CERN Accelerator School
Specialized Course on Magnets
Bruges, Belgium, 16-25 June 2009

Basic design and engineering of normal-conducting, iron-dominated electro-magnets

‘Numerical design’

Th. Zickler, CERN

Numerical design

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

Technique is iterative

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

Advanced codes offer:

- modeller, pre-processor, solver and post processors, optimizer
- mesh with finite elements of various shapes
- multiple solver iterations to simulate non-linear material properties (steel)
- anisotropic material characterisation
- 3-dimensional calculations
- combination with structural and thermal analysis
- time depended analysis (steady state, transient)

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)
- OS compatibility
- License costs

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

Performance

Computing time increases for:

- High accuracy solutions
- Non-linear problems
- 3dimensional calculations
- Time depending analysis

→ Compromise between accuracy and computing time

→ Smart modelling can help to minimize number of elements

FEM codes are powerful tools, but be cautious:

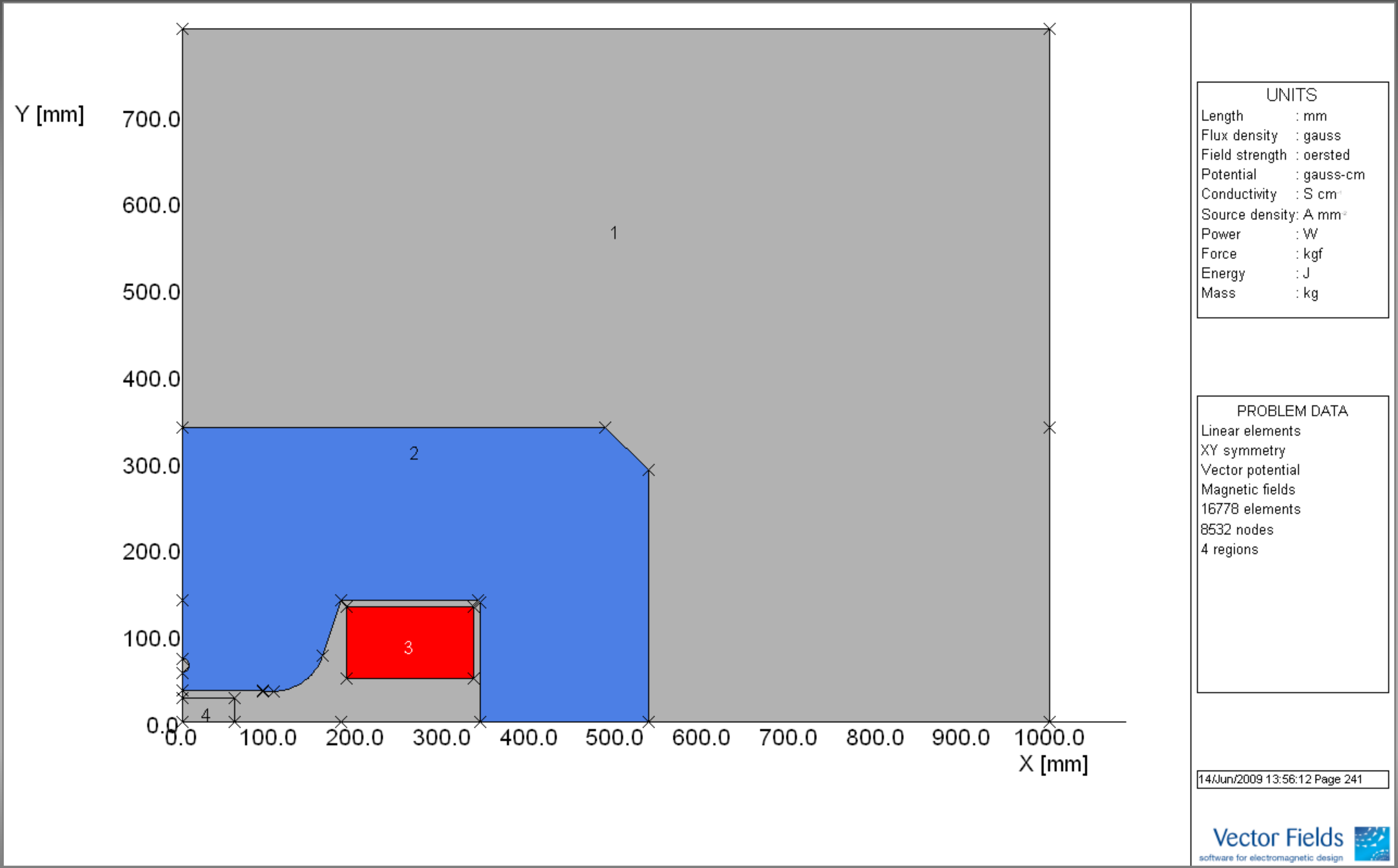
- Like Computers: they don't do what you want, but what you tell them to do!
- Always check results if they are 'physical reasonable'
- Use FEM for quantifying, not to qualify

Numerical design process

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

- Create the model (pre-processor or modeller)
- Defining boundary conditions
- 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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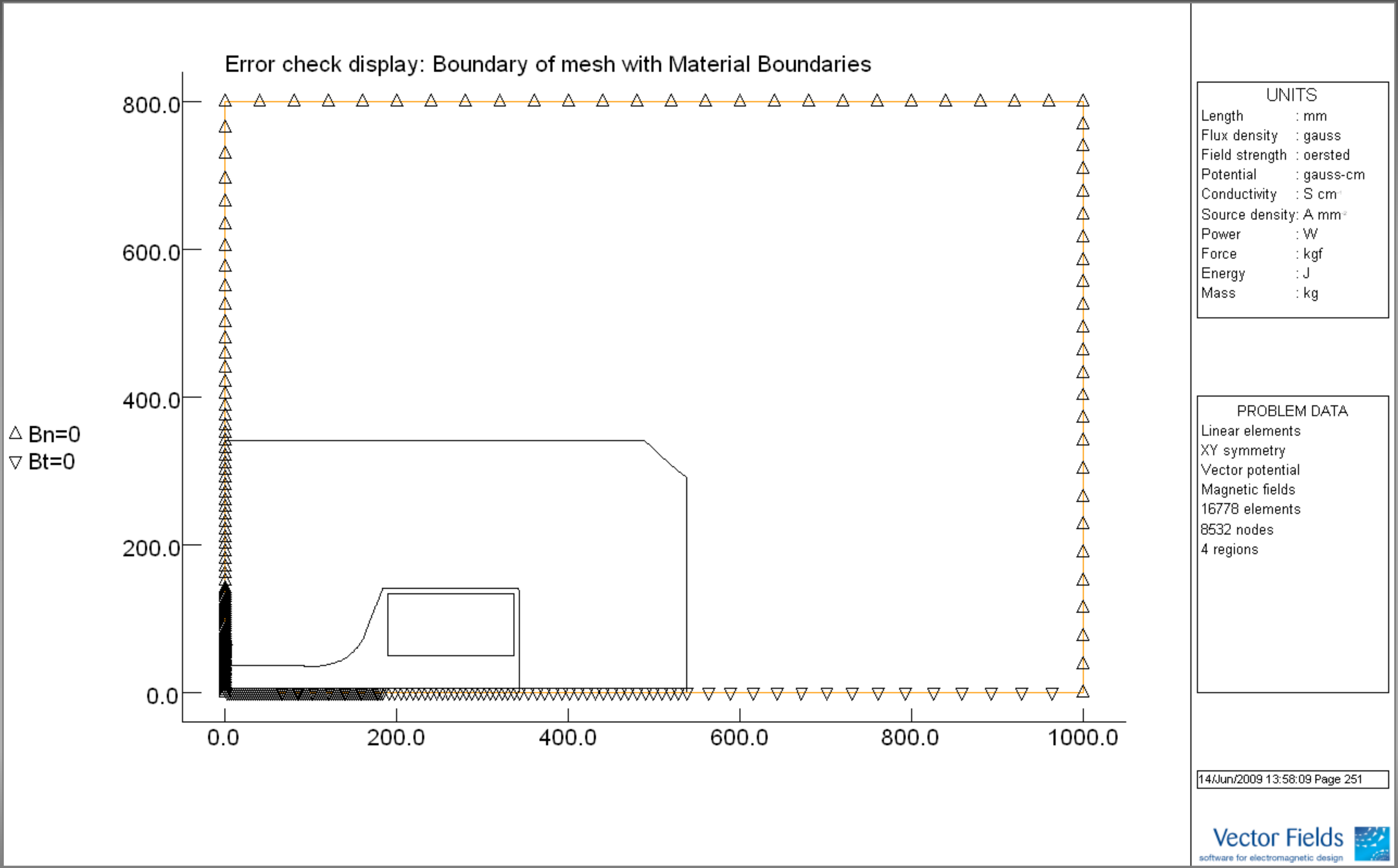
Boundary conditions



Error check display: Boundary of mesh with Material Boundaries

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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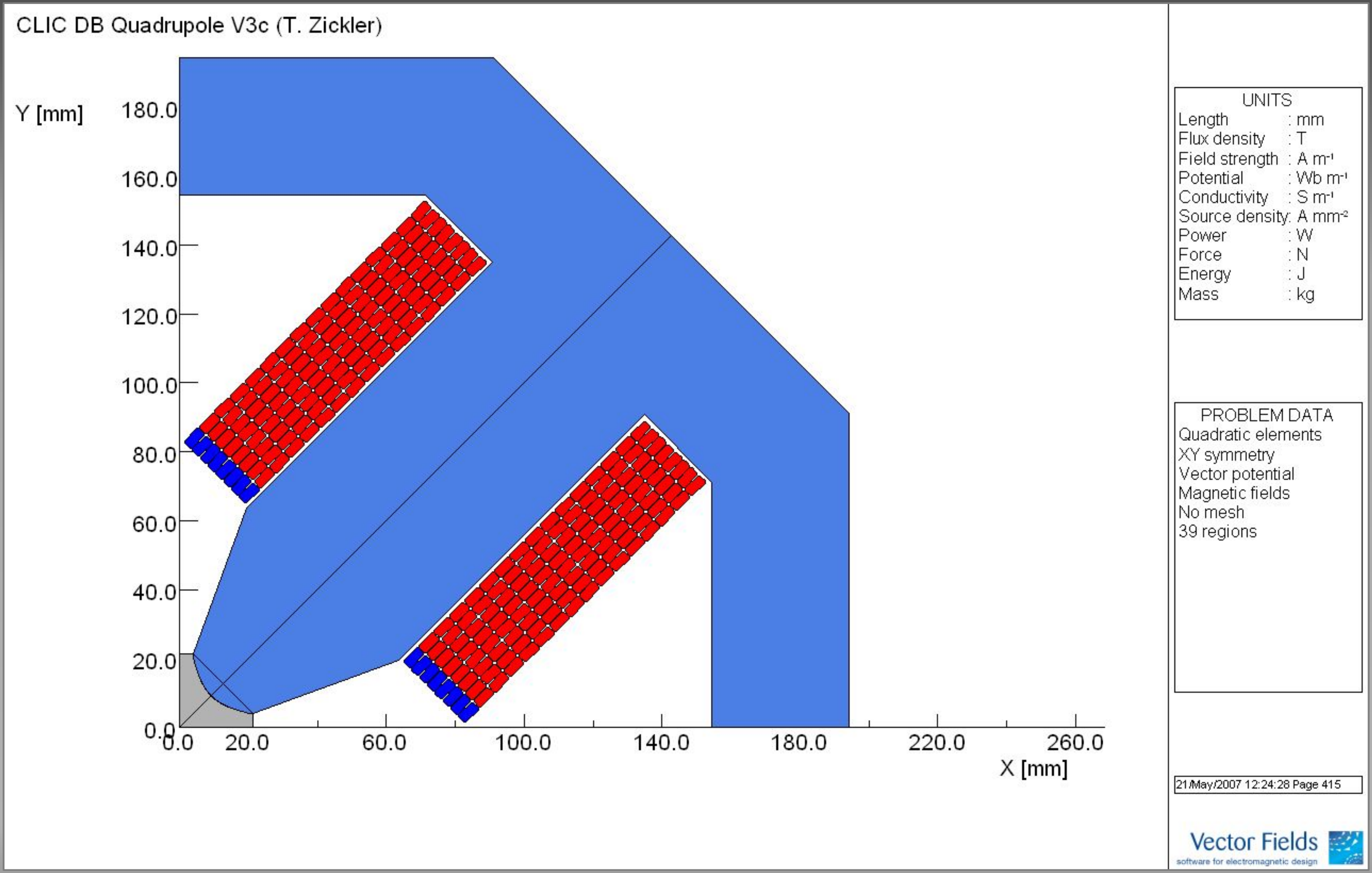
Model symmetries



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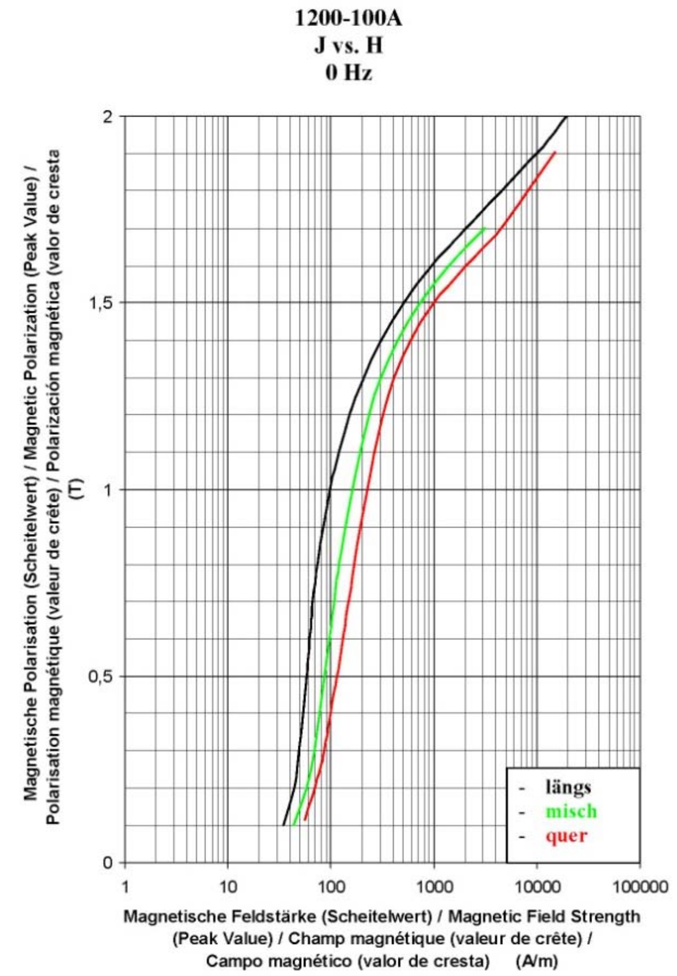
Note: one eighth of quadrupole could be used with opposite symmetries defined on horizontal and y = x axis

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

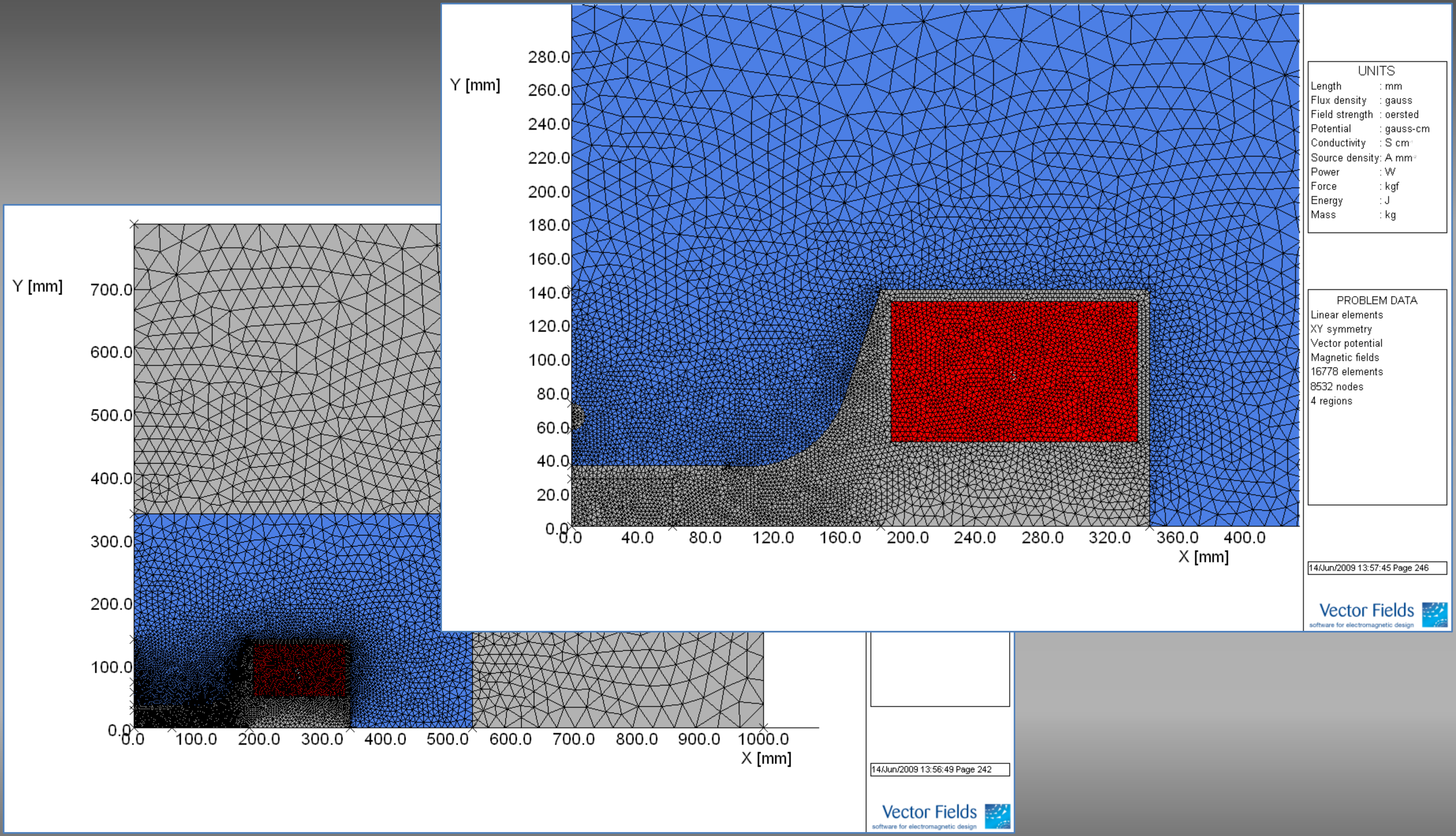
Conductivity:

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

Mechanical and thermal properties:

- in case of combined structural or thermal analysis

Mesh generation



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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Data processing

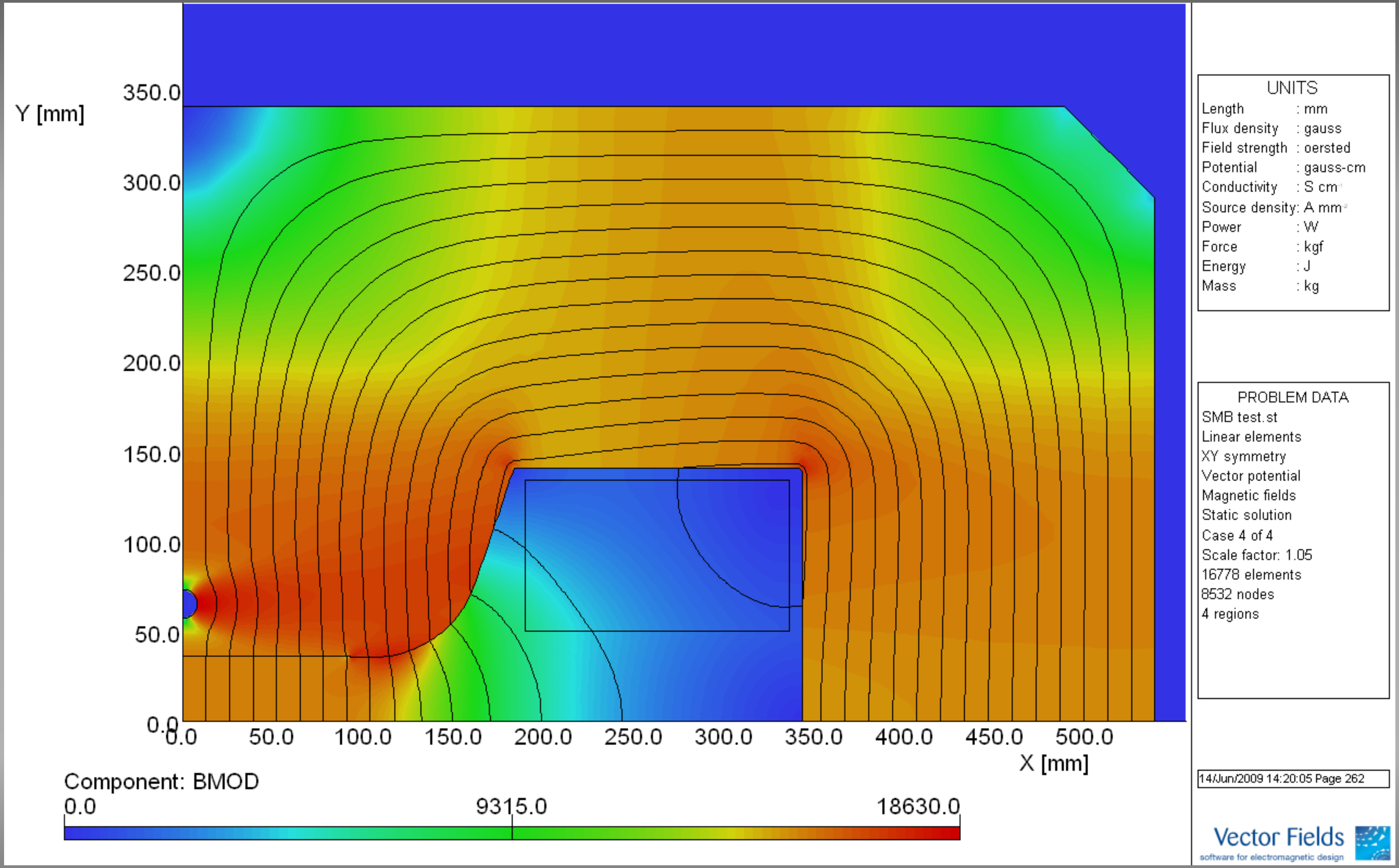
Solution	• linear: uses a predefined constant permeability for a single calculation • non-linear: uses set permeability curve for iterative calculations
Solver types	• Static • Steady state (sine function) • Transient (ramp, step, arbitrary function, ...)
Solver settings	• number of iterations, • convergence 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
- Harmonics

Field and flux lines



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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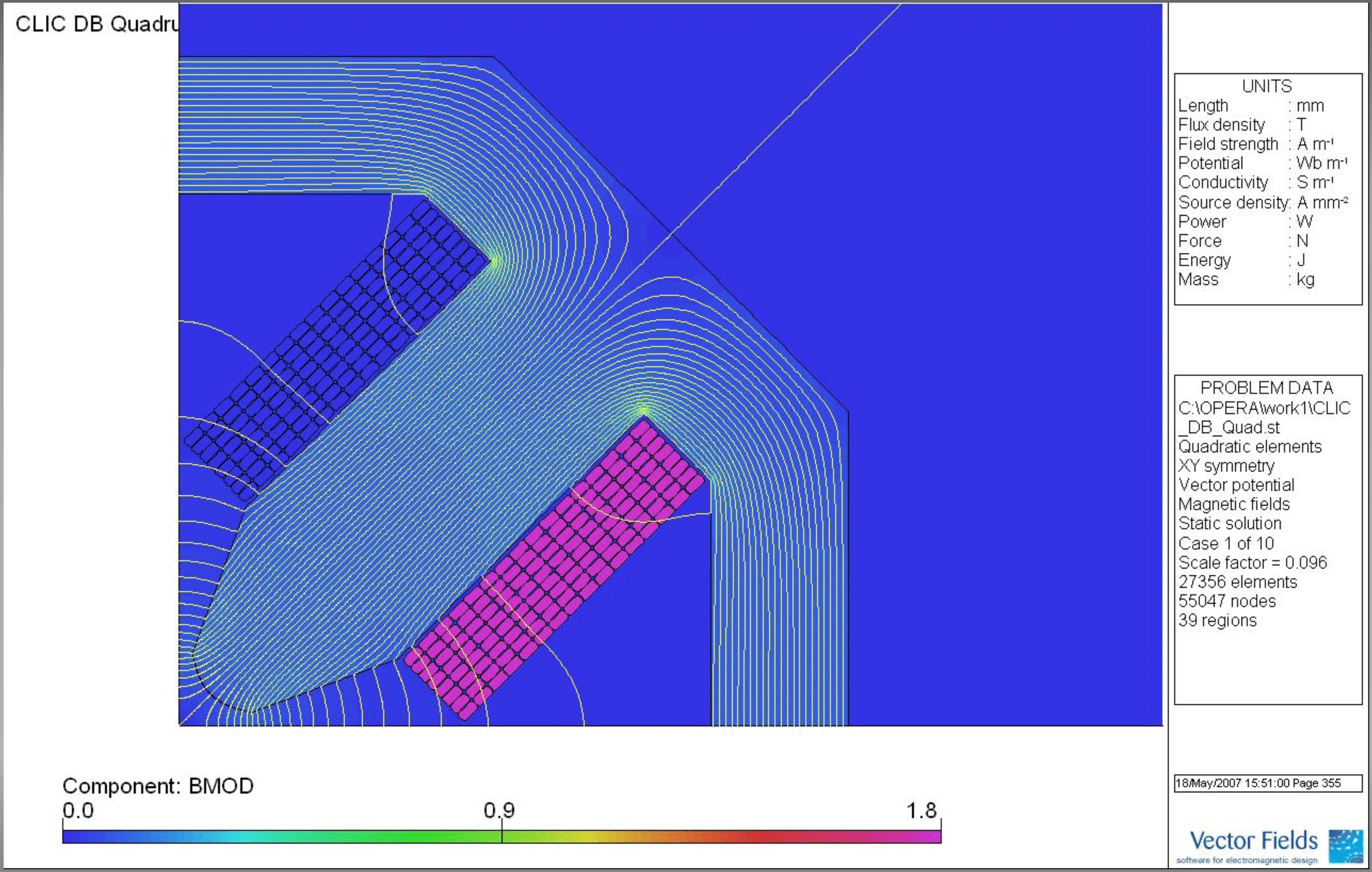
Field and flux lines



CLIC DB Quadru

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
C:\OPERA\work1\CLIC_DB_Quad.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 1 of 10
Scale factor = 0.096
27356 elements
55047 nodes
39 regions

Component: BMOD

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Assessing the field quality

A simple judgment of the field quality can be done by plotting the field (gradient) homogeneity:

Dipole

$$\frac{\Delta B}{B_0} = \frac{B_y(x,y) - B_y(0,0)}{B_y(0,0)}$$

Quadrupole

$$\frac{\Delta B'}{B'_0} = \frac{B'(x,y) - B'(0,0)}{B'(0,0)}$$

$$or: \frac{B_r(x,y) - B'(0,0)\sqrt{x^2+y^2}}{B'(0,0)\sqrt{x^2+y^2}}$$

Sextupole

$$\frac{\Delta B''}{B''_0} = \frac{B''(x,y) - B''(0,0)}{B''(0,0)}$$

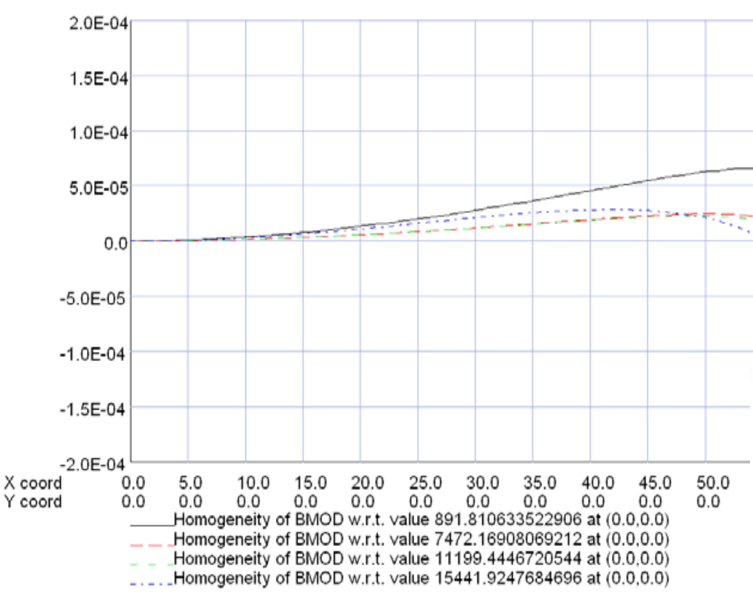
'Typical' acceptable variation inside the good field region:

$$\frac{\Delta B}{B_0} \leq 0.01\%$$

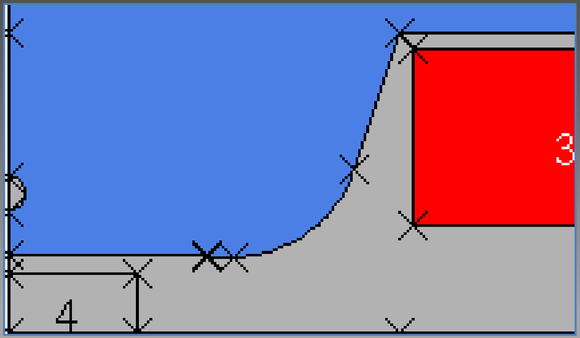
$$\frac{\Delta B'}{B'_0} \leq 0.1\%$$

$$\frac{\Delta B''}{B''_0} \leq 1\%$$

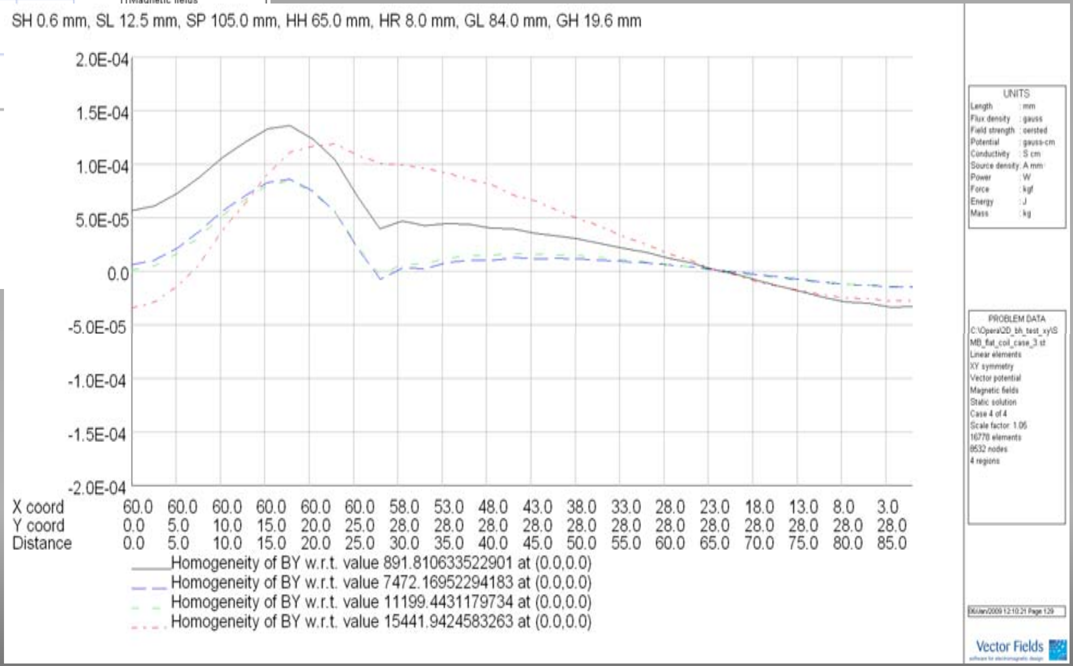
Field homogeneity



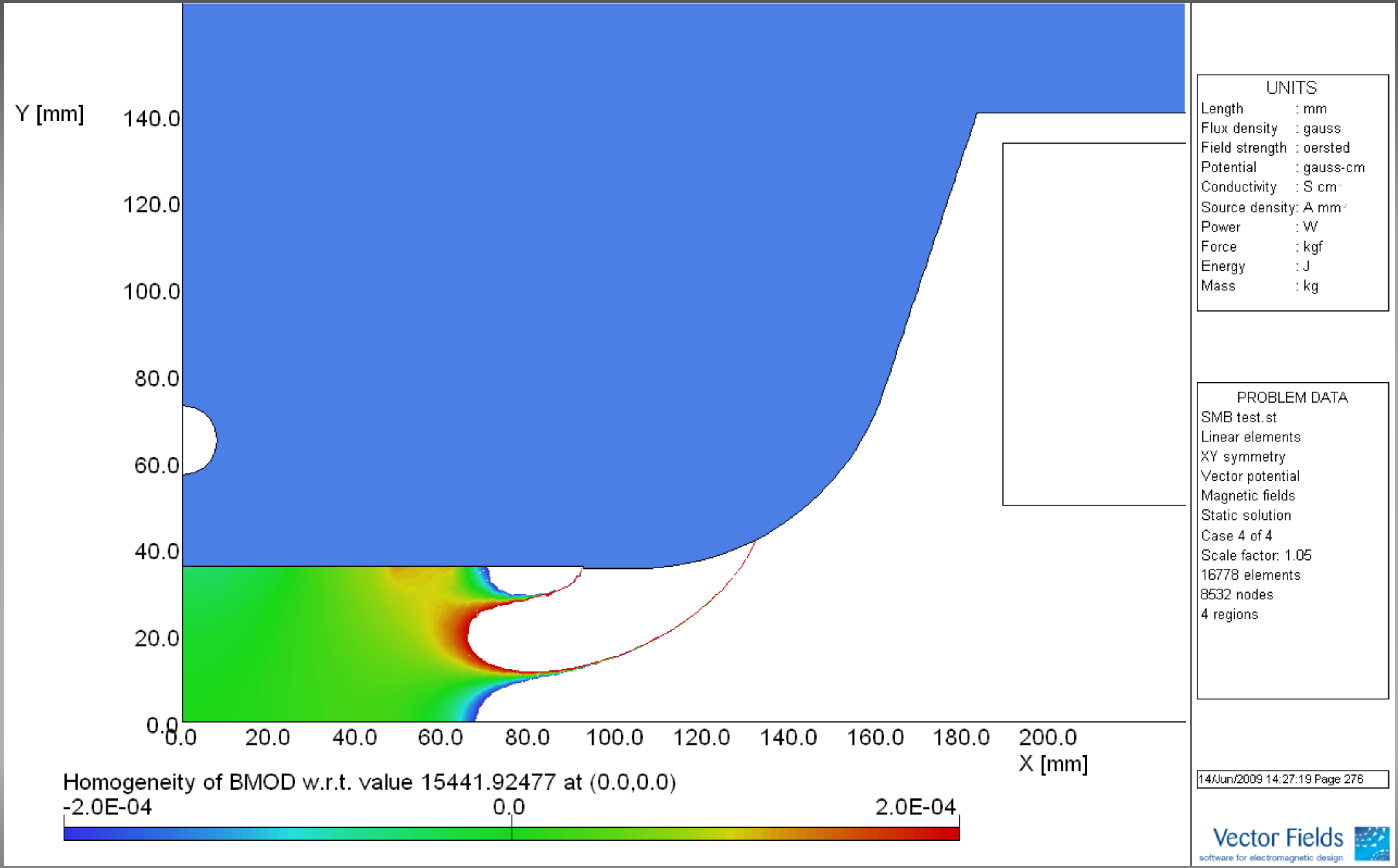
Homogeneity along the x-axis



Homogeneity along GFR boundary



Field homogeneity



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
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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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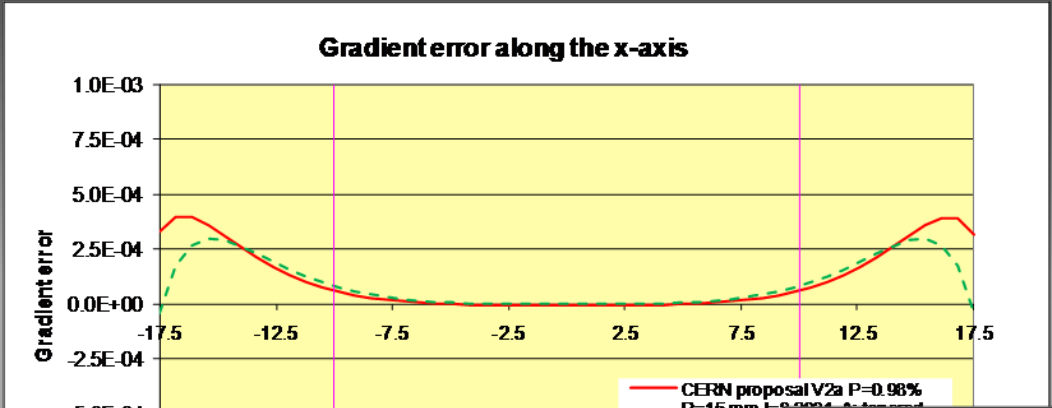
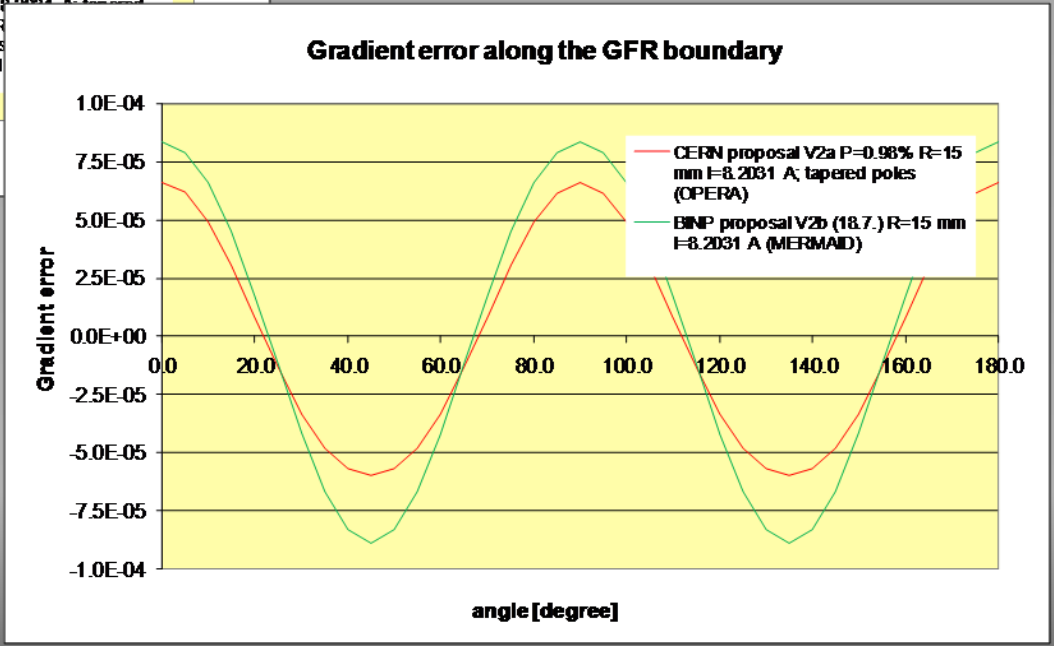
Field homogeneity

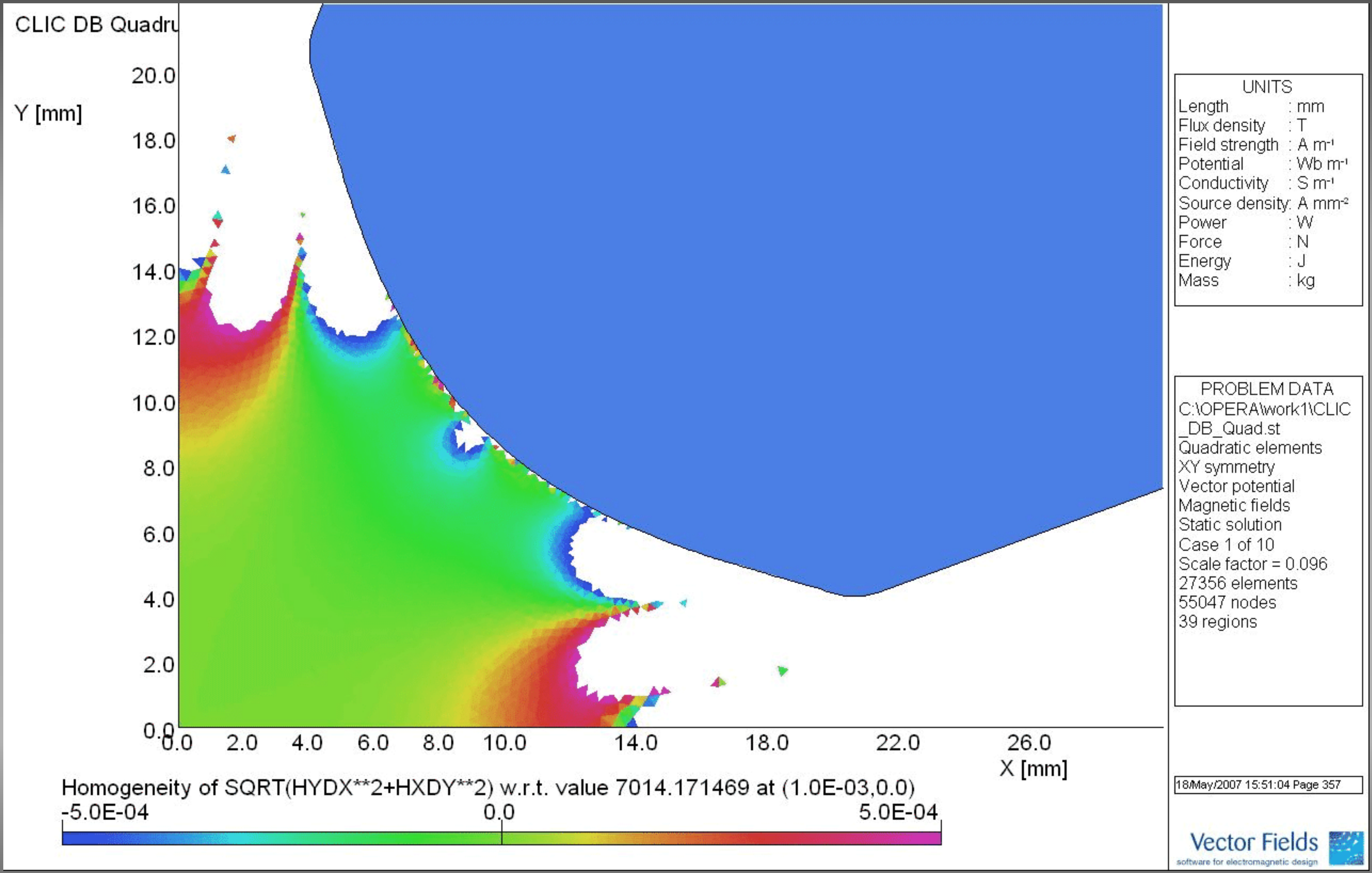


Gradient homogeneity along the x-axis

Gradient homogeneity along GFR



Field homogeneity



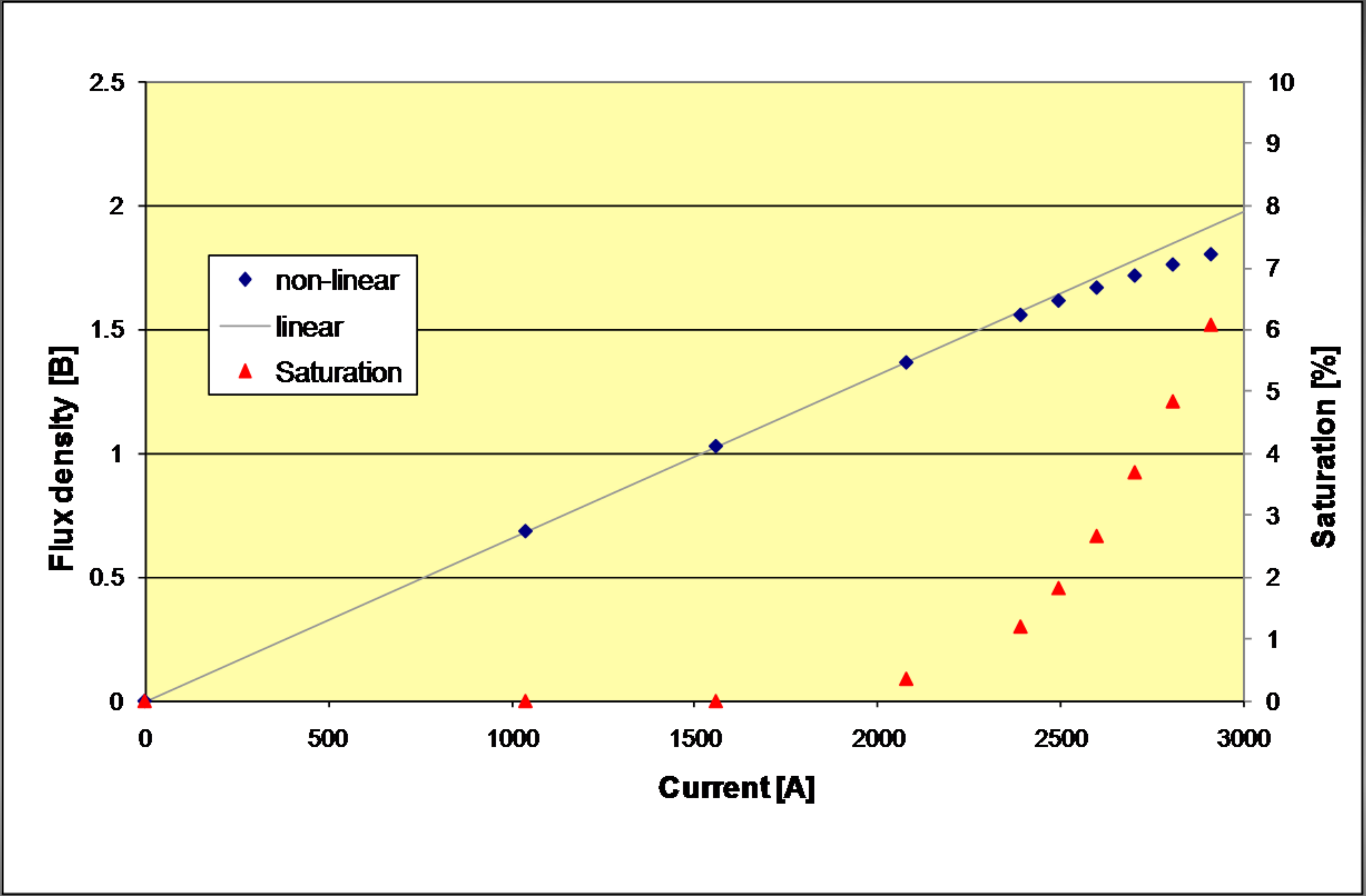
Homogeneity of SQRT(HYDX**2+HXDY**2) w.r.t. value 7014.171469 at (1.0E-03,0.0)

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
C:\OPERA\work1\CLIC_DB_Quad.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 1 of 10
Scale factor = 0.096
27356 elements
55047 nodes
39 regions

Saturation


2.5
2
1.5
1
0.5
0
Flux density [B]
0
500
1000
1500
2000
2500
3000
Current [A]
10
9
8
7
6
5
4
3
2
1
0
Saturation [%]
◆ non-linear
linear
▲ Saturation

Multipole expansion

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

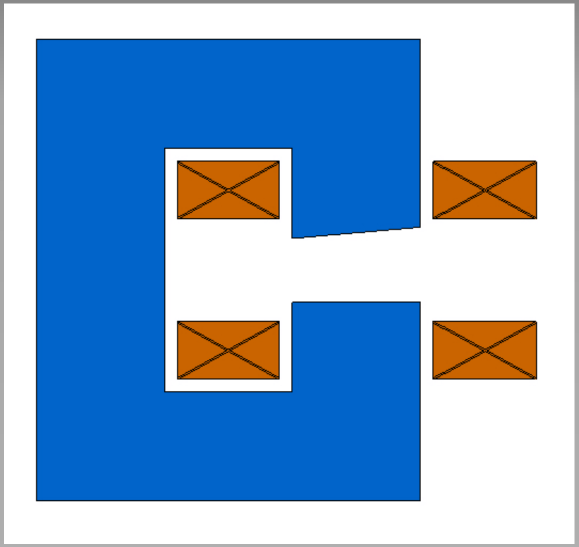
$$B_y + iB_x = B_{ref} \sum_{n=1}^{\infty} \left(b_n + ia_n\right) \cdot \left(\frac{x + iy}{R_{ref}} \right)^{n-1}$$

The normal (b_n) and the skew (a_n) multipole coefficients are useful:

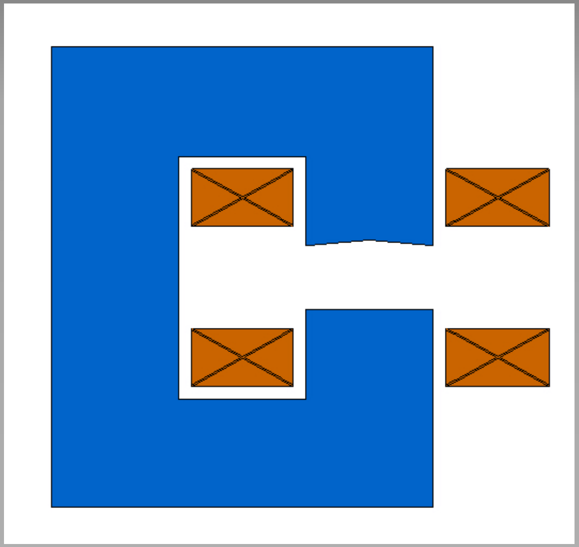
- to describe the field errors and their impact on the beam in the lattice, so the magnetic design can be evaluated
- in comparison with the coefficients resulting from magnetic measurements to judge acceptability of a manufactured magnet

Asymmetries

Asymmetries generating ‘forbidden’ harmonics in a dipole:



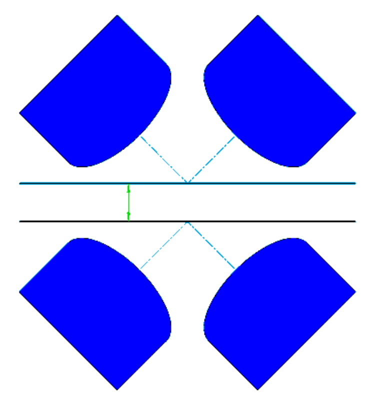
n = 2, 4, 6, ...



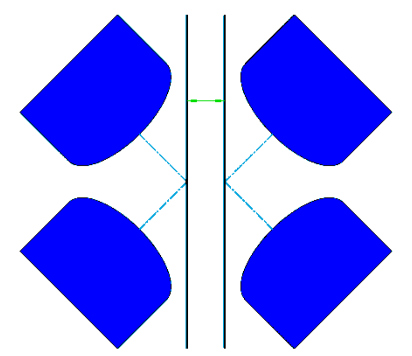
n = 3, 6, 9, ...

Asymmetries

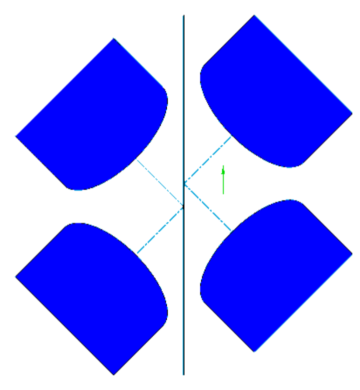
Asymmetries generating ‘forbidden’ harmonics in a quadrupole:



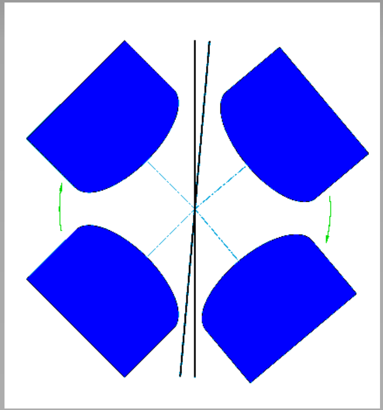
n = 4 (neg.)



n = 4 (pos.)



n = 3



n = 2, 3

- These errors can seriously affect machine behaviour and must be controlled
- Comprehensive studies about the influence of manufacturing errors on the field quality have been done by K. Halbach.

Pole tip design

It is easy to derive perfect mathematical pole configurations for specific fields

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 derive the resulting fields

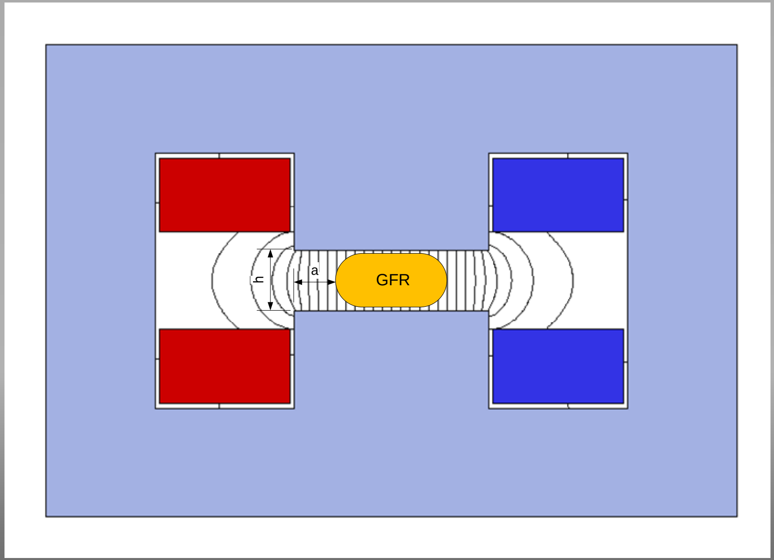
Better approach: calculate the necessary pole overhang using

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

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

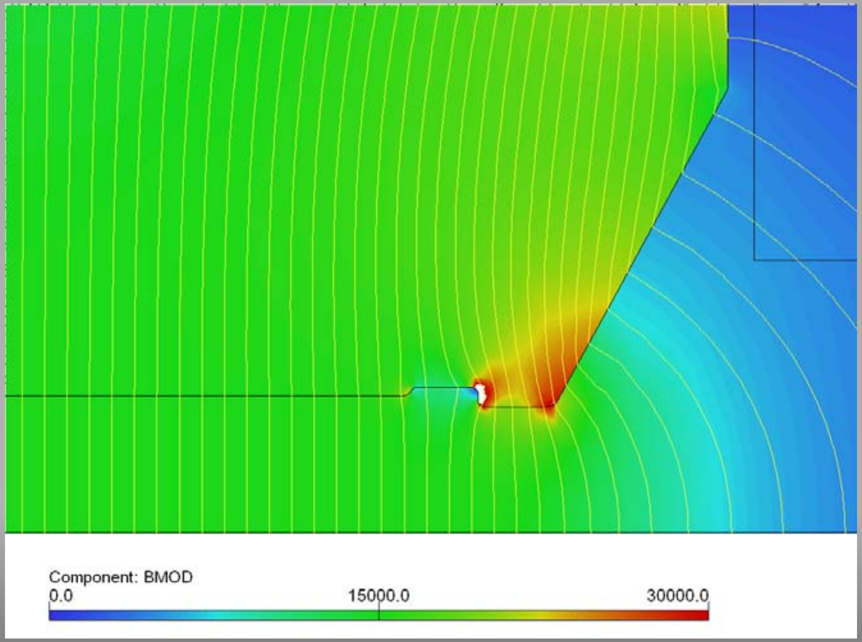
h: magnet gap

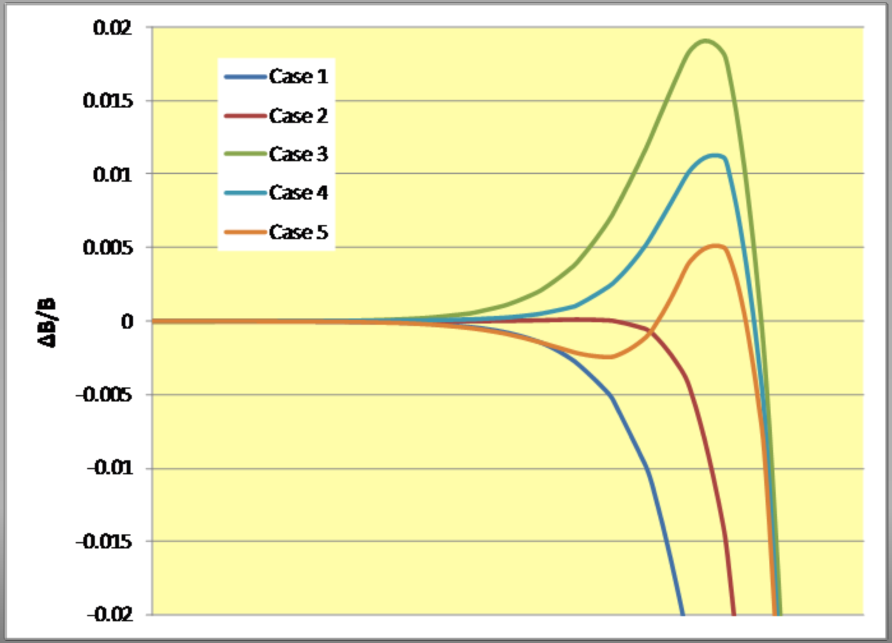


Pole optimization

Shimming:

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 in edges
4. Pole tapering: reduces pole root saturation

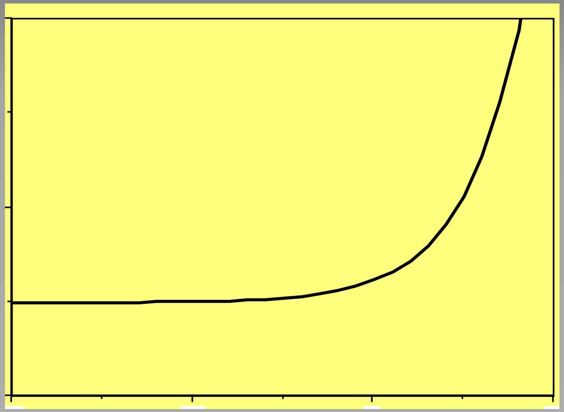




Rogowsky roll-off

Creates surface of constant scalar potential

The edge profile is shaped according to:



$$y = \frac{h}{2} + \left(\frac{h}{\pi}\right)\exp\left(\left(\frac{x\pi}{h}\right) - 1\right) \qquad (34)$$

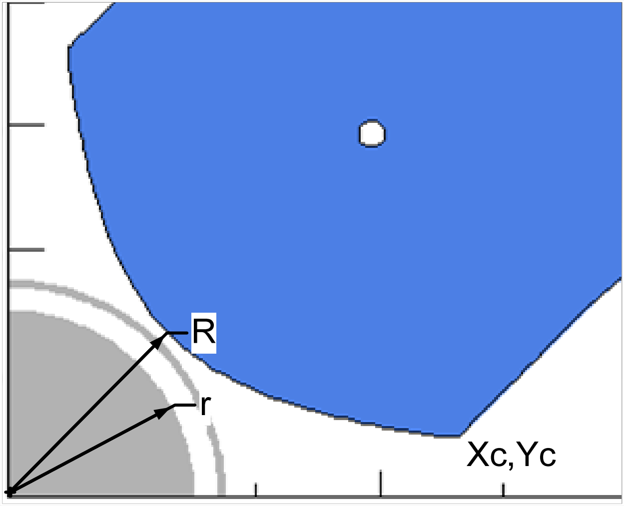
It provides the maximum rate of increase in gap with a monotonic decrease in flux density at the surface (i.e. no saturation!)

For an optimized pole (33) changes to:

$$x_{optimized} = 2\frac{a}{h} = -0.14\ln\frac{\Delta B}{B_0} - 0.25 \qquad (35)$$

Pole optimization

Similar technique can be applied for quadrupoles:



$$\frac{x_c}{R} = \sqrt{\frac{1}{2}\left(\sqrt{\left(\rho^2 + x_d\right)^2 + 1} + \rho^2 + x_d\right)} \qquad (36)$$

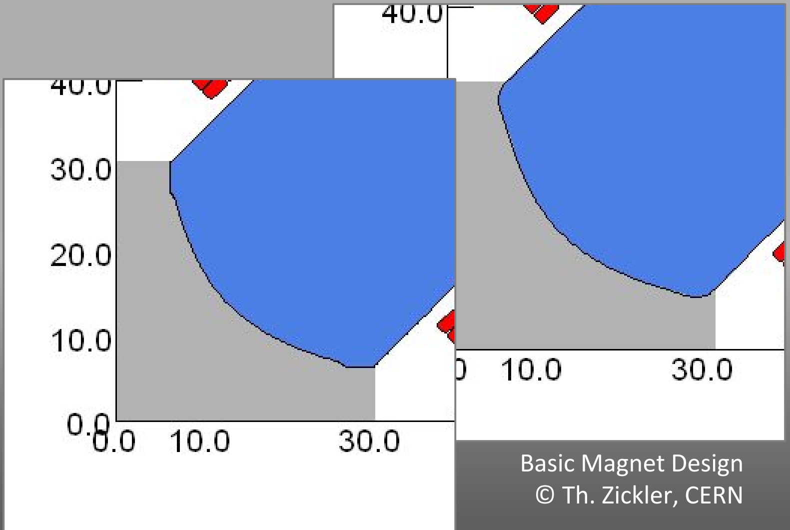
$$\frac{y_c}{R} = \sqrt{\frac{1}{2}\left(\sqrt{\left(\rho^2 + x_d\right)^2 + 1} - \rho^2 - x_d\right)} \qquad (37)$$

x_c: unoptimized resp. optimized pole overhang from (33) resp. (35)

ρ: normalized good field radius r/R

Pole optimization:

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



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

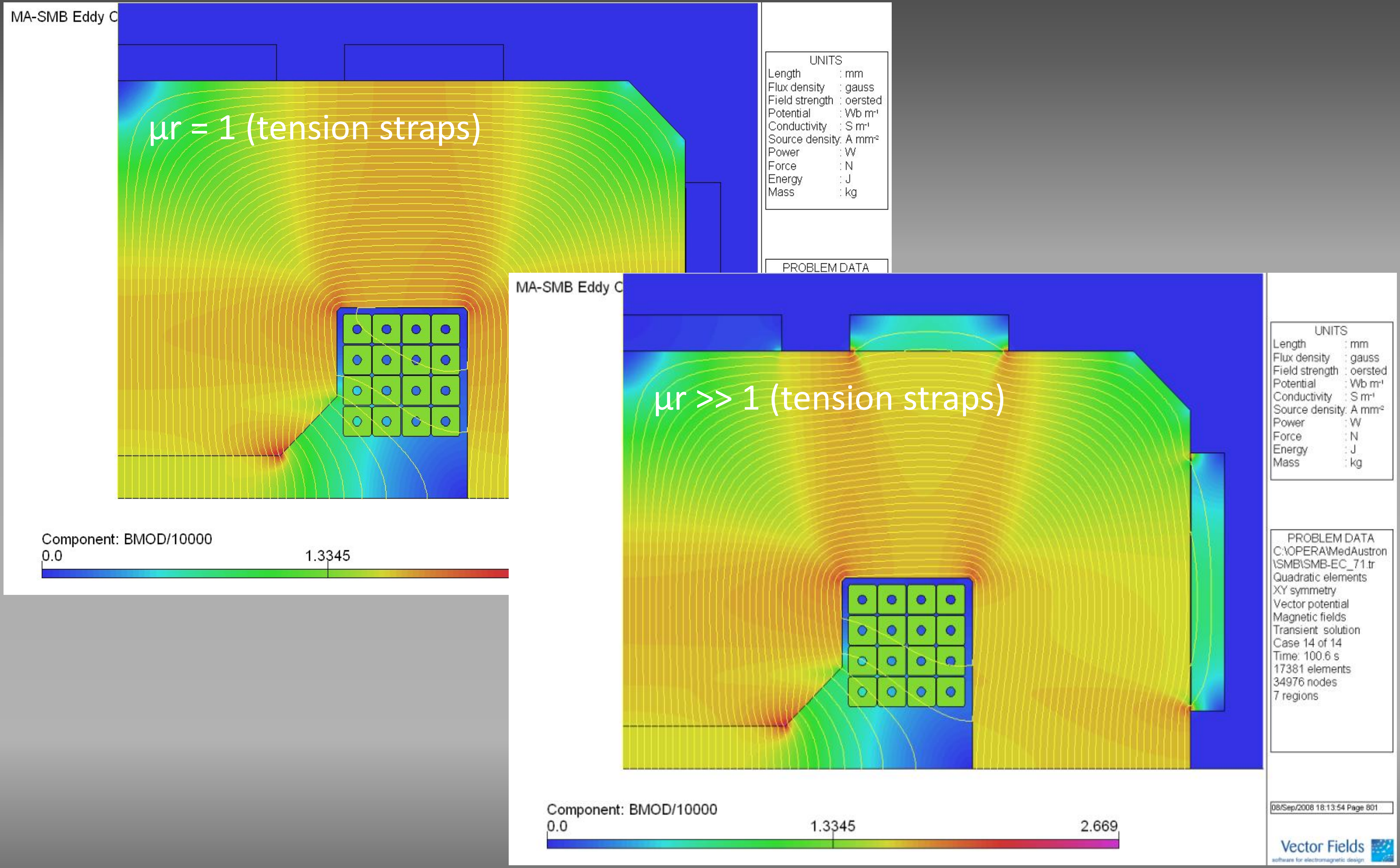
Problem:

- Magnetic field lagging behind the current
- Time constant τ 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



μr = 1 (tension straps)

μr >> 1 (tension straps)

UNITS
Length : mm
Flux density : gauss
Field strength : oersted
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
C:\OPERA\MedAustron
\SMB\SMB-EC_71.tr
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Transient solution
Case 14 of 14
Time: 100.6 s
17381 elements
34976 nodes
7 regions

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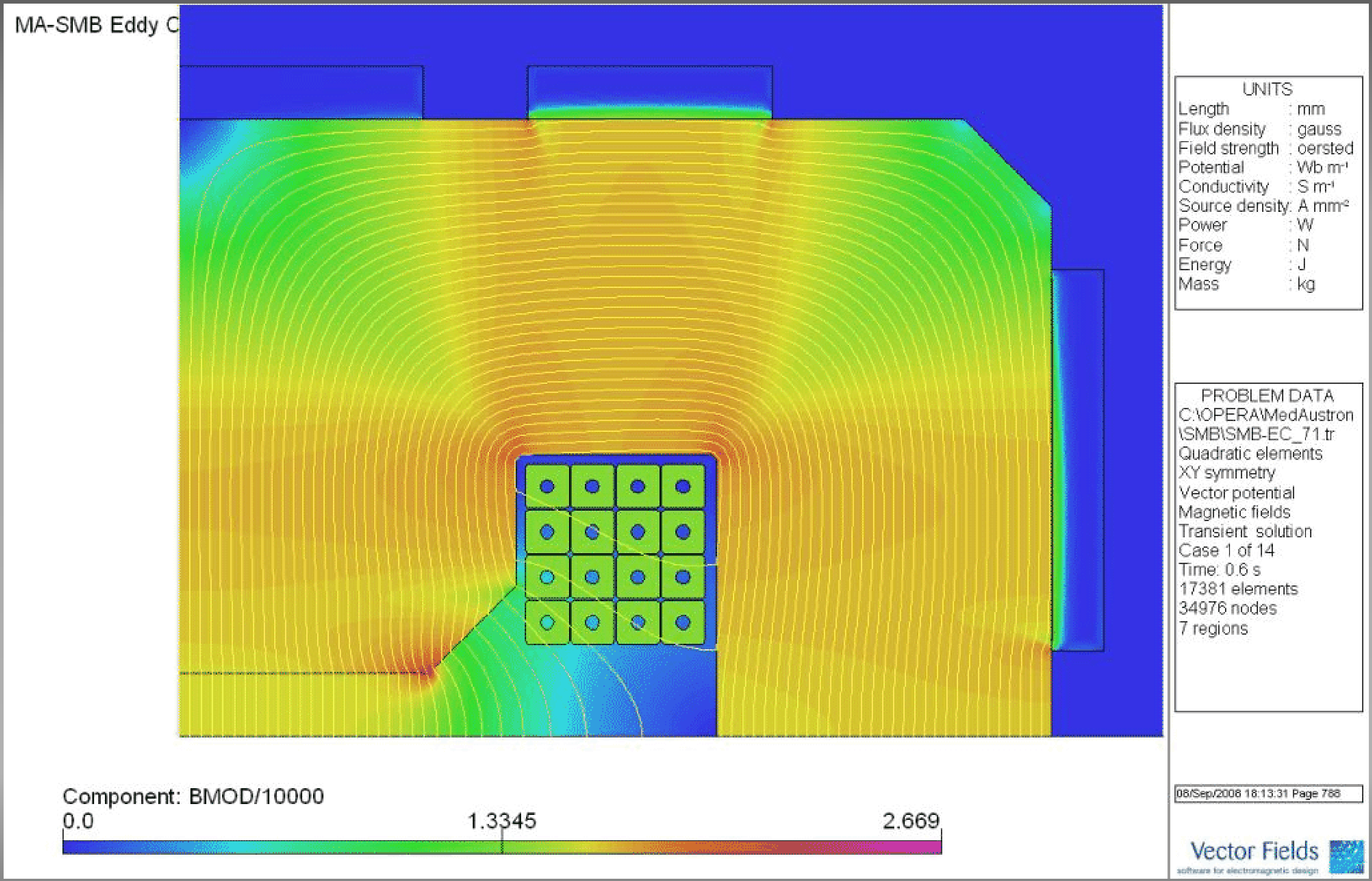
Eddy currents - dynamic behavior



UNITS
Length : mm
Flux density : gauss
Field strength : oersted
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
C:\OPERA\MedAustron
\SMB\SMB-EC_71.tr
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Transient solution
Case 1 of 14
Time: 0.6 s
17381 elements
34976 nodes
7 regions

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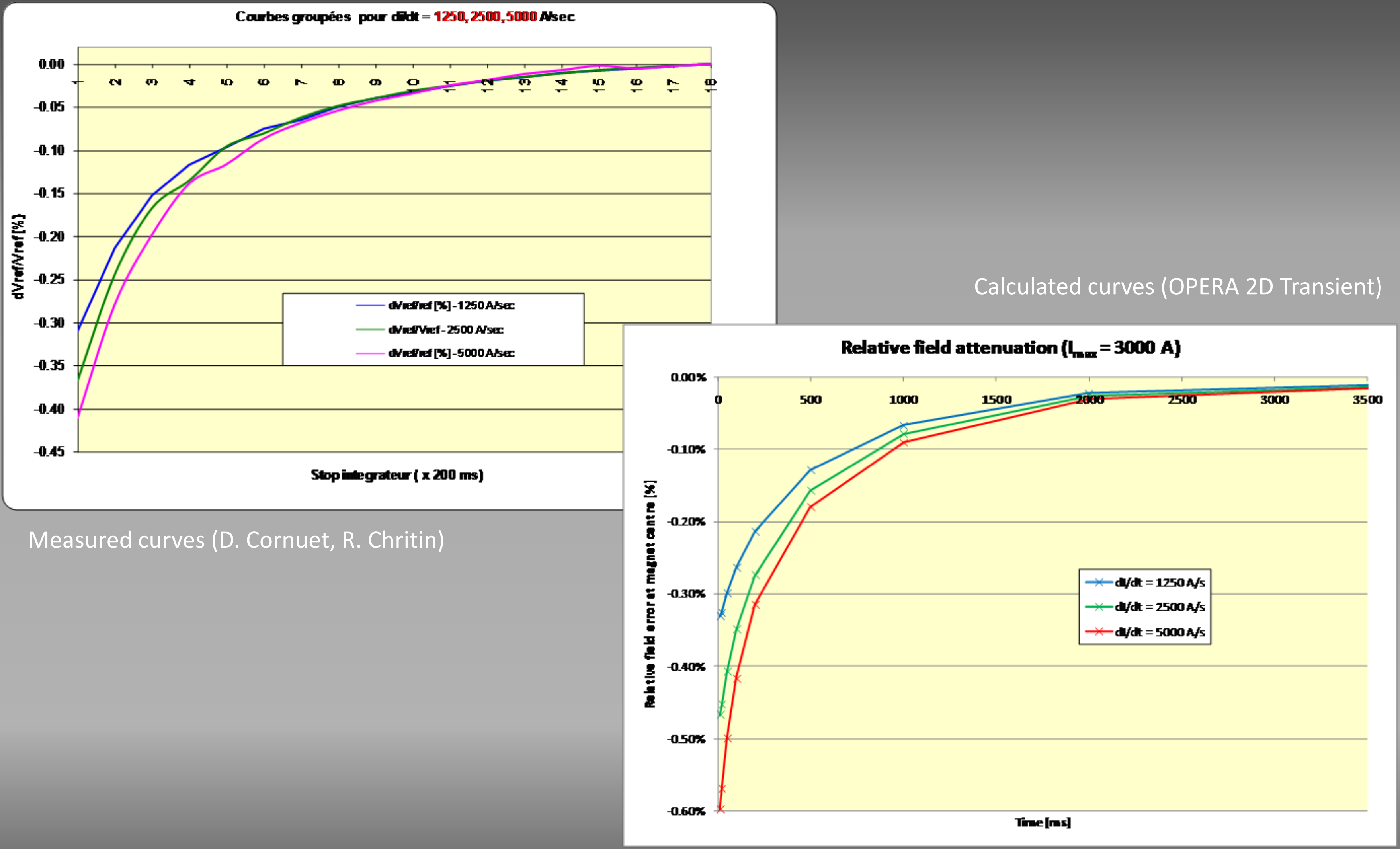
Eddy currents – field lag



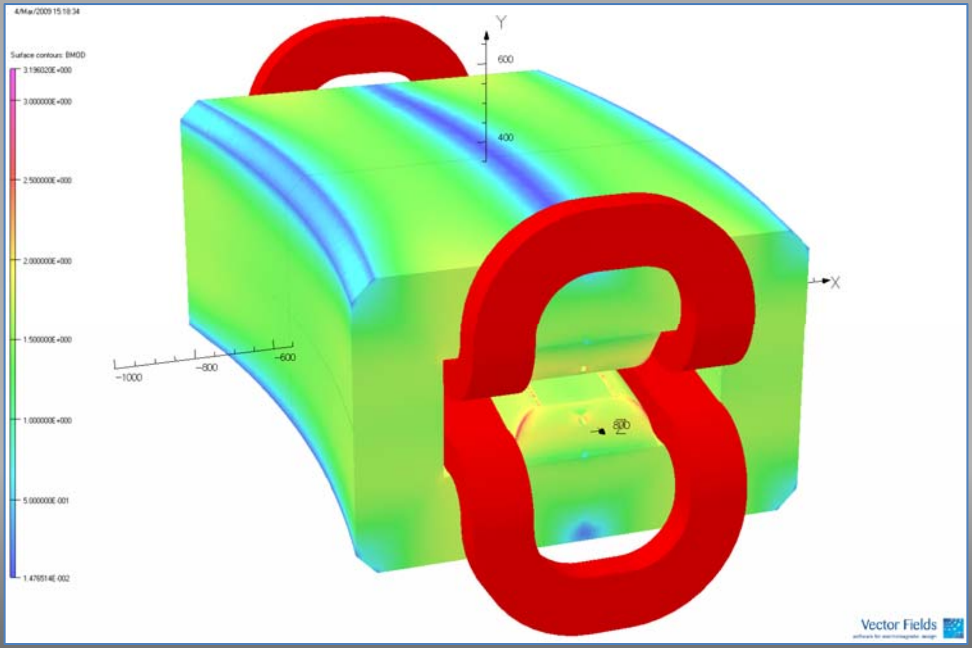
Measured curves (D. Cornuet, R. Chritin)

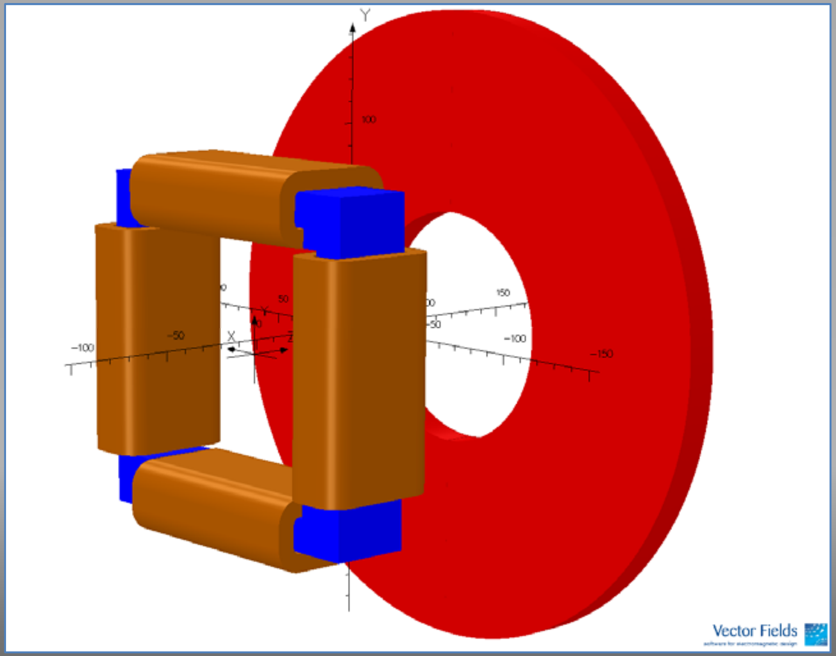
Calculated curves (OPERA 2D Transient)

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

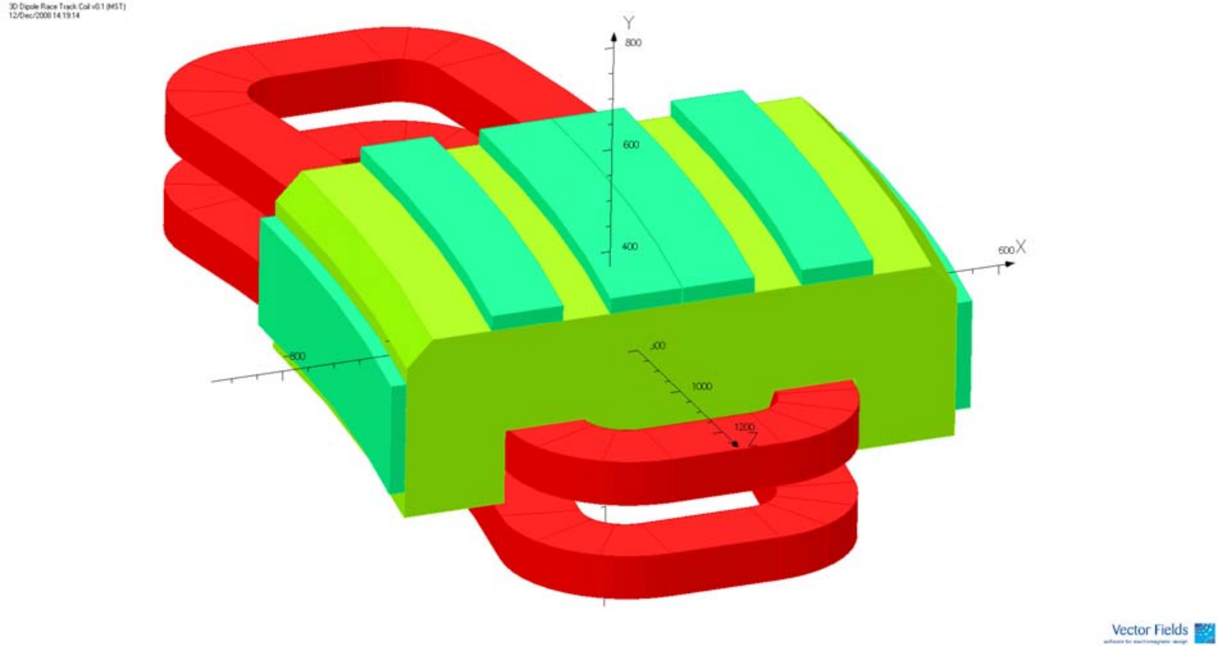




Opera 3D model

Similar to 2D:

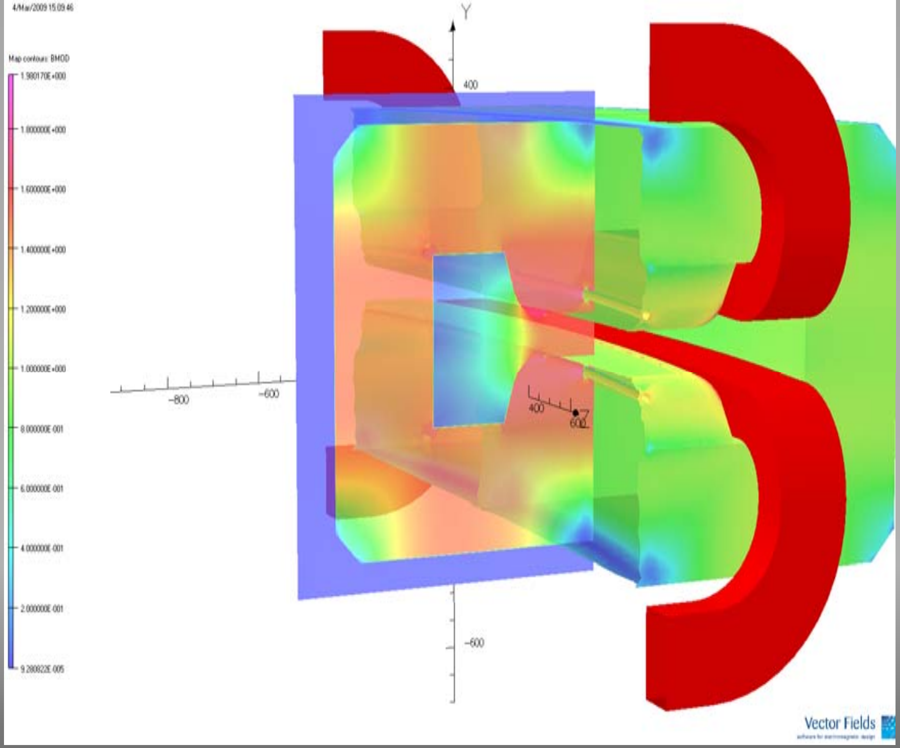
- Use pre-processor or modeller to build geometry
- Profit from symmetries to reduce number of elements
- Difference: all regions with current density have to be modelled completely



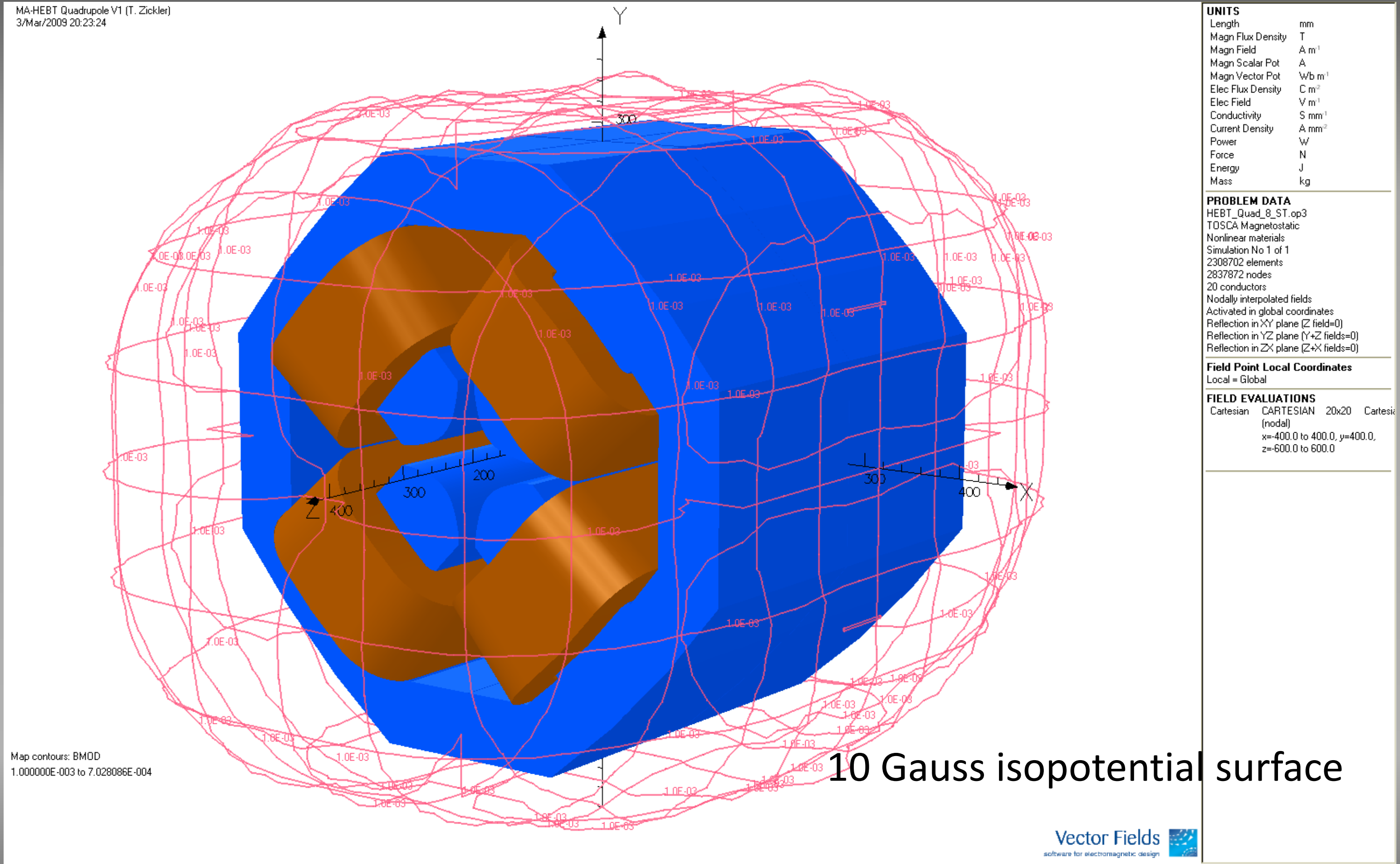
Post-processing

Similar to 2D:

- 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



Isopotential surfaces



MA-HEBT Quadrupole V1 (T. Zickler)
3/Mar/2009 20:23:24

UNITS

Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S mm^{-1}
Current Density	A mm^{-2}
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
HEBT_Quad_8_ST.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
2308702 elements
2837872 nodes
20 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (Y+Z fields=0)
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Cartesian CARTESIAN 20x20 Cartesia
(nodal)
x=-400.0 to 400.0, y=400.0,
z=-600.0 to 600.0

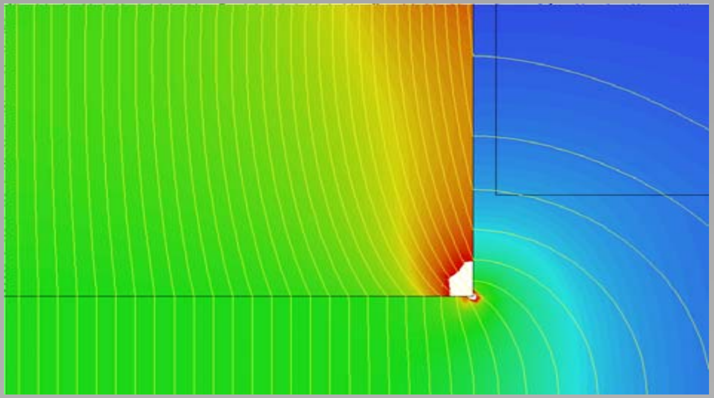
Map contours: BMOD
1.000000E-003 to 7.028086E-004

10 Gauss isopotential surface

Magnet ends

Special attention has to be paid to the magnet ends:

- A square end will introduce significant higher order multipoles
- Therefore, it is necessary to terminate the magnet in a controlled way by shaping the end either by cutting away or adding material
- The end is shaped to give increasing gap (or increasing radius) and lower fields as the end is approached



The goal of successful shimming is to:

- adjust the magnetic length
- prevent saturation in a sharp corner
- maintain magnetic length constant across the good field region
- prevent flux entering perpendicular to the laminations, which induces eddy currents

Longitudinal shimming

Dipoles:

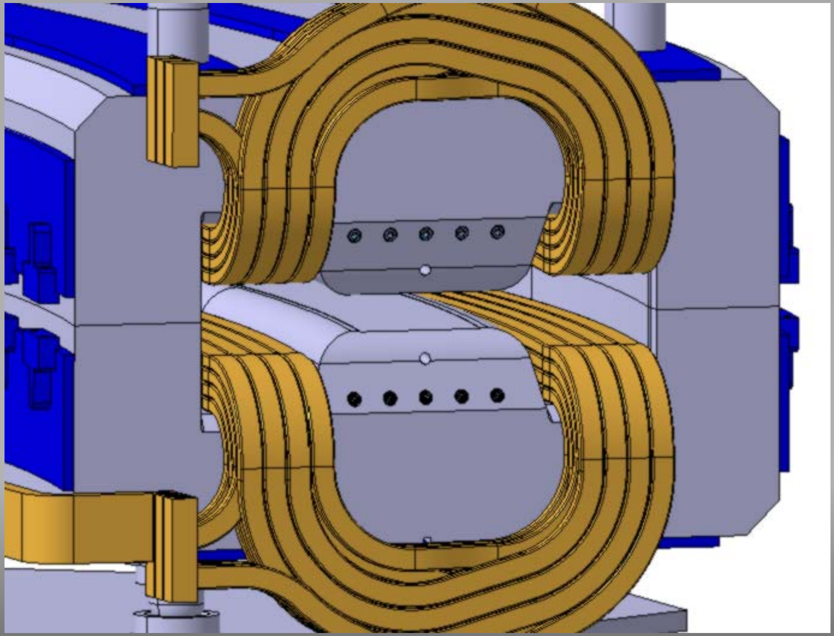
- Rogowsky roll off or angular cut
- Depth and angle adjusted using 3D codes or measurements

Quadrupoles:

- Angular cut at the end

Sextupoles:

- Usually not chamfered



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