Electrical Parameter Integration

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PMIC *Power Management Integration Center*

Dartmouth Magnetics and Power Electronics Research Group

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

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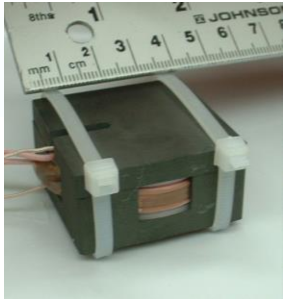
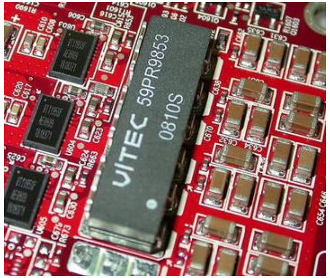
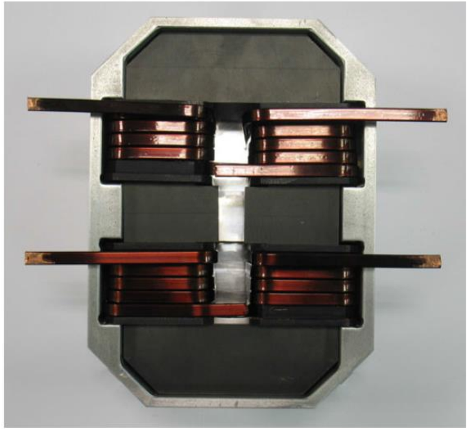
Types of Integration

- 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.

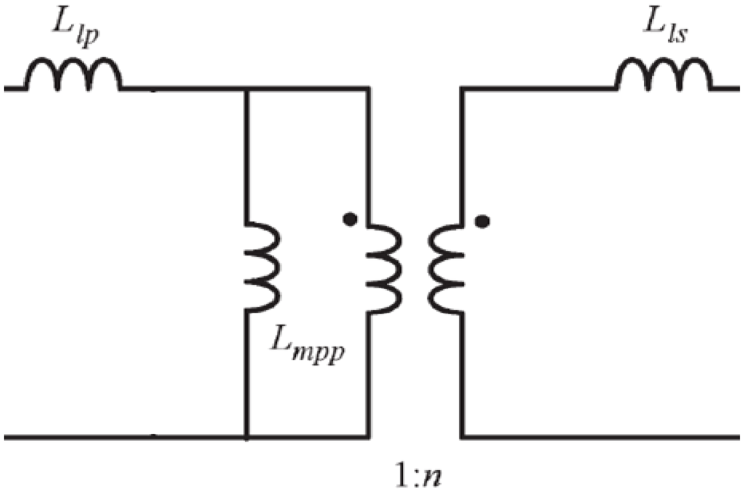






Using transformer parasitic L

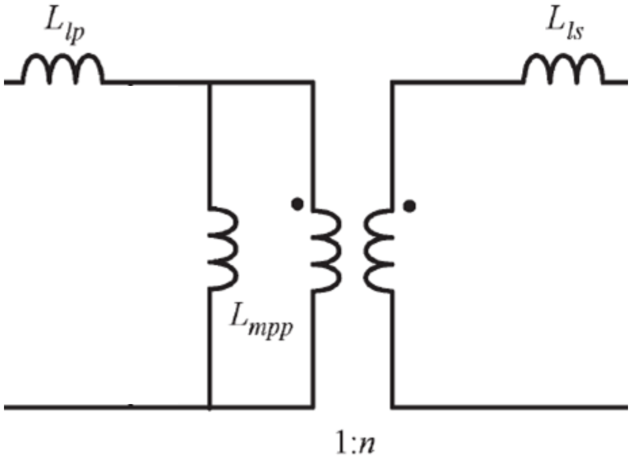
- "Parasitic" inductances:
  - Leakage
  - Magnetizing
- If you need inductor(s) and a transformer, it's usually an option.
  - Leakage: for resonant converters.
  - Magnetizing: for flyback or resonant converters.
- Both can be adjusted in design.



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.

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

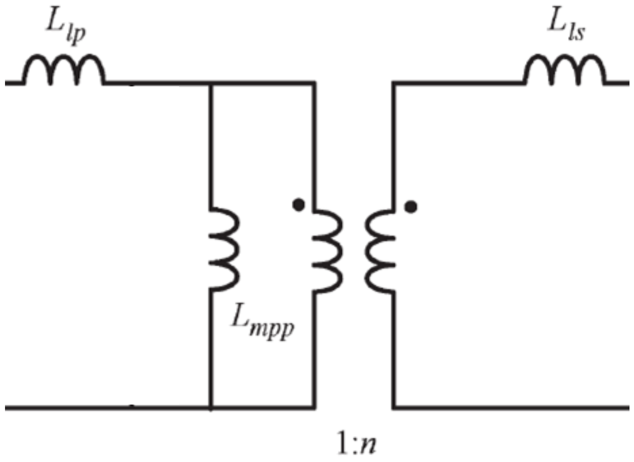


Reference: Guillod, T., Krismer, F. & Kolar, J.W. "Magnetic Equivalent Circuit of MF Transformers: Modeling and Parameters Uncertainties," Electr Eng (2018) 100: 2261. https://doi.org/10.1007/s00202-018-0701-0

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 :



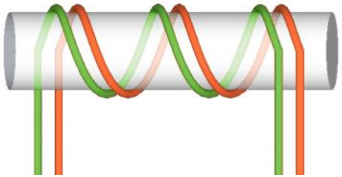
Spec calls for high k, a transformer with "high coupling":

- 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 ; high or low L_ℓ .

~~Improve *k*?~~

- "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.

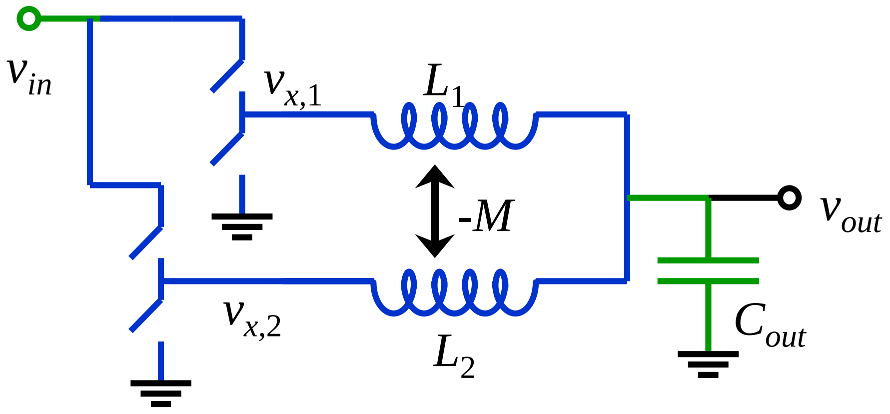
Air-core transformers and wireless power systems:

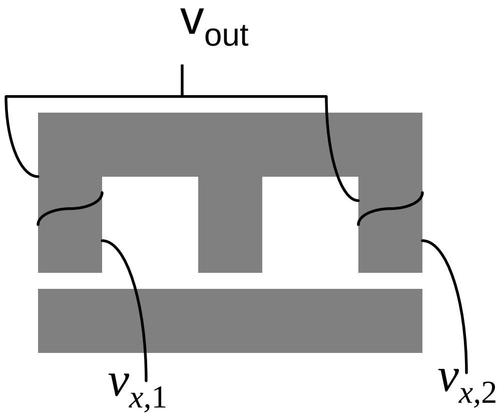
- Without saturation or (much) core loss, N (number of turns) can be chosen without considering B. Changing N just scales all impedances.
- If k is good (what that means depends on the application), adjusting N allows setting both L_ℓ and L_m values to meet the spec.
- **Design process:**
  - Vary geometry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

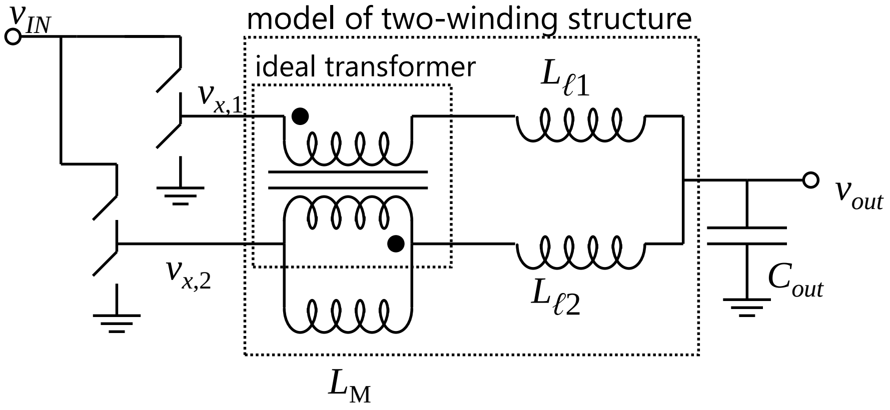


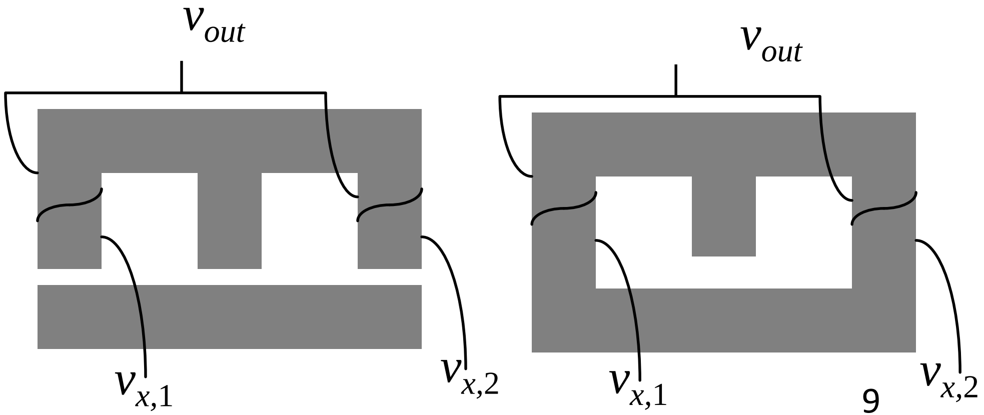


Example where k is misleading

Coupled inductor multi-phase buck.

- Early insight: coupling can help.
- Naïve design approach:
  Find optimal value of k …
  but arbitrarily holding L_{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_{leak} independently.
  - Maximize L_{M}: ungapped structure.
  - Choose L_{leak} based on ripple, transient, and size trade-offs—all mitigated by coupling.





Separately design for L_m and L_ℓ

- 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_ℓ design can be more challenging…

Design for L_ℓ

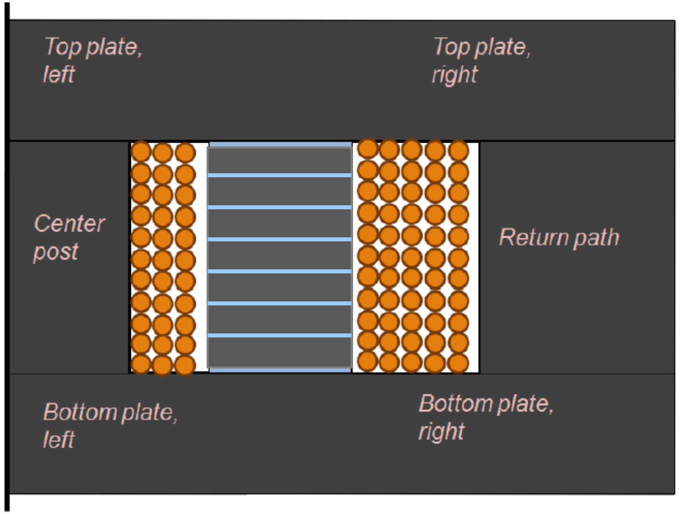
- For low L_ℓ
  - Interleaving (respect symmetry) and/or large winding breadth *b*. Limitation: capacitance.
  - Fewer turns: need larger core area to limit flux density for saturation and core loss.
- For higher L_ℓ
  - Winding configuration
  - Add a shunt
  - Use more turns--reduced core loss mitigates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

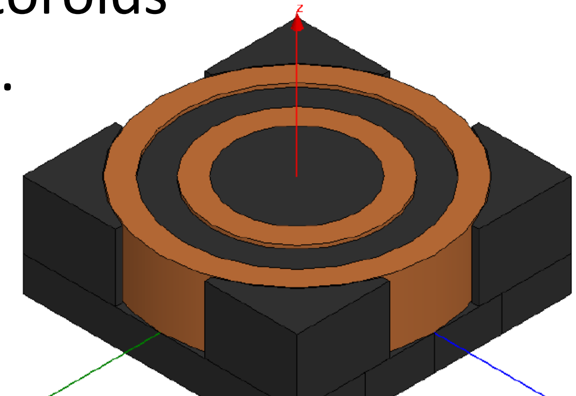
Performance improvement

Functional integration

Shunt to add leakage

- Adjust gaps to get any L_ℓ 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.



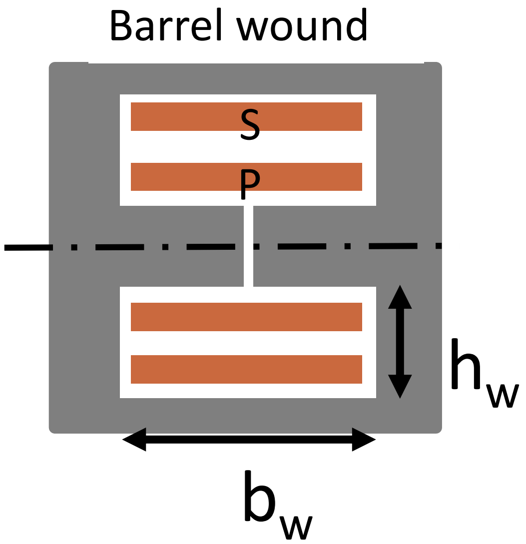


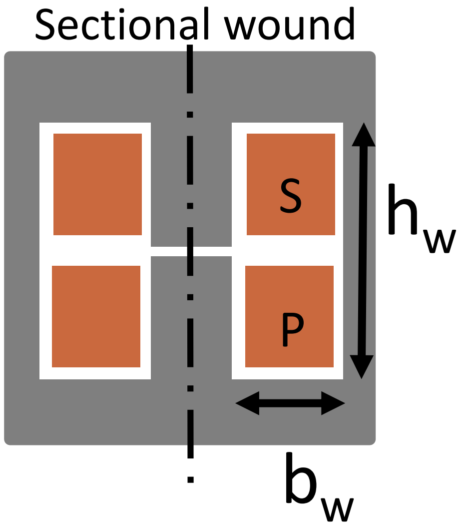
Winding orientation effect

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

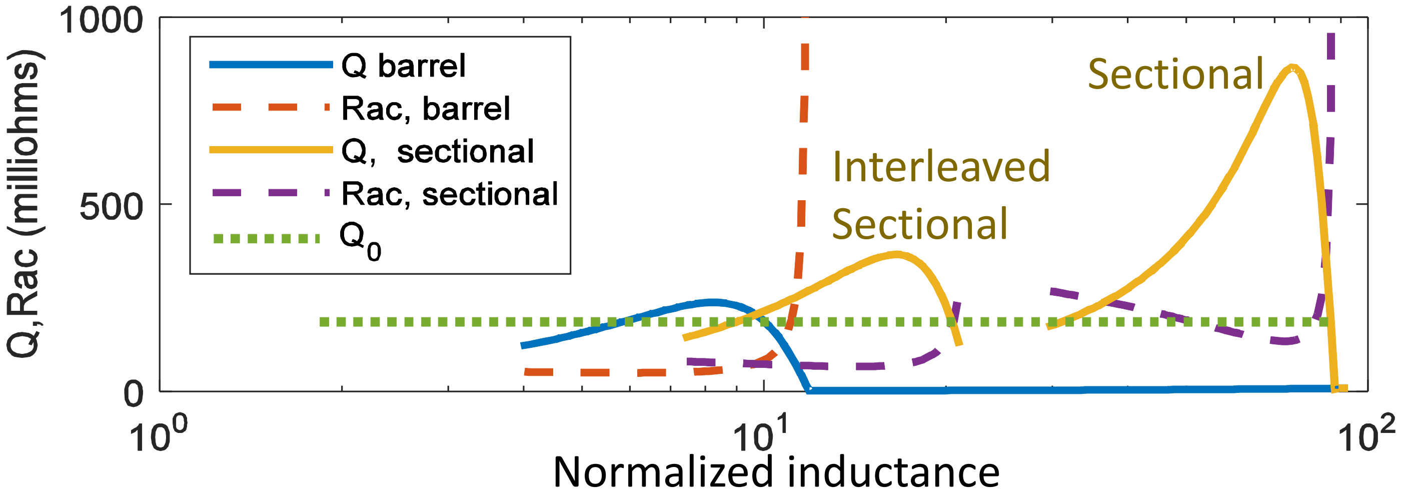
$$L_{leak,p} = \frac{k_L}{b_w}\left(h_w - \left(\frac{2}{3}\right)h_{ps}\right)$$

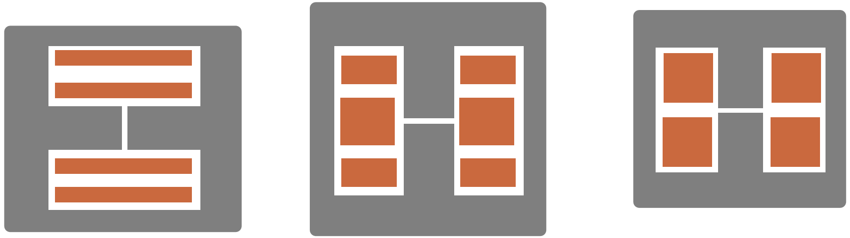
$$k_L = \mu_0 N_p^2 \ell_{turn} \qquad h_{ps} = h_p + h_s$$



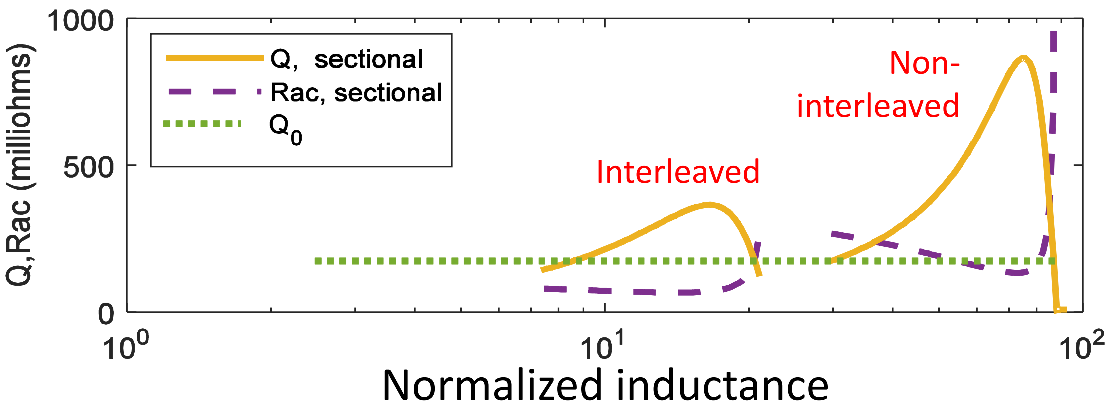


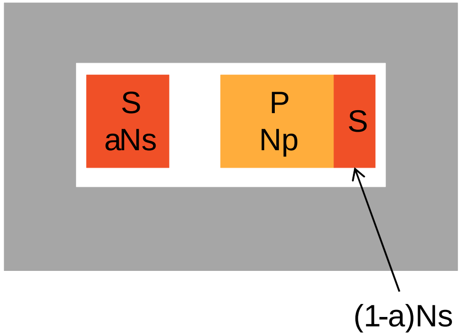
Design options

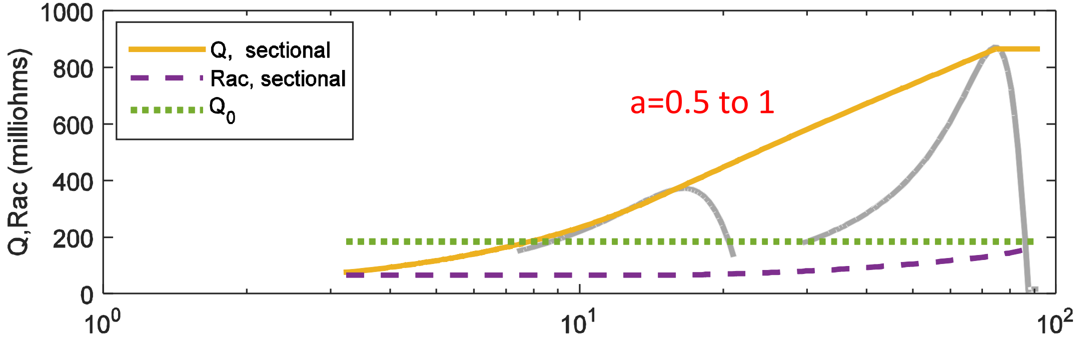




What if the spec is between these peaks?







Comments on integrating inductive functions

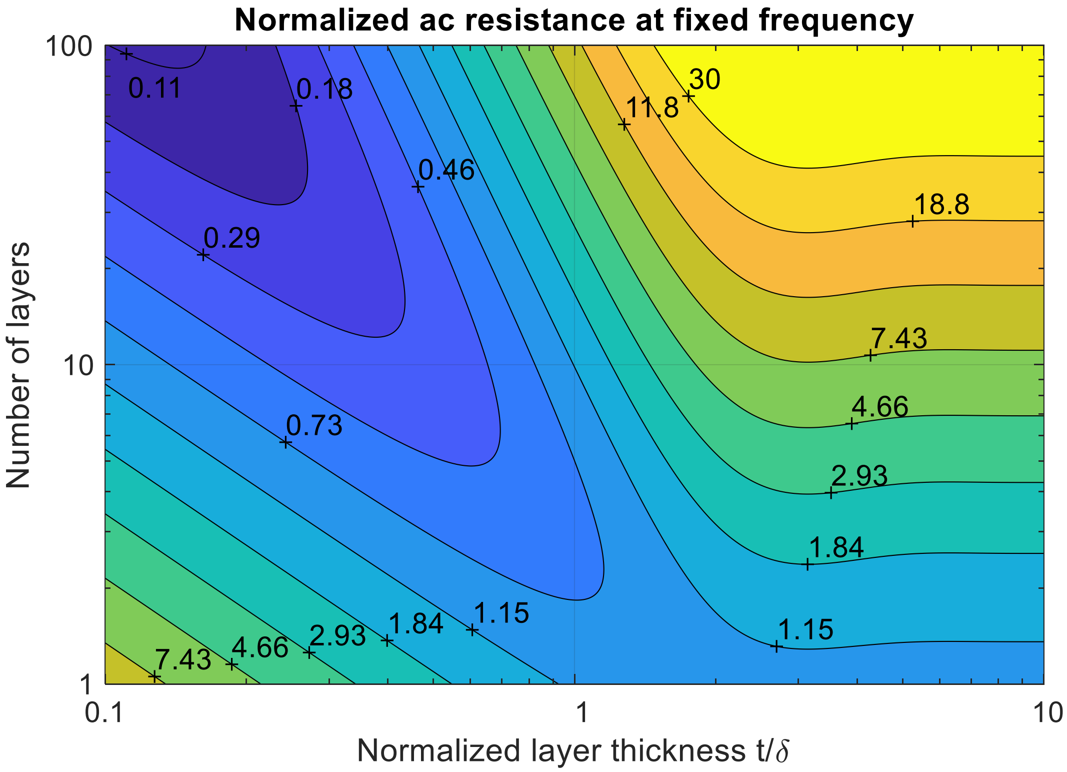
- Design for the L_m and L_ℓ you want, separately, rather than looking at k.
- L_m is easily adjusted with a gap.
- L_ℓ can be reduced with interleaving, limited only by capacitance, and with larger A_c to allow small N.
- L_ℓ can be increased with a shunt or with a "sectional" winding arrangement.
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

Integration of capacitance

- 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 anyay.
  - What if combining L and C could improve ***magnetics*** performance?

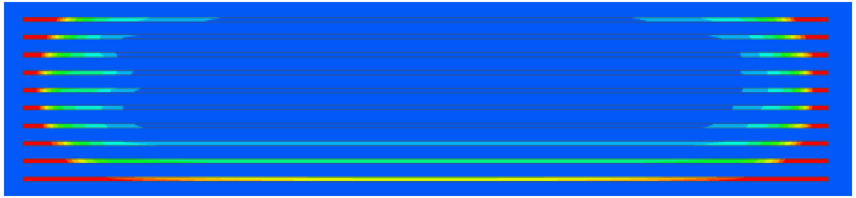
For excellent low ac resistance we need conductor dimensions << skin depth δ

- Litz wire is great, but
  - It's expensive
  - For excellent MHz performance we want dimensions smaller than the **~40 μm** of fine litz strands.
  - We want **< 20 μm,** or even **< 5 μm**



Foil: < 20 µm at low cost

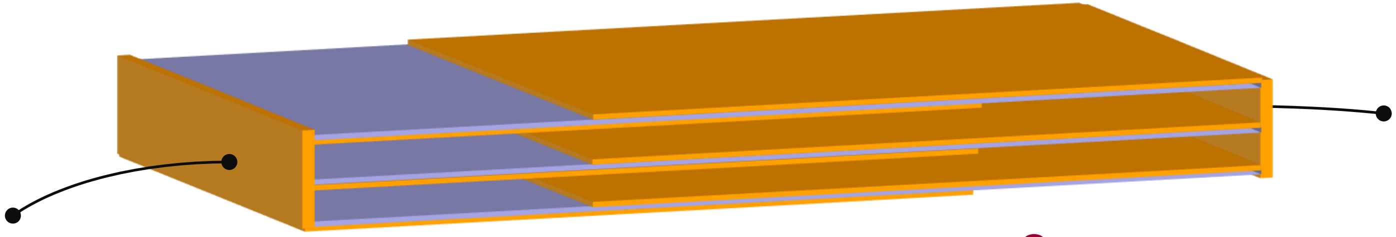
- Easy to get thickness << skin depth.
  - Freestanding foil down to ~ 6 µm.
  - On plastic-film substrates for easier handling down to << 1 µm.
- Thin layers have high dc resistance—need many in parallel.



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

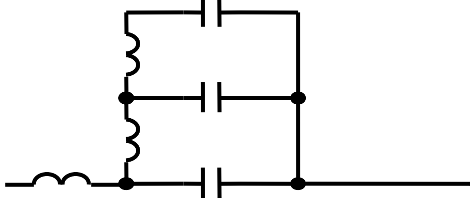
One concept for MHz foil windings: capacitive ballasting

- Overlapping insulated layers create series capacitance for each layer.

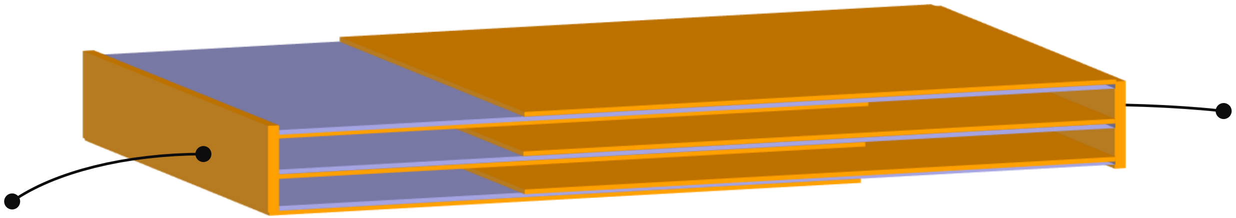


Cartoon—not actual design

- 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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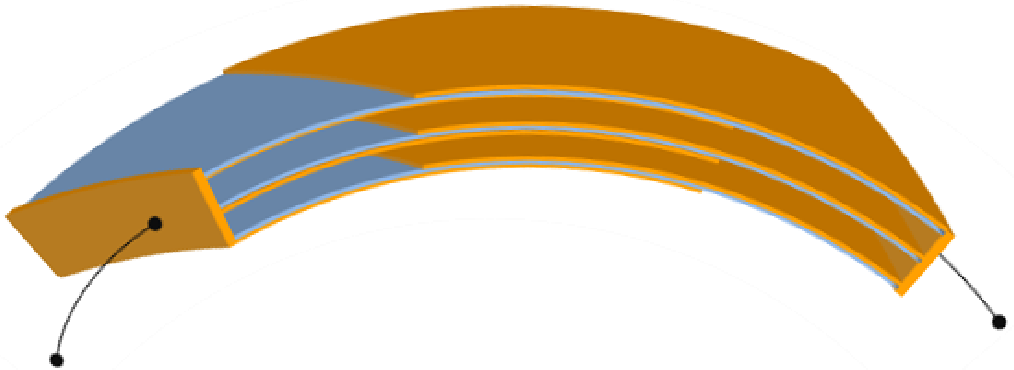

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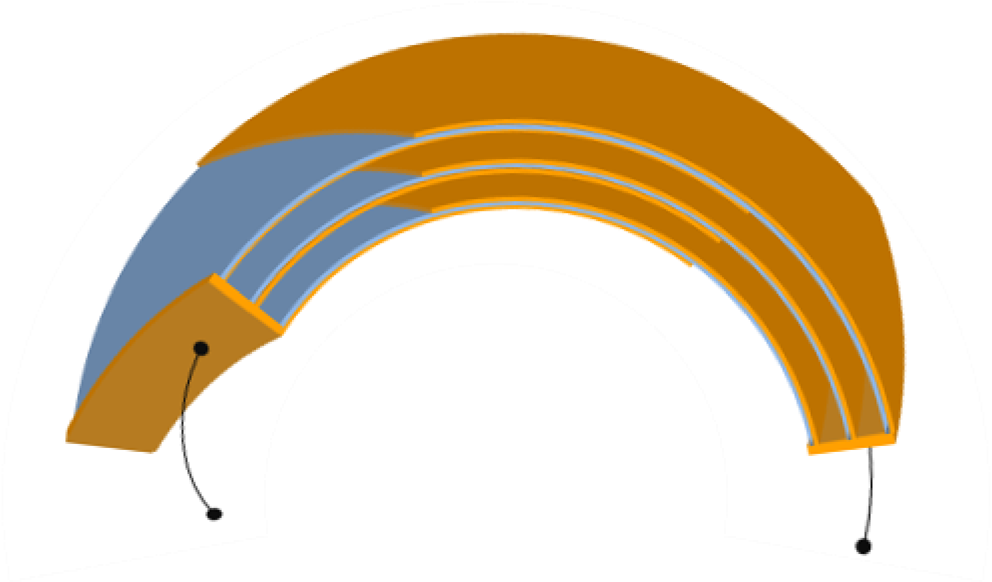
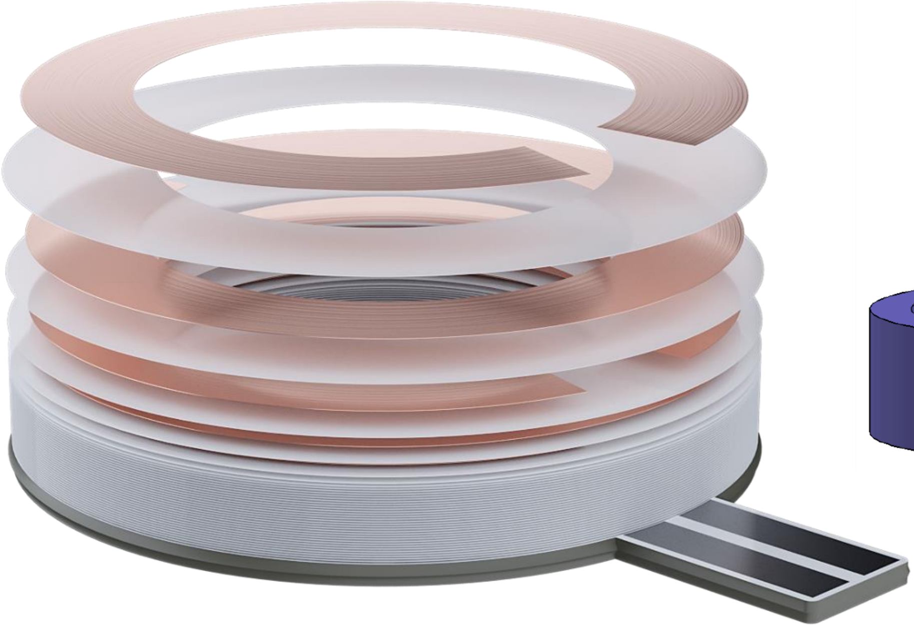
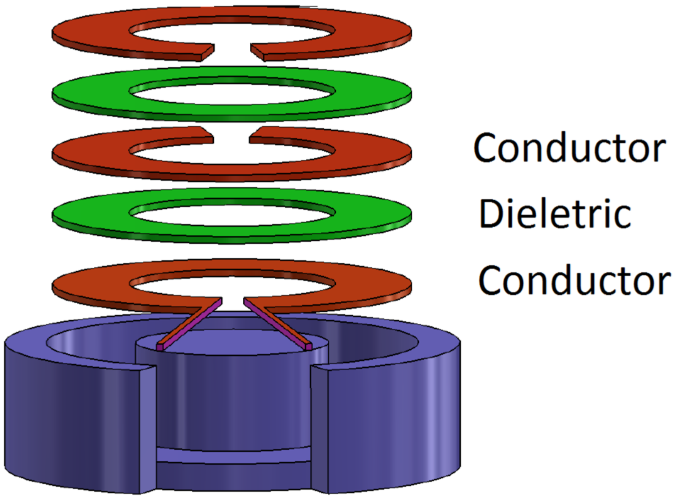


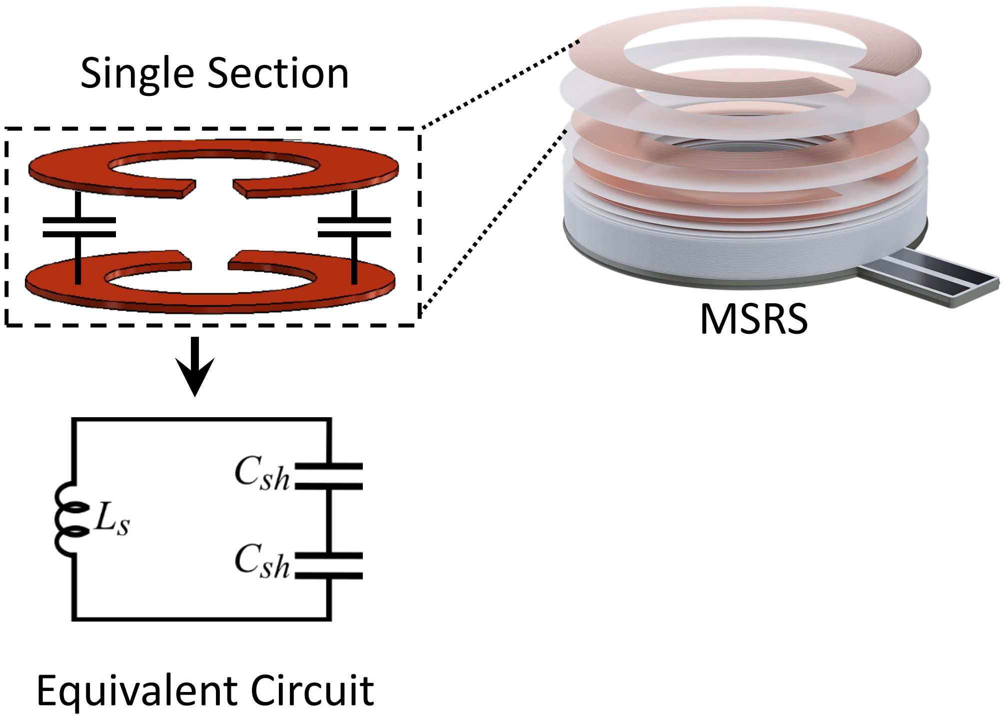
Capacitively ballasted multilayer self-resonant structure (MSRS)





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.

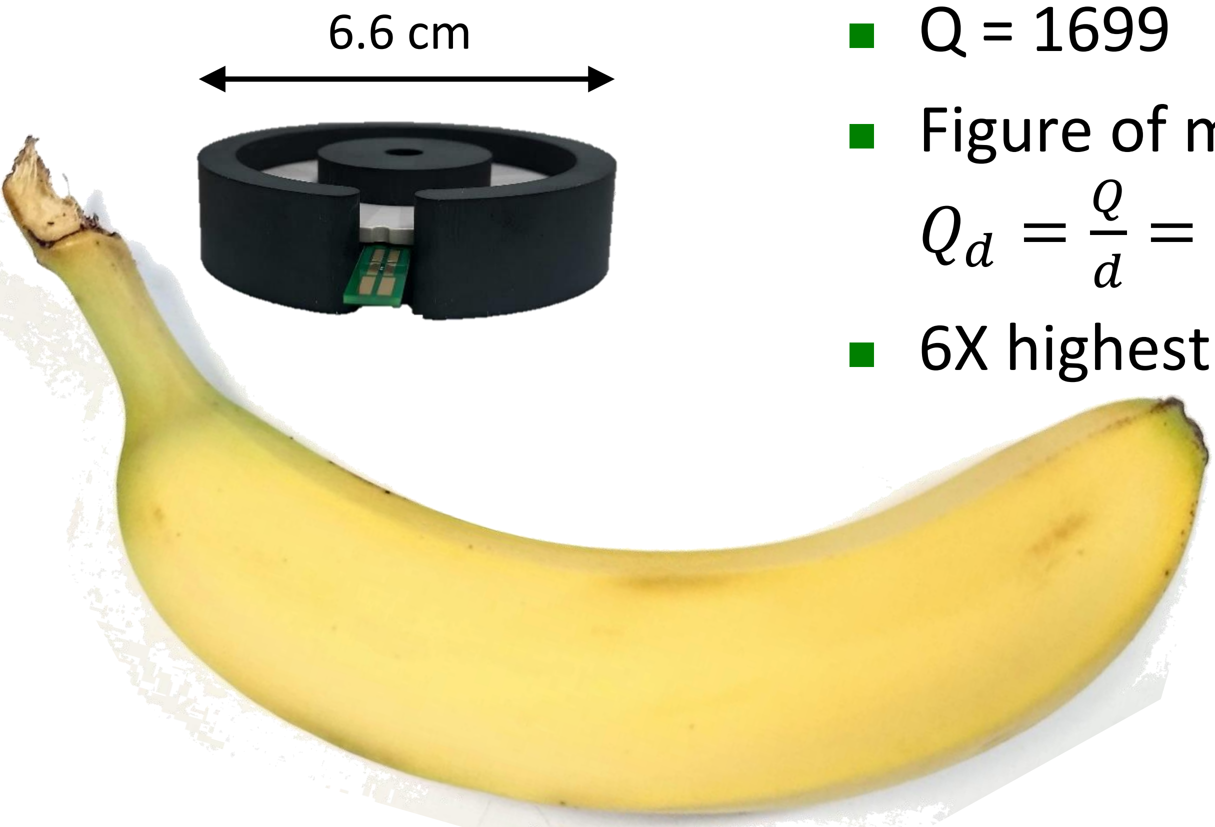


*9 patents pending or granted

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



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

Example implementation

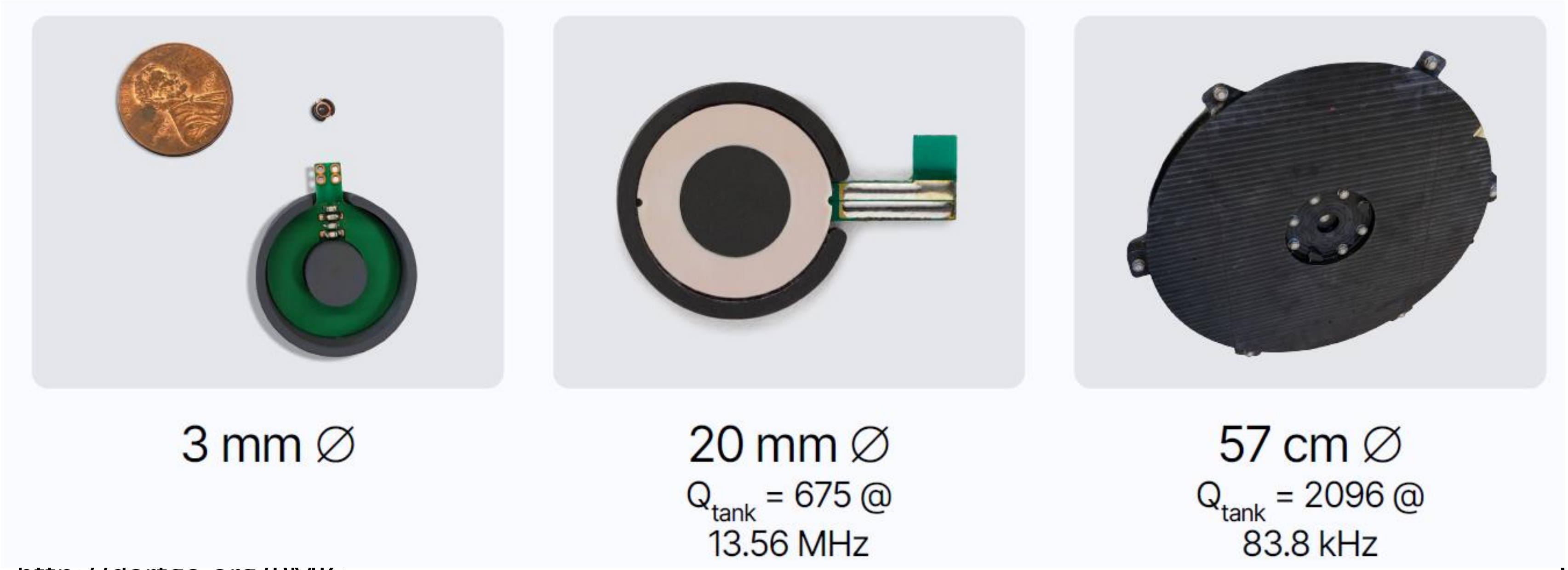
- Q = 1699
- 6X highest Q_d in the literature:

$$Q_d = \frac{Q}{d} = 257\ \text{cm}^{-1}$$

- **1 kW at 19 mm,**
  95% dc-dc efficiency

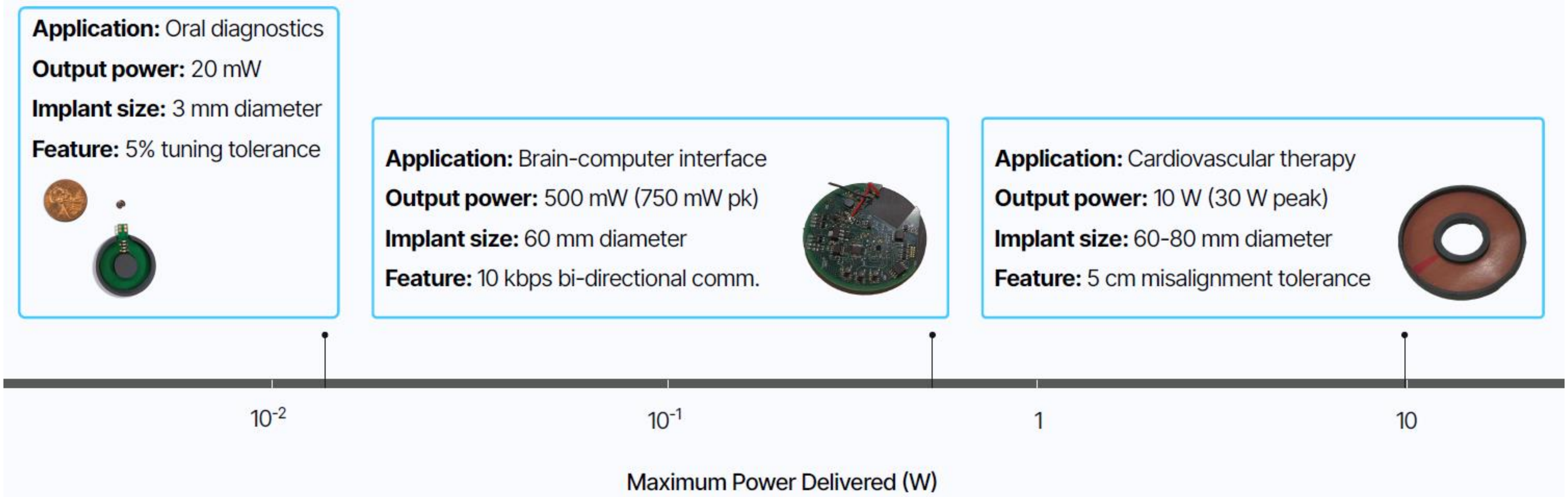
Practical implementations

Scales for different applications developed by Resonant Link, Inc.



Resonant Link Medical

Medical Implants



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

Higher power application

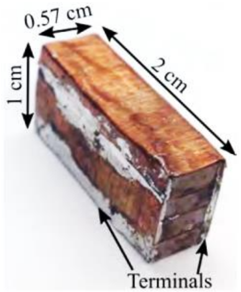
- 19.2 kW, 400 A output
- Air gap up to 10”
- Misalignment +/- 6”

Resonant Link → act

Self resonant components as power-conversion passives

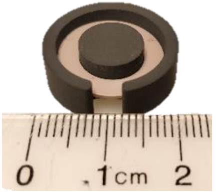
High-density resonant structure, ~1.2 cm^3

- 0.5 mΩ 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.

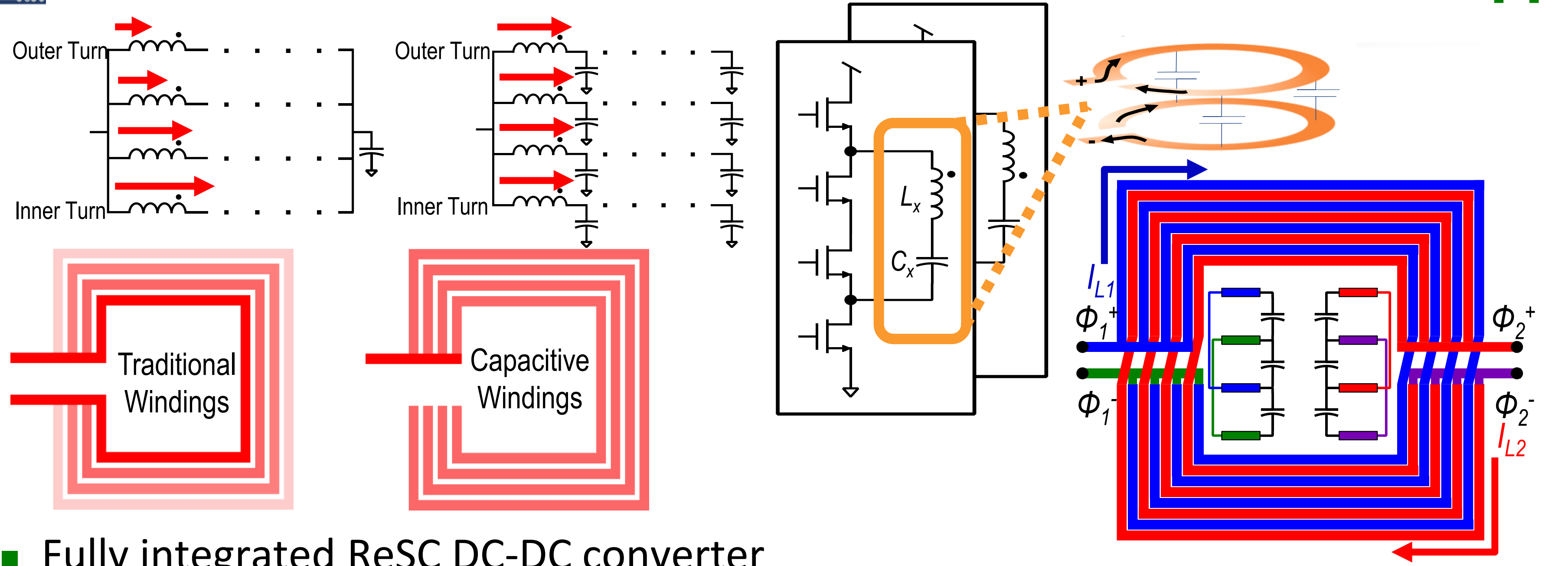


High-Q MLCC-winding components

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



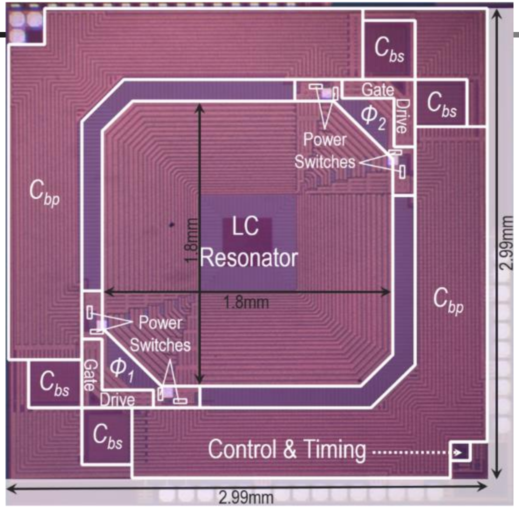
Merged with circuit and fully integrated on die

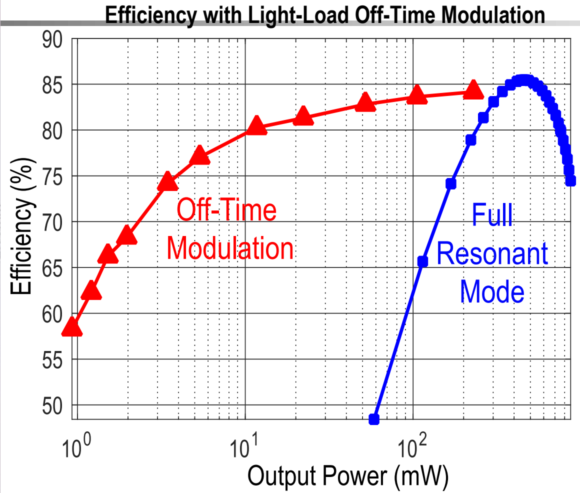


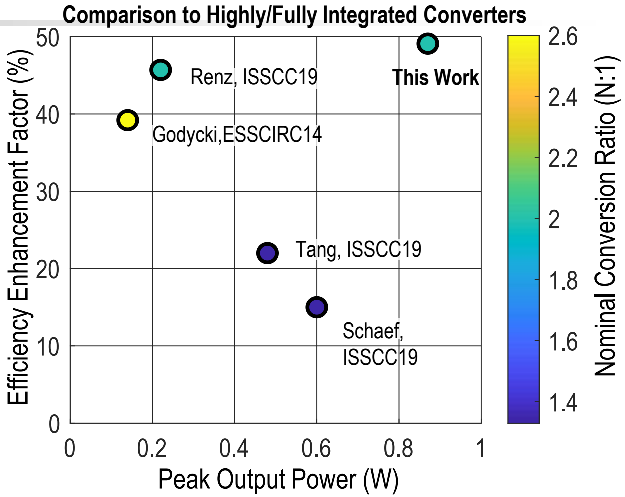
- Fully integrated ReSC DC-DC converter
- Merged multiphase LC resonator on-chip
- Capacitive ballasting → uniform current → decreases ESR

Prescott McLaughlin, Ziyu Xia, Jason Stauth, ISSCC 2020

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/mm² (chip area); 267 mW/mm² (resonator area)

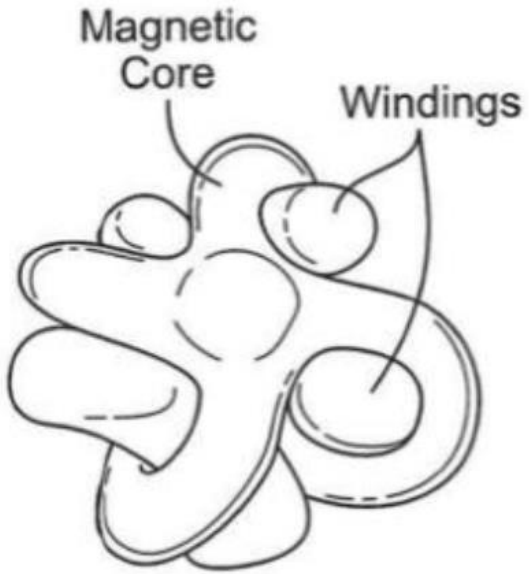
Prescott McLaughlin, Ziyu Xia, Jason Stauth, ISSCC 2020

Electrical Parameter Integration

- Design for the L_m and L_ℓ 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.

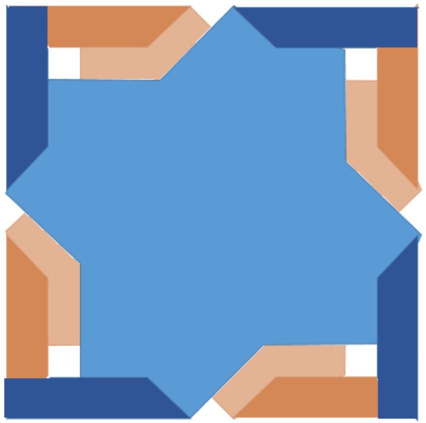
Shape optimization

Free shape concept



Add-constraints:

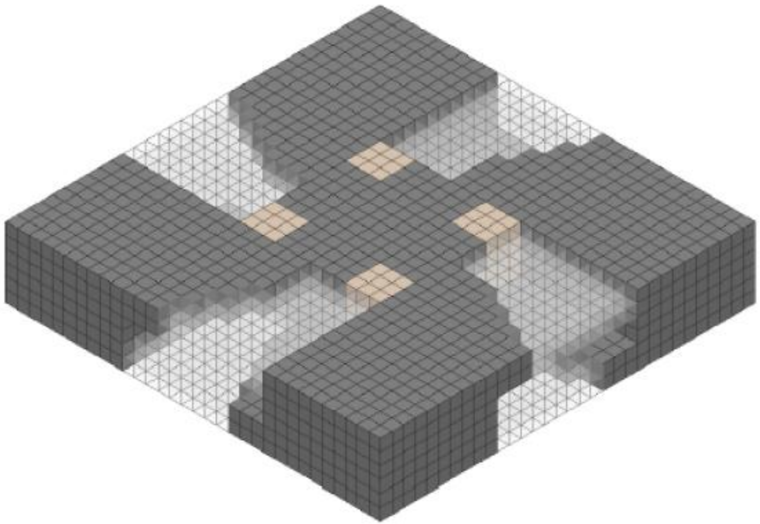
- Drop-in wire for winding
- Two-piece core



Calculated design

PRINCETON UNIVERSITY

Optimized design



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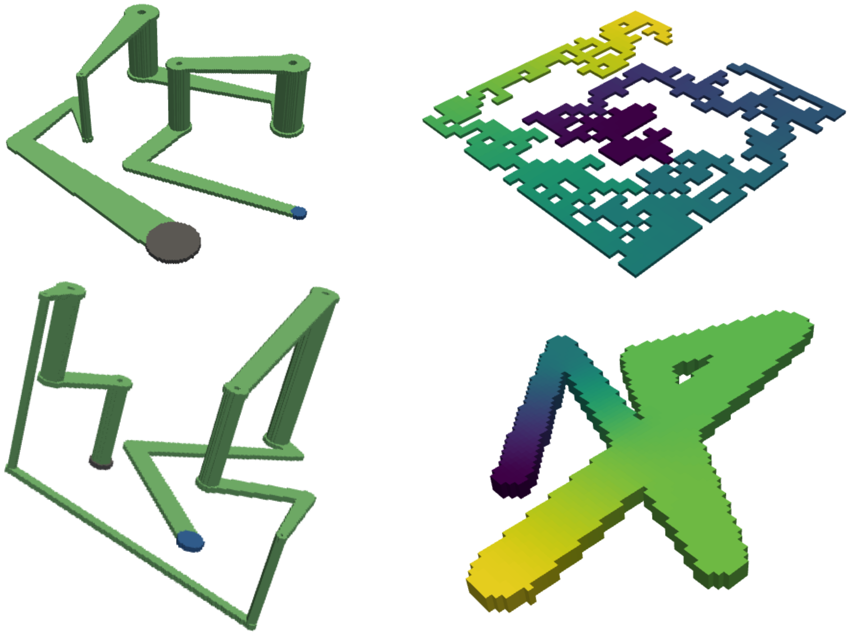
Free shape optimization?

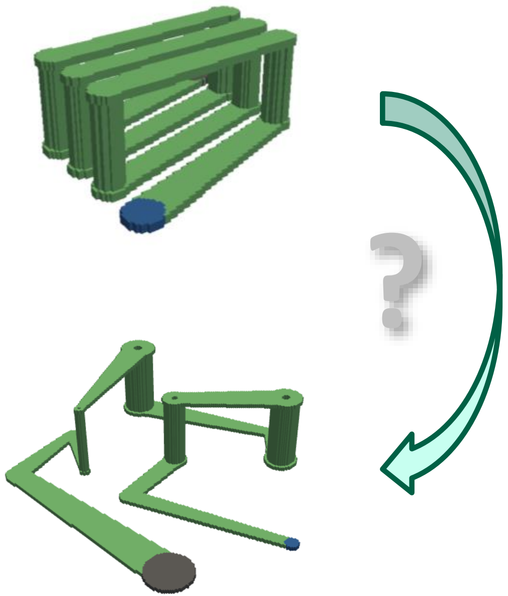
- Optimize air-core inductor on PCB
- OK, we do need constraints:
  - Any 2D shape on each layer + vias.
  - But must be valid—ended up needing 14 rules.
- Also need a fast field solver: FFT Accelerated PEEC method: open source code available.
- Details: presentation by Dr. Thomas Guillod, 11:30 on Th,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

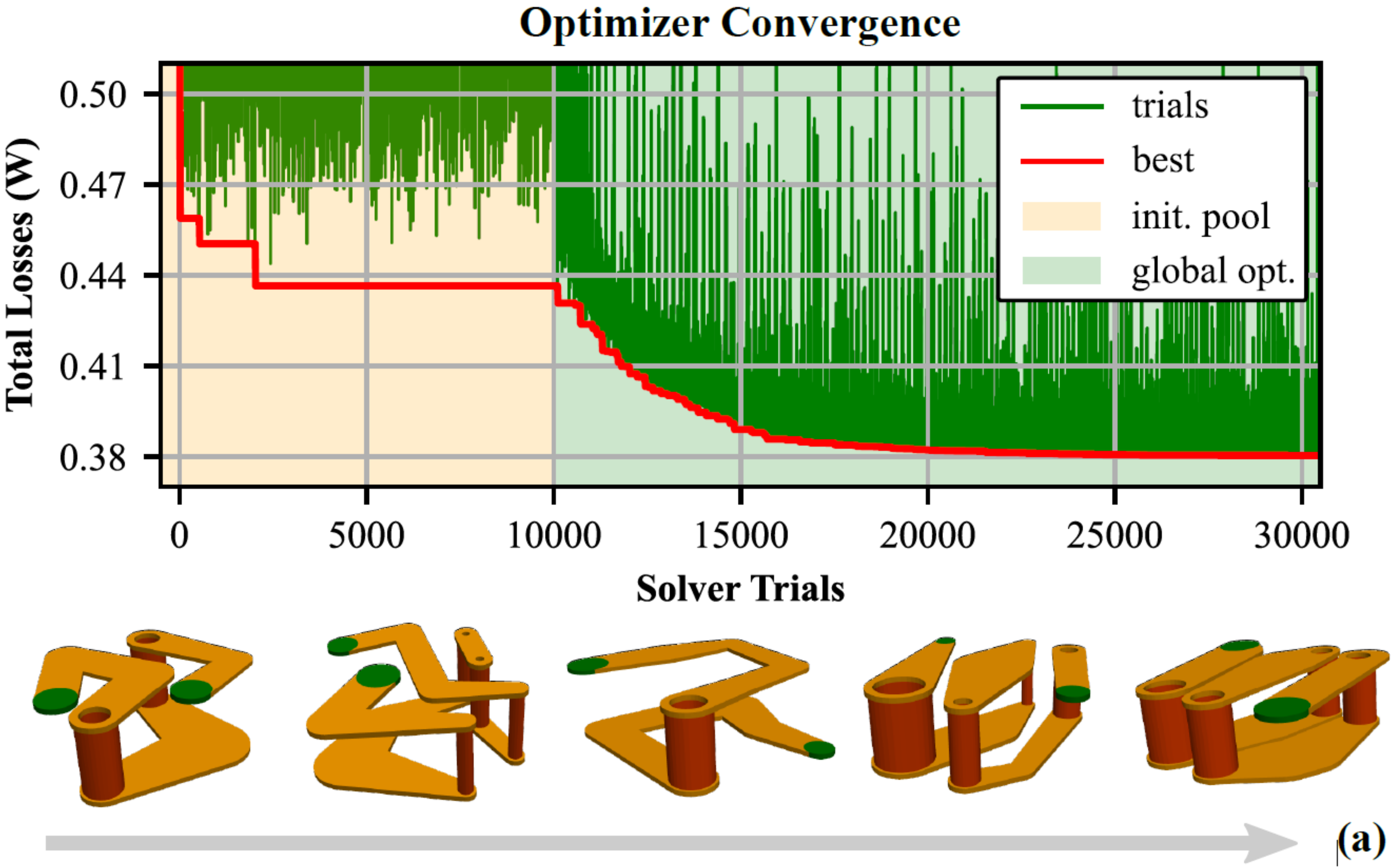
Valid Geom.

Invalid Geom.



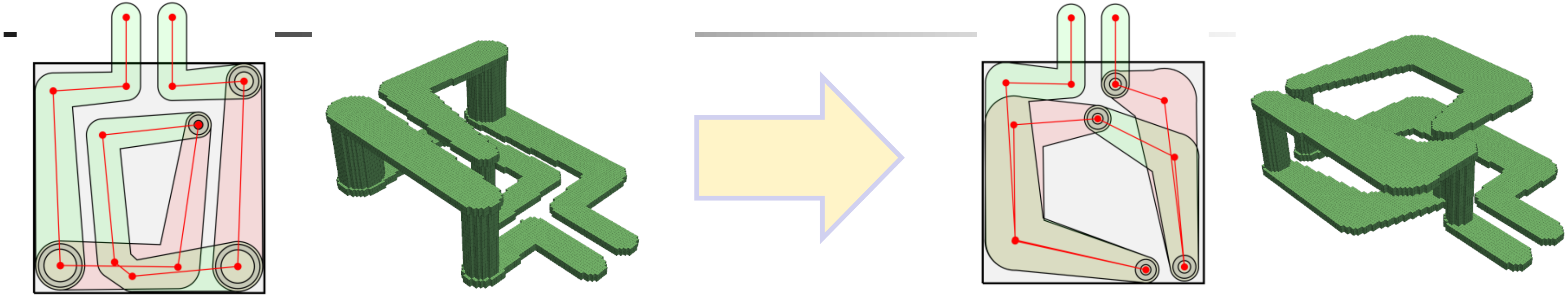
Will it invent something new?





Optimizer Convergence
Total Losses (W)
0.50
0.47
0.44
0.41
0.38
0
5000
10000
15000
20000
25000
30000
Solver Trials
trials
best
init. pool
global opt.
(a)

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

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