Joint Universities Accelerator School

JUAS 2018

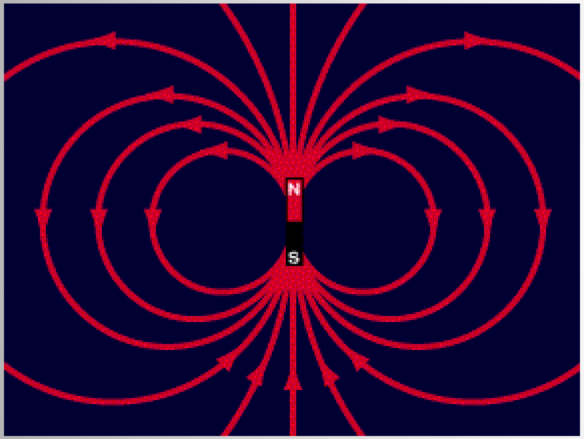
Archamps, France, 26th February – 2nd March 2018

# 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

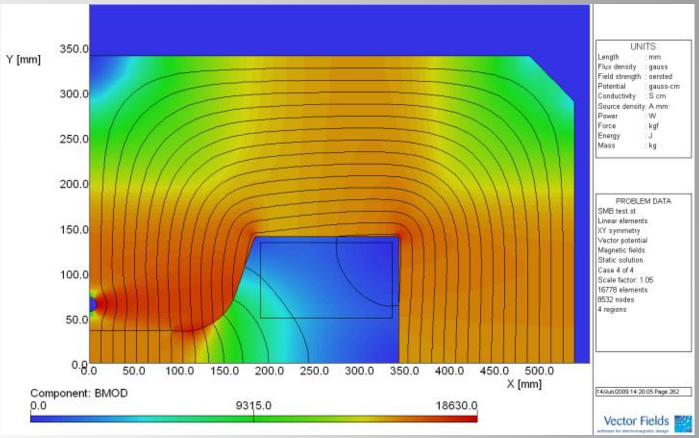
How to evaluate the results

A brief outlook into 3D...

Typical application examples

# Numerical design

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

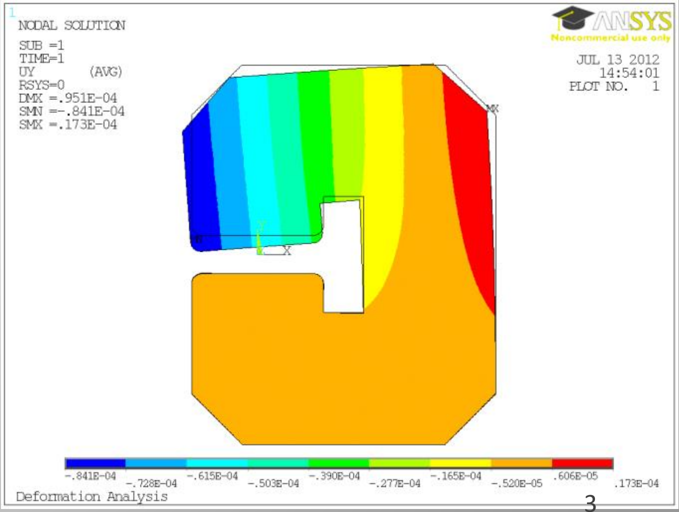



## Technique is iterative

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

## Advanced codes offer:

- modeller, solver and post-processors
- mesh generator with elements of various shapes
- multiple solver iterations for non-linear material properties
- anisotropic material characterisation
- optimization routines
- combination with structural and thermal analysis
- time depended analysis (steady state, transient)




## FEM codes are powerful tools, but be cautious:

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

# Which code shall I use ?

Selection criteria:

- The more powerful, the harder to learn
- Powerful codes require powerful CPU and large memory
- More or less user-friendly input (text and/or GUI, scripts)
- OS compatibility and lincense costs

Computing time increases for high accuracy solutions, non-linear problems and time dependent analysis

- Compromise between accuracy and computing time
- Smart modelling can help to minimize number of elements

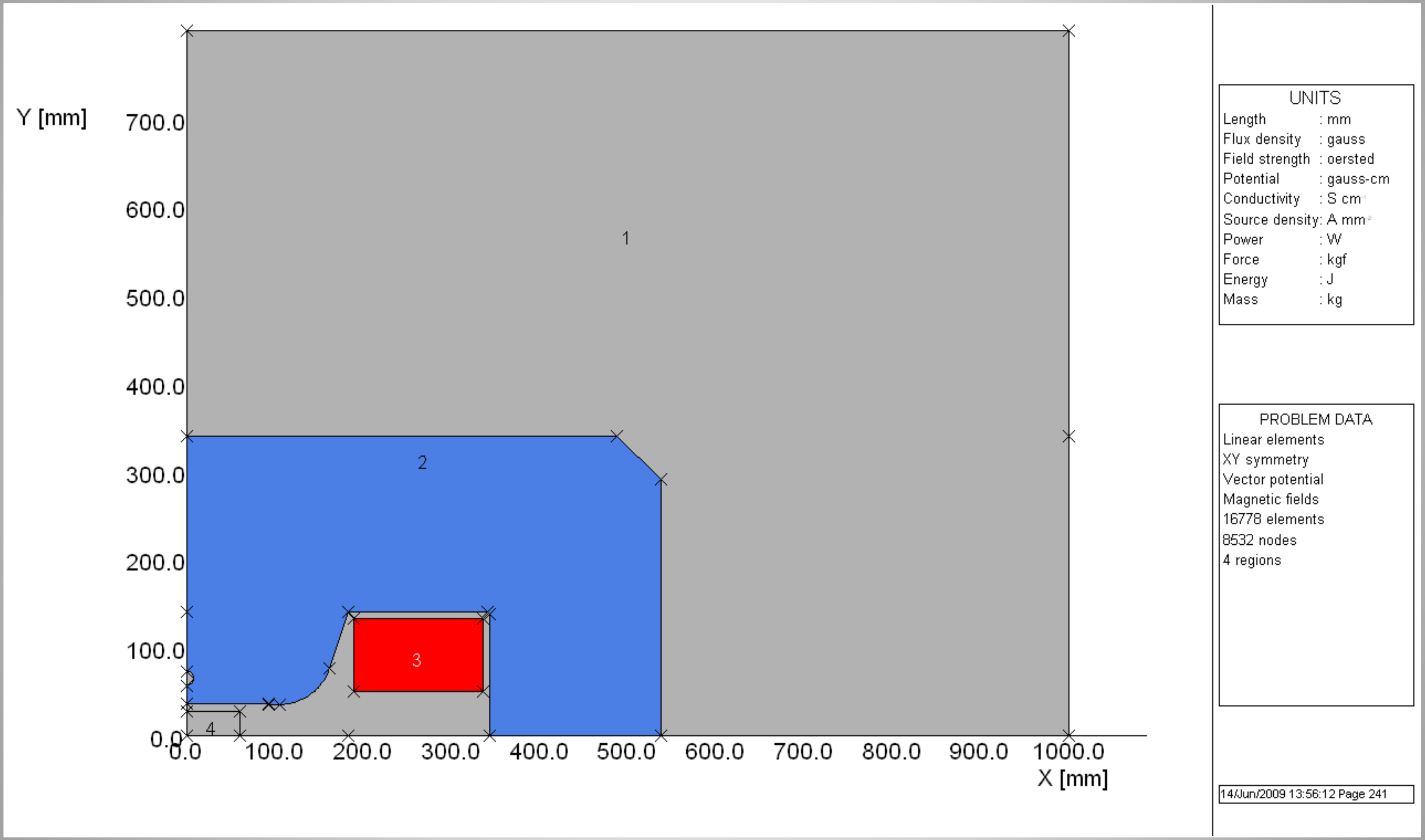
| 2D | 3D |
|---|---|
| • 2D analysis is often sufficient<br>• magnetic solvers allow currents only perpendicular to the plane<br>• fast | • produces large amount of elements<br>• mesh generation and computation takes significantly longer<br>• end effects included<br>• powerful modeller |

# Numerical design process

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

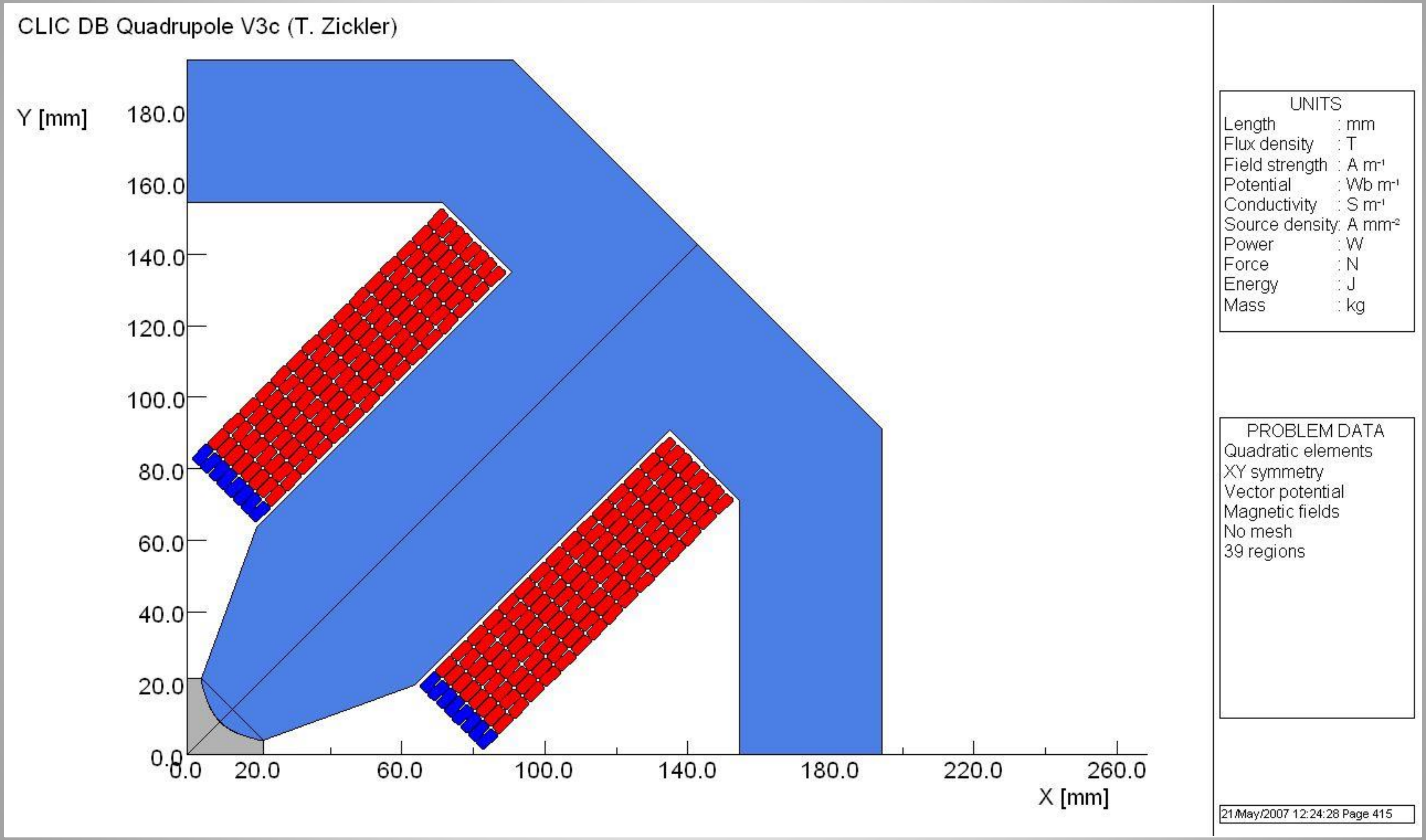
1. Create the model (pre-processor or modeller)
2. Define boundary conditions, set material properties
3. Calculations (solver)
4. Visualize and asses the results (post-processor)
5. Optimization by adjusting the geometry (manually or optimization code)

# Creating the model



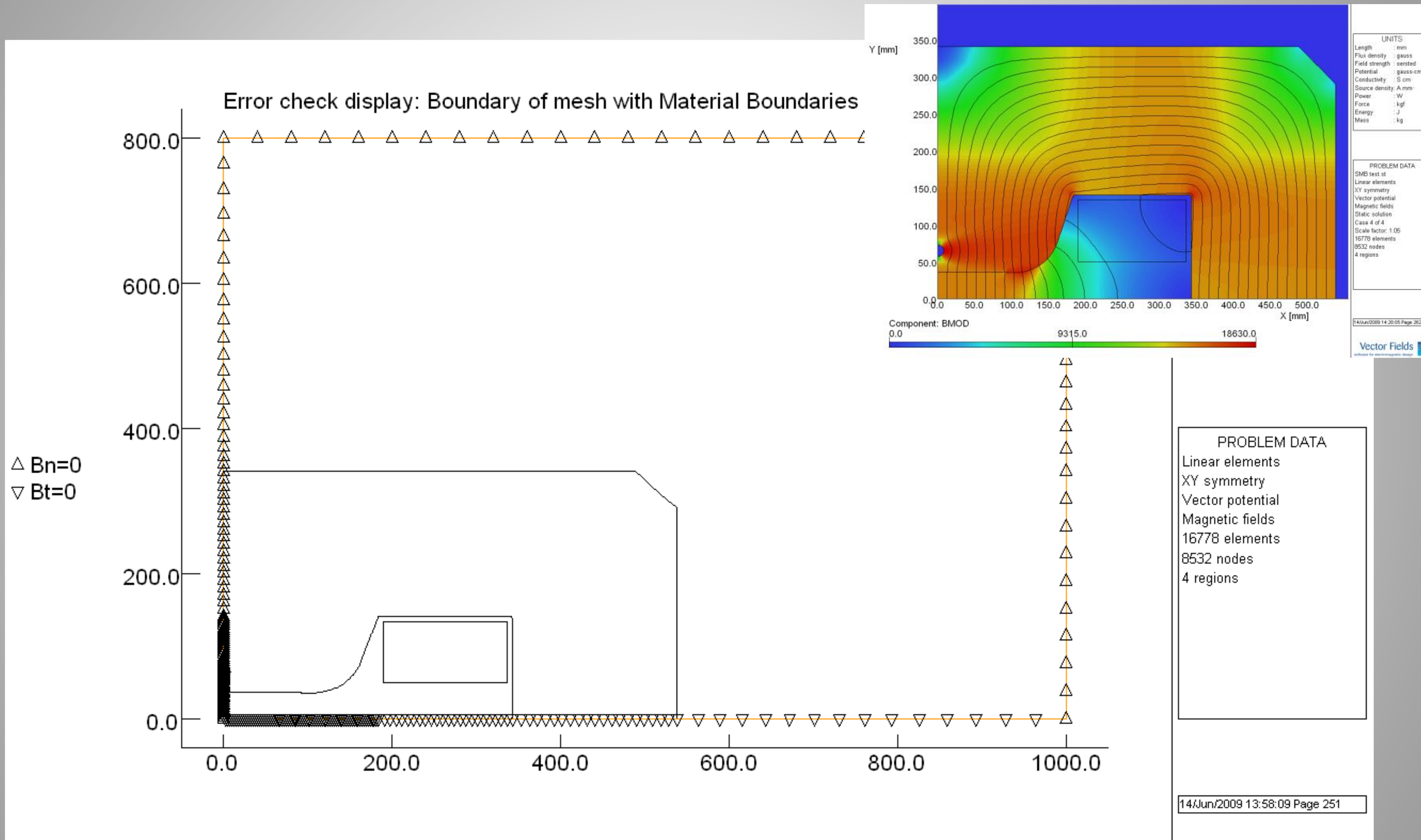

GUI vs. Script

# Model symmetries

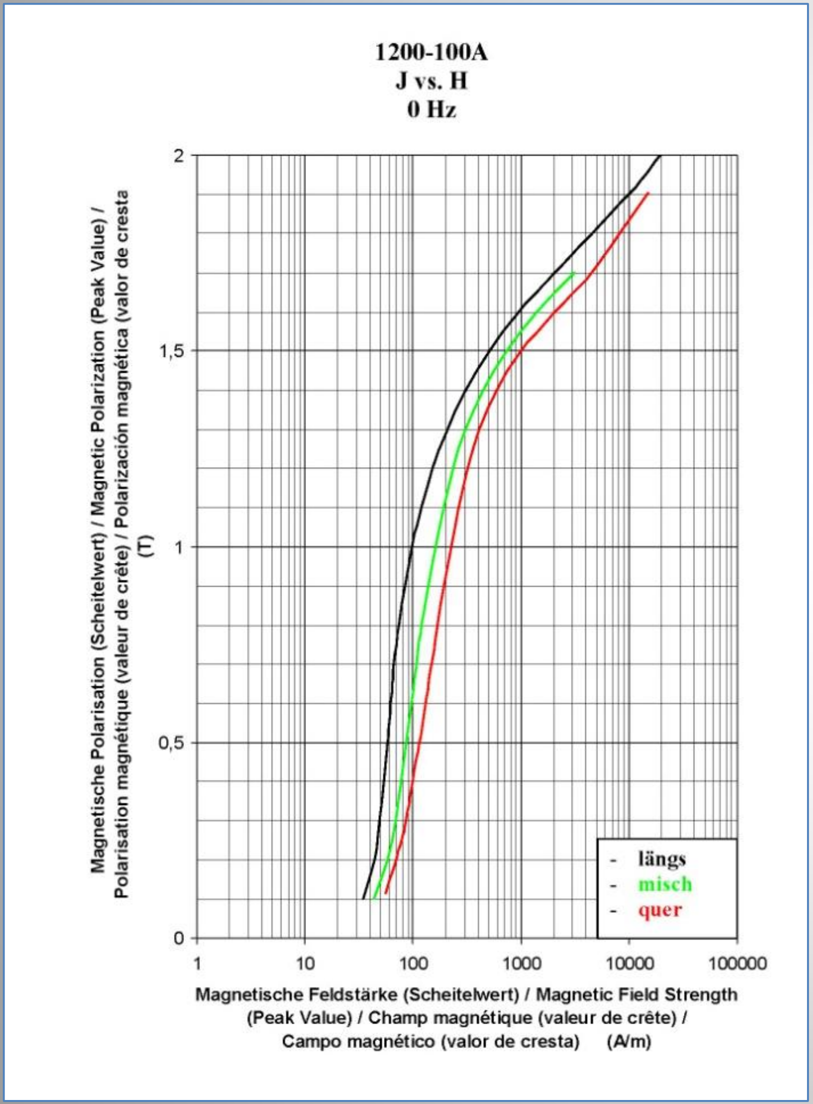



Note: one eighth of quadrupole could be used with opposite symmetries defined on horizontal and y = x axis

# 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

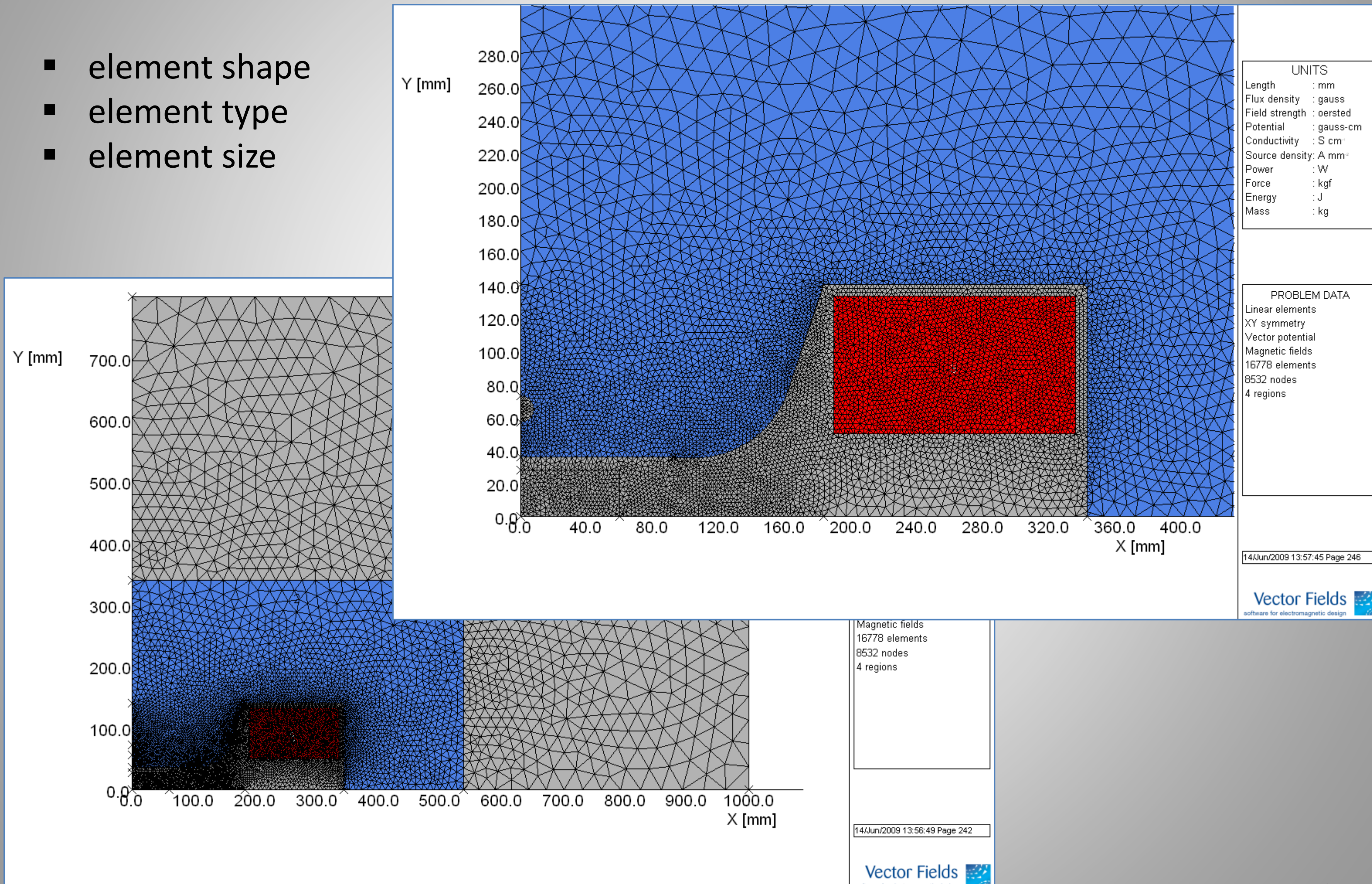
## Mechanical and thermal properties:

- 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, ...)

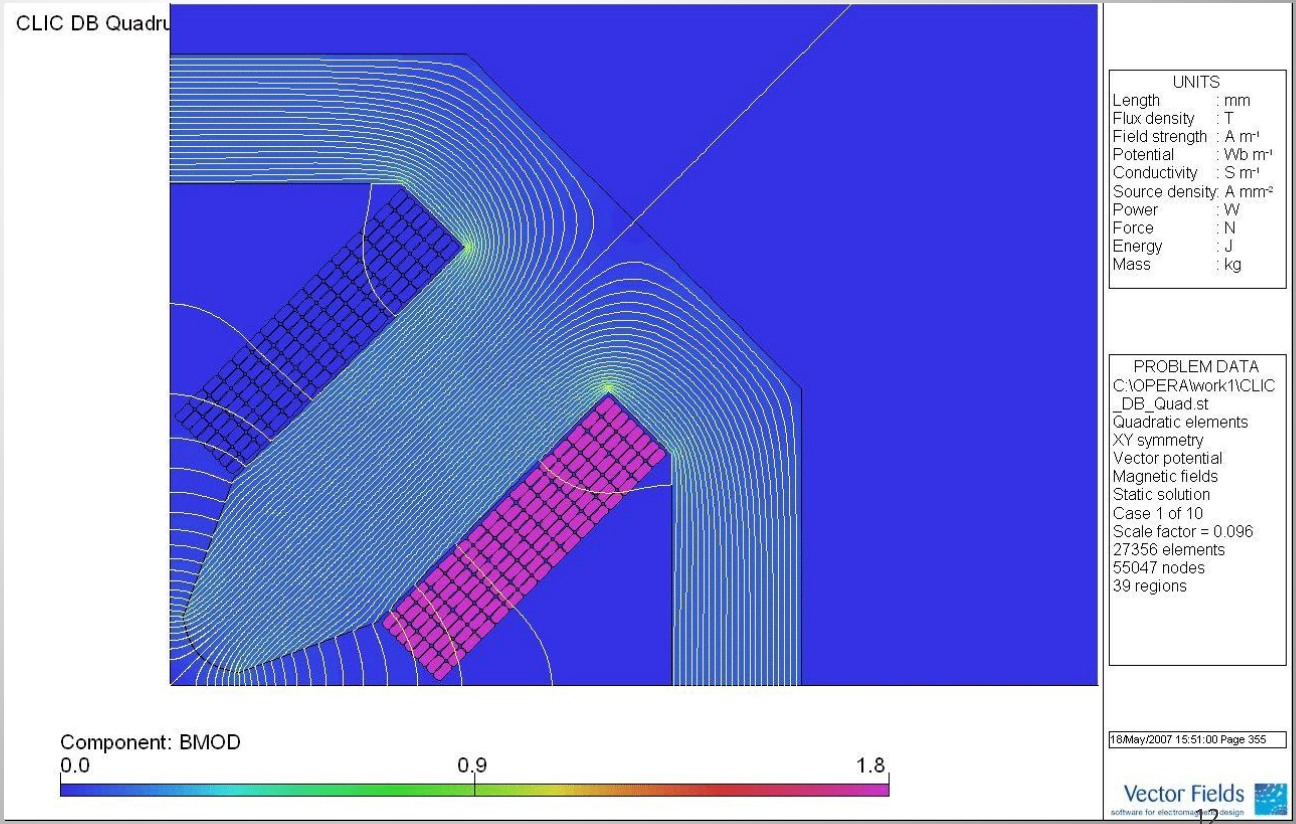
**Solver settings**

- 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:

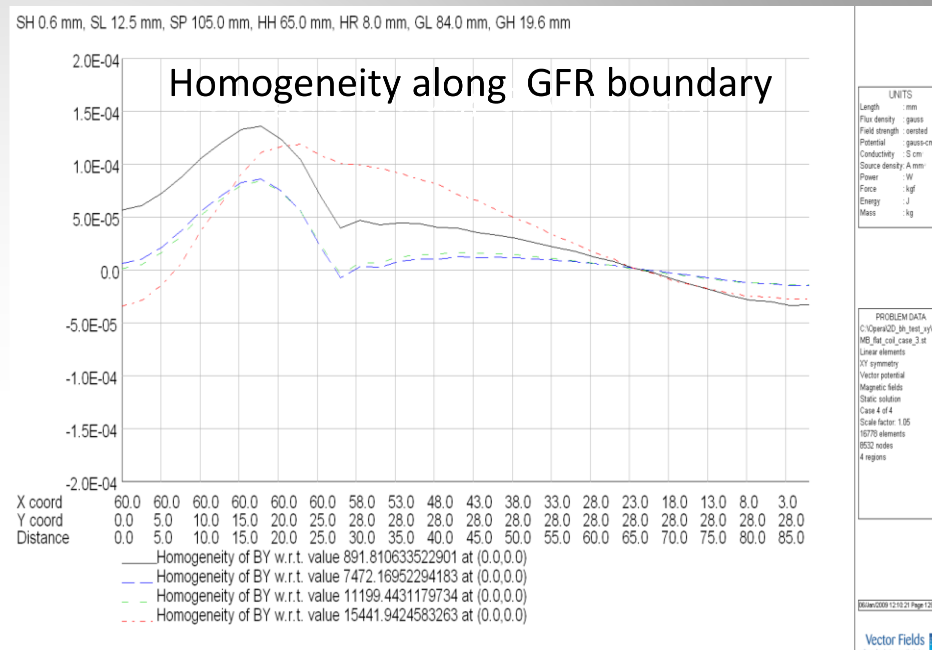
– Field lines and colour contours plots of flux, field, and current density
– Graphs showing absolute or relative field distribution
– Homogeneity plots

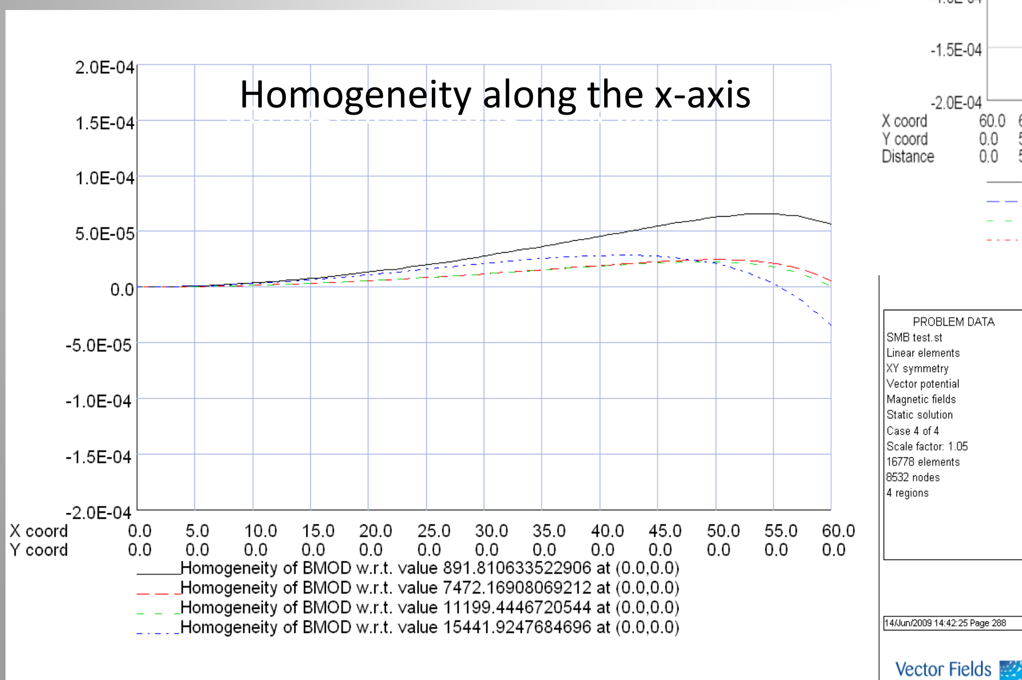


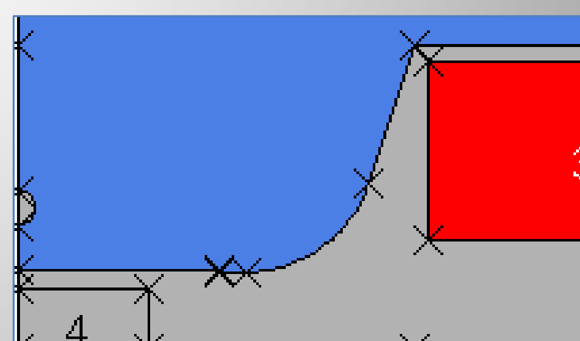
# Field homogeneity in a dipole

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

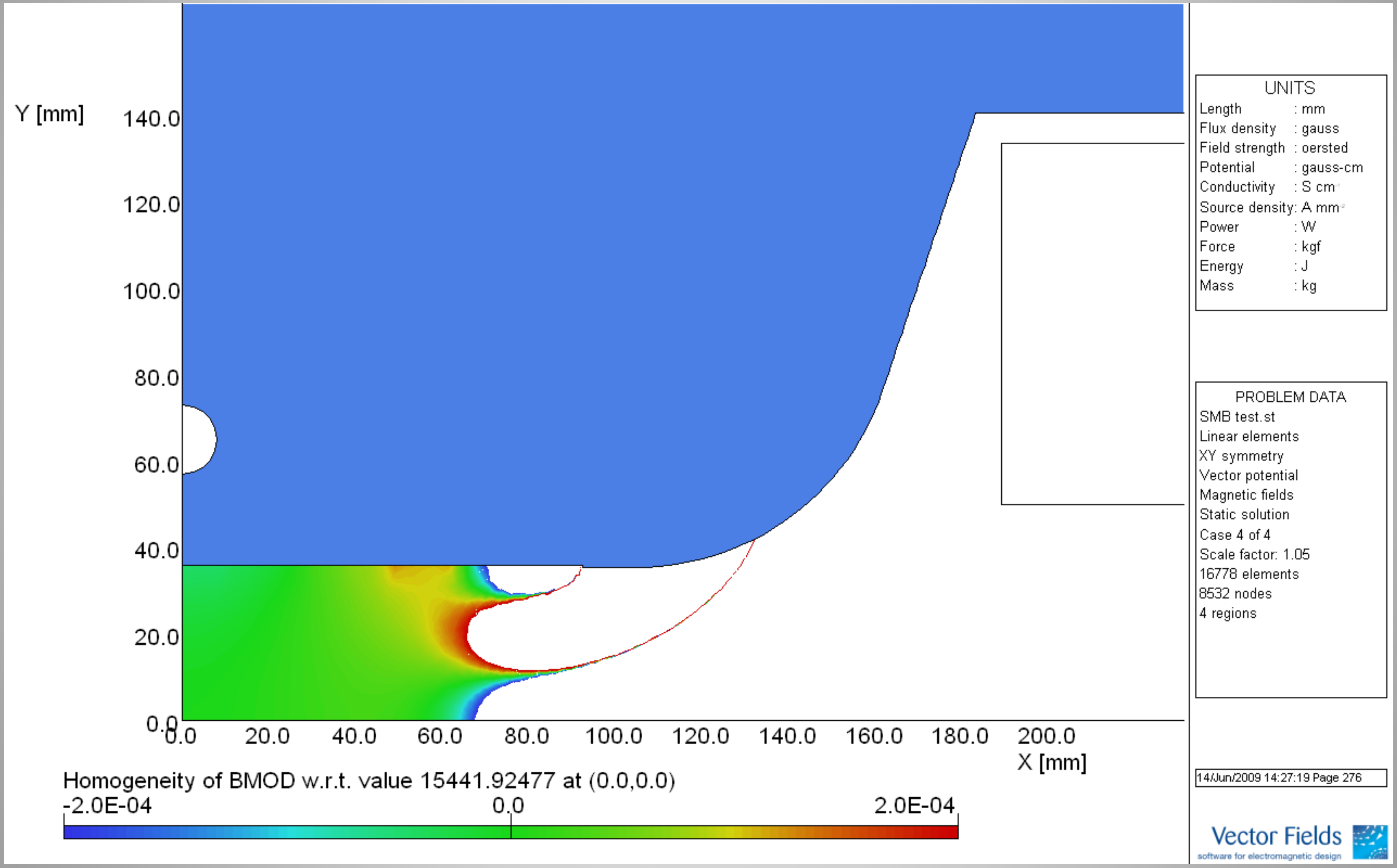
$$\frac{\Delta B}{B_0} = \frac{B_y(x,y)}{B_y(0,0)} - 1 \qquad \frac{\Delta B}{B_0} \leq 0.01\%$$



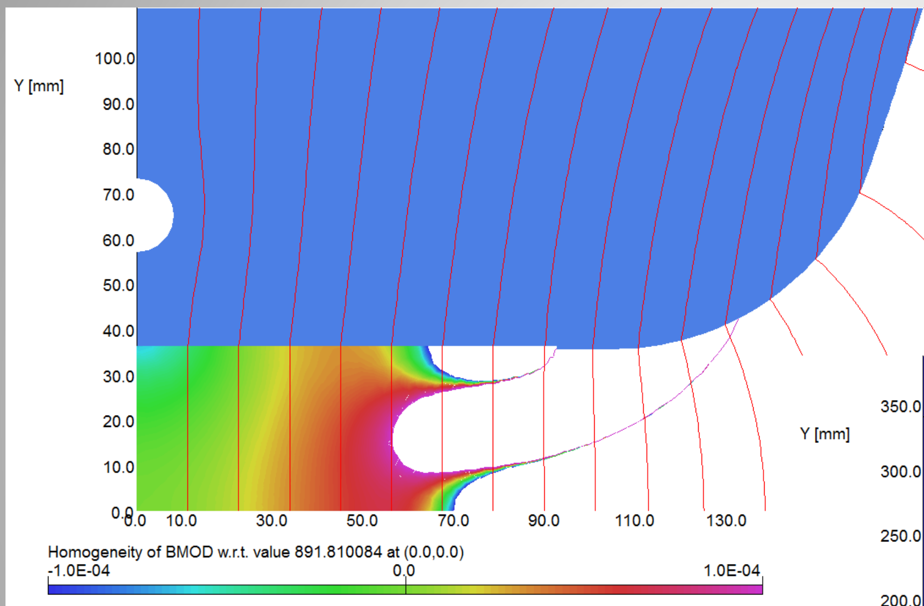



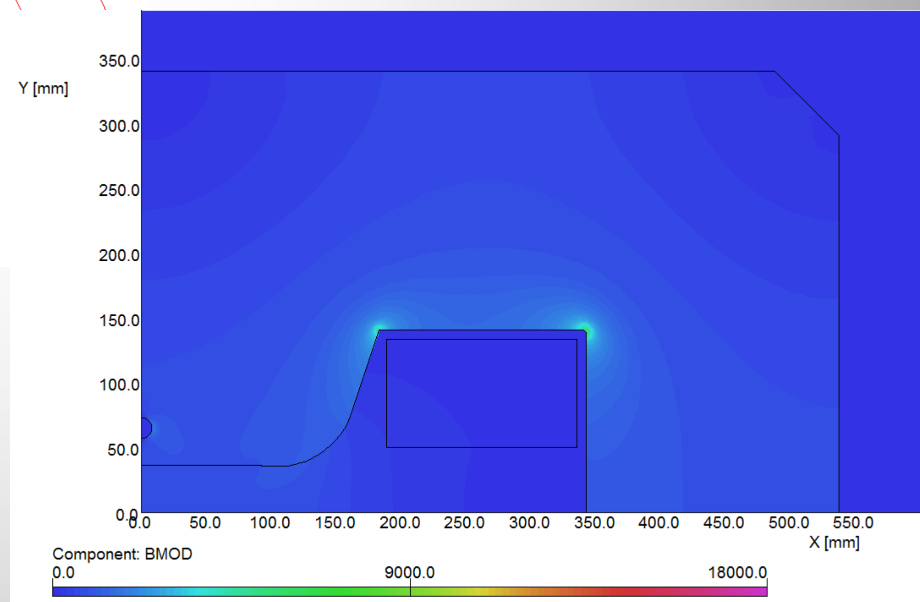
# Field homogeneity in a dipole



# Saturation and field quality

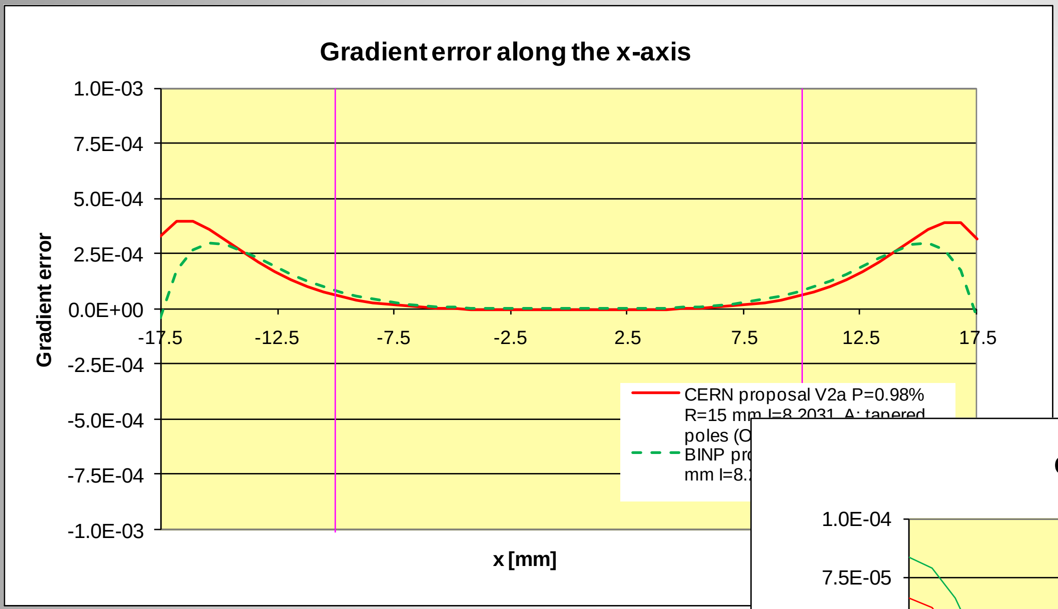



Also very low fields can disturb the field quality significantly




Field quality can vary with field strength due to saturation

# Field quality in a quadrupole

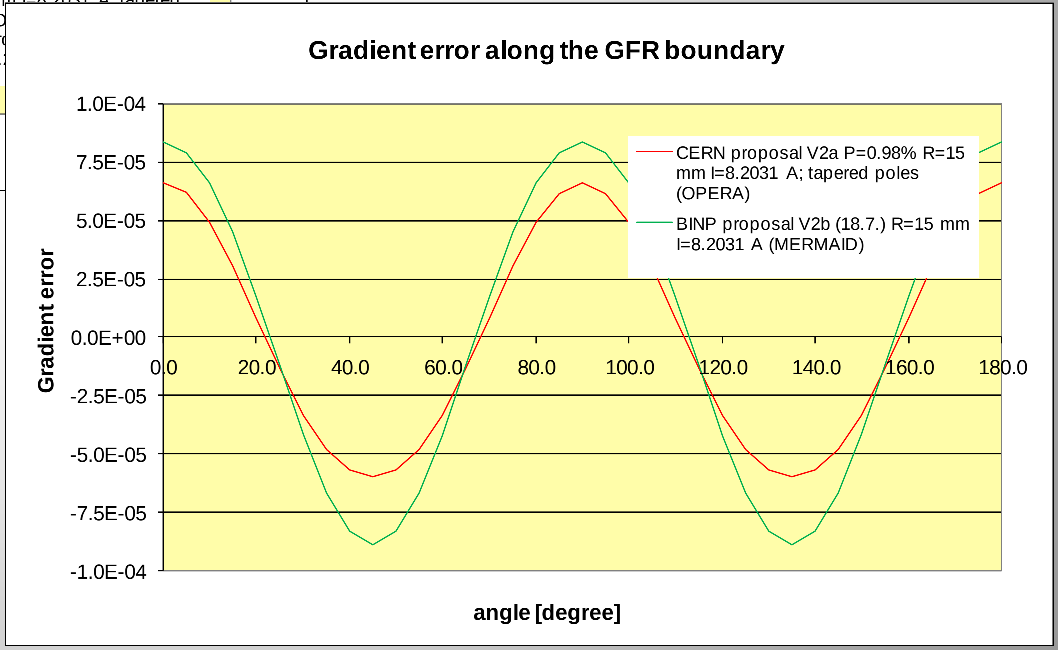



Gradient homogeneity along the x-axis

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

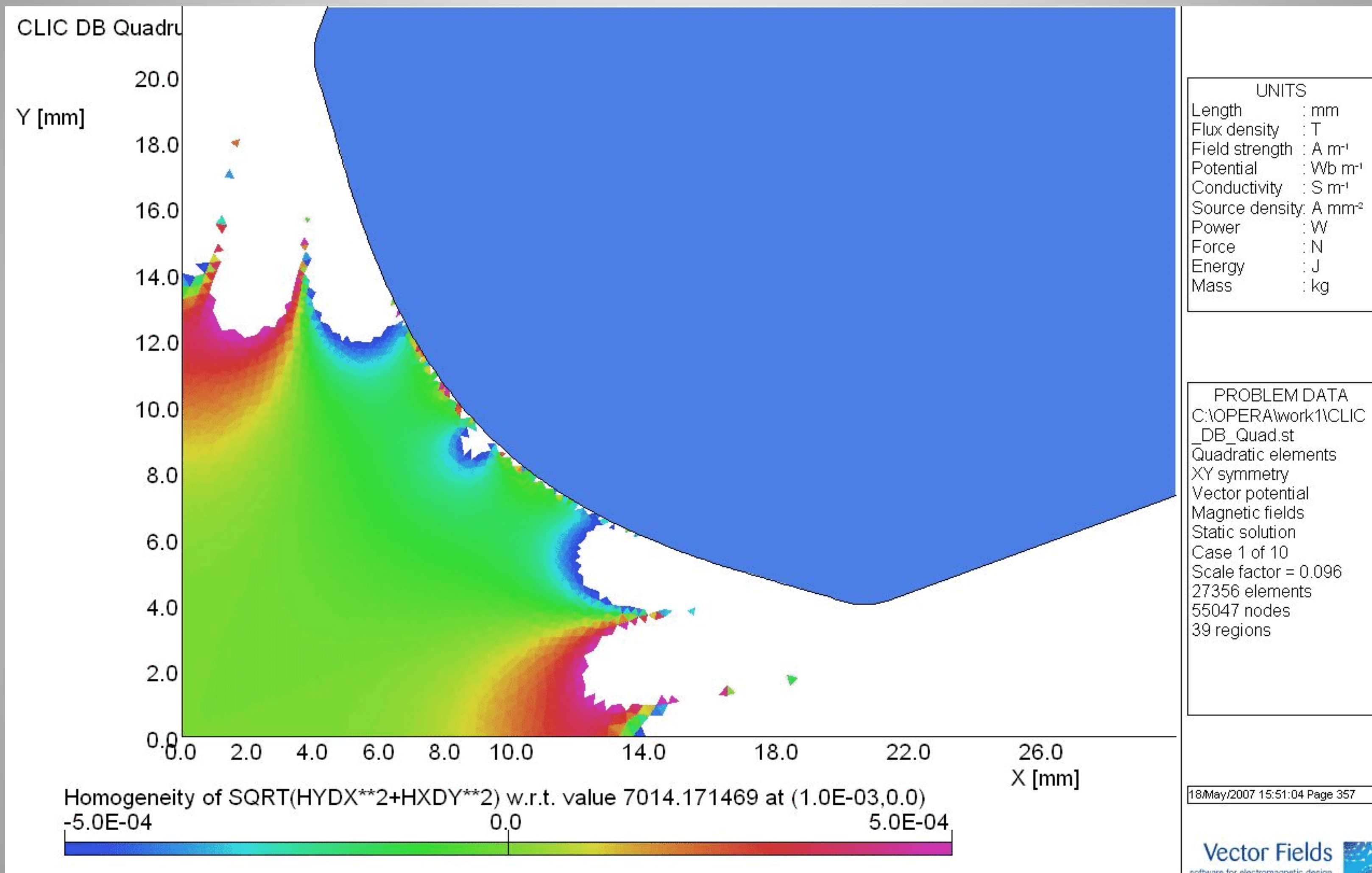
Field error in a quadrupole

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




Gradient homogeneity along circular GFR

# Saturation and field quality




Field quality varies with field strength due to saturation

# Field analysis

Picking up from lecture 1

$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{r_0}\right)^{n-1}$$

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 $B_\mathrm{N}$ 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:

$$B_y(z) + iB_x(z) = \frac{B_N}{10^4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{z}{r_0}\right)^{n-1}$$

The normalized multipole coefficients $b_\mathrm{n}$, $a_\mathrm{n}$ are useful:

- to describe the field errors and their impact on the beam in the lattice, so the magnetic design can be evaluated
- in comparison with the coefficients resulting from magnetic measurements to judge acceptability of a manufactured magnet

# Field analysis

The harmonic components are good indicators to asses the field quality of a magnet i.e. to describe the deviations of the actual field from the ideal one

Normal dipole: $\vec{B}_{id}(x,y) = B_1\vec{j}$

$$B_y(z) + iB_x(z) = B_1 + \frac{B_1}{10^4}\left[ia_1 + (b_2 + ia_2)\left(\frac{z}{r_0}\right) + (b_3 + ia_3)\left(\frac{z}{r_0}\right)^2 + (b_4 + ia_4)\left(\frac{z}{r_0}\right)^3 + \cdots\right]$$

$$b_2 = \frac{B_2}{B_1}10^4 \quad b_3 = \frac{B_3}{B_1}10^4 \quad a_1 = \frac{A_1}{B_1}10^4 \quad a_2 = \frac{A_2}{B_1}10^4 \quad \ldots$$

Normal quadrupole: $\vec{B}_{id}(x,y) = B_2[x\vec{j} + y\vec{i}]\frac{1}{r_0}$

$$B_y(z) + iB_x(z) = B_2\frac{z}{r_0} + \frac{B_2}{10^4}\left[ia_2\left(\frac{z}{r_0}\right) + (b_3 + ia_3)\left(\frac{z}{r_0}\right)^2 + (b_4 + ia_4)\left(\frac{z}{r_0}\right)^3 + \cdots\right]$$

$$b_3 = \frac{B_3}{B_2}10^4 \quad b_4 = \frac{B_4}{B_2}10^4 \quad a_2 = \frac{A_2}{B_2}10^4 \ldots$$

# 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 $B_{y,id}(x) = B_1$

$$B_y(x) = B_1 + \frac{B_1}{10^4}\left[b_2\left(\frac{x}{r_0}\right) + b_3\left(\frac{x}{r_0}\right)^2 + b_4\left(\frac{x}{r_0}\right)^3 + \cdots\right]$$

$$\frac{\Delta B}{B}(x) = \frac{1}{10^4}\left[b_2\left(\frac{x}{r_0}\right) + b_3\left(\frac{x}{r_0}\right)^2 + b_4\left(\frac{x}{r_0}\right)^3 + \cdots\right]$$

- Harmonic distortion factor $F_d$ :

$$F_d(r_0) = \sum_{n=1;n\neq N}^{K} \sqrt{b_n^2(r_0) + a_n^2(r_0)}$$

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

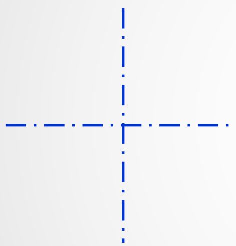
*N*: order of the fundamental field

*m*: integer number (m≥1)

<u>fully symmetric dipole</u>

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

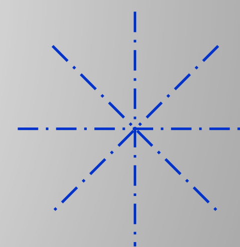
non-allowed: all others



<u>fully symmetric quadrupole</u>

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

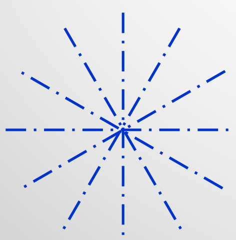
non-allowed: all others



<u>fully symmetric sextupole</u>

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

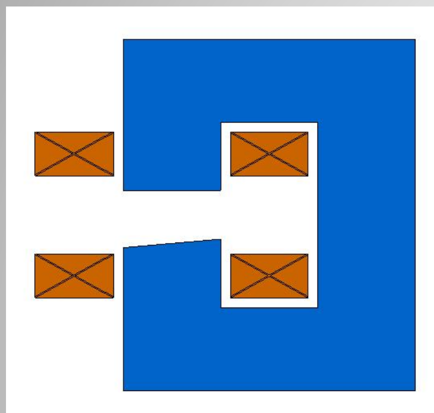
non-allowed: all others



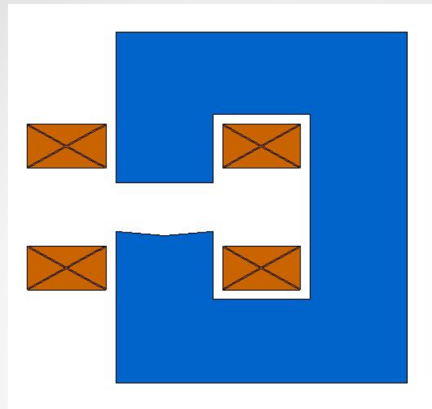
‚Non-allowed' multipoles result from a violation of symmetry and indicate a fabrication or assembly error

# Asymmetries

Asymmetries generating 'non-allowed' harmonics

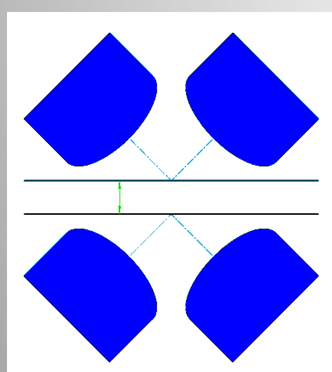


$n$ = 2, 4, 6, ...

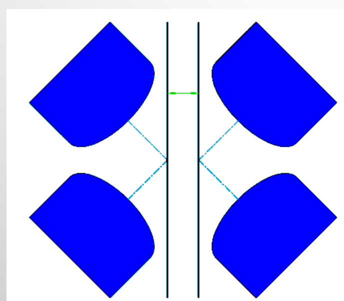


$n$ = 3, 6, 9, ...

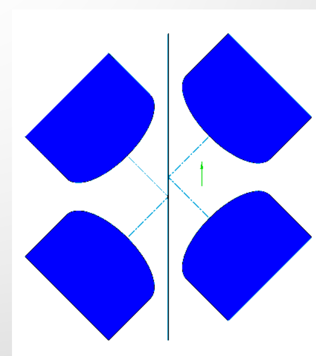
Comprehensive studies about the influence of manufacturing errors on the field quality have been done by K. Halbach.



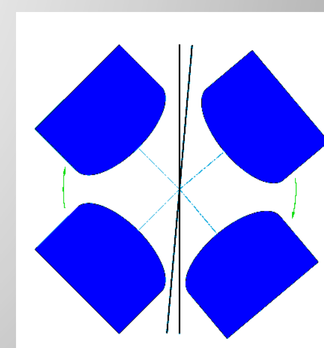
$n$ = 4 (neg.)



$n$ = 4 (pos.)



$n$ = 3

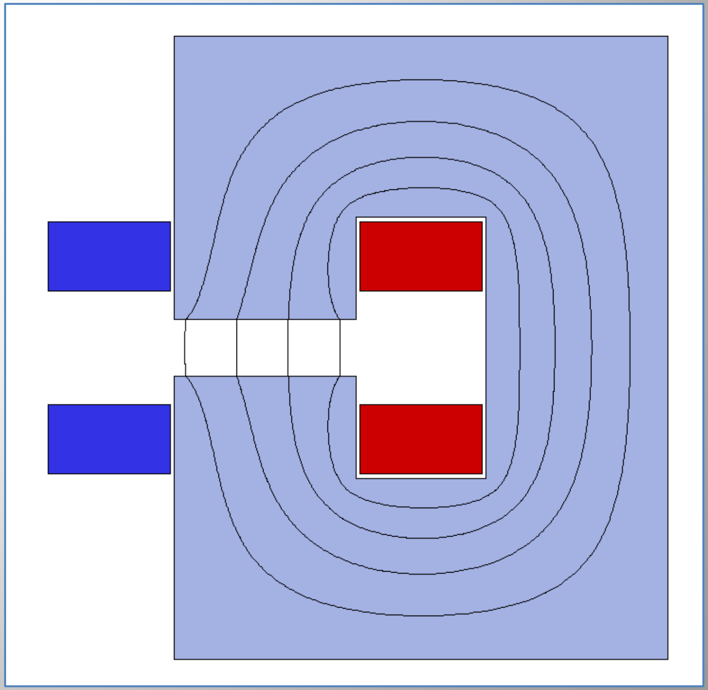


$n$ = 2, 3

These errors can seriously affect machine behaviour and must be controlled!

# Asymmetry in a C-magnet

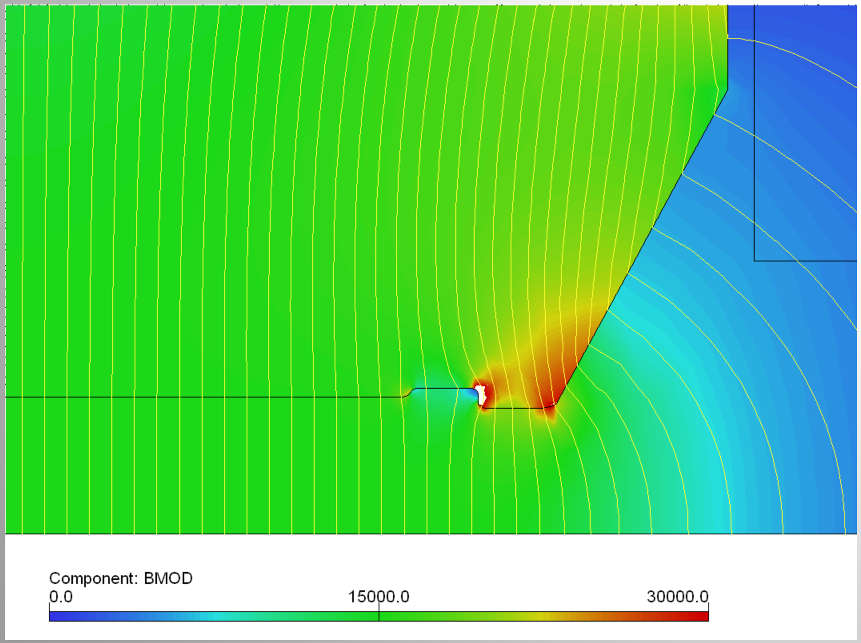
- C-magnet: one-fold symmetry
- Since $NI = \oint \vec{H} \cdot \vec{dl} = const.$ the contribution to the integral in the iron has different path lengths
- Finite (low) permeability will create lower $B$ on the outside of the gap than on the inside
- Generates 'forbidden' harmonics with $n$ = 2, 4,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

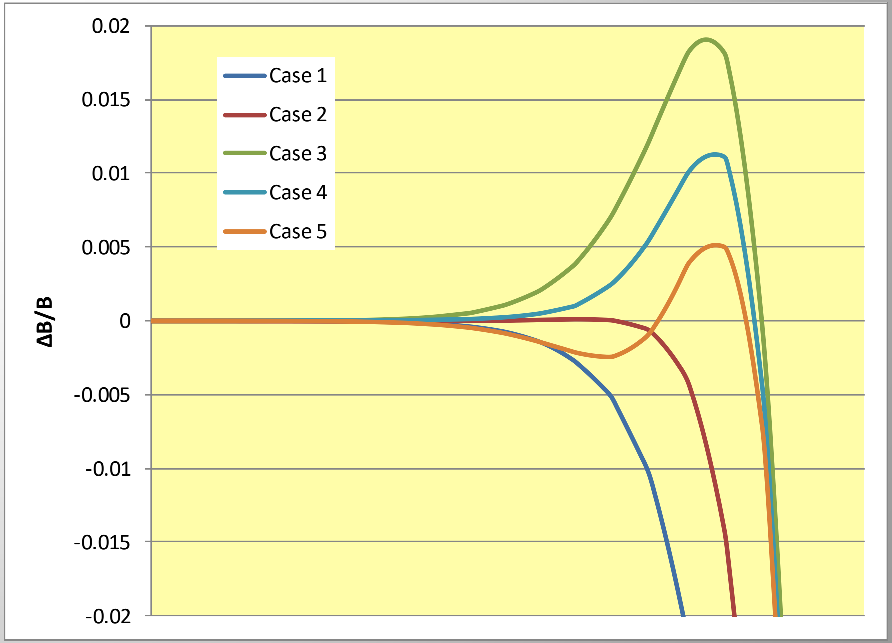


# Pole optimization

‚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

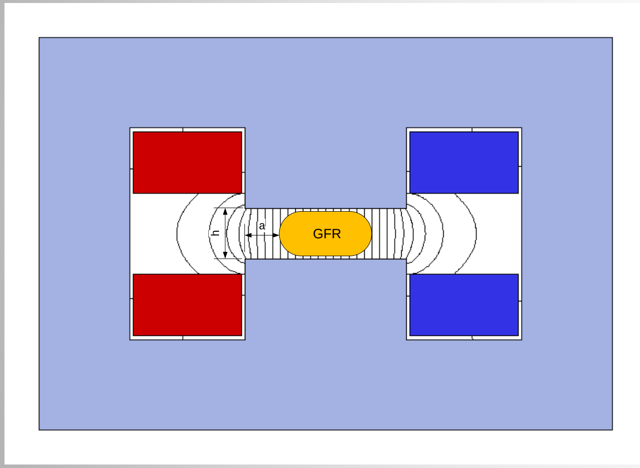


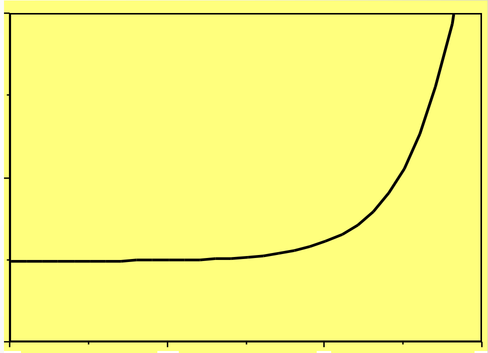



# Rogowsky roll-off

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: $$y = \frac{h}{2} + \left(\frac{h}{\pi}\right)\exp\left(\left(\frac{x\pi}{h}\right) - 1\right)$$



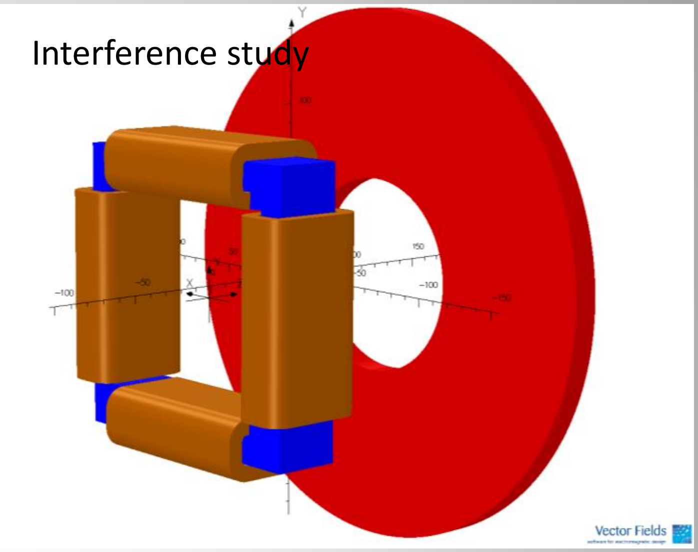
For an optimized pole: $$x_{optimized} = 2\frac{a}{h} = -0.14\ln\frac{\Delta B}{B_0} - 0.25$$

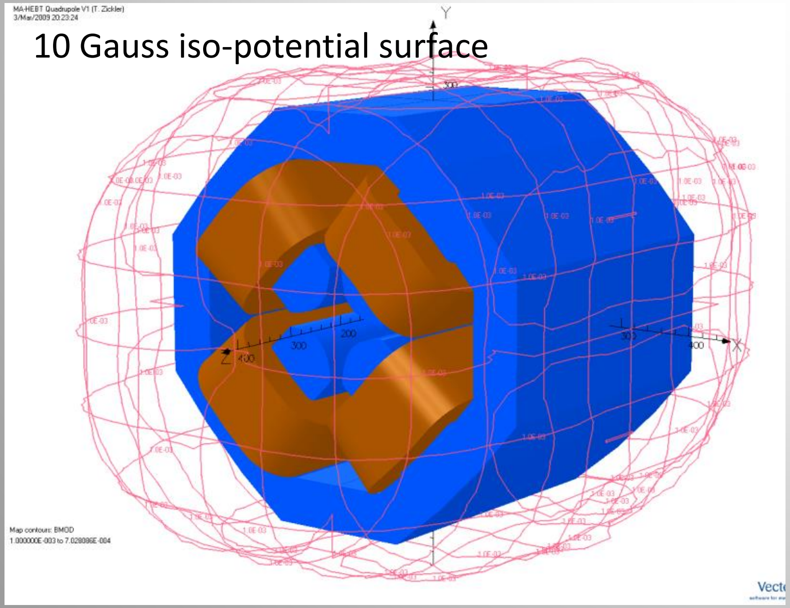
- *x*: pole overhang normalized to the gap
- *a*: pole overhang: excess pole beyond the edge of the good field region to reach the required field uniformity
- *h*: magnet gap

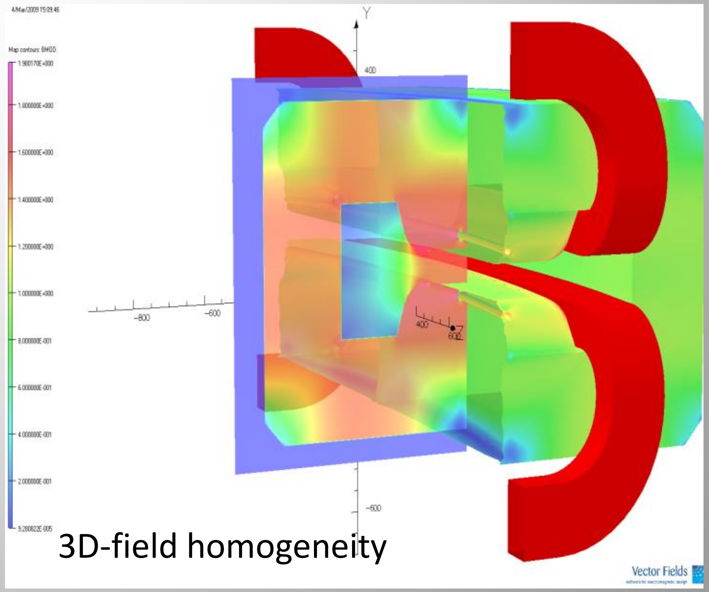
# 3D Design

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



# Magnet ends

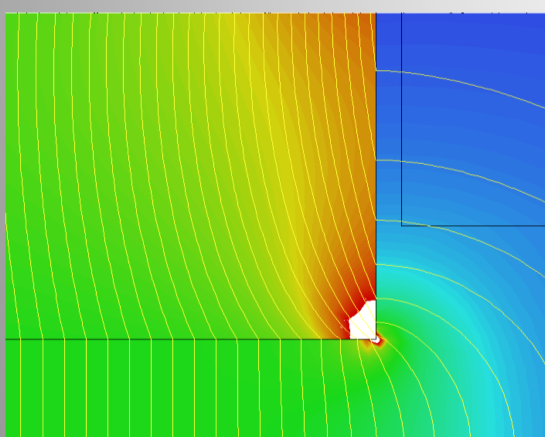
Special attention has to be paid to the magnet ends:

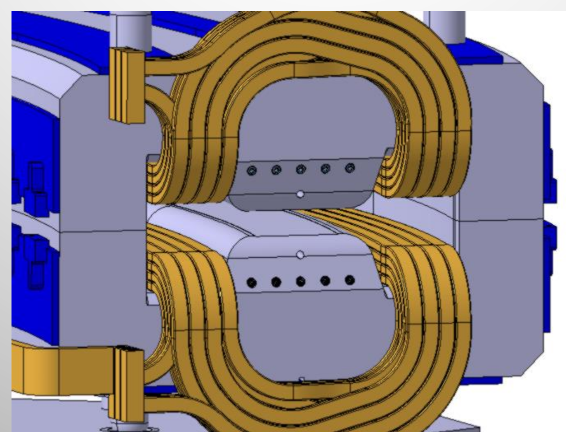
- A square end will introduce significant higher-order multi-poles
- Therefore, it is necessary to terminate the magnet in a controlled way by shaping the end either by cutting away or adding material → longitudinal or end-shimming

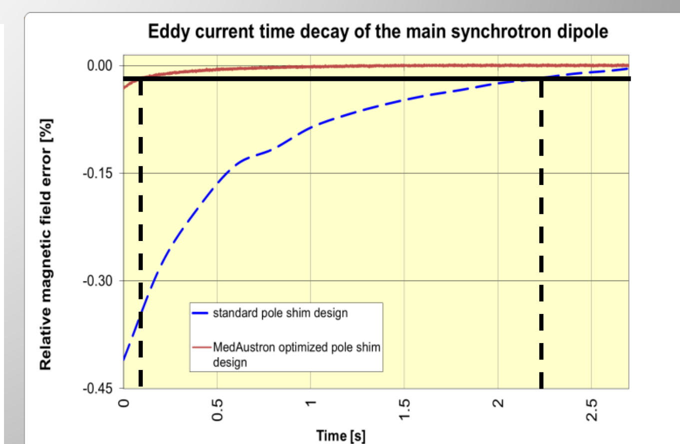
The goal of successful shimming is to:

- adjust the magnetic length
- improve the integrated field homogeneity
- prevent saturation in a sharp corner
- prevent flux entering perpendicular to the laminations inducing eddy currents

Typically, shimming is an iterative process between magnetic measurments and mechanically adjustment of the shim profile



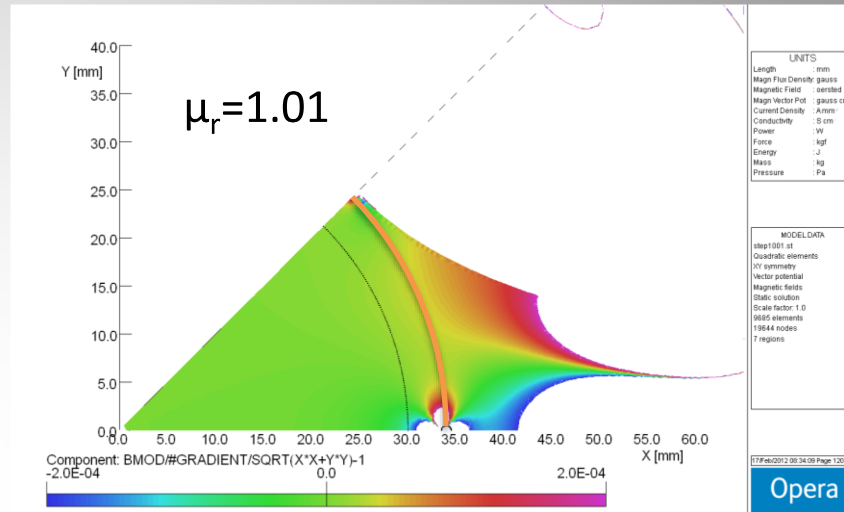


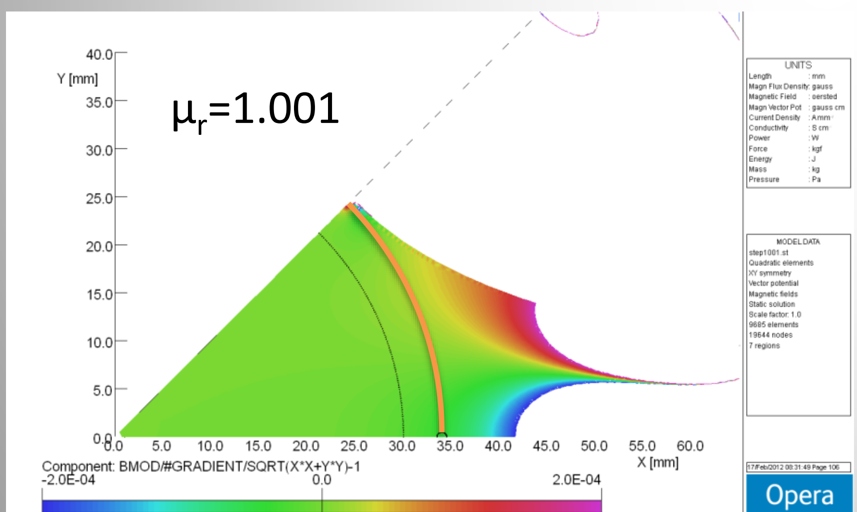


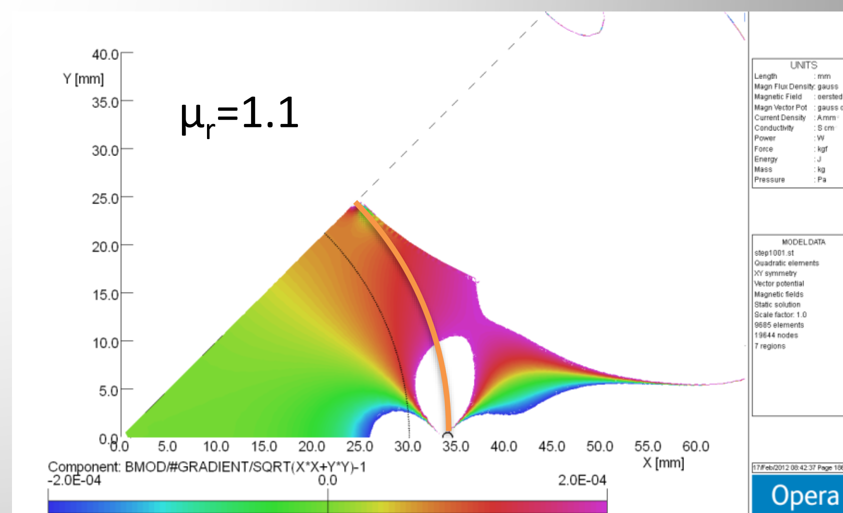
# Case 1: A material problem

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



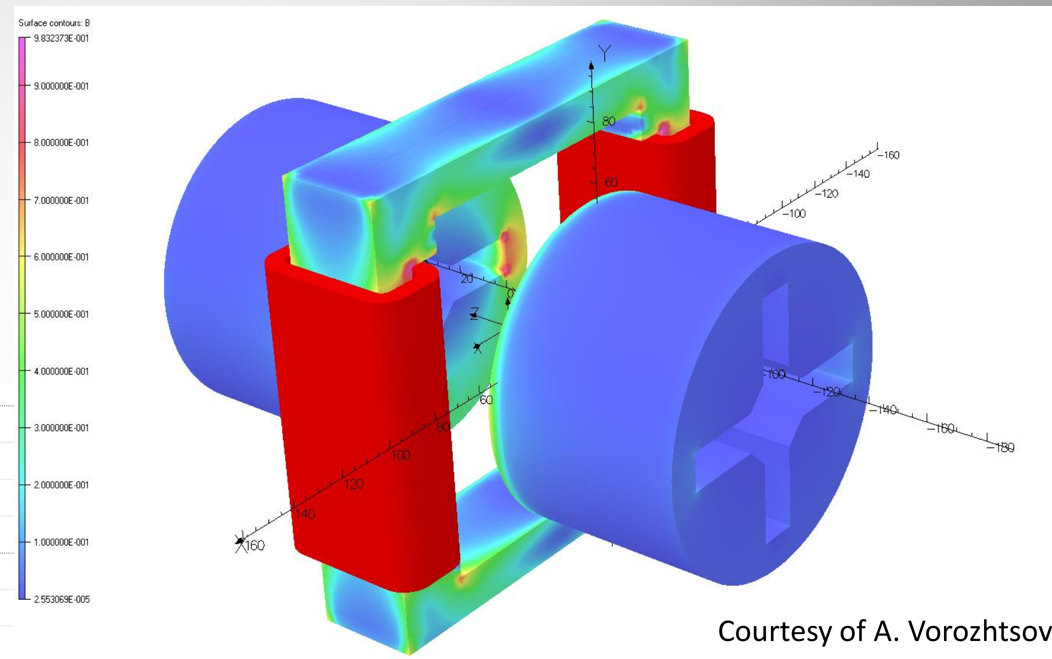



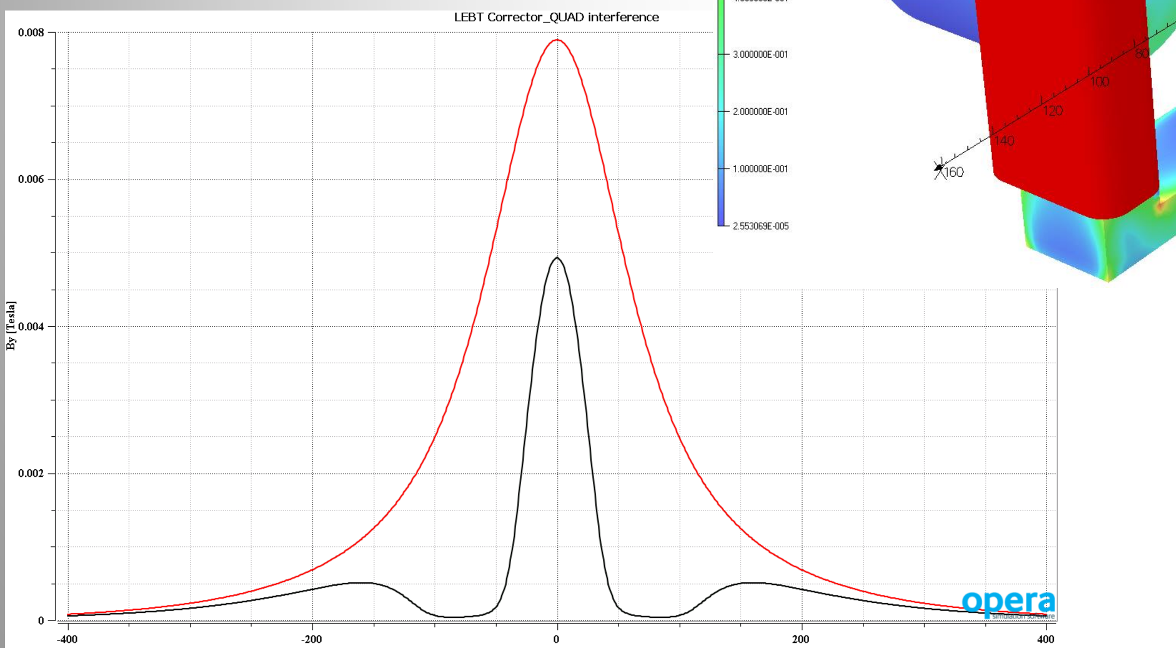

A small distortion can significantly influence the field quality in the GFR!

# Case 2: An interference problem

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

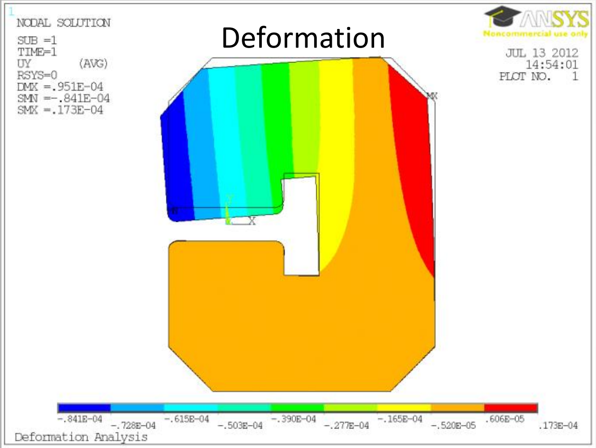


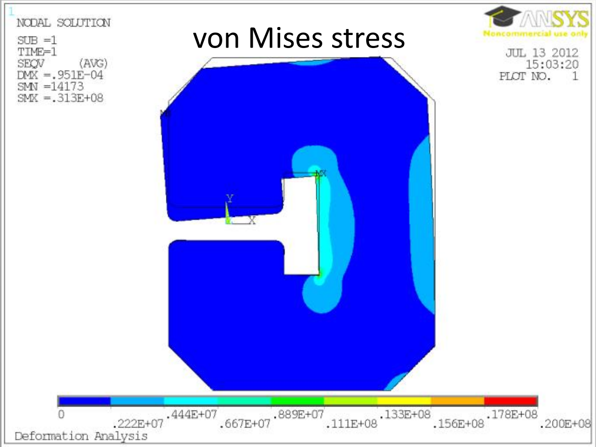

Courtesy of A. Vorozhtsov

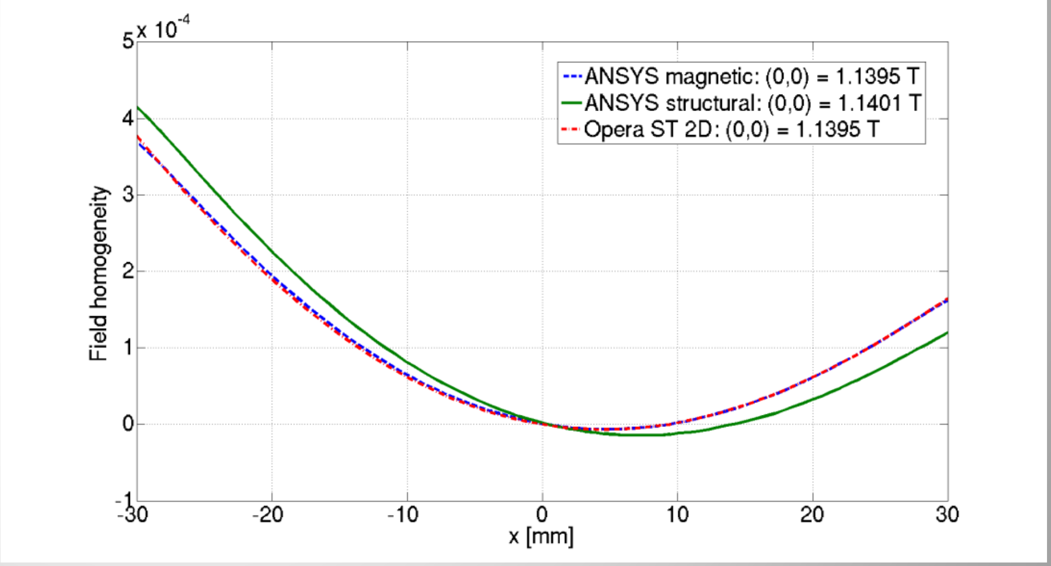


# Case 3: Mechanical deformation

- 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 ($\propto \Delta x^{2\sim3}$ ); 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