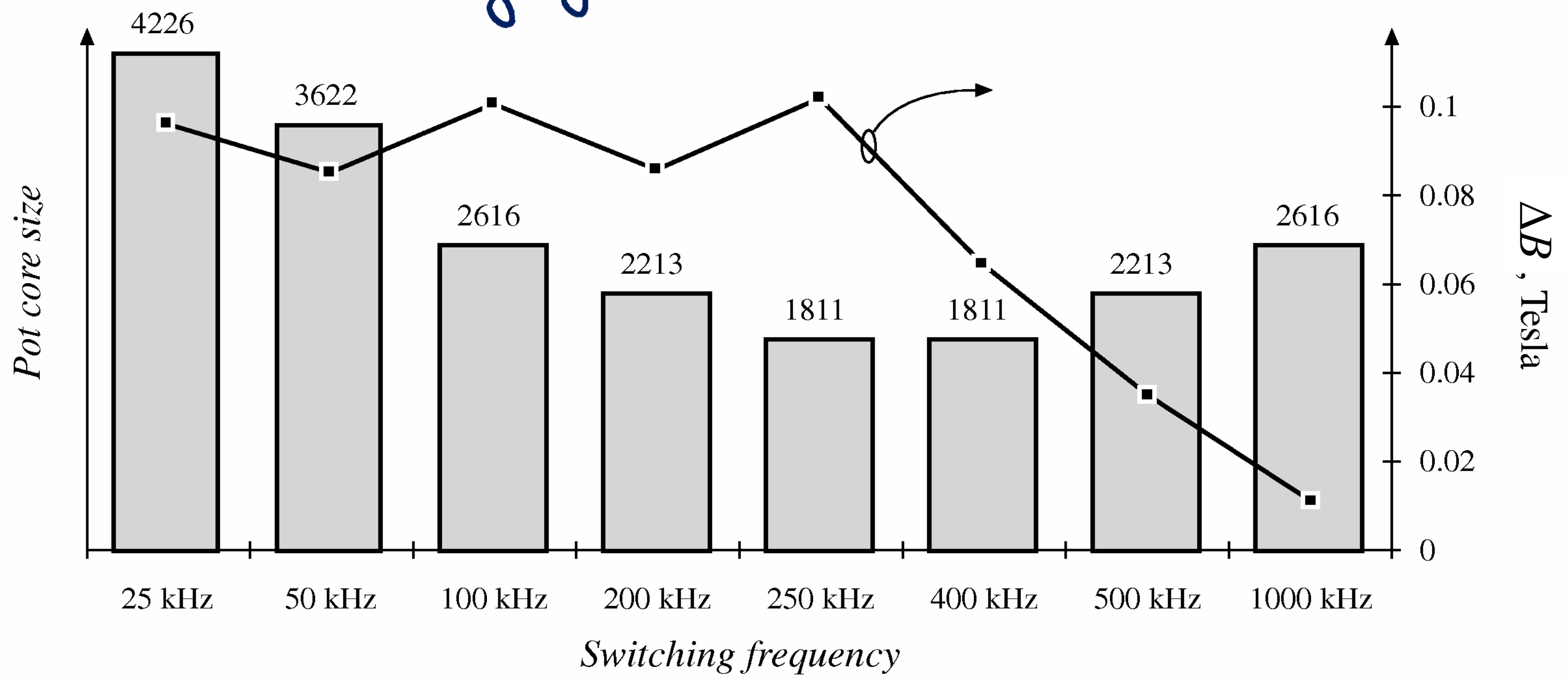
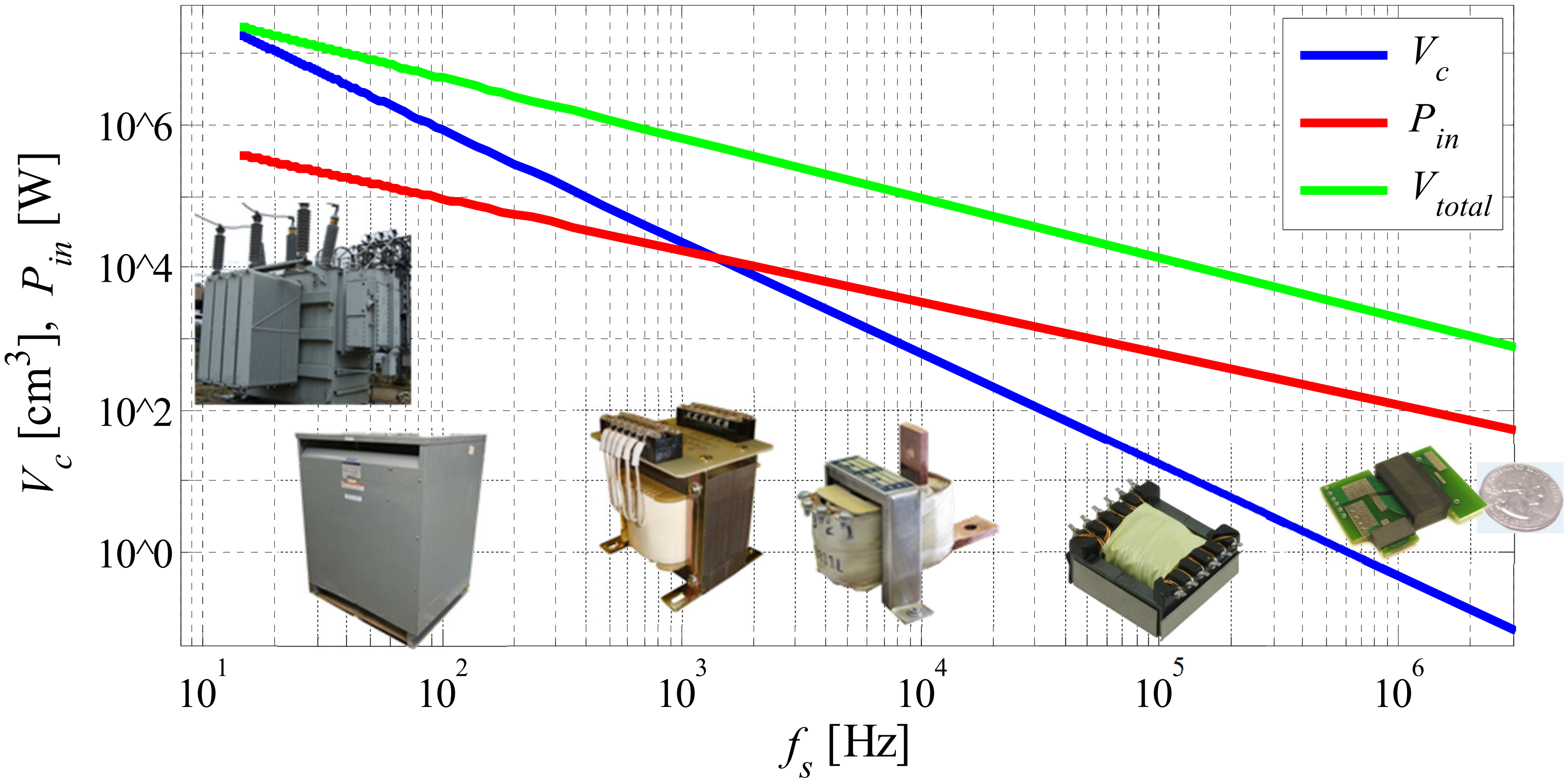
XF Size vs f_s

For a constant P_{XF}
using kgfe :



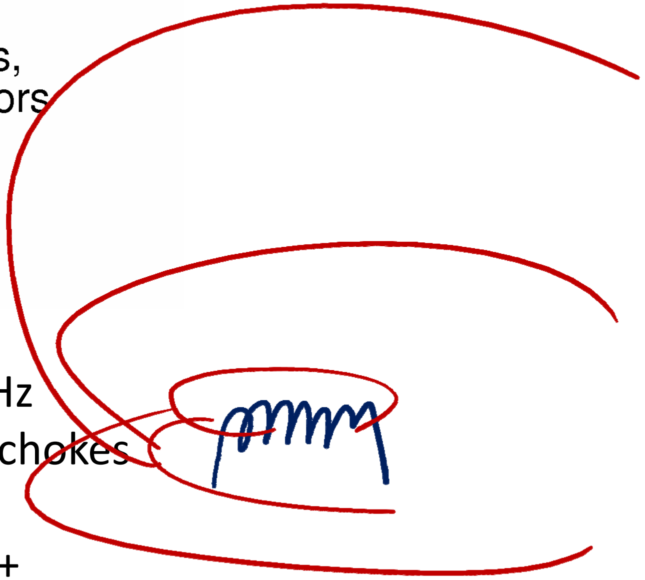
Transformer Size Comparison



- V_{total} is total magnetic volume required to process 500 kW
- $K_U = .5$, $B_{pk} = 200$ mT, $n_1 = 70$, $V_g = 400$ V, $\eta_{XF} = 95\%$

Some Example Core Materials

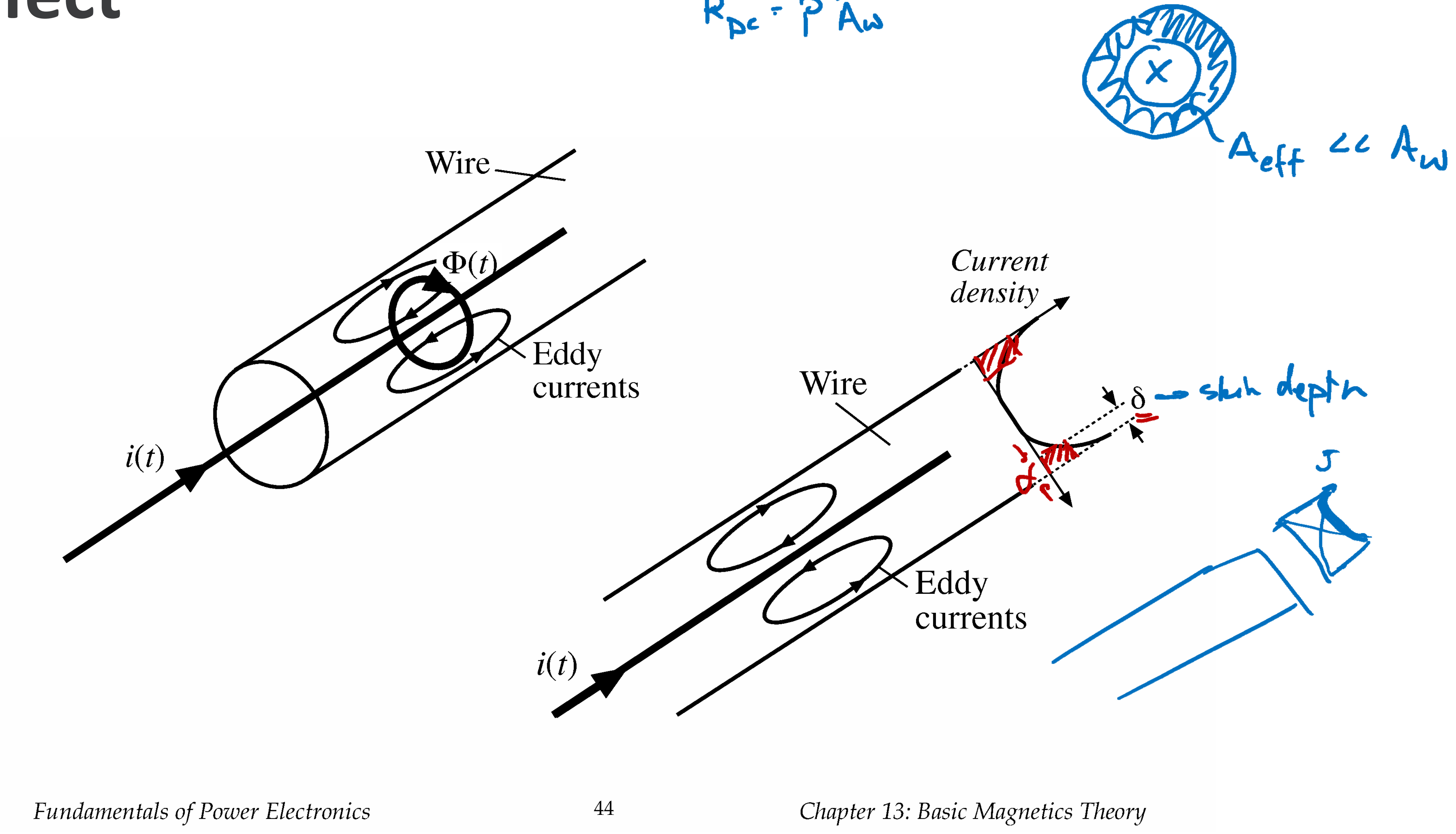
Core type	B_{sat}	Relative core loss	Applications
Laminations iron, silicon steel	1.5 - 2.0 T	high	50-60 Hz transformers, inductors
Powdered cores powdered iron, molypermalloy	0.6 - 0.8 T	medium	1 kHz transformers, 100 kHz filter inductors
Ferrite Manganese-zinc, Nickel-zinc	0.25 - 0.5 T	low	20 kHz - 1 MHz transformers, ac inductors
Laminated nanocrystalline	1.5 - 2.2T	low	5kHz – 500 kHz Transformers, CM chokes
Air	N/A	zero	1 – 100 MHz+ ac inductors
Low-μ powdered iron/carbonyl	0.5-1.2 T (soft)	very low	1 – 100 MHz+ ac inductors



μ : 2-50

Skin Effect

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



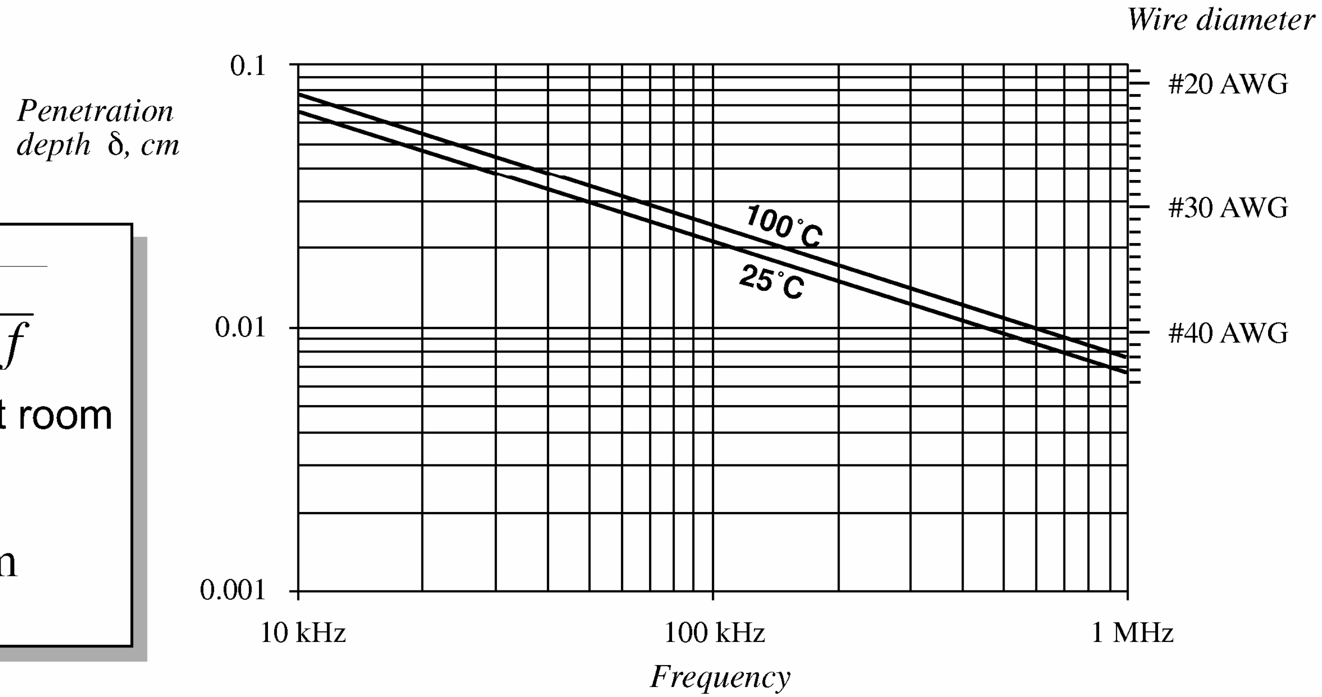
$A_{eff} << A_w$

Skin Depth

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

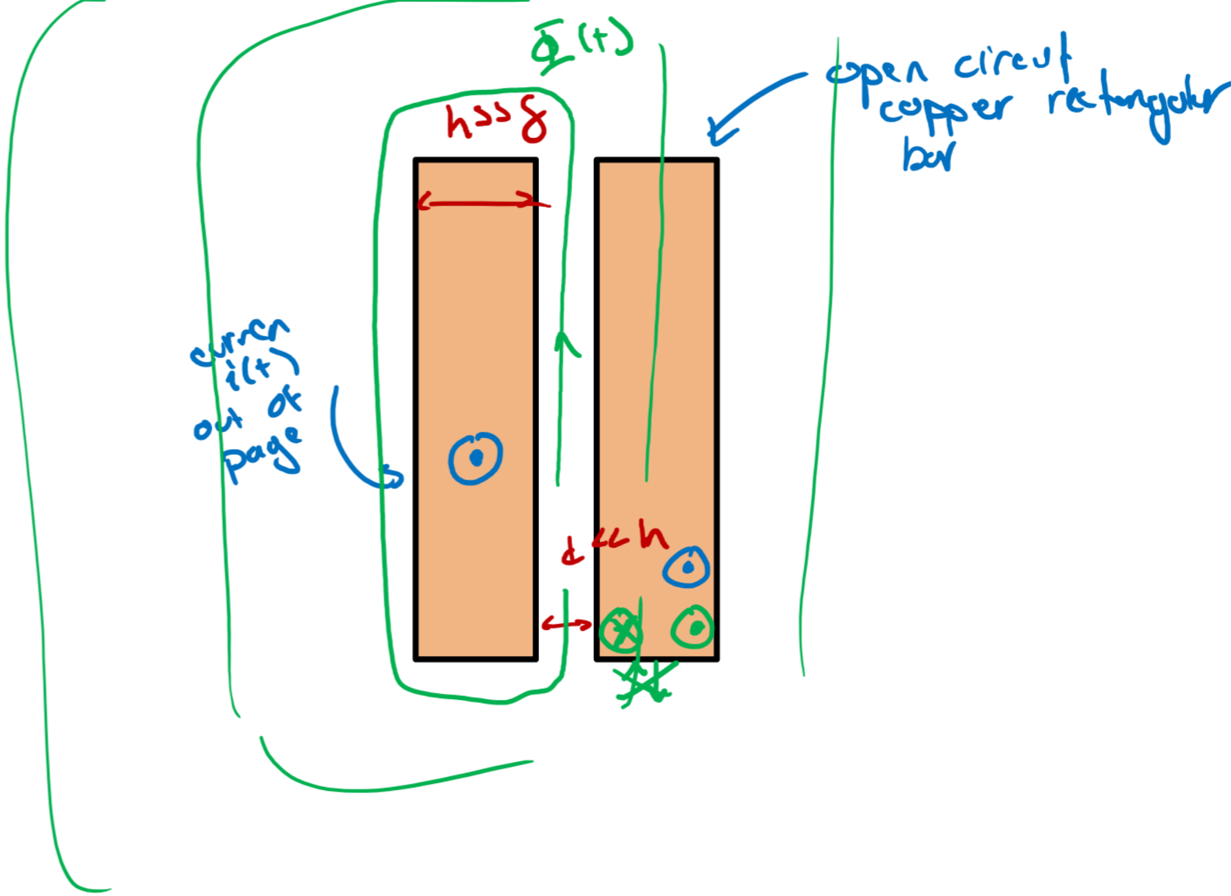
For copper at room temperature:

$$\delta = \frac{7.5}{\sqrt{f}}\ \text{cm}$$

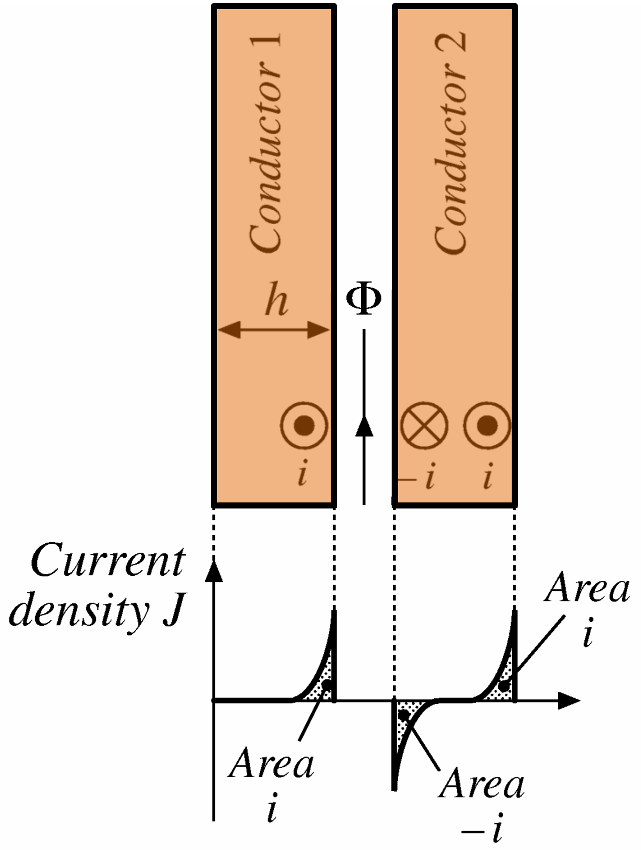


Proximity Effect

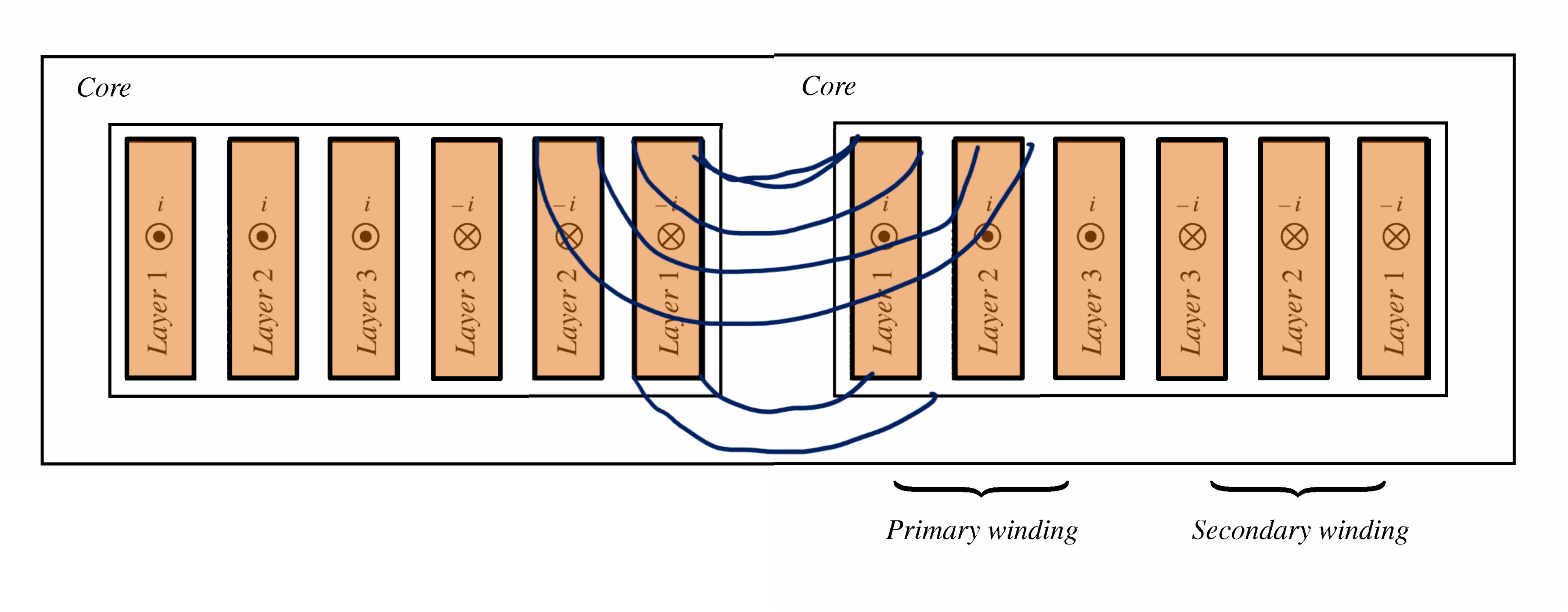
For closely spaced windings with $h >> \delta$, fields from each winding generate eddy currents in adjacent conductors



Proximity Effect



Two-Winding Transformer Example



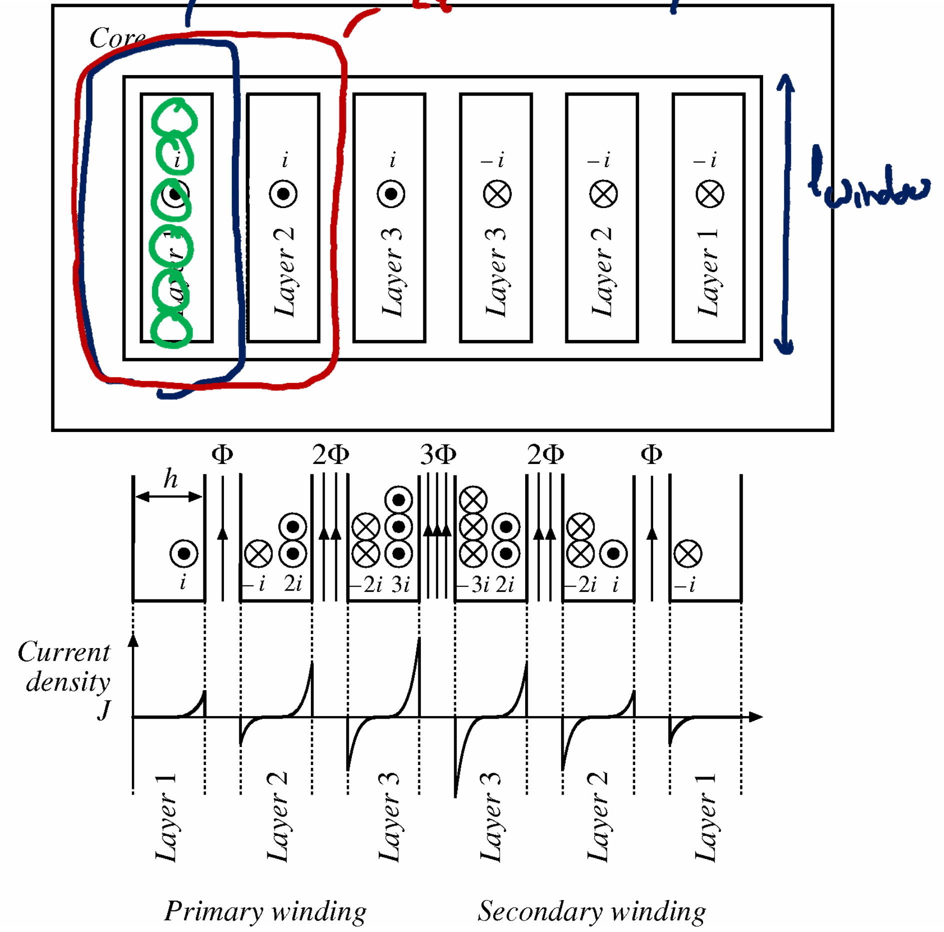
Current Distribution

Ampere: $I_{encl} = \int H \cdot dl$

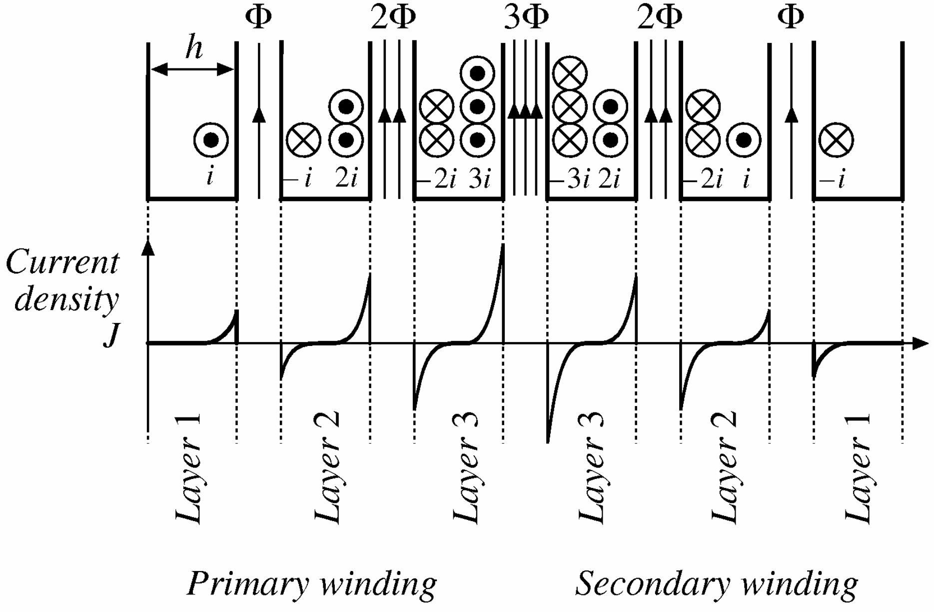
$i \approx H_{window} l_{window}$

$2i \approx H_{window,2} l_{window}$

$\mu >> \mu_0$



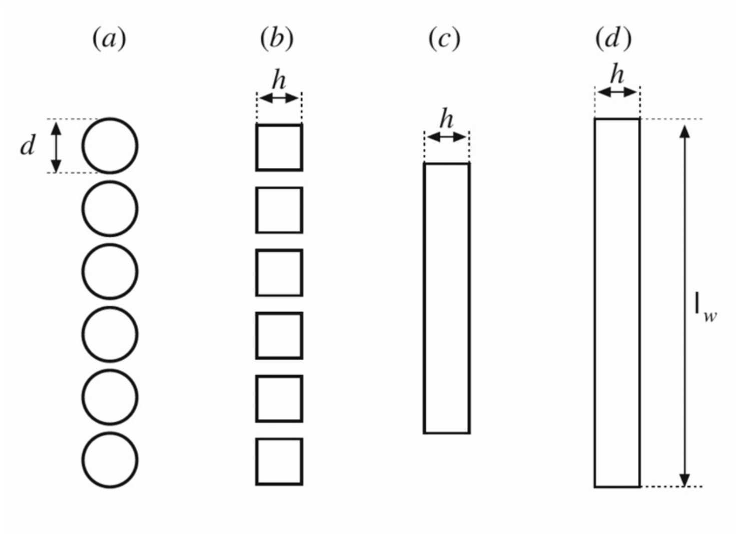
High Frequency Estimation



Power loss P_m in layer m is:

$$P_m = I^2 \left[(m-1)^2 + m^2 \right] \left(\frac{h}{\delta} R_{dc} \right)$$

Equivalent Foil Winding Loss



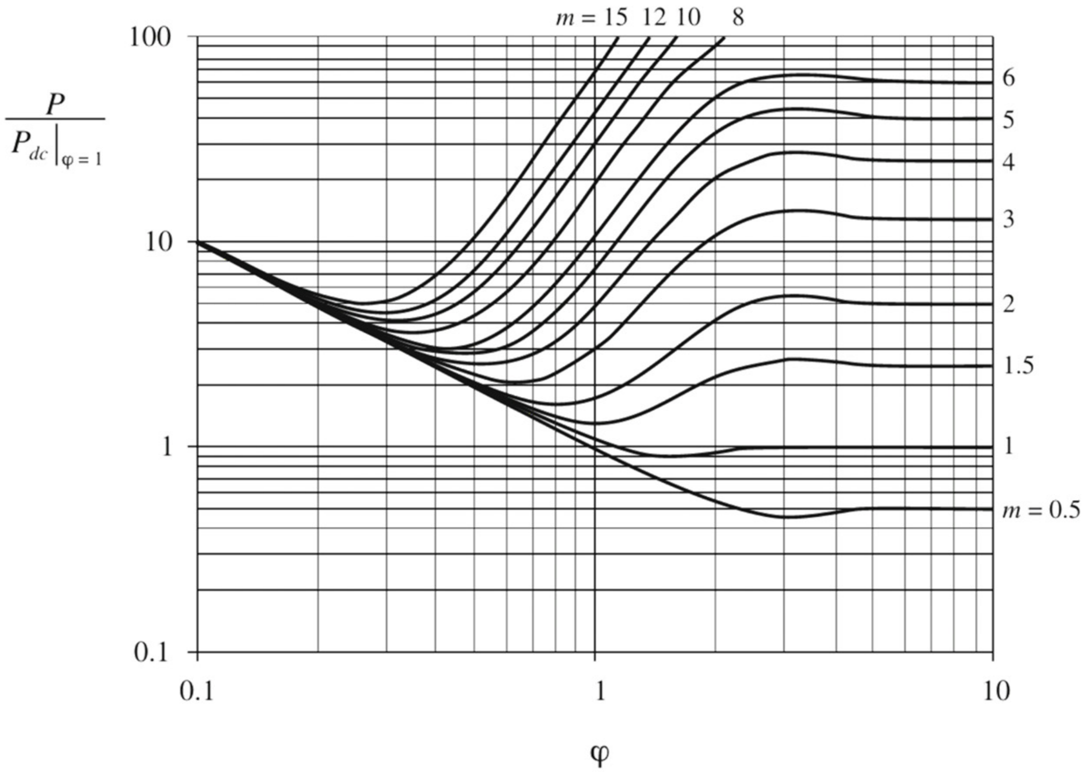
$$\eta = \sqrt{\frac{\pi}{4}}\, d\, \frac{n_\ell}{\ell_w} \qquad \delta' = \frac{\delta}{\sqrt{\eta}}$$

$$\varphi = \frac{h}{\delta'} = \sqrt{\eta}\,\sqrt{\frac{\pi}{4}}\,\frac{d}{\delta}$$

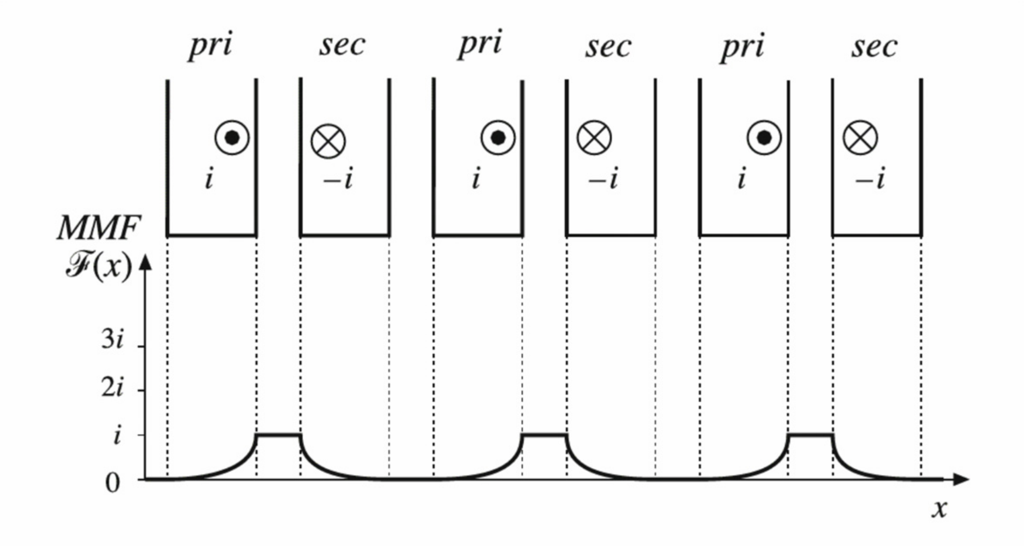
$$P = R_{dc}\frac{\varphi}{n_\ell^2}\left[\left(\mathscr{F}^2(h)+\mathscr{F}^2(0)\right)G_1(\varphi) - 4\mathscr{F}(h)\mathscr{F}(0)G_2(\varphi)\right]$$

$$G_1(\varphi) = \frac{\sinh(2\varphi)+\sin(2\varphi)}{\cosh(2\varphi)-\cos(2\varphi)}$$

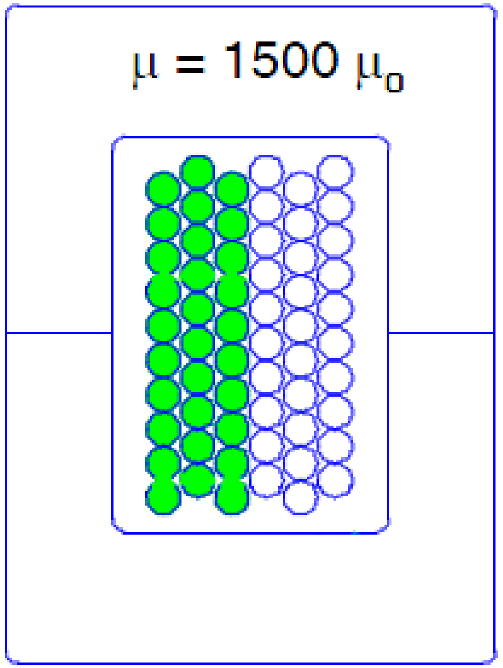
$$G_2(\varphi) = \frac{\sinh(\varphi)\cos(\varphi)+\cosh(\varphi)\sin(\varphi)}{\cosh(2\varphi)-\cos(2\varphi)}$$



Interleaving



Simulation Example

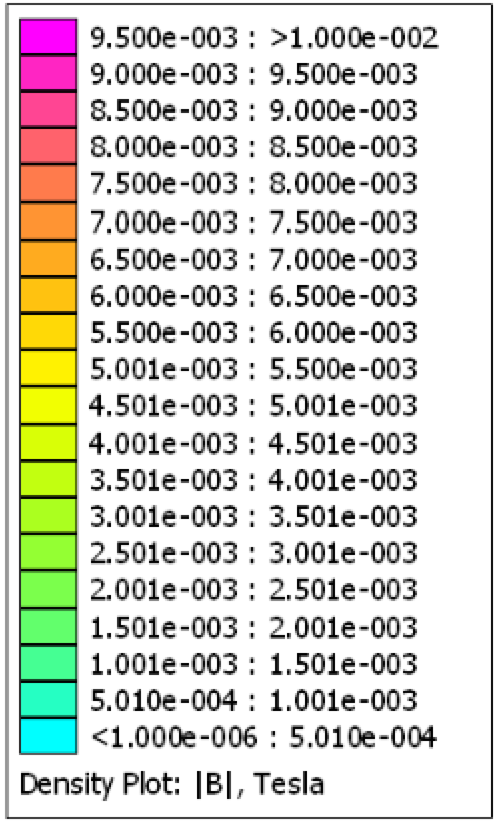


- AWG#30 copper wire
  - Diameter $d = 0.294$ mm
  - $d = \delta$ at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents,

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

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

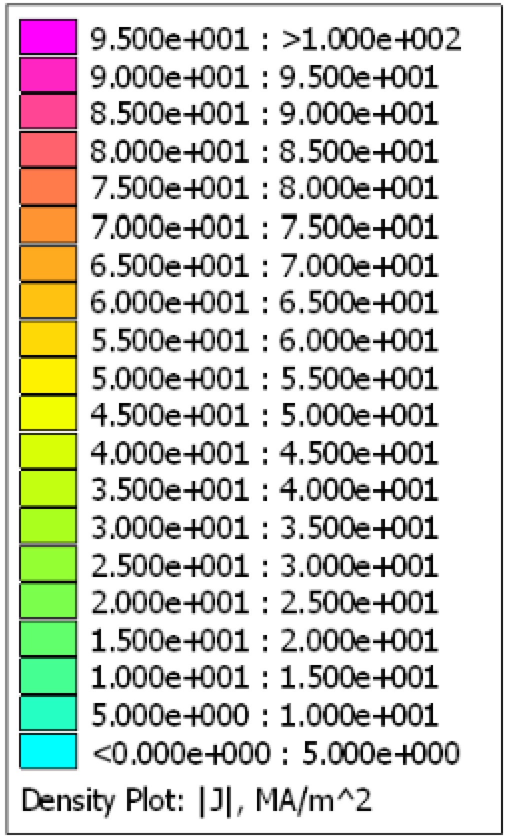
Flux density magnitude



🟪	9.500e-003 : >1.000e-002
🟪	9.000e-003 : 9.500e-003
🟥	8.500e-003 : 9.000e-003
🟥	8.000e-003 : 8.500e-003
🟧	7.500e-003 : 8.000e-003
🟧	7.000e-003 : 7.500e-003
🟧	6.500e-003 : 7.000e-003
🟨	6.000e-003 : 6.500e-003
🟨	5.500e-003 : 6.000e-003
🟨	5.001e-003 : 5.500e-003
🟨	4.501e-003 : 5.001e-003
🟩	4.001e-003 : 4.501e-003
🟩	3.501e-003 : 4.001e-003
🟩	3.001e-003 : 3.501e-003
🟩	2.501e-003 : 3.001e-003
🟩	2.001e-003 : 2.501e-003
🟩	1.501e-003 : 2.001e-003
🟩	1.001e-003 : 1.501e-003
🟩	5.010e-004 : 1.001e-003
🟦	<1.000e-006 : 5.010e-004

Density Plot: |B|, Tesla

Current density magnitude

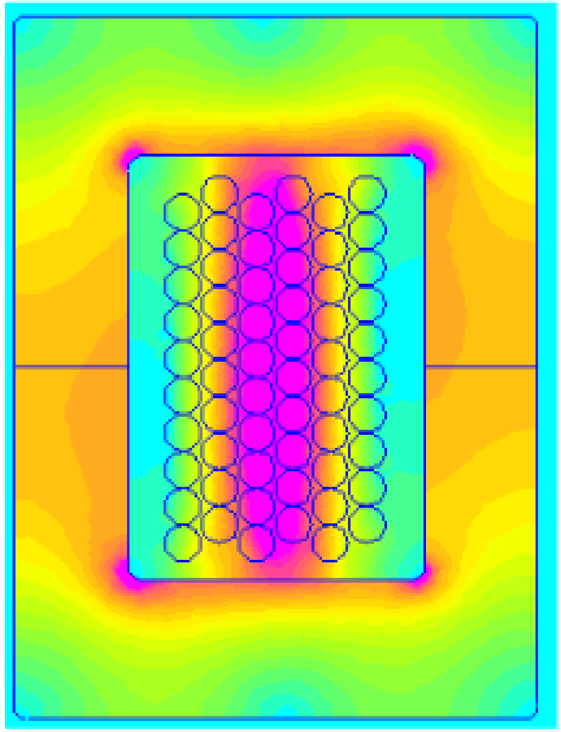


🟪	9.500e+001 : >1.000e+002
🟪	9.000e+001 : 9.500e+001
🟥	8.500e+001 : 9.000e+001
🟥	8.000e+001 : 8.500e+001
🟧	7.500e+001 : 8.000e+001
🟧	7.000e+001 : 7.500e+001
🟧	6.500e+001 : 7.000e+001
🟨	6.000e+001 : 6.500e+001
🟨	5.500e+001 : 6.000e+001
🟨	5.000e+001 : 5.500e+001
🟨	4.500e+001 : 5.000e+001
🟩	4.000e+001 : 4.500e+001
🟩	3.500e+001 : 4.000e+001
🟩	3.000e+001 : 3.500e+001
🟩	2.500e+001 : 3.000e+001
🟩	2.000e+001 : 2.500e+001
🟩	1.500e+001 : 2.000e+001
🟩	1.000e+001 : 1.500e+001
🟩	5.000e+000 : 1.000e+001
🟦	<0.000e+000 : 5.000e+000

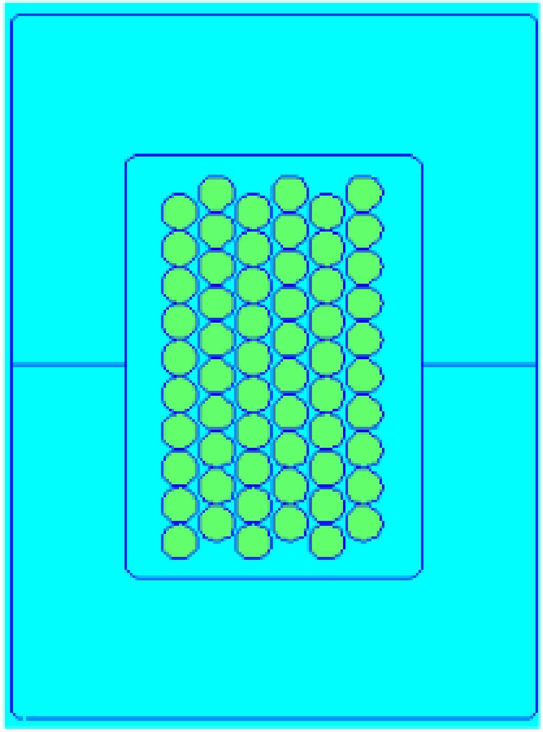
Density Plot: |J|, MA/m^2

Frequency: 1 kHz

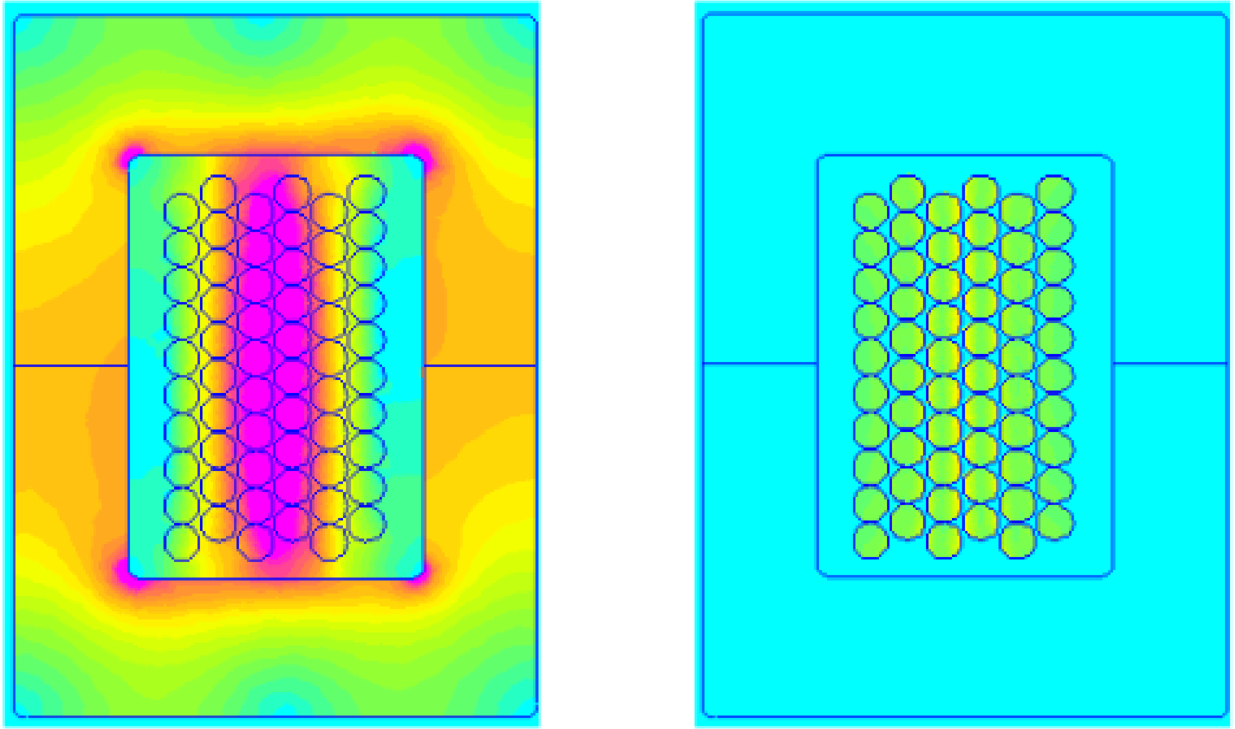
Flux density



Current Density



Frequency: 100 kHz



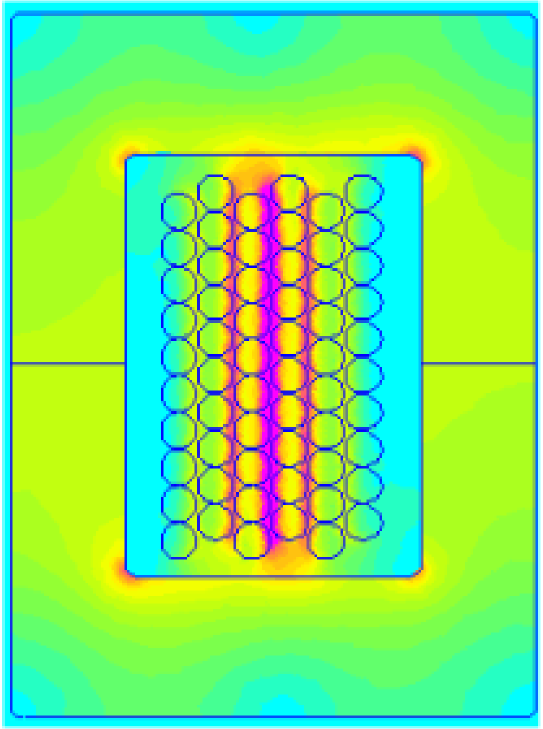
Flux density

Current Density

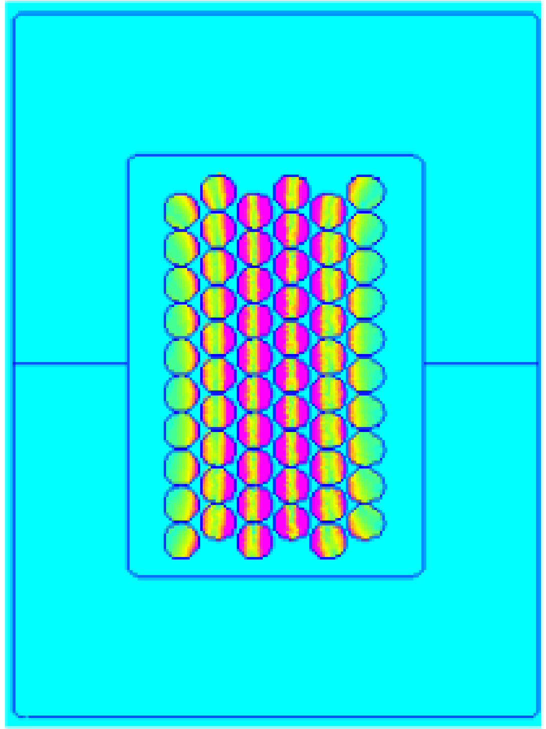
Total copper losses 1.8 larger than at 1 kHz

Frequency: 1 MHz

Flux density



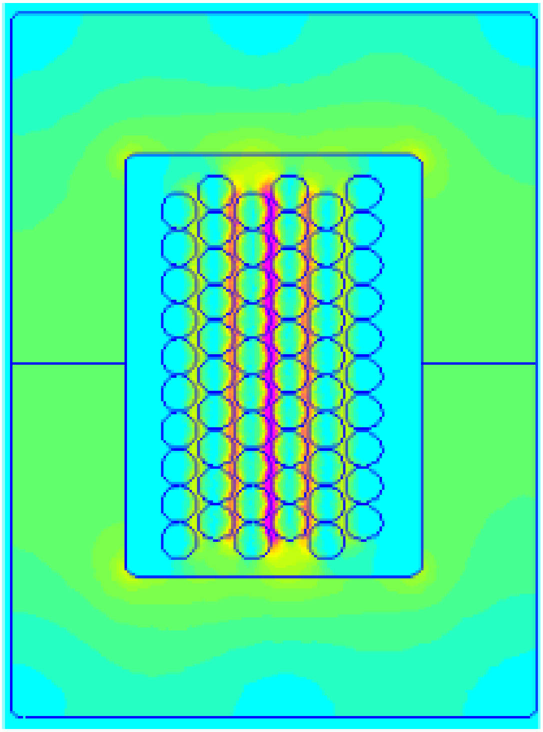
Current Density



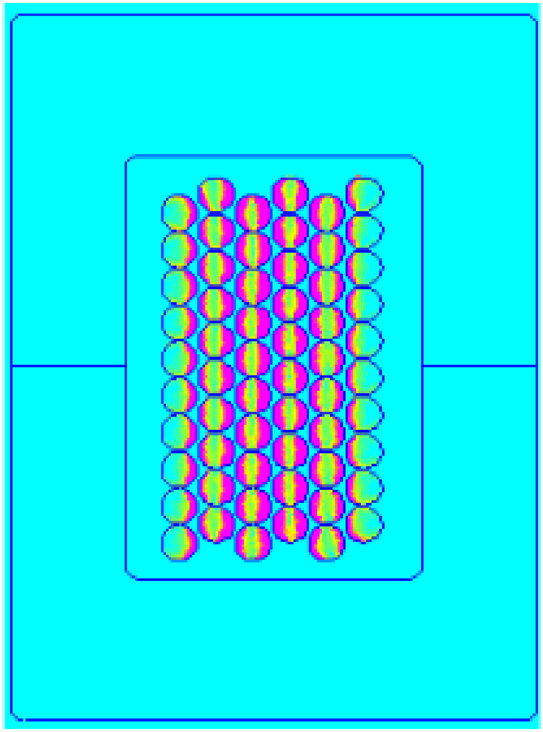
Total copper losses 20 times larger than at 1 kHz

Frequency: 10 MHz

Flux density



Current Density



Very significant proximity effect

Total copper losses = 65 times larger than at 1 KHz