Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

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

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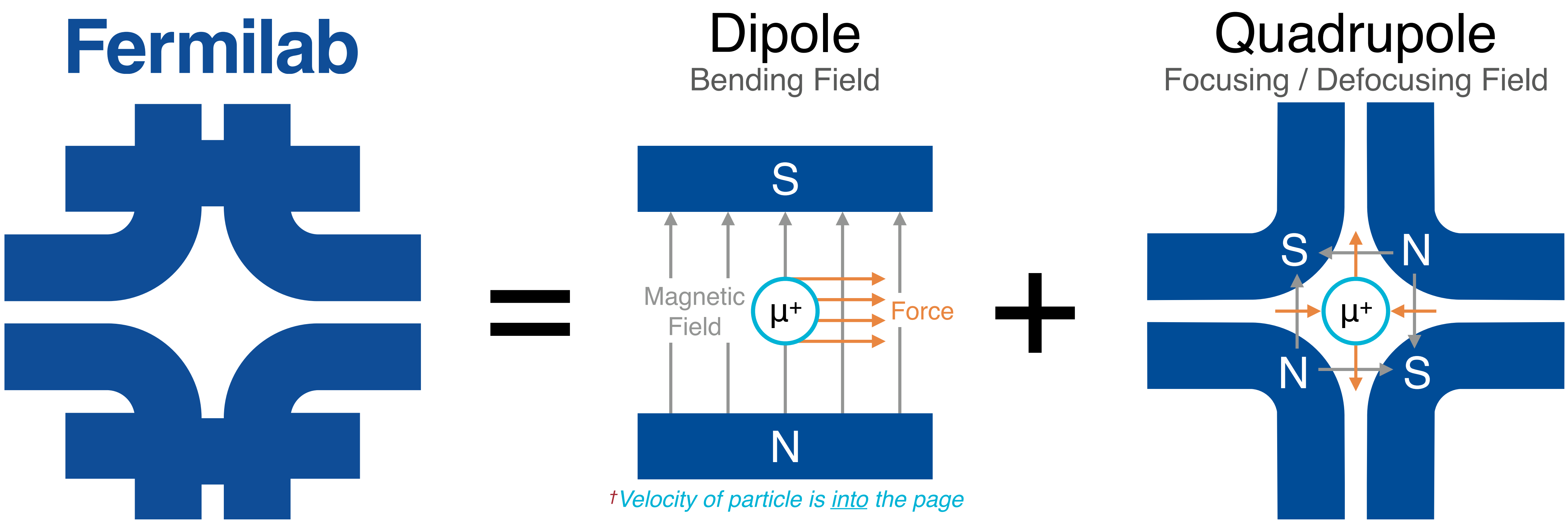
Thu 10 Oct 2019

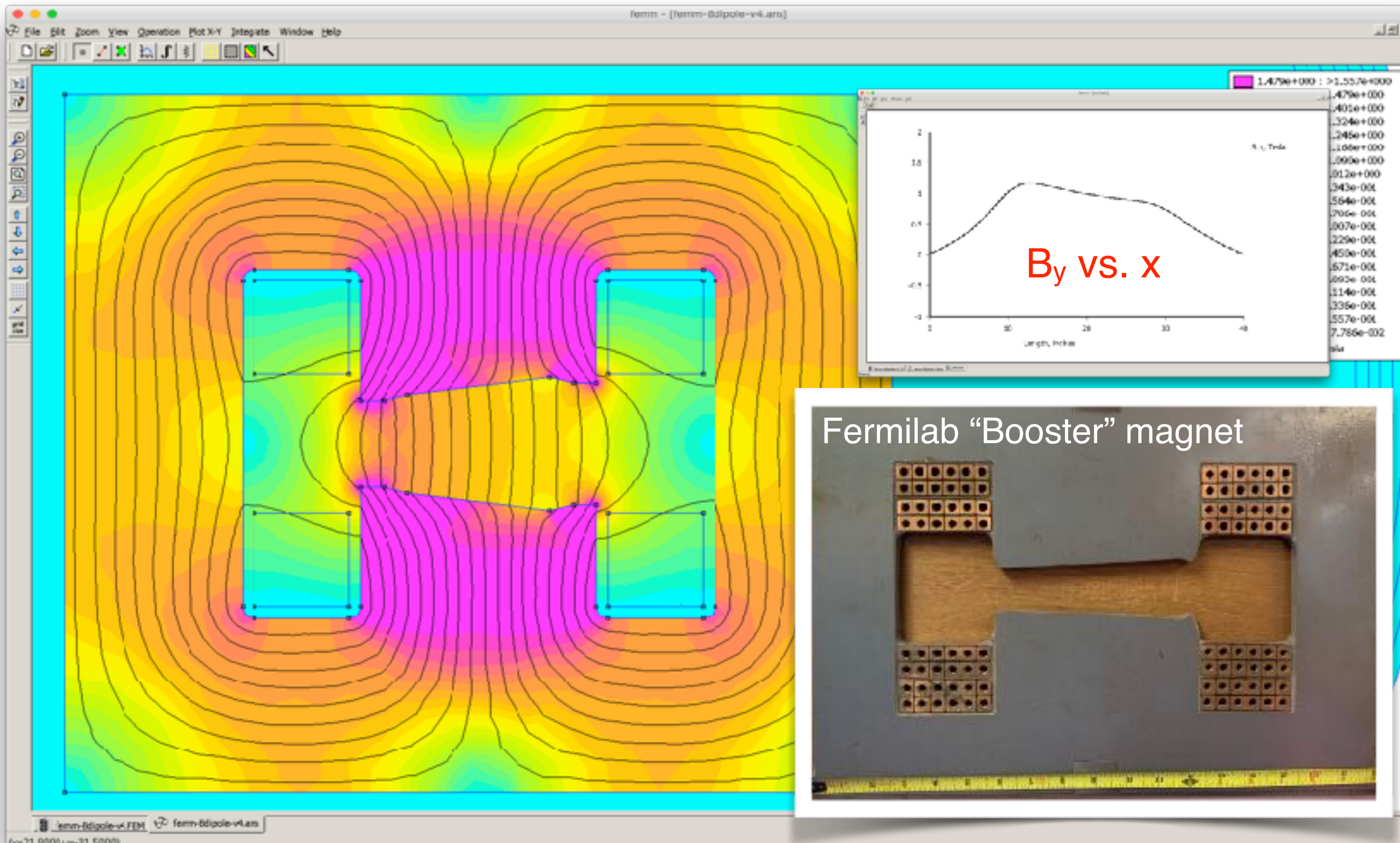
Fermilab's Logo

- 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



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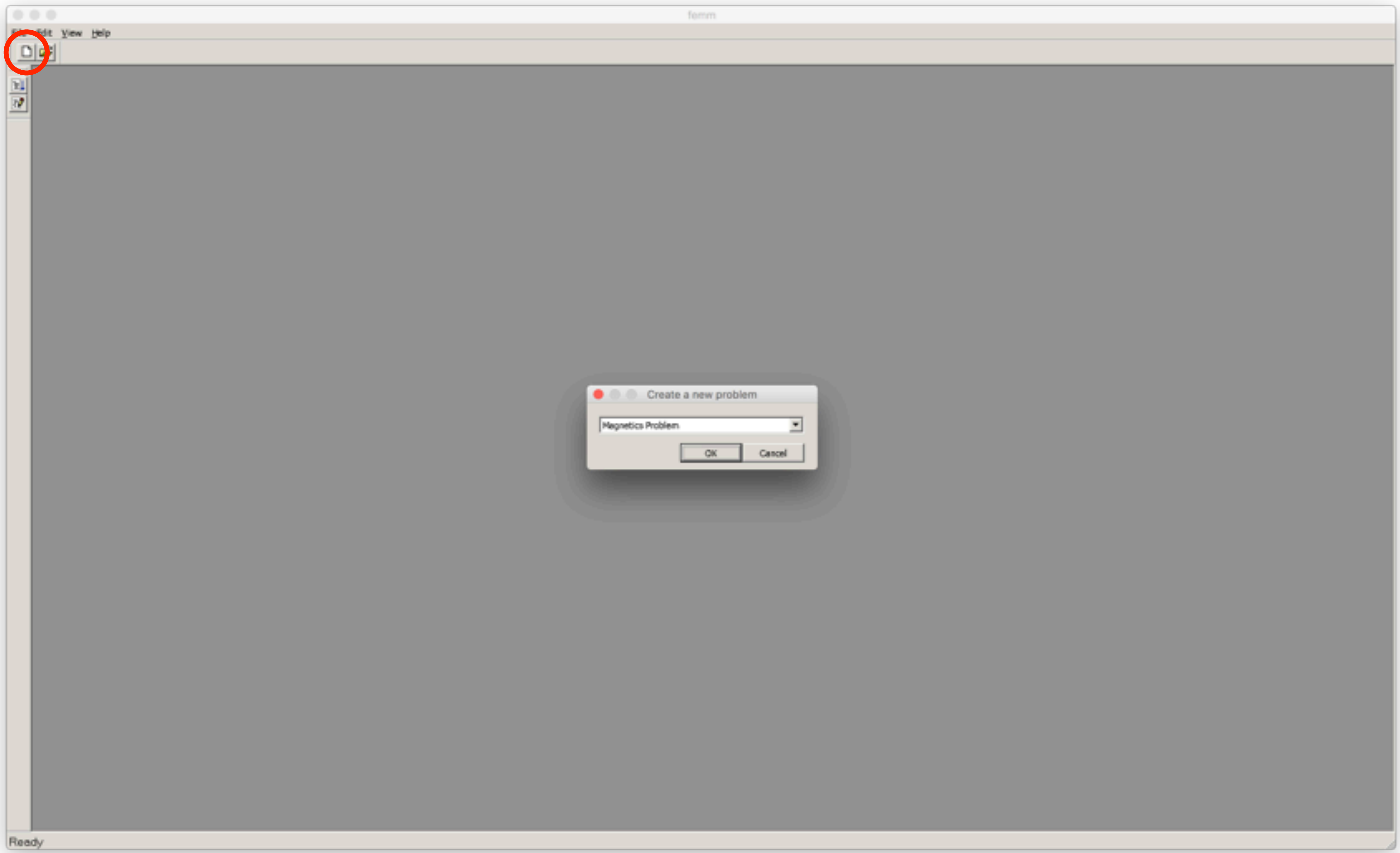
Outline (Picking Up Where We Left Off Last Time)

- 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



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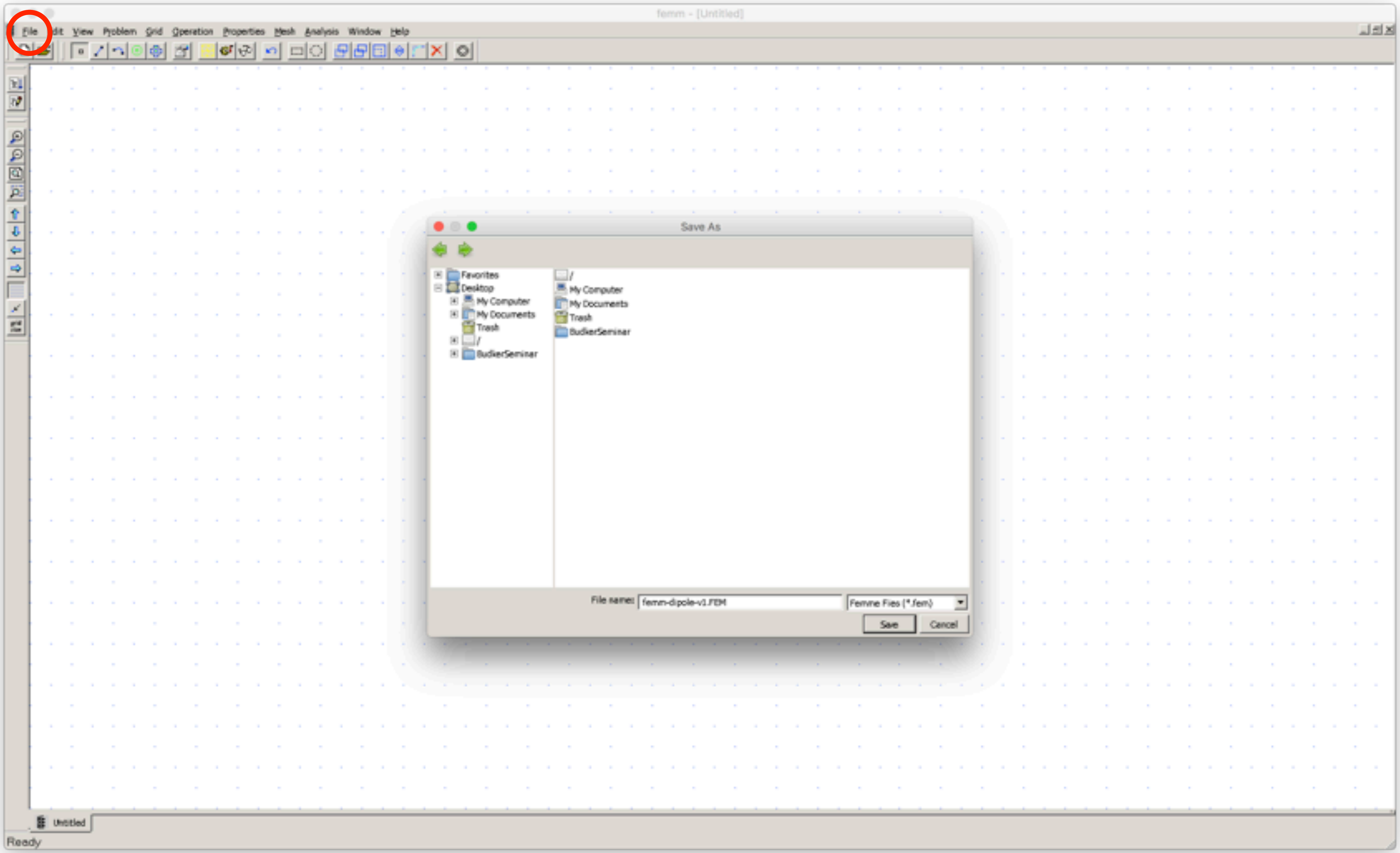
FEMM Tutorial: Magnetostatics

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



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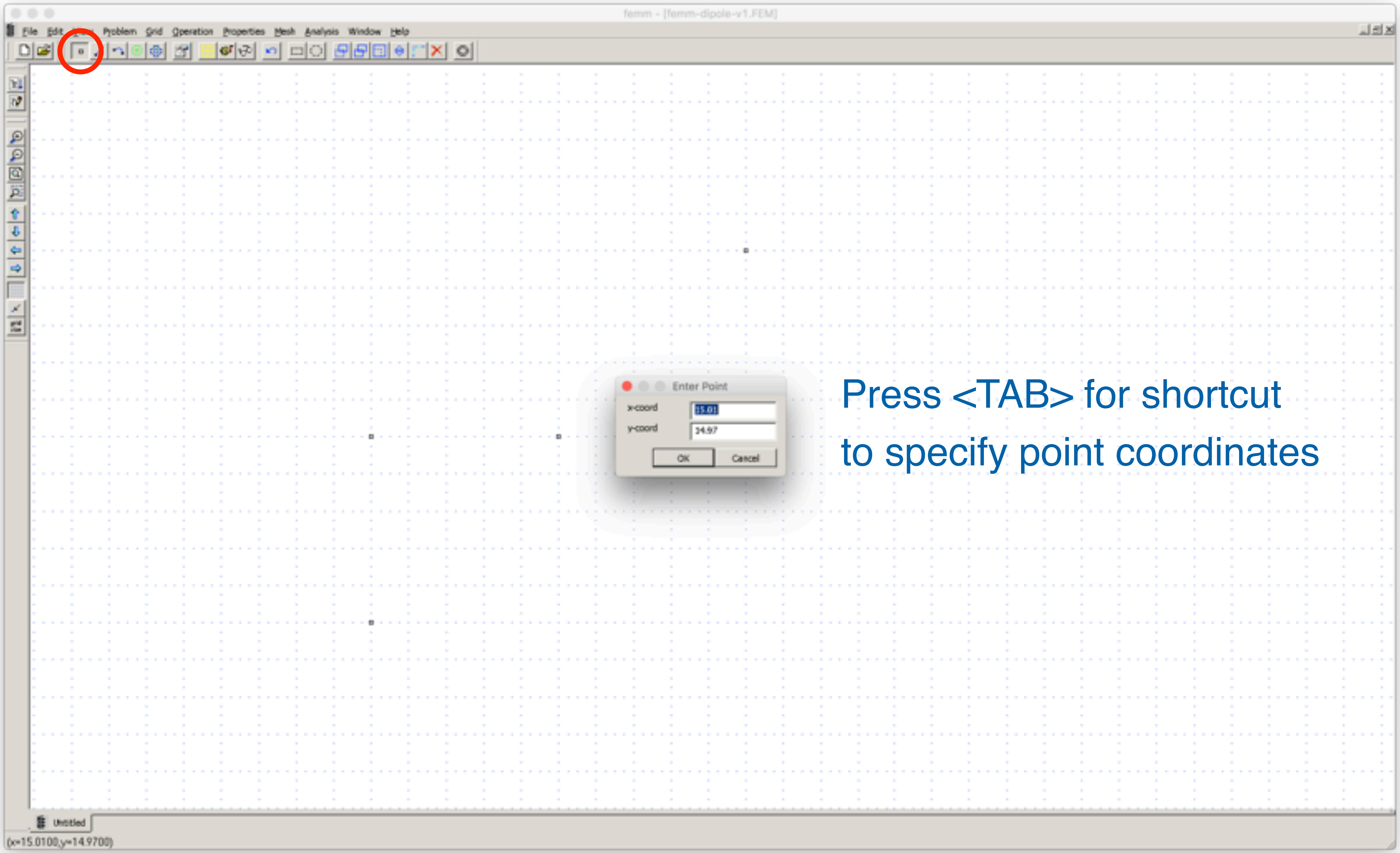
FEMM Tutorial: Magnetostatics

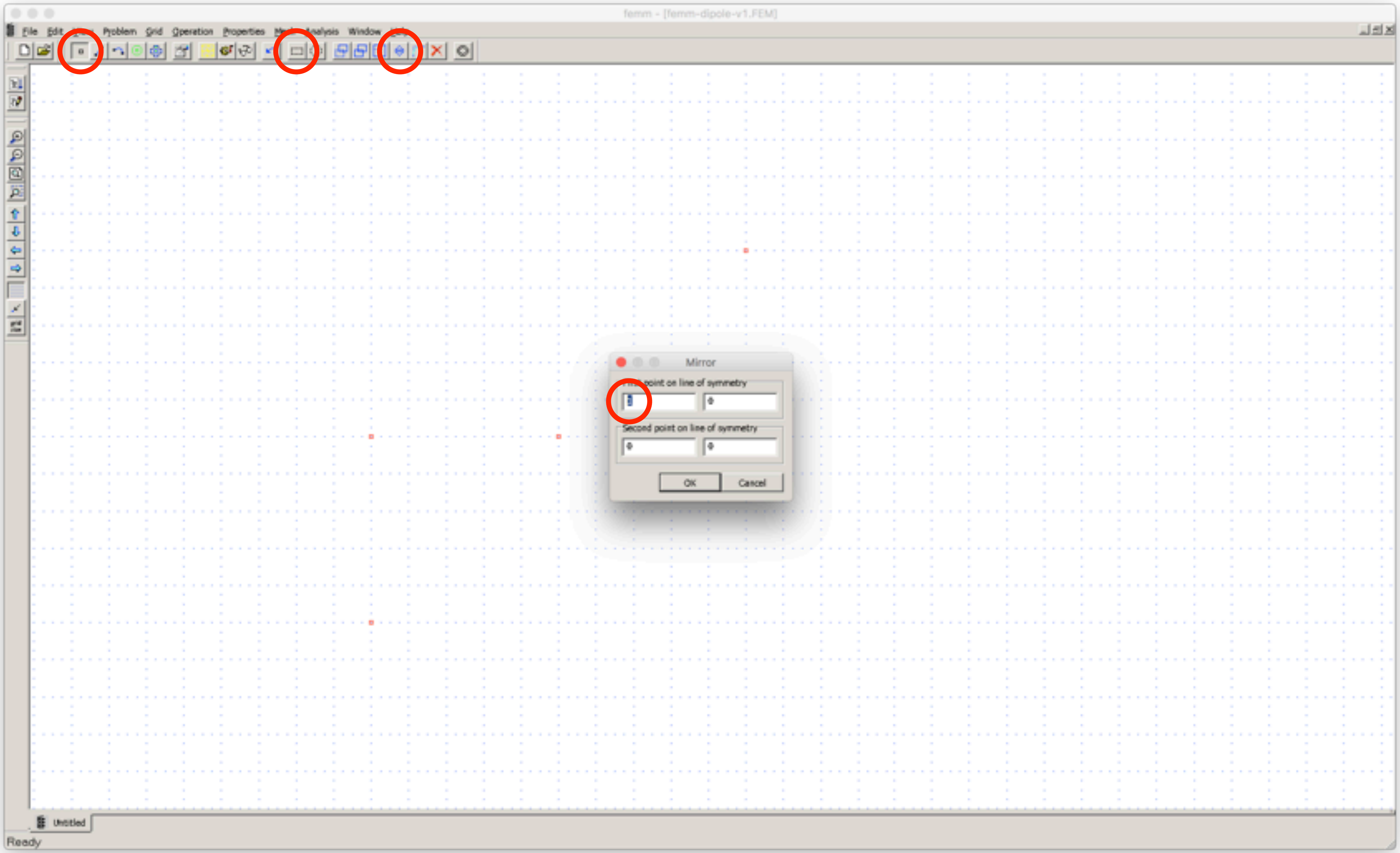
- Add 4 vertices at {(10, 5), (10, 15), (20, 15), (35, 30)}. Length units in “Problem” setup.



Press <TAB> for shortcut
to specify point coordinates

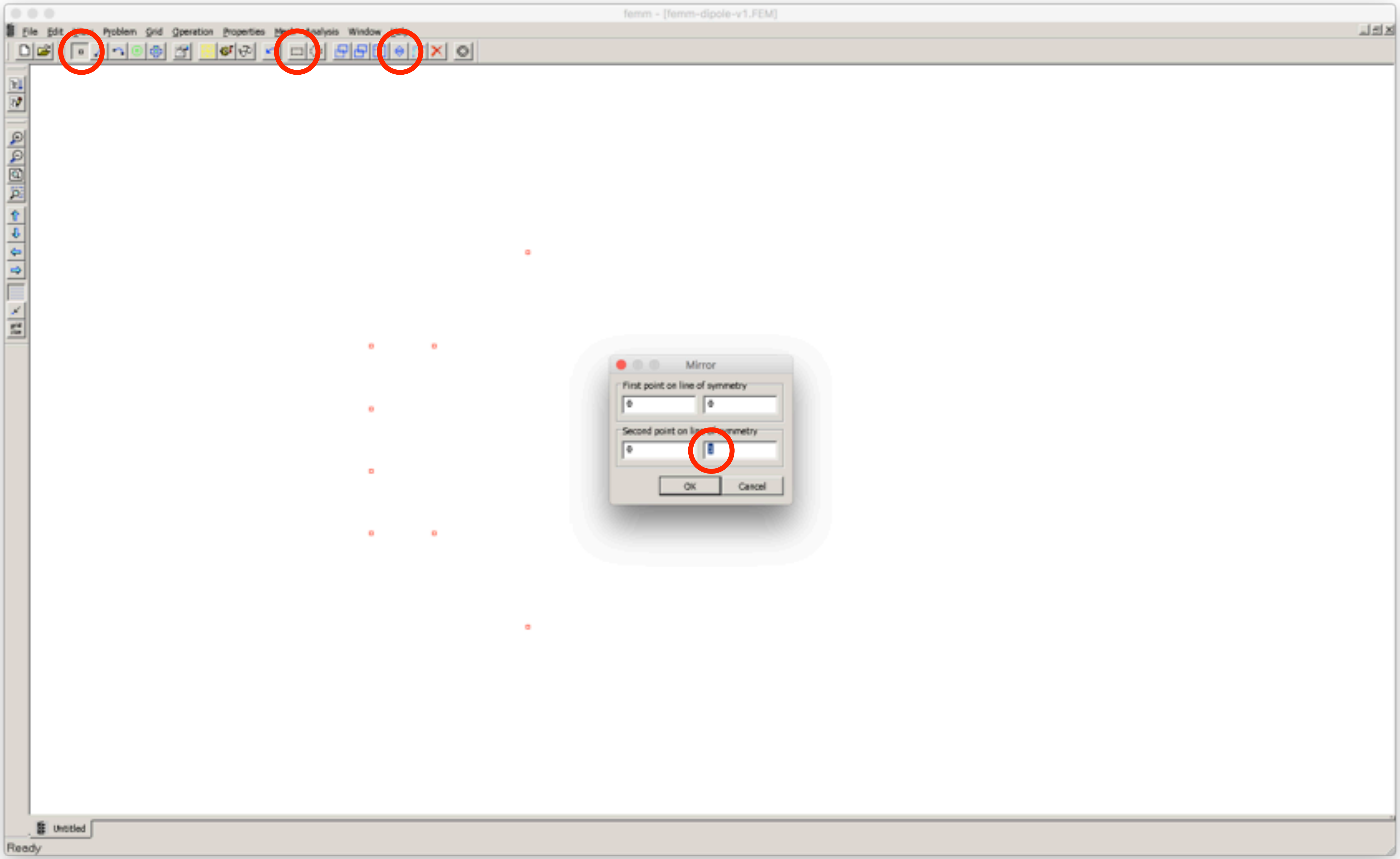
FEMM Tutorial: Magnetostatics

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



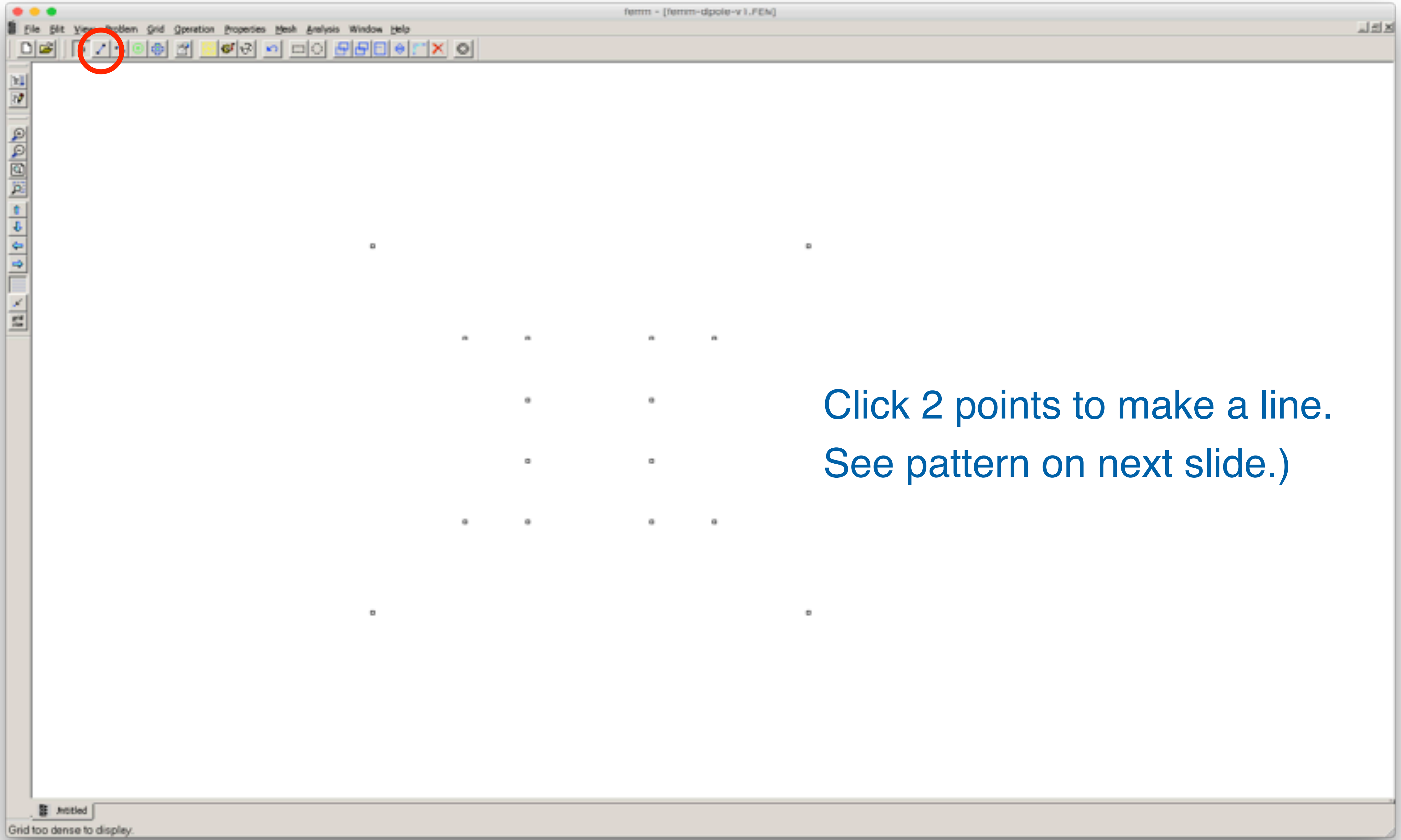
FEMM Tutorial: Magnetostatics

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



FEMM Tutorial: Magnetostatics

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



Click 2 points to make a line.
See pattern on next slide.)

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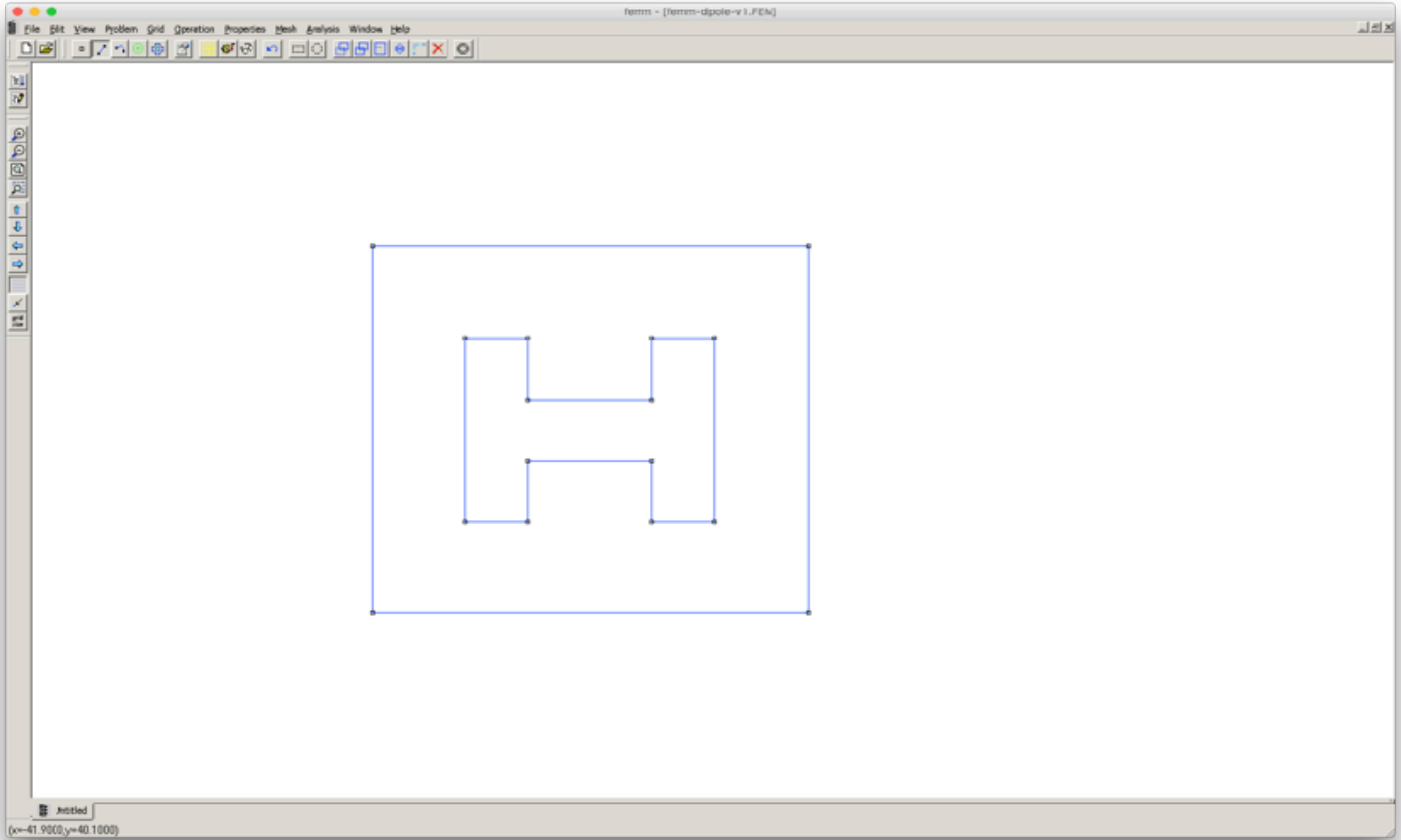
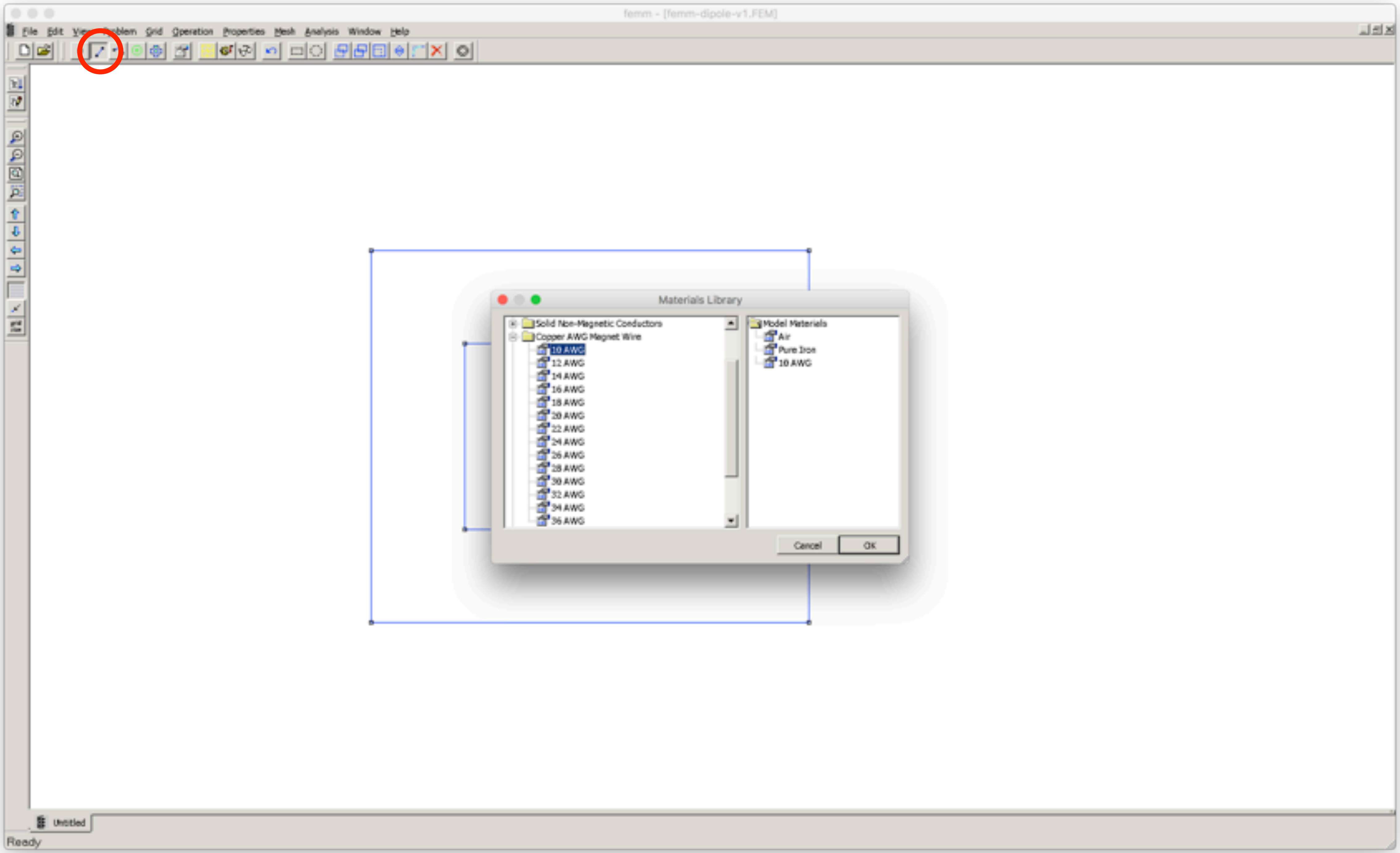
FEMM Tutorial: Magnetostatics

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



FEMM Tutorial: Magnetostatics

- Add materials from Materials Library to the problem definition



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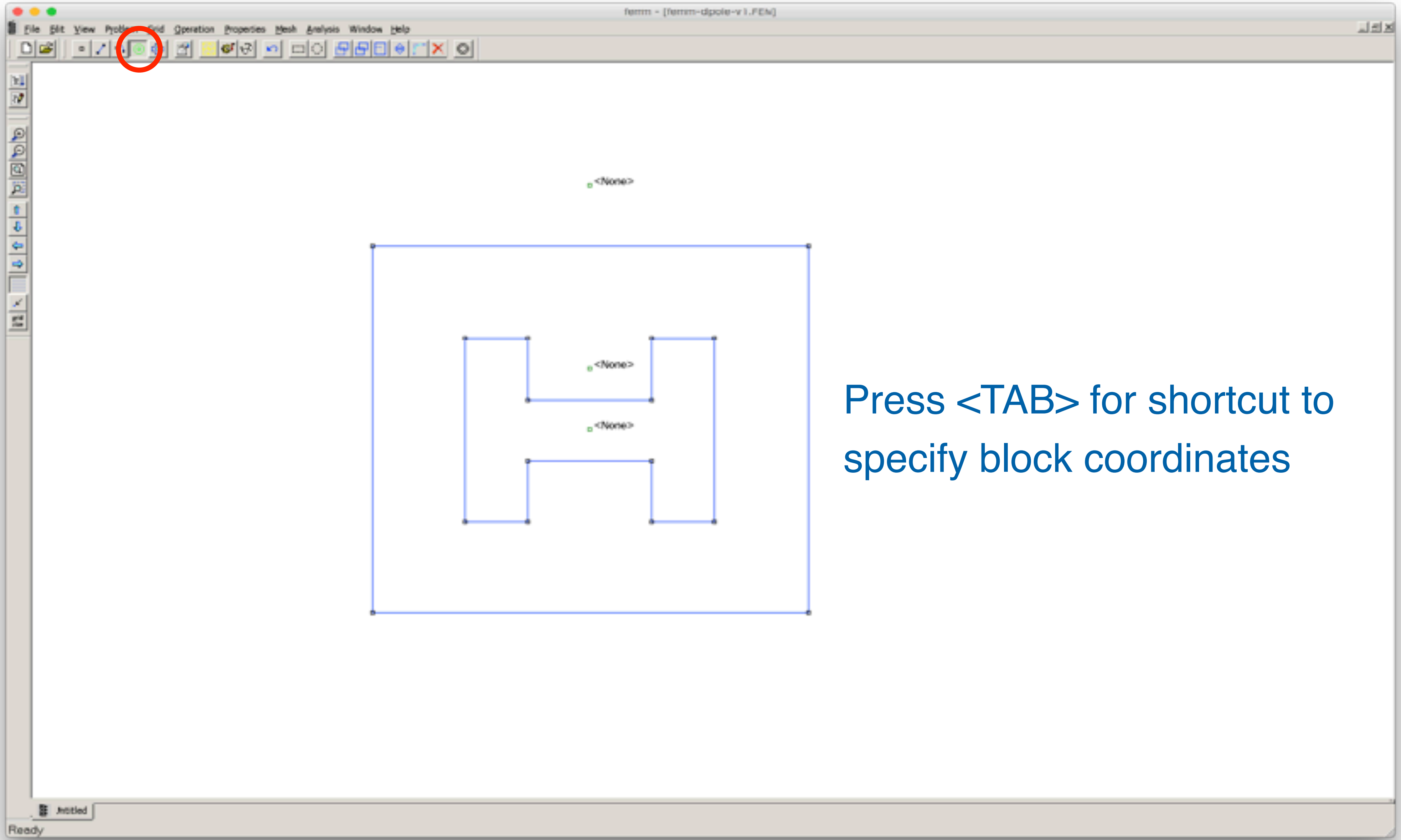
FEMM Tutorial: Magnetostatics

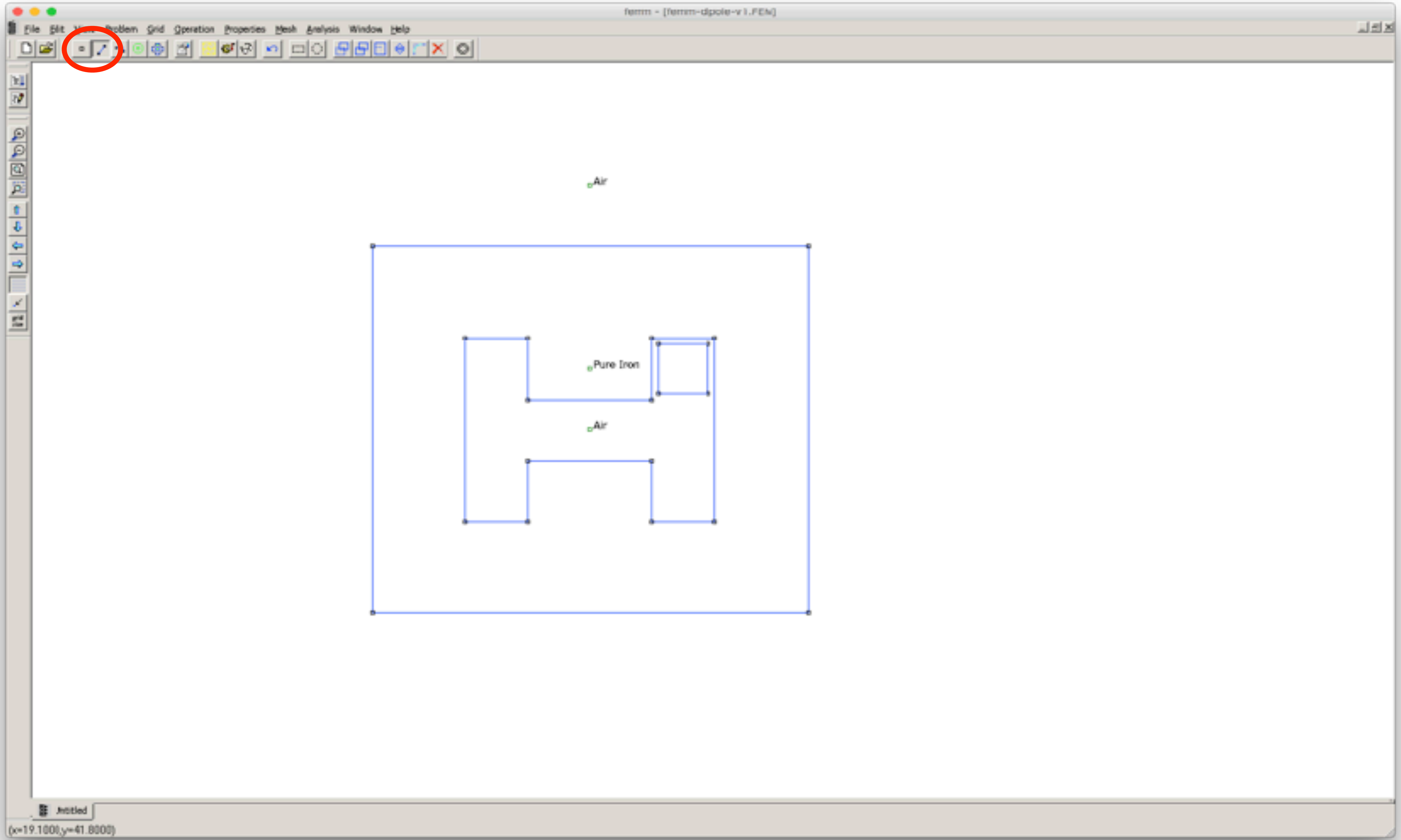
- Add block labels for iron, air. Apply materials to block labels.



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.



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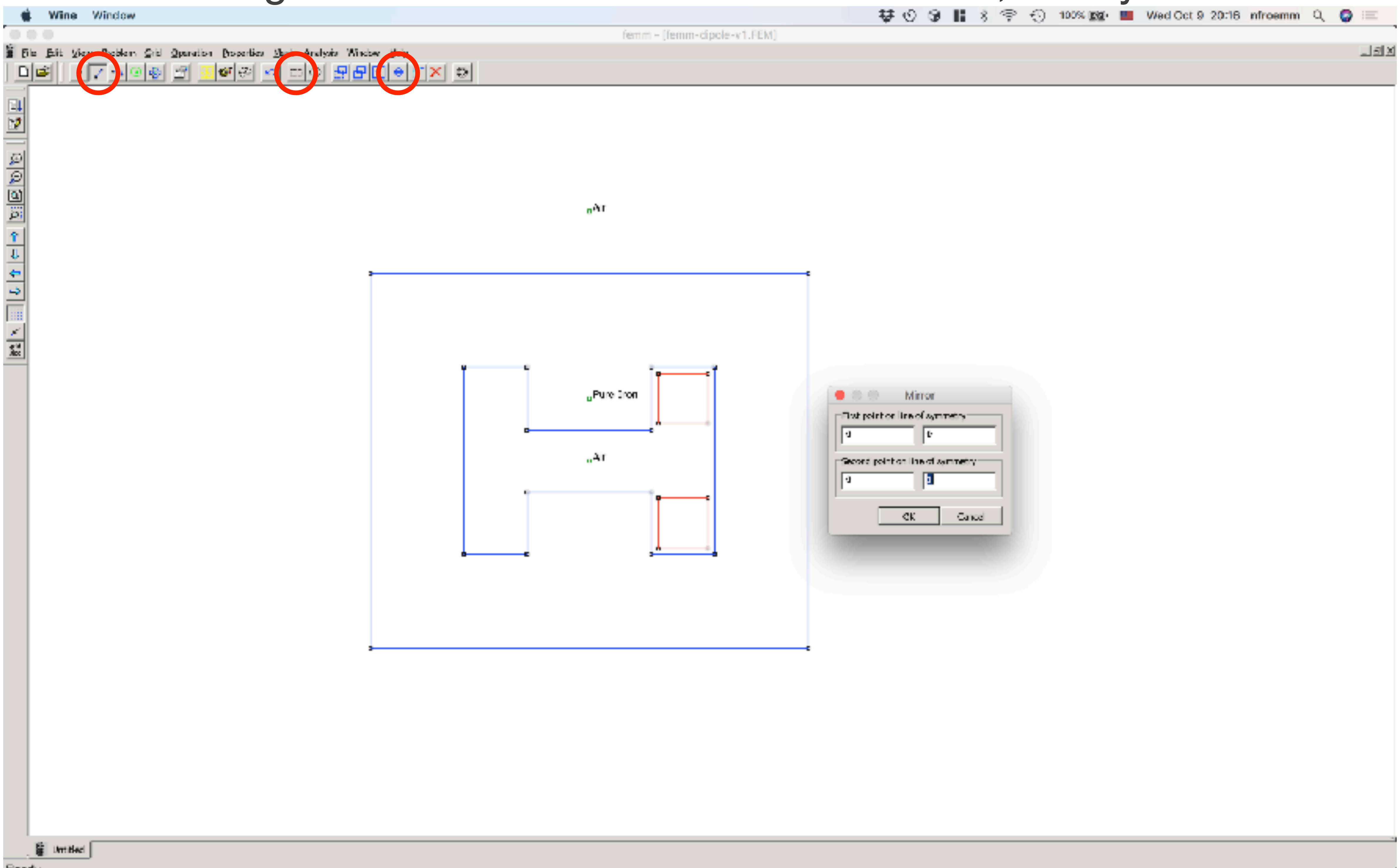
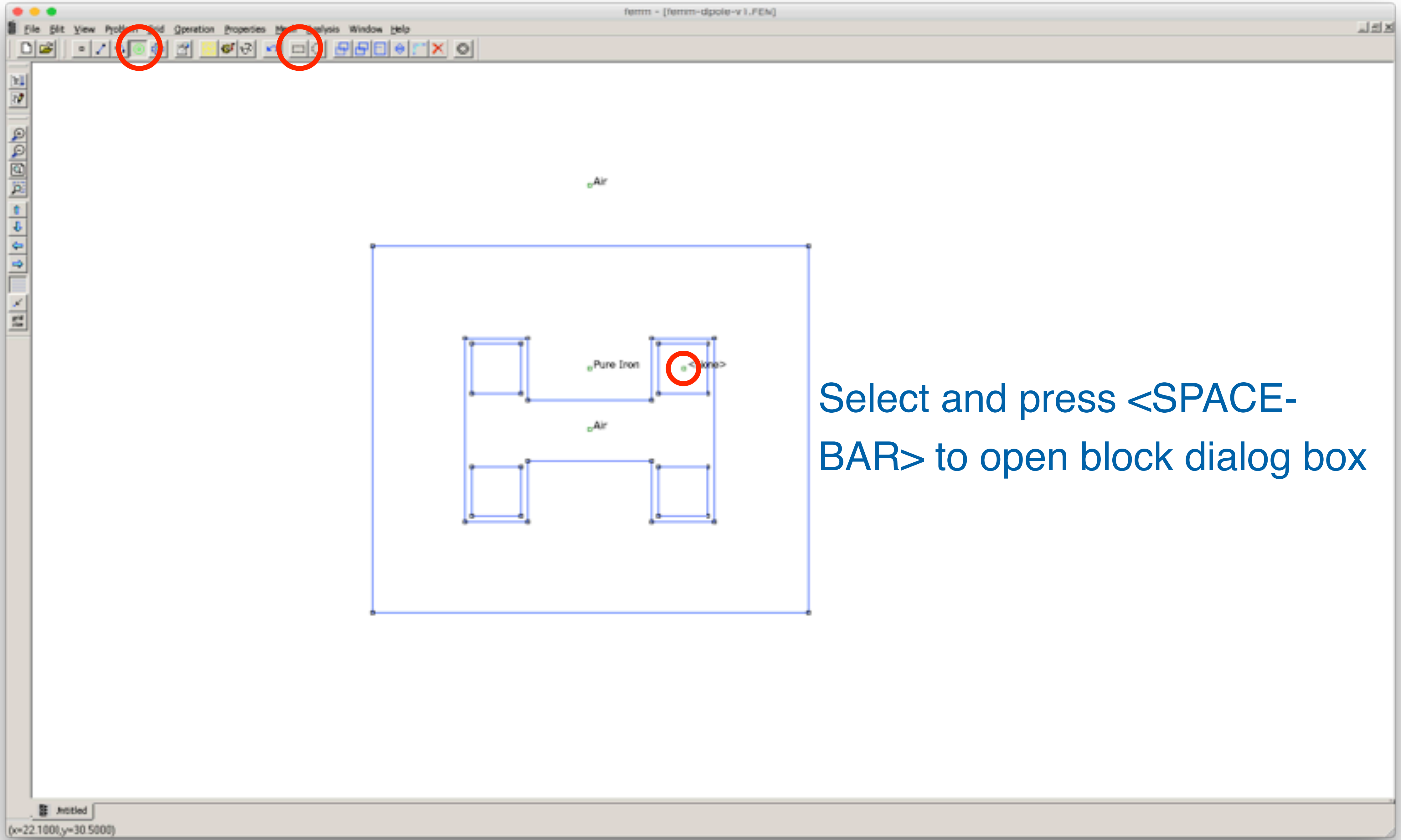
FEMM Tutorial: Magnetostatics

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



FEMM Tutorial: Magnetostatics

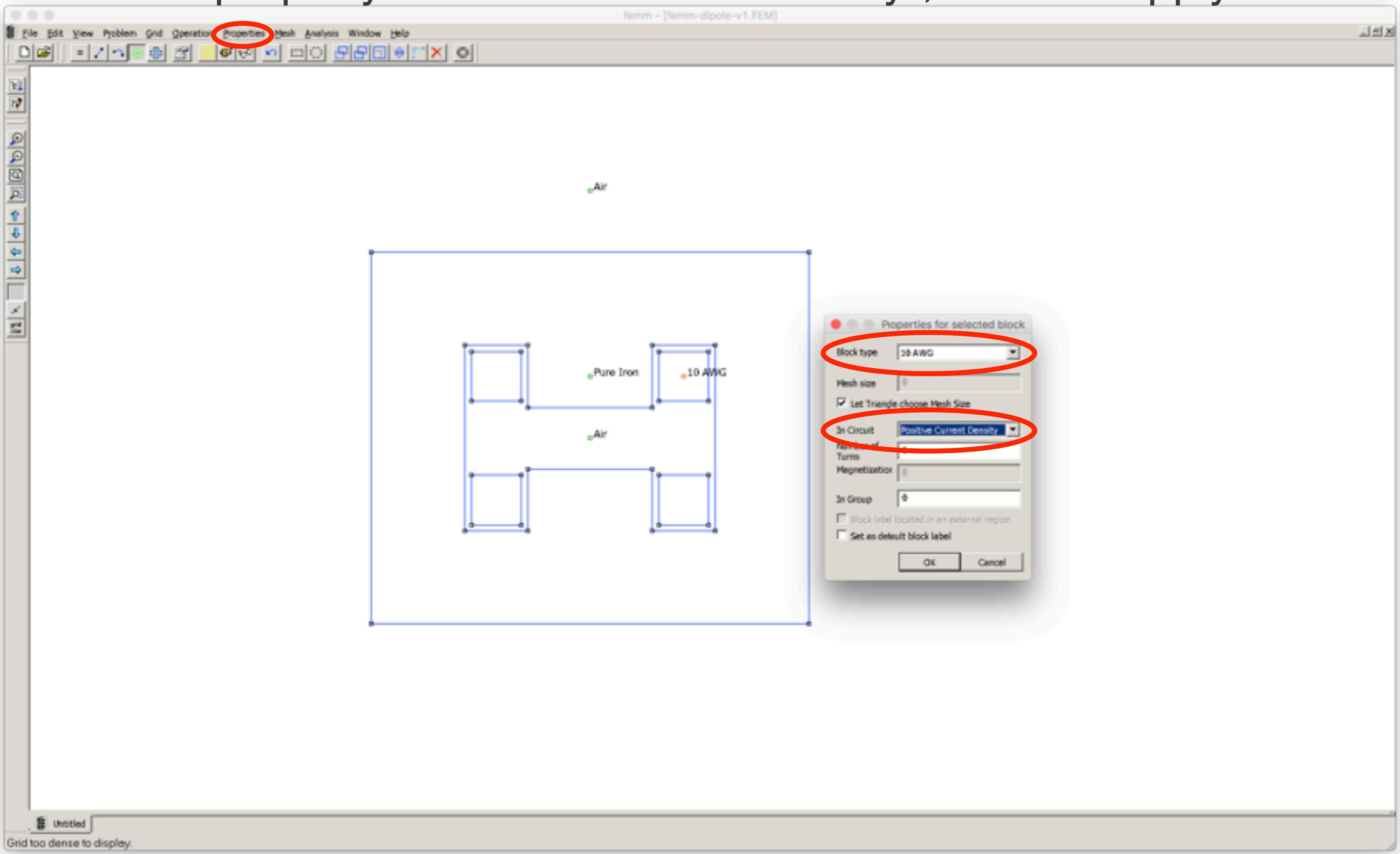
- Add block label at (15, 10) for wires/current



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

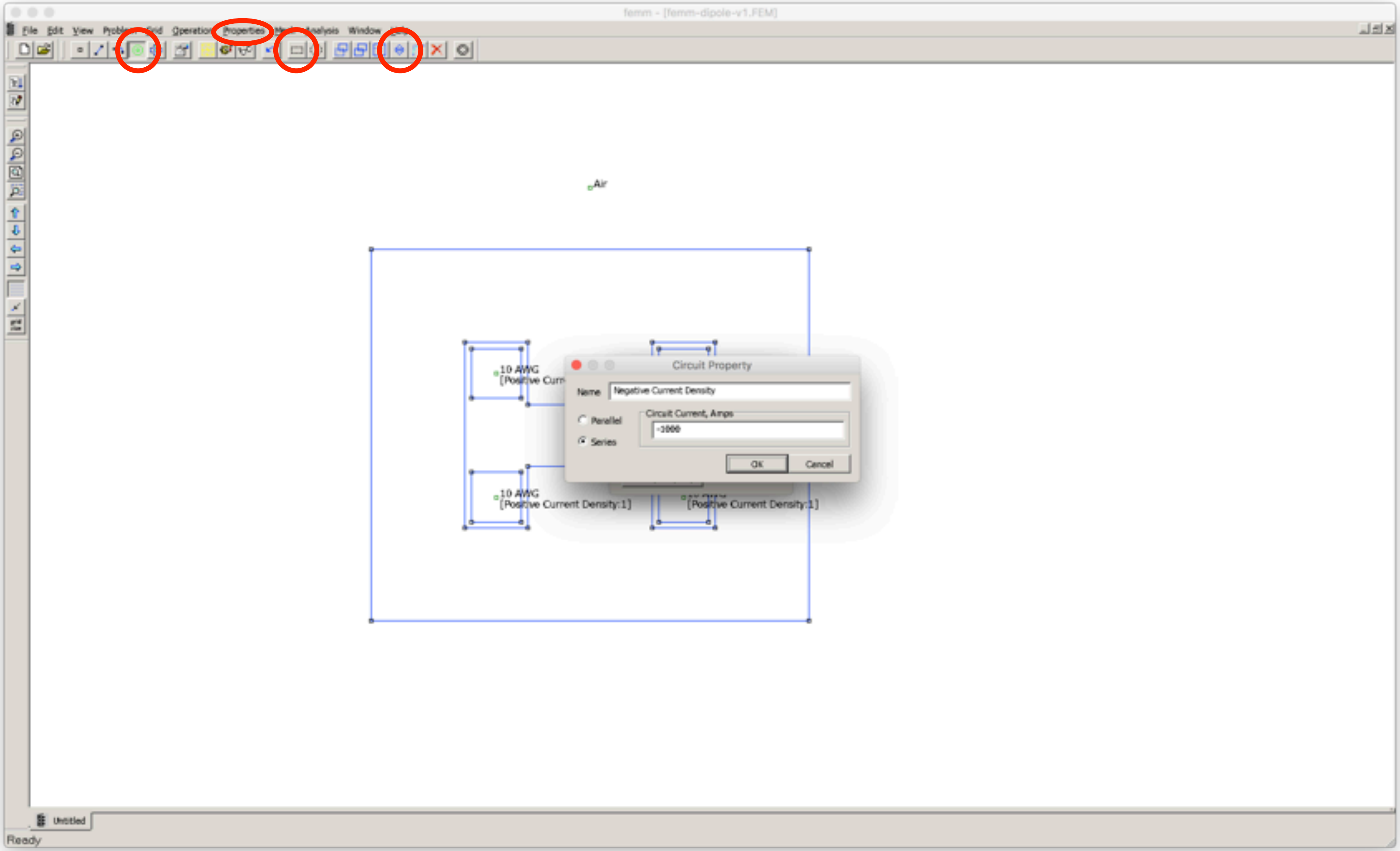
FEMM Tutorial: Magnetostatics

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



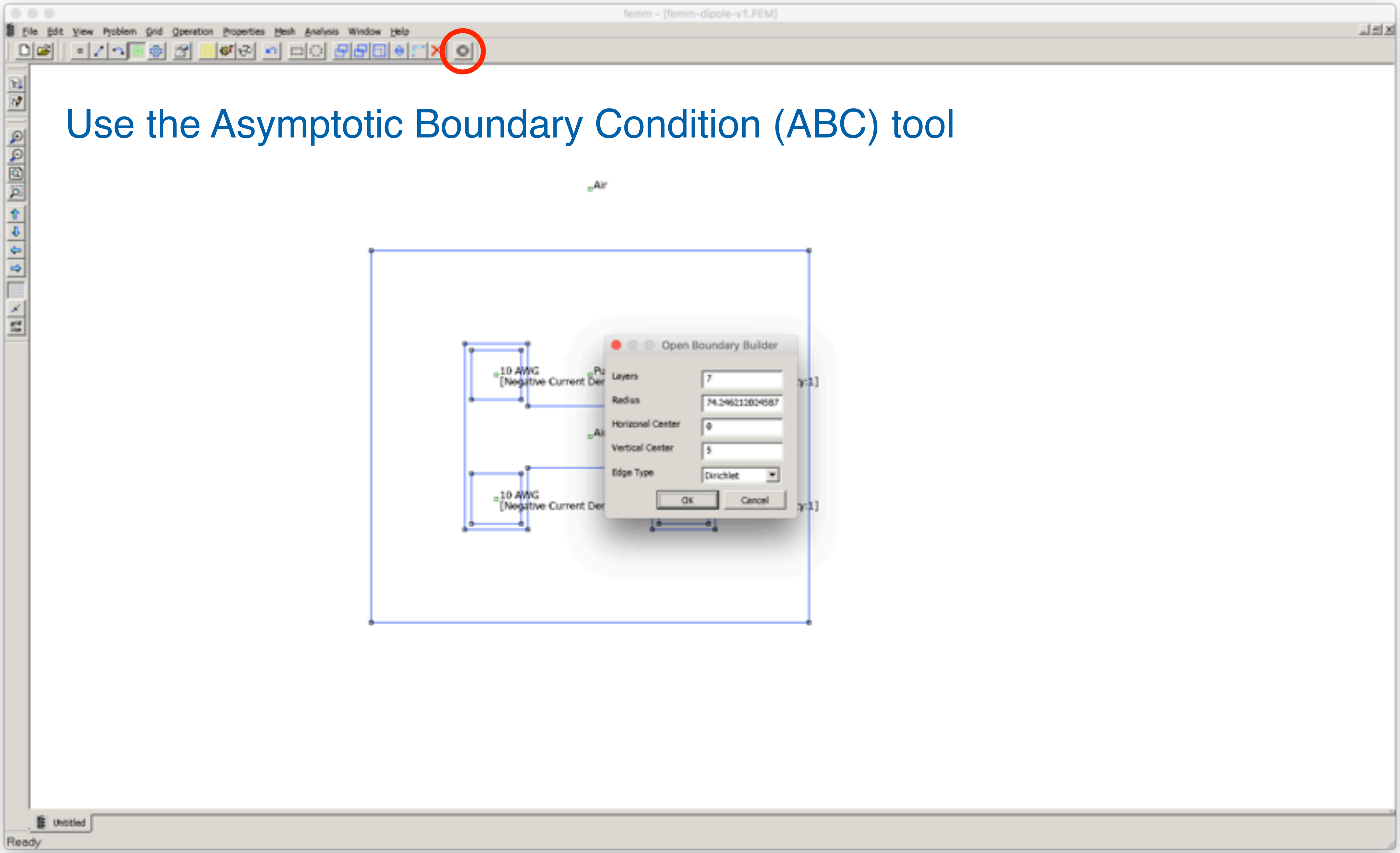
FEMM Tutorial: Magnetostatics

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



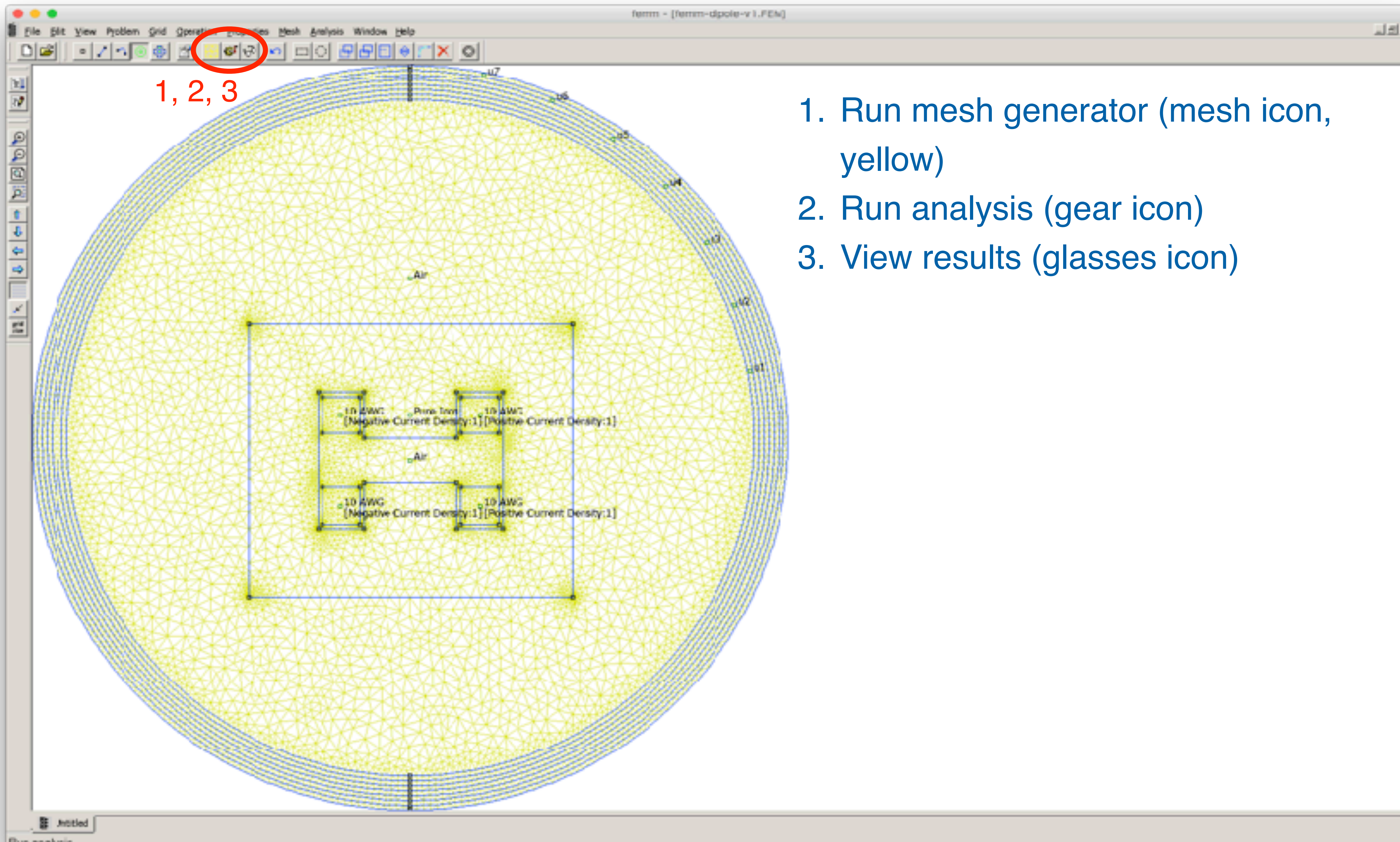
FEMM Tutorial: Magnetostatics

- Add an “open” boundary condition at infinity



FEMM Tutorial: Magnetostatics

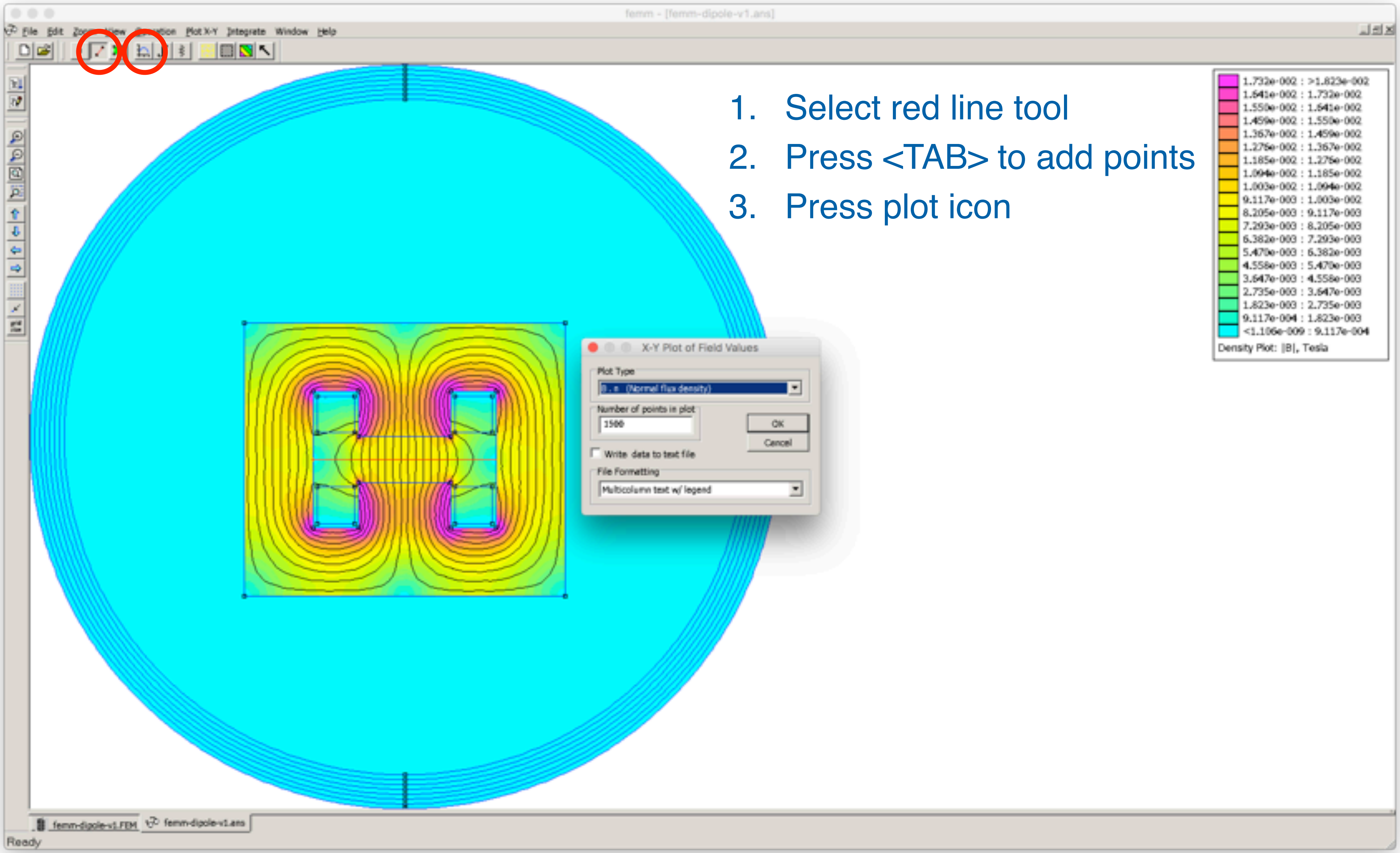
- Mesh and solve the problem



1. Run mesh generator (mesh icon, yellow)
2. Run analysis (gear icon)
3. View results (glasses icon)

FEMM Tutorial: Magnetostatics

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



1. Select red line tool
2. Press <TAB> to add points
3. Press plot icon

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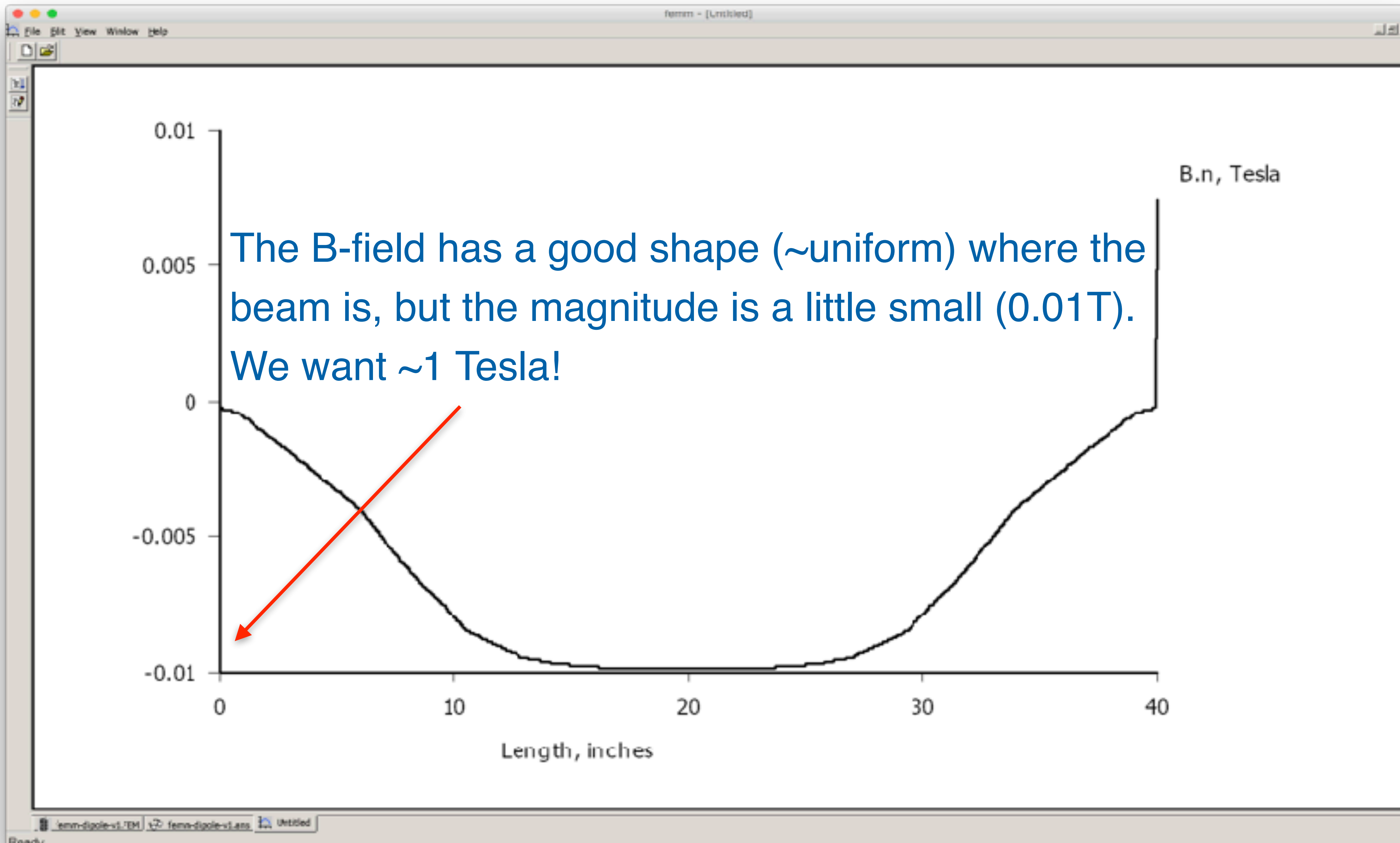
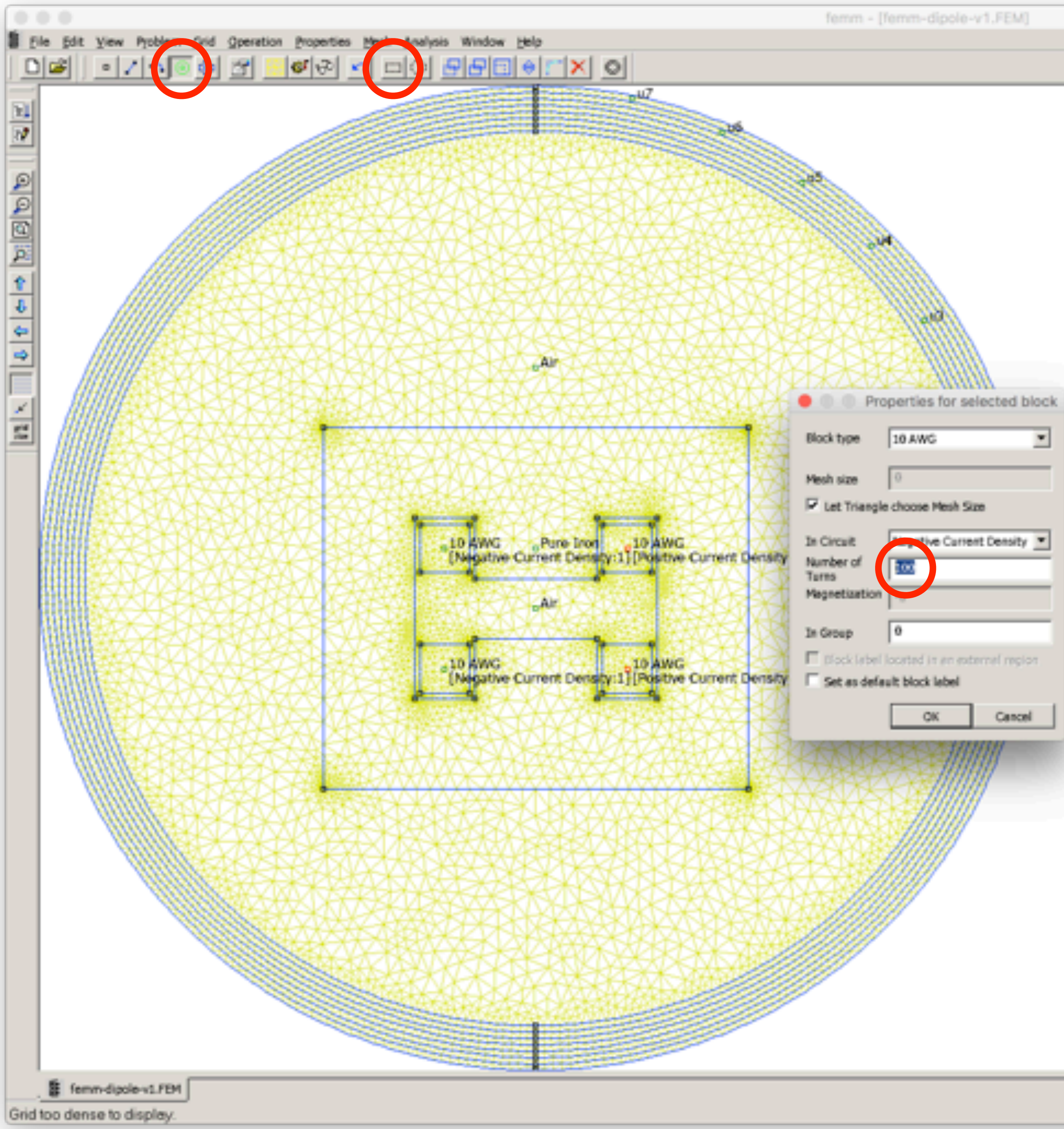
FEMM Tutorial: Magnetostatics

- Our first B-field result! 👍😊

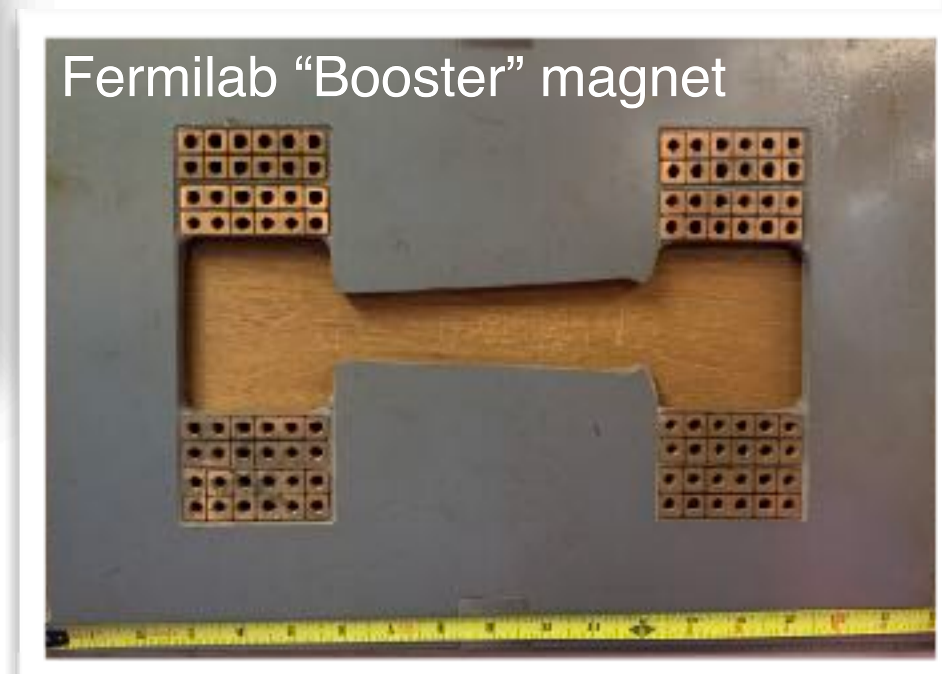


FEMM Tutorial: Magnetostatics

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

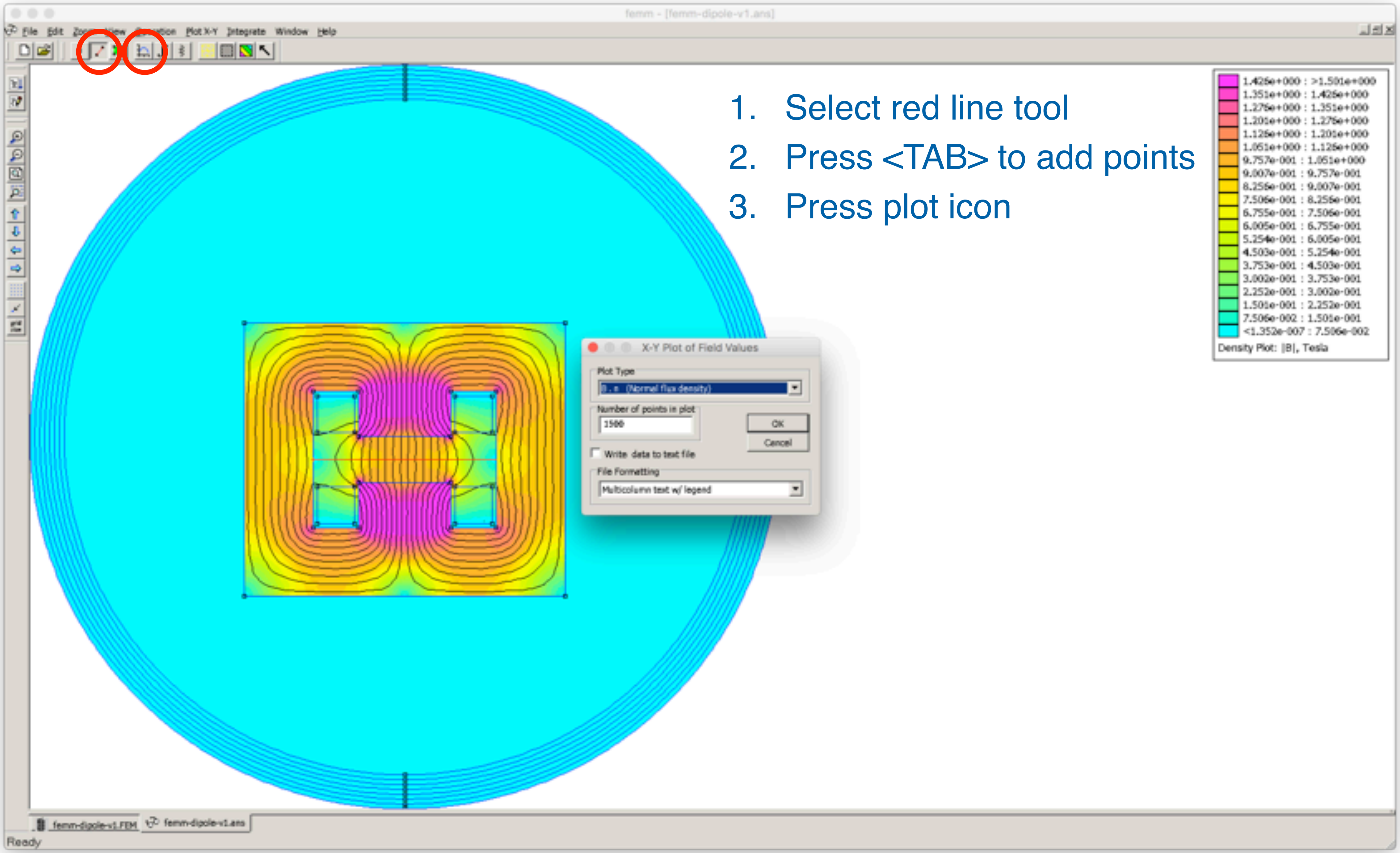


1. Select block(s)
2. Press <SPACE BAR> to open block properties box



FEMM Tutorial: Magnetostatics

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



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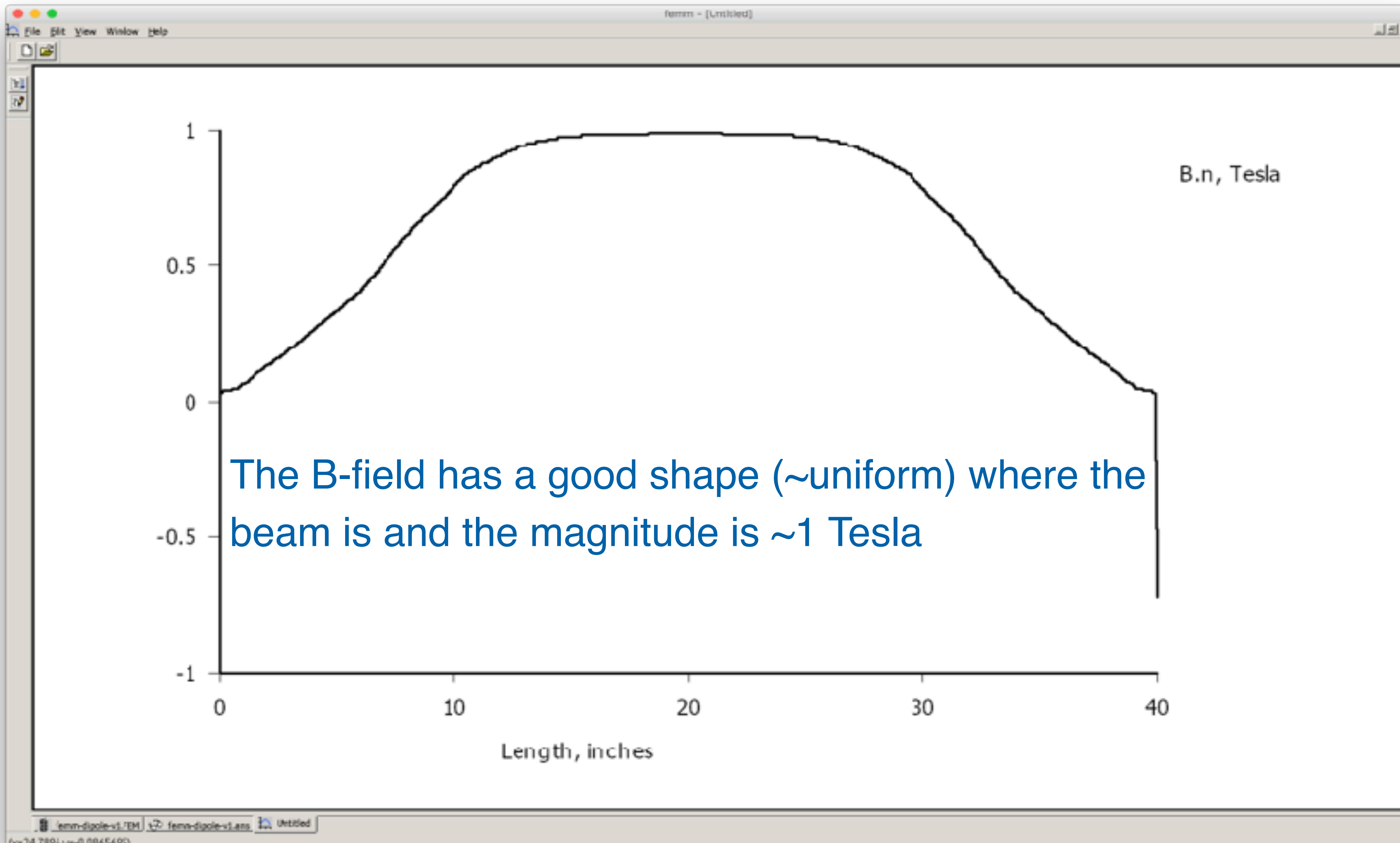
FEMM Tutorial: Magnetostatics

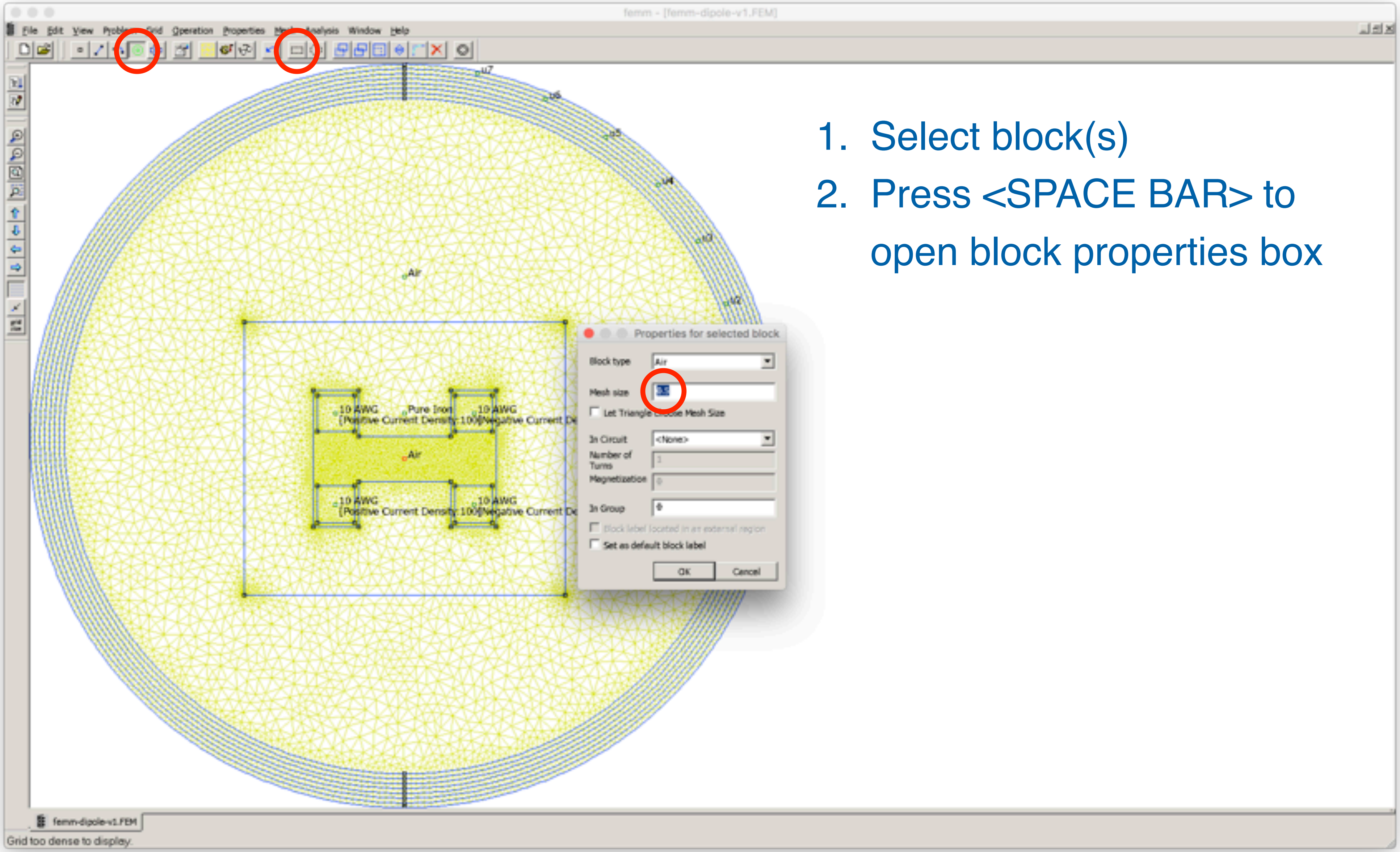
- Wow, this is starting to look pretty good! 👍😁



The B-field has a good shape (~uniform) where the beam is and the magnitude is ~1 Tesla

FEMM Tutorial: Magnetostatics

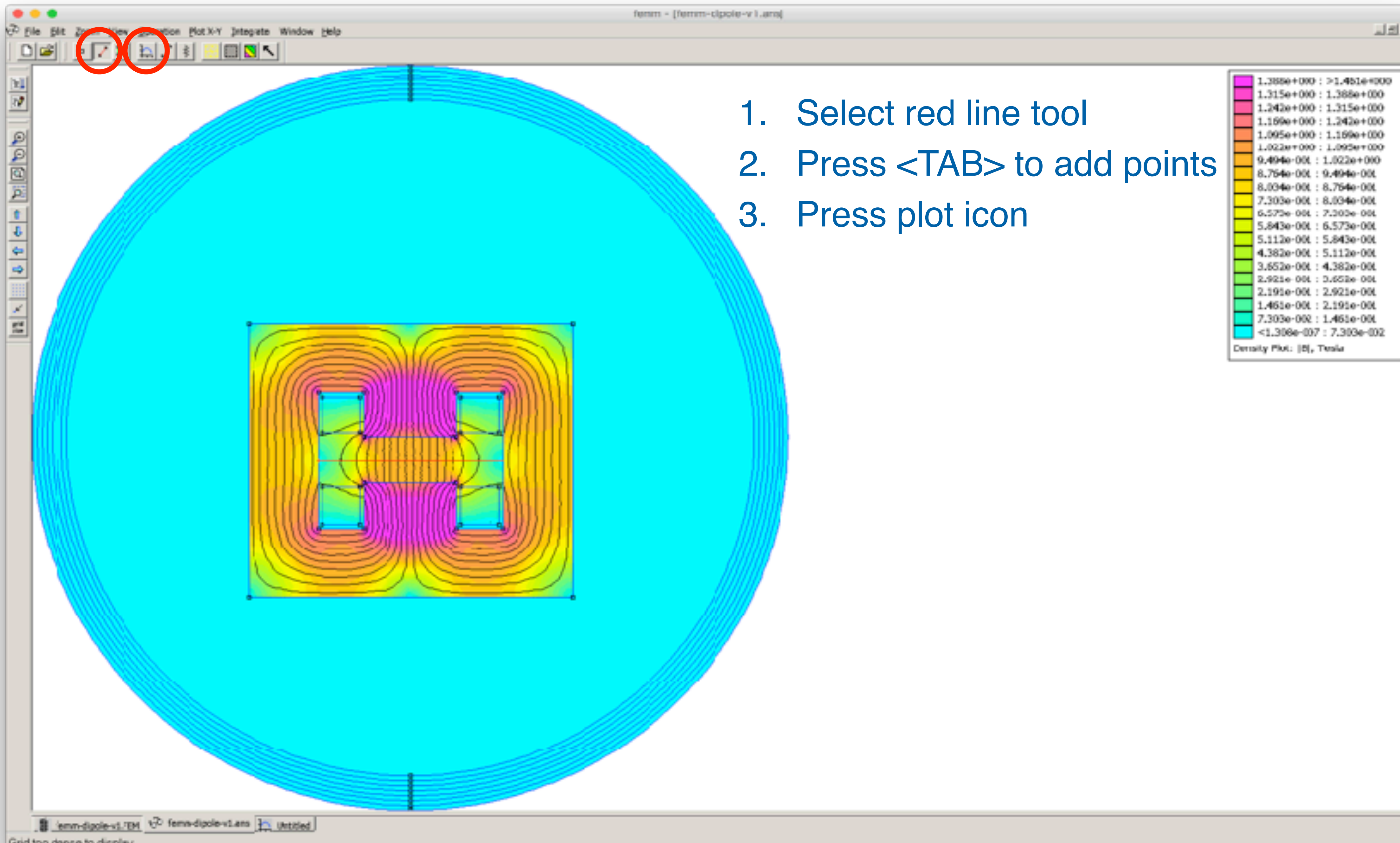
- Pro Tip: Increase mesh density in field region of interest for increased field quality



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

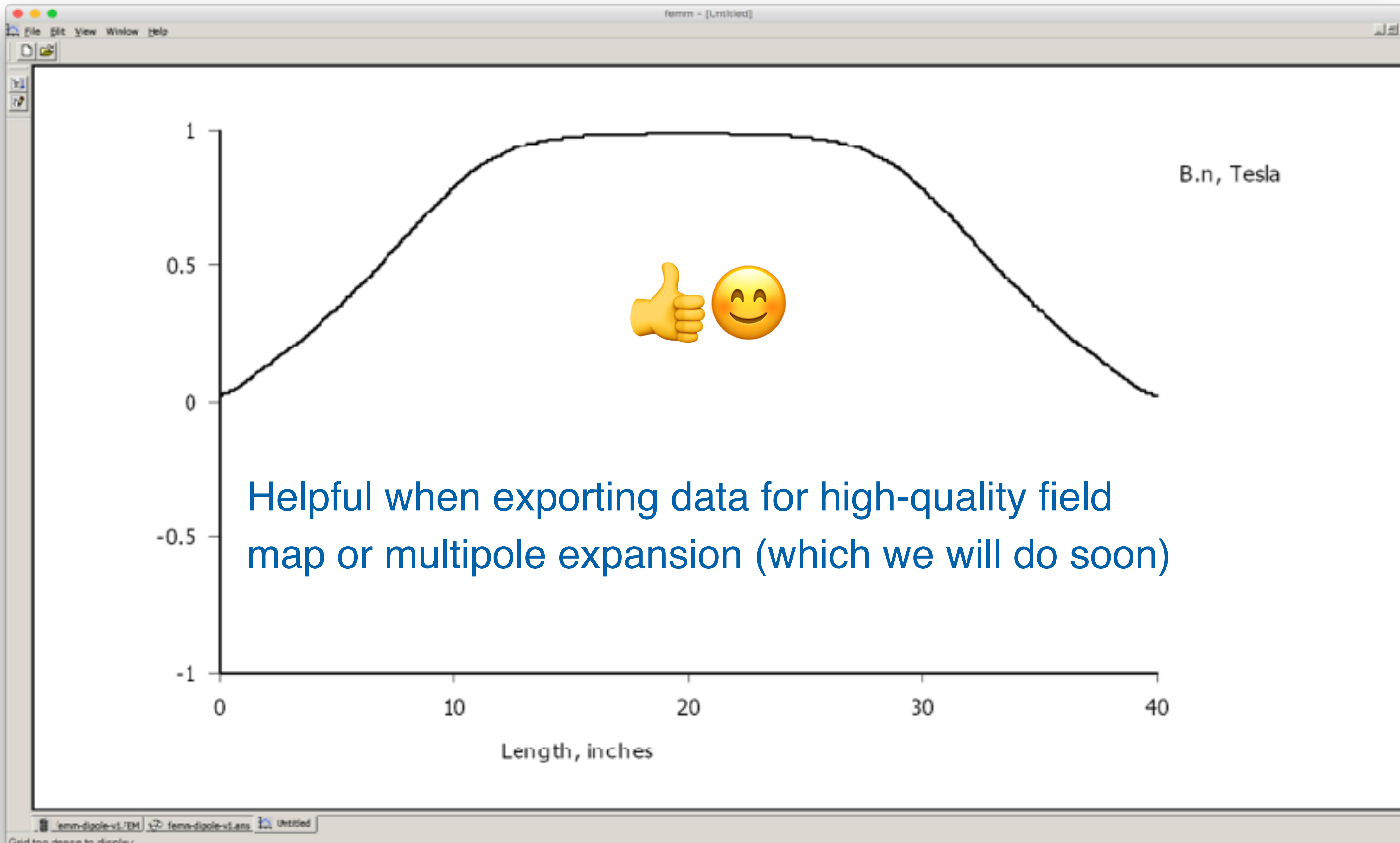
FEMM Tutorial: Magnetostatics

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



FEMM Tutorial: Magnetostatics

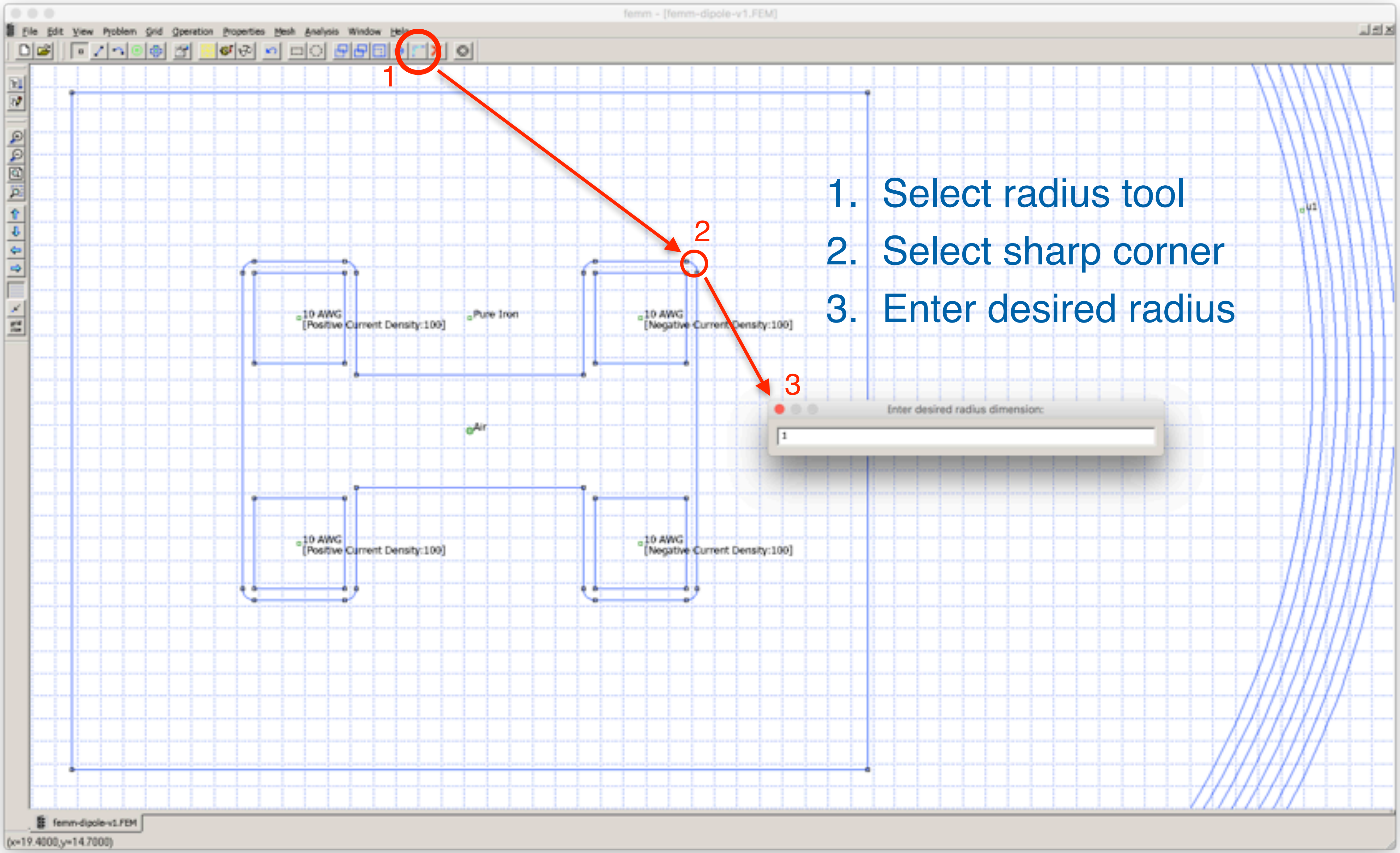
- Increasing mesh density in region of interest increases numerical field quality



Helpful when exporting data for high-quality field map or multipole expansion (which we will do soon)

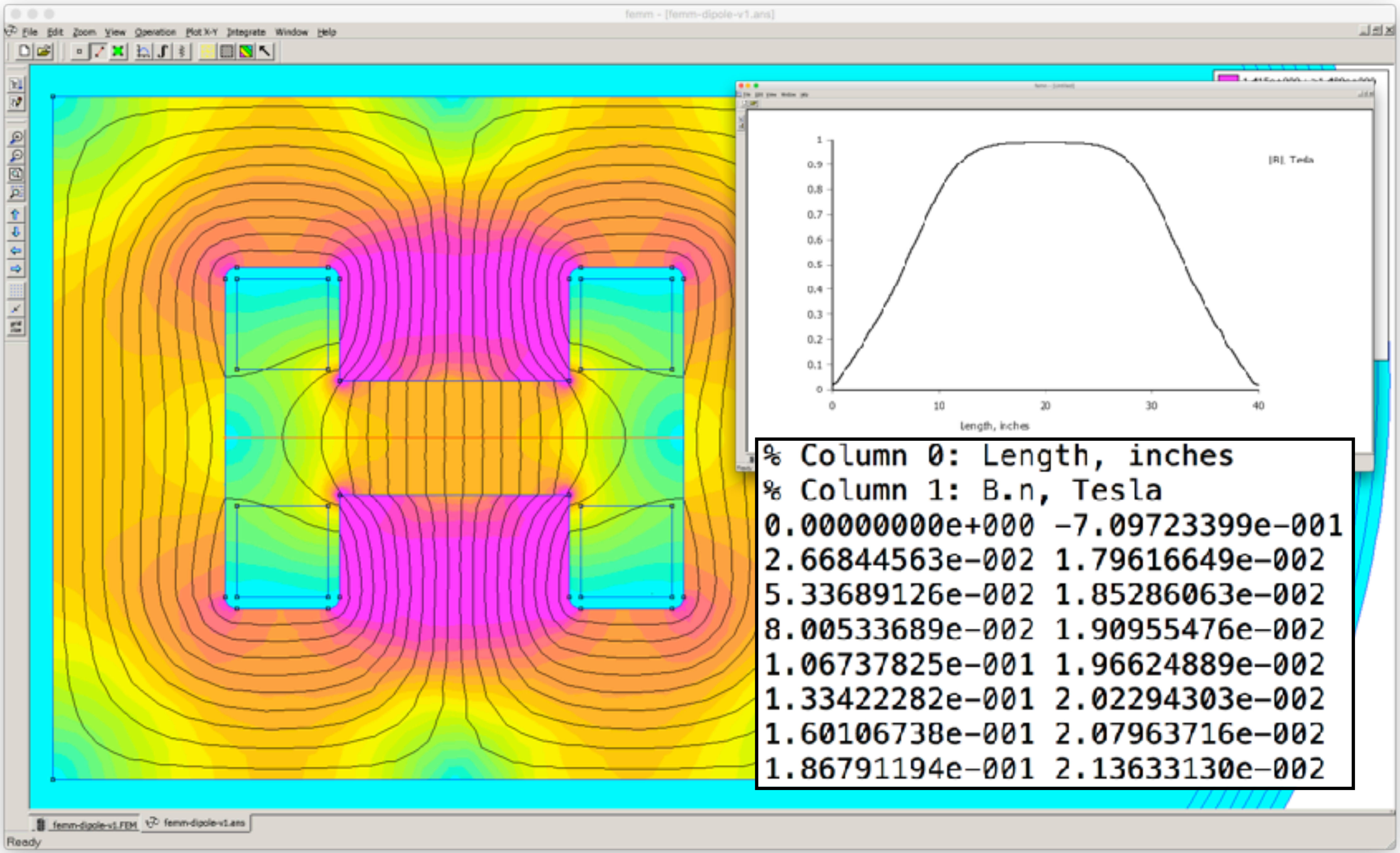
FEMM Tutorial: Magnetostatics

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



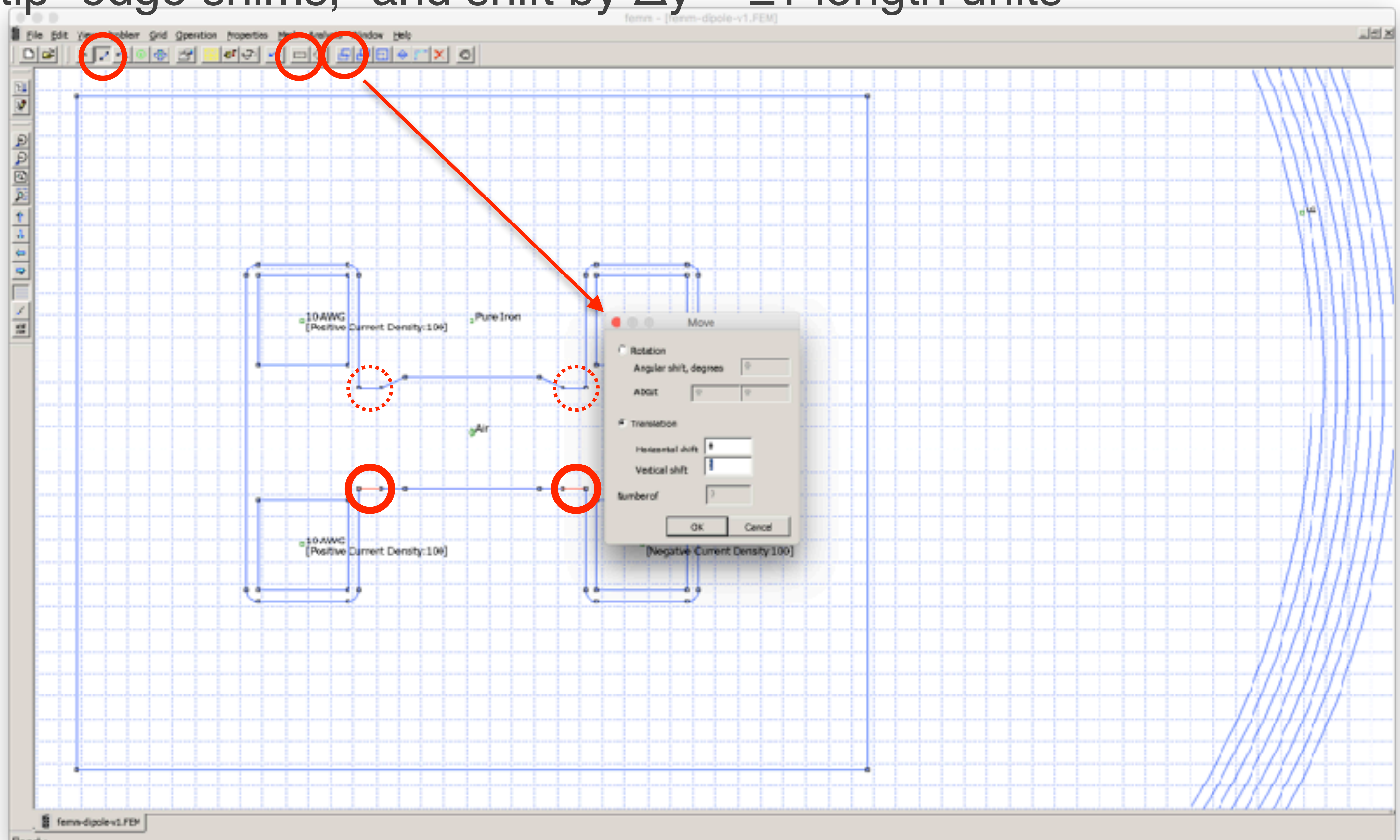
FEMM Tutorial: Magnetostatics

- 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



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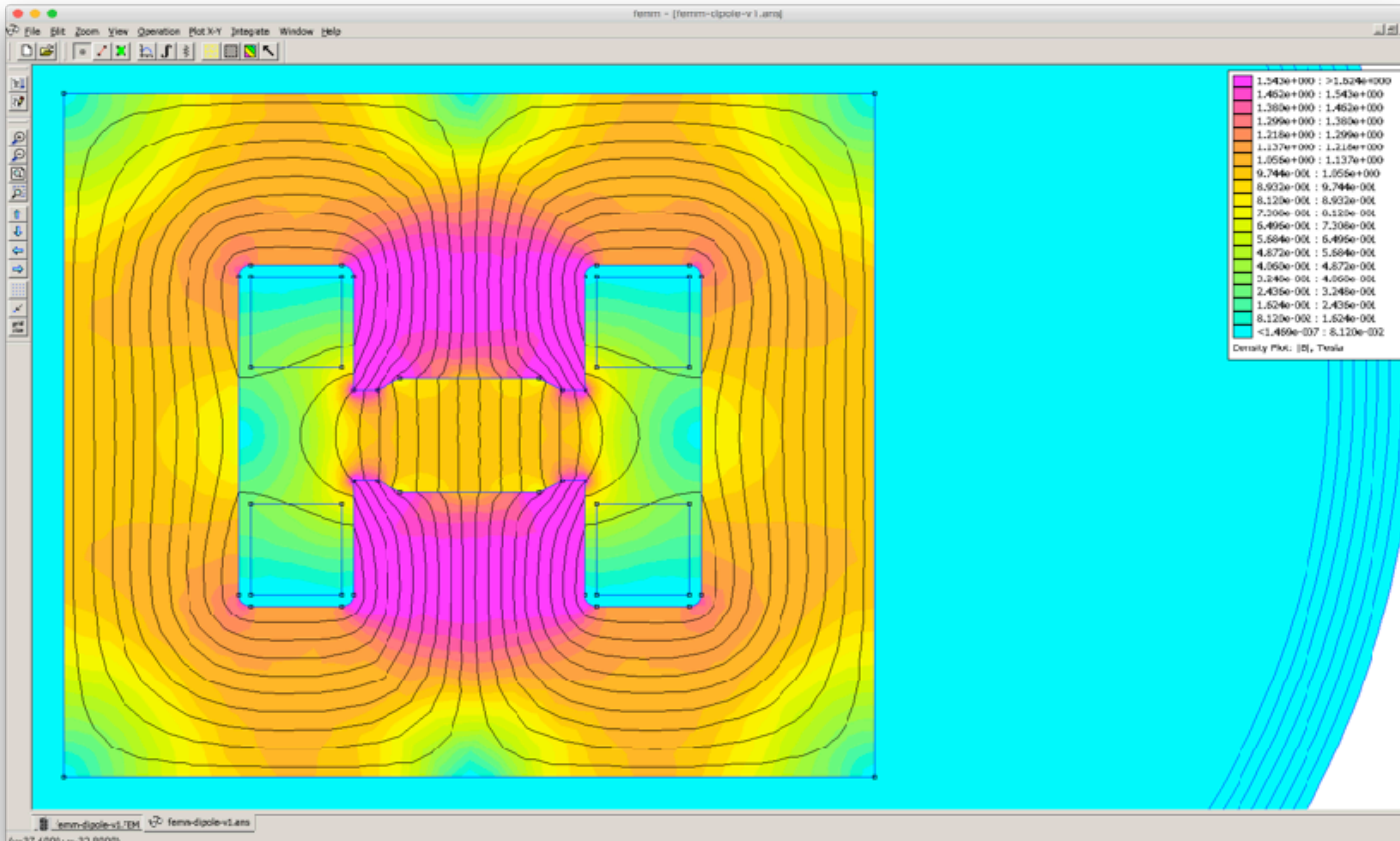
FEMM Tutorial: Magnetostatics

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



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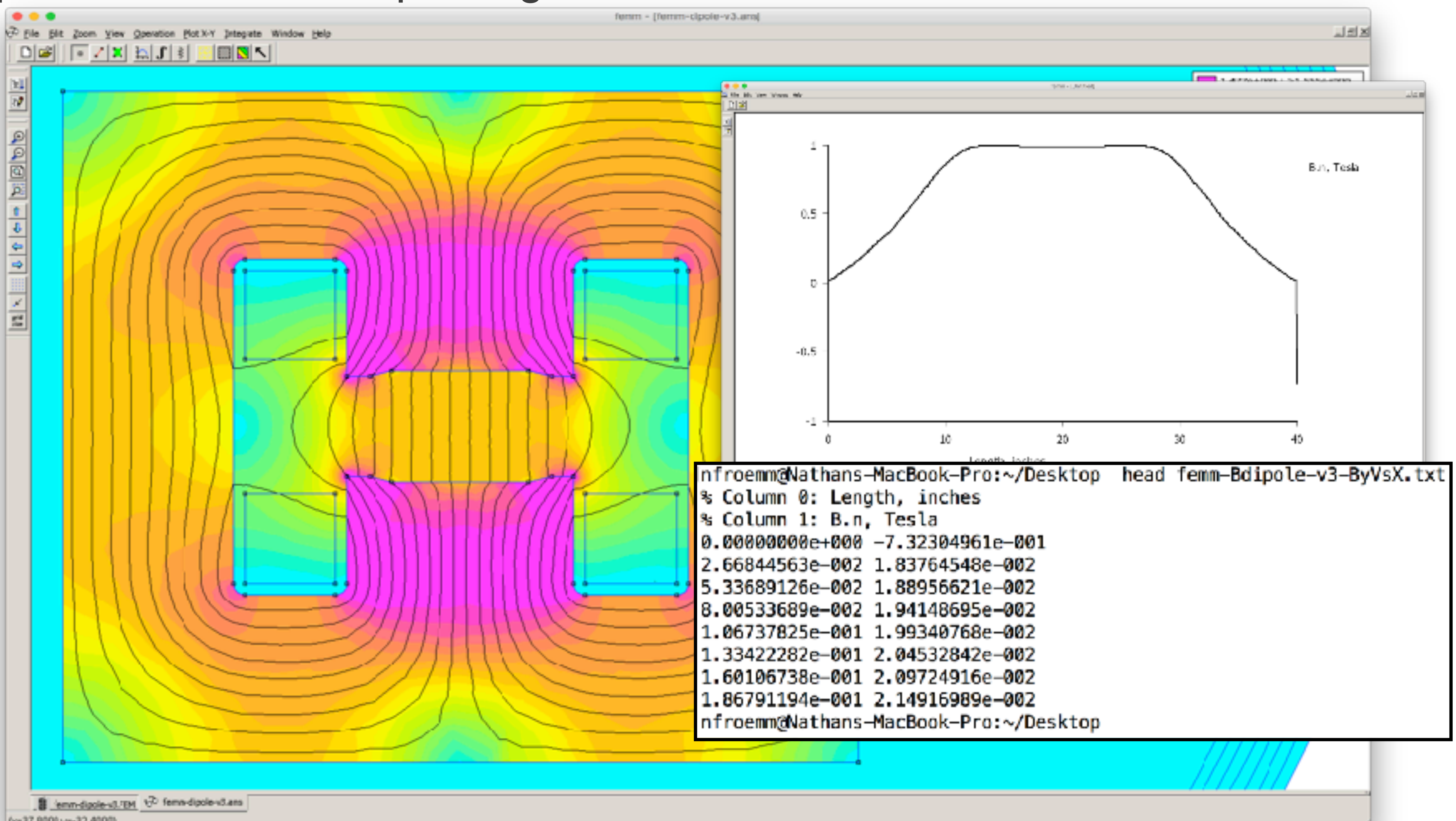
FEMM Tutorial: Magnetostatics

- 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.



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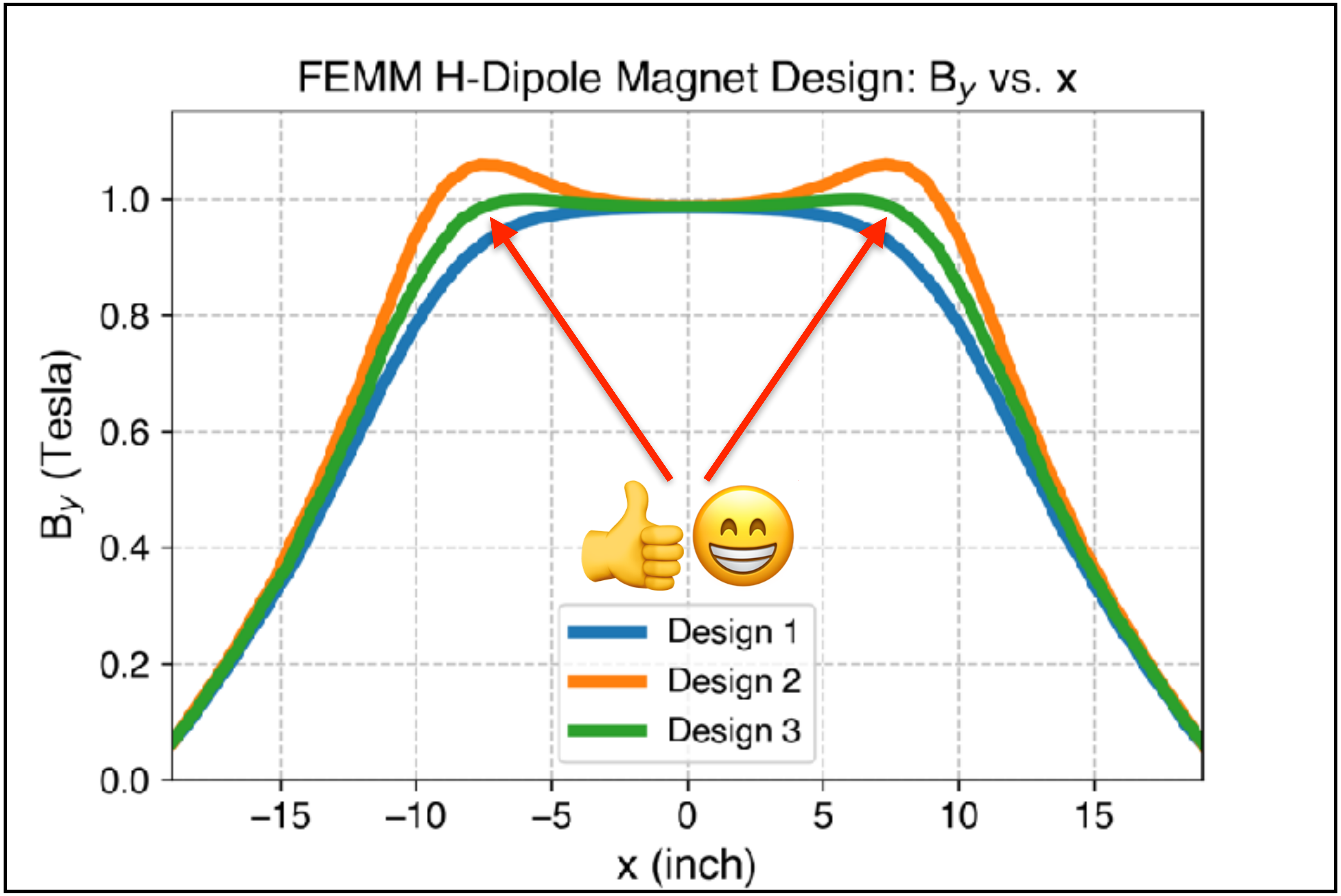
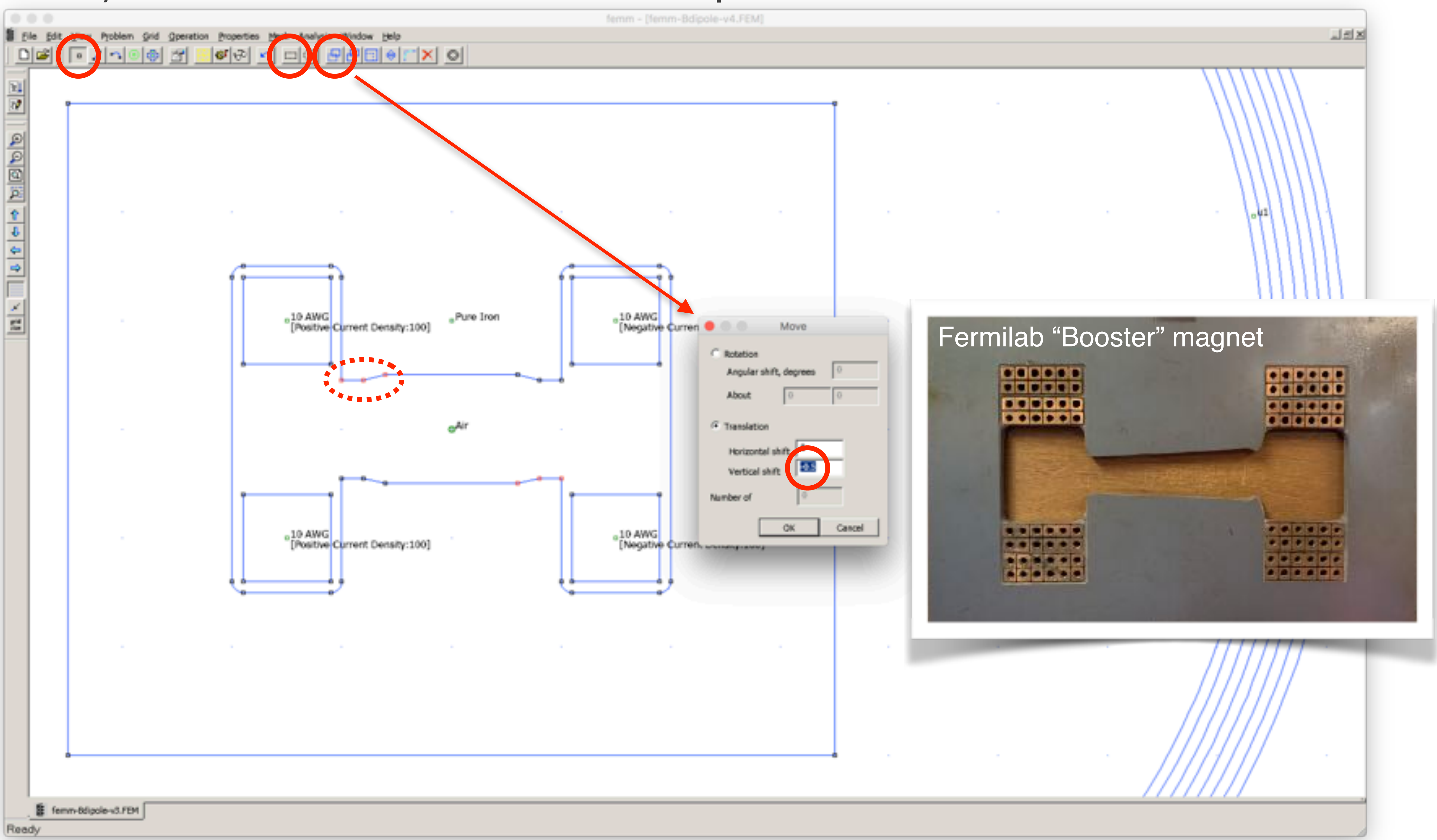
FEMM Tutorial: Magnetostatics

- 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".



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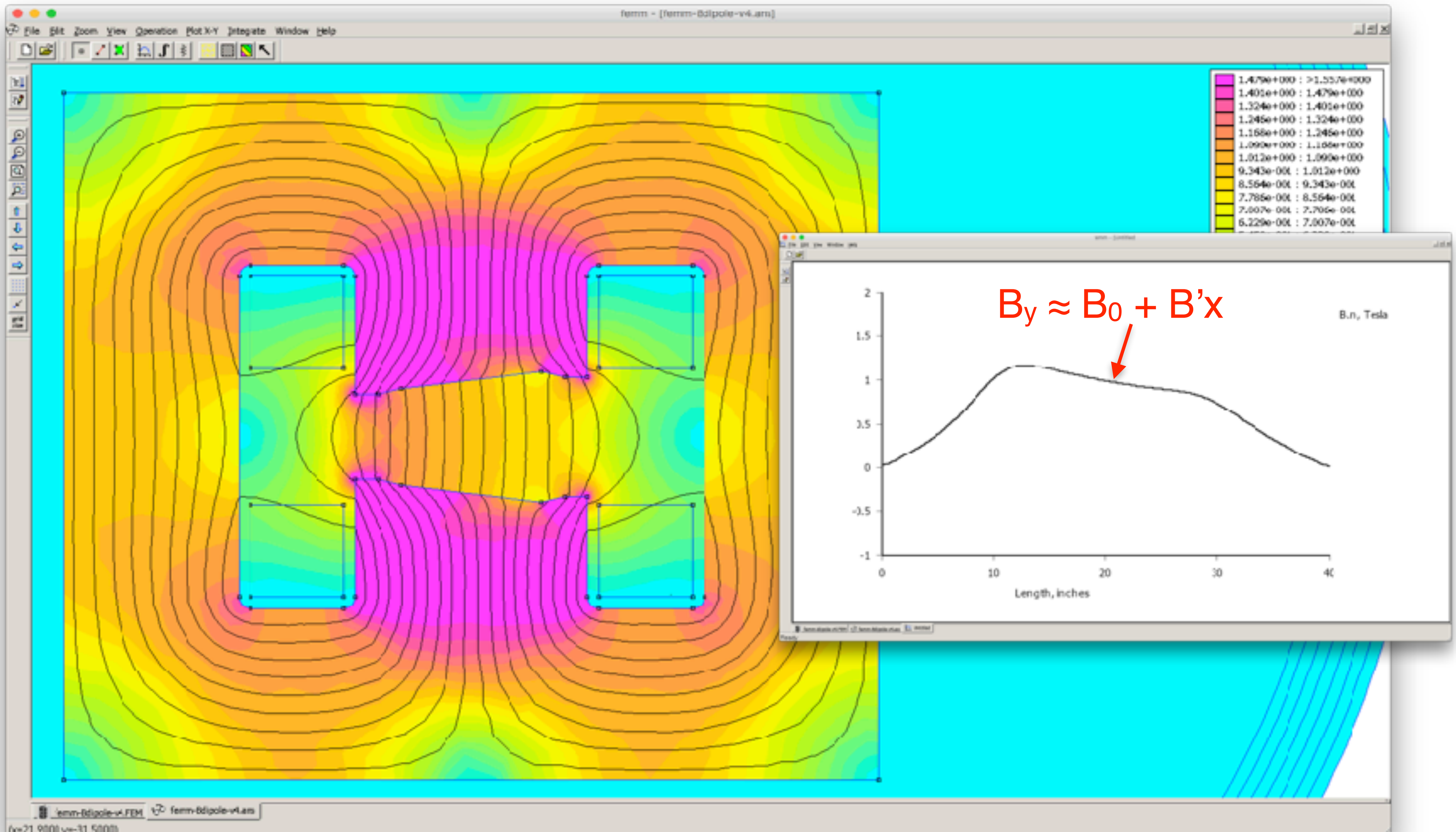
FEMM Tutorial: Magnetostatics

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



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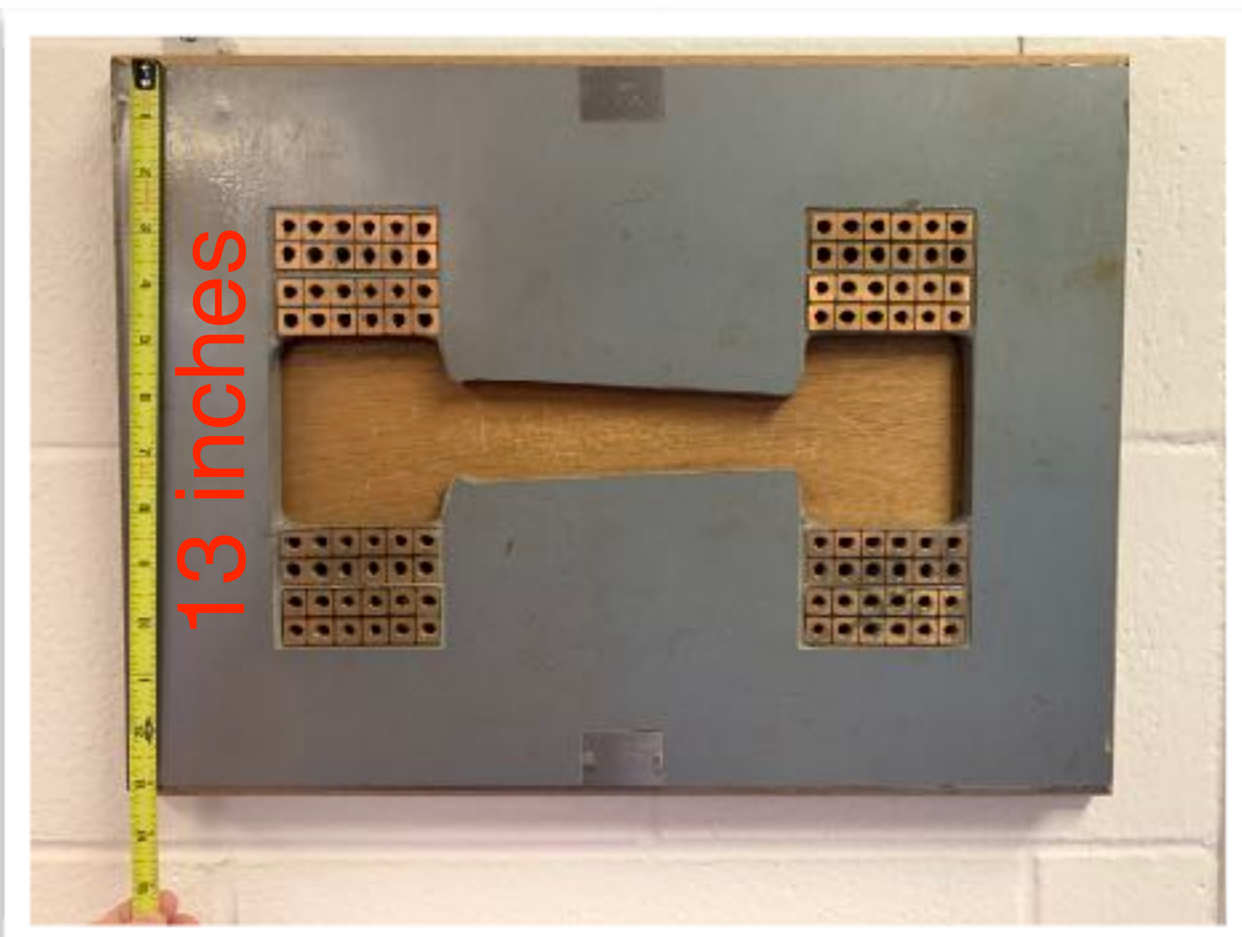
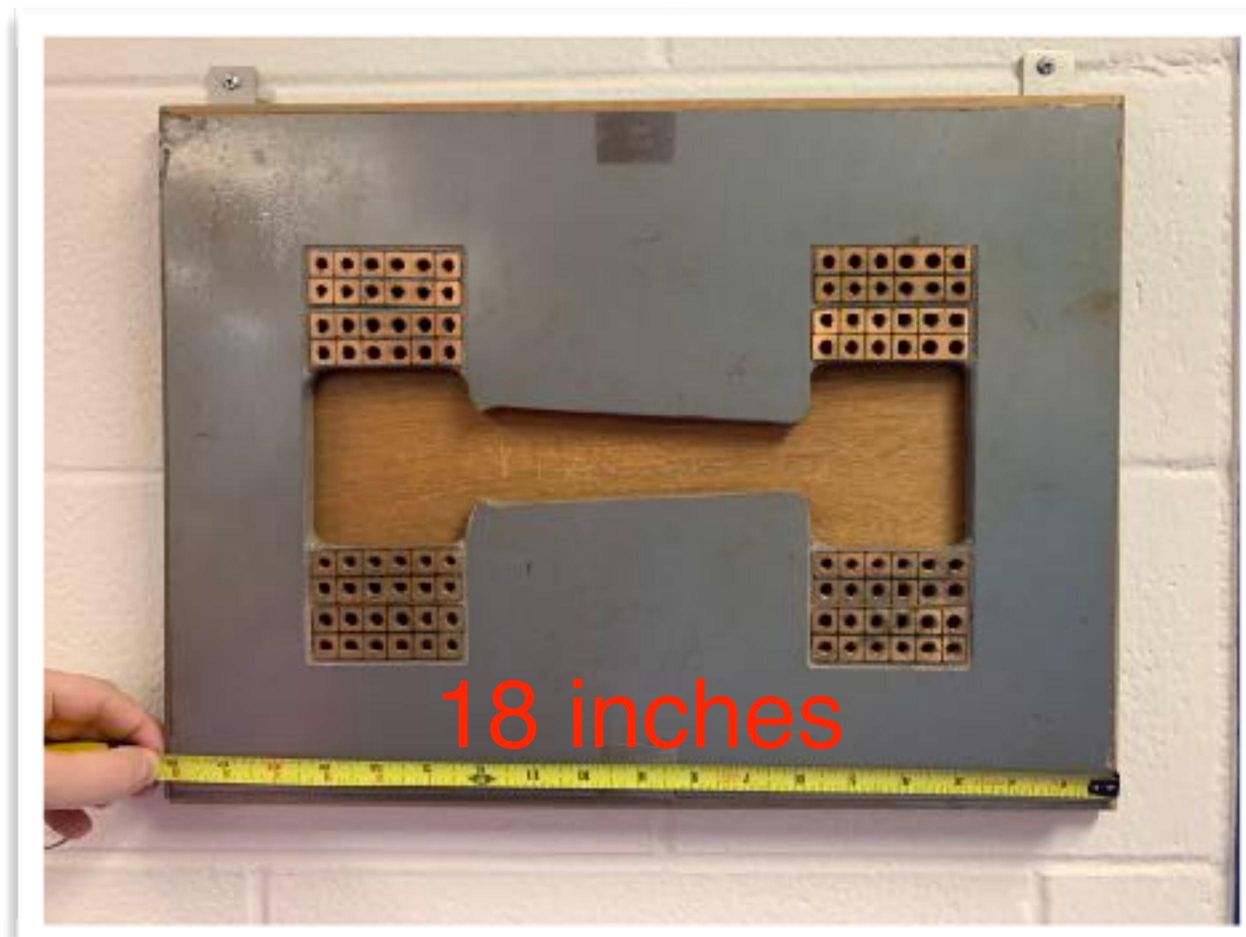
Building A More Realistic Example: FEMM + WebPlotDigitizer

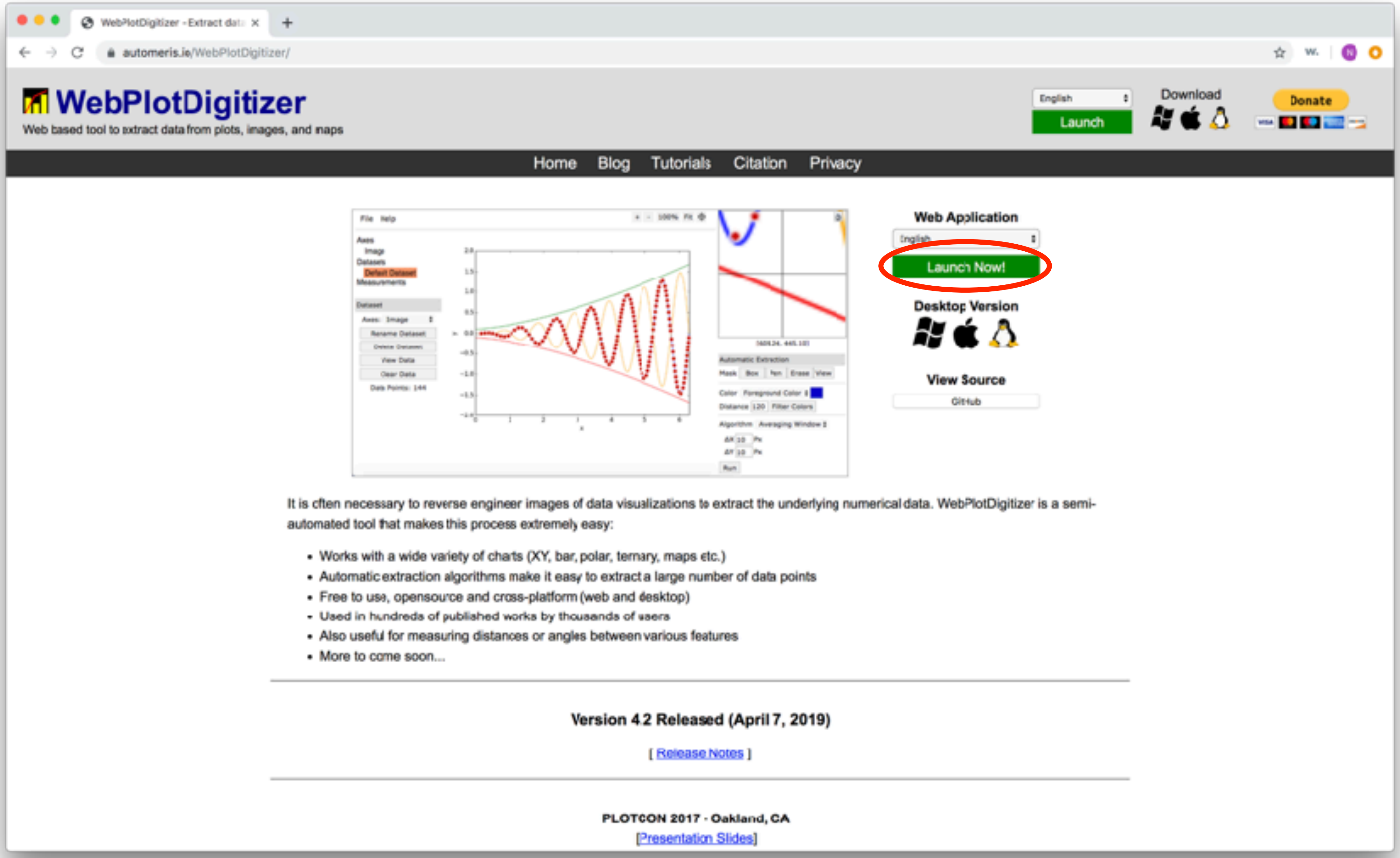
- Can use "WebPlotDigitizer" to get vertices of pole tips, i.e. to create a better model. Simply navigate to WebPlotDigitizer, load image of your choosing, and click desired vertices





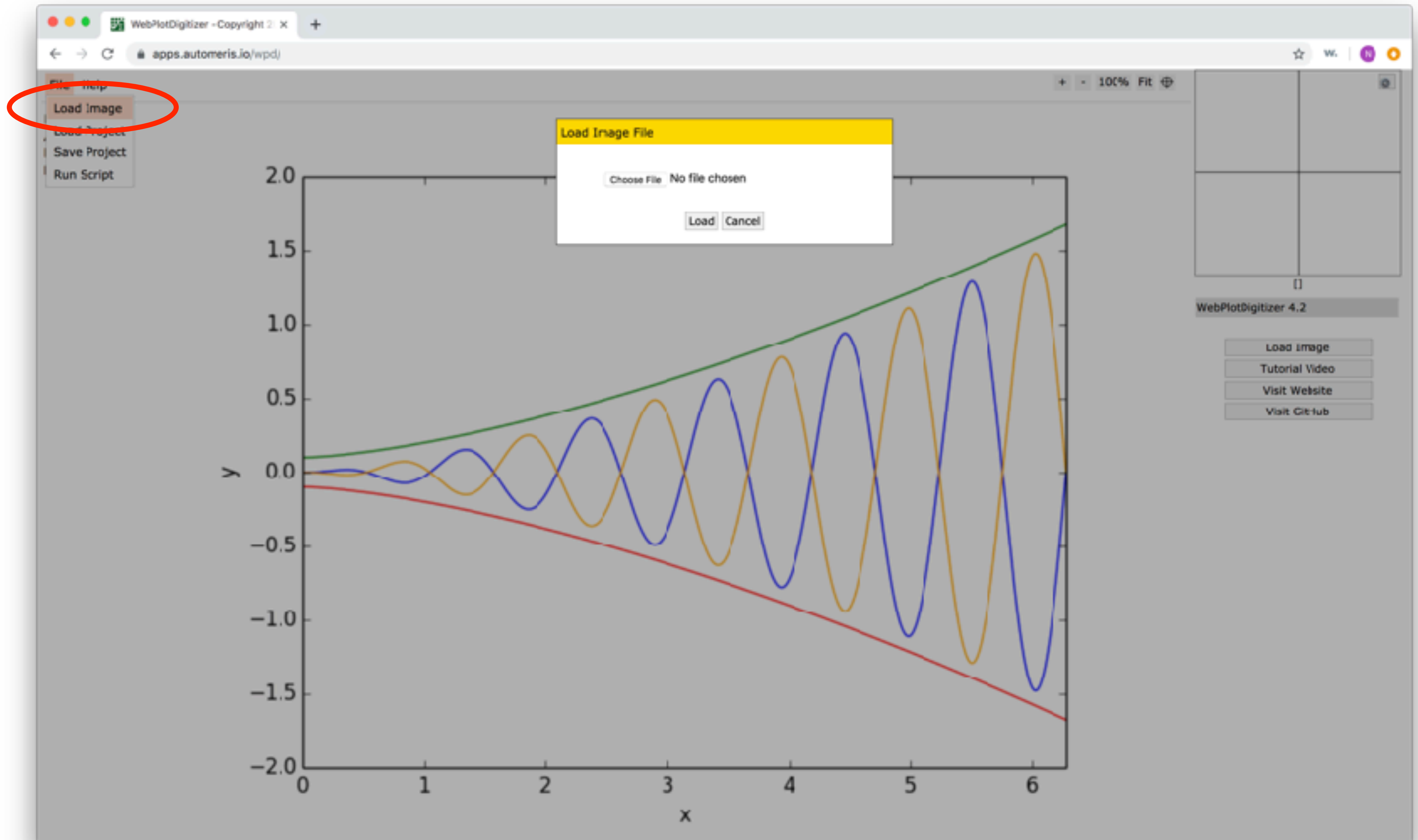
WebPlotDigitizer

- Navigate to WebPlotDigitizer website, click “Launch Now!”



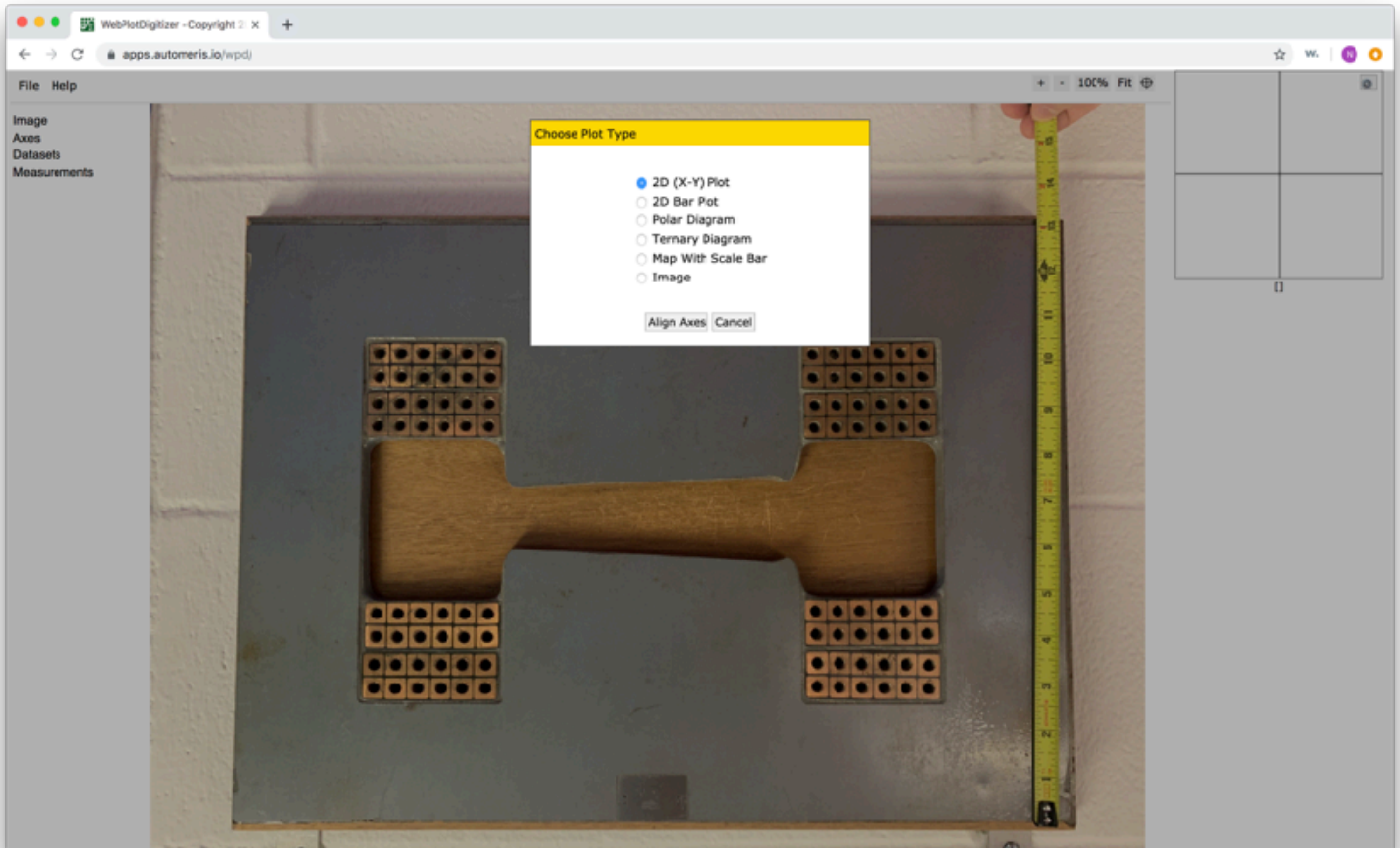
WebPlotDigitizer

- Load the image of your choosing



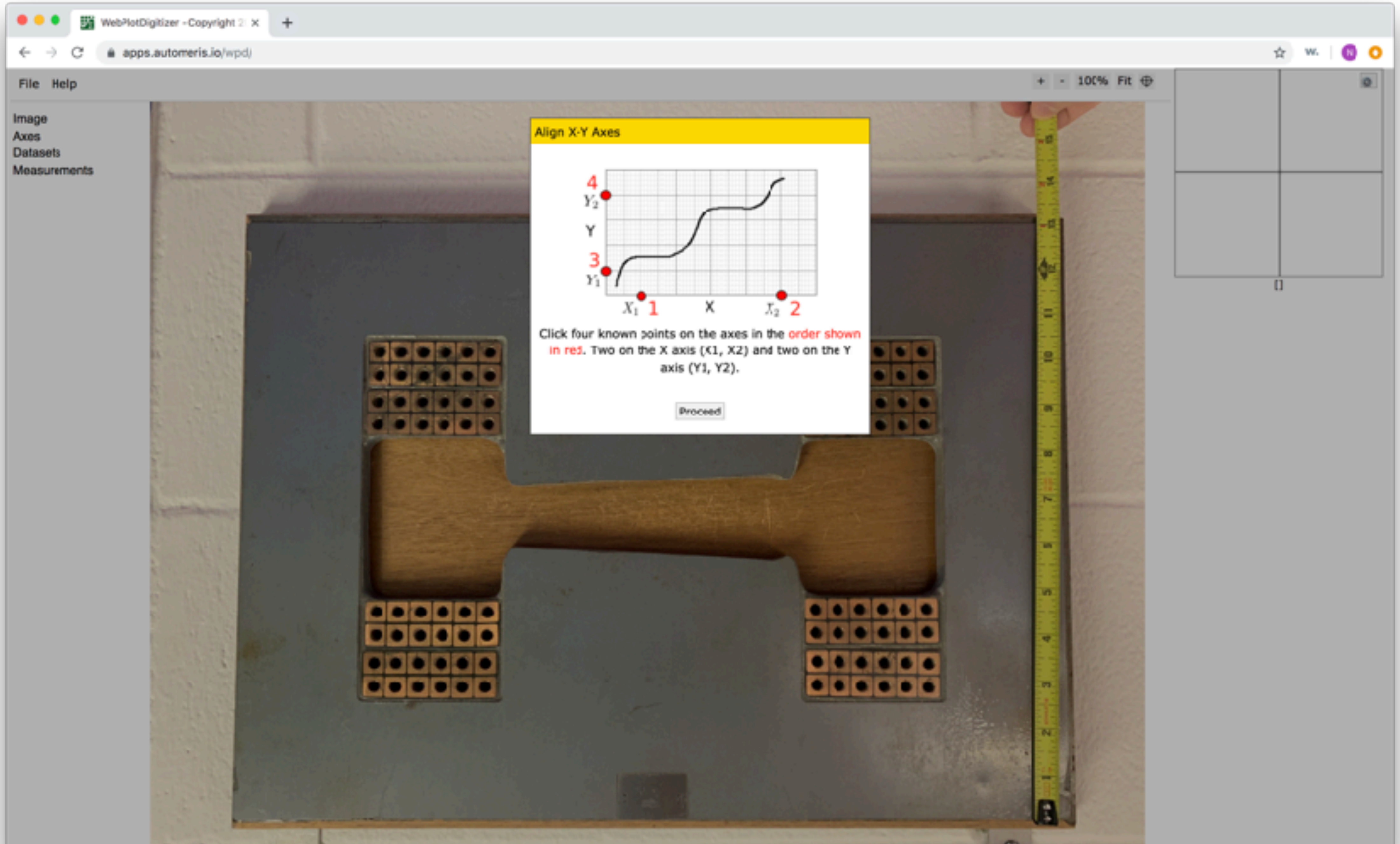
WebPlotDigitizer

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



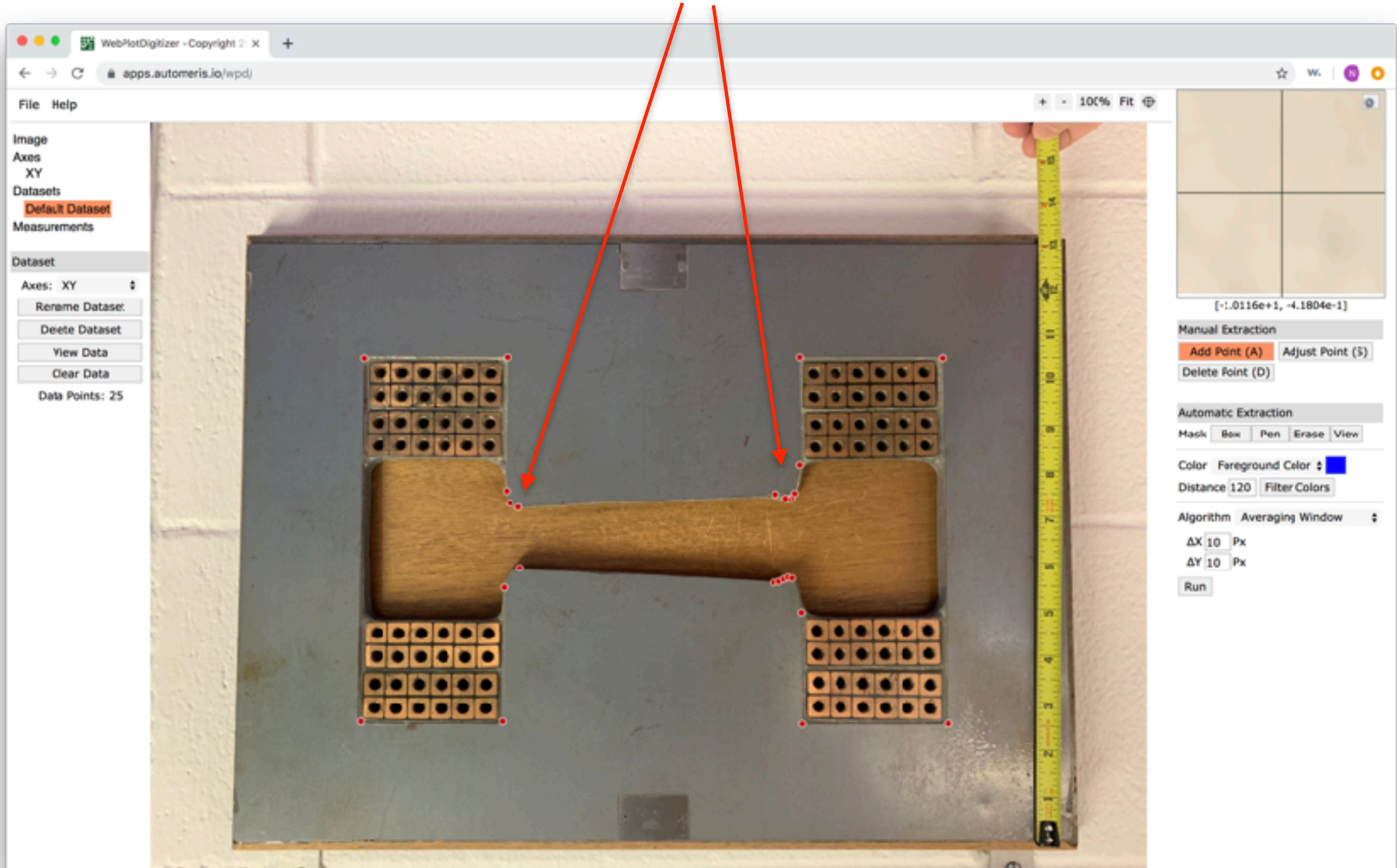
WebPlotDigitizer

- Align the plot axes. I clicked the corners of the iron of the Booster magnet, and used the measurements WxH = 18x13 cm²



WebPlotDigitizer

- Click the data points you'd like to digitize



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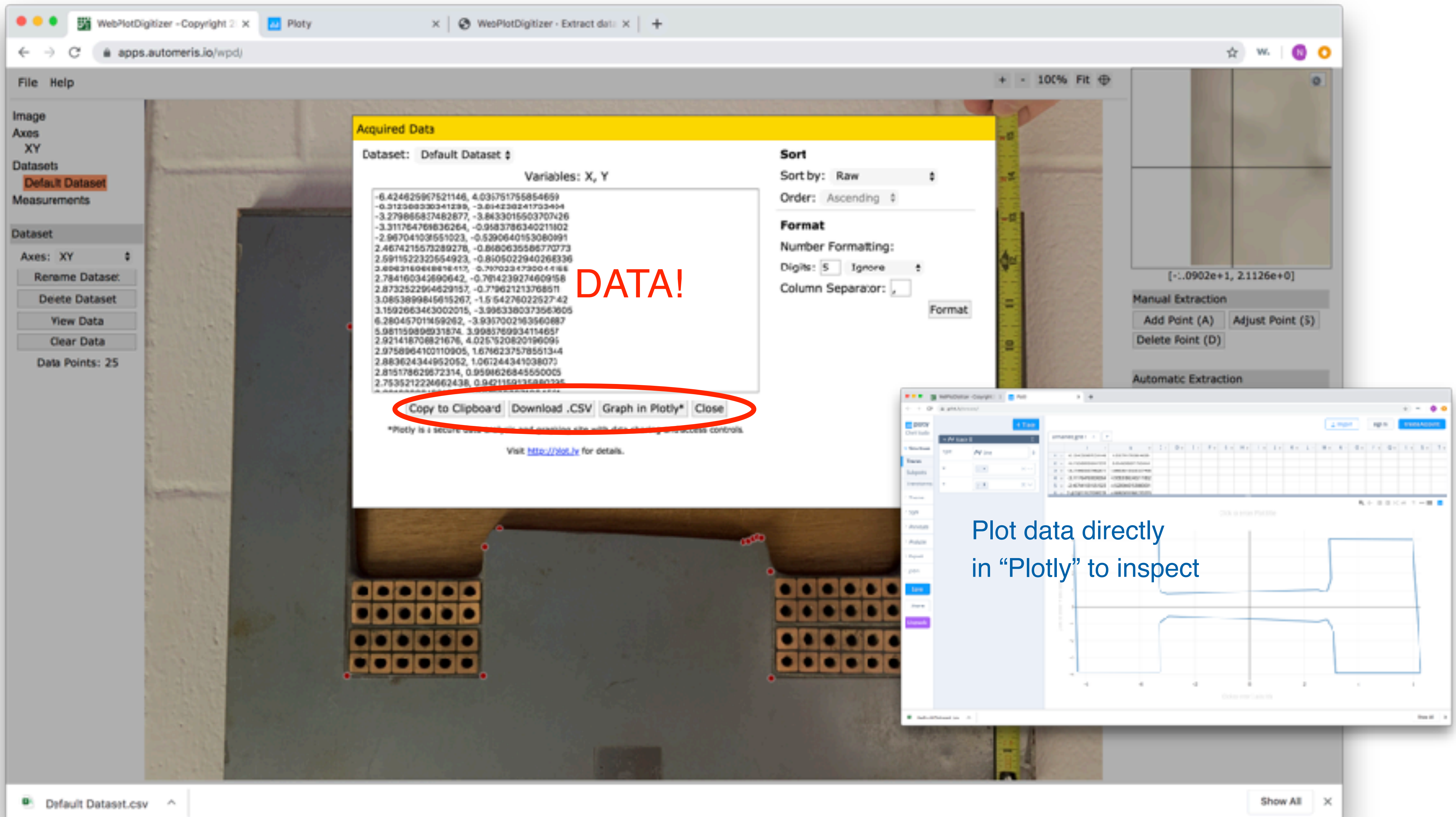
WebPlotDigitizer

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



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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

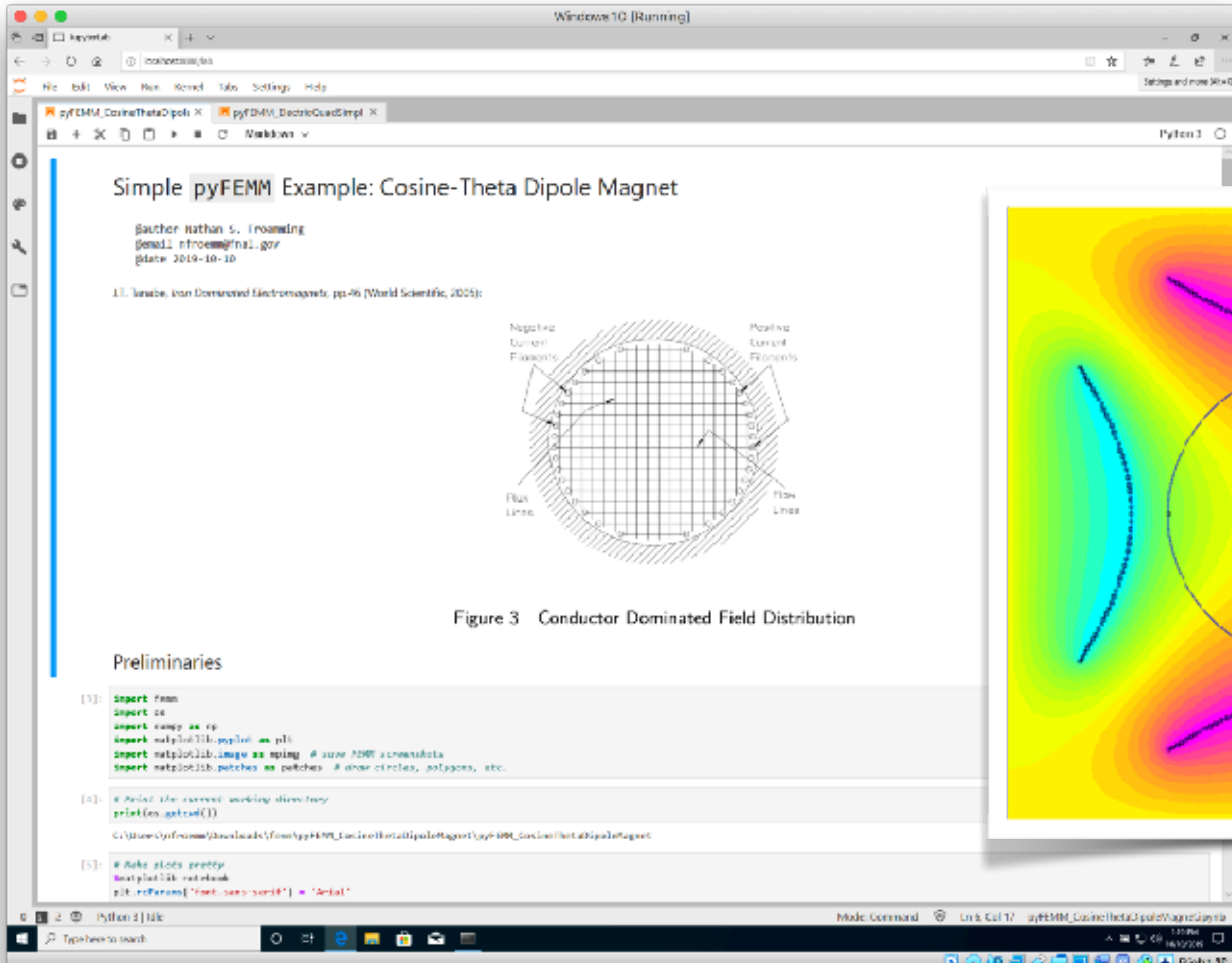
Version 4.2

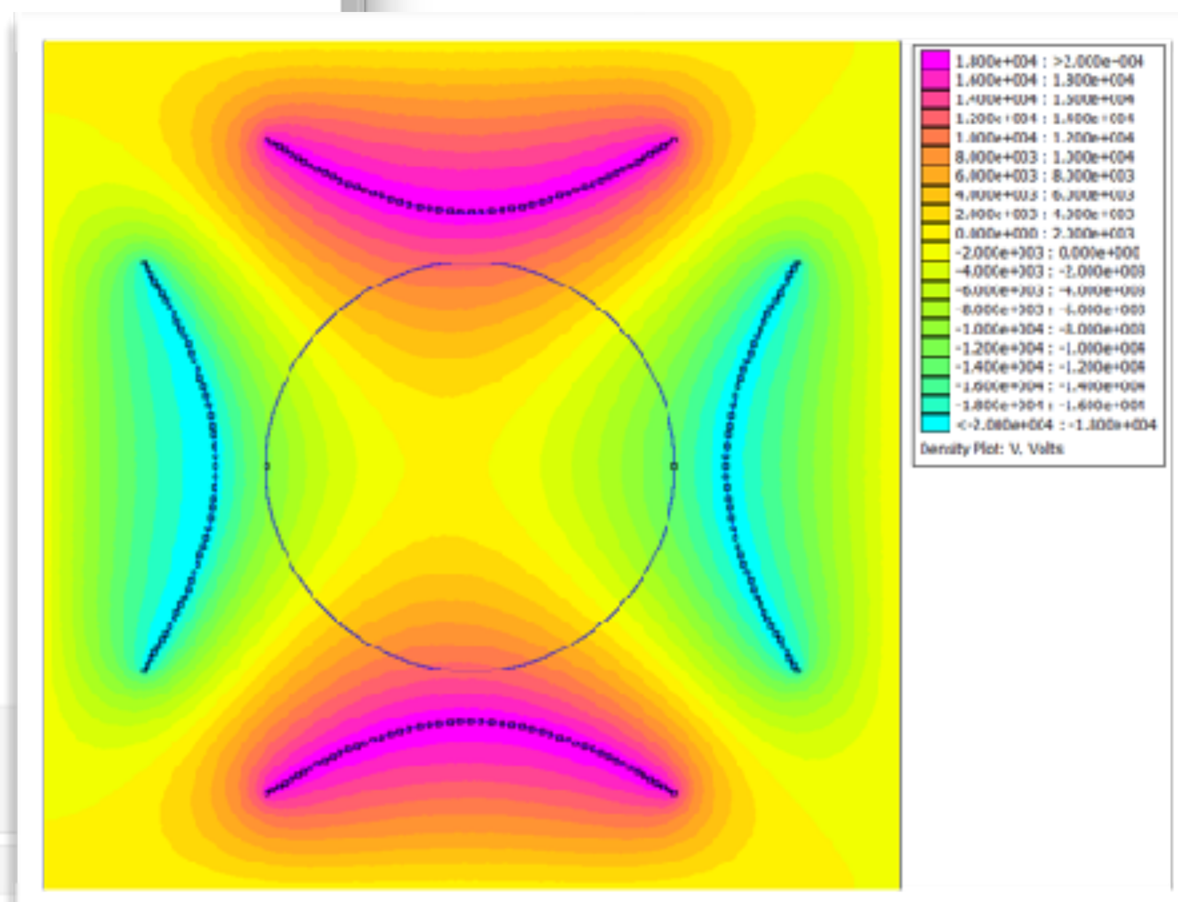
User’s Manual

FEMM Reference Manual (link)

FEMM + Python = `pyFEMM`

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





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-fi EM

- 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