Core Loss Initiative: Technical

Prof. Charles R. Sullivan

chrs@dartmouth.edu

Dartmouth Magnetics and Power Electronics Research Group

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

sites.dartmouth.edu/power-magnetics/

Saturday workshop summary

- Morning topic: **Core loss**
- Afternoon topic: **Fringing**
- My impossible task: **Summarize both sessions.**

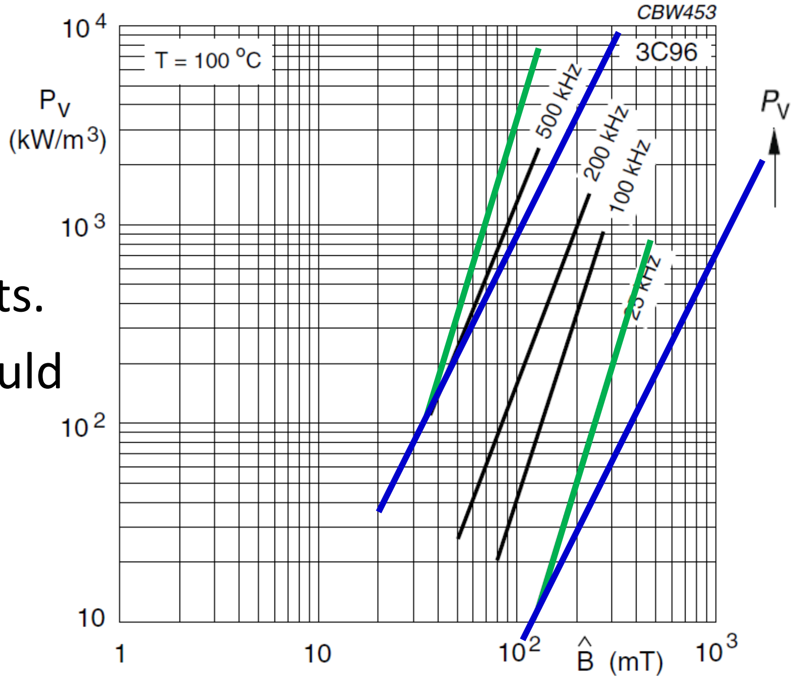
Core loss

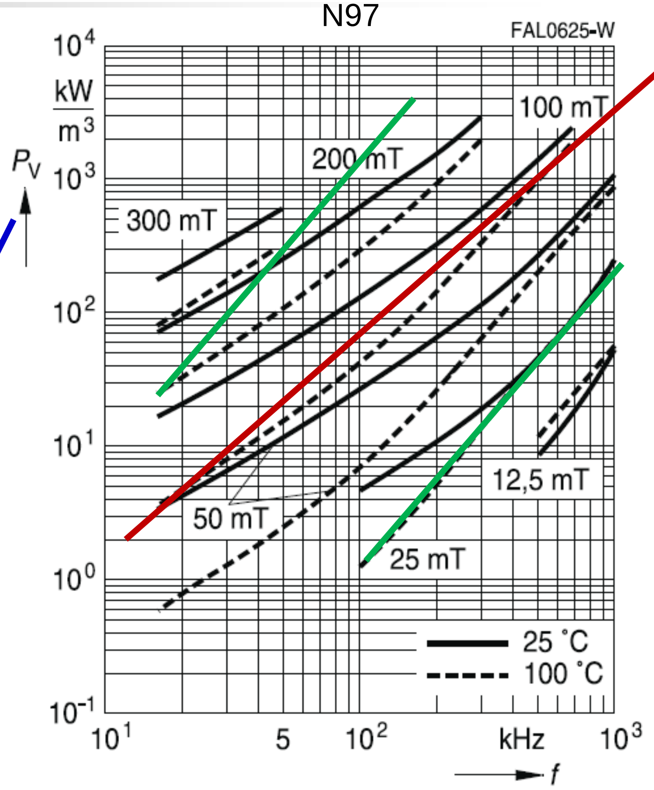
- Behaviors to capture in models, measurements and data sheets.
  - Nonlinearity
  - Different behavior at different frequencies.
  - Effect of complex waveforms.
  - **Impact of physical dimensions.**

- Measurement Accuracy Issues (Stefan Ehrlich, Fraunhofer Institute)
  - Precision needed and how to achieve it.

Nonlinearity and frequency dependence

- Steinmetz model
  $$P = kf^{\alpha}\hat{B}^{\beta}$$
  would mean **straight**, **parallel** lines on both plots.
- **Linear** model would mean β = 2.
- Behavior is more complex.

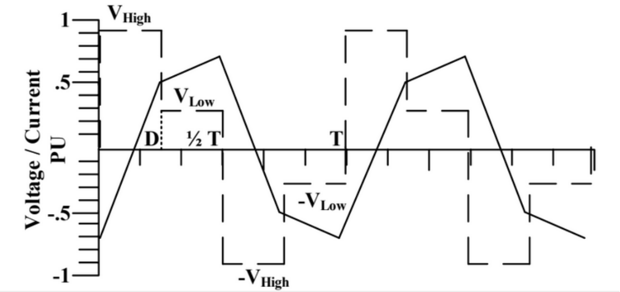




How to capture nonlinear frequency dependent loss data?

- Just collect the data and interpolate.
- Better curve fits.
  - Example: $P = k_1 \cdot f^{\alpha} \cdot B^{\beta} + k_2 \cdot f^{\gamma} \cdot B^{\zeta}$
- Dynamic models that inherently have the right dependence on f and B.
  - Example of a first attempt at this from Ray Ridley—work in progress.

Omitted in all of the above



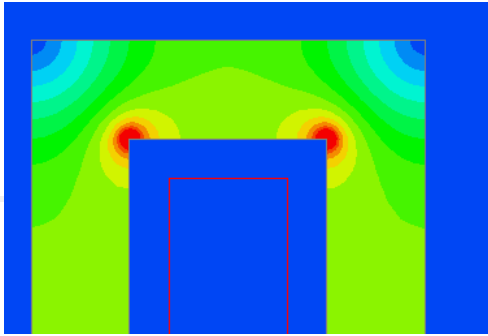
Issue	**Implication**
DC bias effect	Data collection needed
Variety of waveforms	Options include • Extrapolation from limited data (e.g., iGSE method) • Comprehensive “loss map” data collection for waveforms of interest. • e.g., Byron Beddingfield’s DAB tester for “dual slope” waveforms.
Effect of core size and shape	Effects to study: • Skin effect • Wave propagation/dimensional resonance • Mechanical resonance • Simple flux crowding as affected by shape

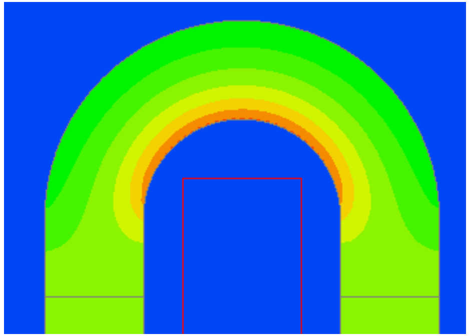
Last year’s talk– slides at URL below

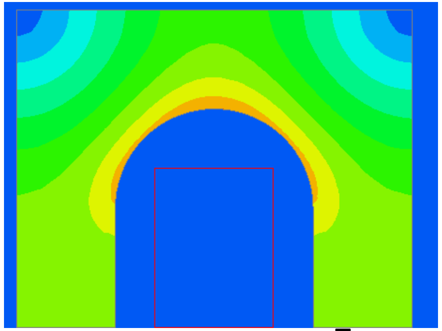
Discussed next

Dimensional Effects

- Straightforward to model and analyze:
  - Flux crowding at corners.
  - Cross section variation.
  - See blog post for more on examples at right.
- Complex, known physics; uncertain parameters:
  - Skin effect and wave propagation
  - Mechanical vibration: See ref [5]*.
- Poorly understood:
  - Higher loss on surfaces than in bulk.





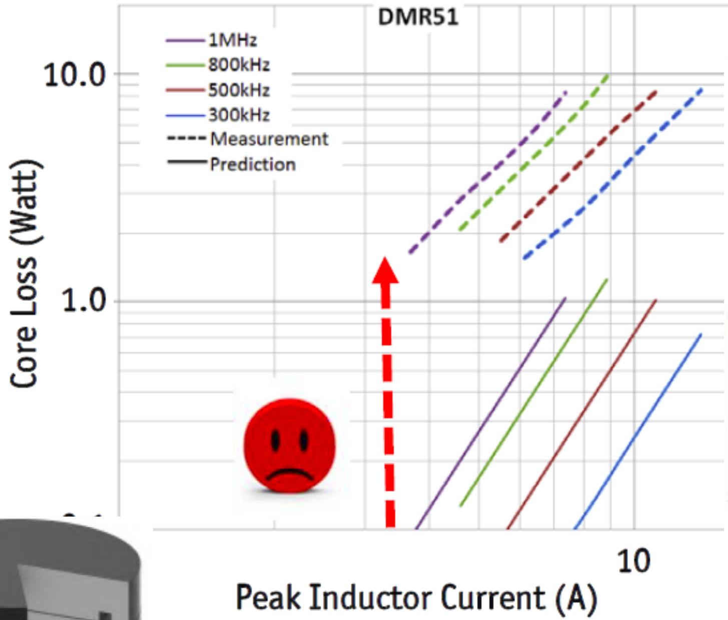


**Slides in on the memory stick are only a placeholder. Find these, with references, at sites.dartmouth.edu/power-magnetics/*

Surface losses in MnZn ferrite confirmed

- Confirmed to be surface effect by dynamic calorimetry. D. Neumayr, D. Bortis, J. W. Kolar, ETH Zurich.
- A prototype with NiZn ferrite does not have this problem.

Talk Wed. 09:45,
“A Low-Loss Inductor ….”,
Session T12, Magnetics,
paper 1487, Yang, Hanson,
Perreault and Sullivan.



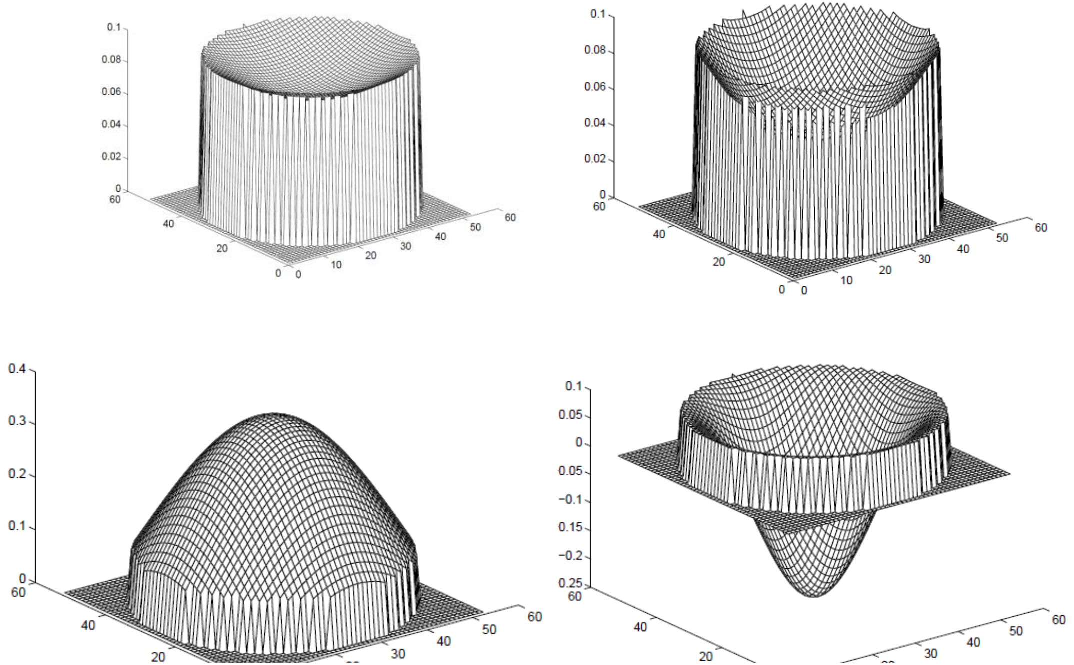
▲ Stack Of 1mm Plates

▲ Solid Sample

Dimensional Effects: plots of |B| in a round centerpost

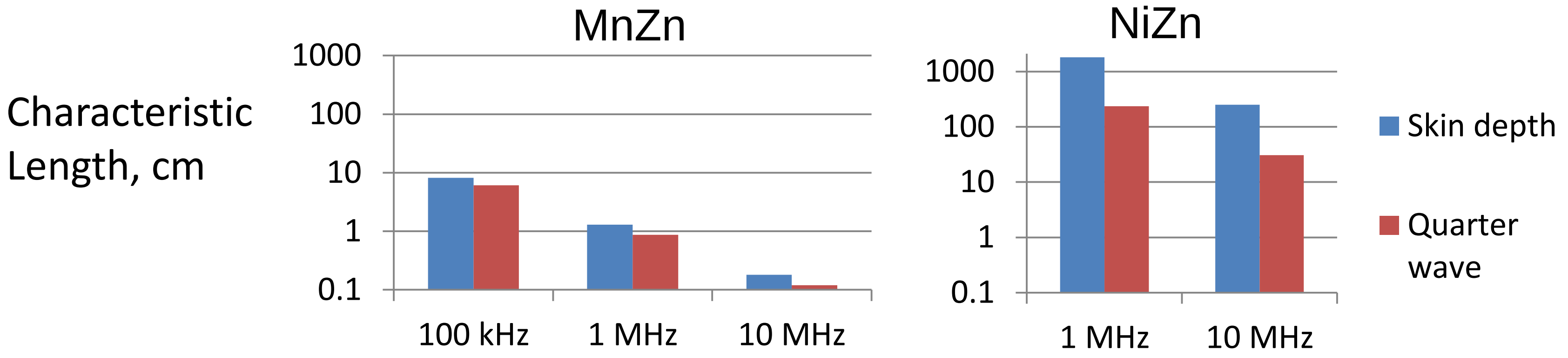
- Skin effect, affected by
  μ and σ
  (permeability and conductivity)

- Wave propagation
  (dimensional resonance)
  affected by μ and ε
  (ε = permittivity or dielectric const.)
  - Typ. $\varepsilon_r = 10^5$ for MnZn ferrite



- Figures from Glenn Skutt's excellent PhD thesis: "High-Frequency Dimensional Effects in Ferrite-Core Magnetic Devices," Virginia Tech, 1996.

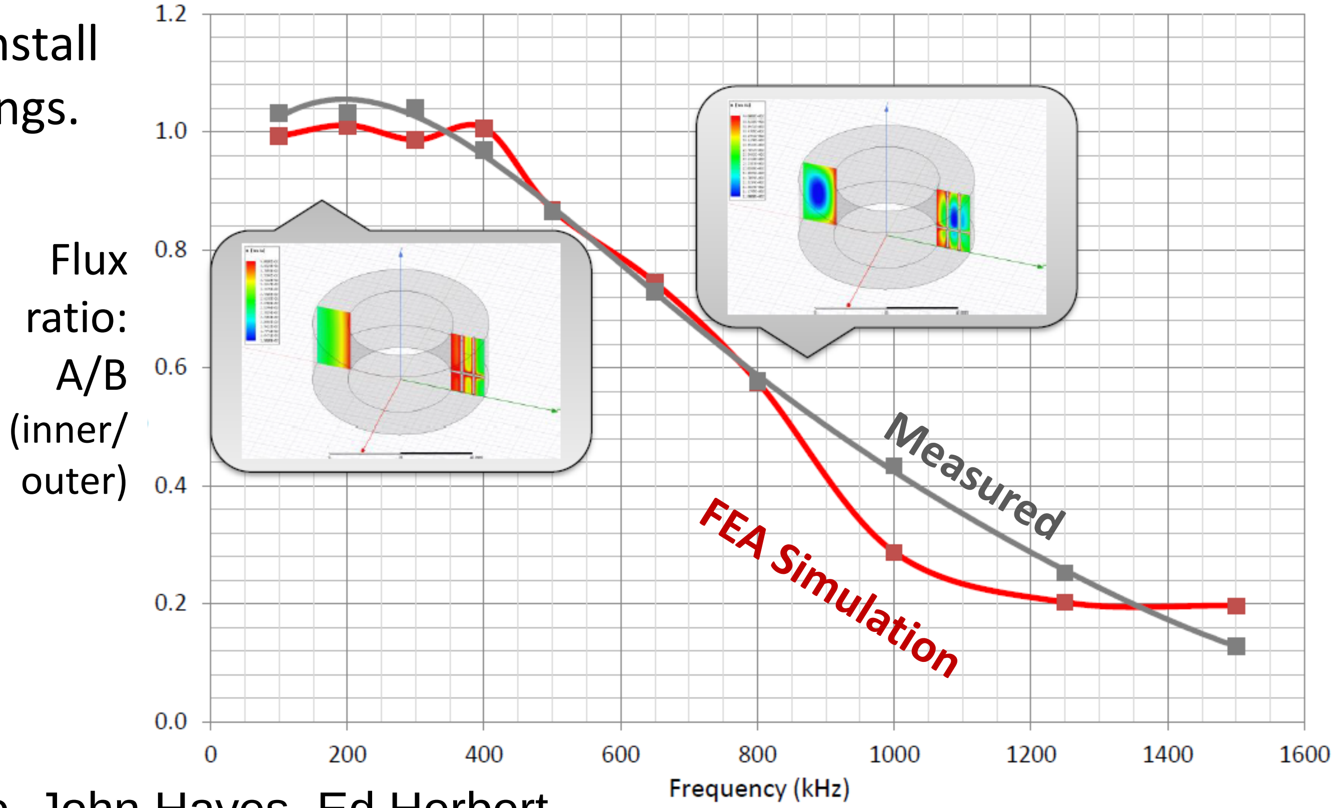
Rough core leg size for these effects



- For low loss, skin effect may be important sooner than shown.

SMA/PSMA/UCC experiments

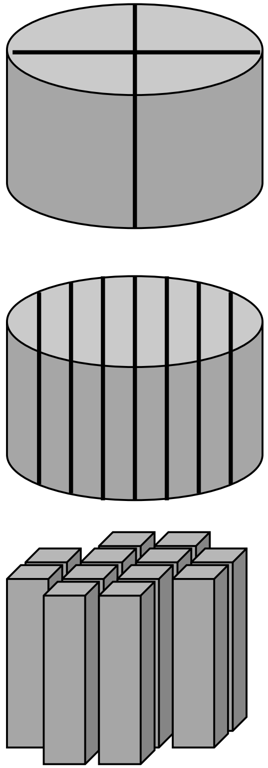
Drilled MnZn core to install sense windings.



Marcin Kacki, Myrek Rylko, John Hayes, Ed Herbert

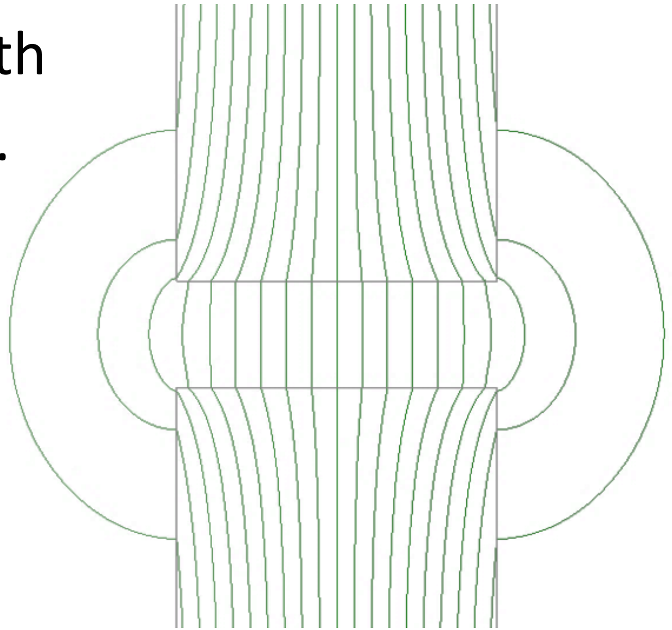
Dimensional effects: implications

- For large area core legs at high frequency:
  - Segmented, laminated, or “bundle of sticks” approach.
  - Measurement data taken on a different core size may not be adequate.
- Very rough idea of size and frequency thresholds
  - ~ 1 cm at 1 MHz with MnZn ferrite.
  - ~ 1 cm at 10 MHz with NiZn ferrite.
- Data on ε and ρ combined with streamlined modeling could avoid the need for loss measurement of every core size.
- Caution: ε and ρ vary with frequency and temperature.

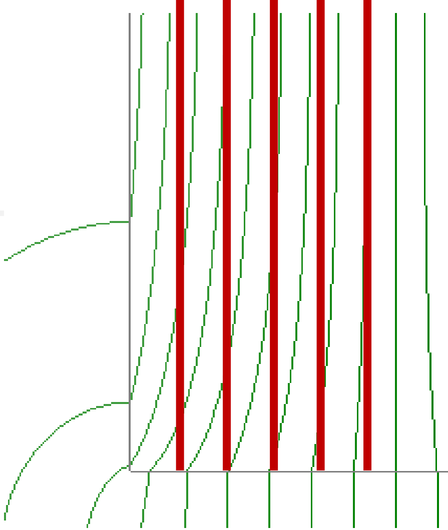


Afternoon: Fringing

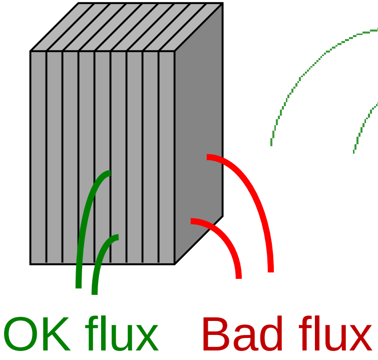
- Changes air-gap reluctance.
  - Calculations rarely needed: design based on reluctance $\mathcal{R}$, not gap length ℓ_g, and find the gap experimentally.
  - If needed, calculations are in the appendix.
- Extra winding loss.
- Extra core loss in laminated/tape wound cores: eddy currents.

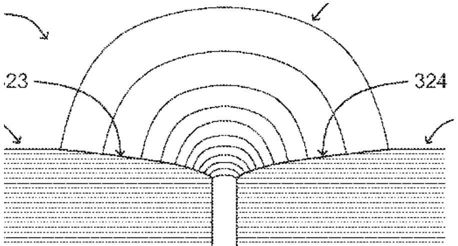


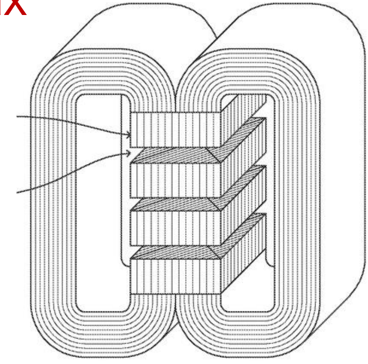
Fringing effect on core loss



- 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.
- Solutions exist: patented shapes and configurations [9],[10].

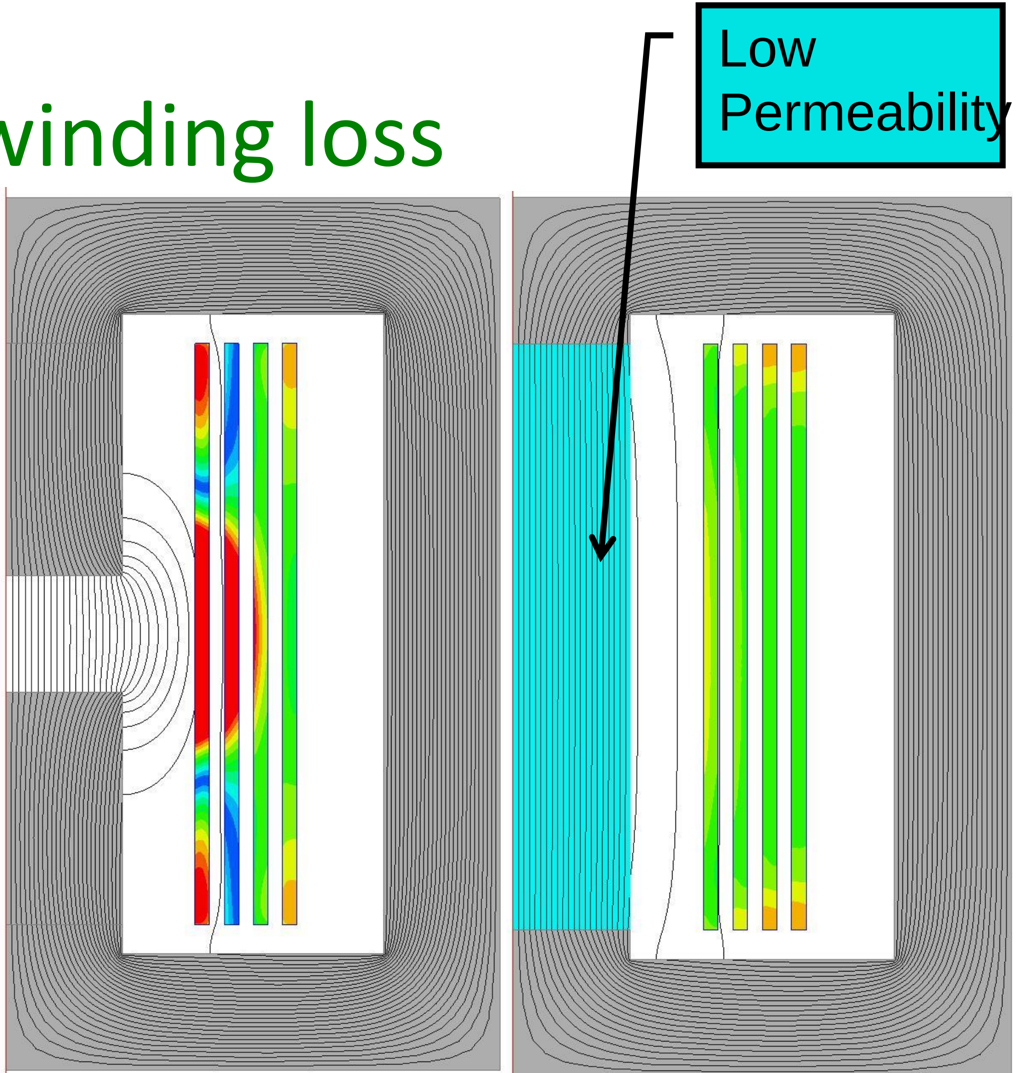






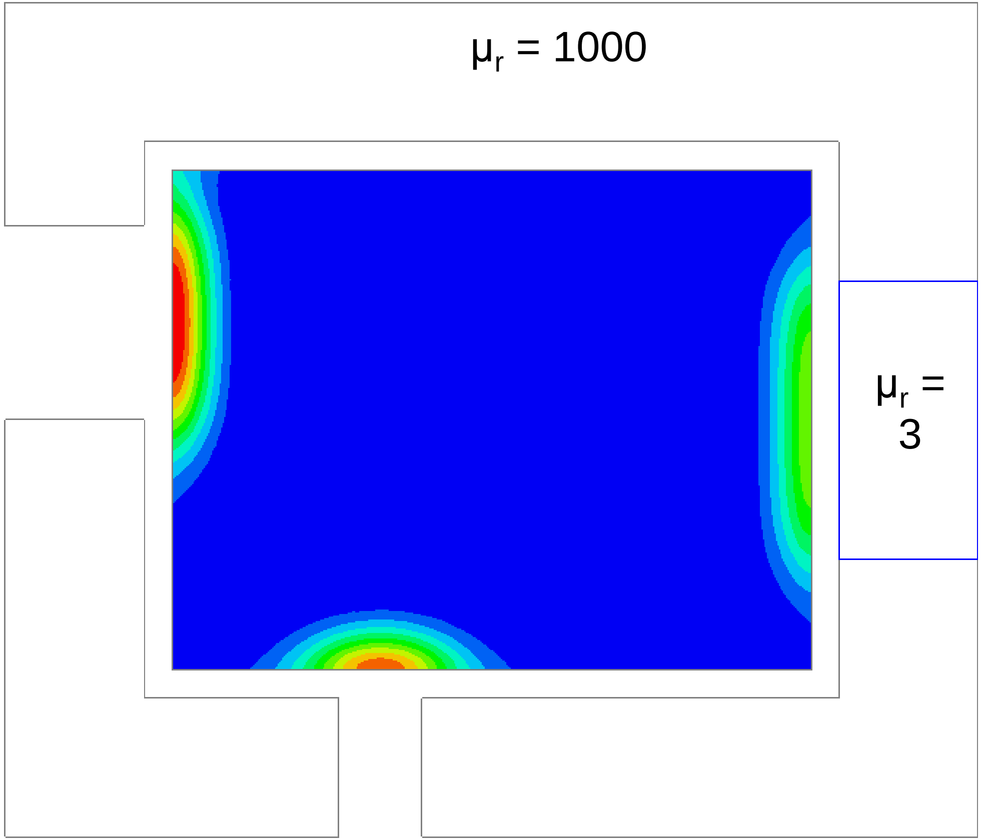
Fringing effect on winding loss

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



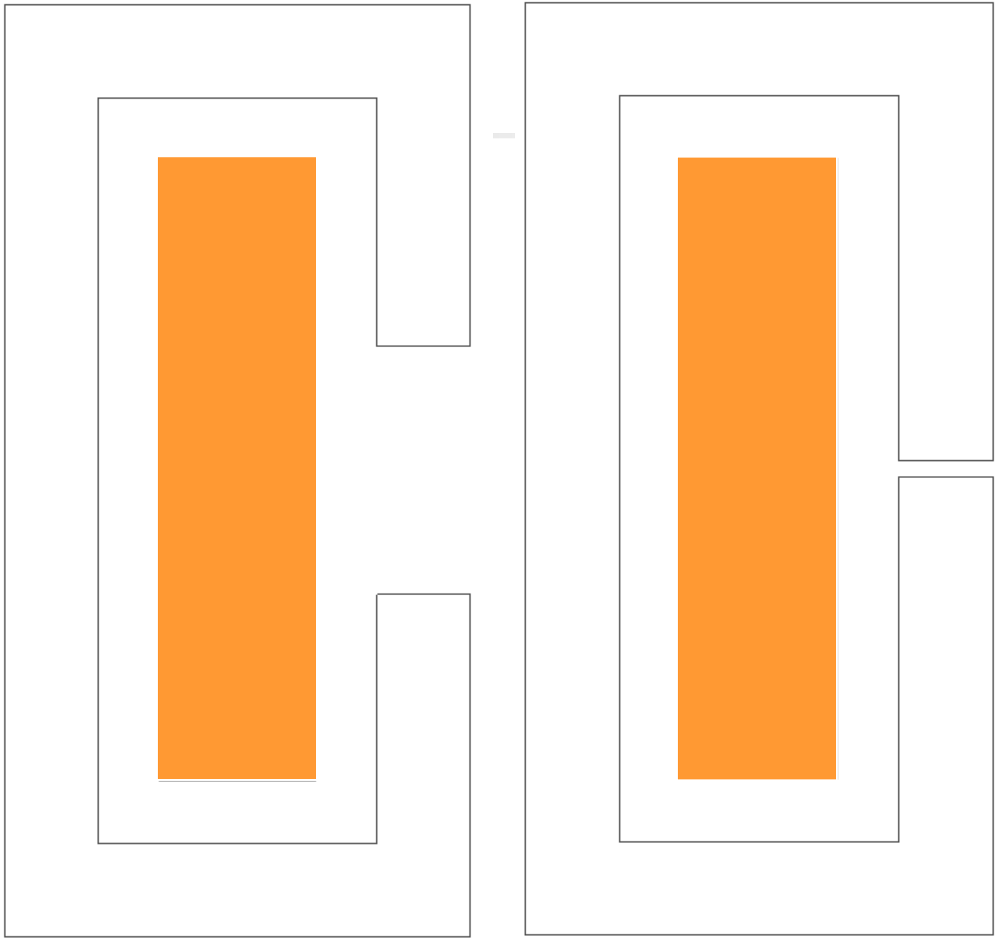
One conceptual approach

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



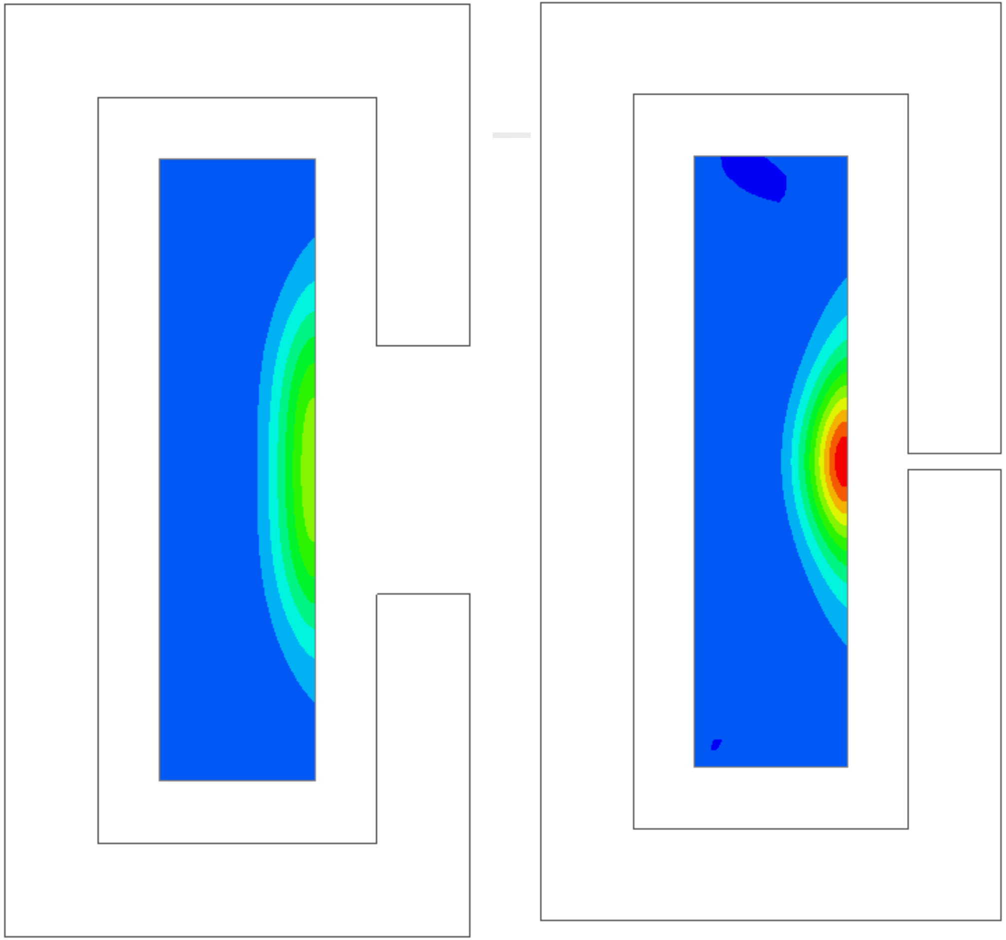
Single gap

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



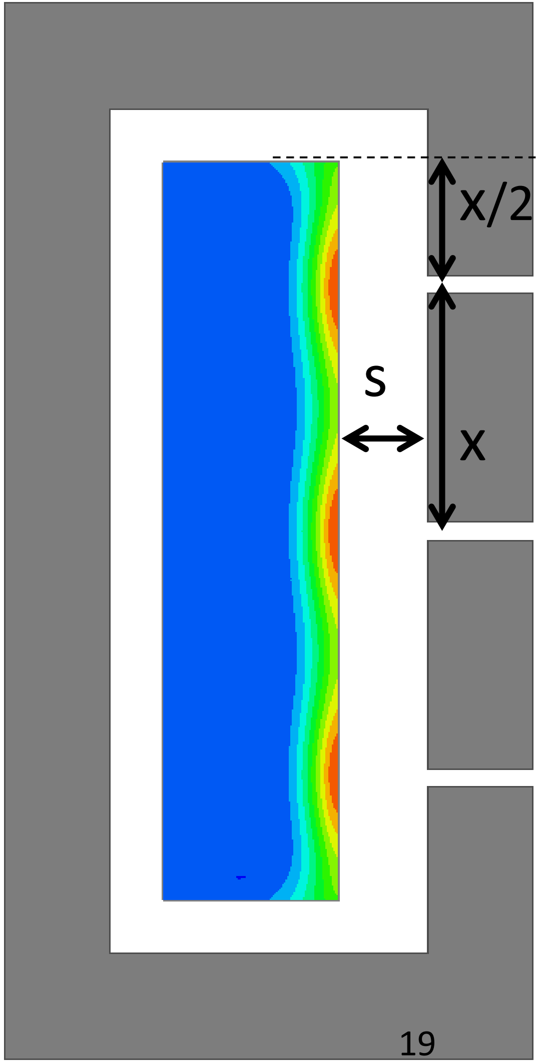
Single gap

- 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.



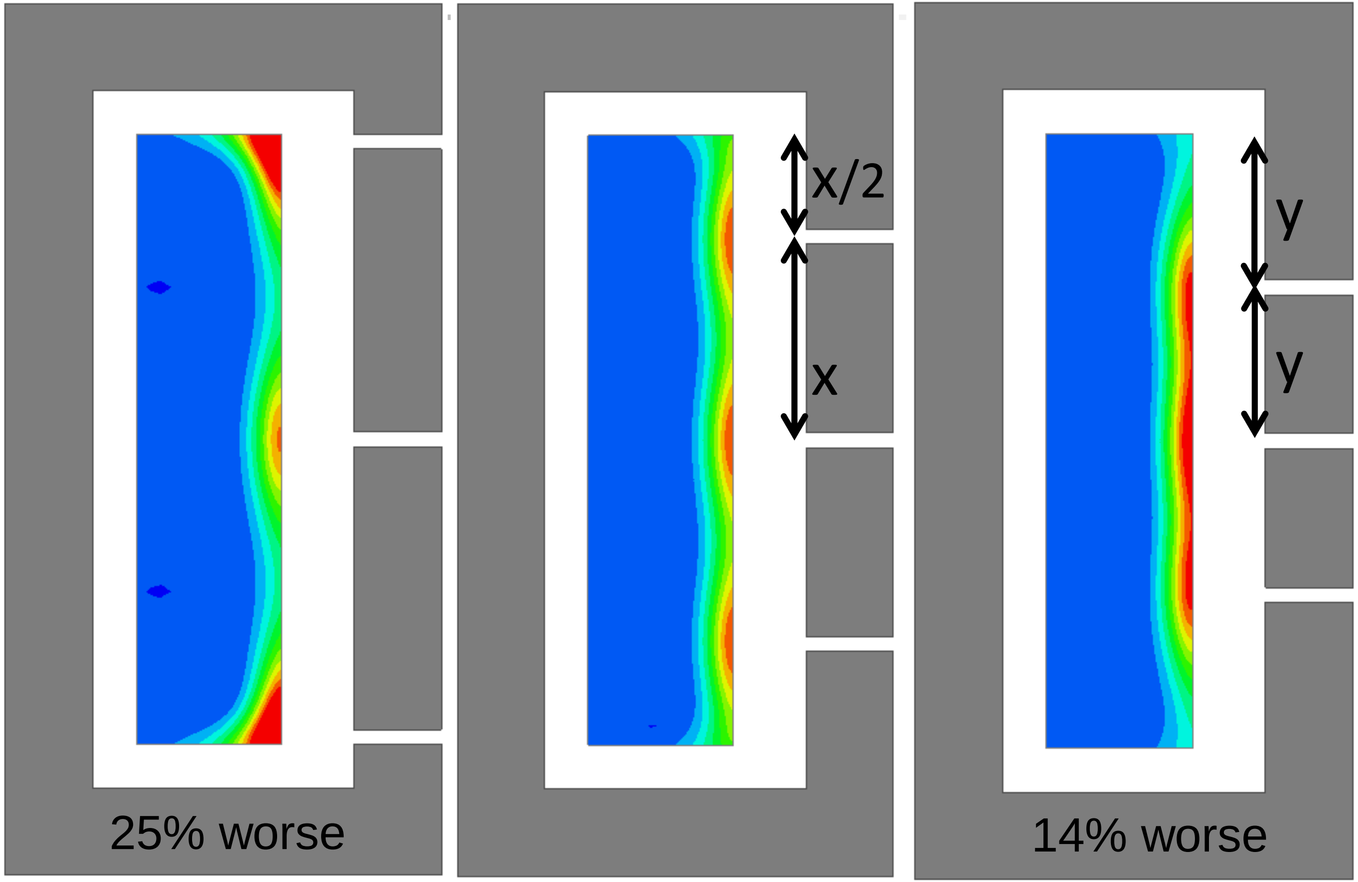
One design approach:

- 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 ref. [1]

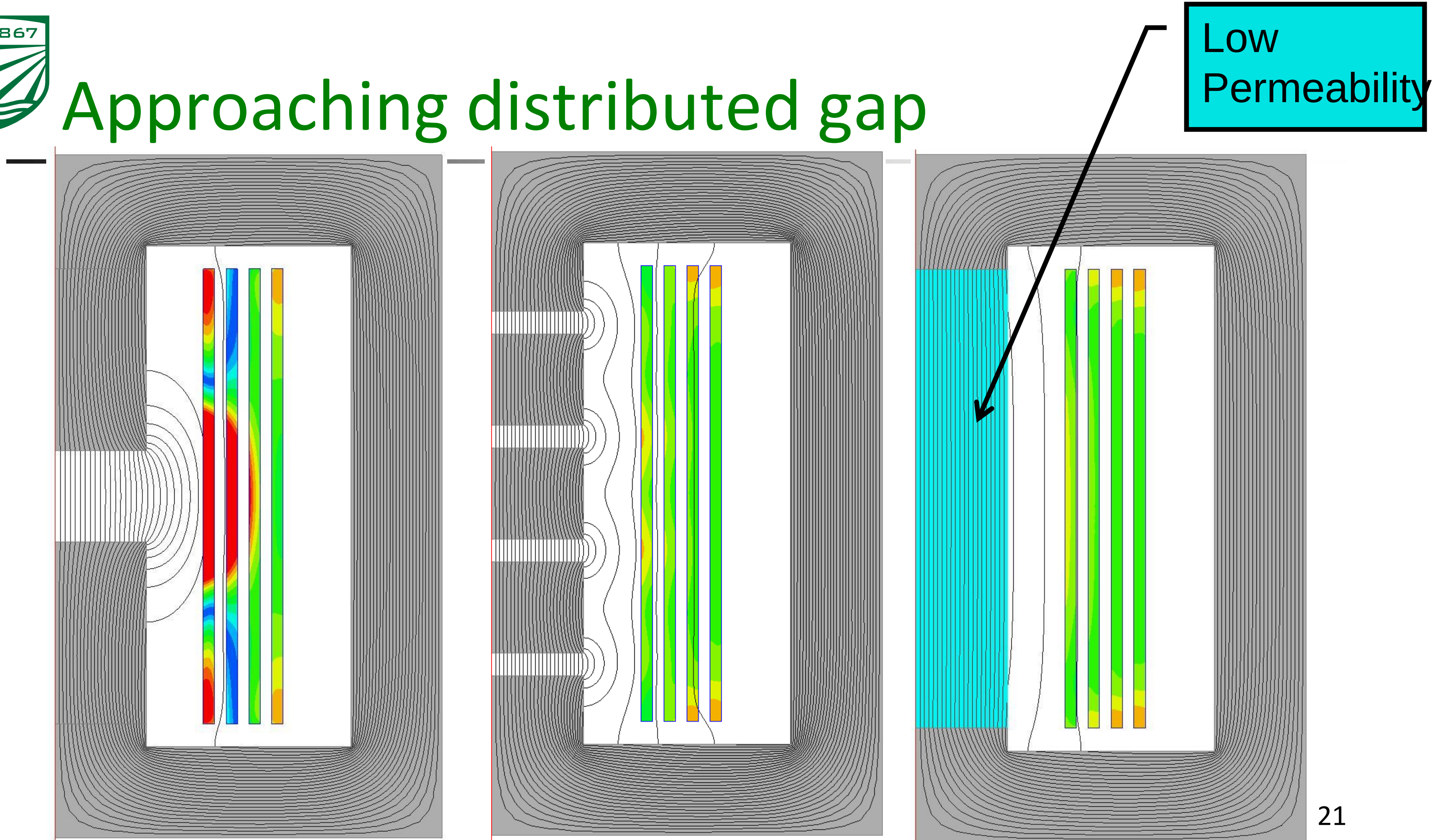


Are all equal spacings gaps equal?

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

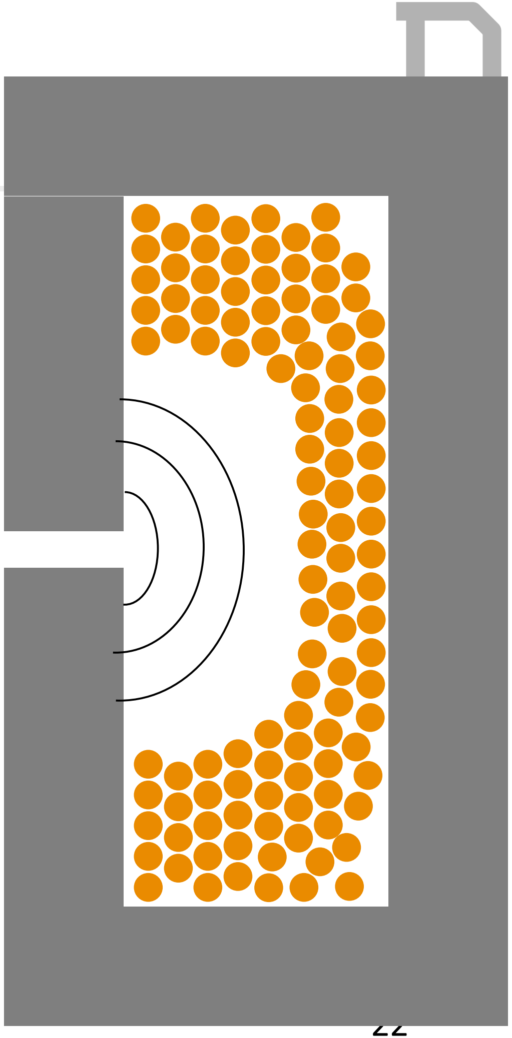


Approaching distributed gap



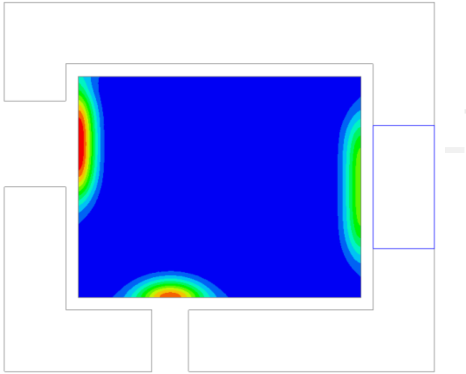
Winding shape optimization

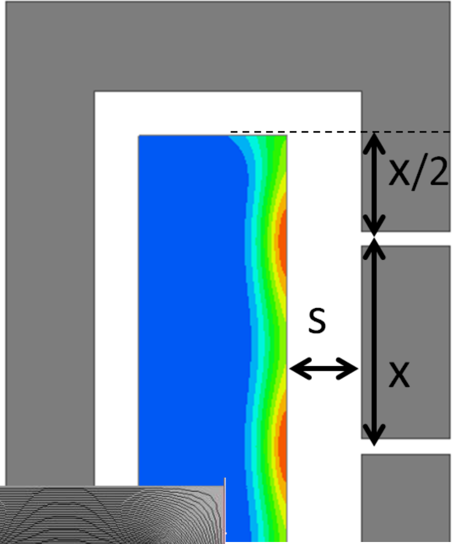
- Shape winding configuration to work ***with*** curved gap field.
- Applies to round wire and litz wire, not foil.
- Can actually work ***better*** than a distributed gap!
- Ad-hoc approach common, but full optimization is available [2,3,4].

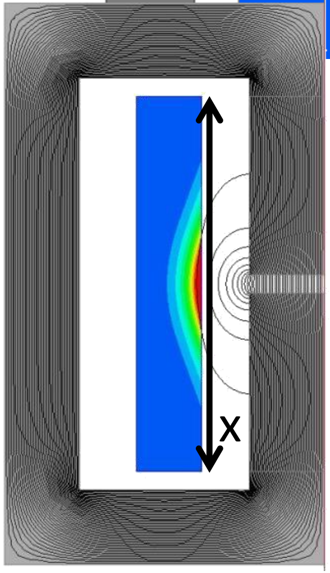


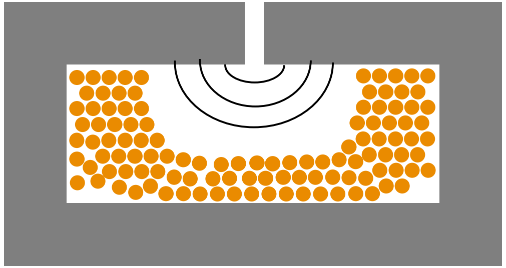
Fringing conclusions

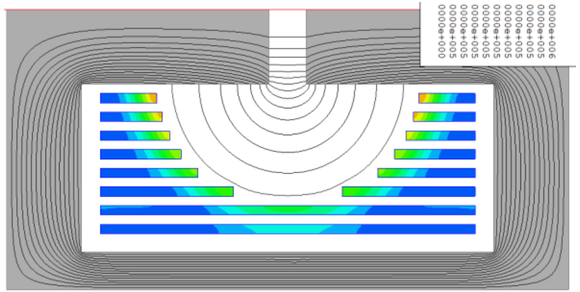
- Current flows near the gaps.
- A wider gap lowers resistance.
- Spacing $s > x/3$ is a good rule.
- Not all equally spaced gaps are equal—first gap x/2 from edge.
- Shaped windings with a single gap.











Ways forward on core loss: Industry

Magnetic material users

- Ask suppliers for data.
- Estimate skin effect for MnZn ferrites; consider segmented core.
- For non-sinusoidal waveforms: Barg refinement of iGSE (different parameters for each segment).

Magnetic material suppliers

- Data with dc-bias.
- Data in electronic form.
- Data for different core sizes.
- Data on resistivity (and permittivity?).
- Tolerances: min and max loss
- Data for square-wave drive.

Ways forward on core loss: research

- Integration of models for different loss effects.
  - Hope: effects considered separate maybe different aspects of the same effect.
  - Comprehensive, accurate, research models.
  - Practical, usable models for designers.
- Simple, nonlinear simulation models.
  - Linear models can't match observed behavior.

References: Core loss

[1] Sobhi Barg, K. Ammous, H. Mejbri, and A. Ammous, *"*An Improved Empirical Formulation for Magnetic Core Losses Estimation Under Nonsinusoidal Induction," IEEE Trans. Pow. Electr. 32(3), March 2017

[2] Benedict Foo, A. Stein, C. Sullivan, "A Step-by-Step Guide to Extracting Winding Resistance from an Impedance Measurement", APEC 2017.

[3] K. Venkatachalam, C. R. Sullivan, T. Abdallah, and H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," in *IEEE Workshop on Computers in Pow. Electr.*, 2002. https://engineering.dartmouth.edu/inductor/papers/IGSE.pdf

[4] Glenn Skutt , "High-Frequency Dimensional Effects in Ferrite-Core Magnetic Devices," Virginia Tech, PhD thesis 1996. Available for download from Virginia Tech.

[5] C. A. Baguley, U. K. Madawala, B. Carsten and M. Nymand, "The Impact of Magnetomechanical Effects on Ferrite B–H Loop Shapes," in *IEEE Transactions on Magnetics*, vol. 48, no. 8, pp. 2284-2292, Aug. 2012. doi: 10.1109/TMAG.2012.2191297

[6] A.P. Van den Bossche, D.M. Van de Sype, V.C. Valchev, "Ferrite Loss Measurement and Models in Half Bridge and Full Bridge Waveforms," IEEE Power Electronics Specialists Conference, 2005. doi: 10.1109/PESC.2005.1581834

Fringing 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.

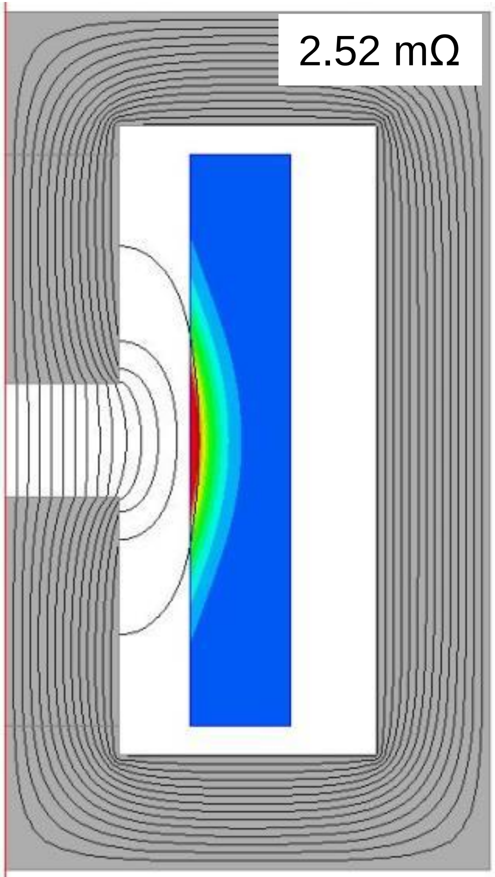
[8] Lundquist, Weyman, Vivien Yang, and Carl Castro. "Low AC resistance foil cut inductor." *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*. IEEE, 2014.

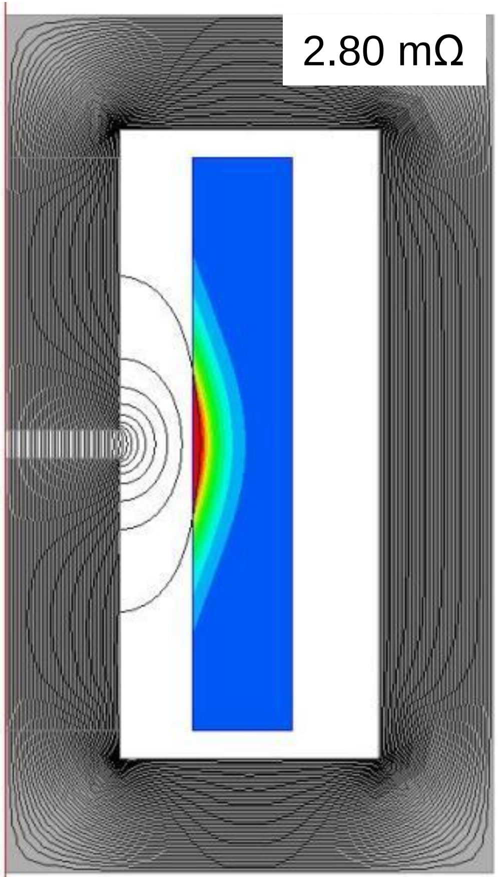
[9] US Pat. No. 9,123,461B2

[10] US Pat. No. 8,466,766

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