Joint Universities Accelerator School

JUAS 2020

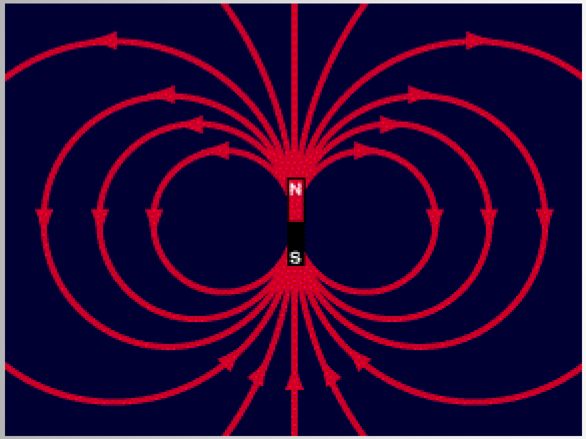
Archamps, France, 2. – 4. March 2020

Normal-conducting accelerator magnets
Lecture 4: Applied numerical design

Thomas Zickler

CERN

Lecture 4: Numerical design



Which code shall I use?

Introduction to 2D numerical design

How to evaluate the results

Field analysis

Typical application examples

Numerical design

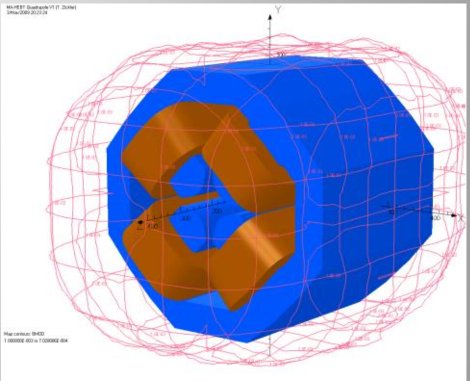
Common computer codes: Opera (2D) or Tosca (3D), Poisson, ANSYS, Roxie, Magnus, Magnet, Mermaid, Radia, FEMM, COMSOL, etc…

Technique is iterative

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

Computing time increases 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:

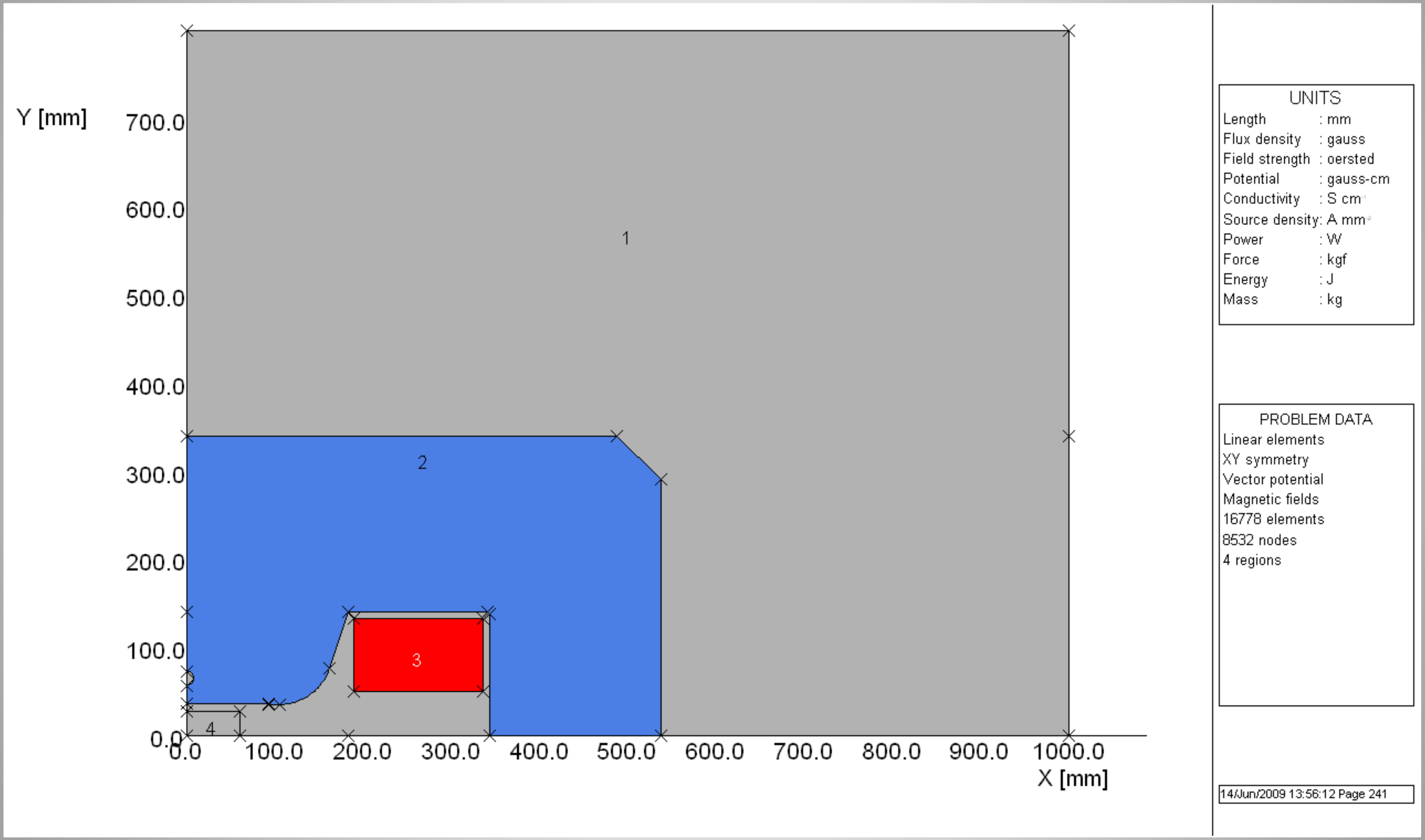
- Always check results if they are 'physical reasonable'
- Use FEM for quantifying, not to qualify

Numerical design process

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

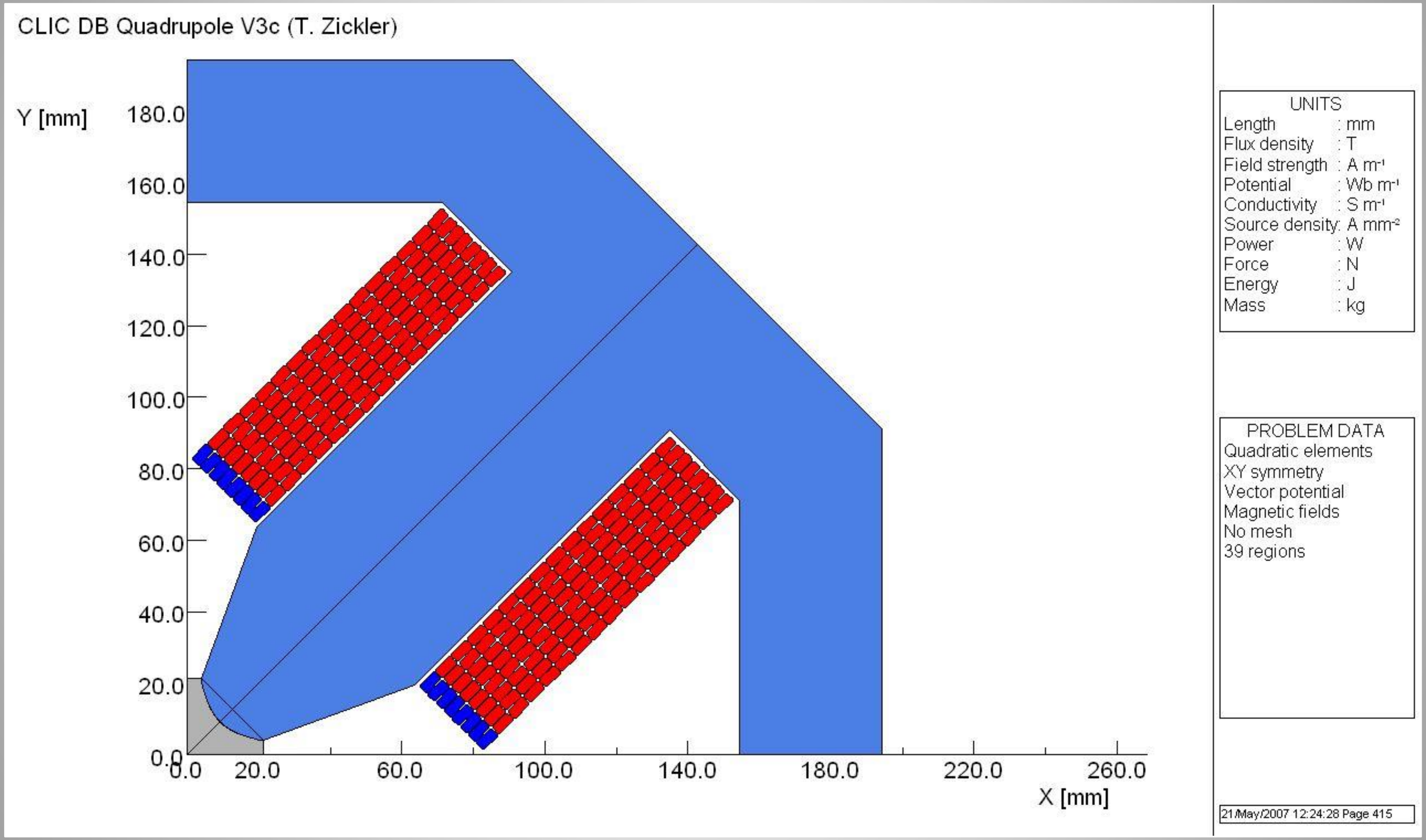
- Create the model (pre-processor or modeller)
- Define boundary conditions, set material properties
- Calculations (solver)
- Visualize and asses the results (post-processor)
- Optimization by adjusting the geometry (manually or optimization code)

Creating the model



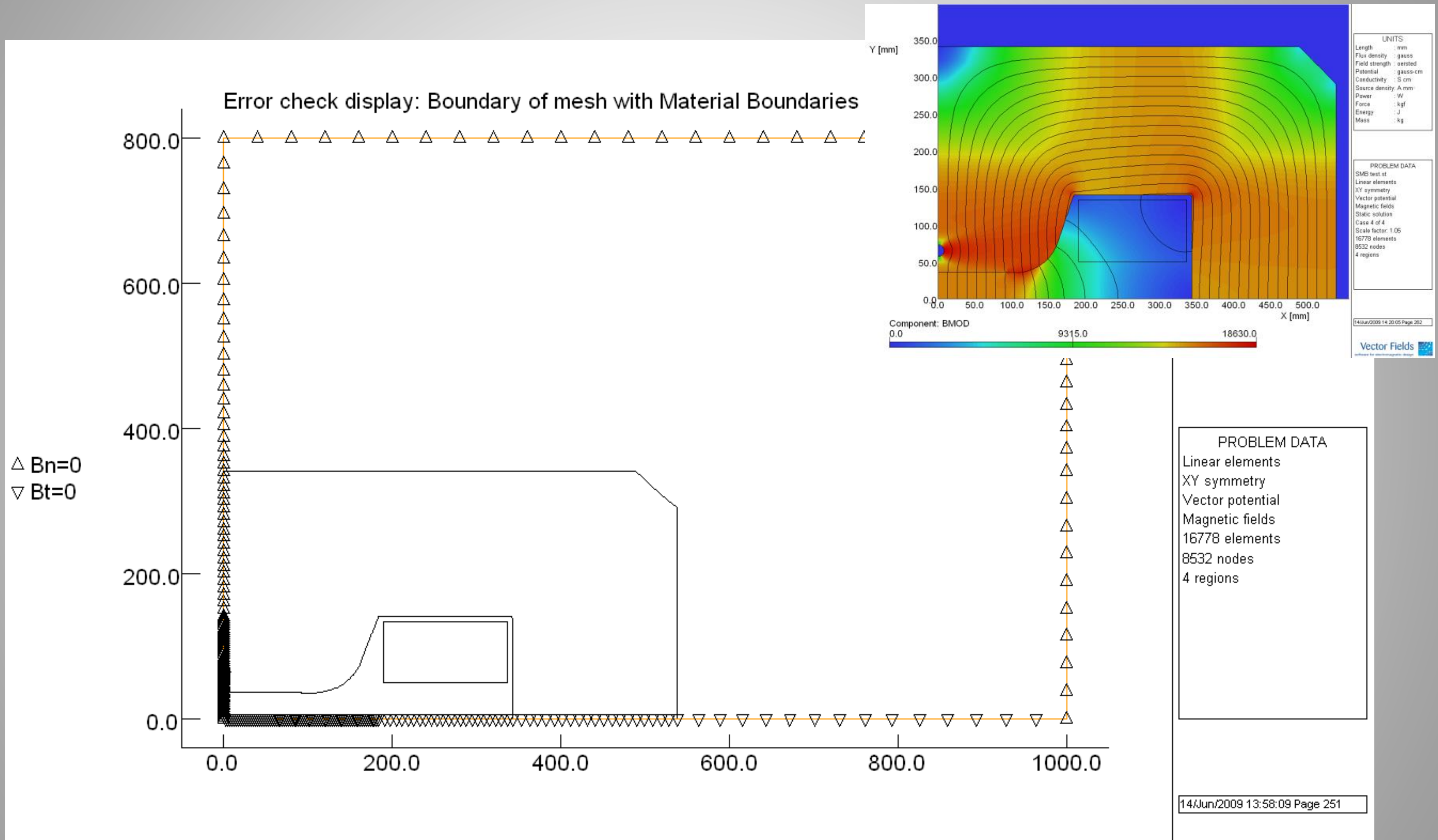
GUI vs. Script

Model symmetries

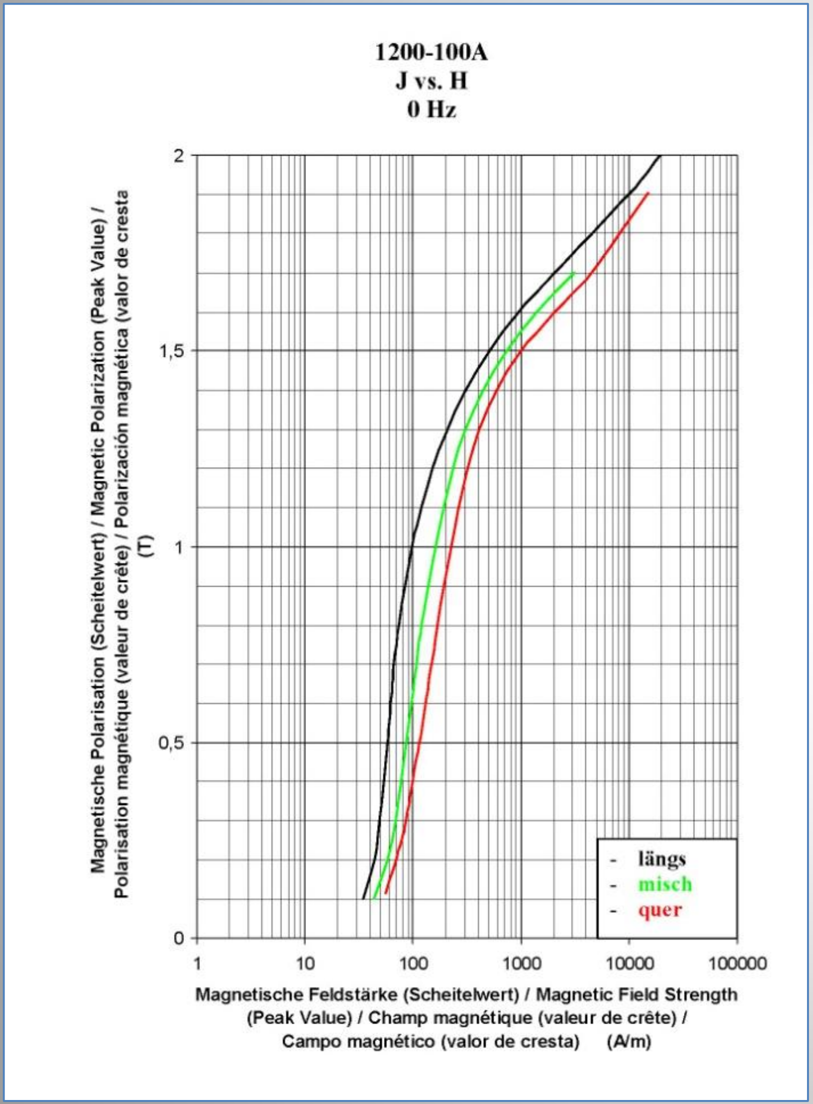


Note: one eighth of quadrupole could be used with opposite symmetries defined on horizontal and y = x axis

Boundary conditions



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

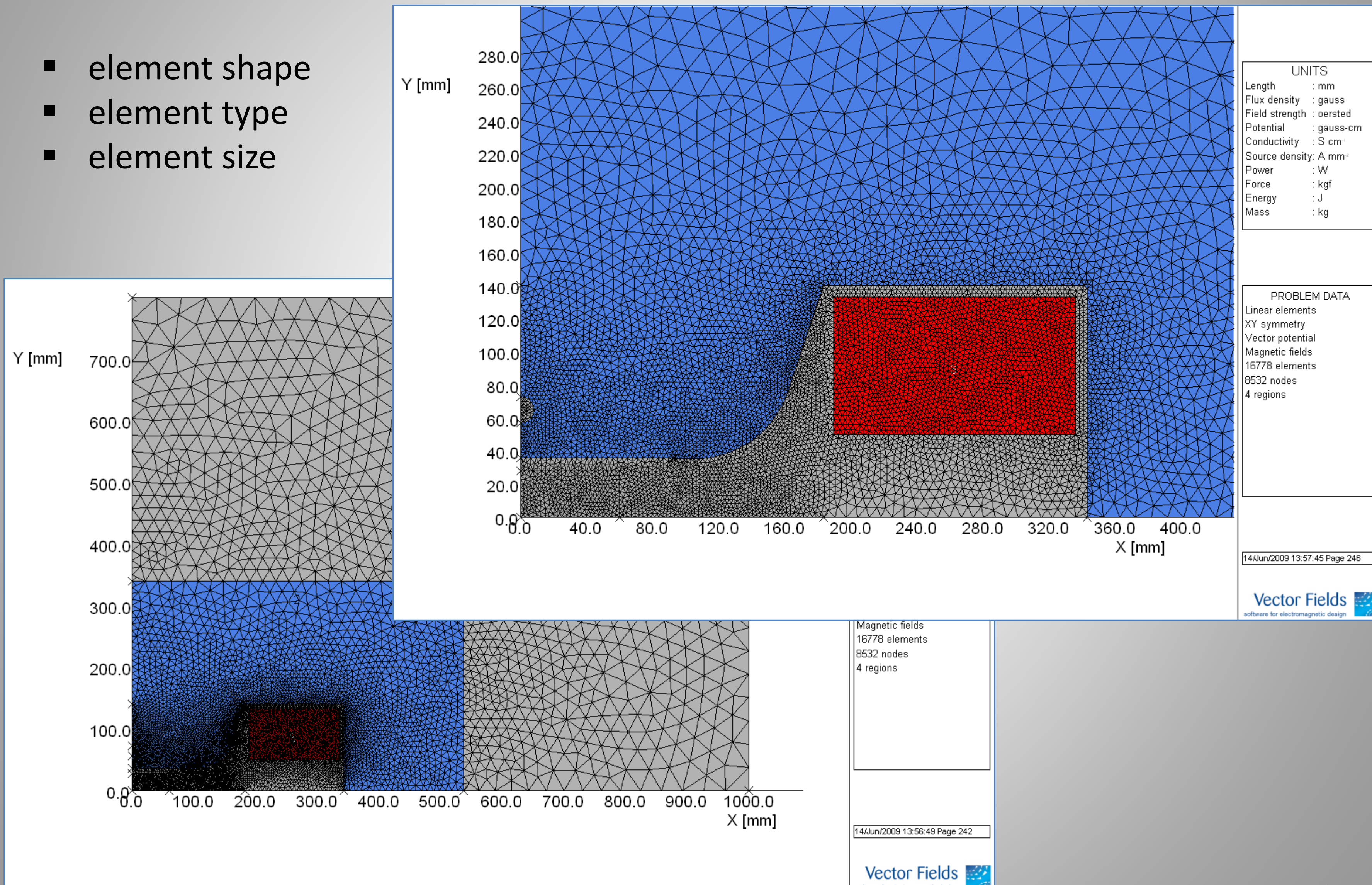
Mechanical and thermal properties:

- in case of combined structural or thermal analysis

Current density in the coils

Mesh generation

- element shape
- element type
- element size



Data processing

Solution

- linear: predefined constant permeability for a single calculation
- non-linear: permeability table for iterative calculations

Solver types

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

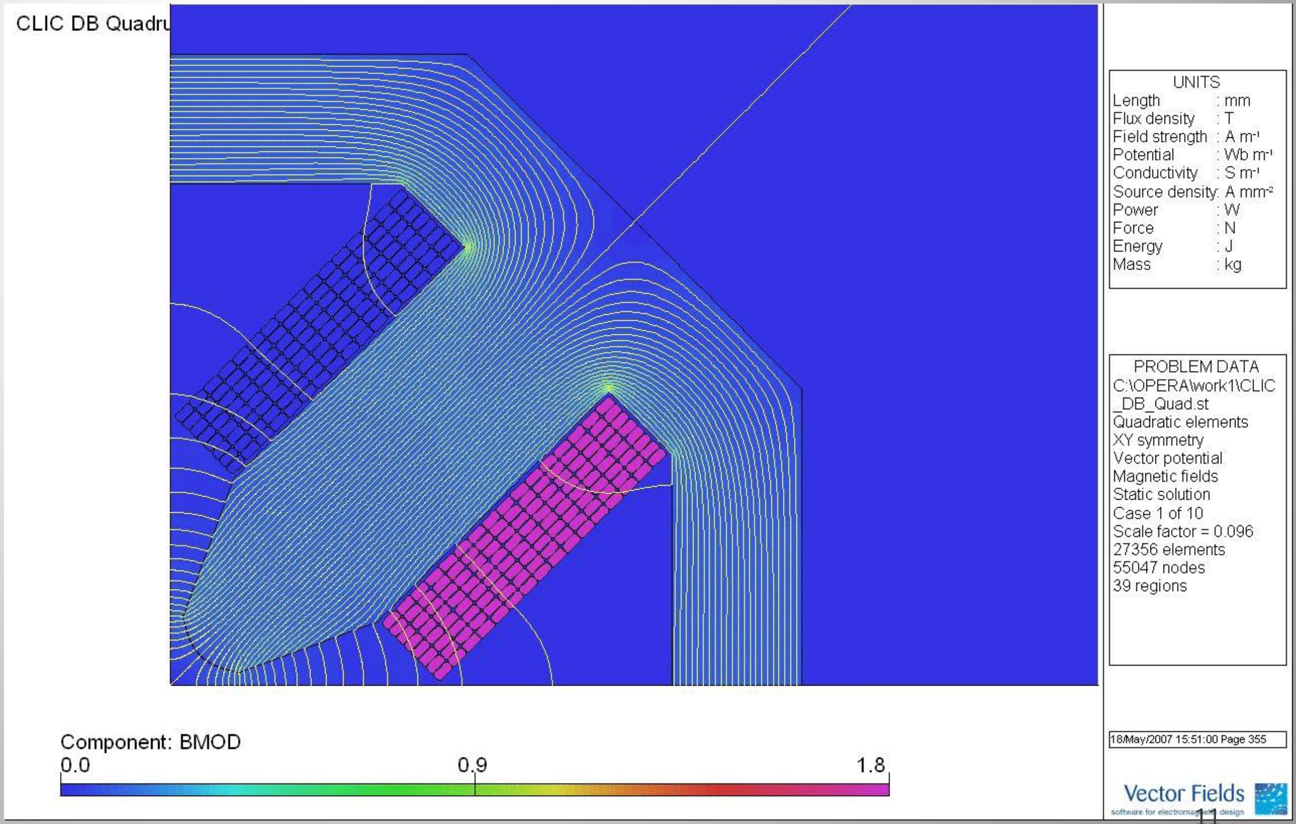
Solver settings

- 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 and be visualized in various forms on the pre-processor model:

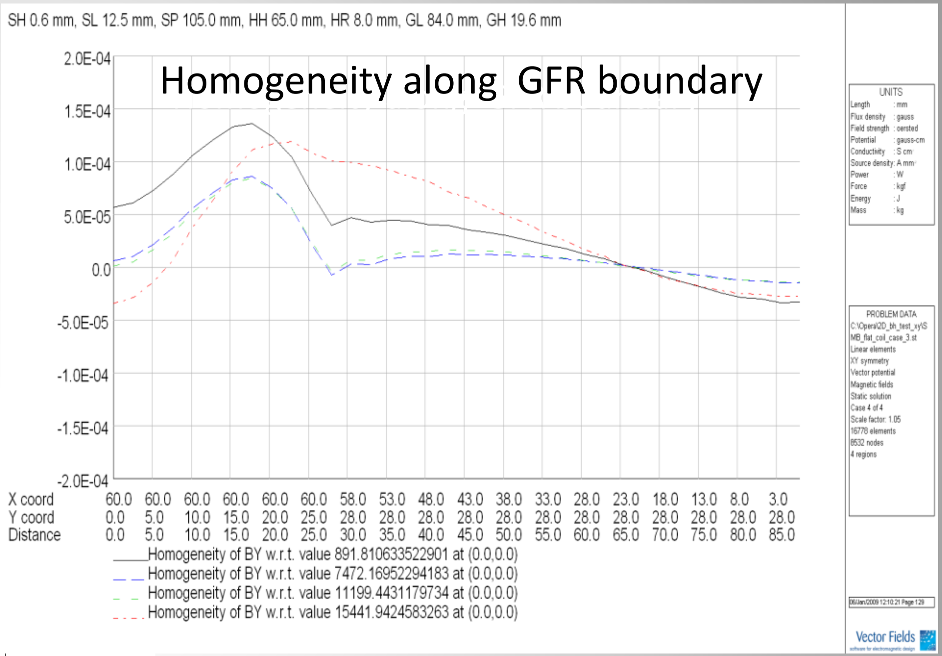
– Field lines and colour contours plots of flux, field, and current density
– Graphs showing absolute or relative field distribution
– Homogeneity plots

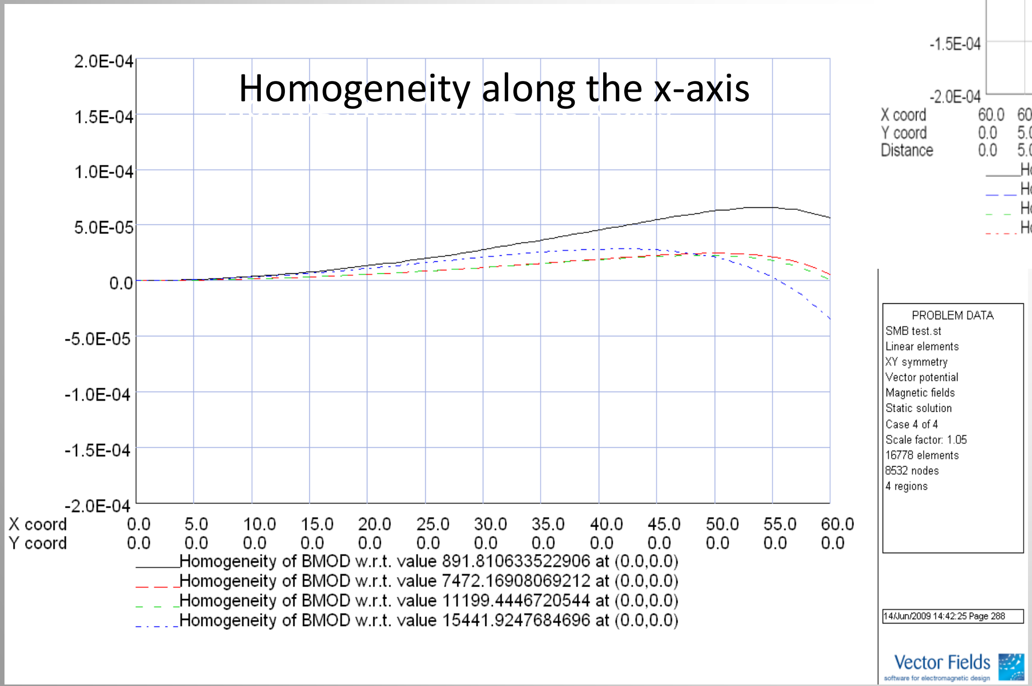


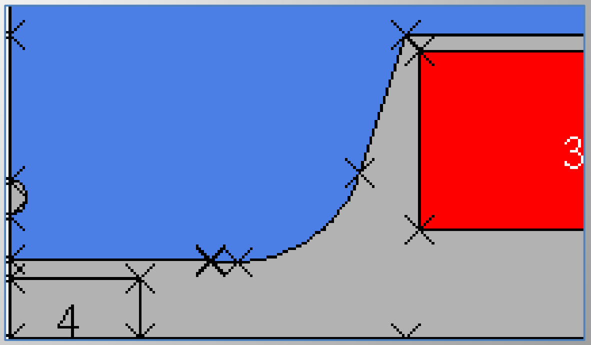
Field homogeneity in a dipole

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

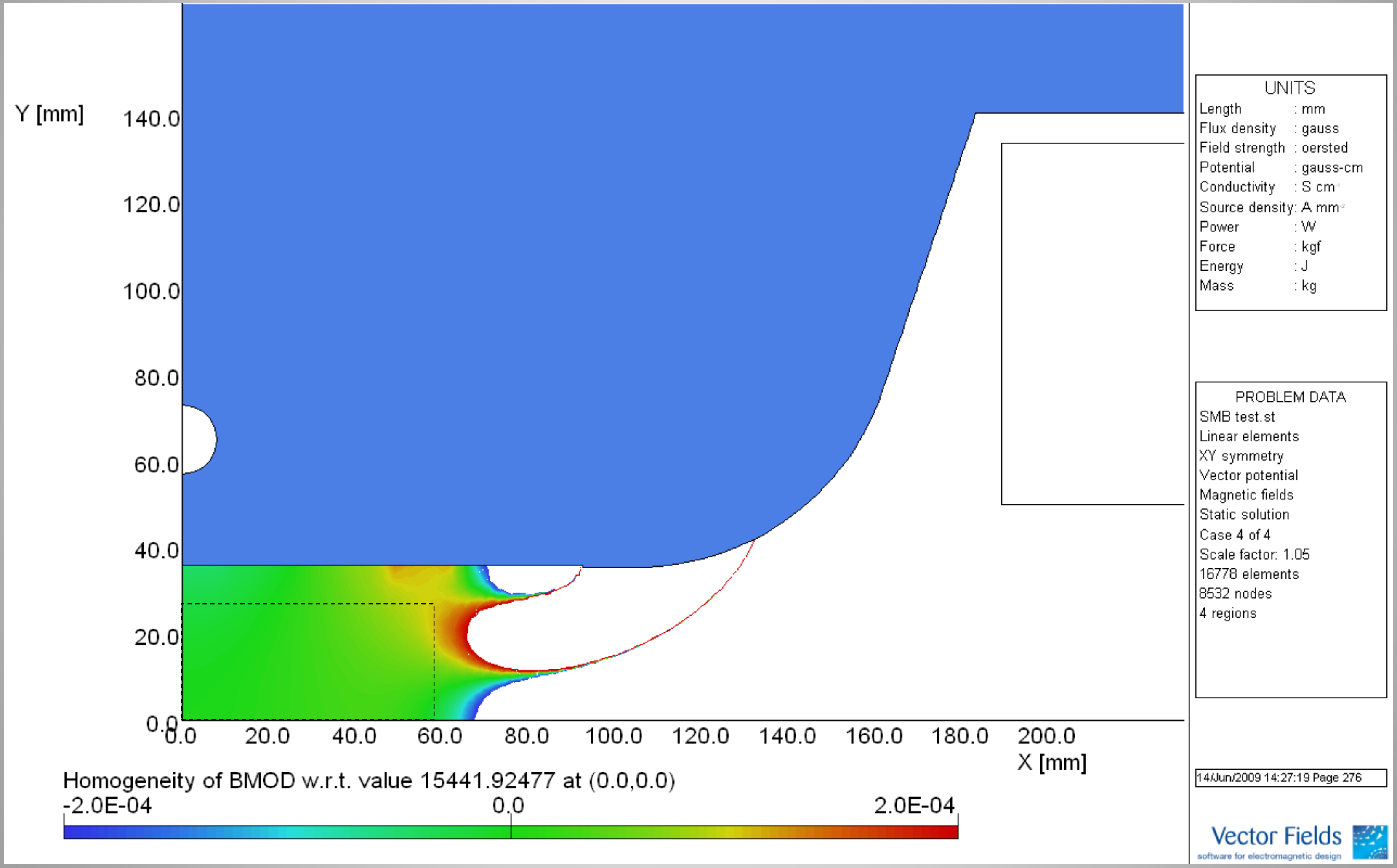
$$\frac{\Delta B}{B_0} = \frac{B_y(x,y)}{B_y(0,0)} - 1 \qquad \frac{\Delta B}{B_0} \leq 0.01\%$$



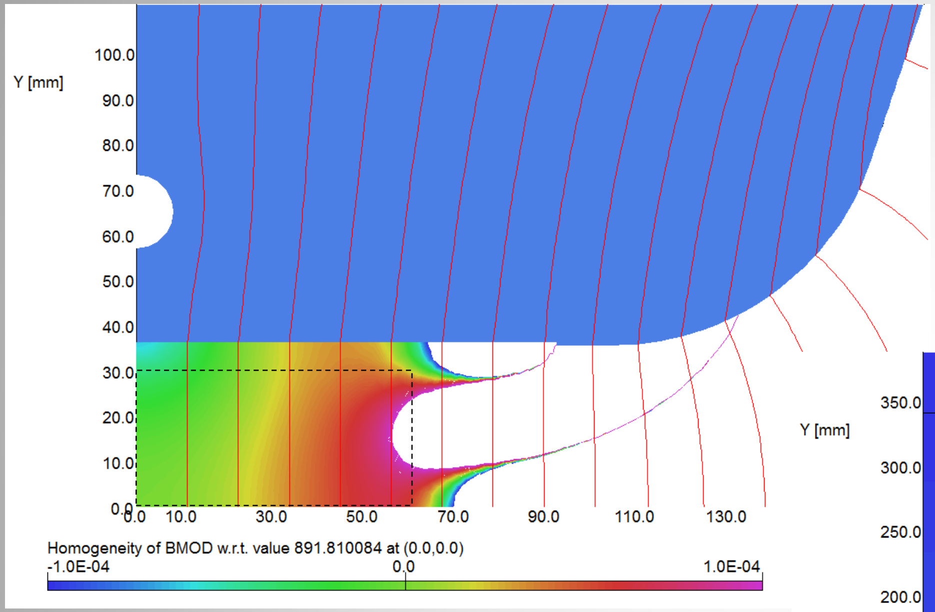




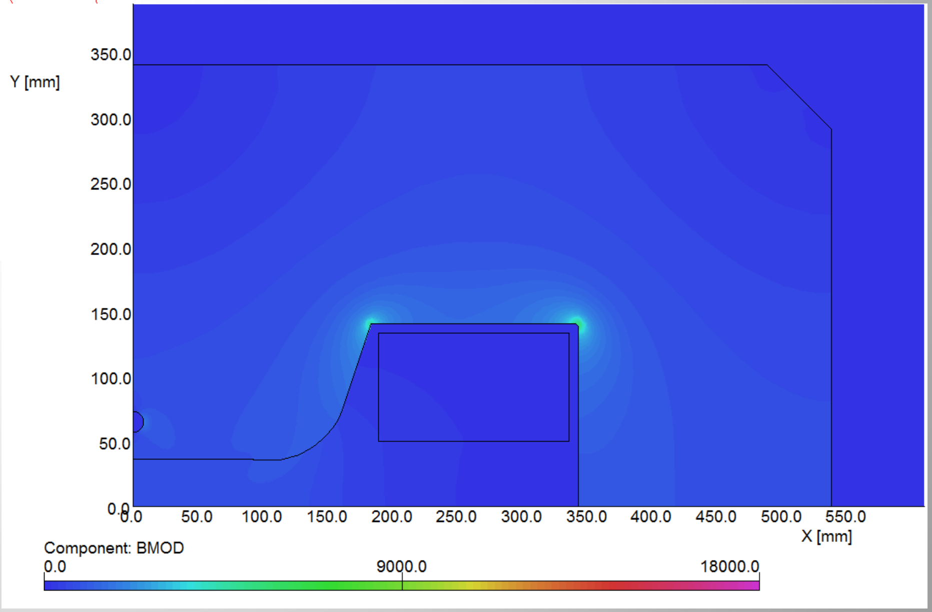
Field homogeneity in a dipole



Saturation and field quality

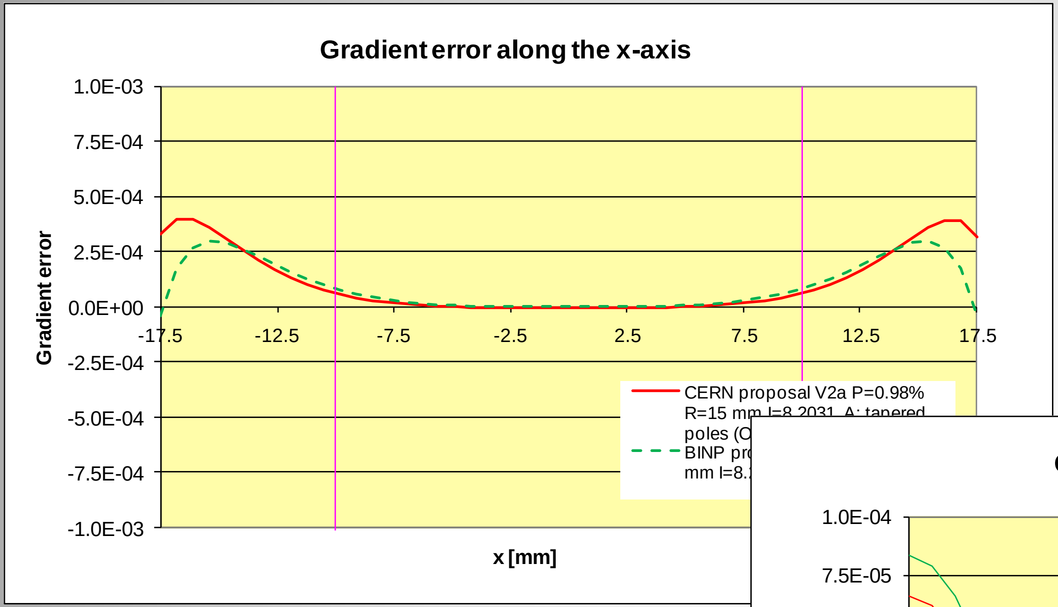


Also very low fields can disturb the field quality significantly



Field quality can vary with field strength due to saturation

Field quality in a quadrupole

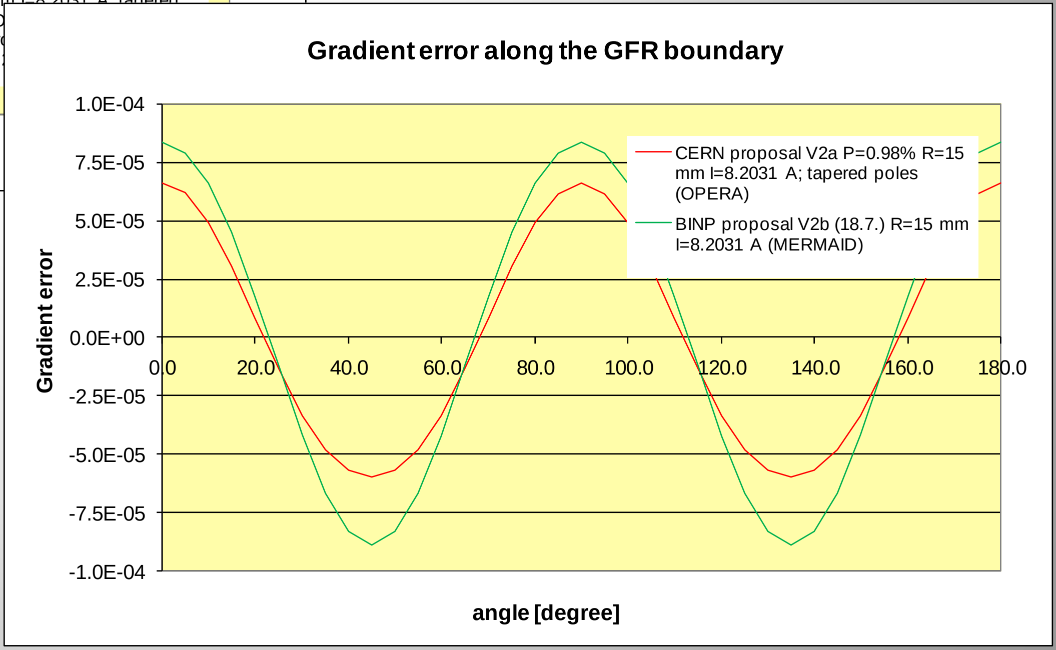


Gradient homogeneity along the x-axis

$$\frac{\Delta B'}{B'_0} = \frac{B'(x,y)}{B'(0,0)} - 1 \qquad \frac{\Delta B'}{B'_0} \leq 0.1\%$$

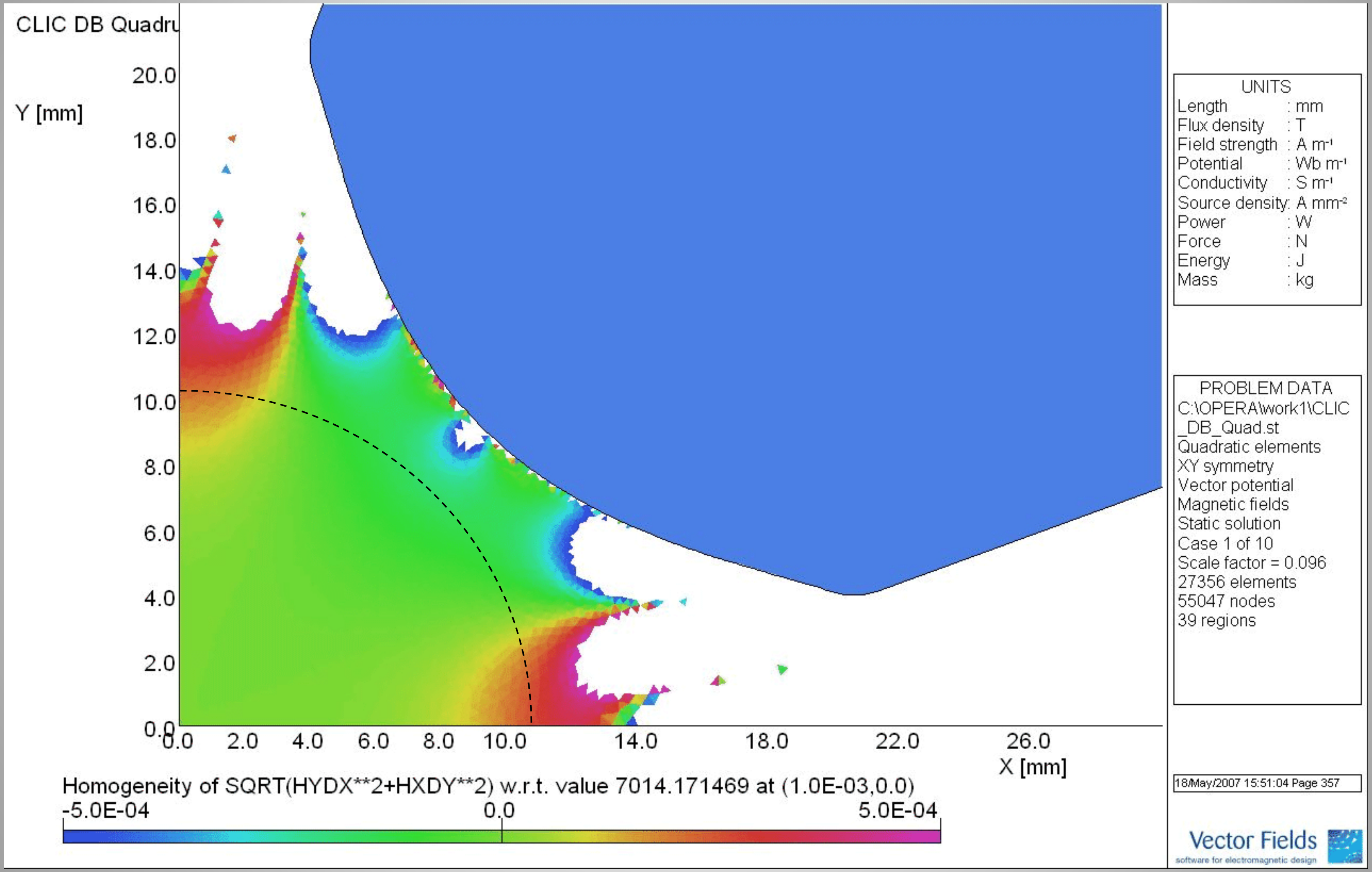
Field error in a quadrupole

$$\varepsilon = \frac{B\,(x,y)}{B'(0,0)\sqrt{x^2+y^2}} - 1$$



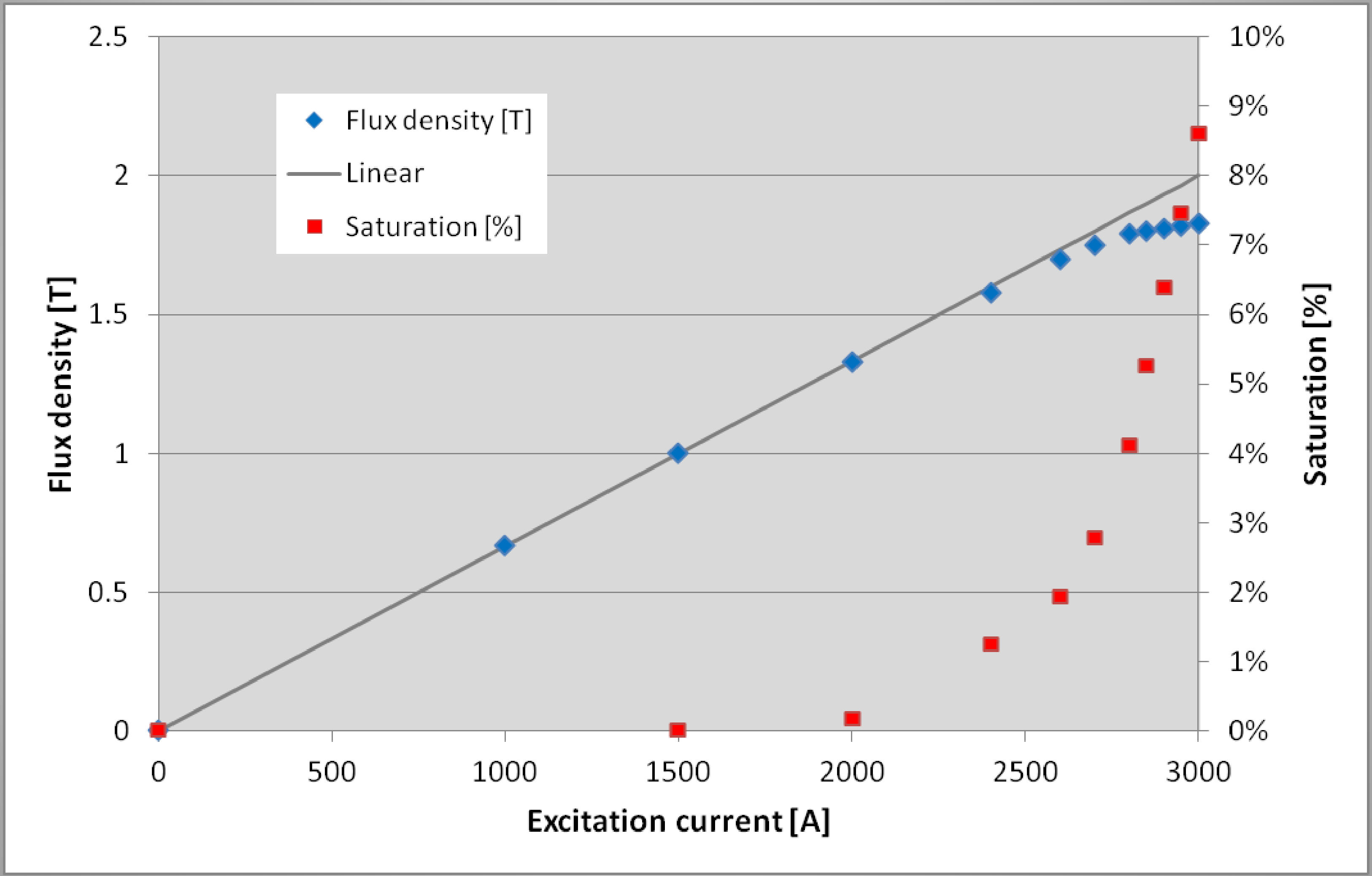
Gradient homogeneity along circular GFR

Saturation and field quality



Field quality varies with field strength due to saturation

Saturation


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

Field analysis

Picking up from lecture 1

$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R_{ref}} \right)^{n-1}$$

and introducing dimensionless normalized multipole coefficients

$$b_n = \frac{B_\mathrm{n}}{B_\mathrm{N}} 10^4 \quad \text{and} \quad a_n = \frac{A_n}{B_\mathrm{N}} 10^4$$

with B_N being the fundamental field of a magnet: $B_{\mathrm{N\ (dipole)}} = B_1$; $B_{\mathrm{N\ (quad)}} = B_2$; ...

we can describe each magnet by its ideal fundamental field and higher order harmonic distortions:

$$B_y(z) + iB_x(z) = \underbrace{\frac{B_N}{10^4}}_{\text{Fundamental field}} \underbrace{\sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{z}{R_{ref}} \right)^{n-1}}_{\text{Harmonic distortions}}$$

Field analysis

The field quality of a magnet can be also described by:

- Homogeneity plot:
  - difference between the actual field B and the ideal field B_{id}, normalized by the ideal field B_{id}

$$\frac{\Delta B}{B} = \frac{B(x,y) - B_{id}(x,y)}{B_{id}(x,y)}$$

  - can be expressed by multipole coefficients: for a dipole with $B_{y,id}(x) = B_1$

$$B_y(x) = B_1 + \frac{B_1}{10^4}\left[b_2\left(\frac{x}{R_{ref}}\right) + b_3\left(\frac{x}{R_{ref}}\right)^2 + b_4\left(\frac{x}{R_{ref}}\right)^3 + \cdots\right]$$

$$\frac{\Delta B}{B}(x) = \frac{1}{10^4}\left[b_2\left(\frac{x}{R_{ref}}\right) + b_3\left(\frac{x}{R_{ref}}\right)^2 + b_4\left(\frac{x}{R_{ref}}\right)^3 + \cdots\right]$$

- Harmonic distortion factor F_{d} :

$$F_d(R_{\mathrm{Re}f}) = \sum_{n=1;n\neq N}^{K} \sqrt{b_n^2(R_{ref}) + a_n^2(R_{\mathrm{Re}f})}$$

Note: For good field quality, F_{d} should be a few units in 10^{-4}

Field analysis

Multipole errors can be divided into two families:

‚Allowed' multipoles are design intrinsic and result from the finite size of the poles

$$n = N(2m+1)$$

n: order of multipole component

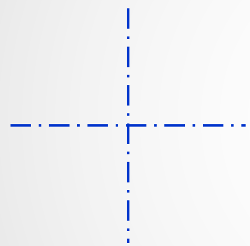
N: order of the fundamental field

m: integer number (m≥1)

<u>fully symmetric dipole</u>

allowed: b_3, b_5, b_7, b_9, etc.

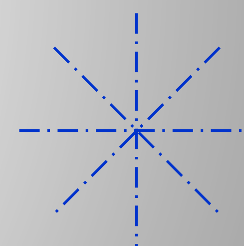
non-allowed: all others



<u>fully symmetric quadrupole</u>

allowed: b_6, b_{10}, b_{14}, b_{18}, etc.

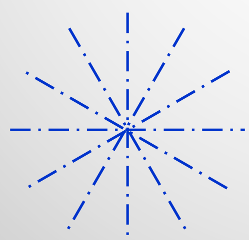
non-allowed: all others



<u>fully symmetric sextupole</u>

allowed: b_9, b_{15}, b_{21}, etc.

non-allowed: all others

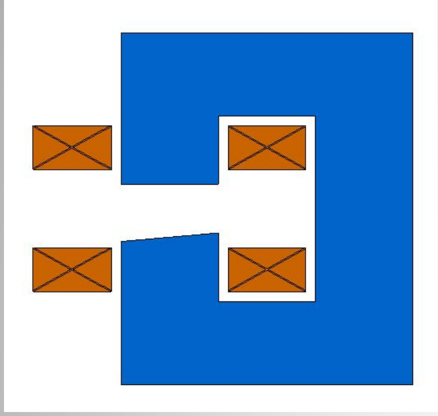


‚Non-allowed' multipoles result from a violation of symmetry and indicate a fabrication or assembly error

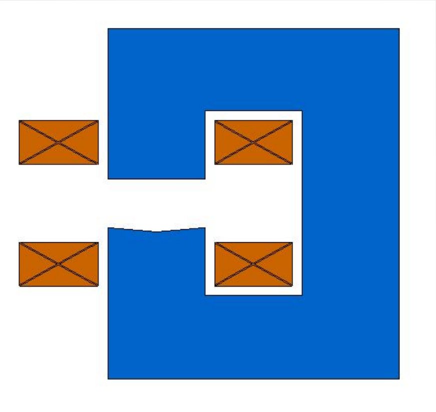
Normal-conducting accelerator magnets
© Thomas Zickler, CERN

Asymmetries

Asymmetries generating 'non-allowed' harmonics

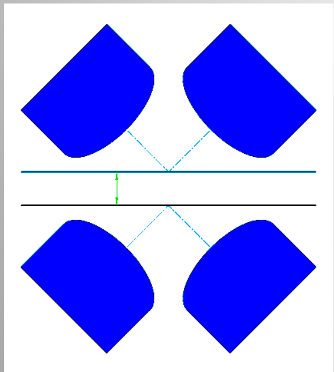


n = 2, 4, 6, ...

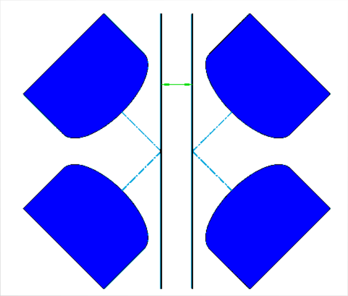


n = 3, 6, 9, ...

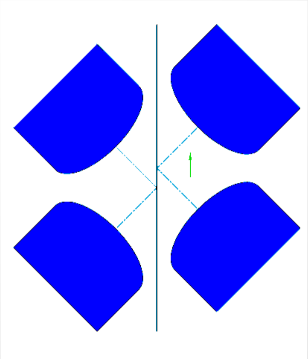
Comprehensive studies about the influence of manufacturing errors on the field quality have been done by K. Halbach.



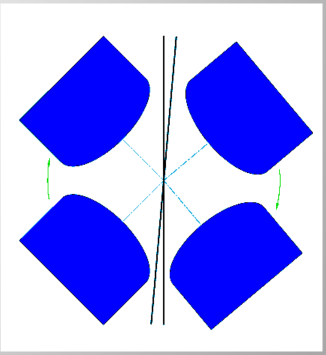
n = 4 (neg.)



n = 4 (pos.)



n = 3

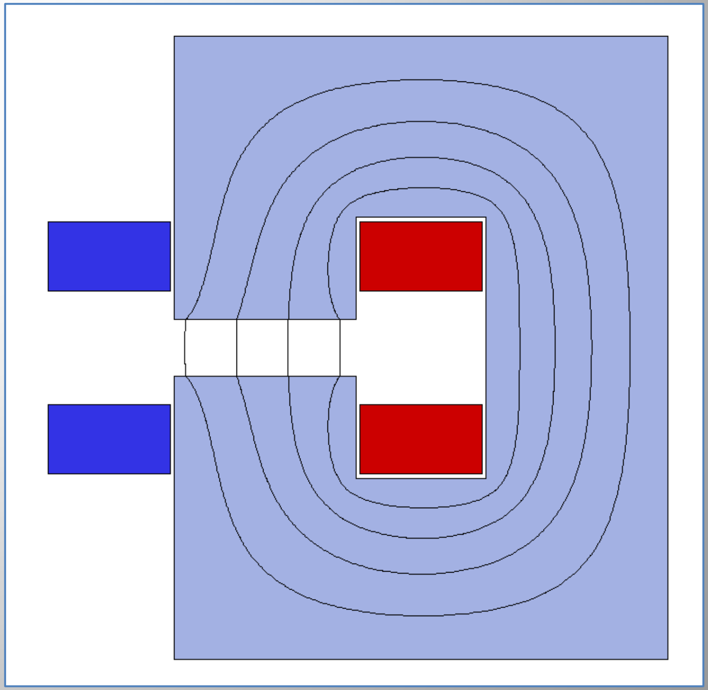


n = 2, 3

These errors can seriously affect machine behaviour and <u>must</u> be controlled!

Asymmetry in a C-magnet

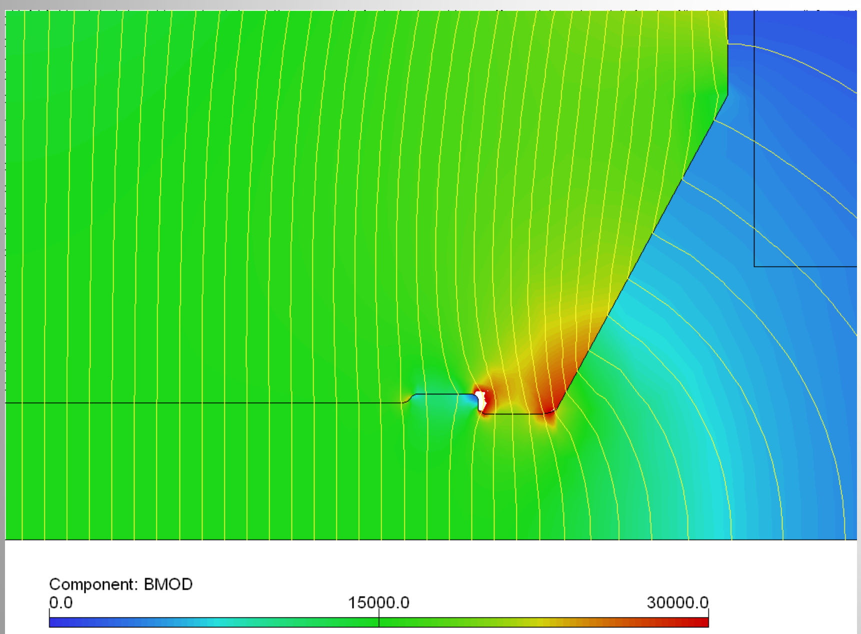
- C-magnet: one-fold symmetry
- Since $NI = \oint \vec{H} \cdot \vec{dl} = const.$ the contribution to the integral in the iron has different path lengths
- Finite (low) permeability will create lower B on the outside of the gap than on the inside
- Generates 'forbidden' harmonics with n = 2, 4, 6, ... changing with saturation
- Quadrupole term resulting in a gradient around 0.1% across the pole

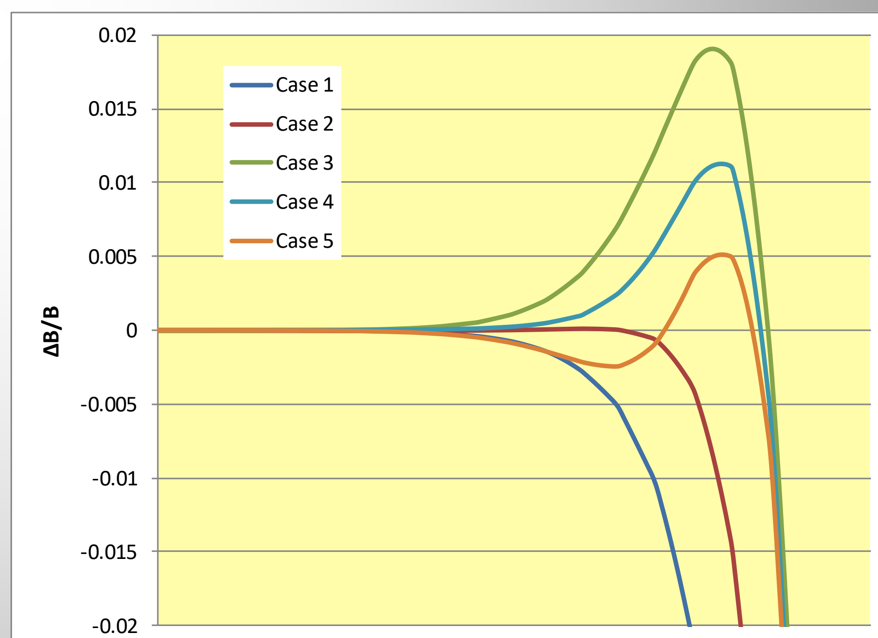


Pole optimization

‚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 -> Rogowsky profile

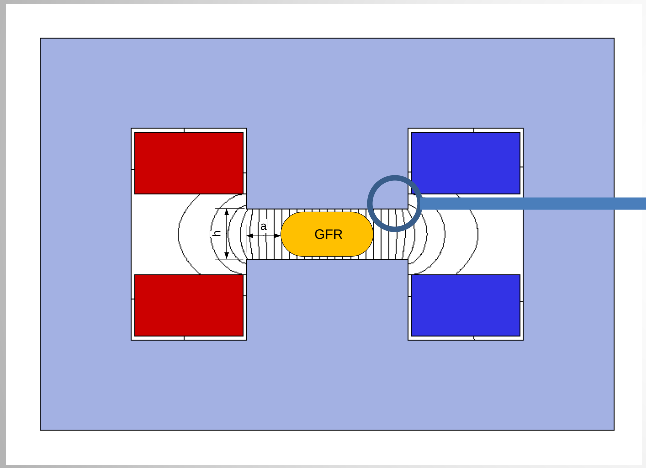


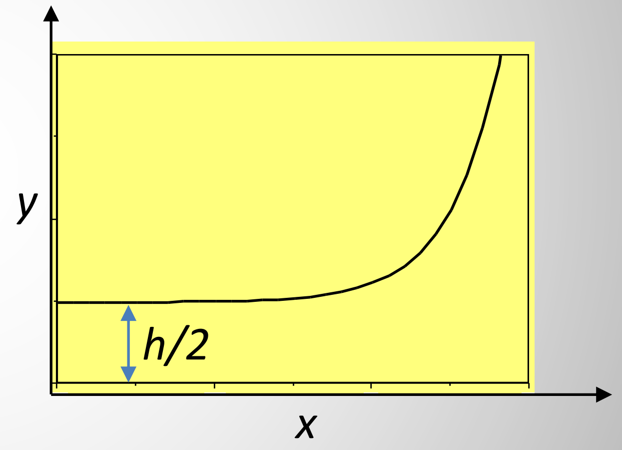


Rogowsky roll-off

The 'Rogowsky' profile provides the maximum rate of increase in gap with a monotonic decrease in flux density at the surface, i.e. no saturation at the pole edges!

The edge profile is shaped according to: $$y = \frac{h}{2} + \left(\frac{h}{\pi}\right)\exp\left(\left(\frac{x\pi}{h}\right) - 1\right)$$





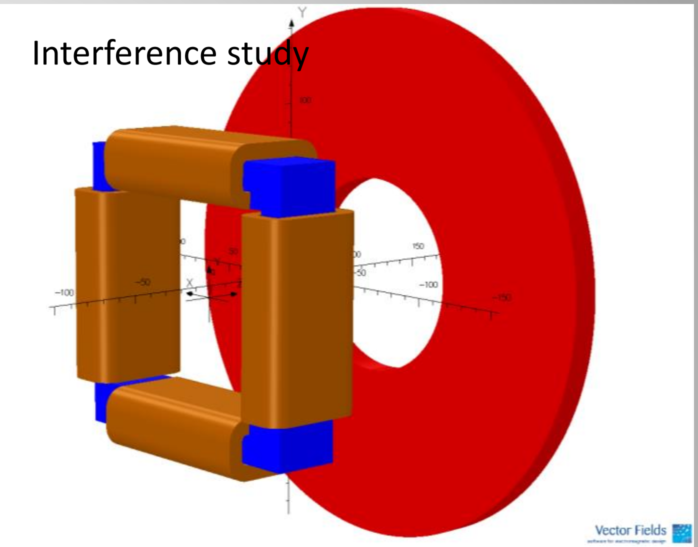
For an optimized pole: $$x_{optimized} = 2\frac{a}{h} = -0.14\ln\frac{\Delta B}{B_0} - 0.25$$

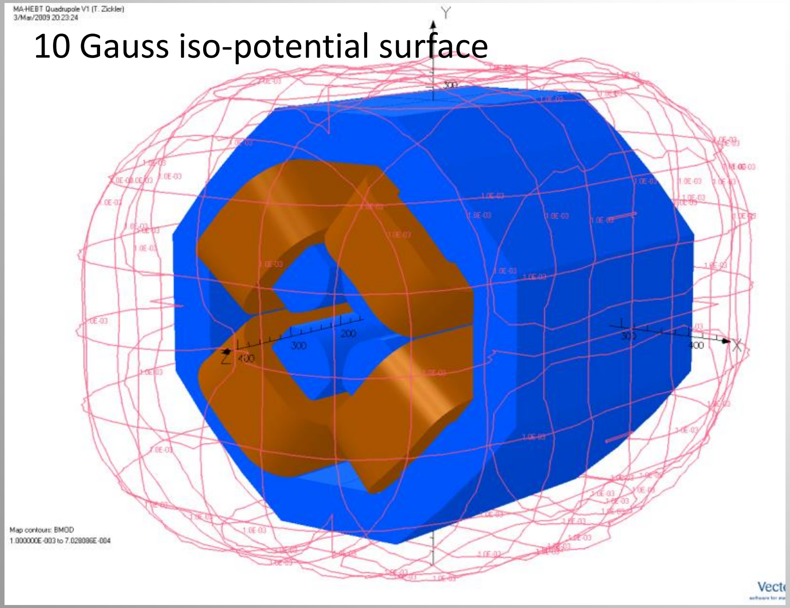
- *x*: pole overhang normalized to the gap
- *a*: pole overhang: excess pole beyond the edge of the good field region to reach the required field uniformity
- *h*: magnet gap

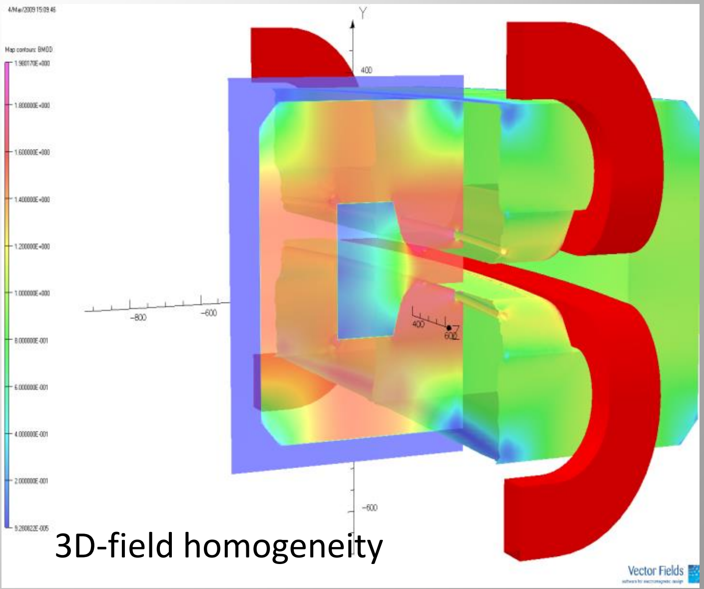
3D Design

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



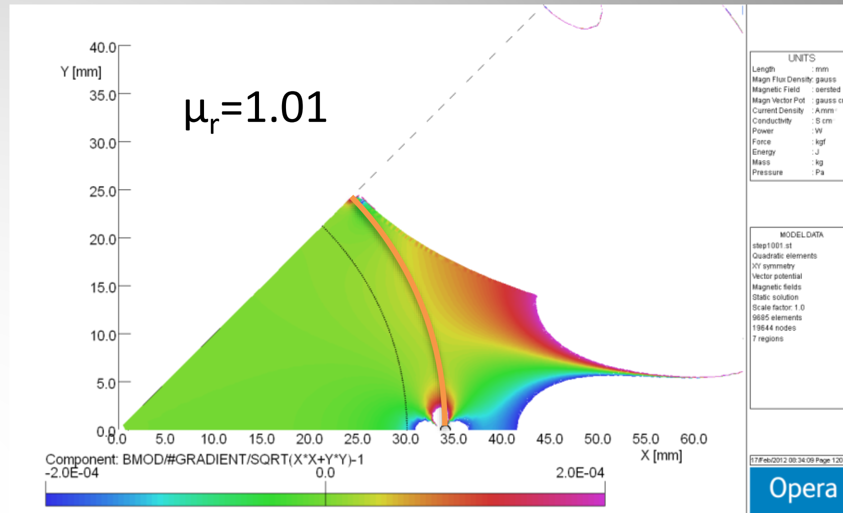


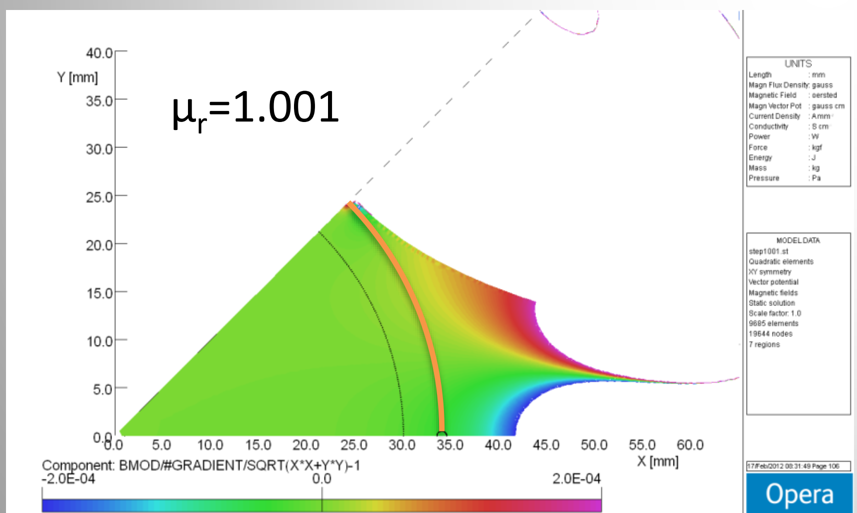


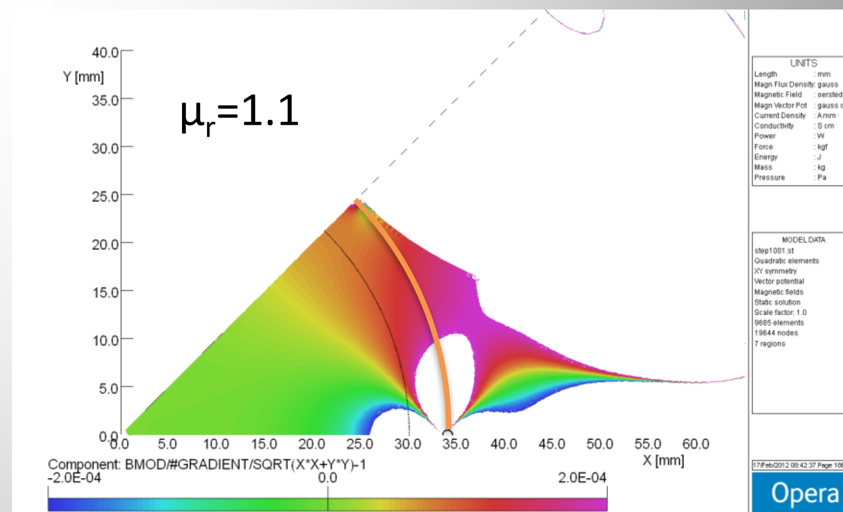
Case 1: A material problem

Welding seam on stainless-steel vacuum chamber:

- GFR radius: 30 mm
- Chamber radius: 35 mm
- Welding seam diameter: 1 mm
- Rel. permeability of 316 LN: < 1.001



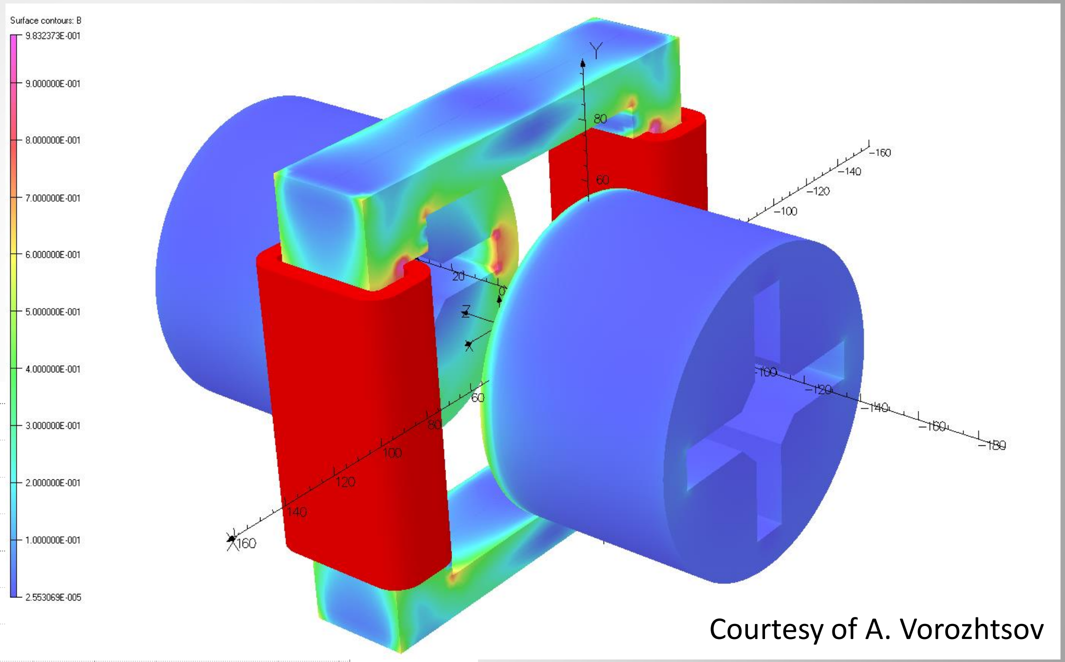




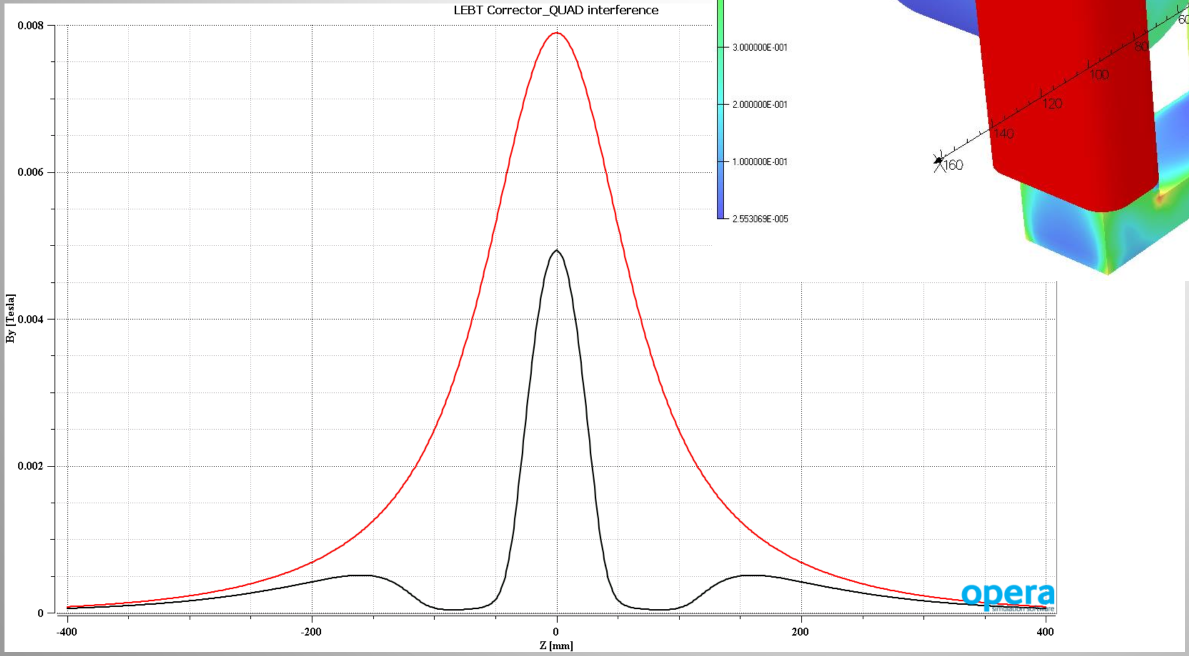
A small distortion can significantly influence the field quality in the GFR!

Case 2: An interference problem

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

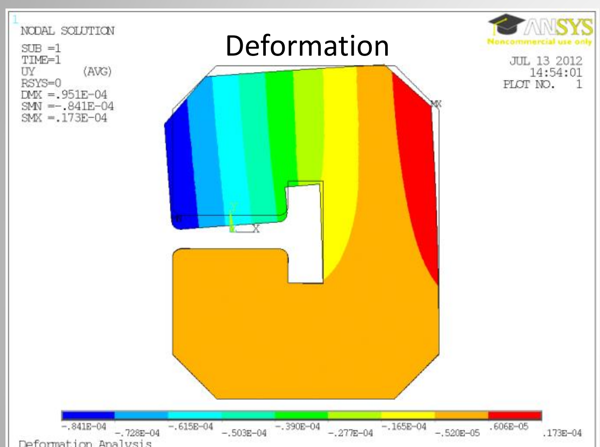


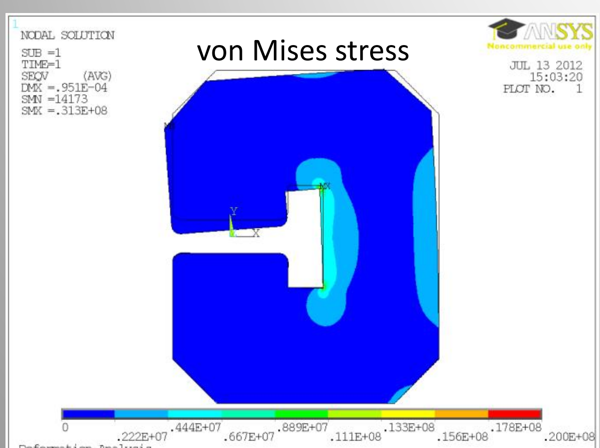
Courtesy of A. Vorozhtsov

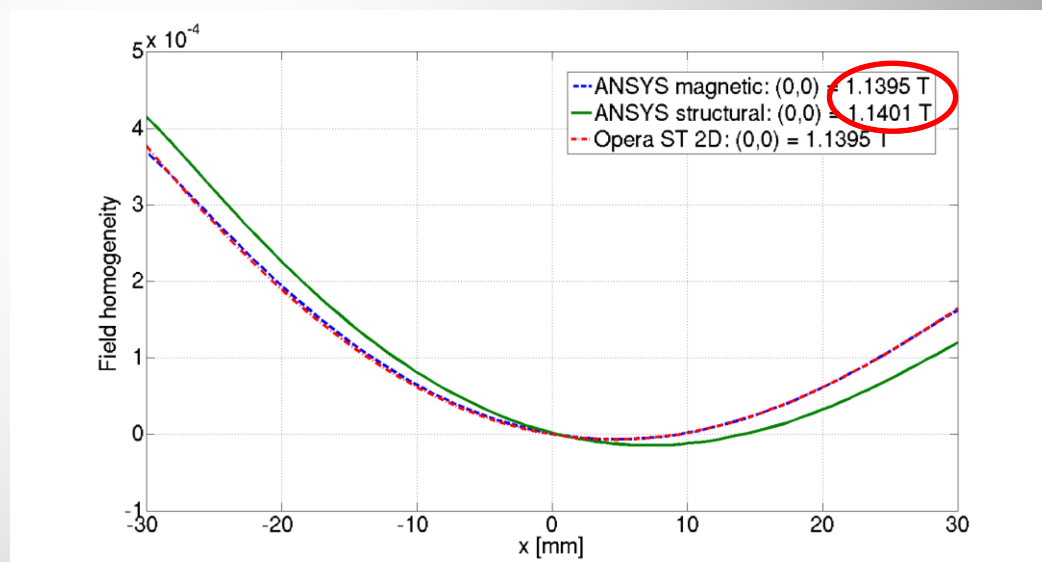


Case 3: Mechanical deformation

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







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

Courtesy of D. Schoerling

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 ($\propto \Delta x^{2\sim 3}$); 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