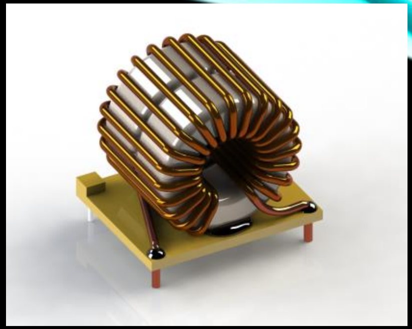
MAGNETICS®



SMALLER-*FASTER*-£OW€R CO$T

Magnetic Materials for Today's High-Power Fast-Paced Designs

Donna Kepcia
Technical Sales Manager
Magnetics

DISCUSSION OVERVIEW

- Semiconductor Materials,
  SiC, Silicon Carbide & GaN, Gallium Nitride -- higher frequency switching
- Available Magnetic Materials
  Ferrite -- Powder Cores—Strip Wound Products
- Usable Flux Density
- Design Trends
  Higher Frequency, Higher Efficiency, Lower Cost, Faster to Market
- 500 Watt Power Factor Correction comparison
- 80 Amp High Current Application comparison
- 0.75 Amp 500 kHz ferrite design

SWITCHING FREQUENCIES INCREASING

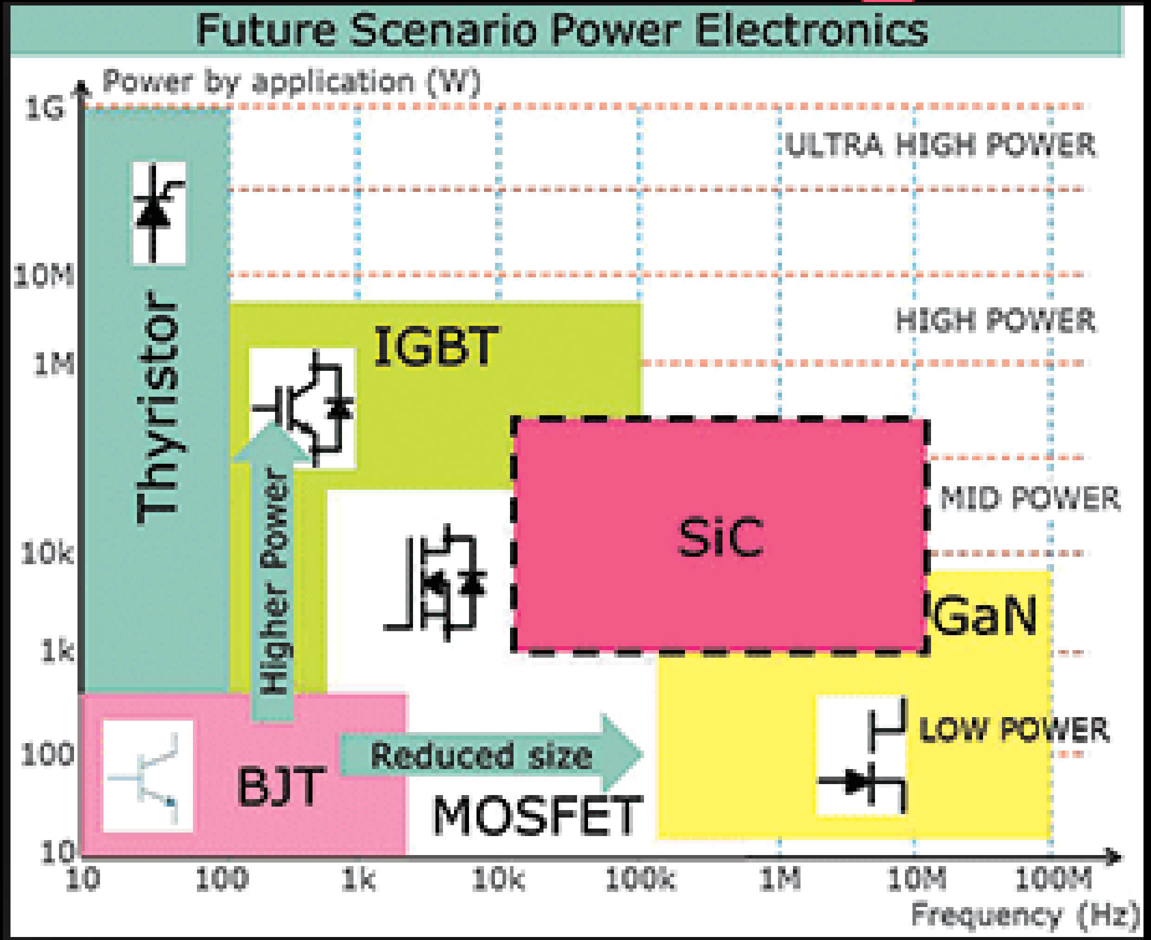
New Semiconductor materials

SiC – Silicon Carbide

GaN—Gallium Nitride

ADVANTAGES IN POWER APPLICATIONS

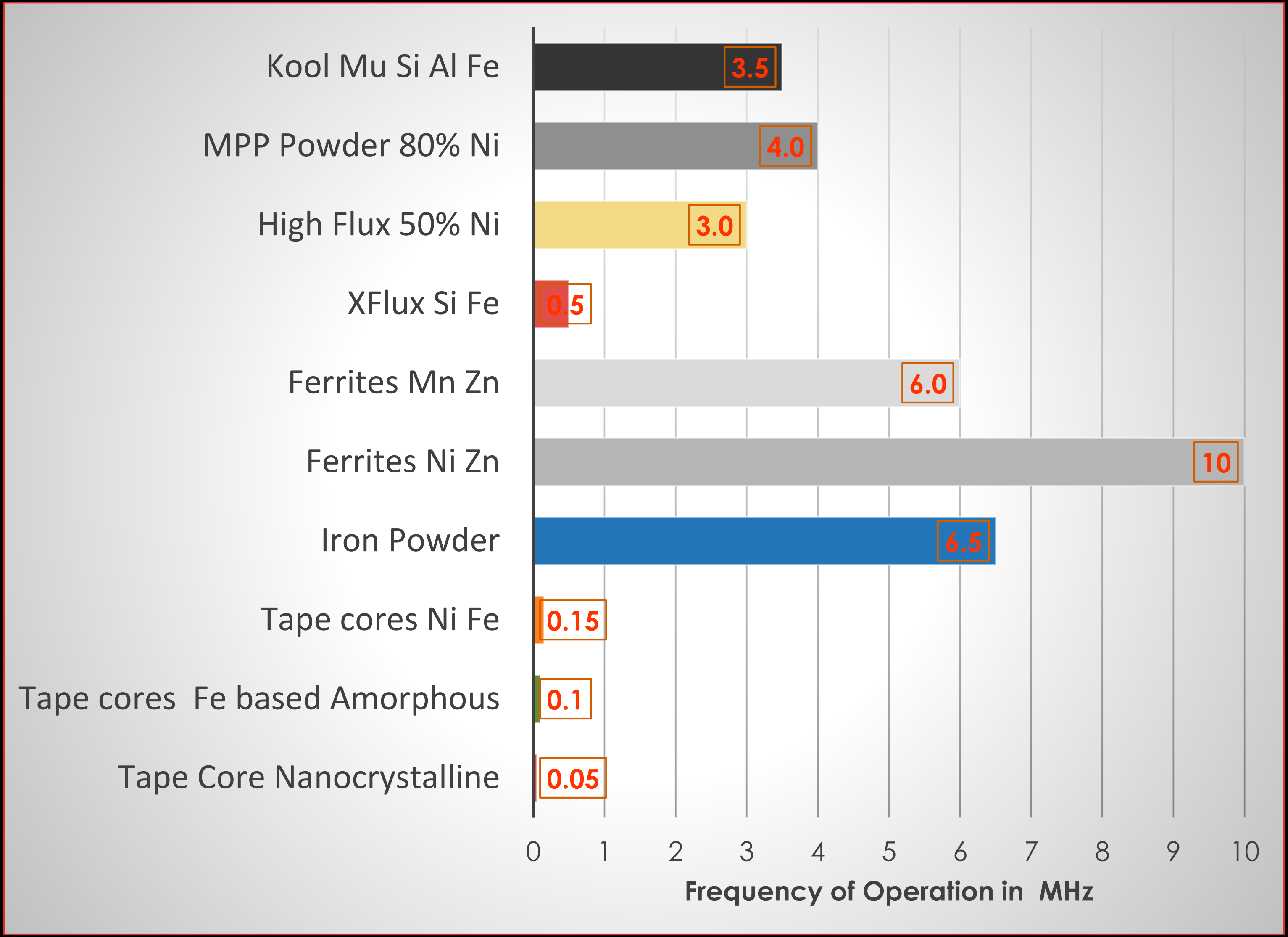
- Higher voltage
- Higher operating temperature & Lower resistance
- Cooling system simpler and smaller
- Higher switching frequency
    - smaller transformers and inductors
    - fewer large capacitors
- Improve the power density and efficiency of the power supply



Switching Frequency

AVAILABLE MAGNETIC MATERIALS

- **Ferrite**
  Manganese Zinc
  Nickel Zinc
- **Powder Cores**
  MPP 80% Nickel Iron
  High Flux 50% Nickel Iron
  Kool Mμ® & Kool Mμ® MAX
  Iron Silicon Aluminum
  XFLUX® Iron Silicon
  Iron Powder
  Amorphous powder
- **Strip Wound Cores**
  Toroids & Cut cores
  Nickel-Iron alloys
  Cobalt-Iron alloys
  Amorphous alloys
  Nanocrystalline alloys



FREQUENCY RANGE OF MAGNETIC MATERIALS

Usable Flux Density vs Frequency for Core Materials

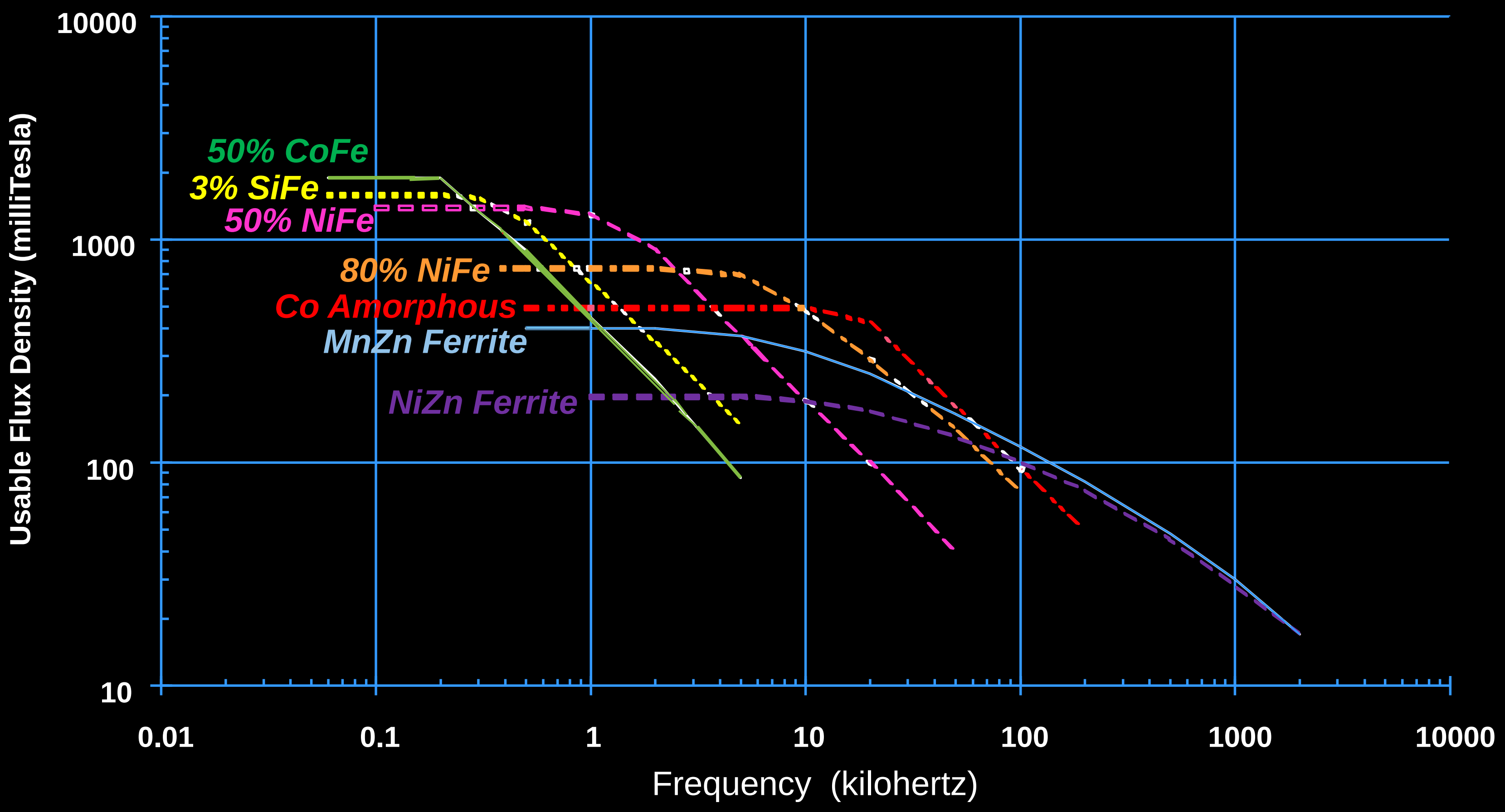
Ampere's Law

$$H = \frac{.4\pi NI}{le}$$

Faraday's law

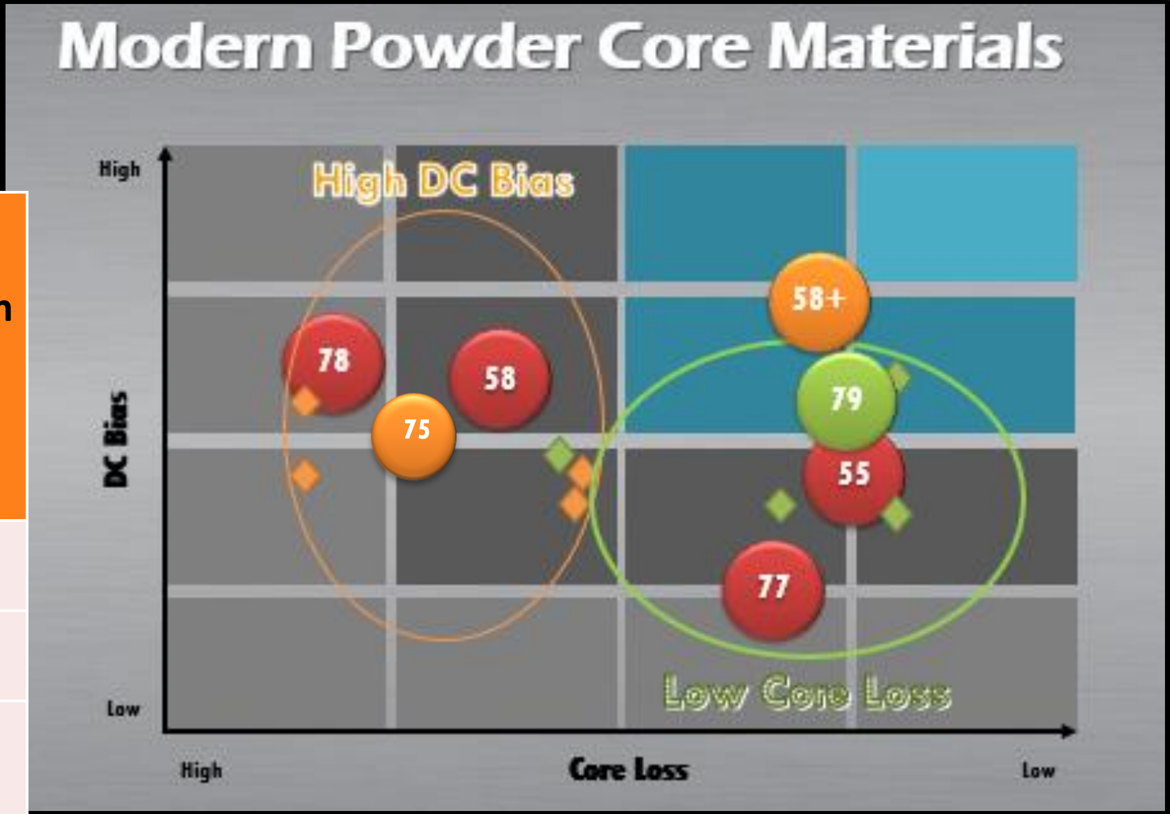
$$V = 4.44B\ Ac\ N\ f \times 10^{-8}$$

ALL MATERIALS ARE GOVERNED BY THE SAME RELATIONS



Inductor Materials

Material	Alloy	Core loss 60 perm 100 kHz, 100 mT mW/cm^3	Core loss 60 perm 200 kHz, 70 mT mW/cm^3	DC Bias 60 perm 50% A-T/cm typ.	Cost 1" toroid powder gapped PQ	Saturation Flux Density
XFLUX®	Fe Si	2000	2400	139	€0.748	1.6 T
High Flux	Fe Ni	900	1463	131	€2.240	1.5 T
Kool Mμ® Max	Fe Si Al	500	632	107	€1.008	1.0 T
Kool Mμ®	Fe Si Al	550	689	75	€0.505	1.0T
MPP	Fe Ni Mo	450	480	84	€3.420	0.75 T
Blends	Custom	450-1500	480-2000	84-139	€0.65-€2.24	0.75 – 1.6T
Ferrite	Fe O	60	70	30	€0.740	0.45 T



Inductor Design Trends

TALL TOROIDS

- Eliminate stacking and cementing
- Adapt to fit space available
- Support more current

DESIGN BOOST PFC—EFFICIENCY TARGET 98%

- Examine inductor current
  - At low line voltage
  - At high line voltage
- Determine the AC ripple permitted
- Inductance required to support worst-case V ripple
- Highest current to be supported
- LI^2 product---Select core
- Using the core chosen recalculate inductor current
  - At low line voltage
  - At high line voltage
- Combine results to obtain waveform and RMS current
- Choose wire
- Calculate losses - Core losses + copper losses
- Estimate temperature rise
- Calculate and measure efficiency.
- Compare costs

PFC Boost 500 Watt

C058071A2 High Flux 2 Toroids stacked

N=104 turns of two strands AWG#21, fill factor 33.6%

L=1320 μH at no load

L= 950 μH at rated current (5.68A)

Inductor Max Ripple = 16%

Core losses 100 kHz = 0.99 W

Copper losses = 4.89 W

Total losses = 5.88 W

ΔT estimate ≈ 43°C

Efficiency = Power Out/Power In

500.00/505.88=98.8% efficient

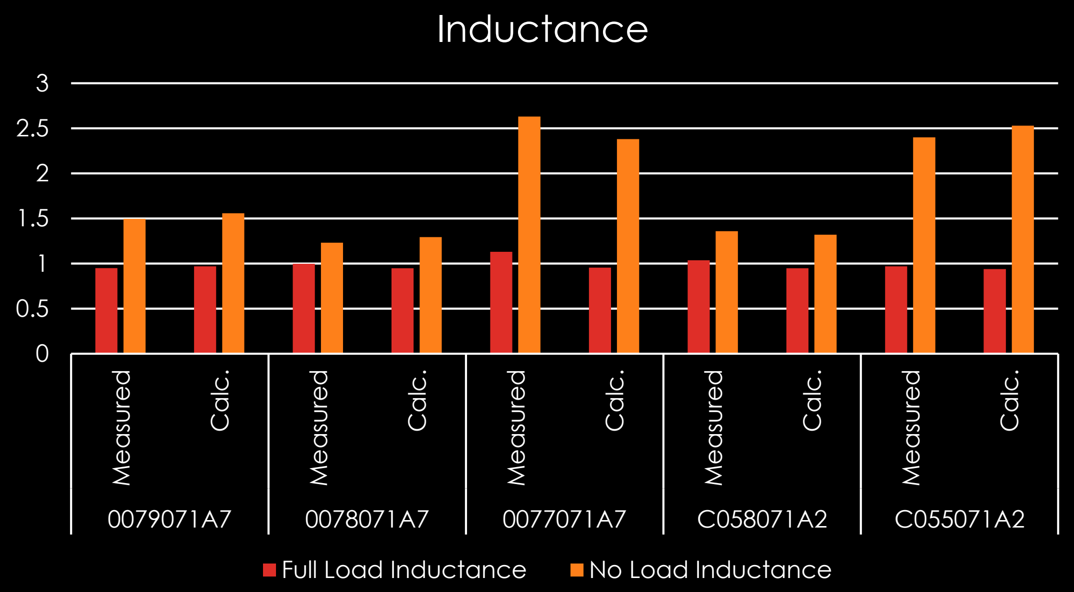
Inductance comparison—Powder Materials

	Kool Mμ® Max		XFLUX®		Kool Mμ®		High Flux		MPP	
	0079071A7		0078071A7		0077071A7		C058071A2		C055071A2	
	Measured	Calc.	Measured	Calc.	Measured	Calc.	Measured	Calc.	Measured	Calc.
Inductance, Full load, mH	0.949	0.970	0.998	0.948	1.13	0.955	1.036	0.948	0.969	0.939
Inductance, No load, mH	1.496	1.558	1.231	1.294	2.63	2.38	1.359	1.32	2.401	2.530
# turns	113	113	103	103	114	114	104	104	144	144

$$I_{avg} = 5.68\ A$$

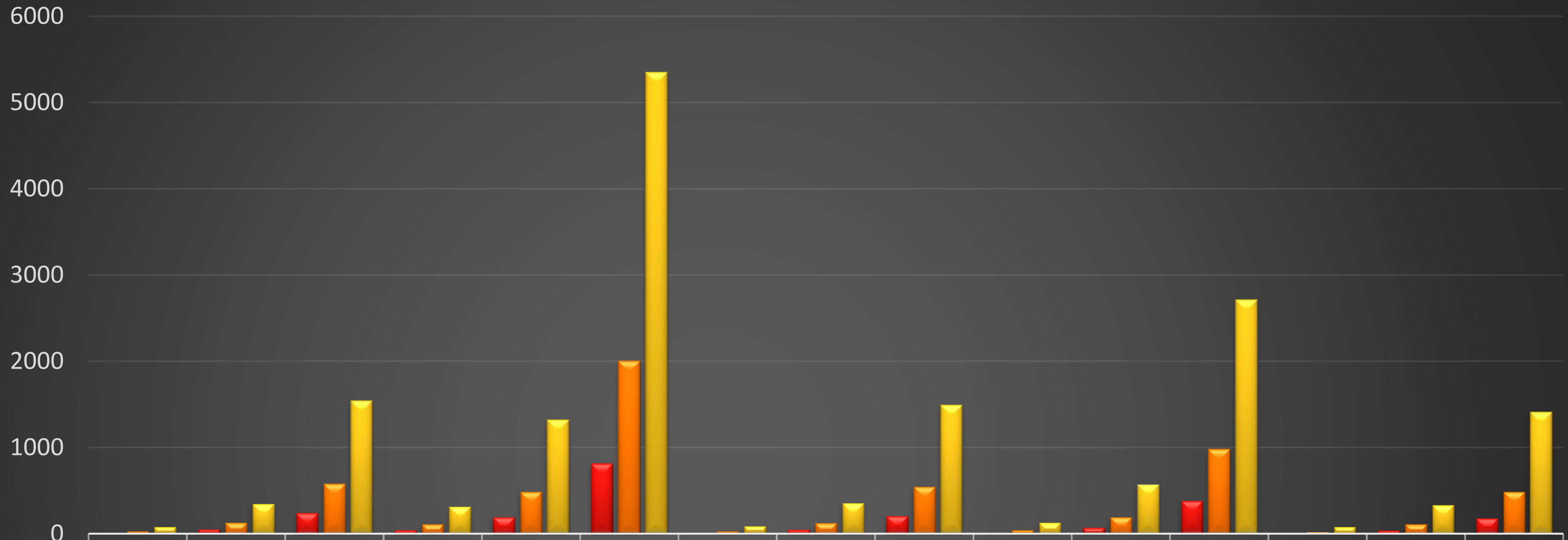
$$I_{pk} = 6.02\ A$$

$$L = 946\ \mu H$$



Summary	Kool Mu® Max		XFlux ®		Kool Mu ®		High Flux		MPP	
	0079071A7		0078071A7		0077071A7		C058071A2		C055071A2	
	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.
Inductance, Full load	0.949	0.970	1.054	0.948	1.06	0.955	1.041	0.950	1.02	0.939
Core losses		0.70		2.64		0.87		0.99		0.24
Copper losses		5.38		4.84		7.22		4.89		7.12
Total losses Watts		6.08		7.48		8.09		5.88		7.36
# turns	113	113	103	103	114	114	104	104	144	144
DCR	194.0	165.9	183.1	149.1	264.1	222.4	180.5	150.8	256.3	219.3
Temperature rise		43.3		52.4		44.4		42.8		48.3
Operating Temp		68.3		77.2		73.6		67.8		73.3
Efficiency		98.7		98.5		98.4		98.8		98.5
Core Cost	2 cores	€2.72	2 cores	€1.62	3 cores	€1.11	2 cores	€5.42	2 cores	€6.64
Estimated Wire Cost		€1.34		€0.91		€1.36		€.92		€1.33
Core & Wire cost		€4.06		€2.53		€2.47		€6.34		€7.97

Core Losses Measured at 50 kHz, 100 kHz 200 kHz



	25 mT, 250 Gauss	50 mT, 500 Gauss	100 mT, 1000 Gauss	25 mT, 250 Gauss	50 mT, 500 Gauss	100 mT, 1000 Gauss	25 mT, 250 Gauss	50 mT, 500 Gauss	100 mT,1000 Gauss	25 mT, 250 Gauss	50 mT, 500 Gauss	100 mT,1000 Gauss	25 mT, 250 Gauss	50 mT, 500 Gauss	100 mT,1000 Gauss
	0079071A7 Kool Mu Max			0078071A7 XFlux			0077071A7 Kool Mu			C058071A2 High Flux			C055071A2 MPP		
mw/cc; 50 kHz	13	54	240	43	193	811	11	47	209	14	72	384	8.5	38	181
mw/cc; 100 kHz	30	131	580	111	486	2003	30	125	548	42	193	982	26	110	488
mw/cc; 200 kHz	82	347	1542	313	1320	5352	88	357	1492	131	572	2713	81	333	1408

mw/cc; 50 kHz   mw/cc; 100 kHz   mw/cc; 200 kHz

INDUCTOR CURRENT

$$I_{avg} = I_{out}\left(\frac{1}{1-D}\right)$$

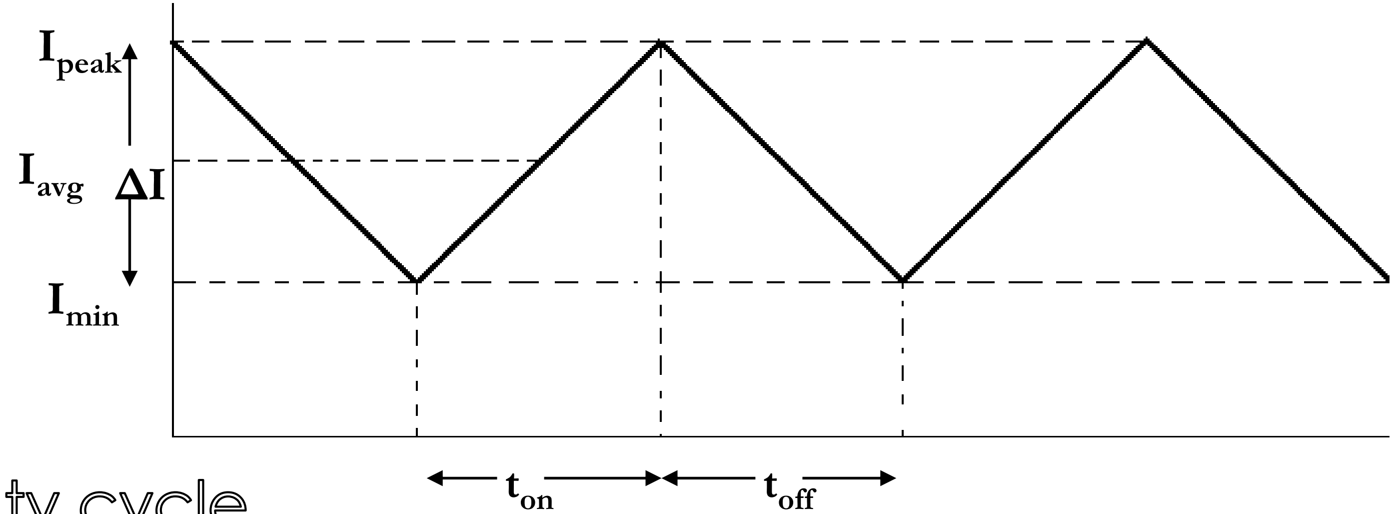
At Low Line Voltage

$$I_{avg} = 1.25\left(\frac{1}{1-0.78}\right) = 5.68\,Amps$$

At High Line Voltage

$$I_{avg} = 1.25\left(\frac{1}{1-0.34}\right) = 1.89\,Amps$$

PFC Boost 500 Watt



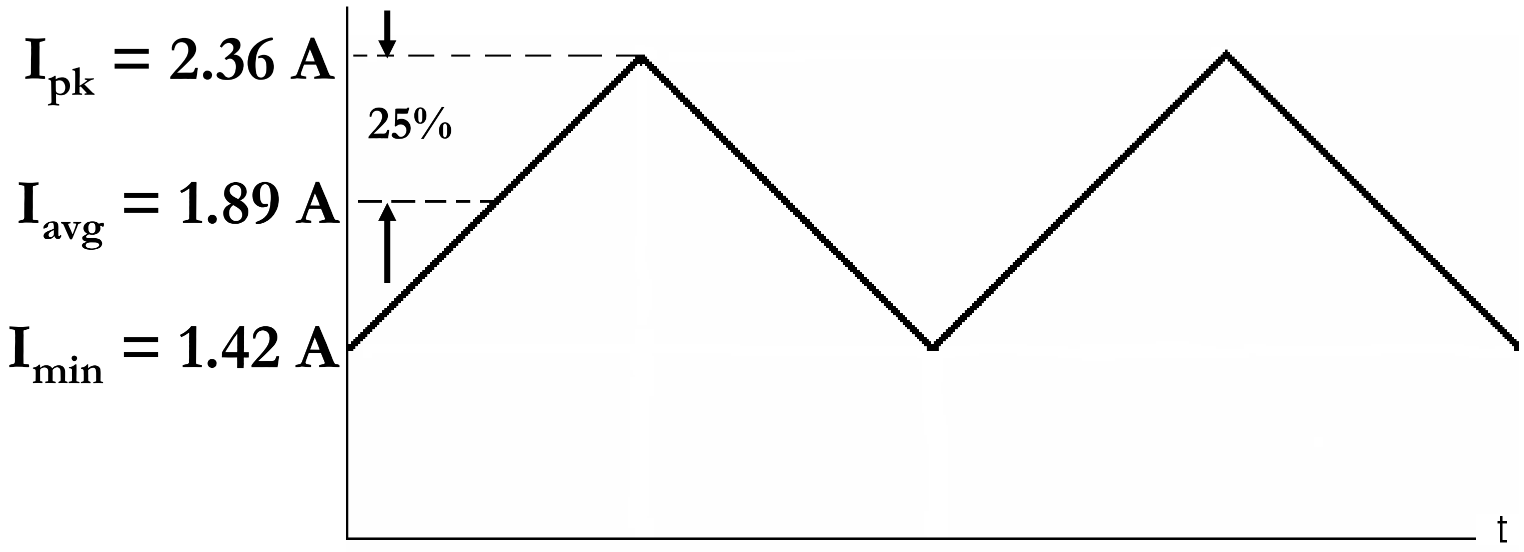
$t_{on} + t_{off} = \mathbf{5.0\ \mu\ seconds}$

$$Duty\ Cycle(D) = \frac{t_{on}}{5.0\mu\sec}$$

At 200 KHz the duty cycle Changes to be 5 μ seconds

PFC Boost 500 Watt

WORST CASE RIPPLE OCCURS AT HIGH LINE VOLTAGE



$$\Delta I = 1.89(25\%)(2)$$

$$\Delta I = 0.945\,A$$

$$I_{pk} = 2.36\ A$$

$$L = 473\mu H$$

$$L = \frac{V\ across\ inductor}{\Delta I}(D_{\min})(t)$$

$$L = \frac{264-1}{0.945}(0.34)(5.0)$$

Now L = half of the original inductance required

C058930A2 High Flux 2 Toroids stacked

N= 50 turns of 2 strands AWG#21, giving a fill factor of 31%

L=785 µH at no load

L=494 µH at rated current (5.68A)

Inductor Max Ripple = 16%

Core losses 200 kHz = 2.93 W

Copper losses = 2.0 W

Total losses =4.93 W

ΔT estimate ≈46°C

Efficiency = Power Out/Power In

500.00/505.25=99% efficient

DESIGN COMPARISON

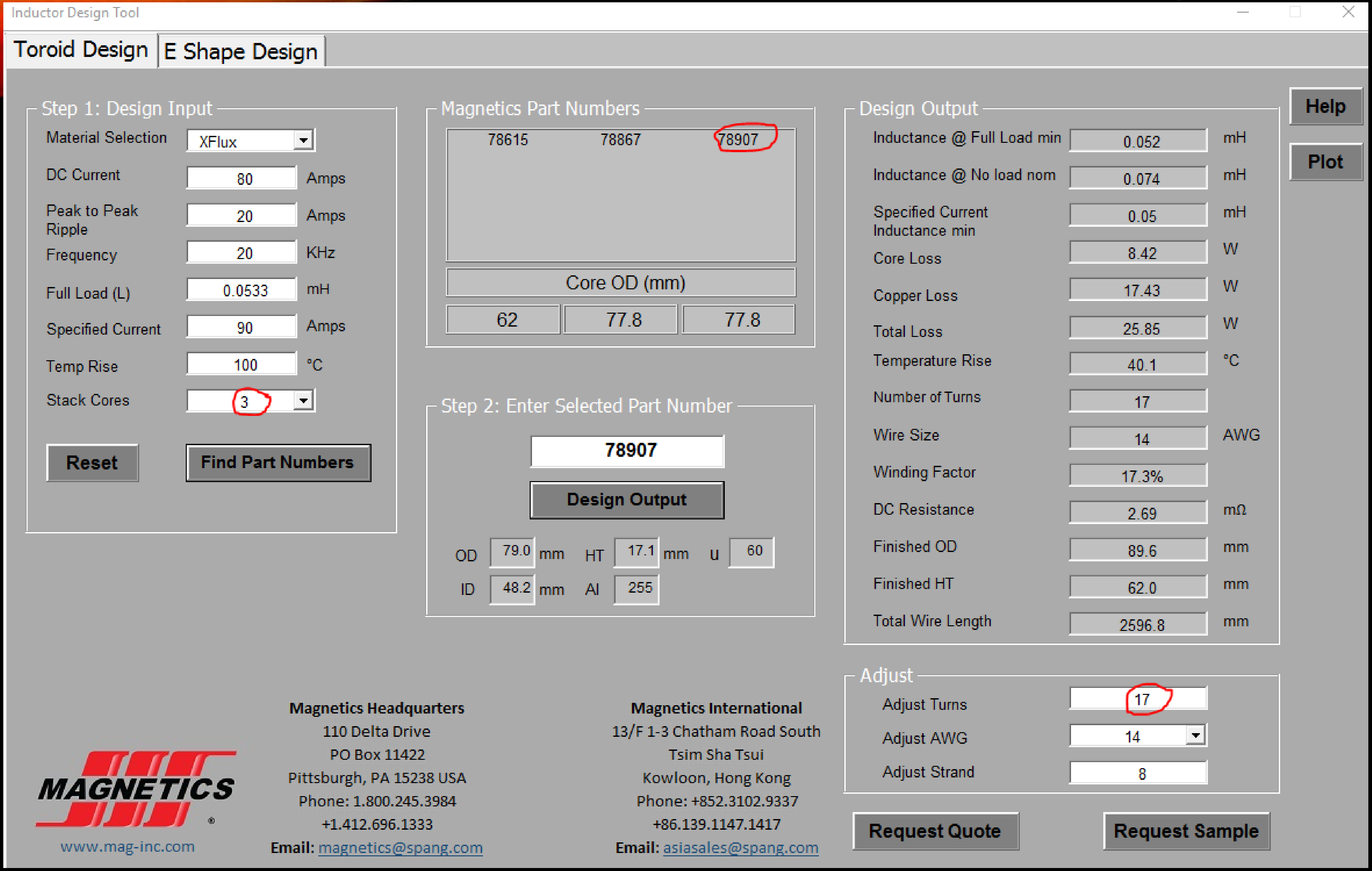
DESIGN OUTPUTS

2 cores each	C058071A2 100 kHz	C058930A2 200 kHz
Inductance @ 5.68 A	949 µH	494 µH
Delta B/2	0.0305 T	0.0357 T
Turns	104	50
Wires	21 AWG x 2	25 AWG x 6
Core loss	2.46 W	2.93 W
Copper loss	6.95 W	2.57 W
Package size	41 x 30 mm	33 x 29 mm
Temp Rise	44°C	46°C
Estimate Cost	Cores €5.42 Wire €0.92 Total €6.34	Cores €3.26 Wire €0.59 Total €3.85

HIGH CURRENT OUTPUT INDUCTOR DESIGN COMPARISON

Output Inductor	20 kHz Si	50 kHz SiC
Inductance	50 µH	20 µH
Frequency	20 kHz	50 kHz
Rated current	80 A	80 A
Ripple current p-p	20 A	20 A

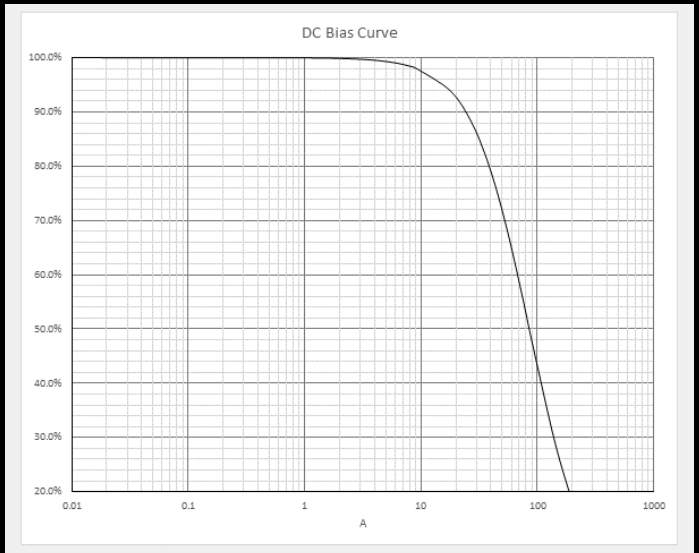
Software Inductor Design Tool



COMPARISON FOR HIGH CURRENT DESIGN

DESIGN OUTPUTS

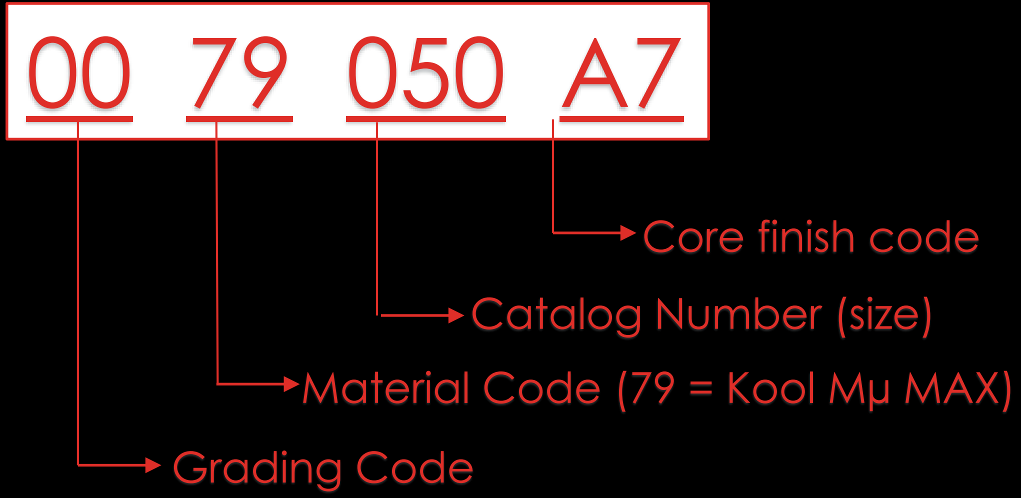
	20 kHz Si	50 kHz SiC
Inductance @ peak 90 Amps	53.3 μH	21.5 μH
Cores	0078907A7 x 3	0077192A7 x 3
Turns	17	11
Wires	14 AWG x 8 strands	17 AWG x 16 strands
Core loss	8.42 W	4.07 W
Copper loss	17.4 W	11.0 W
Package size	90 x 62 mm	69 x 60 mm
Temp Rise	40°C	37°C
Estimate Cost	Cores €12.19 Wire €6.29 Total €18.48	Cores €4.39 Wire €4.11 Total €8.50



INTRODUCING KOOL Mµ MAX®

- Kool Mµ MAX is a superior version of Kool Mµ!
- Improved DC Bias performance and lower losses at a reduced price compared with MPP and High Flux.

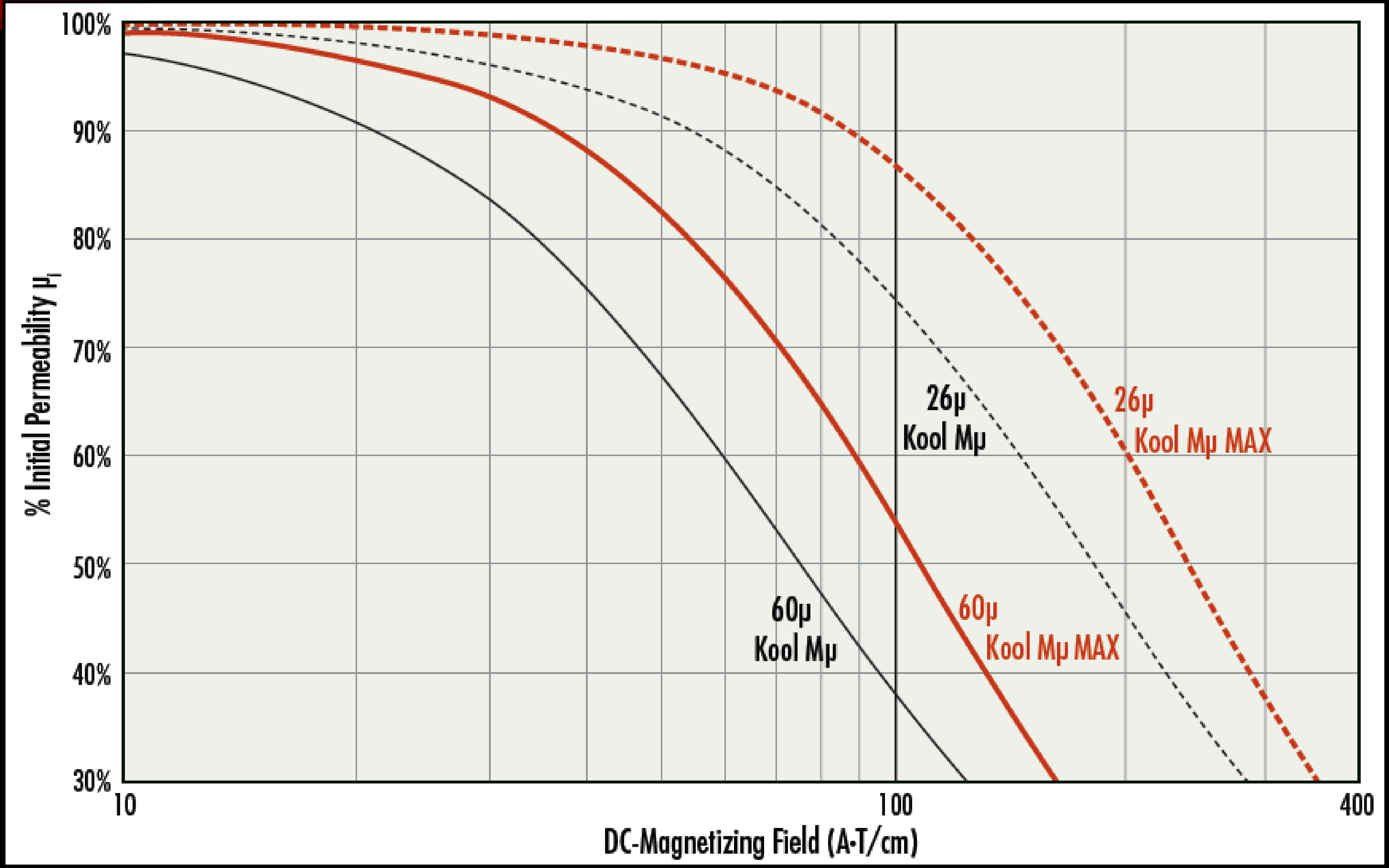
General Information	
Permeability	26µ, 40µ, 60µ
Alloy Composition	Fe/Si/Al
Saturation Flux Density	1 Tesla
Curie Temperature	500°C
Operating Temperature Range	-55 to 200°C
OD Size Range (mm)	13.5 - 134
Coating Color	Black



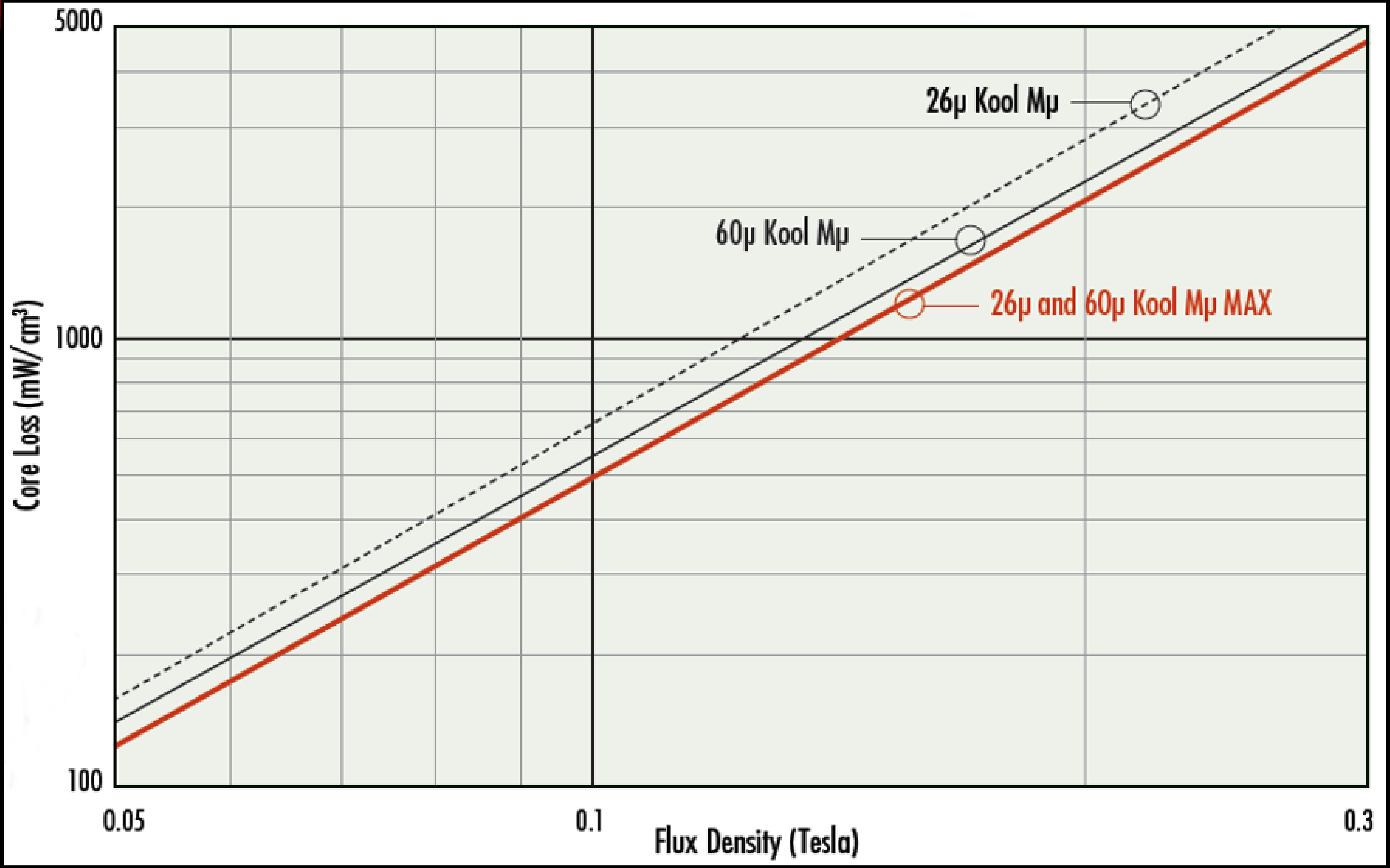
KOOL Mµ MAX

60 Perm Material	DC Bias at x Ls (A-T/cm)		Core Loss (mW/cm³)		Cost Ratio
	80%	50%	$W_{1000\text{ G, }50\text{ kHz}}$	$W_{1000\text{ G, }100\text{ kHz}}$	Price Scale
Kool Mµ® MAX	**54**	**107**	**190**	**500**	**2.0**
Kool Mµ®	34	75	212	550	1.0
75-Series	56	119	570	1515	1.2
XFlux®	70	139	680	1550	1.5
High Flux	69	131	353	900	4.0
MPP	48	84	174	450	7.0

Kool Mµ MAX vs. Kool Mµ - DC Bias



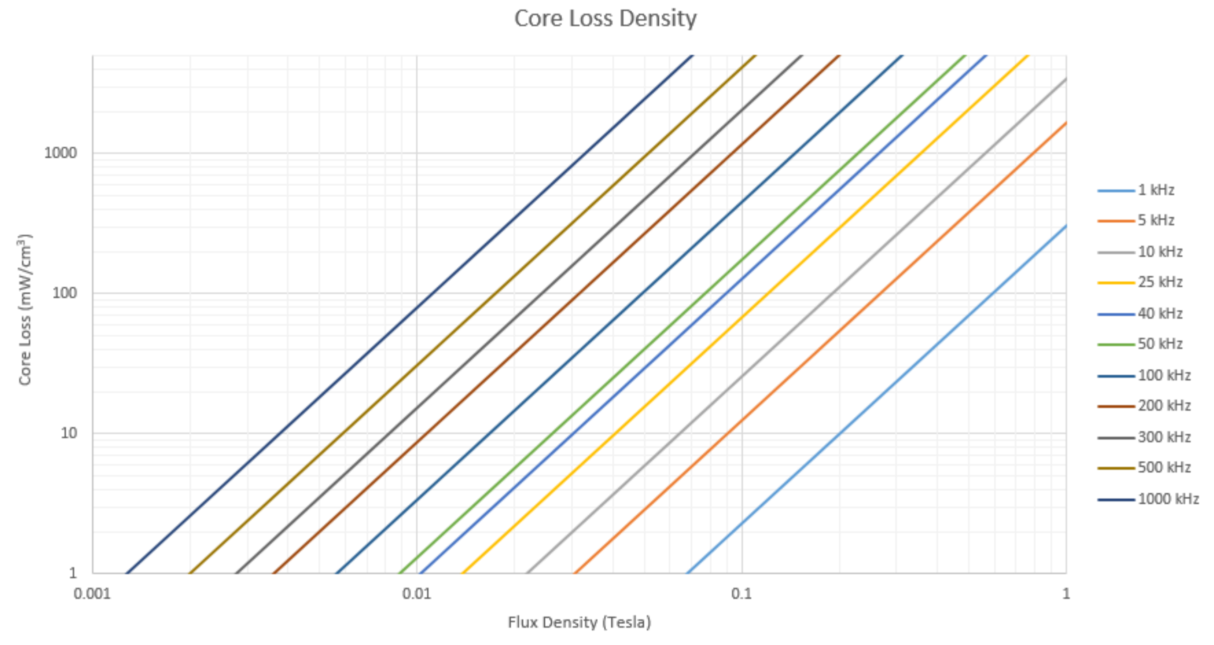
Kool Mµ Max vs. Kool Mµ - Core Loss



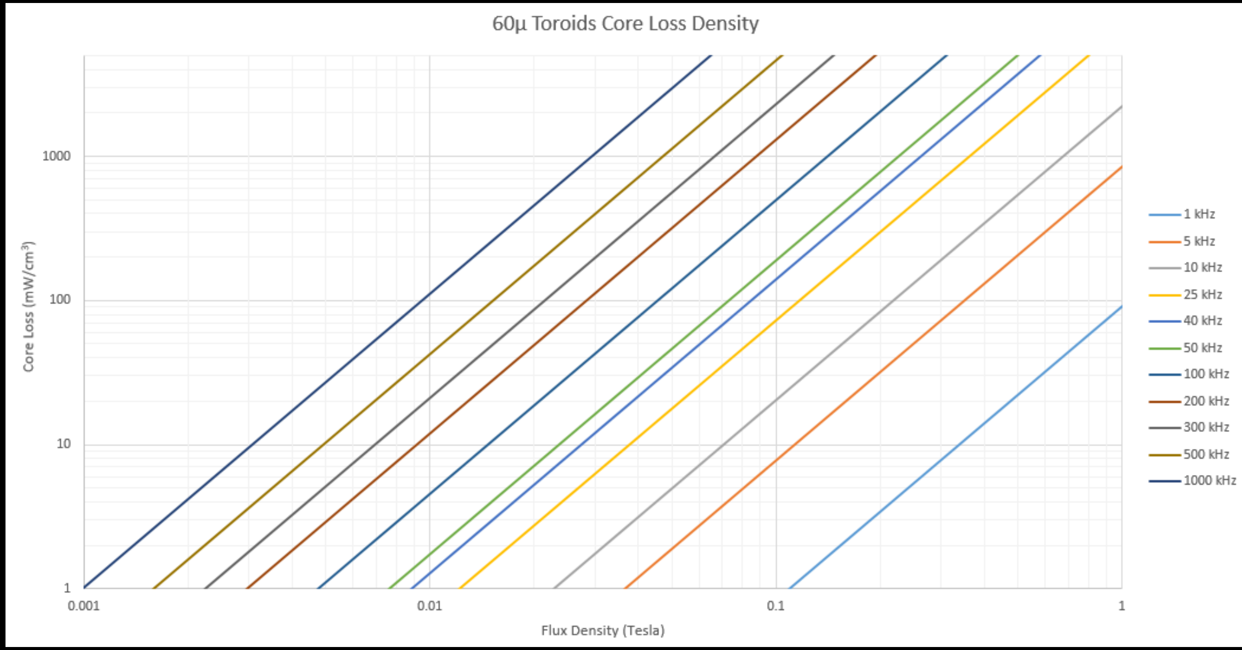
Summary	Kool Mu® Max		XFlux ®		Kool Mu ®		High Flux		MPP	
	0079071A7		0078071A7		0077071A7		C058071A2		C055071A2	
	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.
Inductance, Full load	0.949	0.970	1.054	0.948	1.06	0.955	1.041	0.950	1.02	0.939
Core losses		0.70		2.64		0.87		0.99		0.24
Copper losses		5.38		4.84		7.22		4.89		7.12
Total losses Watts		6.08		7.48		8.09		5.88		7.36
# turns	113	113	103	103	114	114	104	104	144	144
DCR	194.0	165.9	183.1	149.1	264.1	222.4	180.5	150.8	256.3	219.3
Temperature rise		43.3		52.4		44.4		42.8		48.3
Operating Temp		68.3		77.2		73.6		67.8		73.3
Efficiency		98.7		98.5		98.4		98.8		98.5
Core Cost	2 cores	€2.72	2 cores	€1.62	3 cores	€1.11	2 cores	€5.42	2 cores	€6.64
Estimated Wire Cost		€1.34		€0.91		€1.36		€.92		€1.33
Core & Wire cost		€4.06		€2.53		€2.47		€6.34		€7.97

Frequency	Flux Density in Tesla/ Gauss	Core loss mW/cm³
500 kHz	0.010 T / 100 G	42.6
500 kHz	0.025 T / 250 G	276.4
500 kHz	0.030 T / 300 G	400.8
1 MHz	0.001 / 10 G	1.02
1 MHz	0.010 / 100 G	111.6
1 MHz	0.020 / 200 G	458.9

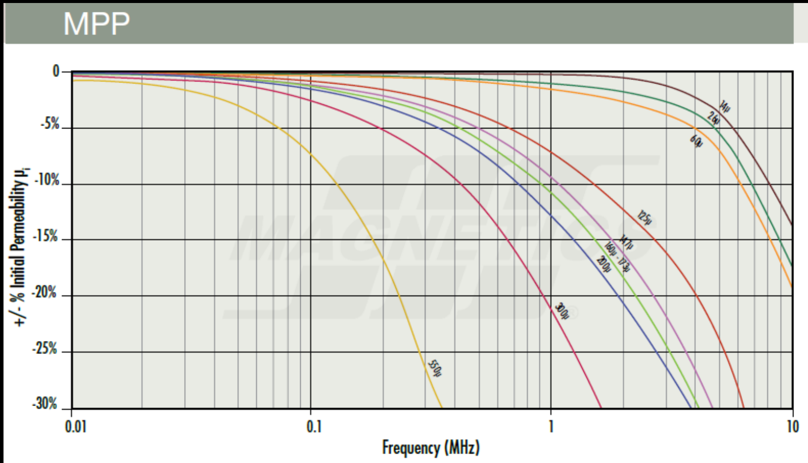
60 perm MPP

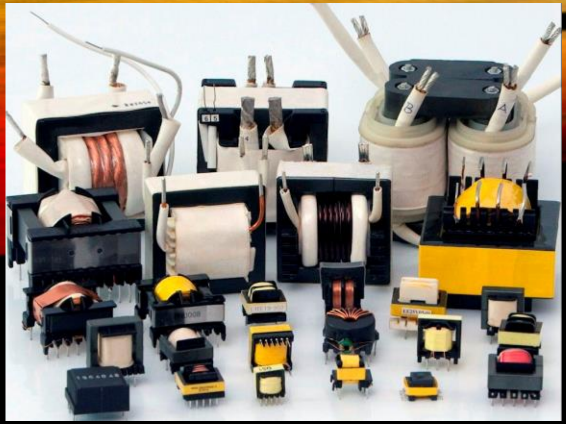


60 perm **Kool Mμ® Max**



MPP 60 perm flat to 1 MHz
- 5% at 4 MHz

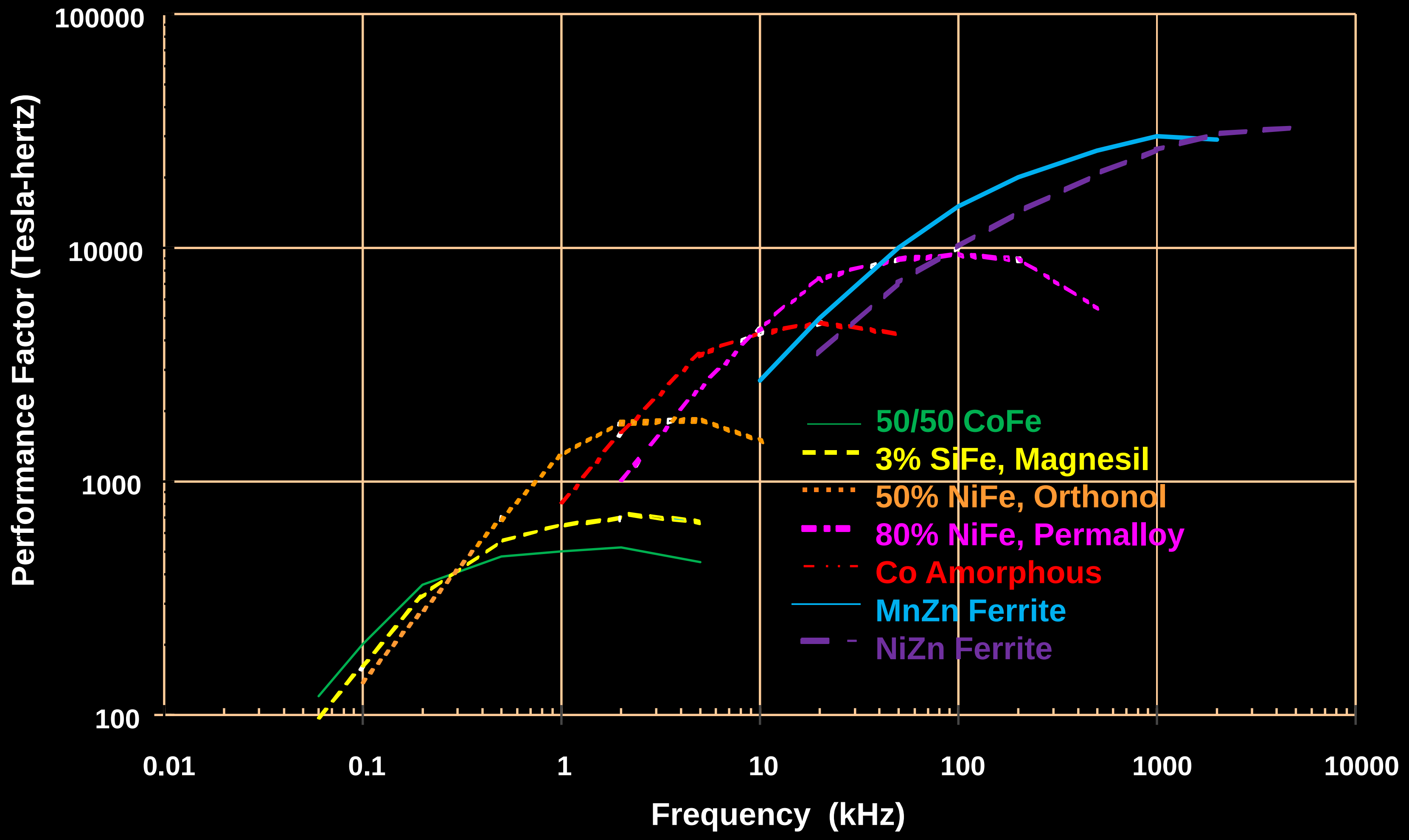




Transformer Core Materials Utility Performance Factor vs. Frequency (at 100 mW/cm^3 max.)

MATERIALS FOR TRANSFORMERS

Power Ferrites
Manganese-Zinc Ferrites
Nickel-Zinc Ferrites
Nanocrystalline and Amorphous strip materials



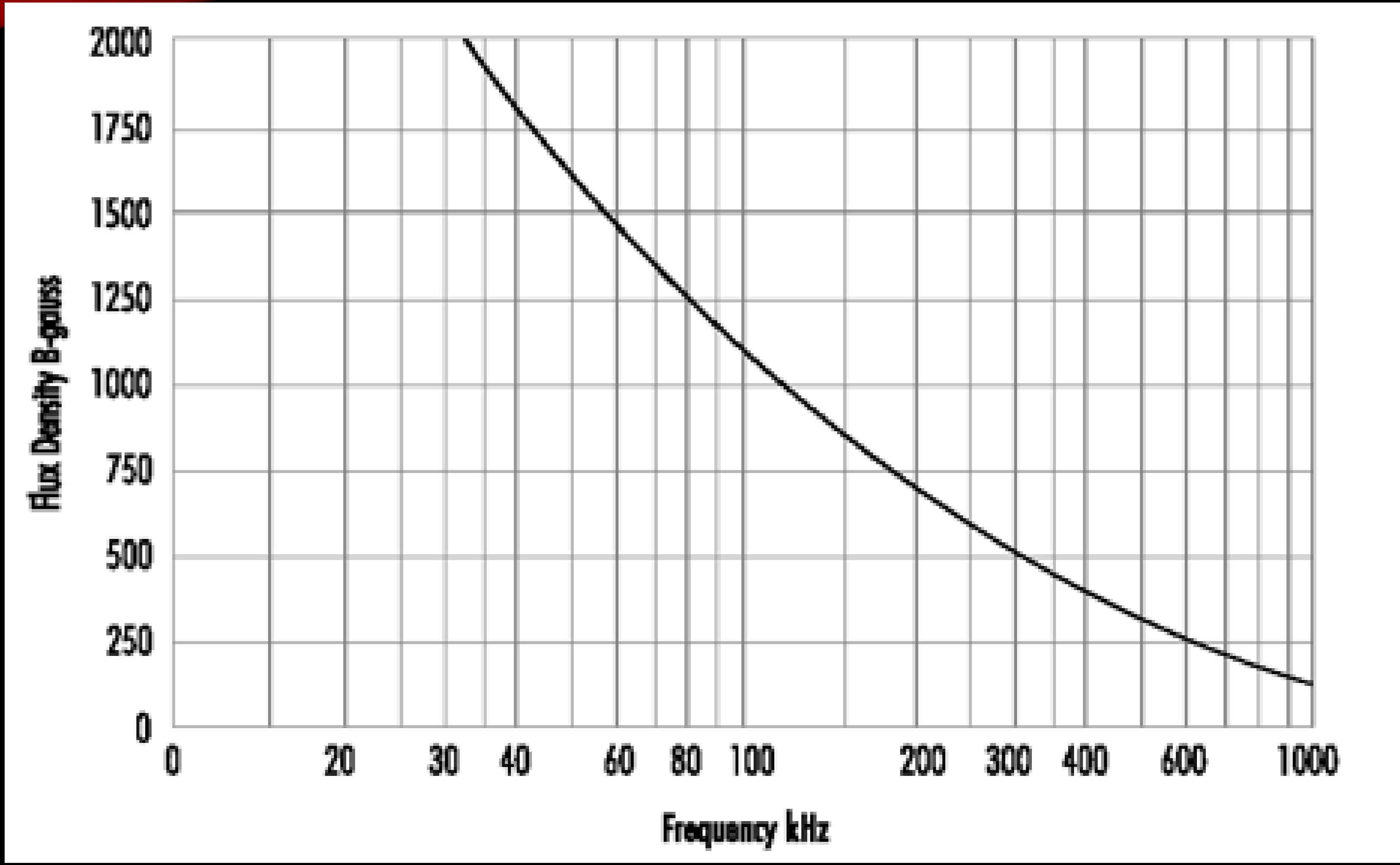
Ferrite Power Materials

Magnetics ferrites R, P, T, F and L materials provide superior saturation, high temperature performance, low losses and product consistency.

T material – 3000 perm is our power material for consistent performance over a wide temperature range.
L material – 900 perm is our new power material for high frequency and high-temperature applications.
R material **-- 2300 perm** provides the best core losses for frequencies up to 500 kHz.
P material **-- 2500 perm** offers similar properties to R material, but is more readily available in some sizes.
F material **-- 3000 perm** is an established material with a relatively high permeability and 210 degree C Curie temperature.

Power Supplies, DC-DC Converters, Handheld Devices, High Power Control (gate drive) and EMI Filters are just a few of the applications that are typical for Magnetics ferrite power materials.

CHOOSING THE APPROPRIATE B LEVEL



P Material 2500 Perm

FERRITE

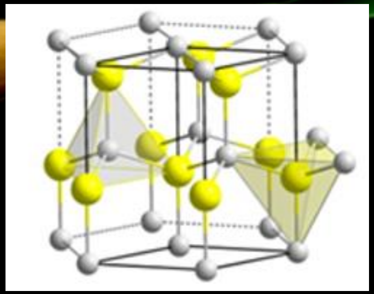
At 100 KHz

assume B = 1000 Gauss as frequency increases decrease B accordingly

At 500 kHz

B = 250 Gauss

GaN HIGH FREQUENCY
LOWER CURRENT



	Si	GaN
Inductance	500 uH	100 uH
Frequency	100 kHz	500 kHz
Rated current	0.75 A	0.75 A
Ripple current p-p	0.1 A	0.1 A

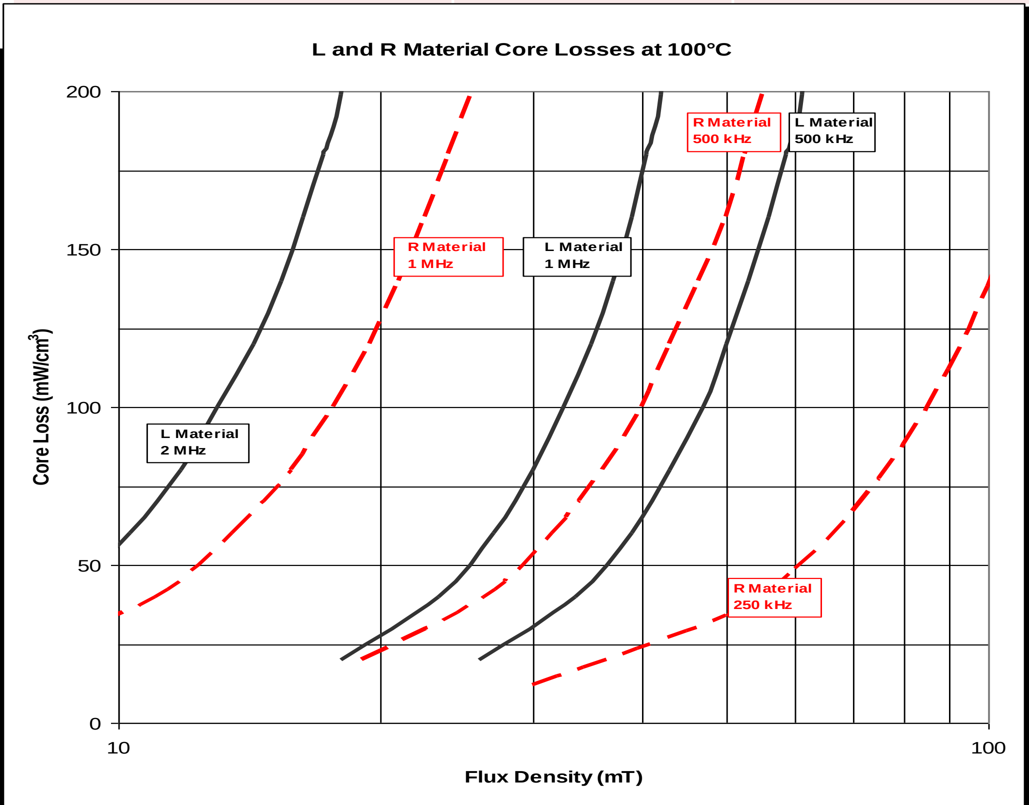
TOPOLOGY CONSTANTS K_t

Forward converter = 0.0005
Half-bridge = 0.0014
Flyback = 0.00033 (single winding)
Push-Pull = 0.001
Full-bridge = 0.0014
Flyback = 0.00025 (multiple winding)

$$WaAc = \frac{P_o D_{cma}}{K_t B_{max} f}$$

Area Product Distribution (WaAc) Chart

WaAc (cm⁴)	RS, DS, HS	E	EC, EER, EFD, ETD	EP, RM	ER	Planar	Pot	PQ	TC	U, UR
<0.001									40200 TC 40301 TC 40502 TC	
0.001									40401 TC 40402 TC 40503 TC 40601 TC	
0.002		40904 EE					40704 UG			
0.003					40906 EE		40905 UG		40603 TC	
0.004			41009 EFD		41126 EE					
0.005				40707 EP						
0.006					41308 EI		41107 UG			
0.008						41434 EI			40705 TC	
0.01			→ 41212 EFD	41010 EP 41110 RM	41308 EE 41426 EE	41425 EE	41109 UG		41003 TC	41106 UI
0.02	41408 RS DS HS	41203 EE	41515 EFD	41510 RM		41434 EE	41408 UG		41005 TC	41106 UU
0.03		41205 EE 41707 EE		41313 EP	→ 41826 EE	42107 EI 41805 EI			40907 TC	



DESIGN COMPARISON FOR GaN

DESIGN OUTPUTS

	Si ER Core	GaN EFD Core
Inductance @ peak 0.8 A	503 uH 100 kHz	100 uH 500 kHz
Cores	0P41826A260	0L41212A160
Turns	44	25
Wires	26 AWG	26 AWG
Copper loss	0.11 W	0.03 W
Package size	18 x 6.6 x 9.7 mm	12.5 x 12.4 x 3.5 mm
Temp Rise	40°C	12°C
Estimate Cost	€0.31	€0.23

Thank you !!!

- Questions???
- Comments
- Suggestions

Magnetics Haicang, Ltd.
No. 599-1, Shanbian Road, Haicang District, Xiamen City, Fujian Province, P.R. China
ISO/TS 16949:2009
Edition 3
Manufacture of soft magnetic cores for automobile
SYSTEM CERTIFICATION ISO TS 16949 SGS

AUTOMOTIVE ELECTRONICS COUNCIL (AEC) Q200

Design Trends Automotive

- PPAP Production Part Approval Process

- **High Temperature Exposure**

Temperature : 150±3℃

Duration : 1000＋12-0 hours

Recovery : 24±2HR

- **Moisture Resistance**

Apply the 24hrs heat (25 to 65°C) and humidity (80 to 98%)

10 consecutive times

Recovery : 24±2HR

- **Biased Humidity**

Temperature : 85±2℃ Humidity : 85%

Applied voltage : 100VDC Duration : 1000 hours

Recovery : 24±2HR

- **Operational Life**

Temperature : 125±3℃ Applied voltage : 200VDC

Duration : 1000＋12-0 hours (*1)

Recovery : 24±2HR

- **Solvent Resistance**

Isopropyl alcohol and three other solvents

- **Shock**

100g, 6msec, Half-sine wave

- **Vibration**

Frequency: 10~2000Hz, Amplitude: 1.5mm
Duration: 24 hours

PFC BOOST WITH TALL TOROIDS PHEV—PFC

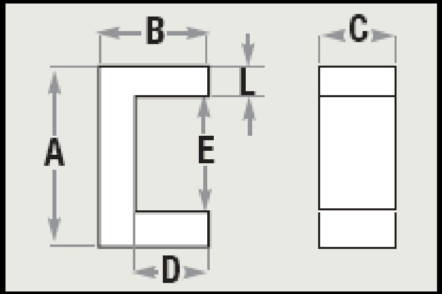
- 3.3 kWatt   70 kHz   15 A   2 A p-p Ripple 400 μH
- Suggested cores:

Part number	Perm	Finished OD	Finished HT	Temp Rise
0077111A7HT30	26	72.5 mm	44.2 mm	57 ^{o}C
0077192A7HT32	60	67.5 mm	41.9 mm	58 ^{o}C
0077189A7HT32	40	72.3 mm	46.6 mm	45 ^{o}C
0078439A7HT38	60	57.1 mm	47.5 mm	58 ^{o}C

EMI FILTERING
DIFFERENTIAL MODE CHOKE
PLANAR POWDER CORES U CORES

Custom sizes available

Coated for direct application to bus bar



PART NO		A	B	C	D(min)	E(min)	L(nom)
00K3112U***	mm in	31.24±0.51 1.230±0.020	11.2±0.26 0.440±0.010	12.1±0.39 0.475±0.015	2.54 0.100	14.2 0.560	8.26 0.325
00K4110U***	mm in	40.64±0.51 1.600±0.020	11.2±0.51 0.440±0.020	9.53±0.39 0.375±0.015	2.54 0.100	23.6 0.930	8.38 0.330
00K4111U***	mm in	40.64±0.51 1.600±0.020	11.2±0.26 0.440±0.010	12.1±0.39 0.475±0.015	2.54 0.100	23.6 0.930	8.38 0.330
00K4119U***	mm in	40.64±0.51 1.600±0.020	11.2±0.26 0.440±0.010	19.1±0.39 0.750±0.015	2.54 0.100	23.6 0.930	8.38 0.330

DIFFERENTIAL MODE CHOKE FOR BUSBAR APPLICATIONS PLANAR POWDER U CORES

				Testing at 10 kHz.				
Copper Bus Bar Dimensions					No-load Inductance			
Length	Width	Height			Calculated Busbar		Measured on Busbar	
100.55 mm	12.8 mm	1.58 mm			0.064 µH		0.094 µH	
	Core Set	Dimensions L X W X H			Inductance/A_L		With Busbar	Core contribution
Core Set		Length	Width	Height				
00K3112U090		31.24 mm	12.1 mm	22.4 mm	179 +/- 8%		0.274 µH	0.180 µH
00K3112U090 coated 0.0015", 0.381 mm.							0.122 µH	0.028 µH
00K3112U060		31.24 mm	12.1 mm	22.4 mm	111 +/- 8%		0.199 µH	0.105 µH
00K3112U060 coated 0.0015", 0.381 mm.							0.110 µH	0.016 µH
00K4110U090		40.64 mm	9.53 mm	22.4 mm	109 +/- 8%		0.208 µH	0.114 µH
00K4110U090 coated 0.0015", 0.381 mm.							0.131 µH	0.037 µH
00K4111U090		40.64 mm	9.53 mm	24.2 mm	138 +/- 8%		0.237 µH	0.143 µH
00K4111U090 coated 0.0015", 0.381 mm.							0.143 µH	0.049 µH
00K4119U090		40.64 mm	9.53 mm	38.2 mm	218 +/- 8%		0.288 µH	0.194 µH
00K4119U090 coated 0.0015", 0.381 mm.							0.165 µH	0.071 µH
Multiple coated cores on one Busbar					Expected sum	Actual sum		
00K4119U090+00K4111U090					0.214 µH	96%	0.205 µH	0.111 µH
00K4119U090+00K4111U090+00K4110U090					0.251 µH	101%	0.255 µH	0.161 µH
Conclusion: Multiple cores on the Busbar impacts the leakage flux and the self-inductance of the busbar slightly.								

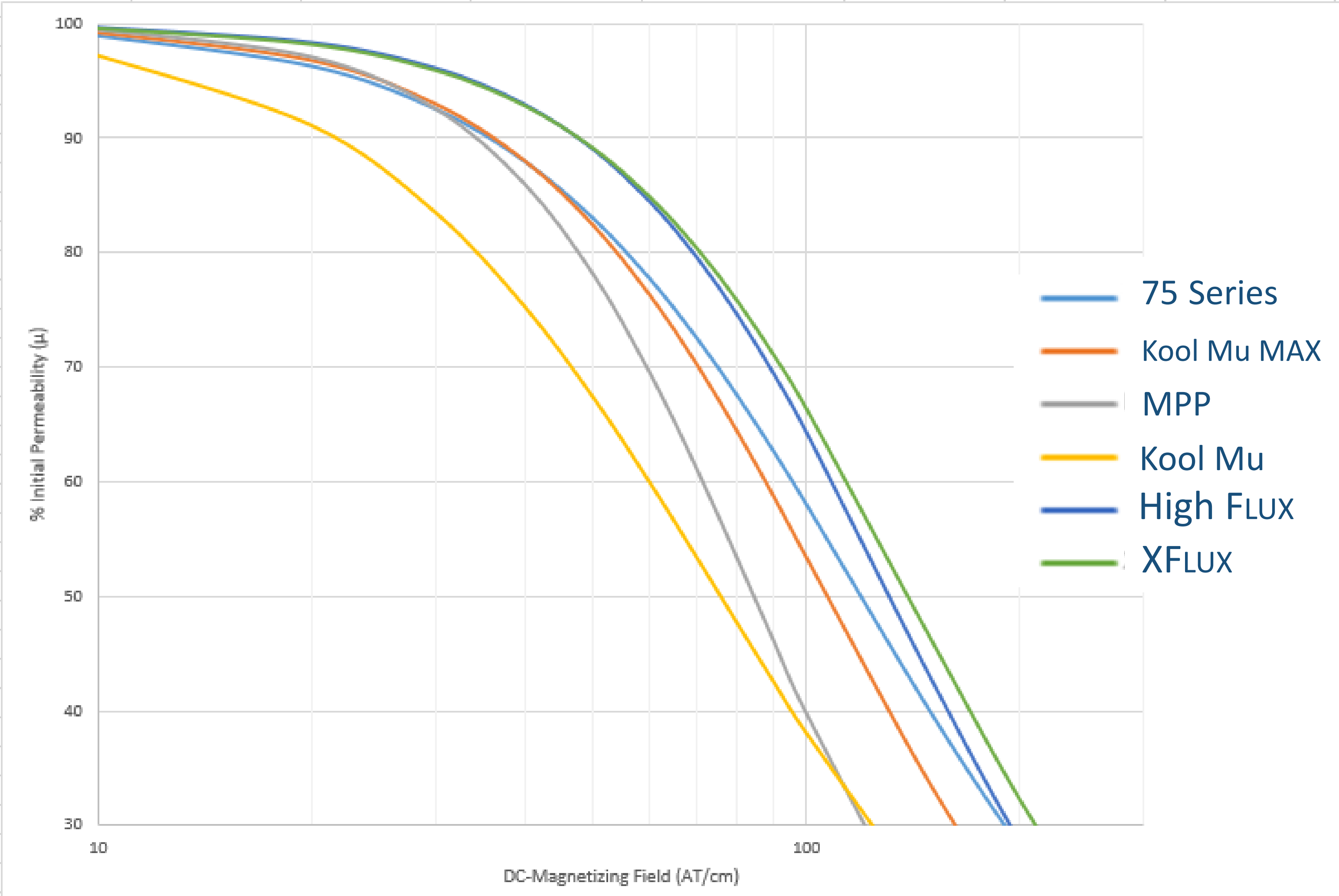
BUS BAR INDUCTANCE

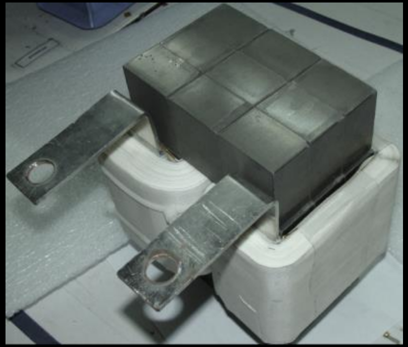
Busbar Inductance Calculator

Self Inductance of Rectangular Copper Conductor		
Conductor Length (cm)	14	cm
Conductor Width (cm)	1.15	cm
Conductor Thickness (cm)	0.12	cm
Inductance of Rectangular Copper Conductor	0.101	µH

Busbar 12 V	Self inductance
Length 10 cm width 1.4 cm height 1.58 cm	0.062 uH calc.
Busbar 48 V	
Length 15 cm width 1.4 cm height 1.58 cm	0.092 uH calc.

Custom Cores



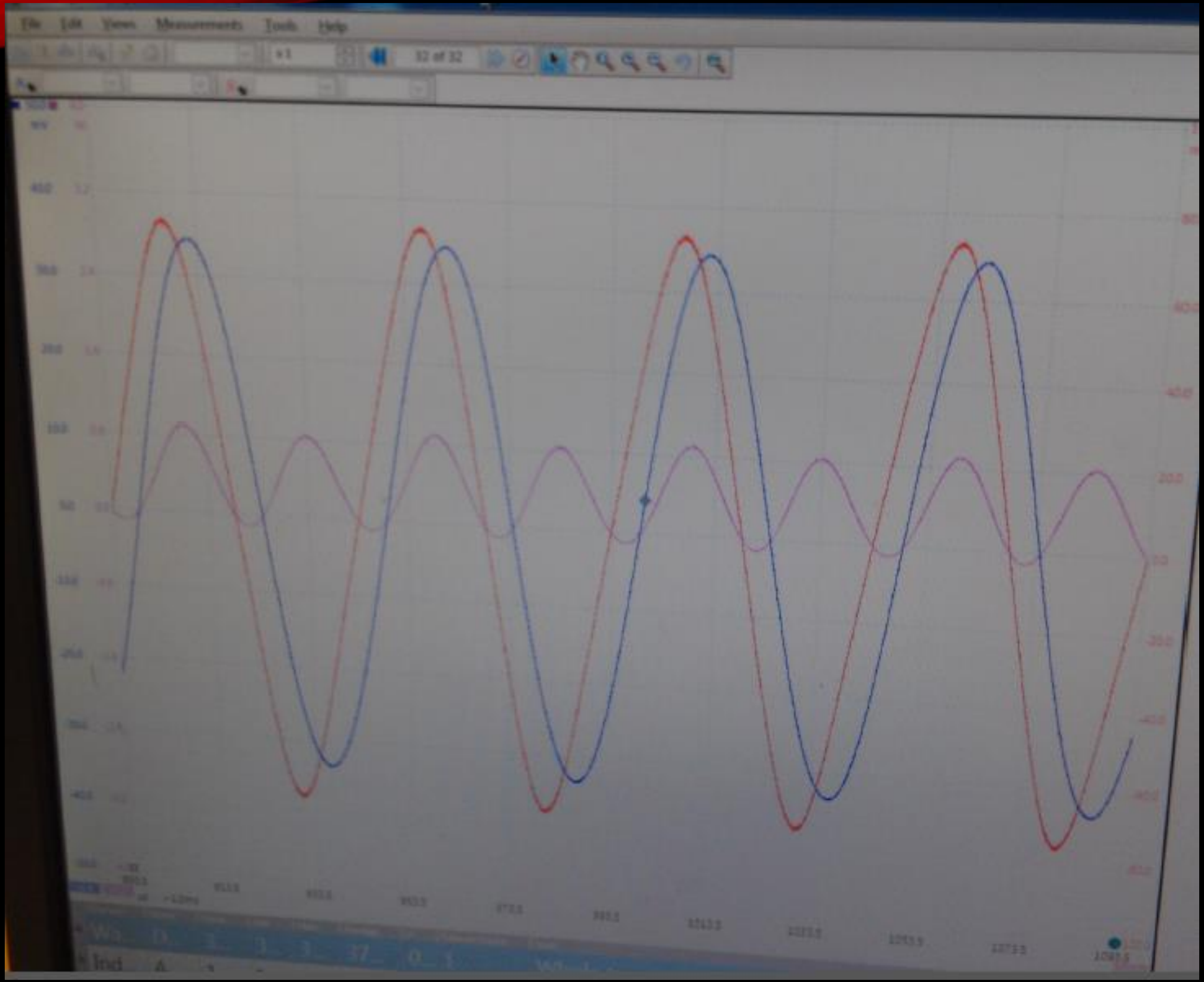


BLENDS
COMBINE MATERIAL CHARACTERISTICS

Blend materials to increase DC Bias and/or reduce losses

Blend Perms to have lower perm material under the windings

Core Watt Loss Testing



- Watt Meters
- Power Analyzers
- BH Loop Tracers
- Q Meters
- LCR Meters
- IEEE 393

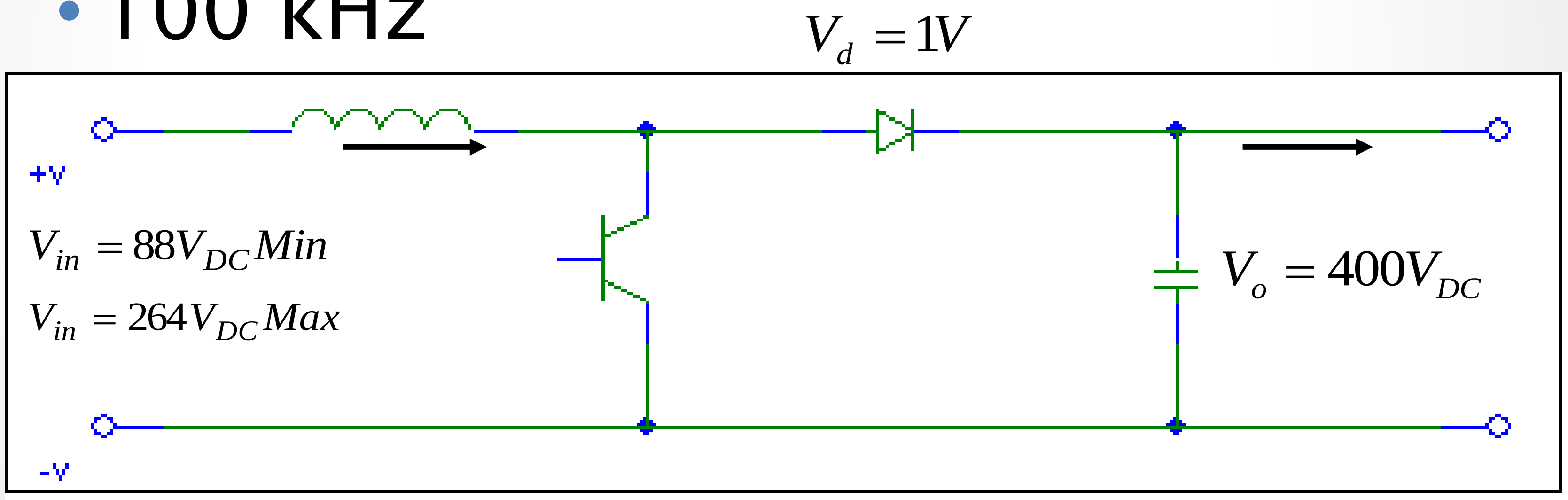
Thank you !!!

- Questions???
- Comments
- Suggestions

EQUATIONS AND CALCULATIONS FOR 500 WATT POWER FACTOR CORRECTION DESIGN

Power Factor Correction

- PFC Boost
  - 500 Watt
  - 88-264 Volts DC in
  - 400 Volts DC out
  - 100 kHz



Typical Boost Circuit Schematic
Input voltage varies 88 V_{DC}–264 V_{DC}

Design Boost PFC—Efficiency target 98%

- Examine inductor current
  - At low line voltage
  - At high line voltage
- Determine the AC ripple permitted
- Inductance required to support worst-case V ripple
- Highest current to be supported
- LI^2 product---Select core
- Using the core chosen recalculate inductor current
  - At low line voltage
  - At high line voltage
- Combine results to obtain waveform and RMS current
- Choose wire
- Calculate losses - Core losses + copper losses
- Estimate temperature rise
- Calculate and measure efficiency.
- Compare costs

Design inputs

Active High Frequency PFC
Continuous Conduction Mode

Power = 500 Watts **Frequency = 100 kHz**

$$T = \frac{1}{f} = 10.0\mu\text{sec.}$$

$$I_{out} = \frac{500Watts}{400Volts} = 1.25Amps$$

$$D_{\max} = 1 - \frac{88V_{in\min}}{400V_{out}} = 0.78 \qquad D_{\min} = 1 - \frac{264V_{in\max}}{400V_{out}} = 0.34$$

$D = Duty\ cycle$

Inductor Current

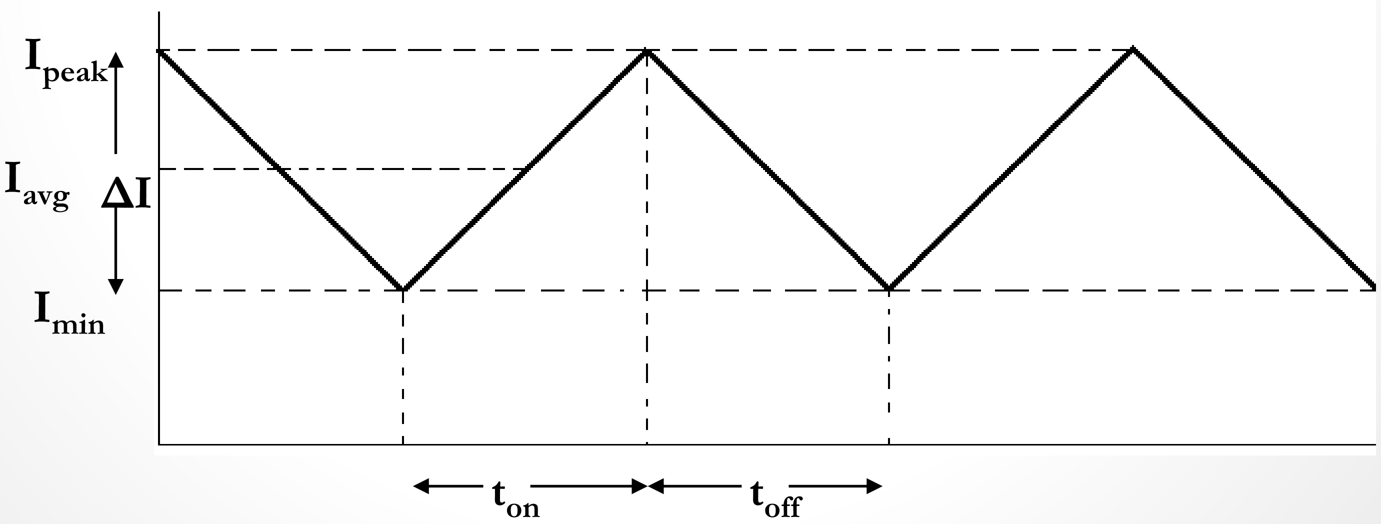
$$I_{avg} = I_{out}\left(\frac{1}{1-D}\right)$$

At Low Line Voltage

$$I_{avg} = 1.25\left(\frac{1}{1-0.78}\right) = 5.68\,Amps$$

At High Line Voltage

$$I_{avg} = 1.25\left(\frac{1}{1-0.34}\right) = 1.89\,Amps$$



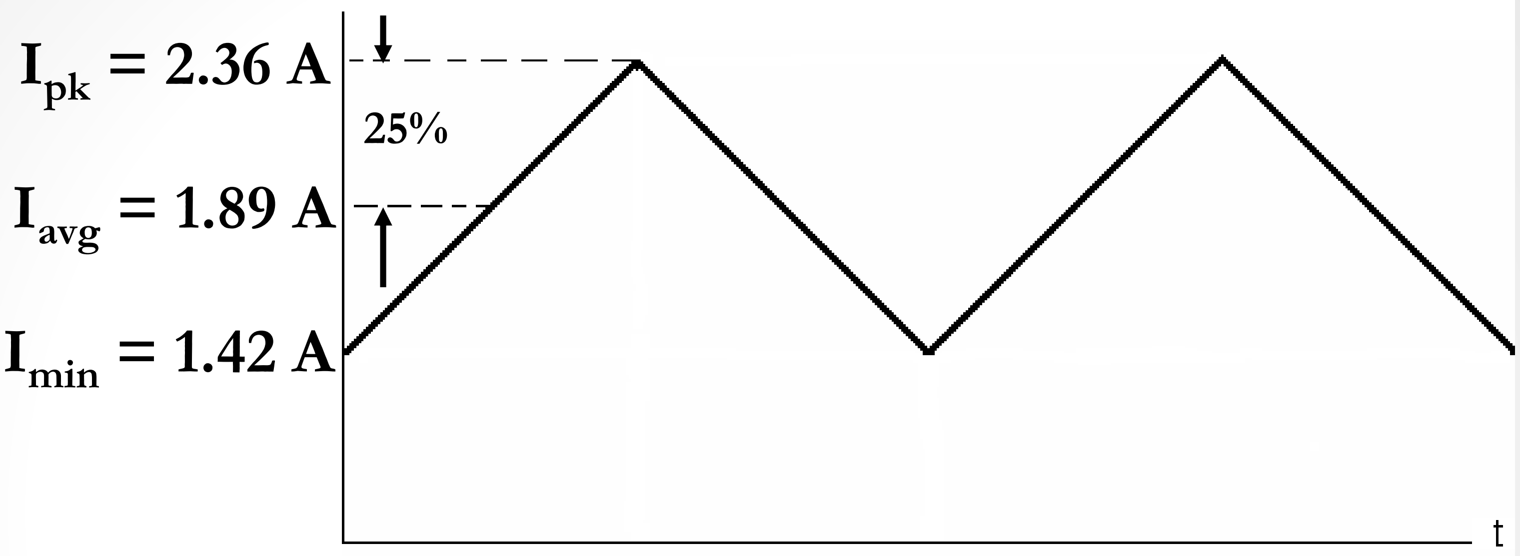
$t_{on} + t_{off} = \mathbf{10.0\ \mu\ seconds}$

$$Duty\ Cycle(D) = \frac{t_{on}}{10.0\mu\sec}$$

Ripple

- Max Current Ripple = 25% for this design based upon the customer's requirement. This is arbitrary. The inductance and loss calculations depend on this value. Actual result will be more robust because the worst case inductance and ripple do not occur together. Design can be iterated to improve ripple or improve cost/space. Typical ripple for CCM 10-35%.
- Typical ripple for CrM, DCM, and FCCrM is 5-15%.

Worst case ripple occurs at high line voltage



$$\Delta I = 1.89(25\%)(2)$$

$$\Delta I = 0.945A$$

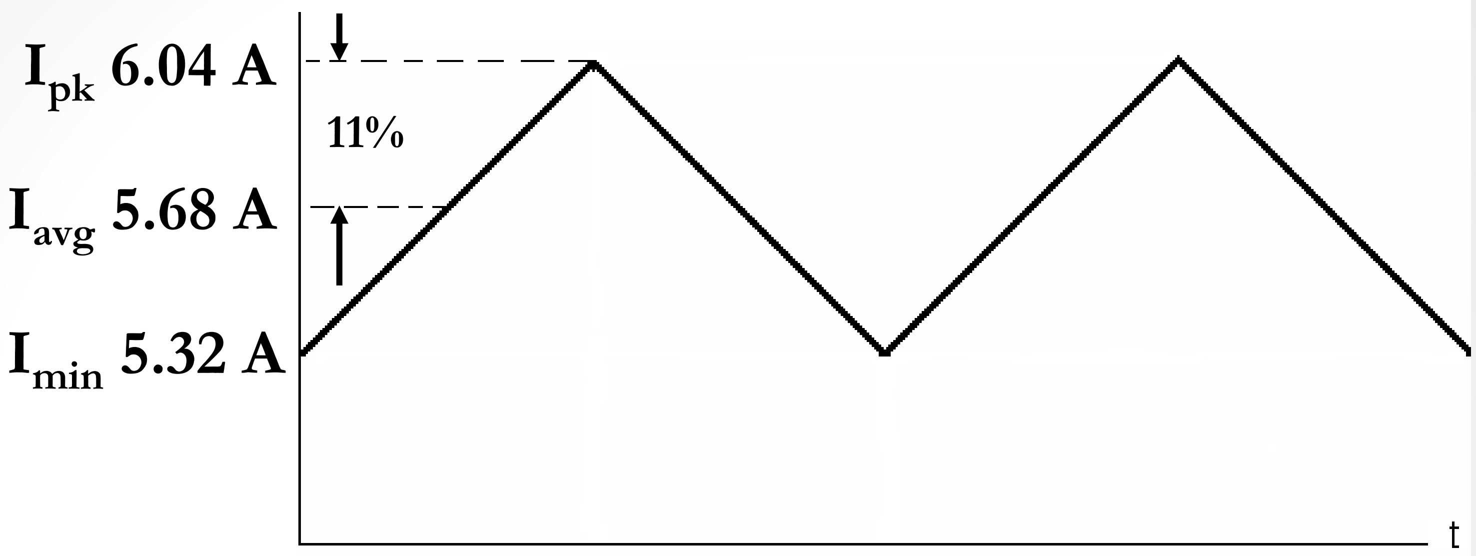
$$I_{pk} = 2.36\ A$$

$$L = \frac{V\ across\ inductor}{\Delta I}(D_{\min})(t)$$

$$L = \frac{264 - 1}{0.945}(0.34)(10.0)$$

$$L = 946\mu H$$

Worst case I_{pk} occurs at low line voltage



$$\Delta I = \frac{88-1}{946}(0.78)(10.0)$$

$$\Delta I = 0.717\,A$$

$$I_{pk} = 5.68 + \frac{0.717}{2} = 6.04\,A$$

$$I_{pk} = 6.04\ A$$

$$L = 946\,\mu H$$

Core Selection Process

$$LI^2 = (0.946)(6.04^2) = 34.5$$

The customer has a width restriction of 1.65” wound. We choose 0079071 because the OD is 1.325”, we will stack two.

Kool Mu Max P/N 0079071A7

$$A_e(2cores) = 1.312\ cm^2$$

$$l_e = 8.14\ cm$$

$$\mu = 60$$

$$V_e = 10.7\ cm^3$$

$$A_L(2cores) = 122$$

$$MLT = 4.72\ cm\ (37\%\ full)$$

Determine # of Turns

$$N = \sqrt{\frac{0.946 \times 10^6}{122}} = 88\ turns$$

$$H = \frac{NI}{le} = \frac{88 \ \times \ 6.04A}{8.14\ cm} \Rightarrow H = {}^{65AT}\!/_{cm} \Rightarrow 27\%\ rolloff \ \ from\ curve$$

Boost turns to achieve required inductance   88/0.73 = 120 turns

$$H = \frac{NI}{le} = \frac{120 \ \times \ 6.04A}{8.14\ cm} \Rightarrow H = {}^{89AT}\!/_{cm} \Rightarrow 41\%\ rolloff \ \ from\ curve$$

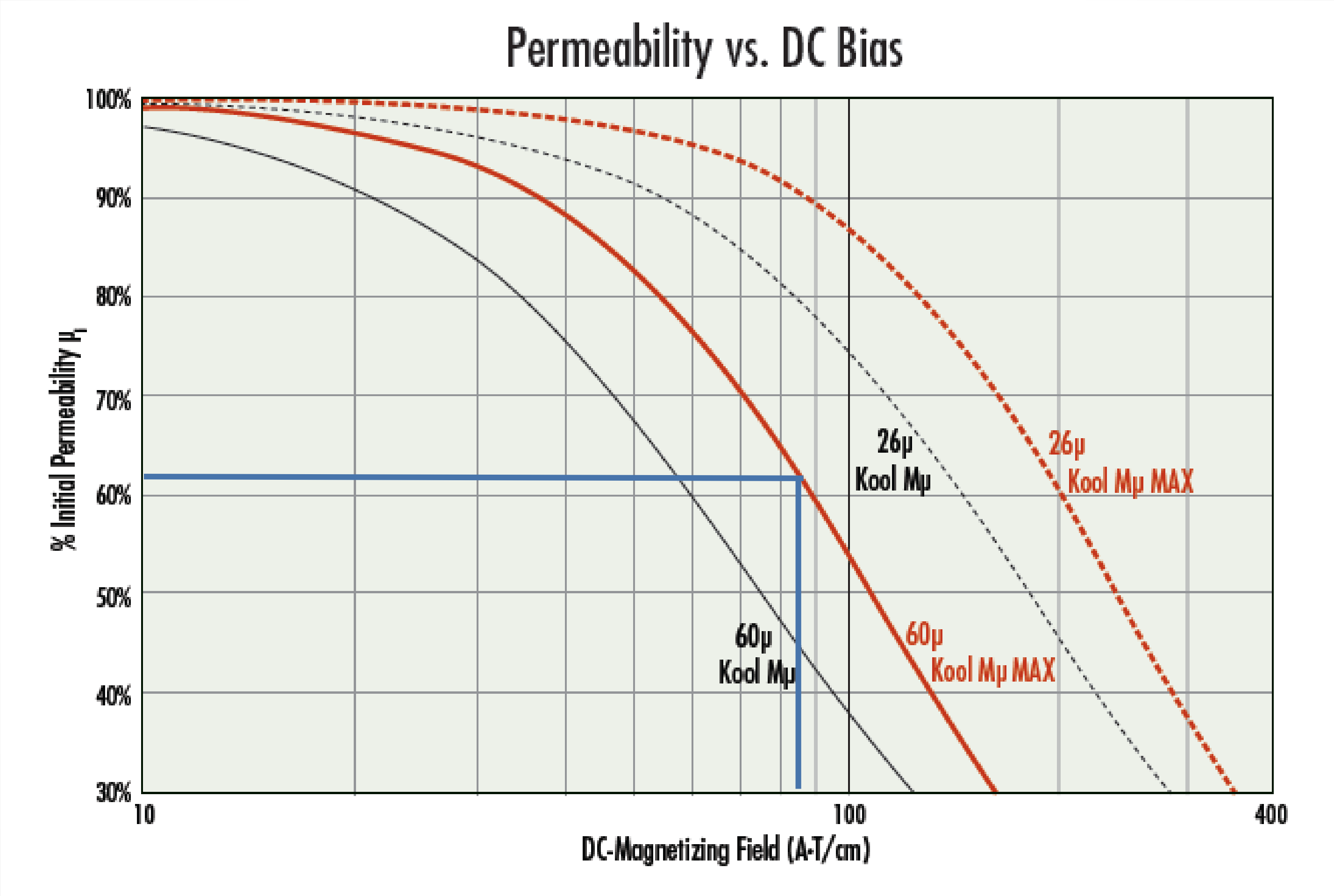
$$L\ full\ load = (0.59)(120^2)(122)(10^{-6}) = 1036\ \mu H$$

$$L\ full\ load = (0.62)(113^2)(122)(10^{-6}) = 966\ \mu H$$

Back off turns $N = 113$ $H = {}^{84AT}\!/_{cm}$

$$L\ at\ no\ load = 1557\ \mu H$$

Kool Mµ® MAX Powder Cores



$$\mu_{eff} = 62\% \; of \; initial \; perm$$

Recalculate Inductor Current

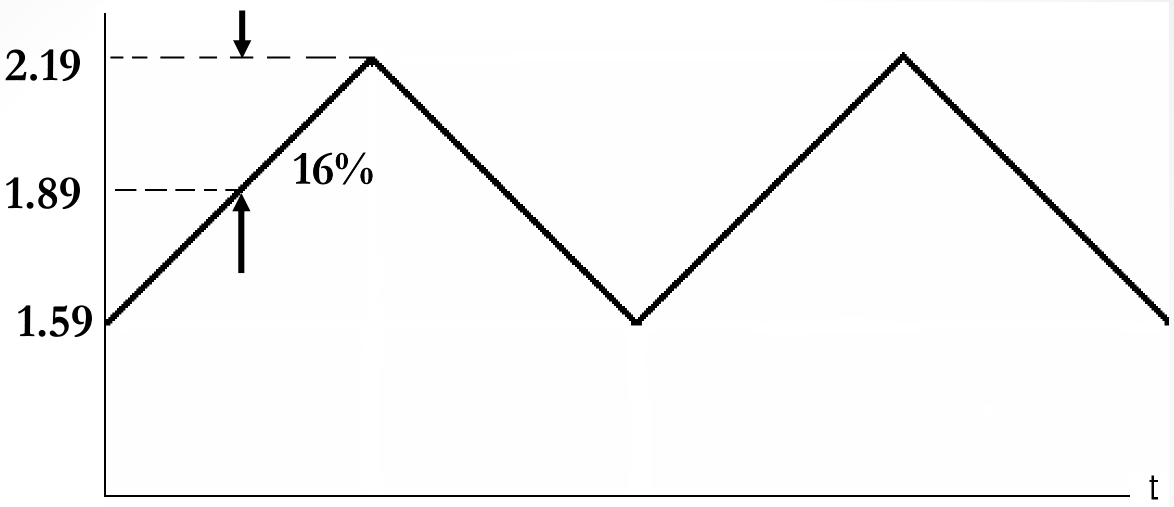
High Line Voltage

$$Initial\ \ I_{pk} = 2.36A \Rightarrow H = \frac{(113)(2.36A)}{8.14\ cm} = 32.8AT/cm \Rightarrow 6\%\ rolloff$$

$$L = 0.94\left(113^2\right)(122)\left(10^{-3}\right) = 1464\mu H$$

$$\Delta I = \frac{264-1}{1464}(0.34)(10.0) = 0.611A$$

Recalculated peak current—High Line Voltage



$$I = 1.89 \pm \frac{.611}{2} A$$

$$I_{pk} = 2.19A \Rightarrow 30.4\, {}^{AT}\!/_{cm} \Rightarrow 6\% rolloff$$

Recalculate Inductor Current

Low Line Voltage

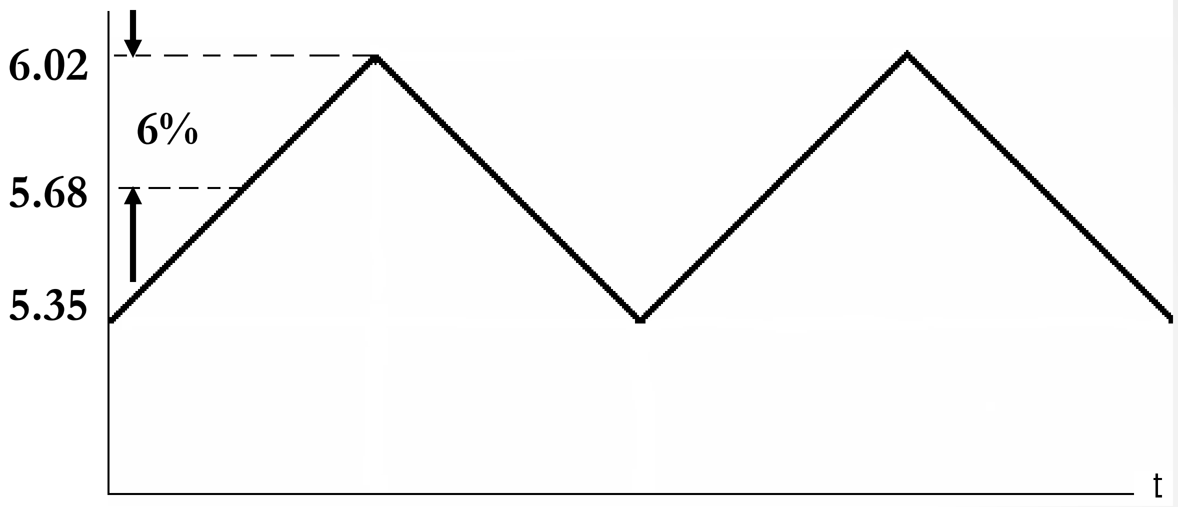
$$Initial\ \ I_{pk} = 6.04A \Rightarrow H = \frac{(113)(6.04A)}{8.14\ cm} = 84AT/cm \Rightarrow 37\%\ rolloff$$

$$L = 0.63(113^2)(122)(10^{-3}) = 981\mu H$$

$$\Delta I = \frac{88-1}{981}(0.78)(10.0) = .692A$$

$$I_{pk} = 5.68A + \frac{.692}{2} = 6.02\ A$$

Recalculated Peak Current—Low Line Voltage

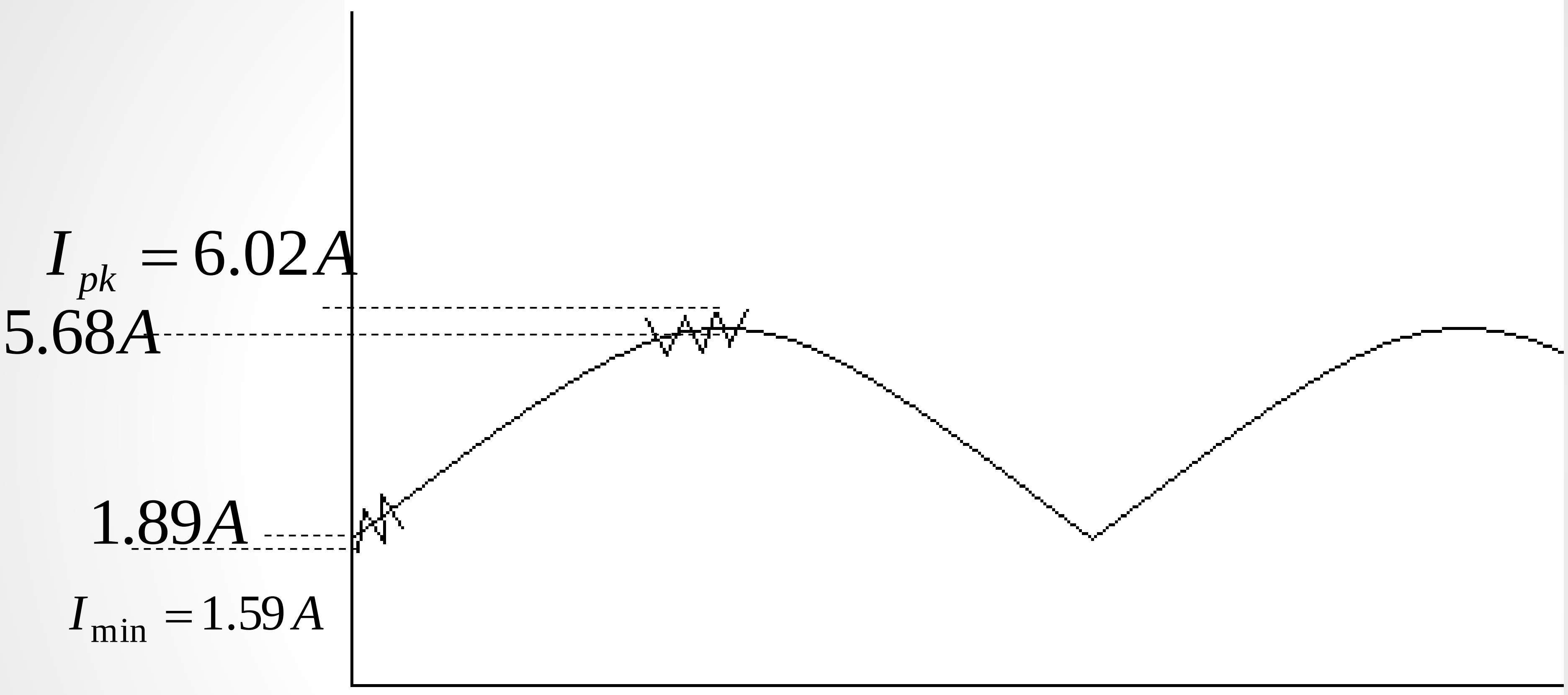


Iterate:

$$\Delta I = \frac{88-1}{981}(0.78)(10.0) = .692A$$

$$I_{pk} = 6.02\ \ A \qquad L = 981\mu H$$

RMS Current



$$I_{RMS} = 1.89 + \frac{1}{\sqrt{2}}\left(5.68 - 1.89\right) = 4.57A$$

Wire

For 4.57 A current use 2 strands of AWG #21 Wire

R =41.9/2=20.9 mΩ/m $W_{a\ 2\ strands}$ = 0.00968 cm^2

A_W=2.97 cm^2

$$Fill\ Factor\ is\ \frac{NW_a}{A_w} = \frac{113(0.00968)}{2.97} = 36.8\%$$

For 2 strands in parallel AWG #21 Wire

R_T= 165.86 mΩ/m W_a=0.00968 cm^2 Fill = 36.8%

Flux Density Calculations

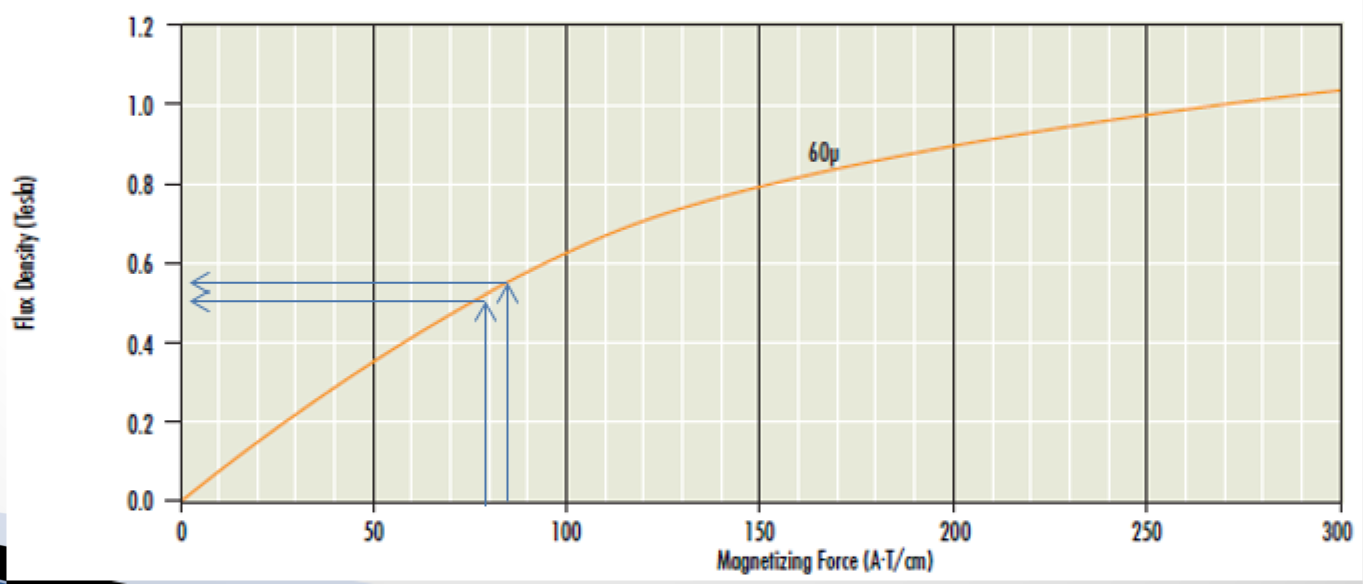
At Low Line Voltage

$$I_{pk} = 6.02A \Rightarrow H_{pk} = 84 \, {AT}/{cm}$$

$$I_{\min} = 5.34A \Rightarrow H_{\min} = 74 \, {AT}/{cm}$$

$$B_{pk} = .056 \;\; Tesla \qquad\qquad B_{\min} = .052 \;\; Tesla$$

$$\tfrac{1}{2} \Delta B = 0.02 \;\; Tesla$$



Flux Density Calculations

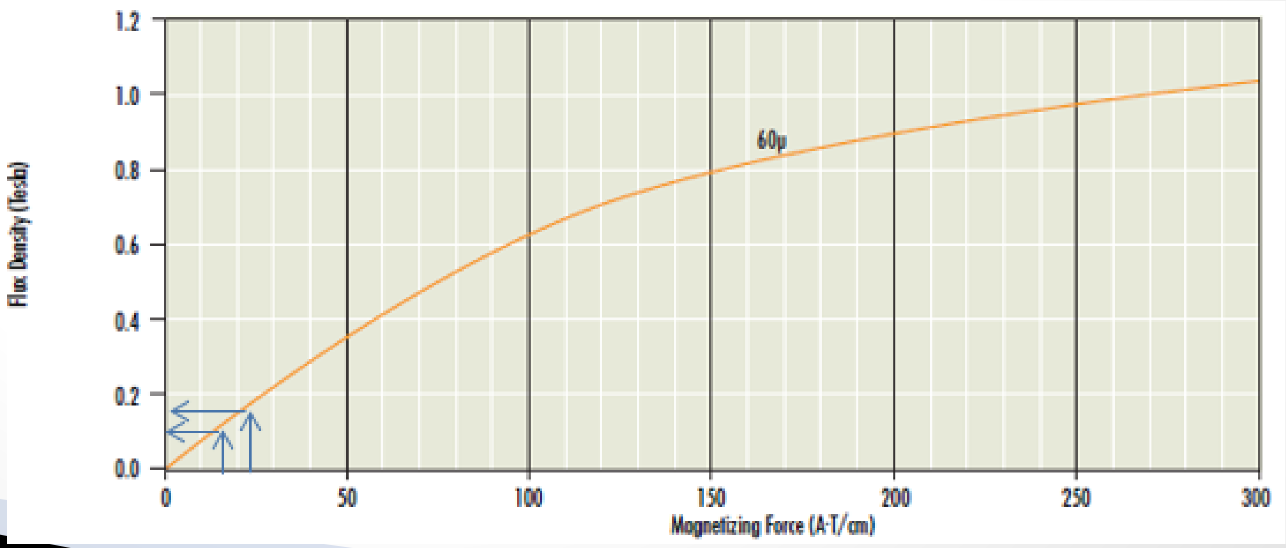
At High Line Voltage

$$I_{pk} = 2.19A \quad H_{pk} = 30.4\, AT/cm$$

$$I_{\min} = 1.59A \quad H_{\min} = 22.0\, AT/cm$$

$$B_{pk} = 0.23 \;\; Tesla \qquad B_{\min} = 0.16 \;\; Tesla$$

$$\tfrac{1}{2}\Delta B = 0.035 \;\; Tesla$$

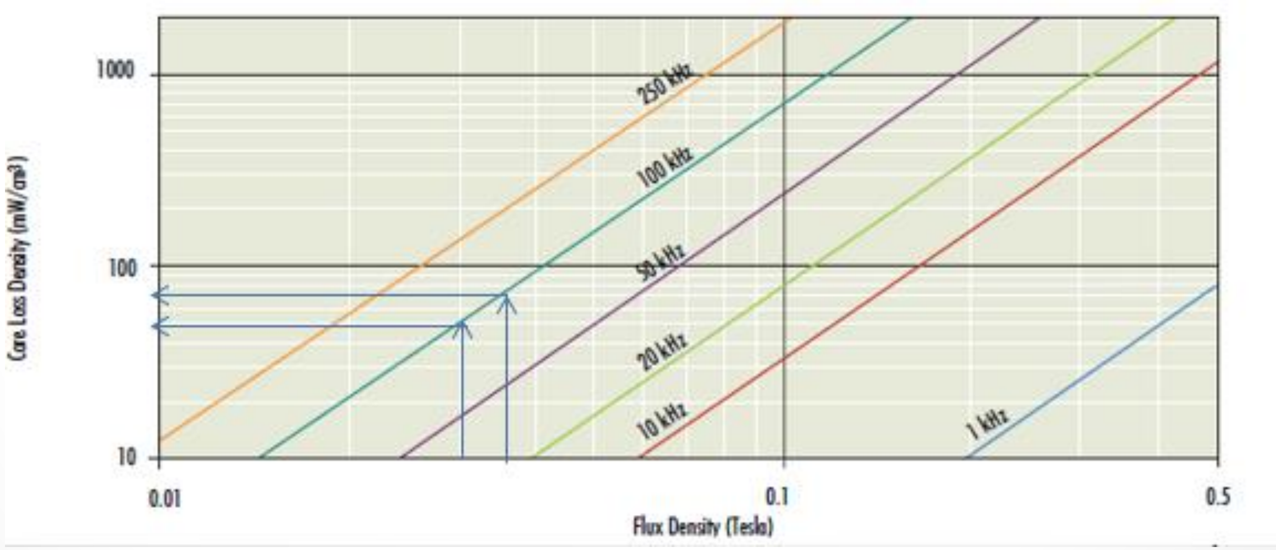


Core Losses

$$P = 91.616 B^{2.039} f^{1.388} \quad for\ 60\mu\ KoolMuMAX$$

$$P = 91.616(0.020)^{2.039}(100)^{1.388} = 19\, mW/cm^3$$ High Line

$$P = 91.616(0.035)^{2.039}(100)^{1.388} = 59\, mW/cm^3$$ Low Line



$$V_e = 10.68\, cm^3 \qquad Power\ \ Loss = \left({}^{mW}\!/_{cm^3}\right)\left(cm^3\right)$$

$$Core\ losses\ are\ 203 - 630\ mW$$

Copper Losses

For #21 Wire, 2 strands

$$R_{coil} = MLT(N)(R/length)$$

$$R_{coil} = \left(70\ {}^{mm}\!/\!_{turn}\right)(113T)\left(2.094\times10^{-5}\ {}^{\Omega}\!/\!_{mm}\right)$$

$$R_{coil} = 165.8m\Omega$$

$$Power\ \ Loss_{Copper} = (I)^2(R)$$

$$P_{cu} = (4.57)^2(0.166) = 3467mW$$

Total Losses and Estimated Temperature Rise

Total losses 203 – 630 + 3467= 4097 mWatts

Temperature rise with no active air flow

Wound inductor surface area **S**

$$OD = 3.383\ cm\ \ \text{max},\ \ Hgt = 2.31\ cm\ \ \text{max}$$

$$S = 2 \times \left[\ \pi(3.383cm)(2.31cm) + 2\left(\pi\left(\frac{2.31}{2}\right)^2\right)\ \right] = 65.86cm^2$$

$$\Delta T \approx \left[\frac{mW}{S}\right]^{0.833} = \left[\frac{4097}{65.86}\right]^{0.833} = 31.2^\circ C$$

With airflow, ΔT would improve

Summary

0079071A7 Kool Mu MAX 2 Toroids stacked

N=113 turns of two strands AWG#21, giving a fill factor of 36.8%

L=1557μH at no load

L=981μH at peak (6.02A)

Inductor Max Ripple = 16%

Core losses = 203-630 mW

Copper losses = 3,467 mW

Total losses =4,097 mW

ΔT estimate ≈ 31.2°C

Efficiency = Power Out/Power In

500.00/504.097=99% efficient

THANK YOU AGAIN!

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