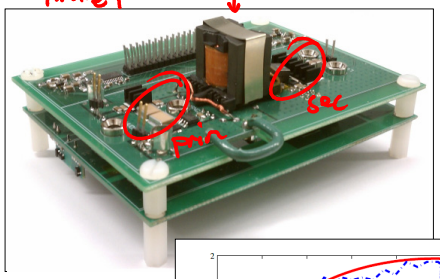
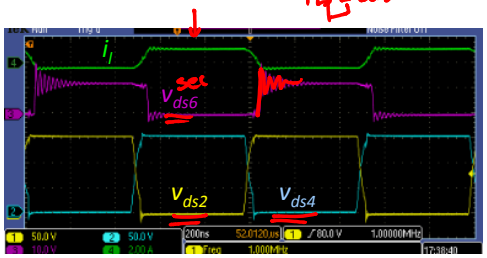
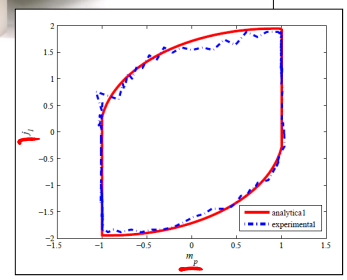
DAB: Experimental Results

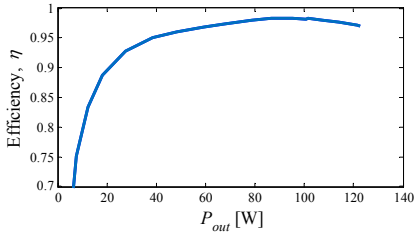
150-12V
1MHz, 120W

XF









D. Costinett, D. Maksimovic, and R. Zane, "Design and control for high efficiency in high step-down dual active bridge converters operating at high switching frequency," IEEE Trans. Power Electron., vol. PP, no. 99, p. 1, 2012.

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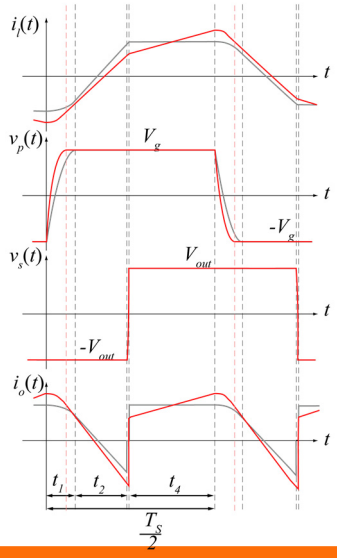
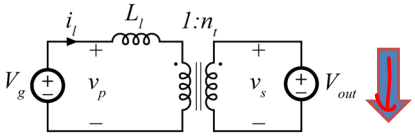
Operation with $V \neq nV_g$

$\frac{V}{nV_g} \neq 1$





- E.g. Decrease to

  $M_N < 1$

  by decreasing output voltage
- Current now ramping, causing more energy available for primary ZVS, but higher RMS currents
- Can use behavior to extend ZVS range of one bridge

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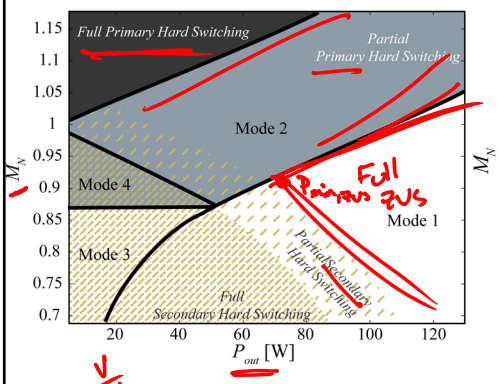
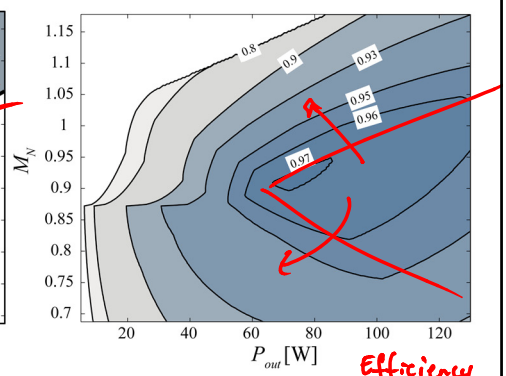
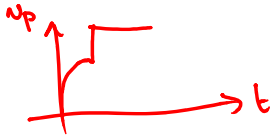
Soft Switching Range with Varying V_{out}

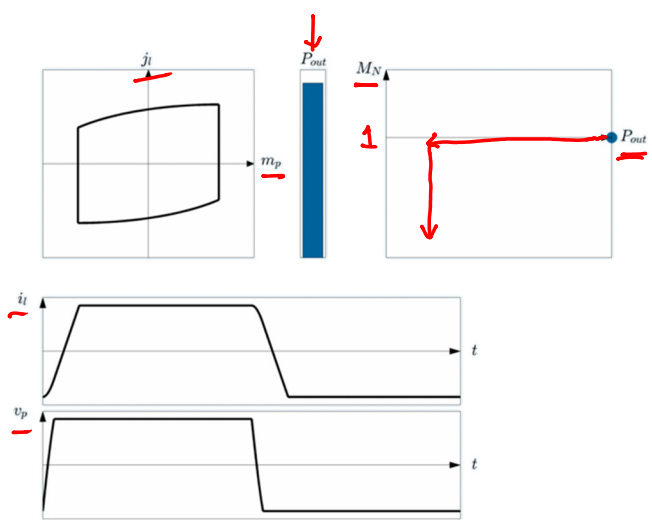




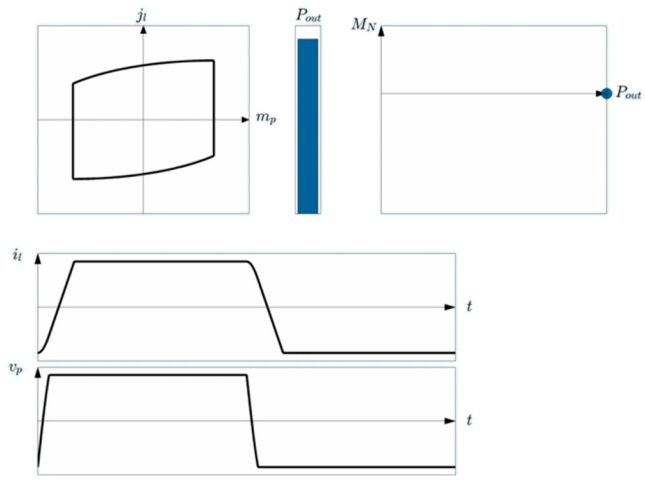
$M_N = \frac{V}{nV_g}$



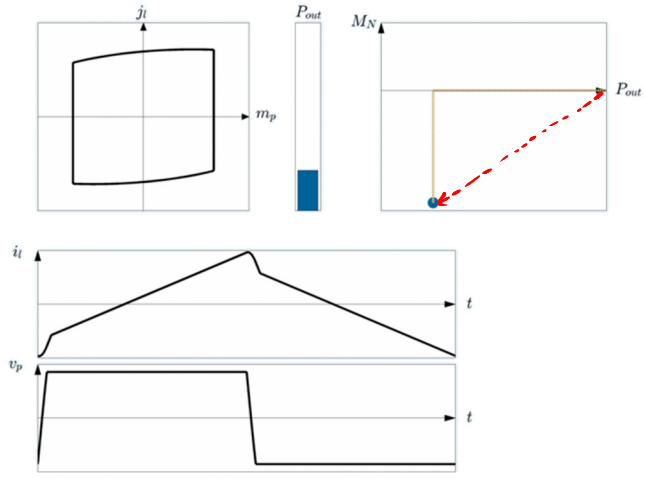
Design Trajectory Example: Operation



Design Trajectory Example: Operation



Design Trajectory Example: Operation



Application Example: Automotive

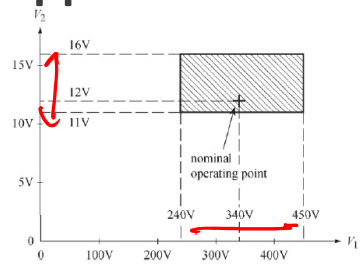
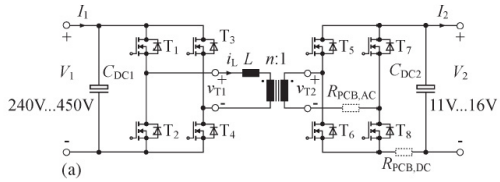


Fig. 1. Converter operating voltage ranges required for automotive application.



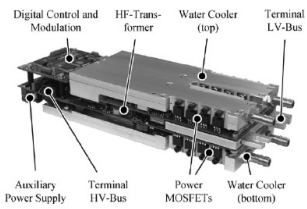


Fig. 3. Automotive DAB converter (273 × 90 × 53 mm).

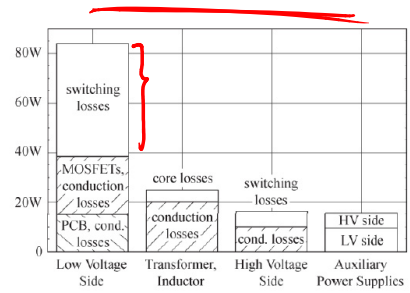


Fig. 13. Calculated distribution of the power losses for operation at V_1 = 340 V, V_2 = 12 V, and P_2 = 2 kW.

*F. Krismer, J.W.Kolar, "Accurate Power Loss Model Derivation of a High-Current Dual Active Bridge Converter for an Automotive Application, IEEE Trans. On Industrial Electronics, March 2010

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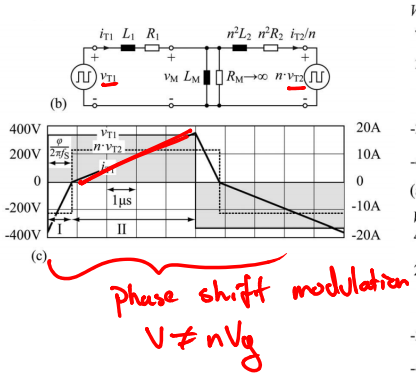
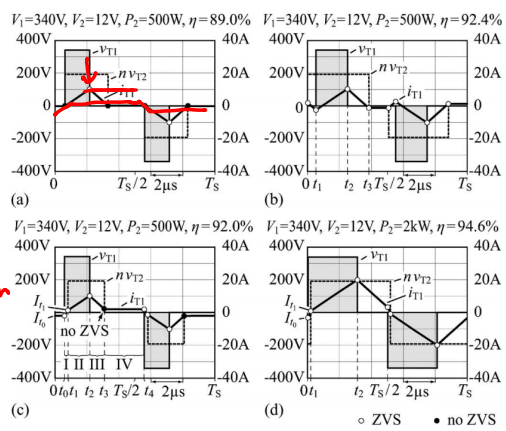
Alternate Modulation Schemes



Phase shift modulation

$V \neq nV_g$



Florian Krismer; Johann W. Kolar, "Closed Form Solution for Minimum Conduction Loss Modulation of DAB Converters"

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Efficiency Results

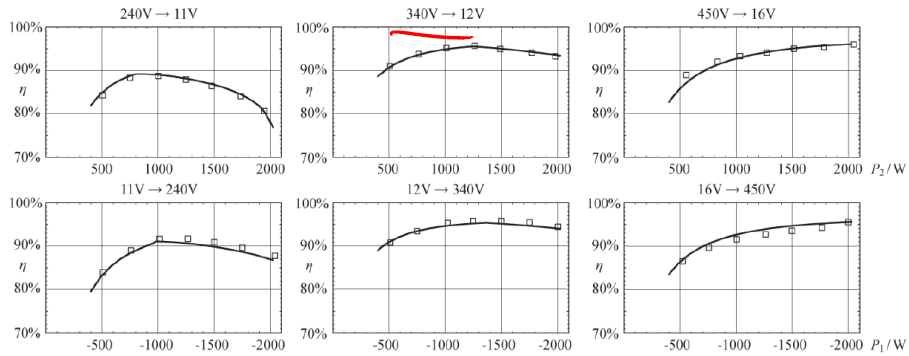


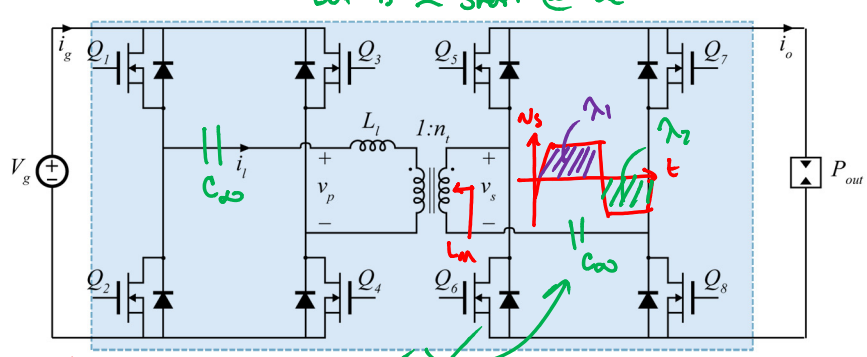
Fig. 12. (Solid lines) Predicted efficiencies and (□) measured efficiencies for different operating conditions. The efficiencies are calculated with the improved DAB loss model which includes all methods discussed in Section IV.

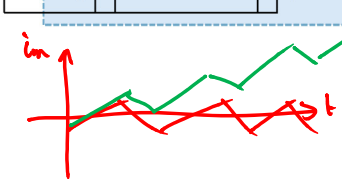
Transformer Saturation

$\frac{1}{\sqrt{L_l C_\infty}} \ll f_s$

C_∞ blocks DC

but is ≈ short @ ac





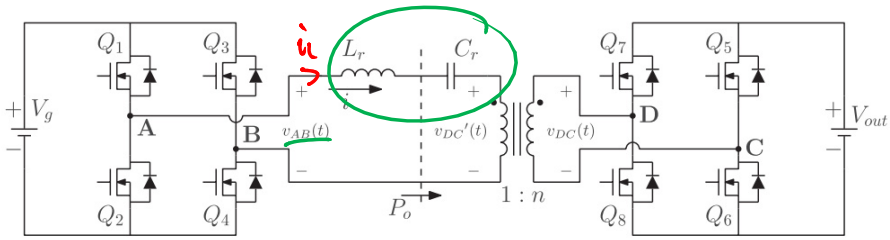
$\lambda_1 \neq \lambda_2$

$\langle v_s \rangle T_s \neq 0$

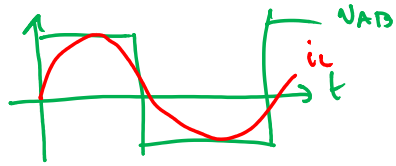
$\langle v_{L_m} \rangle = \phi$

Next: SRC

Series Resonant Converter

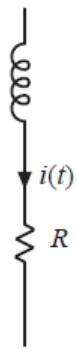


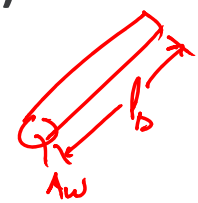
$$\frac{1}{\sqrt{L_r C_r}} \approx f_s$$



Magnetics Losses

Magnetics Winding Loss (DC)





- DC Resistance given by

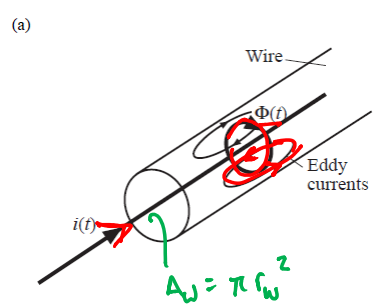
$$R_{DC} = \rho \frac{l_b}{A_w}$$

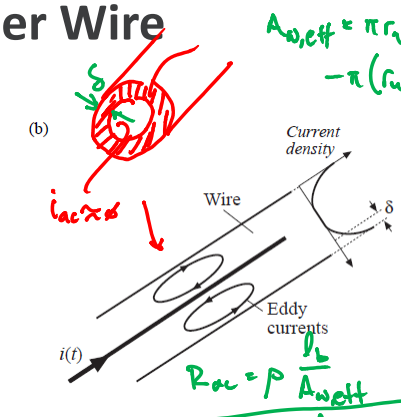
- At room temp, ρ = 1.724·10^{-6} Ω-cm
- At 100°C, ρ = 2.3·10^{-6} Ω-cm
- Losses due to DC current:

$$P_{cu,DC} = {I_{L,rms}}^2 R_{DC}$$

Skin Effect in Copper Wire

$A_{w,eff} = \pi r_w^2 - \pi (r_w - \delta)^2$





$$R_{ac} = \rho \frac{l_b}{\pi (2 r_w - \delta)\delta}$$

- Current profile at high frequency is exponential function of distance from center with characteristic length δ

Skin Depth

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

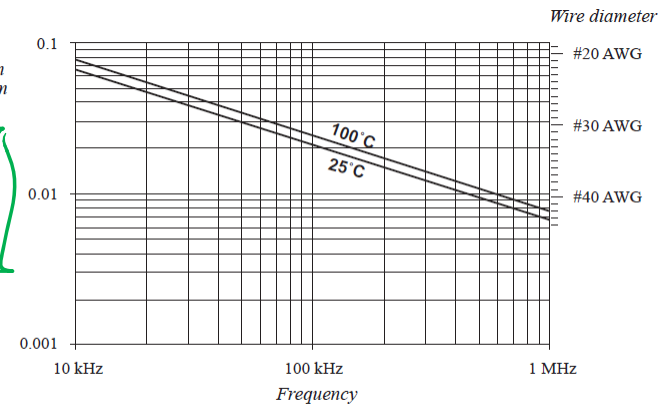
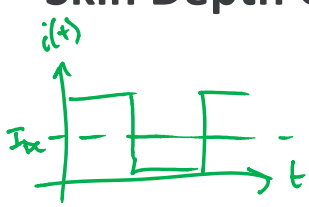
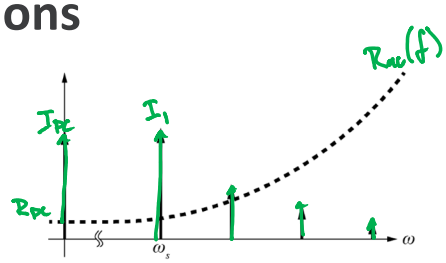


Fig. 13.23 Penetration depth δ, as a function of frequency *f*, for copper wire.

Skin Depth Calculations





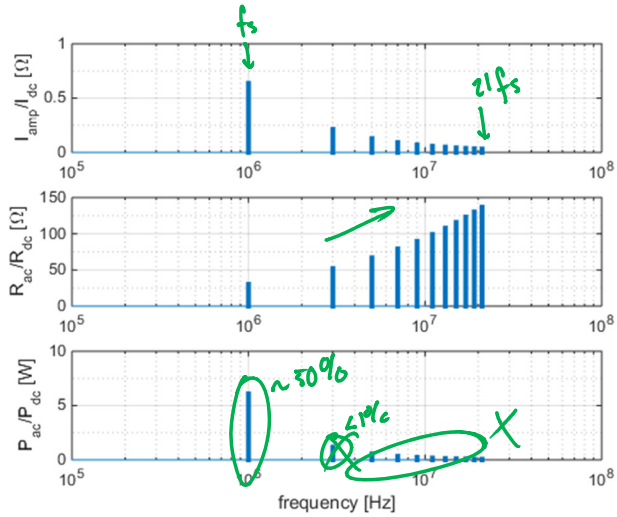
Example Calculation

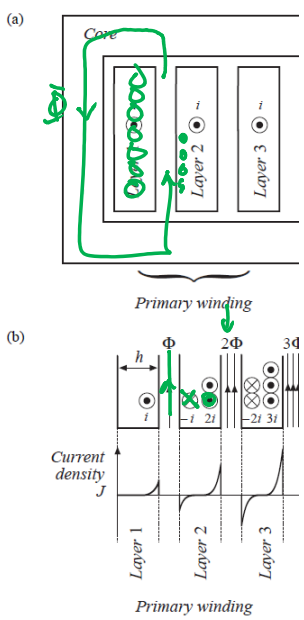
AWG40

1A DC, 1A pk square wave current

1m long

1MHz = fs





Proximity Effect

- In *foil* conductor closely spaced with $h >> \delta$, flux between layers generates additional current according to Lentz's law.

$$P_1 = {I_{L,rms}}^2 R_{ac}$$

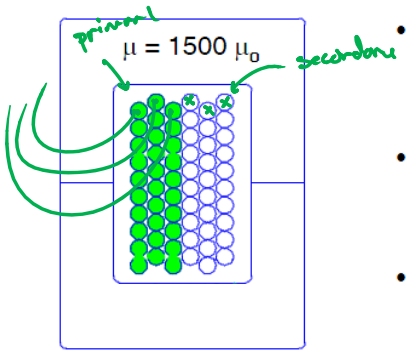
- Power loss in layer 2:

$$P_2 = {I_{L,rms}}^2 R_{ac} + \left(2I_{L,rms}\right)^2 R_{ac}$$

$$P_2 = 5P_1$$

See *Fundamentals of Power Electronics*, Section 13.4

Simulation Example



- AWG#30 copper wire
  - Diameter d = 0.294 mm
  - $d = \delta$ at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents,

  $I_{1rms} = I_{2rms} = 1$ A

Numerical field and current density solutions using FEMM (Finite Element Method Magnetics), a free 2D solver, http://www.femm.info/wiki/HomePage

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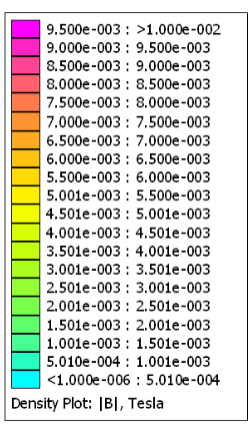
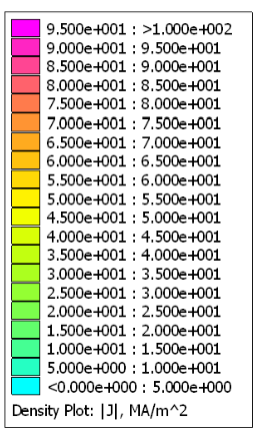
Flux density magnitude



Current density magnitude



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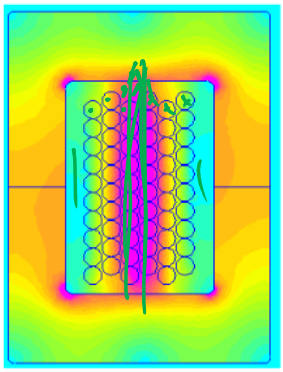
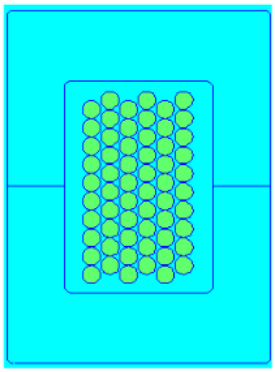
Frequency: 1 kHz

Flux density

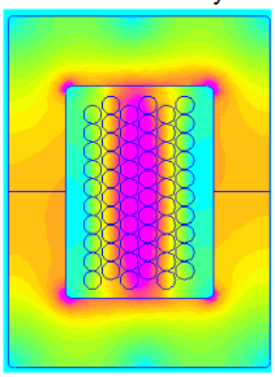


Current Density

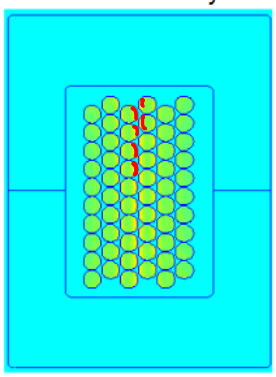


Frequency: 100 kHz

Flux density



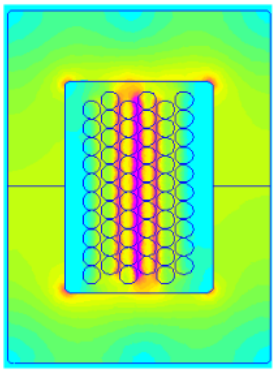
Current Density



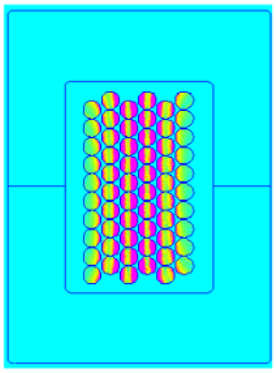
Total copper losses 1.8 larger than at 1 kHz

Frequency: 1 MHz

Flux density



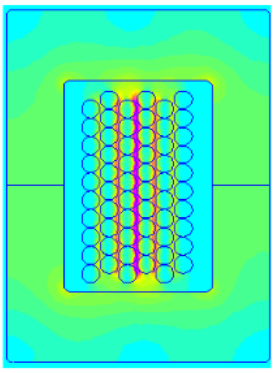
Current Density



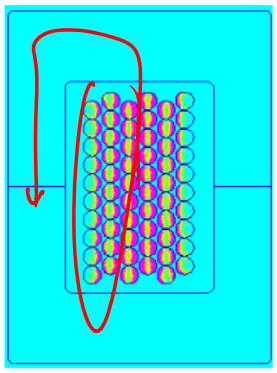
Total copper losses 20 times larger than at 1 kHz

Frequency: 10 MHz

Flux density

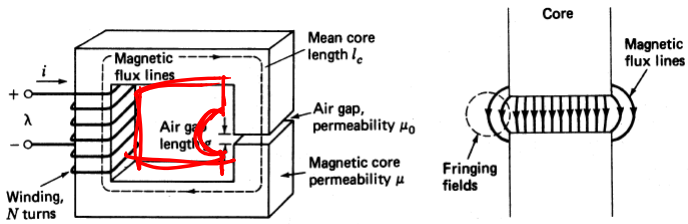


Current Density



Very significant proximity effect
Total copper losses = 65 times larger than at 1 KHz

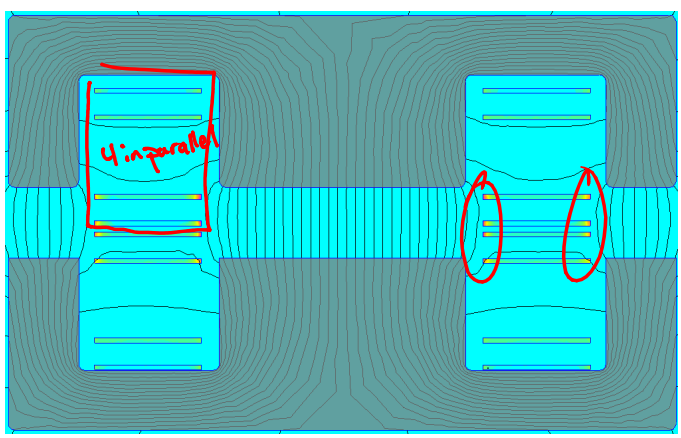
Fringing



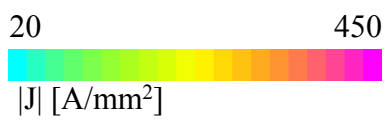
A simple magnetic circuit with an air gap

- Near air gap, flux may bow out significantly, causing additional eddy current losses in nearby conductors

Finite Element Simulation

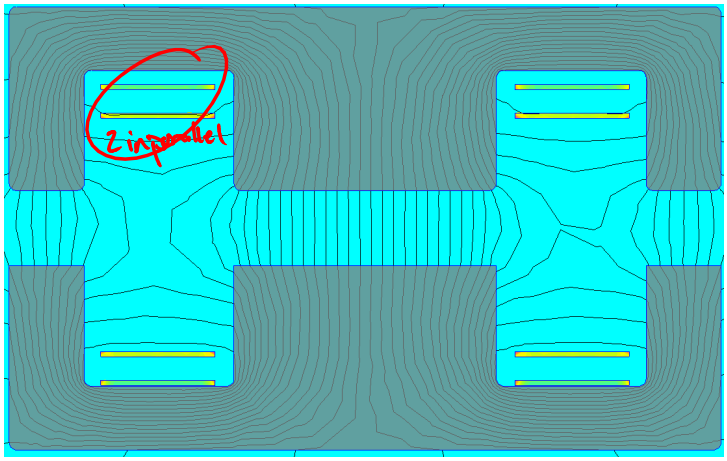


$P_{cond} = 330$ W



http://www.femm.info/wiki/HomePage

Removing Copper From Fringing Field



P_{cond} = 180 W

15 280

|J| [A/mm^2]