Boost Inductors:

Optimal Winding Design

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EDN INNOVATION
Honoring Excellence in Electronics
FINALIST 2009

ISO9001:2008 Registered

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Topics

Will discuss:

Winding design for inductors operating at SMPS frequencies of 10 kHz and higher.

Applicable to inductors with HF AC ripple and DC or low frequency AC fundamental.

Components of Inductor Loss

dc loss

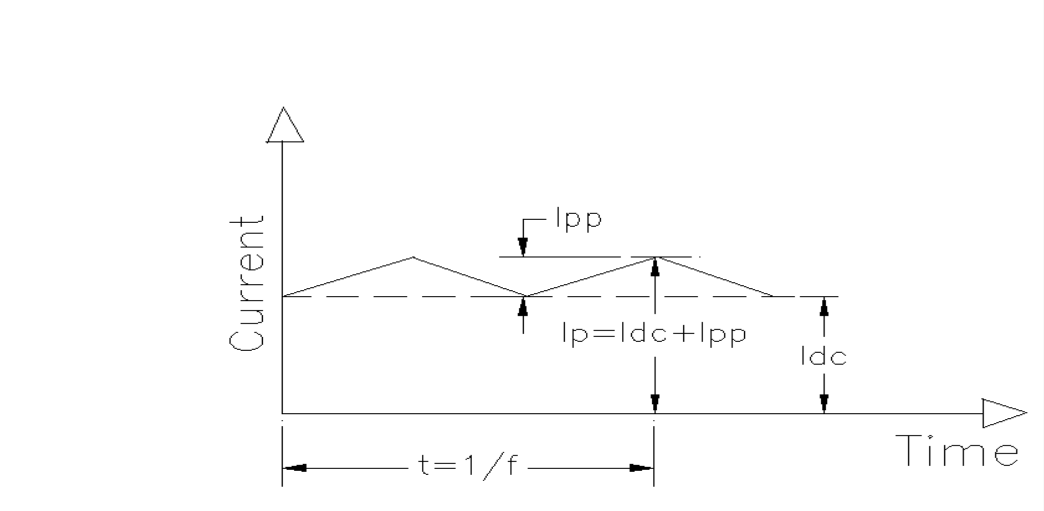
$$P_{dc} = I_{dc}^2 R_{dc}$$

Winding only

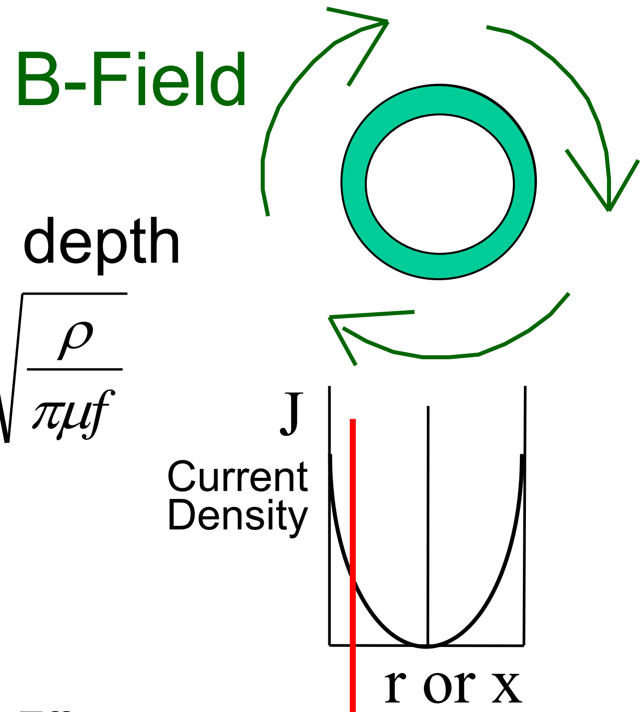
ac loss

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

Core and winding

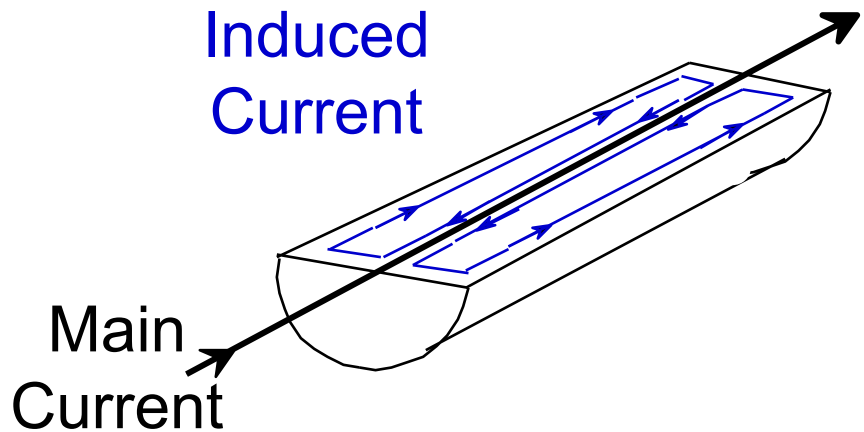


SKIN EFFECT



Skin depth

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



- Skin Effect
  - An isolated conductor carrying high-frequency current which generates a field in itself that forces the current to flow near the surface of the conductor.
  - Skin depth is the distance below the surface of an infinitely thick plane conductor where the field magnitude and current density decrease to 1/*e* of those at the surface

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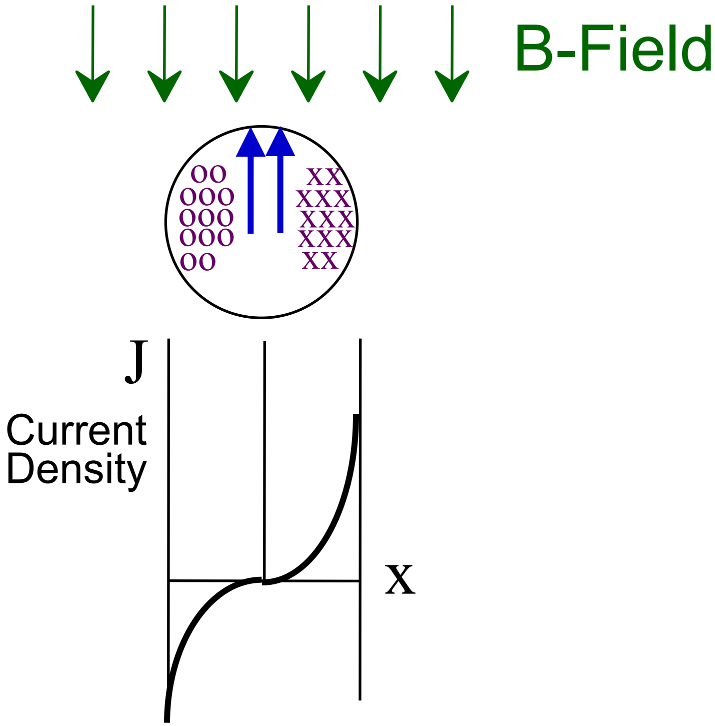
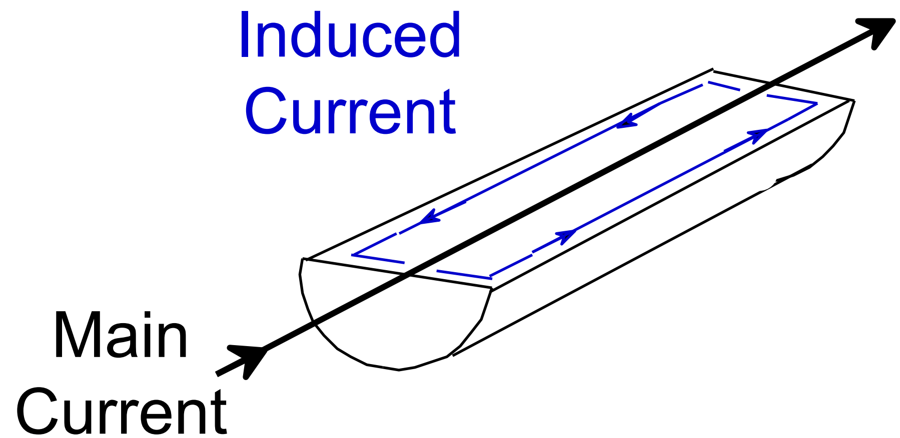
Original drawing from Snelling

PROXIMITY EFFECT



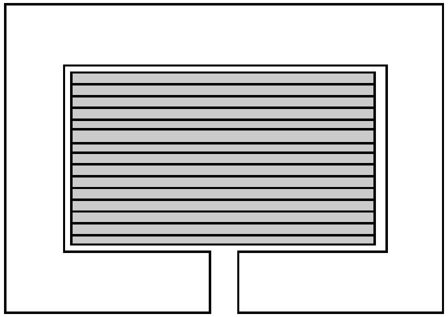


- Proximity Effect
  - An isolated conductor is placed in an uniform external field
  - External field results from other wires and windings near the conductor and from the field present in a gapped core.

Original drawing from Snelling

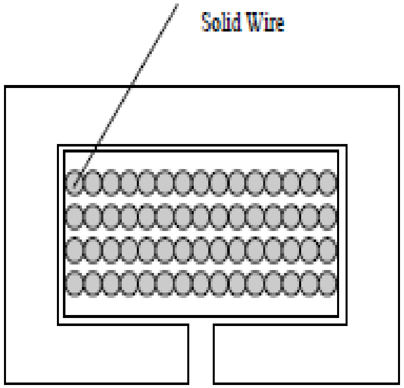
Comparison of Solid Wire, Litz Wire and Foil

FOIL



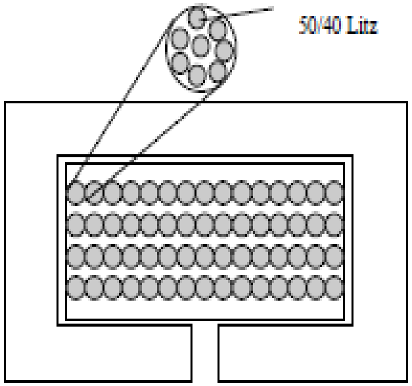
DCR = very low
ACR = medium

SOLID WIRE



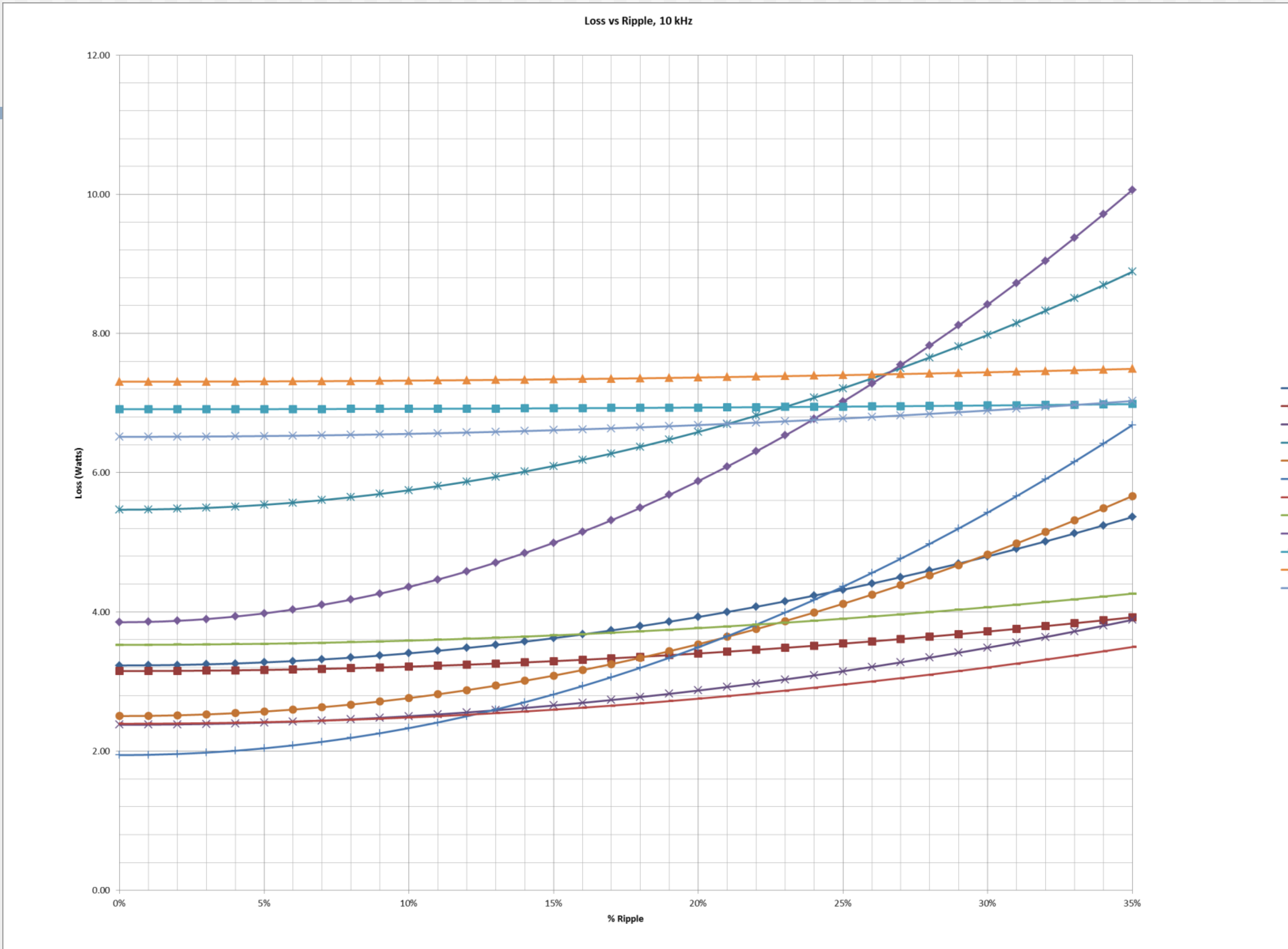
DCR = low
ACR = high

50/40 awg LITZ WIRE

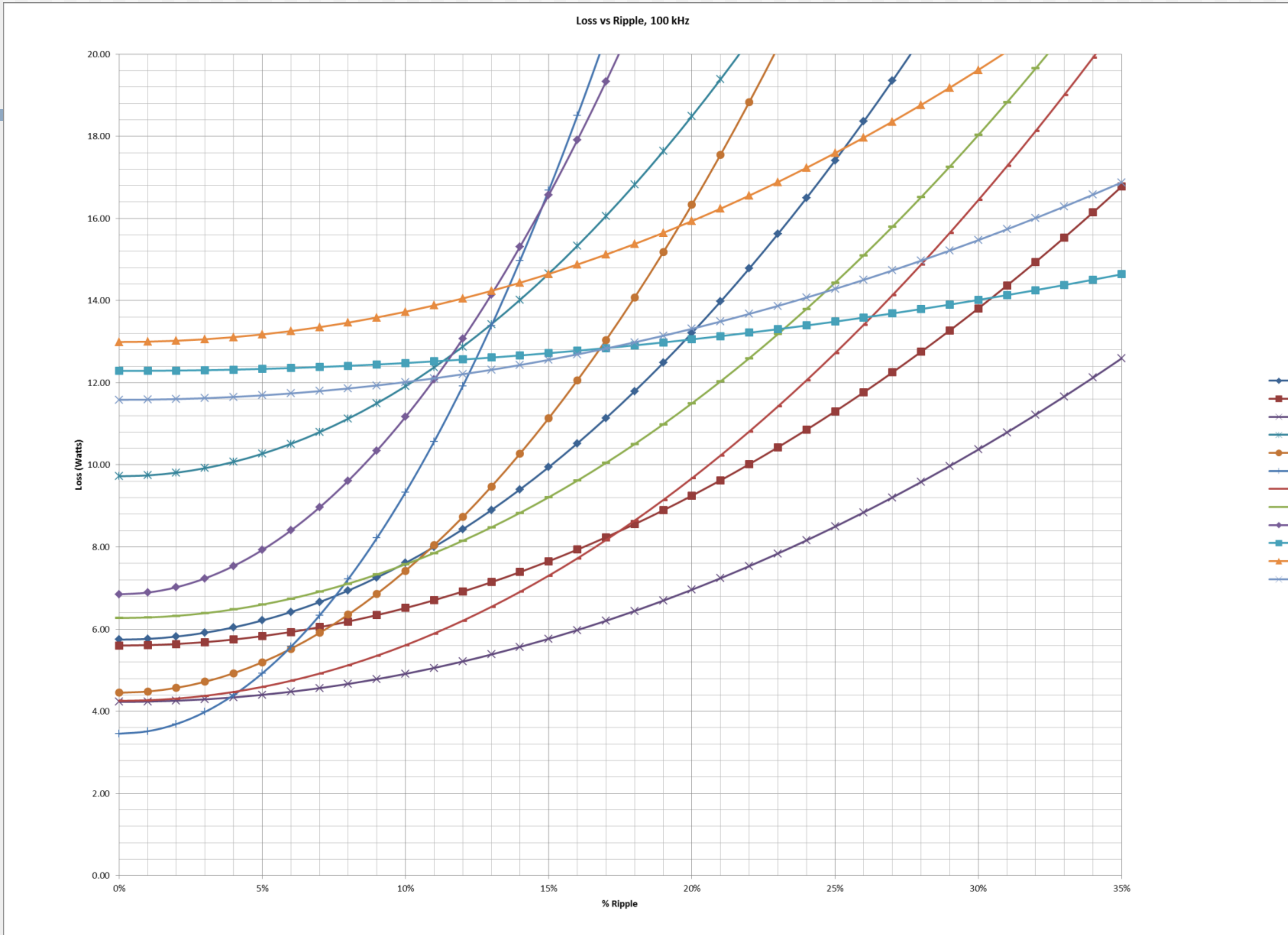


DCR = medium/high
ACR = low

Total Winding Loss vs.
Ripple Current 10 kHz, Single Gap, Center Leg

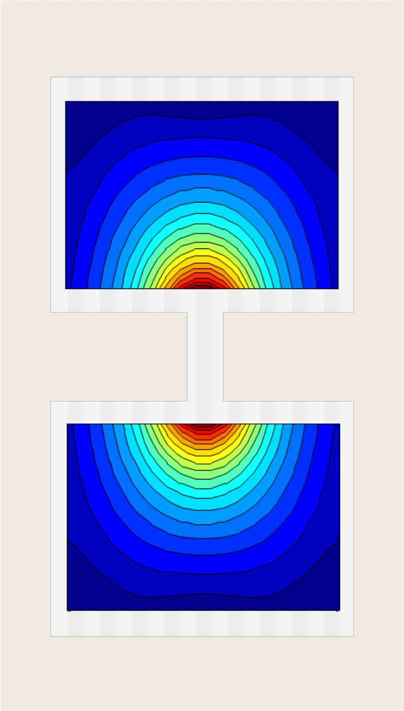


Total Winding Loss vs. Ripple Current 100 kHz, Single Gap Center Leg

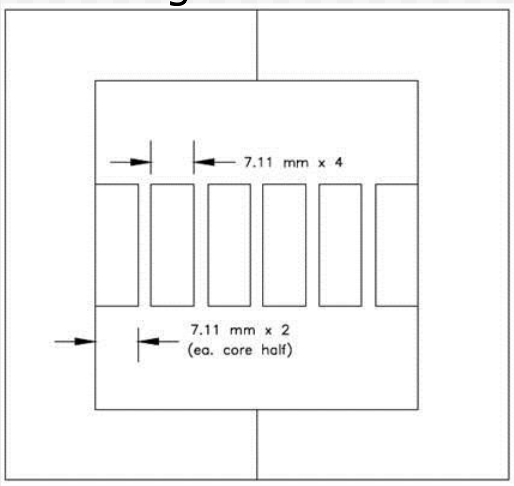


Core Gap Options

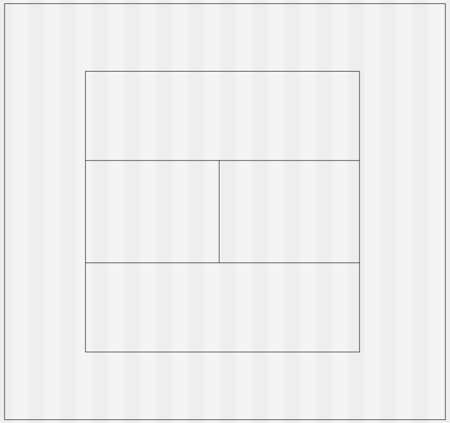
One Gap
Center Leg



Multiple
Gaps Center
Leg

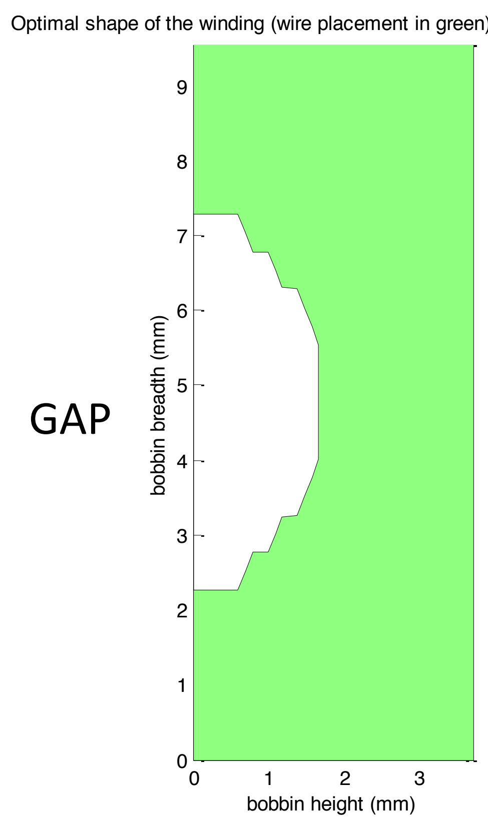


No Gap:
Distributed
Gap Core



Core gaps have traditionally been thought of as creating winding loss. They can also be used to steer AC and DC current into different sections of the windings or into different windings to reduce overall copper losses!

WHAT IS THE OPTIMAL SOLUTION OF WINDING PLACEMENT FOR A LITZ WIRE WINDING IN A GAPPED CORE



Green: wire fill OK
Blank: no wire

Simulation from Shapeopt Software developed by the Thayer School of Engineering at Dartmouth

SHAPE OPT EXPERIMENT: HOLD ALL THE DESIGN PARAMETERS CONSTANT
AND VARY THE GAUGE OF THE INDIVIDUAL LITZ STRANDS
10 uH, 4 amp, 250 kHz INDUCTOR

Wire Gauge	Number of Strands	DCR (mOhms)	AC Loss (watts)	DC loss (watts)	Total Loss (watts)
30	5	36.80	0.53	0.54	1.07
32	9	30.50	0.40	0.47	0.87
34	17	25.70	0.31	0.40	0.71
36	32	21.30	0.25	0.34	0.59
38	55	19.10	0.19	0.31	0.50
40	109	16.60	0.14	0.27	0.41
42	181	15.30	0.11	0.24	0.35
44	314	14.00	0.09	0.22	0.31
46	527	13.00	0.07	0.21	0.28
48	918	12.50	0.05	0.20	0.25
50	1465	12.00	0.04	0.19	0.23

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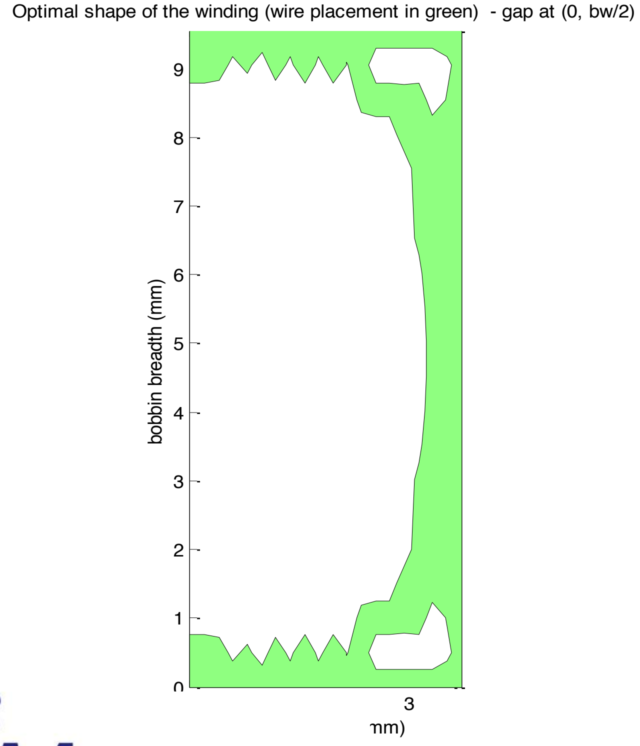
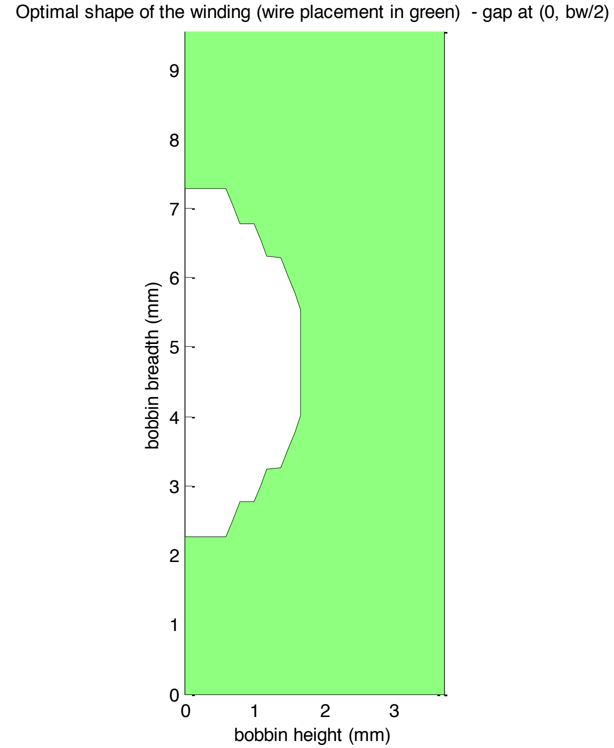
OPTIMAL WINDING SHAPE: 10 uH, 4 amp, 250 kHz Inductor

5 strands 30 AWG



314 strands 44 AWG



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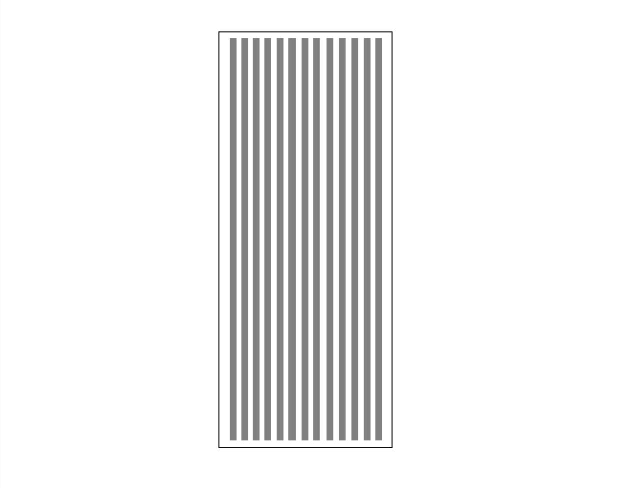
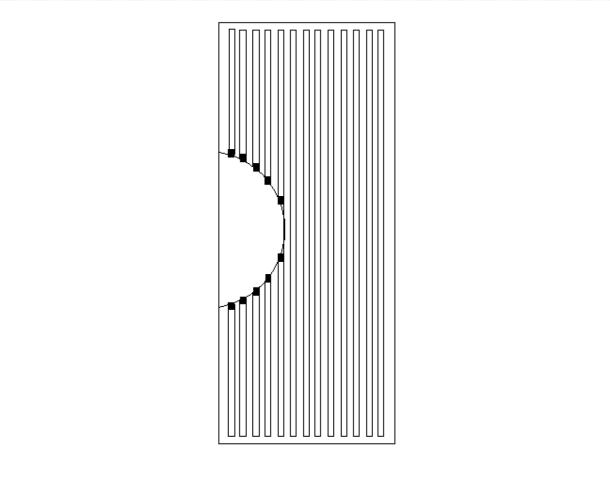
Current Distribution: Ungapped E-Core and Gapped E-Core

Full Foil:
Ungapped Core



AC current evenly distributed on surface of foil across full width of foil.

Shaped Foil:
Gapped Core



AC current pulled to small copper cross section in the vicinity of the gap.

Shaped Foil is a patented technology developed by
Professor Charles Sullivan and Dr. Jennifer Pollock at Dartmouth College.

Experiment: What is the Loss/Cost Tradeoff for the Different Windings?

- Step 1: Define the Inductor
  - Inductance: 70 uH
  - Current: 40 Adc
  - Core: E70/33/32 Ferroxcube 3C90 material
  - Gap: 2.64 mm (1.32 mm each center leg)
  - Turns: 16
- Step 2: Wind inductors with conventional windings using best practices
  - Full window
  - Single layer
- Step 3: Determine winding losses for each inductor as a function of ripple magnitude

shaped foil™

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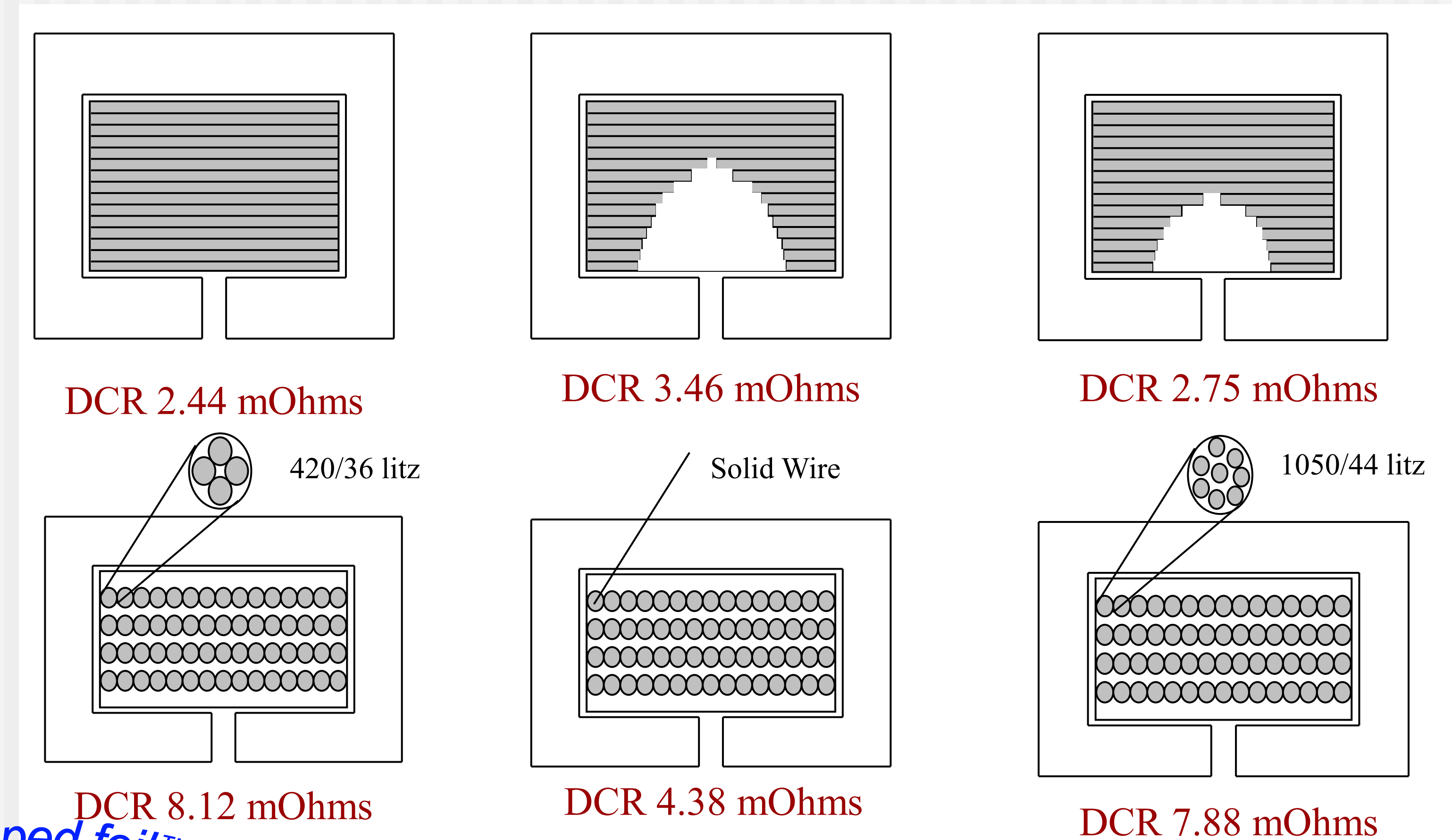
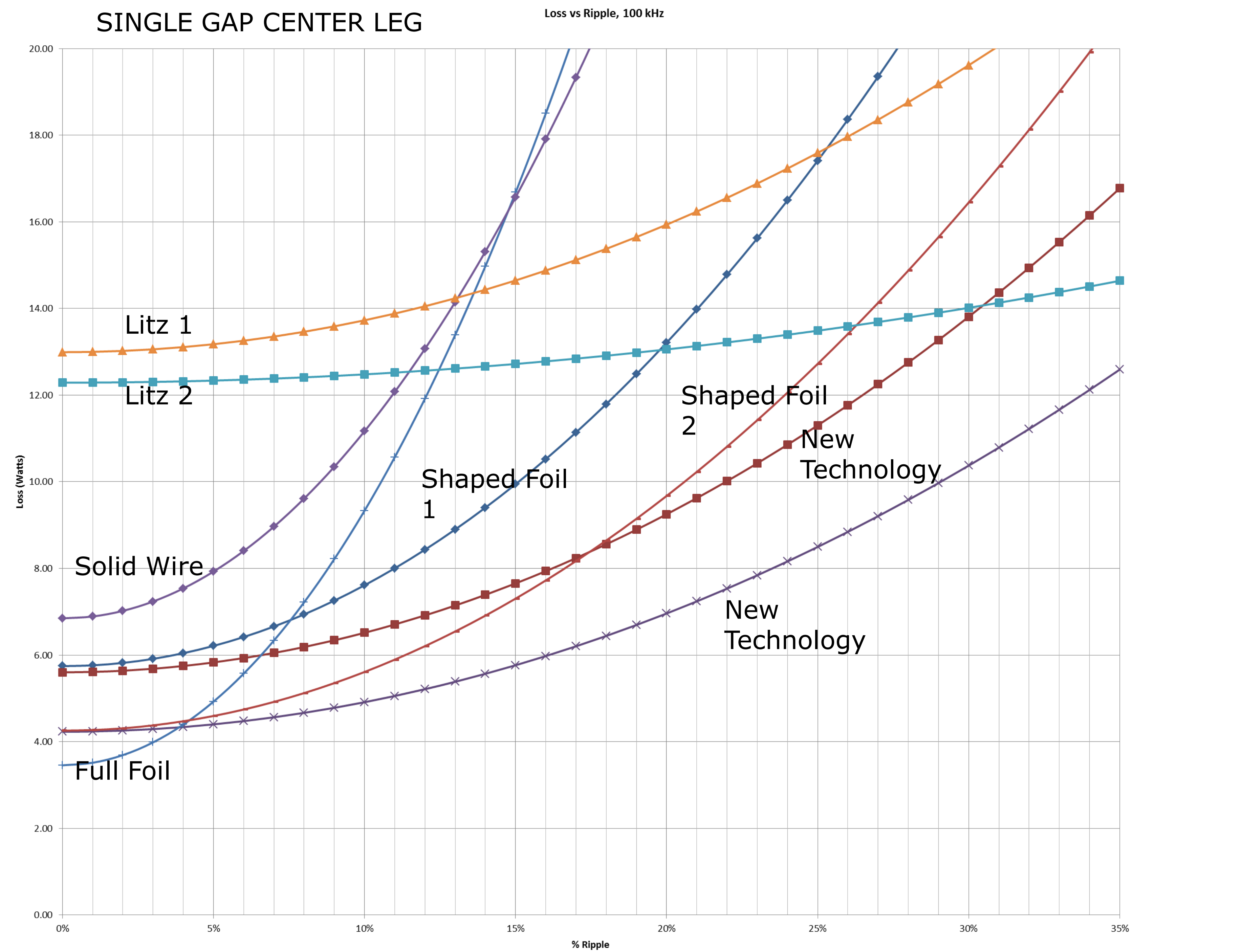
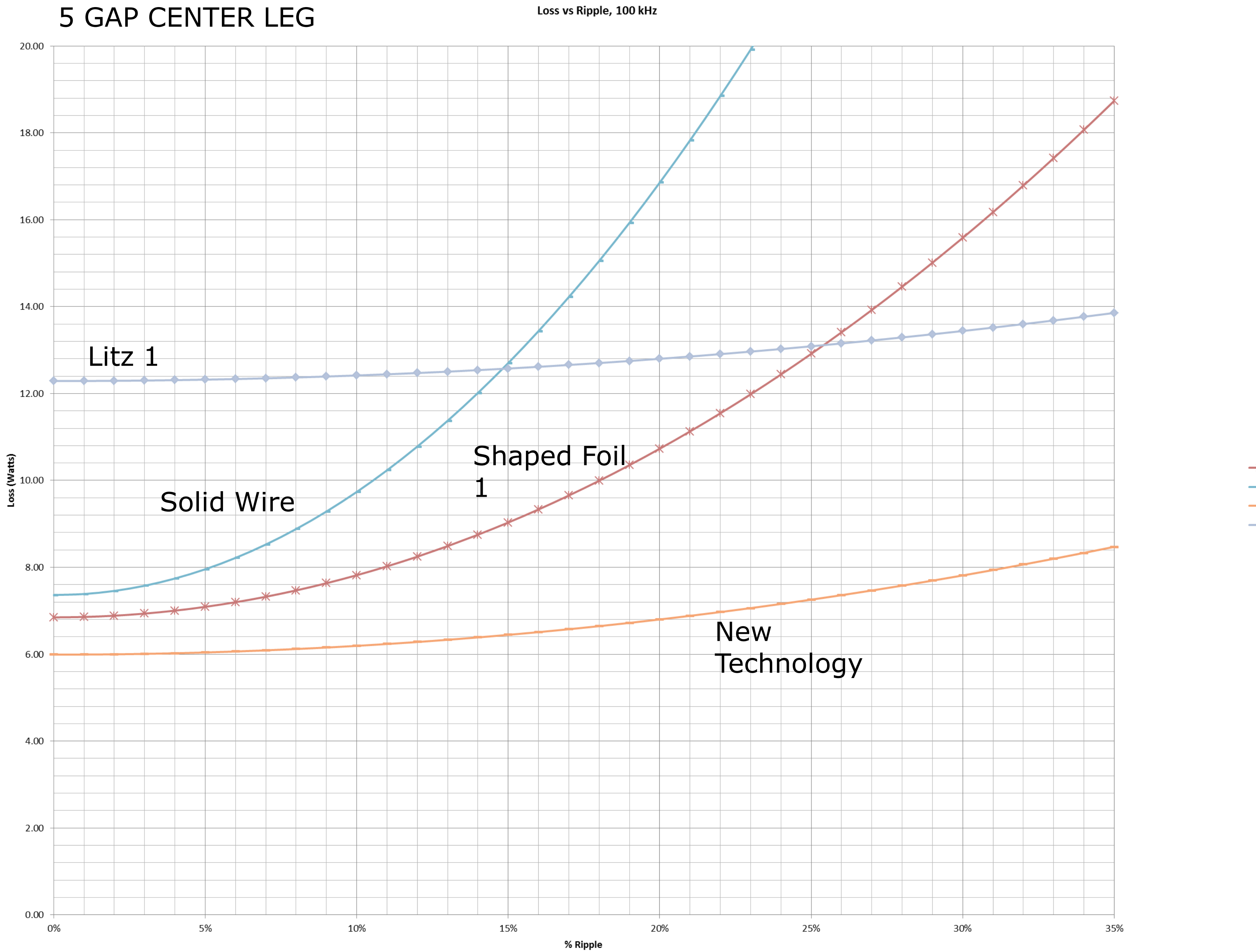
Winding Cross Sections




SINGLE GAP CENTER LEG
Loss vs Ripple, 100 kHz
Loss (Watts)
% Ripple
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0%
5%
10%
15%
20%
25%
30%
35%
Litz 1
Litz 2
Solid Wire
Full Foil
Shaped Foil 1
Shaped Foil 2
New Technology
New Technology

5 GAP CENTER LEG



Winding Cost Comparison

	12 awg	1050/44	400/38	full foil	0.4 cut out	new technology
$/LB	$5.061	$49.74	$19.81	$5.18	$5.18	$4.60
$/LB regained	-	-	-	$4.00	$4.00	$4.00
Bobbin	$3.06	$3.06	$3.06	-	-	-
Tape 3M56 for 1000 parts	$100.00	$100.00	$100.00			
Cost 3M Tufquin for 1000 parts	-	-	-	$341.99	$341.99	$341.99
weight with bobbin	0.50766	0.35805	0.37	-	-	-
without bobbin	0.48802	0.33841	0.35036	1.14248	1.14248	0.737083871
LBs for 1000 parts	488.02	338.41	350.36	1142.48	1142.48	737.083871
Cost for 1000 parts (copper)	$2,470	$16,833	$6,941	$5,918	$5,918	$3,391
Recovered cost for 1000 parts	-	-	-	-	$1,135	-
Total Cost for 1000 parts	**$5,630**	**$19,993**	**$10,101**	**$6,260**	**$5,125**	**$3,733**

shaped foil™

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Thank you for your time

Weyman Lundquist, President

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