West Coast Magnetics

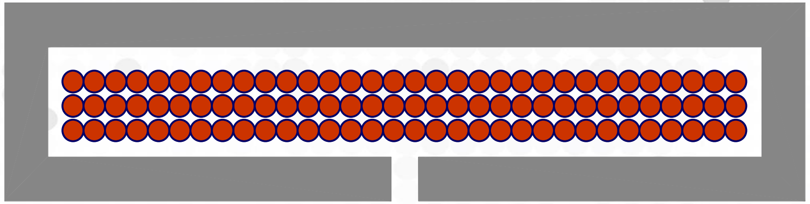
Advancing Power Electronics

FOIL WINDINGS FOR SMPS INDUCTORS AND TRANSFORMERS

Weyman Lundquist, CEO and Engineering Manager

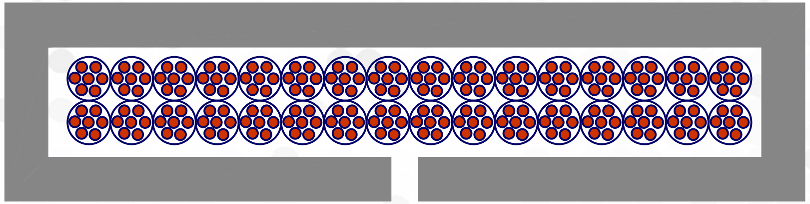
TYPES OF WINDINGS

- Solid wire



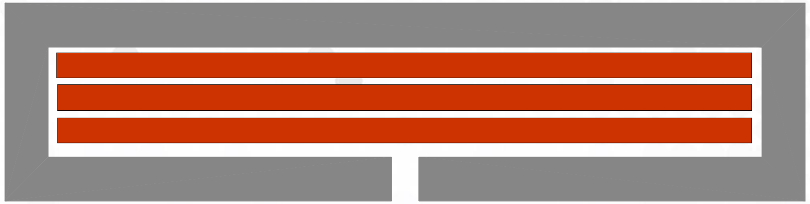
Lowest cost
Low DC resistance
High AC winding loss

- Litz wire



Easy to wind
Highest cost
Higher DC resistance
Potential for low AC winding loss
Practical limitation of 500 kHz due to loss

- Foil



Inexpensive
Very Low DC resistance
Potential for low AC winding loss

WINDING LOSS COMPONENTS

Resistive loss

Eddy-current loss

$$P_{total} = I_{dc}^2 R_{dc} + I_{ac,rms}^2 R_{dc} + P_{skin} + P_{proximity}$$

dc loss

ac loss

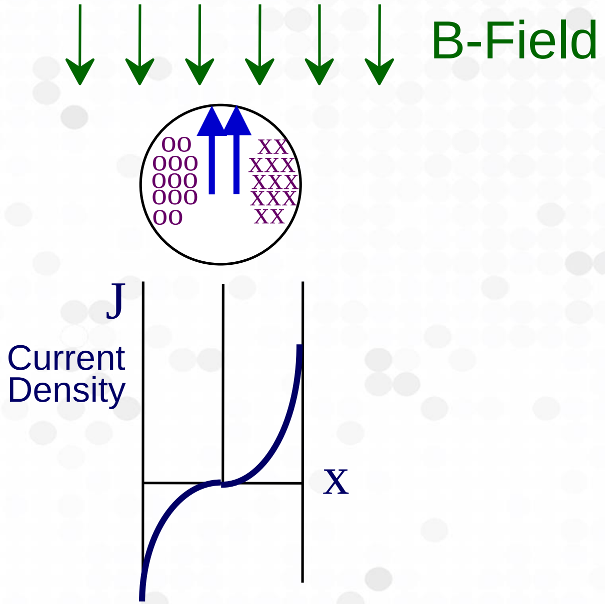
$$P_{dc} = I_{dc}^2 R_{dc}$$

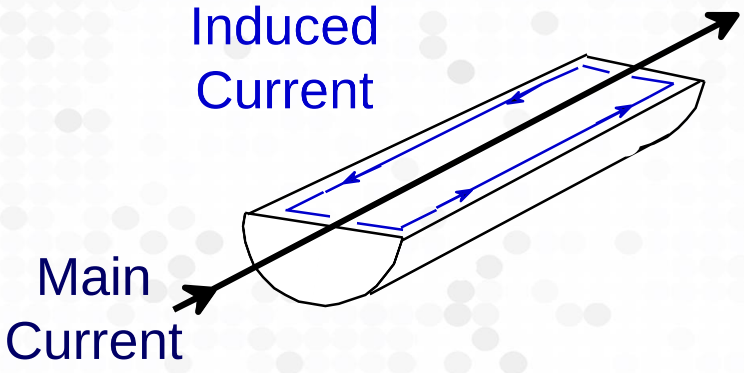
$$P_{ac} = I_{ac,rms}^2 R_{ac}$$

"ac resistance"

$$R_{ac} = \frac{P_{ac}}{I_{ac,rms}^2}$$

PROXIMITY EFFECT





- Proximity Effect
  - An isolated conductor is placed in an uniform external field
  - External field results from other wires and windings near the conductor (transformer) and from the field present in the core winding window (inductor)

Original drawing from Snelling

• Design and Test Verification

- Measure DCR (high accuracy)
- Thermal measurement under load
- Measure ESR (good for comparison of different windings, includes core loss induced by LCR meter)
- Isolate winding loss using Network Analyzer *

- Simulation Software

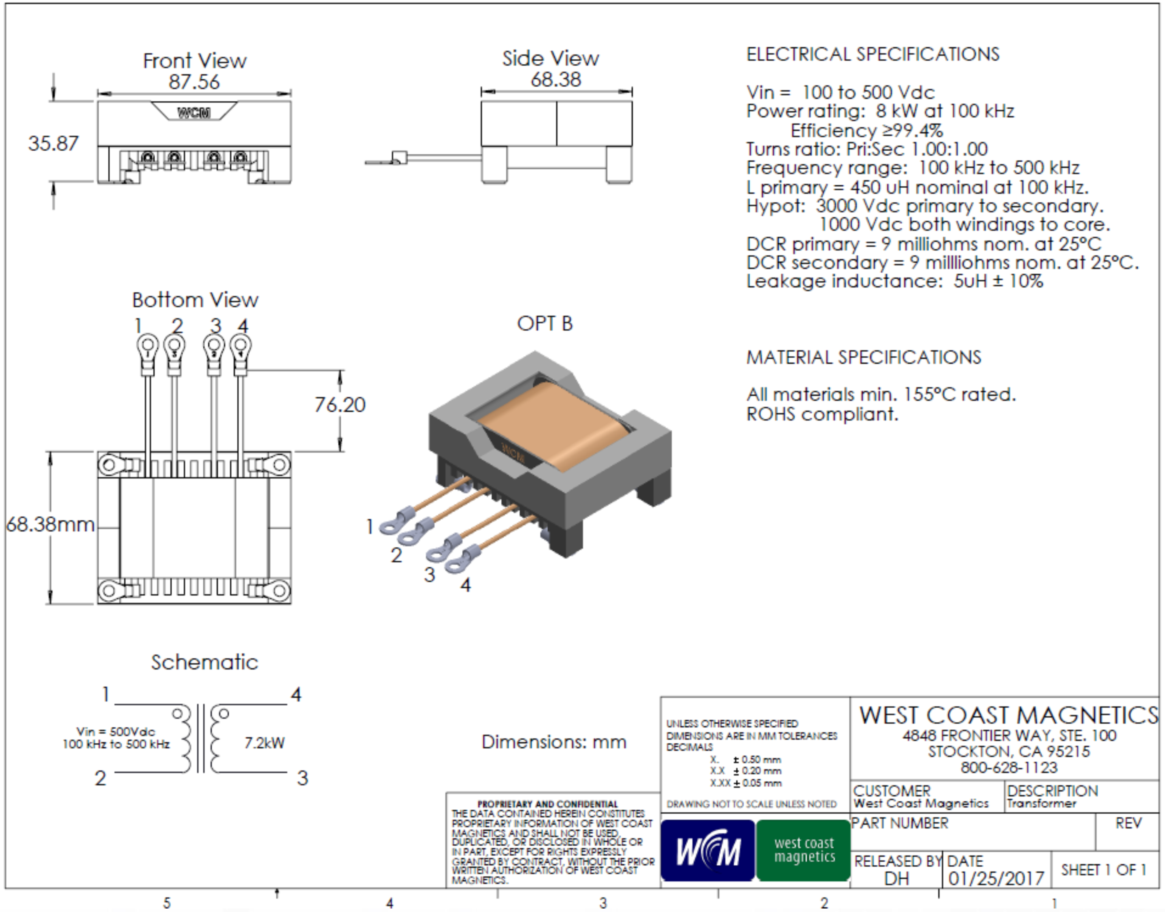
	Transformer	Inductor	Conductor	Complexity	Core gap	Wave form
Dowell	Yes	yes	Solid wire, foil	1 D	No	Sinusoidal
Litz opt	Yes	No	Litz	2D	Yes	Sinusoidal
Shape Opt	No	Yes	Litz	2D	Yes	Any
Ansys	Yes	Yes	All	2D 3D	Yes	Yes

* C.R. Sullivan, "A Step by Step Guide to Extracting Winding Resistance from an Impedance Measurement", IEEE Apec 2017

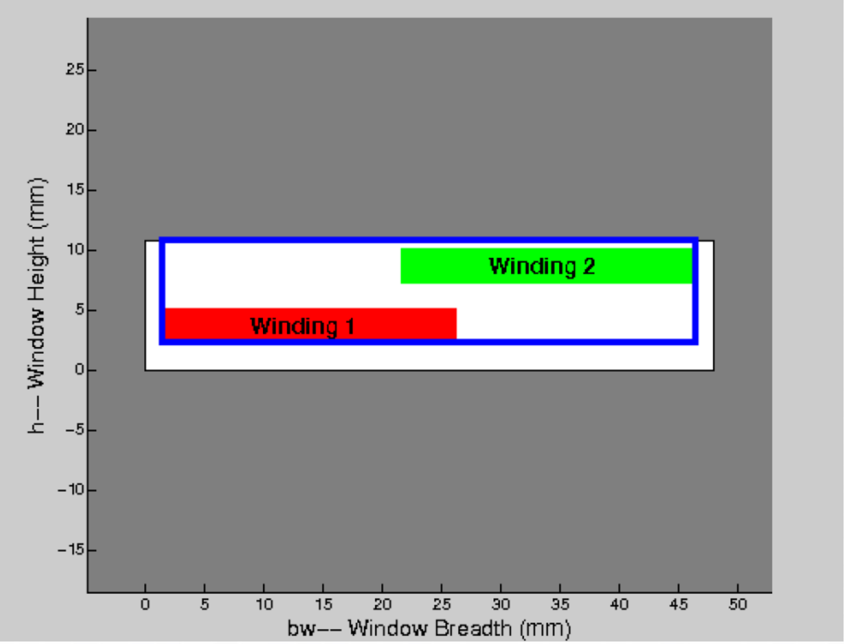
• Strategies for Loss Minimization in Foil Windings

Optimize foil thickness
Minimize number of layers
Shape foil to take advantage of core geometry effects (WCM, Dartmouth Patent)
Use multiple parallel foils and swap layers
Use different foil thicknesses for different turns.
Use a parallel litz or thin foil winding in the vicinity of a gap
Interleave winding (transformers only)
Use a low permeability material for core leg

TRANSFORMER WINDING LOSS – CASE STUDY



TRANSFORMER WINDING LOSS – LITZ WIRE OPTIMIZATION



Design and Test Verification:

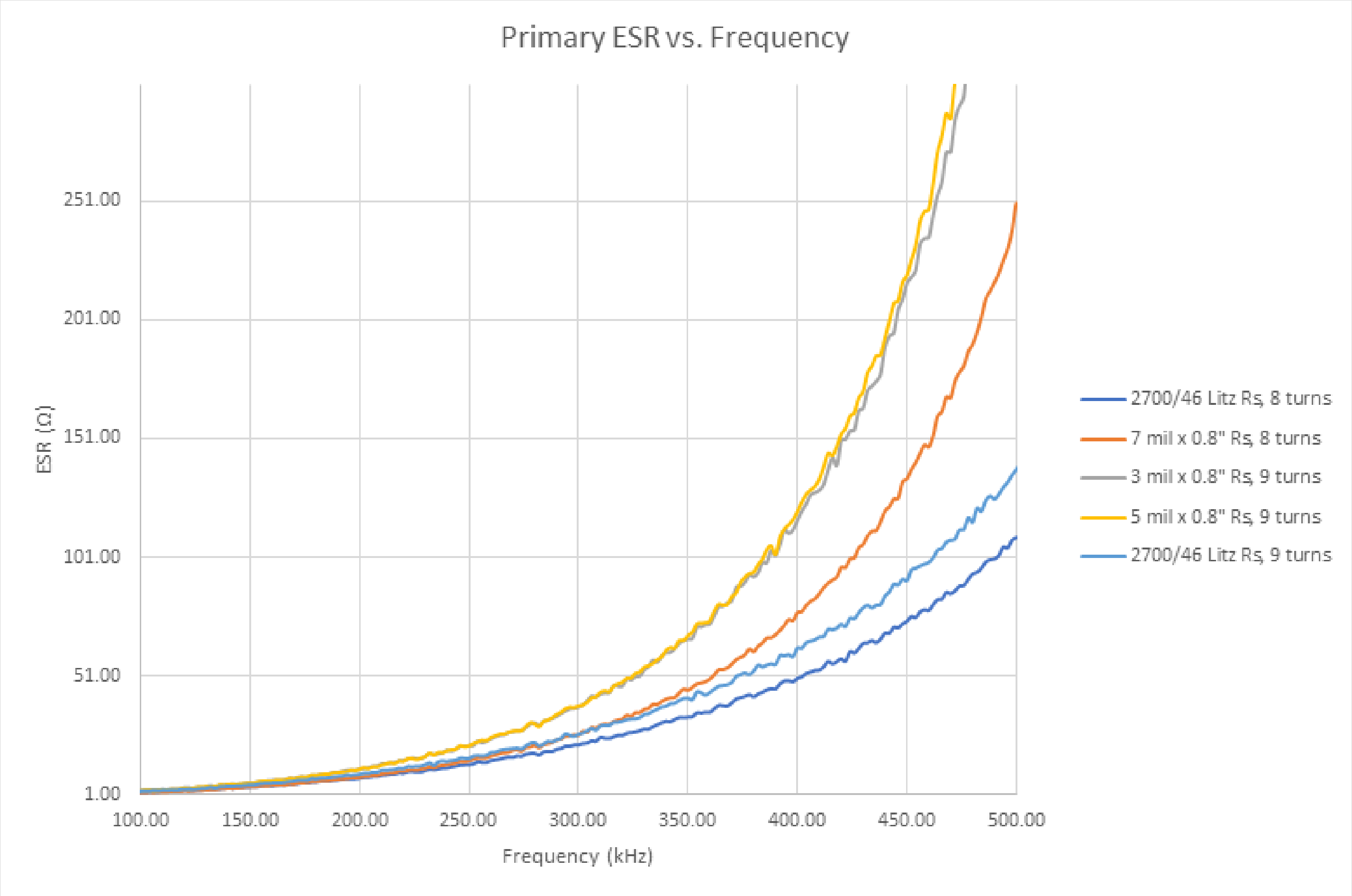
- Model litz options: Litz opt
- Test ESR from 100 kHz to 500 kHz to compare foil and litz.
- Choose lowest loss option.

Litz opt result:

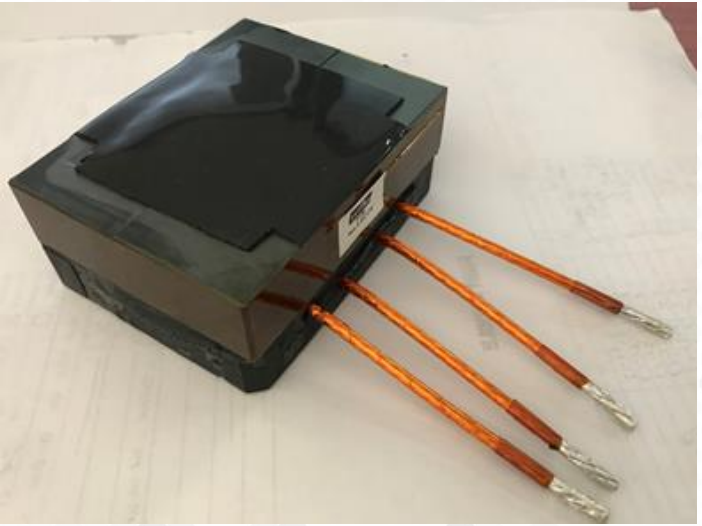
- 48 awg litz is lowest loss option.
- 46 awg litz chosen due to cost.
- 100 kHz: optimal number of strands: 3210
- 500 kHz: optional number of strands: 871

Choose 2700 strands, single layer, position as indicated in cross sectional view.

TRANSFORMER WINDING LOSS – CASE STUDY



RESULTS – TRANSFORMER DESIGN



Litz is lowest loss option

Transformer constructed with 2700/46.

Leakage L not sufficiently high.

Bench testing indicates acceptable performance with room for loss reduction.

NEXT STEP

Use leakage layer to reduce space between windings, increase leakage L, and reduce loss. Investigate lower capacitance foil winding.

INDUCTOR WINDING LOSS – CASE STUDY

Inductance: 700 nH

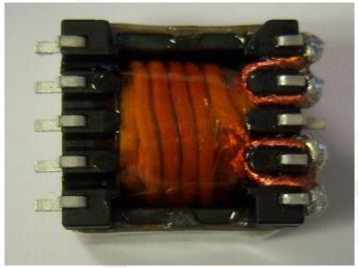
DC Current: 10 amps

Ripple: 23 App

Frequency: 500 kHz

Design: 4 turns on EP13, gap of 1 mm

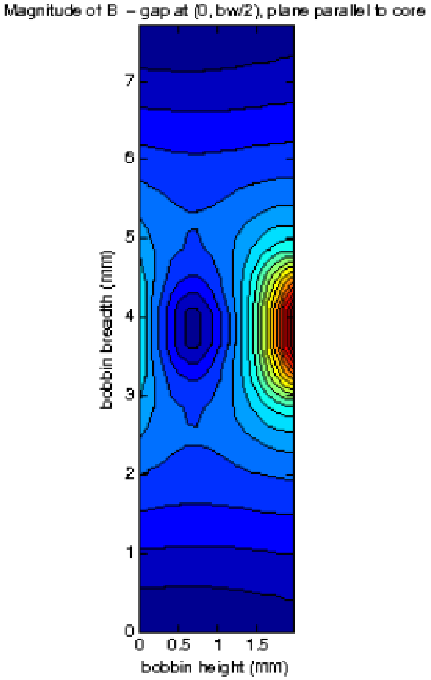
Solution: Shape opt optimization, test ESR and DCR to estimate loss
Compare to full foil and shaped foil.



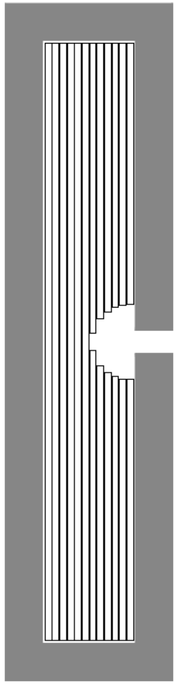
Shaped foil/cutout foil patent issued and second patent pending
WCM and Dartmouth

Inductor Window Cross Section – Center Leg Gap

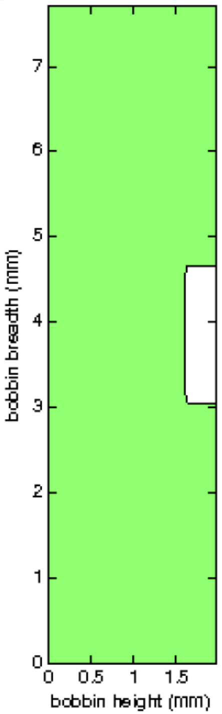
Field Lines: Shape Opt



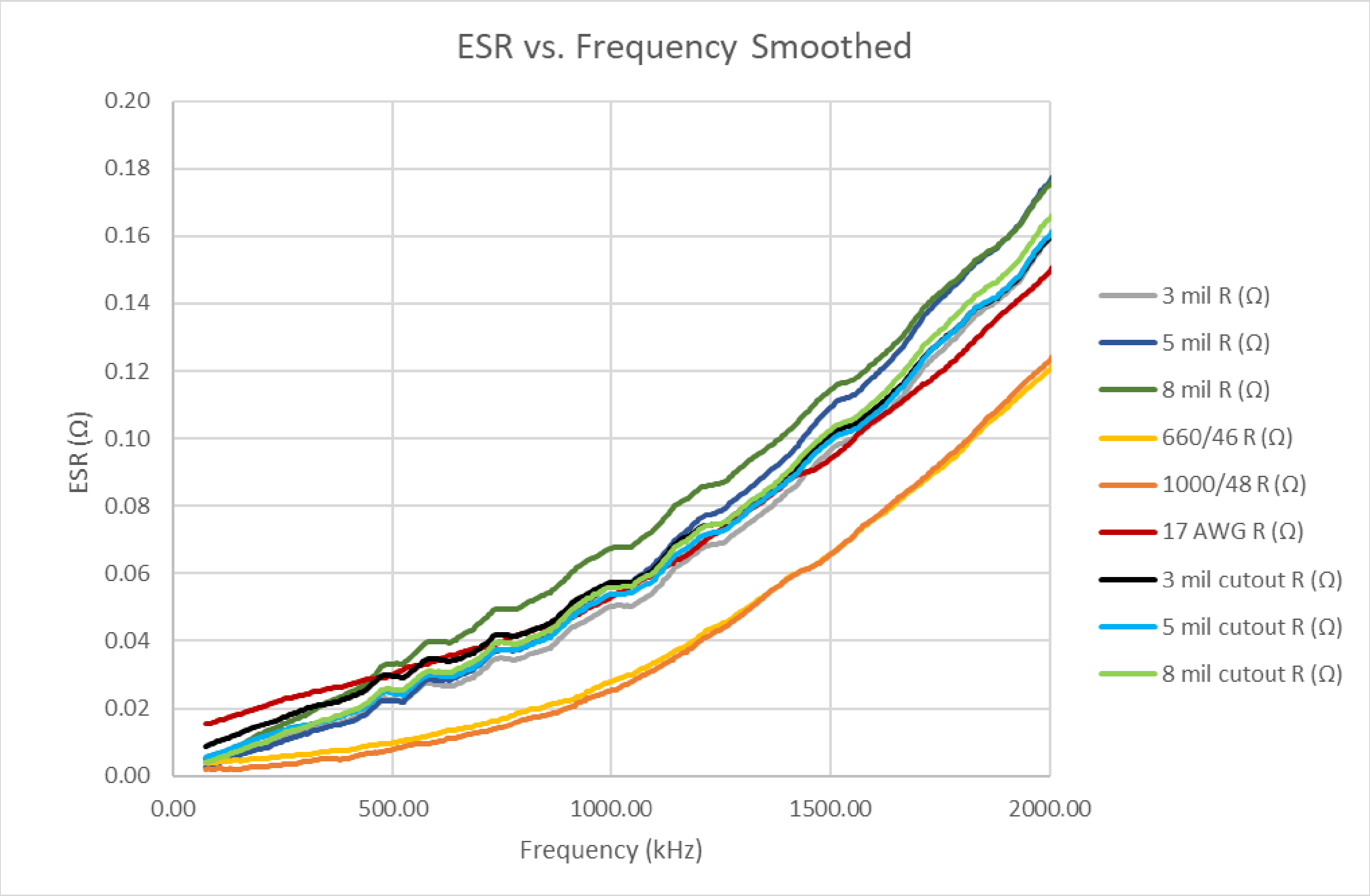
Foil Cutout Cross Section



Wire Placement: Shapeopt

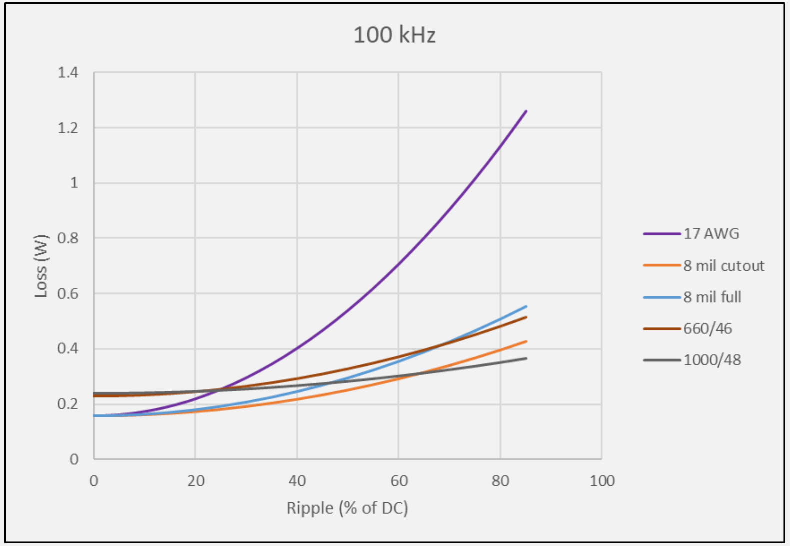


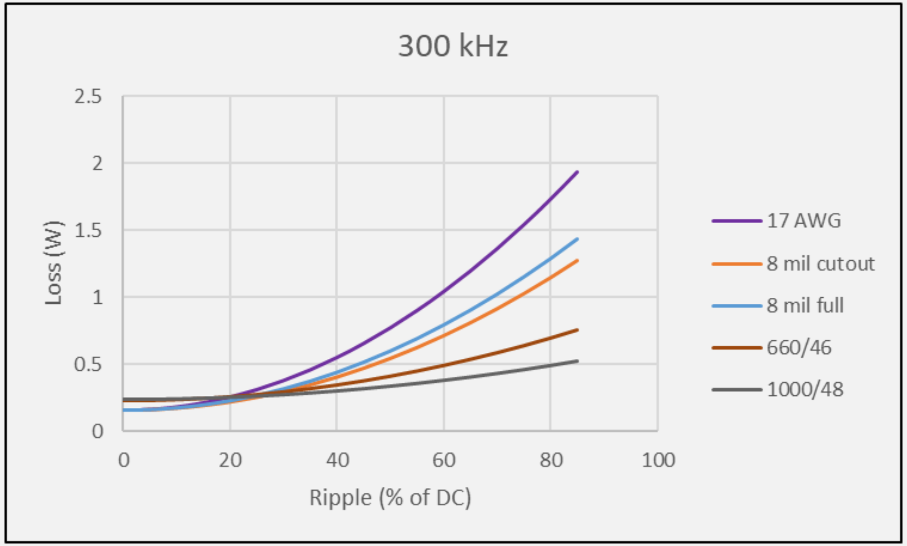
ESR vs. Frequency Measurement 700 nH Inductor

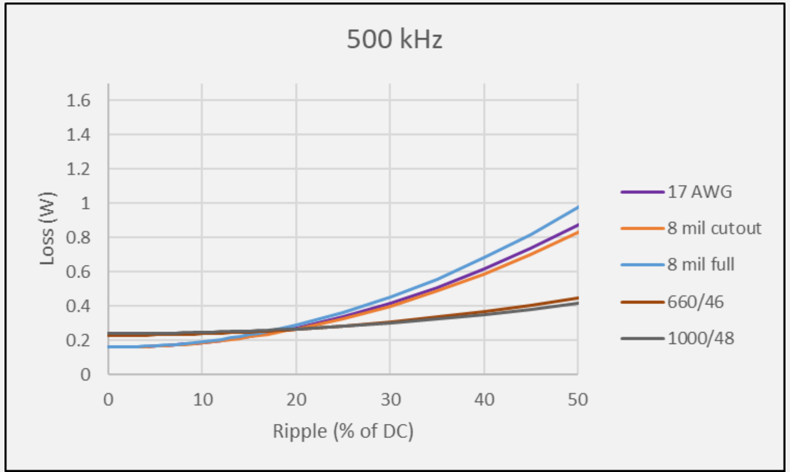


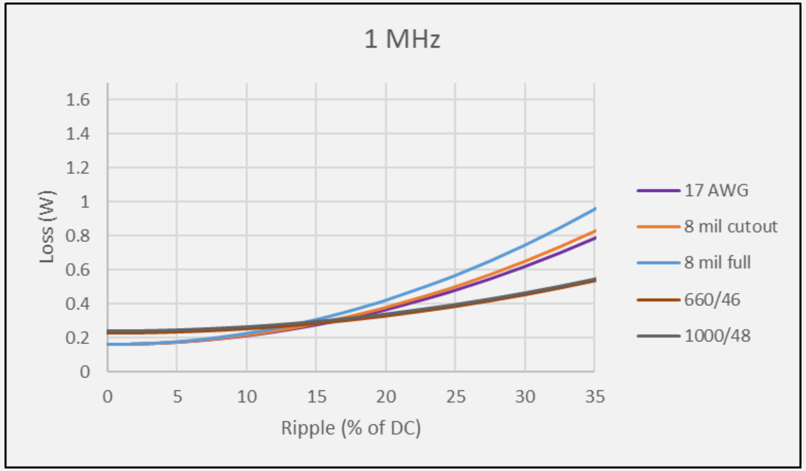
Cutout: patent pending

Inductor Total Winding Loss Including DC









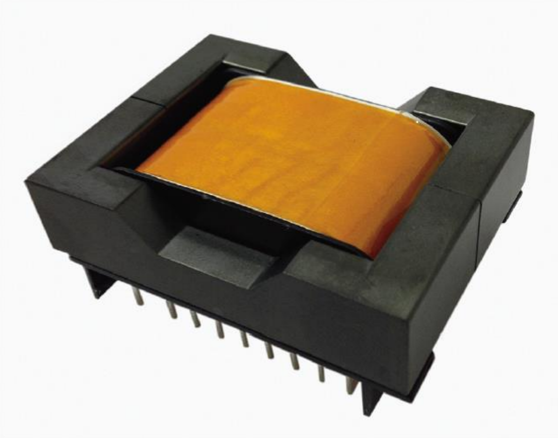
Ripple magnitude above which litz has lower loss than copper foil for a 4 turn boost inductor

		Frequency Percent Product
100 kHz	63%	6300
200 kHz	37%	7400
300 kHz	26%	7800
400 kHz	23%	9200
500 kHz	20%	10000
1 MHz	18%	18000
2 MHz	15%	30000

WCM Shaped Foil Inductors

Low loss gapped ferrite core, shaped foil winding.

Product Code	Inductance (μH) ± 10%	DCR (mΩ)	idc amps INPUT	Schematic
WCM319-01	380.8	44.90	7.00	A
WCM319-02	169.0	16.95	12.00	A
WCM319-03	141.6	13.70	13.00	A
WCM319-04	116.4	10.58	15.00	A
WCM319-05	83.5	7.20	18.00	A
WCM319-06	49.7	4.40	22.00	A
WCM319-07	41.5	3.83	24.00	A
WCM319-08	36.1	3.25	26.00	A
WCM319-09	29.3	2.83	28.00	A
WCM319-10	23.6	2.30	32.00	B
WCM319-11	18.6	1.90	37.00	B
WCM319-12	14.4	1.53	41.00	B
WCM319-13	10.4	1.28	45.00	B



Patent pending: Dartmouth and WCM

Comparison of 10 uH, 55 amp inductors

Inductor Design	100 kHz losses (W)	250 kHz losses (W)	Total Volume (cm^3)	Weight (g)	Cost per Part ($)
Shaped Foil	5.45	7.65	93.72	303.45	$4.69
Iron Nickel Toroid	10.35	13.89	99.87	295.29	$16.18
High Iron Toroid	14.19	16.40	130.65	475.59	$9.48
22 Turn Helical	50.74	61.73	109.55	449.06	$6.69
12 Turn Helical	15.67	27.28	109.55	447.92	$6.66

Based on 2015 WCM study, copies available

Winding Loss: Gapped Ferrite

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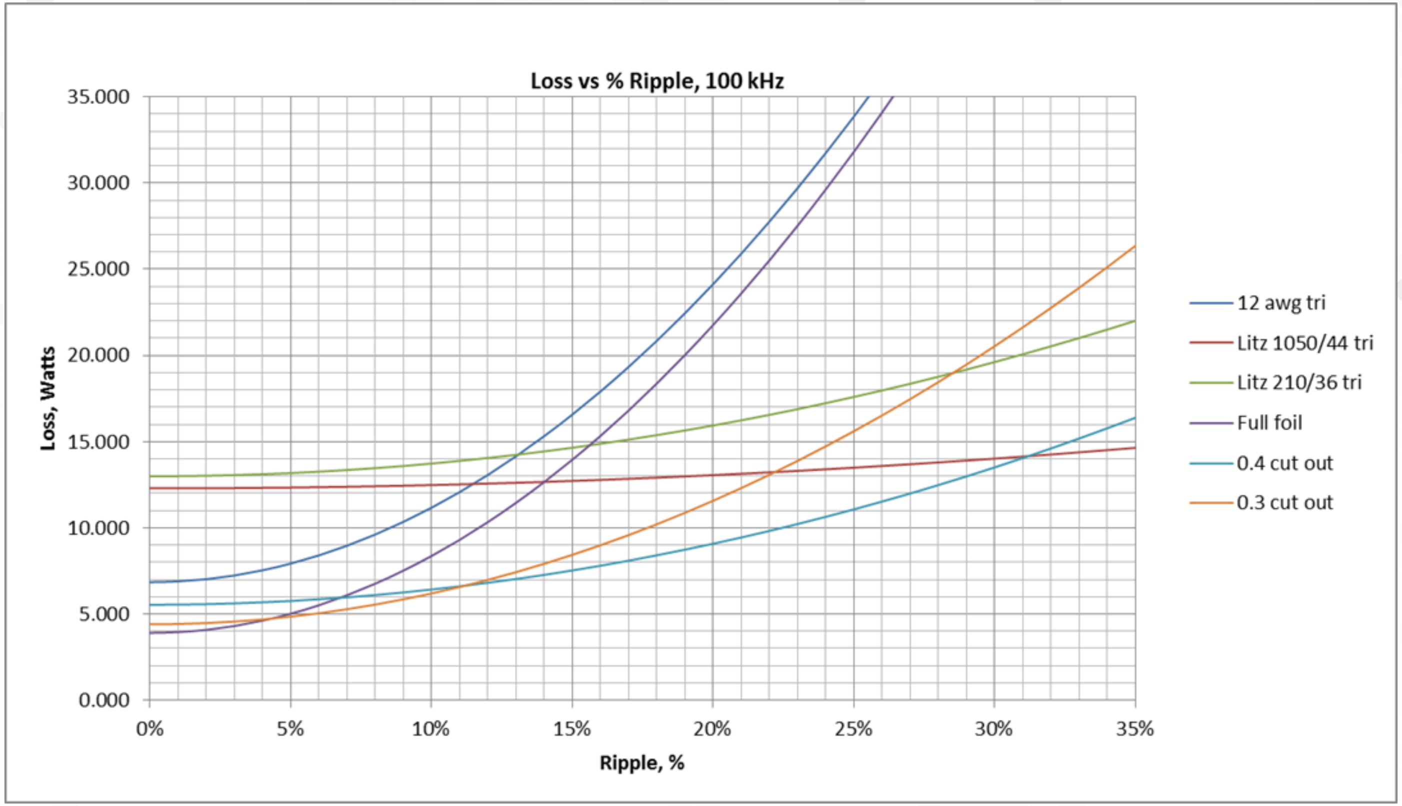

Cutout Patent issued: Dartmouth and WCM

CONCLUSIONS

Cut out foil for gapped inductor designs is the lowest loss option for inductors with DC current up to a ripple frequency product of about 7000. (% ripple * kHz)

Both foil and litz are usable for inductors at frequencies up to 2 MHz as long as the ripple is less than 20%.

Litz is very expensive with the cost increasing exponentially with frequency. In the cases noted in the presentation the litz wire cost was 60% to 70% of the total material cost.

For transformers, many high power applications require more turns, making foil winding optimization critical.

For gapped inductors shaped cutout foil has lower loss than full width foil, provided copper cross section is the same.

Future work to further examine effect of foil thickness as well as methods of reducing winding capacitance in foil windings to extend performance to higher ripple and frequency values and to windings with more layers.

Shaped foil/cutout foil patent issued and second patent pending WCM and Dartmouth

Thank you