Fringing effects

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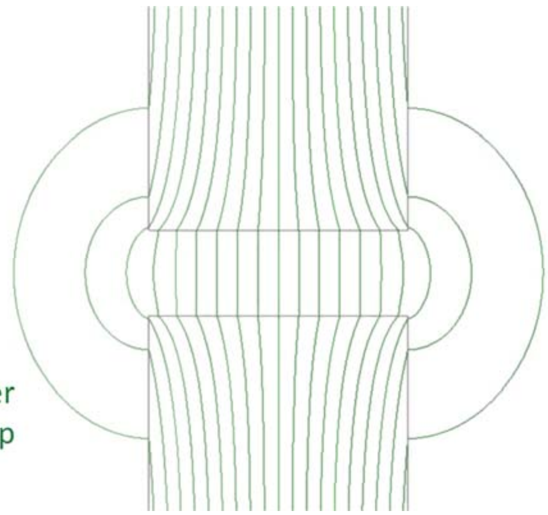
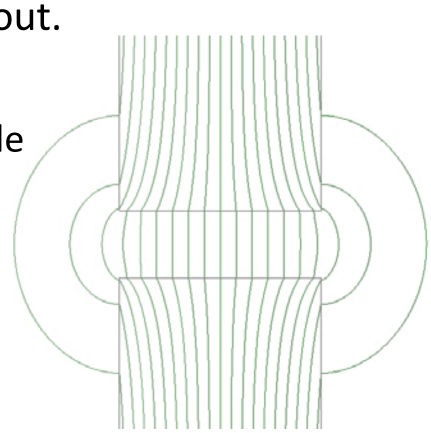


What's a fringing effect?

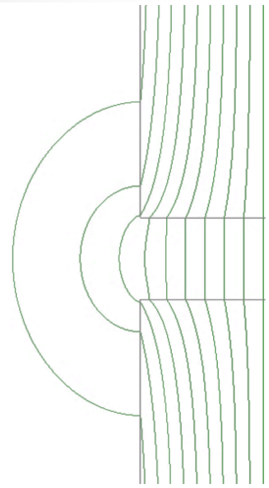
- Flux near a core air-gap that bends out.
- Fringing causes:
  - Lower air-gap reluctance than simple predictions.
  - Extra winding loss.
  - Extra core loss in laminated/tape wound cores: eddy currents.



Fringing effect on air-gap reluctance

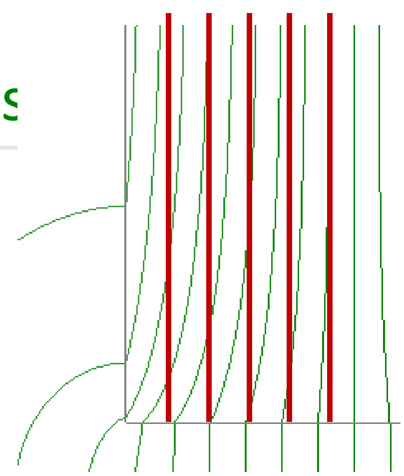
$\mathcal{R} < \frac{\ell_g}{\mu_0 A_{core}}$ because effective area > A_{core}

- 2D: exact model by conformal mapping.
- 3D effects include corners and curvature of a round centerpost.
  - Usually significant; for simple model see [1] or appendix.
- Non-issue for design calculations:
  - Design based on reluctance $\mathcal{R}$, not gap length ℓ_g.
  - Find necessary gap length experimentally.

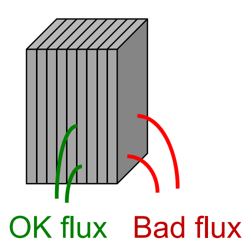


[1] Hoke & Sullivan. "An improved two-dimensional ..." *APEC 2002.*

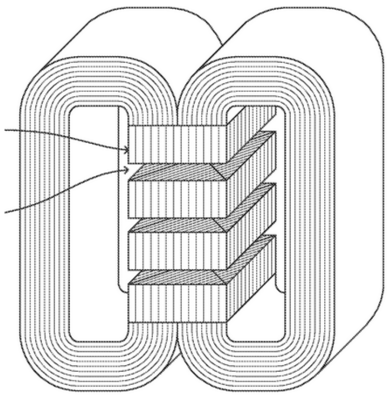
Fringing effect on core loss

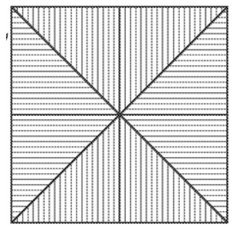


- Flux crosses perpendicular to laminations, inducing loss.
- The "out-of-plane flux" (OOPF) causes excess power loss P_{OOFP}.
- Only a problem on two sides of a post.

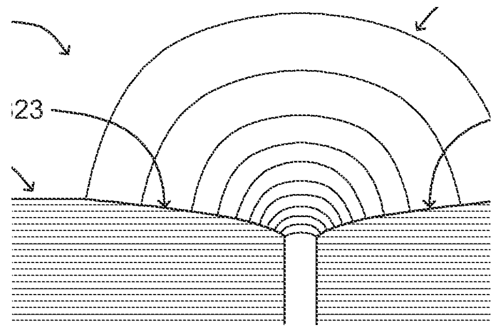


Carsten patents to reduce fringing loss in laminated/tape-wound cores, 2013





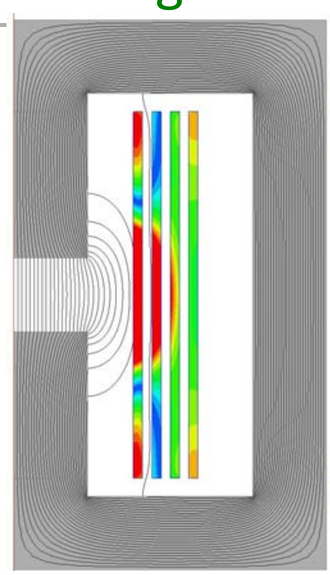
US Pat. No. 9,123,461B2

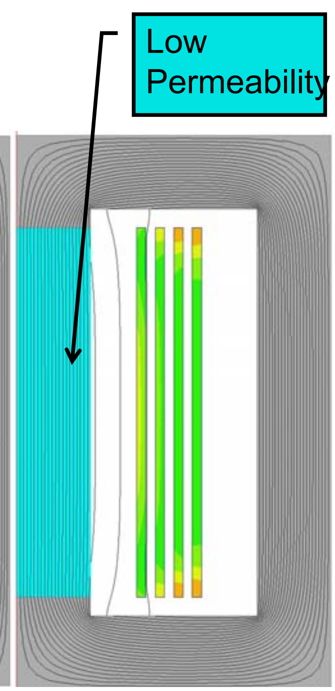


US Pat. No. 8,466,766

Fringing effect on winding loss

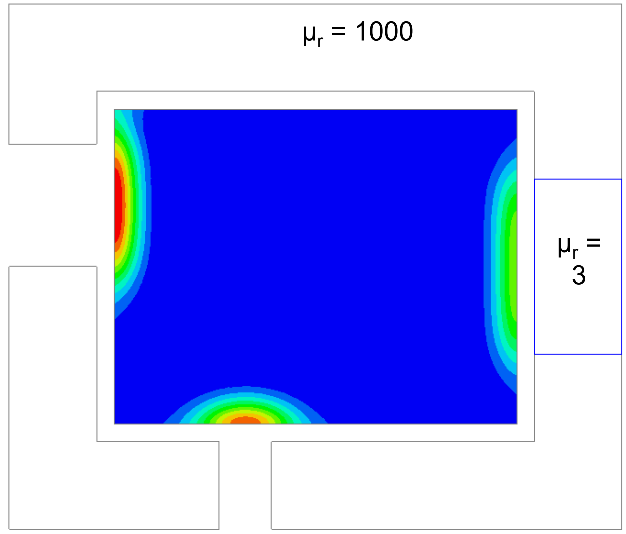
- Strong field near the gap causes increased eddy-current winding loss.
- Curved field is bad for foil windings:





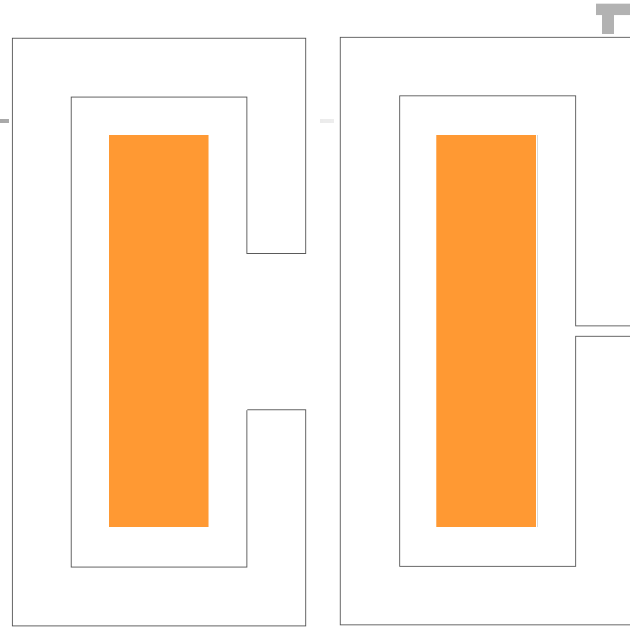
One conceptual approach

- Solid winding.
- Current flow is attracted to gaps.
- Amount of current is proportional to gap reluctance.



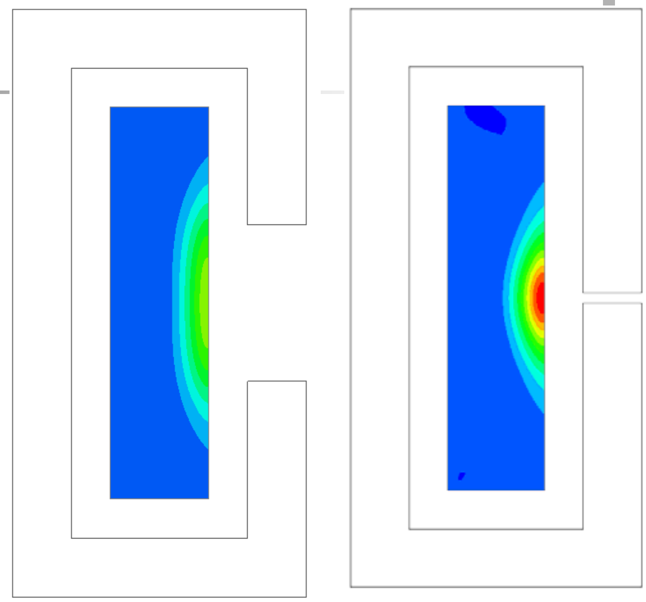
Single gap

- Which winding has larger loss, with the same ac current in each winding?



Single gap

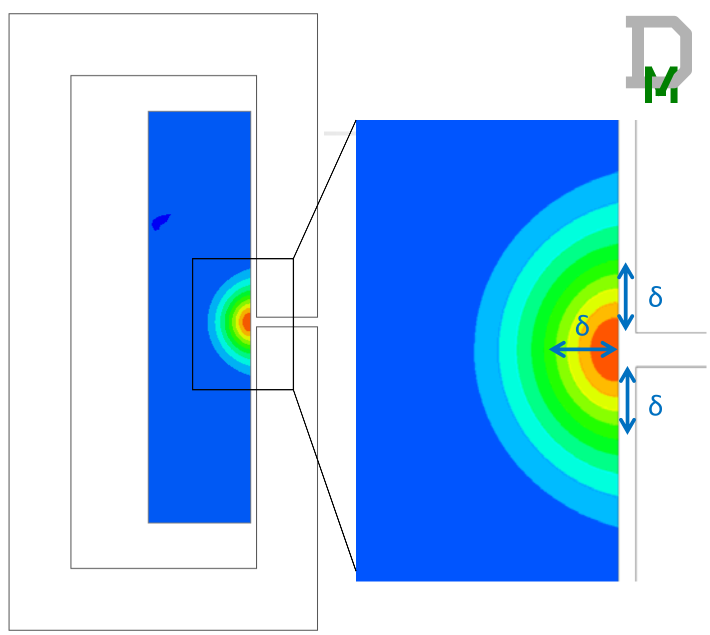
- All current flows near the gap.
- Longer gap → Current is spread over a larger area → lower loss.
- Current with small gap is spread wider than gap.



Spread of current near a small gap

Case 1:
Winding close to gap.

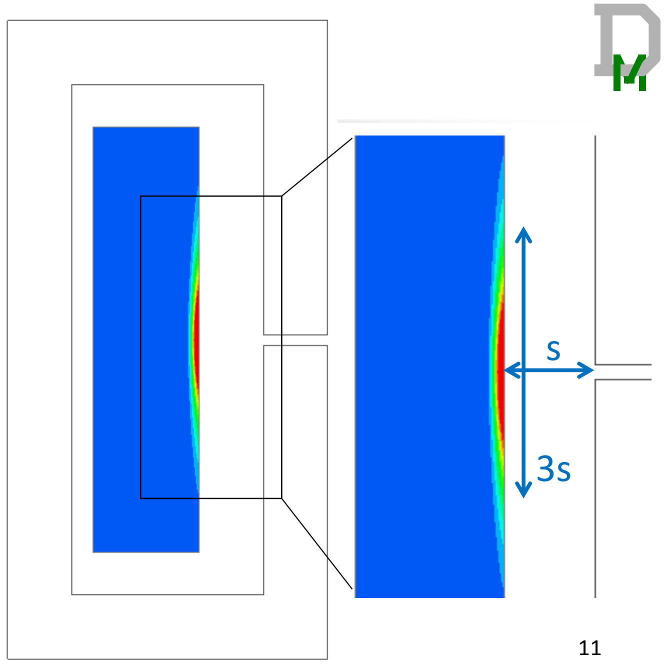
- Current spreads beyond the edges of the gap according to the skin depth δ



Spread of current near a small gap

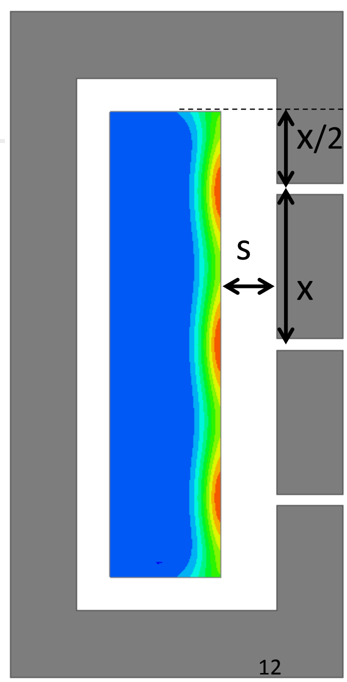
Case 2: Small skin depth; winding spaced from gap.

- Current spreads over a width ~3s.



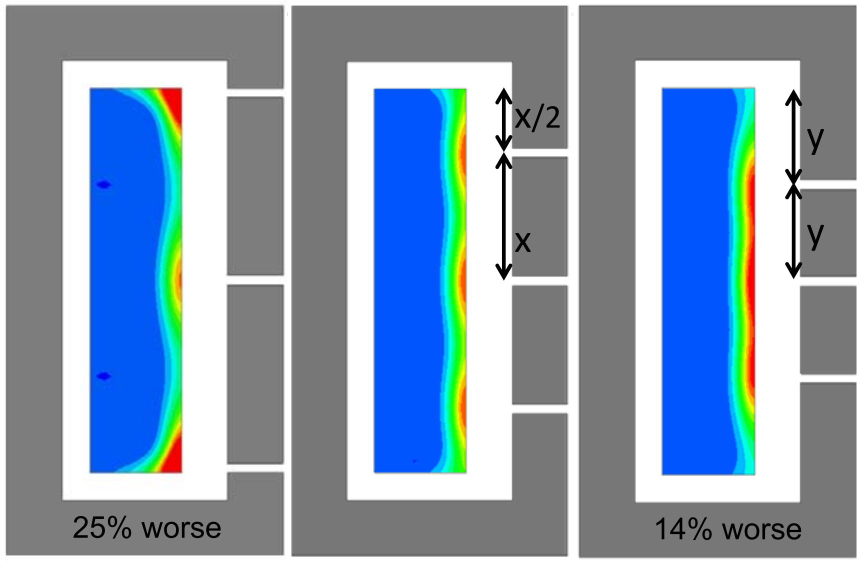
One design approach:

- Spread several gaps evenly:
  - Spacing x between gaps.
  - Distance x/2 from edge of winding.
- Choose spacing s < x/3.
- Current distribution is not perfect, but "pools" of current overlap and impact on loss is small.
- For details, see [1] Jiankun Hu, C. R. Sullivan, "AC Resistance of Planar Power Inductors and the Quasidistributed Gap Technique", *IEEE Tran. on Power Electr.,* 16(4), pp. 558–567, 2001. https://engineering.dartmouth.edu/inductor/papers/qdgj.pdf



Are all equal spacings gaps equal?

- Current spreads to both sides of gap.
- Position accordingly: x/2 on edges.



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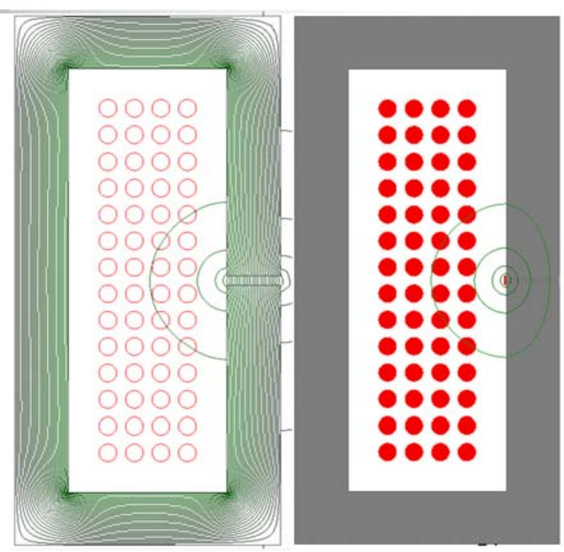
A second conceptual approach

- MMF across gap = MMF generated by the winding.
- Replace gap with a single-turn ribbon carrying a current NI.
- The field is identical.



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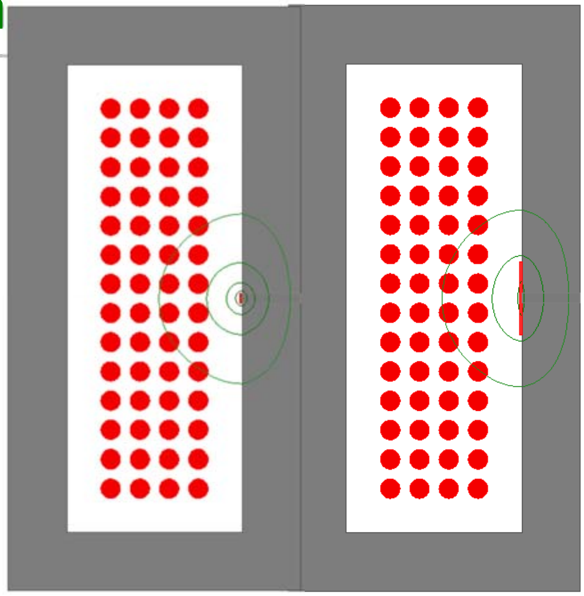
Effect of gap length

- Same NI in ribbon representing the gap—more concentrated vs. more widely spread out.
- Easy to see that the longer gap will have a less intense fringing field near the gap.
- Far from the gap, the two are identical.



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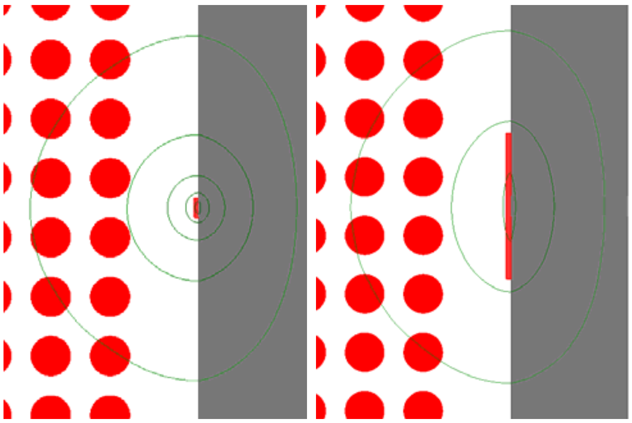

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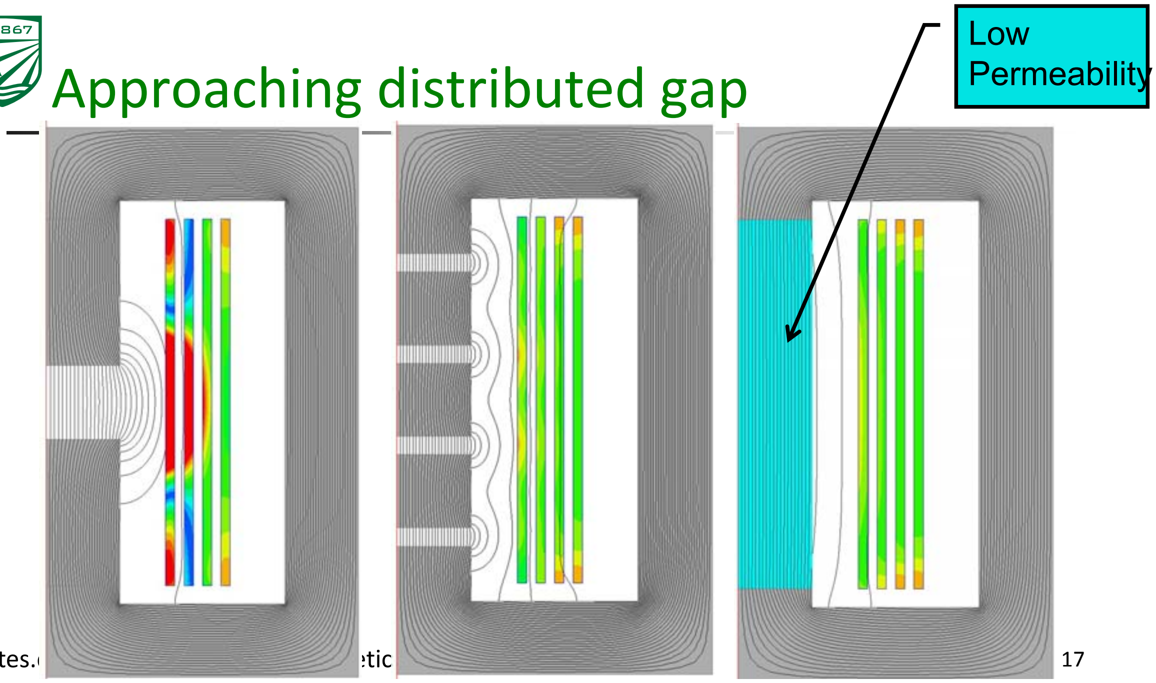
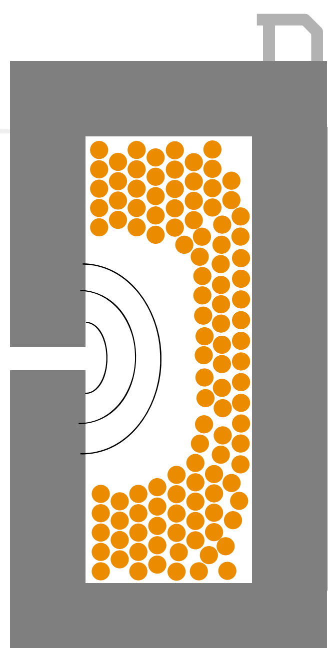
Approaching distributed gap



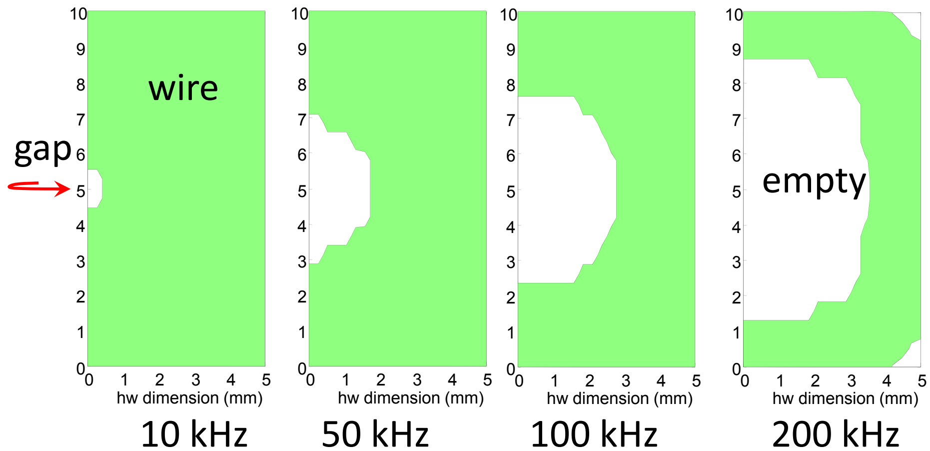
Winding shape optimization

- 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.



Examples of optimized shapes

Dartmouth "shapeopt" software, available free on our web site.



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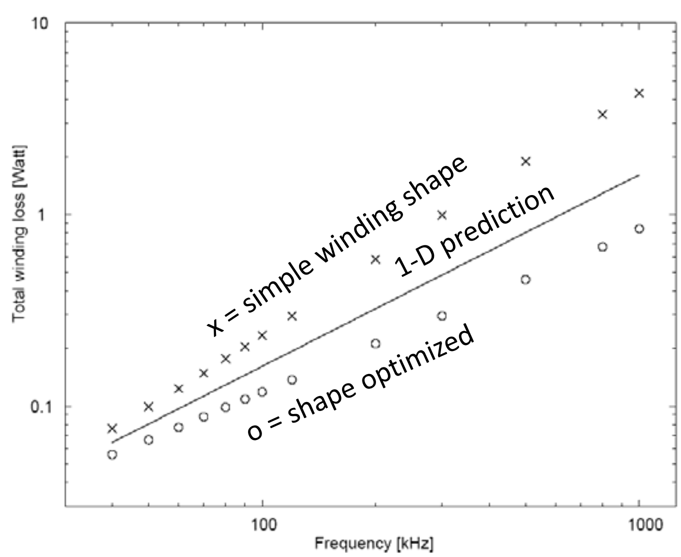
How much benefit from shape optimization?

- Compare designs optimized based on
  1-D analysis to true shape-optimized designs.
- Up to 4X improvement.
- AWG 38 strand litz.
- Optimization tool available for download or on our site

https://engineering.dartmouth.edu/inductor/shapeopt.shtml

- References 2-4.



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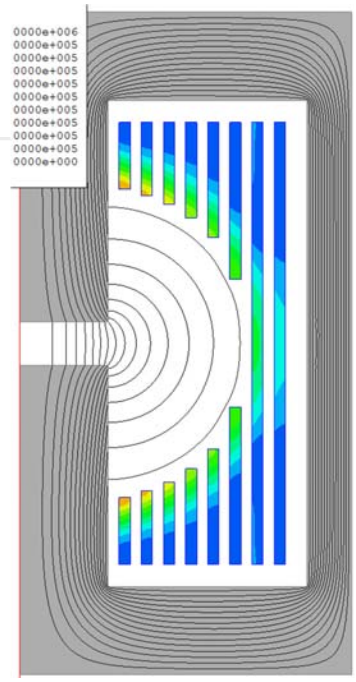
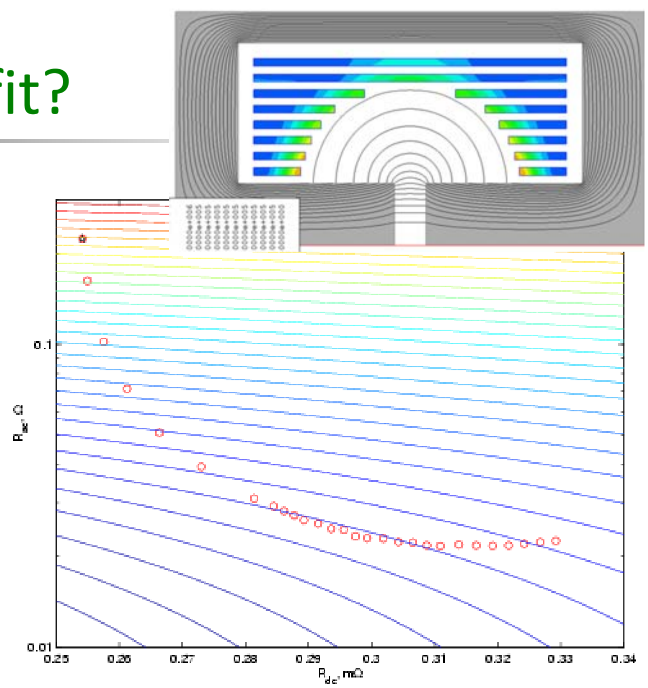
Shaped foil winding

- "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.



How much benefit?

- Optimum cutout size depends on ripple ratio
- Contour lines of total power loss at 20% ripple
- The optimum circular cutout reduces loss by 63%.
- References 5.



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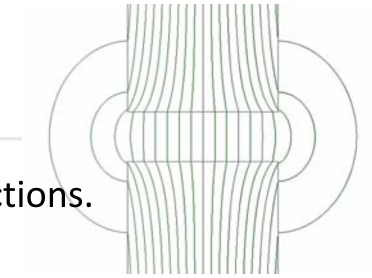
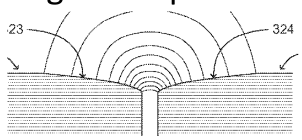
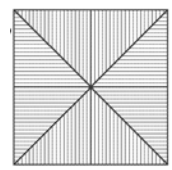
Conclusions I



- Lower air-gap reluctance than simple predictions.
  - Calculations are rarely needed.
  - If needed, the appendix has an accurate, simple calculation from [1].
- Extra core loss in laminated/tape wound cores: eddy currents.
  - Some mitigation options:

US Pat. No. 8,466,766





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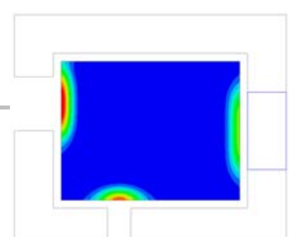
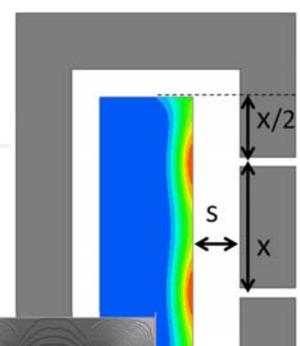
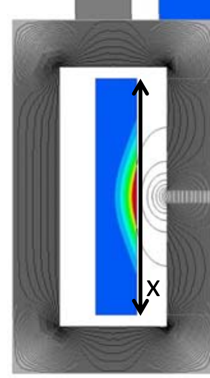
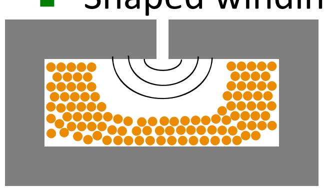
Conclusions II

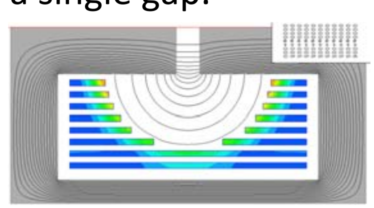




- Current flows near the gaps.
- A wider gap lowers resistance.
- Spacing $s > x/3$ is a good rule.
- Not all equally spaced gaps are equal—first gap x/2 from edge.
- Shaped windings with a single gap.







References

[1] Jiankun Hu, C. R. Sullivan, "AC Resistance of Planar Power Inductors and the Quasidistributed Gap Technique", *IEEE Tran. on Power Electr.,* 16(4), pp. 558–567, 2001. https://engineering.dartmouth.edu/inductor/papers/qdgj.pdf

[2] Jiankun Hu, C. R. Sullivan, "Analytical Method for Generalization of Numerically Optimized Inductor Winding Shapes", *IEEE Power Electronics Specialists Conference*, pp. 568–573, June 1999.

[3] 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.

[4] C. R. Sullivan, J. D. McCurdy, R. A. Jensen, "Analysis of Minimum Cost in Shape-Optimized Litz-Wire Inductor Windings", *IEEE Power Electronics Specialists Conference*, June 2001.

[5] 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.

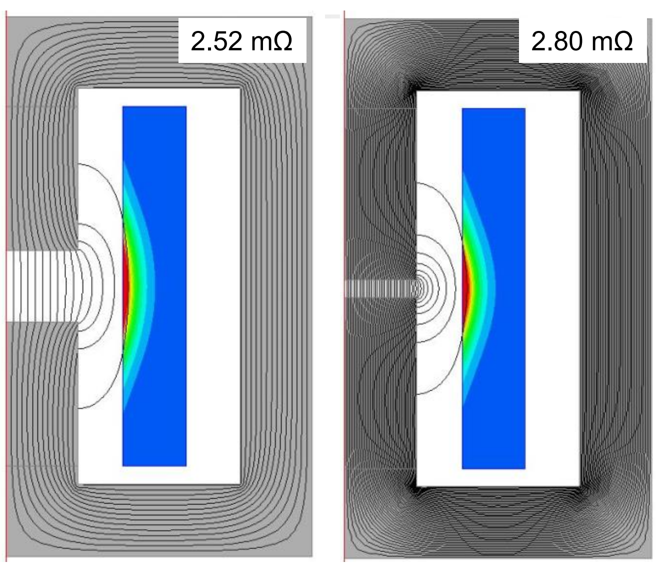
[6] J. D. Pollock, C. R. Sullivan, "Modelling Foil Winding Configurations with Low AC and DC Resistance", *IEEE Power Electronics Specialists Conference*, pp. 1507–1512, June 2005.

[7] J. Pollock, C. R. Sullivan, "Gapped-Inductor Foil Windings with Low AC and DC Resistance", *IEEE Industry Applications Society Annual Meeting*, pp. 557–663, Oct. 2004.

[8] Lundquist, Weyman, Vivien Yang, and Carl Castro. "Low AC resistance foil cut inductor." *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*. IEEE, 2014.

Another example

- Both gaps are small enough that it doesn't matter much.
- Shorter gap is worse.



Fringing reluctance calculation

$$\mathcal{R}_{faces} = \frac{\pi}{p \cdot \mu_0 \left(1 + \ln \frac{\pi \ell}{2\ell_{gap}}\right)}$$

$$\mathcal{R}_{corners} = \frac{1}{\mu_0 k \ell}$$

where

p = perimeter = 2(w+d)

k = 1.23