Core Loss Initiative: Technical

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Dartmouth Magnetics and Power
Electronics Research Group

THAYER SCHOOL OF
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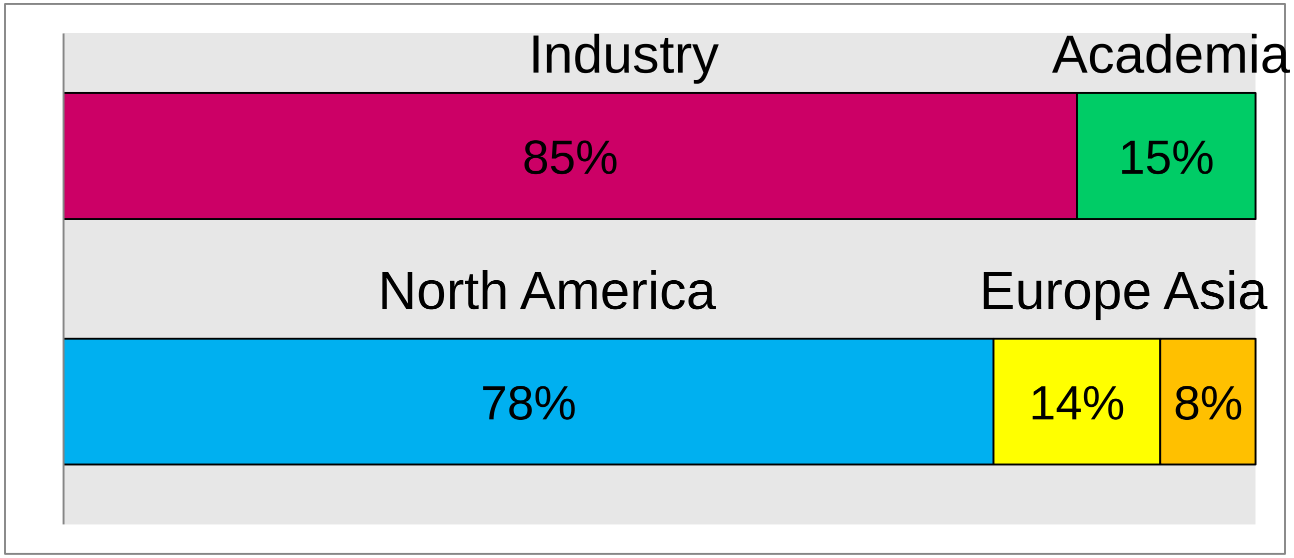
Saturday PSMA/PELS Magnetics Workshop

- 2nd Annual Workshop last Saturday, March 25.
- Approximately 150 attendees



- Presentations, panel discussions, technology demonstrations.

This talk

- Brief review/overview of Saturday's workshop.
- Follow-up on topics of interest that came up.

Topics discussed at Saturday workshop

- Discussed:
  - New and improved core materials
  - Core loss measurement
  - Modelling approaches for core and winding loss
- Topics of interest for future:
  - Fringing losses
  - Core dimensional effects
  - Impact of eddy currents on inductance; physics of ac losses.
- To-do: Cooperation on core loss data and modeling standardization with
  - Electronics Transformers Technical Committee (ETTC),
  - PSMA magnetics committee (Power Sources Manufacturers' Association)
  - IMA (International Magnetics Assoc. sub-group of TTA (The Transformer Assoc.))

Winding models vs. Core models

- Linear, well known material properties.
- Behavior is a solution to Maxwell's equations.
- Numerical, analytical, or mixed solutions.
- Can be accurately approximated by linear circuit networks, given enough RLC elements (usually just RL).

- Nonlinear material properties, known only through measurements.
- Models are behavioral, based on measurements.
  - Physics-based micromagnetic models exist, but can't address ferrite loss yet.
- Circuit models based on RLC elements only can't capture nonlinear behavior.

Needs in core loss data, testing, and modeling

- **Material data and testing**
  - Data consistency between manufacturers:
    More from Chuck Wilde, Dexter, at 10:40
  - Material data in standardized electronic form.
  - More comprehensive data:
    - DC bias effect
    - Waveform effect
  - Tolerance: batch-to-batch variations.
- Influence of core shape on loss
- **Modeling**
  - Improve accuracy while retaining modest data requirements.
  - Dynamic simulation models for SPICE and time-domain field simulation.

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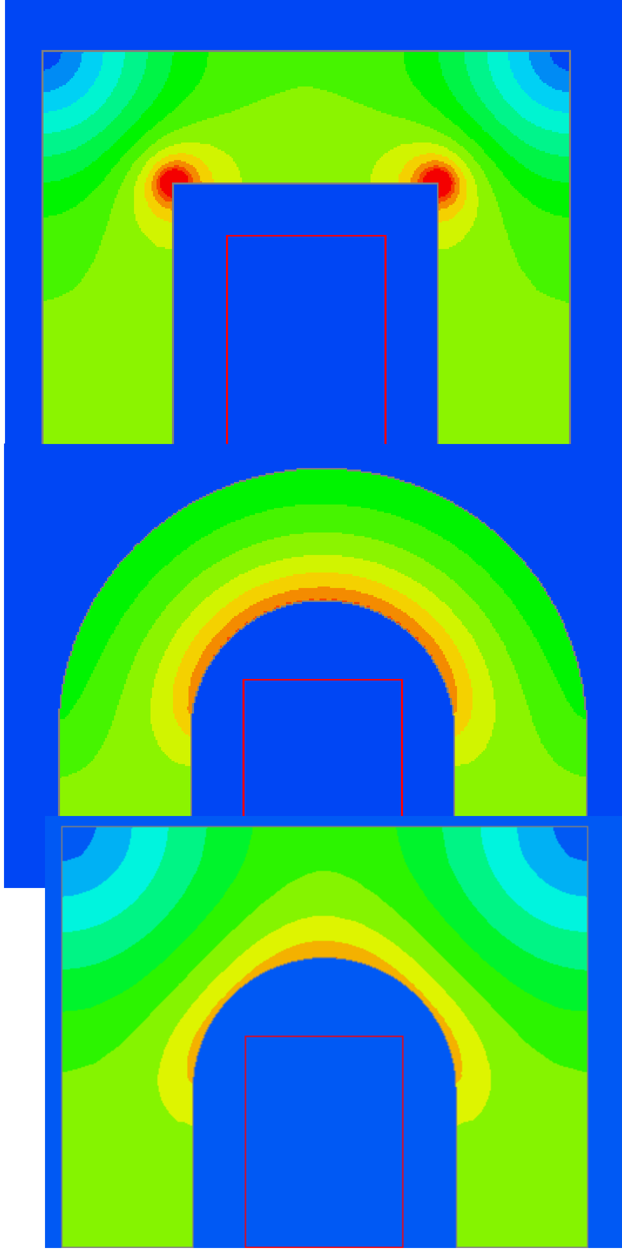
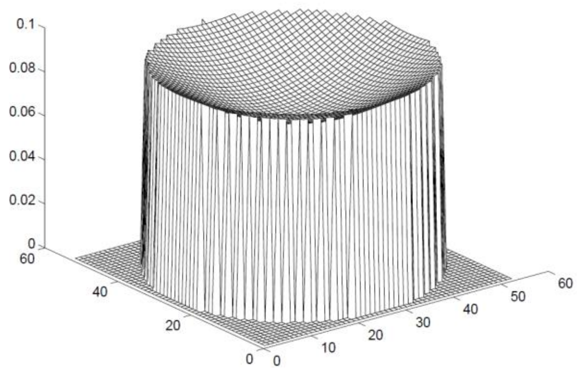
Influence of core shape and size

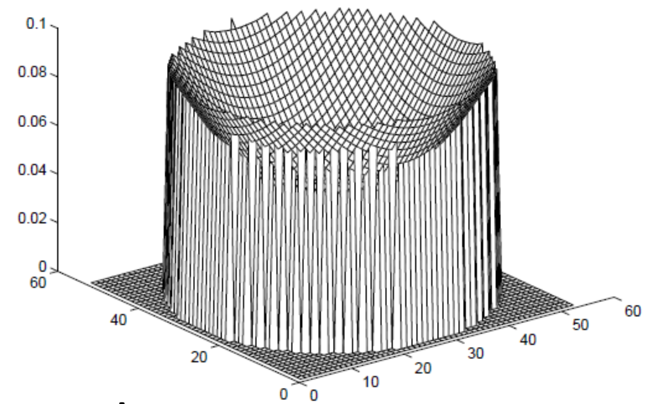


- Straightforward to model and analyze:
  - Flux crowding at corners.
  - Cross section variation.
- Complex, known physics; uncertain parameters:
  - Skin effect in core
  - Dimensional resonance
- Poorly understood:
  - Higher loss on surfaces than in bulk.
    - Loss when flux crosses surface similar to loss in several mm of bulk.
    - See Johan Kolar's examination of this issue.

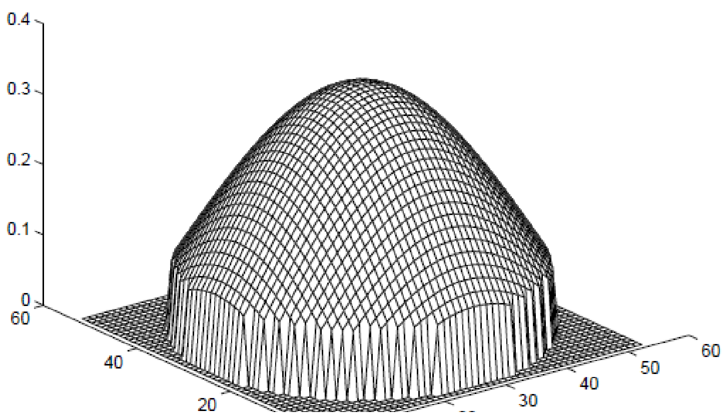
Dimensional Effects: plots of |B| in a round centerpost

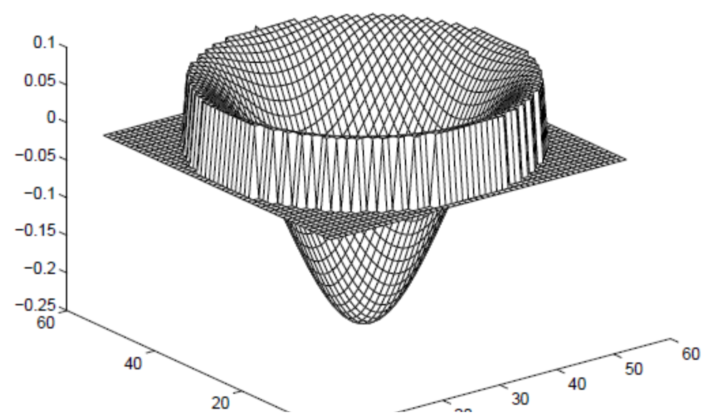
- Skin effect, affected by μ and σ (permeability and conductivity)





- Wave propagation, affected by μ and ε (permittivity and dielectric const.)





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

Typical skin depths and wavelengths: 1^{st} order calculation

Skin depth

	100 kHz	1 MHz	10 MHz
MnZn Ferrite (3F46)	8.2 cm	1.3 cm	0.18 cm
NiZn Ferrite (67)	80 m	18 m	2.5 m

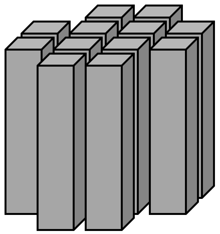
$\lambda/4$

	100 kHz	1 MHz	10 MHz
MnZn Ferrite (3F46)	6.1 cm	0.87 cm	0.12 cm
NiZn Ferrite (67)	2 m	237 cm	30.6 cm

- Approximate values: based on typical resistivity and permittivity vs. frequency from Ferroxcube catalog: not for these specific materials.
- For cross sections (e.g., centerpost diameter) at or below these sizes, there shouldn't be much effect.
- However, Fair-Rite data presented Saturday shows that 10 MHz performance of 67 material starts to drop at 1.25 cm cross section.

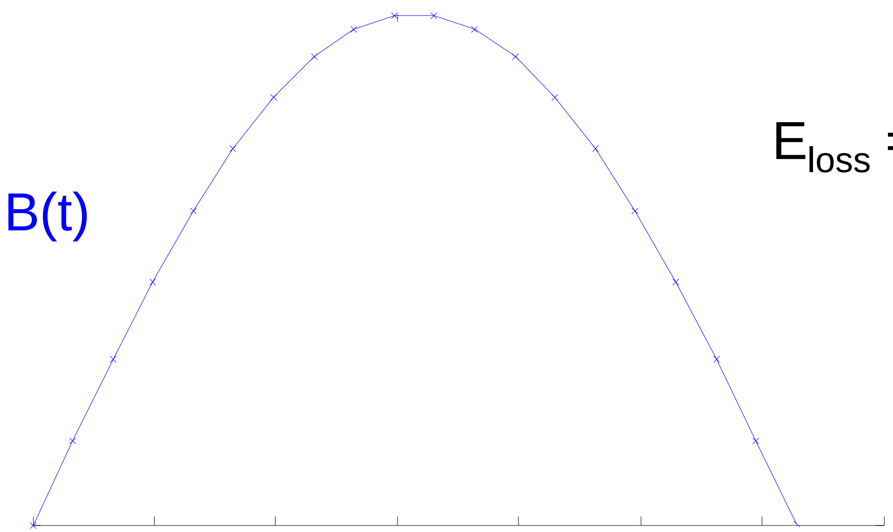
Dimensional effects: implications

- For large area core legs at high frequency:
  - A "bundle of sticks" approach may be useful.
  - 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.
- More data and streamlined modeling could help avoid the need for full loss measurement of every core size.

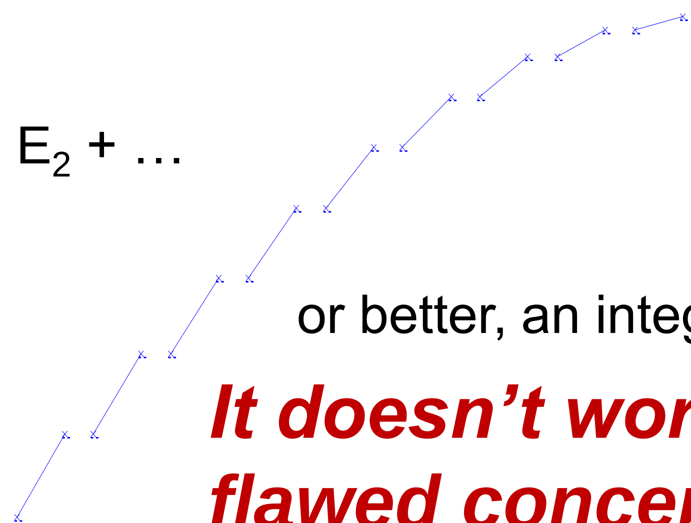


Waveform effect on core loss: Concepts, rather than how-to

- Initial hope in GSE model: instantaneous loss depends on B and dB/dt: $p(t) = p(B(t), dB/dt)$
  - If this worked, you could add up loss for incremental time segments:



$E_{loss} = E_1 + E_2 + \ldots$

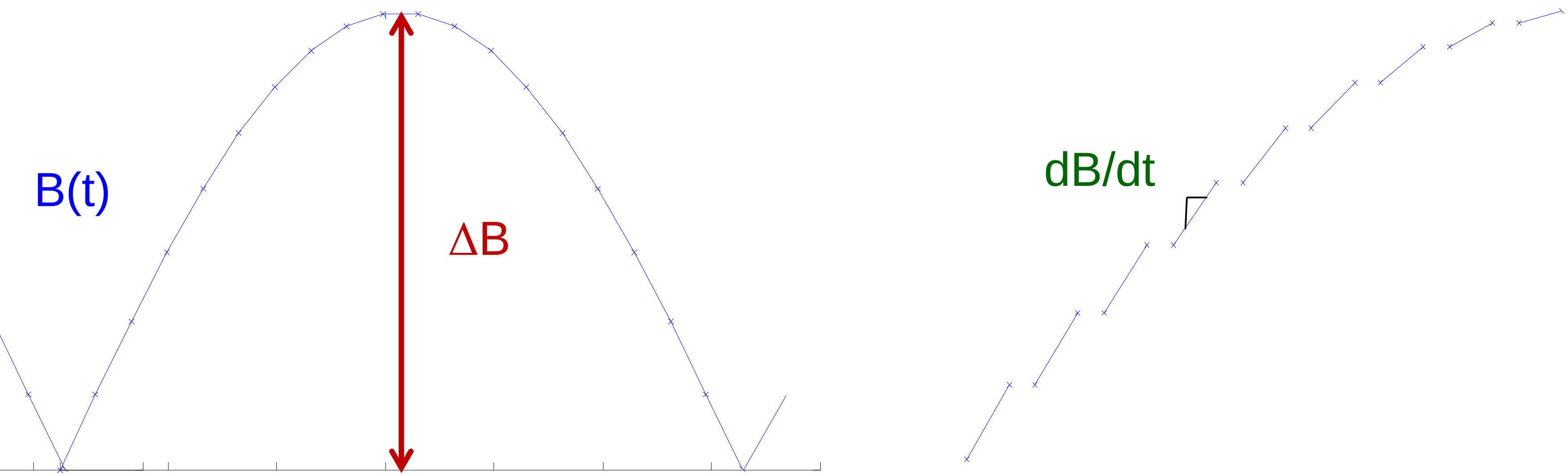


or better, an integral…

It doesn't work: flawed concept

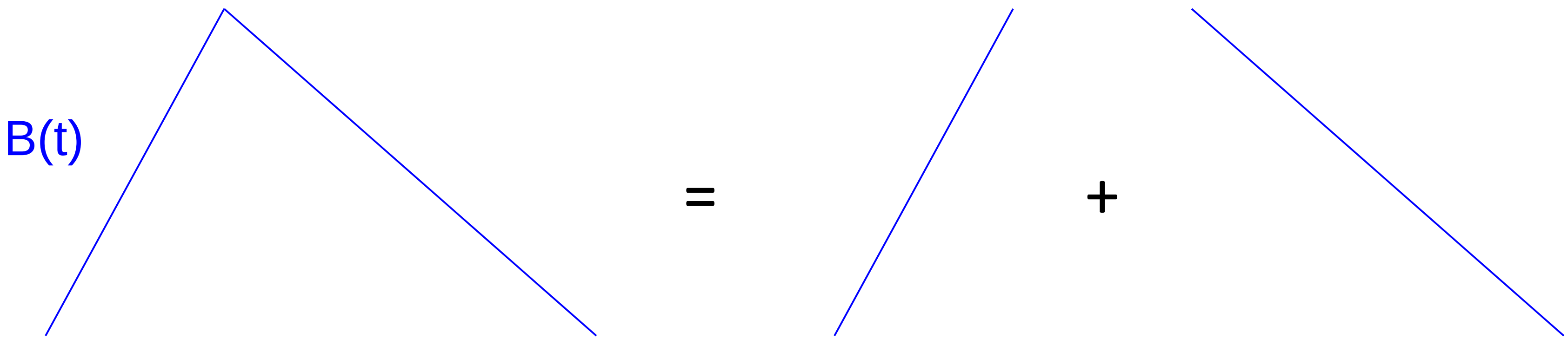
Improvement that enabled iGSE

- Loss depends on segment dB/dt and on ***overall*** ΔB



Composite waveform method

- Same concept as GSE: add up independent loss for each segment.

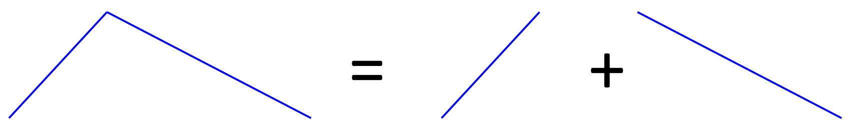


$$E_{loss} = E_1 + E_2$$

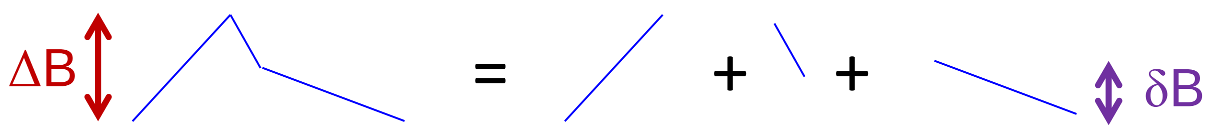
- Unlike the GSE, this works pretty well in simple cases:
  - Waveforms where ΔB is the same for the segment and the whole waveform!
  - It reduces to the same assumptions as the iGSE.

What we know how to do for non-sinusoidal waveforms:

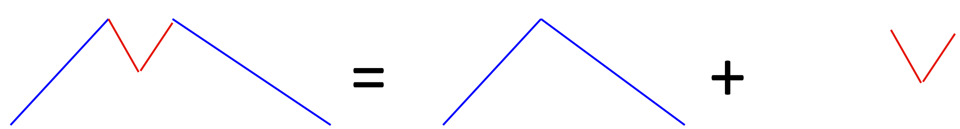
- For simple waveforms, add up the loss in each segment.



- For waveforms with varying slope, add up the loss for each segment, considering overall ΔB and segment δB.



  - See iGSE paper for how those factor in.
- For waveforms with minor loops, separate loops before calculating loss (see iGSE paper).

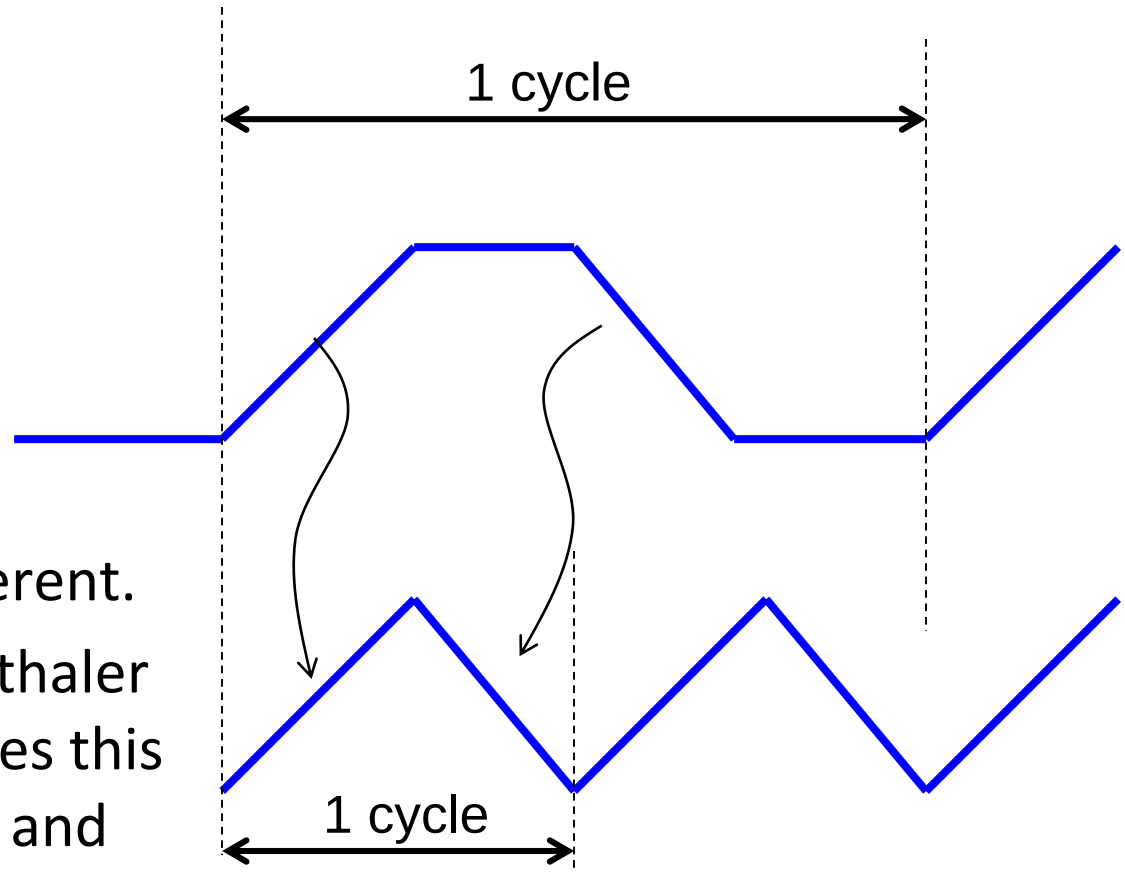


Loss models for each segment

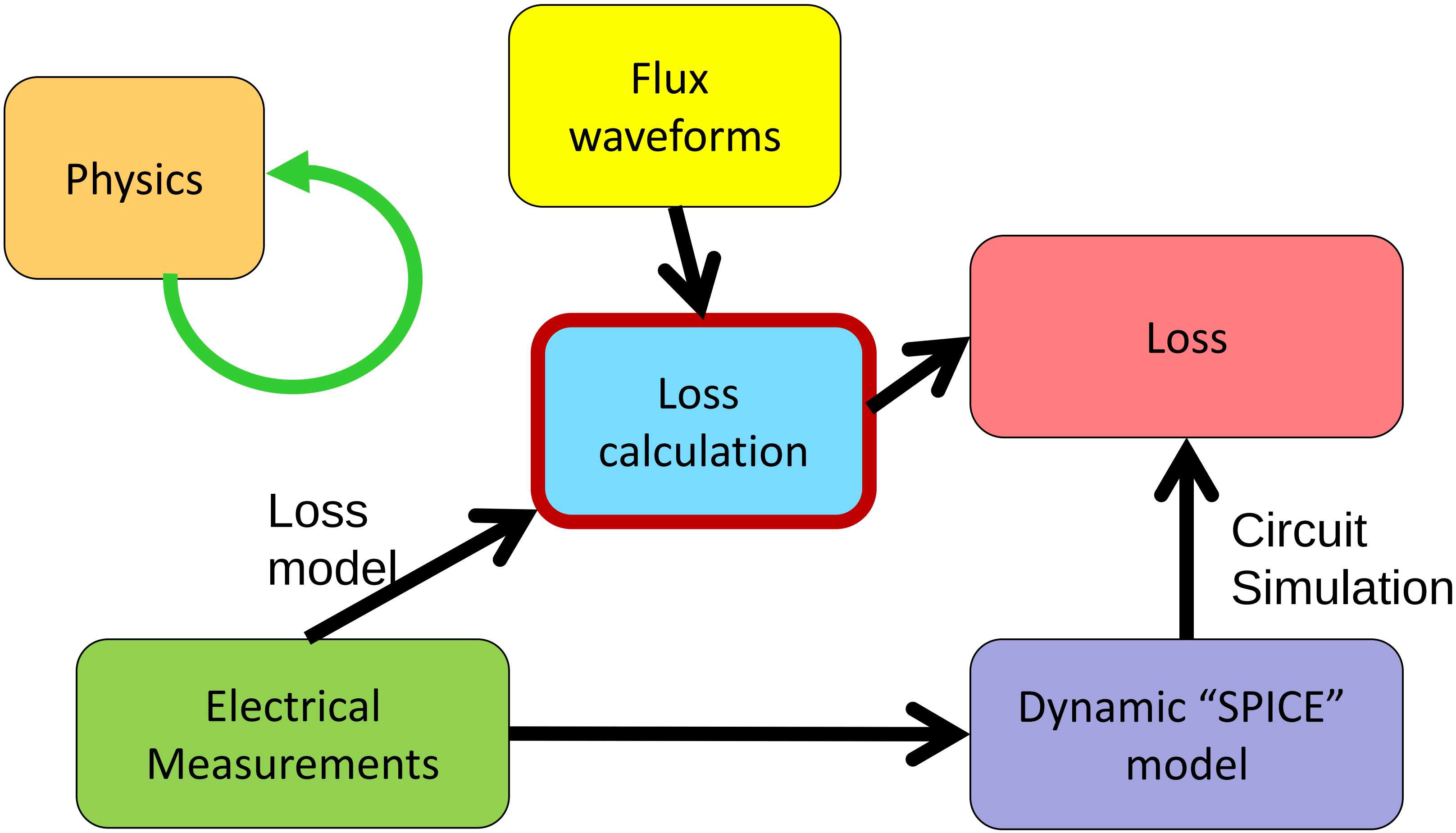
- iGSE derives them from a Steinmetz model
  - Limitation: Steinmetz model holds over a limited frequency range.
- Loss map model uses square-wave data directly for a wide frequency range.
  - Clearly better if you have the data.
  - Can also map with different dc bias levels.
- Sobhi Barg (Trans. Pow. Electr., March 2017) shows that the iGSE gets much more accurate if you use different Steinmetz parameters for each time segment in a triangle wave.

Limitation for all of the above

- “Relaxation effect”
- Simple theory says loss for one cycle should be the same for both flux waveforms.
- In practice, it’s different.
- i^2GSE (Jonas Mühlethaler and J. Kolar) captures this but is cumbersome and requires extensive data.



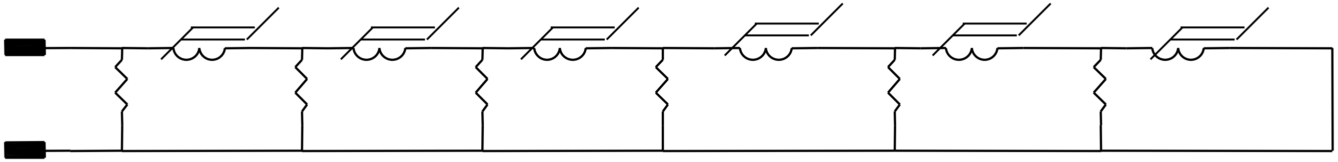
Core models



Flux waveforms
Physics
Loss
Loss calculation
Loss model
Circuit Simulation
Electrical Measurements
Dynamic "SPICE" model

Core simulation models

- Challenge: how to include nonlinearity.
- ***Example:*** Cauer 1 network to model saturation behavior and frequency-dependent permeability in nanocrystalline tape-wound cores.



  - Successfully matched pulse behavior in high-amplitude operation (Sullivan and Muetze, IAS 2007)
  - Did not examine loss behavior.
- Open question: what model structures capture dynamic nonlinear behavior correctly?

Winding models

- I presented more topics on Saturday—slides will be available.
- Today: two things that were left out Saturday:
  - ***Simple*** litz-wire modeling.
    (Winging it with litz can result in higher loss than solid wire.)
  - Another free tool to generate a SPICE model based on a 1-D winding model.

Litz wire can be easy to model

- Sounds complicated to model accurately, but actually easier than Dowell's analysis:

Number of strands

Number of turns

Strand diameter

$$F_R = \frac{R_{ac}}{R_{dc}} = 1 + \frac{(\pi n N_s)^2 \, d_s^6}{192 \cdot \delta^4 b^2}$$

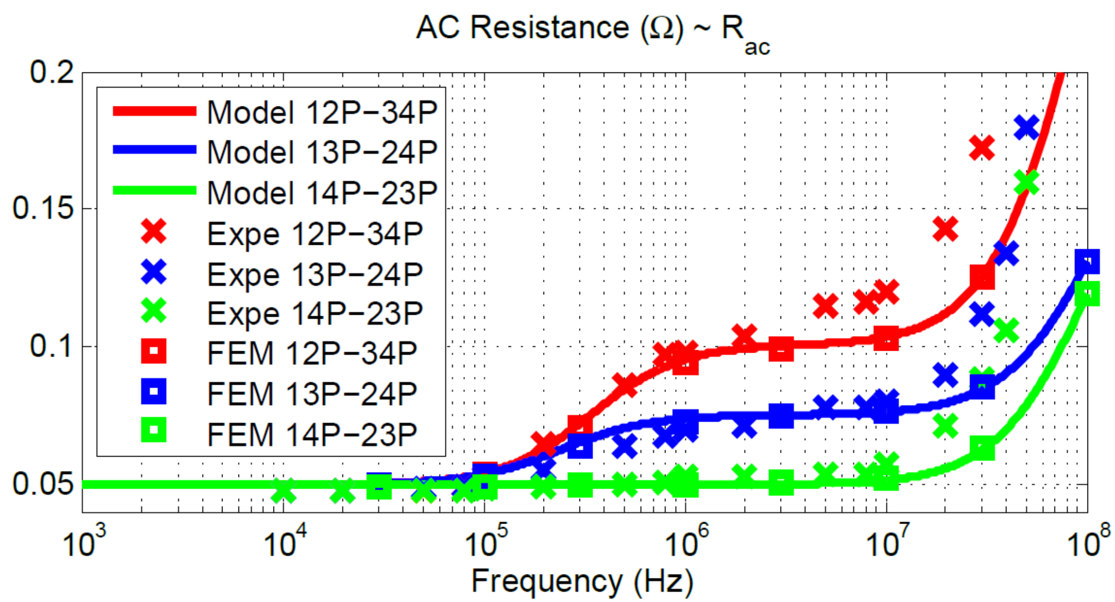
Window breadth

Skin depth

- No PhD needed.
- Full explanation at http://bit.do/simplitz , plus:
  - Even simpler calculation of recommended n.
  - Simple wire construction guidelines to avoid problems.
  - Easy calculation of fringing loss.
  - Excel spreadsheet.
  - Based on 2014 APEC, "Simplified Design Method for Litz Wire"

SPICE models for 1D winding structures: foil, PCB, etc.

- M2Spice: free tool to automatically generate a SPICE model .
- No limit on interleaving, parallel windings, etc.
  - Model correctly predicts distribution of current between parallel windings when you run SPICE!
- By Minjie Chen (Princeton), Dave Perreault, Stephanie Pavlick and Samantha Gunter (MIT)
- Sample results:



Summary

- Discussions underway to obtain better core-loss data: ETTC, PSMA magnetics, IMA.
- Core loss dimensional effects: skin effect and wave propagation (dimensional resonance).
  - With nominal parameters, becomes an issue ~1 cm or bigger and 1 MHz or higher for MnZn ferrite. Perhaps also ~ 1 cm for NiZn ferrite.
  - We need easy-to-use models and better data.
- Waveform-based core loss models can work well, but data with dc bias is the most important missing piece.
- Dynamic (SPICE) core-loss models need to include nonlinearity correctly: more work is needed.
- Litz wire can be easy to model: http://bit.do/simplitz.
- Automatic SPICE models for 1D geometries, including complex ones: M2SPICE.