



# Introduction to Finite-Element-Methods In Electromagnetism (Part 2)

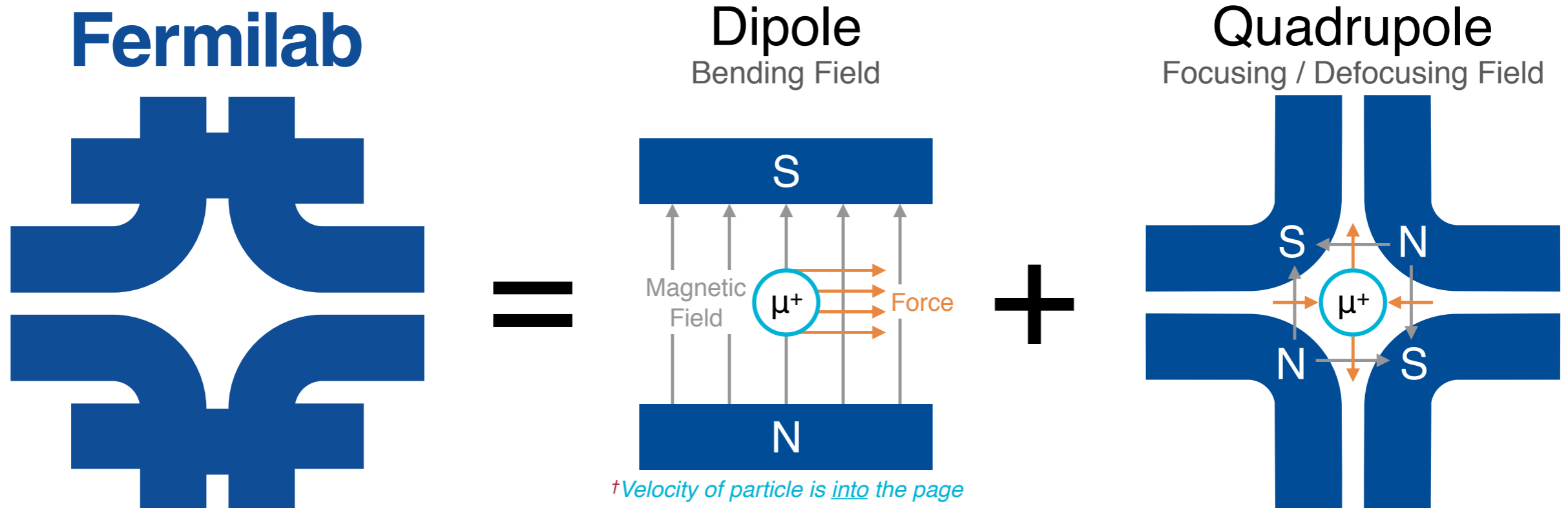
Nathan S. Froemming (nfroemm@fnal.gov)

Northern Illinois University, PHYS 790D

Thu 10 Oct 2019

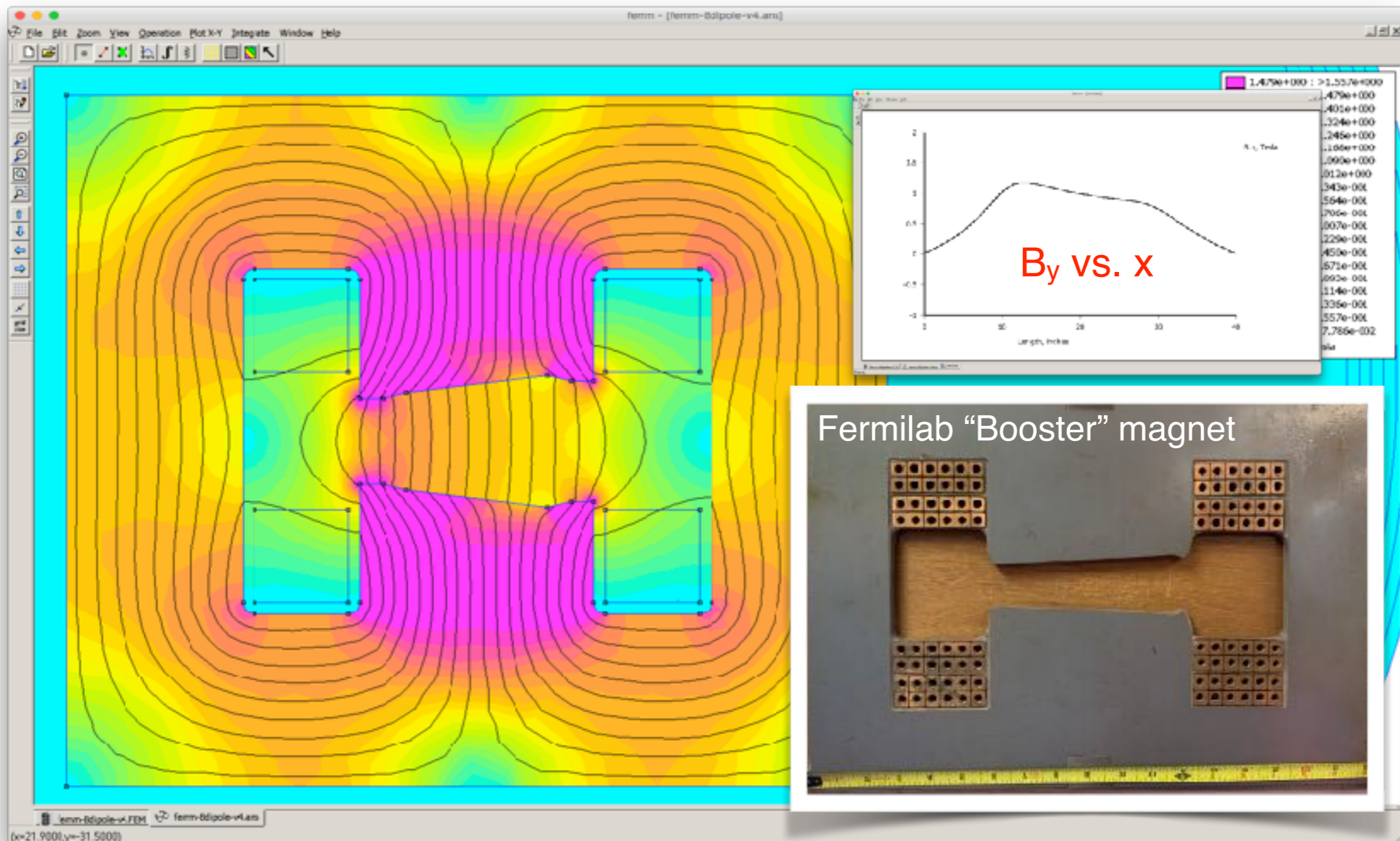
# Fermilab's Logo

- Fun fact: Fermilab's logo is a dipole plus a quadrupole — for good reason!
- Dipoles and quadrupoles are ubiquitous in beamlines since they give rise to constant and linear fields, respectively [=> transport matrices, etc.]



# Main Goal For Today....

- Build a model of a dipole + quadrupole magnet using FEMM

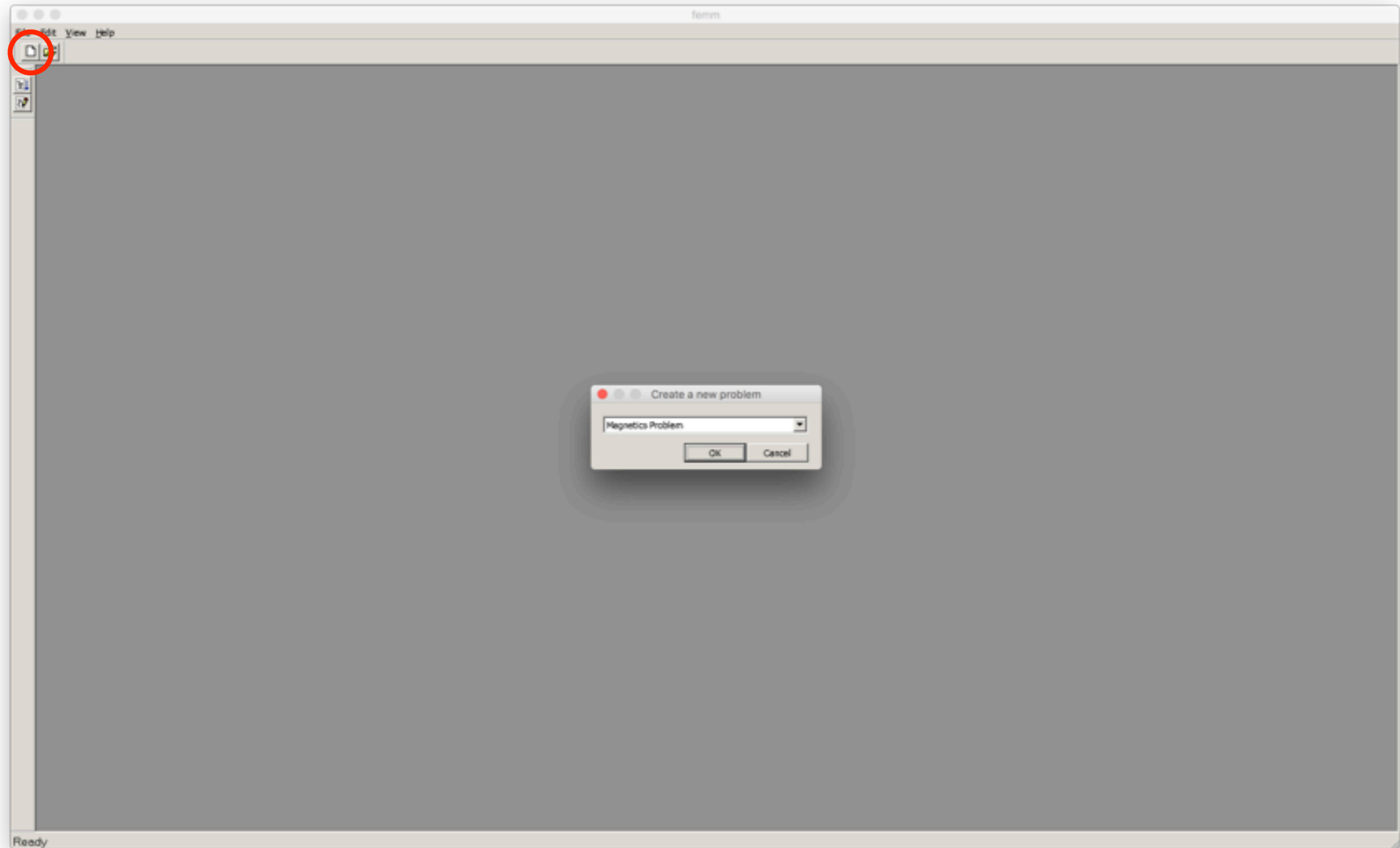


# Outline (Picking Up Where We Left Off Last Time)

- Overview Laplace's equation and solutions
  - Cauchy-Riemann equations; Connection to electromagnetism (EM)
  - Conformal mappings
  - Shortcomings
- Finite-Element methods and codes (OPERA, COMSOL, FEMM, ...)
- Getting FEMM setup on your local machine
- FEMM electric example
  - Problem setup: Electric dipole/quadrupole
  - How to extract the potential/E-field from FEMM
- **FEMM magnetic example**
  - Problem setup: H-dipole + quadrupole, pole-tip design, combined-function magnet
  - How to extract the potential/B-field from FEMM
- Pro Tips And Tricks
  - Scripting in `lua` and `python`; Jupyter notebooks; WebPlotDigitizer; etc.
- Conclusions

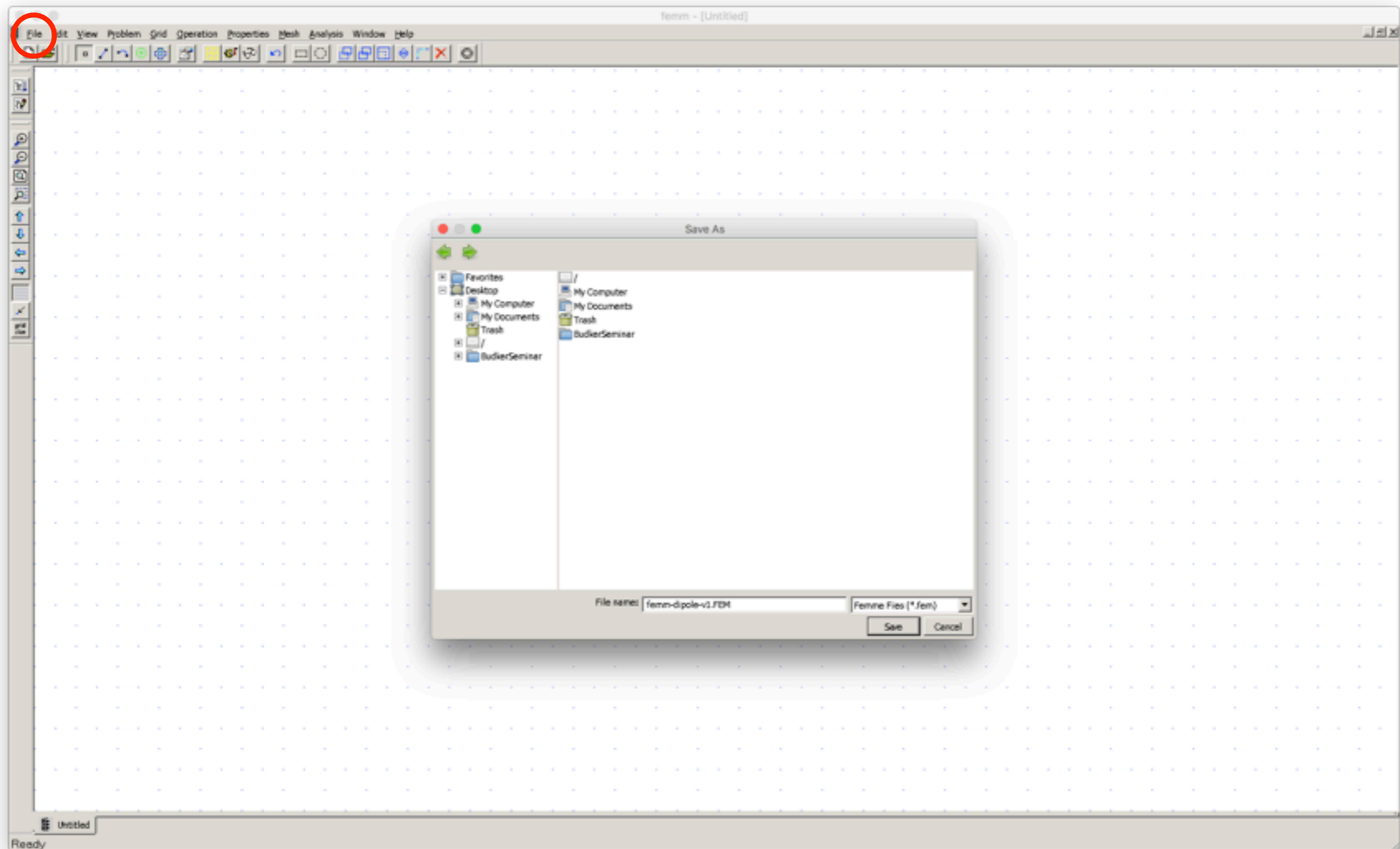
# FEMM Tutorial: Magnetostatics

- Open FEMM, and create a new magnetics problem



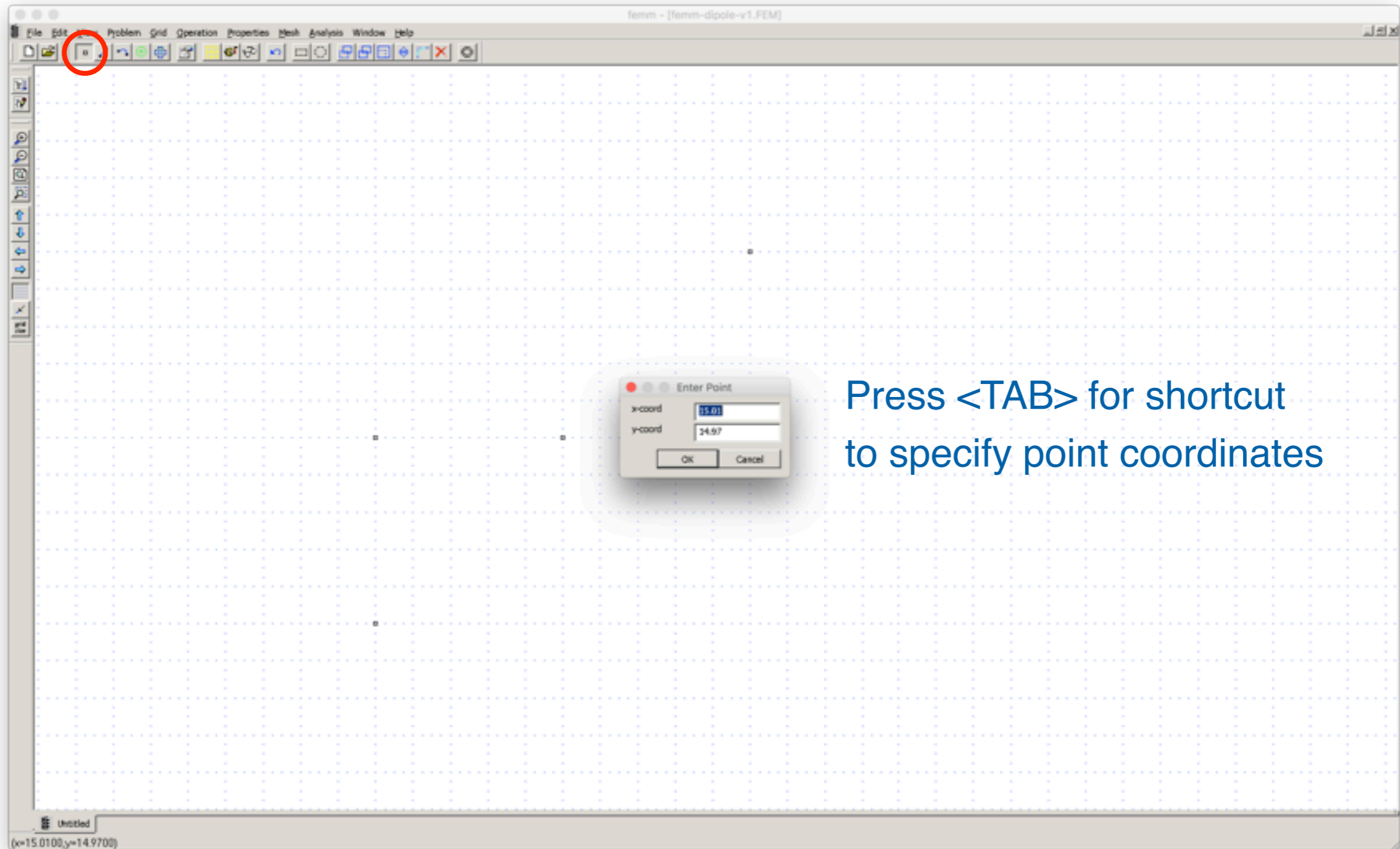
# FEMM Tutorial: Magnetostatics

- Always save your work (e.g. “femm-hdipole-v1” )



# FEMM Tutorial: Magnetostatics

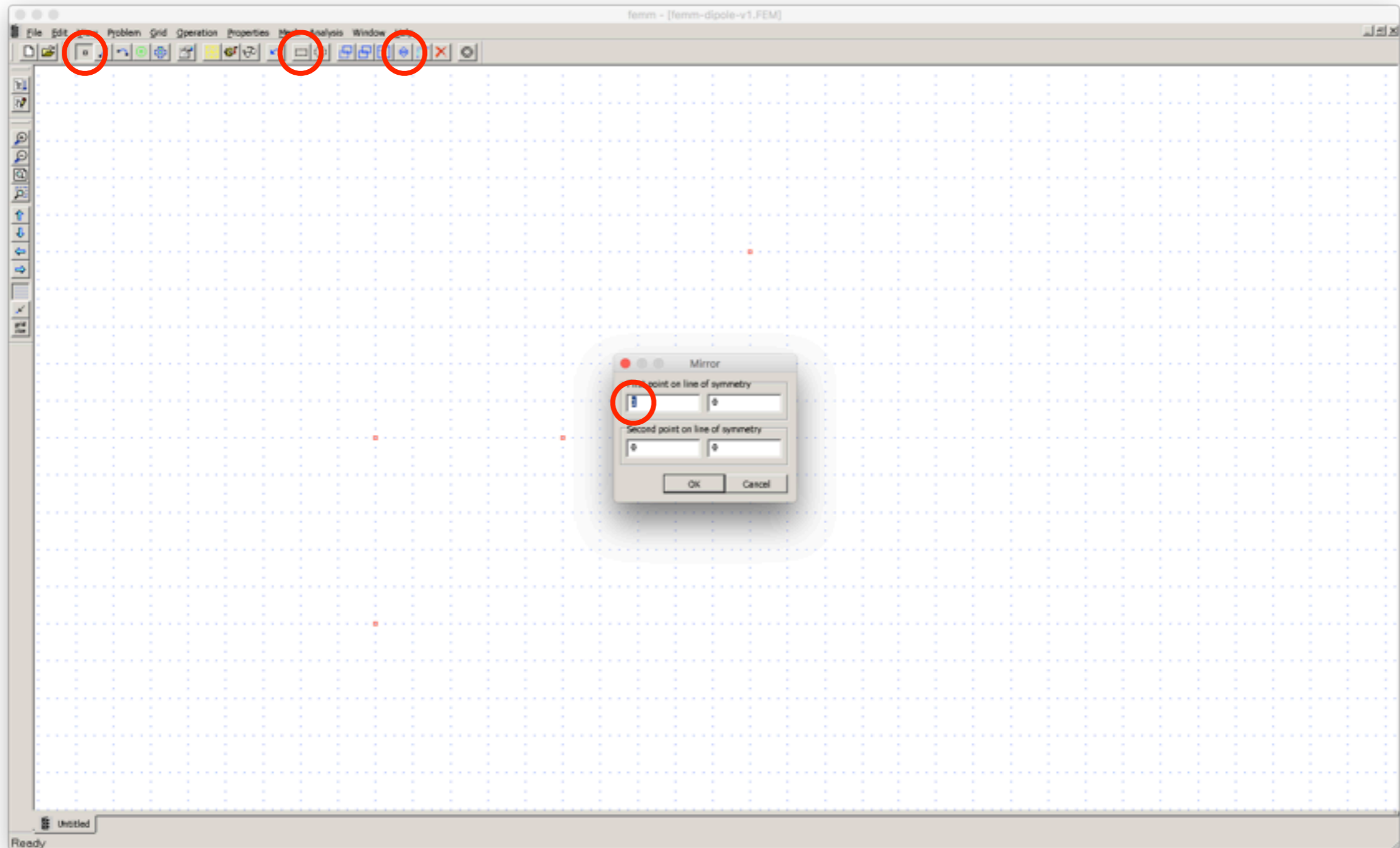
- Add 4 vertices at  $\{(10, 5), (10, 15), (20, 15), (35, 30)\}$ . Length units in “Problem” setup.



Press <TAB> for shortcut  
to specify point coordinates

# FEMM Tutorial: Magnetostatics

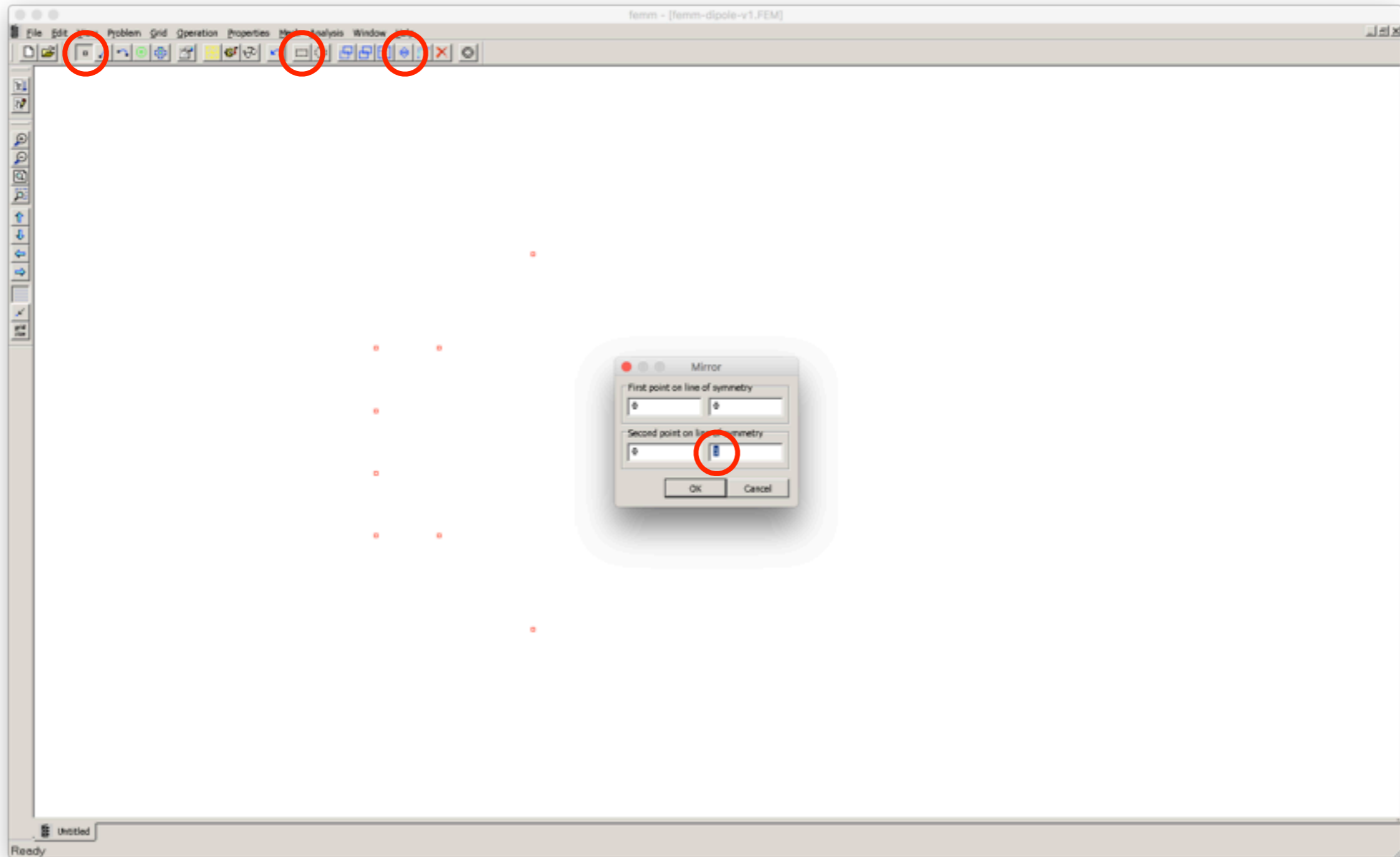
- Select all 4 vertices. Mirror about the x-axis





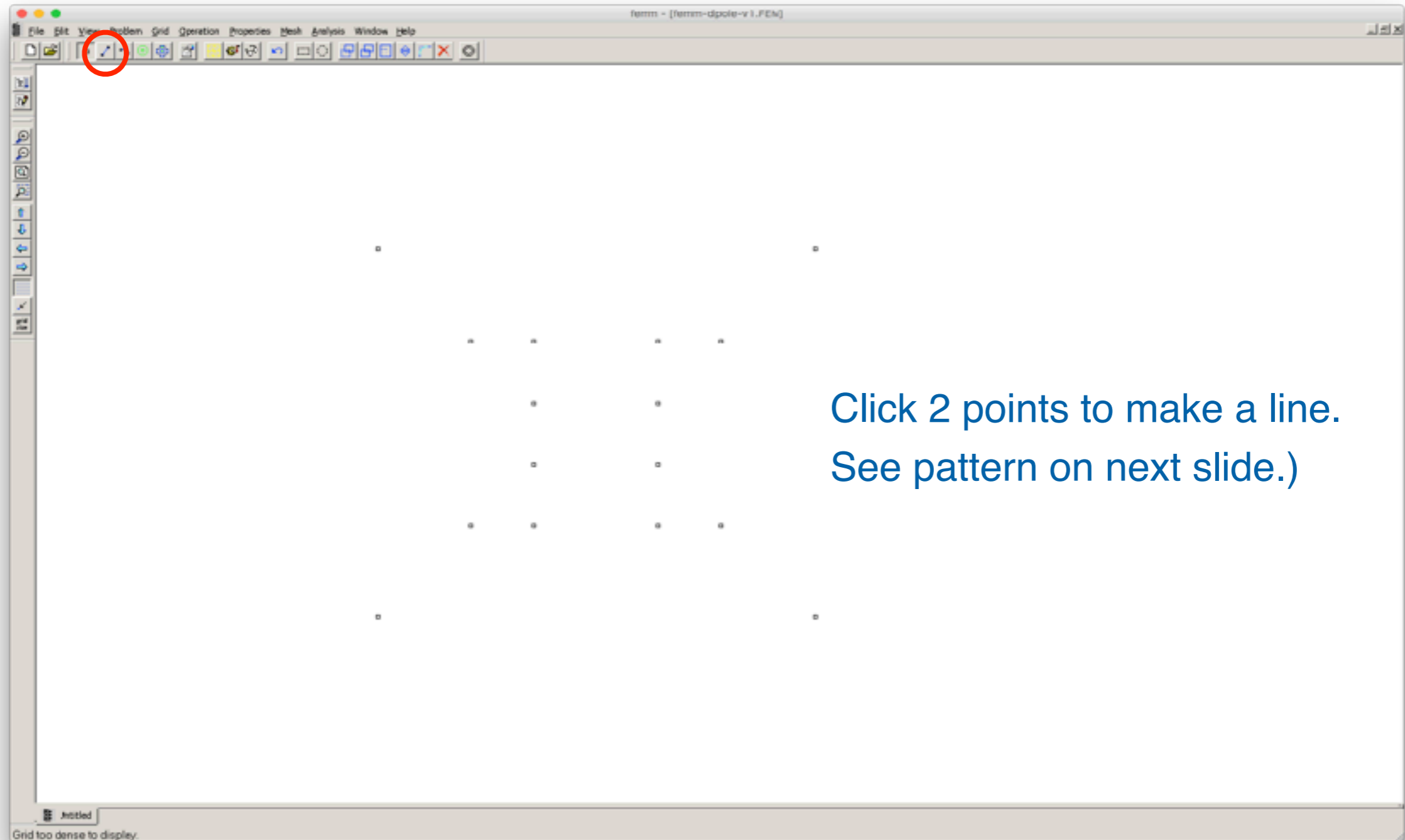
# FEMM Tutorial: Magnetostatics

- Select all 8 vertices. Mirror about the y-axis



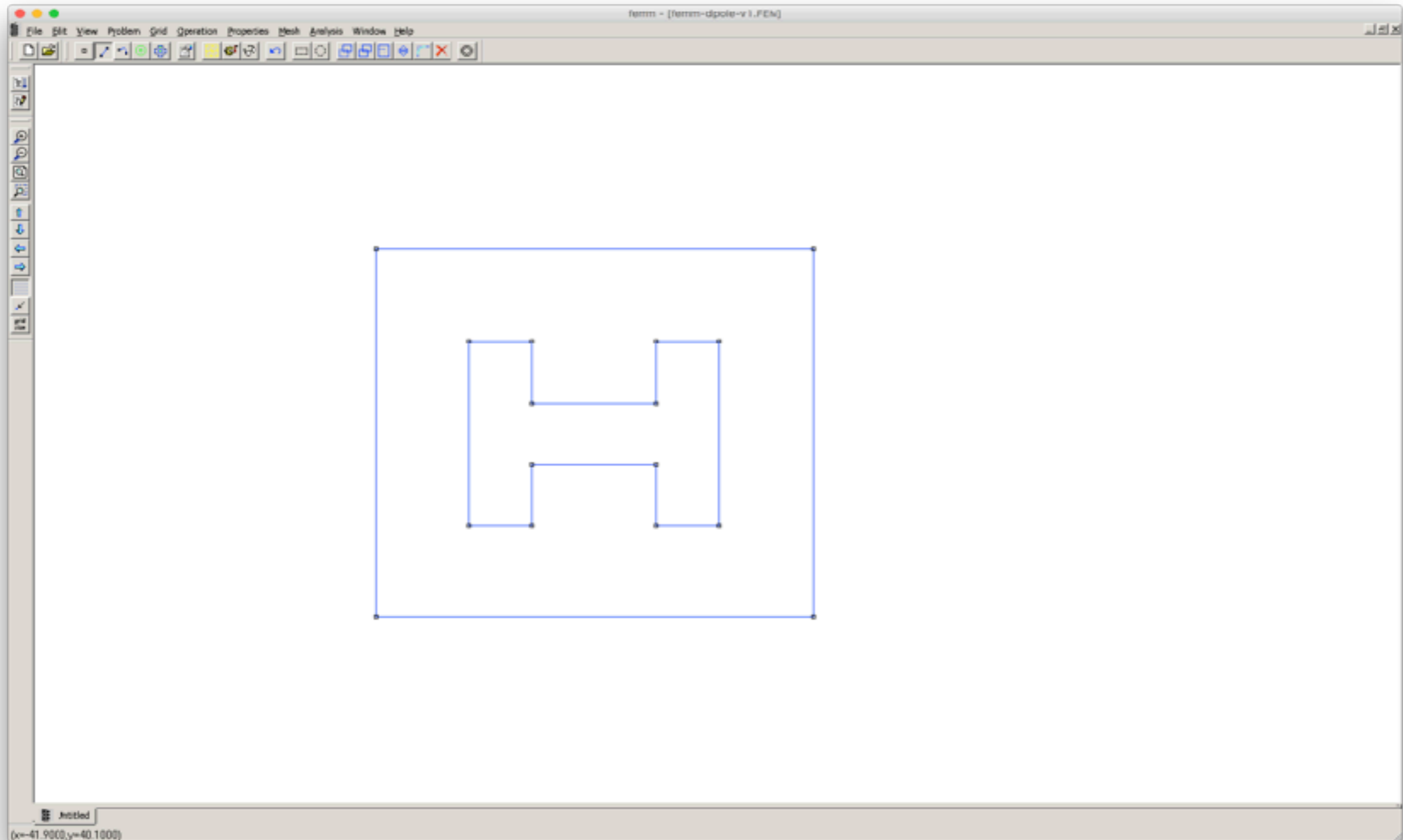
# FEMM Tutorial: Magnetostatics

- Join vertices with line segments in the shape of and “H-magnet”



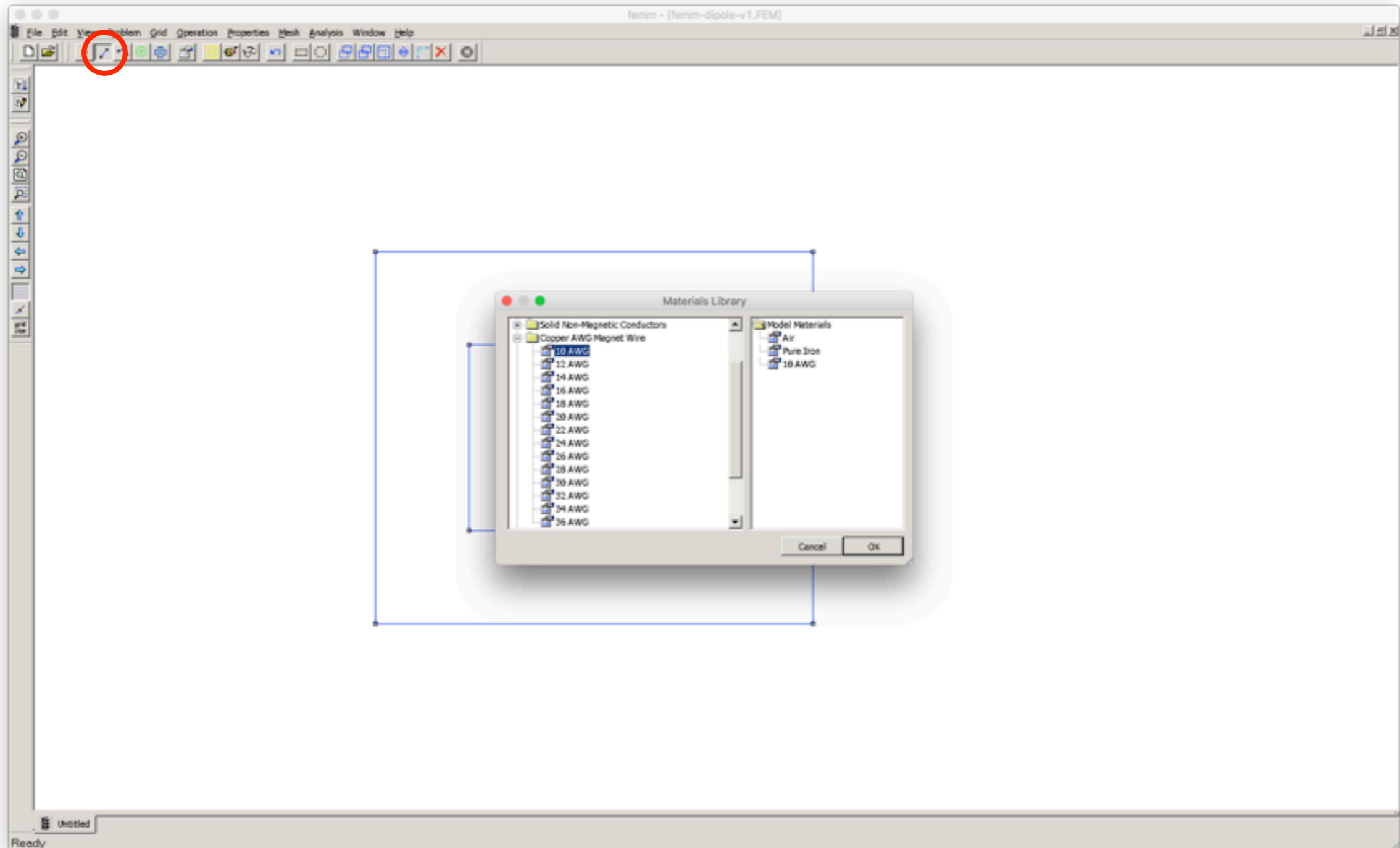
# FEMM Tutorial: Magnetostatics

- Join vertices with line segments in the shape of and “H-magnet”



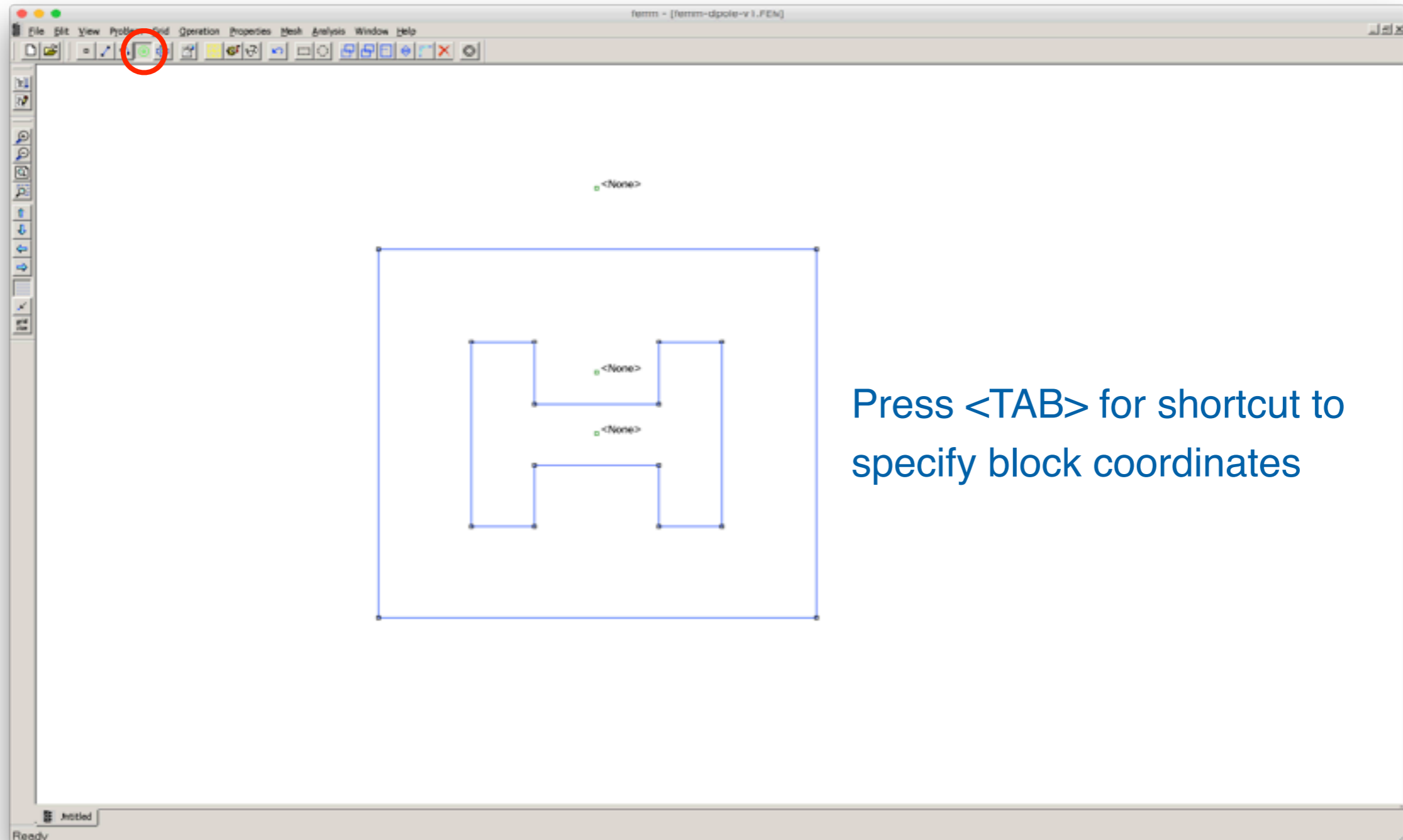
# FEMM Tutorial: Magnetostatics

- Add materials from Materials Library to the problem definition



# FEMM Tutorial: Magnetostatics

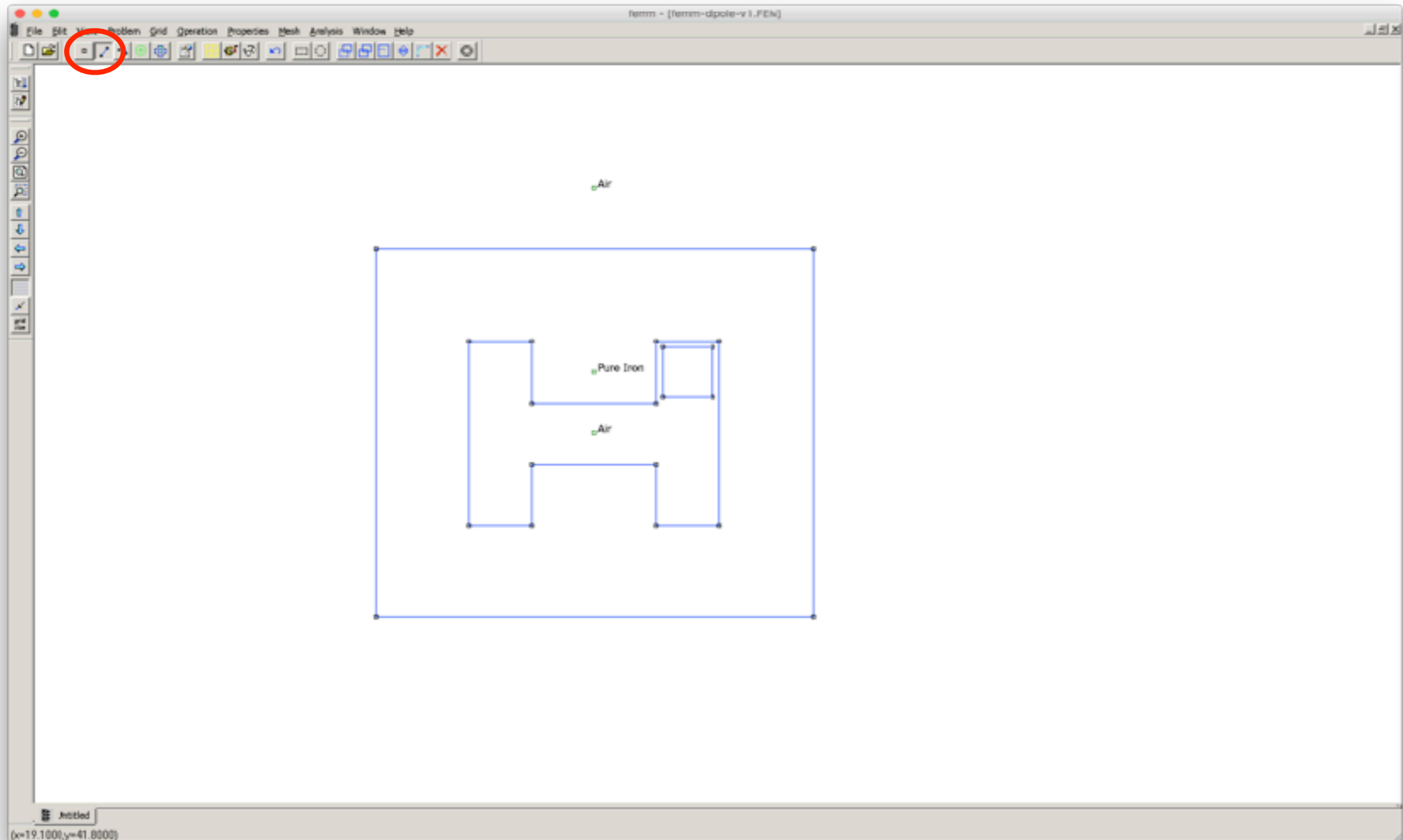
- Add block labels for iron, air. Apply materials to block labels.



Press <TAB> for shortcut to specify block coordinates

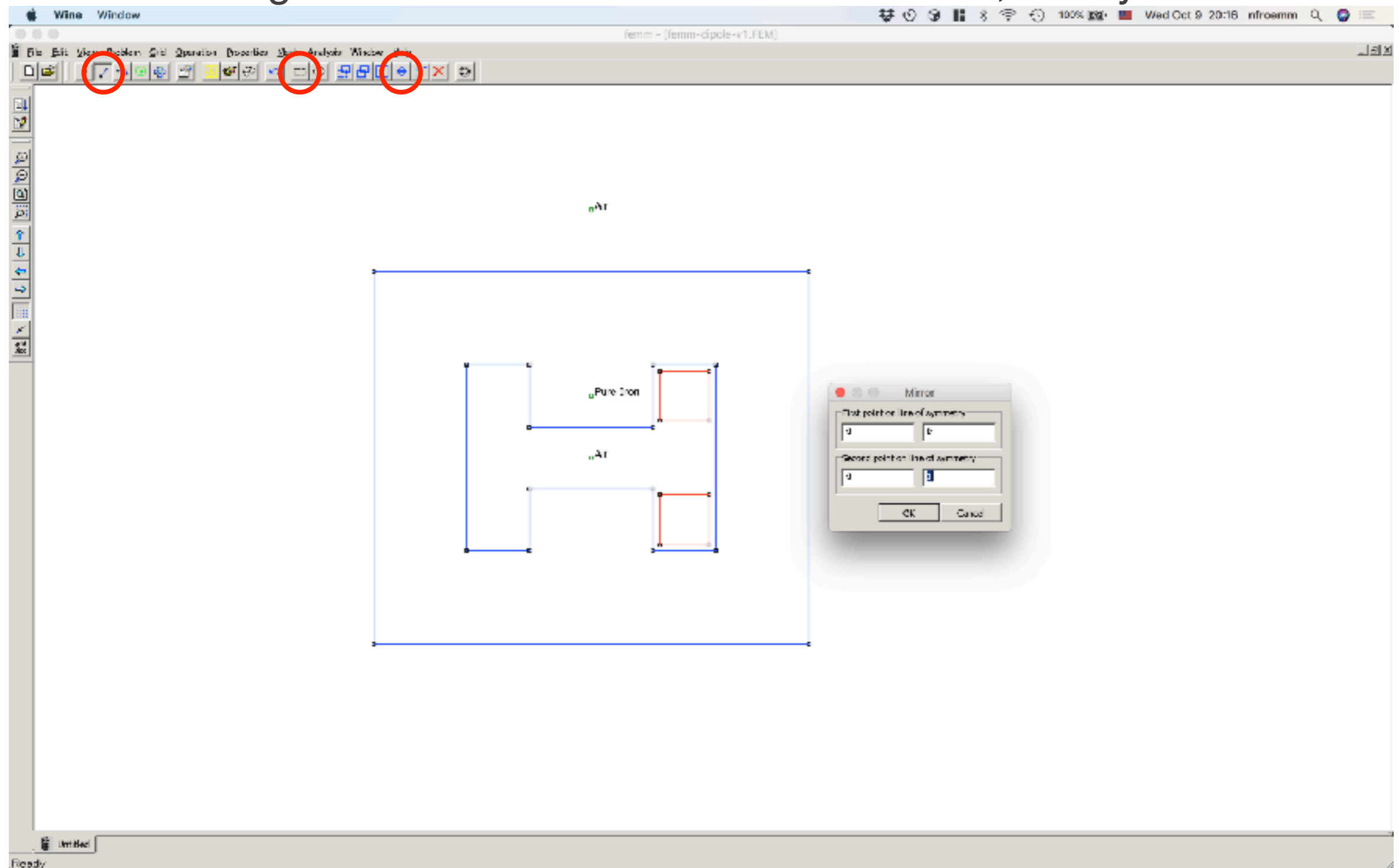
# FEMM Tutorial: Magnetostatics

- Add vertices for coils at  $\{(11,6), (11,14), (19,14), (19,6)\}$ . Join with lines.



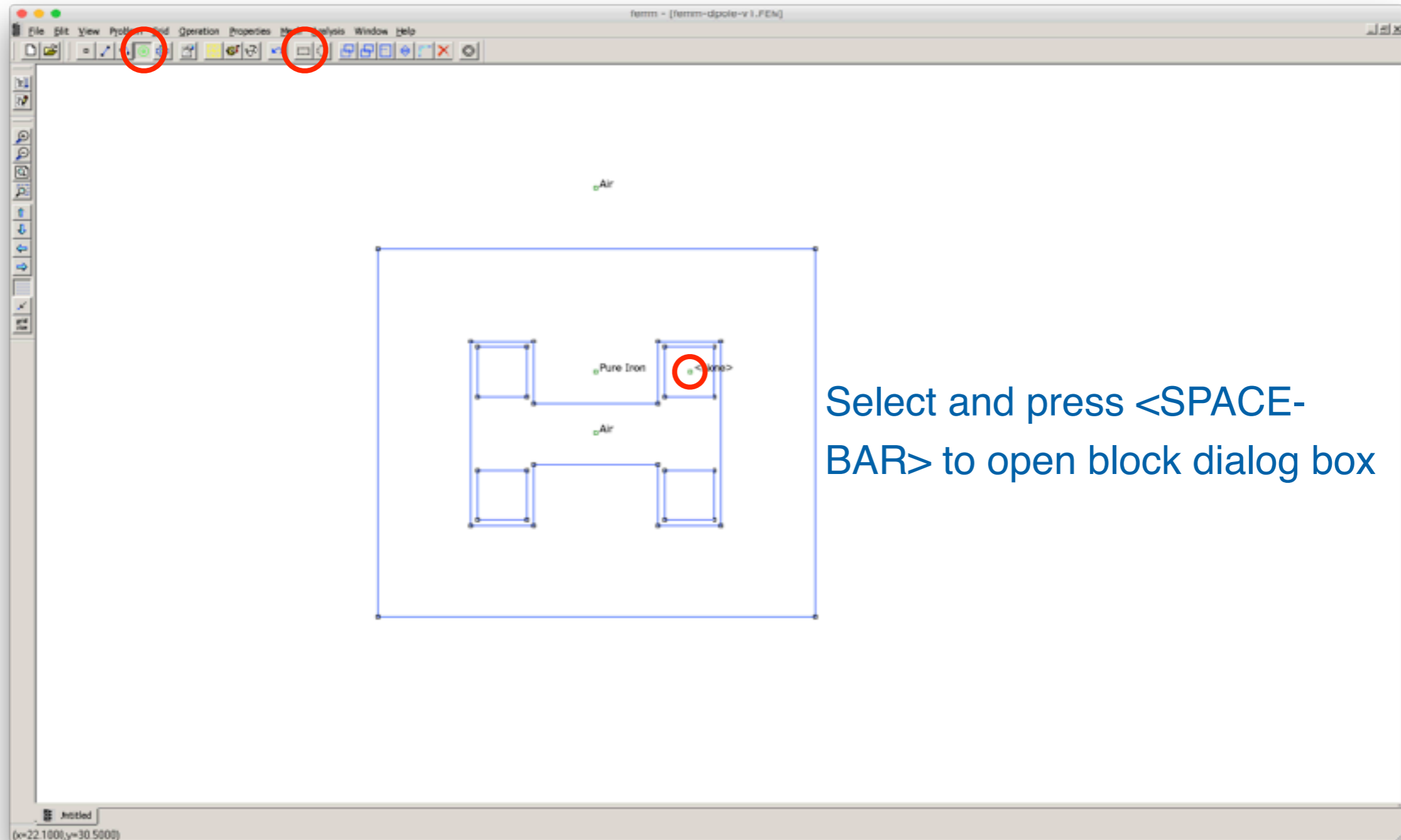
# FEMM Tutorial: Magnetostatics

- Select 4 line segments of coil and mirror about x-axis, then y-axis



# FEMM Tutorial: Magnetostatics

- Add block label at (15, 10) for wires/current

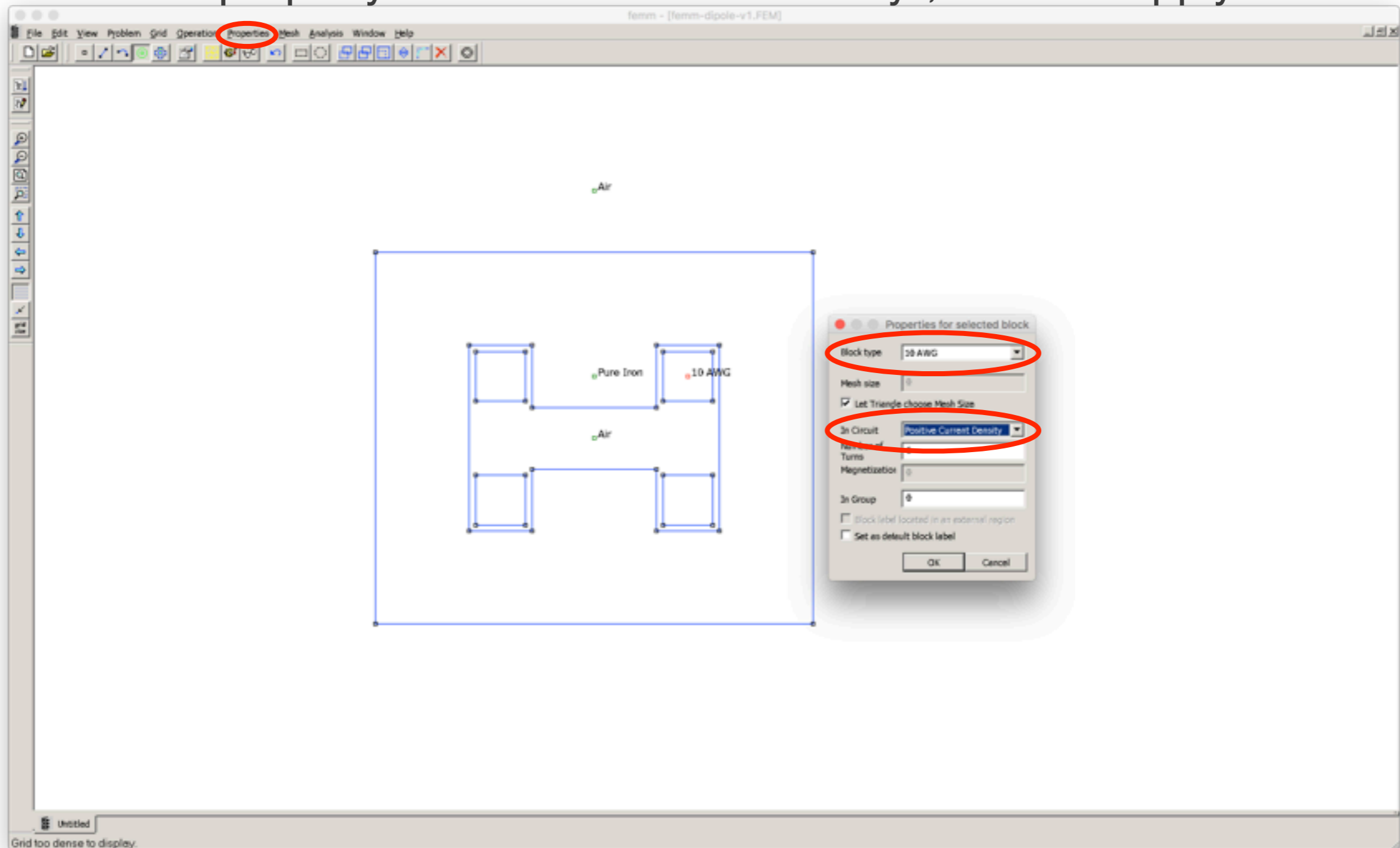


Select and press <SPACE-BAR> to open block dialog box



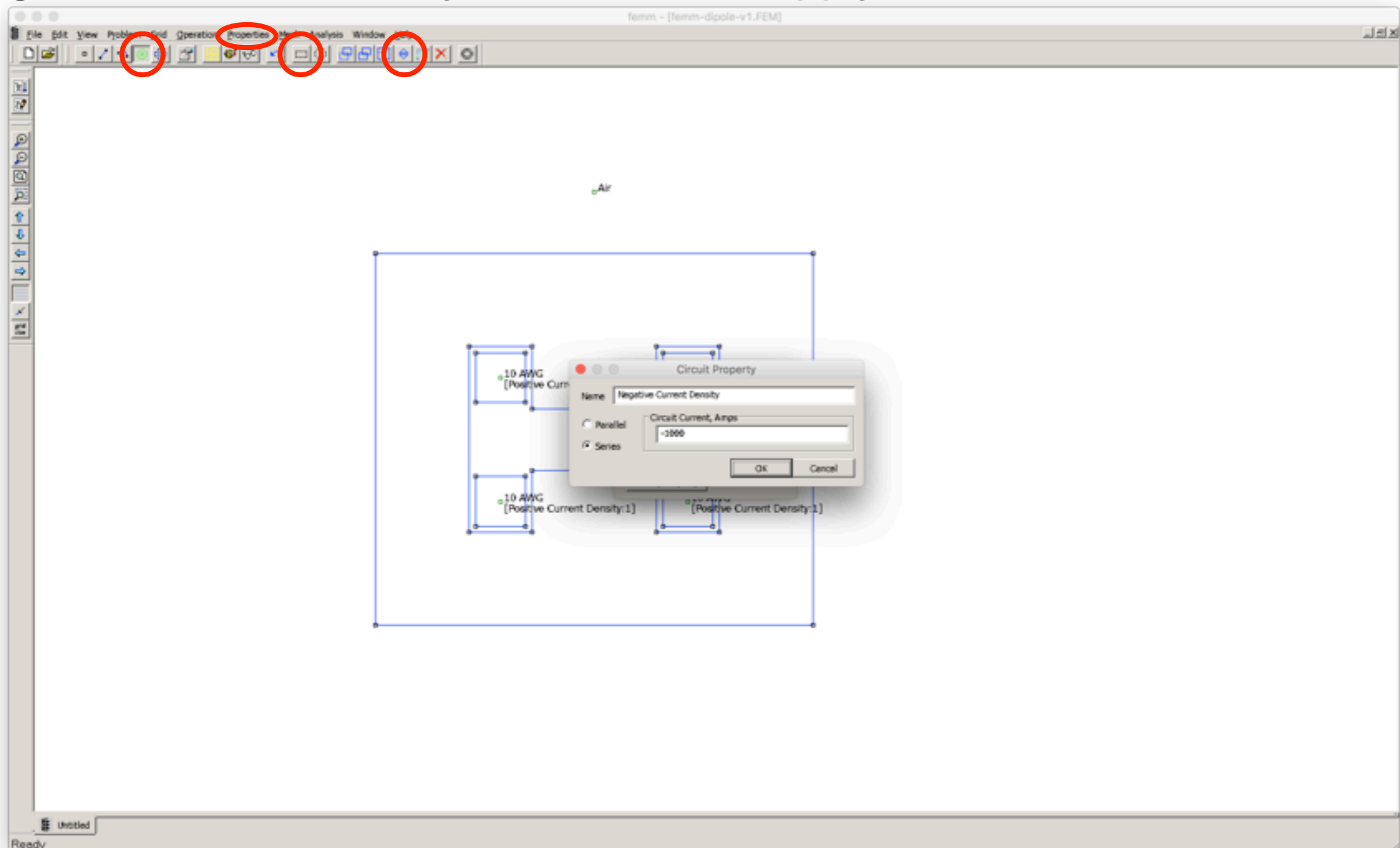
# FEMM Tutorial: Magnetostatics

- Apply material “10 AWG” copper wire to block
- Create circuit property “Positive Current Density”, 1000A. Apply to block.



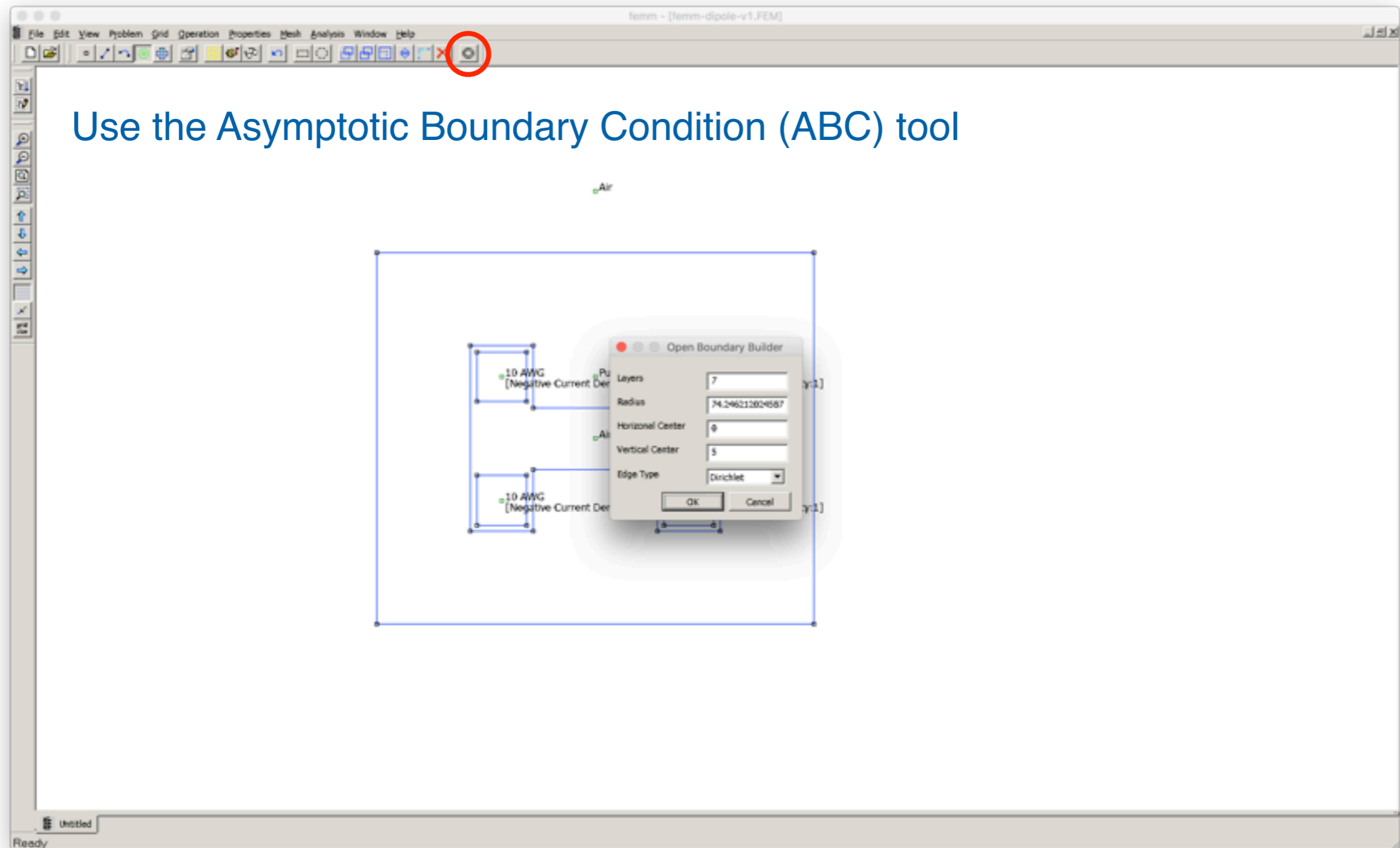
# FEMM Tutorial: Magnetostatics

- Mirror block label about horizontal and vertical axes. Add circuit property “Negative Current Density”, -1000A, and apply to left-most blocks (“coils”)



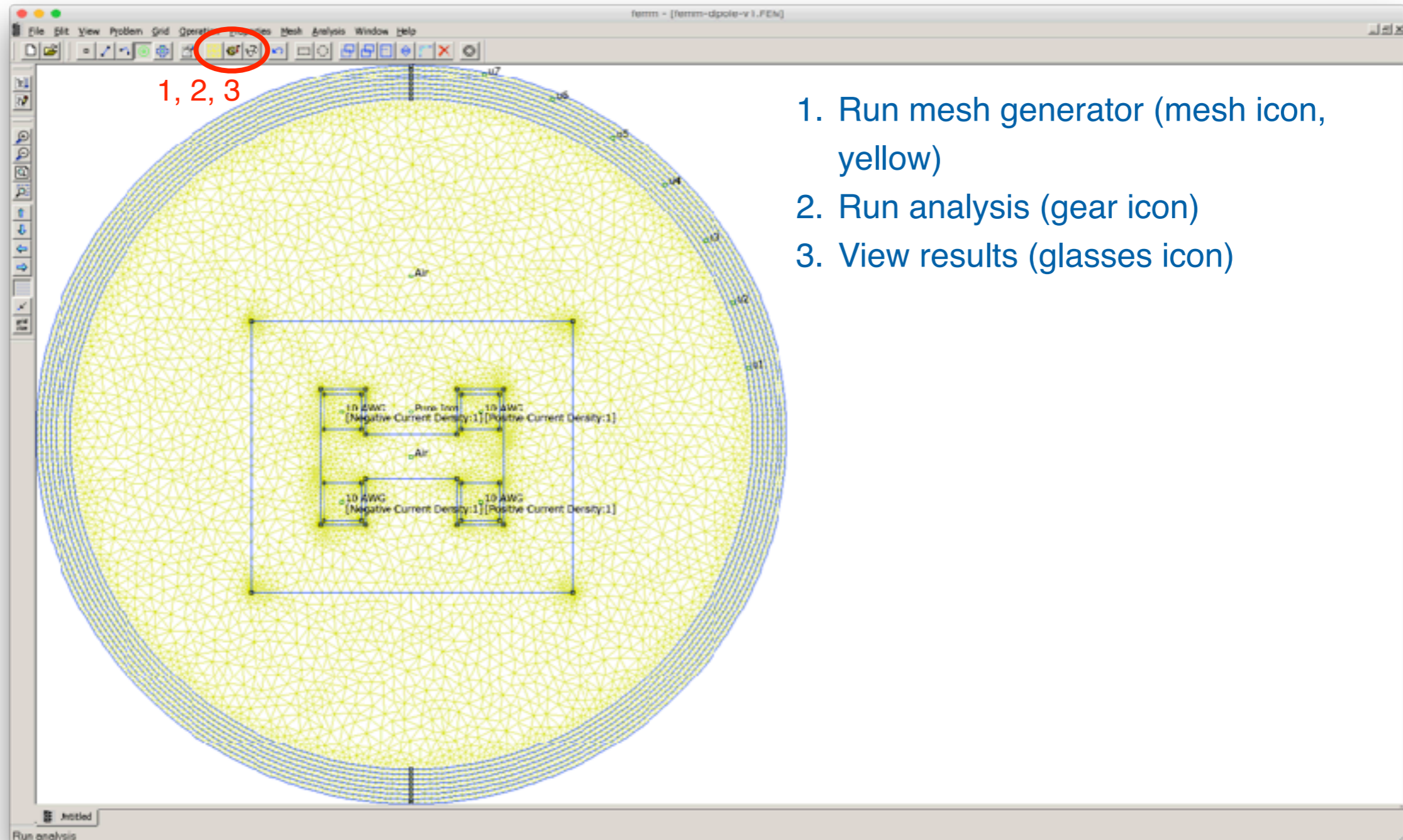
# FEMM Tutorial: Magnetostatics

- Add an “open” boundary condition at infinity



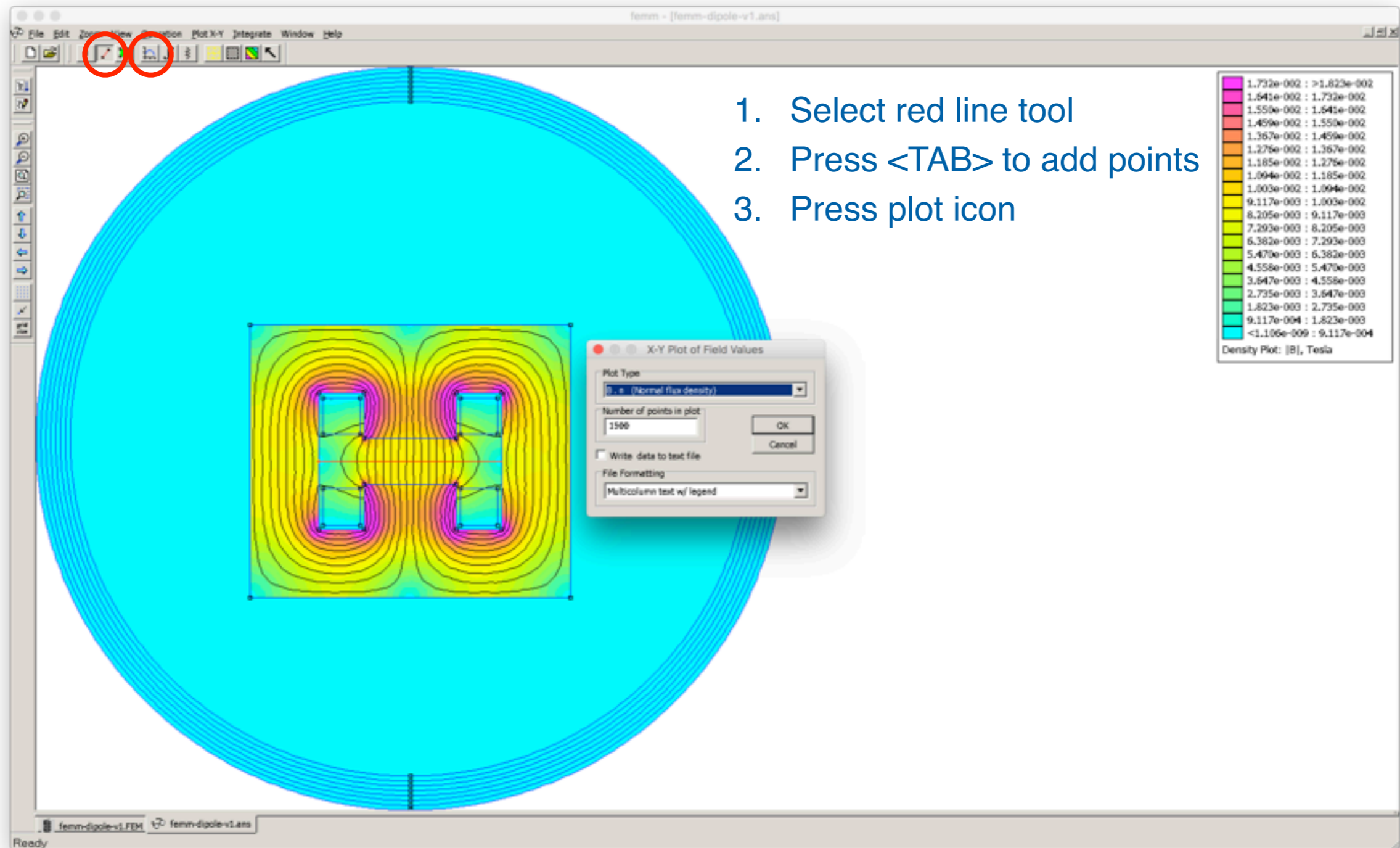
# FEMM Tutorial: Magnetostatics

- Mesh and solve the problem



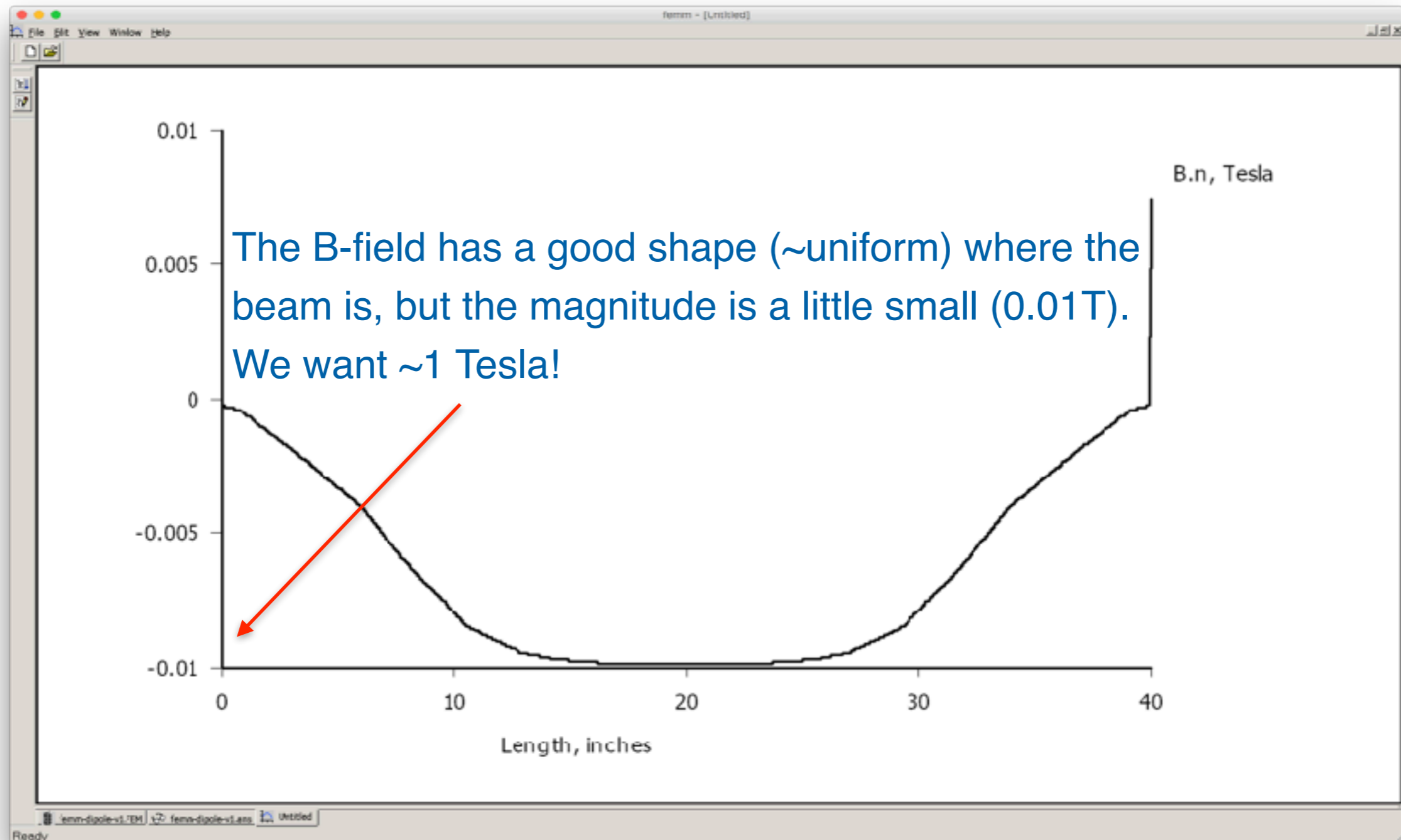
# FEMM Tutorial: Magnetostatics

- Plot the B-field from  $\{(-20, 0), (+20, 0)\}$  in the horizontal midplane



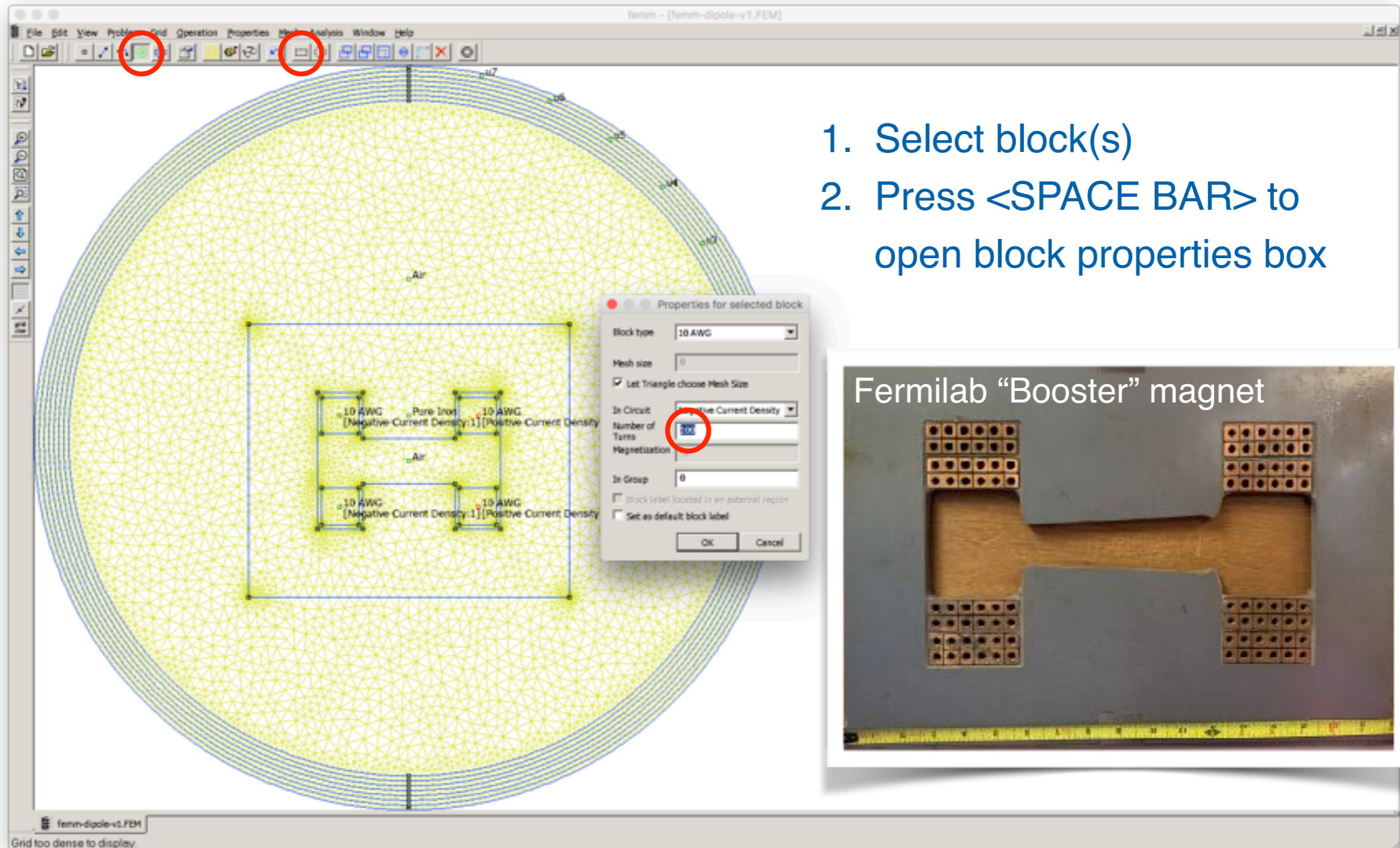
# FEMM Tutorial: Magnetostatics

- Our first B-field result! 👍😊



# FEMM Tutorial: Magnetostatics

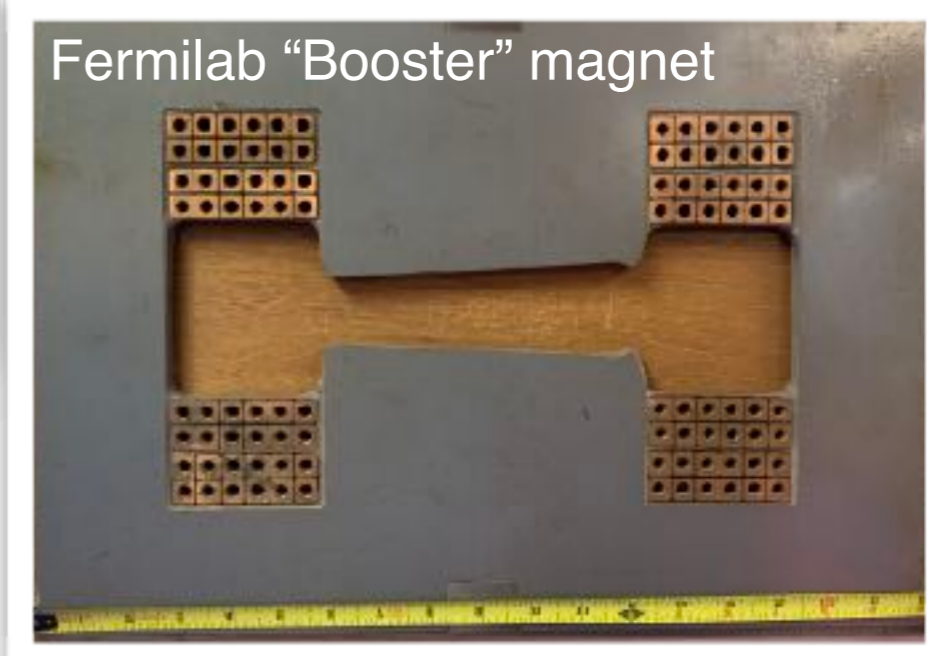
- Increase # current wrappings to “100 turns”. (Flip polarity if desired.)



The screenshot shows the FEMM software interface. The main window displays a circular magnetostatic model with a yellow triangular mesh. A central rectangular region contains four current-carrying blocks labeled "10 AWG" with "Negative Current Density" and "Positive Current Density" labels. A "Properties for selected block" dialog box is open, showing the "Number of Turns" field set to "100", which is circled in red. The dialog also shows "Block type" as "10 AWG" and "Mesh size" as "0".

1. Select block(s)
2. Press <SPACE BAR> to open block properties box

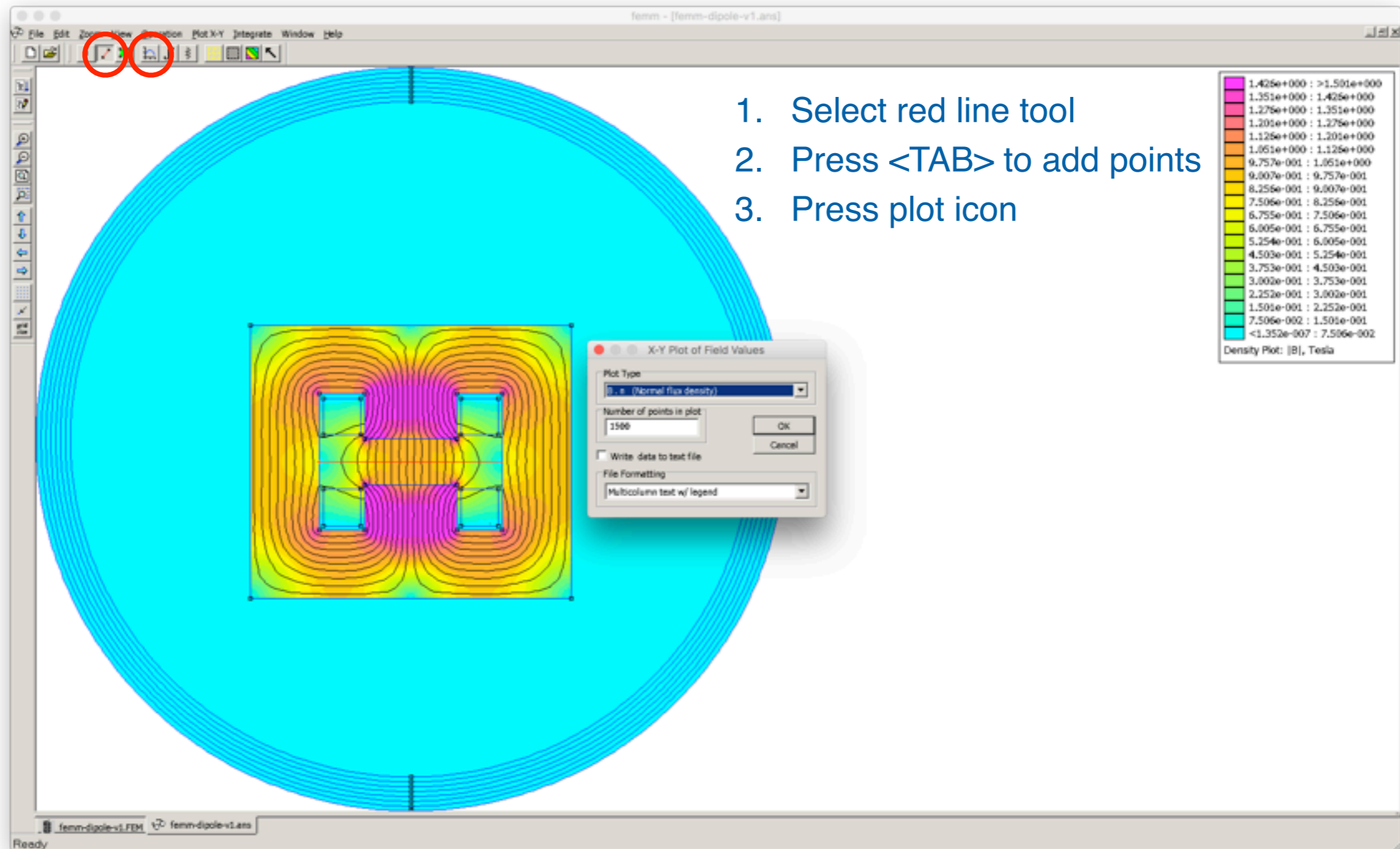
Fermilab “Booster” magnet



The photograph shows the physical Fermilab “Booster” magnet assembly, which is a large, rectangular, dark-colored metal structure with a central cutout. It is surrounded by a grid of copper-colored electrical terminals. A yellow ruler is placed at the bottom for scale.

# FEMM Tutorial: Magnetostatics

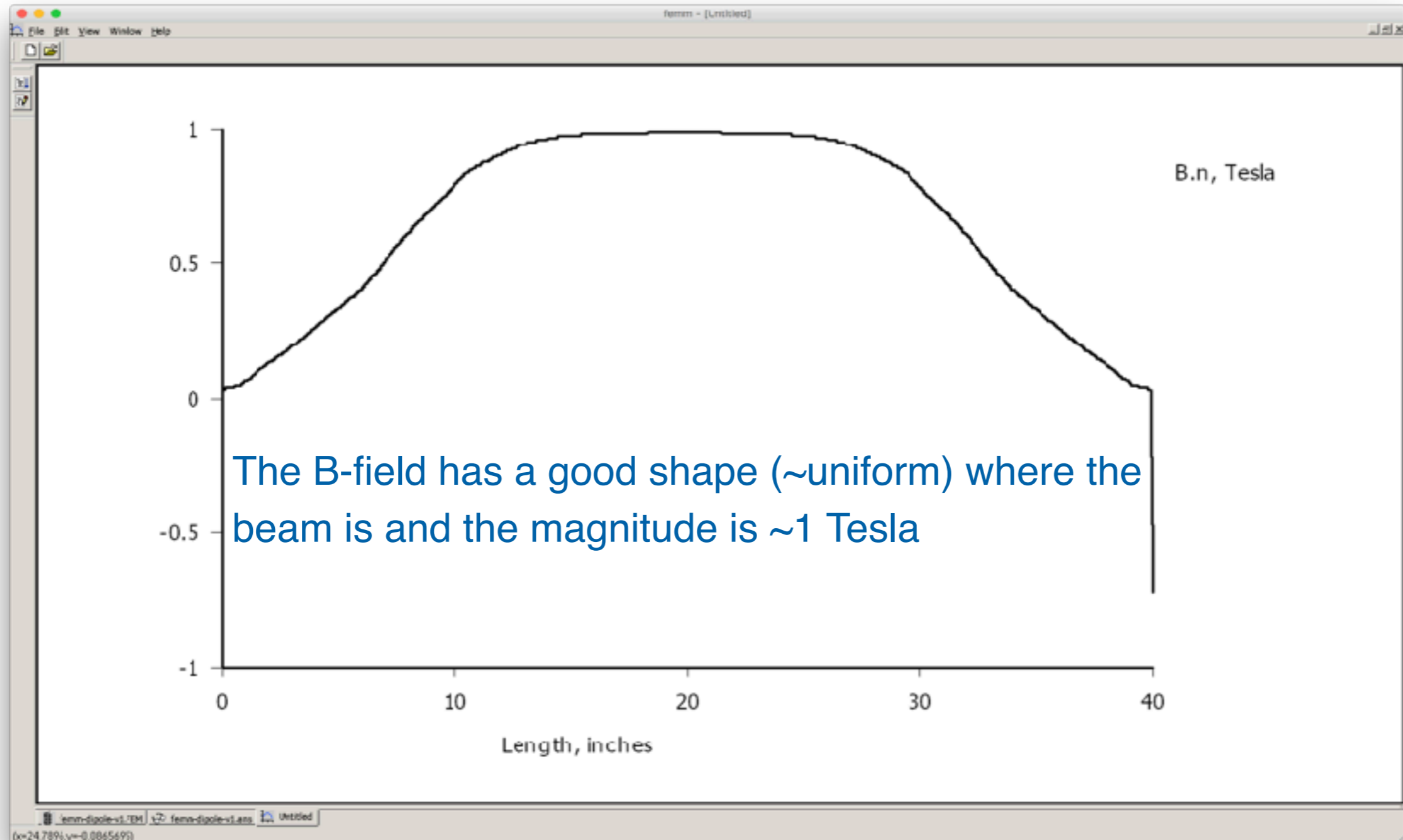
- Mesh, solve, and plot B-field in horizontal midplane





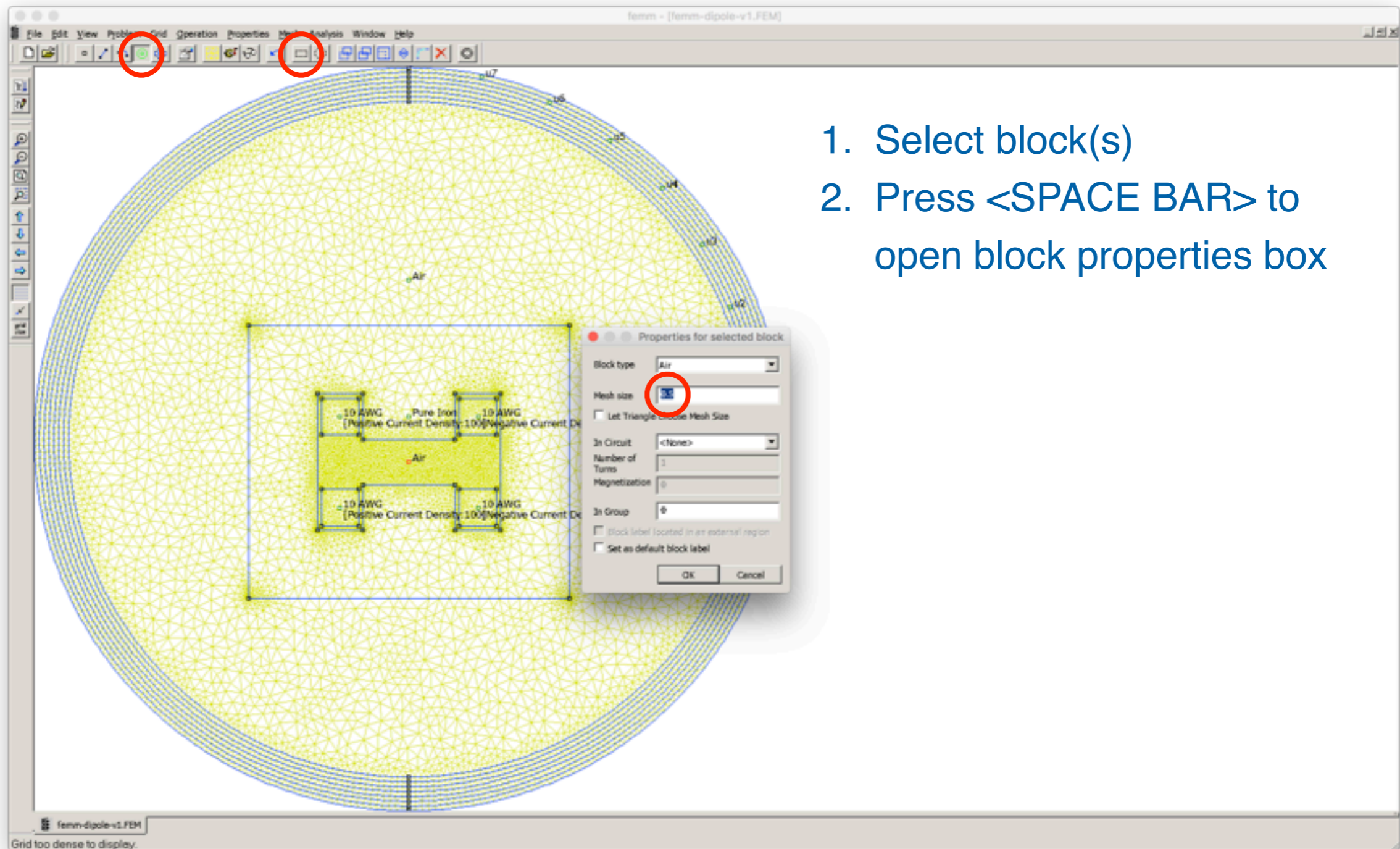
# FEMM Tutorial: Magnetostatics

- Wow, this is starting to look pretty good! 👍 😊



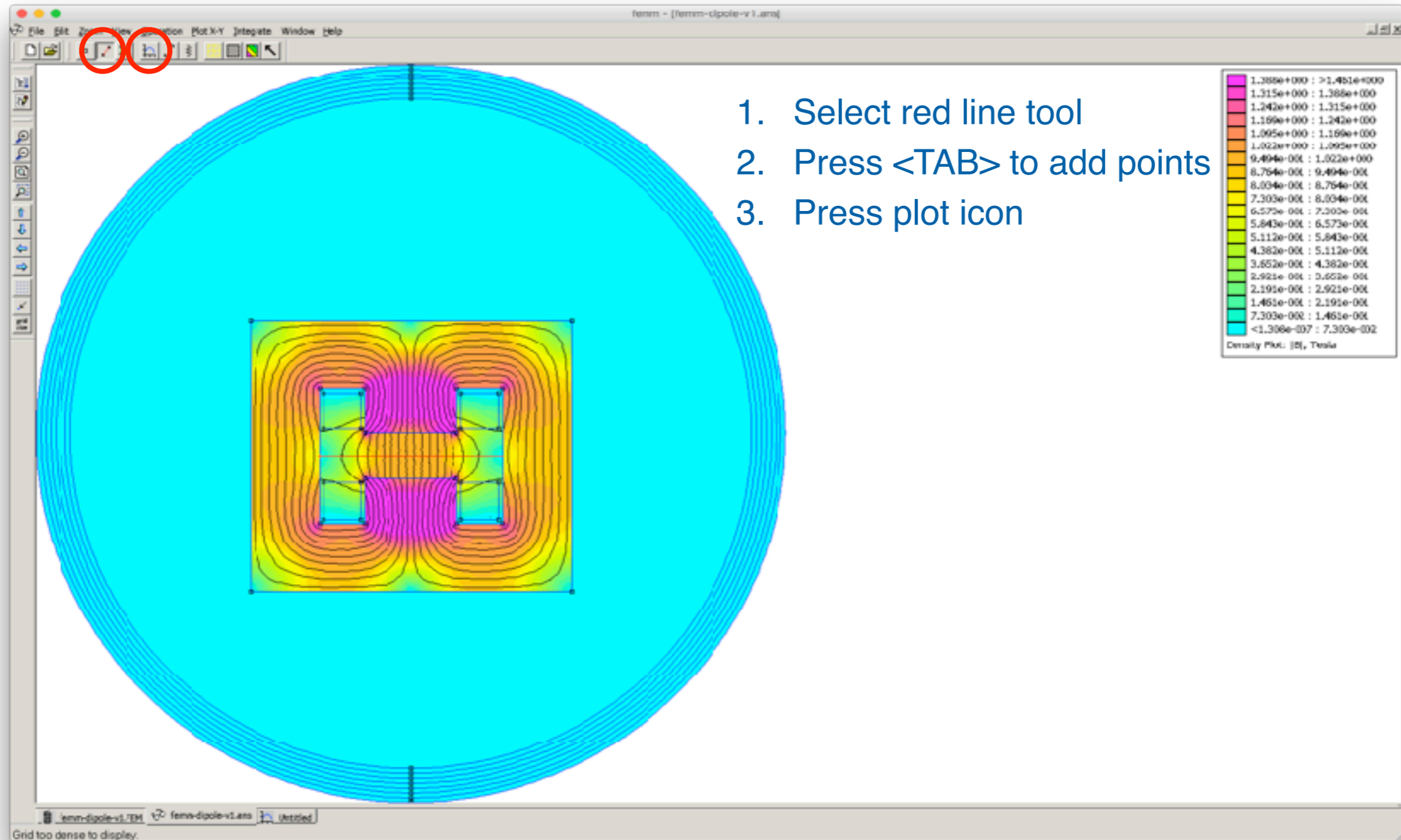
# FEMM Tutorial: Magnetostatics

- Pro Tip: Increase mesh density in field region of interest for increased field quality



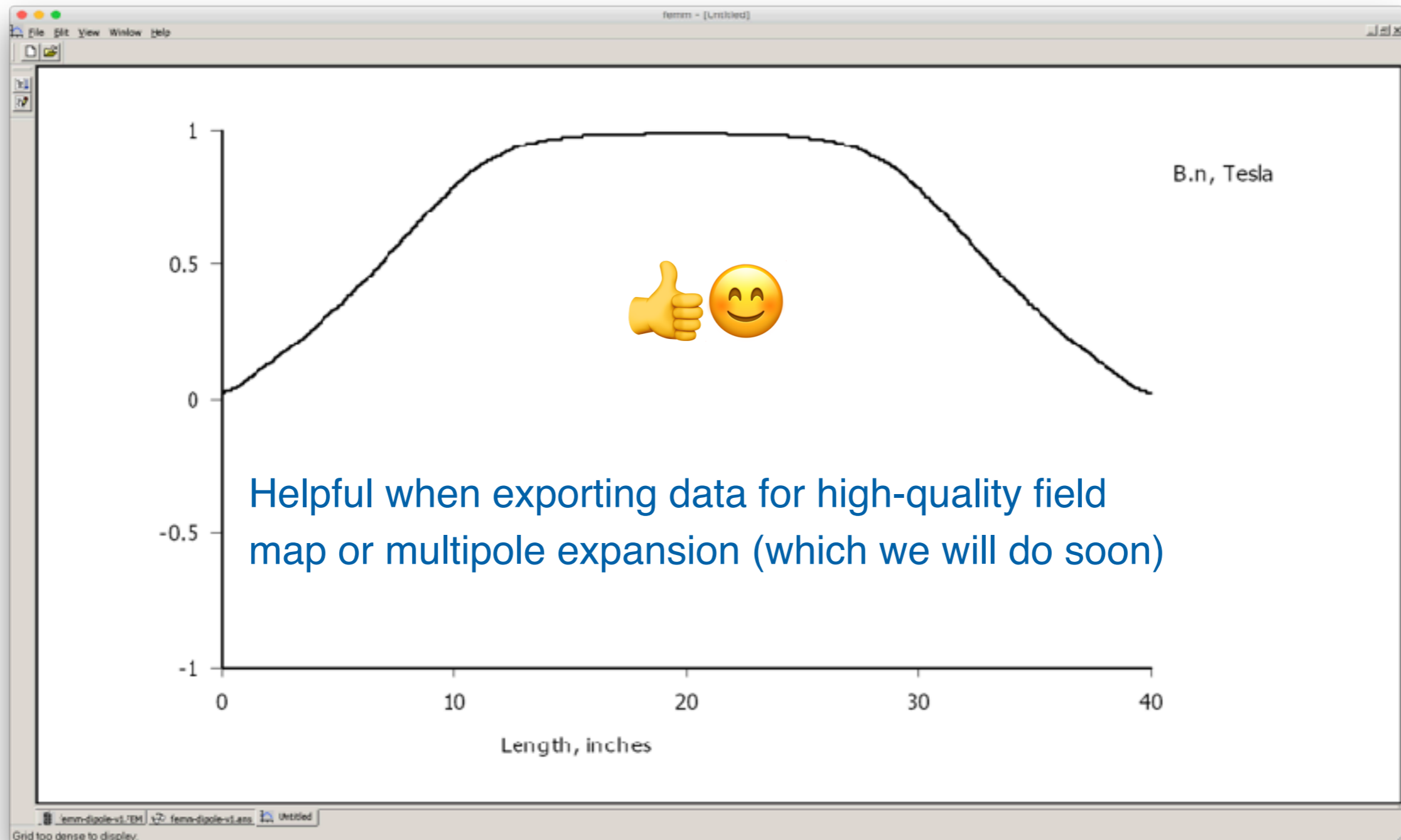
# FEMM Tutorial: Magnetostatics

- Mesh, solve, and plot B-field in horizontal midplane



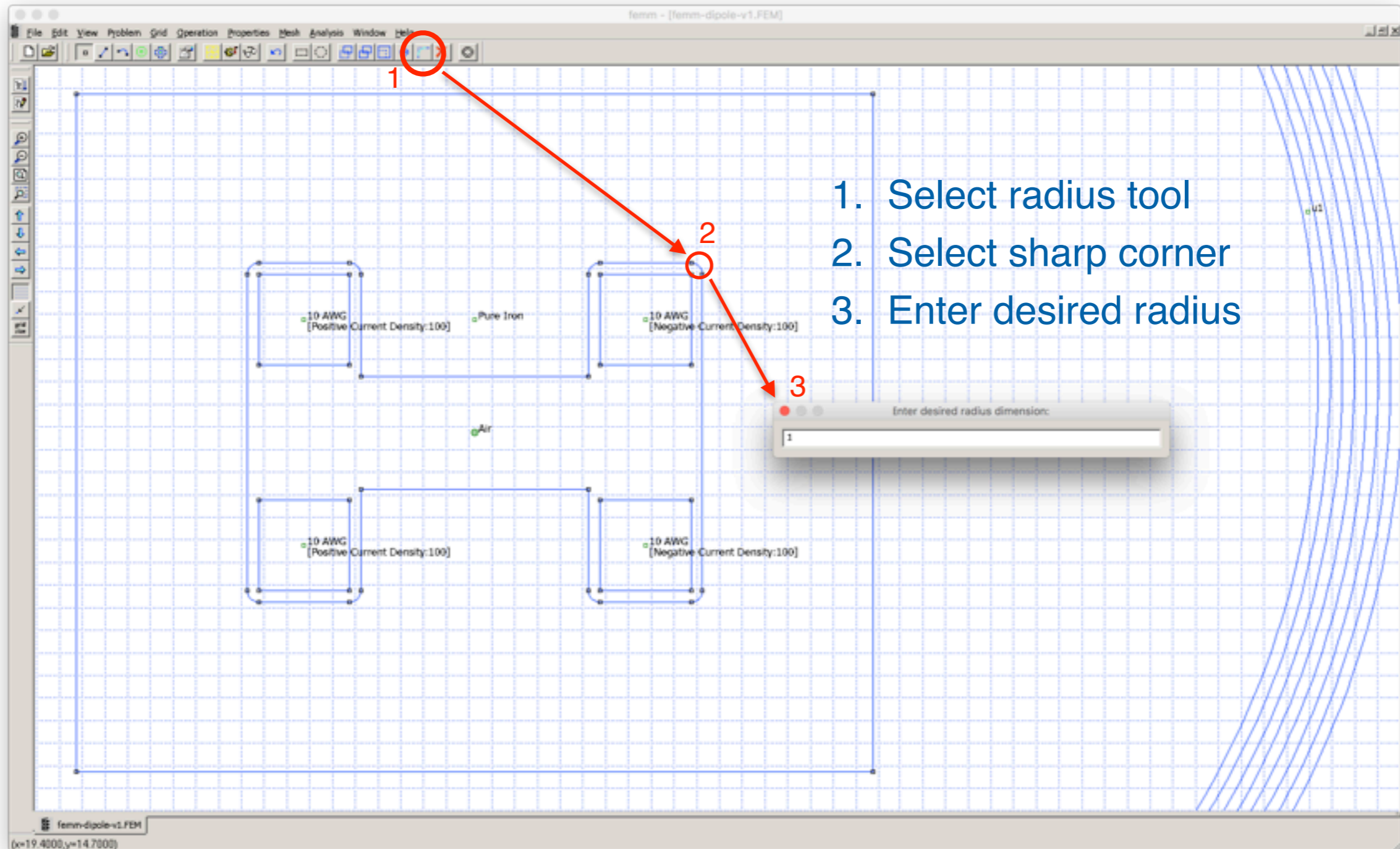
# FEMM Tutorial: Magnetostatics

- Increasing mesh density in region of interest increases numerical field quality



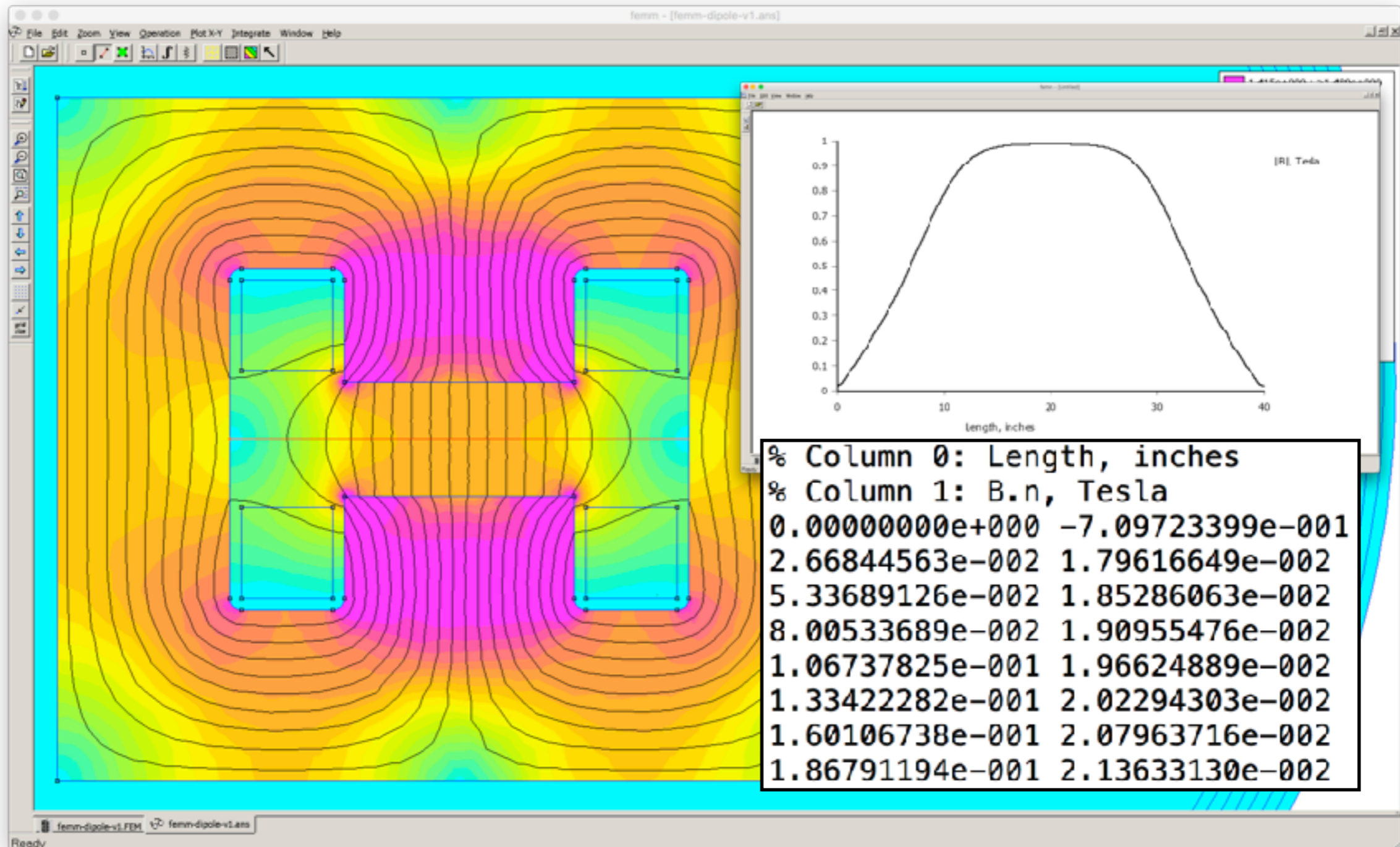
# FEMM Tutorial: Magnetostatics

- Pro Tip: Generally speaking, avoid sharp corners. Use “radius tool”



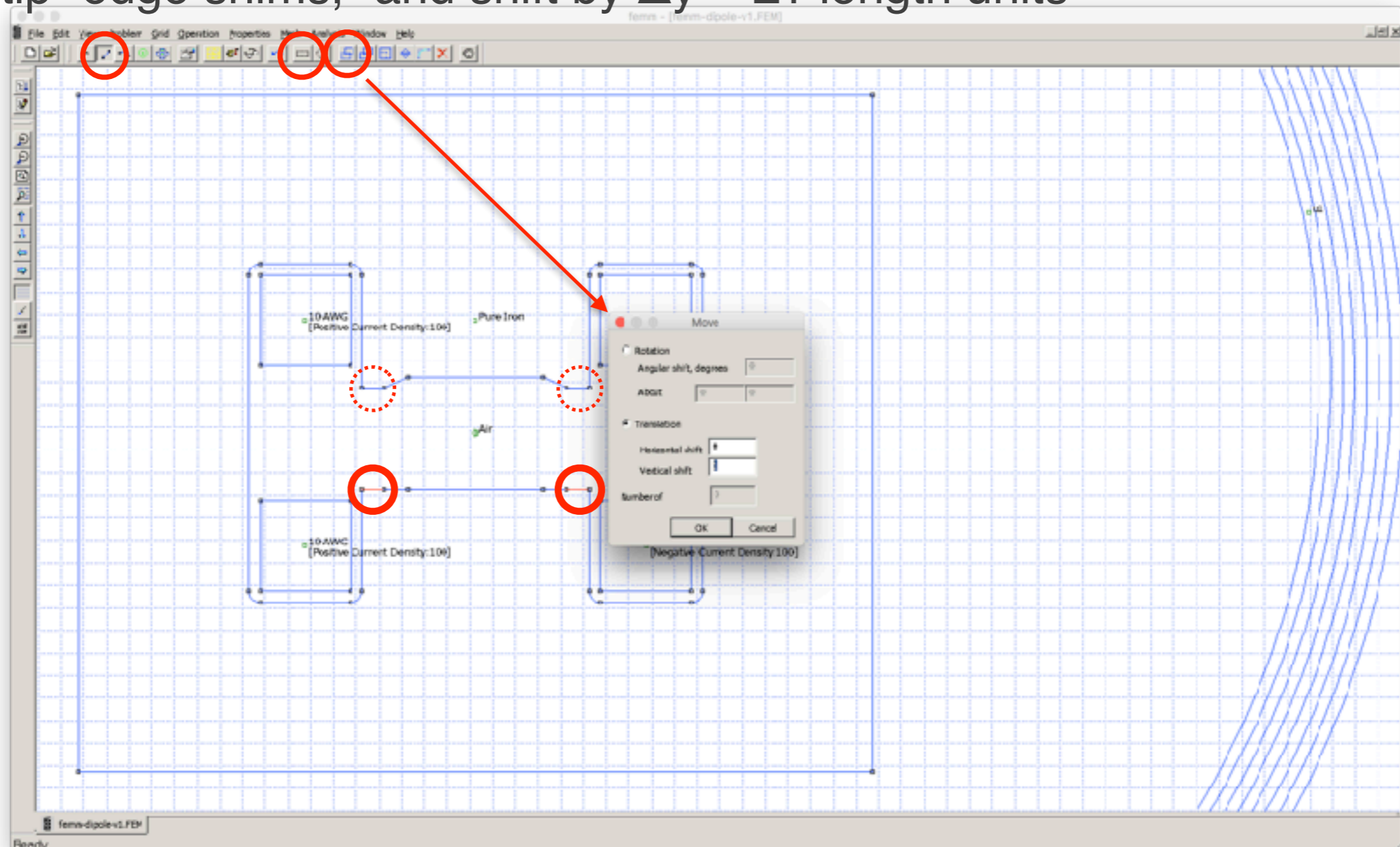
# FEMM Tutorial: Magnetostatics

- Plot the  $B_y$  vs.  $x$  from  $\{(-20, 0), (+20, 0)\}$  in the horizontal midplane. Save data to text file for future comparisons of pole-tip designs.



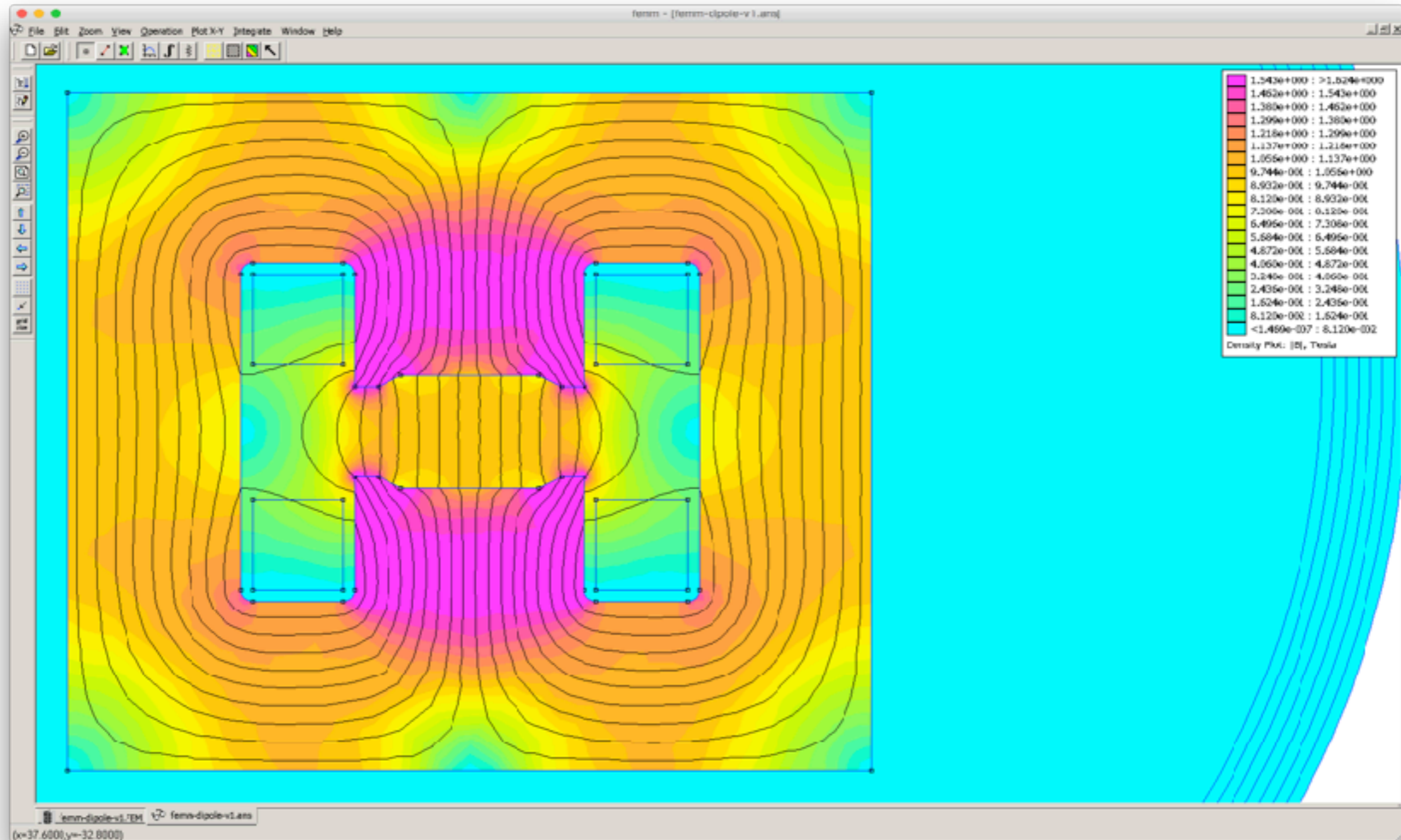
# FEMM Tutorial: Magnetostatics

- Now let's change the pole tips to modify the B-field profile.
- First, save a fresh copy of your work ("femm-dipole-v2"). Add 8 vertices for pole-tip "edge shims," and shift by  $\Delta y = \pm 1$  length units



# FEMM Tutorial: Magnetostatics

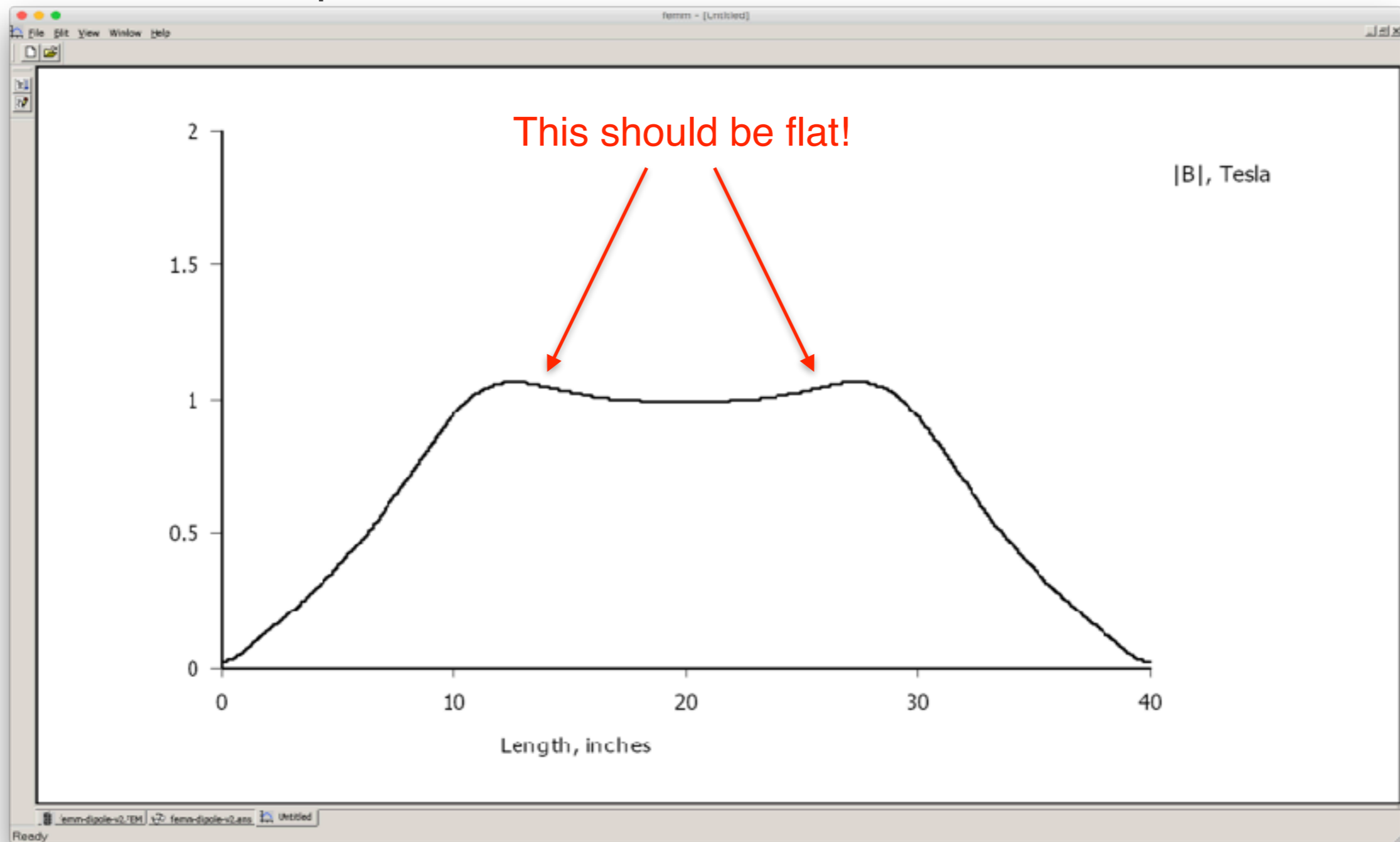
- Mesh, solve, and plot B-field in horizontal midplane as usual





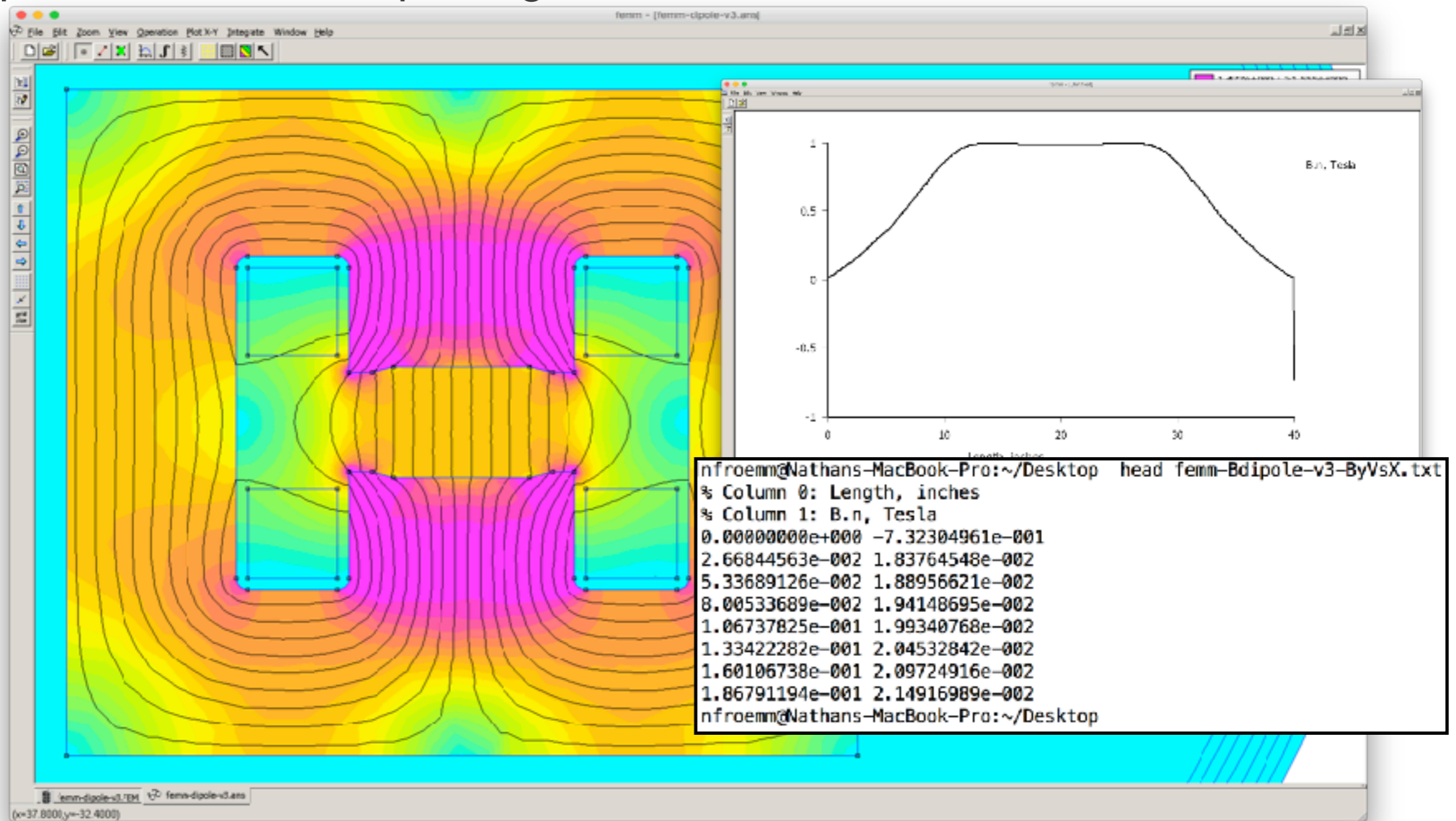
# FEMM Tutorial: Magnetostatics

- Is the field uniformity improved at all? Hmm, looks like I was a little too aggressive...let's split the difference. First, save a "v3."



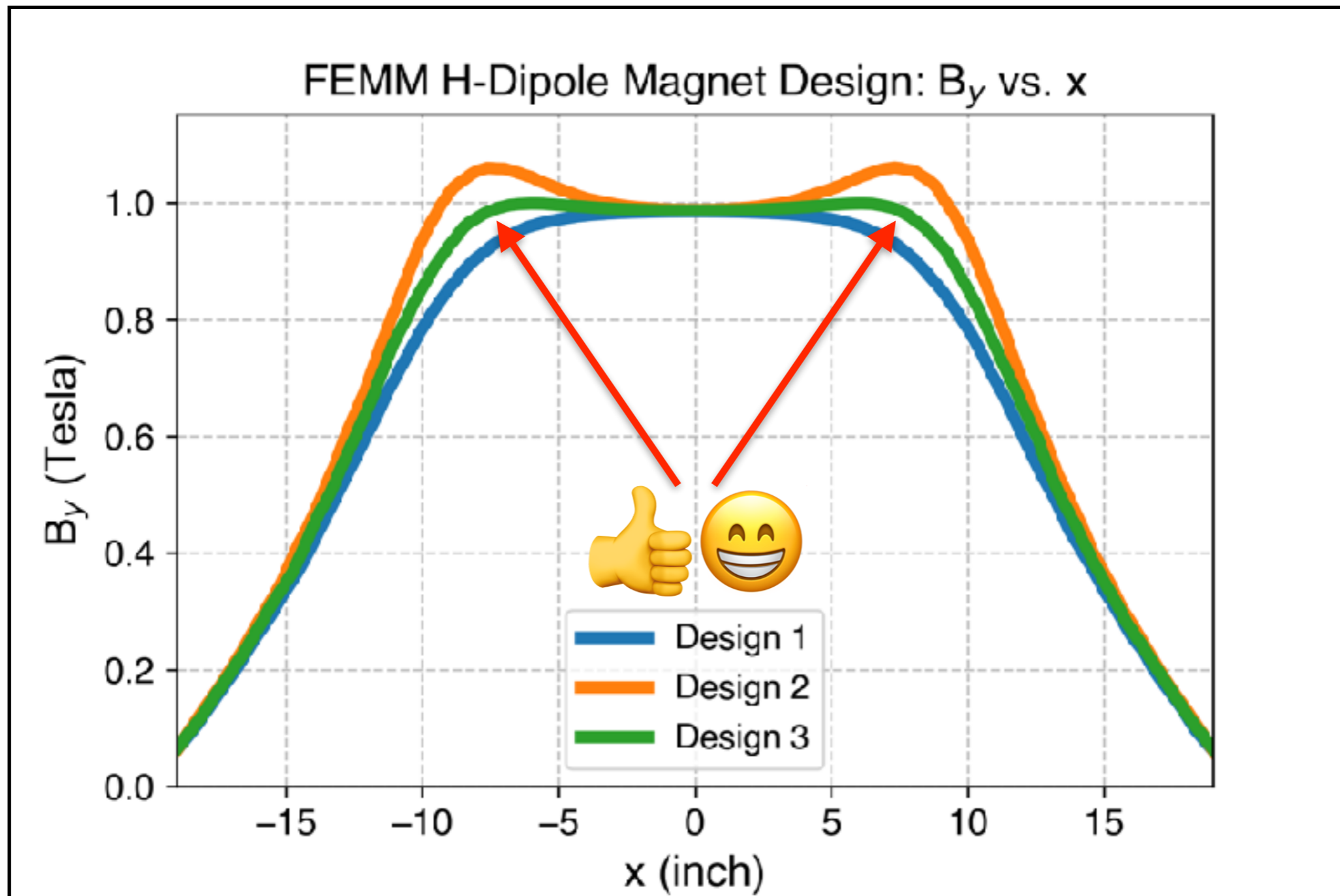
# FEMM Tutorial: Magnetostatics

- Split the difference—looks pretty good! Save the B-field in the horizontal midplane to text file for plotting later.



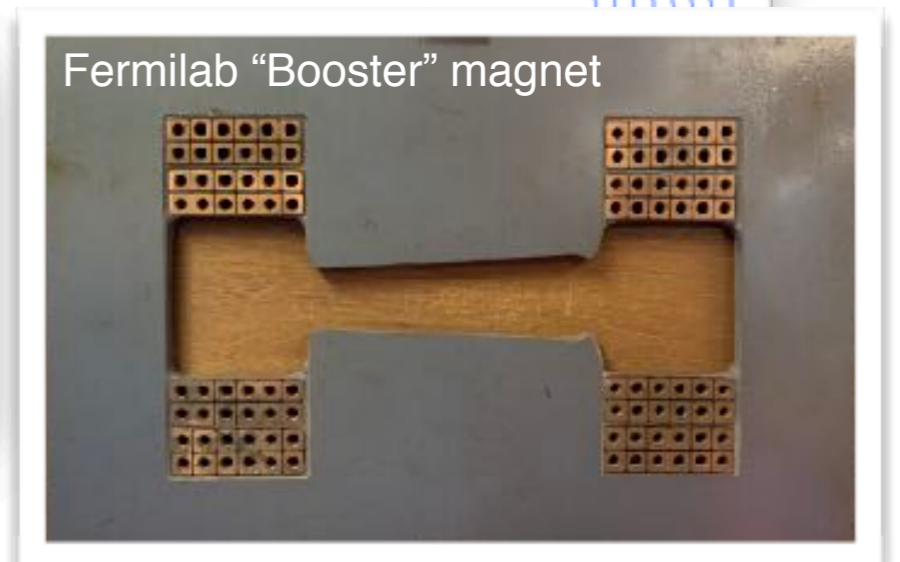
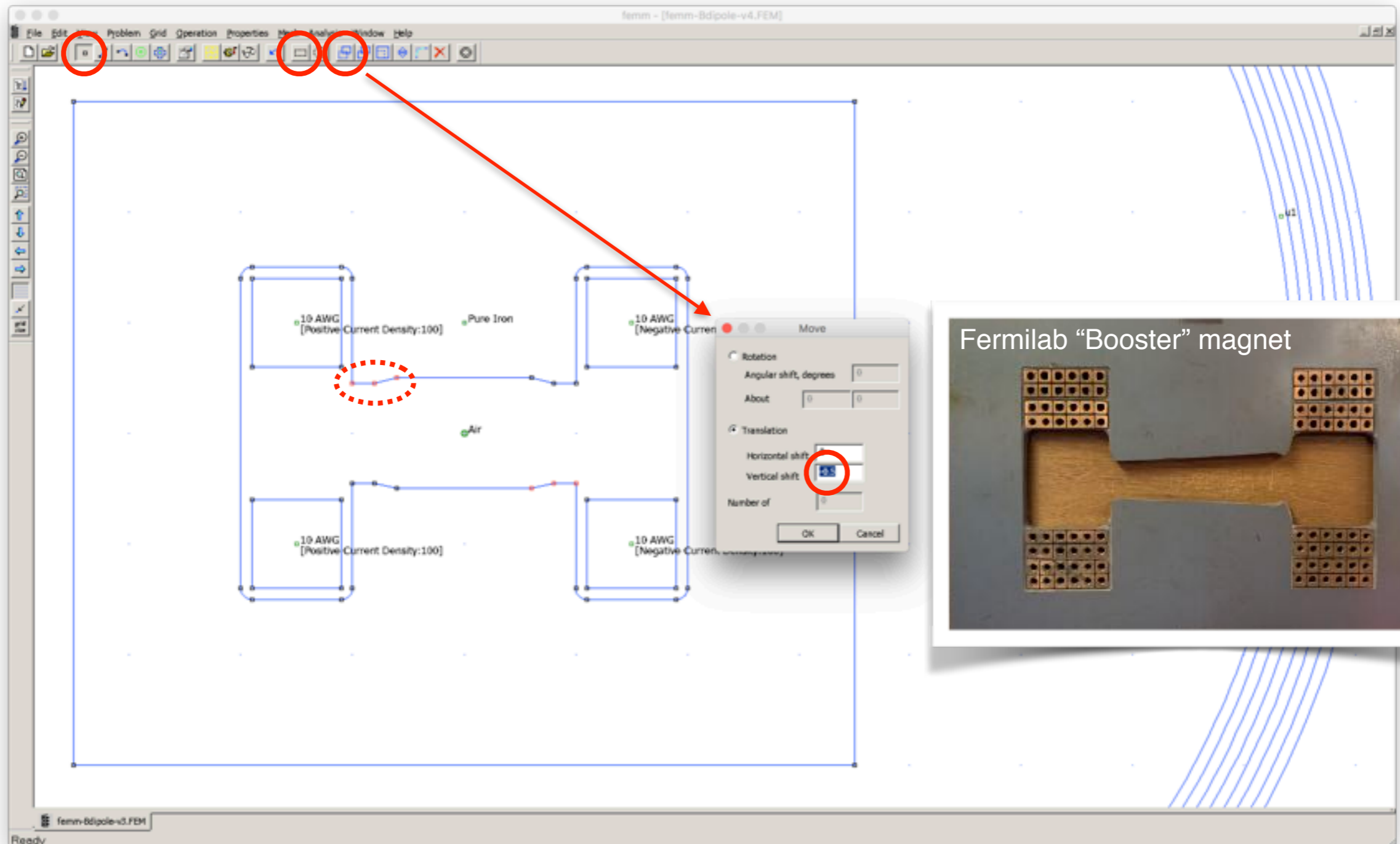
# FEMM Tutorial: Magnetostatics

- Compare B-field profiles (I quickly plotted our saved B-fields using `python`.)



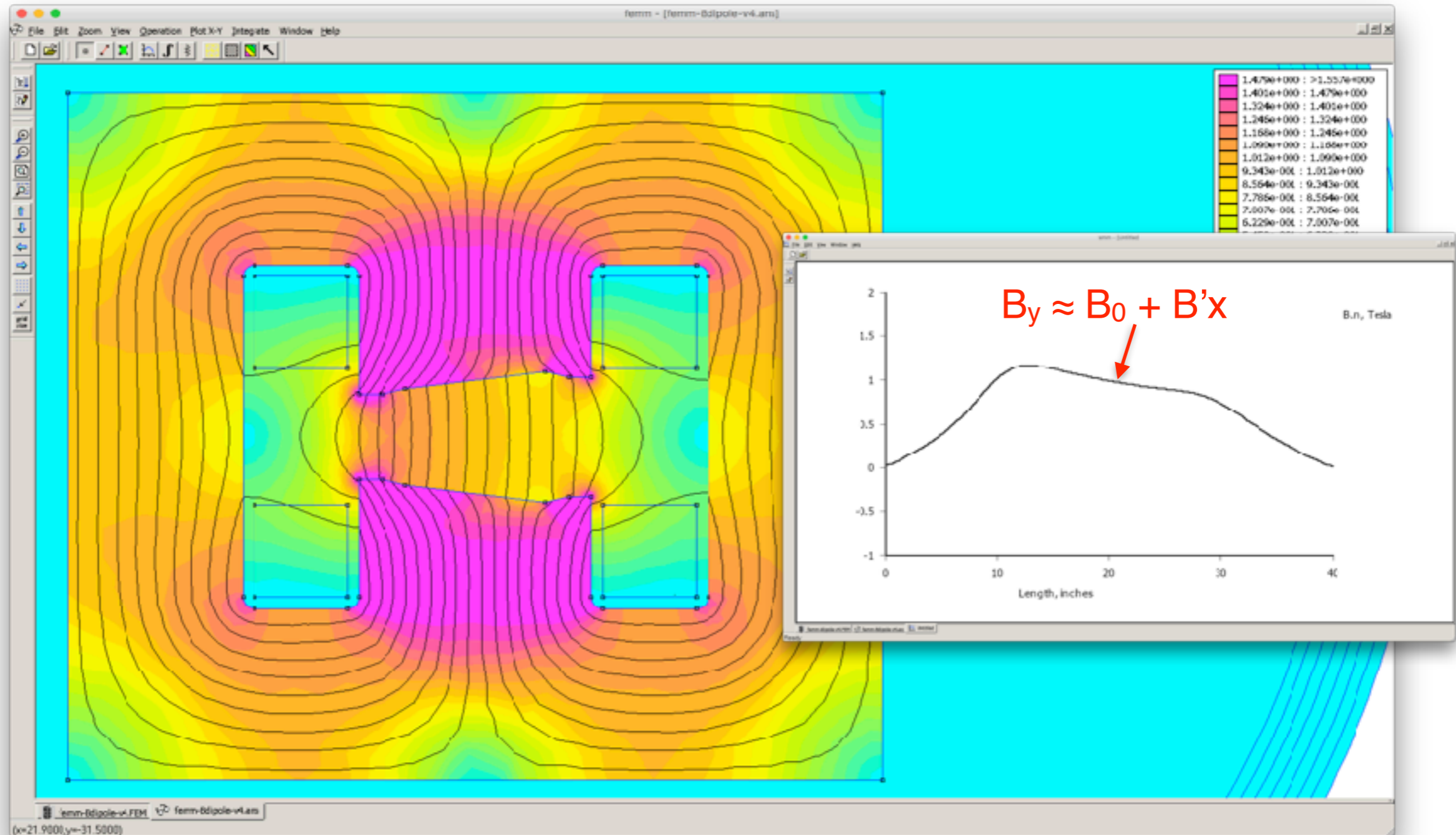
# FEMM Tutorial: Magnetostatics

- Combined-Function Dipole-Quadrupole Magnet (@Fermilab's "Booster" machine). Need to add a "slant" to the pole faces. First, save a "v4".



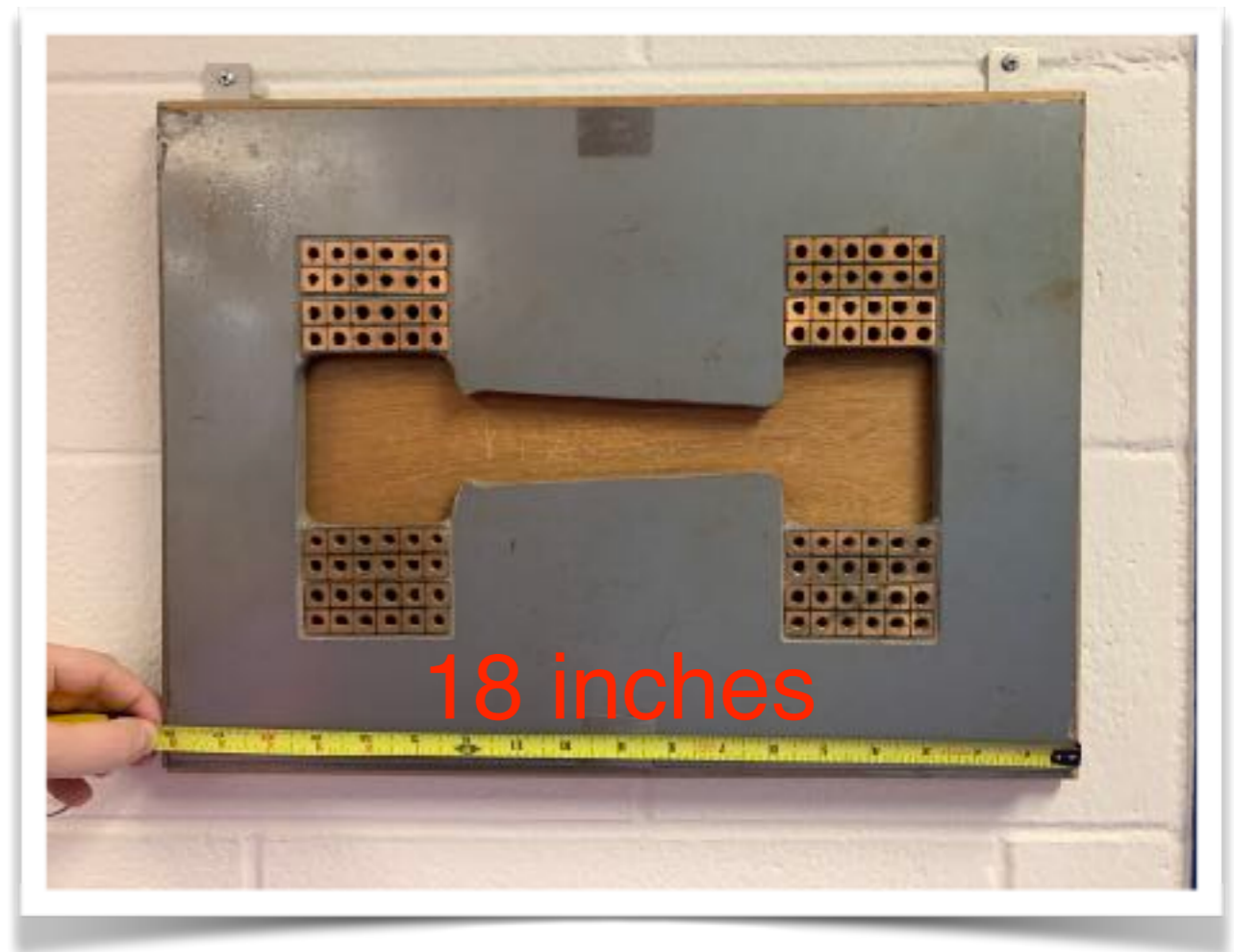
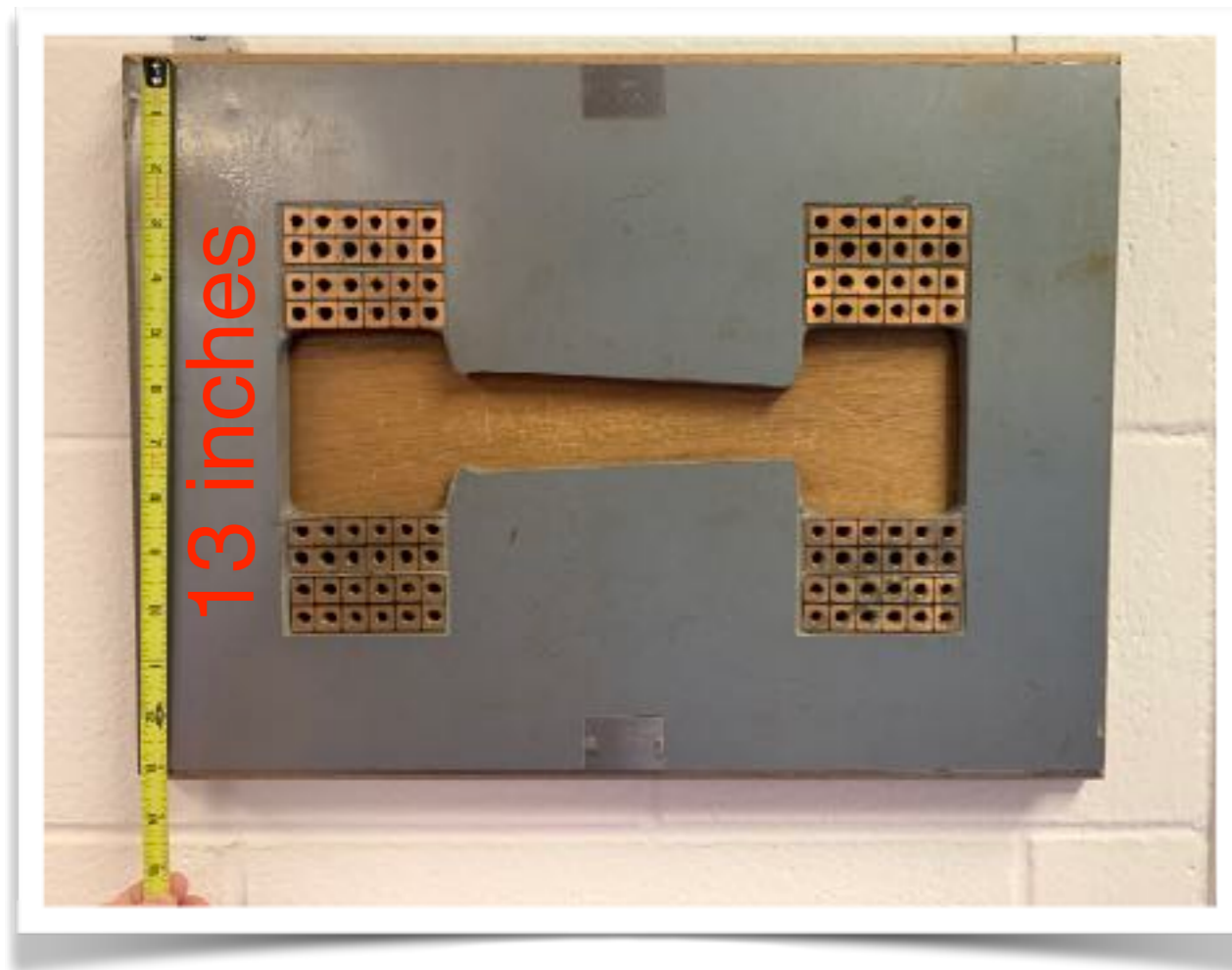
# FEMM Tutorial: Magnetostatics

- Dipole = constant B-field, quad = linear B-field. Looks pretty good!



# Building A More Realistic Example: FEMM + WebPlotDigitizer

- Can use “[WebPlotDigitizer](#)” to get vertices of pole tips, i.e. to create a better model. Simply navigate to [WebPlotDigitizer](#), load image of your choosing, and click desired vertices



# WebPlotDigitizer

- Navigate to [WebPlotDigitizer](https://automeris.io/WebPlotDigitizer/) website, click “Launch Now!”

WebPlotDigitizer  
Web based tool to extract data from plots, images, and maps

English Download Donate  
Launch

Home Blog Tutorials Citation Privacy

File Help  
Axes Image  
Datasets  
Measurements  
Dataset  
Axes: Image  
Rename Dataset  
Delete Overlays  
View Data  
Clear Data  
Data Points: 144

Automatic Extraction  
Mask Box Pen Erase View  
Color: Foreground Color 1  
Distance: 120 Filter Colors  
Algorithm: Averaging Window 2  
AR 10 \_Px  
AR 10 \_Px  
Run

Web Application  
English  
**Launch Now!**  
Desktop Version  
View Source  
GitHub

It is often necessary to reverse engineer images of data visualizations to extract the underlying numerical data. WebPlotDigitizer is a semi-automated tool that makes this process extremely easy:

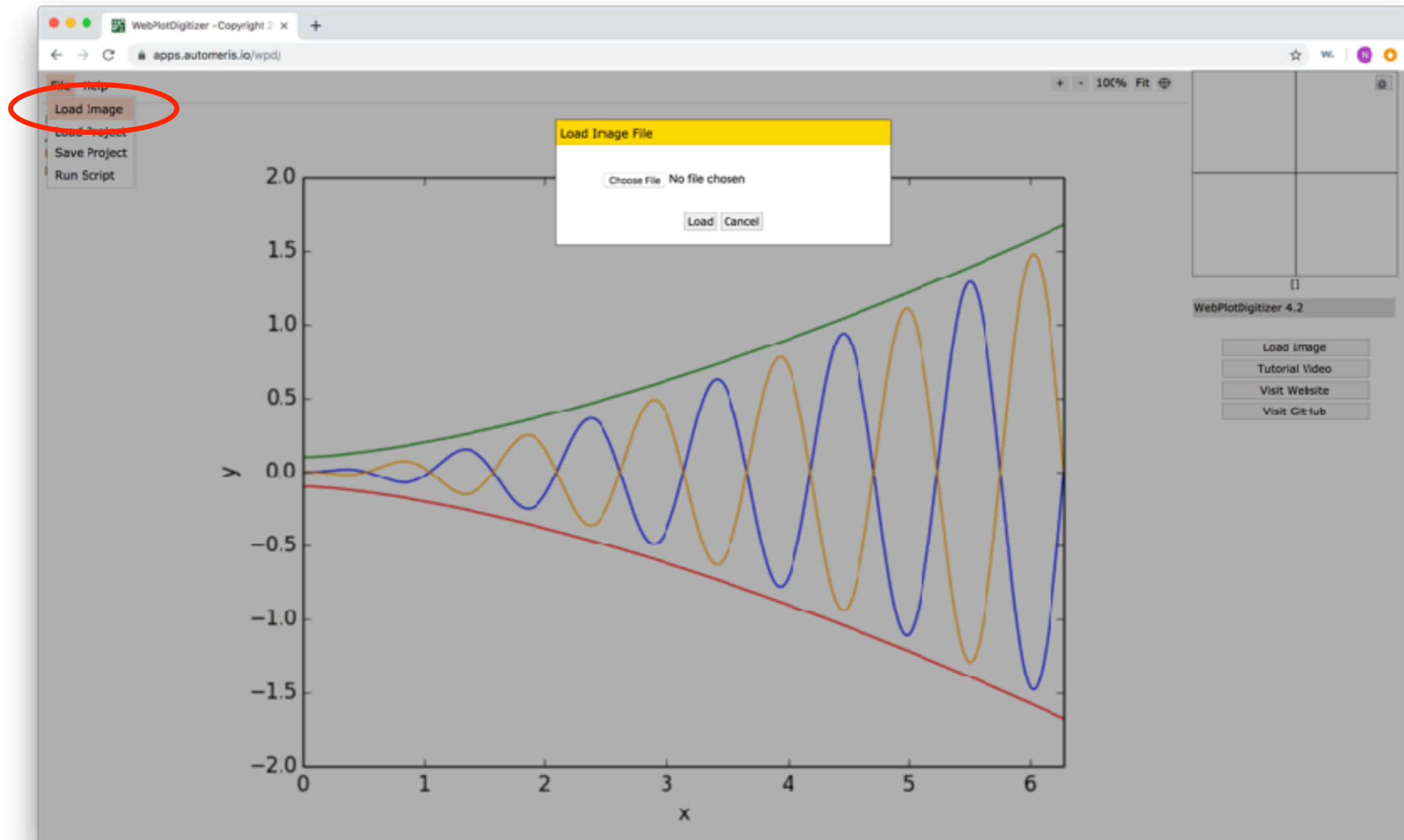
- Works with a wide variety of charts (XY, bar, polar, ternary, maps etc.)
- Automatic extraction algorithms make it easy to extract a large number of data points
- Free to use, opensource and cross-platform (web and desktop)
- Used in hundreds of published works by thousands of users
- Also useful for measuring distances or angles between various features
- More to come soon...

Version 4.2 Released (April 7, 2019)  
[\[ Release Notes \]](#)

PLOTCON 2017 - Oakland, CA  
[\[ Presentation Slides \]](#)

# WebPlotDigitizer

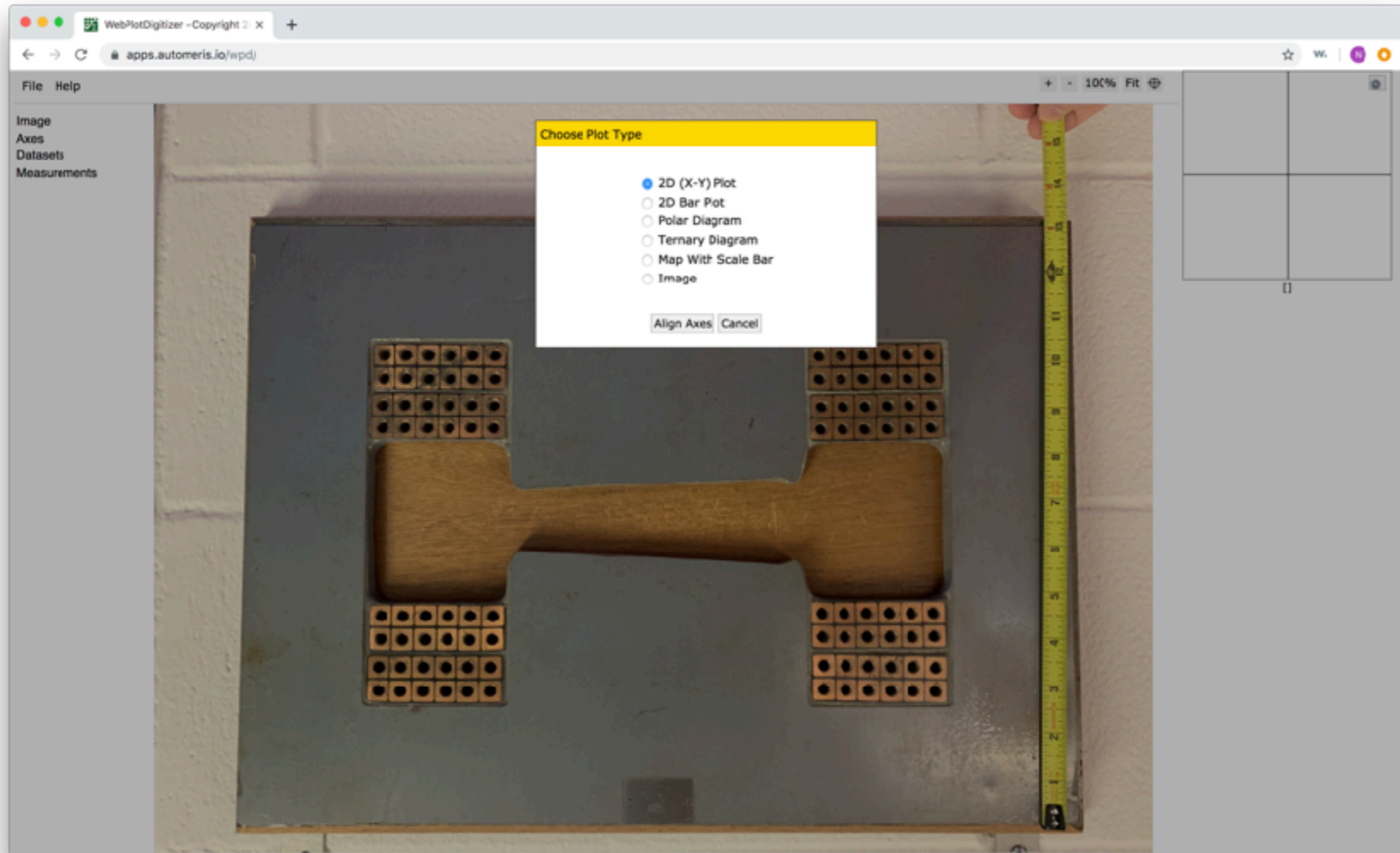
- Load the image of your choosing





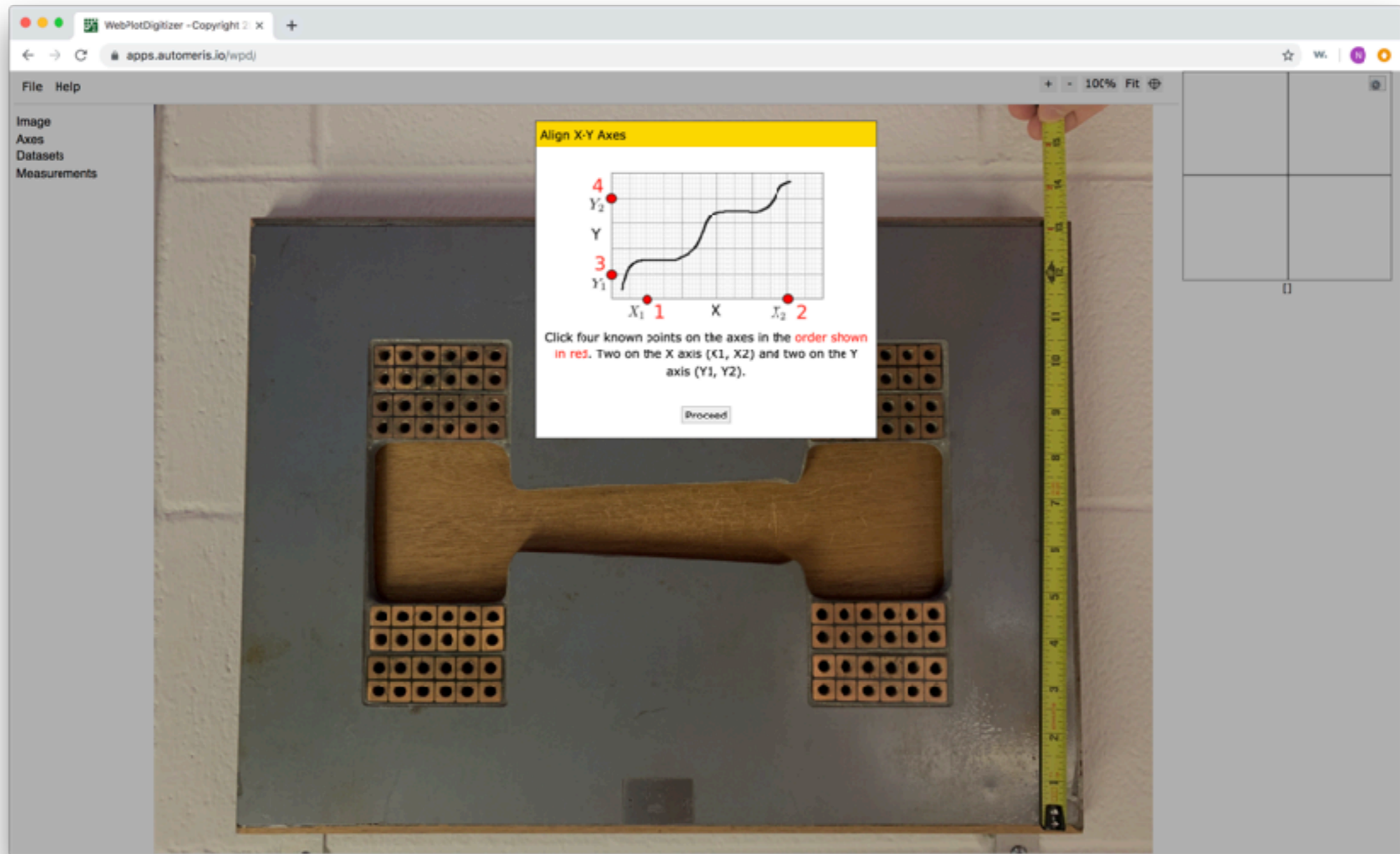
# WebPlotDigitizer

- Select plot type. I chose “2D (X-Y) Plot” for the Fermilab Booster magnet



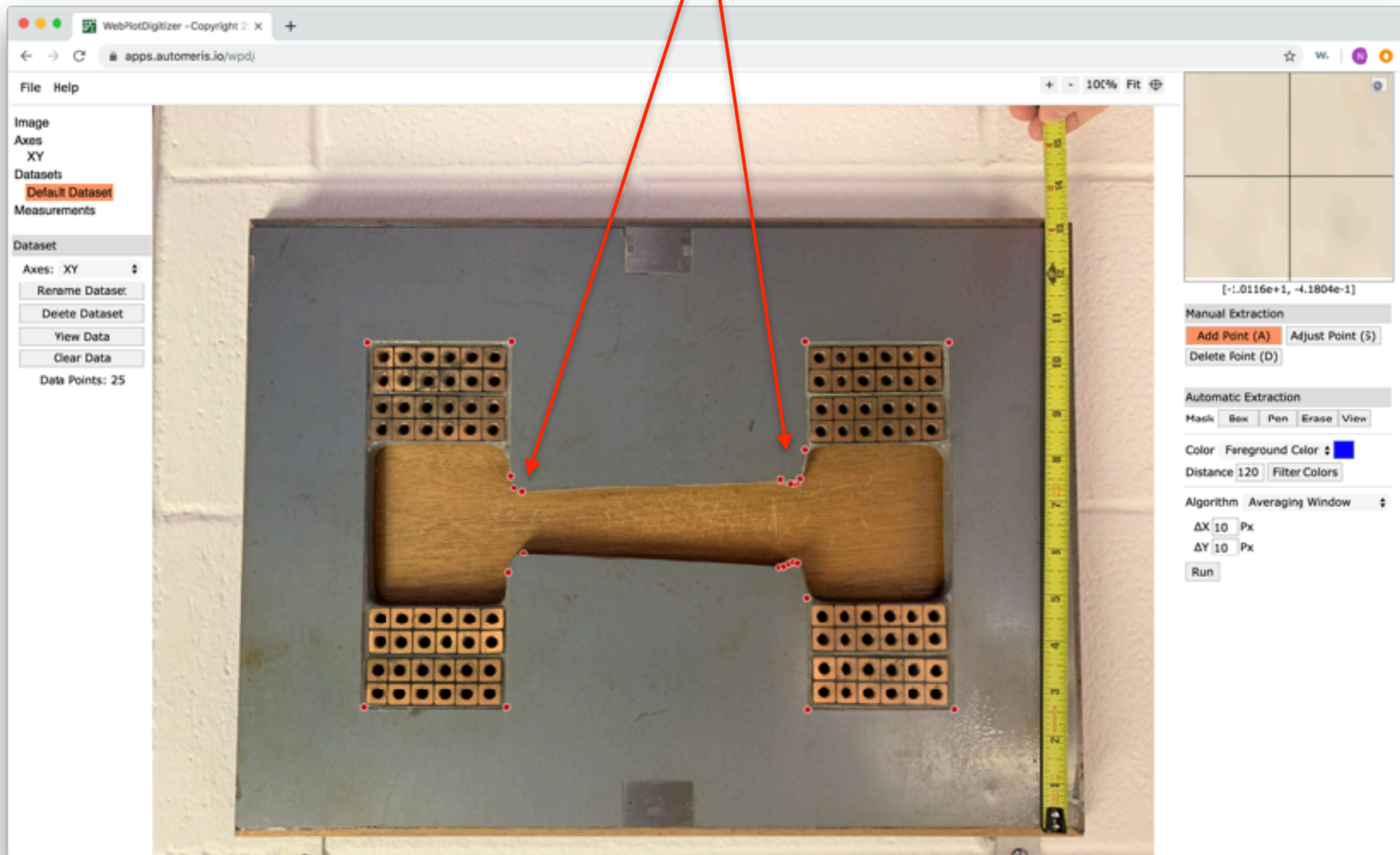
# WebPlotDigitizer

- Align the plot axes. I clicked the corners of the iron of the Booster magnet, and used the measurements  $W \times H = 18 \times 13 \text{ cm}^2$



# WebPlotDigitizer

- Click the data points you'd like to digitize



# WebPlotDigitizer

- Export the data, copy to clipboard, plot in Plotly, etc.

The screenshot displays the WebPlotDigitizer web application interface. The main window shows a digitized image of a circuit board with a yellow 'Acquired Data' dialog box overlaid. The dialog contains a list of 25 data points (X, Y coordinates) and options for sorting and formatting. A red circle highlights the 'Copy to Clipboard', 'Download .CSV', 'Graph in Plotly\*', and 'Close' buttons. A red text label 'DATA!' is placed over the data list. To the right, a 'Plotly' window is open, showing a line graph of the digitized data points. A blue text label 'Plot data directly in "Plotly" to inspect' is overlaid on the Plotly window. The background shows a circuit board with a yellow ruler for scale.

Acquired Data

Dataset: Default Dataset

Variables: X, Y

```
-6.424625967521146, 4.031751755854659
-0.212368230341239, -3.814230241732454
-3.279865837482677, -3.8433015503707426
-3.311764761836264, -0.9183786340211102
-2.96704103551023, -0.5290640153080191
2.467421557329278, -0.8180635586770773
2.5911522322554923, -0.8105022940268336
3.484216048816417, 0.797023473004488
2.784160342690642, -0.7614239274609158
2.8732522914629157, -0.719621213768511
3.0853899845615267, -1.516427602252742
3.1592663443002015, -3.9963380373563605
6.280457011469262, -3.9317002163560687
5.981150898931874, 3.9985769934114657
2.921418708821676, 4.0251520820196095
2.9758964102110905, 1.678237578551344
2.883624344952052, 1.061244341038073
2.815178629672314, 0.9591626845550005
2.7535212224662438, 0.9421150135880335
```

Sort

Sort by: Raw

Order: Ascending

Format

Number Formatting:

Digits: 5 Ignore

Column Separator: ,

Format

Manual Extraction

Add Point (A) Adjust Point (S)

Delete Point (D)

Automatic Extraction

Copy to Clipboard Download .CSV Graph in Plotly\* Close

Plot data directly in "Plotly" to inspect

# FEMM + “Lua” Scripting Language

- You should know that FEMM comes with `lua` scripting language. It can be quite powerful. Let's run `femm42/examples/Force-vs-Position.lua`

`femm42/examples/Force-vs-Position.lua`

```
showconsole()
clearconsole()
print("position in inches | force in lbf")
open("Roters-Ch9Fig6.fem")
mi_saveas("temp.fem")
for n=0,20,1 do
  mi_analyze()
  mi_loadsolution()
  mo_groupselectblock(1)
  f=mo_blockintegral(19)/4.4482
  print(0.1*n,f)
  mo_close()
  mi_seteditmode("group")
  mi_selectgroup(1)
  mi_movetranslate(0,-0.1)
end
```

## Finite Element Method Magnetics

Version 4.2

User's Manual

[FEMM Reference Manual \(link\)](#)

3	<b>Lua Scripting</b>	<b>82</b>
3.1	What Lua Scripting? . . . . .	82
3.2	Common Lua Command Set . . . . .	82
3.3	<b>Magnetics Preprocessor Lua Command Set . . . . .</b>	<b>84</b>
3.3.1	Object Add/Remove Commands . . . . .	84
3.3.2	Geometry Selection Commands . . . . .	84
3.3.3	Object Labeling Commands . . . . .	85
3.3.4	Problem Commands . . . . .	86
3.3.5	Mesh Commands . . . . .	86
3.3.6	Editing Commands . . . . .	87
3.3.7	Zoom Commands . . . . .	88
3.3.8	View Commands . . . . .	88
3.3.9	Object Properties . . . . .	88
3.3.10	Miscellaneous . . . . .	92

# FEMM + Python = `pyFEMM`

- We'll look at two examples I coded in Jupyter notebooks: (1) cosine-theta dipole magnet, (2) electric quad with hyperbolic electrodes

Simple pyFEMM Example: Cosine-Theta Dipole Magnet

Gauthier Nathan S. Froemming  
[email: nath@fnal.gov]  
[date: 2019-10-10]

L.L. Tsai, *Iron Dominated Electromagnets*, pp-96 (World Scientific, 2005):

Negative Current Filaments Positive Current Filaments  
Flux Lines Field Lines

Figure 3 Conductor Dominated Field Distribution

Preliminaries

```
[1]: import femm
import os
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.image as mimg # show FEM screenshots
import matplotlib.patches as patches # show circles, polygons, etc.

[2]: # Print the current working directory
print(os.getcwd())

C:\Users\Nathan\Downloads\FEMM\pyFEMM_CosineThetaDipoleMagnet\pyFEMM_CosineThetaDipoleMagnet

[3]: # Make plots pretty
matplotlib.notebook
plt.rcParams['font.family'] = 'Arial'
```

Density Plot: V. Volts

1.800e+04	> 2.000e+04
1.600e+04	1.800e+04
1.400e+04	1.600e+04
1.200e+04	1.400e+04
1.000e+04	1.200e+04
8.000e+03	1.000e+04
6.000e+03	8.000e+03
4.000e+03	6.000e+03
2.000e+03	4.000e+03
0.000e+00	2.000e+03
-2.000e+03	0.000e+00
-4.000e+03	-2.000e+03
-6.000e+03	-4.000e+03
-8.000e+03	-6.000e+03
-1.000e+04	-8.000e+03
-1.200e+04	-1.000e+04
-1.400e+04	-1.200e+04
-1.600e+04	-1.400e+04
-1.800e+04	-1.600e+04
< -2.000e+04	< -1.800e+04

# ALL DONE! I Hope You Learned A Thing Or Two! THANK YOU!

- Overview LaPlace's equation and solutions
  - Cauchy-Riemann equations; Connection to electromagnetism (EM)
  - Conformal mappings
  - Shortcomings
- Finite-Element methods and codes (OPERA, COMSOL, FEMM, ...)
- Getting FEMM setup on your local machine
- FEMM electric example
  - Problem setup: Electric dipole/c
  - How to extract the potential/E-f
- FEMM magnetic example (this time)
  - Problem setup: H-dipole + quadrupole, pole-tip design (more challenging)
  - How to extract the potential/B-field from FEMM
- Pro Tips And Tricks (next time)
  - Scripting in `lua` and `python`; Jupyter notebooks; WebPlotDigitizer; etc.
- Conclusions

