SUPERCONDUCTING MAGNETS EXERCISES - FEM

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PLAN

- This is a 6 hour module, spilt in two days (3+), and repeated four times
  - Each time it is given to about 25 participants
- The six-hour module is structured as follows
  - Day 1:
    - 30 minutes: recap of the main equations, plus exercise description
    - 2 h: exercise on analytical tools
    - 30 minutes correction and discussion
  - Day 2:
    - 30 minutes: tutorials about how using a finite element model, plus exercise description
    - 2 h: exercise on finite element tools
    - 30 minutes corrections and discussion

CONTENTS

- Day 1
  - Recap of the theory
  - Exercise
  - (solutions in a separate word file)
- Day 2
  - The FEMM code
  - Exercise

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The FEMM code

- Finite Element Method Magnetics (FEMM) written by David Meeker is a finite element package for solving 2D planar and axisymmetric problems in low frequency magnetics and electrostatics.

- The program can be obtained via the FEMM home page at http://www.femm.info/wiki/HomePage. The package is composed of an interactive shell encompassing graphical pre- and post-processing, a mesh generator, and various solvers.
  - User manual: https://www.femm.info/Archives/doc/manual42.pdf

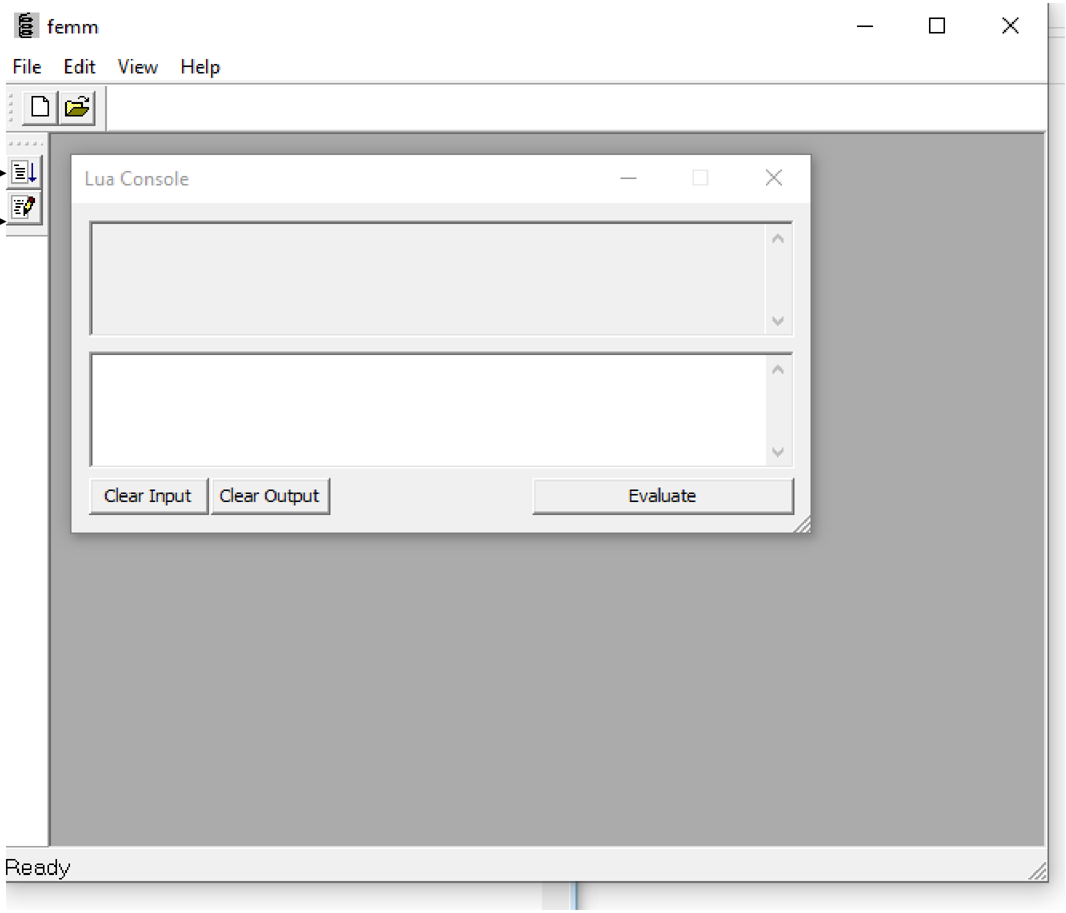
- A scripting language, Lua , is integrated with the program. Lua allows users to create batch runs, describe geometries parametrically, perform optimizations. It is available from http://www.lua.org.
  - User manual https://www.femm.info/Archives/doc/refman-4.0.pdf

Lua in FEMM

- To save a bit of time, we prepared some scripts
  - sector_dipole.lua
  - multipoles_femm.lua

Run a Lua script

Launch a Lua script

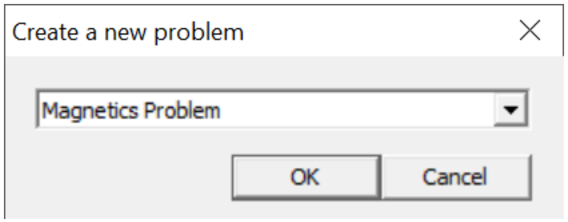


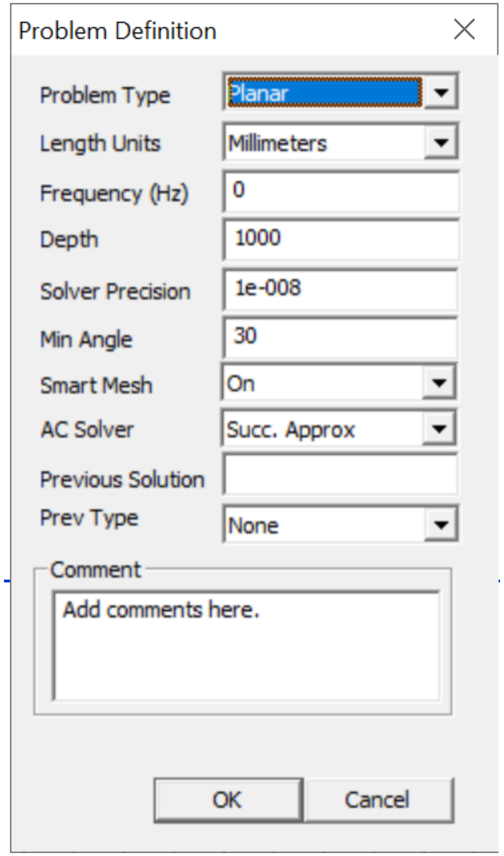
Walk-through FEMM

1. Create a new file, “magnetics” category and set main problem parameters
2. Set few variables
3. Load or prepare material properties, boundary conditions and circuit elements
4. Define geometry
5. Save and mesh
6. Solve
7. Post-process

1. Create new file

---> File ---> New ---> Problem

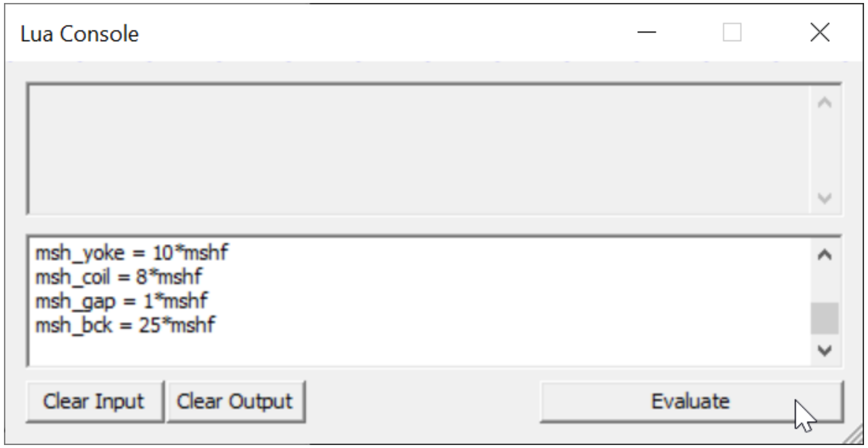




1 m depth, so results (energy, inductance, force, … will be per m length

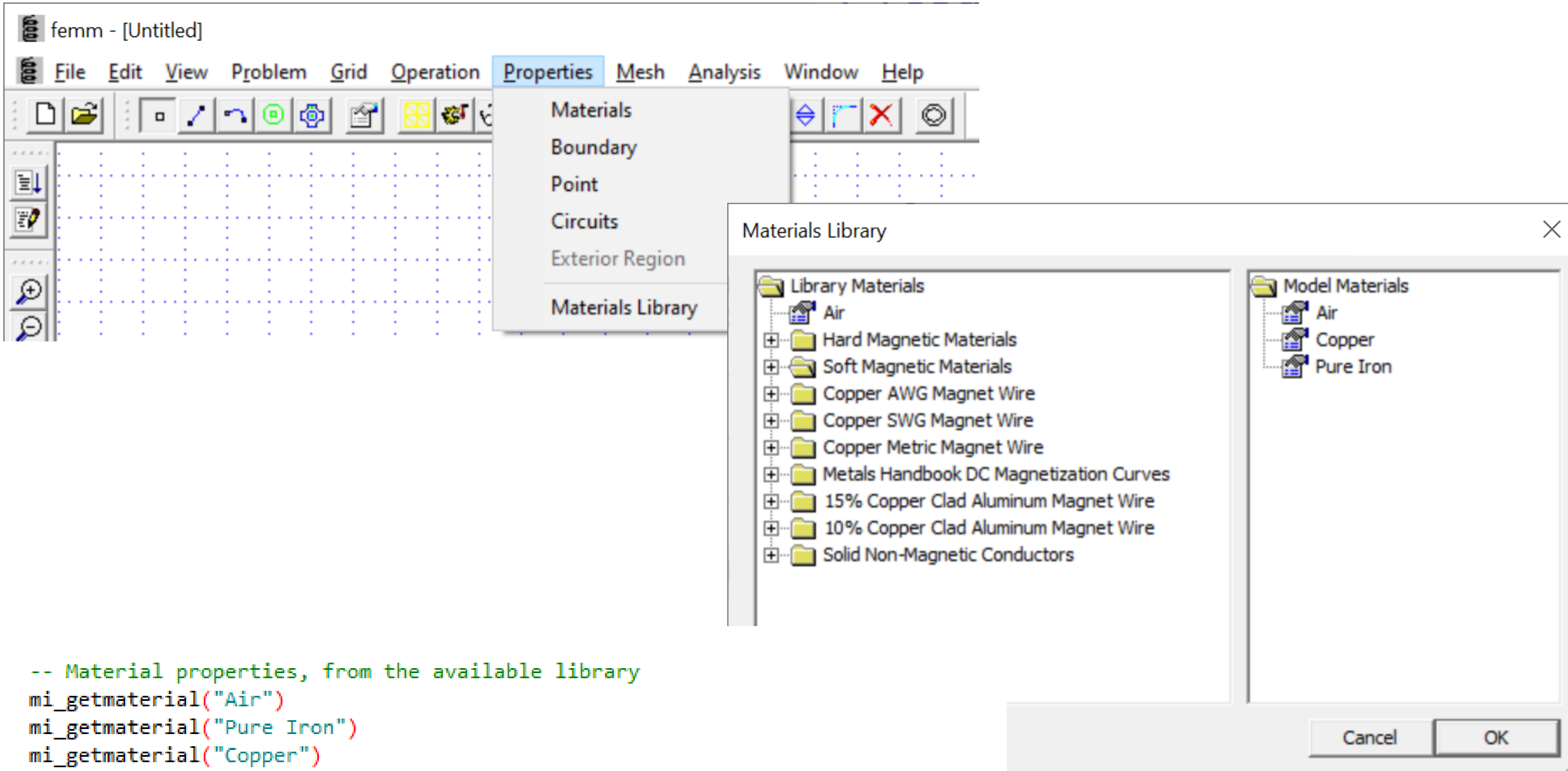
```
-- Creates a new preprocessor document (magnetics problem)
newdocument(0)

-- Main problem parameters
--    0 frequency
--    mm units
--    planar problem
--    solver precision
--    depth, set to 1 m so to have results per m length
mi_probdef(0, "millimeters", "planar", 1e-8, 1000)
```

Write (or copy & paste) in Lua console, then click Evaluate



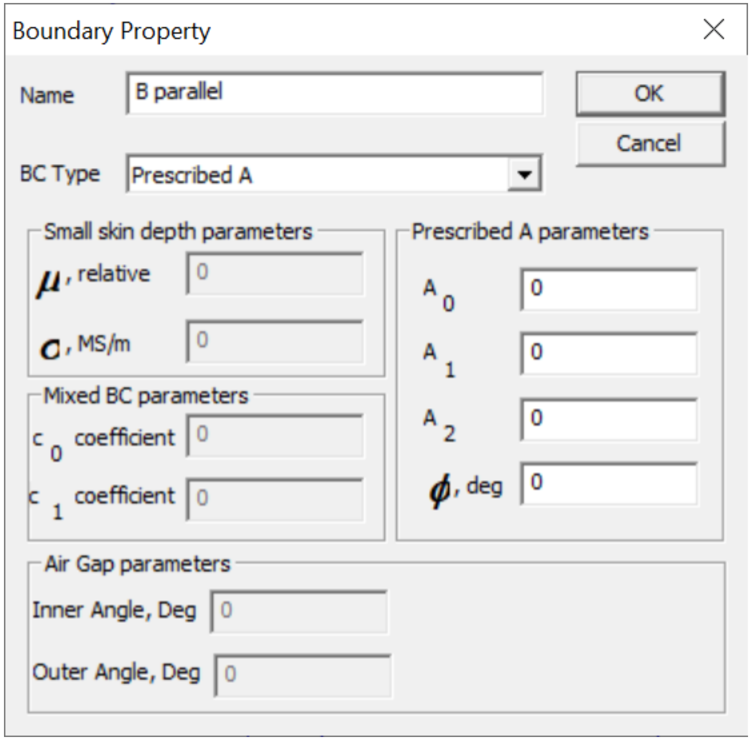

```
-- A few variables
pi=3.141592653589
aperture = 50                                   -- mm (aperture diameter)
w_coil = 15                                     -- mm (coil width)
alphad_coil =  60                               -- deg
alpha_coil = alphad_coil*pi/180                 -- rad
w_collar = 65-aperture/2-w_coil                 -- mm (collar width)
w_iron = 134-aperture/2-w_coil-w_collar         -- mm
w_air  = 400                                    -- mm
workfolder = "\\cernbox-smb\eos\user\s\suizquie\conferences\2311_CAS\Exercise\FEMM\final"
filename = "sector_dipole_exercise.fem"         -- needs to have fem extension

-- Input current density
Joverall = 385 --A/mm2
A_coil   = alpha_coil/2*((aperture/2+w_coil)^2-(aperture/2)^2)
current = A_coil*Joverall -- A

-- Mesh parameters
mshf = 1
msh_yoke = 5*mshf
msh_collar = 8*mshf
msh_coil = 8*mshf
msh_ap = 1*mshf
msh_bck = 25*mshf
```

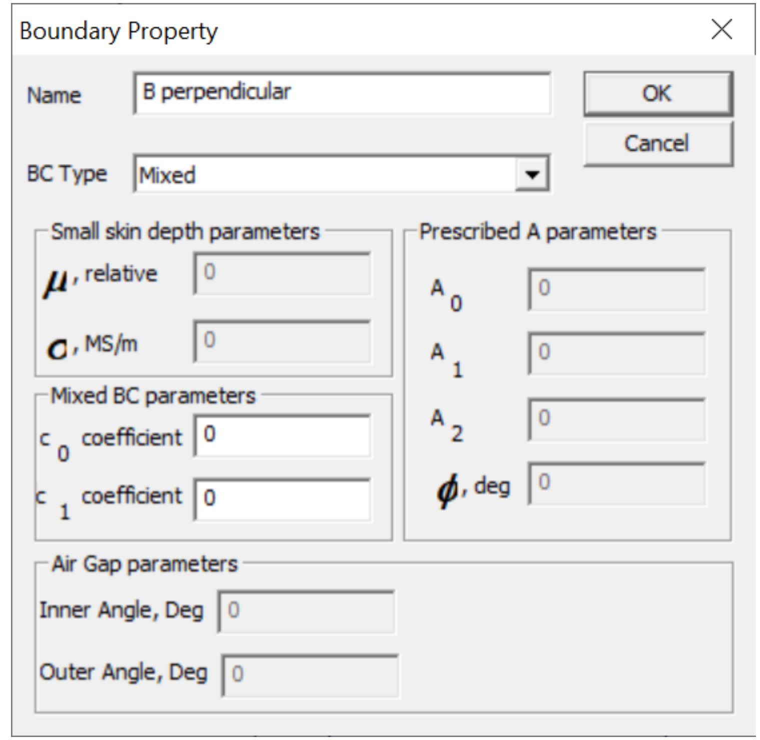
3. Material properties, boundary conditions and circuit elements




```
-- Material properties, from the available library
mi_getmaterial("Air")
mi_getmaterial("Pure Iron")
mi_getmaterial("Copper")
mi_getmaterial("316 Stainless Steel")

-- Create material for those not existing in the library
mi_addmaterial("NbTi", 1, 1,0, current,0,58,0,0,1,0)
```

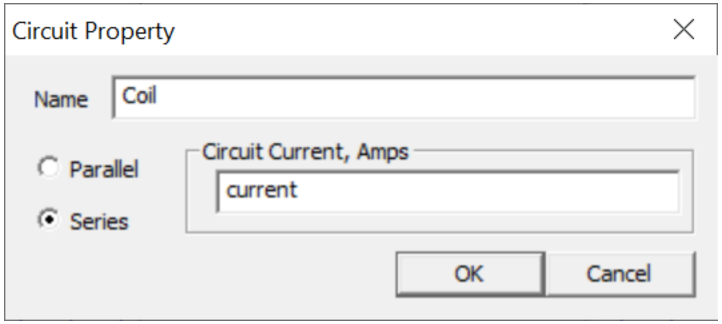
3. Material properties, boundary conditions and circuit elements






```
-- Boundary conditions
mi_addboundprop("B parallel", 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)
mi_addboundprop("B perpendicular", 0, 0, 0, 0, 0, 0, 0, 0, 2, 0, 0)
```

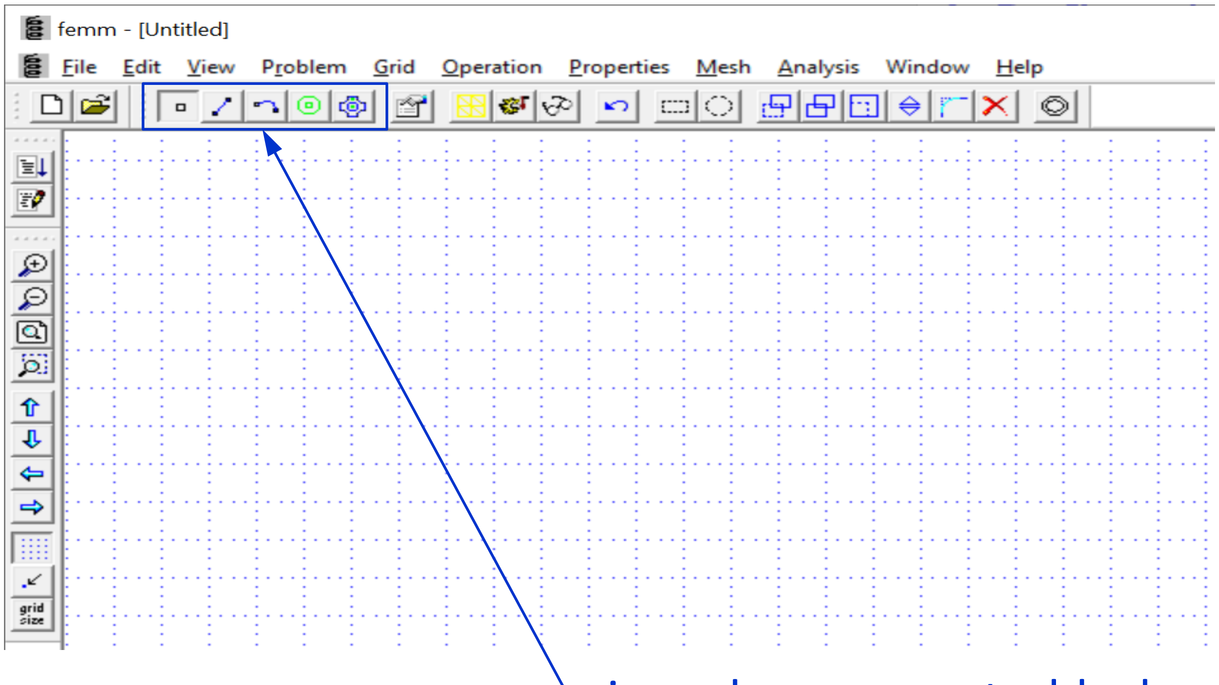
3. Material properties, boundary conditions and circuit elements



"current" is a previously defined variable, alternatively you can enter a number

```
-- A circuit, multiple ones are possible
mi_addcircprop("Coil", current, 1)
```

4. Define geometry



via nodes, segments, blocks, etc…

Hot keys are particularly useful, also the grid can be handy

Previously defined variables can be used to describe the geometry

Copy and paste in the Lua console is also a possibility

Another approach is to import a DXF

4. Define geometry

```
-- Coil

x11_coil=aperture/2
y11_coil=0
x12_coil=aperture/2+w_coil
y12_coil=0
x13_coil=(aperture/2+w_coil)*cos(alpha_coil)
y13_coil=(aperture/2+w_coil)*sin(alpha_coil)
x14_coil=(aperture/2)*cos(alpha_coil)
y14_coil=(aperture/2)*sin(alpha_coil)

mi_addnode(x11_coil,y11_coil)
mi_addnode(x12_coil,y12_coil)
mi_addnode(x13_coil,y13_coil)
mi_addnode(x14_coil,y14_coil)

mi_addsegment(x11_coil, y11_coil, x12_coil, y12_coil)
mi_addarc(x12_coil, y12_coil, x13_coil, y13_coil, alphad_coil, 1)
mi_addsegment(x13_coil, y13_coil, x14_coil, y14_coil)
mi_addarc(x14_coil, y14_coil, x11_coil, y11_coil, -alphad_coil, 1)

mi_addblocklabel((x11_coil+x12_coil)/2, 5)
mi_selectlabel((x11_coil+x12_coil)/2, 5)
mi_setblockprop("NbTi", 0, msh_coil, "Coil", 0, 0, turns)
mi_clearselected()
```

← nodes

← segments

← blocks

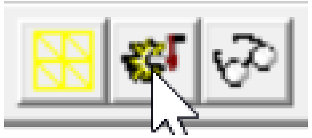
5. Save and mesh

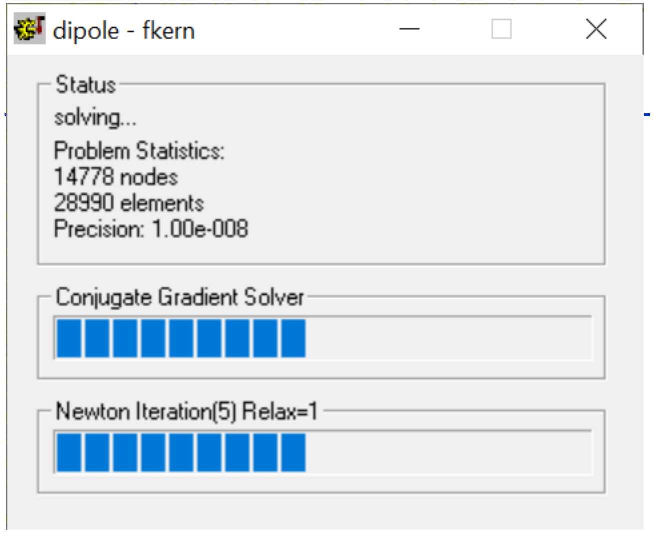
Probably best to save before, in any case you need to save before you mesh

---> Mesh ---> Create Mesh

```
-- Save
mi_saveas(filename)

-- Mesh
mi_zoomnatural()
mi_createmesh()
```

---> Analysis ---> Analyze






```
-- Solve
mi_analyze()
```

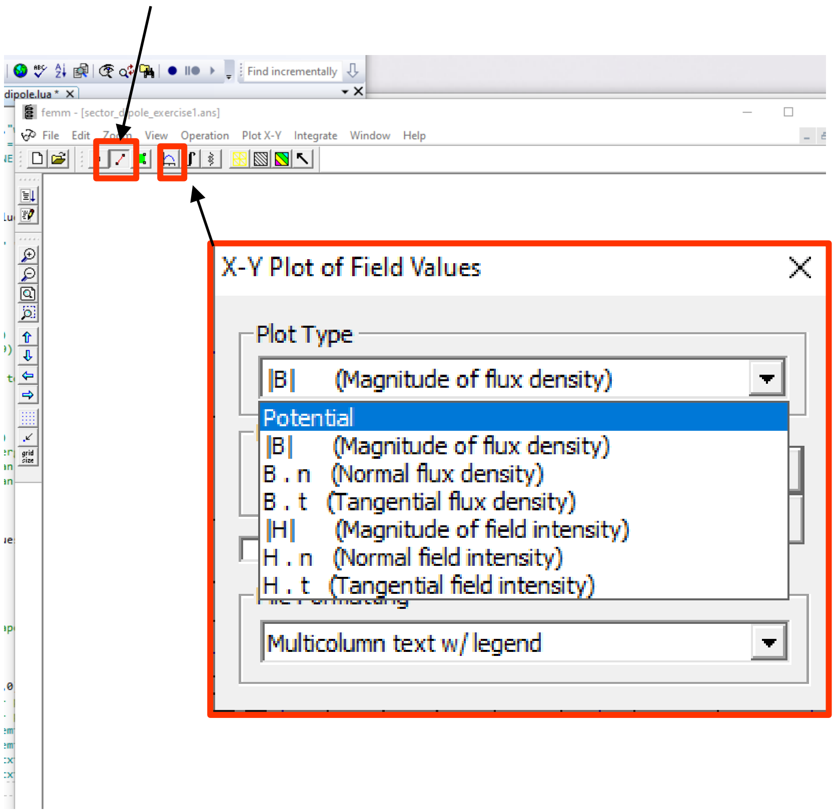
7. Post-processing: load solution

---> Analysis ---> View Results

```
-- Post-processing
mi_loadsolution()
```

7. Post-Processing: Line plots.

Select a contour (right click in the mouse to add more points in your contour line; Esc to un-select the contour)

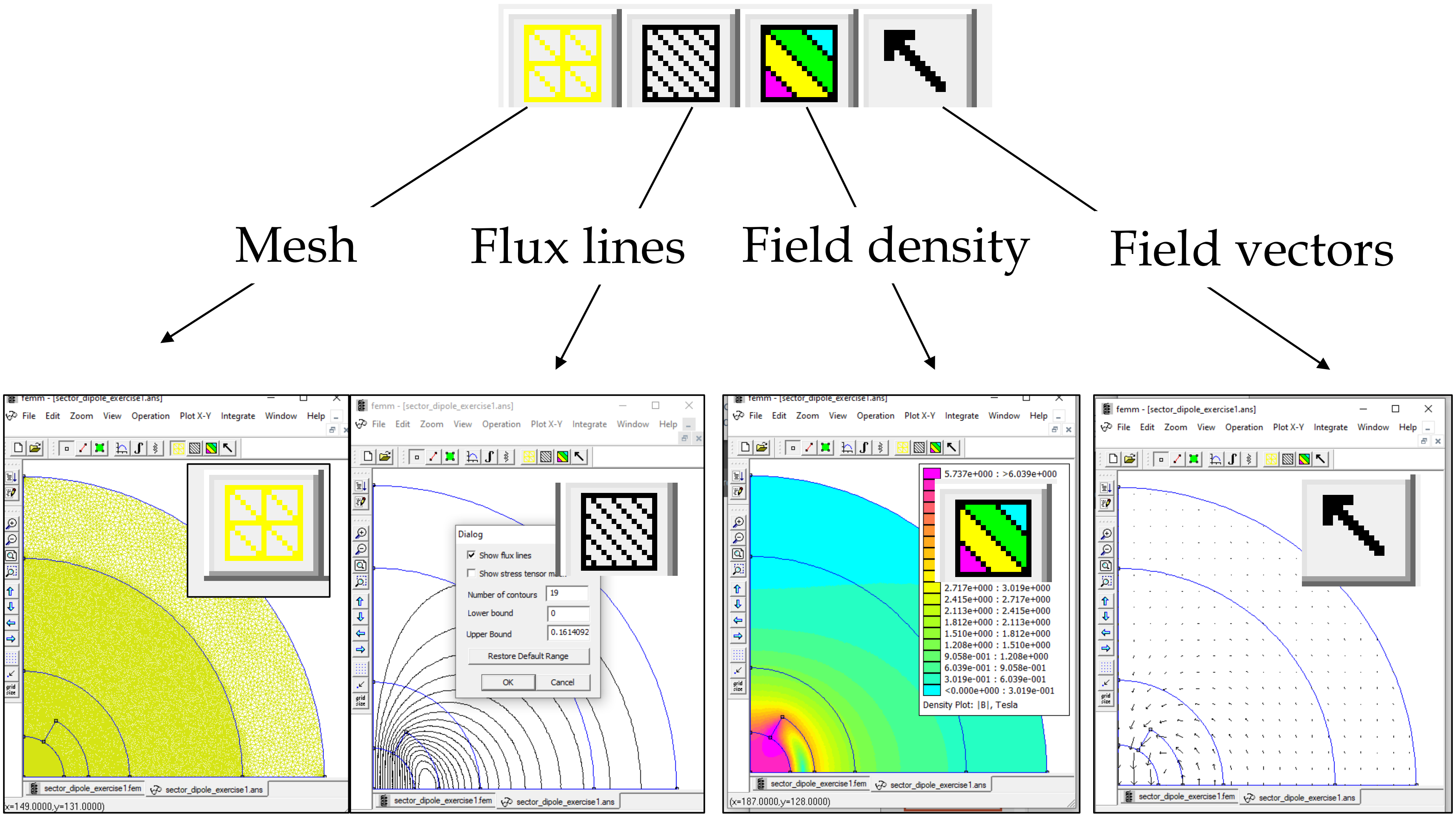


In LUA:

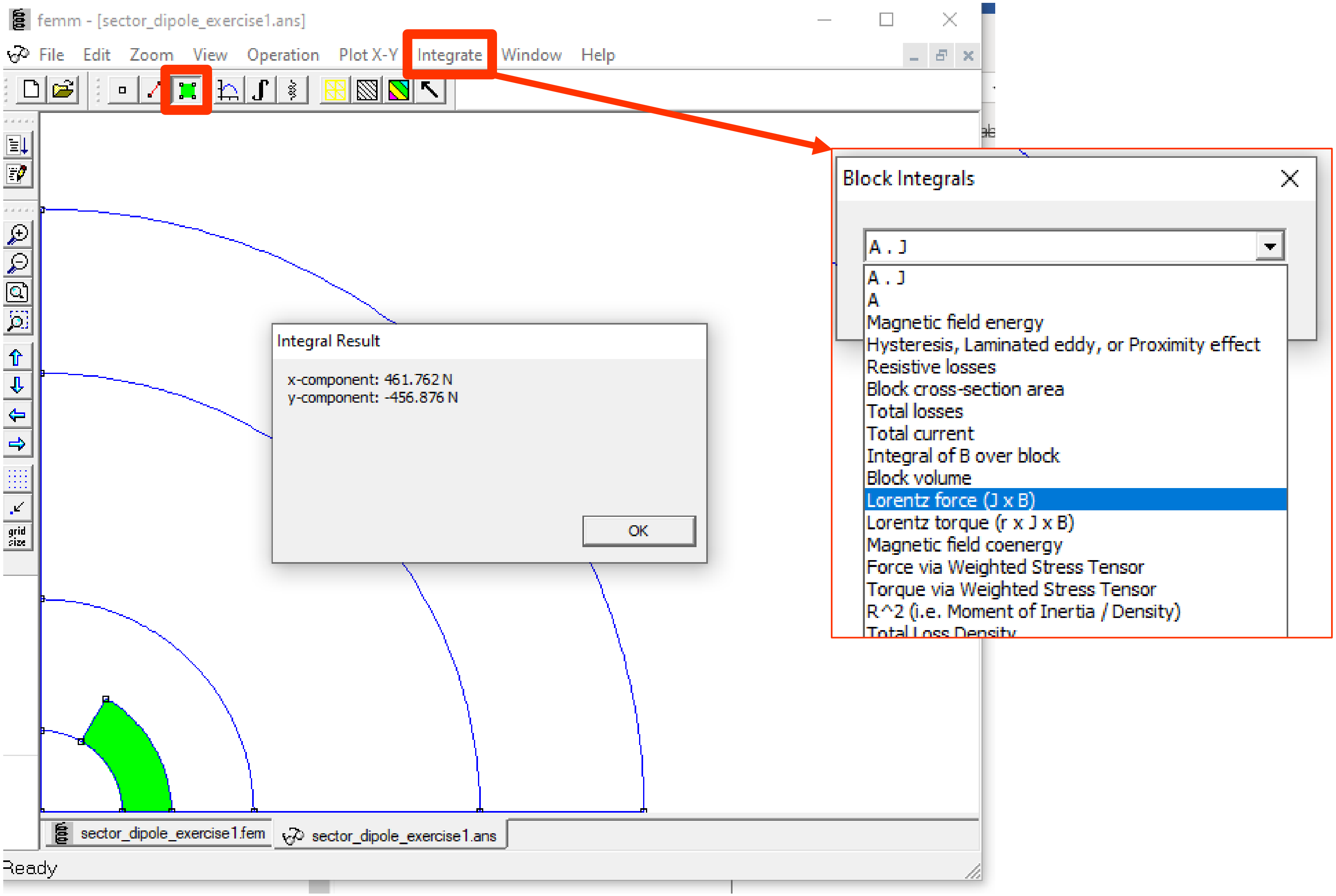
```
-- Plot field in the aperture

-- Select a line
mo_addcontour(0,0)
mo_addcontour(aperture,0)
--mo_makeplot(2,200) -- plot in FEMM
--mo_makeplot(3,200) -- plot in FEMM
mo_makeplot(2,200,"Bx.emf") -- save image
mo_makeplot(3,200,"By.emf") -- save image
mo_makeplot(2,200,"Bx.txt",0) -- print it to a file
mo_makeplot(3,200,"By.txt",0) -- print it to a file
```

To script it in Lua, see https://www.femm.info/Archives/doc/manual42.pdf section 3.4 (Magnetics Post Processor Command Set)

7. Post-Processing: 2D plots.



7. Post-Processing: Integrals over a block



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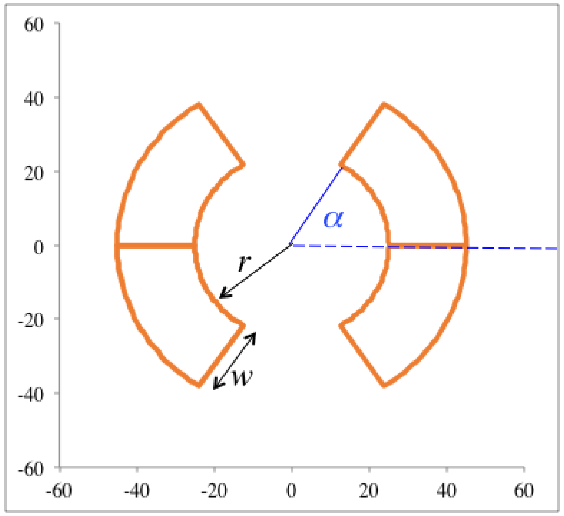
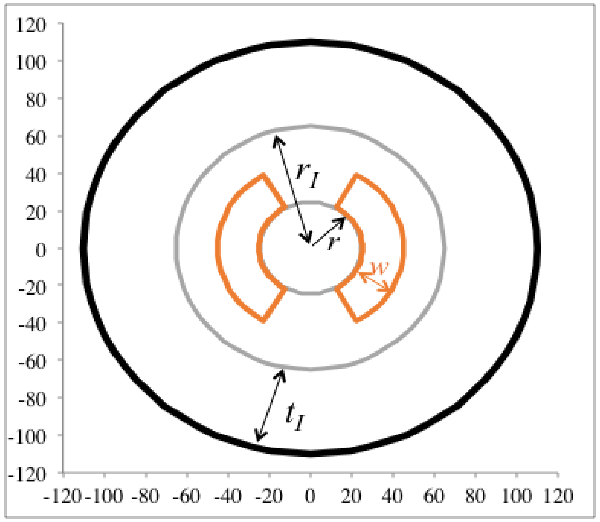
  - (script and solution in separate files)

Day 2 - Exercise

- Exercise 1: We consider a dipole made as a 60° sector coil, with 50 mm aperture (diameter) and 15 mm width cable, without iron as in the exercise 1 of Day 1
  - Estimate via FEMM the overall current density needed to have a 5 T bore field , and compare to the analytical values;
  - Compute the field harmonics b_3, b_5 and b_7, using 17 mm as reference radius, and compare to the analytical values;
  - Verify how b_3 approaches to zero with finer meshes;
  - Verify that your solution does not change when increasing the size of the air region, and what is the minimum amount of air you need around the coil to have a converged solution



- <u>Exercise 2</u>:
  - Estimate via FEMM the relative field increase due to the presence of iron with 65 mm inner radius and 134 mm outer radius and compare to the analytical values;
  - Keeping the same 5 T field, estimate via FEMM the reduction of the current density given by the iron contribution compare to the analytical values;
  - In this last case, estimate via FEMM the field in the midplane at 140 mm and at 200 mm from the magnet centre; if the field at 140 mm is larger than 5 mT, estimate the required increase in thickness to have less than 5 mT at 140 mm from the centre



Day 2 - Exercise

- Exercise 3:
  - Estimate via FEMM the peak field in the coil;
  - Estimate via FEMM the pressure given by the accumulation of azimuthal stress in the midplane, for the case without iron and with iron, and compare to the analytical values;
  - Estimate via FEMM the stored energy. What fraction of the energy is in the air/coil/collar/iron?

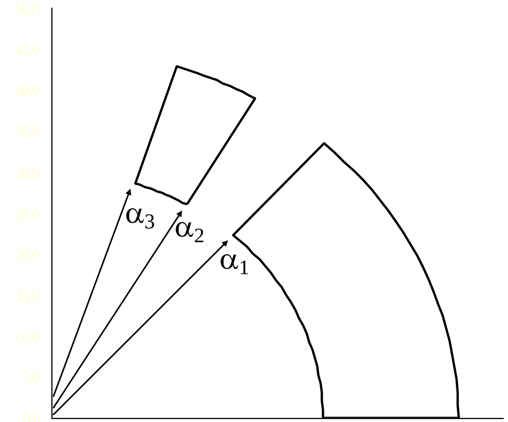
- Congratulations, you completed the exercise ☺
- A good time to look at your results and play a bit with the model?
  - How the field quality in the aperture and peak field in the coil changes as a function of the current?
  - What if you reduce the collar thickness to 10 mm? How the bore field to peak field ratio changes? And what about b_3?
- If you still have some time, try out the extra exercises

Day 2 – Extra 1

- For a coil with 2 blocks, one can find solutions to set to zero B3 and B5

$$B_3 = \frac{\mu_0 j R_{ref}^2}{\pi} \frac{\sin 3\alpha_3 - \sin 3\alpha_2 + \sin 3\alpha_1}{3} \left(\frac{1}{r} - \frac{1}{r+w} \right)$$

$$B_5 = \frac{\mu_0 j R_{ref}^4}{\pi} \frac{\sin 5\alpha_3 - \sin 5\alpha_2 + \sin 5\alpha_1}{5} \left(\frac{1}{r^3} - \frac{1}{(r+w)^3} \right)$$



  - Note: we have to work with non-normalized multipoles, which can be added together

- Equations to set to zero B_3 and B_5

$$\begin{cases} \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) = 0 \\ \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) = 0 \end{cases}$$

- One can compute numerically the solutions
  - [0°-24°, 36°-60°]
  - [0°-36°, 44°-64°]
  - [0°-48°, 60°-72°]
  - [0°-52°, 72°-88°]
- Modify the coil geometry in the FE model to have a 2 blocks coil:
  - Compare the harmonics to the 1 block coil
  - Find the required coil width to reach the same field in the aperture

Day 2 – Extra 2

- Typically, finite element methods are best suited to problems with well-defined, closed solution regions. However, a large number of problems that one might like to address have no natural outer boundary. The boundary condition that one would like to apply is $A = 0$ at $r = \infty$.
- Fortunately, there are methods that can be applied to get solutions that closely approximate the "open boundary" solution using finite element methods. FEMM provides different options, look to the manual (link) and test the different options (section 1.3.1 and annex A3)

ANNEX

- You should able to open and edit *.lua scripts in any text editor
- If you really like when the editor is helping you with colors to guide, you can:
  - Download TextPad https://www.textpad.com/download#v9
  - Download lua.syn file in https://www.textpad.com/pt/addons/syntax-h2m
  - Copy the file to the textpad system folder (typically would be C:\Program Files\TextPad 8\system)
  - Create a new document class in textpad (Configure/New Document Class…)