Power Electronics Notes 30D
Magnetic FEA Examples

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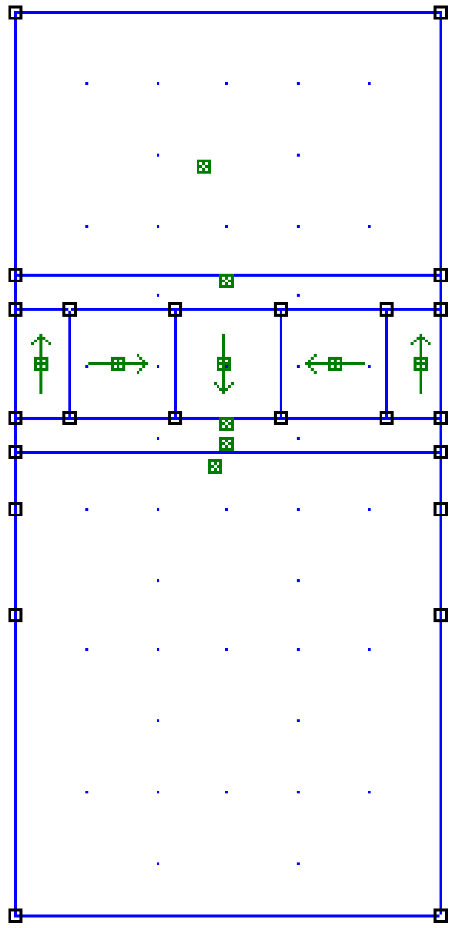
FEA (Finite Element Analysis)

- Powerful technique for analyzing 2D and 3D structures
- 2D is simpler, but is often an approximation
- 3D takes a lot longer to setup and run
- 2D types:
  - Planar (infinitely long into the page)
  - Axisymmetric: symmetric about the vertical axis
- We’ll show some examples using FEMM (Finite Element Method Magnetics) a freeware 2D solver

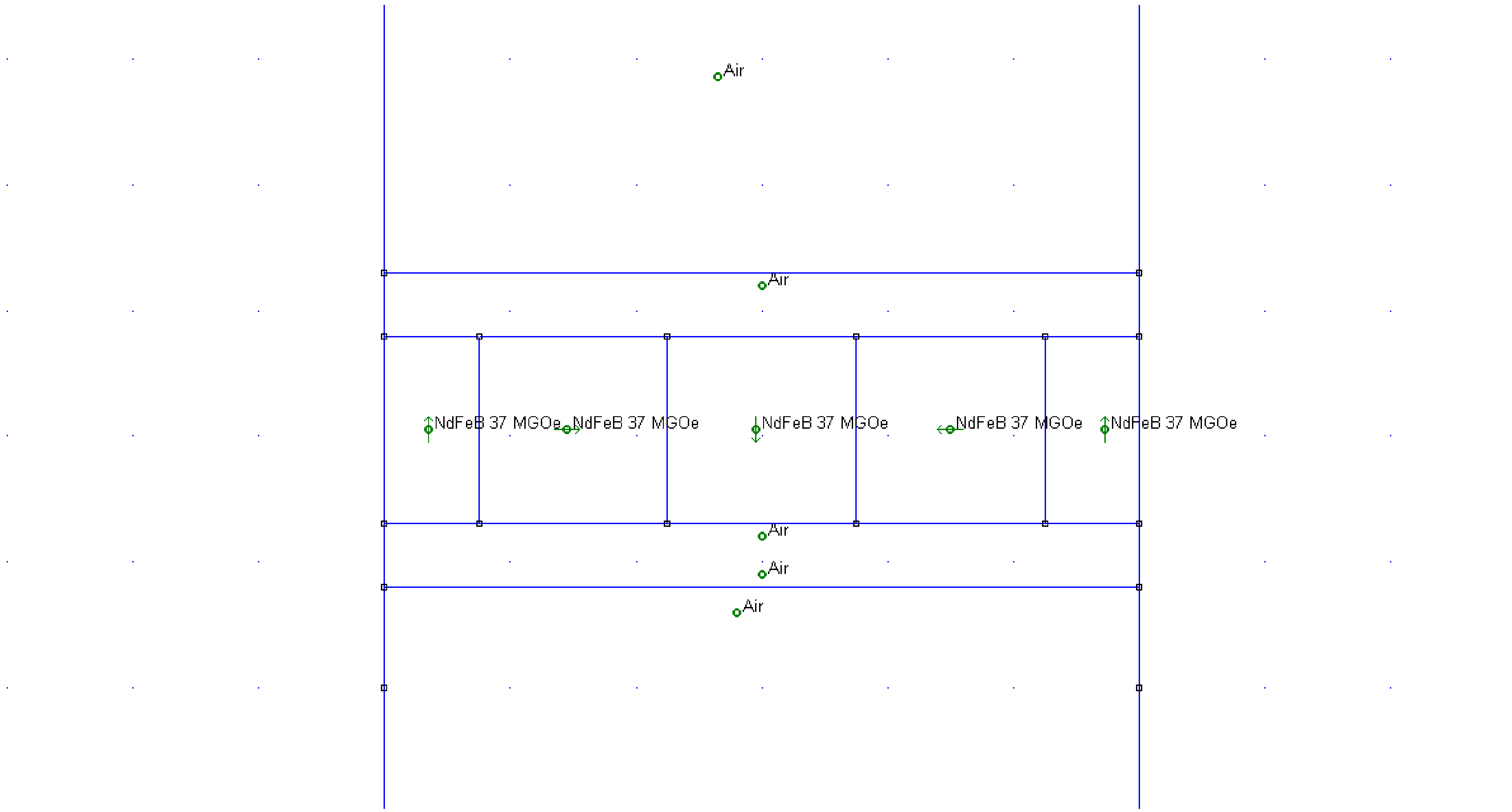
Example 1: Halbach Array

- Interesting permanent magnet array which maximizes the field on one side of the array, and minimizes the field on the weak side



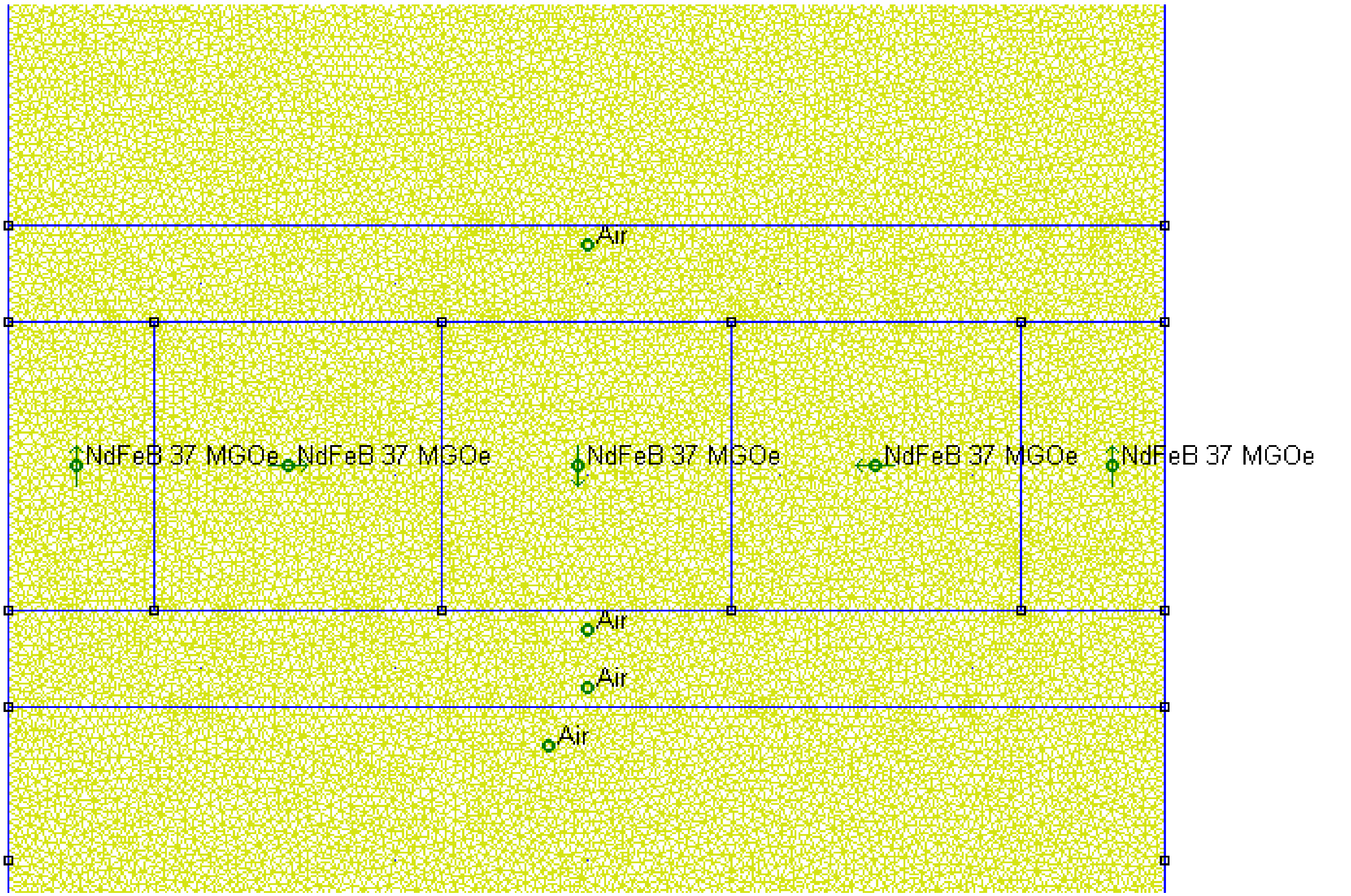
Example 1: Halbach Array

- Closeup
- Note we're exploiting symmetry



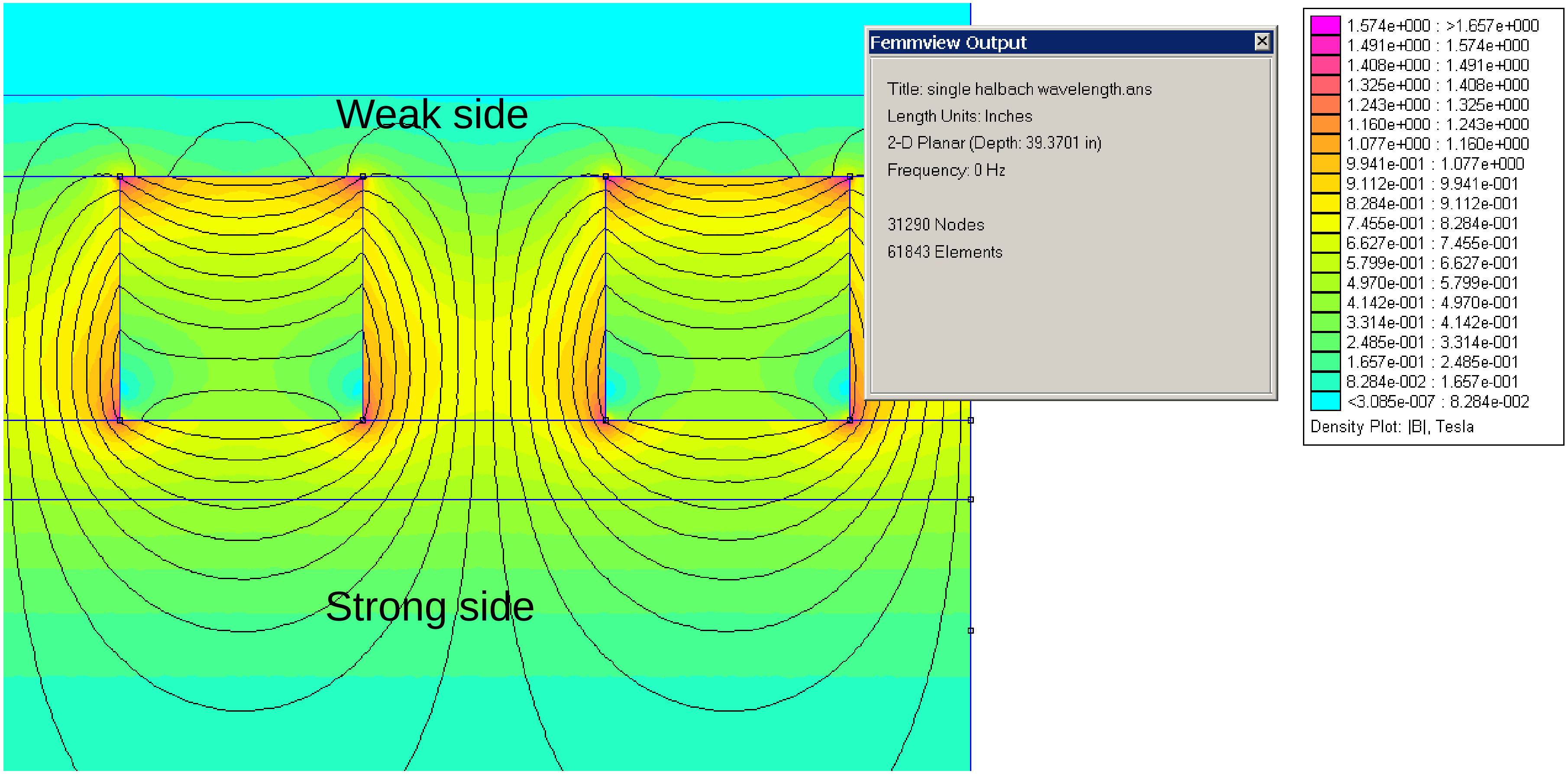
Example 1: Halbach Array

- Mesh



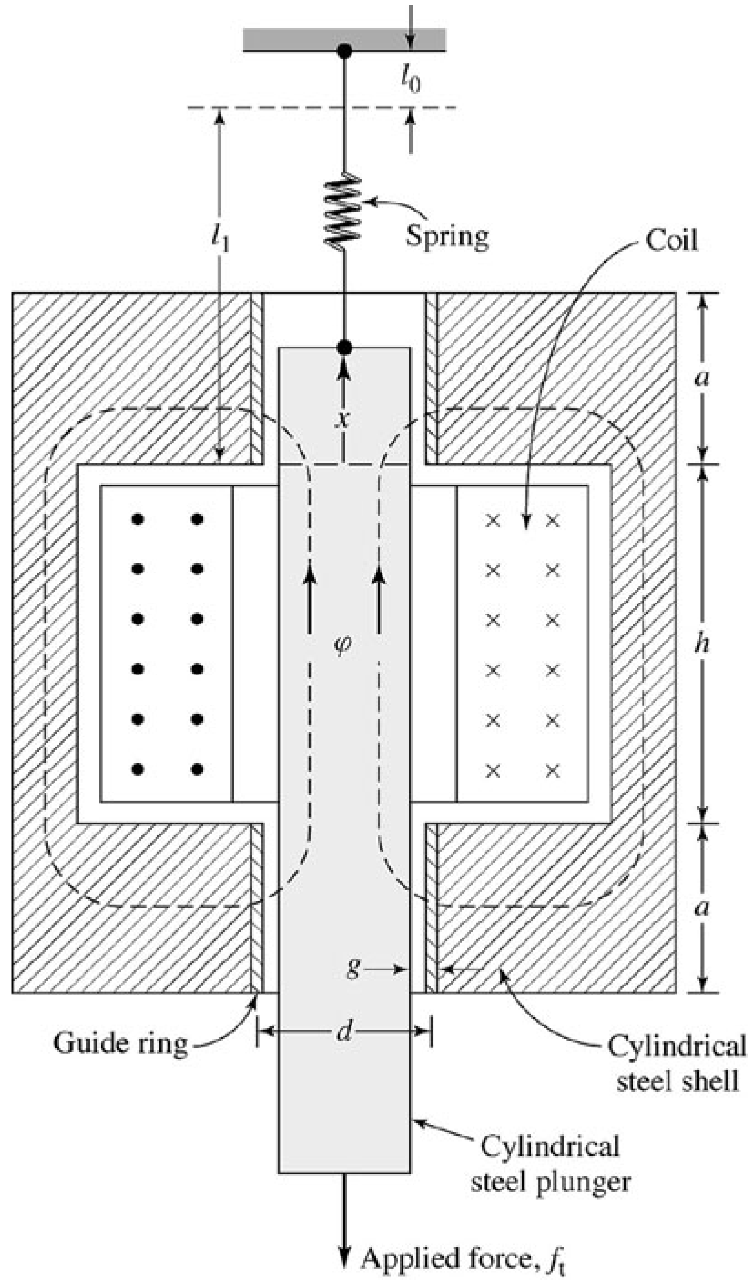
Example 1: Halbach Array

- Solution



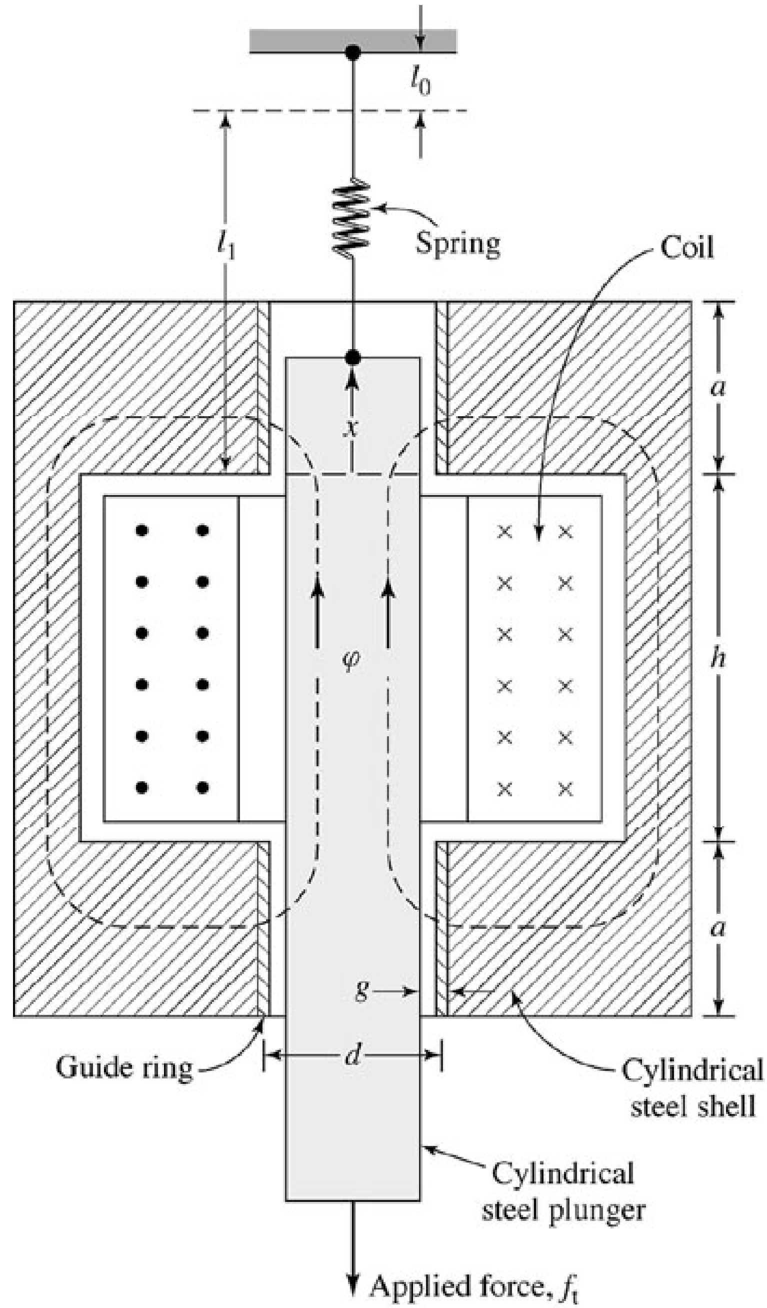
Example 2: Solenoid

- Follows Example 3.10 in *Fitzgerald* (pp. 153-155)
- Note that dimension x is the distance from the top of the plunger to the top of the coil
- As this dimension x varies, axial force on the plunger varies as well



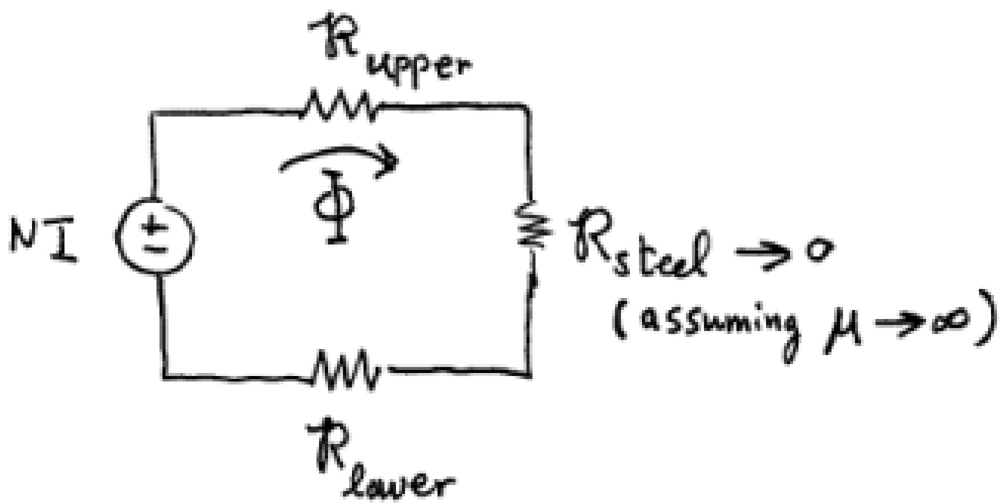
Example 2: Strategy

- Use reluctance model
- Find flux Φ
- From flux, find flux linkage λ
- From flux linkage, find inductance as a function of plunger position x
- From L(x), find force

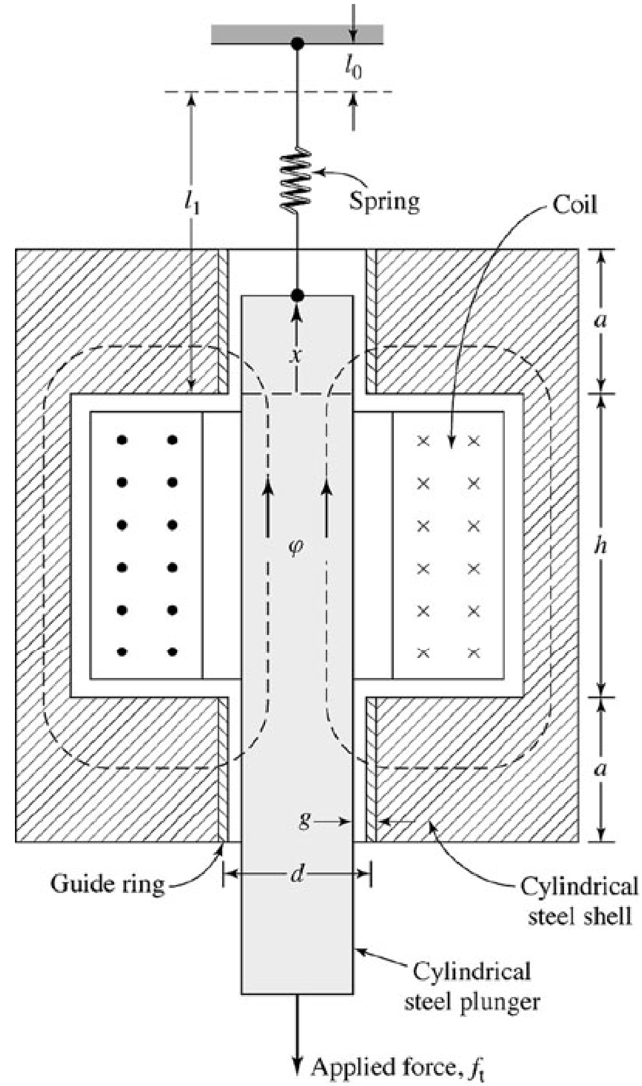


Example 2: Reluctance Model

• Reluctance of steel is very small if the steel doesn't saturate

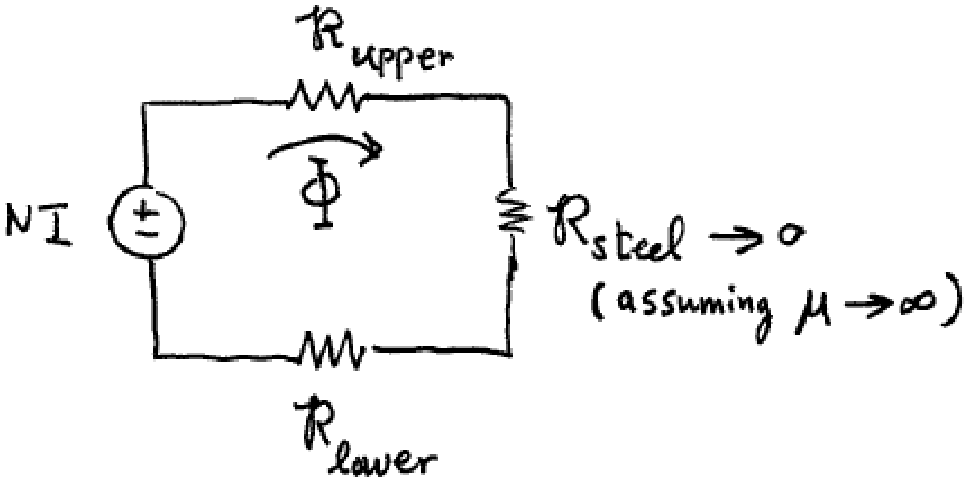


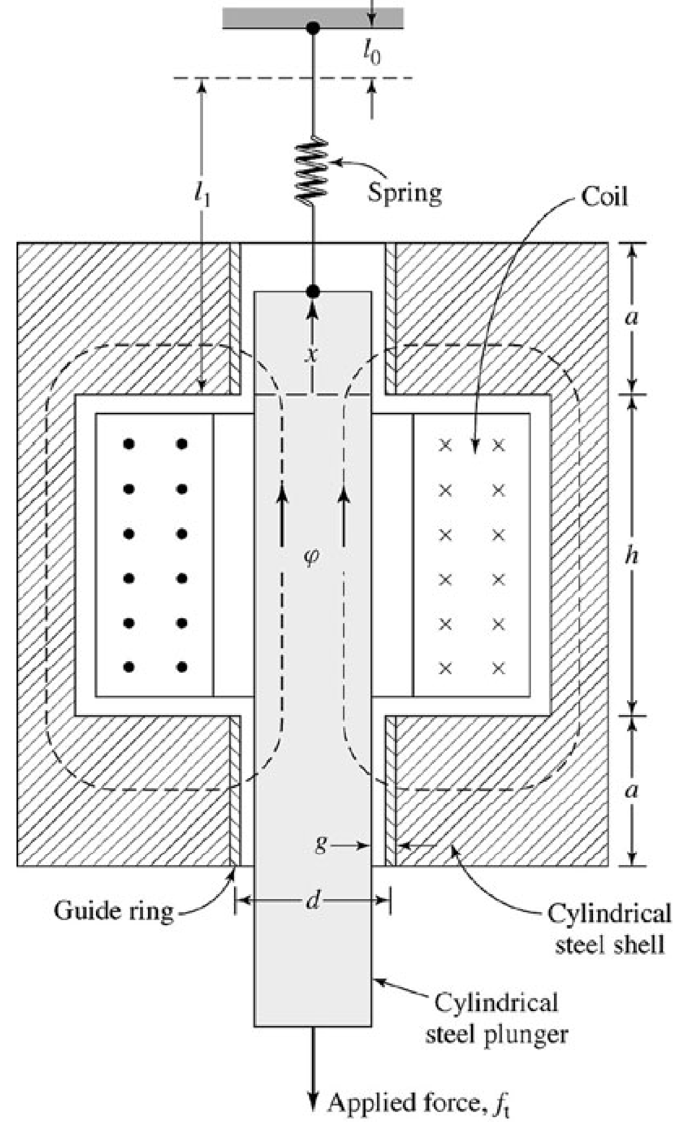
$$\Re = \frac{Path\ length\ in\ direction\ of\ field}{\mu\left(Area\ of\ flux\ path\ perpendicular\ to\ field\right)}$$



Example 2: Reluctance Model

- Different reluctance for 2 gaps

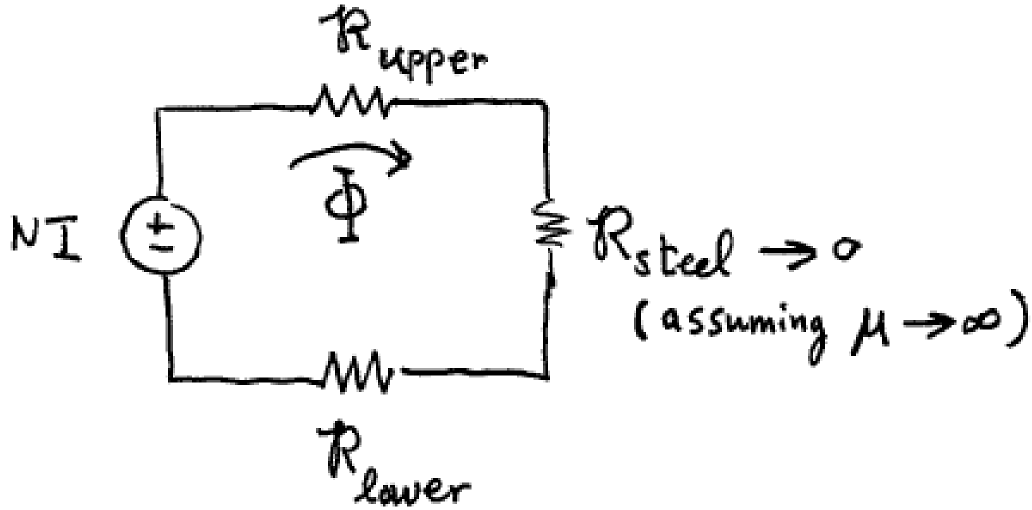




Upper gap: $\Re_{upper} = \dfrac{g}{\mu_o(\pi d)x}$

Lower gap: $\Re_{lower} = \dfrac{g}{\mu_o(\pi d)a}$

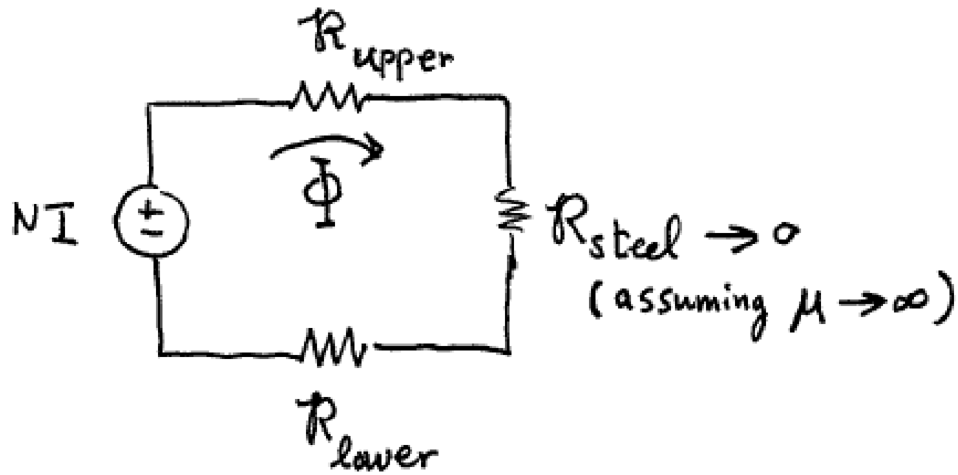
Example 2: Flux



Flux:

$$\Phi = \frac{NI}{\Re_{upper} + \Re_{lower}}$$

Example 2: Flux Linkage



Flux linkage:

$$\lambda = N\Phi = \frac{N^2 I}{\Re_{upper} + \Re_{lower}}$$

Example 2: Inductance

Inductance:

$$L = \frac{\lambda}{I} = \frac{N^2}{\Re_{upper} + \Re_{lower}}$$

$$\Re_{upper} + \Re_{lower} = \frac{g}{\mu_o \pi dx} + \frac{g}{\mu_o \pi da} = \left(\frac{g}{\mu_o \pi da}\right)\left(\frac{a+x}{x}\right)$$

$$L(x) = \left(\frac{\mu_o \pi da N^2}{g}\right)\left(\frac{x}{a+x}\right) = L_o\left(\frac{x}{a+x}\right)$$

Example 2: Find Force

Once you know the inductance, calculating the force is easy:

$$f_x = \frac{I^2}{2}\frac{dL(x)}{dx}$$

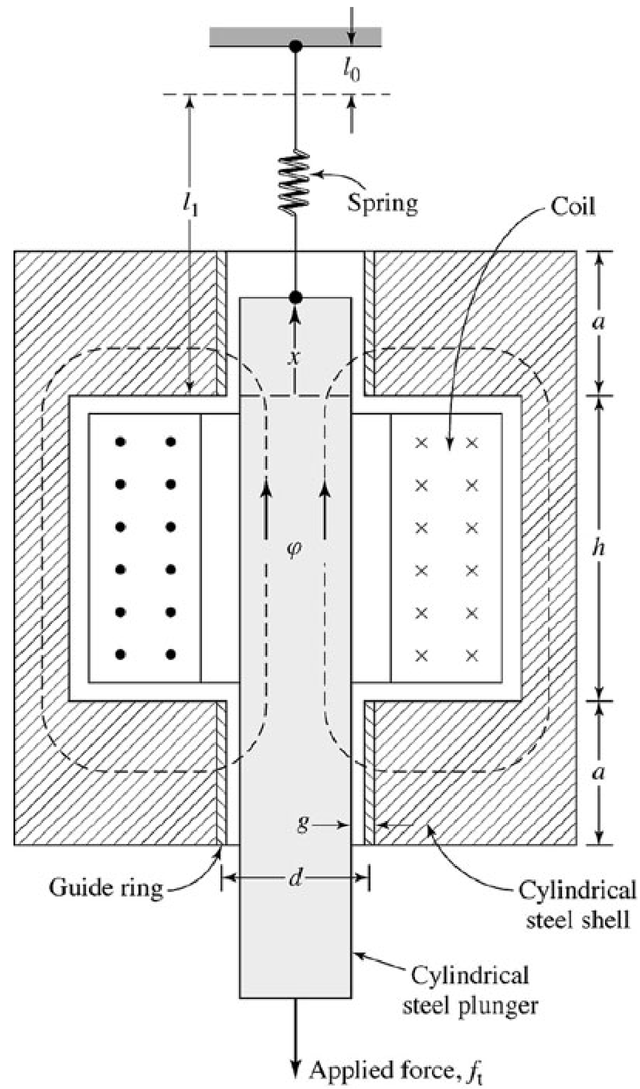
$$= \frac{I^2}{2} L_o \frac{d}{dx}\left(\frac{x}{a+x}\right)$$

$$= \frac{I^2}{2} L_o \frac{a}{(a+x)^2}$$

Example 2: Solenoid Design

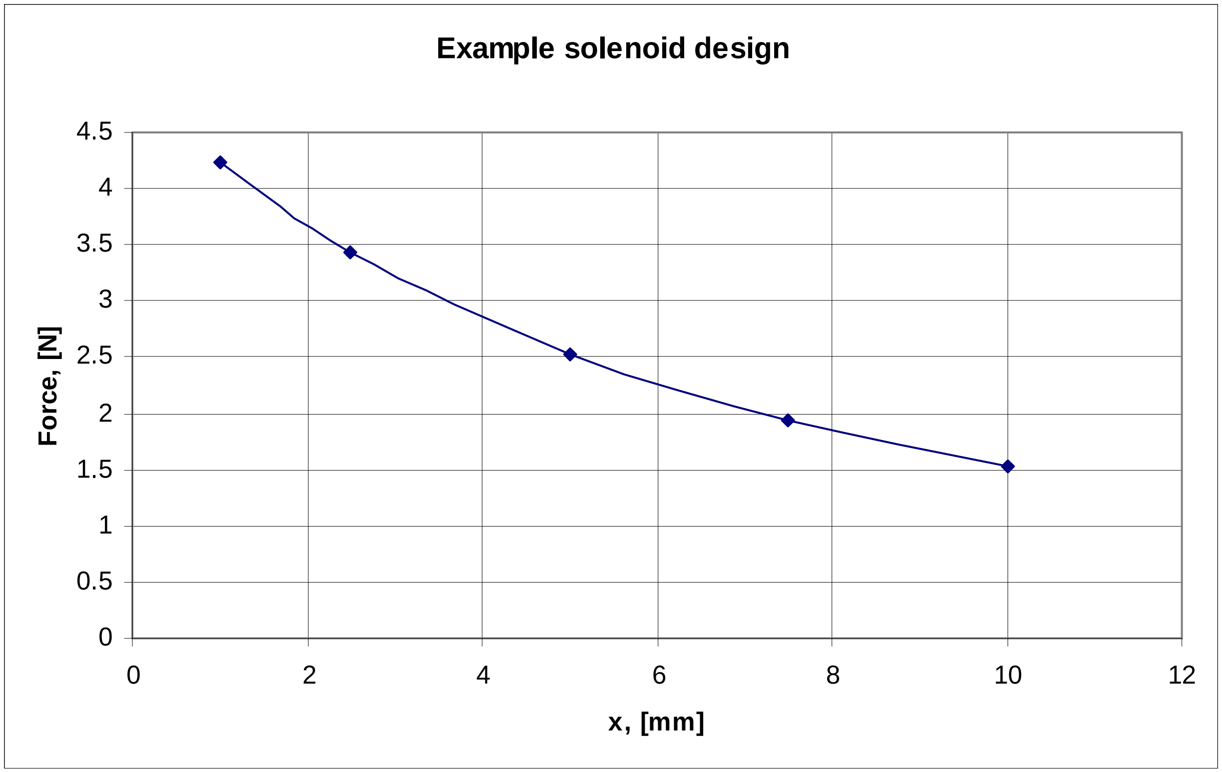
Dimensions of solenoid design example

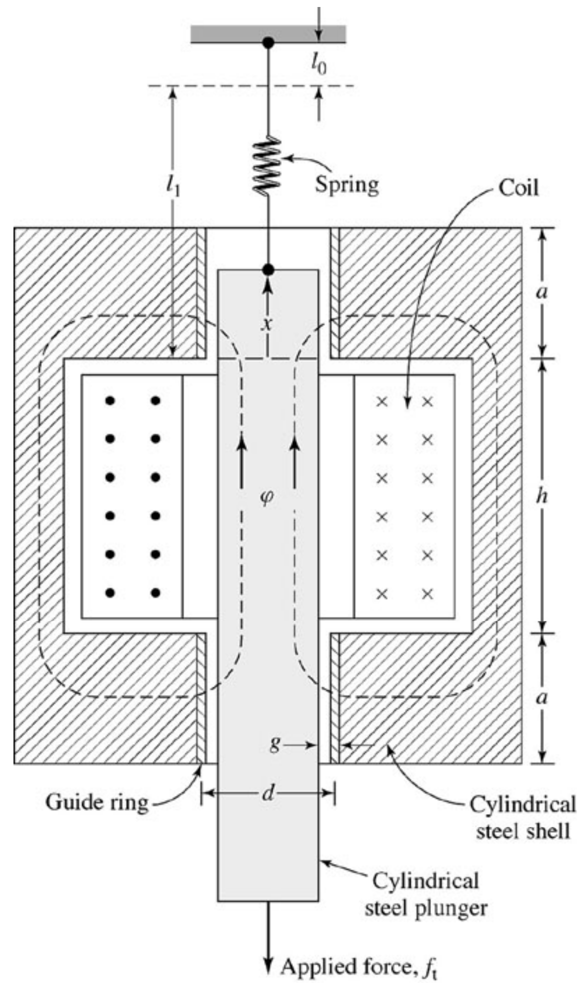
Item	Description	Dimension
a	Height of solenoid backiron arm	12.5 mm
h	Height of solenoid center backiron arm	10 mm
d	Radius to backiron	10 mm
g	Airgap	0.5 mm
r_{coil}	Coil mean radius	7.75 mm
x	Variable offset of plunger top from top of coil	5 mm (variable)
$r_{plunger}$	Plunger radius	9.5 mm



Example 2: Design Example --- Analytic Result

- For NI = 354 A-turns (DC)
- Coil power dissipation ~ 3.5 Watts

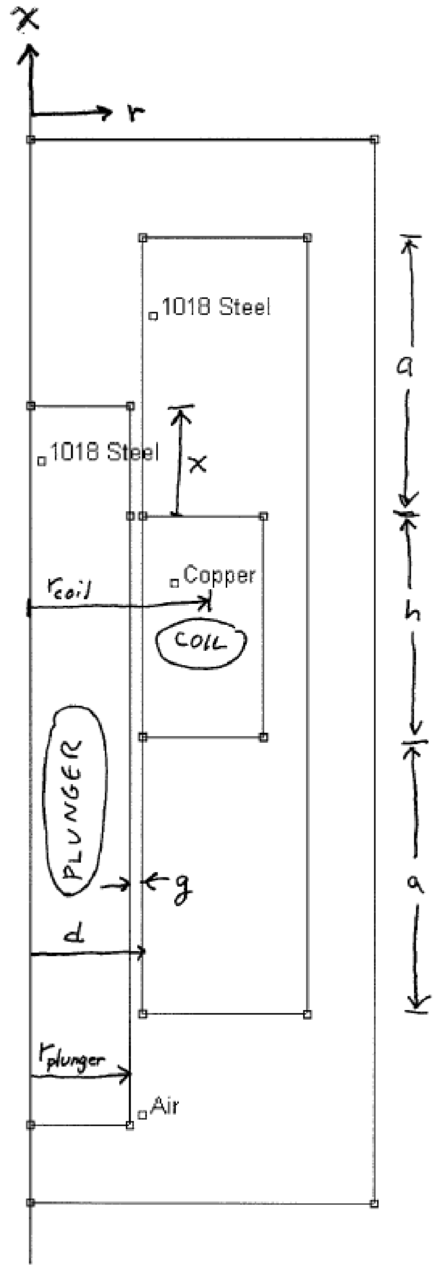




Example 2: Simulation

- "Trust, but verify" (R. Reagan, c. 1985)

Example 2: Simulation --- 2D Axisymmetric FEA



DIMENSIONS

$a = 12.5\ mm$

$h = 10\ mm$

$d = 10\ mm$

$g = 0.5\ mm$

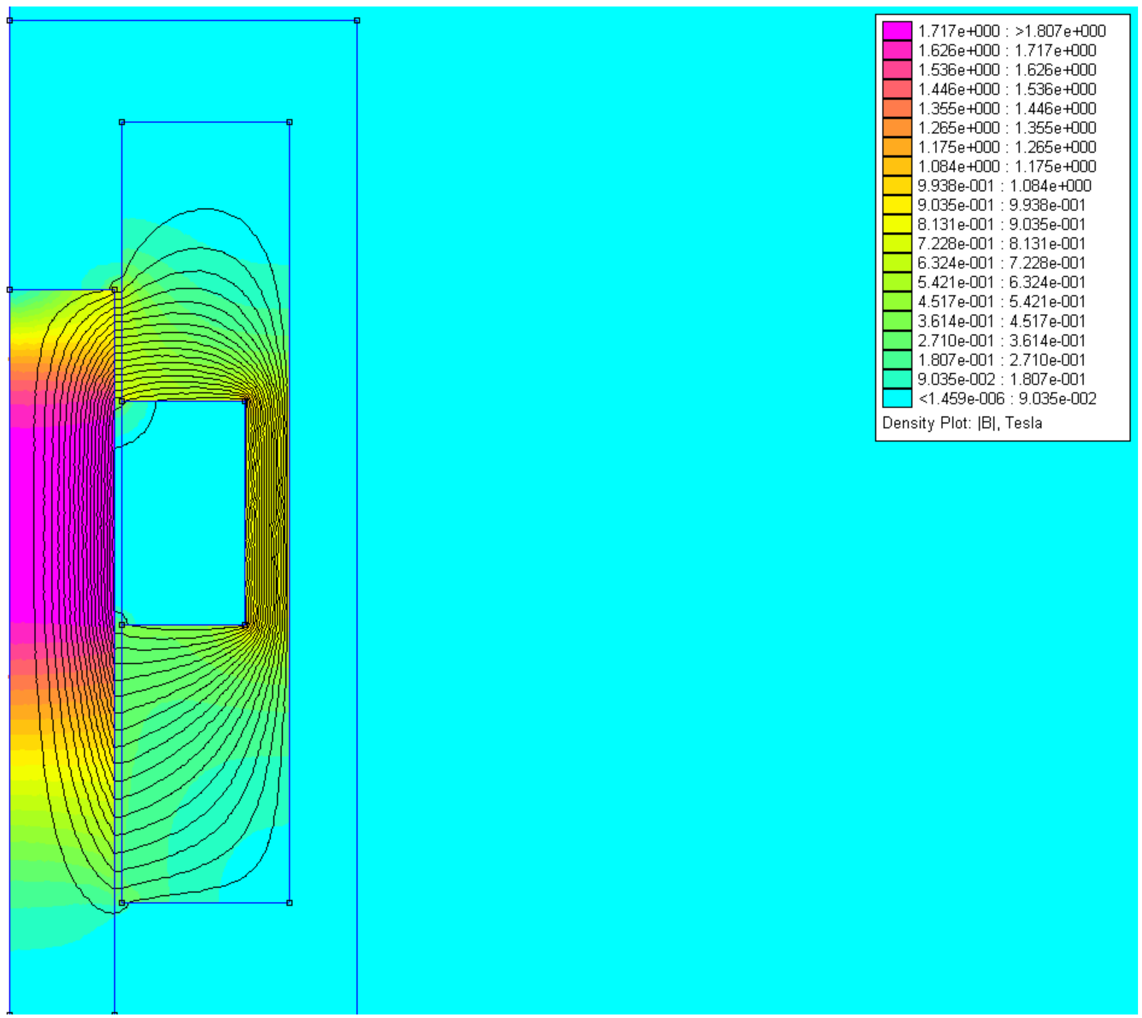
$r_{coil} = 7.75\ mm$

$x = 5\ mm$

$r_{plunger} = 4.5\ mm$

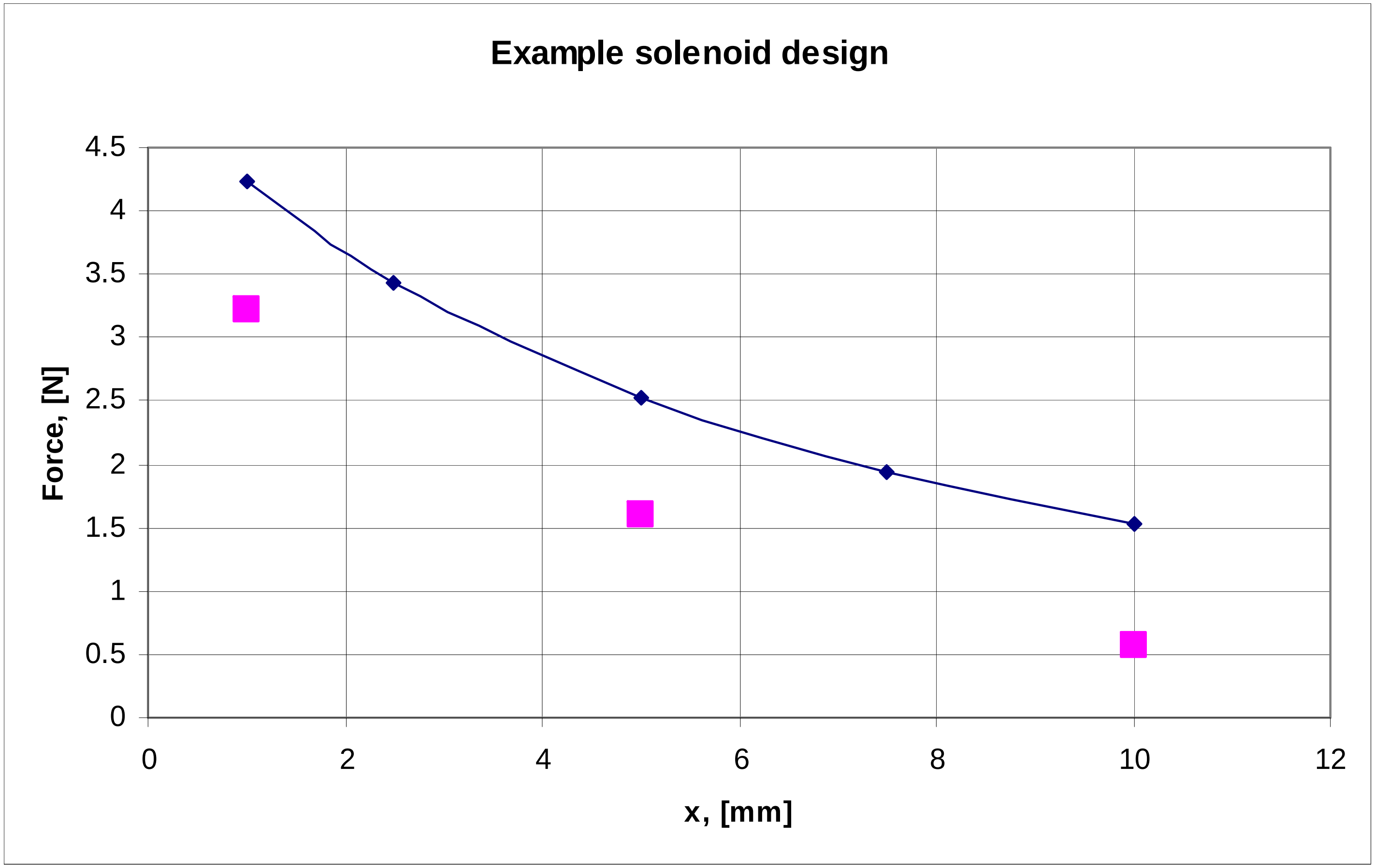
Example 2: Simulation --- 2D Axisymmetric FEA

- Shown for x = 5 mm
- FEA shows f_x = 1.6 Newtons, P_{diss} = 3.5 Watts



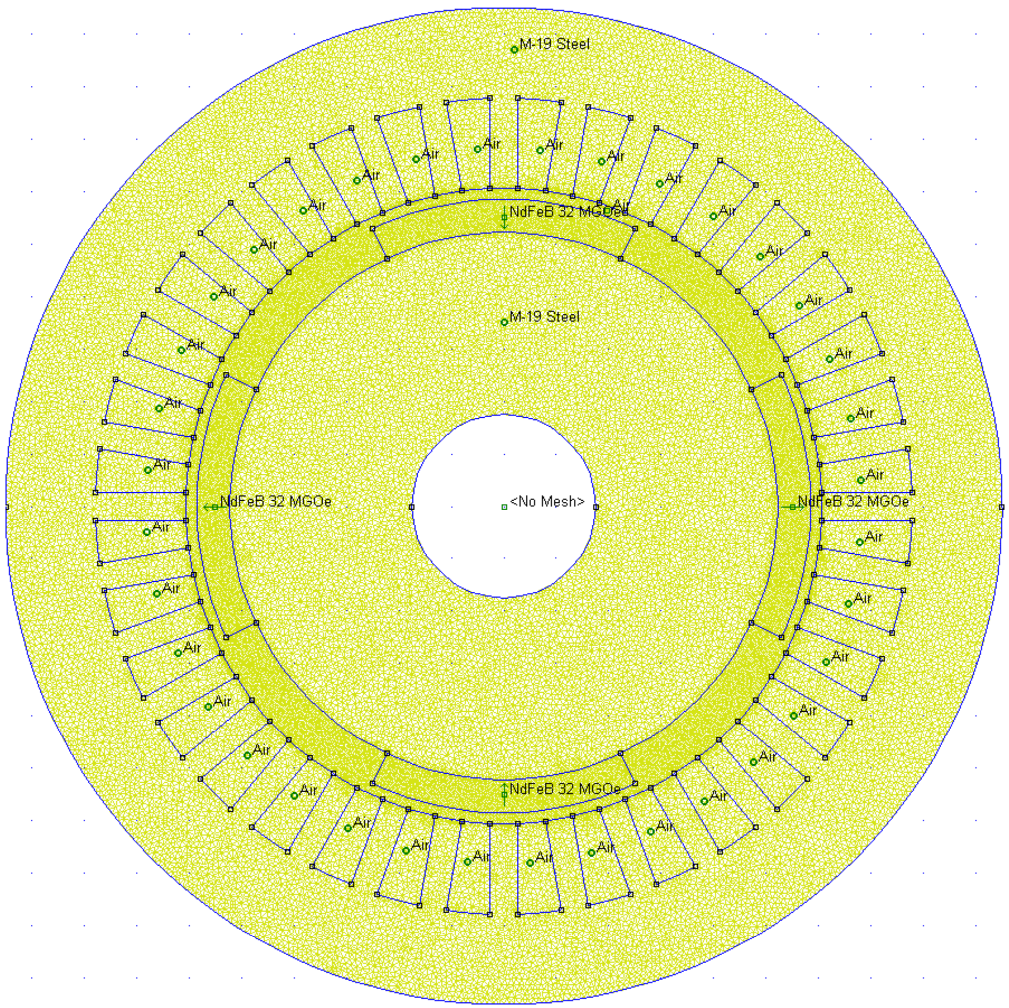
Example 2: Comparison of Analytic vs. FEA

- Note that FEA shows lower force than that predicted analytically
- Probably due to saturating iron reducing B and hence force



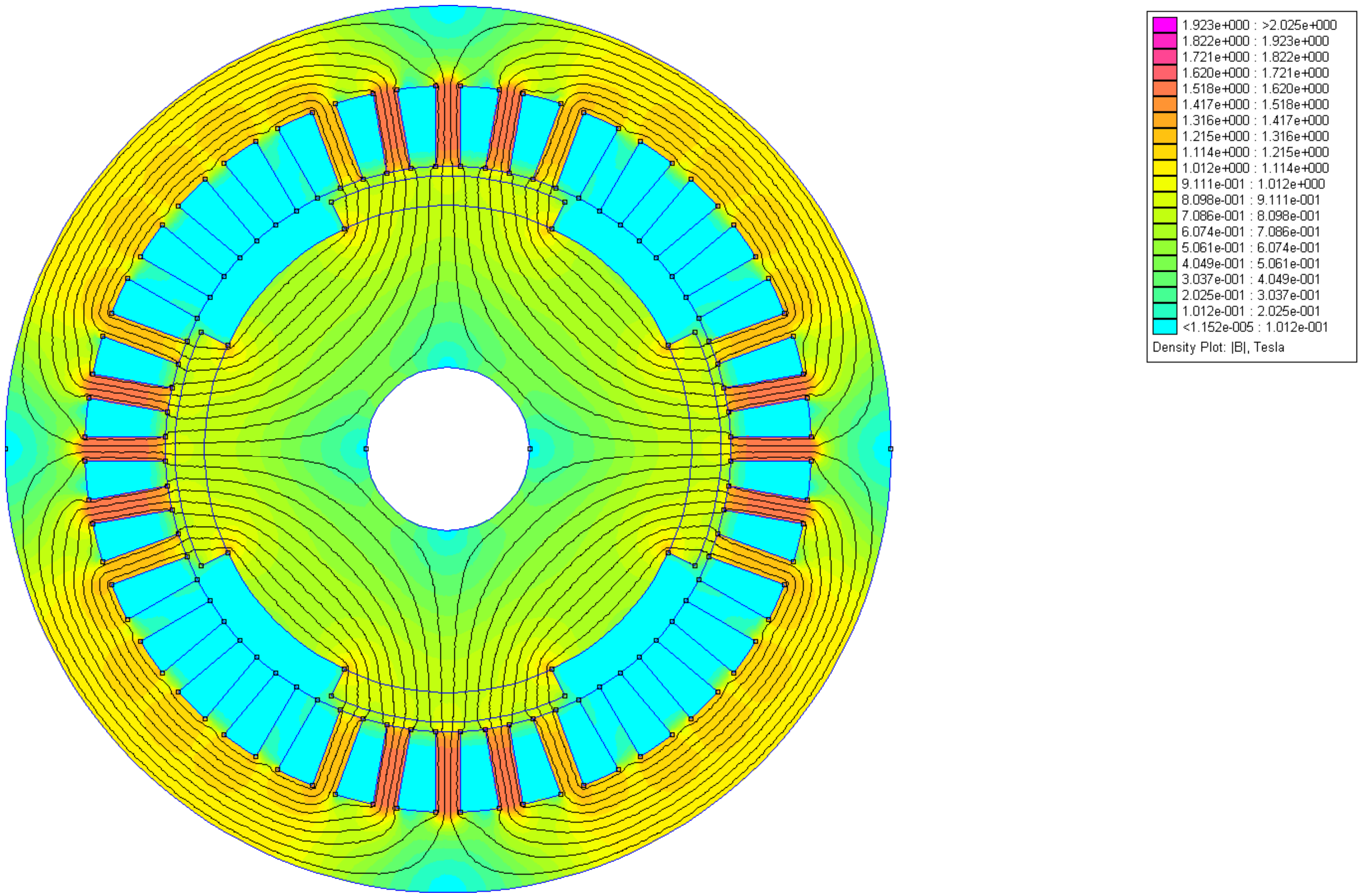
Example 3: PM Machine

• 4 pole machine; field provided by NdFeB magnets



Example 3: PM Machine

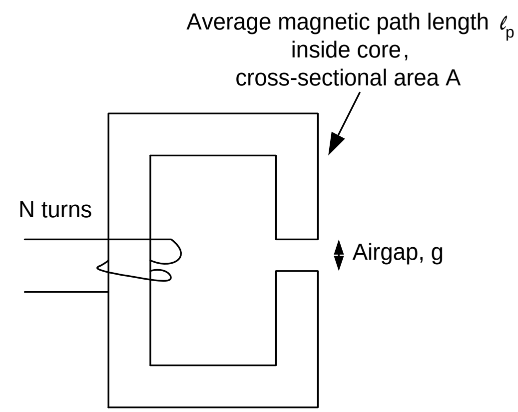
• 4 pole machine; field provided by NdFeB magnets



C-Core with Gap --- Using Magnetic Circuits

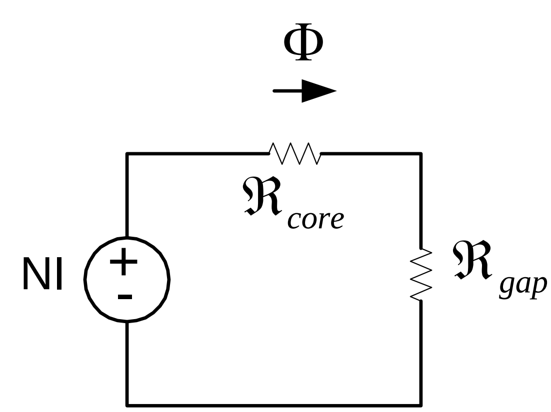
- Flux in the core is easily found by:

$$\Phi = \frac{NI}{\Re_{core} + \Re_{gap}} = \frac{NI}{\frac{l_p}{\mu_c A_c} + \frac{g}{\mu_o A_c}}$$



- Now, note what happens if $g/\mu_o >> l_p/\mu_c$: The flux in the core is now approximately independent of the core permeability, as:

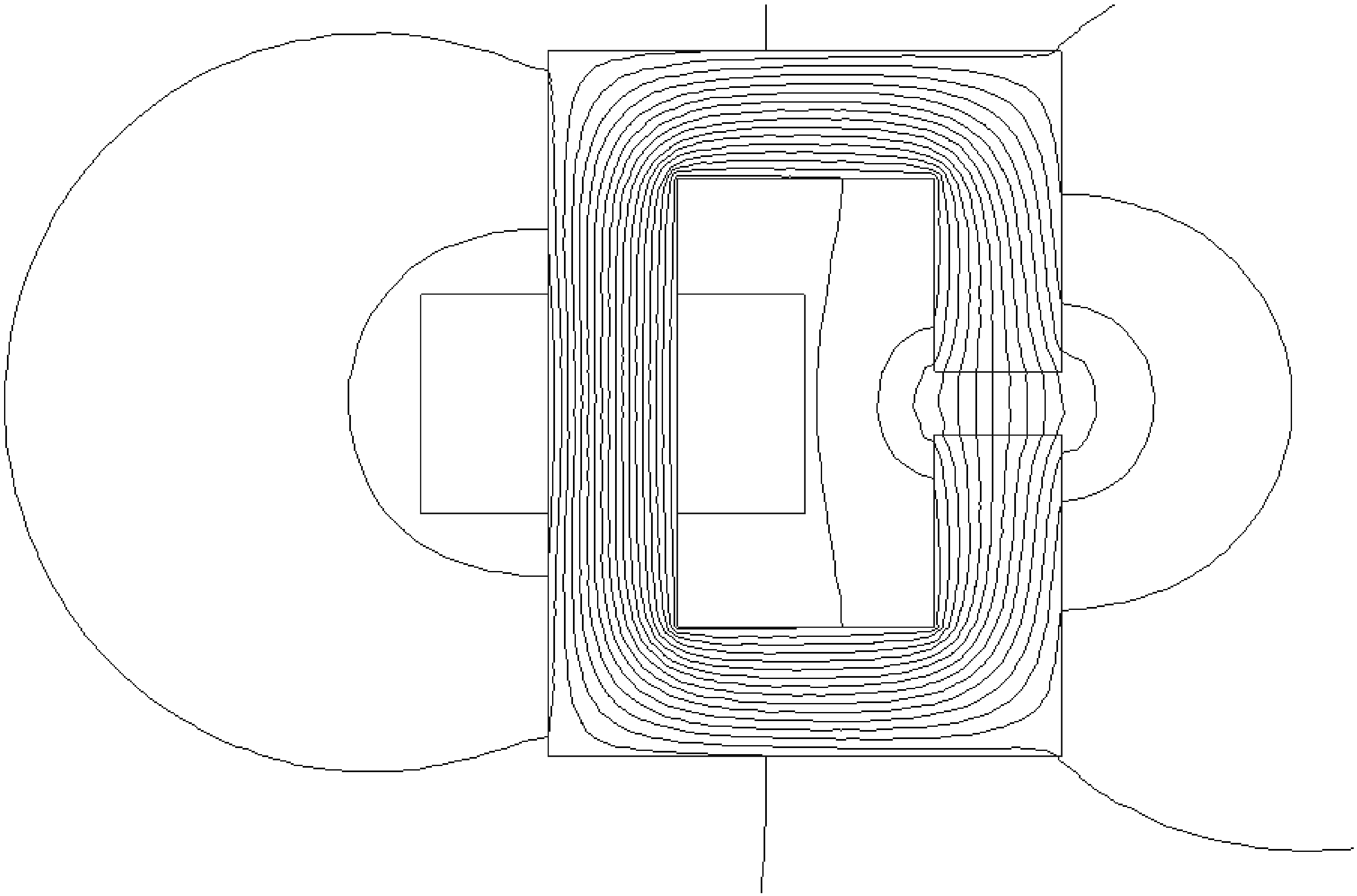
$$\Phi \approx \frac{NI}{\Re_{gap}} \approx \frac{NI}{\frac{g}{\mu_o A_c}}$$



- Inductance:

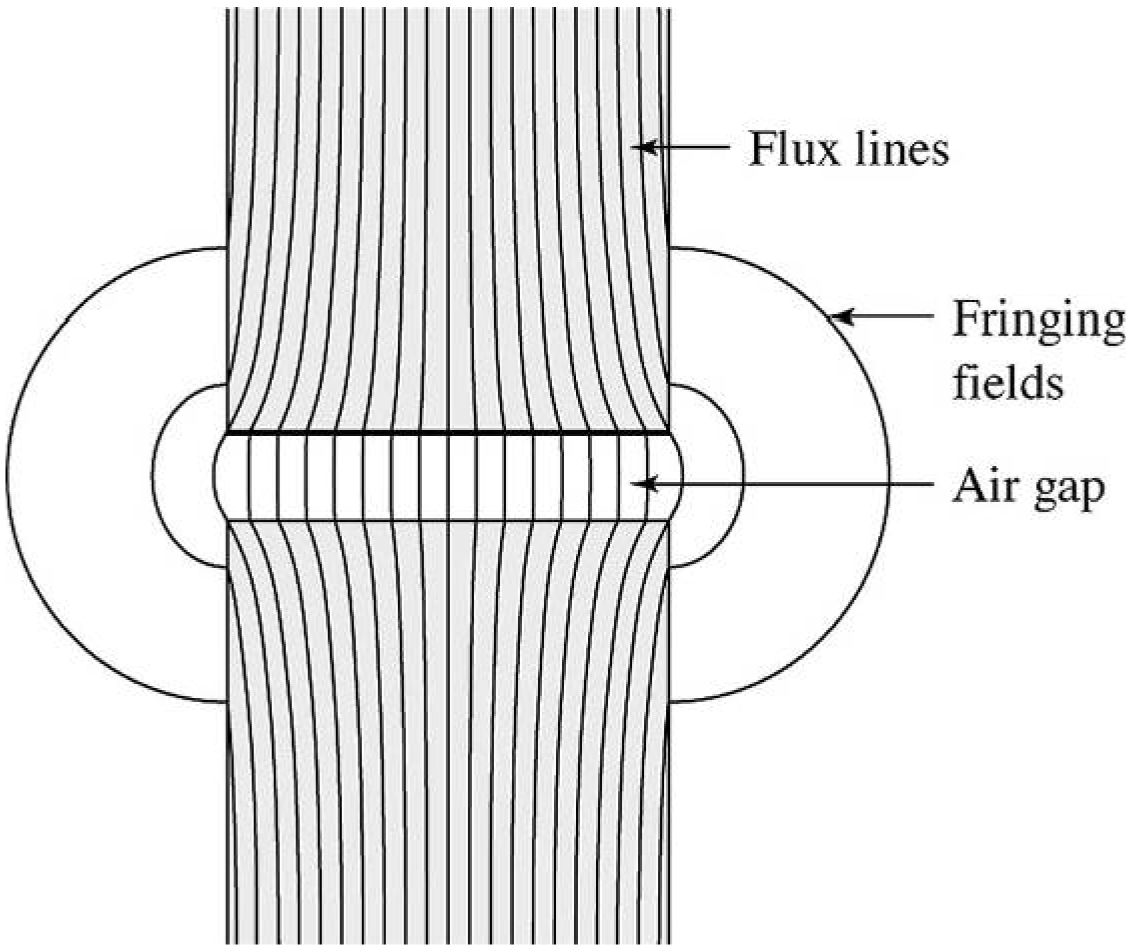
$$L = \frac{N\Phi}{I} \approx \frac{N^2}{\Re_{gap}} \approx \frac{N^2}{\frac{g}{\mu_o A_c}}$$

C-Core with Gap --- FEA



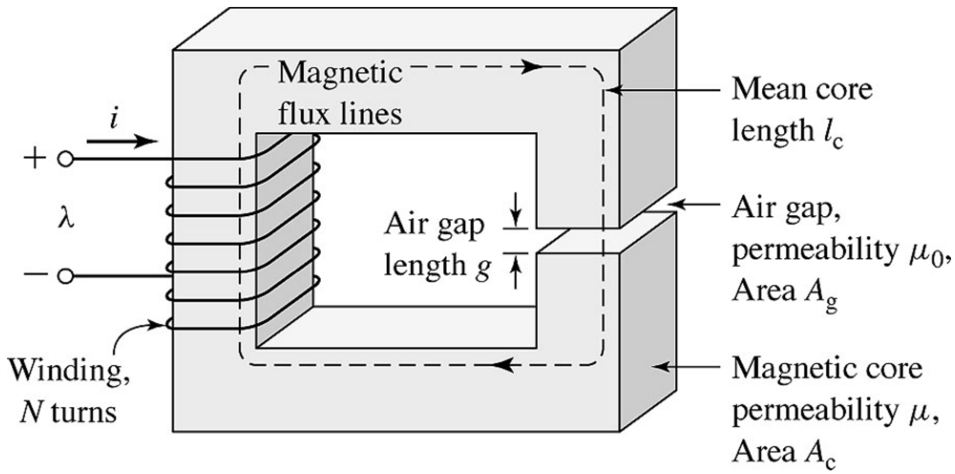
Fringing Fields in Airgap

- If fringing is negligible, $A_c = A_g$



Example 4: C-Core with Airgap

- *Fitzgerald*, Example 1.1; with B_c = 1.0T, find reluctances, flux and coil current



$A_c = A_g = 9\ \text{cm}^2$

$g = 0.05\ \text{cm}$

$l_c = 30\ \text{cm}$

$N = 500$

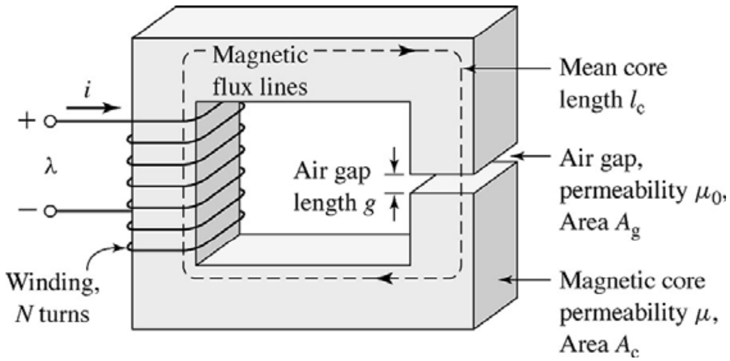
$\mu_r = 70{,}000$

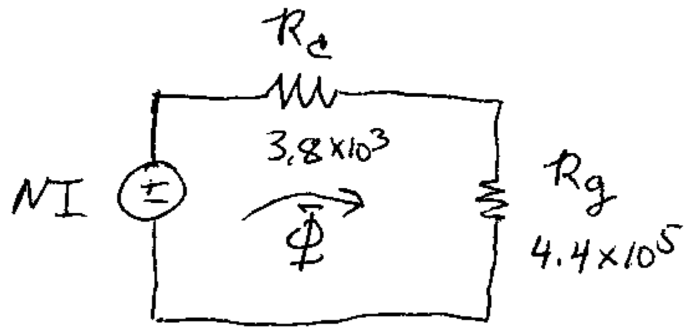
$$\Re_c = \frac{l_c}{A_c \mu_c} = \frac{0.3}{(70{,}000)(4\pi\times10^{-7})(9\times10^{-4})} = 3.8\times10^3\ \frac{A-turns}{Wb}$$

$$\Re_g = \frac{g}{A_g \mu_o} = \frac{5\times10^{-4}}{(4\pi\times10^{-7})(9\times10^{-4})} = 4.4\times10^5\ \frac{A-turns}{Wb}$$

Note that $R_g >> R_c$

Example 4: C-Core with Airgap





Flux:

$$\Phi = B_c A_c = (1.0)(9\times10^{-4}) = 9\times10^{-4}\ Wb$$

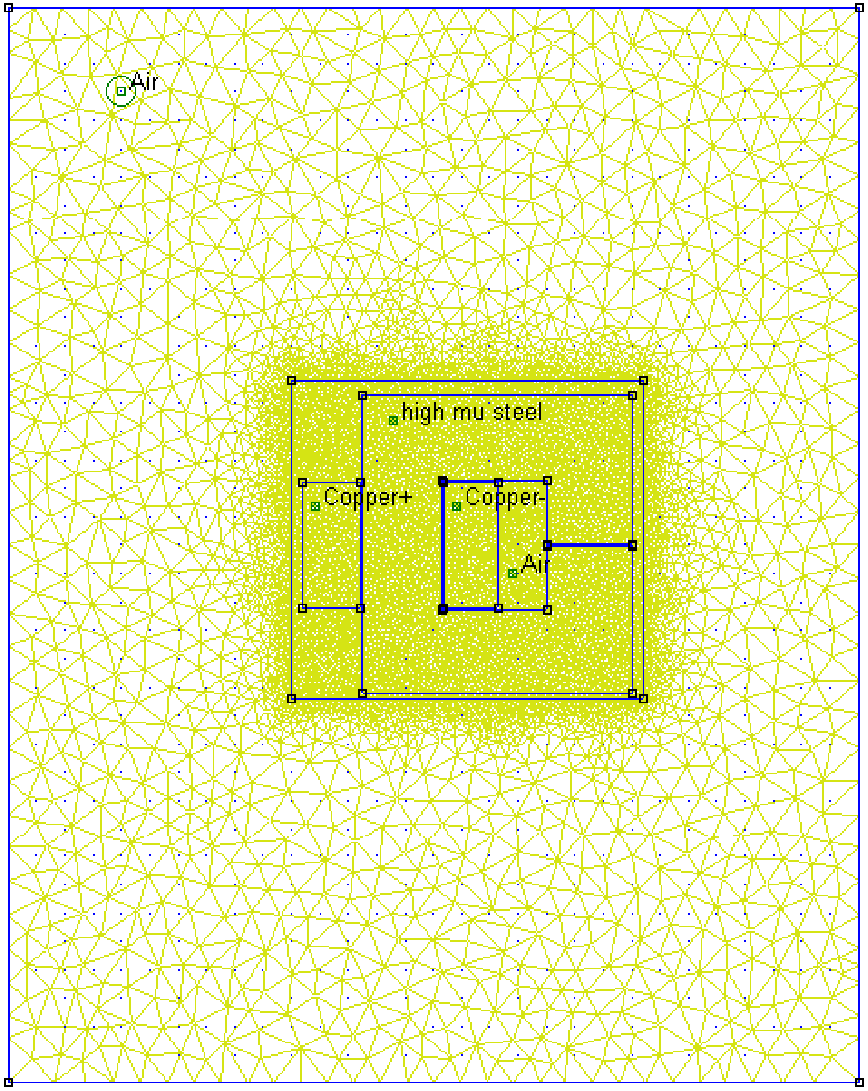
Coil current:

$$NI = \Phi(\Re_c + \Re_g)$$

$$\Rightarrow I = \frac{\Phi(\Re_c + \Re_g)}{N} = \frac{(9\times10^{4})(4.46\times10^{5})}{500} = 0.8\ A$$

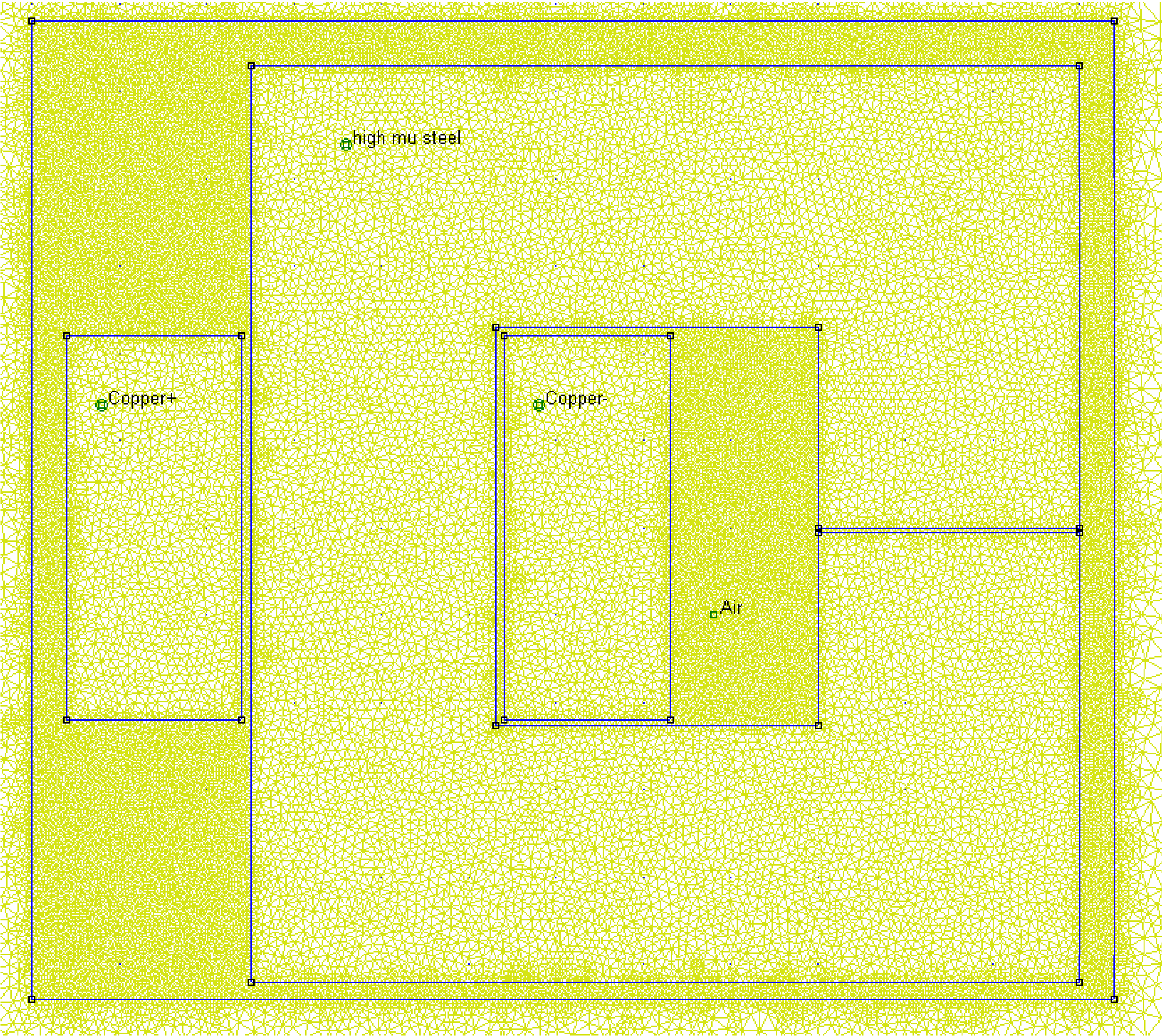
Example 4: C-Core with Airgap --- FEA

- NI = 400 A-turns



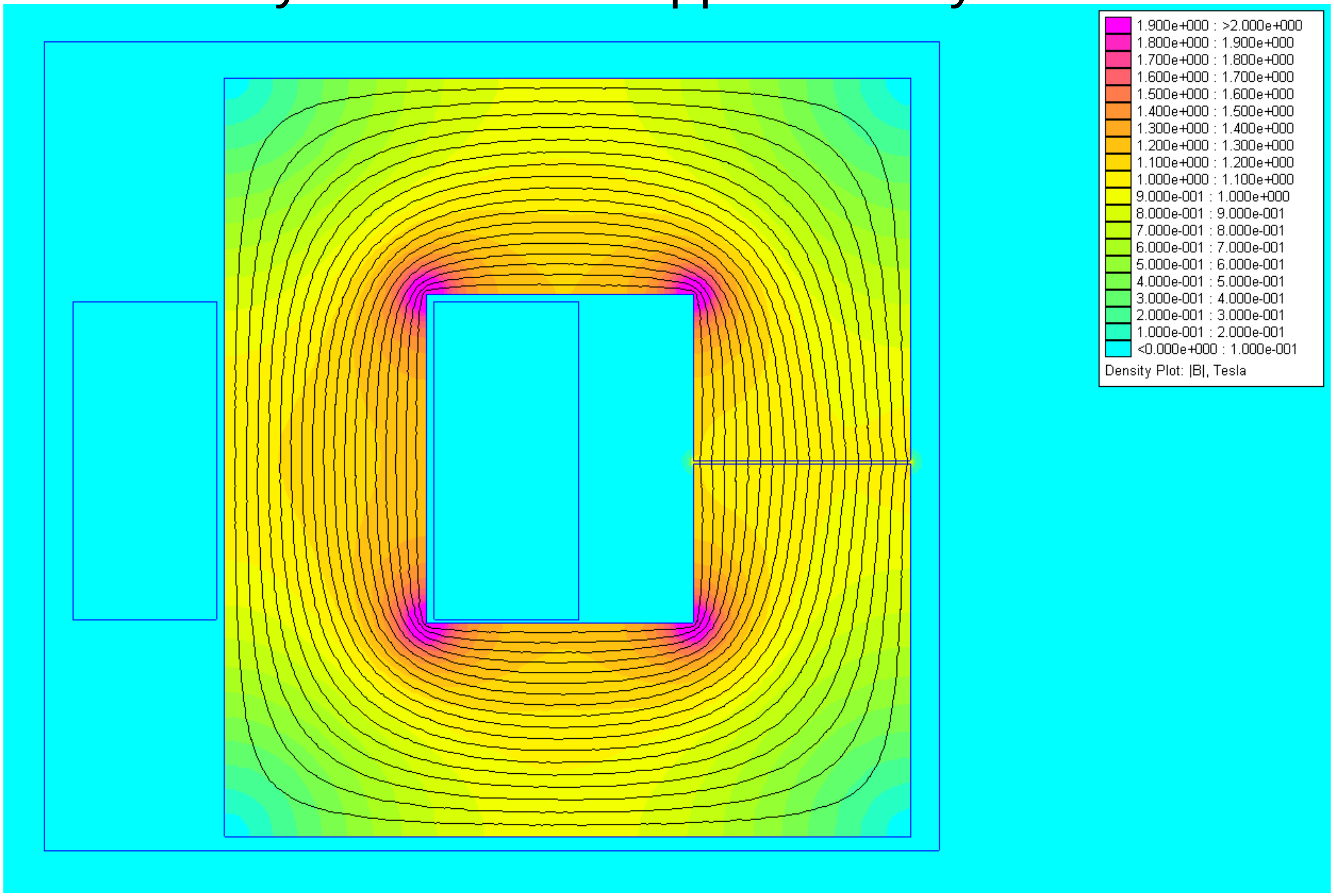
Example 4: C-Core with Airgap --- FEA

- NI = 400 A-turns

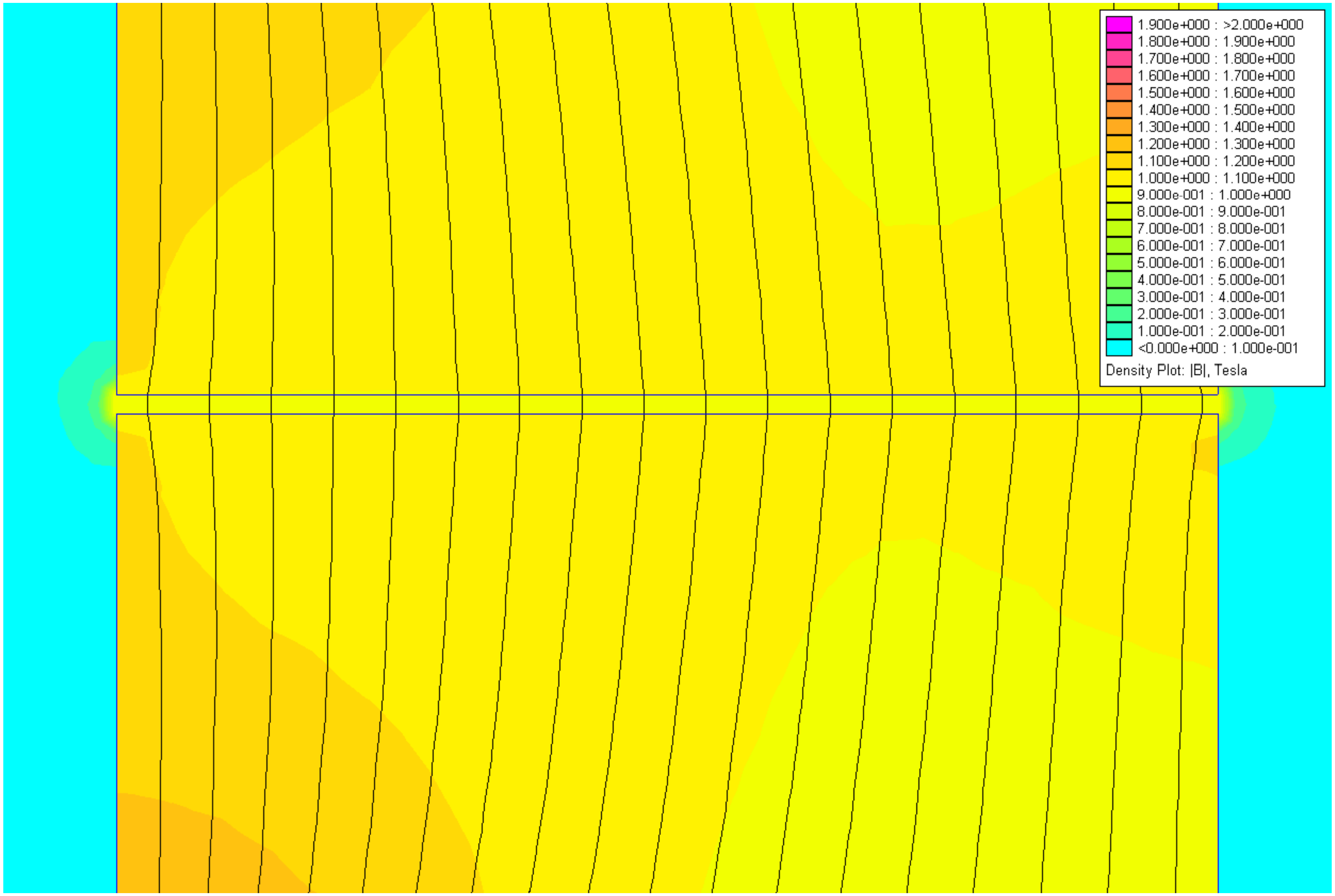


Example 4: C-Core with Airgap --- FEA Result

- Flux density in the core is approximately 1 Tesla

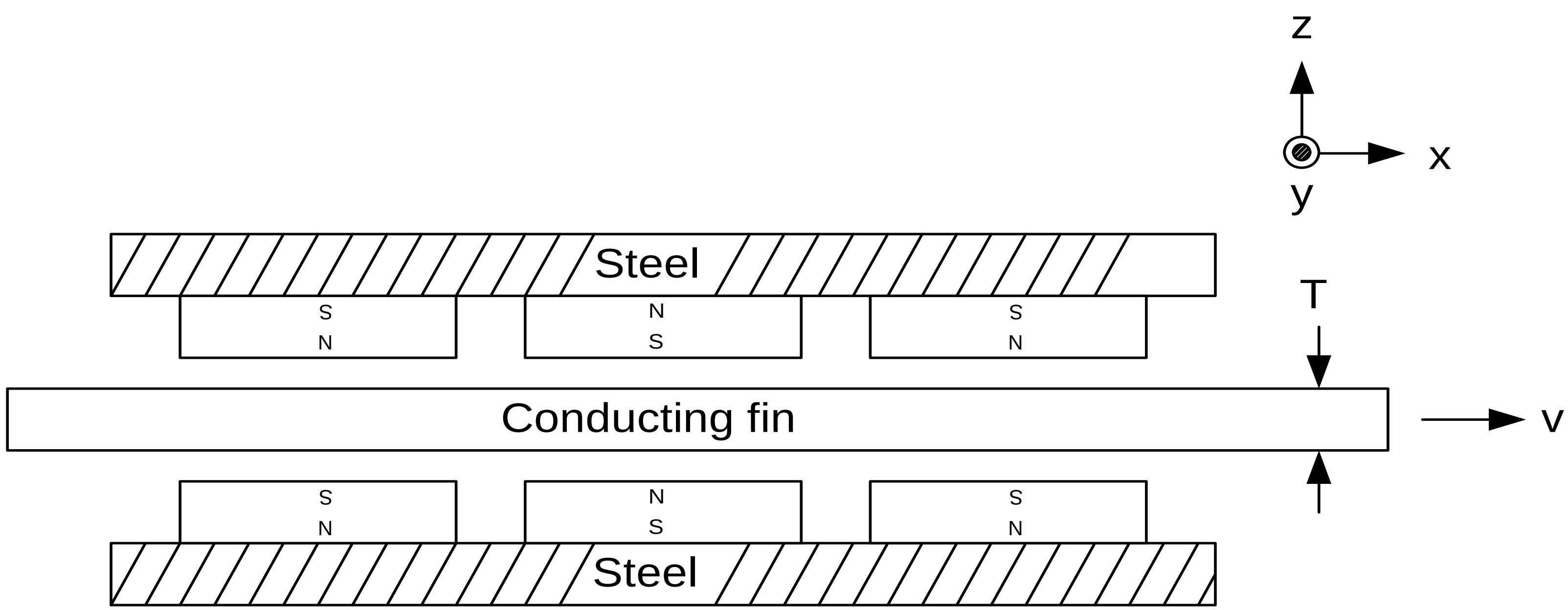


Example 4: C-Core with Airgap --- Gap Detail



Basic Eddy Current Brake

- Magnetic field created by high strength magnets
- Relative motion between field and conducting fin creates eddy currents and hence braking force
- Design variables: magnetic strength, fin material and fin thickness, airgap



Magnetic Induction in ECBs

- Relative motion between permanent magnets and conducting sheet means that there is a time-varying magnetic field impinging on the sheet
  - Magnets or conducting sheet can be moving; it's relative movement that's important
- This time varying magnetic field creates circulating (eddy) currents in conducting sheet
  - Magnetic induction is the principle by which these eddy currents are induced (by Faraday's Law)
- Eddy currents mean power dissipation in sheet, and a magnetic drag force acting on the sheet

$$\frac{d\vec{B}}{dt} \rightarrow \vec{E} \rightarrow \vec{J} \rightarrow < P_{diss} > \rightarrow \; forces$$

Eddy Current Brake

- Implemented on rollercoasters in the US
  - (Magnetar, Inc., Seal Beach CA)
- No contacting parts

Reference: http://www.magnetarcorp.com

Eddy Current Brake

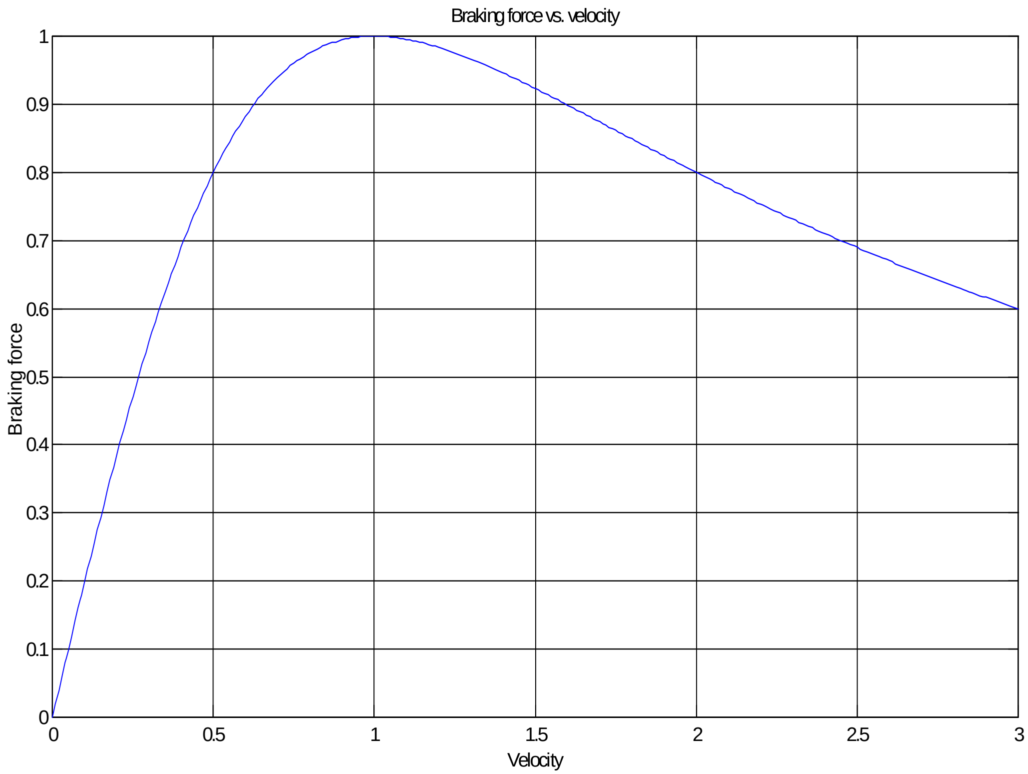
Reference: www.magnetarcorp.com

Braking Force vs. Velocity

- From electrodynamic analysis, braking force is:

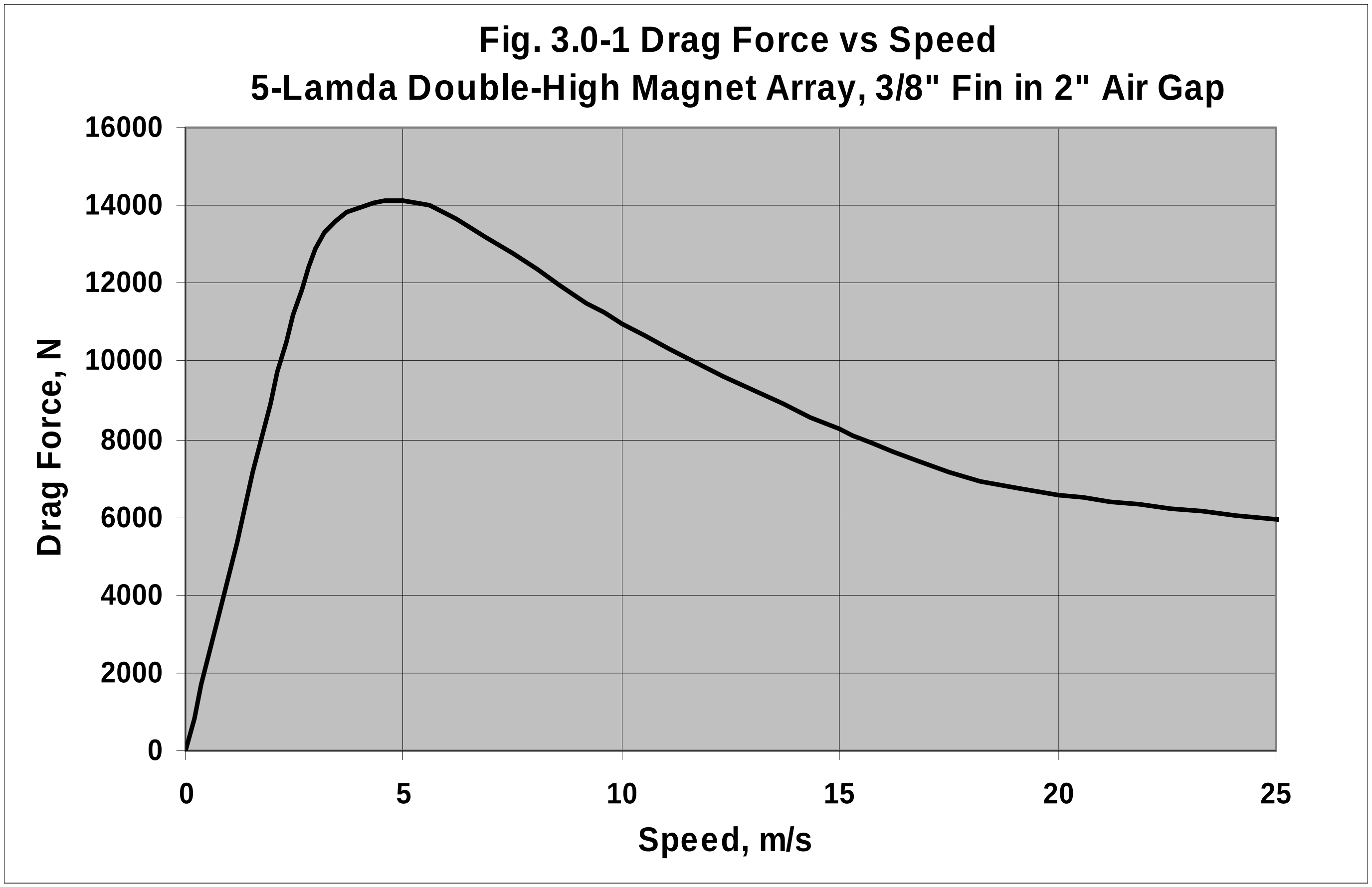
$$f_b = F_o \frac{v v_{pk}}{v^2 + v_{pk}^2}$$

- F_o depends on magnet strength, airgap, and magnet area



Back to ECBs: Result of 3D FEA

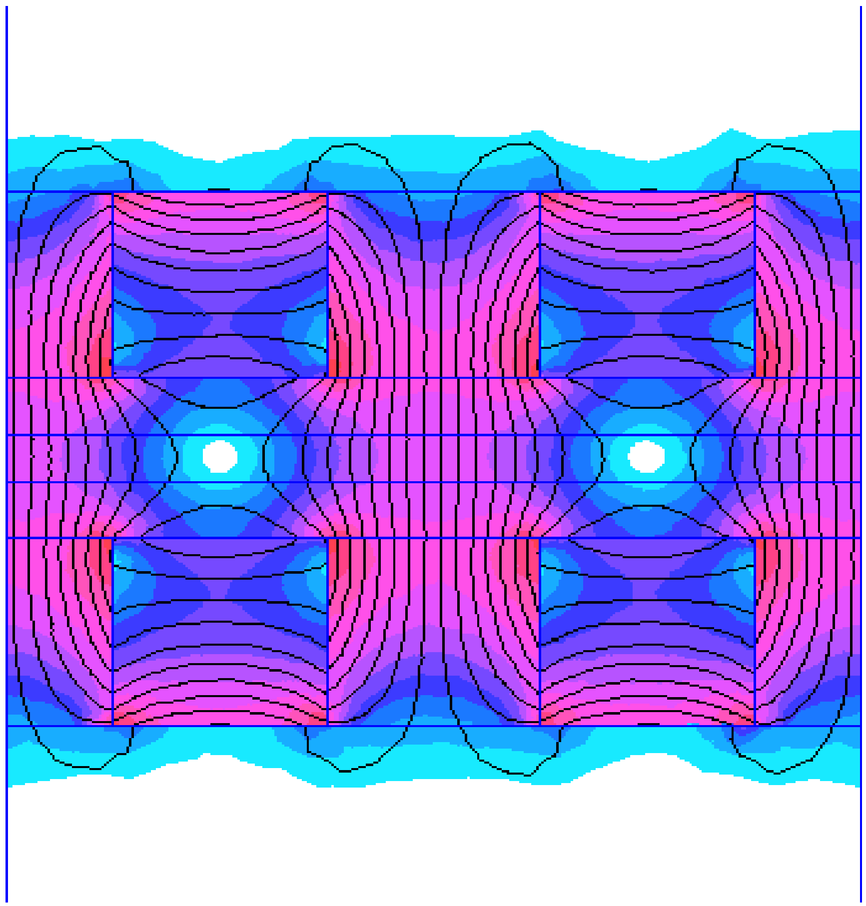
- Note that braking force is maximum at the “drag peak” velocity



3D FEA done by Myatt Consulting, Inc., Norfolk, MA

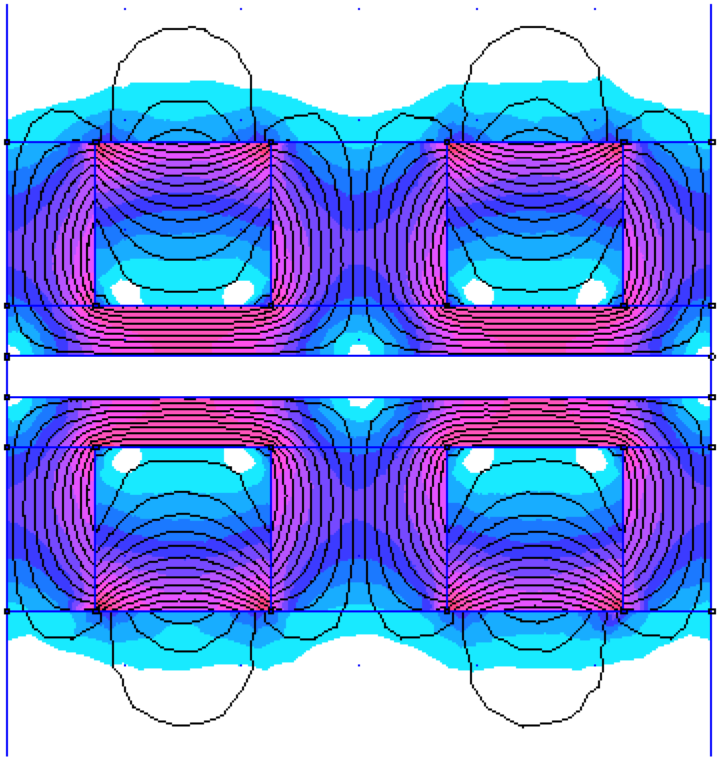
Example 5: 2D FEA: Low Speed Flux Line Plot

- At low speed, force between magnetic rails is attractive
  - North pole attracts to South Pole across airgap



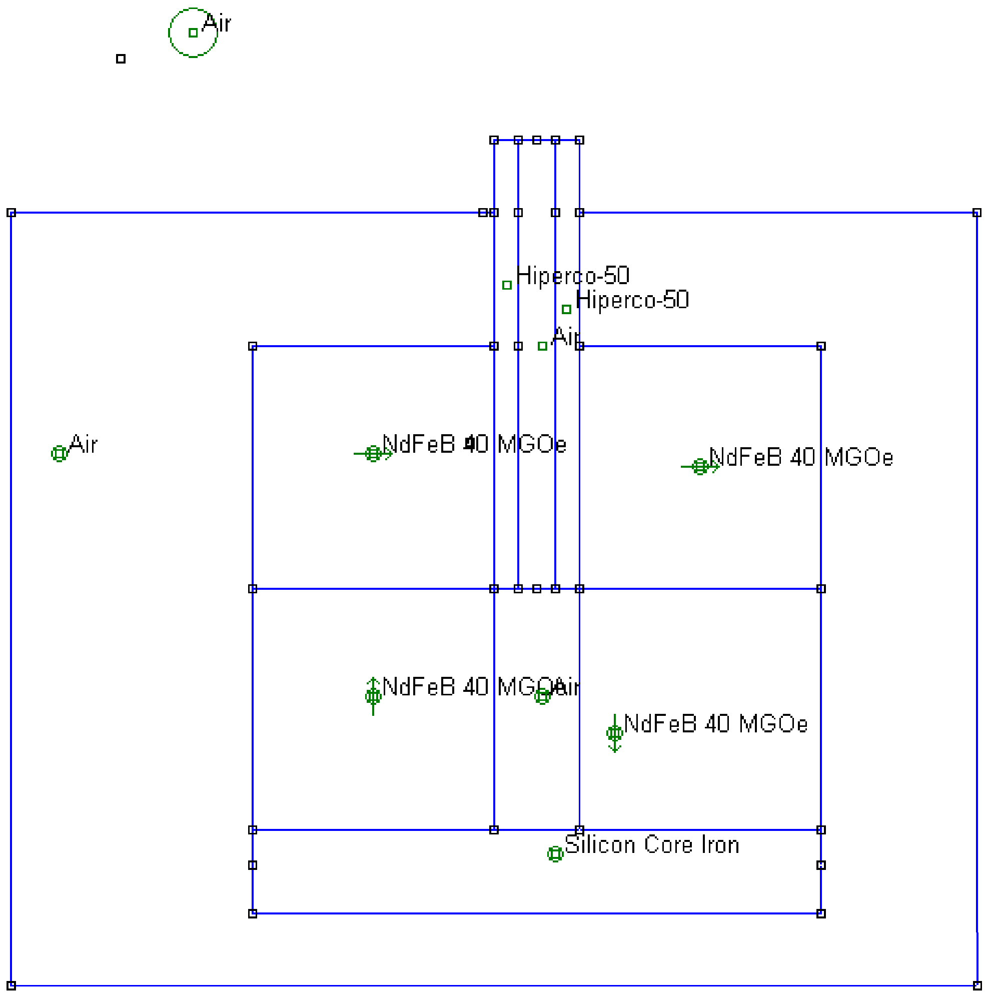
Example 5: 2D FEA: Approximate High Speed Flux Line Plot

- At high speed, force between magnetic rails is repulsive
  - North pole is repelled from induced North pole in conducting fin

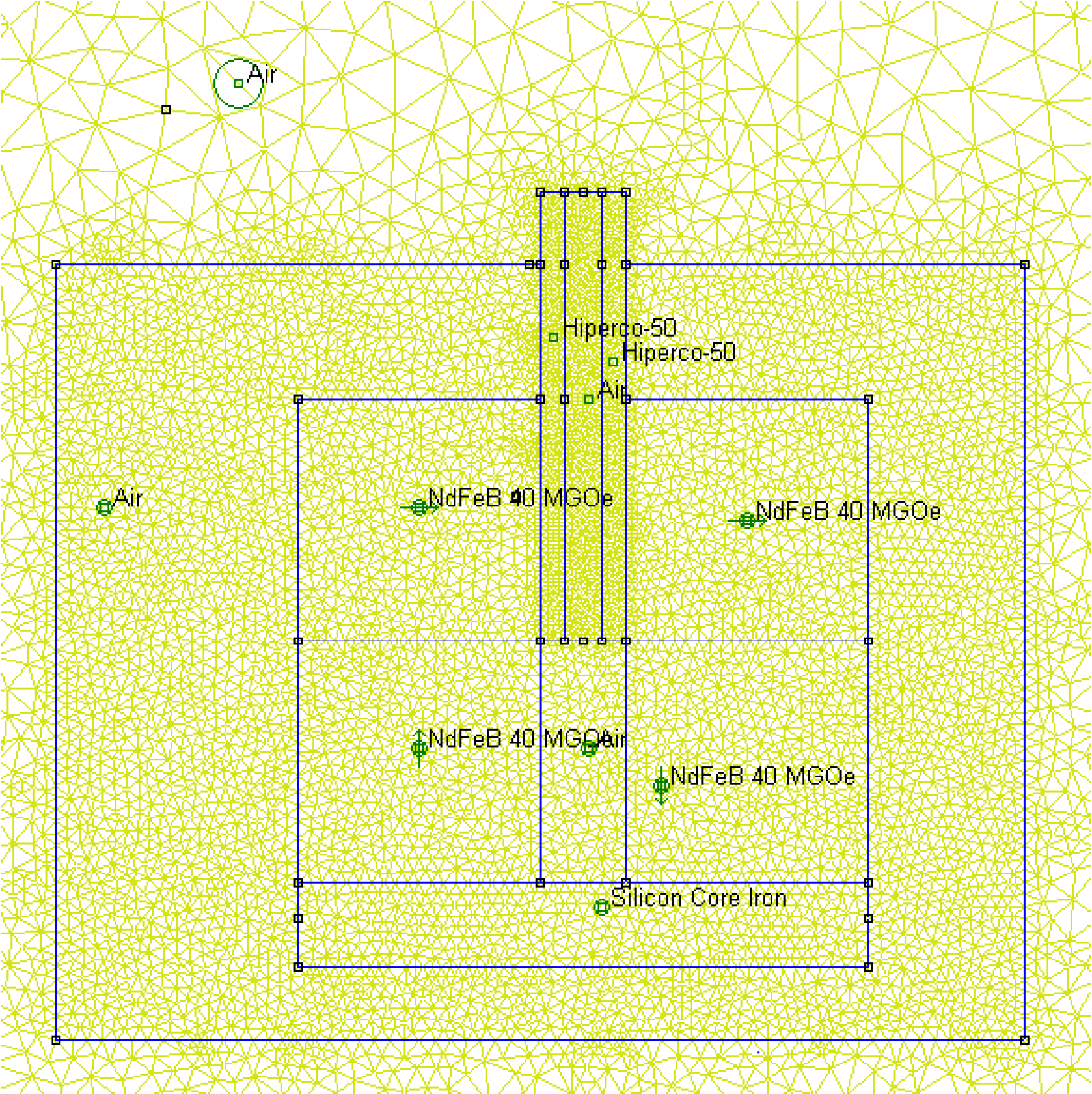


Example 6: Magnetic Ribbon Microphone

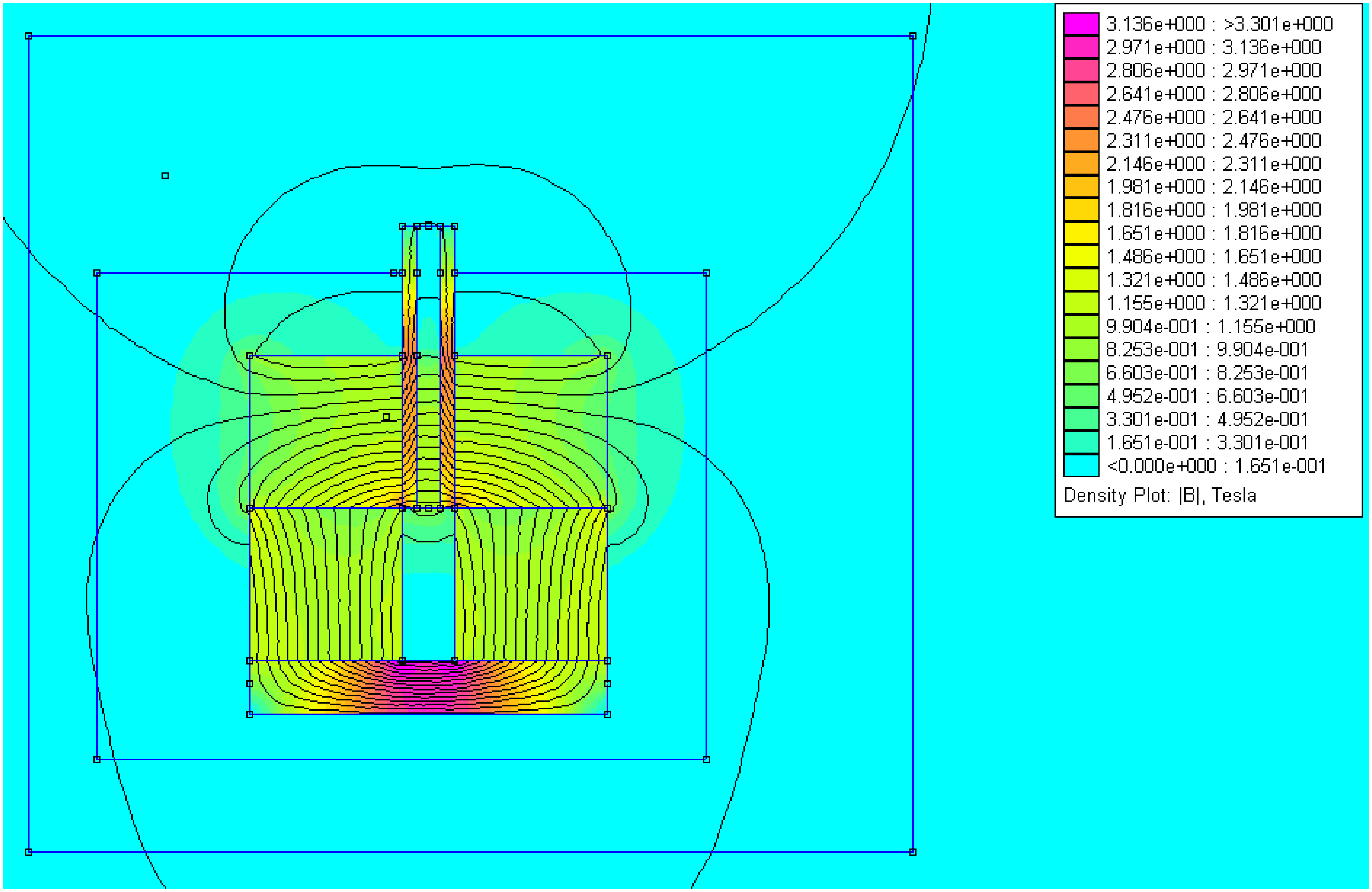
- Uses fancy high saturation steel (hiperco)



Example 6: Magnetic Ribbon Microphone

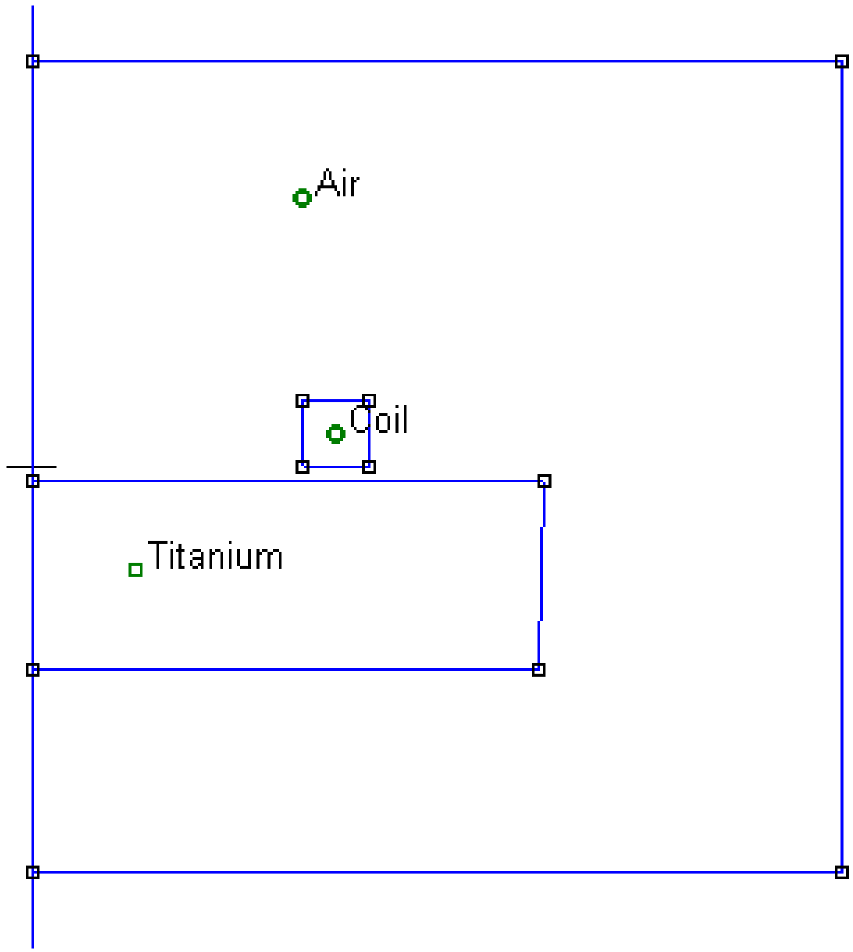


Example 6: Magnetic Ribbon Microphone

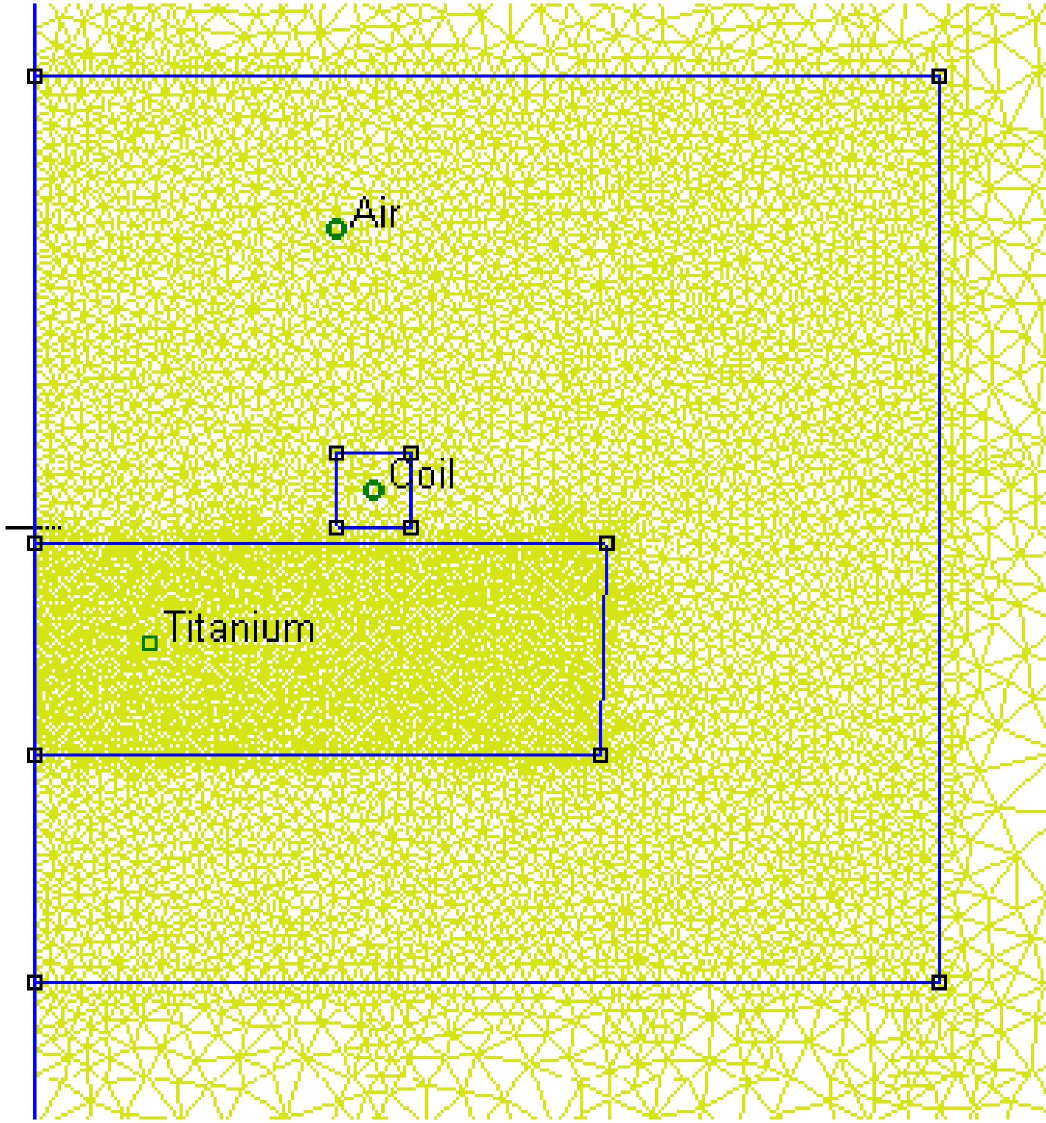


Example 7: Induction Coil for NDE

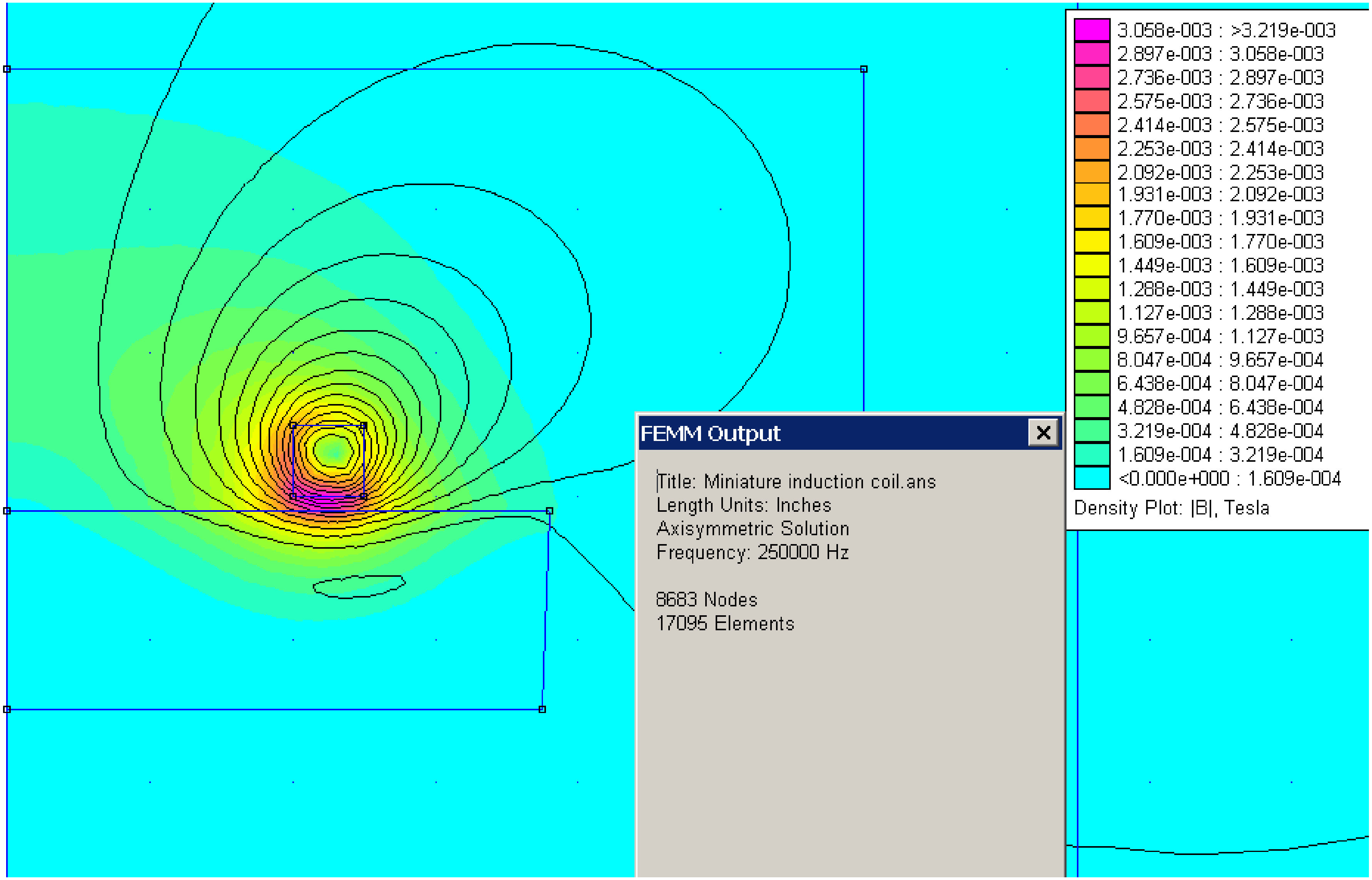
- NDE --- non-destructive evaluation
- Uses AC coil above a conducting material



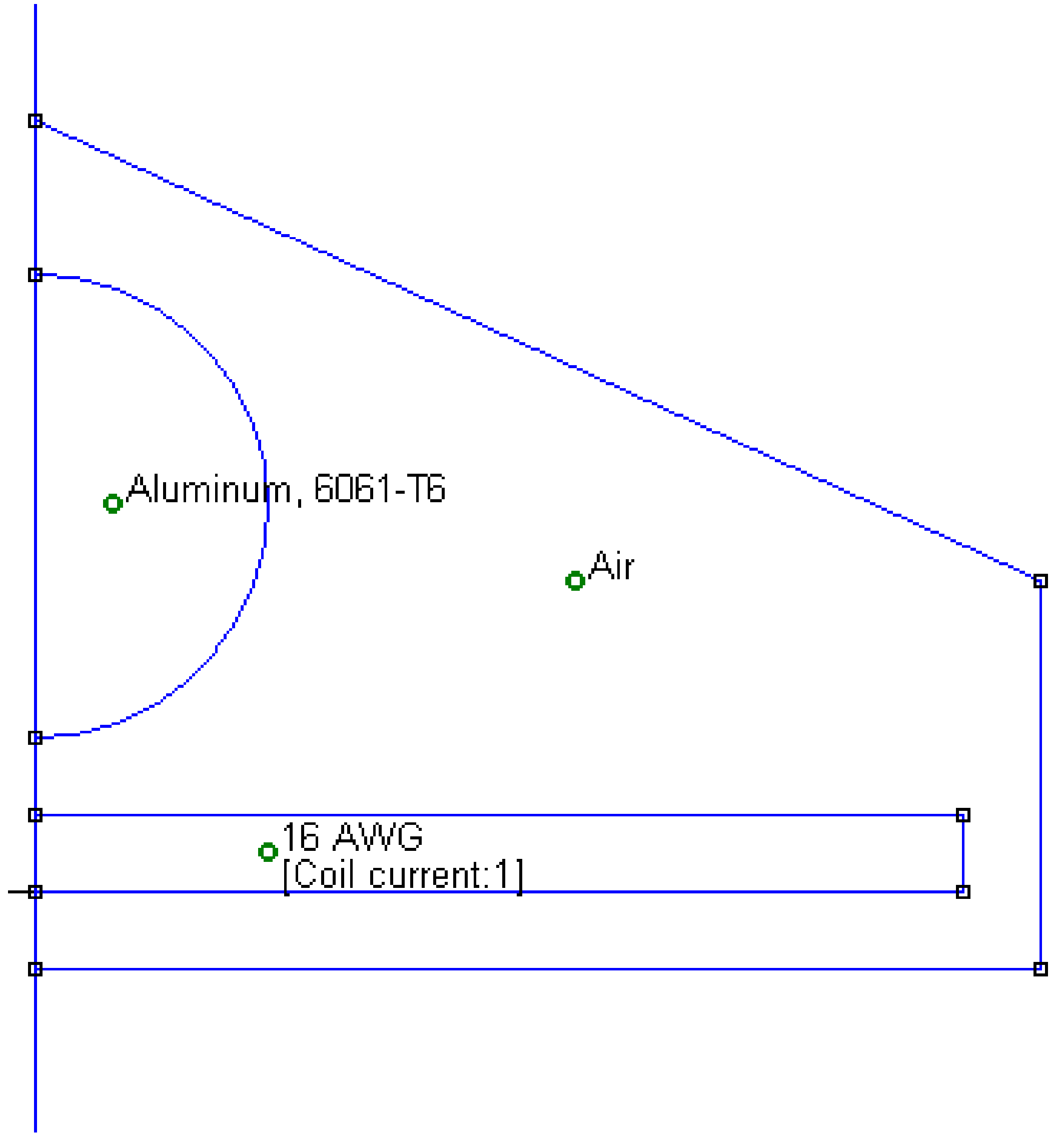
Example 7: Induction Coil for NDE



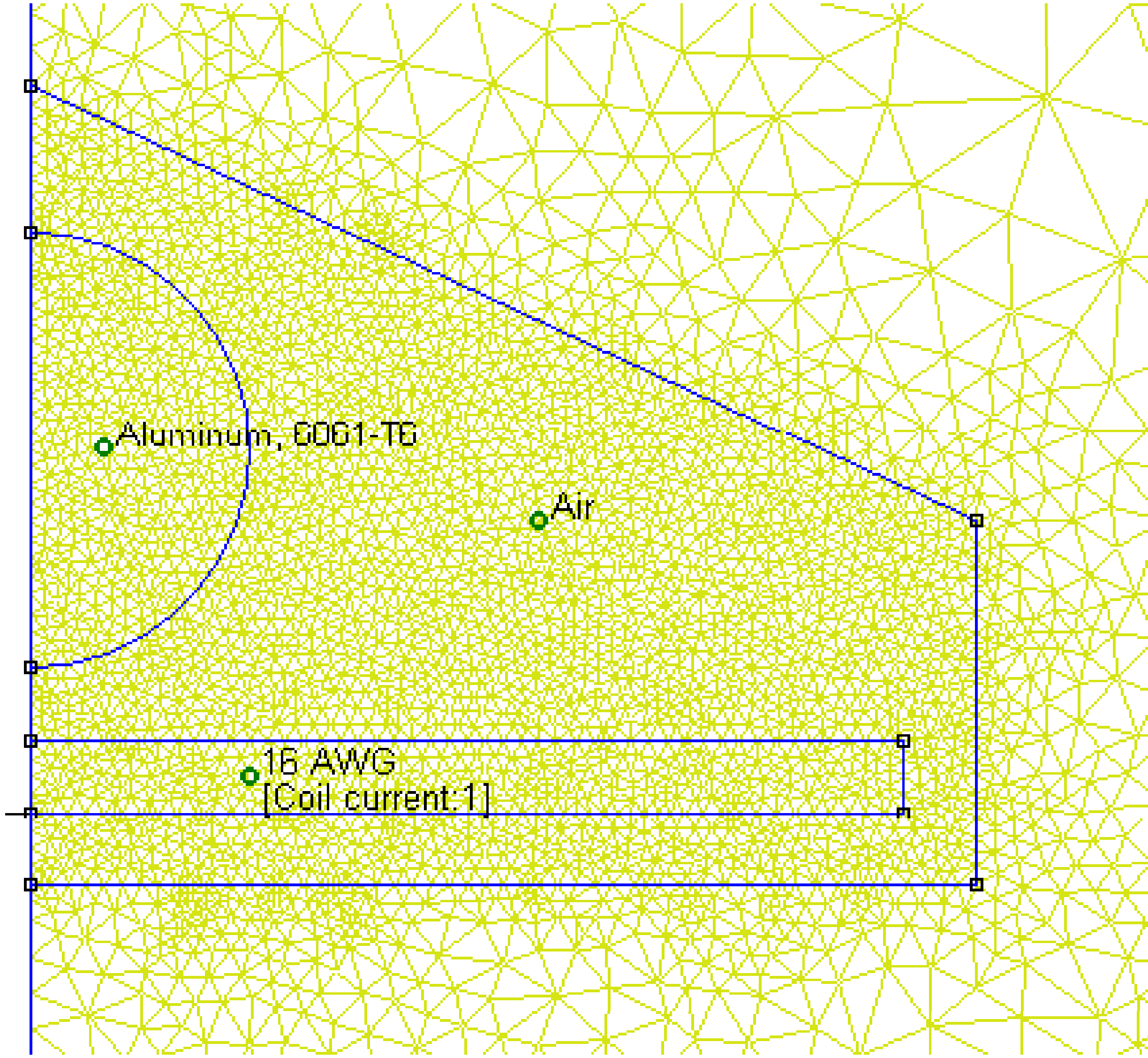
Example 7: Induction Coil for NDE



Example 8: Induction Separation



Example 8: Induction Separation



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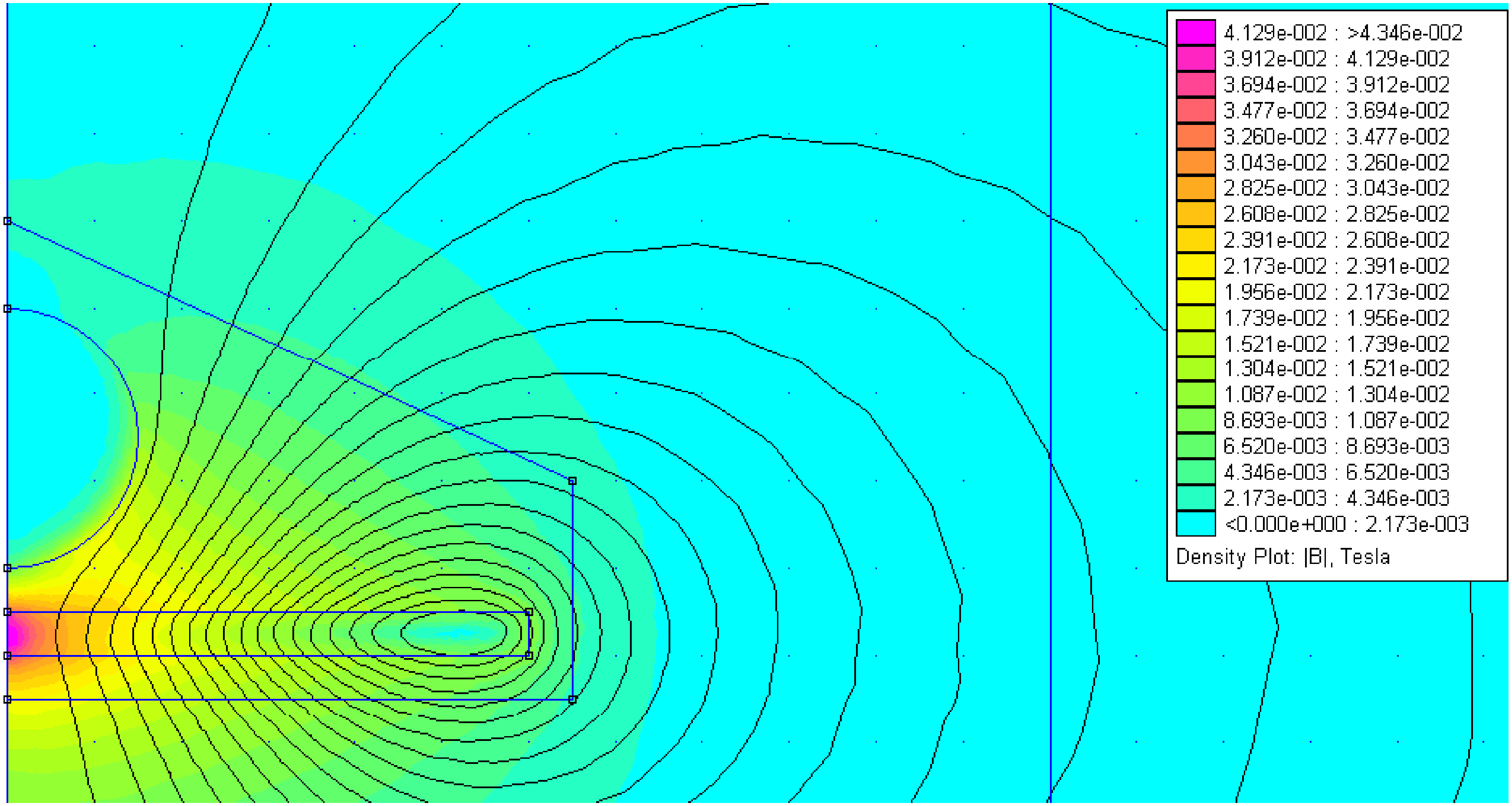

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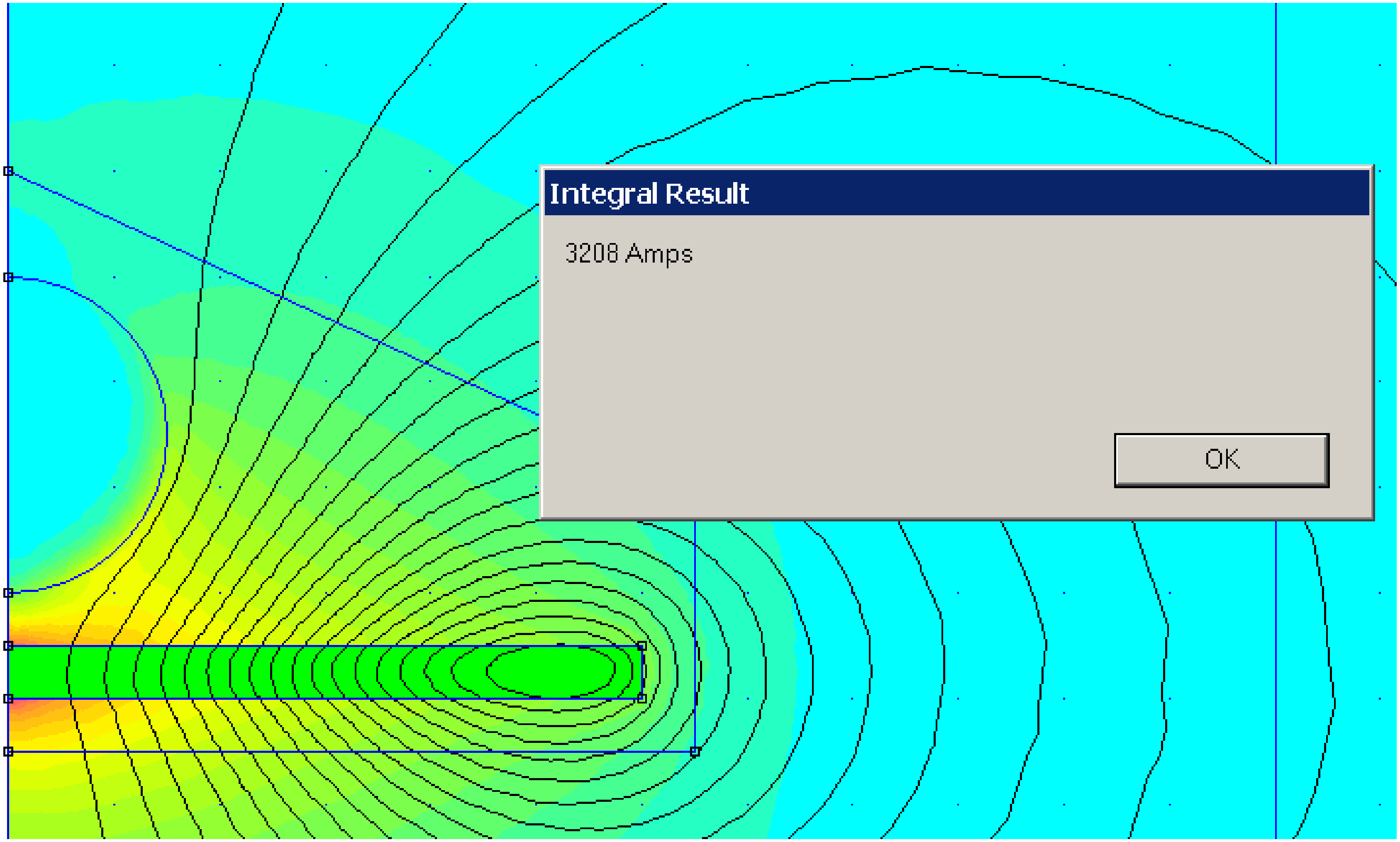
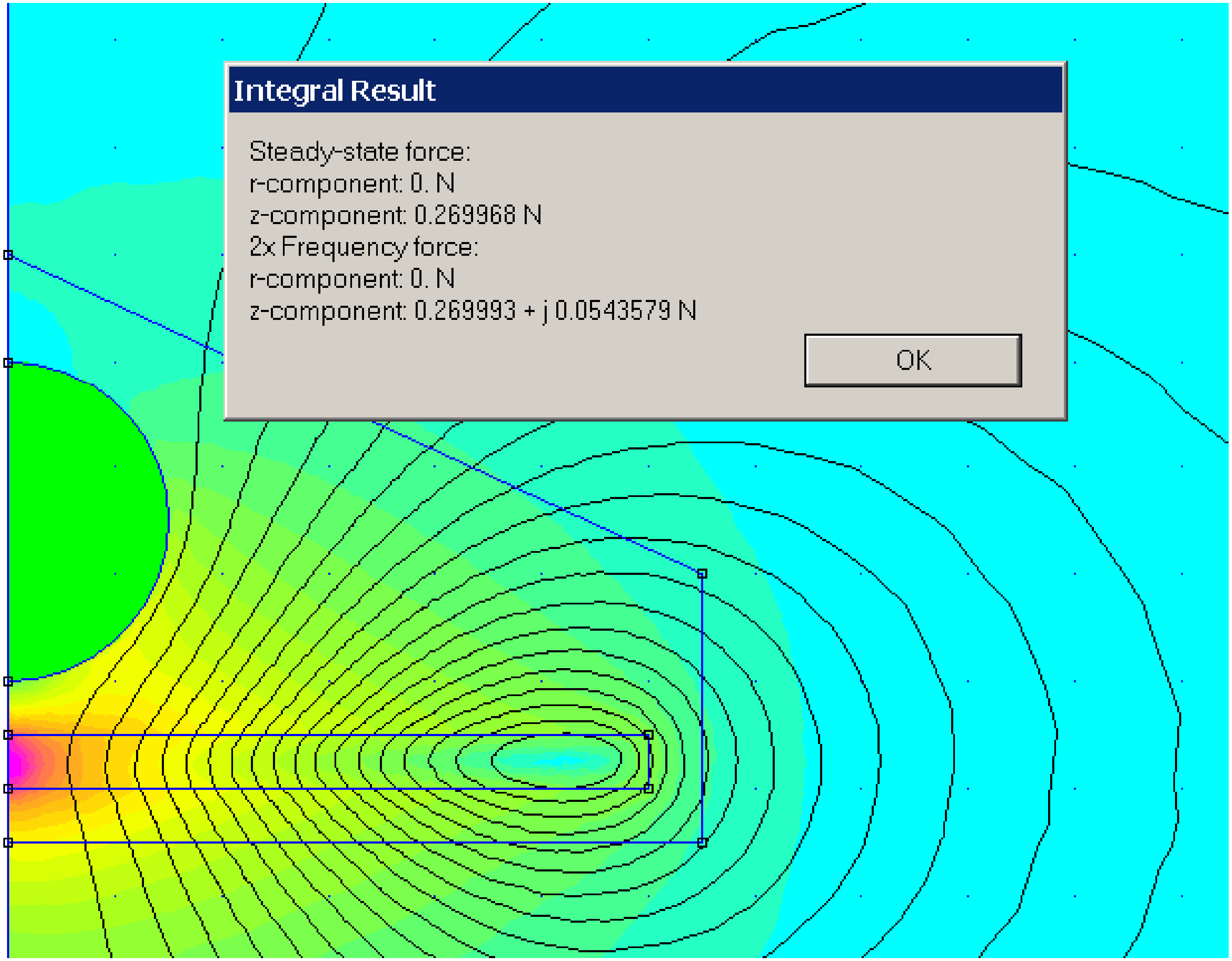
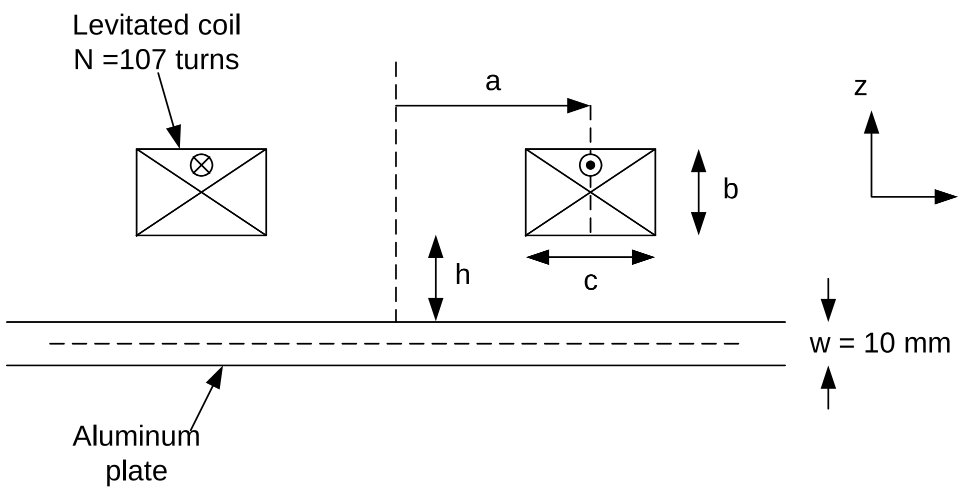
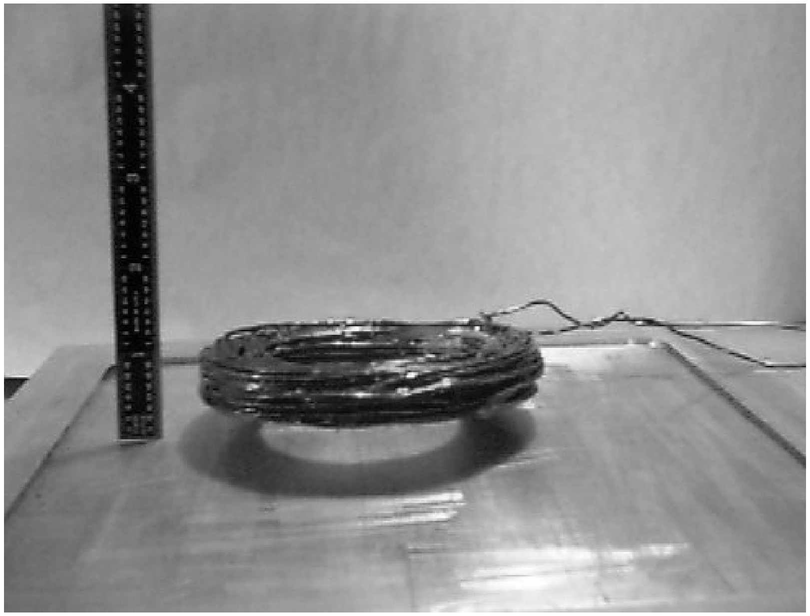


Example 8: Induction Separation



Example 9: AC Eddy Current Suspension Experiment

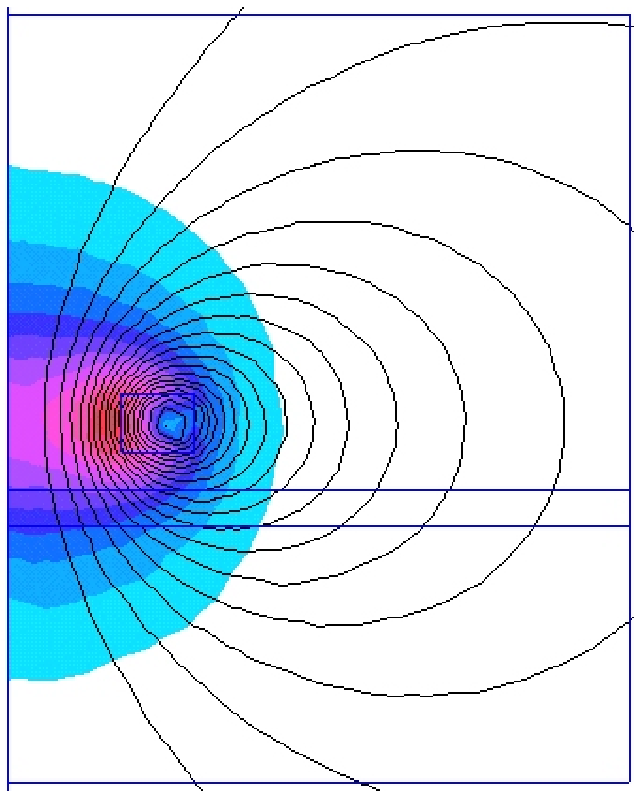


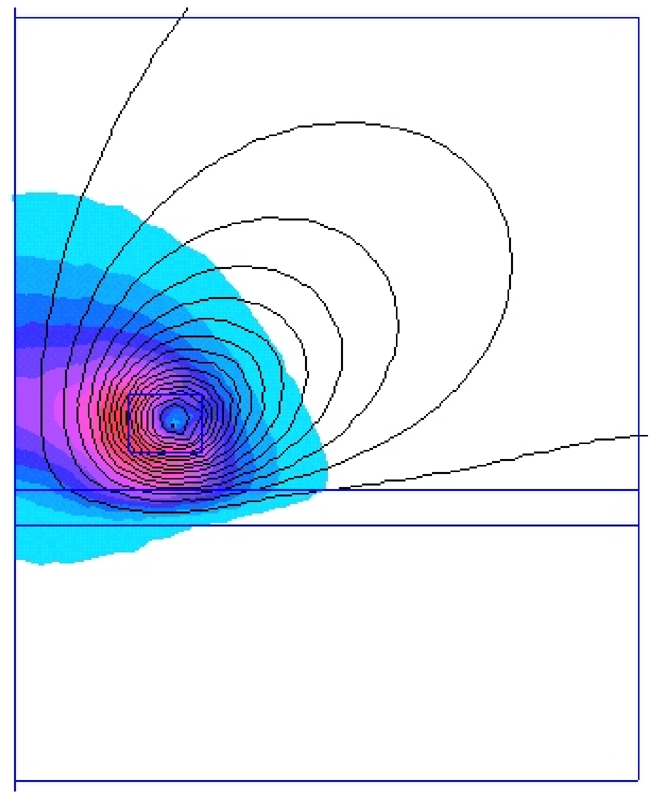


References:
1. Marc T. Thompson, "Eddy Current Magnetic Levitation--- Models and Experiments," *IEEE Potentials*, vol. 19, no. 1, Feb./March 2000, pp. 40-44
2. Marc T. Thompson, "Electrodynamic Magnetic Suspension --- Models, Scaling Laws and Experimental Results," *IEEE Transactions on Education*, vol. 43, no. 3, August 2000, pp. 336-342

Example 9: Flux Plot at DC and 60 Hz

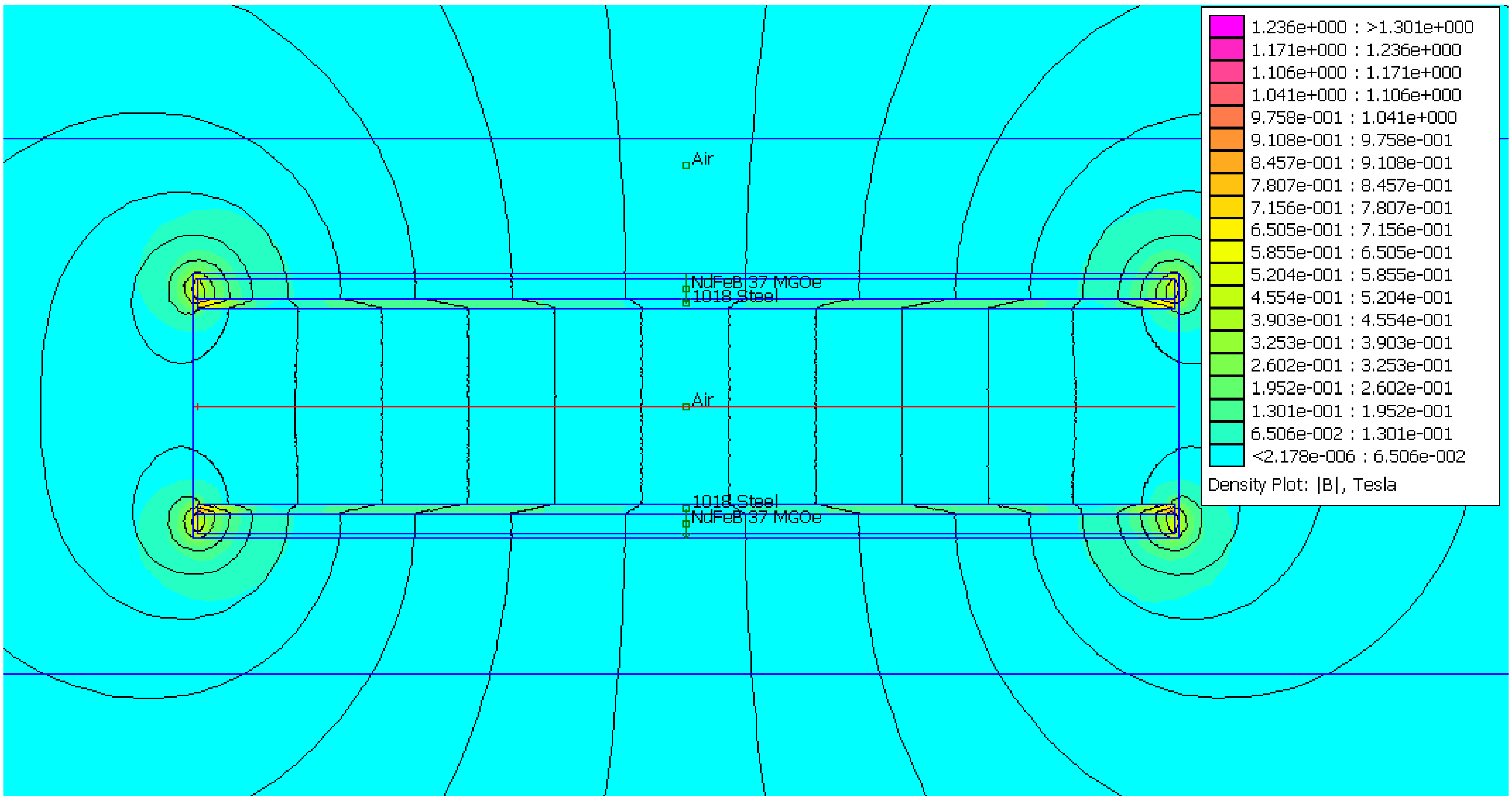
- At sufficiently high frequency and coil current, induced magnetic pole in conductor creates enough force to lift coil





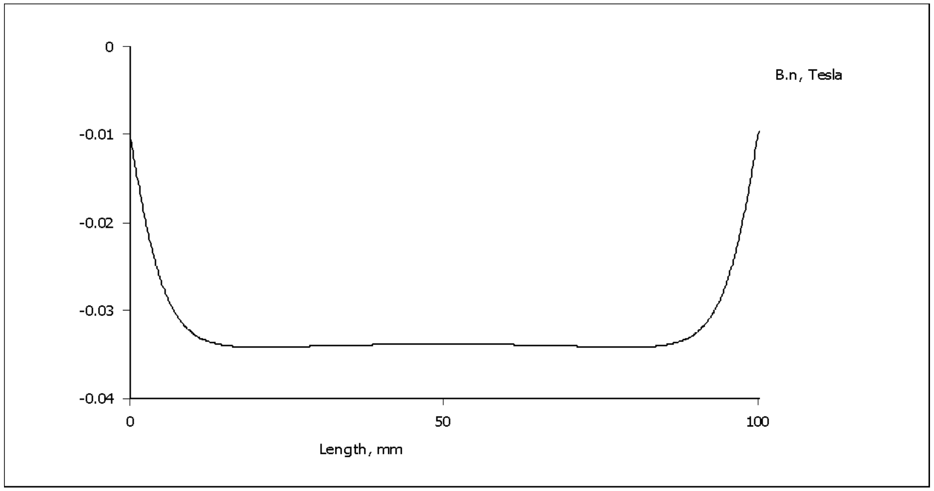
Example 10: Uniform Field Inside Airgap with PMs

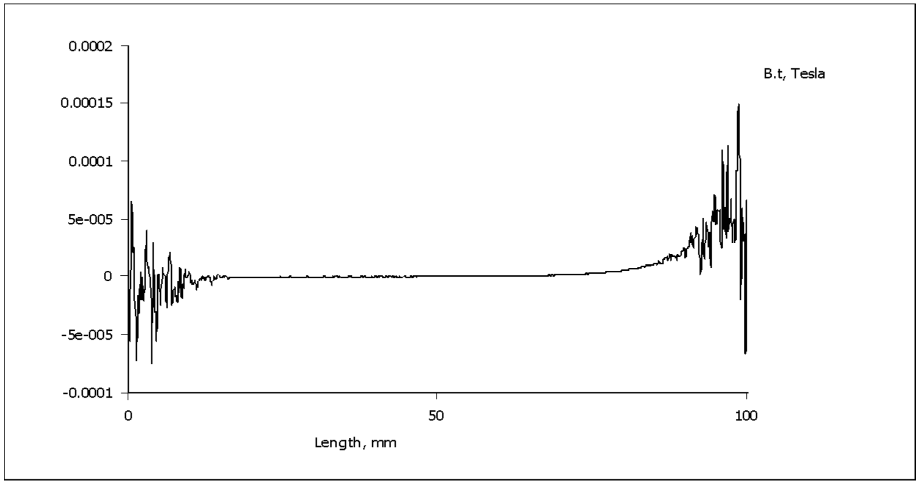
- Goal: generate uniform field inside 100 mm wide gap



Example 10: Vertical and Horizontal Fields

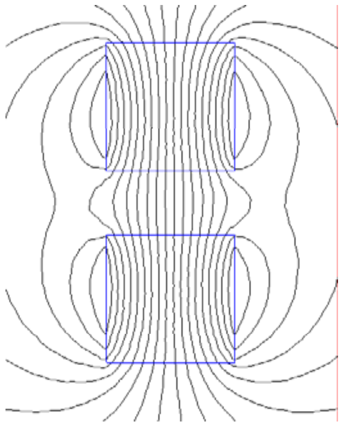
- Goal: generate uniform field inside 100 mm wide gap



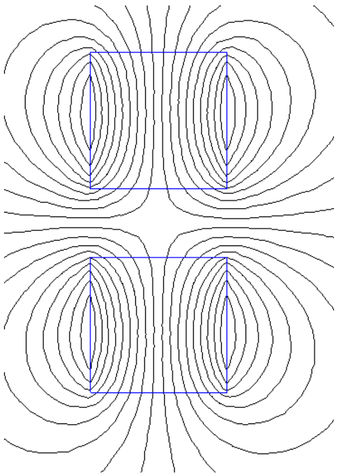


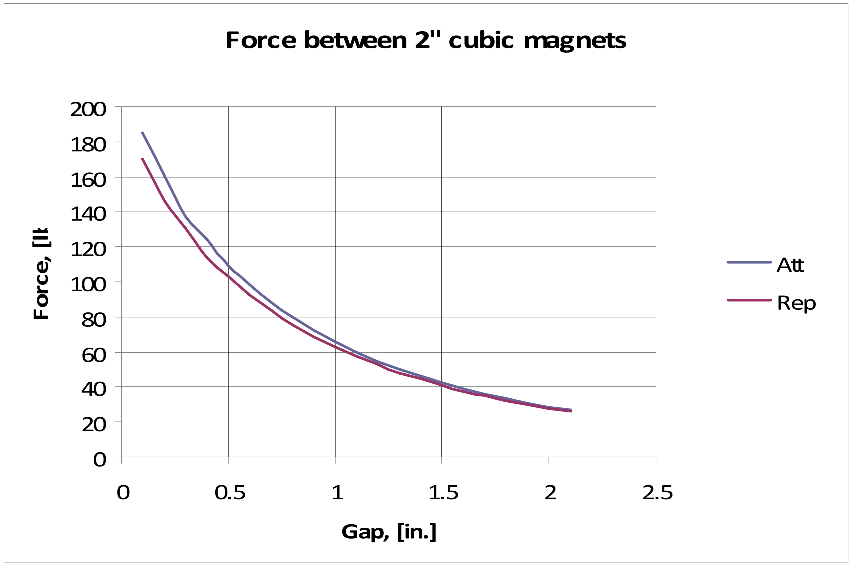
Example 11: Force Between 2" NdFeB Magnet Cubes

Attraction



Repulsion





References

- David Meeker, Ph.D., (Foster-Miller), FEMM (Finite Element Method Magnetics