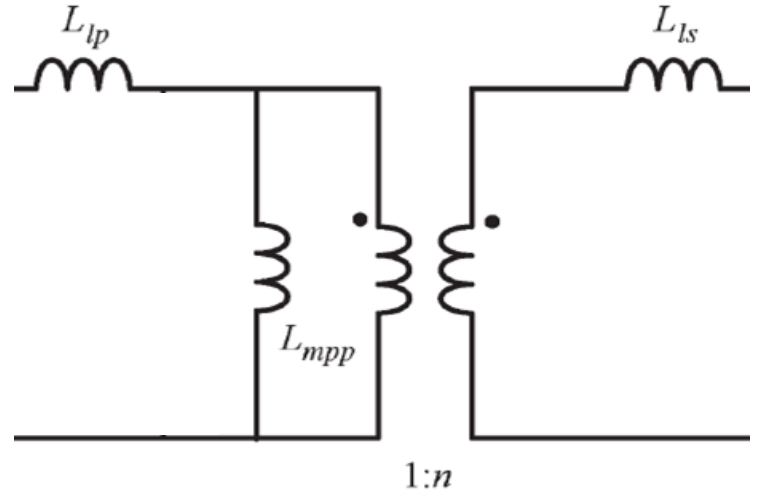


\* Nickel shown for scale



# Using transformer parasitic $L$

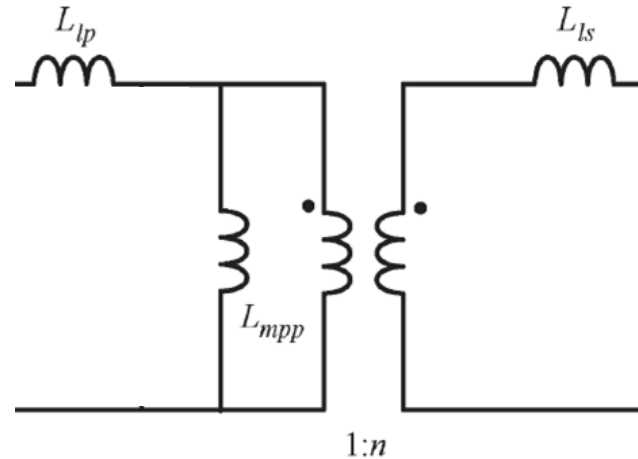
- “Parasitic” inductances:
  - Leakage
  - Magnetizing
- If you need inductor(s) and a transformer, it’s usually an option.
  - Leakage: for resonant converters.
  - Magnetizing: for flyback or resonant converters.
- Both can be adjusted in design.



# Matrix vs. T-model

- Both capture full behavior (Assuming linear, lossless, and no capacitance)
- Matrix: 3 degree of freedom vs. Transformer: 4 degrees of freedom.
  - Can choose one parameter arbitrarily.
  - Common choice:  $n$  = the physical turns ratio.

$$\begin{bmatrix} v_p \\ v_s \end{bmatrix} = \begin{bmatrix} L_p & M \\ M & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_p \\ i_s \end{bmatrix}$$





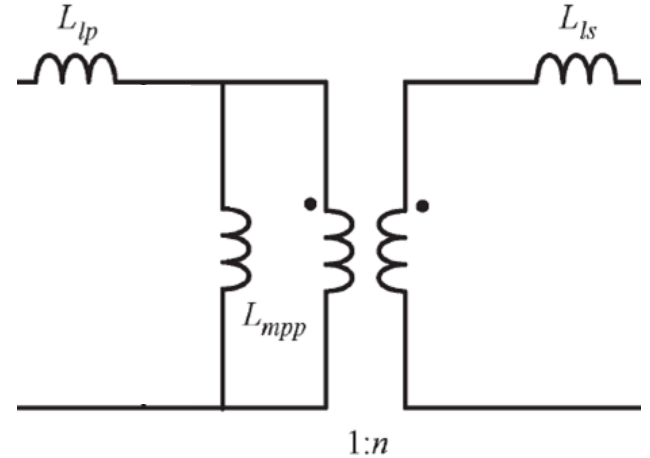
# Coupling factor $k$

$$\begin{bmatrix} v_p \\ v_s \end{bmatrix} = \begin{bmatrix} L_p & M \\ M & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_p \\ i_s \end{bmatrix}$$

- Good simplification? **No.**
- Definition: ratio of mutual to self inductance. Specifically,  
the geometric mean:  $k = M / \sqrt{L_p L_s}$
- Problems with  $k$ :

Spec calls for high  $k$ , a transformer with “high coupling”:

- Might mean low leakage is needed
- Or, might mean high magnetizing inductance is needed.
- If you improve the wrong one, you can get high  $k$  without meeting the real spec.

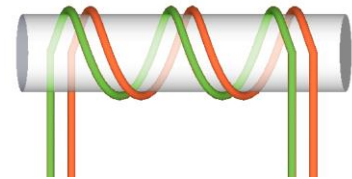




# Spec what you want: high or low $L_m$ ; ~~Improve $k$ ?~~ high or low $L_\ell$ .



- “A high-permeability core improves coupling factor”.
  - It increases magnetizing inductance, but does not reduce leakage.
- “A bifilar winding improves coupling factor”.
  - It increases magnetizing inductance, but does not reduce leakage.
- If you ask for high  $k$  (or low  $k$ ), you might not get what you really need.





# An exception: when $k$ is useful.

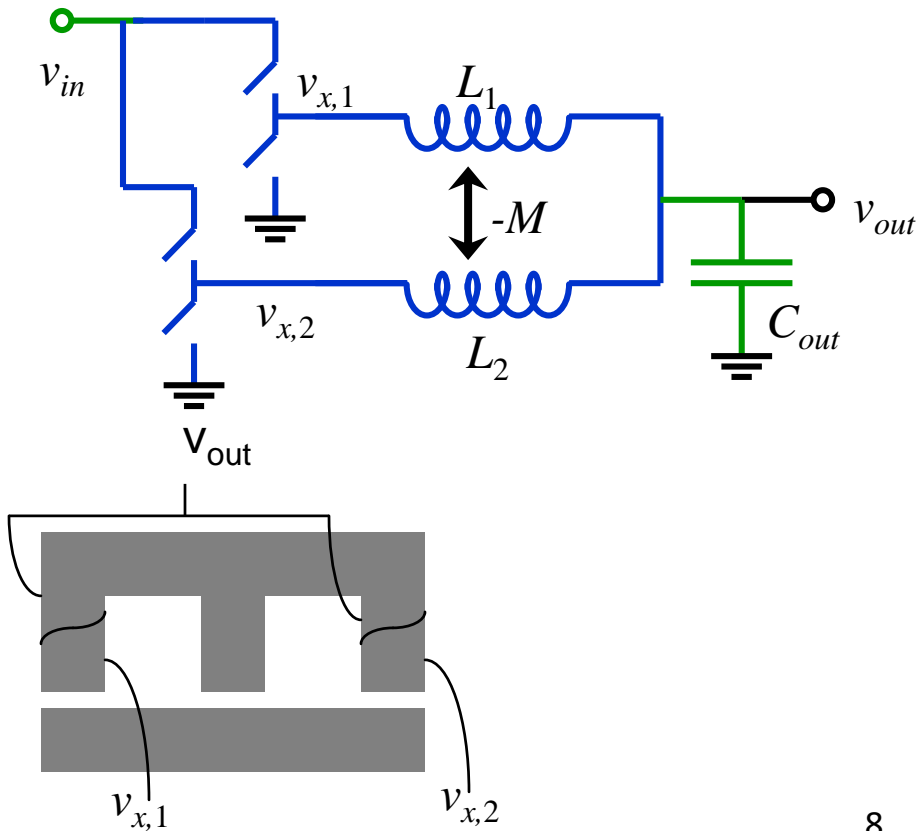
## Air-core transformers and wireless power systems:

- Without saturation or (much) core loss,  $N$  (number of turns) can be chosen without considering  $B$ . Changing  $N$  just scales all impedances.
- If  $k$  is good (what that means depends on the application), adjusting  $N$  allows setting both  $L_\ell$  and  $L_m$  values to meet the spec.
- **Design process:**
  - Vary geometry to get  $k$  you want.
  - Vary  $N$  to get the right  $L_\ell$  and  $L_m$  values.

# Example where $k$ is misleading

Coupled inductor multi-phase buck.

- Early insight: coupling can help.
- Naïve design approach:  
Find optimal value of  $k$  ...  
but arbitrarily holding  $L_{\text{self}}$  constant.

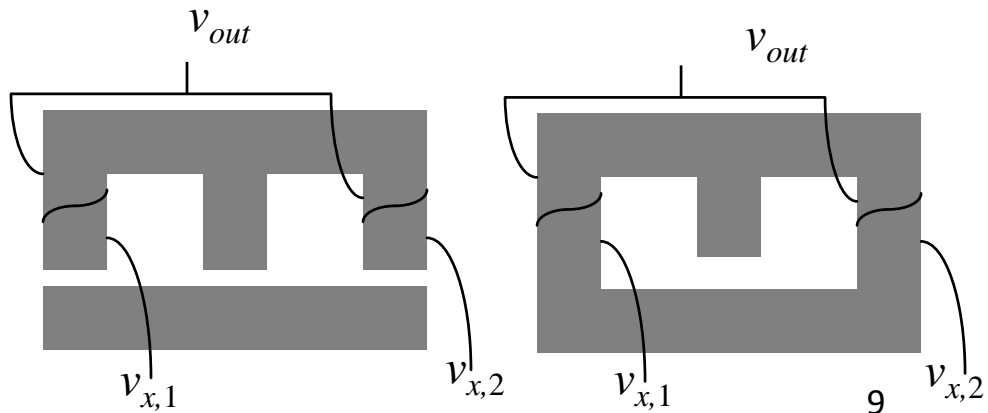
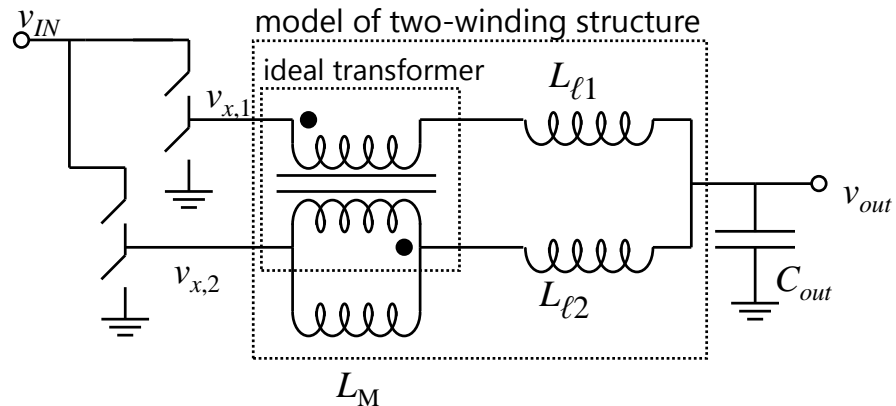




# Example where $k$ is misleading

Coupled inductor multi-phase buck.

- Early insight: coupling can help.
- Naïve design approach:  
Find optimal value of  $k$  ...  
but arbitrarily holding  $L_{\text{self}}$  constant.
  - Low  $k$  means no benefit, but high  $k$  would mean low leakage and excessive ripple: chose moderate  $k$ .
- **Better approach:**  
Consider  $L_M$  and  $L_{\text{leak}}$  independently.
  - Maximize  $L_M$ : ungapped structure.
  - Choose  $L_{\text{leak}}$  based on ripple, transient, and size trade-offs—all mitigated by coupling.





# Separately design for $L_m$ and $L_\ell$

- $L_m$  is easy: add a gap or adjust the gap to hit the target value.
  - Tradeoffs between core loss, winding loss, and saturation effected via gap and number of turns, as in standard inductor design.
- $L_\ell$  design can be more challenging...



# Design for $L_\ell$

- For low  $L_\ell$ 
  - Interleaving (respect symmetry) and/or large winding breadth  $b$ .  
**Limitation: capacitance.**
  - Fewer turns: need larger core area to limit flux density for saturation and core loss.
- For higher  $L_\ell$ 
  - Winding configuration
  - Add a shunt
  - Use more turns--reduced core loss mitigates increased winding loss.

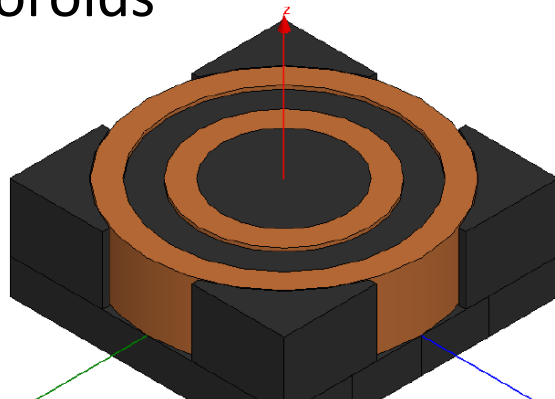
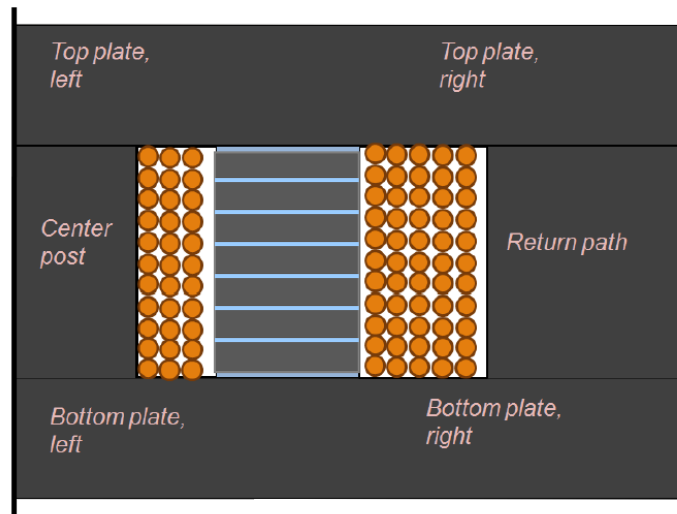
Performance improvement

**Functional integration**



# Shunt to add leakage

- Adjust gaps to get any  $L_\ell$  value.
- Fringing flux increases winding loss: in this design mitigated by carefully chosen litz wire.
- Or, stack multiple thin shunt toroids to get “quasi distributed gap”.
- Consider cooling for floating shunt.

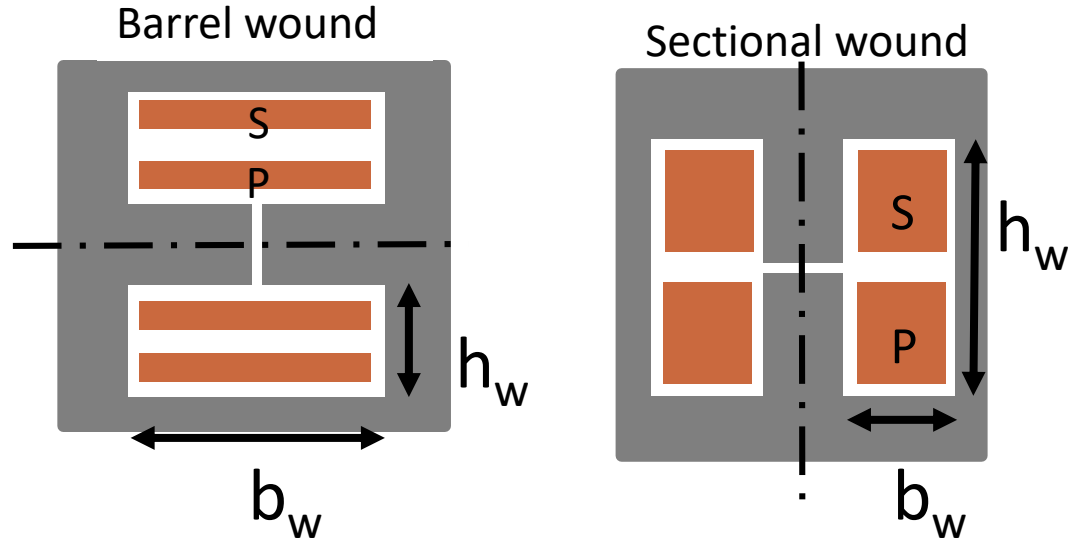


# Winding orientation effect

- Sectional wound gives much higher leakage.
- Can tune winding build and spacing to set leakage.

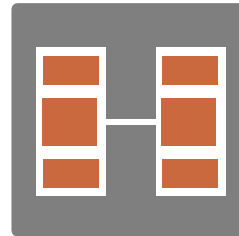
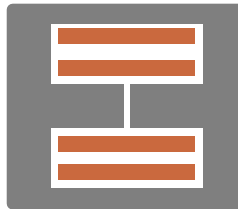
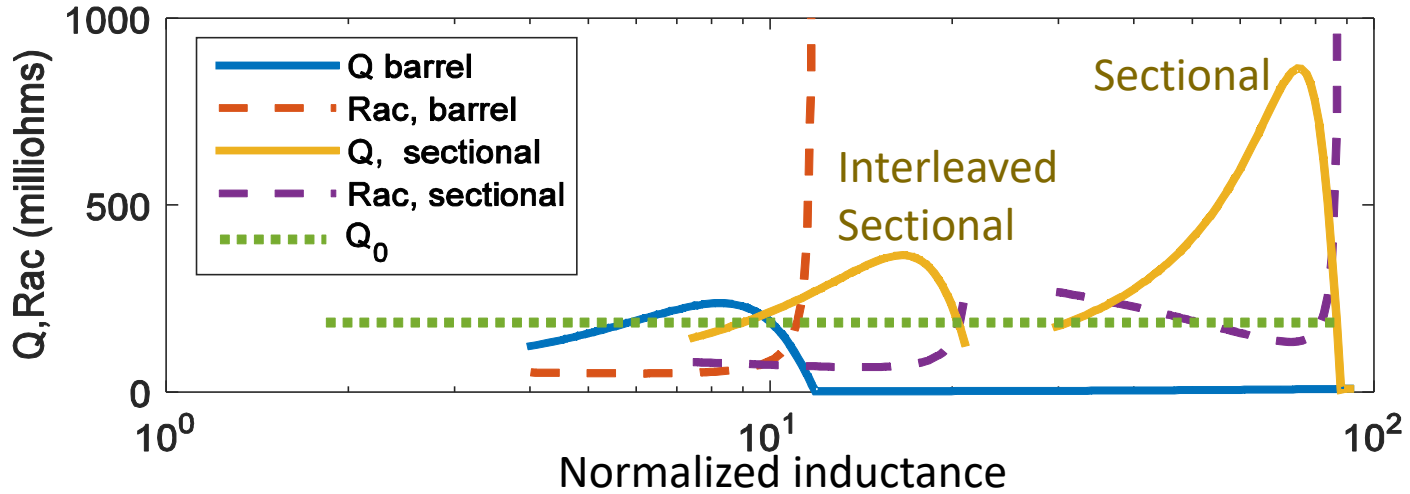
$$L_{leak,p} = \frac{k_L}{b_w} \left( h_w - \left( \frac{2}{3} \right) h_{ps} \right)$$

$$k_L = \mu_0 N_p^2 \ell_{turn} \quad h_{ps} = h_p + h_s$$



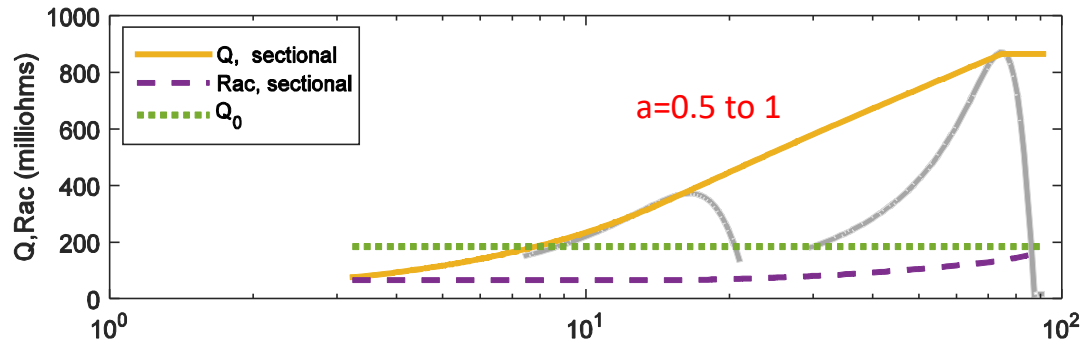
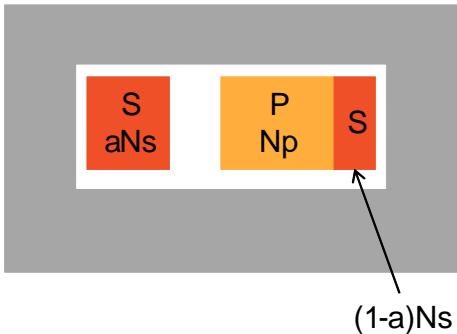
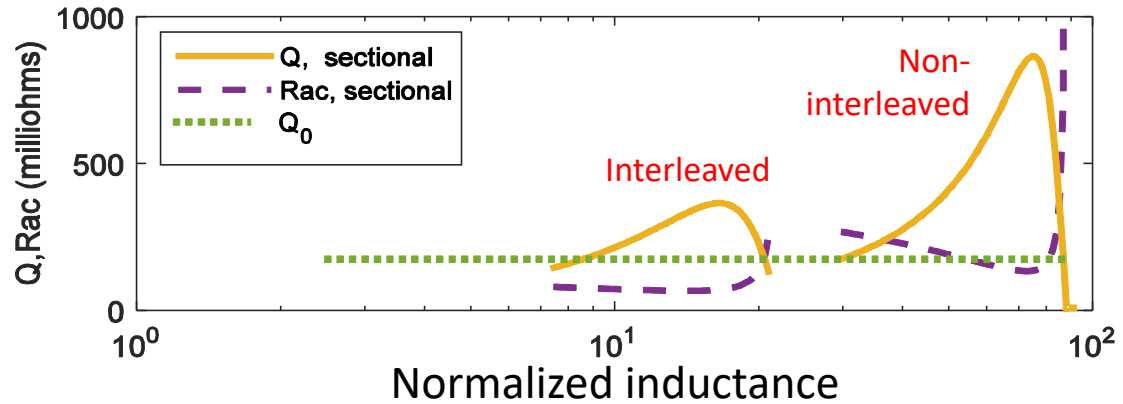


# Design options





# What if the spec is between these peaks?





# Comments on integrating inductive functions

- Design for the  $L_m$  and  $L_\ell$  you want, separately, rather than looking at  $k$ .
- $L_m$  is easily adjusted with a gap.
- $L_\ell$  can be reduced with interleaving, limited only by capacitance, and with larger  $A_c$  to allow small  $N$ .
- $L_\ell$  can be increased with a shunt or with a “sectional” winding arrangement.
  - Partial interleaving can adjust leakage without hurting  $R_{ac}$ .



# Integration of capacitance

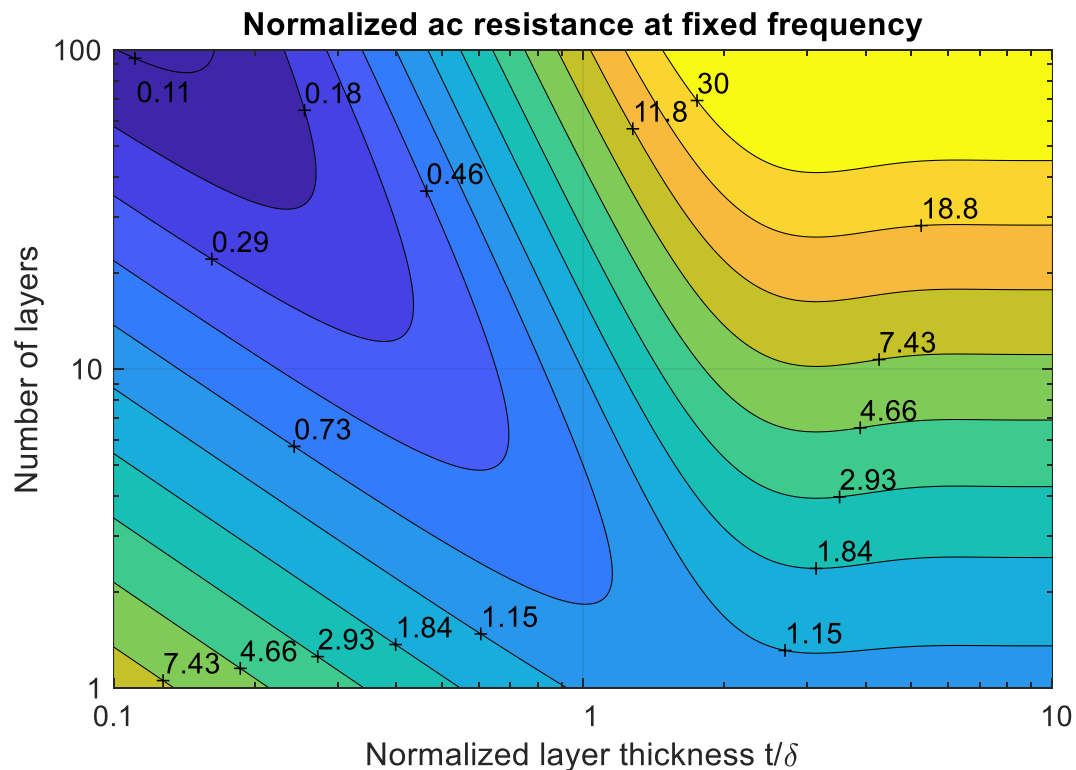
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- Proliferation of types of resonant converters.
- Need C and well as L.
- Magnetic components have dielectrics in them anyway—can we use these to form the capacitor(s) for a resonant converter?
  - Yes, we can: has been demonstrated back in the 1990s by Ferreira, Van Wyk, and others.
  - But is it useful to do so?
    - Capacitors are cheap and have low loss anyway.
  - What if combining L and C could improve *magnetics* performance?



# For excellent low ac resistance we need conductor dimensions $\ll$ skin depth $\delta$

- Litz wire is great, but
  - It's expensive
  - For excellent MHz performance we want dimensions smaller than the  $\sim 40 \mu\text{m}$  of fine litz strands.
  - We want  $< 20 \mu\text{m}$ , or even  $< 5 \mu\text{m}$





# Foil: $< 20 \mu\text{m}$ at low cost



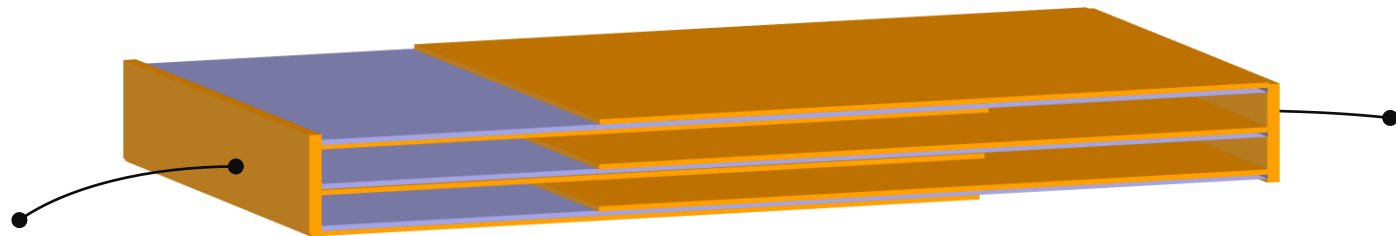
- Easy to get thickness  $\ll$  skin depth.
  - Freestanding foil down to  $\sim 6 \mu\text{m}$ .
  - On plastic-film substrates for easier handling down to  $\ll 1 \mu\text{m}$ .
- Thin layers have high dc resistance—  
need many in parallel.
- Challenges:
  - Achieving uniform current density—laterally and among layers.
  - High capacitance between layers.
  - Terminations





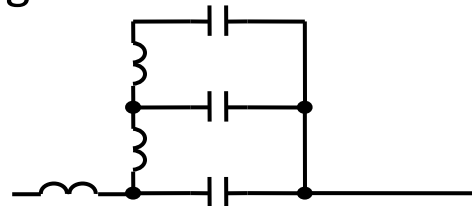
# One concept for MHz foil windings: capacitive ballasting

- Overlapping insulated layers create series capacitance for each layer.



Cartoon—not actual design

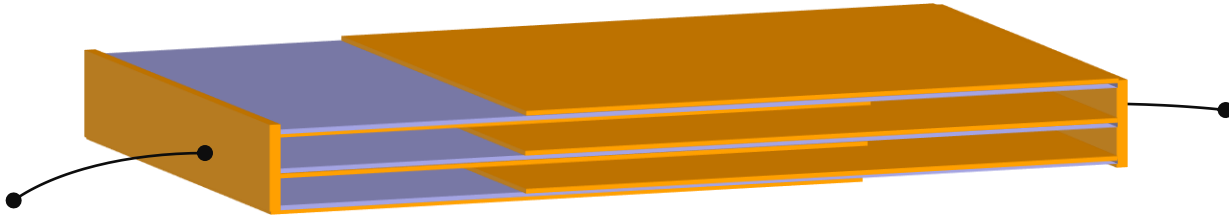
- Capacitive ballasting forces equal current sharing.
- Goal in previous integrated LC structures: combine functions in single volume.
- Our goal: Not just integration, but creating a new type of ultra-low-loss winding.
- Best application fit: resonator (LC tank).





# Can we make an inductor coil out of this?

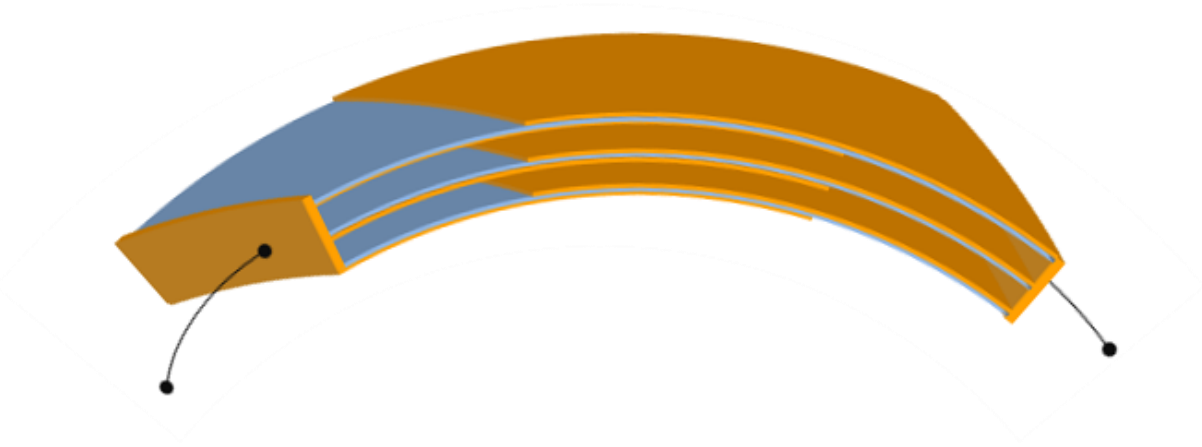
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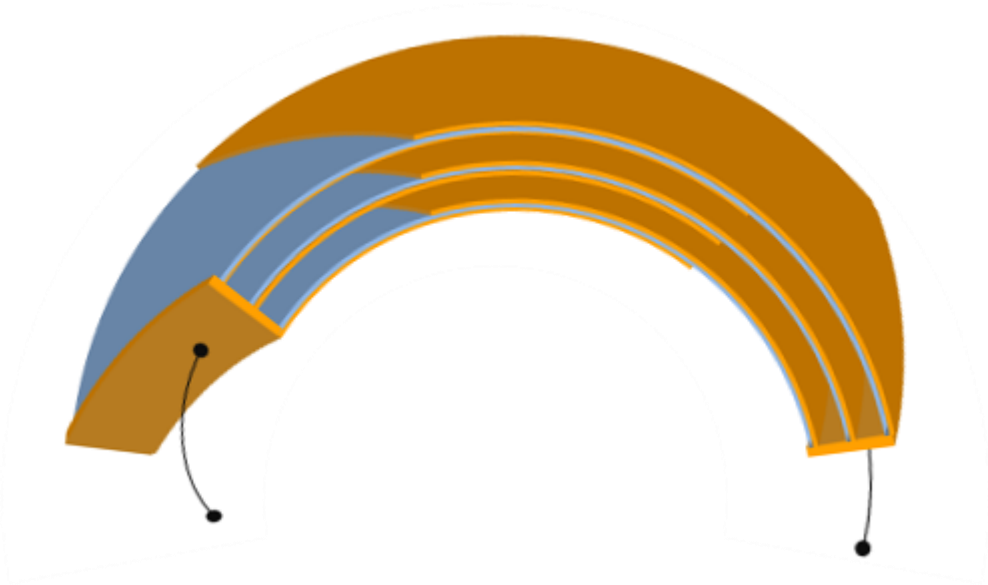
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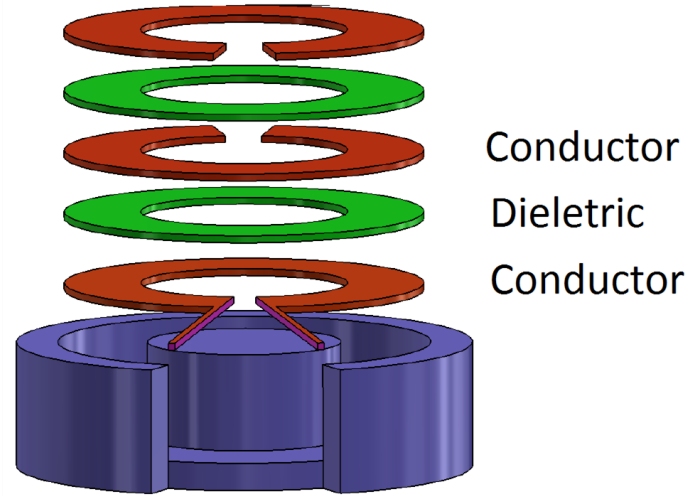
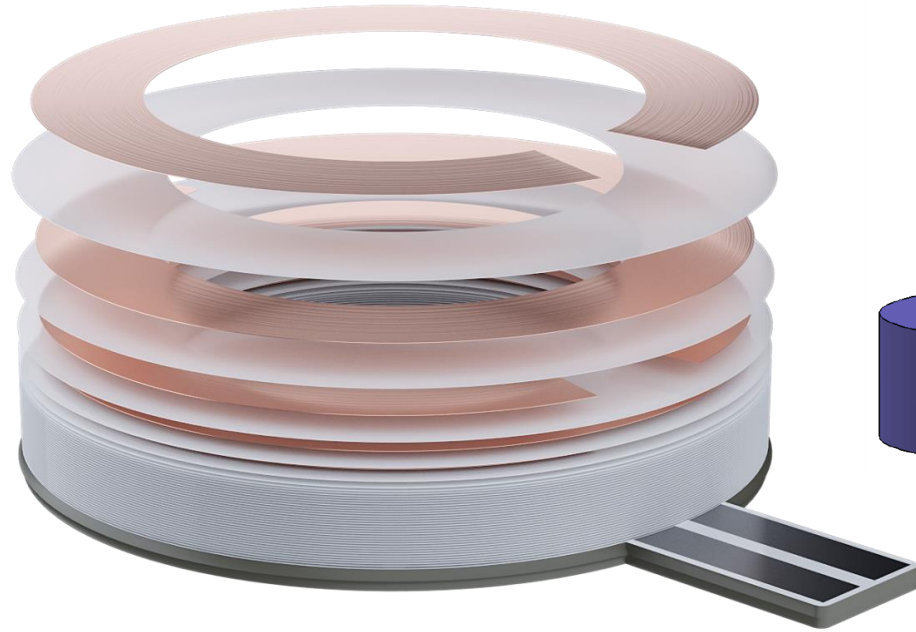
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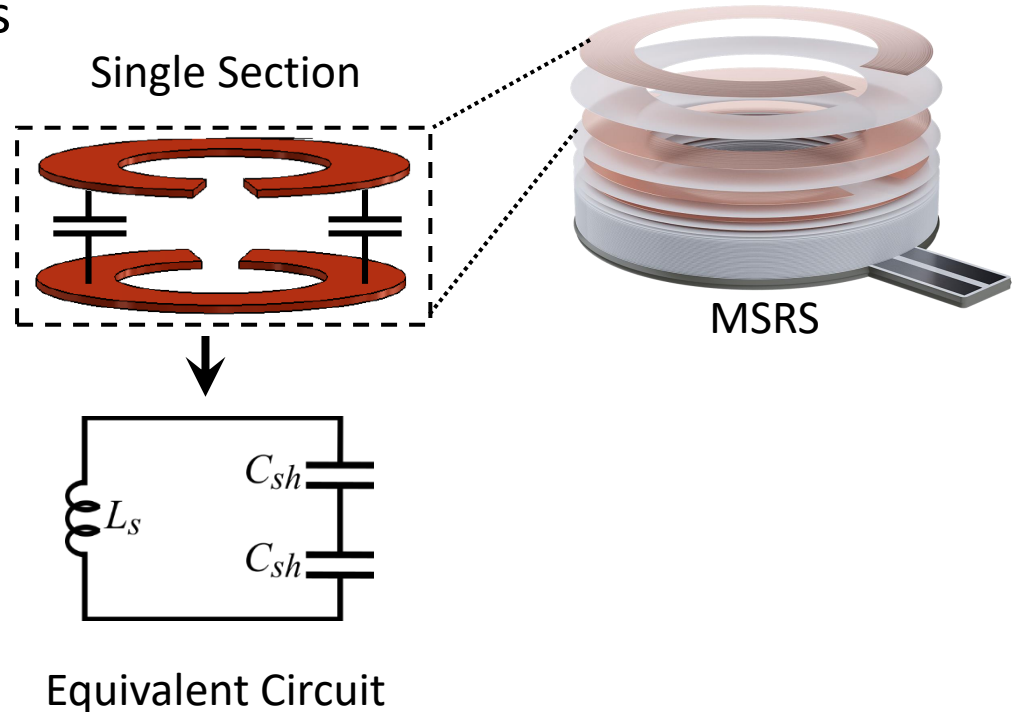
# Capacitively ballasted multilayer self-resonant structure (MSRS)





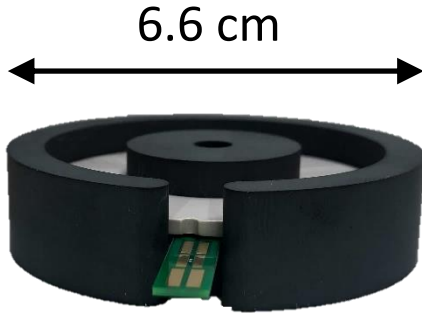
# Multilayer self-resonant structure (MSRS) functionality

- Stack of LCC resonator loops
- All magnetically coupled.
- Solves coil challenges and achieves very high Q
  - Thin foils minimize skin & proximity effects
  - No additional losses in capacitor plates.
  - No vias or high-current or voltage terminations.



\*9 patents pending or granted

# Example implementation



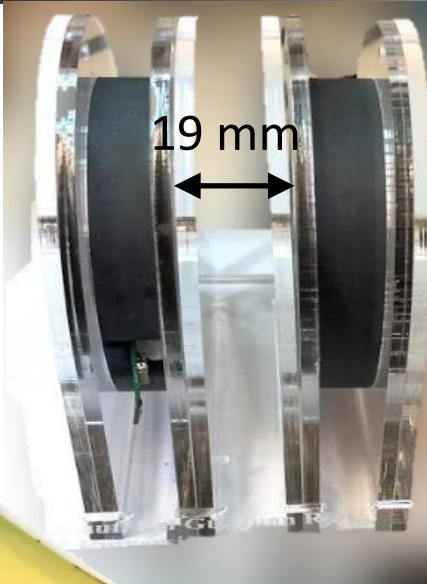
- $Q = 1699$
- Figure of merit
$$Q_d = \frac{Q}{d} = 257 \text{ cm}^{-1}$$
- 6X highest  $Q_d$  in the literature.

# Example implementation



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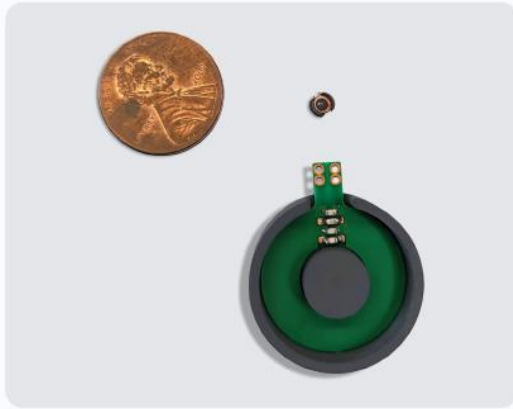


- $Q = 1699$
- 6X highest  $Q_d$  in the literature:  
$$Q_d = \frac{Q}{d} = 257 \text{ cm}^{-1}$$
- **1 kW at 19 mm,  
95% dc-dc efficiency**

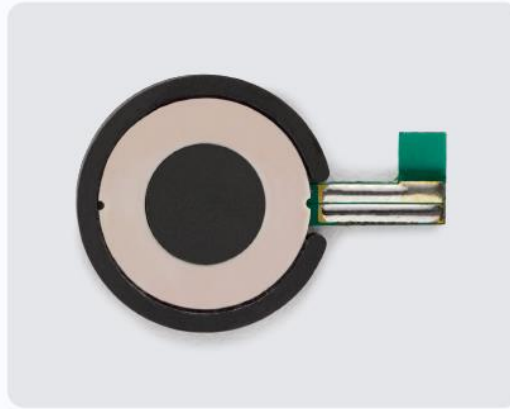


# Practical implementations

Scales for different applications developed by Resonant Link, Inc.



3 mm  $\varnothing$



20 mm  $\varnothing$   
 $Q_{\text{tank}} = 675 @$   
13.56 MHz



57 cm  $\varnothing$   
 $Q_{\text{tank}} = 2096 @$   
83.8 kHz



**Application:** Oral diagnostics

**Output power:** 20 mW

**Implant size:** 3 mm diameter

**Feature:** 5% tuning tolerance

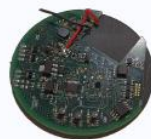


**Application:** Brain-computer interface

**Output power:** 500 mW (750 mW pk)

**Implant size:** 60 mm diameter

**Feature:** 10 kbps bi-directional comm.



**Application:** Cardiovascular therapy

**Output power:** 10 W (30 W peak)

**Implant size:** 60-80 mm diameter

**Feature:** 5 cm misalignment tolerance



$10^{-2}$

$10^{-1}$

1

10

Maximum Power Delivered (W)

- Low temperature rise and low tissue heating enables applications that couldn't be done before.



# Higher power application

- 19.2 kW, 400 A output
- Air gap up to 10"
- Misalignment +/- 6"

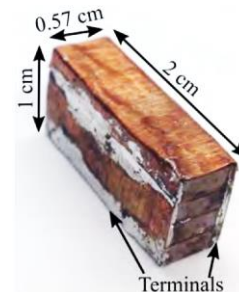




# Self resonant components as power-conversion passives

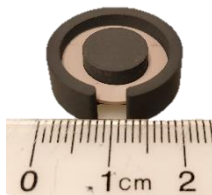
High-density resonant structure,  $\sim 1.2 \text{ cm}^3$

- 0.5 m $\Omega$  ESR in a 250 V dc rated component.
- Without considering any limitations of today's power switches, over 10 kW would be possible at over 99% efficiency.

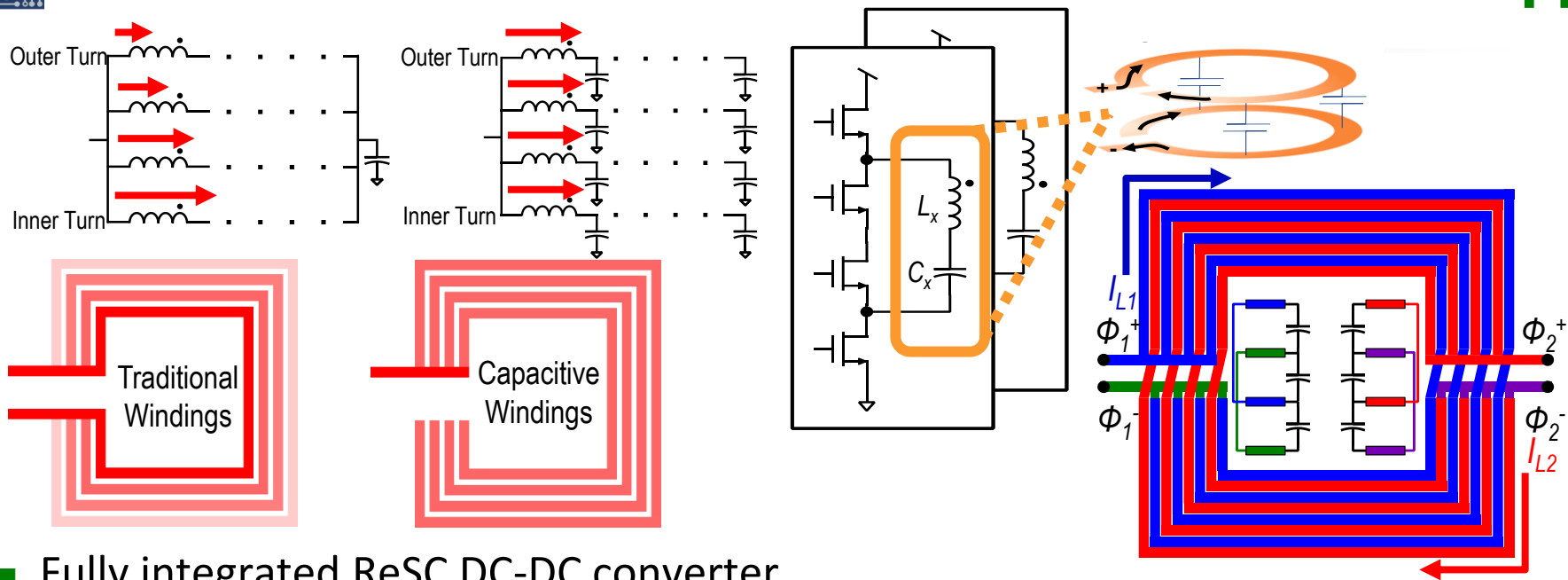


High-Q MLCC-winding components

- Developed for wireless power transfer,  $Q = 675 \sim 1699$
- More flexibility to match circuit applications.

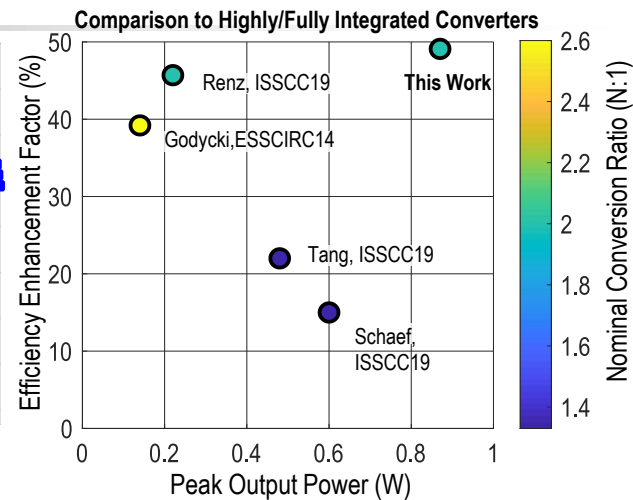
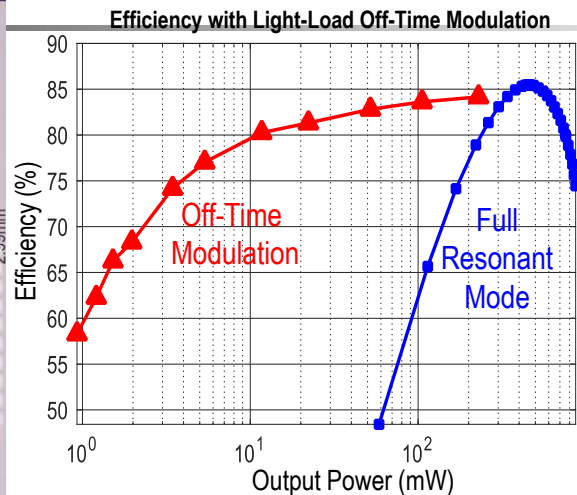
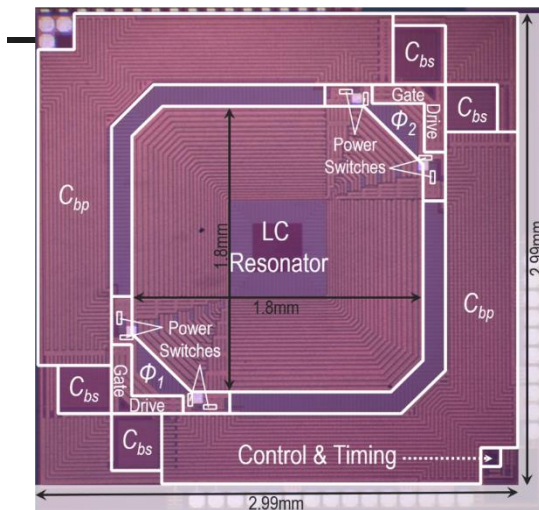


# Merged with circuit and fully integrated on die



- Fully integrated ReSC DC-DC converter
- Merged multiphase LC resonator on-chip
- Capacitive ballasting  $\rightarrow$  uniform current  $\rightarrow$  decreases ESR

# Merged and fully integrated—results



- 49.1% efficiency enhancement over LDO
- 2.4–4.4 V in, 1–2.2 V out, 870 mW, 48 MHz
- 85.5% peak efficiency
- 97 mW/mm<sup>2</sup> (chip area); 267 mW/mm<sup>2</sup> (resonator area)

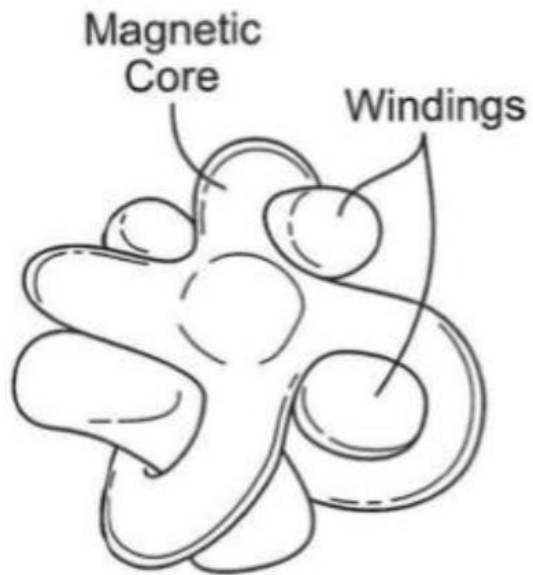


# Electrical Parameter Integration

- Design for the  $L_m$  and  $L_\ell$  you want, separately, rather than looking at  $k$ .
- Integrating functions can be nice, but look for bigger benefits to make it worthwhile:
  - Coupled inductors that circumvent the transient response/ripple tradeoff while reducing size, loss and energy storage.
  - LC structures that use C not only to resonate, but also to ballast current, sharing it between parallel paths, without the twisting used in litz wire.

# Shape optimization

Free shape concept

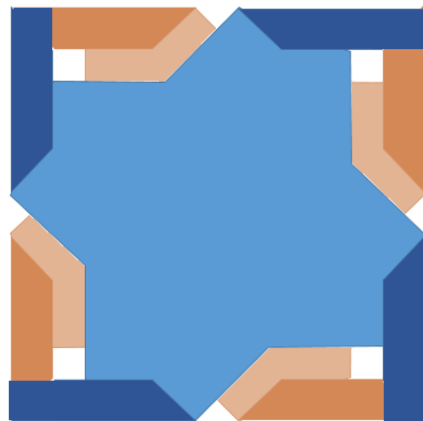


Add-constraints:

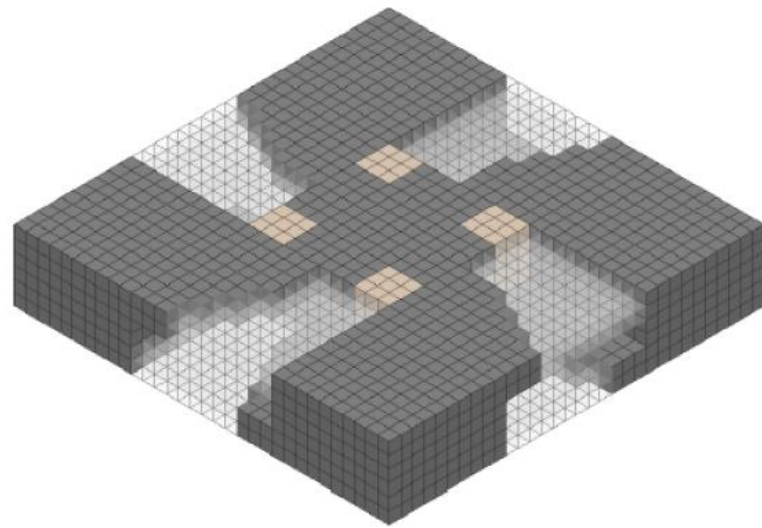
- Drop-in wire for winding
- Two-piece core



Optimized design



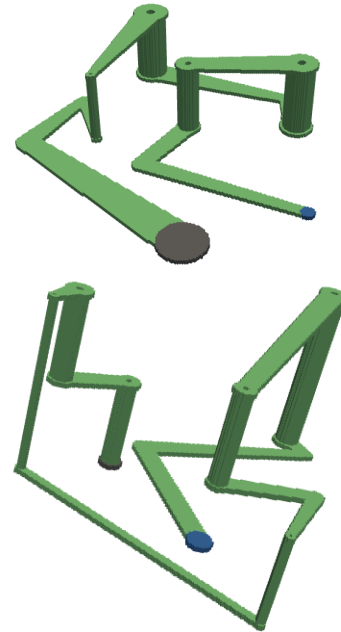
Calculated design



# Free shape optimization?

- Optimize air-core inductor on PCB
- OK, we do need constraints:
  - Any 2D shape on each layer + vias.
  - But must be valid—ended up needing 14 rules.
- Also need a fast field solver: FFT Accelerated PEEC method: open source code available.
- Details: presentation by Dr. Thomas Guillod, 11:30 on Th, T36.5 room A312

Valid Geom.



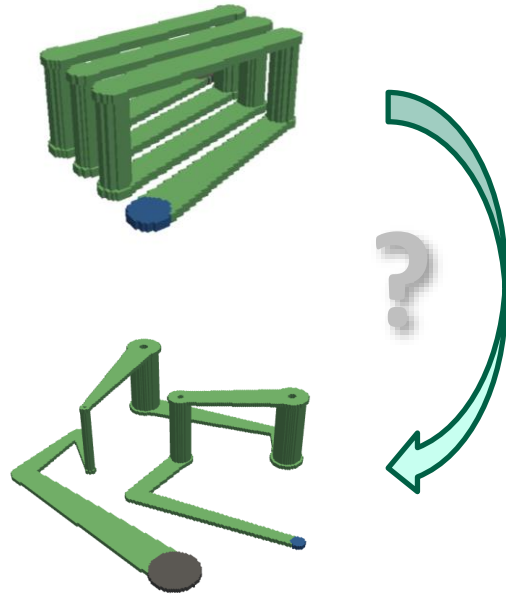
Invalid Geom.



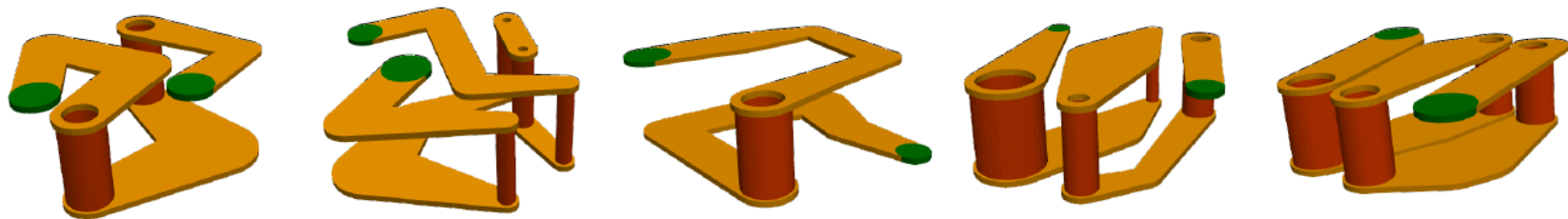
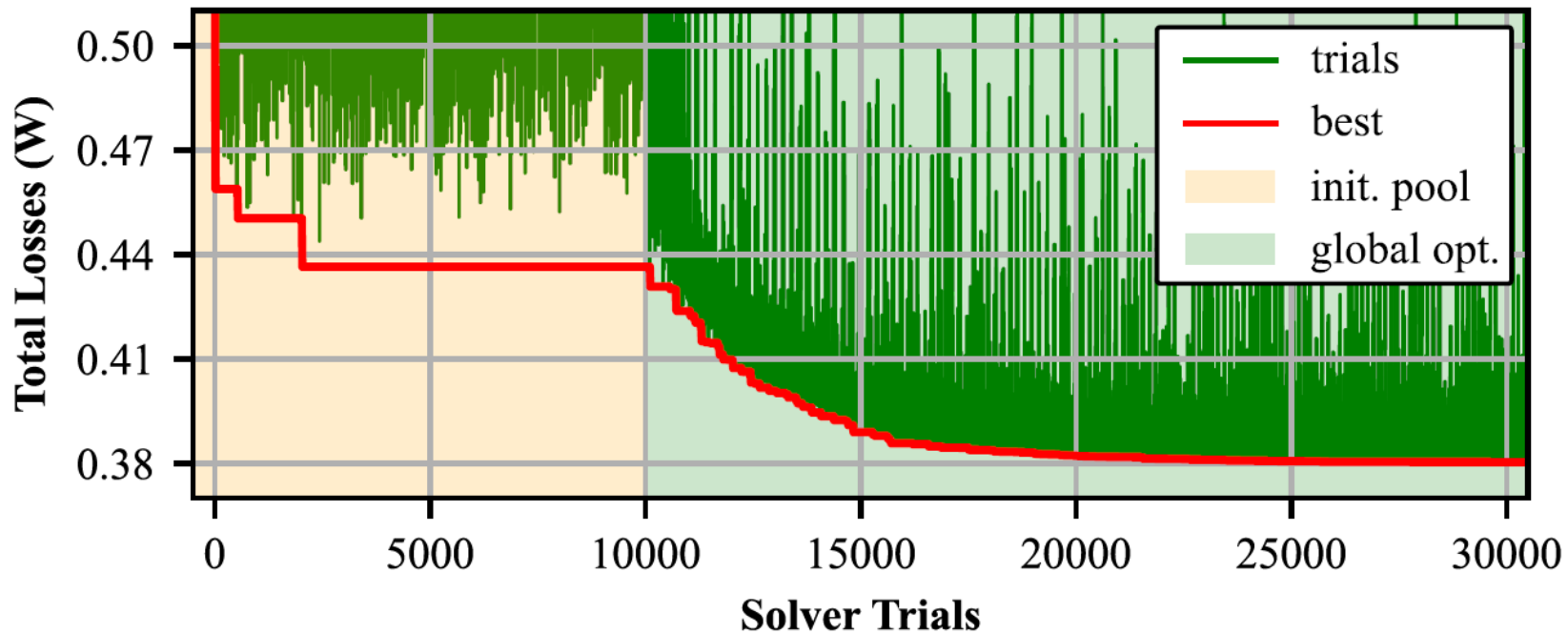


# Will it invent something new?

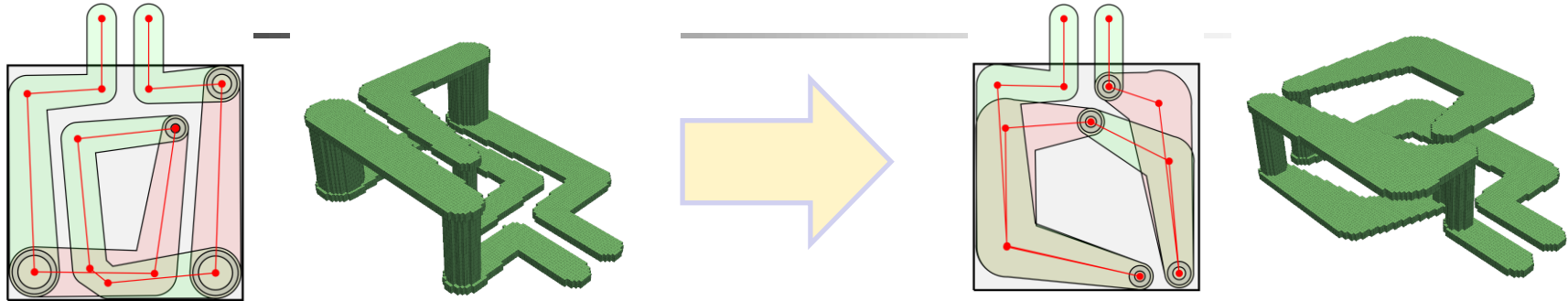
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# Optimizer Convergence



# Add constraints: terminal location and external field limit



	Without Near-Field Opt.		With Near-Field Opt.
Total Efficiency	80.8%	- 2%	78.9%
Inductor Efficiency	89.7%		88.1%
DC Near-Field	1247 A/m	0.45x	441 A/m
AC Near-Field	660 A/m		300 A/m

- **Shape optimization is very powerful for addressing constraints**



# Conclusions

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- Electrical Parameter Integration
  - Design for  $L_m$  and  $L_\ell$
  - Look for benefits beyond parts count
- Shape optimization
  - New capabilities emerging.
  - Presentation by Dr. Thomas Guillod,  
11:30 on Th, T36.5 room A312