Joint Universities Accelerator School

JUAS 2025

18. – 24. February 2025

Normal-conducting accelerator magnets
Case study: FEMM tutorial

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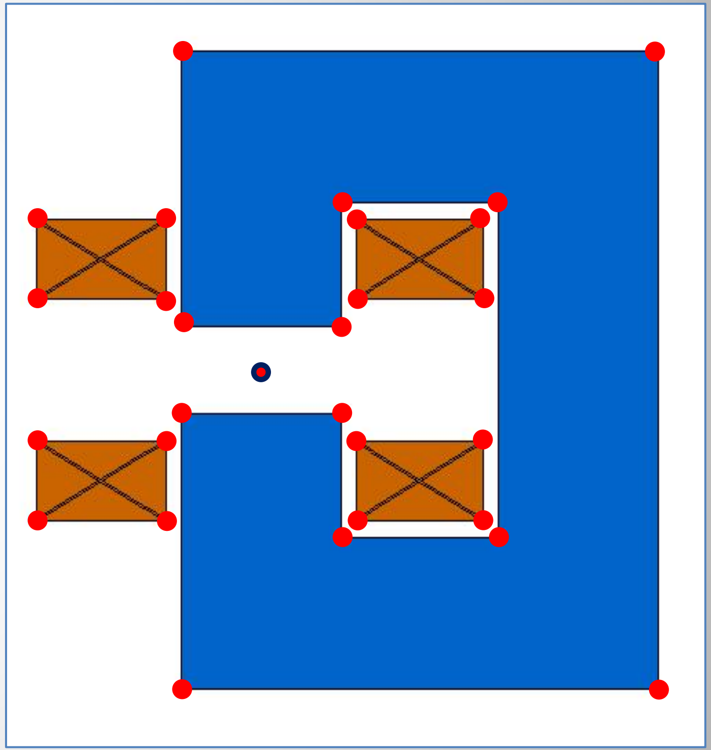
CERN

Results from Analytical Design

For the computer work with FEMM, you will need the following magnet parameters:

- Aperture height
- Pole width (as small as possible)
- Yoke dimensions (horizontal and vertical)
- Coil window width and height
- Coil dimensions (width and height)
- Coil position
- Coil excitation (ampere-turns)



Hint: prepare a sketch identifying the key-point coordinates (x/y)
wrt the beam axis

How to follow this tutorial…

- You are supposed to follow this tutorial “**live**” by working directly in FEMM
- Supporting material (BH-curve, FEMM-examples, written tutorial) can be found in the .zip file on the Indico page of this course
- In case of questions, please let us know
- If you got lost or stuck, please let us know
- However, you can always:
  - get help from these slides using the 3 provided samples
  - consult the ‘’Case study FEMM tutorial 2025.pdf’’
  - read the official FEMM manual on FEMM wiki page
- Please note that the magnet parameters (dimensions, ampere-turns, etc) in this tutorial will be different from your magnet parameters

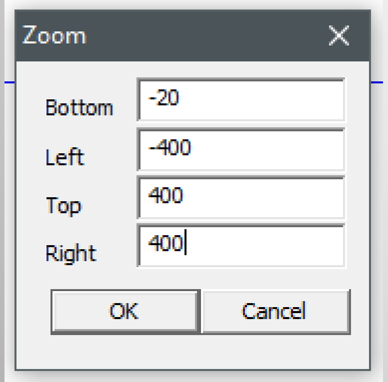
Introduction

2D Numerical calculations with FEMM:

- FEMM: 2D FE code for magnetics, electrostatic, heat flow and current flow problems with graphical pre- and post-processors
- Licensed under the terms of the Aladdin Free Public License
- Input via GUI or scripts (LUA or Octave scripting engine) or .dxf import
- More info (wiki) and download from the web: http://www.femm.info/wiki/HomePage

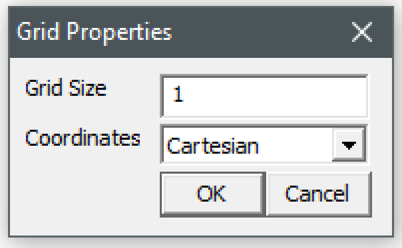
Get Started

- Download, install and run the FEMM application
- *Create a new problem* (Magnetics Problem)
- Define problem type, units and model parameters in *Problem Definition*
- Select *view,* select *grid size* and *Snap to grid*
- *Save* under *“Case study example.FEM”*



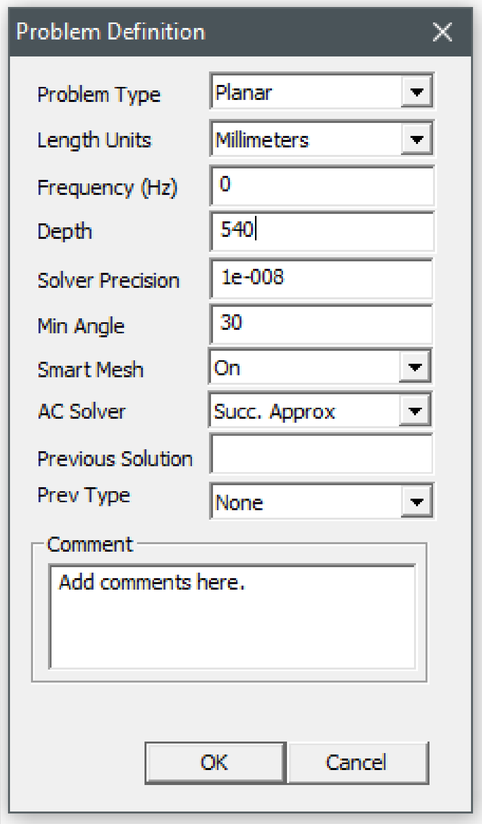
Zoom

Bottom	-20
Left	-400
Top	400
Right	400



Grid Properties

Grid Size	1
Coordinates	Cartesian



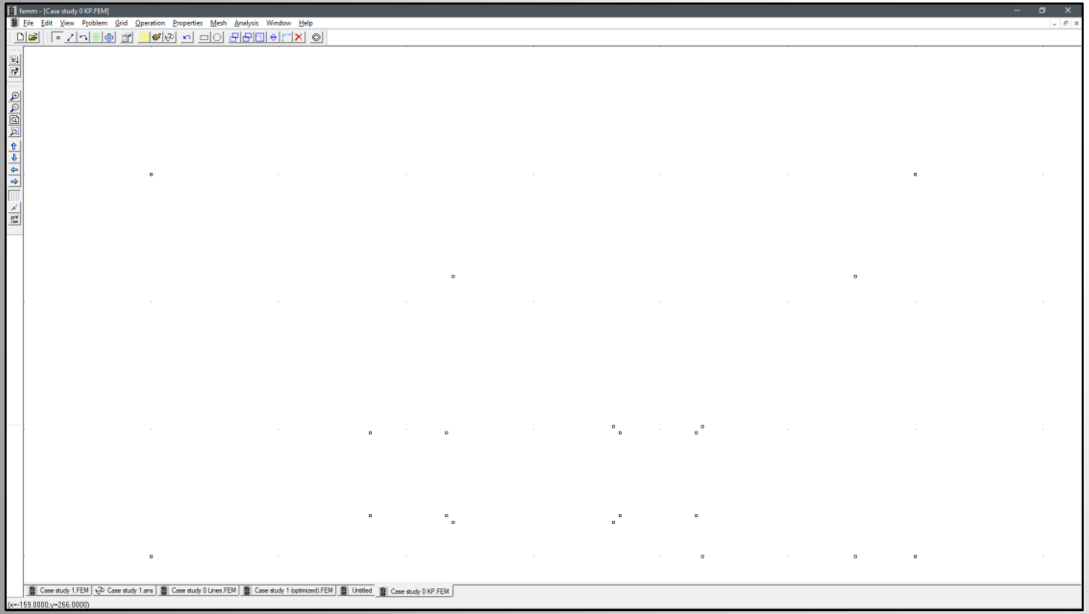
Problem Definition

Problem Type	Planar
Length Units	Millimeters
Frequency (Hz)	0
Depth	540
Solver Precision	1e-008
Min Angle	30
Smart Mesh	On
AC Solver	Succ. Approx
Previous Solution	
Prev Type	None

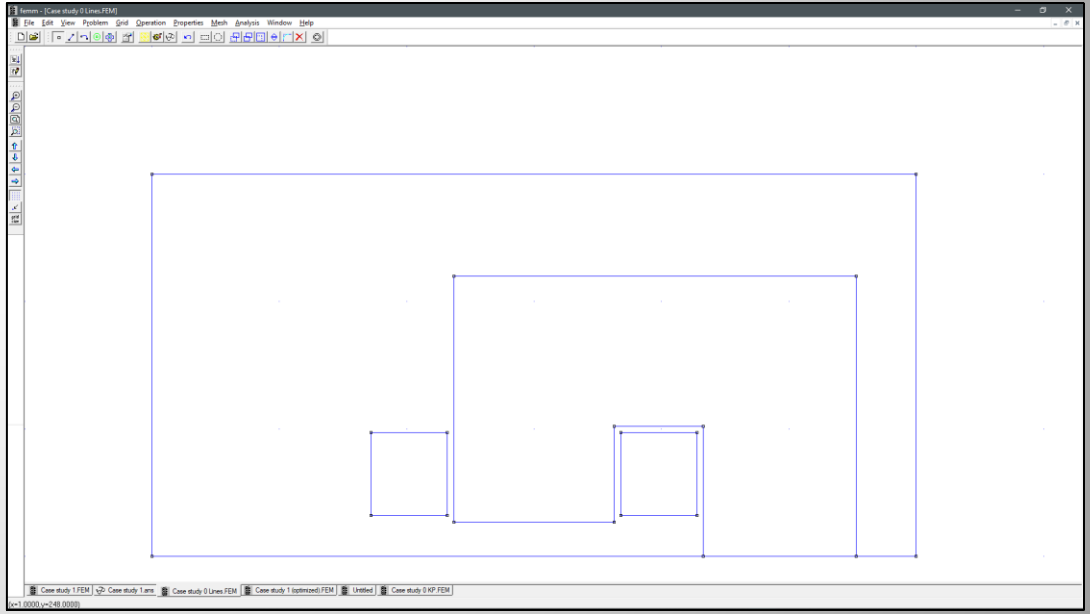
Comment: Add comments here.

Model Boundaries

- Set the key-points of your yoke, coil and background areas using the key-point coordinates derived in the analytical design
- Remember: you can profit from symmetry conditions
- Connect the key-points accordingly with straight lines or arcs



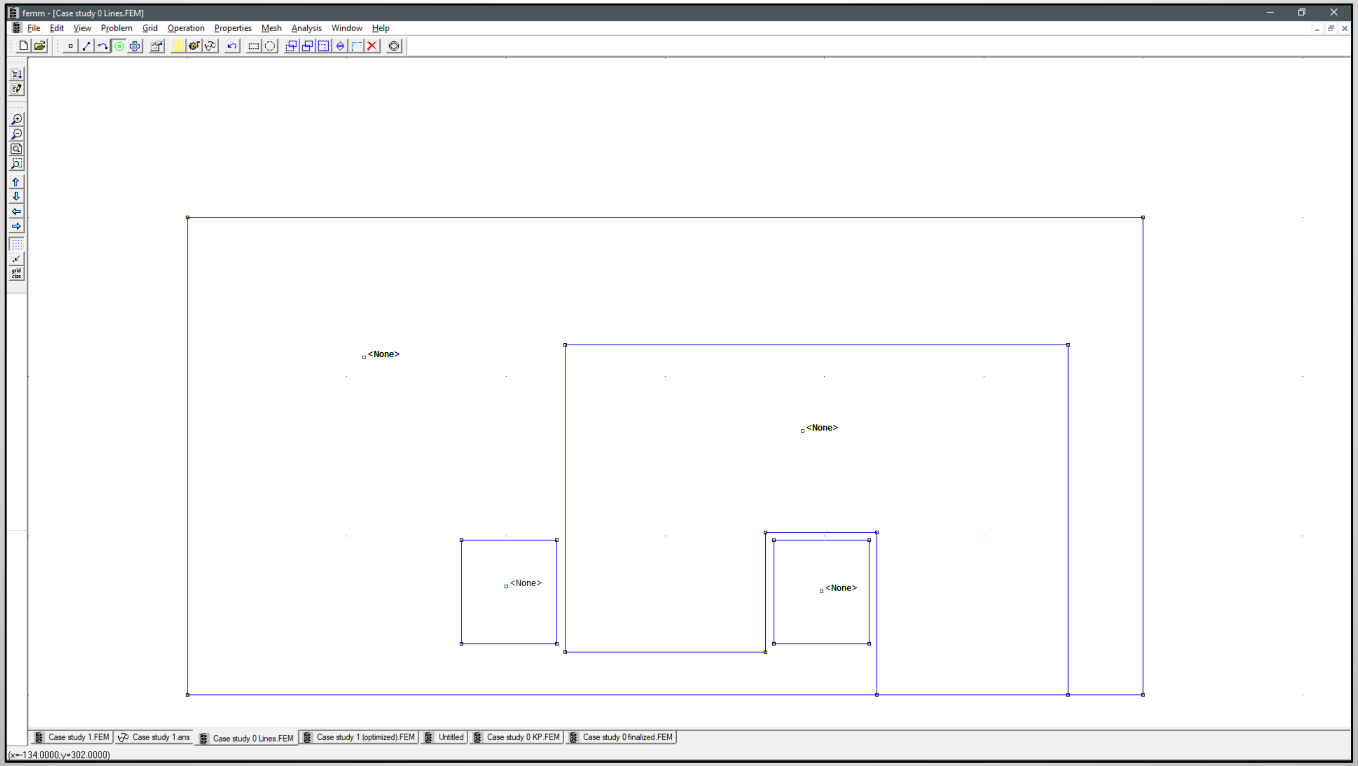
Case study example (KP).FEM



Case study example (contour).FEM

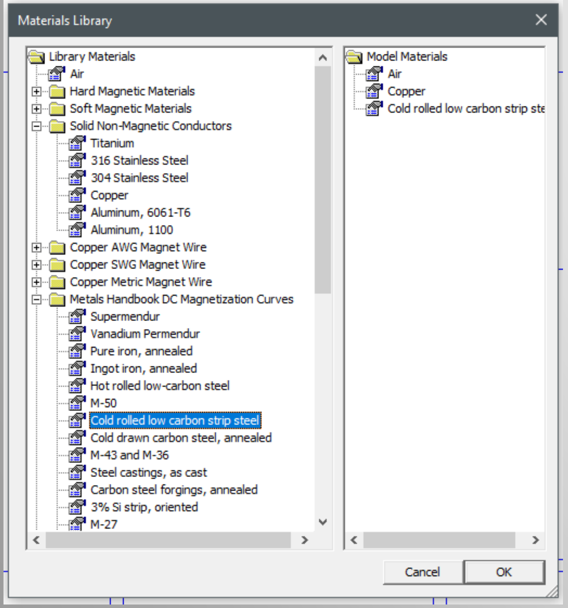
Block Labels

- Place block labels on each of the areas which have been previously defined (yoke, coils, background)



Material & Circuit Properties

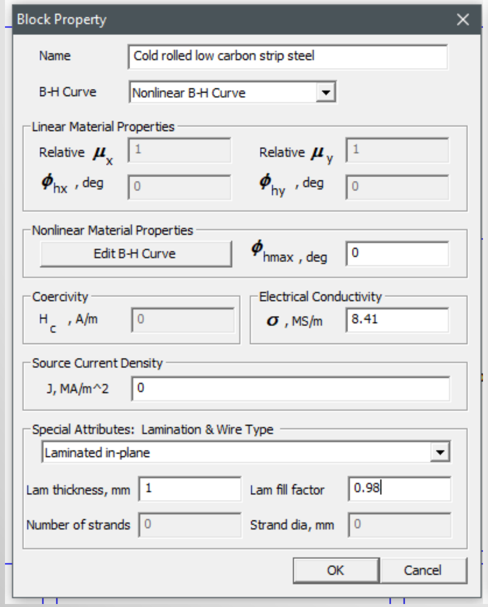
- Select the required materials from the *Properties|Materials Library*: Air, Copper & Cold rolled low carbon strip steel
- Edit/modify the material properties according to your needs (in particular the yoke material)



Materials Library

- Library Materials
  - Air
  - Hard Magnetic Materials
  - Soft Magnetic Materials
  - Solid Non-Magnetic Conductors
    - Titanium
    - 316 Stainless Steel
    - 304 Stainless Steel
    - Copper
    - Aluminum, 6061-T6
    - Aluminum, 1100
  - Copper AWG Magnet Wire
  - Copper SWG Magnet Wire
  - Copper Metric Magnet Wire
  - Metals Handbook DC Magnetization Curves
    - Supermendur
    - Vanadium Permendur
    - Pure iron, annealed
    - Ingot iron, annealed
    - Hot rolled low-carbon steel
    - M-50
    - Cold rolled low carbon strip steel
    - Cold drawn carbon steel, annealed
    - M-43 and M-36
    - Steel castings, as cast
    - Carbon steel forgings, annealed
    - 3% Si strip, oriented
    - M-27

- Model Materials
  - Air
  - Copper
  - Cold rolled low carbon strip ste



Block Property

Name: Cold rolled low carbon strip steel

B-H Curve: Nonlinear B-H Curve

Linear Material Properties

Relative μ_x: 1 Relative μ_y: 1

ϕ_{hx}, deg: 0 ϕ_{hy}, deg: 0

Nonlinear Material Properties

ϕ_{hmax}, deg: 0

Coercivity

H_c, A/m: 0

Electrical Conductivity

σ, MS/m: 8.41

Source Current Density

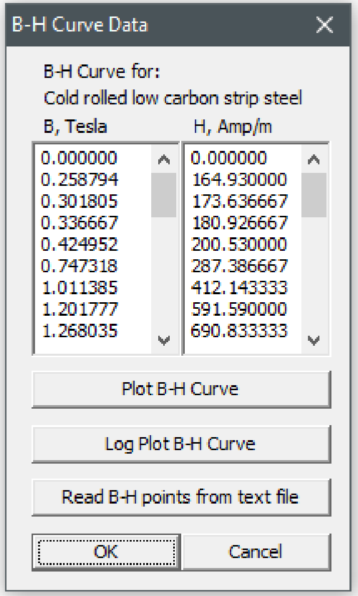
J, MA/m^2: 0

Special Attributes: Lamination & Wire Type

Laminated in-plane

Lam thickness, mm: 1 Lam fill factor: 0.98

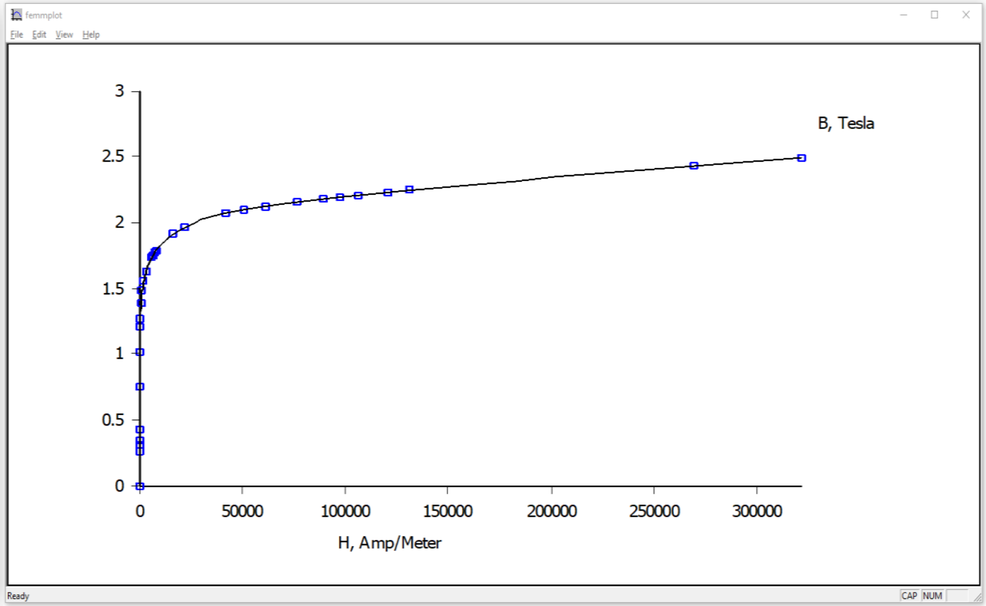
Number of strands: 0 Strand dia, mm: 0



B-H Curve Data

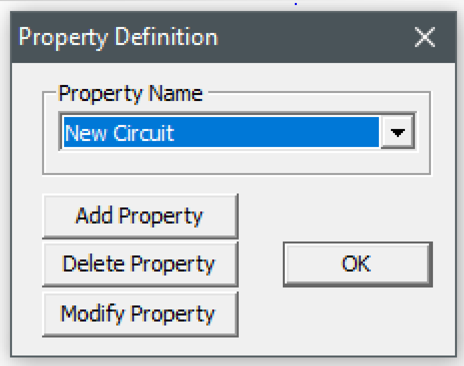
B-H Curve for:
Cold rolled low carbon strip steel

B, Tesla	H, Amp/m
0.000000	0.000000
0.258794	164.930000
0.301805	173.636667
0.336667	180.926667
0.424952	200.530000
0.747318	287.386667
1.011385	412.143333
1.201777	591.590000
1.268035	690.833333

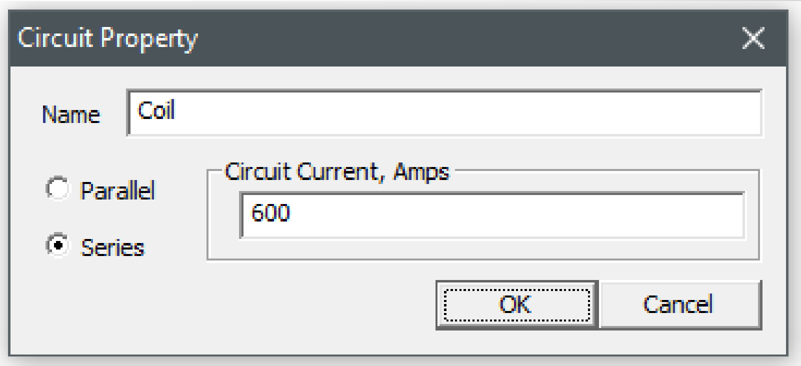


Material & Circuit Properties

- Add a *Circuit Property* for the coils



Property Name: New Circuit



Name: Coil

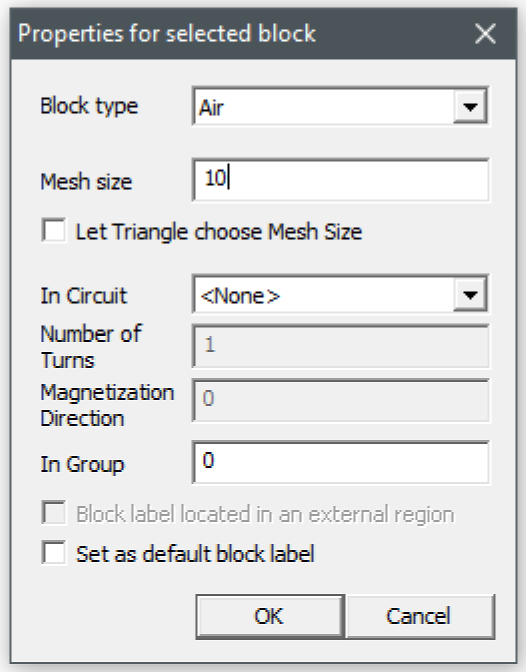
○ Parallel

● Series

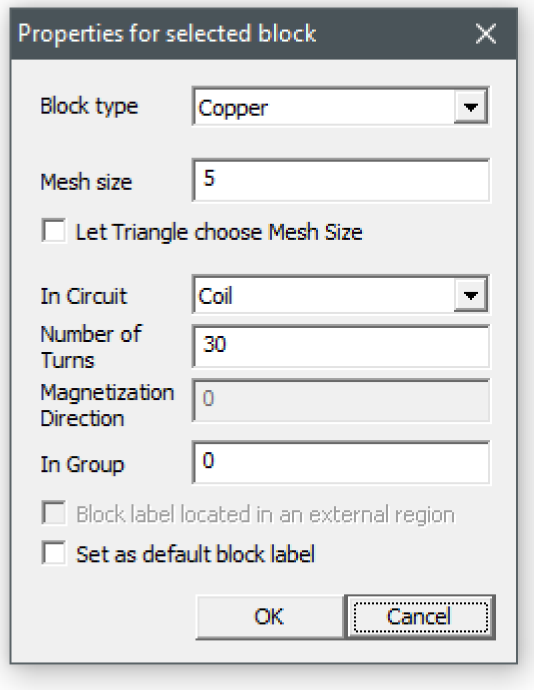
Circuit Current, Amps: 600

Material & Circuit Properties

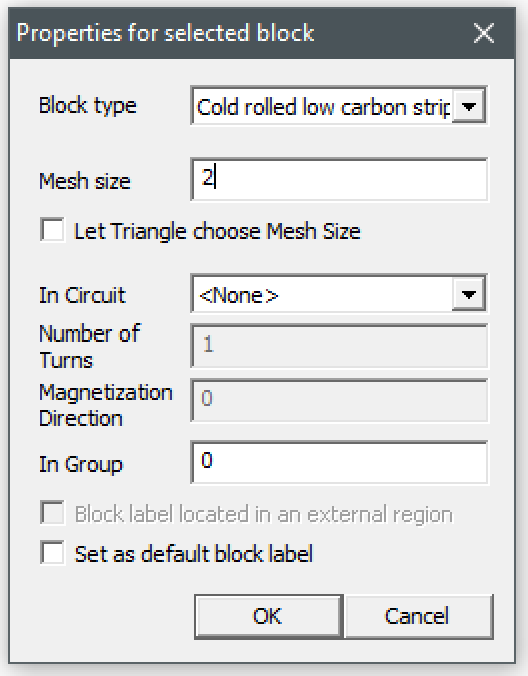
- Associate these properties with the individual block labels and define mesh sizes
- <u>Attention</u>: for a negative coil current you need to change the sign in the “Number of Turns” field!


Properties for selected block

Block type: Air
Mesh size: 10
☐ Let Triangle choose Mesh Size
In Circuit: <None>
Number of Turns: 1
Magnetization Direction: 0
In Group: 0
☐ Block label located in an external region
☐ Set as default block label


Properties for selected block

Block type: Copper
Mesh size: 5
☐ Let Triangle choose Mesh Size
In Circuit: Coil
Number of Turns: 30
Magnetization Direction: 0
In Group: 0
☐ Block label located in an external region
☐ Set as default block label


Properties for selected block

Block type: Cold rolled low carbon strip
Mesh size: 2
☐ Let Triangle choose Mesh Size
In Circuit: <None>
Number of Turns: 1
Magnetization Direction: 0
In Group: 0
☐ Block label located in an external region
☐ Set as default block label

Normal-conducting accelerator magnets
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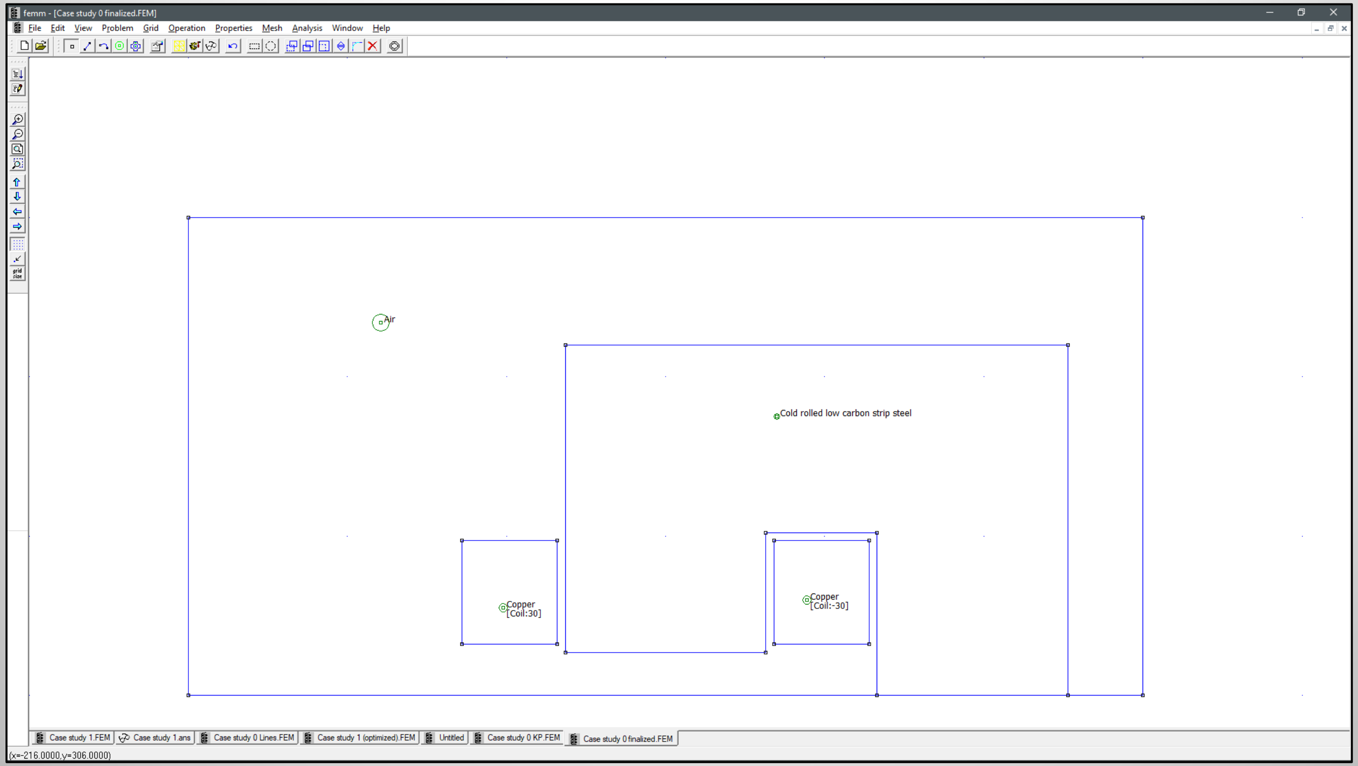
Material & Circuit Properties

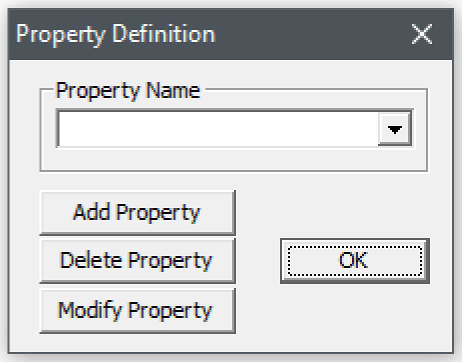
- Associate these properties with the individual block labels and define mesh sizes

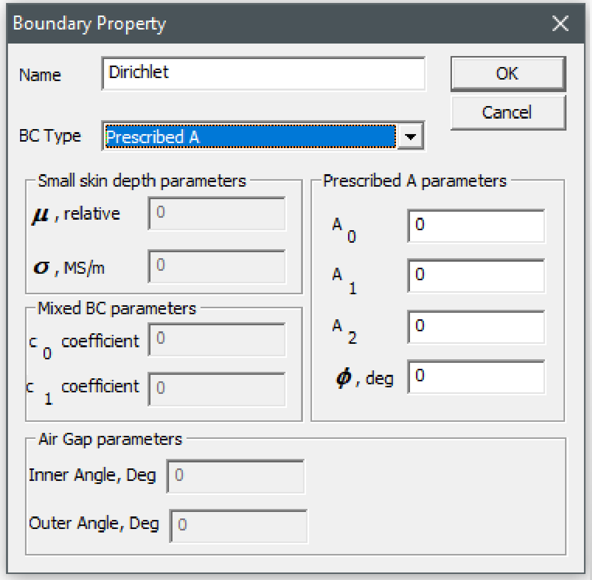


JUAS 2025
18. – 24. February 2025

Boundary Conditions

- Define the required boundary conditions from *Properties|Boundaries*:
  - Dirichlet condition = no normal flux component, only tangential flux component)
  - Neumann condition = no tangential flux component, only normal flux component) is assigned automatically by default
- Associate the correct boundary conditions to your model boundary lines:
  - Dirichlet condition for boundaries with zero magnetic flux trough the plane
  - Neumann condition is assigned automatically by default if no other condition has been defined





Name: Dirichlet

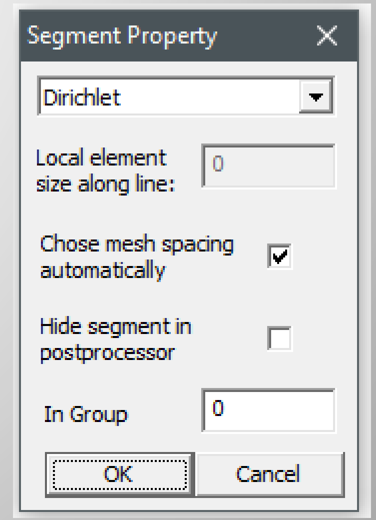
BC Type: Prescribed A

Small skin depth parameters
μ, relative: 0
σ, MS/m: 0

Mixed BC parameters
c_0 coefficient: 0
c_1 coefficient: 0

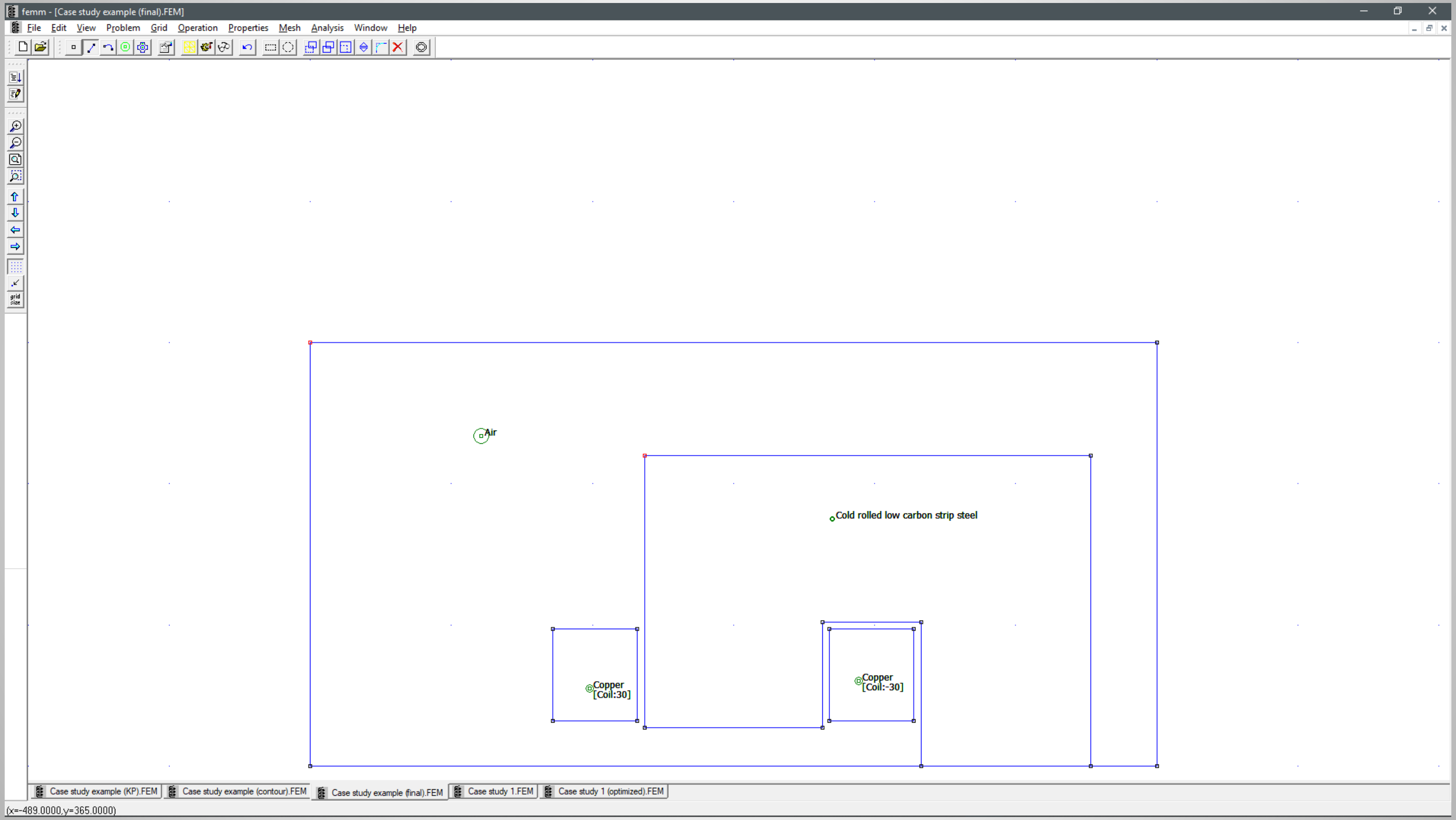
Prescribed A parameters
A_0: 0
A_1: 0
A_2: 0
ϕ, deg: 0

Air Gap parameters
Inner Angle, Deg: 0
Outer Angle, Deg: 0



Dirichlet
Local element size along line: 0
Chose mesh spacing automatically ☑
Hide segment in postprocessor ☐
In Group: 0

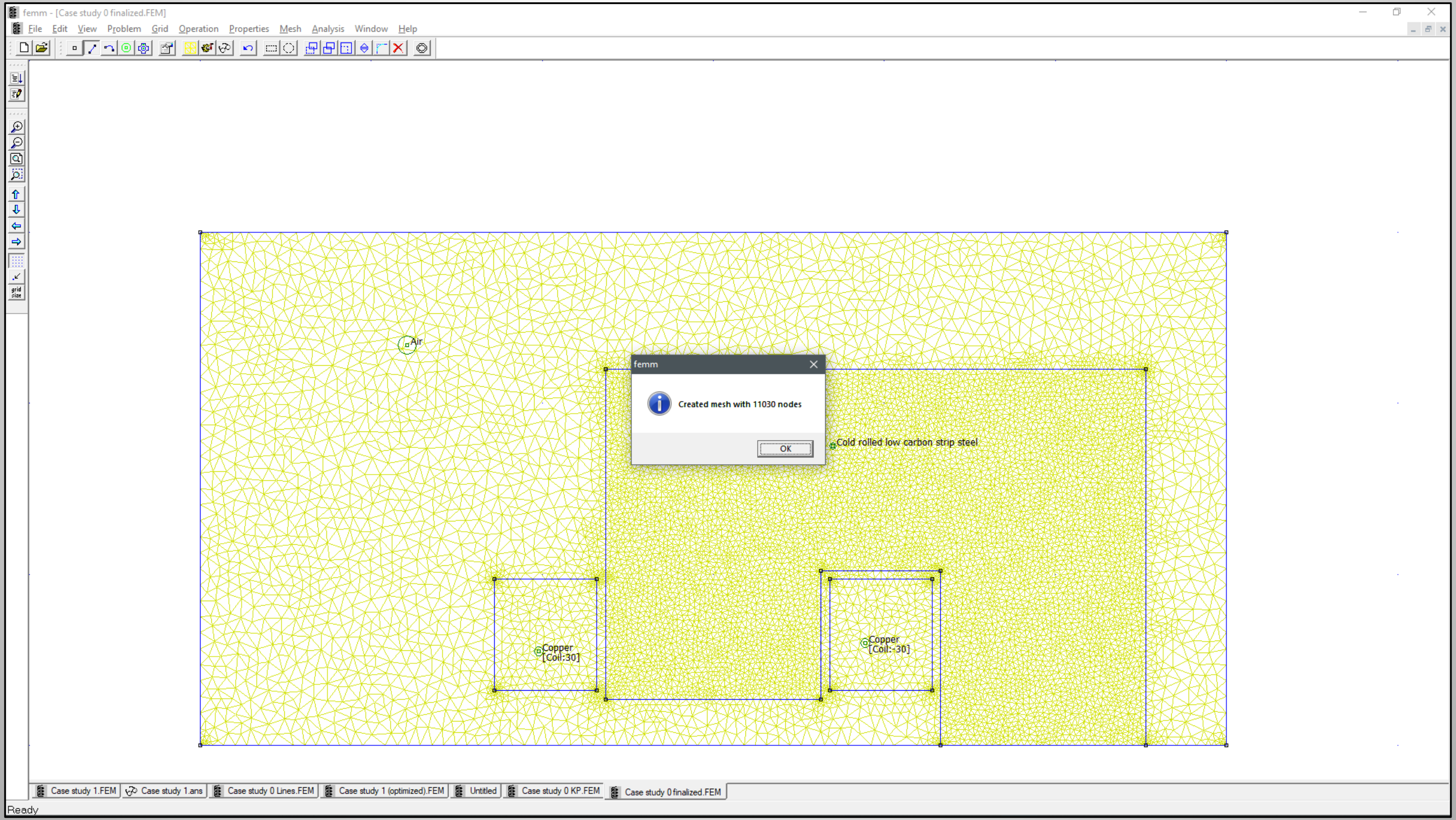
Final model



Case study example (final).FEM

Mesh & Solver

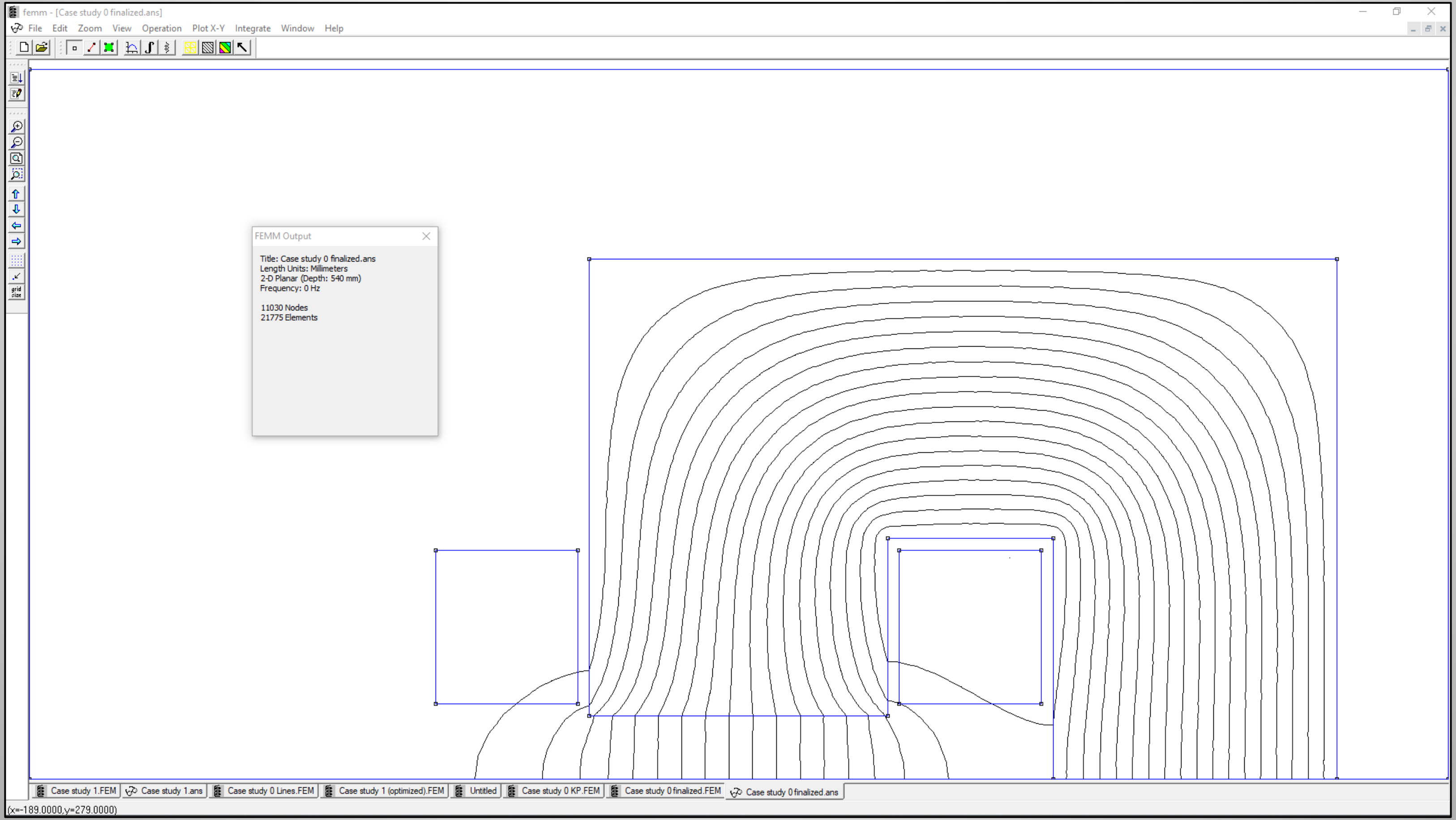
- Generate the mesh
- Run the FEA Solver



Created mesh with 11030 nodes

Result Analysis

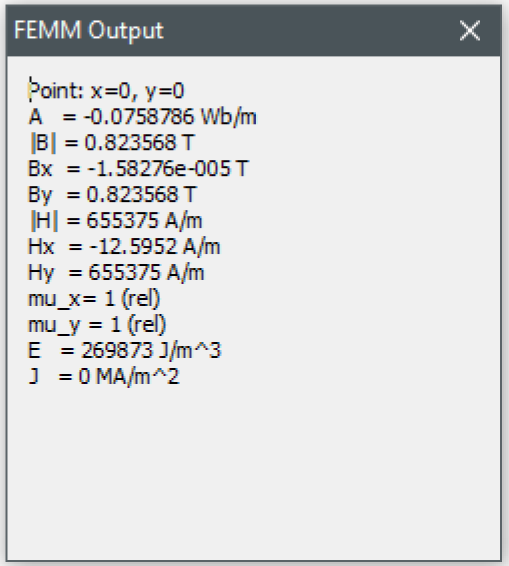
- Start the post-processor
- With the help of flux lines verify if the model is physically reasonable



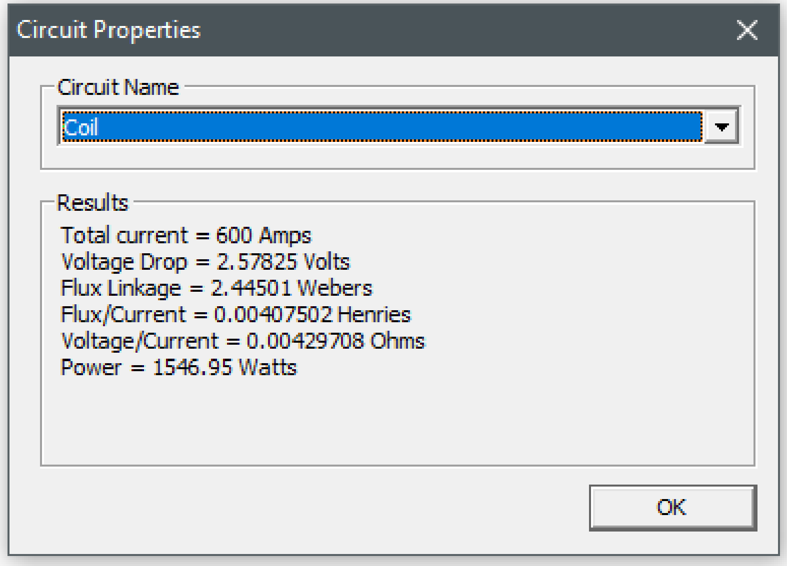
```
Title: Case study 0 finalized.ans
Length Units: Millimeters
2-D Planar (Depth: 540 mm)
Frequency: 0 Hz

11030 Nodes
21775 Elements
```

Result Analysis

- By probing point values, check if the field in the center corresponds to your expectation
- Analyse the coil terminal properties
- Probe point value in the coil region

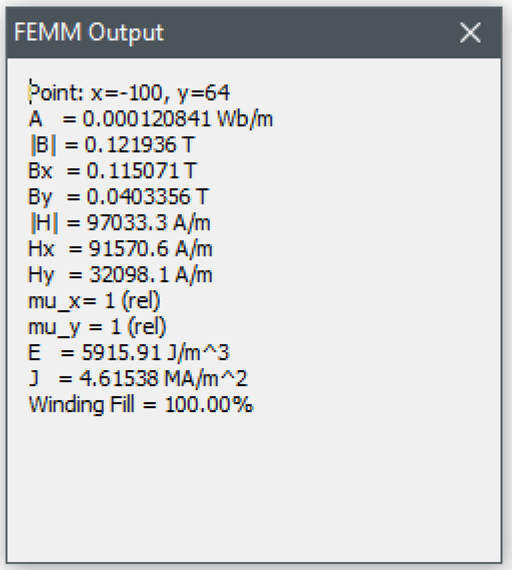


```
Point: x=0, y=0
A   = -0.0758786 Wb/m
|B| = 0.823568 T
Bx  = -1.58276e-005 T
By  = 0.823568 T
|H| = 655375 A/m
Hx  = -12.5952 A/m
Hy  = 655375 A/m
mu_x= 1 (rel)
mu_y = 1 (rel)
E   = 269873 J/m^3
J   = 0 MA/m^2
```



Circuit Name: Coil

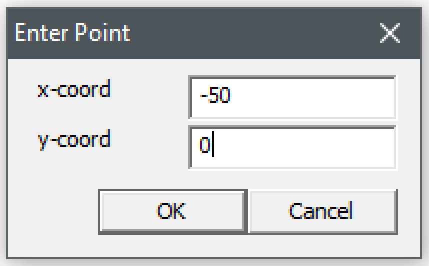
```
Results
Total current = 600 Amps
Voltage Drop = 2.57825 Volts
Flux Linkage = 2.44501 Webers
Flux/Current = 0.00407502 Henries
Voltage/Current = 0.00429708 Ohms
Power = 1546.95 Watts
```



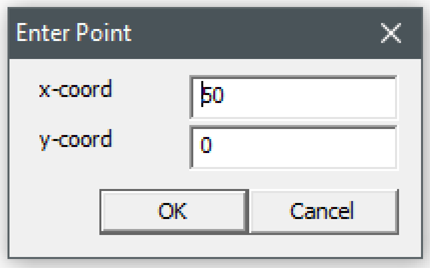
```
Point: x=-100, y=64
A   = 0.000120841 Wb/m
|B| = 0.121936 T
Bx  = 0.115071 T
By  = 0.0403356 T
|H| = 97033.3 A/m
Hx  = 91570.6 A/m
Hy  = 32098.1 A/m
mu_x= 1 (rel)
mu_y = 1 (rel)
E   = 5915.91 J/m^3
J   = 4.61538 MA/m^2
Winding Fill = 100.00%
```

Result Analysis

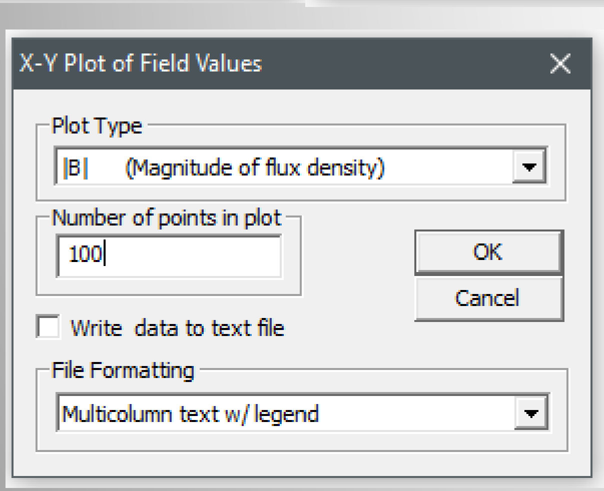
- Plot the field values along a contour (e.g. mid plane) and analyse the field “quality”



x-coord: -50
y-coord: 0



x-coord: 50
y-coord: 0

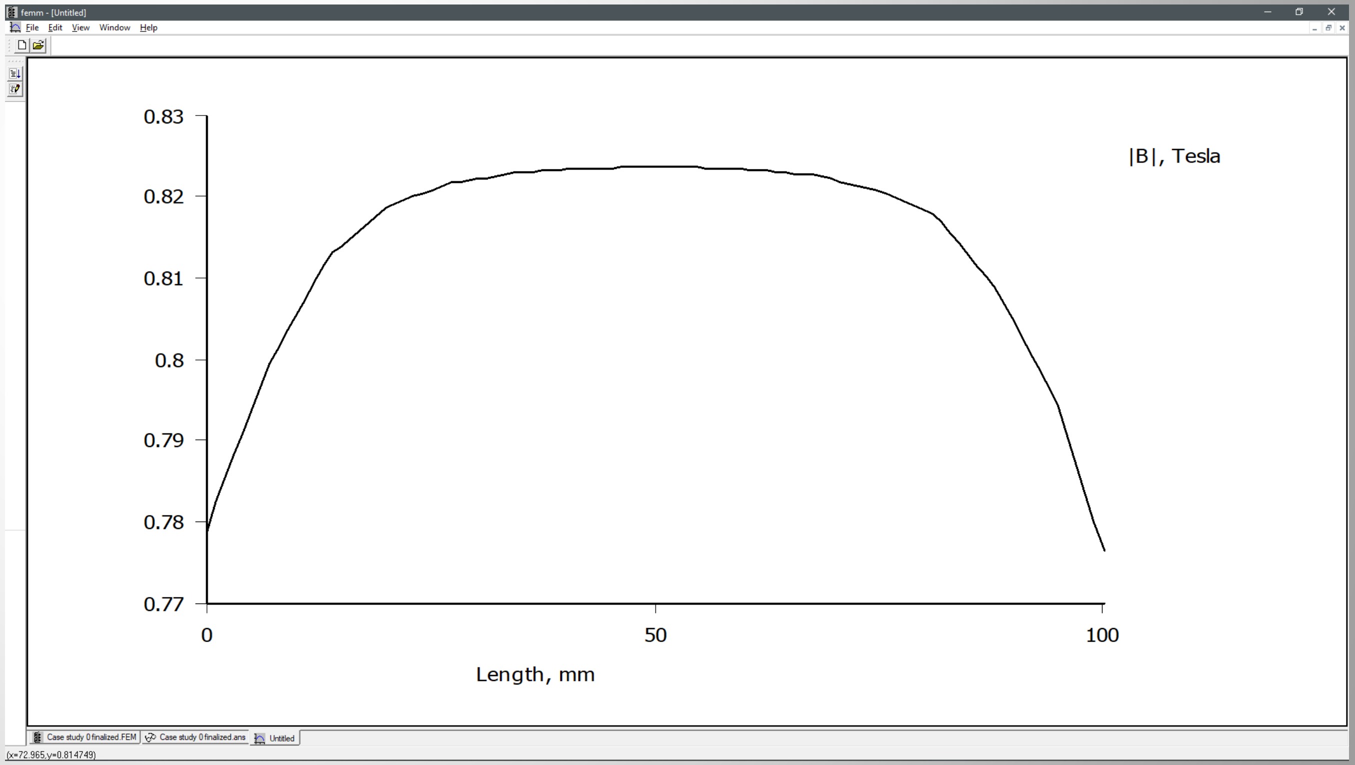


Plot Type: |B| (Magnitude of flux density)

Number of points in plot: 100

☐ Write data to text file

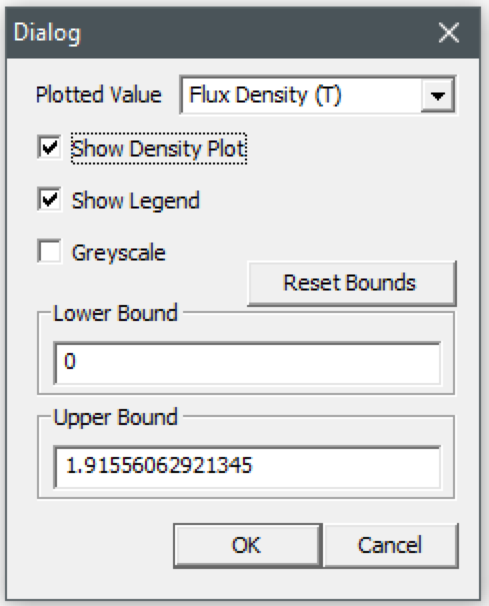
File Formatting: Multicolumn text w/ legend



(x=72.965,y=0.814749)

Result Analysis

- Plot the flux lines and check for saturated areas
- Probe specific point values in the yoke and check if the local field is within the saturation limits



Dialog

Plotted Value: Flux Density (T)

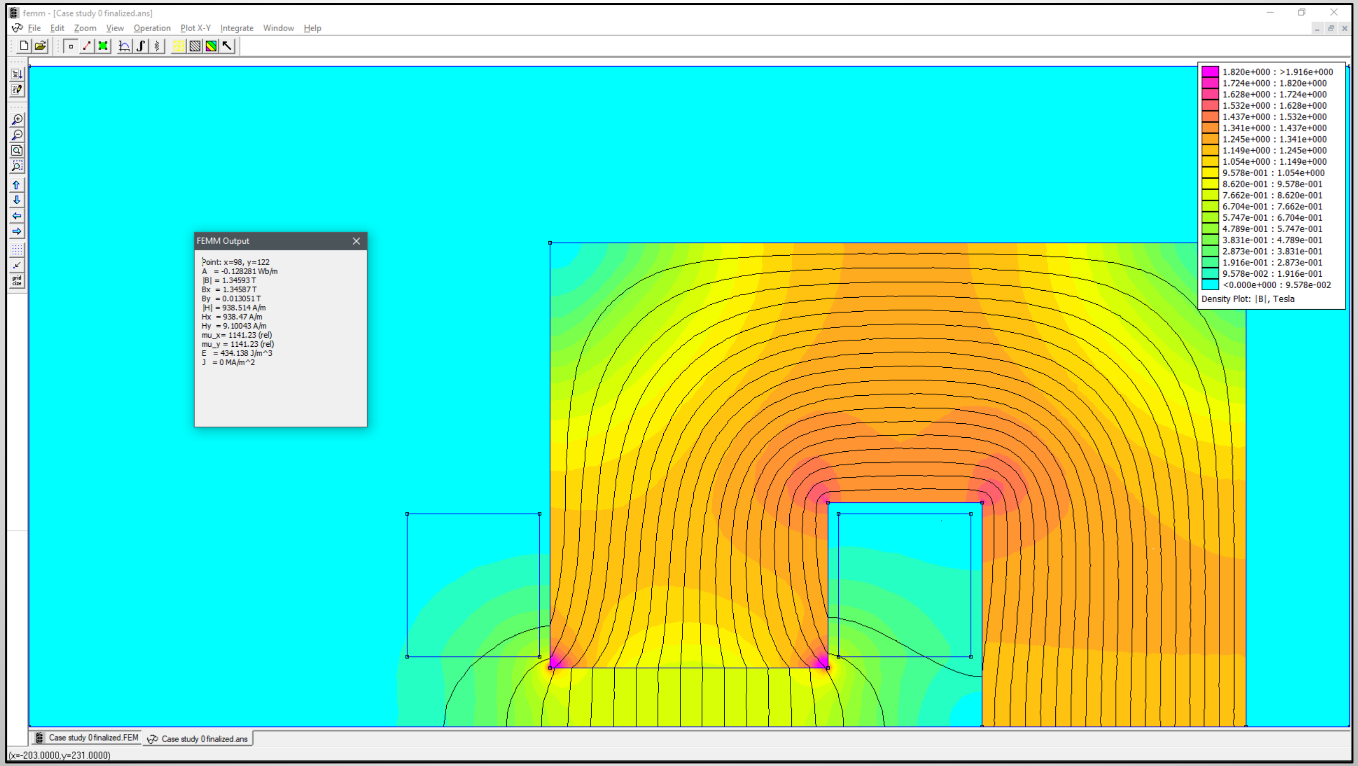
☑ Show Density Plot

☑ Show Legend

☐ Greyscale

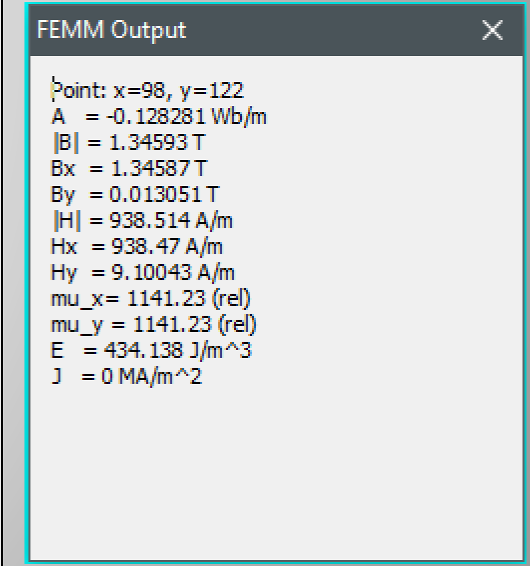
Lower Bound: 0

Upper Bound: 1.91556062921345



femm - [Case study 0 finalized.ans]

(x=-203.0000,y=231.0000)

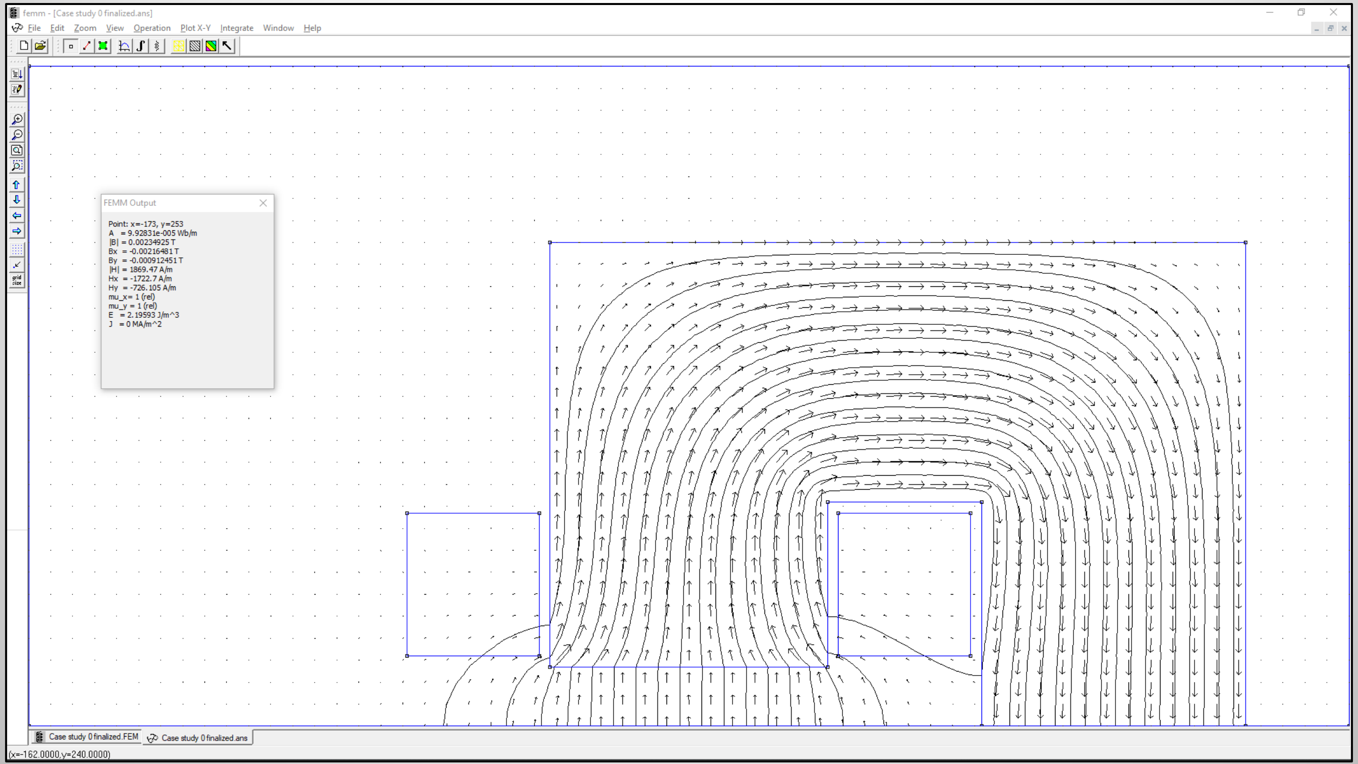


FEMM Output

```
Point: x=98, y=122
A   = -0.128281 Wb/m
|B| = 1.34593 T
Bx  = 1.34587 T
By  = 0.013051 T
|H| = 938.514 A/m
Hx  = 938.47 A/m
Hy  = 9.10043 A/m
mu_x= 1141.23 (rel)
mu_y = 1141.23 (rel)
E   = 434.138 J/m^3
J   = 0 MA/m^2
```

Result Analysis

- Alternatively you can also plot the field vectors

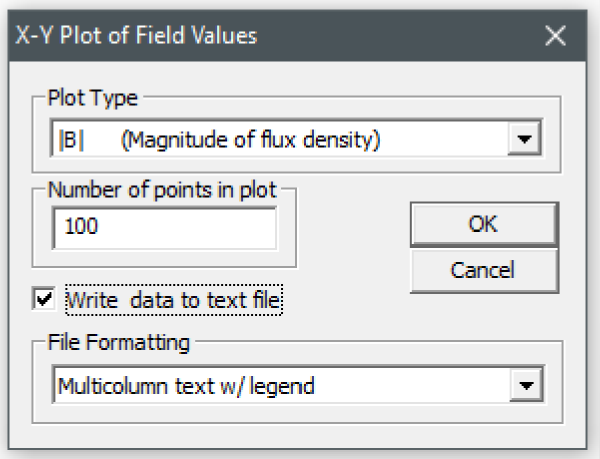


```
FEMM Output
Point: x=-173, y=253
A   = 9.92831e-005 Wb/m
|B| = 0.00234925 T
Bx  = -0.00216481 T
By  = -0.000912451 T
|H| = 1869.47 A/m
Hx  = -1722.7 A/m
Hy  = -726.105 A/m
mu_x= 1 (rel)
mu_y = 1 (rel)
E   = 2.19593 J/m^3
J   = 0 MA/m^2
```

```
(x=-162.0000,y=240.0000)
```

Advanced Analysis

- Plotting only the field is often not sufficient to evaluate the field quality
- Better: plot the field homogeneity $\frac{\Delta B}{B_0} = \frac{B_y(x,y)}{B_y(0,0)} - 1$
- Unfortunately, you cannot do that with FEMM, but with Excel
- Work-around: export the field values from FEMM and do the math in Excel

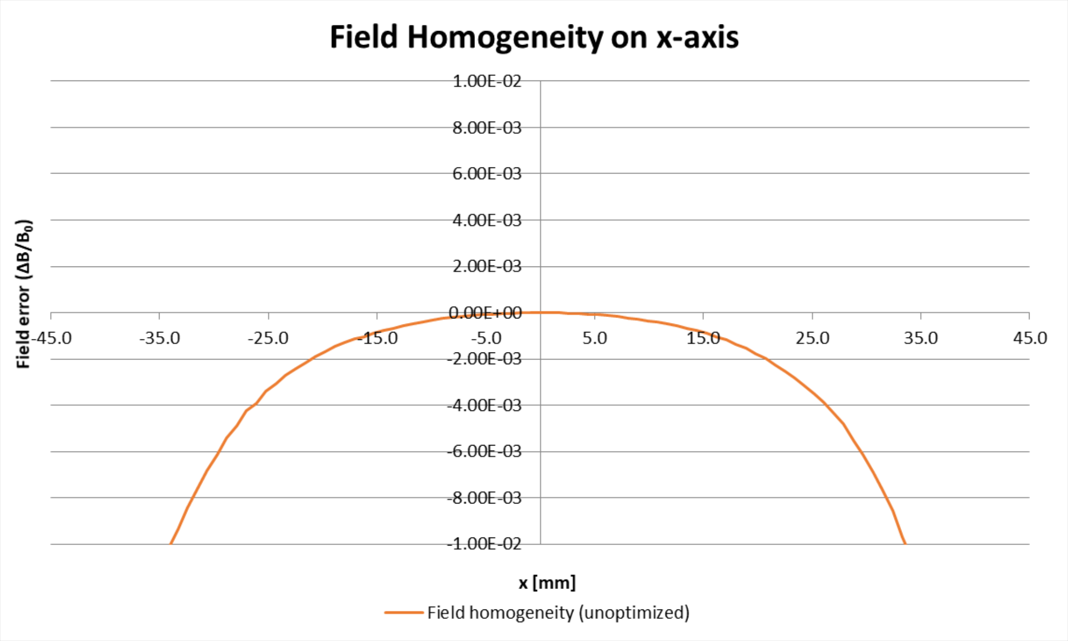

X-Y Plot of Field Values

Plot Type: |B| (Magnitude of flux density)

Number of points in plot: 100

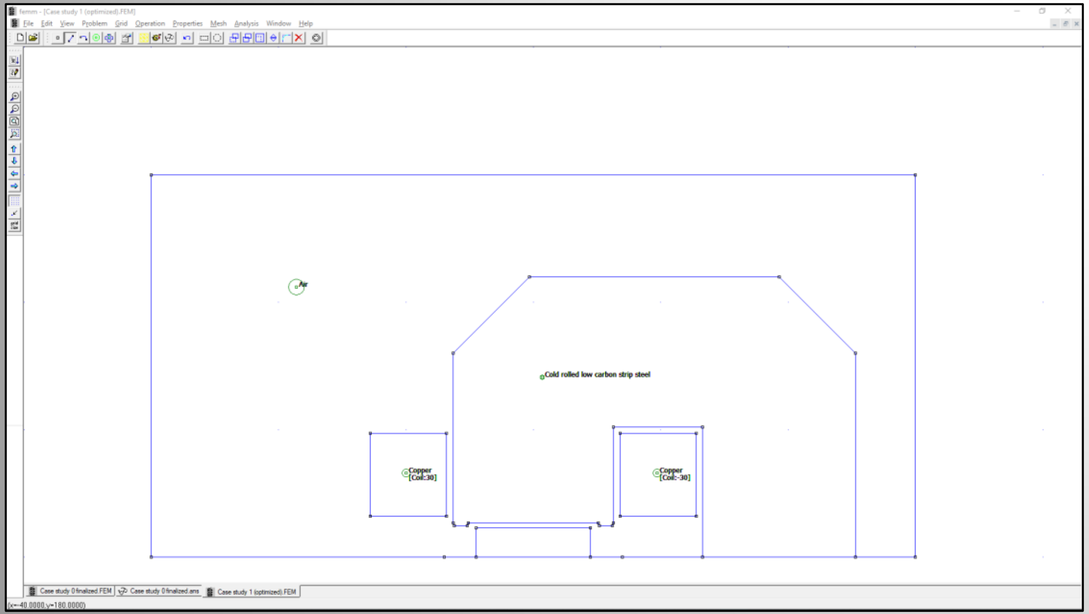
☑ Write data to text file

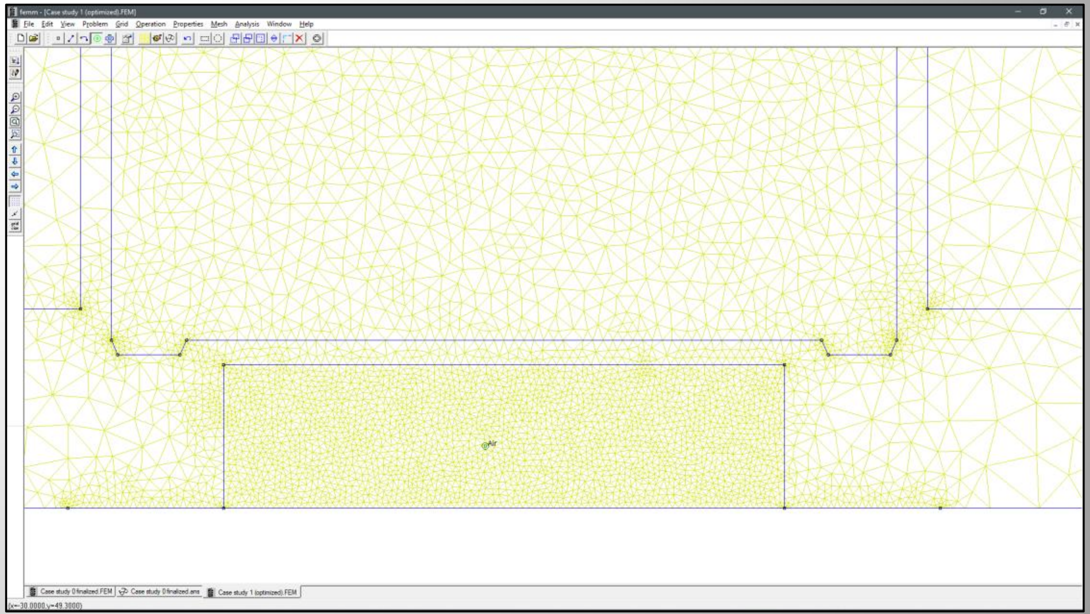
File Formatting: Multicolumn text w/ legend



Optimization

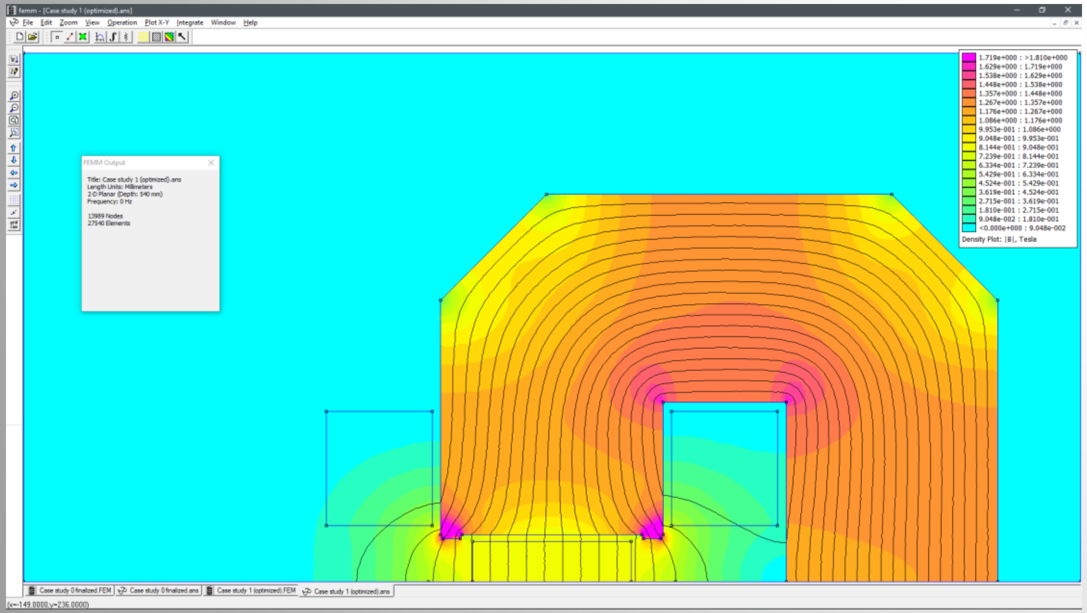
- Optimization includes:
  - Avoiding saturated areas (if possible) by providing a sufficiently large cross-section in the circuit
  - Remove excess of iron in regions where is no or only low flux density
  - Adapt the ratio *coil width : coil hight* if necessary
  - Shape the poles (by adding shims) in order to reach the required field quality
  - Reduce the *pole width* to a minimum
  - Add regions of special interest (good-field-region)





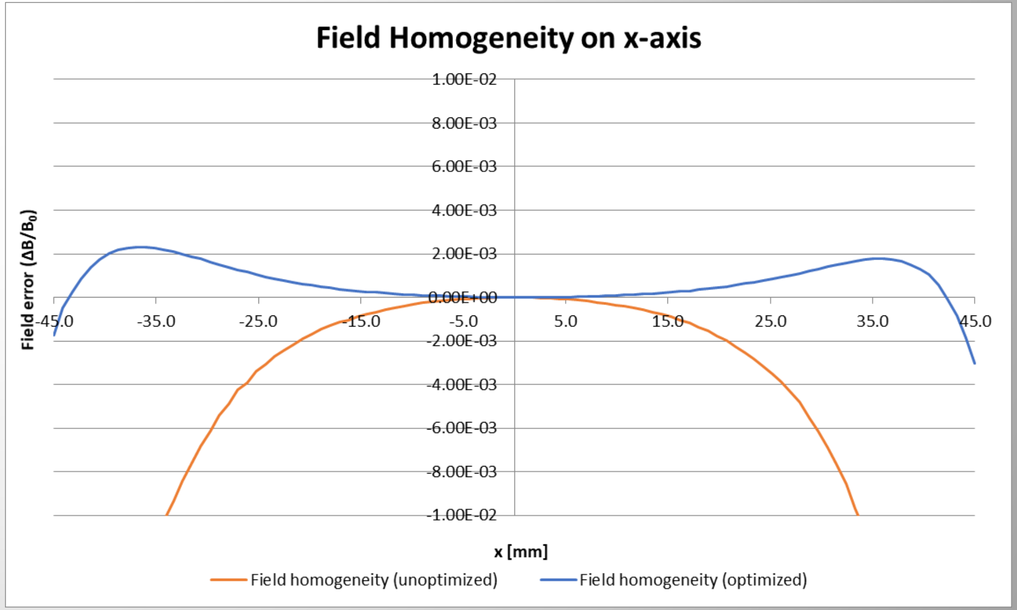
Final Results

- Do not forget: the field quality needs to be evaluated
  - for the entire operation range (B_{min} to B_{max})
  - not only on the midplane, but also on the boundary of the GFR



```
Title: Case study 1 (optimized).ans
Length Units: Millimeters
2-D Planar (Depth: 540 mm)
Frequency: 0 Hz

13989 Nodes
27540 Elements
```

```
(x=-149.0000,y=236.0000)
```



Design report

Students are expected to deliver a written magnet design report which should include at least:

- Detailed magnet parameter list summarizing the outcome of the analytical design
- Explanation for your design choice
- Magnet cross-section based on analytical calculations with yoke and coil shape
- Optimized cross-section (pole profile) based on numerical computations fulfilling the field quality requirements
- Results from the numerical simulation (field quality plot) for the entire operation range
- Note: the reports will be evaluated and contribute to the total score together with the results of the exam
- Please send the final report (1 per group) in electronic form plus the FEMM input file (*.FEM) of your final FE-model to the JUAS secretary
- Submission deadline: Monday, 3rd March 2025 at 12:00 (sharp!)