Overview of Modelling Methods

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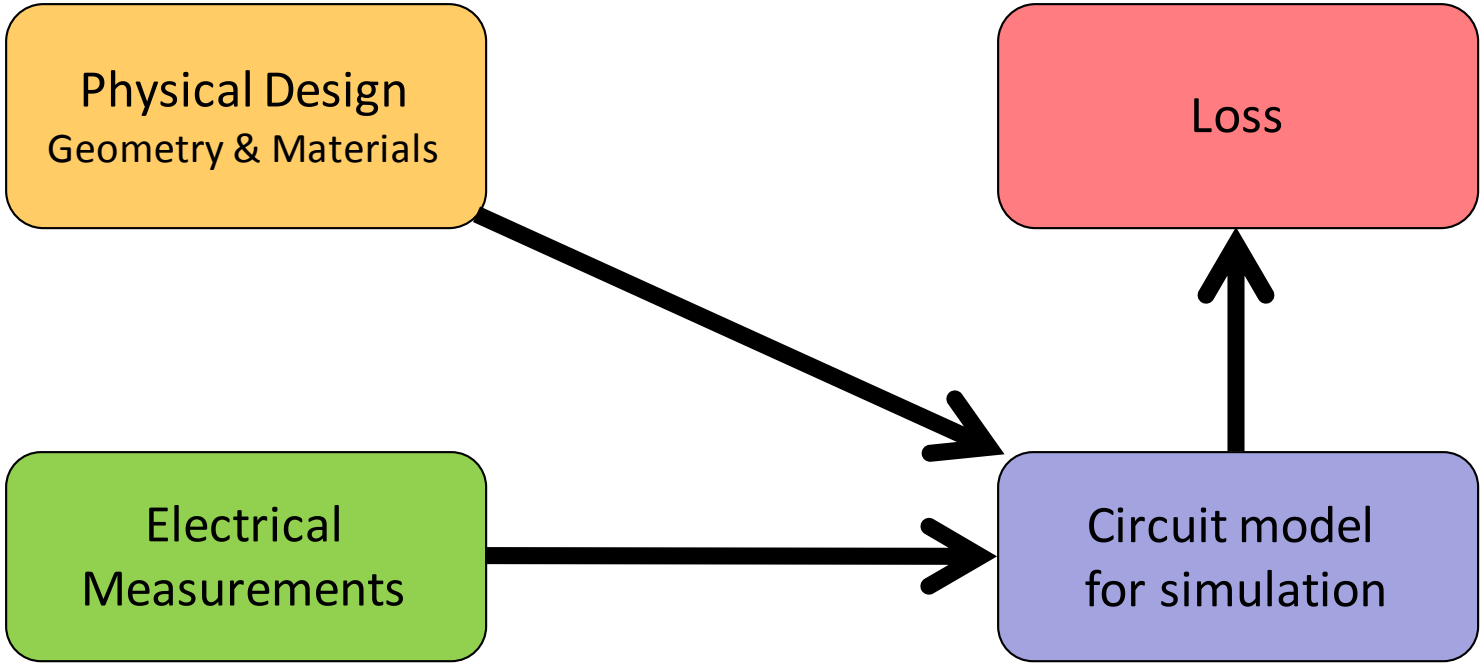
Winding models vs. Core models

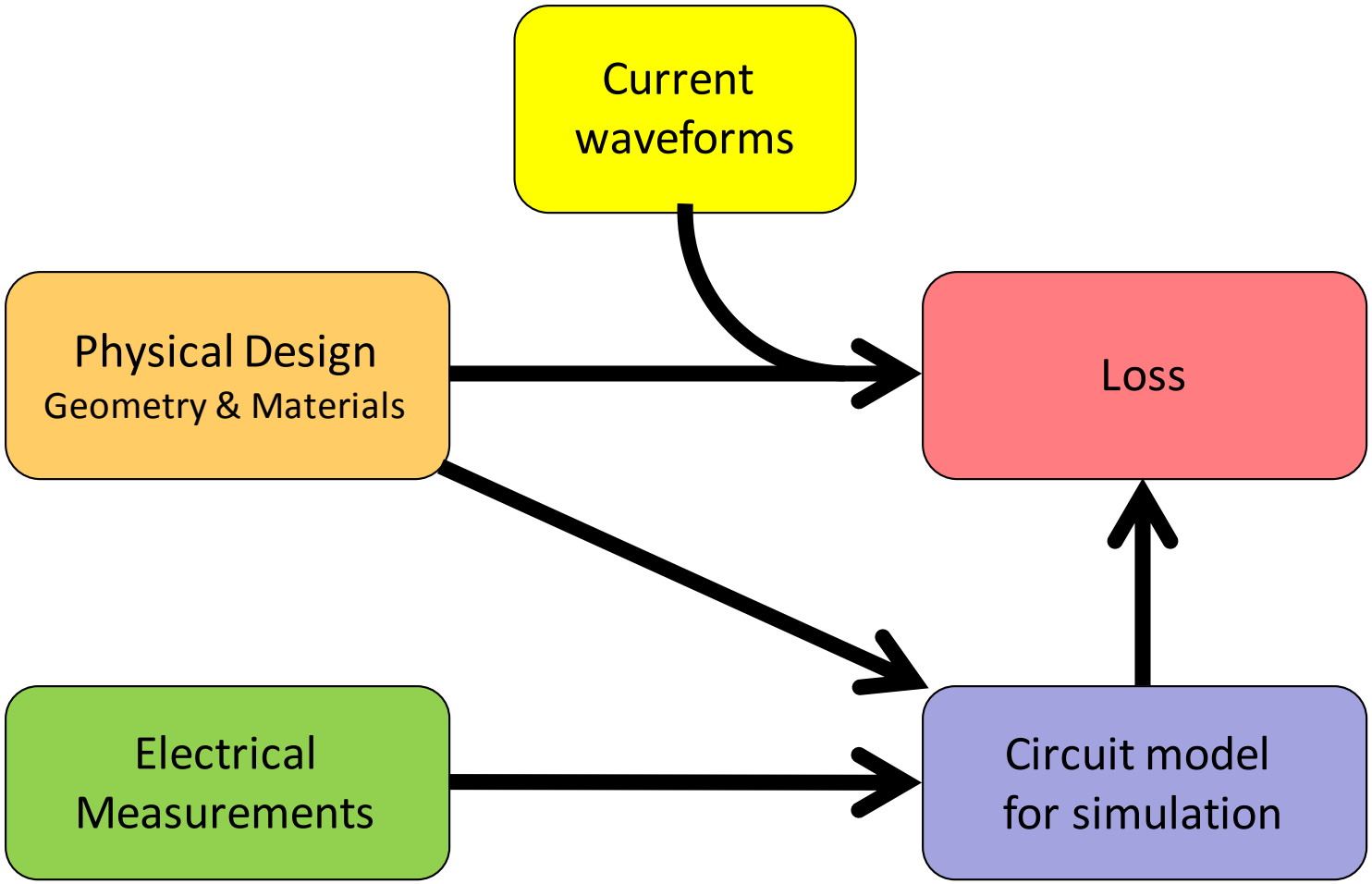
- Linear, well known material properties.
- Behavior is a solution to Maxwell's equations.
- Numerical, analytical, or mixed solutions.
- Can be accurately approximated by linear circuit networks, given enough RLC elements (usually just RL).

- 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.

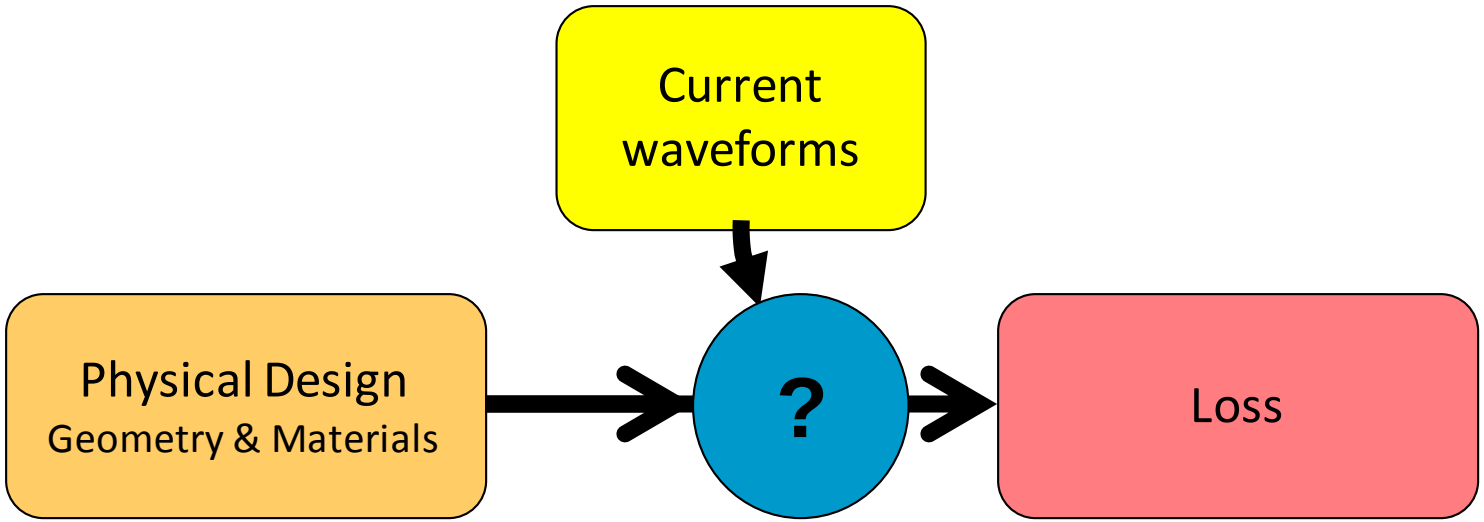
Winding models



Winding models



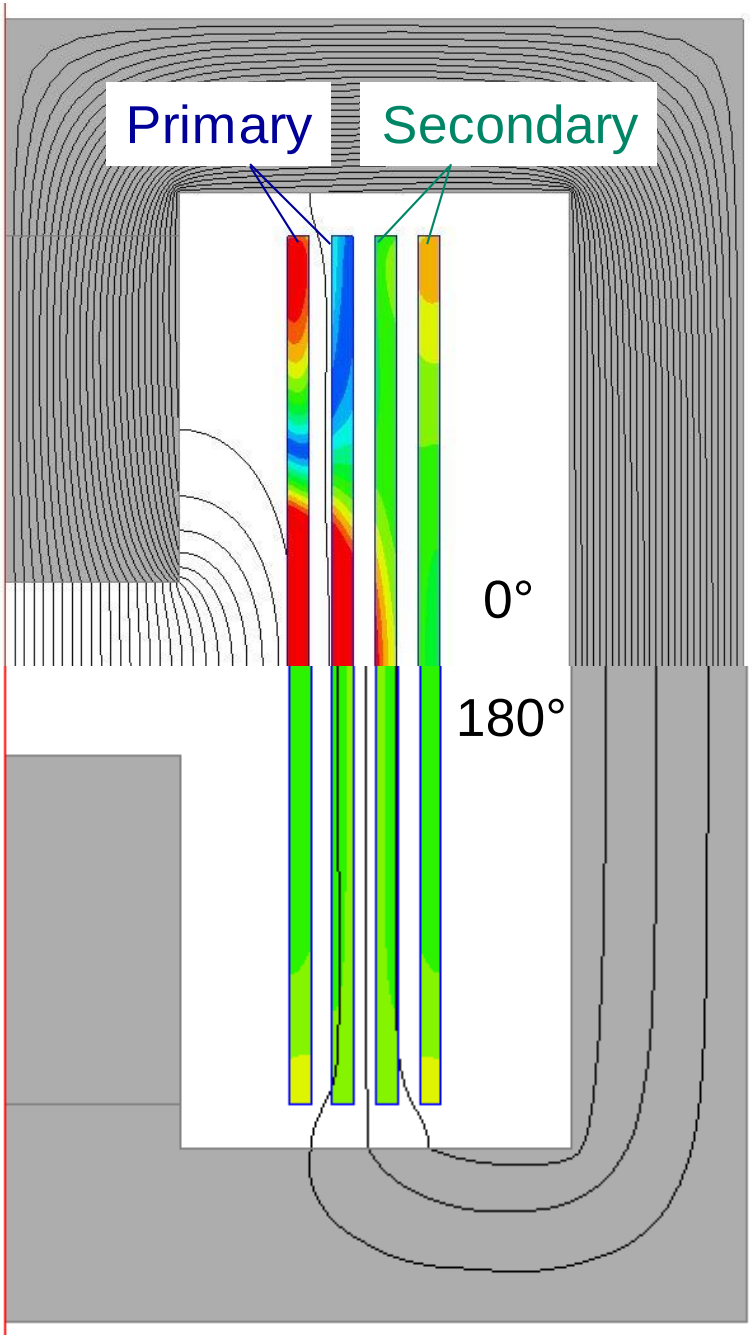
Winding models



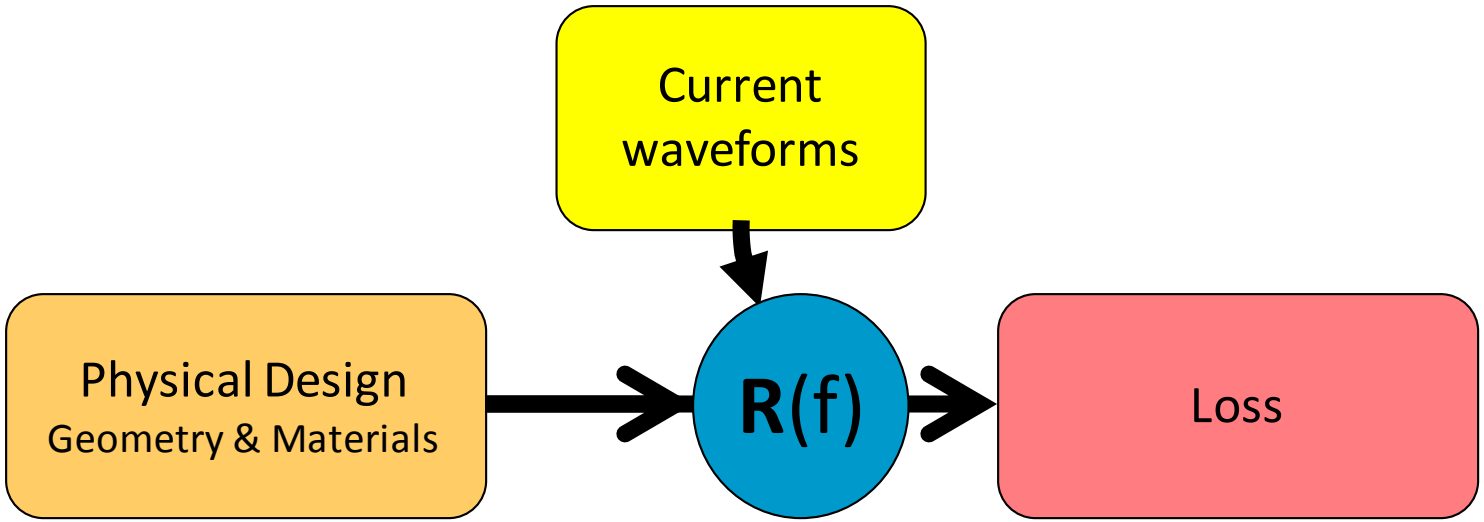
- Winding ac resistances?

Loss calculated from currents

- Conventional, incorrect, model for transformer winding loss (assume sine waves for now).
  - $P_{\text{winding}} = I_1^2 R_1 + I_2^2 R_2$
  - Problem: Loss varies drastically depending on relative phase/polarity.
  - Factor of 4 error in this case.
- Correct model options:
  - R_1 and R_2 that are only for specific phase relationship.
  - **Resistance matrix.**

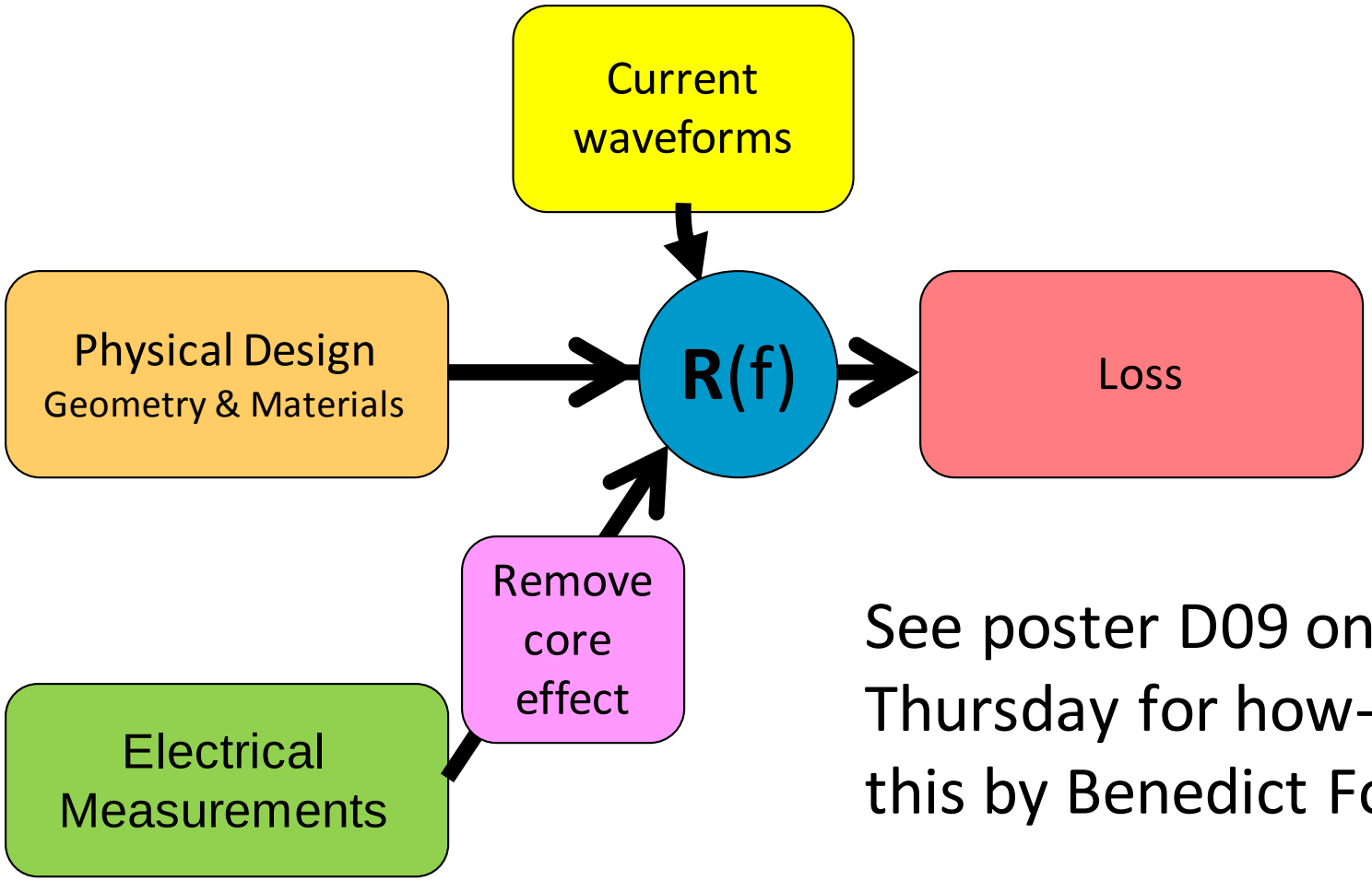


Winding models



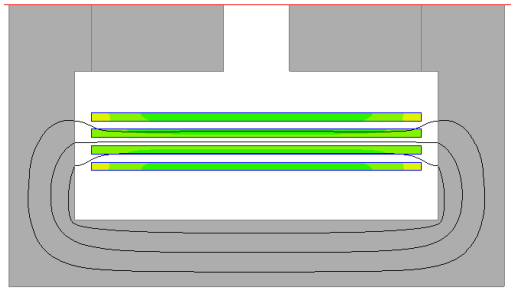
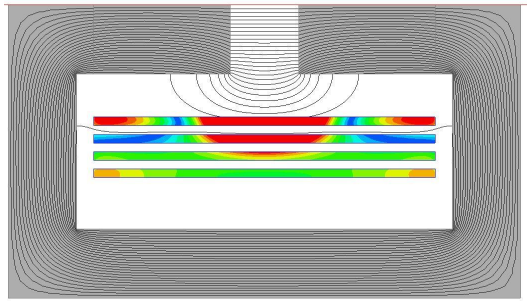
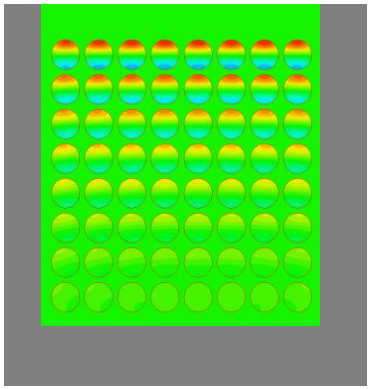
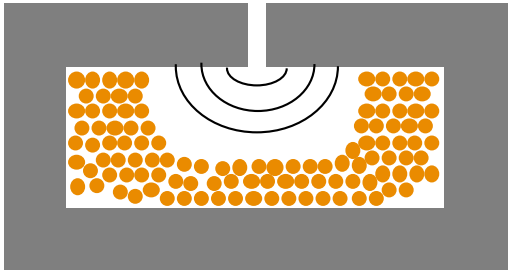
- ~~Winding ac resistances?~~
- Frequency-dependent resistance matrix **R**(f).
- Captures interactions between windings.

Winding models

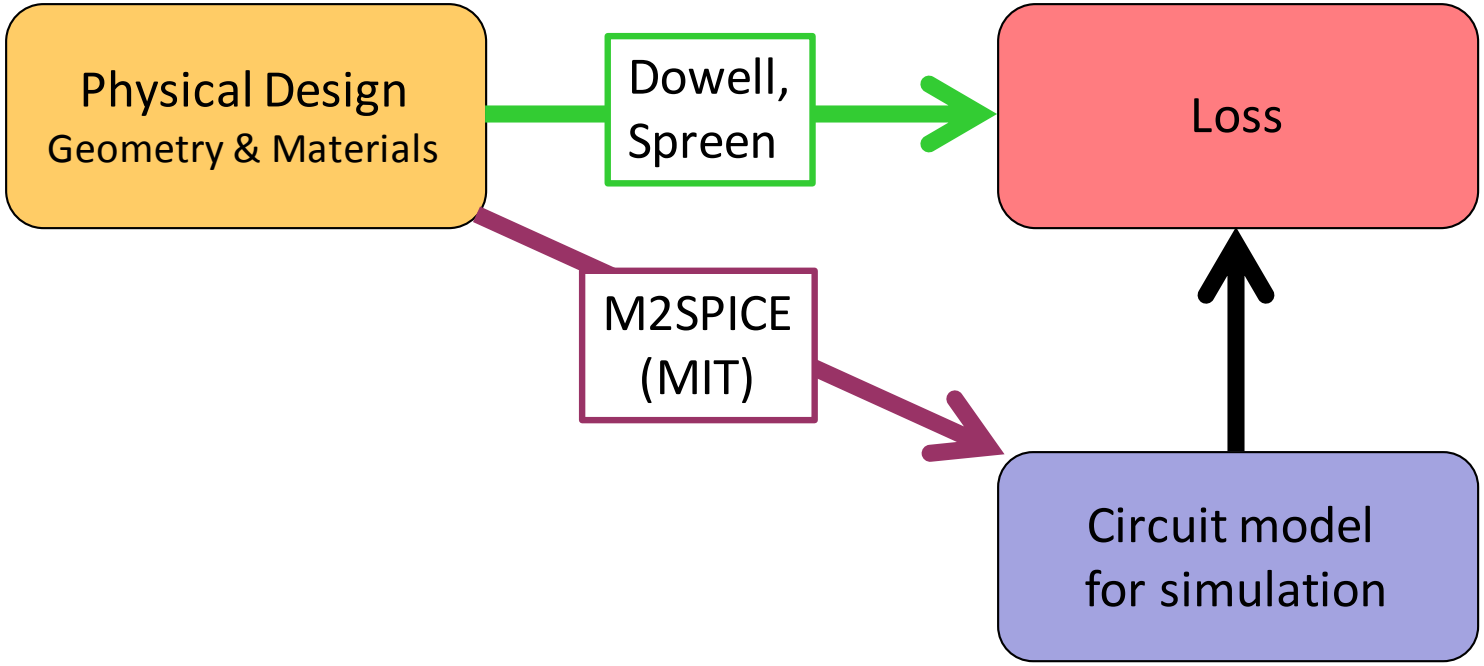


See poster D09 on Thursday for how-to on this by Benedict Foo.

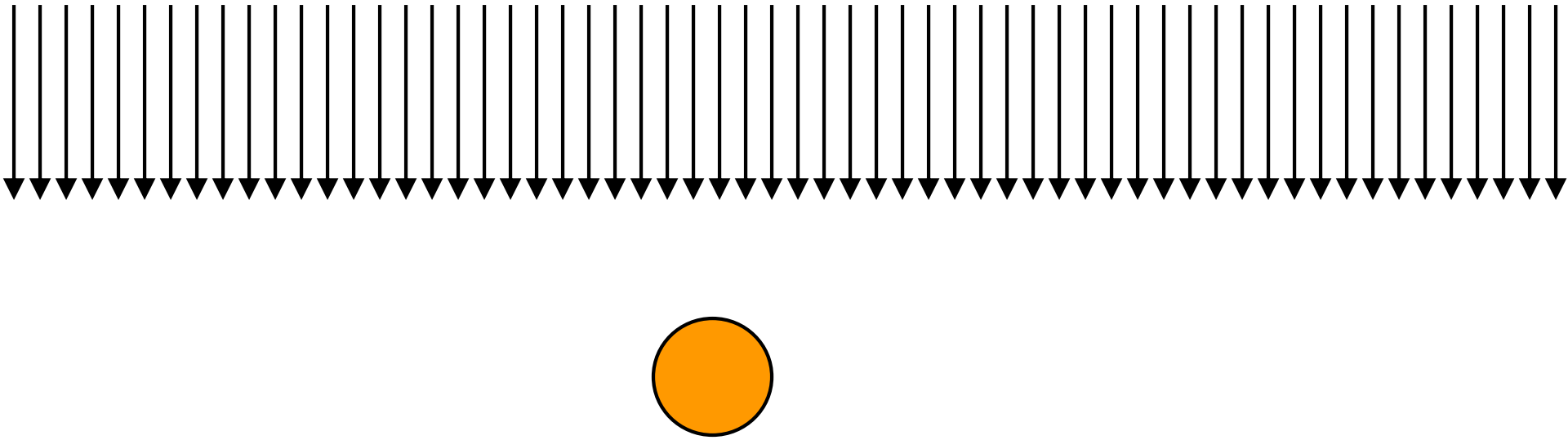
Predictions from physical structure

	1-D fields	2-D or 3-D fields
Rectangular conductors (e.g. foil and PCB)	Analytical 	Numerical (Finite Element, PEEC, etc.) 
Round-wire conductors (including litz)	Simulation-tuned physical model 	Simulation-tuned physical model + dc field simulation 

Winding models: 1D, rectangular conductors

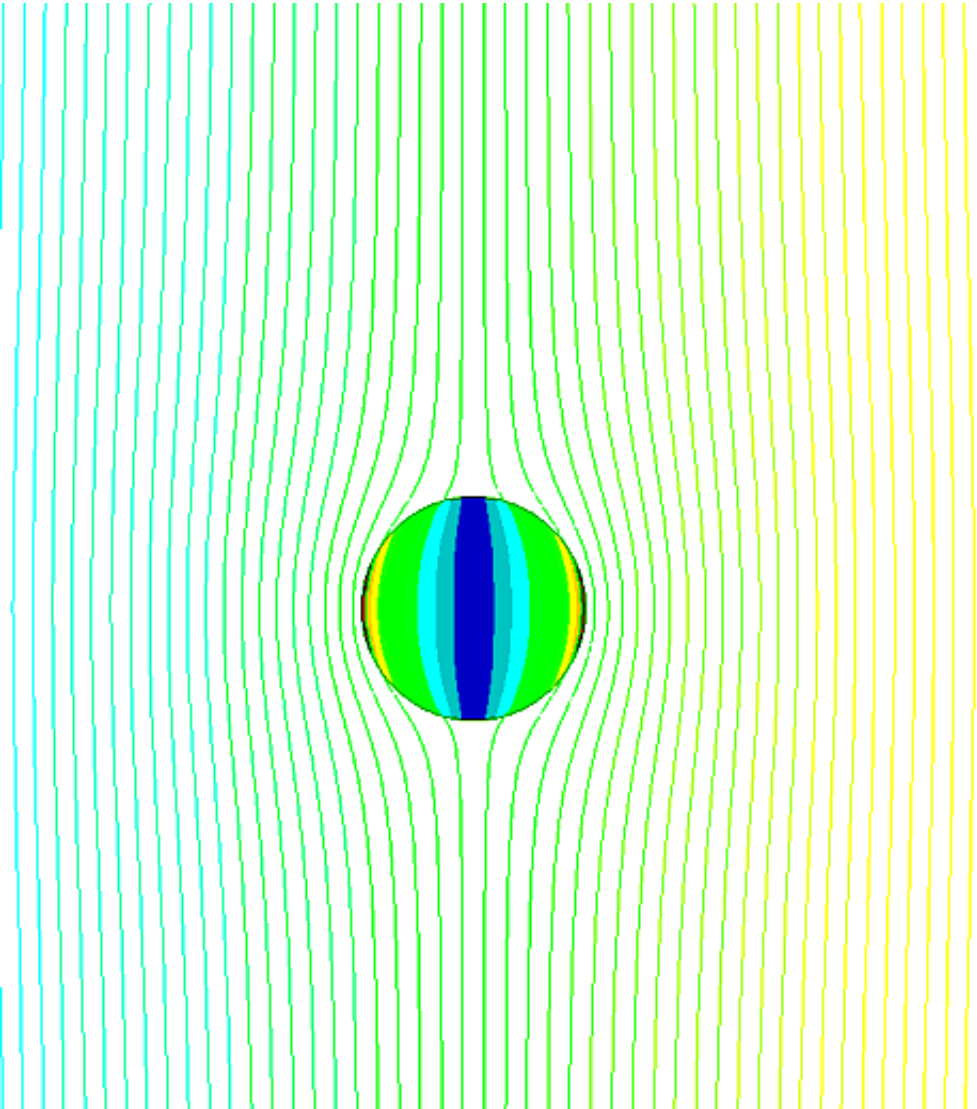


Round conductor: Textbook problem



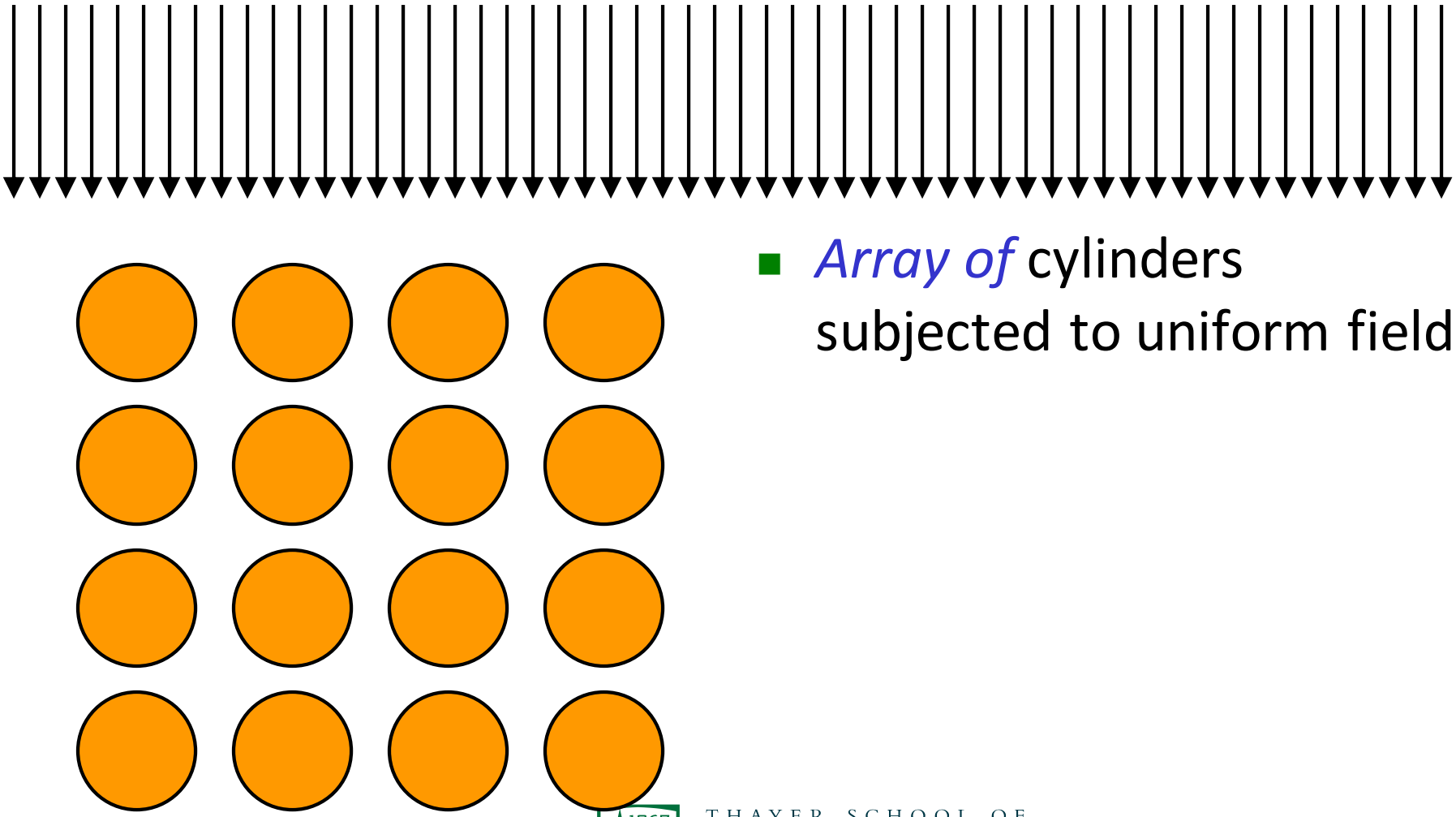
- Cylinder subjected to uniform field
- Dowell's model is a crude approximation.

Textbook solution



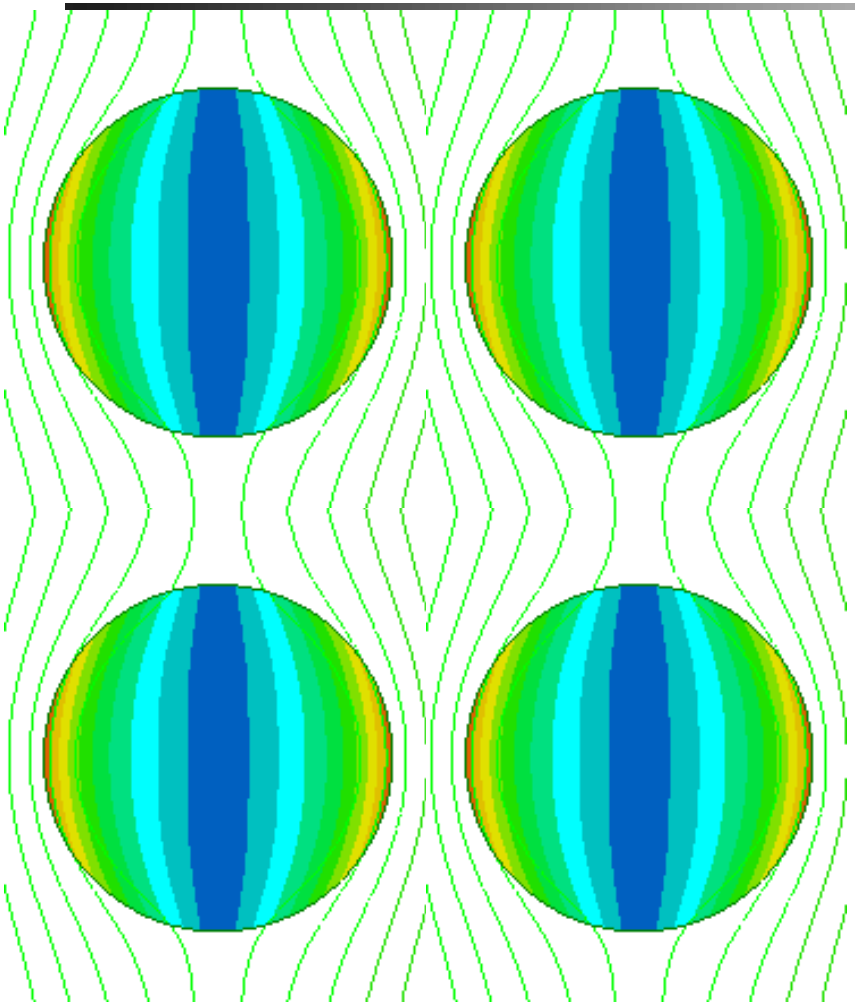
- Exact solution, described by Bessel functions.
- Use for winding loss analysis pioneered by Ferreira.

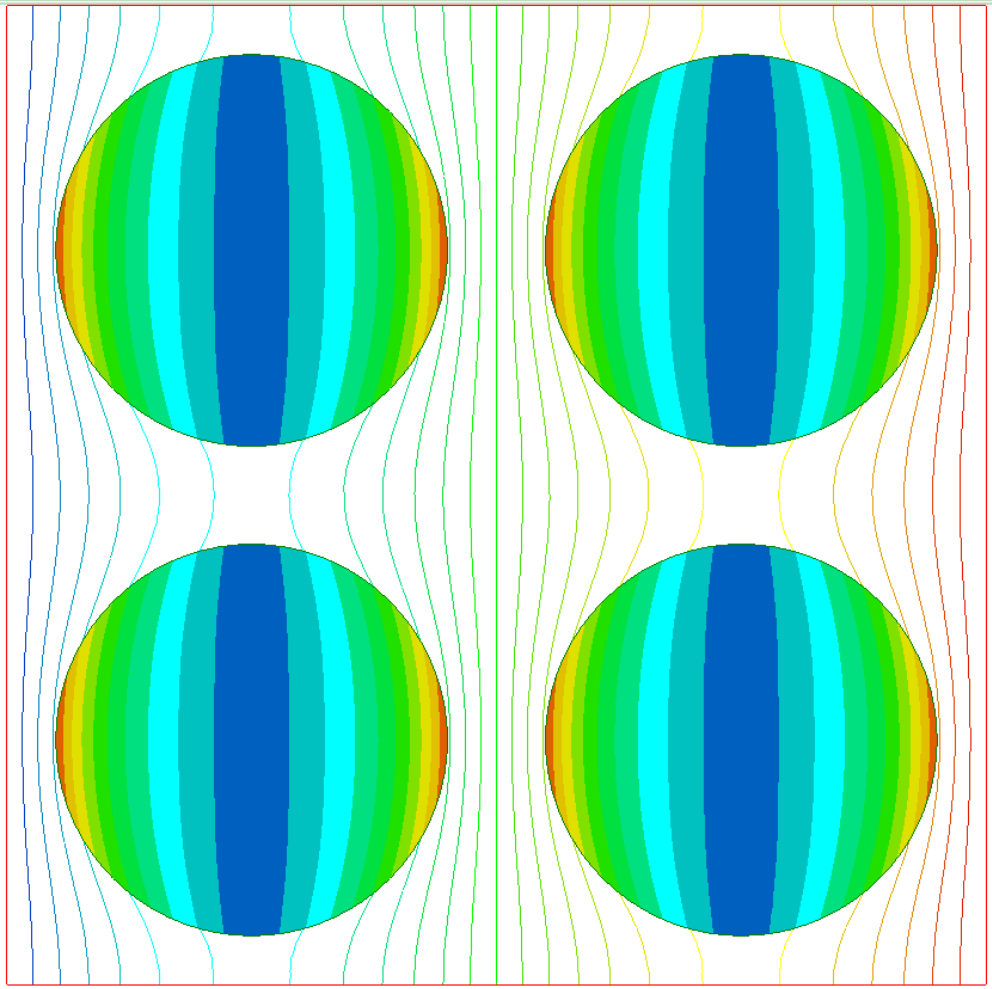
Actual problem



- *Array of* cylinders subjected to uniform field

Using the Bessel solution for the real problem

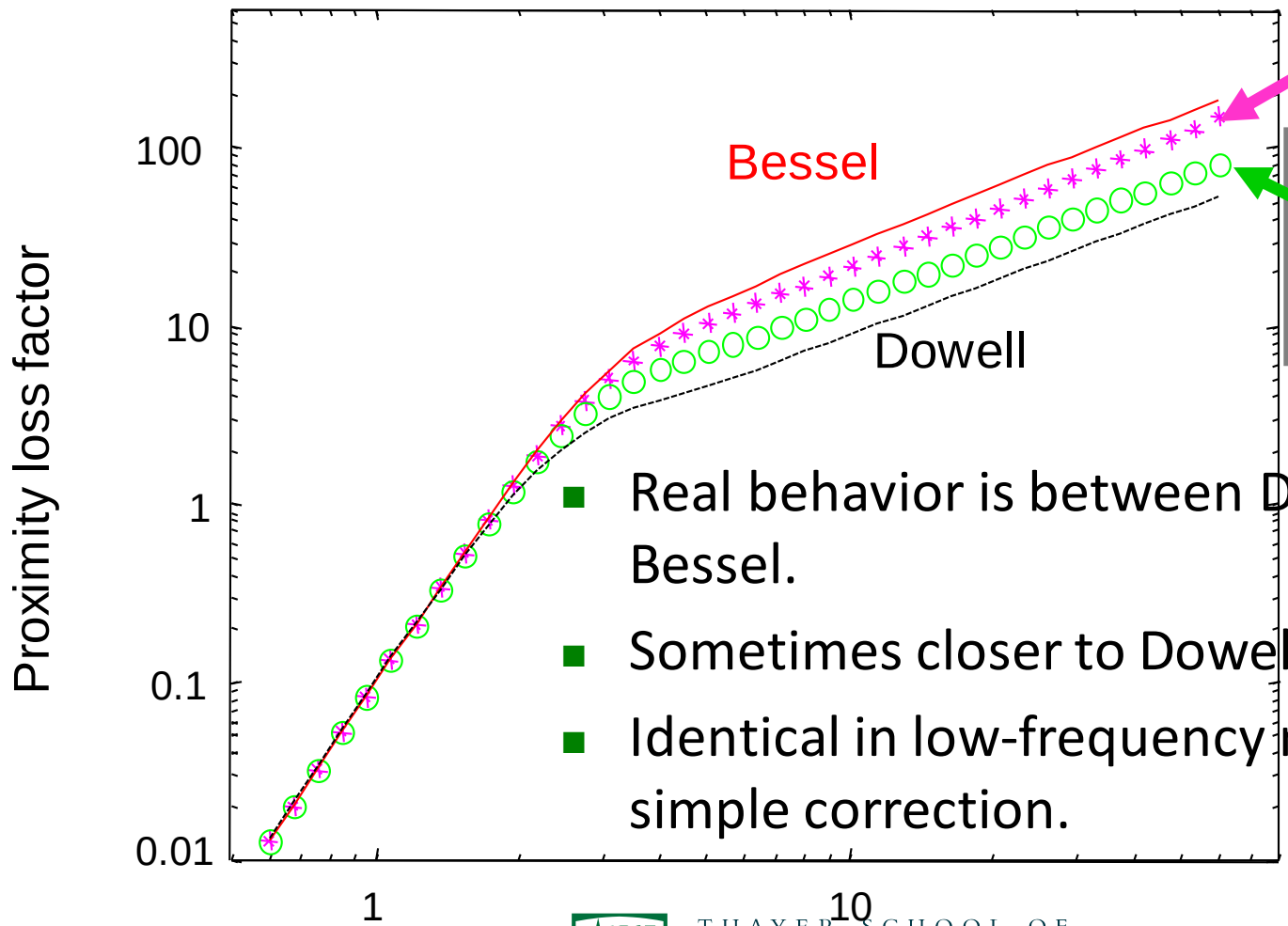


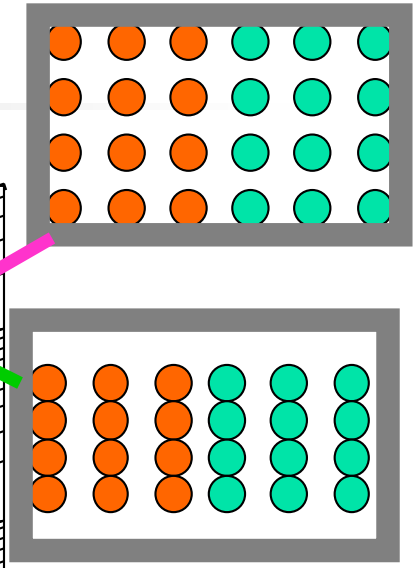


Not a valid solution!

Real Solution (FEA)

Simulation Results

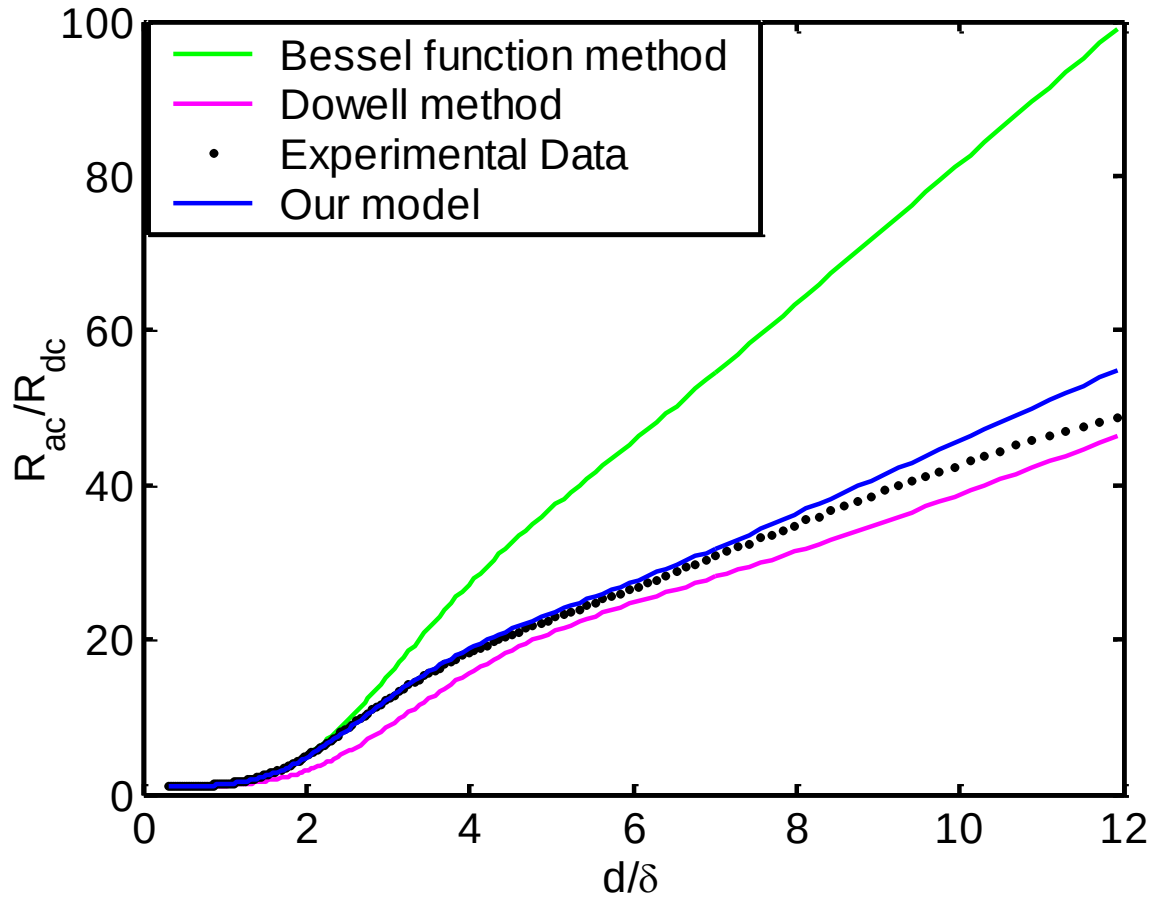




- Real behavior is between Dowell and Bessel.
- Sometimes closer to Dowell.
- Identical in low-frequency range with simple correction.

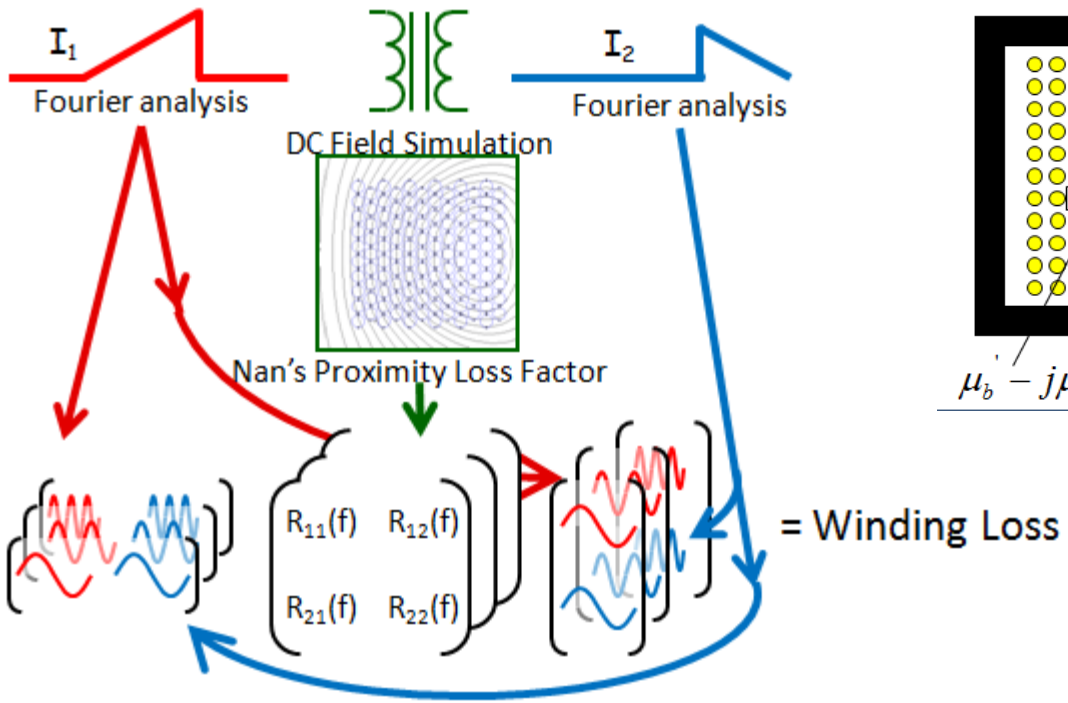
Xi Nan's model

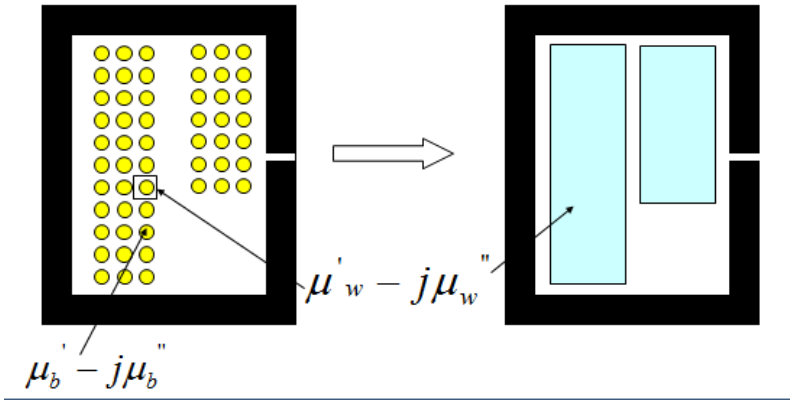
- Weighted average of Dowell-like and Bessel-like behavior: "Simulation tuned physical model"
- Fits experimental results better than Dowell or Bessel.
- Can be applied to 2D or 3D field configurations …



Full winding loss model: 2-D, full frequency range, multi-winding interactions

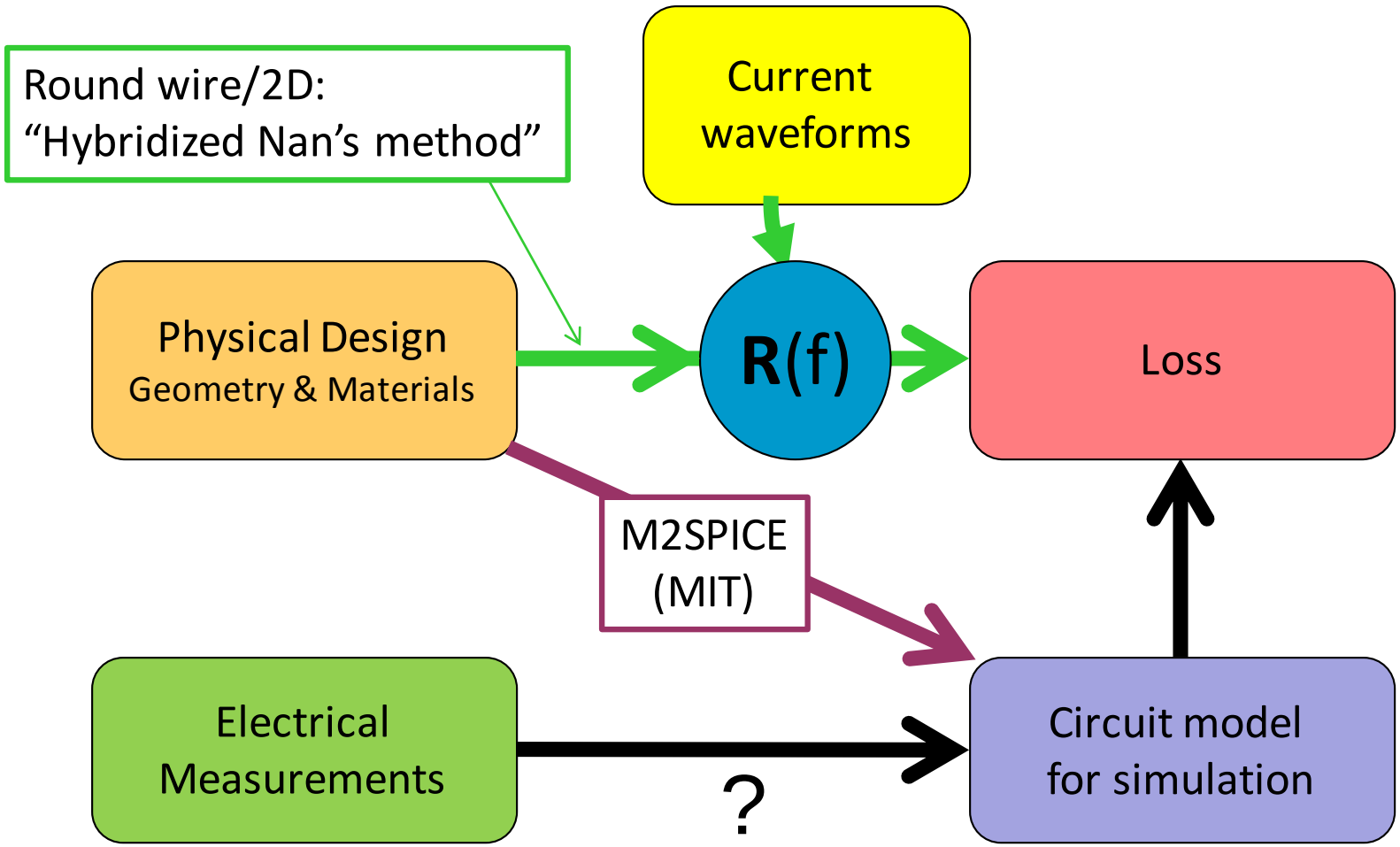
- Hybridized Nan's method (Zimmanck, 2010)
- Homogenization with complex permeability (Nan 2009, Meeker, 2012)





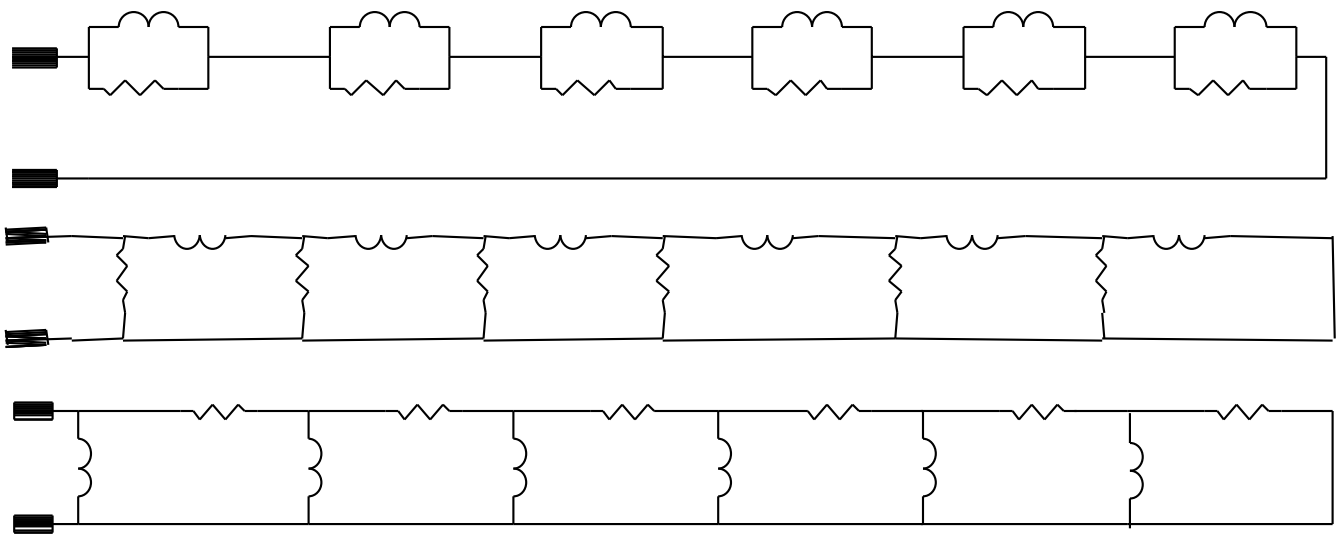
Available in FEMM

Winding models



Linear RL networks for winding models

- Three standard networks topologies that provide:
  - R increases with frequency.
  - L decreases with frequency.
- Can obtain identical behavior with any of the three.
- Can use any one to match measured behavior.

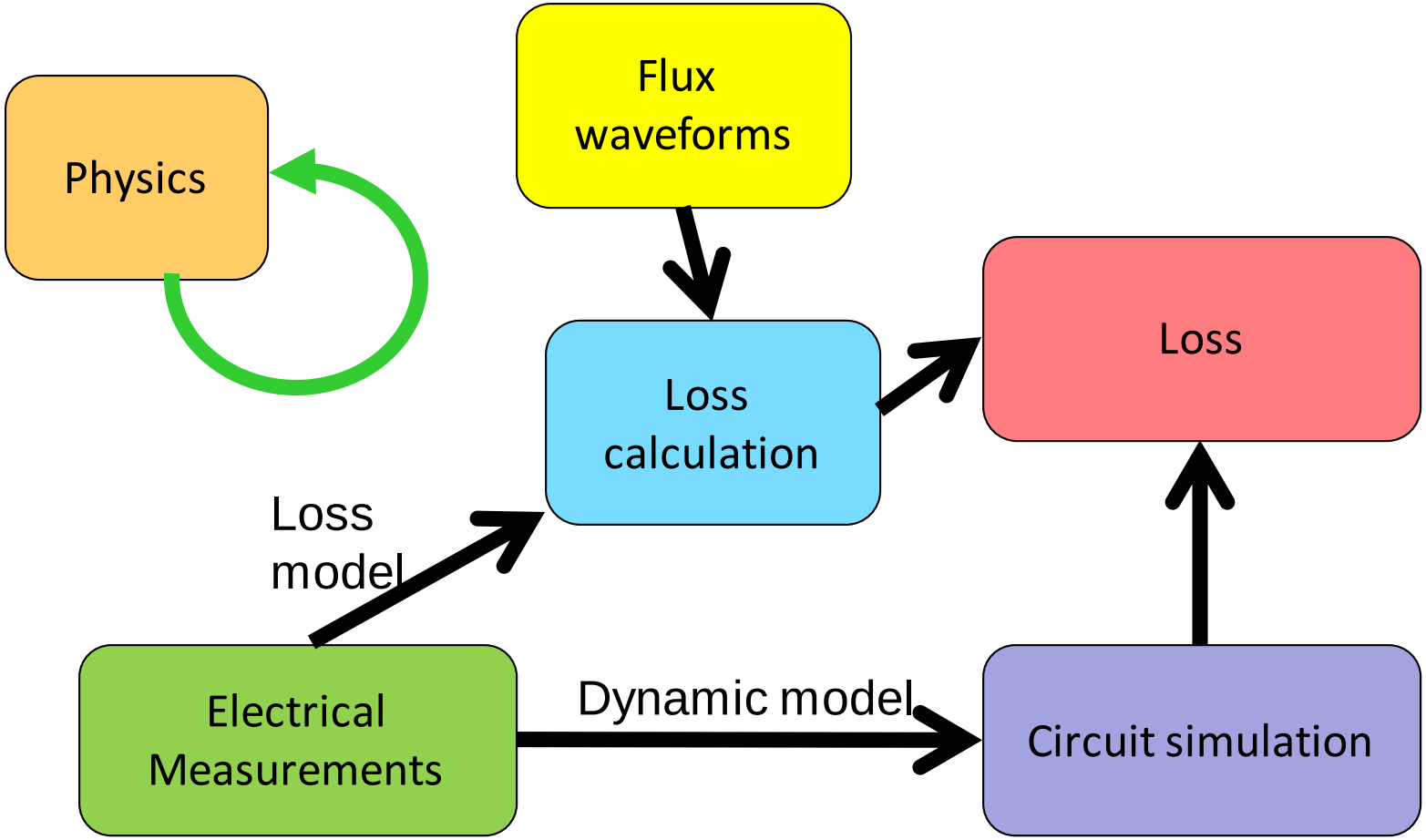


Foster

Cauer 1

Cauer 2

Core models


Physics
Flux waveforms
Loss calculation
Loss
Loss model
Electrical Measurements
Dynamic model
Circuit simulation

Loss Calculation Models

- Steinmetz equation:
  - Sinusoidal waveforms only
- Various types of modified/generalized/etc. Steinmetz equations.
  - Extend to non-sinusoidal waveforms.
  - Most common: improved Generalized Steinmetz Equation (iGSE).
- Loss Map/Composite Waveform Method.

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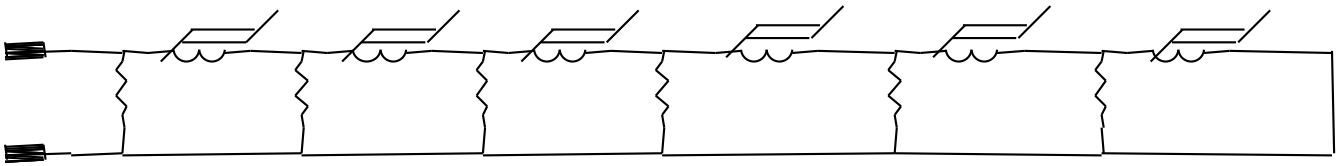
Comments:

- iGSE vs. Loss Map:
  - Same predictions if you use the same data.
    - iGSE: sinusoidal data.
    - Loss Map
  - Loss map database can include dc bias effects.
  - iGSE can do any wave shape, whereas Loss Map is for rectangular only.
- Barg 2017 improves iGSE for extreme duty cycles.
- Weakness of most of these: "Dead time" affects loss in practice but not in the model. "Relaxation effects."

Core simulation models

- Need to include nonlinearity.
- ***Example:*** Cauer 1 network to model saturation behavior and frequency-dependent permeability in nanocrytalline 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?

Conclusions

- Winding loss:
  - Complex but feasible to model accurately.
  - For 2 or more windings, need resistance ***matrix***.
  - 1D rectangular conductors: analytical solutions.
  - 2D rectangular conductors: numerical simulations.
  - 1D or 2D round wire: Simulation-tuned physical models are better than Dowell or Bessel.
- Core loss
  - Nonlinear and can only be found experimentally.
  - Open questions on data needed and models.

References

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

Spreen

Zimmanck

Meeker

Nan

Sullivan and Muetze, IAS 2007

Appendix:
Further slides for reference or questions

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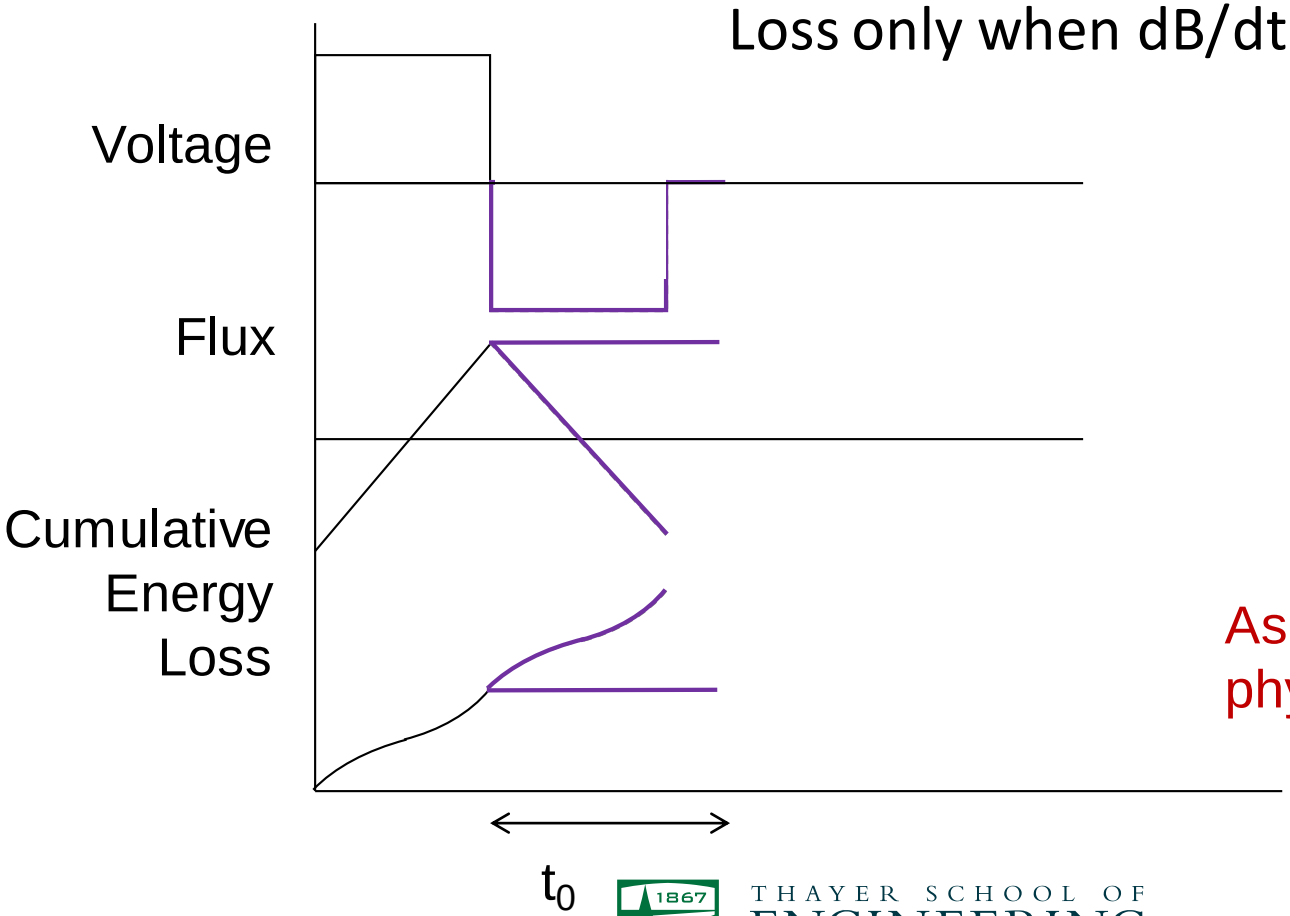
Relaxation effect

(Core loss reference 7, 13)

Assumption: *Energy* loss per cycle doesn't change if waveform pauses.

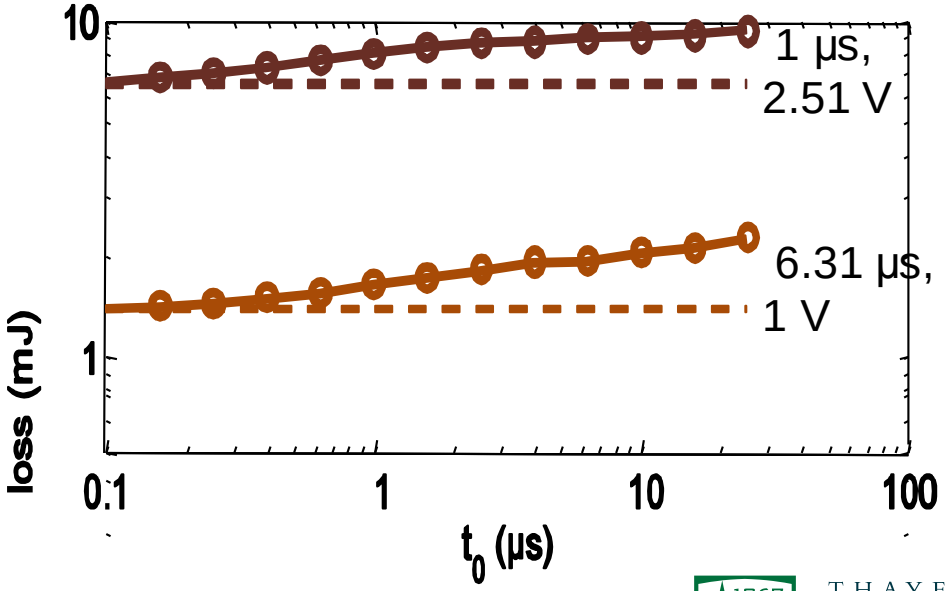
Loss only when dB/dt >0.

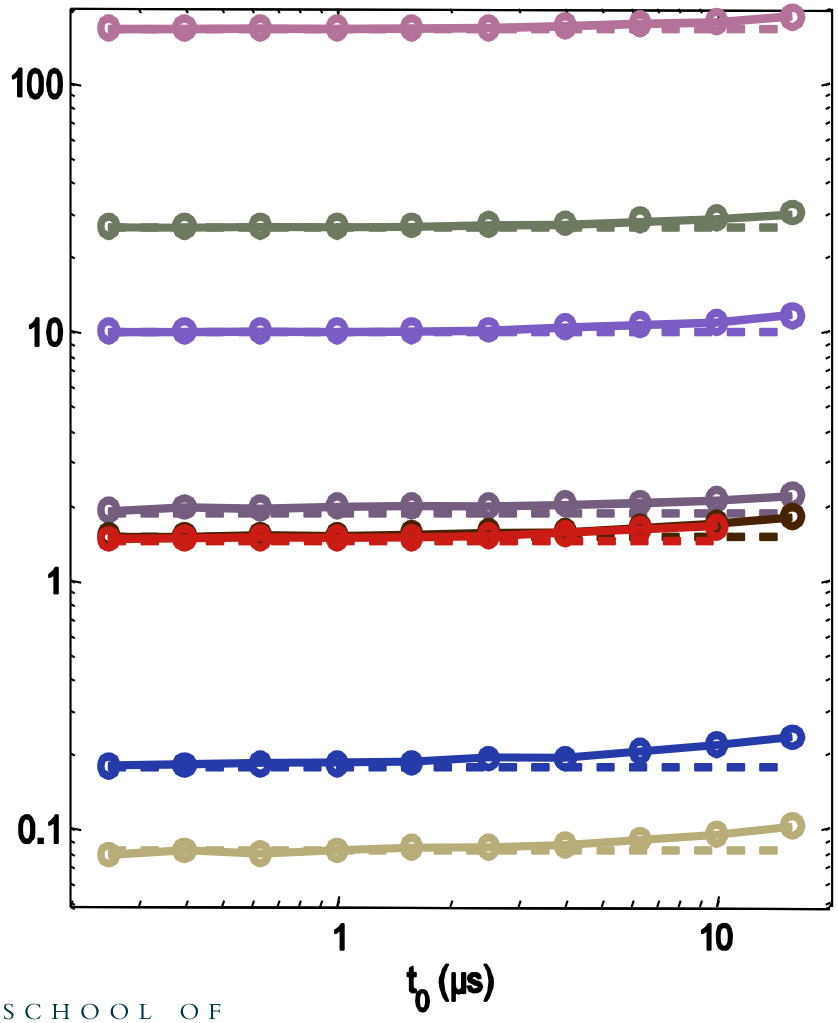


Assumed ***without*** physical basis

Measurements prove assumption wrong (Core loss reference 7, 13)

- Increase in loss per cycle with increasing off-time (ferrite (below)).
- Not observed in powdered iron (right).





iGSE (improved Generalized SE)

- Based on $\overline{P(t)} = k_i (\Delta B)^w \overline{\left|\frac{dB}{dt}\right|^z}$, plus compatibility with Steinmetz equation for sine waves.
- Result: $\overline{P(t)} = k_i (\Delta B)^{\beta-\alpha} \overline{\left|\frac{dB}{dt}\right|^\alpha}$
- Formula to get ki from sinsoidal data:

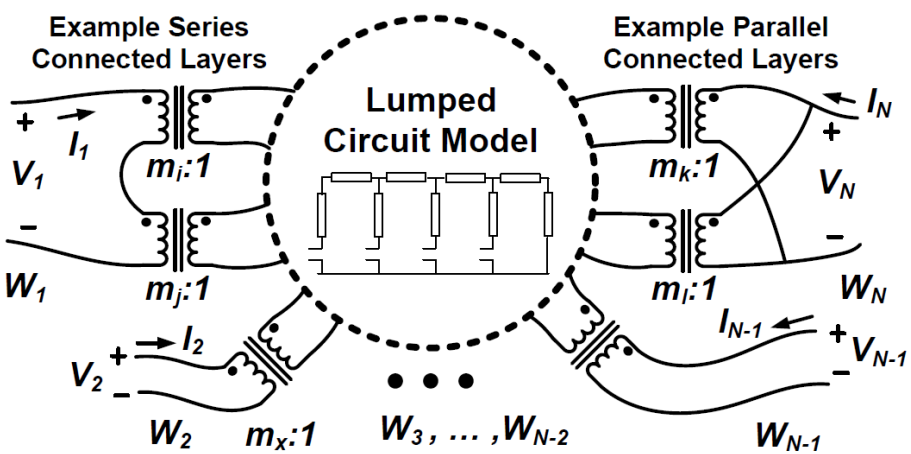
$$k_i \cong \frac{k}{2^{\beta+1}\pi^{\alpha-1}\left(0.2761 + \frac{1.7061}{\alpha+1.354}\right)}$$

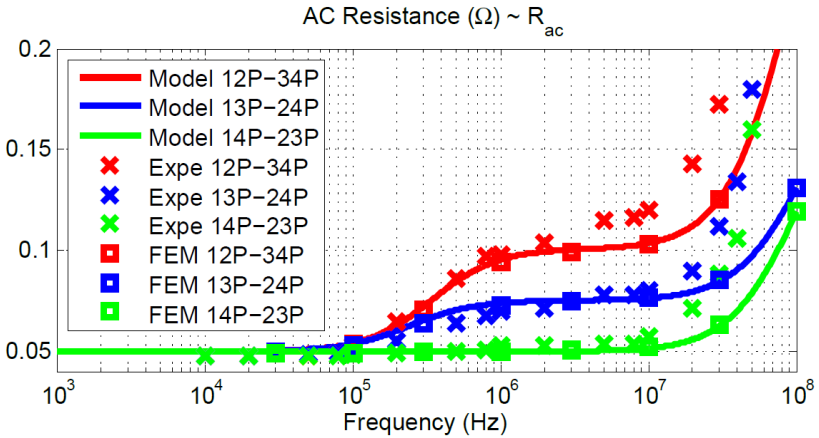
- Formula for PWL waveforms:

$$\overline{P_v} = \frac{k_i(\Delta B)^{\beta-\alpha}}{T} \sum_m \left|\frac{B_{m+1} - B_m}{t_{m+1} - t_m}\right|^\alpha (t_{m+1} - t_m)$$

Rectangular conductors with 1-D fields

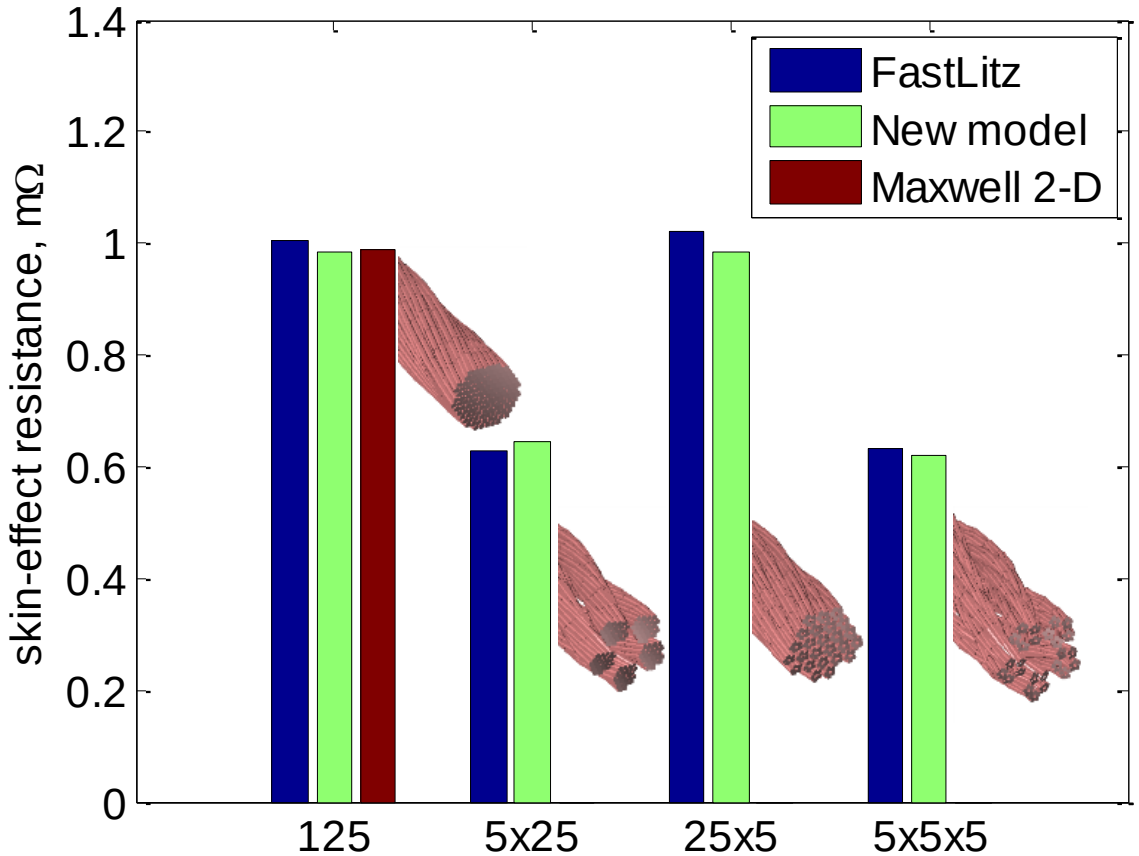
- Dowell's analysis is correct, but limited.
  - Parallel windings and layers?
  - Extract inductance matrix as well as resistance matrix?
- M2Spice: automatic generation of a SPICE model for a 1D system of windings.
  - Minjie Chen (Princeton) and Dave Perreault (MIT)
  - Result:





Litz wire

- Basic model is the same as for round wire.
- Full model now available to predict effect of construction.
- Simple rules to avoid problems due to poor construction can avoid the need for the full model



1D, 2D and 3D modeling approaches

- 1D: can use analytical models.
  - For Xfrmers and good (quasi-) distributed gap Ls.
    - Dowell isn't precise but we know how to do better.
- 2D: Fast, easy, low-cost simulations.
    - Naïve sections for E-cores can be misleading.
    - Mimic return path for to reduce error 5X.
- 3D: Use for verification, not design.