Optimizing Magnetics for Inverters

Charles R. Sullivan

chrs@dartmouth.edu

Dartmouth Magnetics and Power Electronics Research Group

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

http://power.engineering.dartmouth.edu

Core losses vs. winding losses

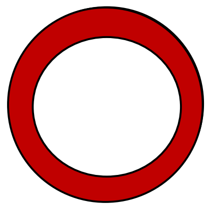
- **Winding** losses:
  - Material properties: Linear and well known.
  - Loss prediction: analytical or FEA solutions.
  - Many variables to optimize—design opportunity!
- **Core** losses:
  - Material properties: nonlinear; not well understood.
  - Loss prediction: generalization of empirical measurements.
  - Few variables: material choice and flux density.

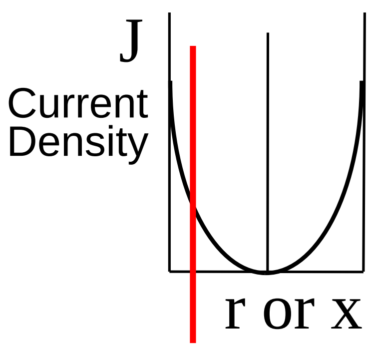
Winding losses: Skin Effect

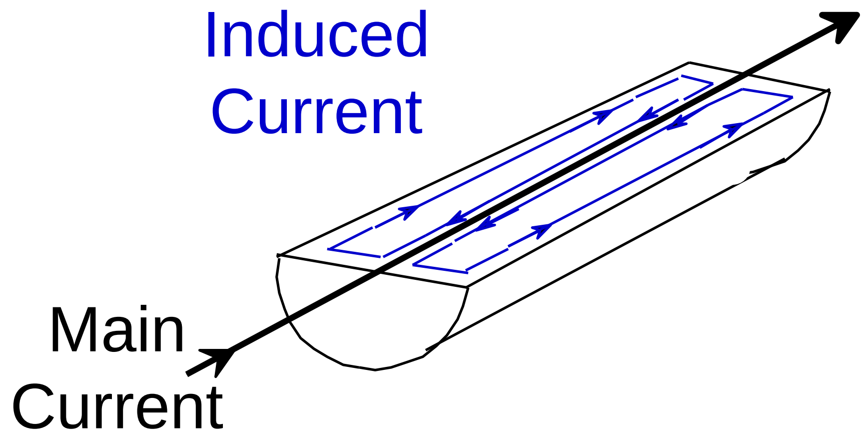
Well known effect, but not the full story.

Skin depth

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

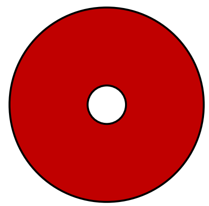






Original drawing from Snelling

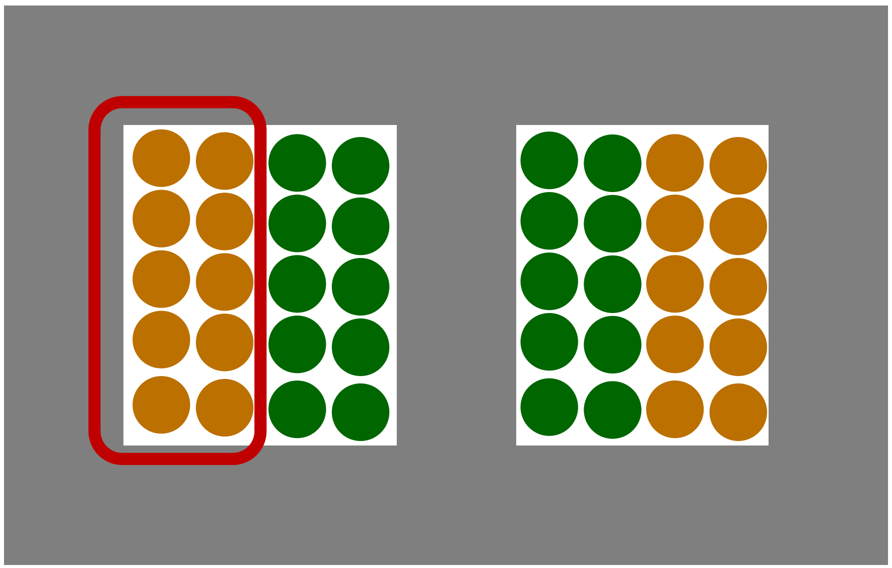
Naïve idea to overcome skin effect



- Use diameter no bigger than ~2 skin depths…

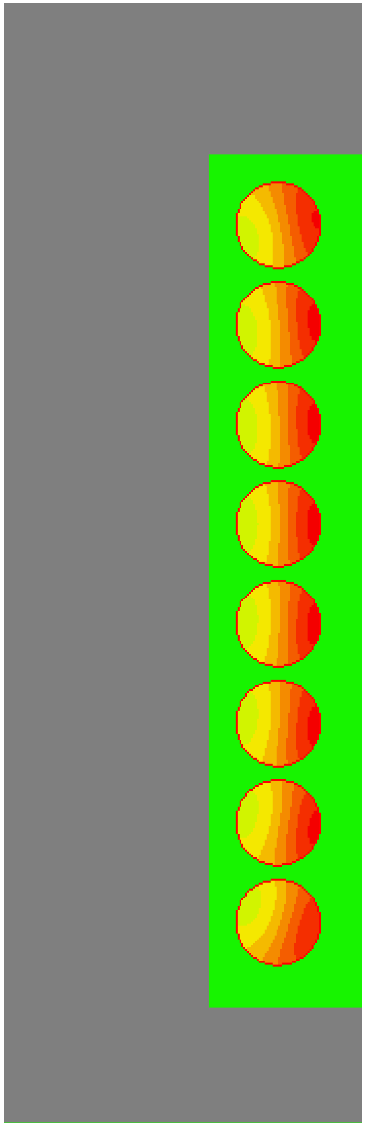
f	60 Hz	20 kHz	200 kHz	1 MHz	10 MHz
δ	8.5 mm	0.467 mm	0.148 mm	66 µm	21 µm
	AWG 0	AWG 24	AWG 35	AWG 42	AWG 51
2δ	17 mm	0.93 mm	0.30 mm	132 µm	42 µm
	AWG 7/0	AWG 18	AWG 29	AWG 36	AWG 45

Example transformer geometry

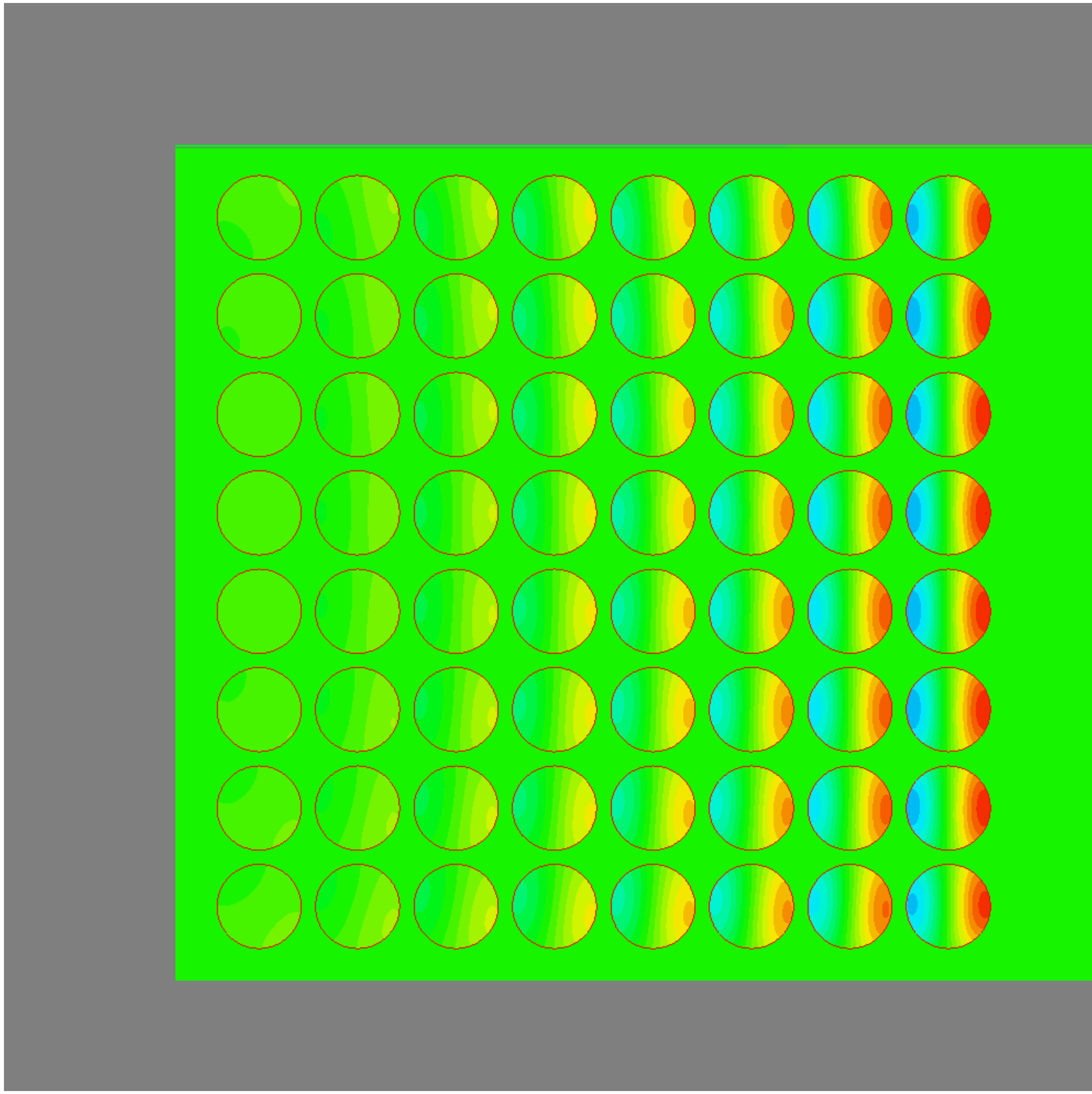


Diameter = 2 skin depths

200 kHz
d = 0.3 mm



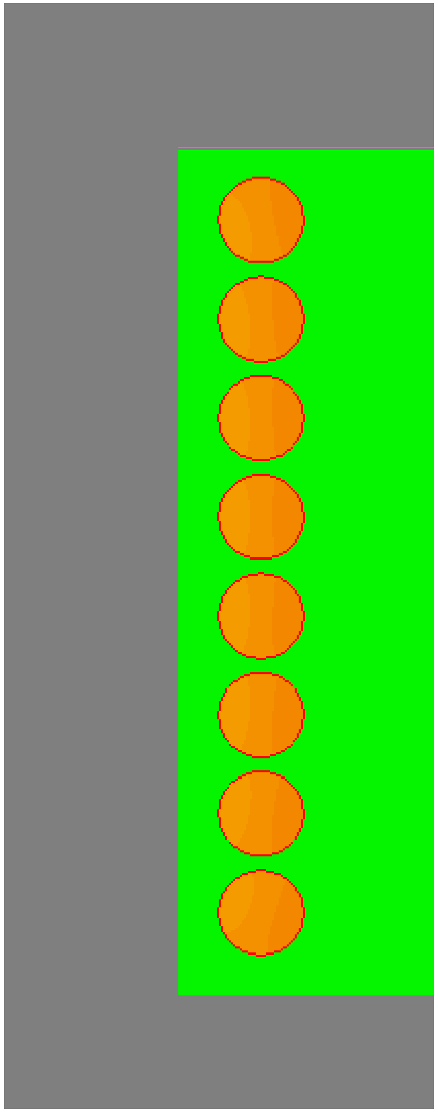
Rac/Rdc = 1.36



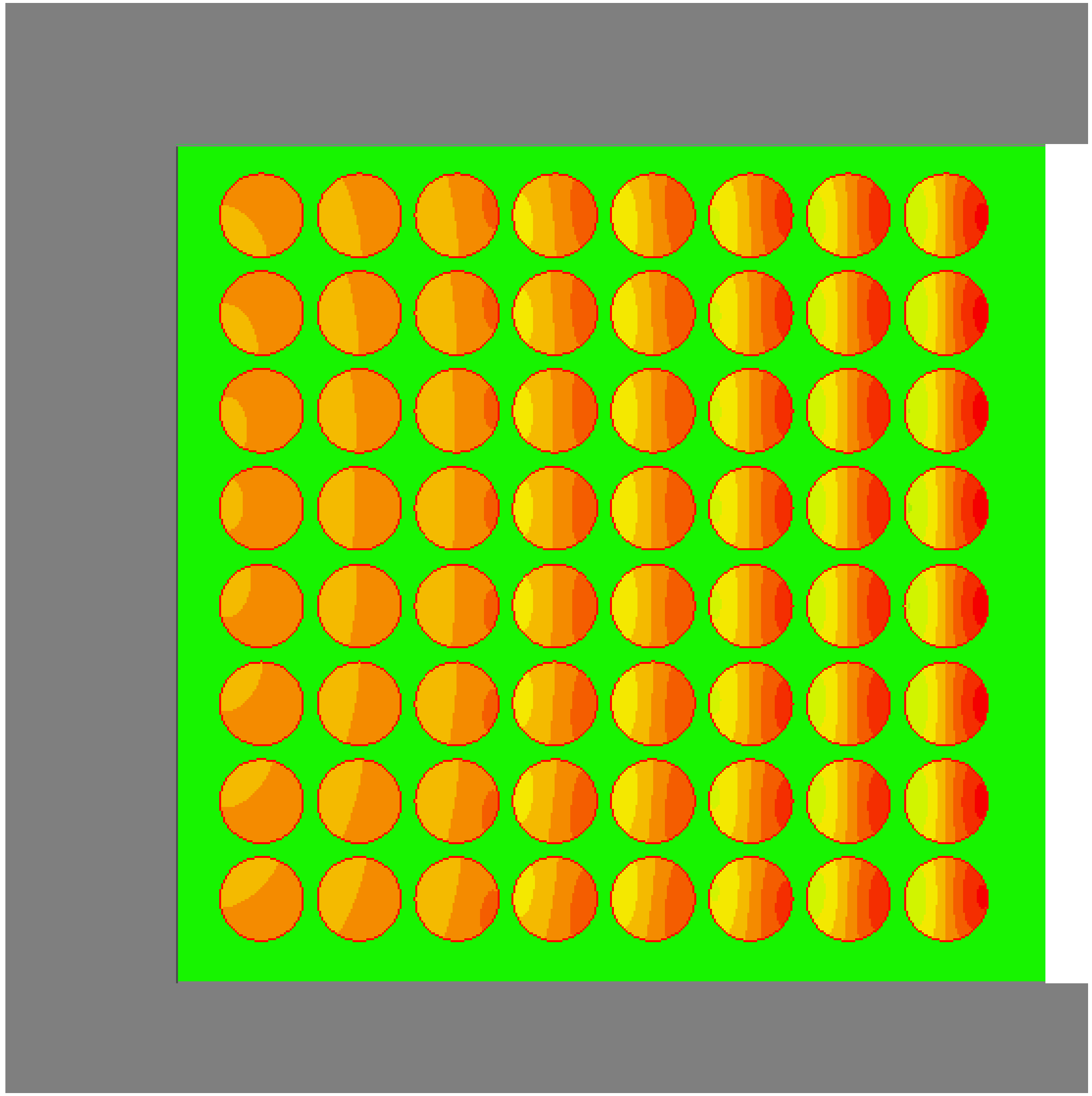
Rac/Rdc = 27.7

Diameter = skin depth

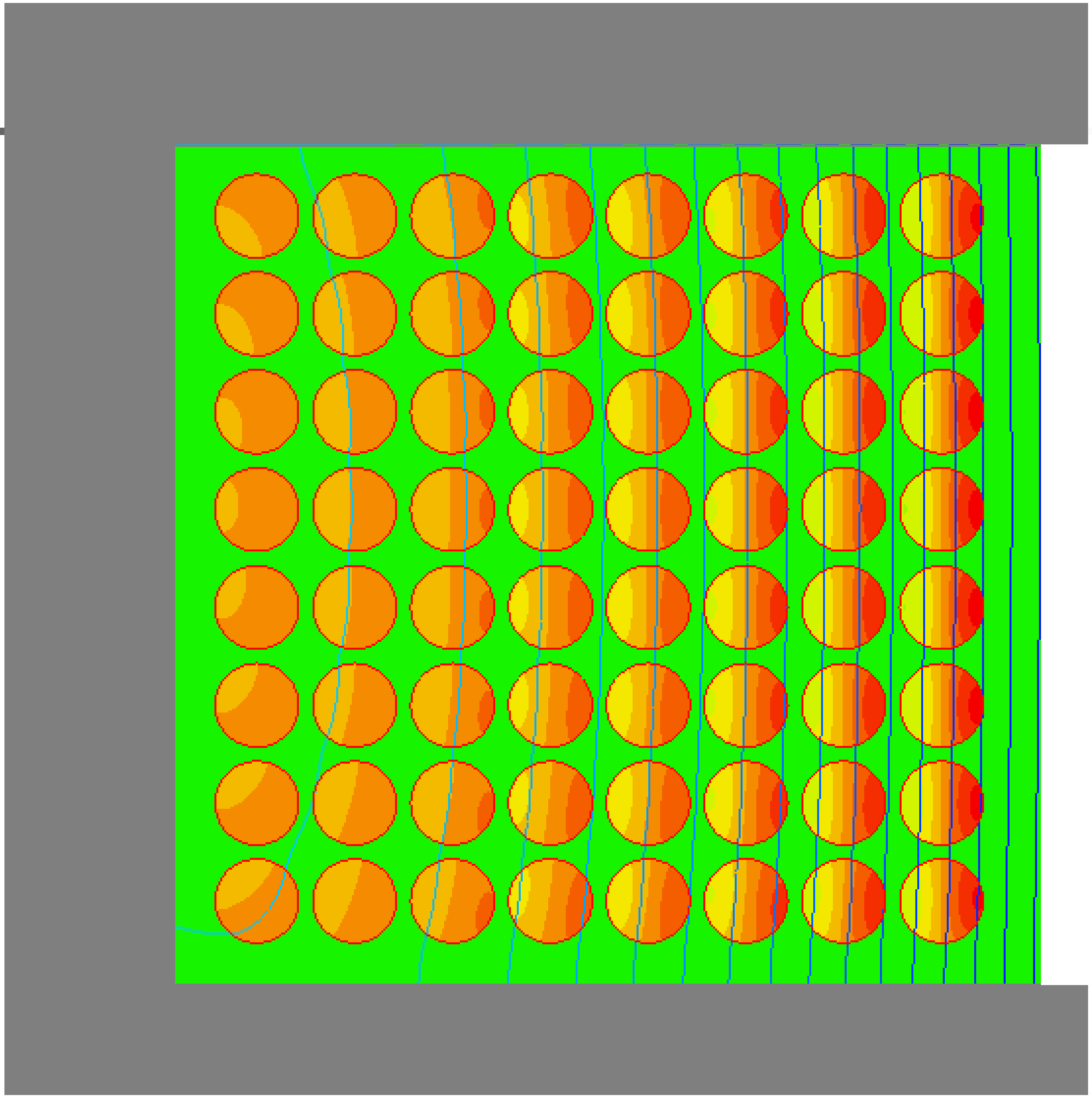
50 kHz
d = 0.3 mm



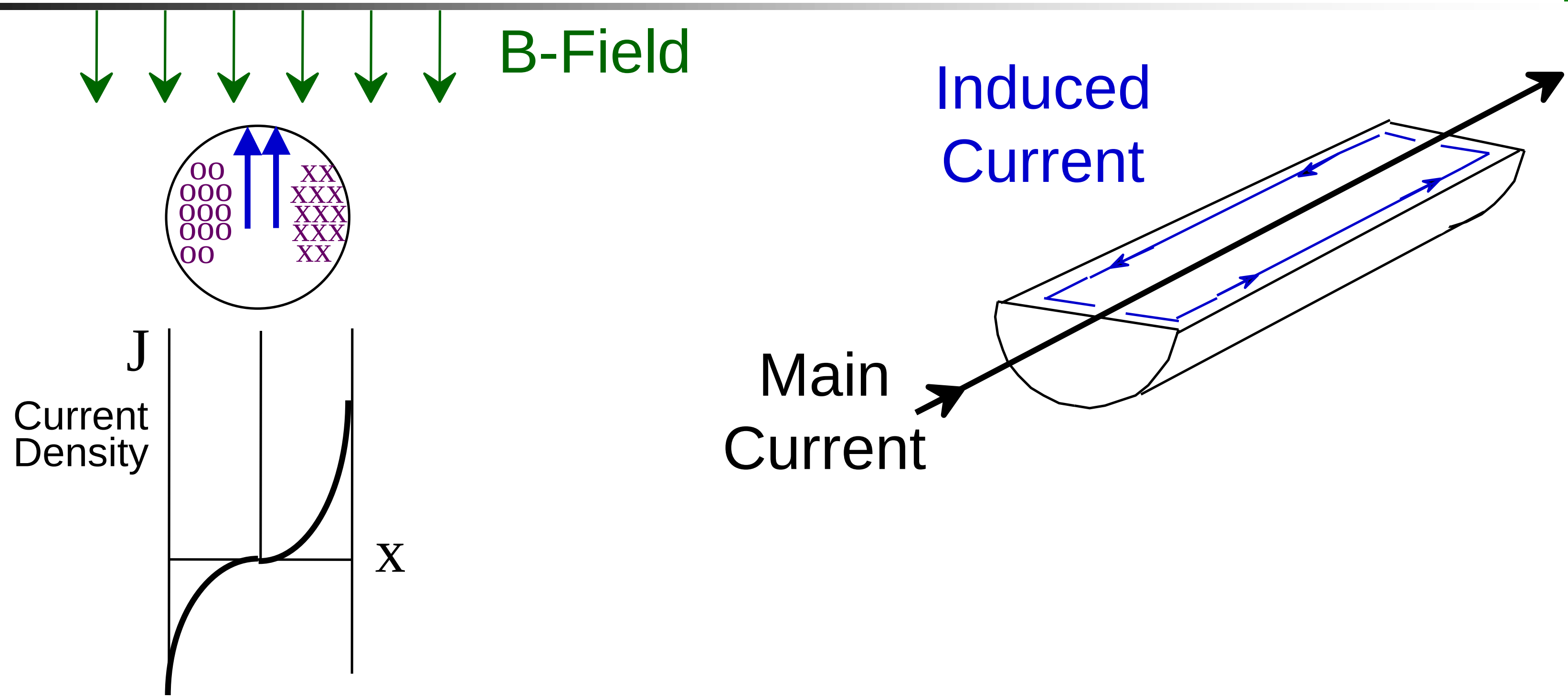
Rac/Rdc = 1.03



Rac/Rdc = 3.01



Proximity Effect



- Maybe a misnomer: effect of external field, including the effect of other wires and the effect of the core.

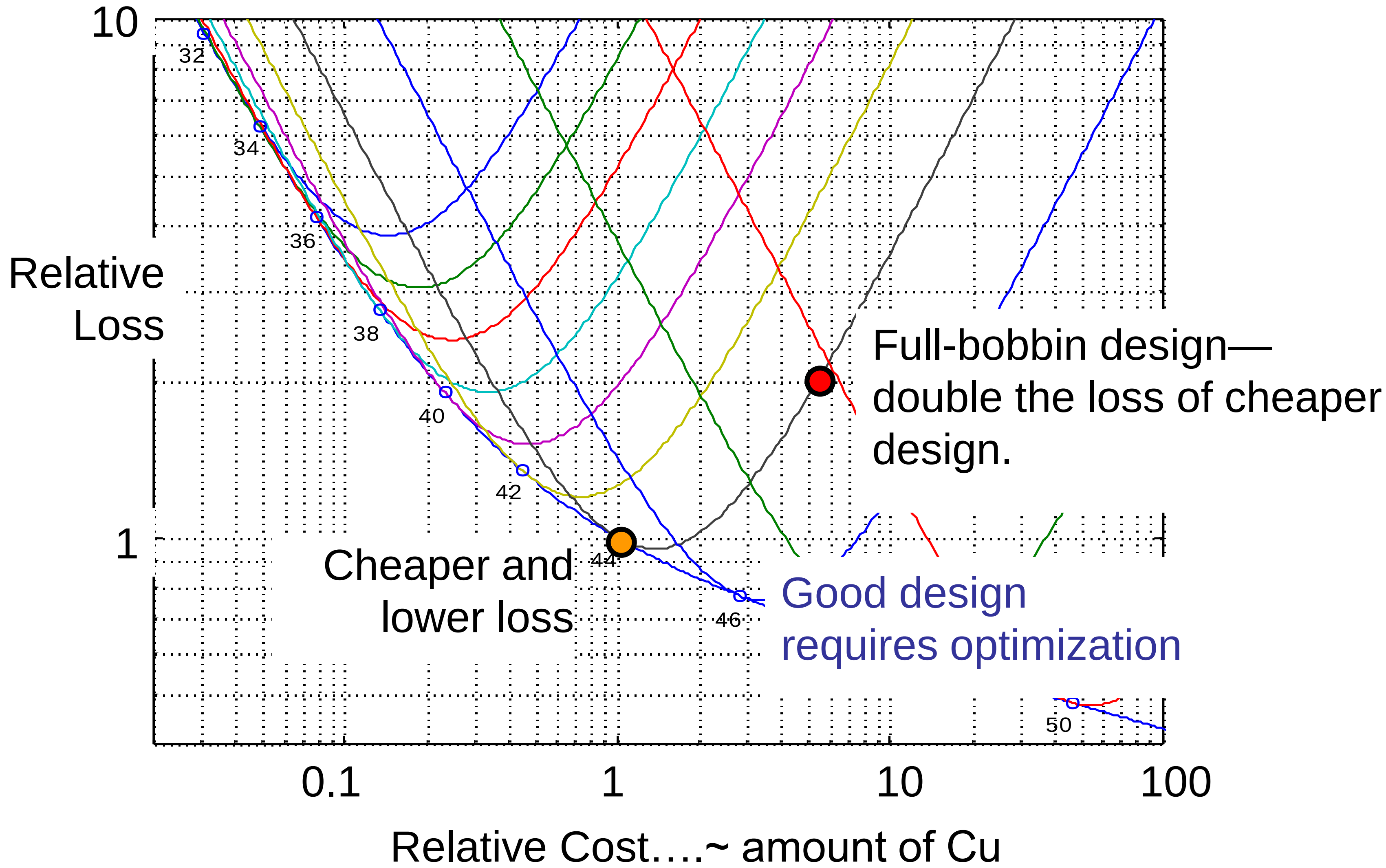
Original drawing from Snelling

Litz wire

Image: Noah Technologies

- Reduce ac resistance—skin and proximity effects.
- Invention: 1888, Sebastian de Ferranti.
- Analysis 1917 Howe; 1926 Butterworth.
- Two main parameters to choose number of strands and their diameter.
- Double jeopardy: can have high cost ***and high loss***

Litz-wire design options



Simple litz optimization (APEC 2014) see http://bit.do/simplitz

- Target number of strands:

$$n_e = k \frac{\delta^2 b}{N_s}$$

Skin depth (δ); Window breadth (b); Number of turns per winding section (N_s)

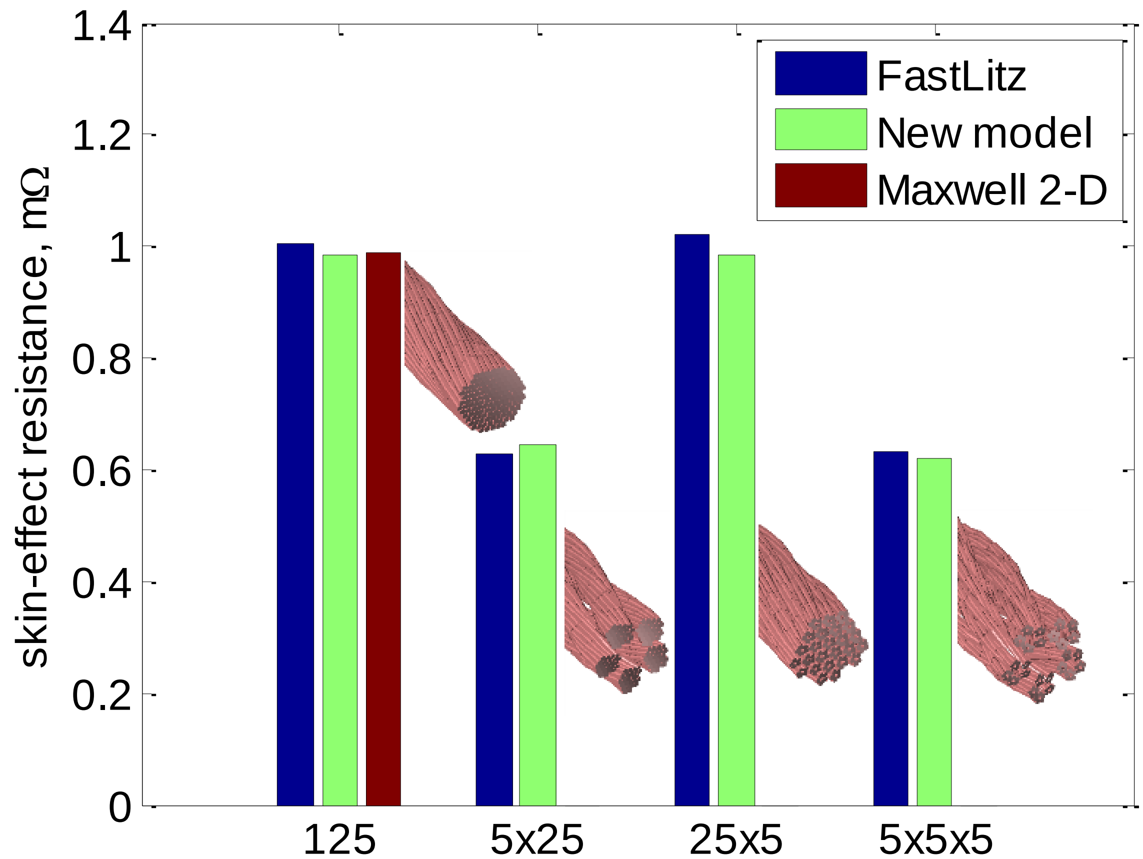
AWG strand size	32	34	36	38	40	42	44	46	48
k (mm^{-3})	114	280	694	1.73k	4.29k	10.6k	25.5k	56.5k	118k

- Example: 200 kHz, 48 turns in 3 mm width (vs. 0.3 mm wire):

AWG	36	38	40	42	44	46	48
Strands	1	2	6	15	35	77	162
% Rac	23.3%	15.9%	10.8%	7.8%	5.7%	4.4%	3.4%

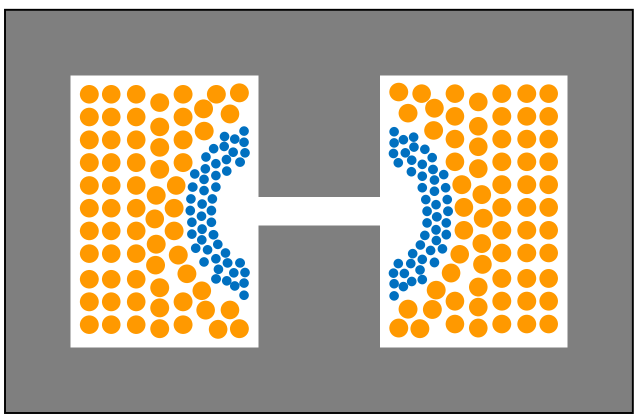
Litz wire construction details

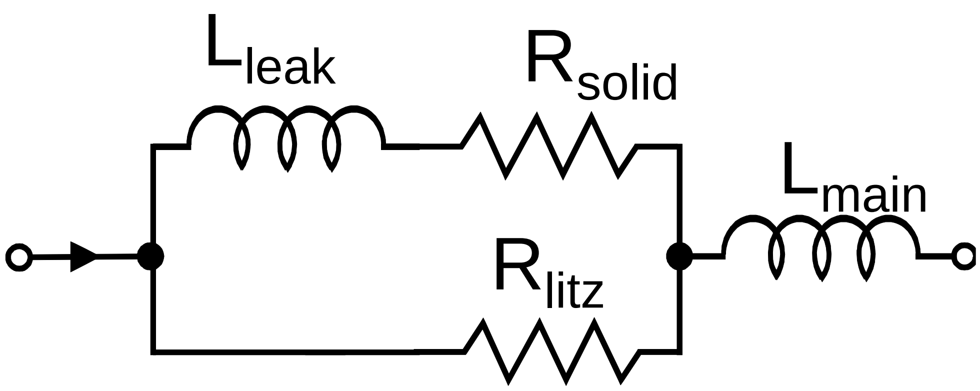
- Full model now available to predict effect of construction.
- Simple rules to avoid problems are in the 2014 simple litz paper.



Inductor for a dc-dc converter: DC current plus HF ripple

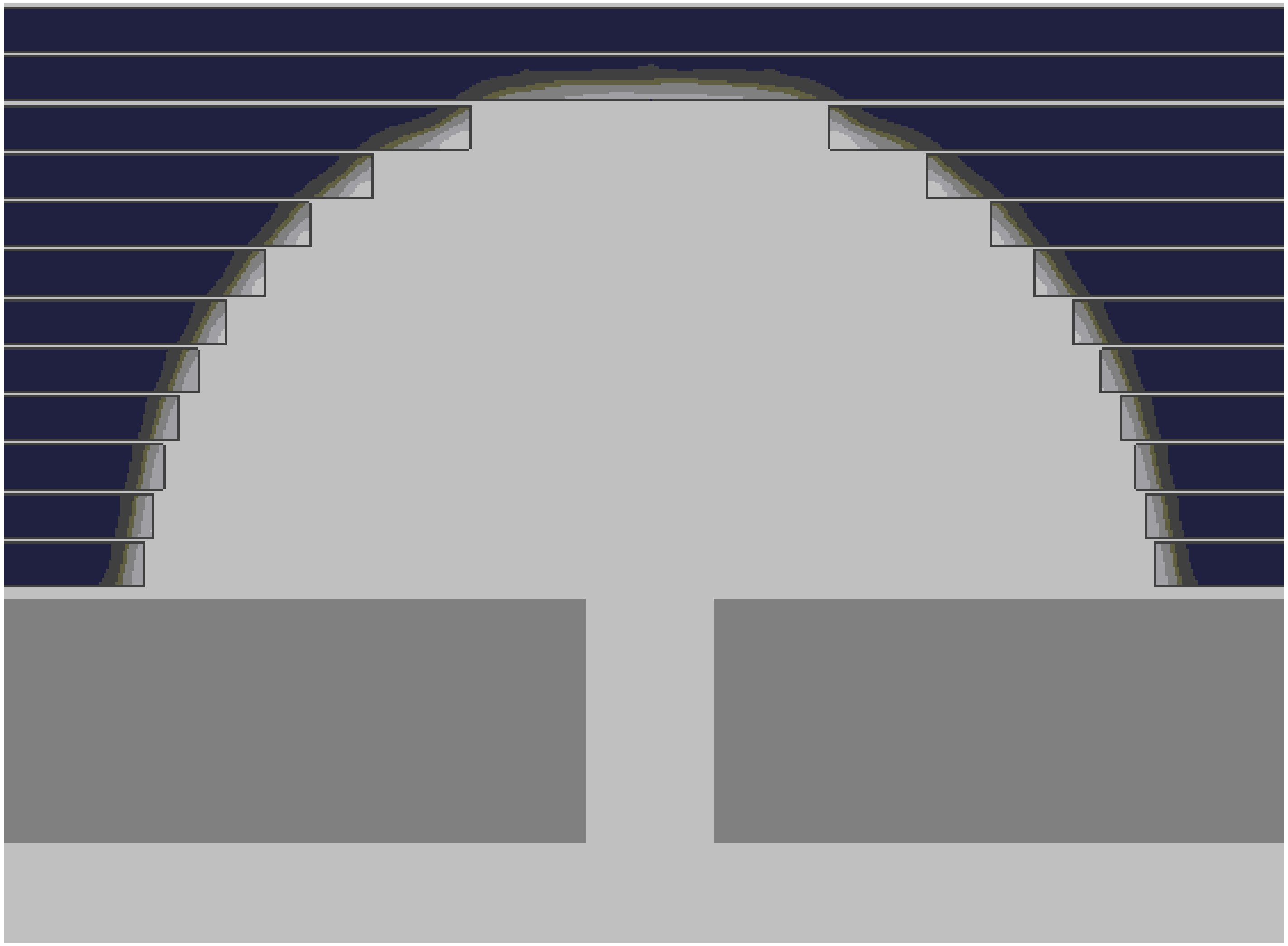
- Use a combination of a solid-wire winding (copper color) and a litz winding (blue).
- DC distributes to minimize loss (mostly in solid wire).
- Leakage inductance forces most HF current through the litz winding.
- Spacing from gap keeps wire out of intense field.





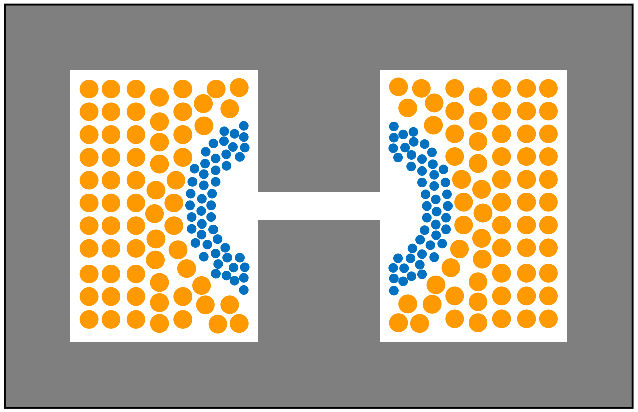
Foil winding with circular cutout

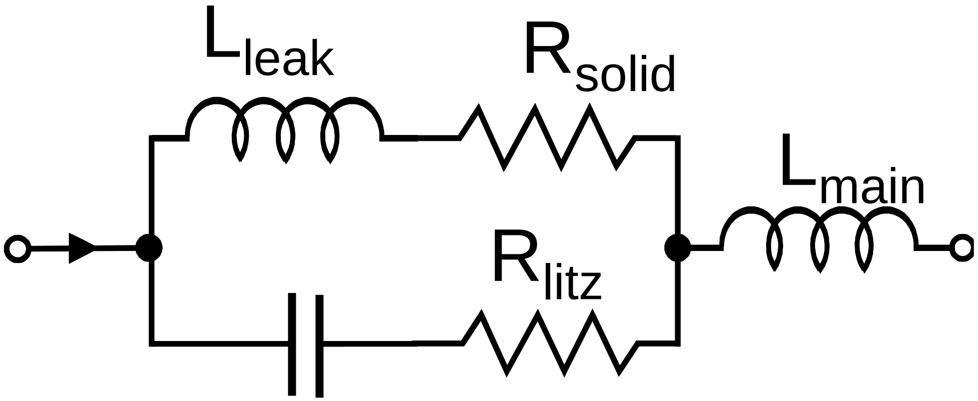
Very low dc resistance with good ac resistance



Inductor for an inverter:
LF AC current plus HF ripple

- Same structure with litz wire and solid wire.
- Challenge: keep LF out of litz winding.
- Solution: series capacitor for litz winding only.
- Can now use a small inductor value: high ripple no longer leads to high loss.





THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Other metals?

Metal	Resistivity ρ (conductor grade)
Silver (Ag)	1.59 μΩ·cm
Copper (Cu)	1.72 μΩ·cm
Gold (Au)	2.44 μΩ·cm
Aluminum (Al)	2.83 μΩ·cm

- Note units: cm not kg
- Price per kg is not the right metric: consider price per volume.

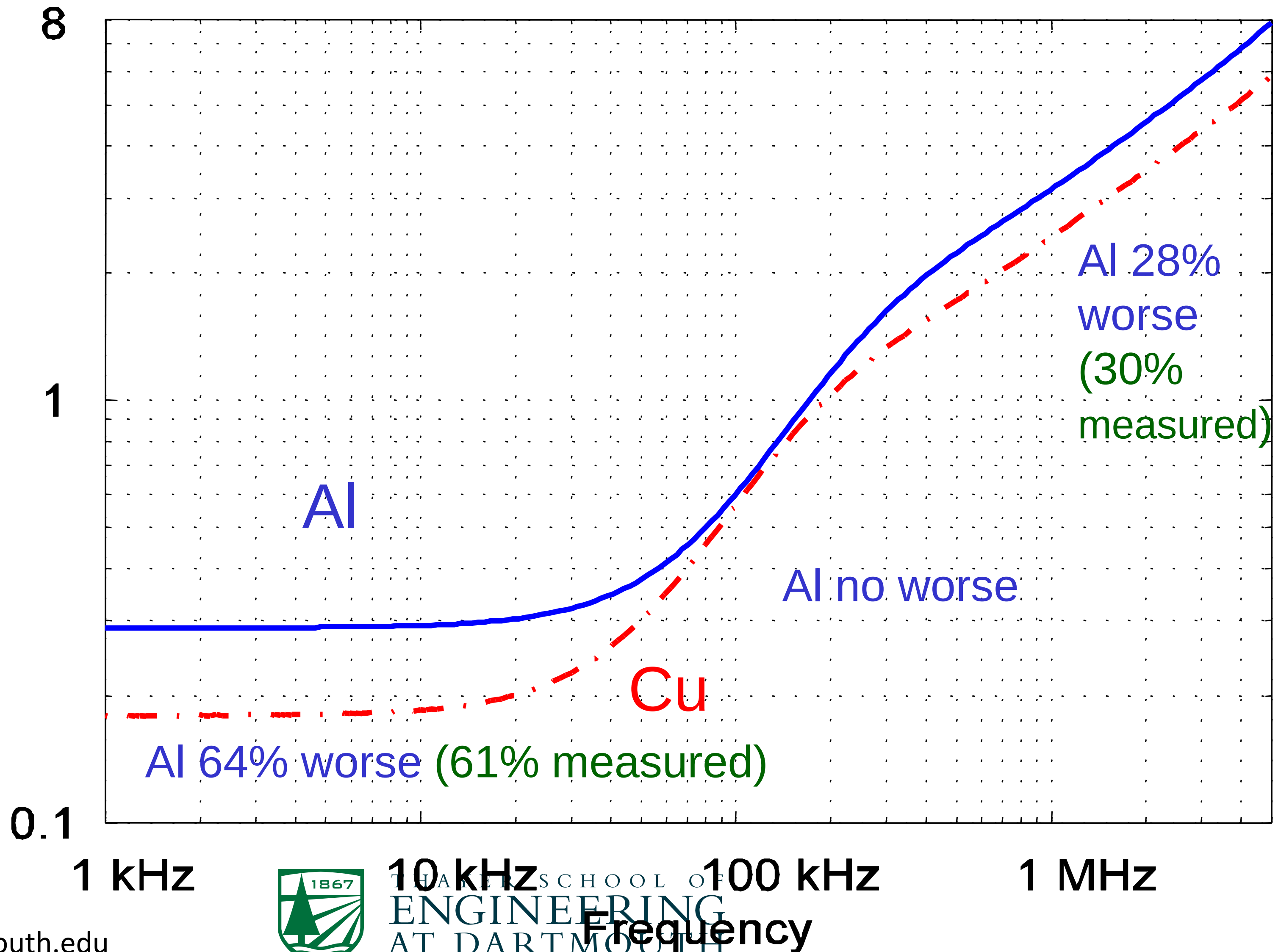
Costs: Cu vs. Al (old numbers, but ratios are still the same)

- Mass:
  \$9.20/kg vs. \$2.40/kg (wrong metric)
- Volume:
  8.2 ¢/cm³ vs. 0.65 ¢/cm³ 12X
- Resistance:
  $14 \frac{\$\mu\Omega}{m^2}$ vs. $1.8 \frac{\$\mu\Omega}{m^2}$ 7.7X
- Actual Al magnet wire prices aren't that good, but even at the same price per kg, Al would be ½ the price for the same resistance!

Can Al work at high frequency?

Measured transformer ac resistance

- 29 turns of 0.5 mm (AWG 24) wire.
- Two layers on EE19 core.



Cost and loss of Al vs. Cu

- For same dc resistance,
  Al is >7X cheaper (commodity price).
- Advantages at high frequency are even greater than at low frequency.
- Only reasons for Cu:
  - Where compact size is more important than efficiency, cost, temperature or weight.
  - If termination cost difference exceeds wire cost difference.

Conclusions

- Litz wire is ideal for high-power, high-frequency windings, e.g. in transformers.
  - Without explicit design calculations, litz wire can make loss worse at high cost.
  - Simple litz design method and spreadsheet available at http://bit.do/simplitz.
- For DC-DC converter inductors, shaped foil and dual-winding designs can provide low AC and DC resistance.
- Inverter output inductors are trickier, but it's possible to use dual-winding inductors with a capacitor added.
- Consider aluminum if you care about cost or weight.