

Joint Universities Accelerator School

JUAS 2014

Archamps, France, 17<sup>th</sup> – 21<sup>st</sup> February 2014

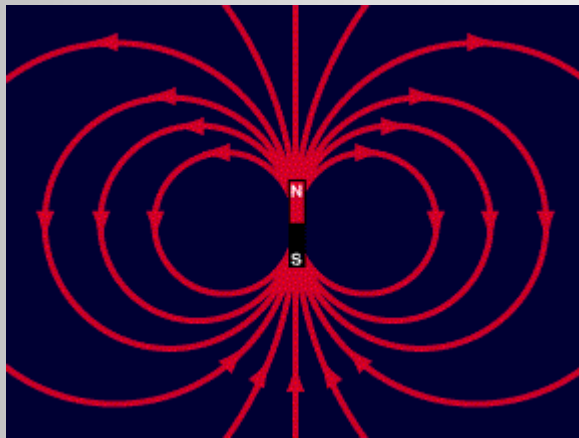
# Normal-conducting accelerator magnets

Thomas Zickler,

CERN



# Lecture 3: 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**, etc...

Technique is iterative

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

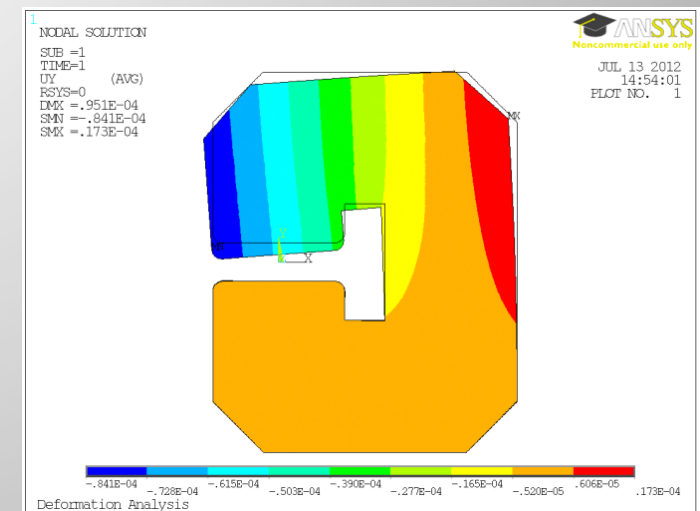
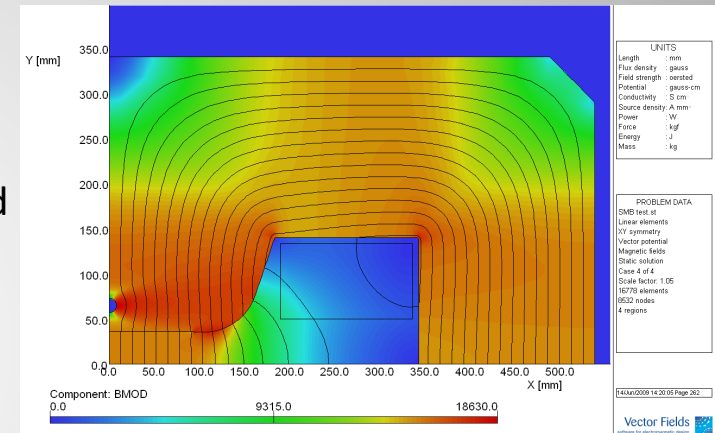
Advanced codes offer:

- 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 license 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

- 2D analysis is often sufficient
- magnetic solvers allow currents only perpendicular to the plane
- fast

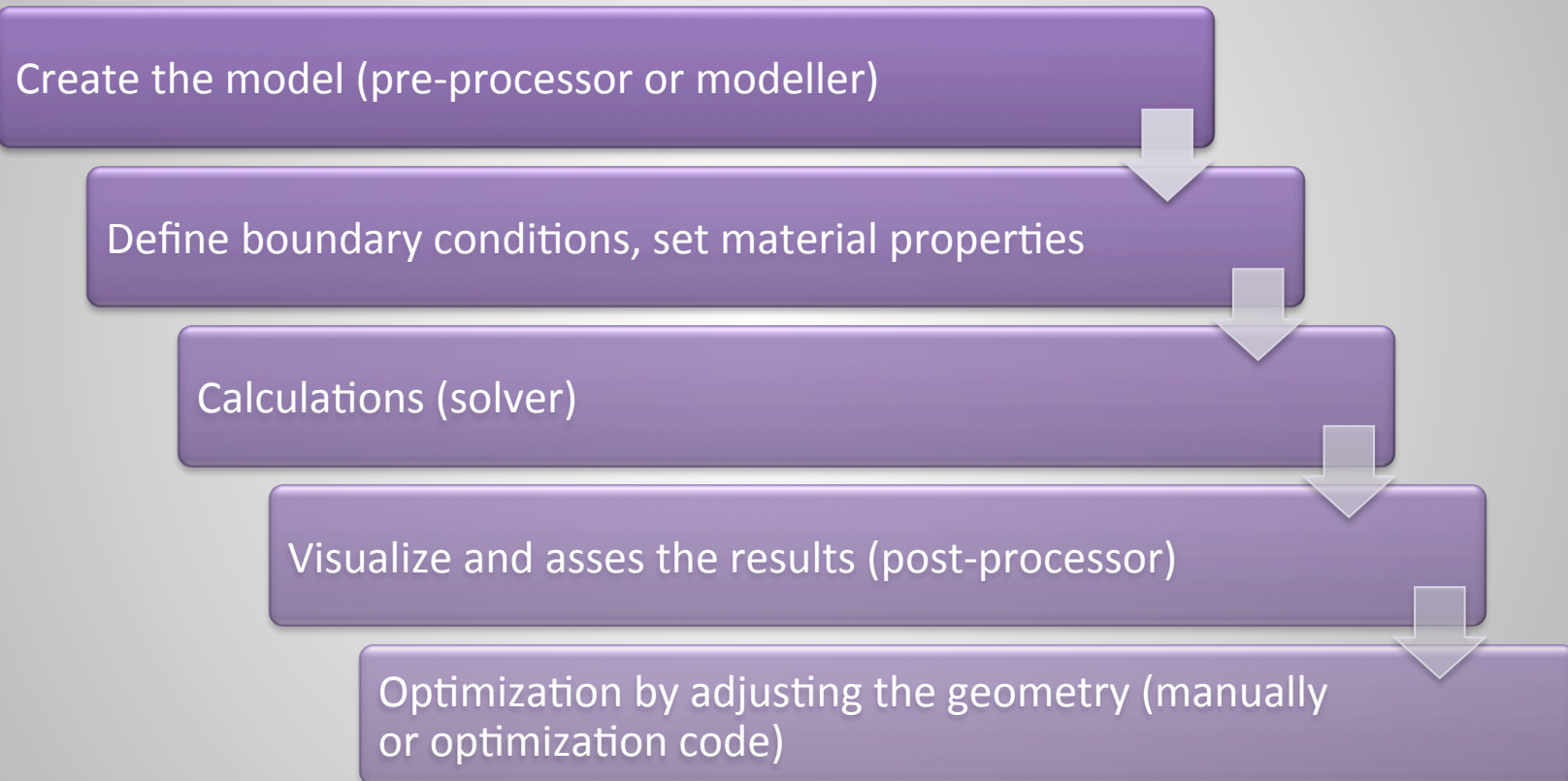
### 3D

- produces large amount of elements
- mesh generation and computation takes significantly longer
- end effects included
- powerful modeller



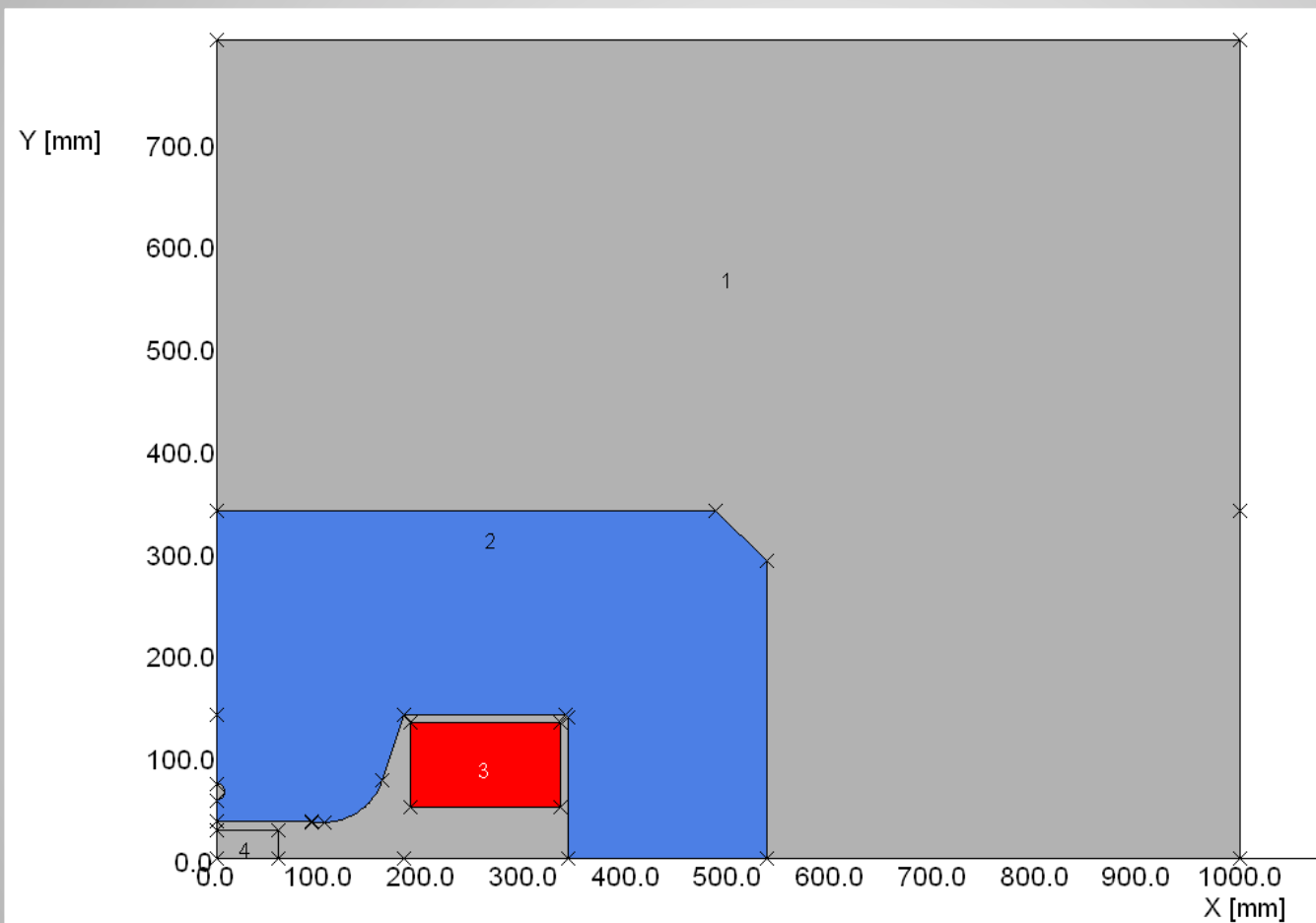
# Numerical design process

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





# Creating the model



UNITS	
Length	: mm
Flux density	: gauss
Field strength	: oersted
Potential	: gauss-cm
Conductivity	: S cm <sup>-1</sup>
Source density	: A mm <sup>-2</sup>
Power	: W
Force	: kgf
Energy	: J
Mass	: kg

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

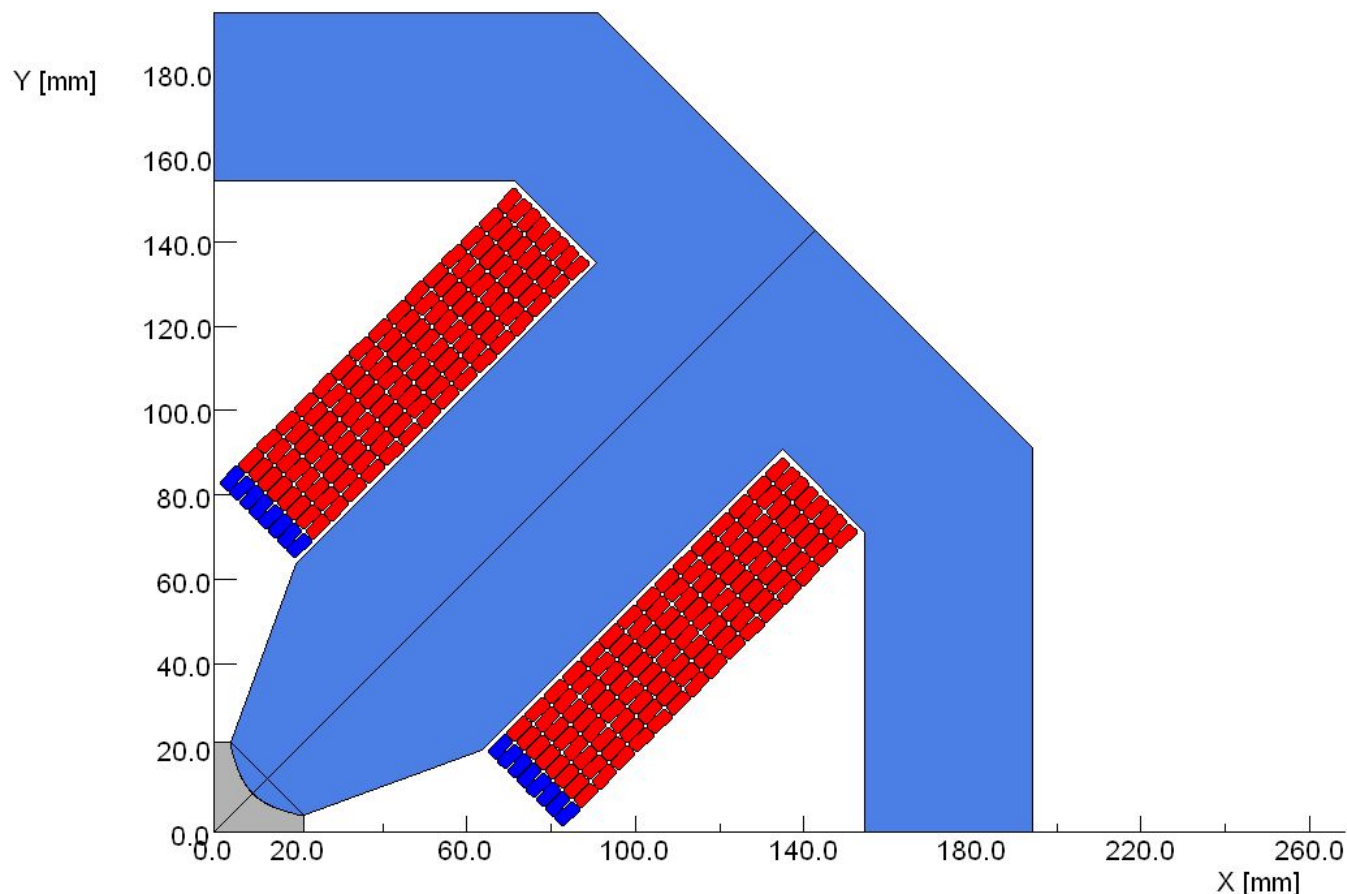
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# Model symmetries



CLIC DB Quadrupole V3c (T. Zickler)



UNITS	
Length	: mm
Flux density	: T
Field strength	: A m <sup>-1</sup>
Potential	: Wb m <sup>-1</sup>
Conductivity	: S m <sup>-1</sup>
Source density	: A mm <sup>-2</sup>
Power	: W
Force	: N
Energy	: J
Mass	: kg

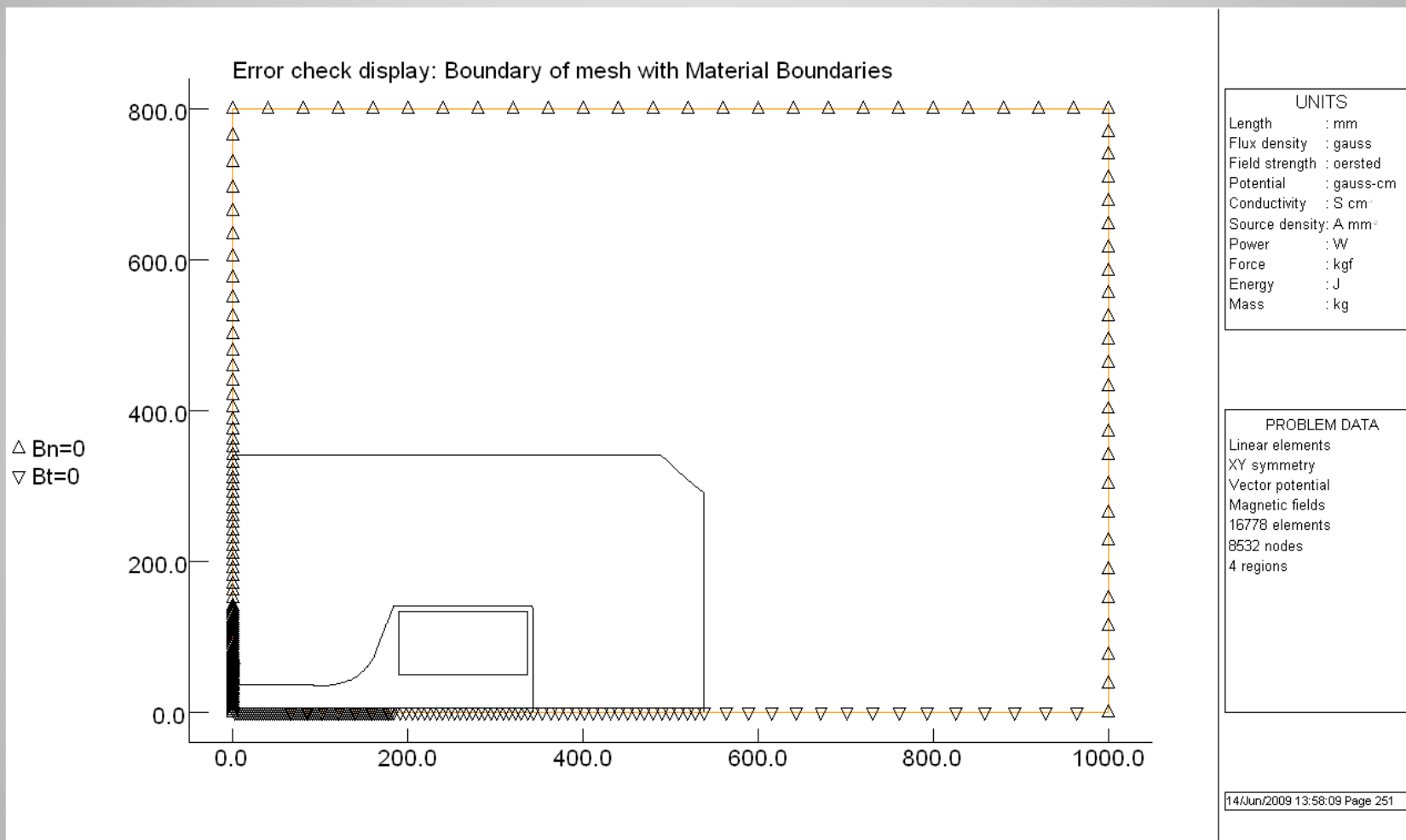
PROBLEM DATA  
 Quadratic elements  
 XY symmetry  
 Vector potential  
 Magnetic fields  
 No mesh  
 39 regions

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

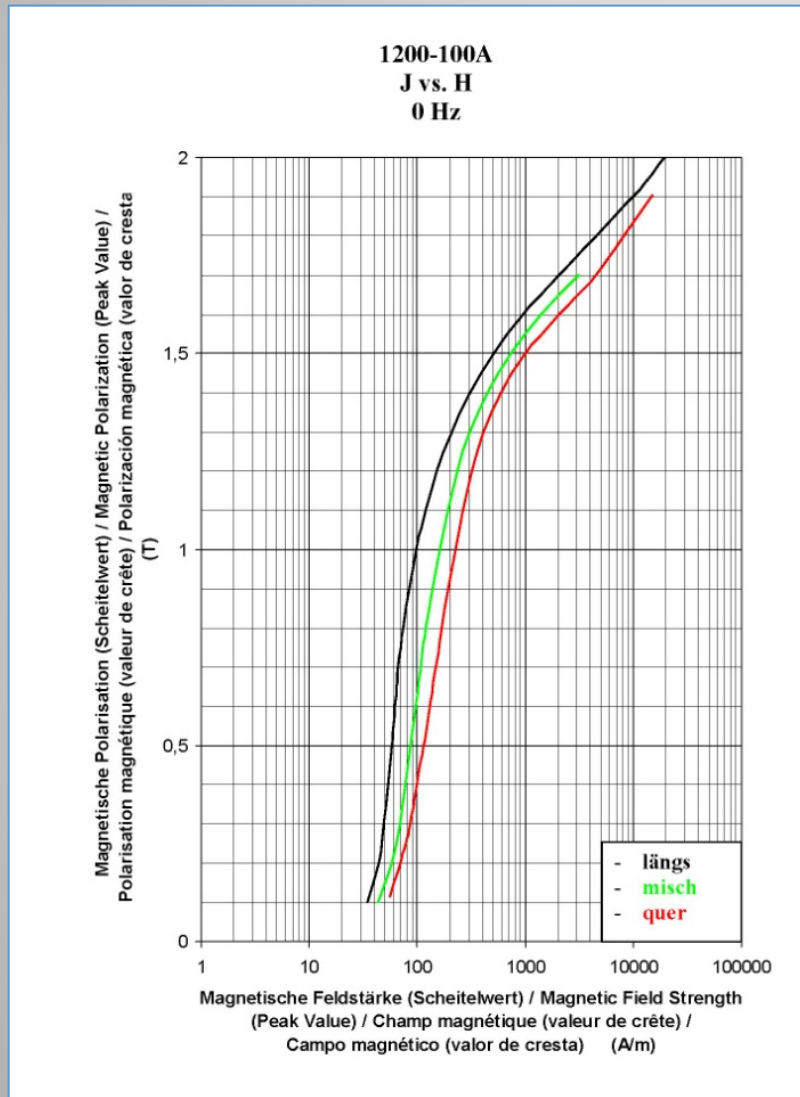


# Boundary conditions





# 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

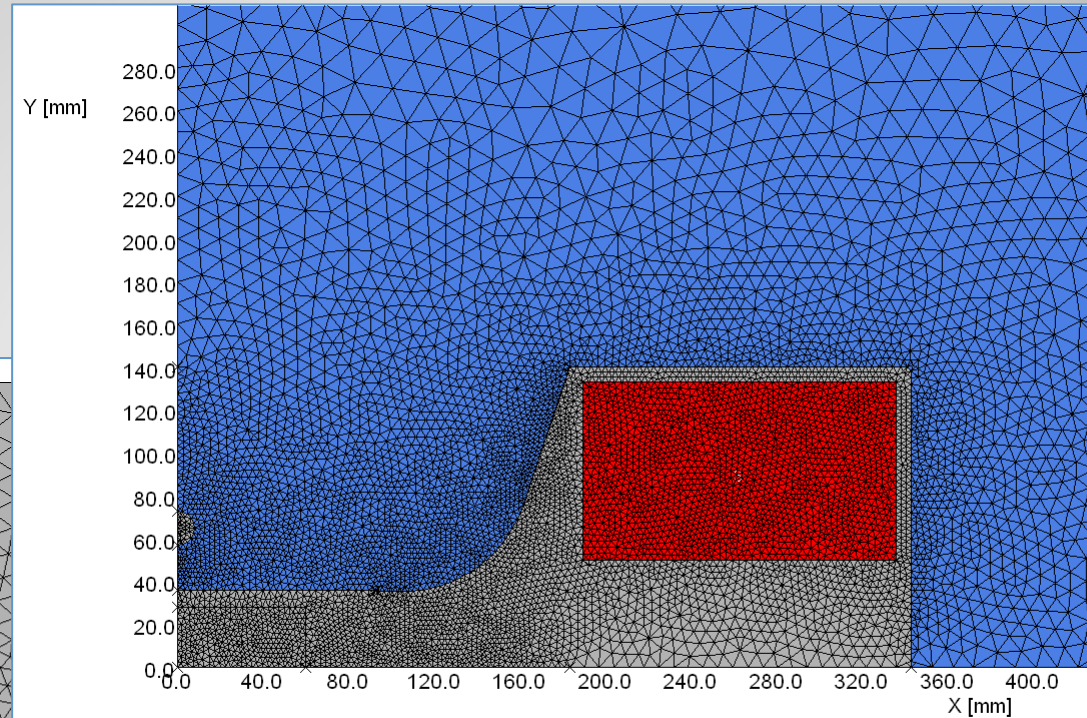
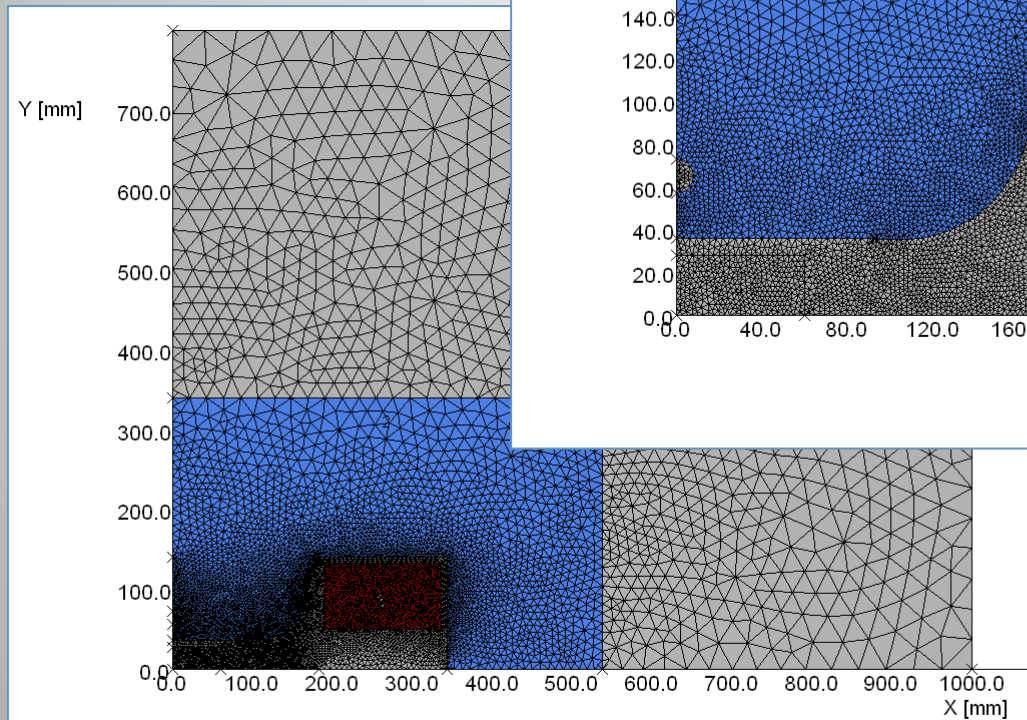
## Mechanical and thermal properties:

- in case of combined structural or thermal analysis

## Current density in the coils



# Mesh generation



UNITS	
Length	: mm
Flux density	: gauss
Field strength	: oersted
Potential	: gauss-cm
Conductivity	: S cm
Source density	: A mm <sup>2</sup>
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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Vector Fields  
software for electromagnetic design

Magnetic fields  
16778 elements  
8532 nodes  
4 regions

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Vector Fields  
software for electromagnetic design



# 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...

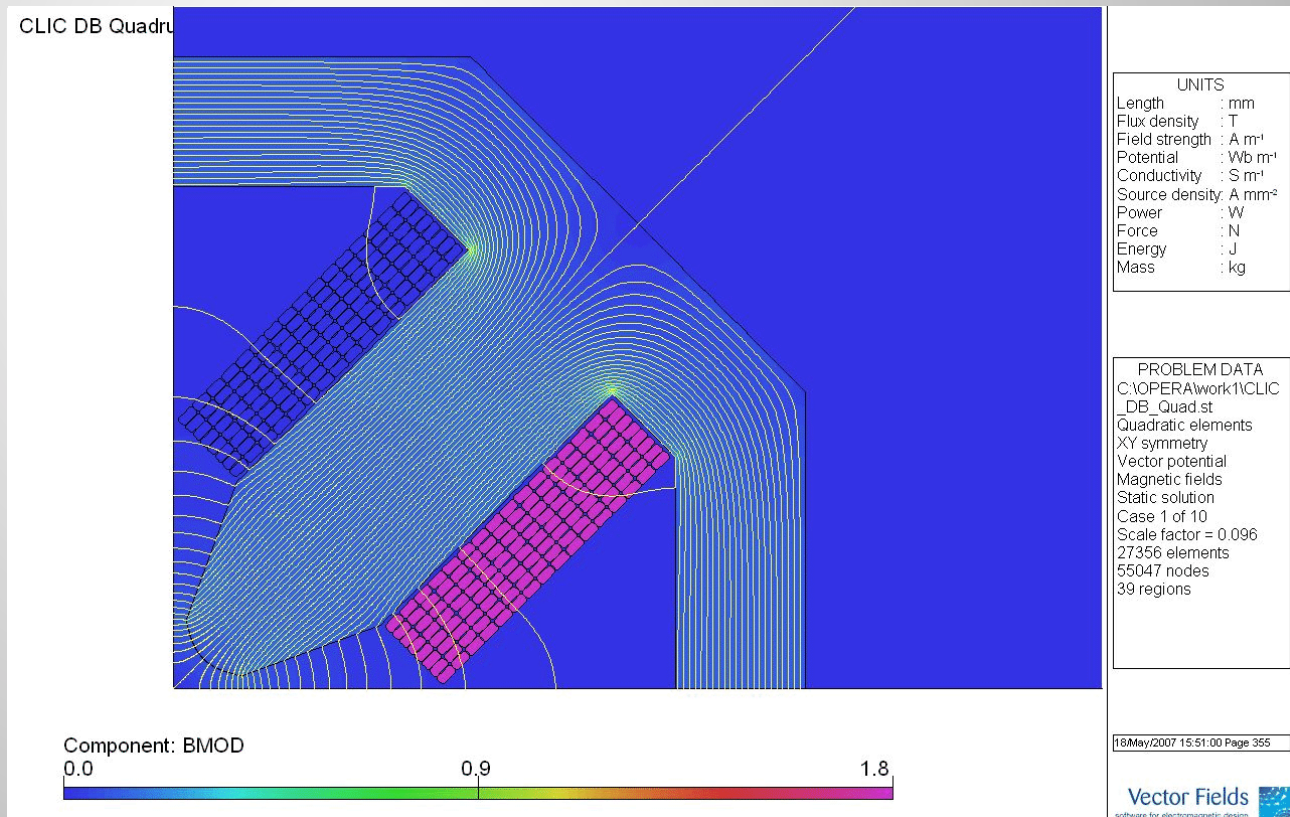


# Analyzing the results



With the help of the post-processor, field distribution and field quality 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

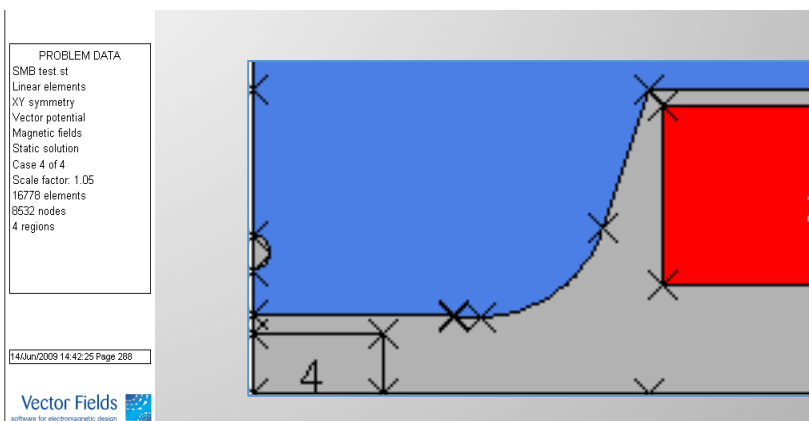
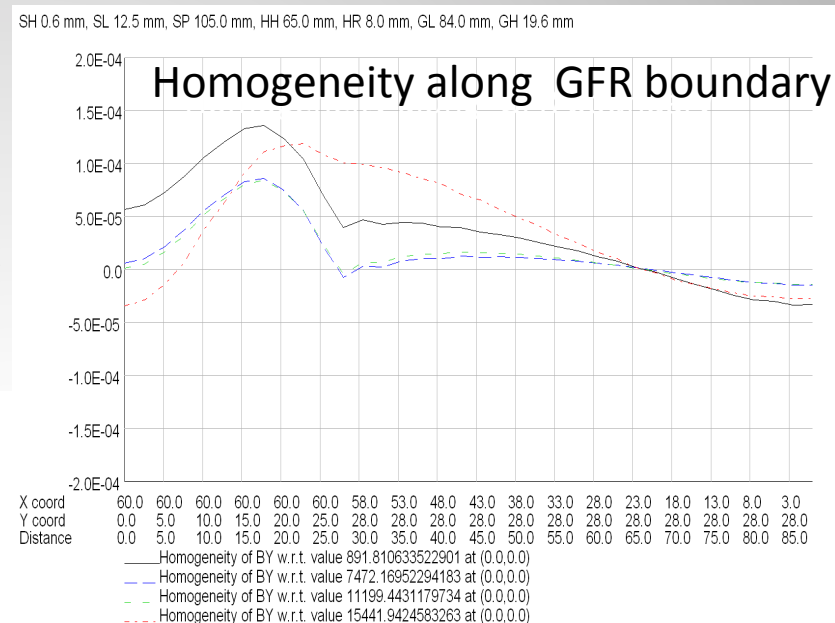
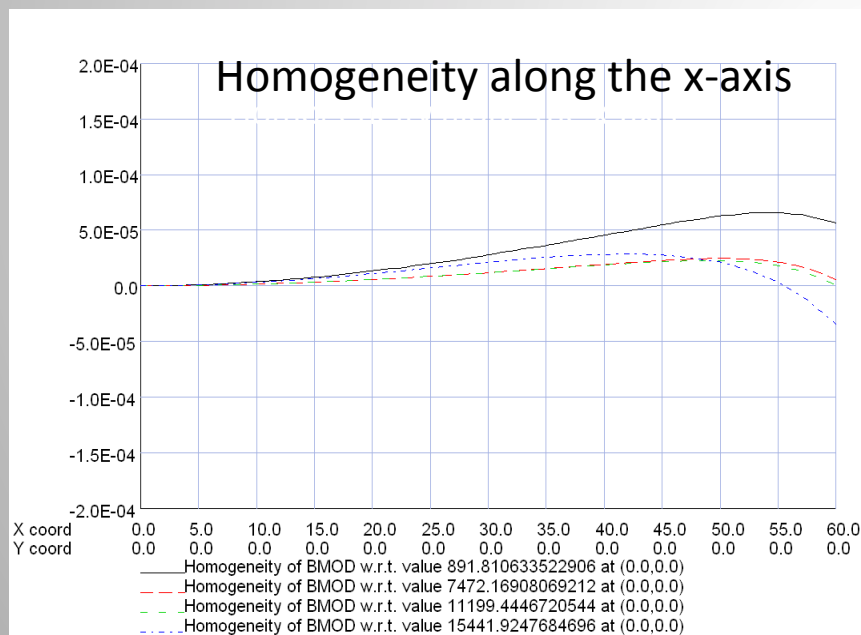




# Field homogeneity in a dipole

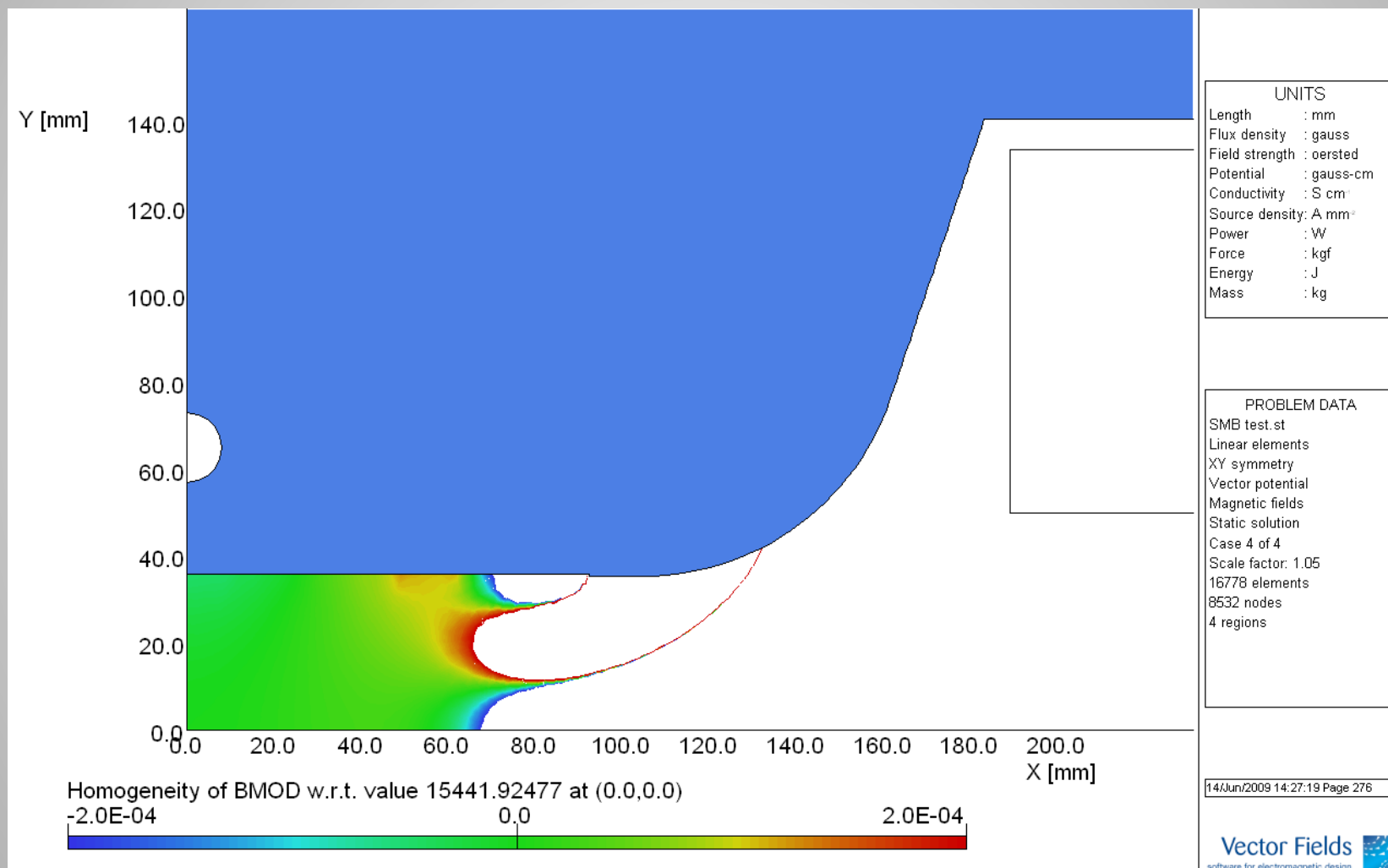
A simple judgment of the field quality can be done by plotting the field homogeneity

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



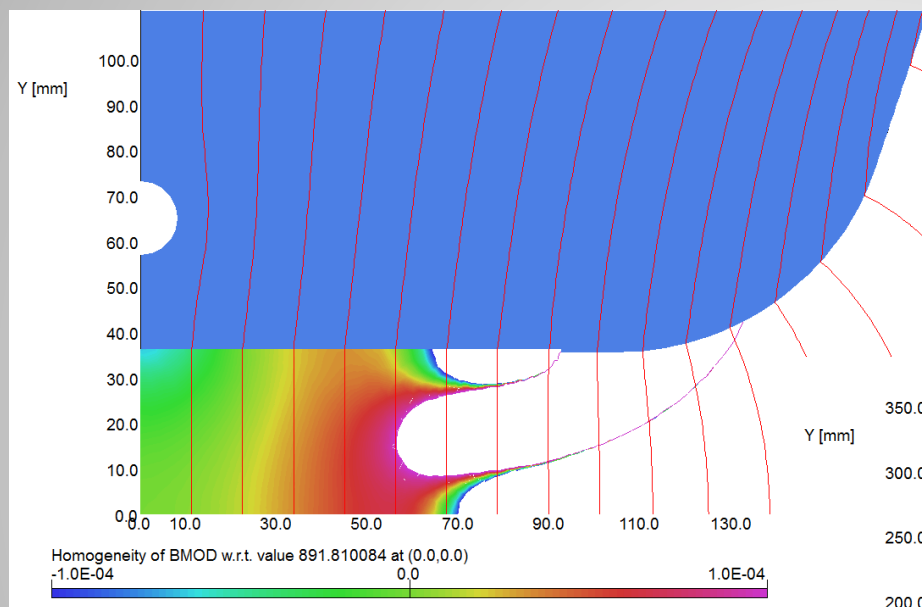


# Field homogeneity in a dipole

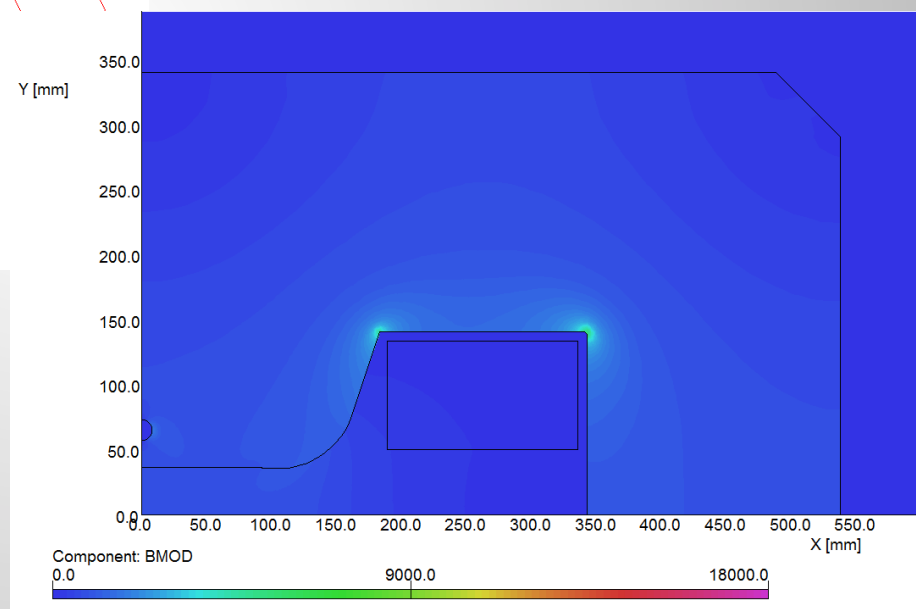




# Saturation and field quality



Also very low fields can disturb the field quality significantly



Field quality can vary with field strength due to saturation

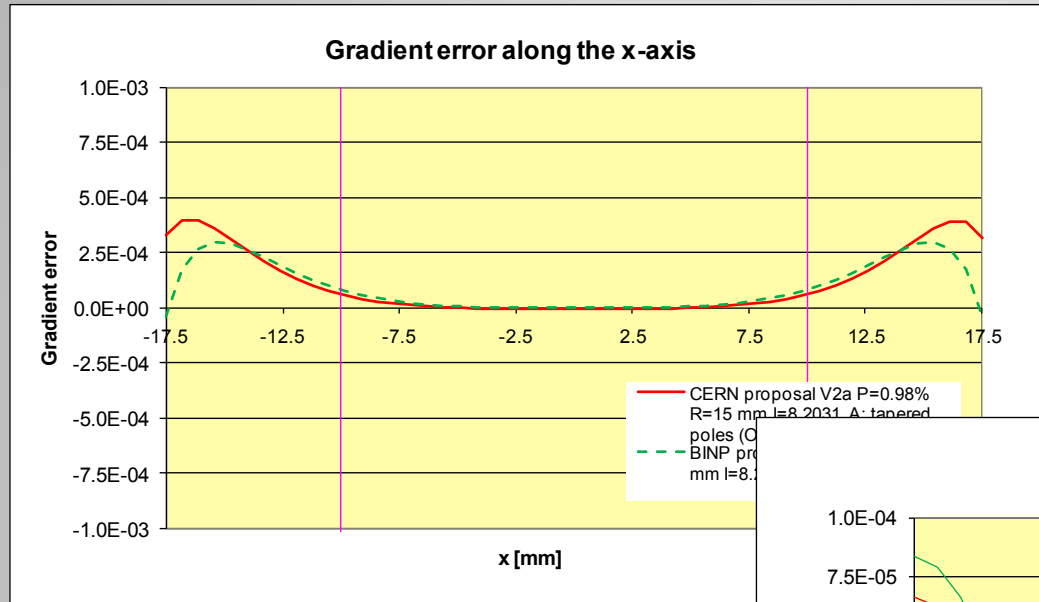


# Field homogeneity in a quadrupole



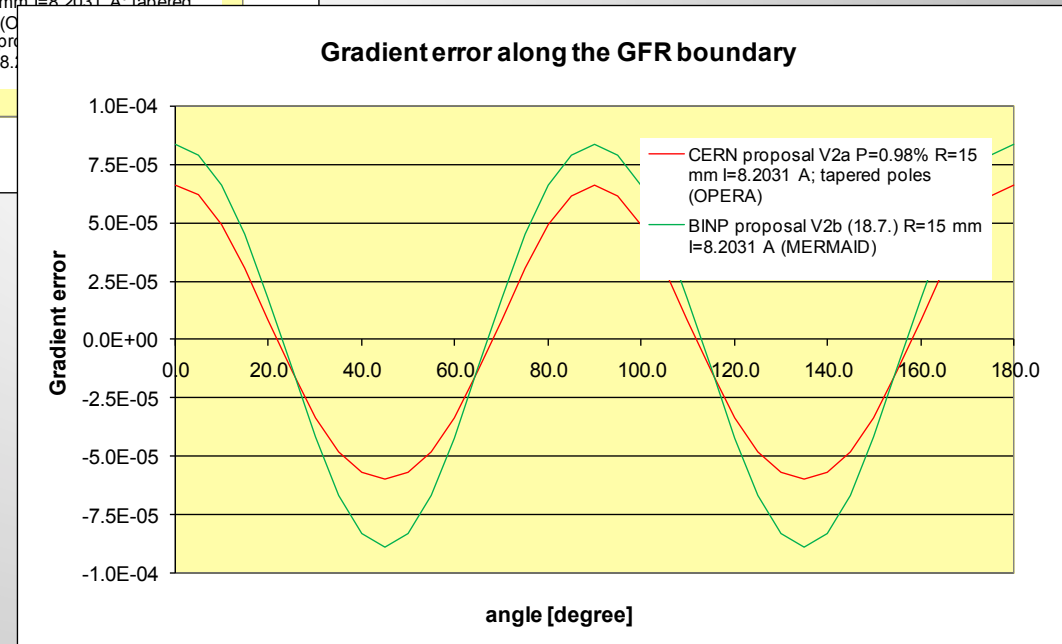
Field homogeneity in a quadrupole

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



Gradient homogeneity along the x-axis

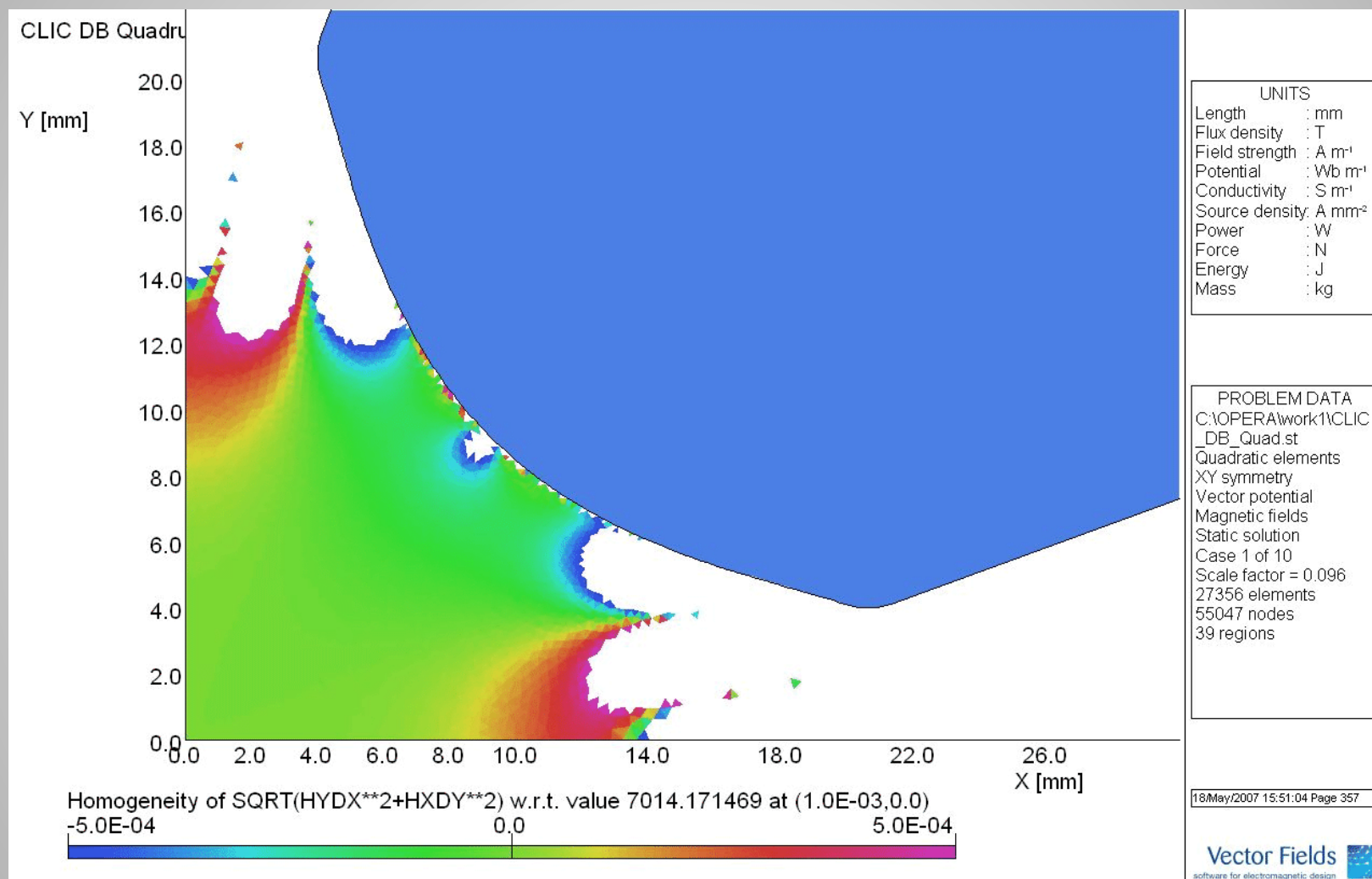
$$\frac{\Delta B'}{B'_0} \leq 0.1\%$$



Gradient homogeneity along circular GFR



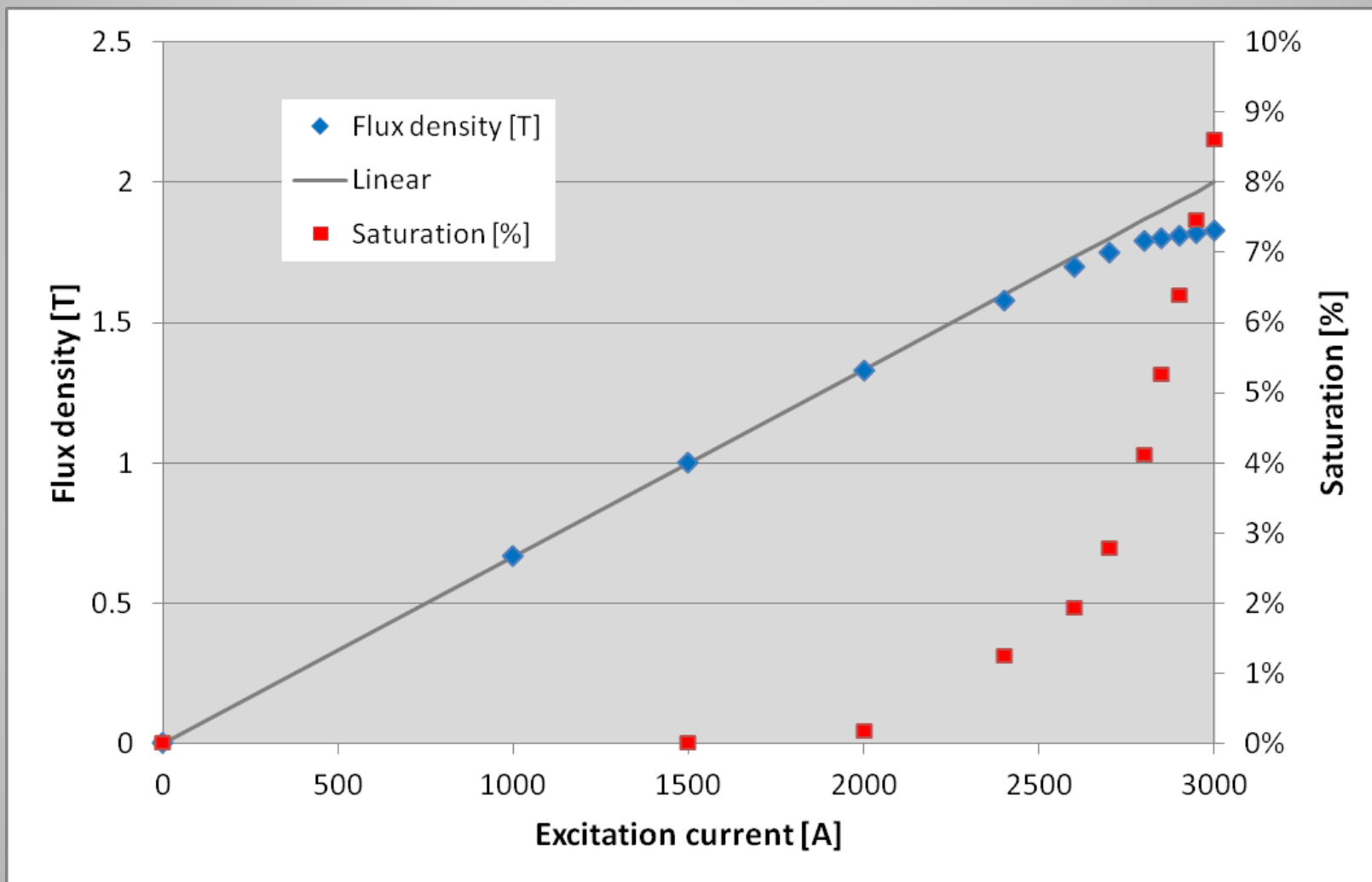
# Saturation and field quality



Field quality varies with field strength due to saturation



# Saturation





# Pole tip design



It is easy to derive perfect mathematical pole configurations for a specific field configuration

In practice poles are not ideal: finite width and end effects result in multipole errors disturbing the main field

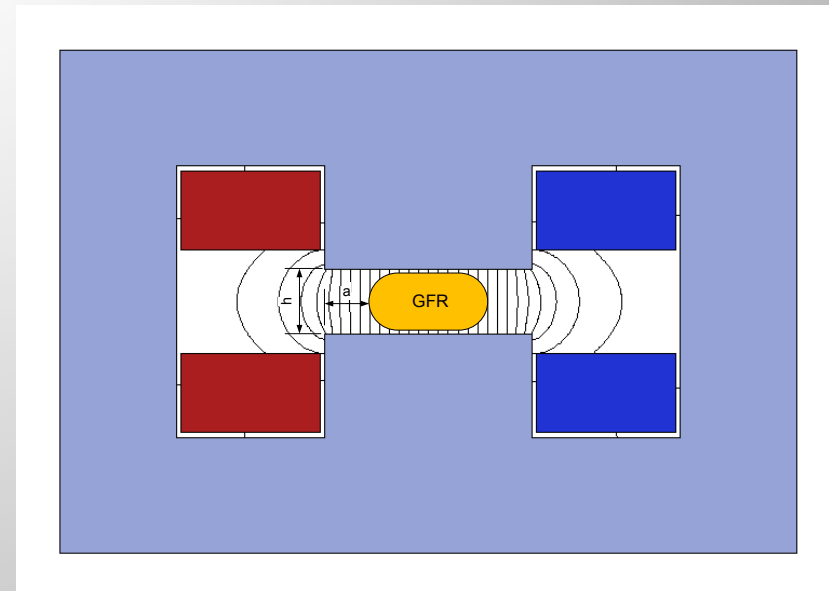
The uniform field region is limited to a small fraction of the pole width

Estimate the size of the poles and calculate the resulting fields

Better approach: calculate the necessary pole overhang using:

$$x_{unoptimized} = 2 \frac{a}{h} = -0.36 \ln \frac{\Delta B}{B_0} - 0.90$$

- $x$ : 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



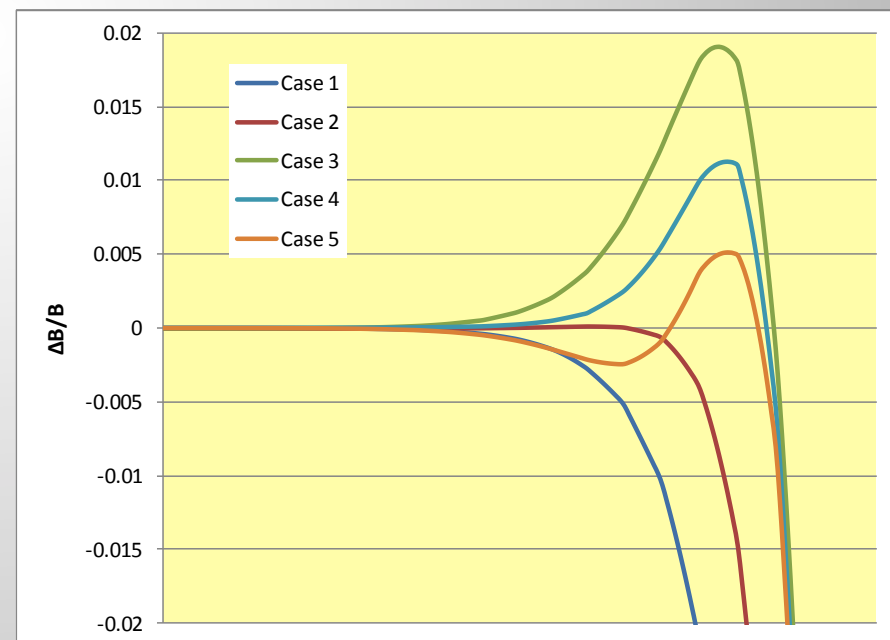
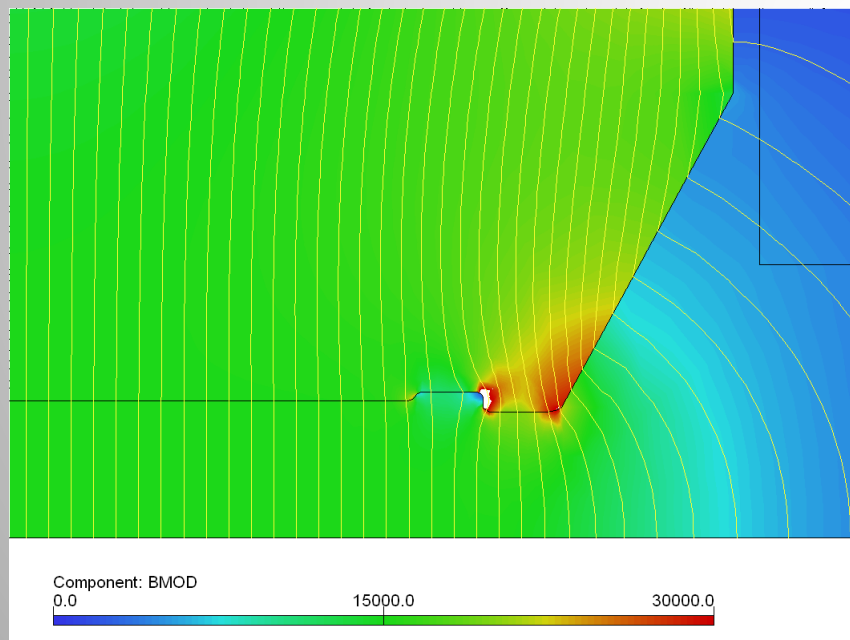


# Pole optimization



„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



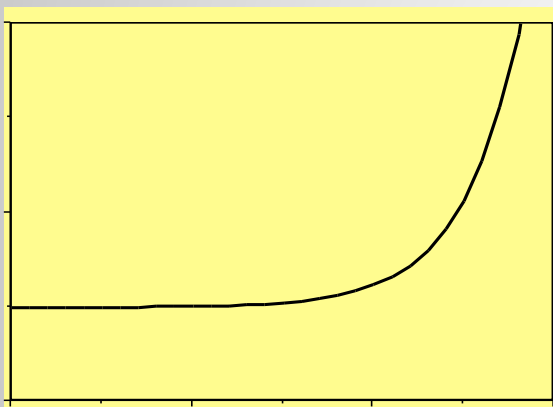


# Rogowsky roll-off



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



# Pole optimization

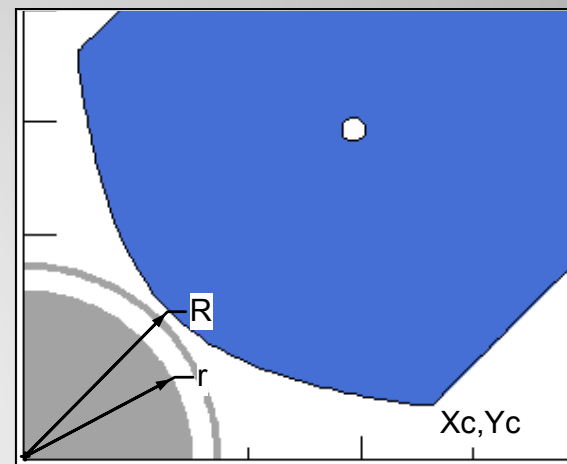


Similar technique can be applied for quadrupoles:

$$\frac{x_c}{R} = \sqrt{\frac{1}{2} \left( \sqrt{(\rho^2 + x_d)^2 + 1} + \rho^2 + x_d \right)}$$

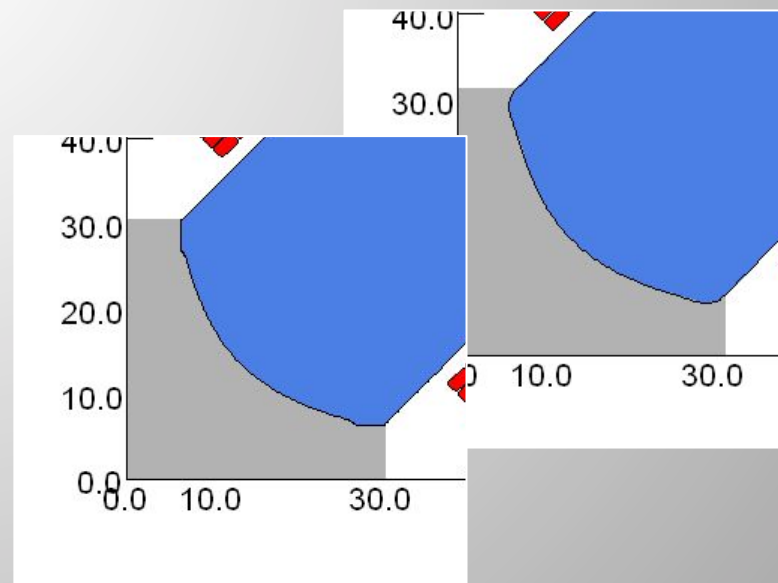
$$\frac{y_c}{R} = \sqrt{\frac{1}{2} \left( \sqrt{(\rho^2 + x_d)^2 + 1} - \rho^2 - x_d \right)}$$

- $x_c$ : un-optimized resp. optimized pole overhang from dipole
- $\rho$ : normalized good field radius  $r/R$



Pole optimization:

- Tangential extension of the hyperbola
- Additional bump = shim
- Round off sharp edge
- Tapered pole





# Multipole expansion

The amplitude and phase of the harmonic components in a magnet are good ‘figures of merit’ to assess the field quality of a magnet

$$B_y + iB_x = B_{ref} \sum_{n=1}^{\infty} (b_n + ia_n) \cdot \left( \frac{x + iy}{R_{ref}} \right)^{n-1}$$

- The normal ( $b_n$ ) and the skew ( $a_n$ ) multipole coefficients 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
- Due to the finite size of the poles, higher order multipole components appear
- They are intrinsic to the design and called ‘allowed’ multipoles

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

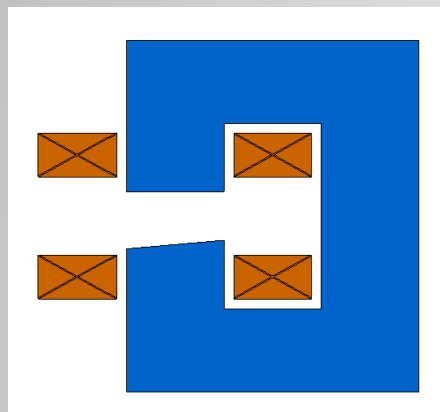
- $n$ : order of multipole component
- $N$ : order of the fundamental field
- $m$ : integer number ( $m \geq 1$ )

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

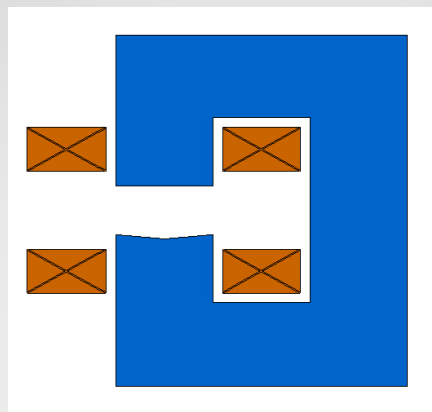


# Asymmetries

## Asymmetries generating 'non-allowed' harmonics

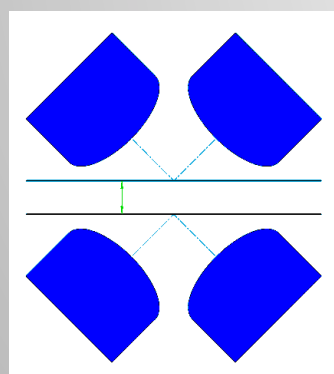


$n = 2, 4, 6, \dots$

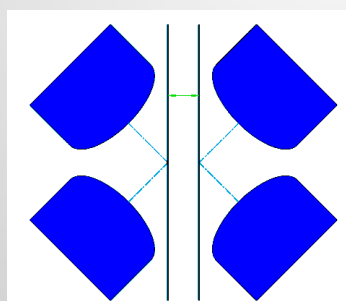


$n = 3, 6, 9, \dots$

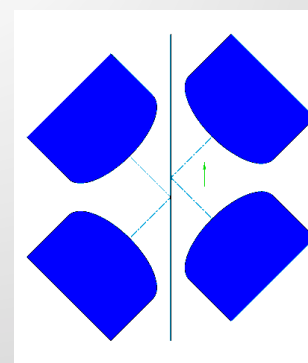
Comprehensive studies about the influence of manufacturing errors on the field quality have been done by [K. Halbach](#).



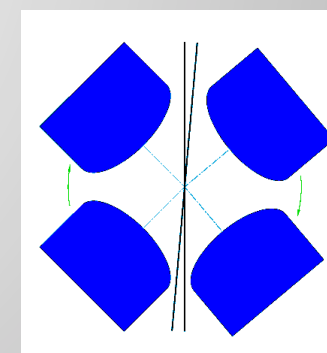
$n = 4$  (neg.)



$n = 4$  (pos.)



$n = 3$



$n = 2, 3$

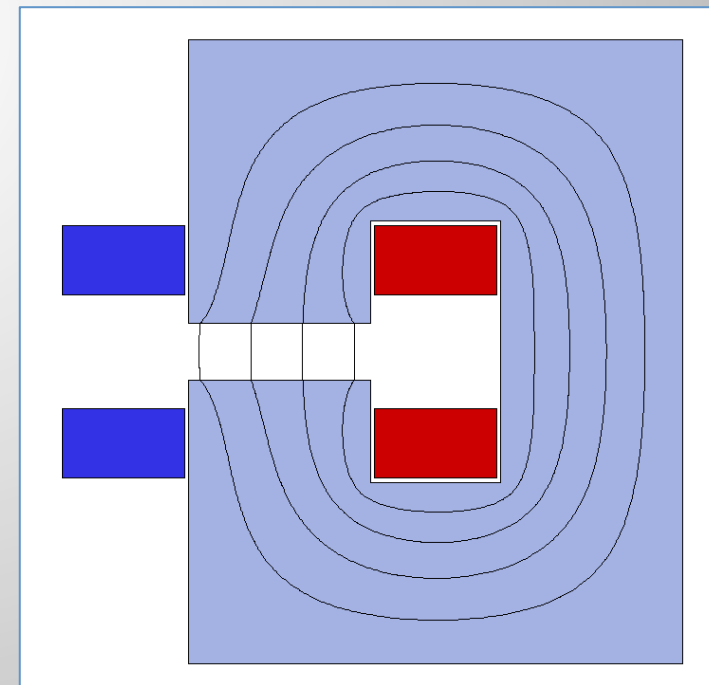
These errors can seriously affect machine behaviour and must be controlled!



# Asymmetry in a C-magnet



- C-magnet: one-fold symmetry
- Since  $NI = \oint \vec{H} \cdot d\vec{l} = \text{const.}$  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  $n = 2, 4, 6, \dots$  changing with saturation
- Quadrupole term resulting in a gradient around 0.1% across the pole





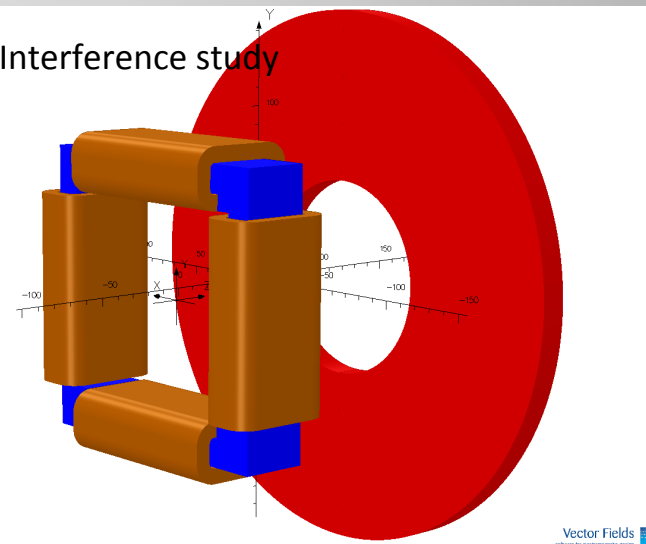
# 3D Design



Becomes necessary to study:

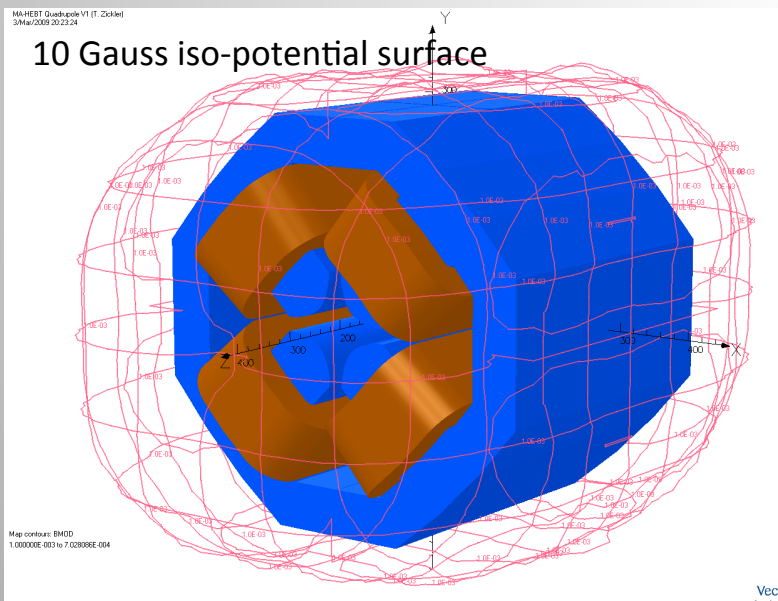
- the longitudinal field distribution
- end effects in the yoke
- end effects from coils
- magnets where the aperture is large compared to the length
- spacial field distribution

Interference study



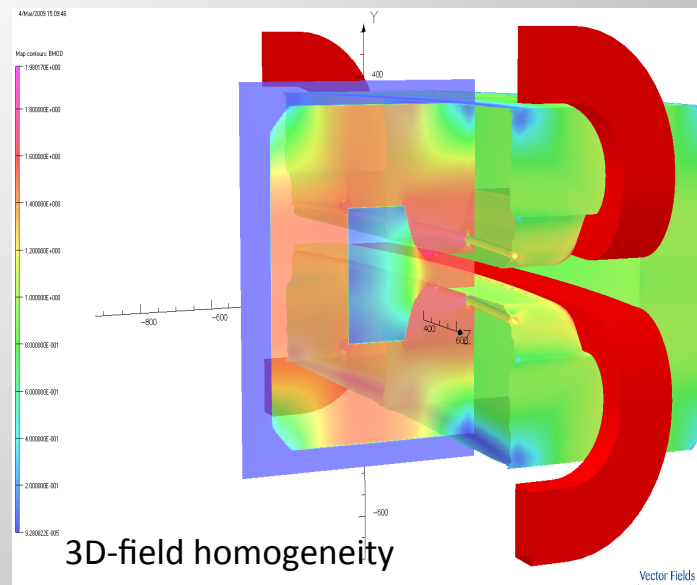
Vector Fields  
software for electromagnetic design

10 Gauss iso-potential surface



Vector  
software for electromagnetic design

3D-field homogeneity



Vector Fields  
software for electromagnetic design



# 3D Design



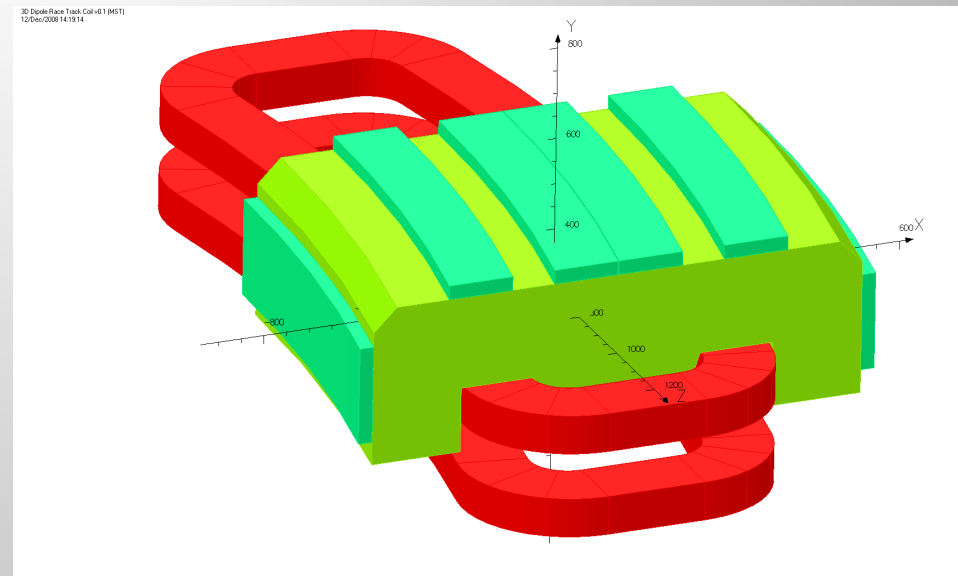
Similar to 2D

Creating the 3D model:

- Use pre-processor or modeller to build geometry
- Profit from symmetries to reduce number of elements
- Difference: all regions with current density have to be modelled completely

Postprocessing:

- Field lines and color contours plots of flux, field, current density
- Graphs showing absolute or relative field distribution
- Homogeneity plots
- Harmonics
- In addition: particle tracking





# Magnet ends

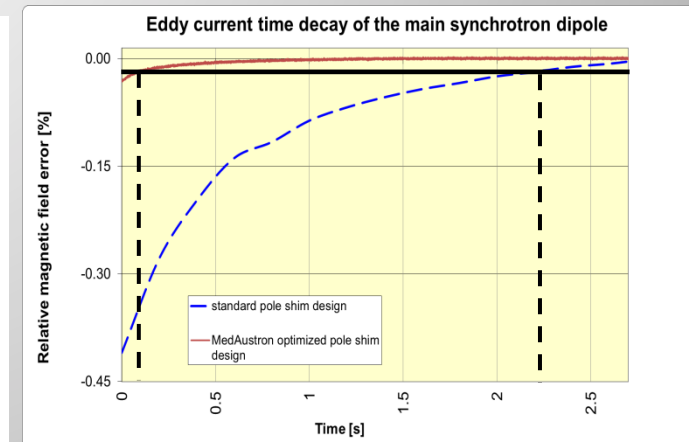
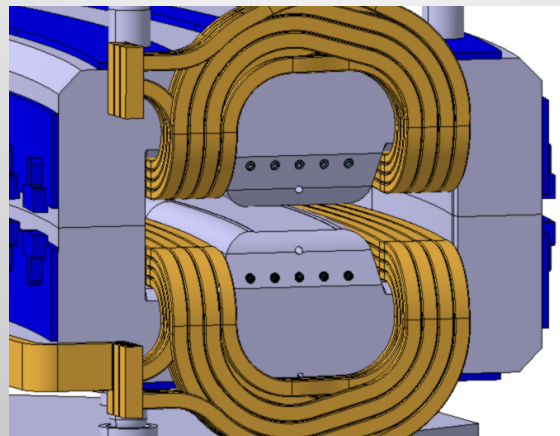
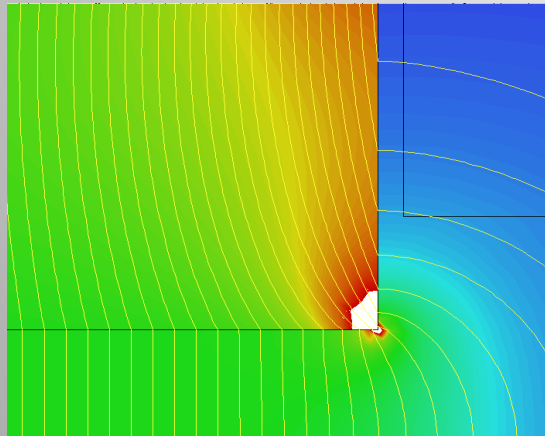


Special attention has to be paid to the magnet ends:

- 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
- maintain magnetic length constant across the good field region
- prevent flux entering perpendicular to the laminations inducing eddy currents





# Shimming procedure

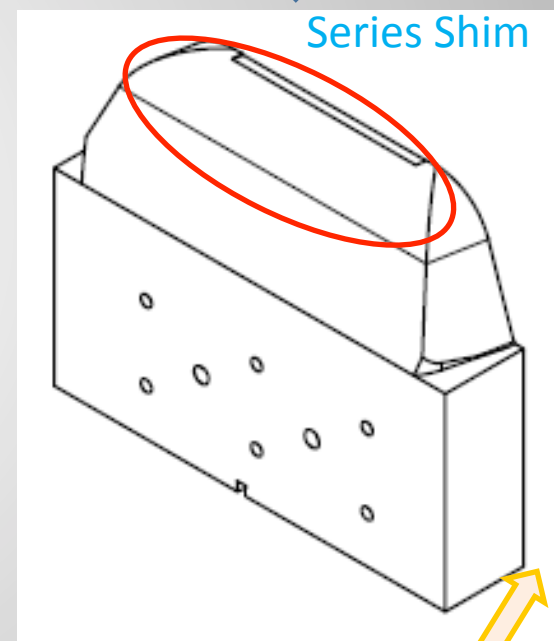
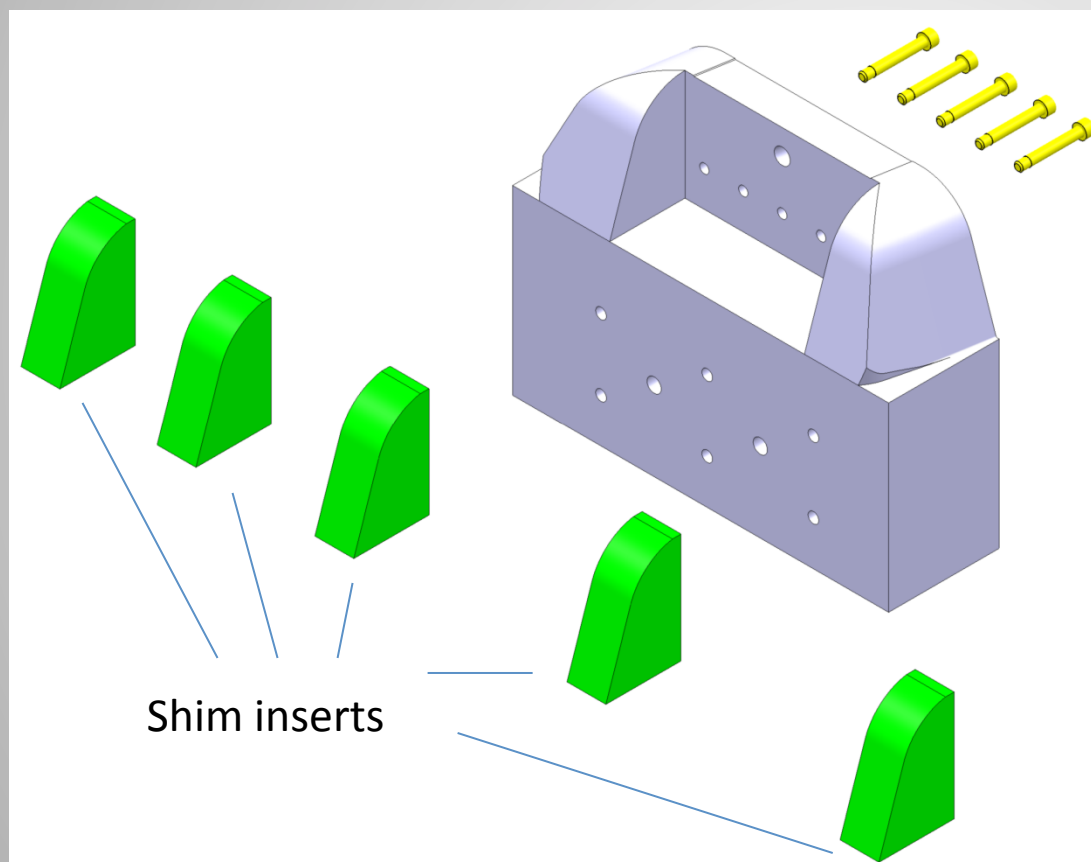
Prototype Shim



Standard pole end profile



Series Shim



Add thin laminations

Typically, shimming is an iterative process between magnetic measurements and mechanical adjustment of the shim profile

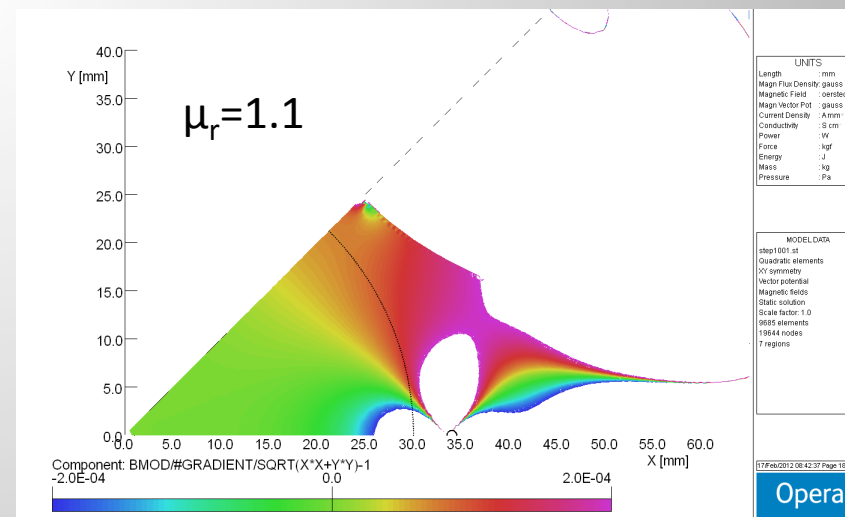
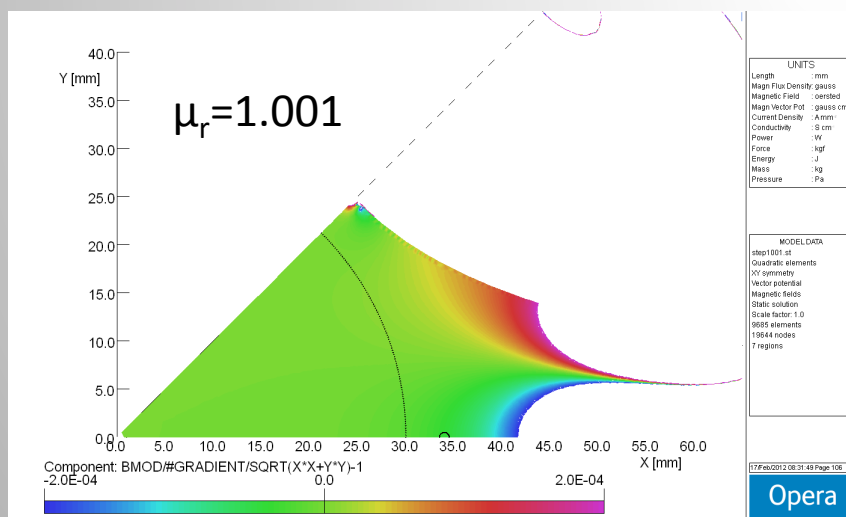
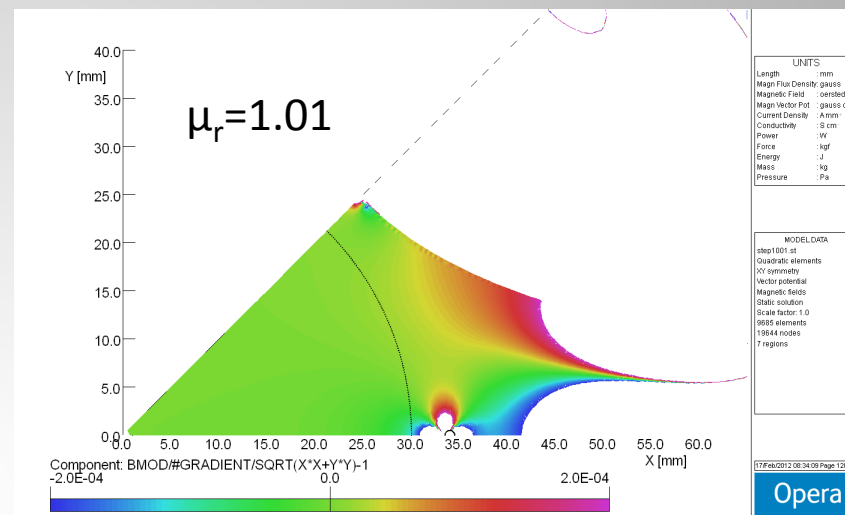


# Case 1: A material problem



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 in the GFR can **significantly** influence the field quality!



## Case 2: An eddy current problem



### Eddy currents:

- Because of the electrical conductivity of steel, eddy currents can be generated in solid magnet cores
- This is the reason why pulsed magnets are made of laminated steel
- Nevertheless, some parts remain massive in order to assure the mechanical strength
- Usually they can be ignored, if they don't contribute to carry magnetic flux and hence see no significant field or a possible dB/dt

### Problem:

- Magnetic field lagging behind the current
- Time constant  $\tau$  in the order of few hundred ms
- Missing field: 0.5 %

### Explanation:

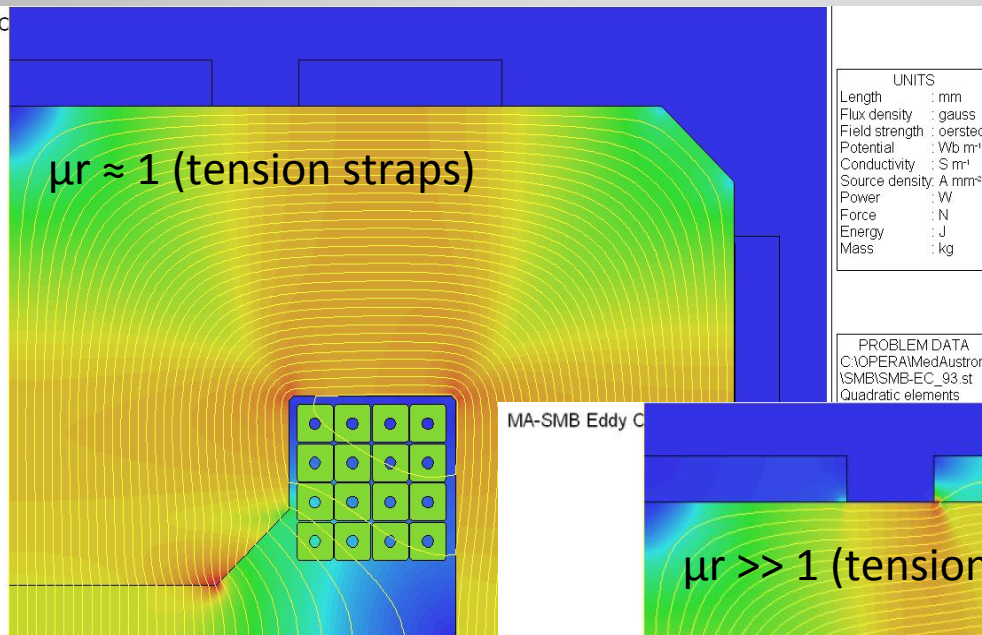
- Eddy currents in the tension bars welded onto the laminated magnet yoke
- The partly saturated return yoke forces the flux into the tension bars
- Only after eddy current have decayed, the flux can enter into the tension bars and reduce the saturation effects in the laminated yoke
- Increase of the central field after the eddy currents have decayed



# Eddy currents - static case



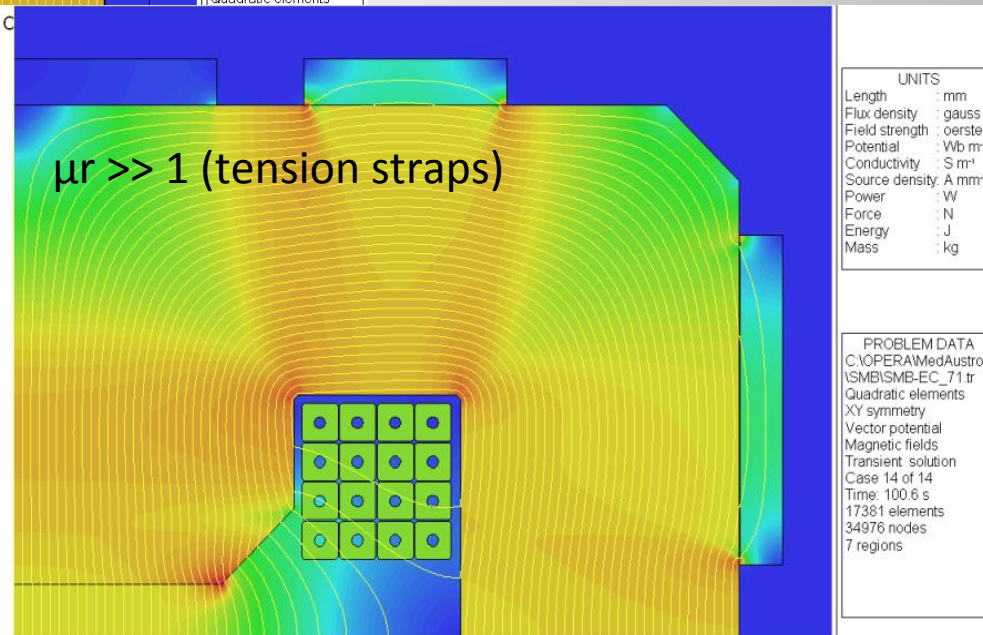
MA-SMB Eddy C



Component: BMOD/10000  
0.0

1.3345

MA-SMB Eddy C



Component: BMOD/10000

0.0

1.3345

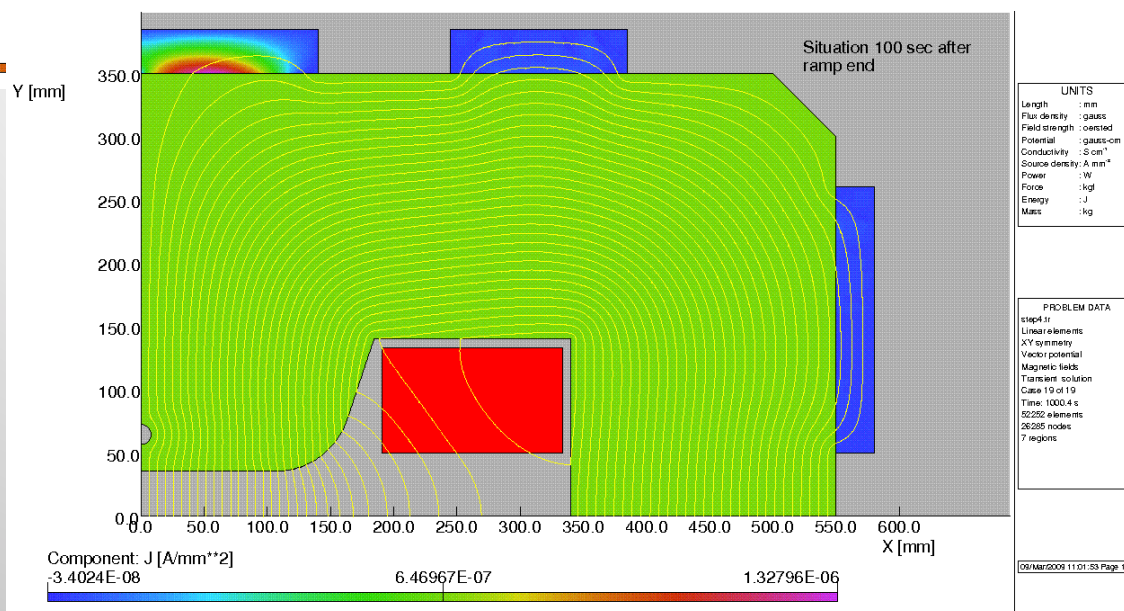
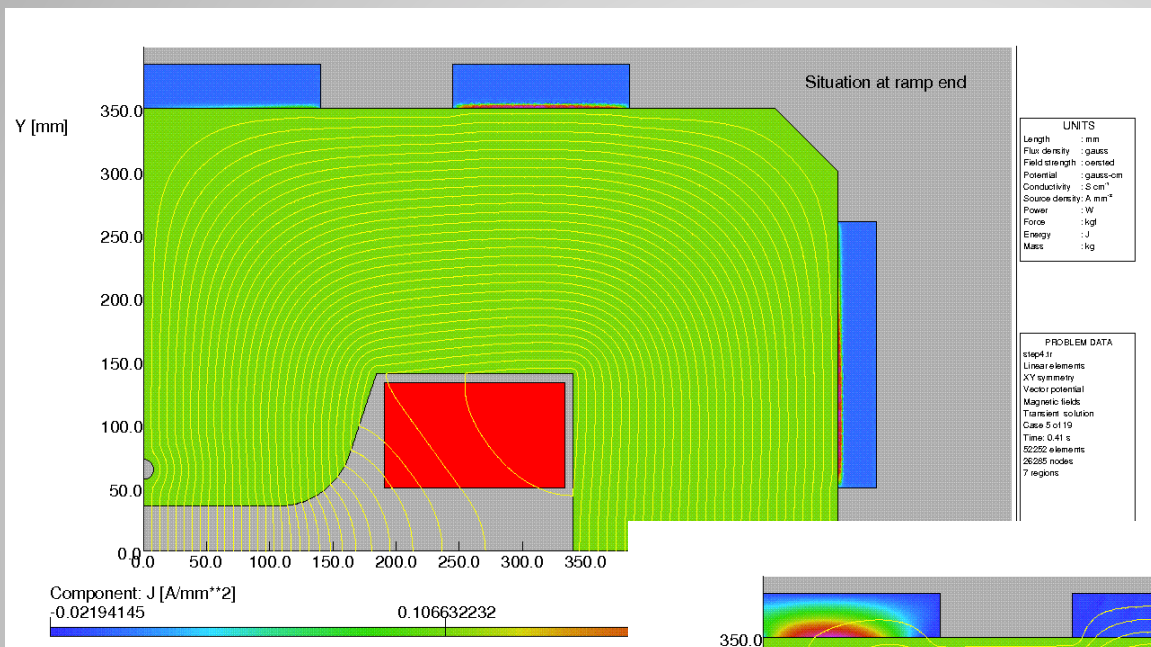
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Vector Fields  
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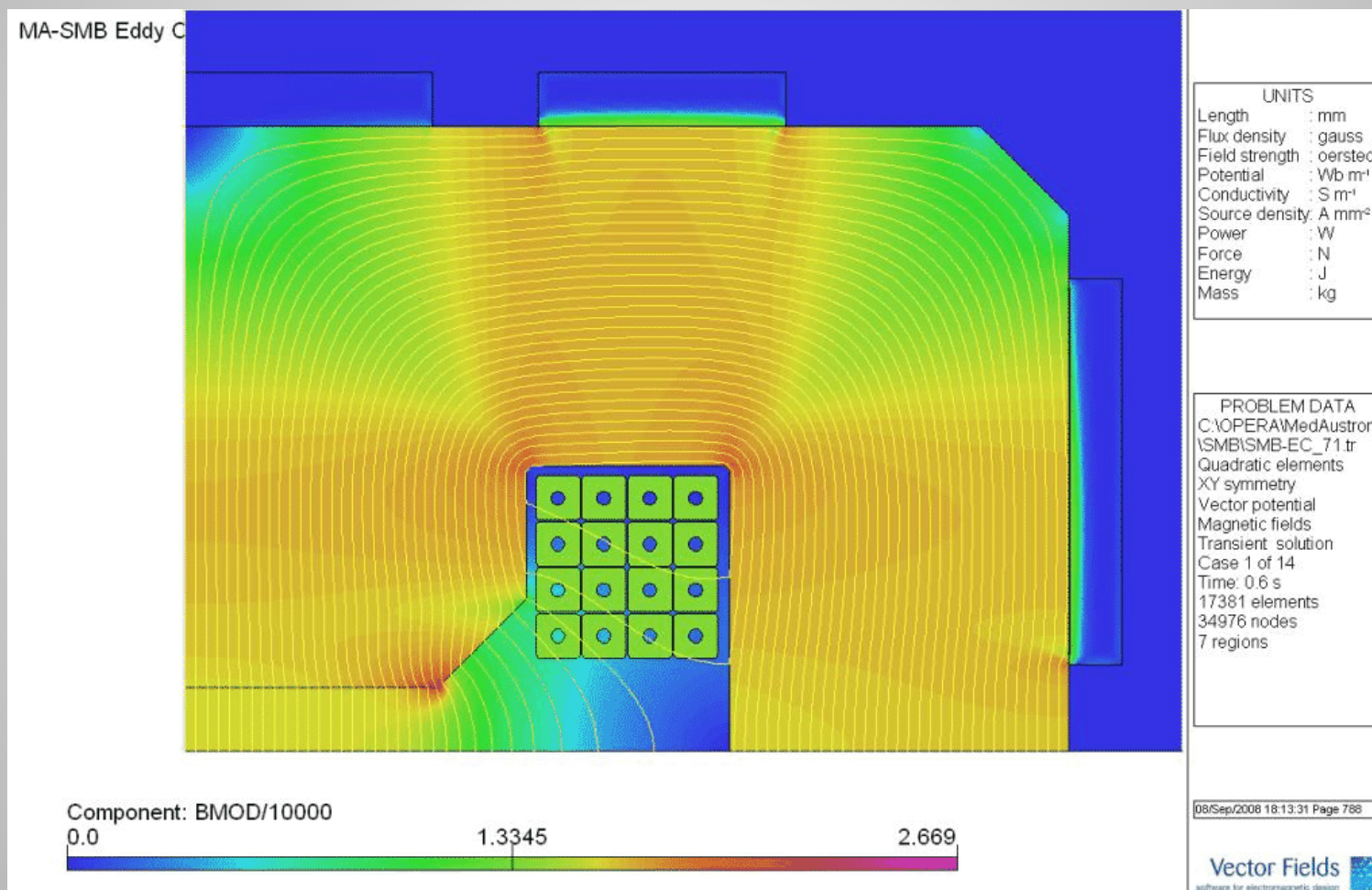


# Eddy currents - dynamic behavior



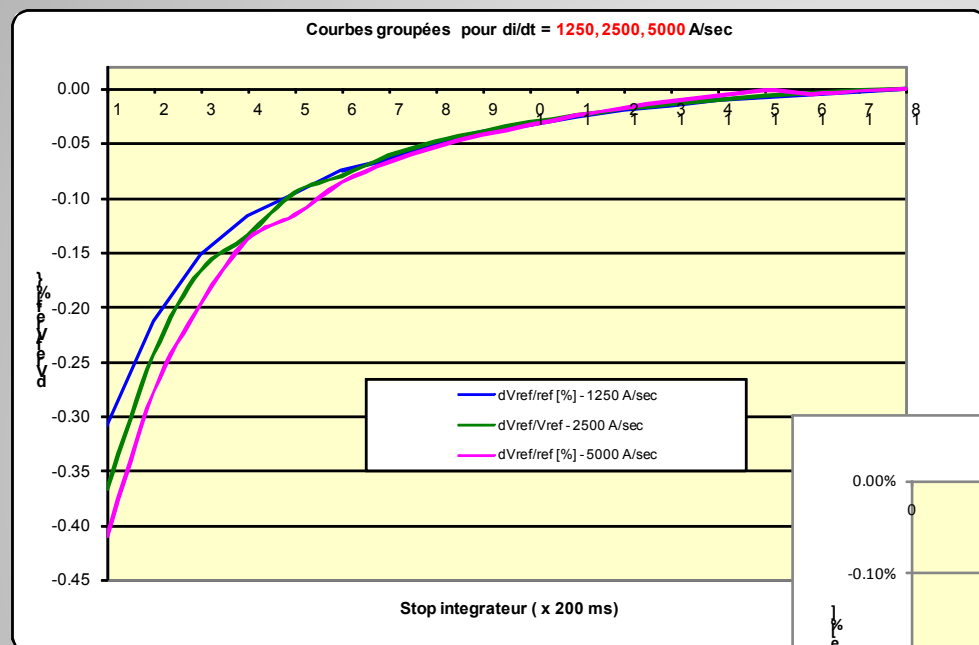


# Eddy currents - dynamic behavior



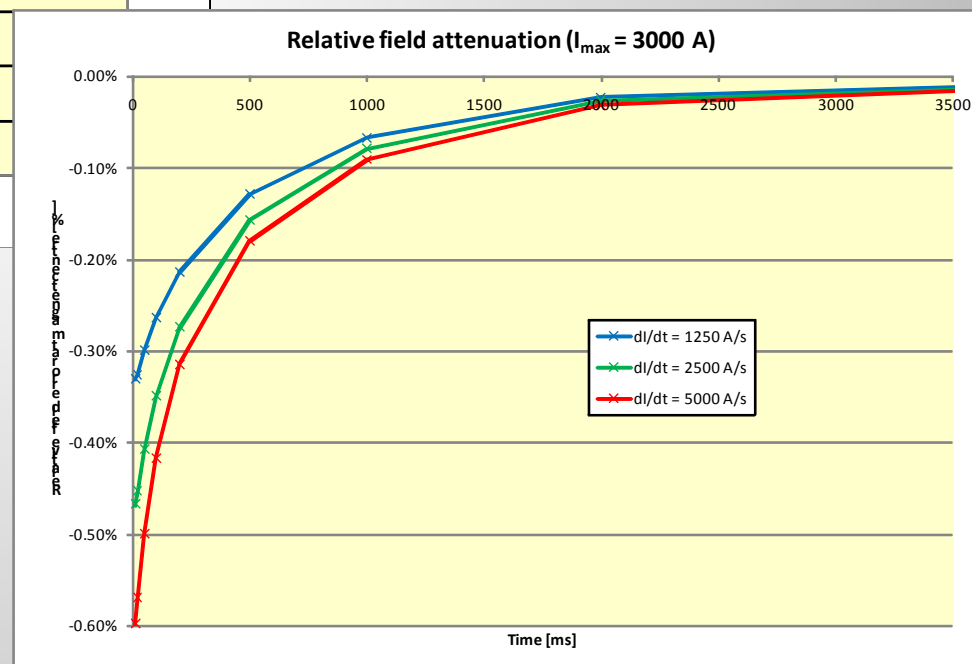


# Eddy currents – field lag



Measured curves (D. Cornuet, R. Chritin)

Calculated curves (OPERA 2D Transient)

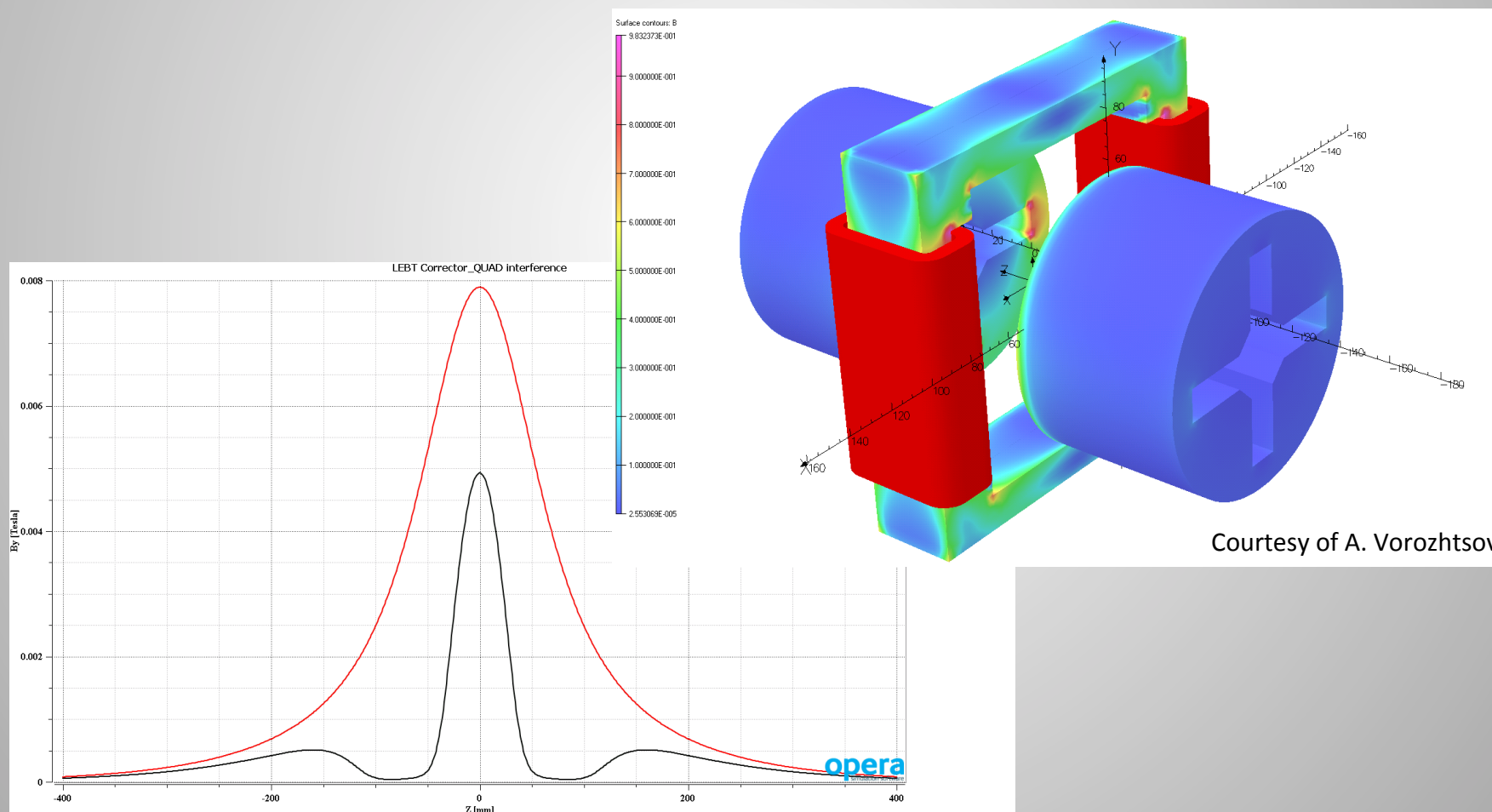




## Case 3: An interference problem



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



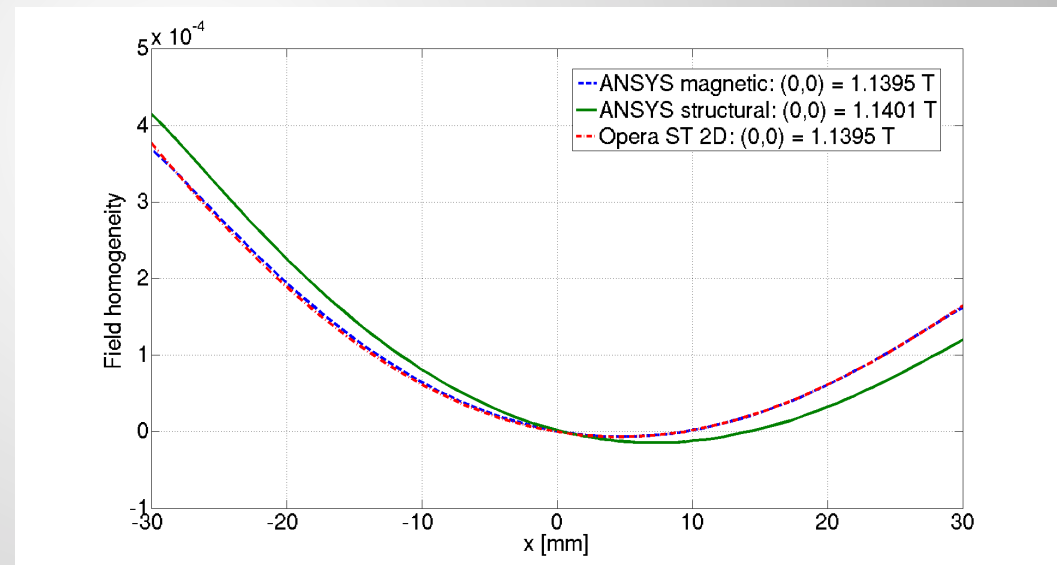
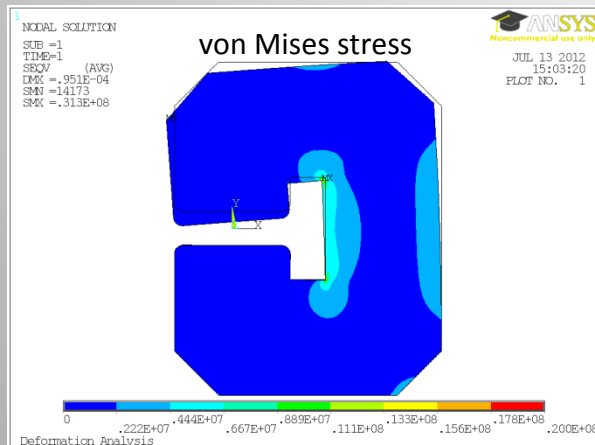
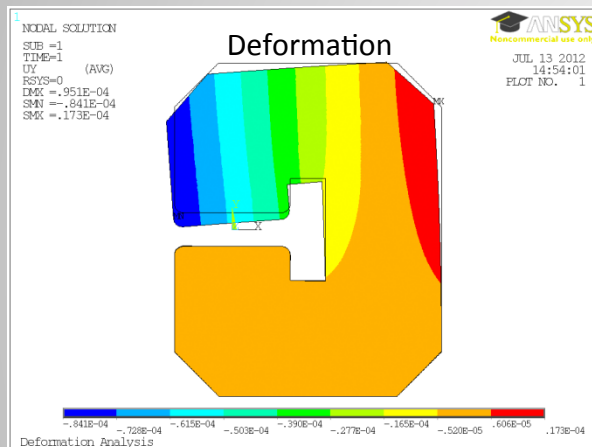
Courtesy of A. Vorozhtsov



## Case 4: 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 numerical 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 variety 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