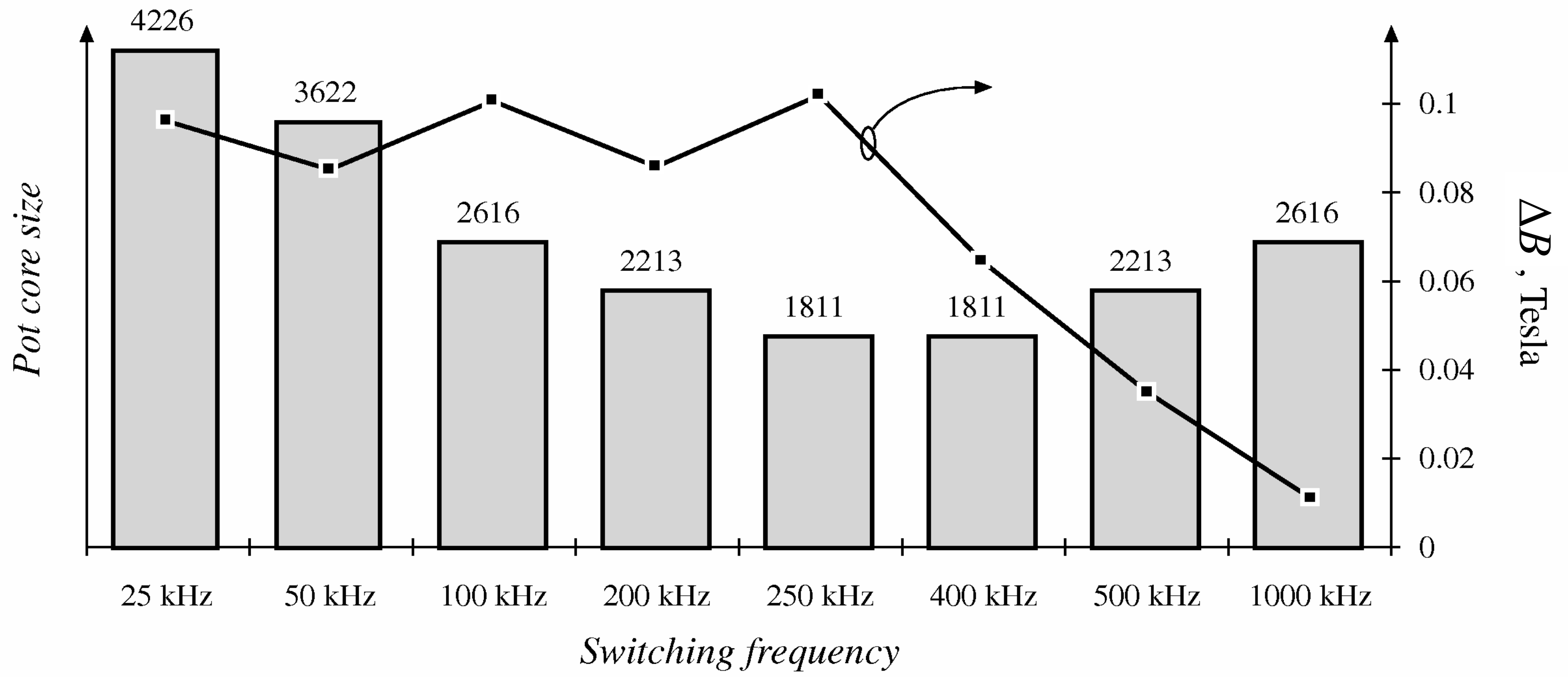
XF Size vs f_s

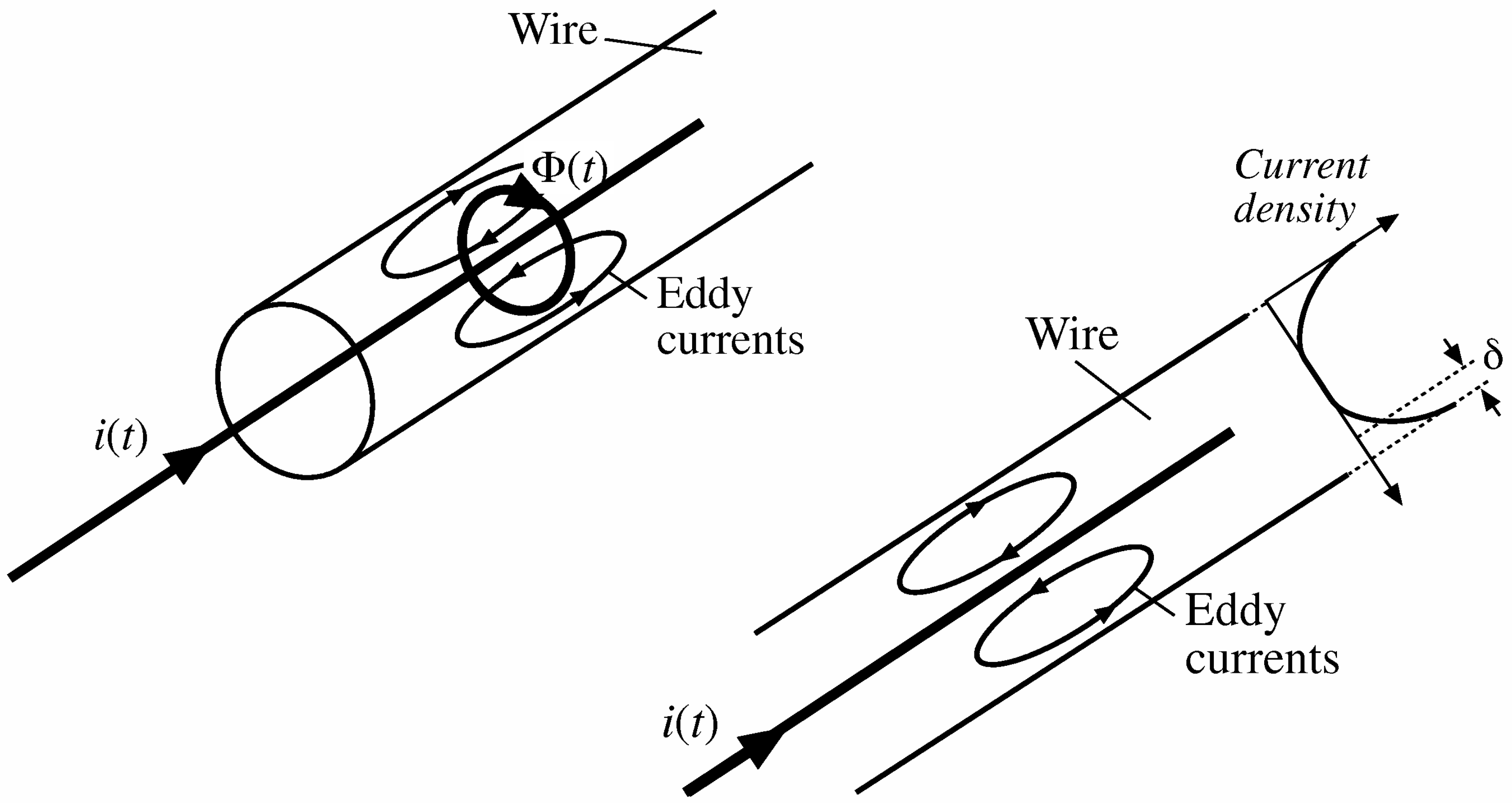


4226
3622
2616
2213
1811
1811
2213
2616
Pot core size
0.1
0.08
0.06
0.04
0.02
0
ΔB , Tesla
25 kHz
50 kHz
100 kHz
200 kHz
250 kHz
400 kHz
500 kHz
1000 kHz
Switching frequency

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

Skin Effect



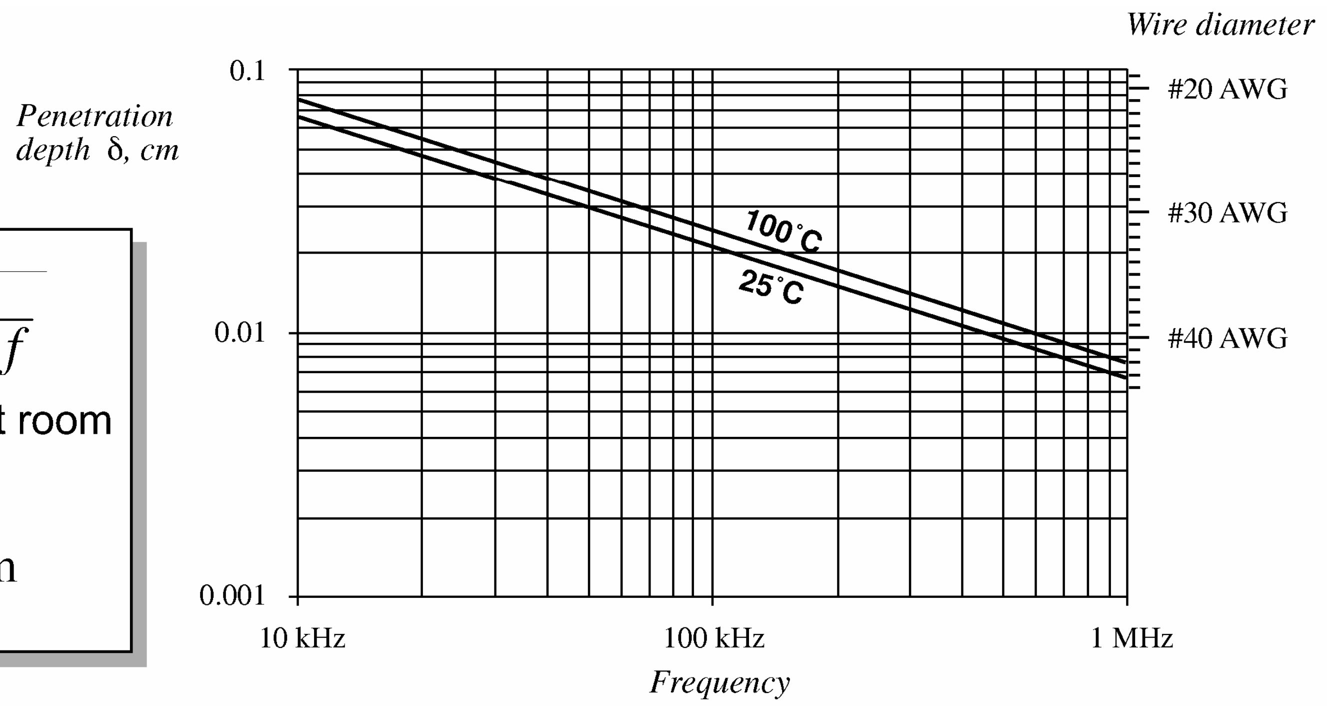
Wire
Φ(t)
Eddy
currents
i(t)
Current
density
Wire
δ
Eddy
currents
i(t)

Skin Depth

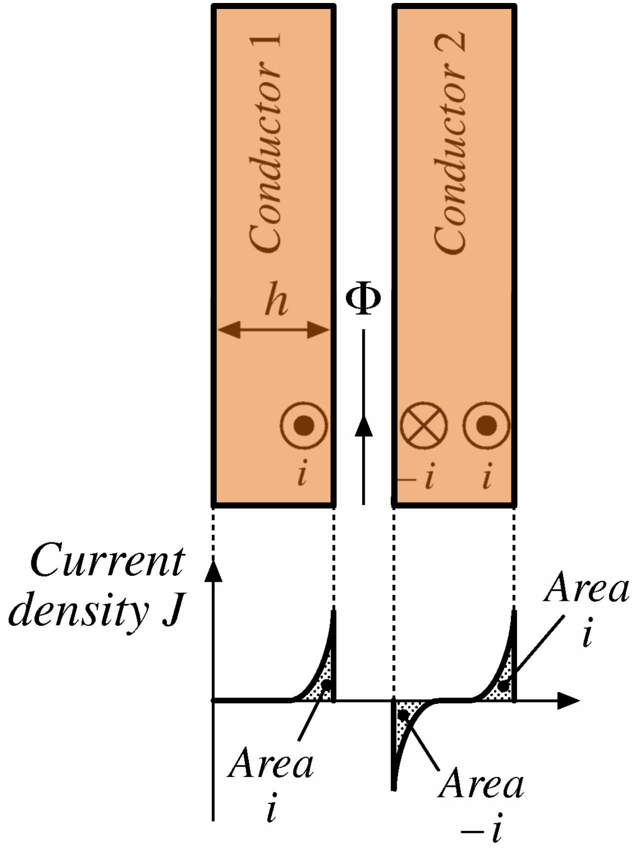
$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

For copper at room temperature:

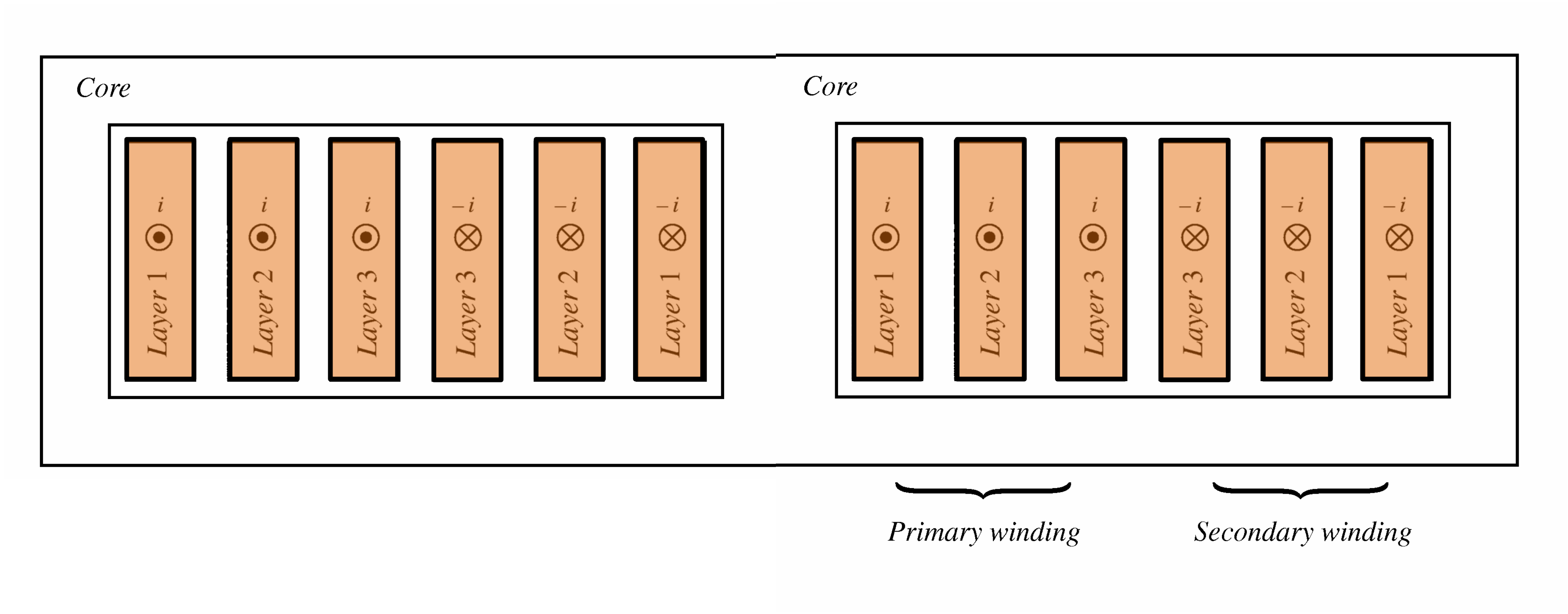
$$\delta = \frac{7.5}{\sqrt{f}} \text{ cm}$$



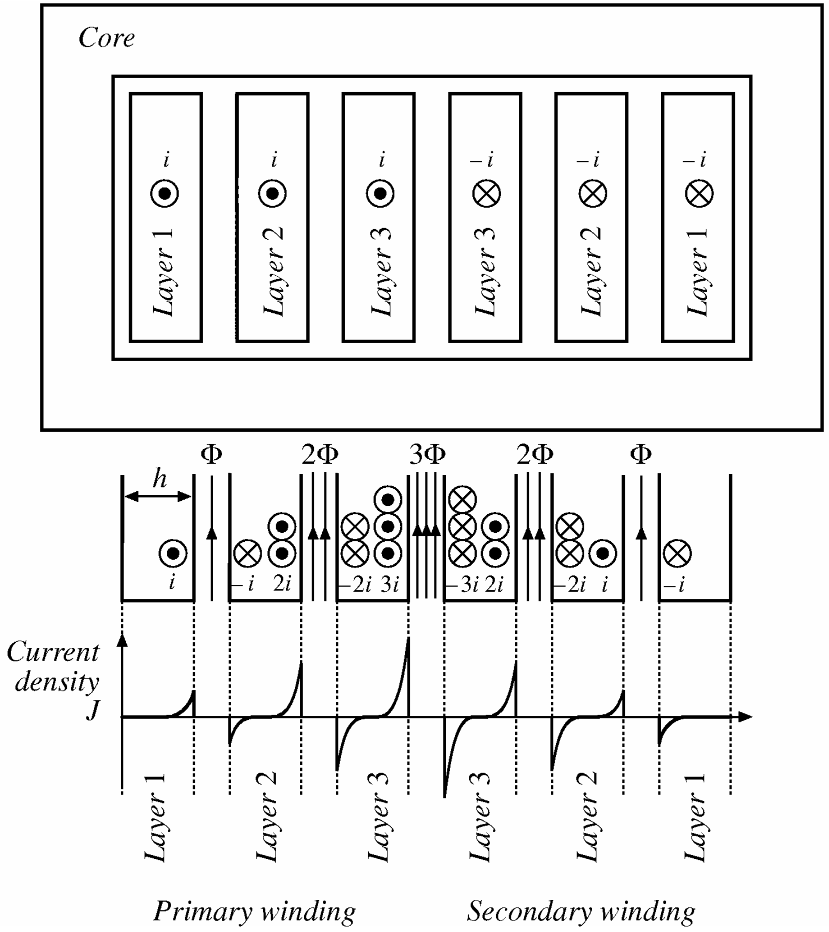
Proximity Effect



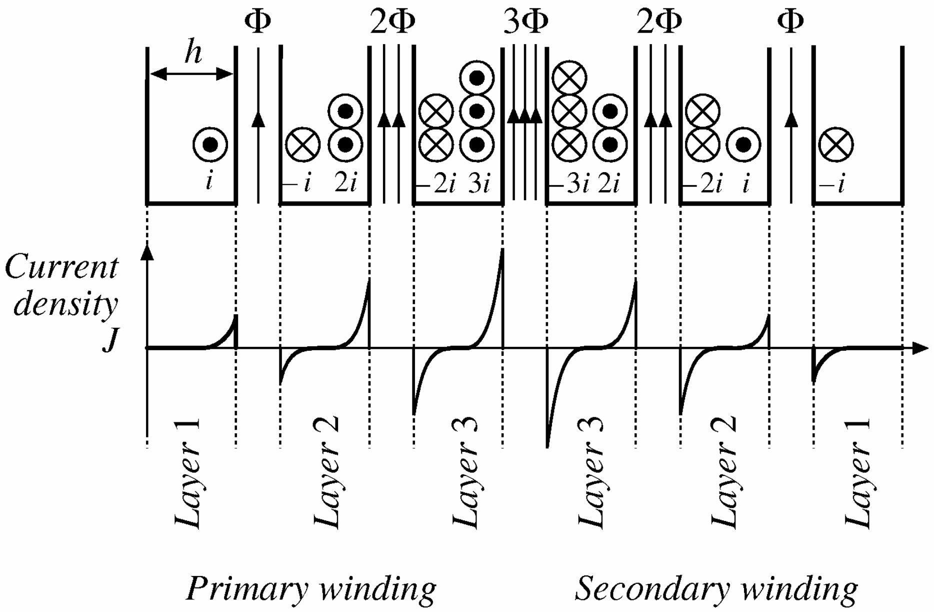
Two-Winding Transformer Example



Current Distribution



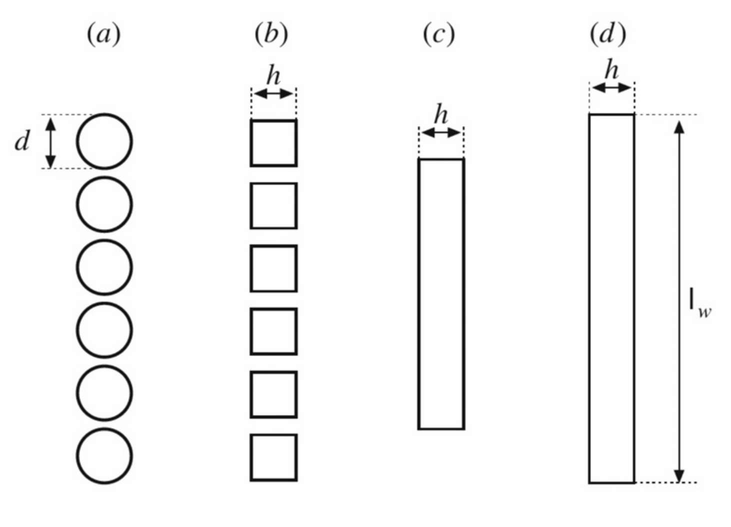
High Frequency Estimation



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



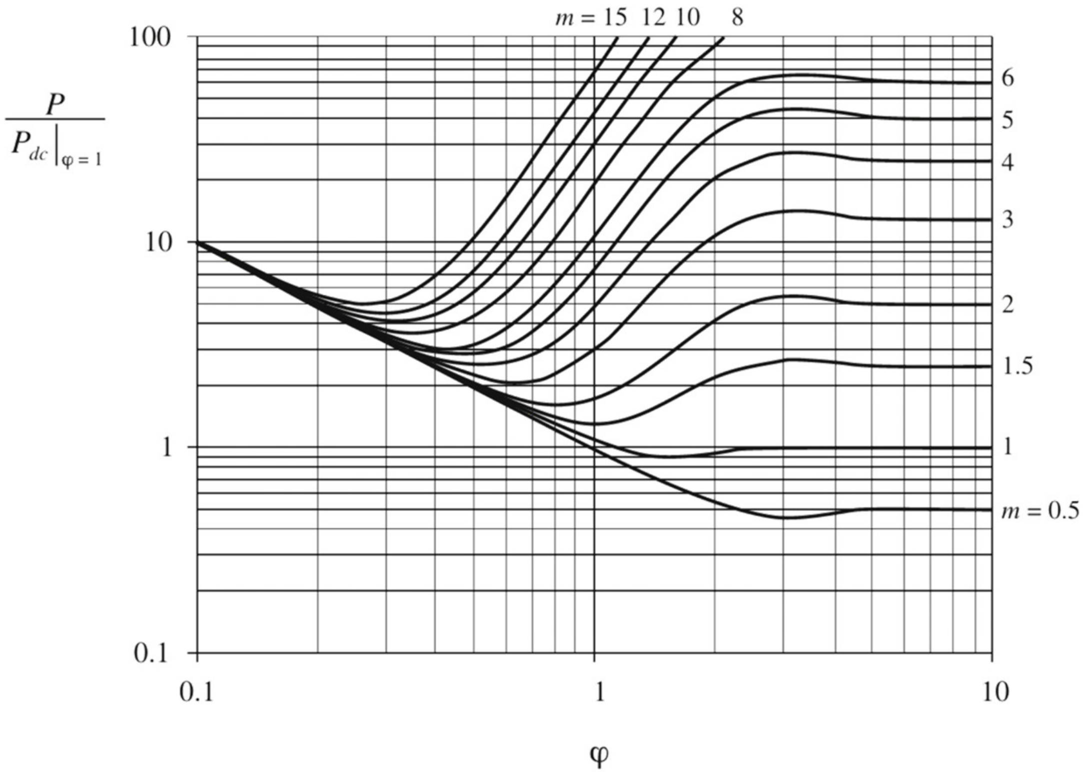
$$\eta = \sqrt{\frac{\pi}{4}}\, d\, \frac{n_\ell}{\ell_w} \qquad \delta' = \frac{\delta}{\sqrt{\eta}}$$

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

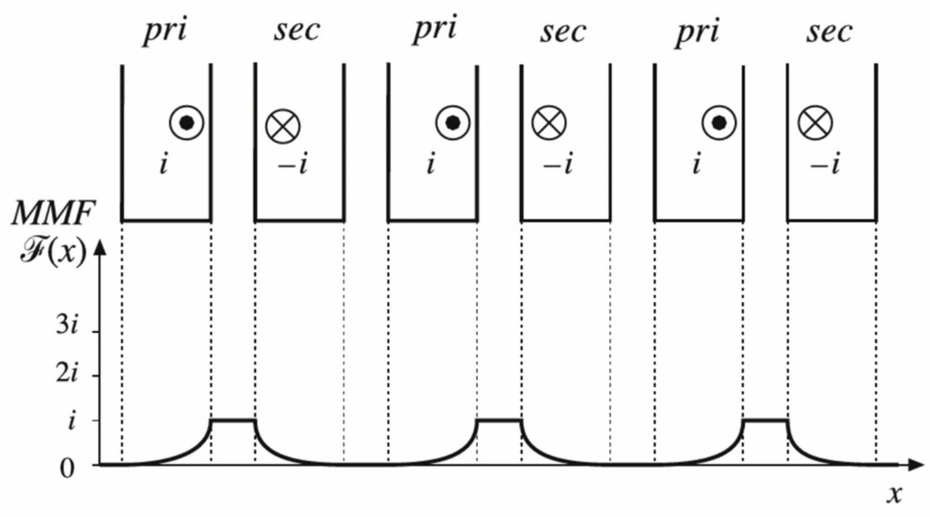
$$P = R_{dc}\frac{\varphi}{n_\ell^2}\left[\left(\mathscr{F}^2(h)+\mathscr{F}^2(0)\right)G_1(\varphi) - 4\mathscr{F}(h)\mathscr{F}(0)G_2(\varphi)\right]$$

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

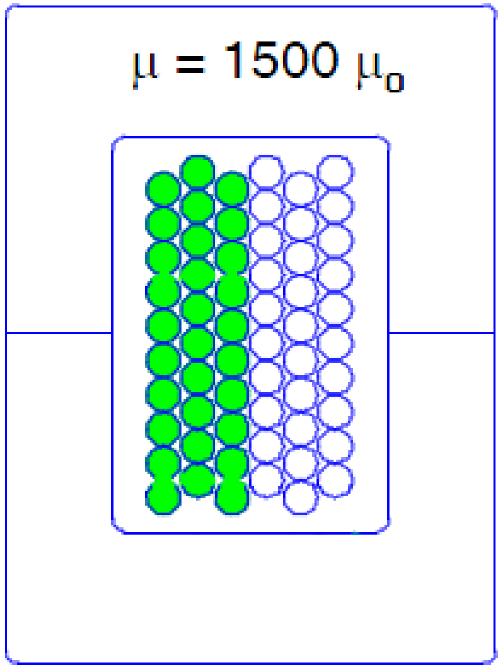
$$G_2(\varphi) = \frac{\sinh(\varphi)\cos(\varphi)+\cosh(\varphi)\sin(\varphi)}{\cosh(2\varphi)-\cos(2\varphi)}$$



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

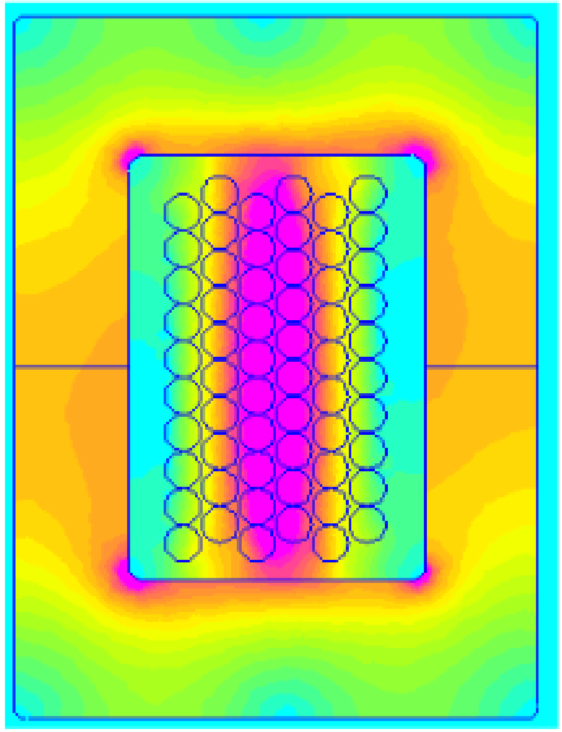
Current density magnitude

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

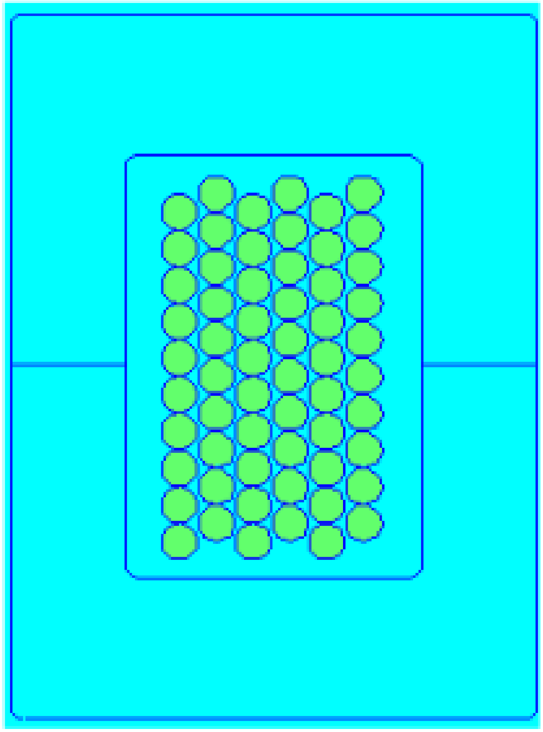
Density Plot: |J|, MA/m^2

Frequency: 1 kHz

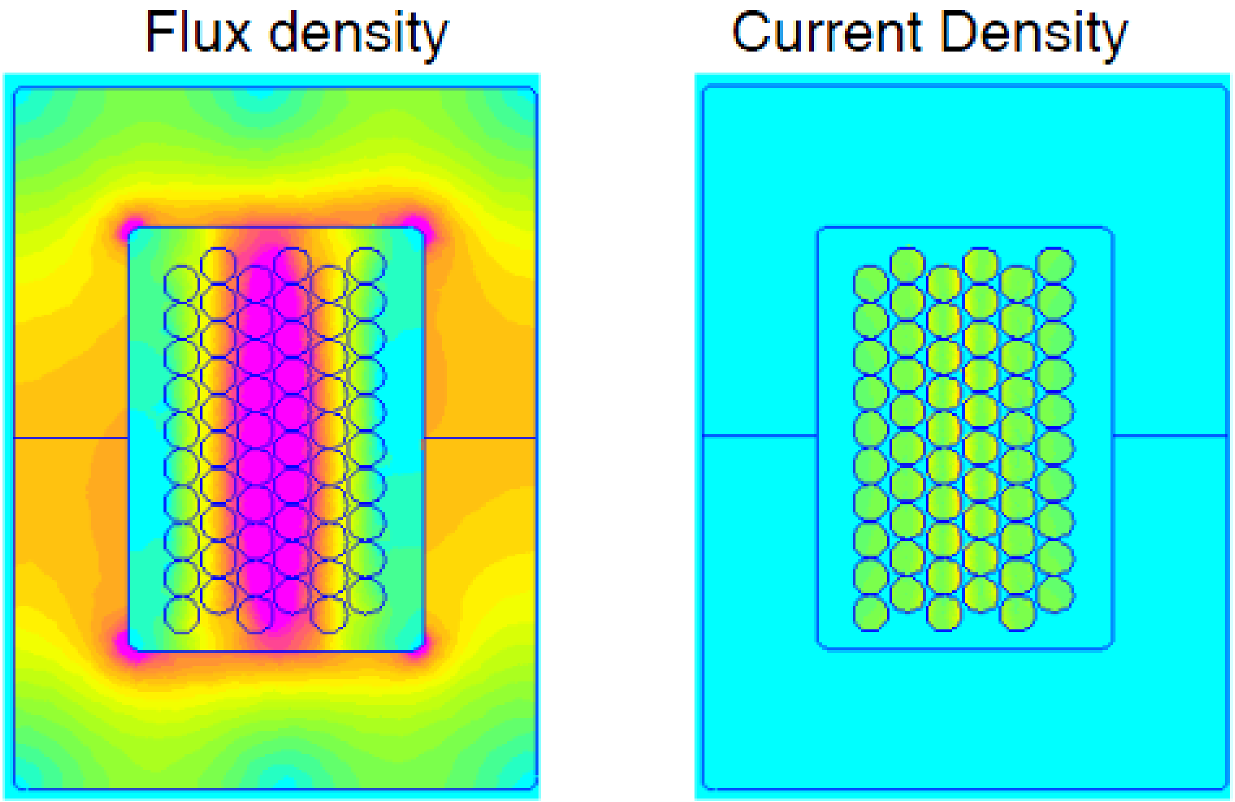
Flux density



Current Density

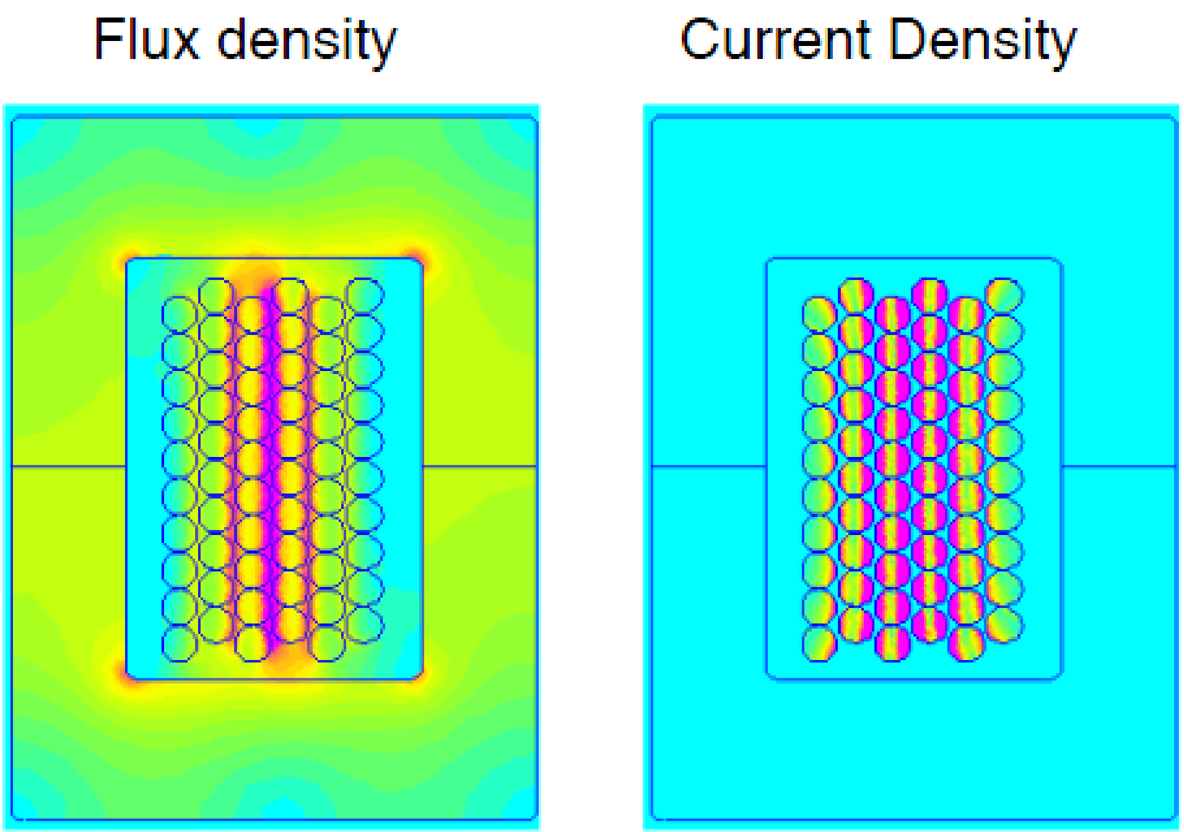


Frequency: 100 kHz



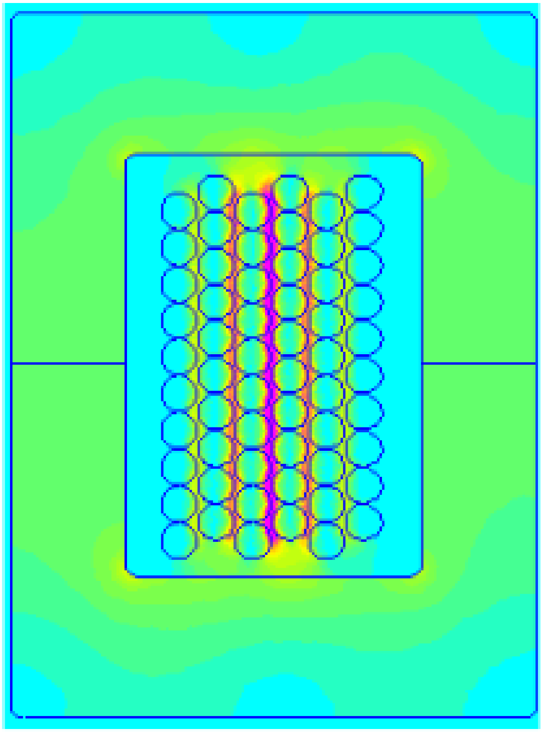
Total copper losses 1.8 larger than at 1 kHz

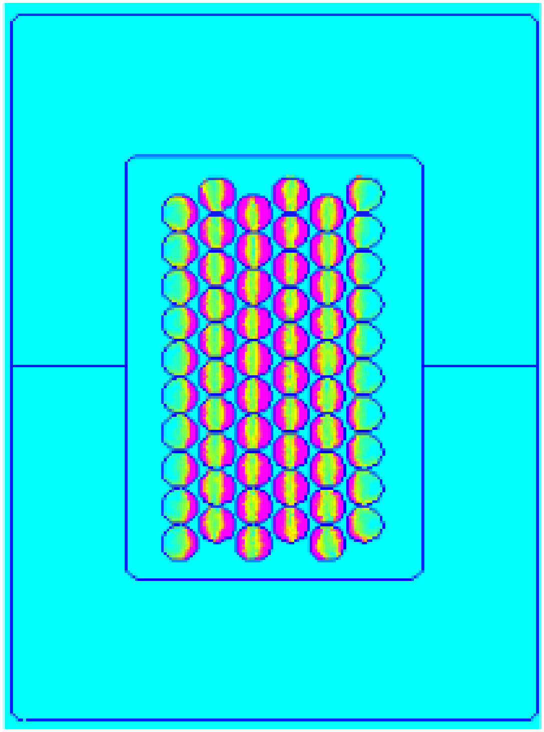
Frequency: 1 MHz



Total copper losses 20 times larger than at 1 kHz

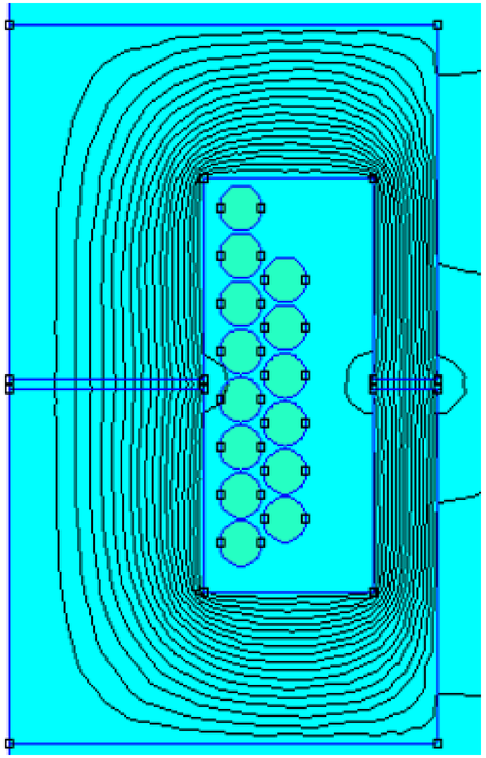
Frequency: 10 MHz



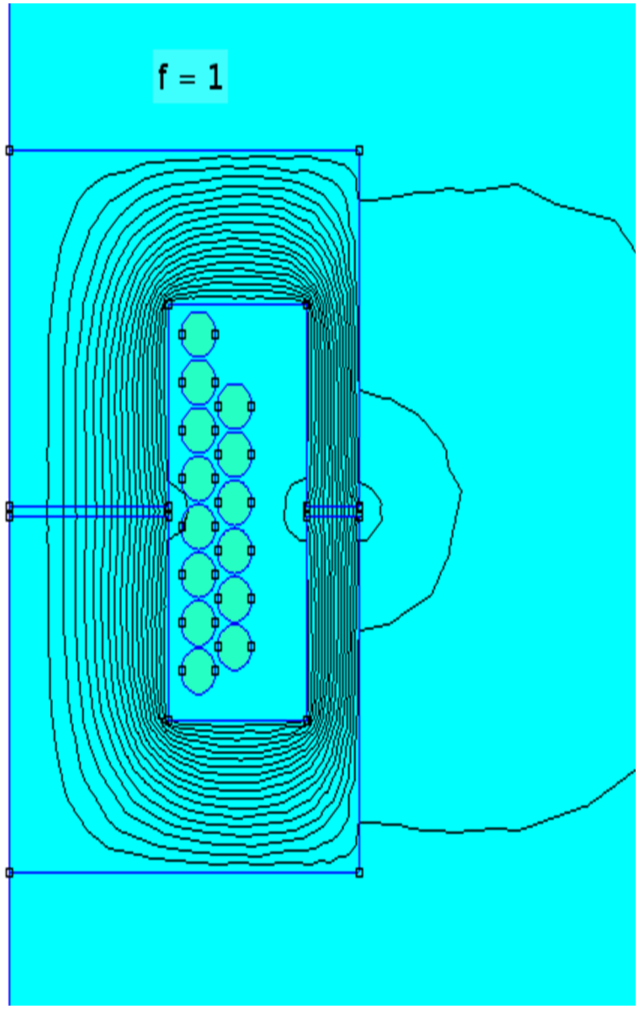


Very significant proximity effect
Total copper losses = 65 times larger than at 1 KHz

Fringing Flux



Fringing Flux Simulation



Litz Wire