Joint Universities Accelerator School

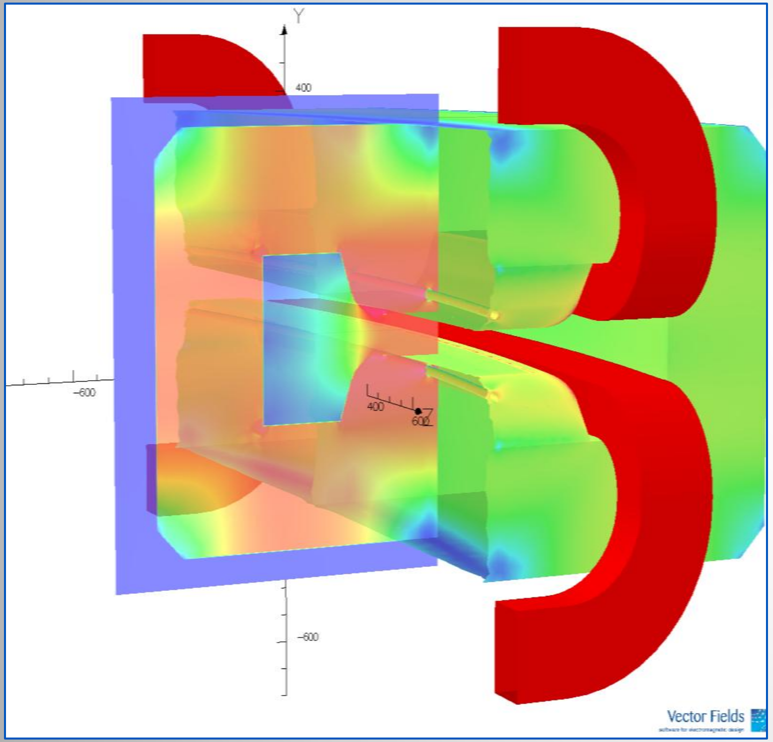
JUAS 2025

18. – 24. February 2025

Normal-conducting accelerator magnets
Lecture 6: Applied numerical design

Thomas Zickler
CERN

Numerical design



Which code shall I use?

Introduction to 2D numerical design

How to evaluate the results

Application examples

Numerical design

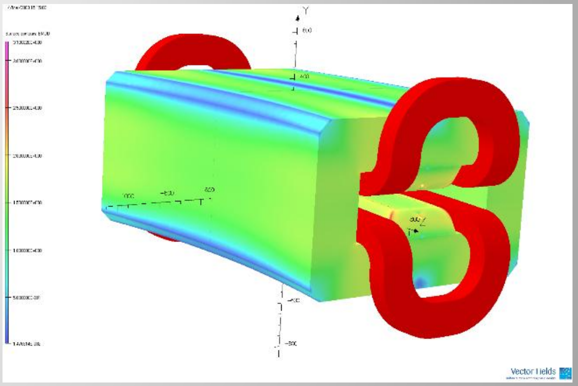
Common computer codes: Opera (2D) or Tosca (3D), Poisson, ANSYS, Roxie, Magnus, Magnet, Mermaid, Radia, FEMM, COMSOL, etc…

Technique is iterative

- calculate field generated by a defined geometry
- adjust geometry until desired distribution is achieved

Computing time <u>increases</u> for high accuracy solutions, non-linear problems and time dependent analysis → compromise between accuracy and computing time

2D	3D
• 2D analysis is often sufficient • magnetic solvers allow currents only perpendicular to the plane • fast	• produces large amount of elements • mesh generation and computation takes significantly longer • end effects included • powerful modeller



FEM codes are powerful tools, but be cautious:

- Always check results if they are ‘physical reasonable’
- Use FEM for quantifying, not to qualify

Numerical design process

Design process in 2D (similar in 3D):

Create the model (pre-processor or modeller)

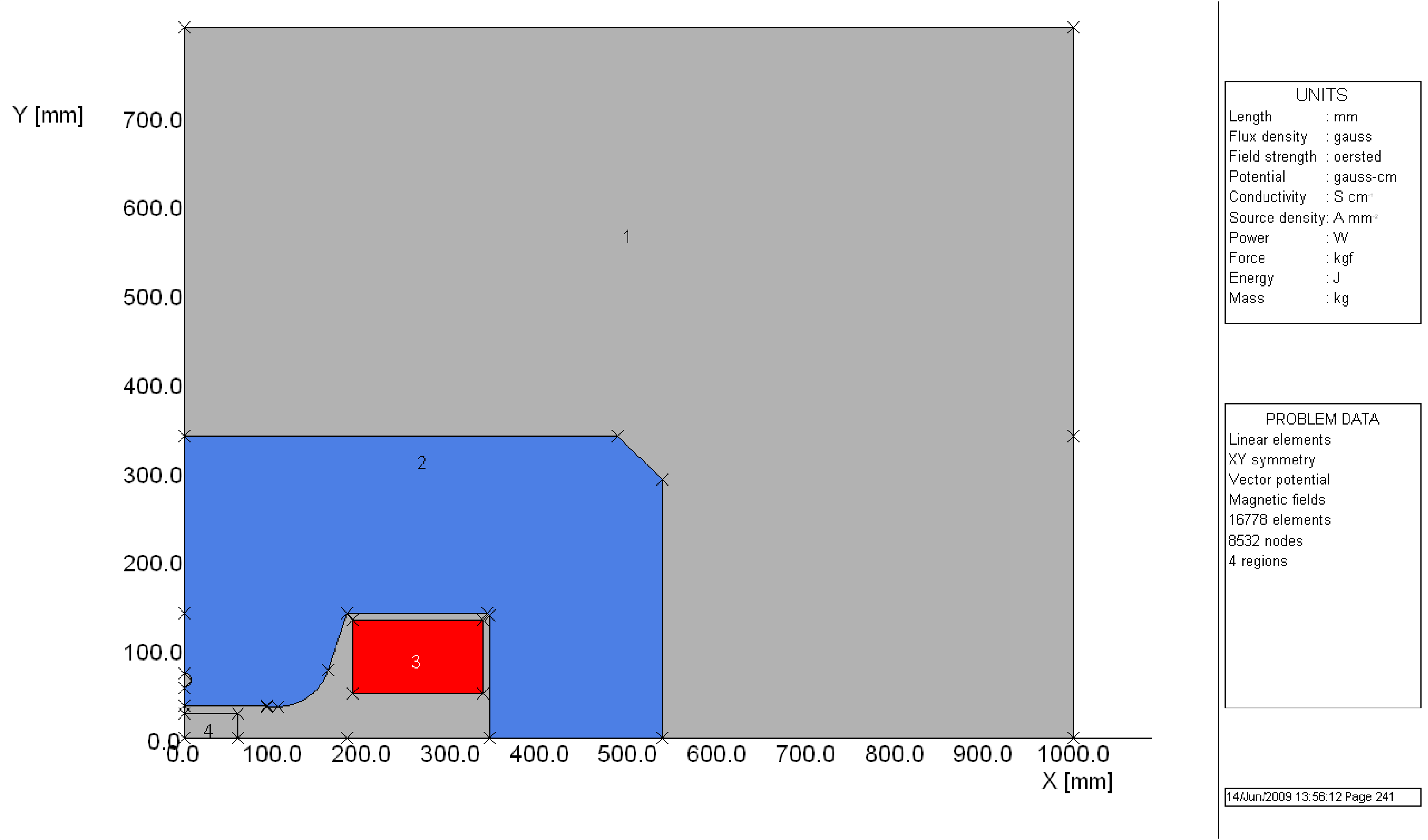
Define boundary conditions, set material properties

Run calculations (solver)

Visualize and asses the results (post-processor)

Optimization by adjusting the geometry (manually or optimization code)

Creating the model



UNITS
Length : mm
Flux density : gauss
Field strength : oersted
Potential : gauss-cm
Conductivity : S cm^{-1}
Source density: A mm^{-2}
Power : W
Force : kgf
Energy : J
Mass : kg

PROBLEM DATA
Linear elements
XY symmetry
Vector potential
Magnetic fields
16778 elements
8532 nodes
4 regions

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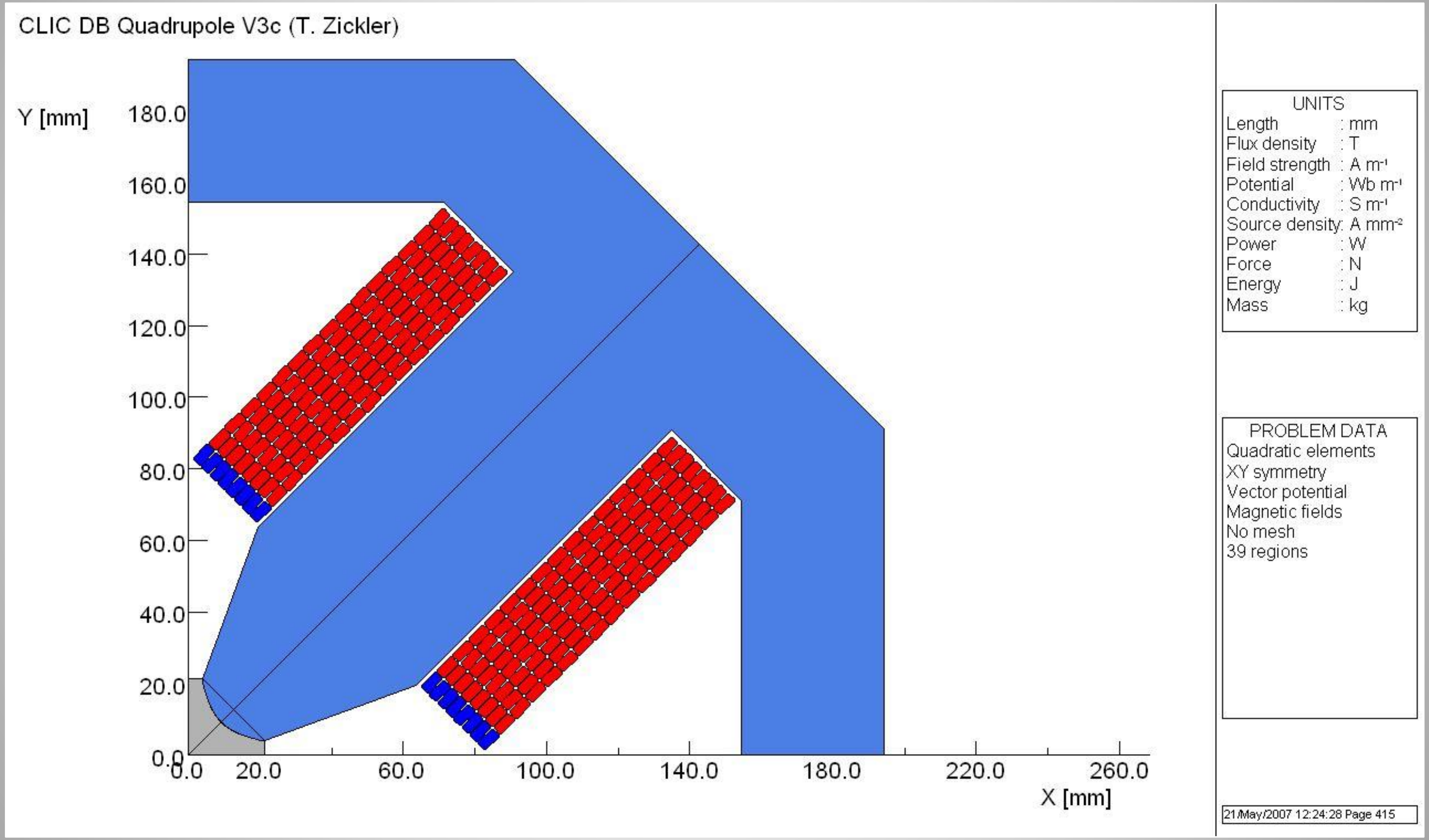
GUI vs. Script

Model symmetries


CLIC DB Quadrupole V3c (T. Zickler)

UNITS

Length	: mm
Flux density	: T
Field strength	: A m^{-1}
Potential	: Wb m^{-1}
Conductivity	: S m^{-1}
Source density	: A mm^{-2}
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
No mesh
39 regions

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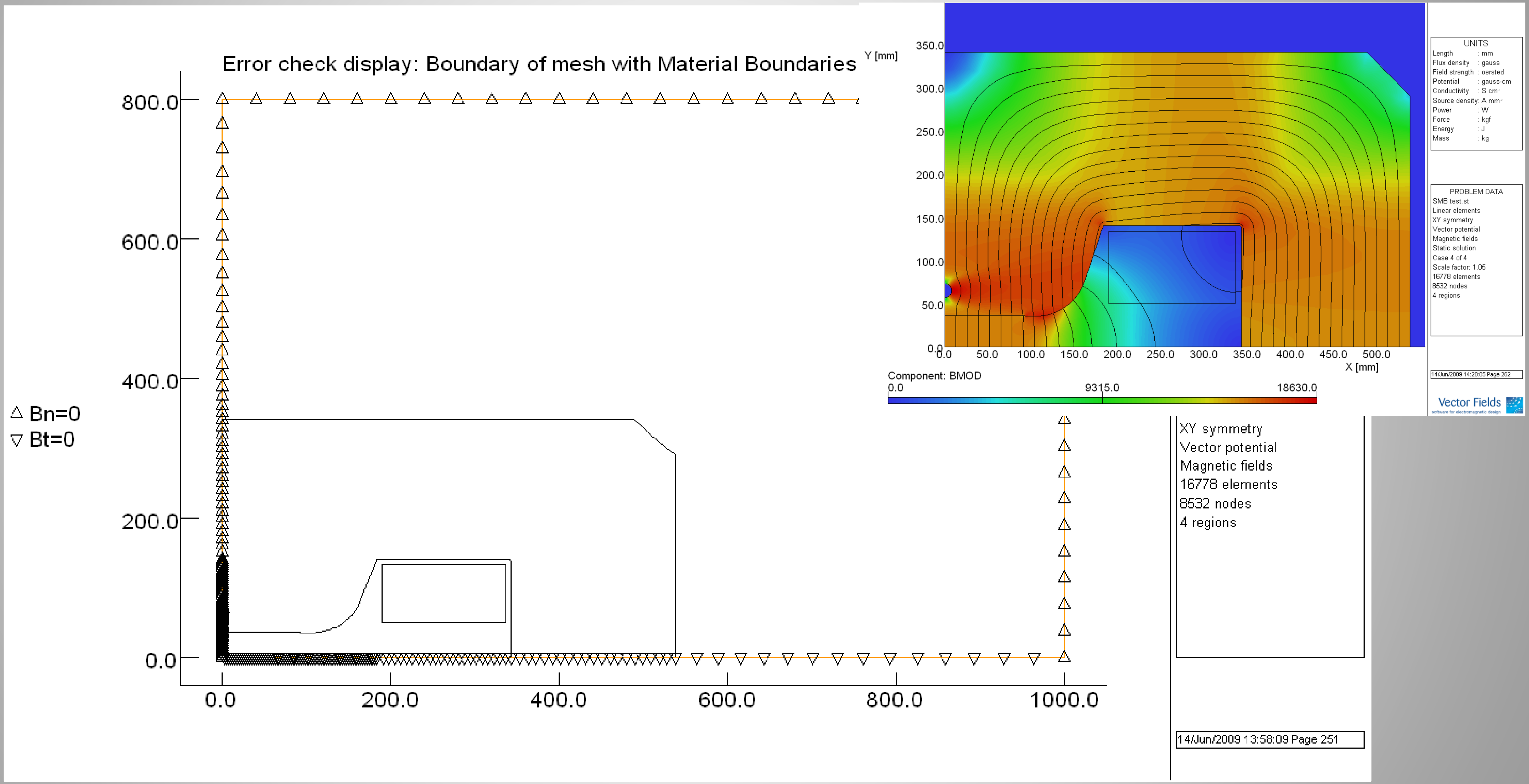
Note: one eighth of quadrupole could be used with opposite symmetries defined on horizontal and y = x axis

Boundary conditions



UNITS

Length : mm
Flux density : gauss
Field strength : oersted
Potential : gauss-cm
Conductivity : S cm^{-1}
Source density: A mm^{-2}
Power : W
Force : kgf
Energy : J
Mass : kg

PROBLEM DATA

SMB test.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 4 of 4
Scale factor: 1.05
16778 elements
8532 nodes
4 regions

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XY symmetry
Vector potential
Magnetic fields
16778 elements
8532 nodes
4 regions

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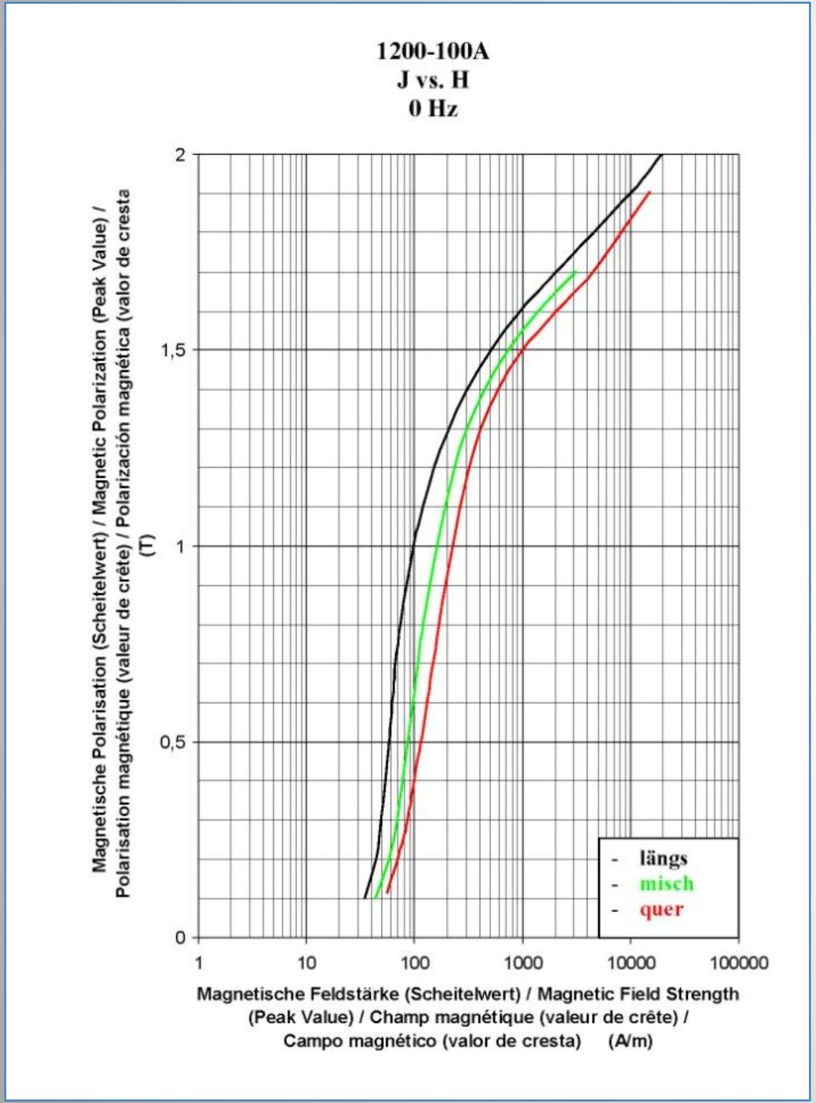
Dirichlet condition = no normal flux components, only tangential flux components
Neumann condition = no tangential flux components, only normal flux components

Material properties



Data source: Thyssen/Germany

Permeability:

- either fixed for linear solution
- or permeability curve for non-linear solution
- can be anisotropic
- apply correction for steel packing factor
- pre-defined curves available

Conductivity:

- for coil and yoke material
- required for transient eddy current calculations

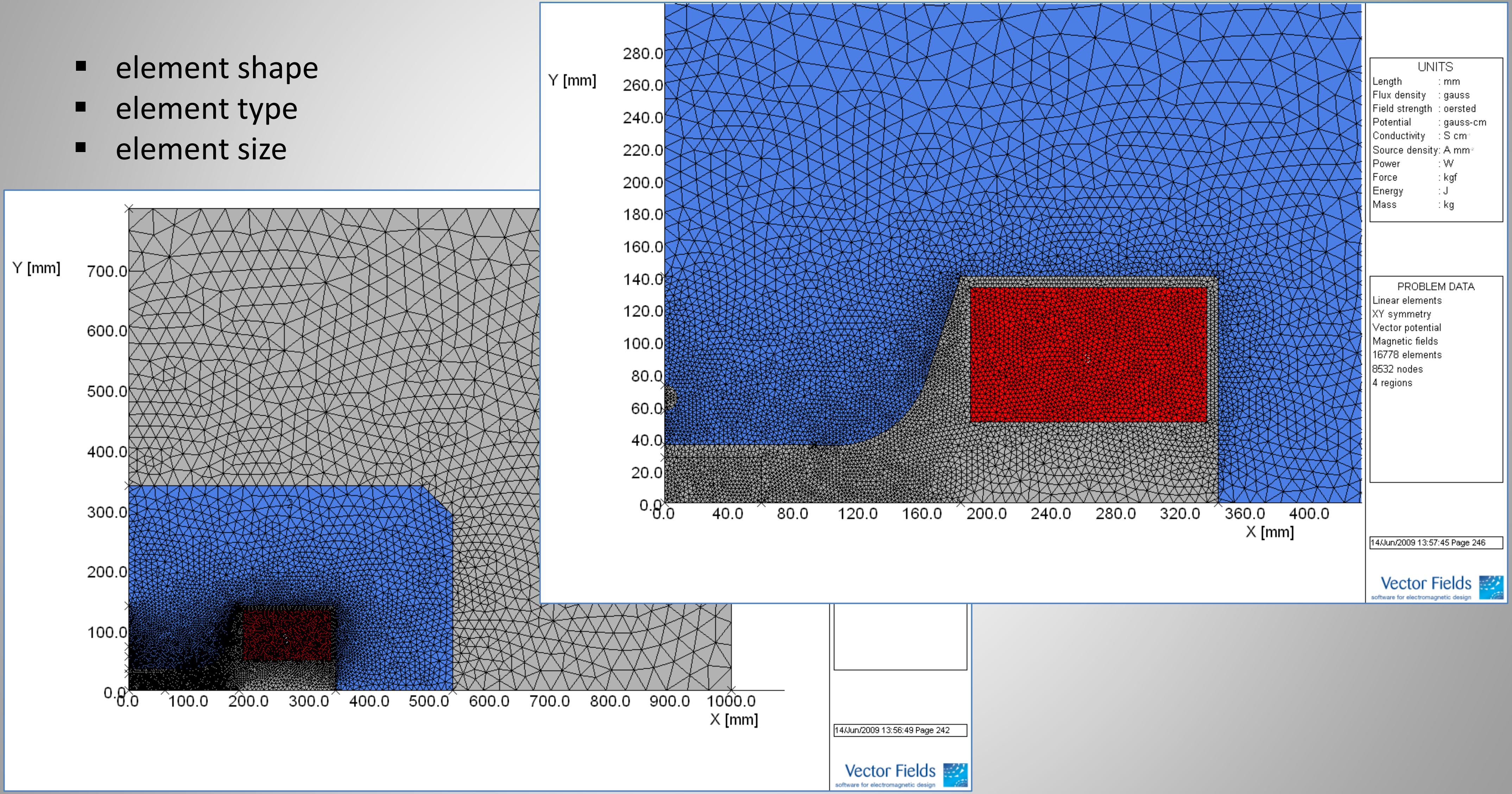
Mechanical and thermal properties:

- in case of combined structural or thermal analysis

Current density in the coils

Mesh generation

- element shape
- element type
- element size



UNITS
Length : mm
Flux density : gauss
Field strength : oersted
Potential : gauss-cm
Conductivity : S cm^{-1}
Source density: A mm^{-2}
Power : W
Force : kgf
Energy : J
Mass : kg

PROBLEM DATA
Linear elements
XY symmetry
Vector potential
Magnetic fields
16778 elements
8532 nodes
4 regions

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Solver

Solution

- linear: single calculation with constant permeability
- non-linear: iterative calculations using permeability table

Solver types

- static
- steady state (sine function)
- transient (ramp, step, arbitrary function, ...)

Solver settings

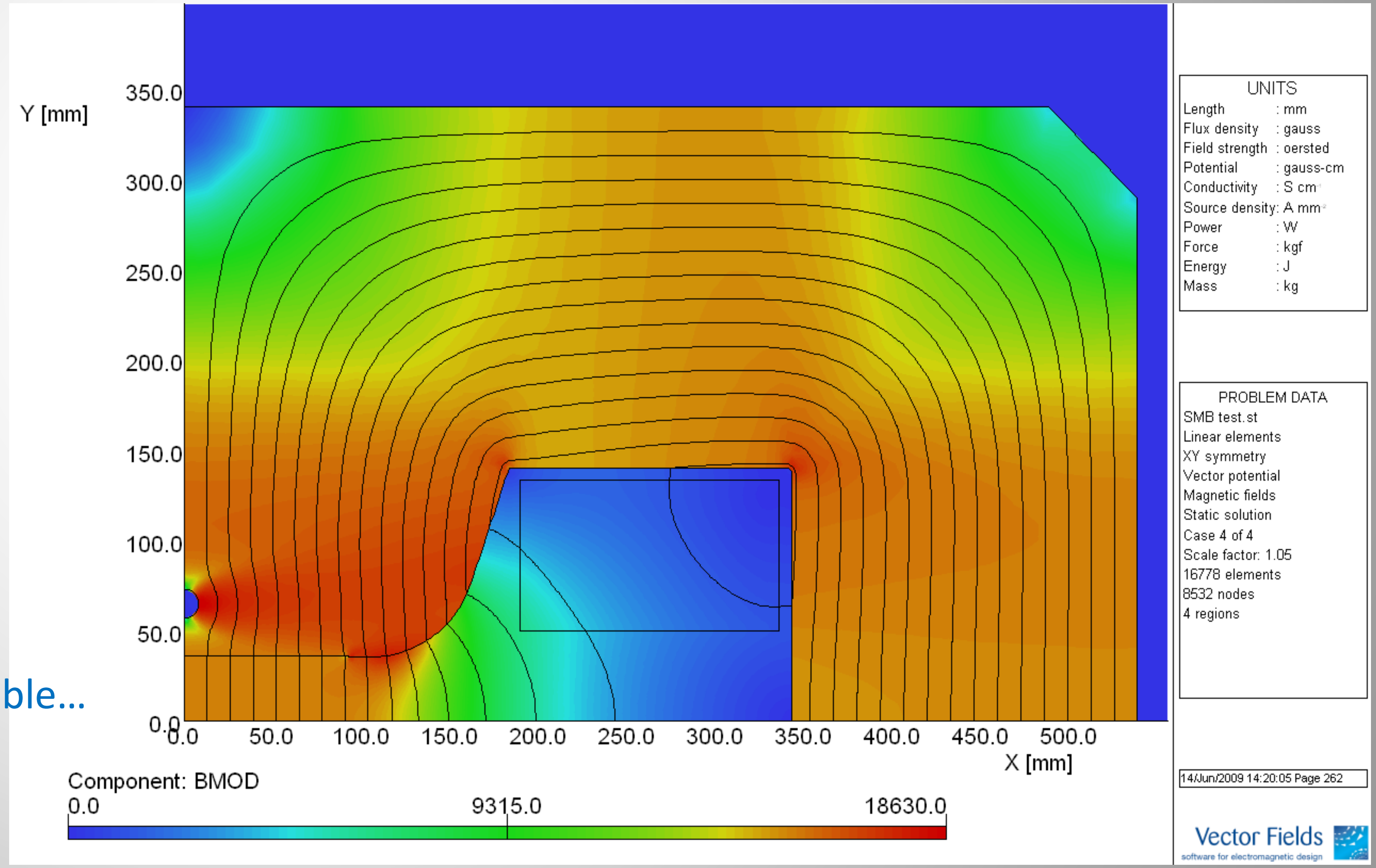
- number of iterations,
- convergence criteria
- precision to be achieved, etc...

Analyzing the results

With the help of the post-processor, field distribution and field quality can be visualized in various forms on the pre-processor model:

- Field lines and colour contours plots of flux, field, and current density
- Graphs showing absolute or relative field distribution
- Homogeneity plots
- Etc…

First check if the result is physically reasonable…



UNITS
Length : mm
Flux density : gauss
Field strength : oersted
Potential : gauss-cm
Conductivity : S cm^{-1}
Source density: A mm^{-2}
Power : W
Force : kgf
Energy : J
Mass : kg

PROBLEM DATA
SMB test.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 4 of 4
Scale factor: 1.05
16778 elements
8532 nodes
4 regions

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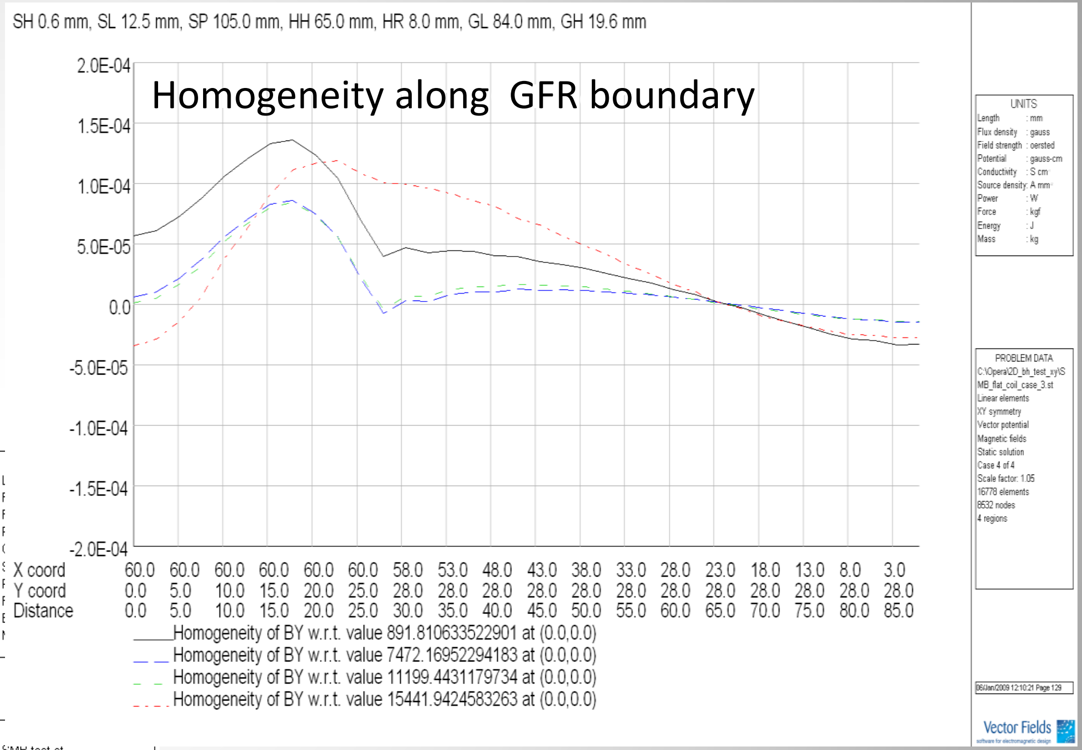
Field homogeneity in a dipole

A simple judgment of the field quality can be done by plotting the field homogeneity

$$\frac{\Delta B}{B_0} = \frac{B_y(x,y)}{B_y(0,0)} - 1 \qquad \frac{\Delta B}{B_0} \leq 0.01\%$$



SH 0.6 mm, SL 12.5 mm, SP 105.0 mm, HH 65.0 mm, HR 8.0 mm, GL 84.0 mm, GH 19.6 mm

Homogeneity of BY w.r.t. value 891.810633522901 at (0.0,0.0)
Homogeneity of BY w.r.t. value 7472.16952294183 at (0.0,0.0)
Homogeneity of BY w.r.t. value 11199.4431179734 at (0.0,0.0)
Homogeneity of BY w.r.t. value 15441.9424583263 at (0.0,0.0)

UNITS

Length	: mm
Flux density	: gauss
Field strength	: oersted
Potential	: gauss-cm
Conductivity	: S cm
Source density	: A mm
Power	: W
Force	: kgf
Energy	: J
Mass	: kg

PROBLEM DATA
C:\Opera\2D_bh_test_xy\SMB_flat_coil_case_3.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 4 of 4
Scale factor: 1.05
16778 elements
8532 nodes
4 regions

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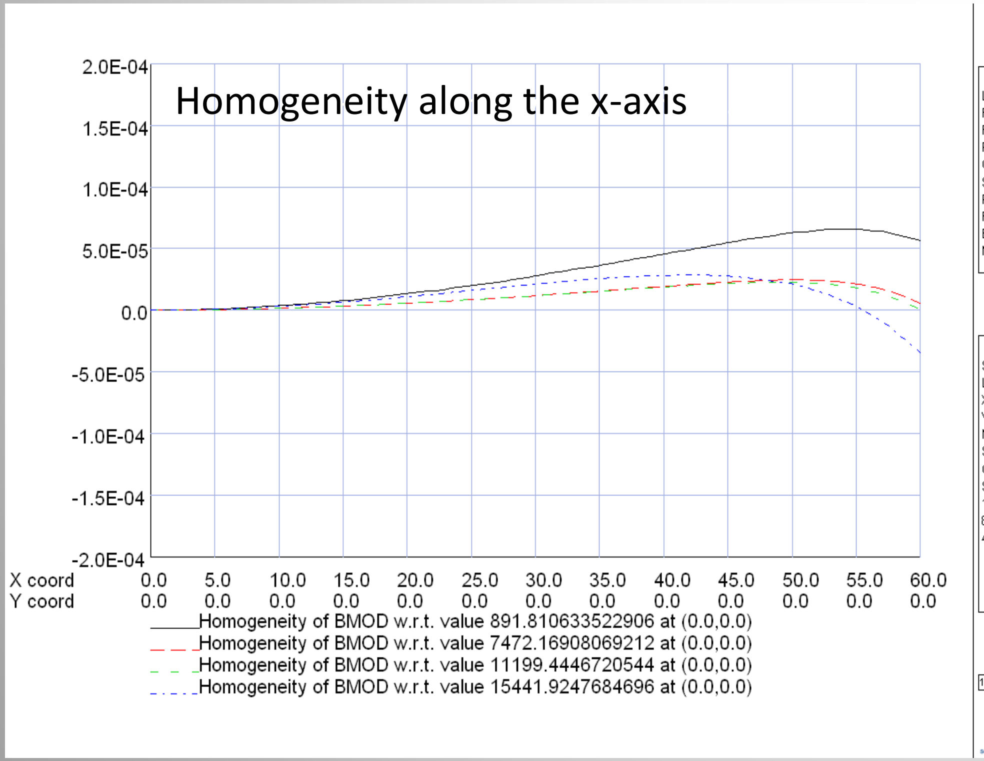

Homogeneity of BMOD w.r.t. value 891.810633522906 at (0.0,0.0)
Homogeneity of BMOD w.r.t. value 7472.16908069212 at (0.0,0.0)
Homogeneity of BMOD w.r.t. value 11199.4446720544 at (0.0,0.0)
Homogeneity of BMOD w.r.t. value 15441.9247684696 at (0.0,0.0)

SMB test.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 4 of 4
Scale factor: 1.05
16778 elements
8532 nodes
4 regions

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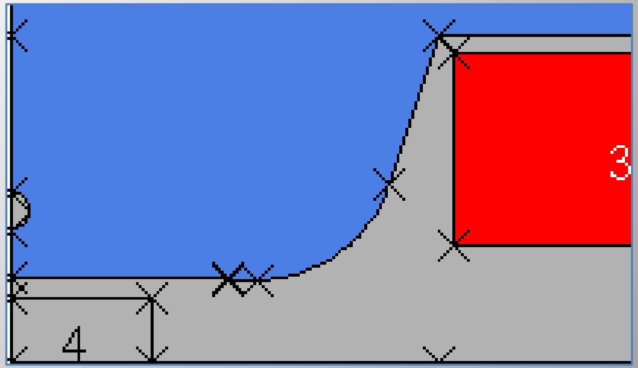
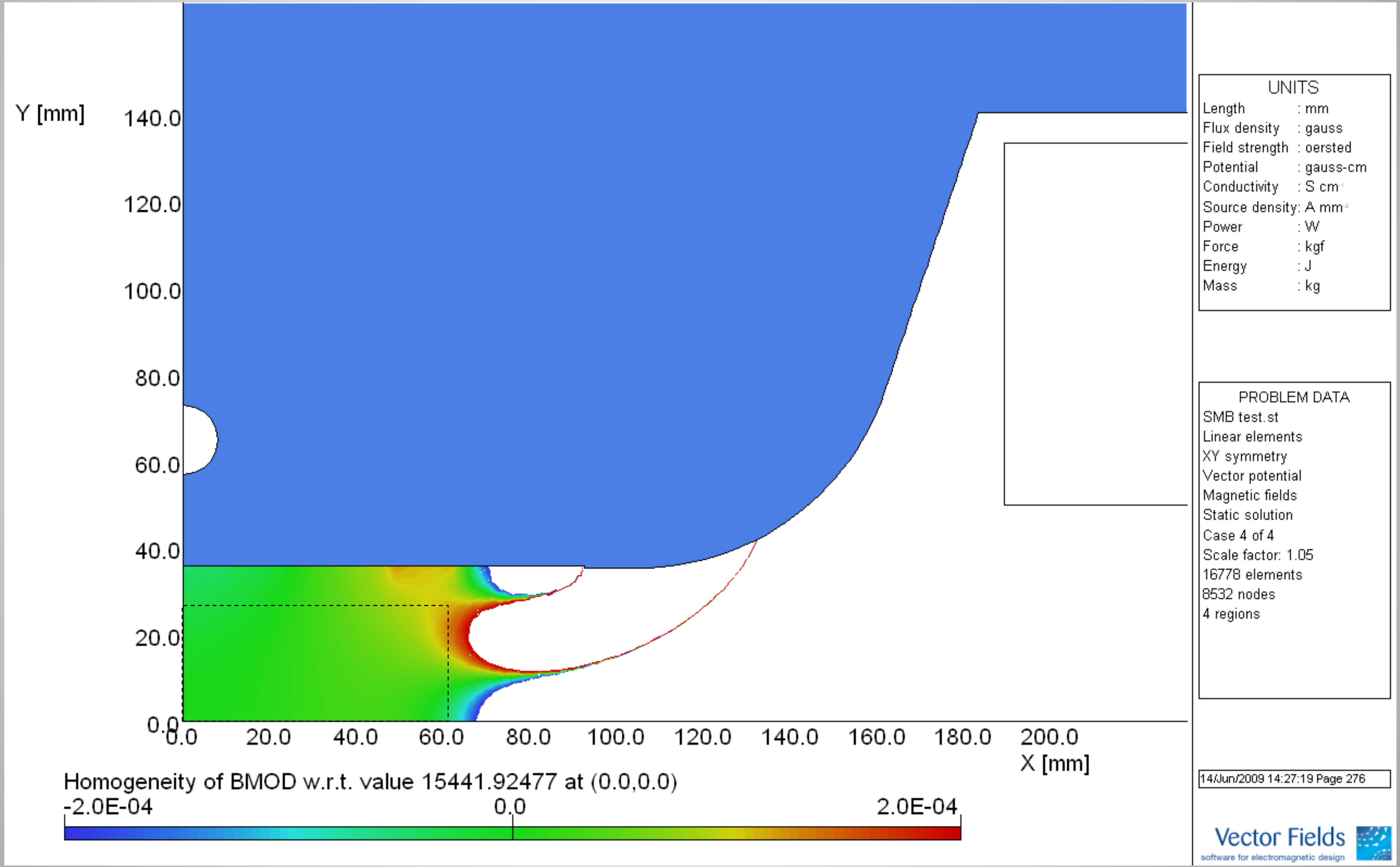
Vector Fields
software for electromagnetic design



Field homogeneity in a dipole



Homogeneity of BMOD w.r.t. value 15441.92477 at (0.0,0.0)

UNITS

Length	: mm
Flux density	: gauss
Field strength	: oersted
Potential	: gauss-cm
Conductivity	: S cm
Source density	: A mm
Power	: W
Force	: kgf
Energy	: J
Mass	: kg

PROBLEM DATA
SMB test.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 4 of 4
Scale factor: 1.05
16778 elements
8532 nodes
4 regions

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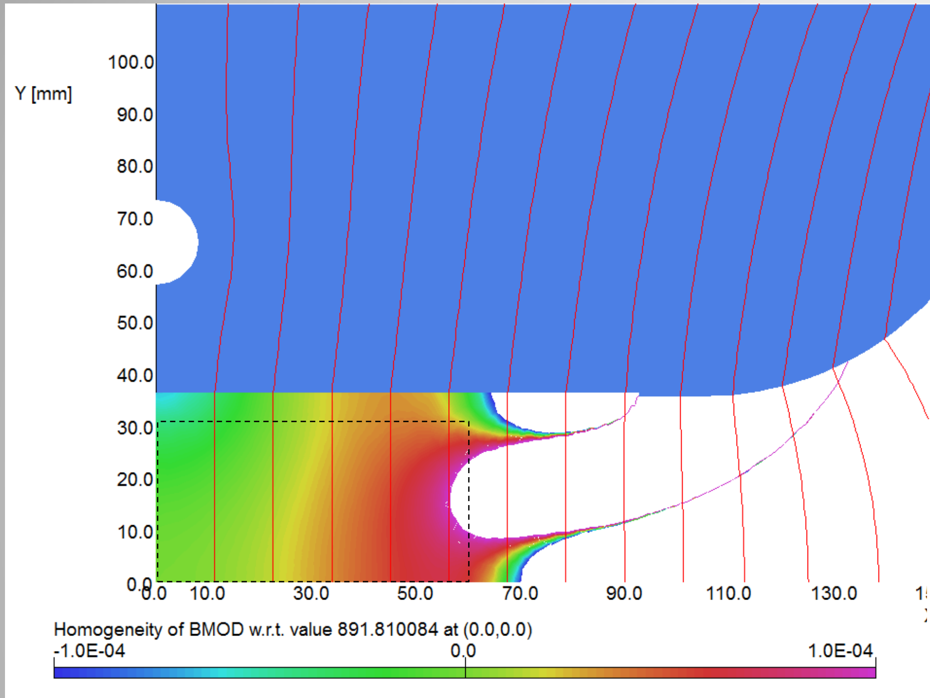
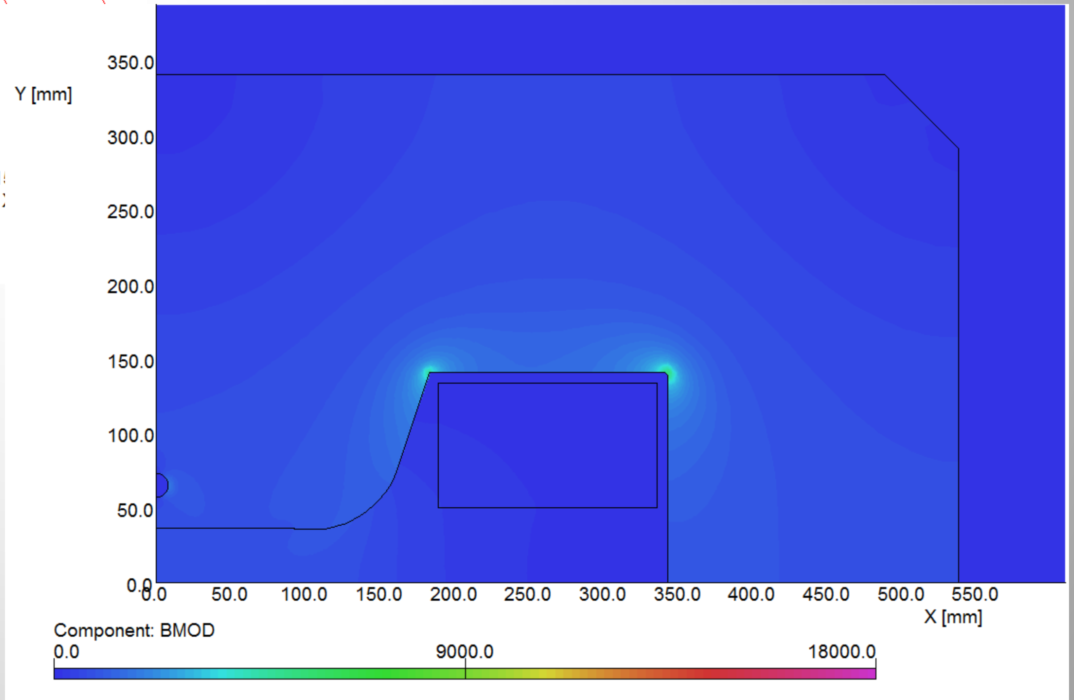
Saturation and field quality

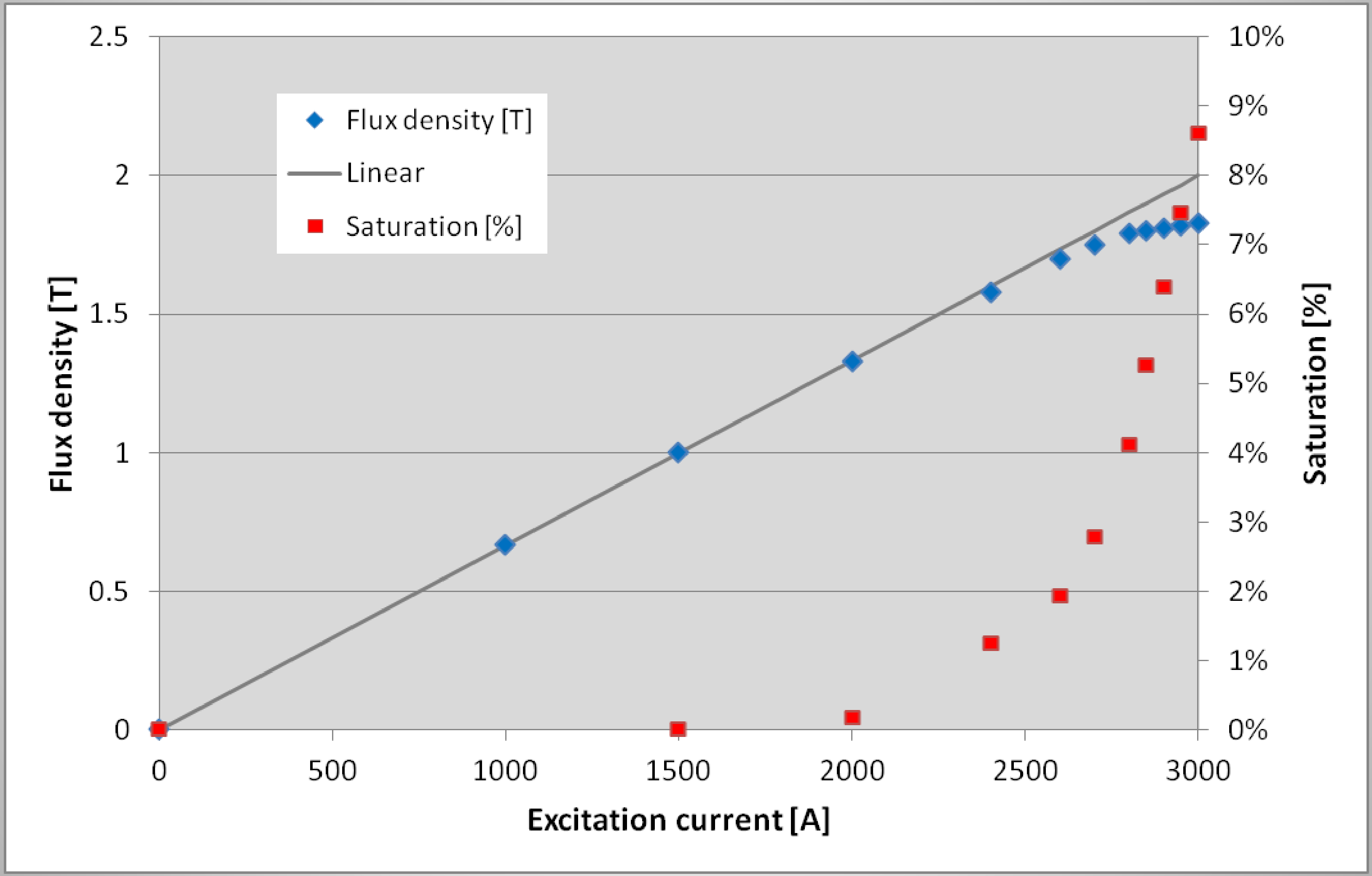


Field quality can vary with field strength due to saturation

Also very low fields can disturb the field quality significantly



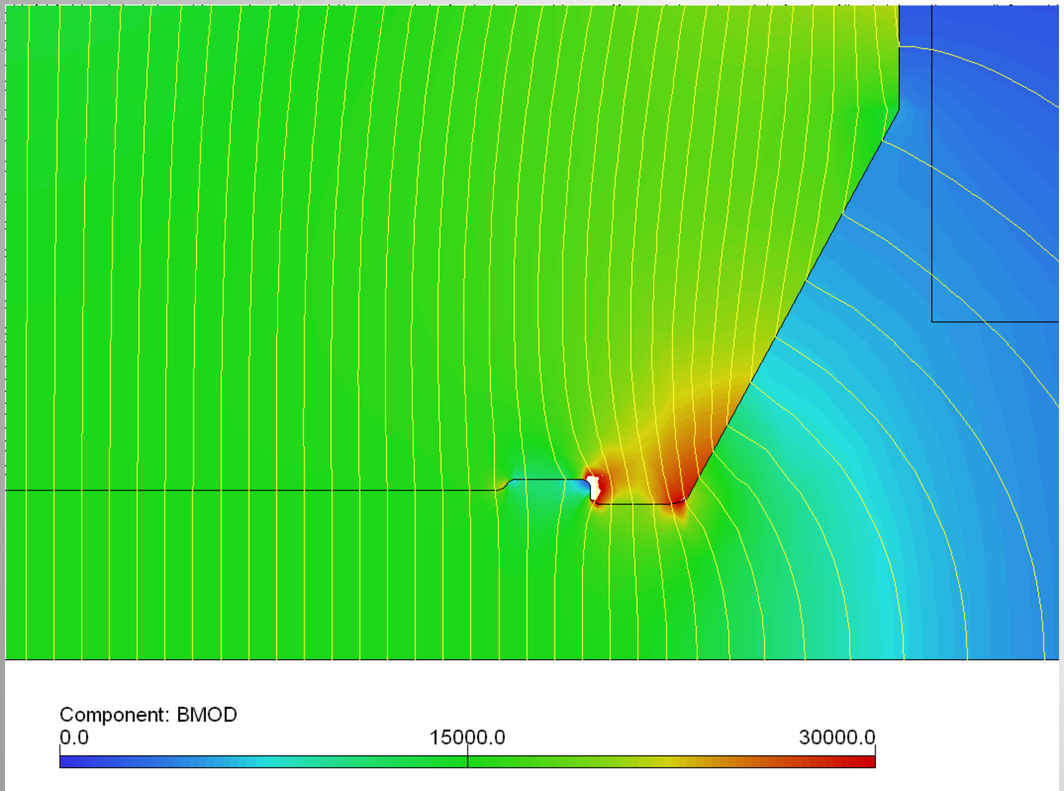
Saturation

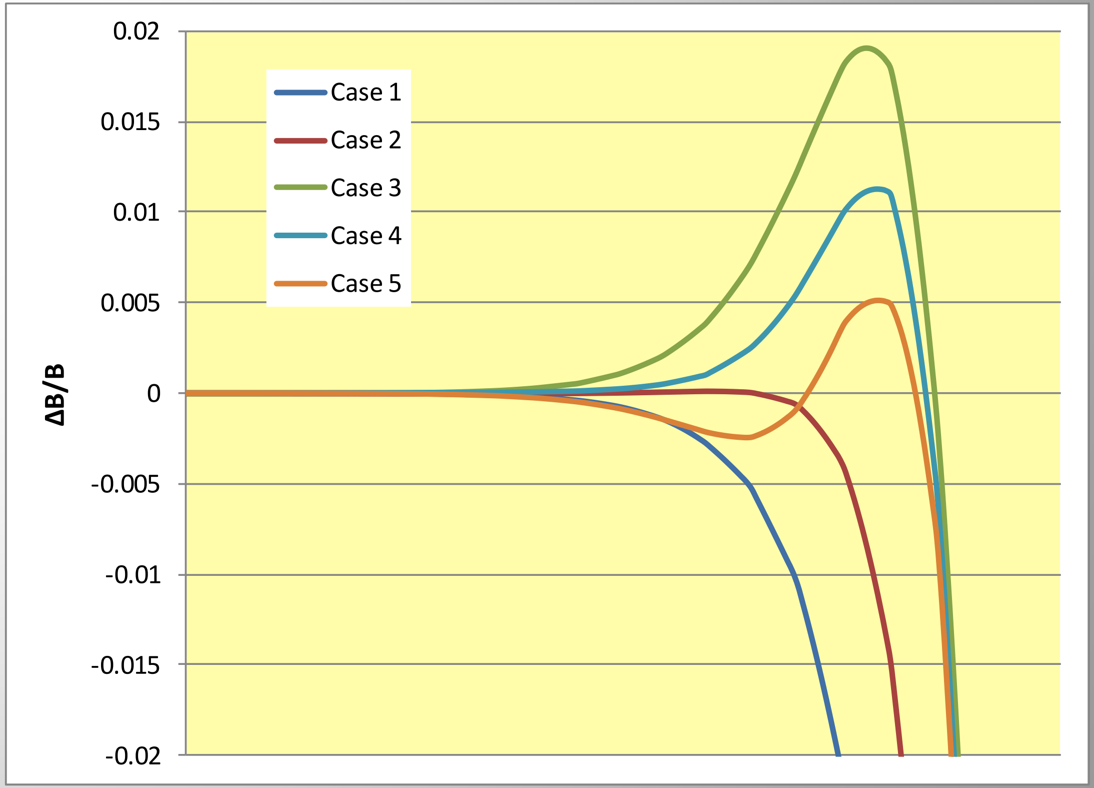

2.5
2
1.5
1
0.5
0
Flux density [T]
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
Saturation [%]
0
500
1000
1500
2000
2500
3000
Excitation current [A]
◆ Flux density [T]
— Linear
■ Saturation [%]

Pole optimization

‚Shimming‘ (often done by ‘try-and-error’) can improve the field homogeneity

1. Add material on the pole edges: field will rise and then fall
2. Remove some material: curve will flatten
3. Round off corners: takes away saturation peak on edges
4. Pole tapering: reduces pole root saturation

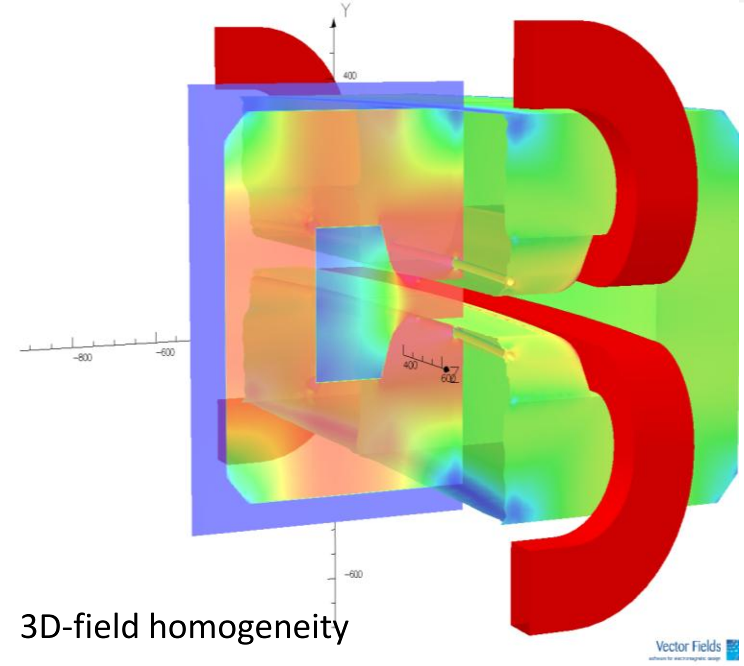




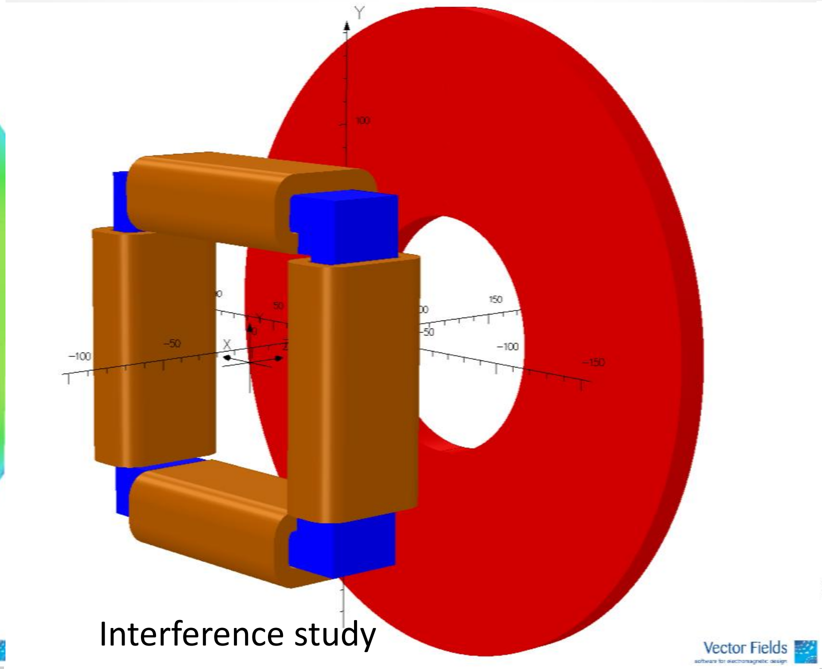
3D Design

Becomes necessary to study:

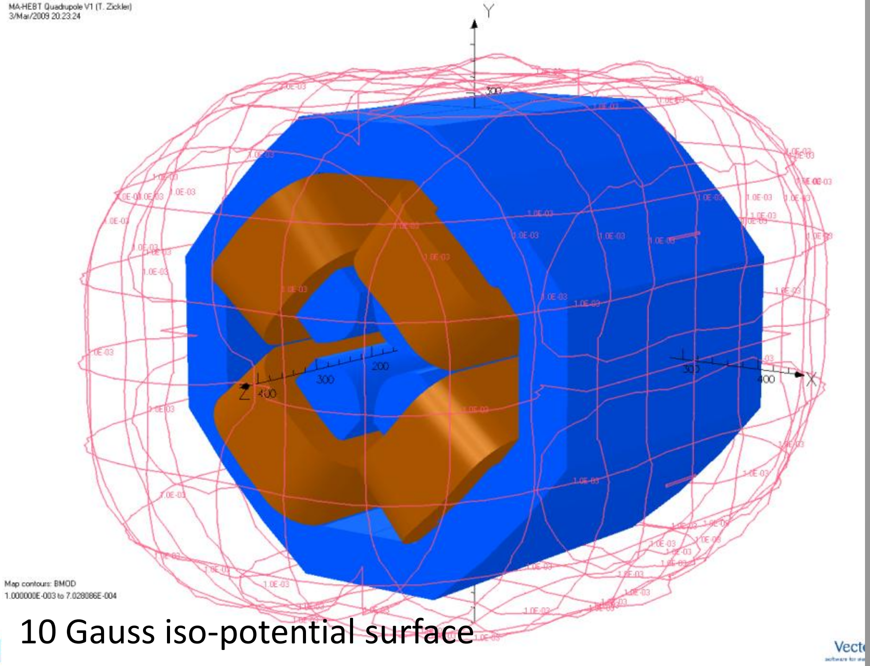
- the longitudinal field distribution
- end effects in the yoke
- end effects from coils
- magnets where the aperture is large compared to the length
- spacial field distribution
- particle motion in electro-magnetic fields



3D-field homogeneity

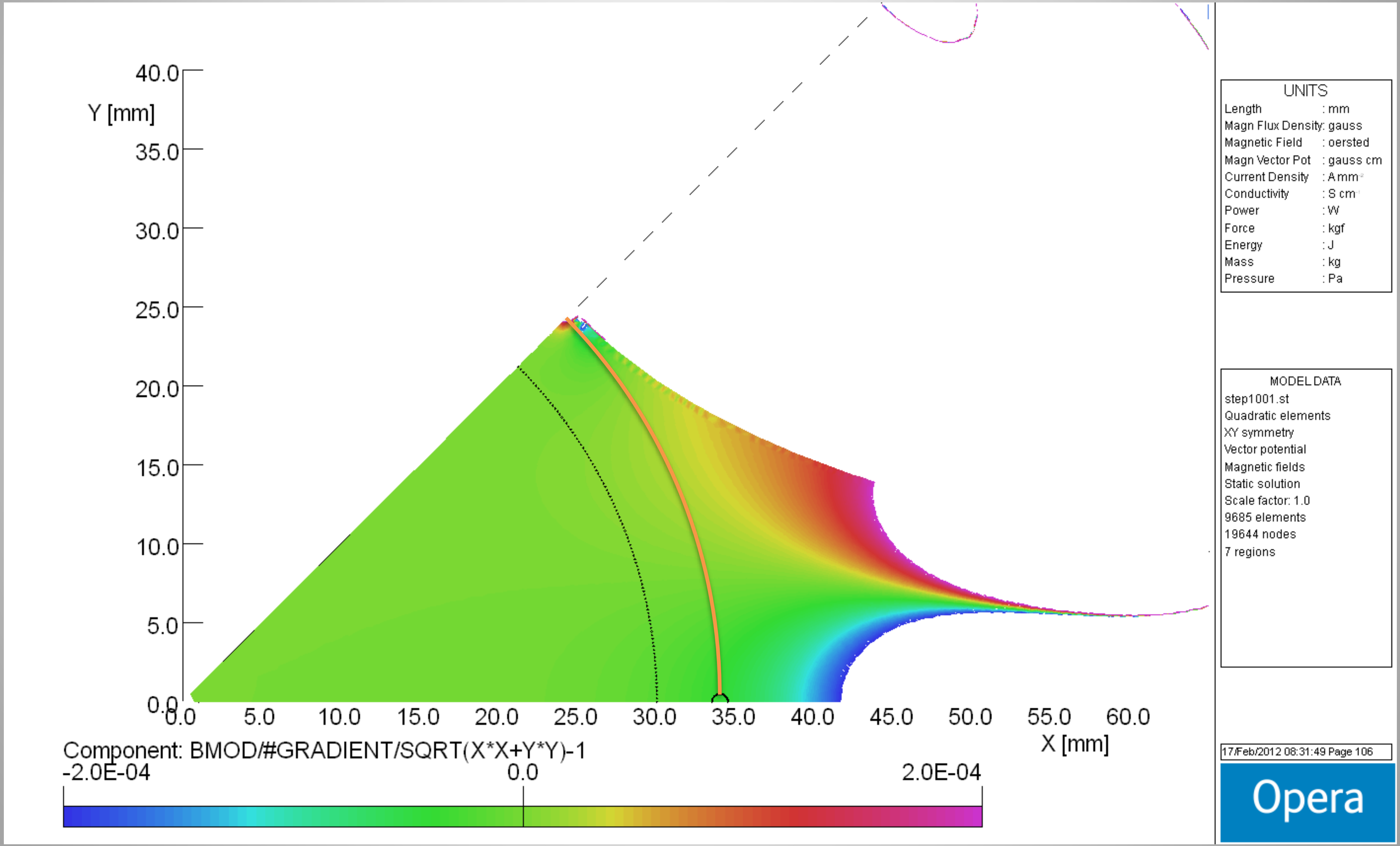


Interference study



10 Gauss iso-potential surface

Case 1: A material problem



UNITS
Length : mm
Magn Flux Density: gauss
Magnetic Field : oersted
Magn Vector Pot : gauss cm
Current Density : A mm^{-2}
Conductivity : S cm^{-1}
Power : W
Force : kgf
Energy : J
Mass : kg
Pressure : Pa

MODEL DATA
step1001.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor: 1.0
9685 elements
19644 nodes
7 regions

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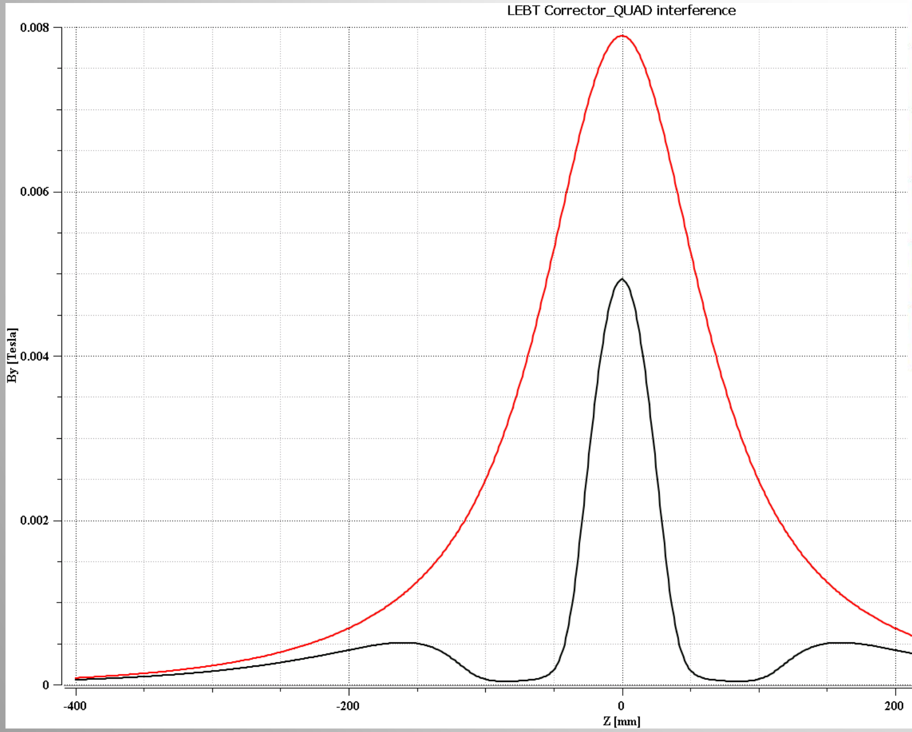
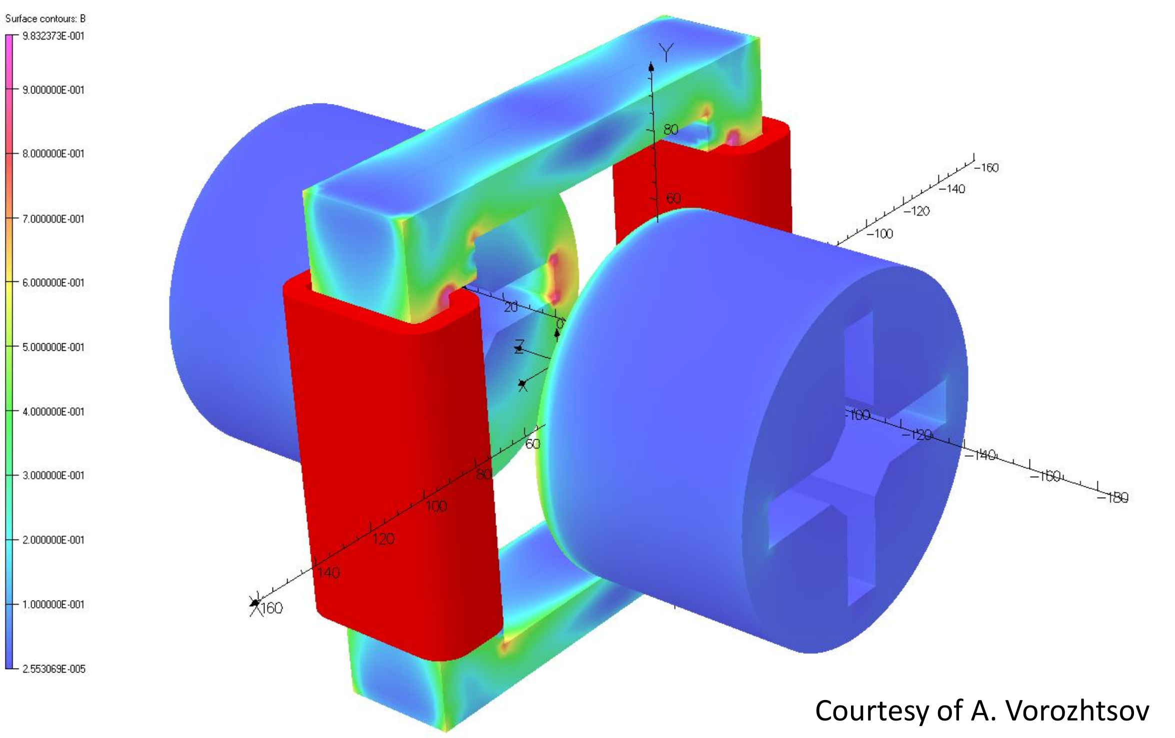
Case 2: An interference problem

Significant attenuation of the corrector field due to the close presence of two quadrupole yokes

Vertical field component B_y along the z-axis



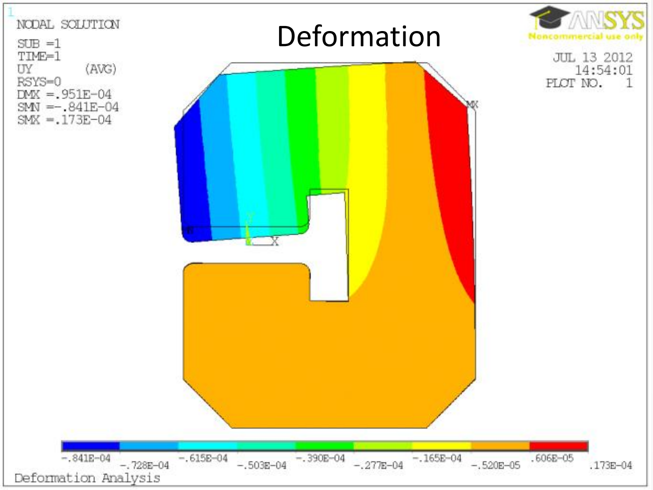


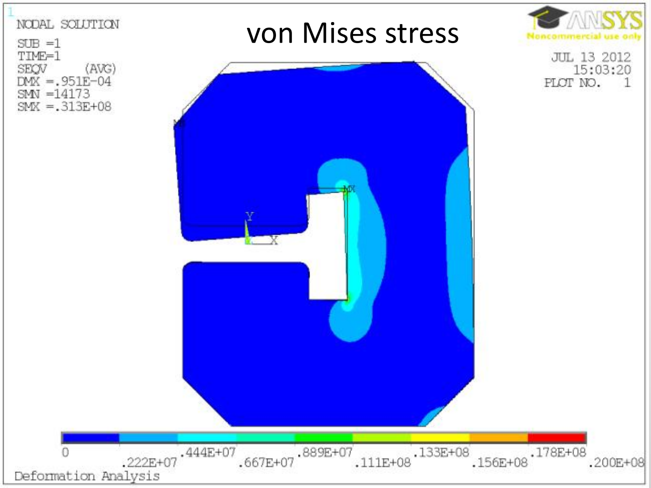
Courtesy of A. Vorozhtsov

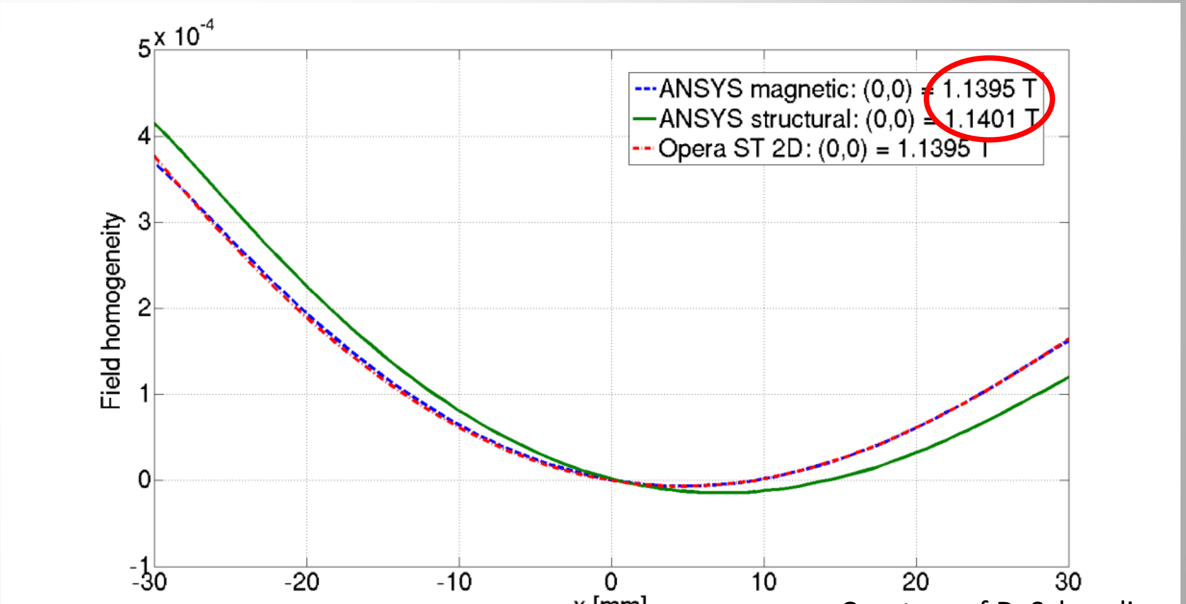
The attenuation of the corrector integrated field $\int B_y dz$ due to the presence of the quadrupole yokes is 71 %.

Case 3: Mechanical deformation

- Mechanical deformation due to magnetic pressure can influence the field homogeneity
- Multi-physics models can help to quantify the effect







Courtesy of D. Schoerling

Field homogeneity calculated for the center line of the magnet with ANSYS magnetic, ANSYS structural + magnetic, and Opera ST 2D

Limitations of numerial calculation

Advantages

- predict behaviour without having the physical object
- for relatively simple cases they are fast and inexpensive

Limitations

- **multi-physics model**: including all couplings (thermal, mechanical) and phenomena (magnetostriction, magneto-resistivity …) that *may* be relevant is very complex and expensive
- **off-nominal geometry**: random assembly errors can dominate field distribution and quality; often, a large number of degrees-of-freedom and the resulting combinatorial explosion makes Monte Carlo prediction costly
- **material properties uncertainty :** inhomogeneous properties cannot practically be measured throughout volume; even homogeneous materials can be measured only within 2-5% typical accuracy
- **numerical errors**: e.g. singularities in re-entrant corners, boundary location of open regions may spoil results; special techniques (special corner elements, BEM) require special skills and time
- **high cost** of detailed 3D models ($\propto \Delta x^{2\sim3}$); transient simulations increase computing time significantly

Computer simulation targeting <10^{-4} accuracy are difficult and expensive

Summary

- A large varity of FE-codes with different features exist – the right choice depends of the complexity of the problem
- The FE-models shall be as simple as possible and adapted to the problem to reduce computing time
- Numeric computations should be used to quantify, not to qualify
- Benchmarking the results with measurements is a good practice
- Computer simulations have a lot of advantages, but also their limitations

Homework - Practical example

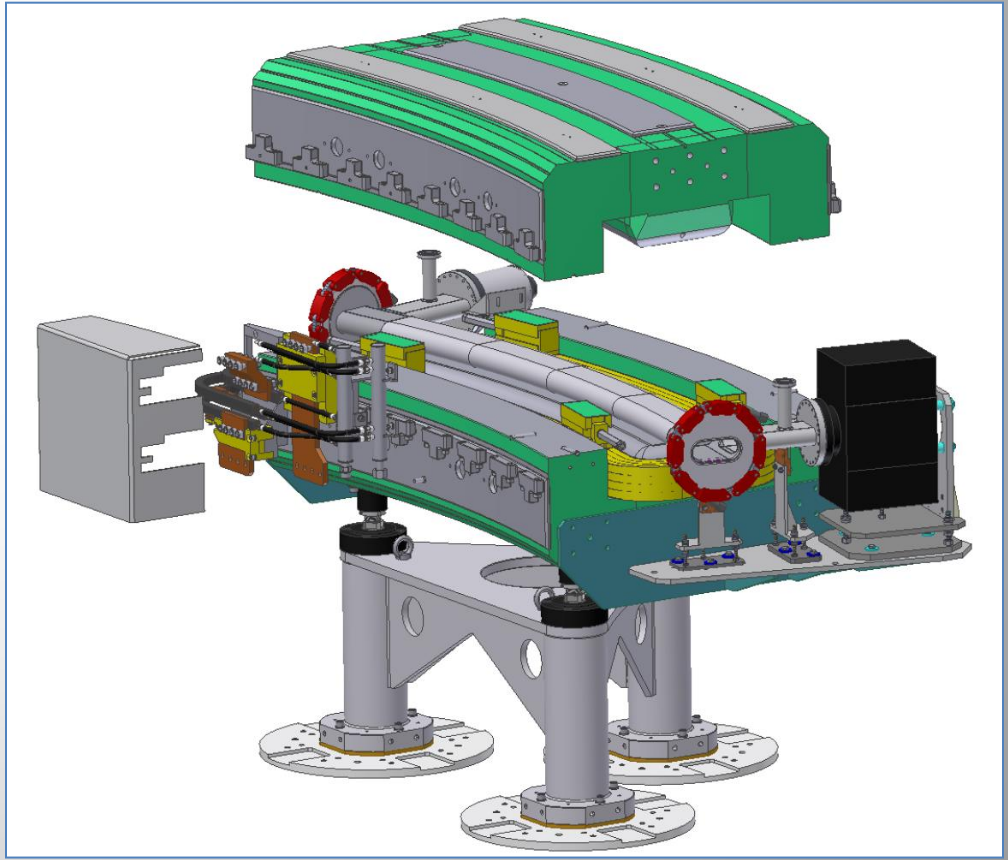
MedAustron: ion therapy facility near Vienna/Austria

ebg *Med*Austron

Providing beam energies from 120 to 400 MeV/u for carbon ions (C^{6+}) and from 60 to 220 MeV for protons

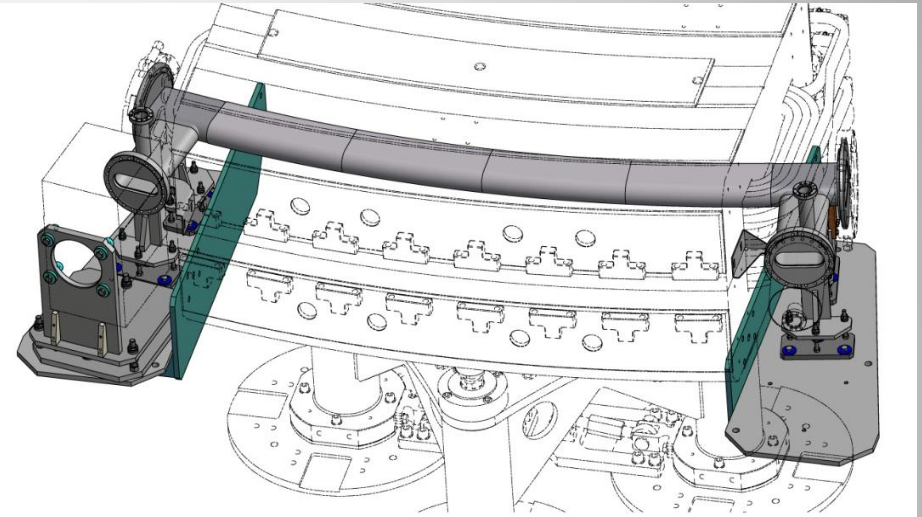
16 synchrotron bending magnets:

- Bending angle: 22.5°
- Bending radius: 4.231 m
- Field ramp rate: 3.75 T/s
- Max. current*: 3000 A
- Overall length: < 2 m
- Field quality: $\frac{\Delta \int B \cdot dl}{\int B \cdot dl} = 2 \cdot 10^{-4}$



*) which can be delivered from the power converter

Homework - Practical example

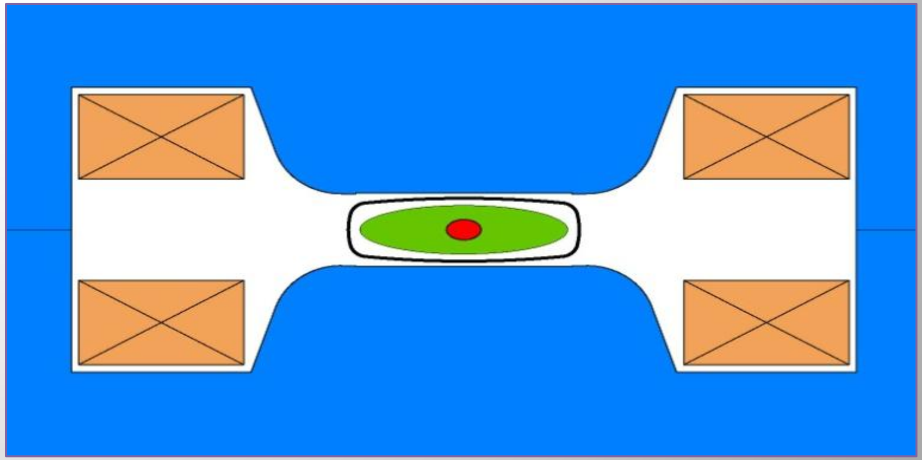


Magnet aperture:

Horizontal GFR: ±60 mm

Vertical GFR: ±28 mm

Vacuum chamber thickness: 5 mm



Requested:

Max. required B = ?

Required Ampere-turns NI = ?

Excitation current I = ?

Number of turns N (per pole) = ?

Thanks for your attention…

… and see you again at the case study