STRESS COMPUTATION IN THE C400 SUPERCONDUCTING COIL USING THE OPERA-2D STRESS ANALYSIS MODULE

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OVERVIEW

- Main cyclotron parameters
- Coil requirements and choices
- Radial stress and hoop stress
- Modelling the cyclotron in 2d
- Describing the coil for stress analysis
- The simplest model and its limitations
- A better model
- Modifying resin properties
- Full model with support
- Tilting the coil
- Differences in stresses

MAIN CYCLOTRON PARAMETERS

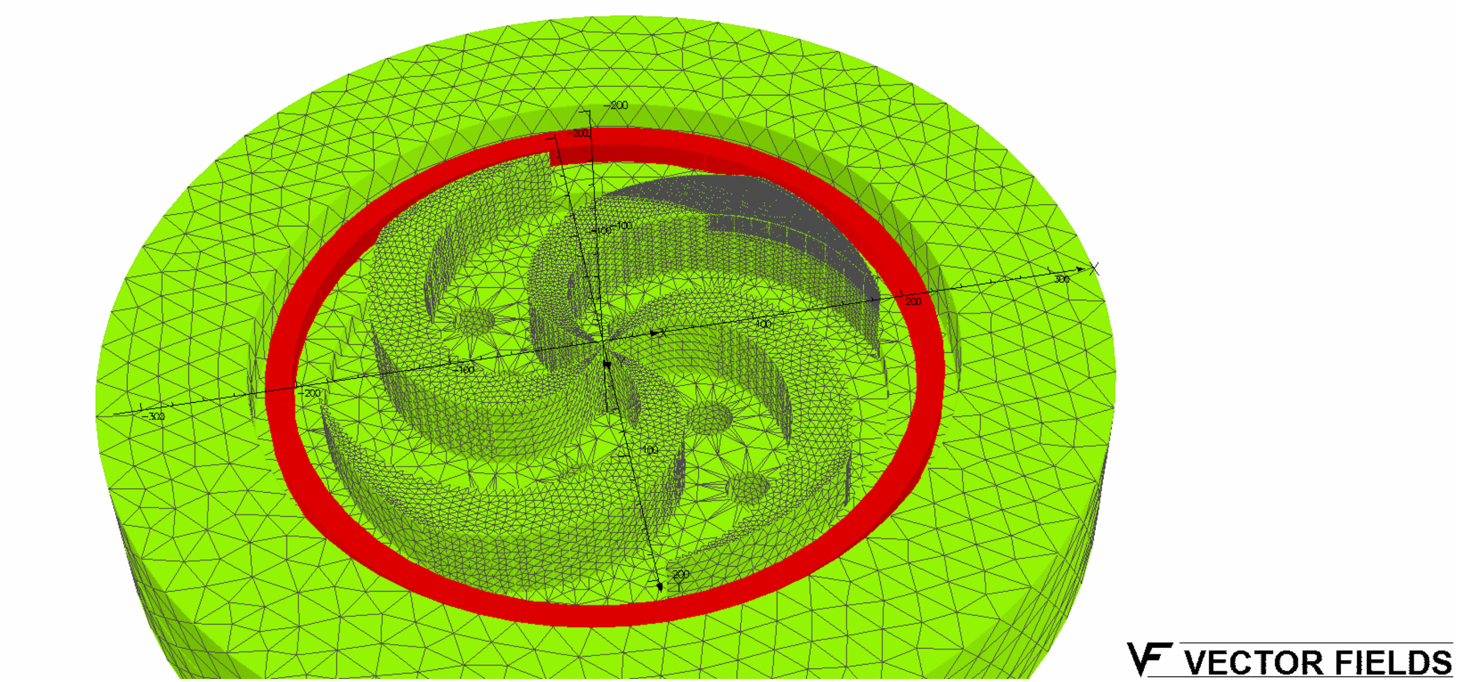
400 MeV/u carbon ions – rigidity 6.38 T.m

4 spiral sectors cyclotron – gap variable with radius

Average field from 2.5 T in centre to 3.5 T at extraction

Minimum field in valley 2.4 T

Maximum field on hills 4.5 T



VECTOR FIELDS

COIL REQUIREMENTS AND CHOICES (1)

4.5 T → superconductive

1000 Amps – about 2700 turns total

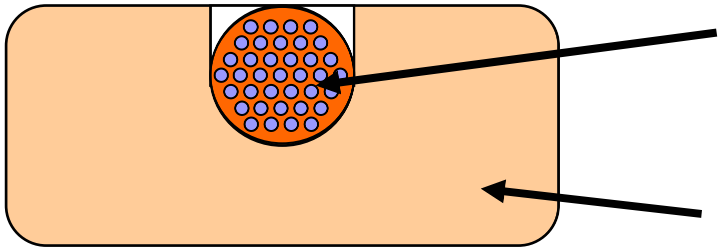
Moderate current density 55 A/mm²

Inductance ~110 H – Stored Energy 55 MJ

Cheap conductor → MRI type "wire in channel" cable

Average coil radius 2.2 m – 200 x 200 mm section

Insulated by double wrap of glass fiber tape



NbTi wires in Cu matrix soldered in Cu channel

Pure Cu channel

Area of copper decided by allowable maximum hoop stress

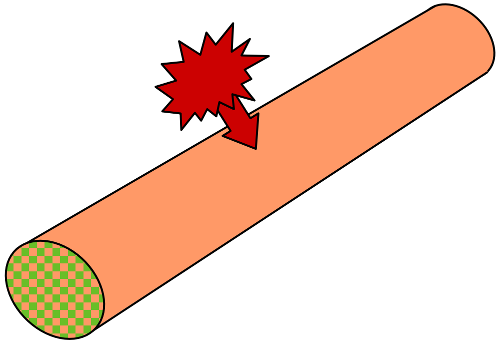
COIL REQUIREMENTS AND CHOICES (2)

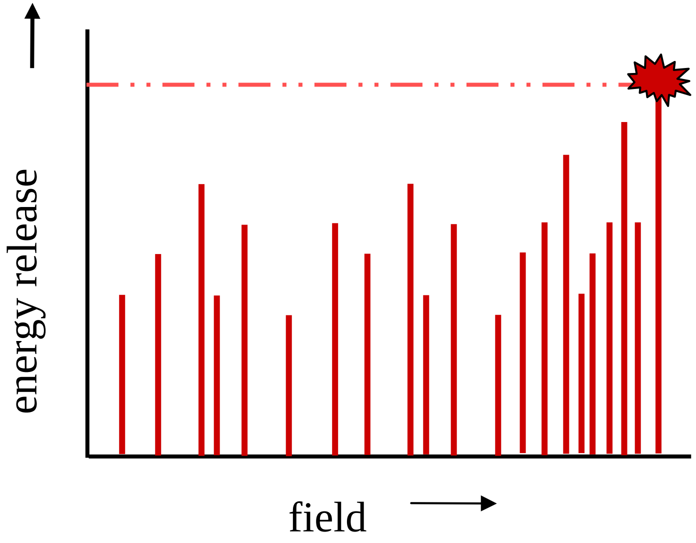
- fully impregnated coils should give better long term reliability than cryostability, but slight risk of training
- taking the hoop stress in the conductor avoids the need for reinforcing structure
- conductor design is dominated by tensile strength
- hardened copper can provide sufficient tensile strength while keeping an acceptably low resistivity

material for the channel	OFHC copper
condition of copper channel (suggested)	¼ hard to ½ hard
yield strength of copper channel	> 300MPa @ 4K
residual resistivity ratio of Cu in channel (preferred)	RRR = 100
residual resistivity ratio of Cu in channel (minimum)	RRR = 50

MINIMUM QUENCH ENERGY

- measure the stability of conductor against transient disturbances by the minimum quench energy MQE.
- energy input at a point in very short time which is just enough to trigger a quench.
- input > MQE ⇒ quench
- input < MQE ⇒ recovery
- energy disturbances occur at random as a magnet is ramped up to field
- for good magnet performance we want a high MQE

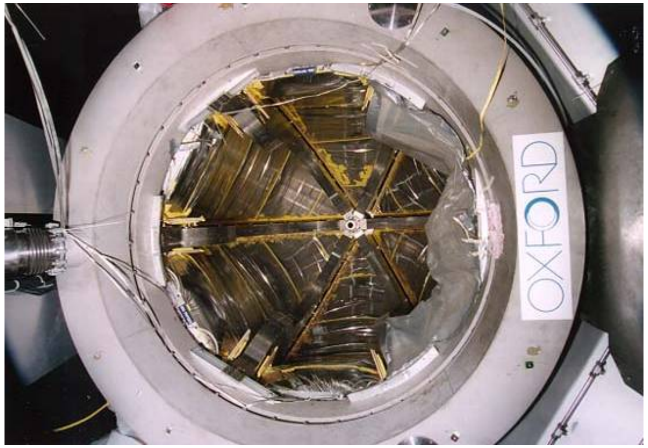


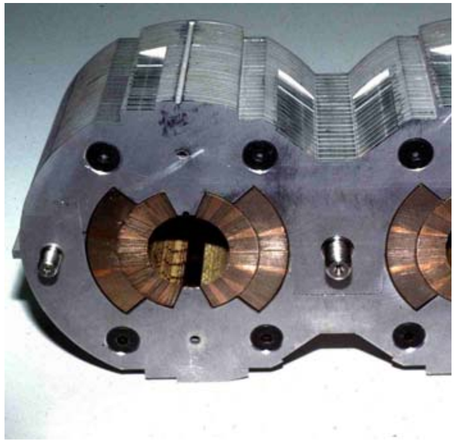


MQE COMPARISON

MAGNETS AND BEAM TRANSPORT

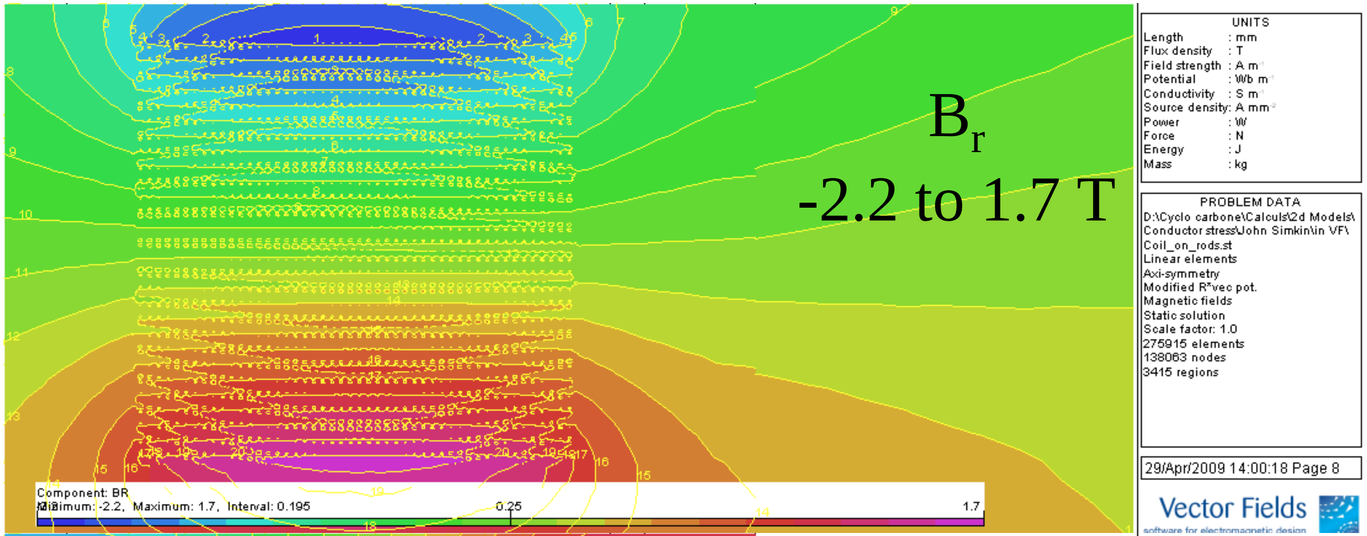
magnet	Grenoble Hybrid	MRI magnet	CLAS Torus	LHC dipole	C400 RRR 50
peak field (T)	8.5	6.09	3.5	8.4	4.5
operating current (A)	1330	461	3790	11500	1000
MQE (mJ)	1.735	0.2515	44.65	1.5	16.3
MQE scaled to C400 current and field (mJ)	0.68	0.39	14.83	0.07	16.3





FIELDS AT THE COIL

Coil located in high magnetic field – self + iron yoke



B_r
-2.2 to 1.7 T

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
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Conductor stress\John Simkin\in VF\
Coil_on_rods.st
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
275915 elements
138063 nodes
3415 regions

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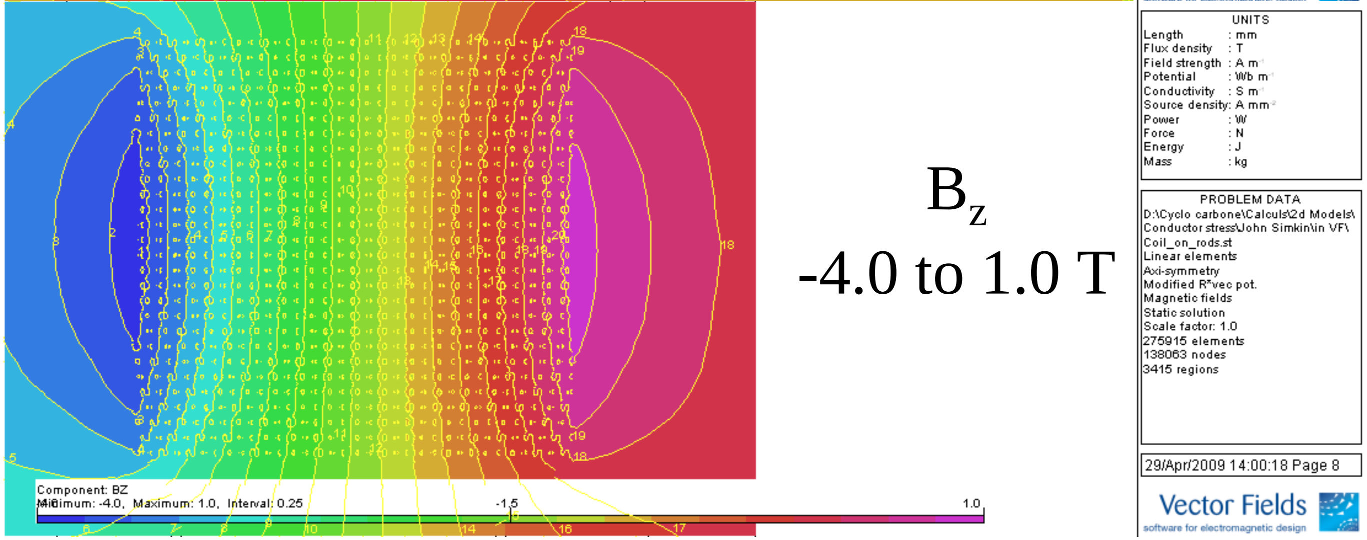

B_z
-4.0 to 1.0 T

UNITS
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Field strength : $A\,m^{-1}$
Potential : $Wb\,m^{-1}$
Conductivity : $S\,m^{-1}$
Source density: $A\,mm^{-2}$
Power : W
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Conductor stress\John Simkin\in VF\
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RADIAL STRESS (1)

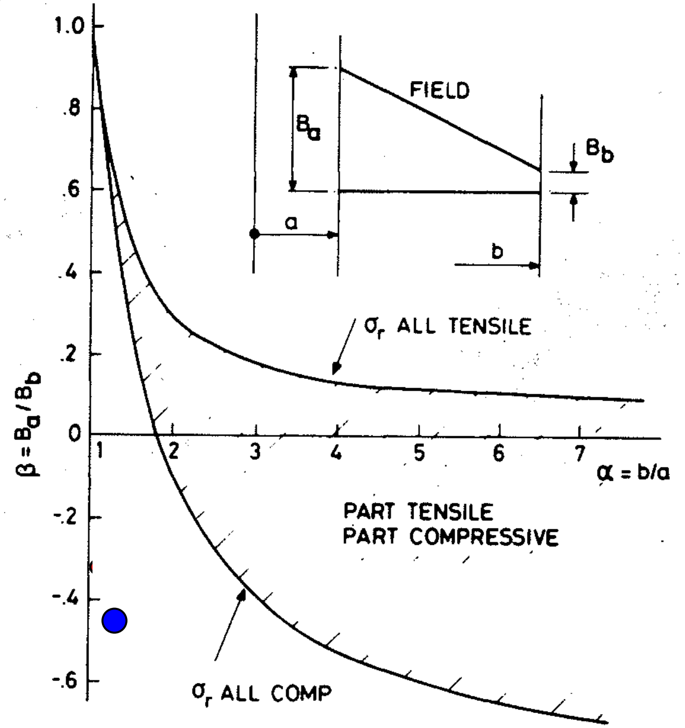
Each wire experiences a force pulling it outwards

A/ is the layout stable?

i.e. is the inner diameter pulled more than the outer diameter and the whole coil is in compression ? If not, the outer wires tend to be pulled apart from the more inner wires and the whole structure is in tension.

Resin becomes brittle at 4K → must avoid tensile stress (which often occurs in thick coils)

RADIAL STRESS (2)



Radial stress as a function of coil geometry using α and β parameters

From graph, we see coil is always compressive

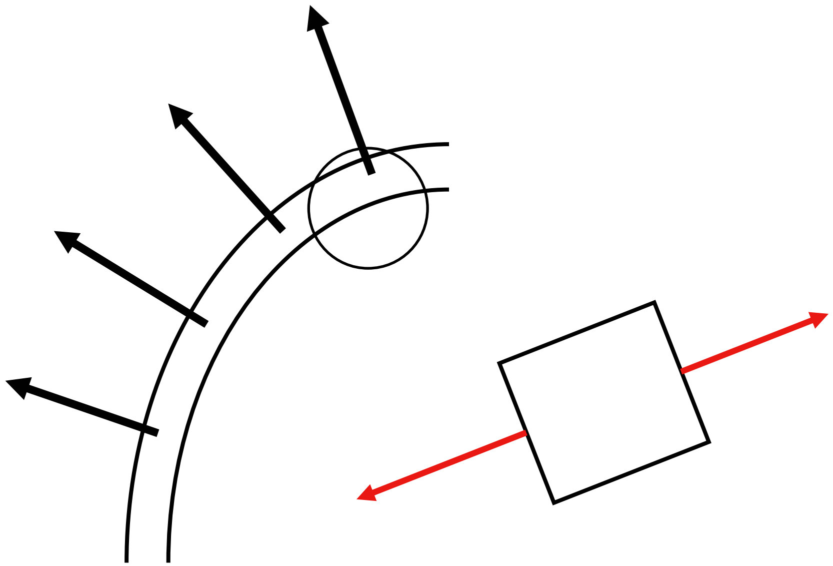
	Mod1	Mod2
α = outer radius / inner radius	1.10	1.19
β = inner field / outer field	-4.71	-4.74

HOOP STRESS (1)

B/ is the cable able to withstand the force ?

i.e. the wire is pulled outwards radially therefore generating a traction in the cable and stressing it.

Is the material able to withstand this *hoop stress* by itself or does it need some backing structure ?



HOOP STRESS (2)

Different models deliver different values

a/ Iwasa - mean field at mean radius

$$\langle \sigma \rangle = \langle r \rangle \langle B \rangle J$$

<B> = 1.5 T, <r>= 2.2 m and J=55 A/mm² → <σ>=180 MPa

b/ Wilson – infinite solenoid σ=140 MPa

c/ Unsupported inner single turn

B = 4.0 T, r= 2.0 m and J=50 A/mm² → <σ>=400 MPa

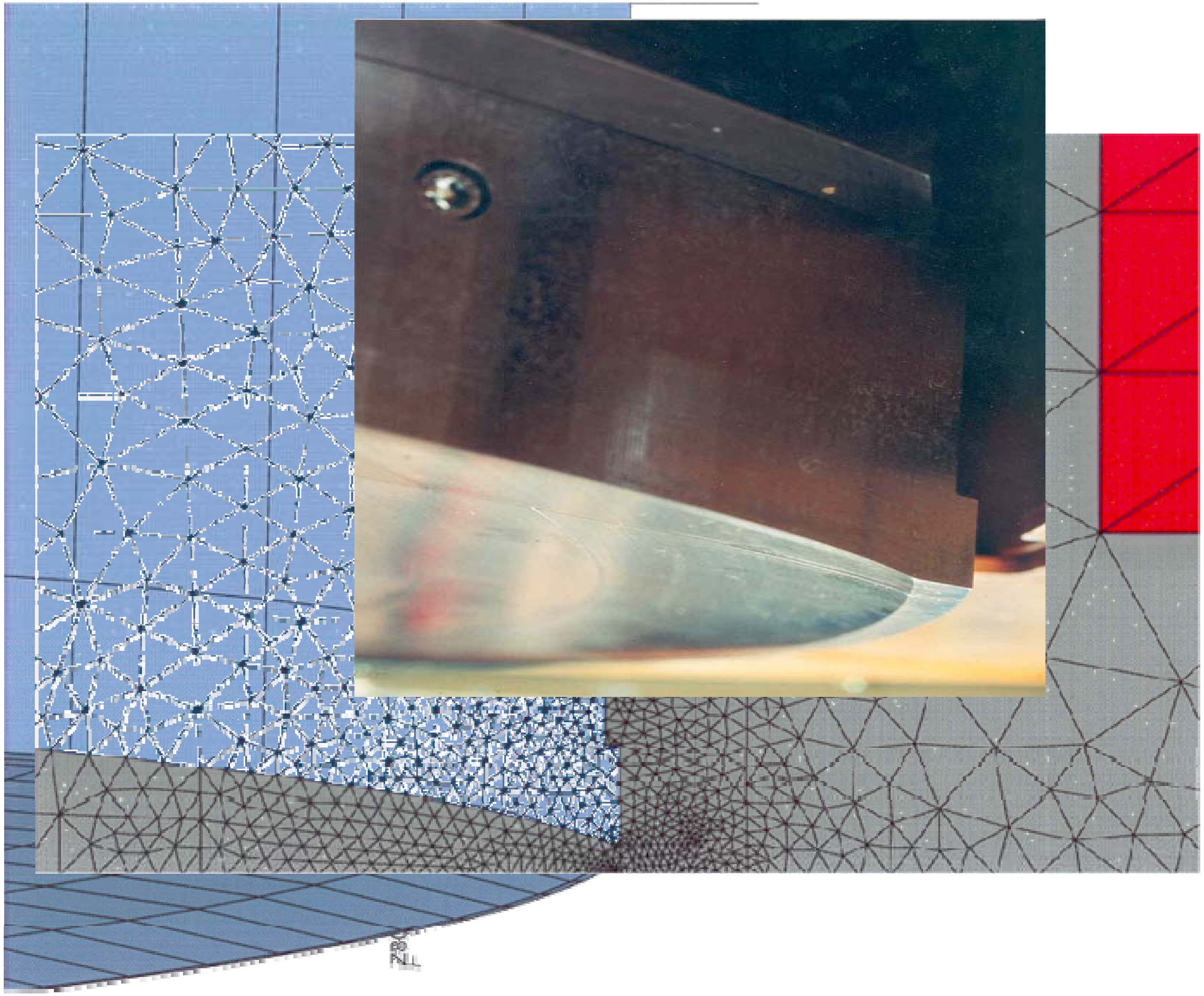
Unsupported turn clearly pessimistic. Other methods in the same range but working hypotheses are far from being.

Very high hoop stress → risk of material damage

We need a more accurate computation : finite elements

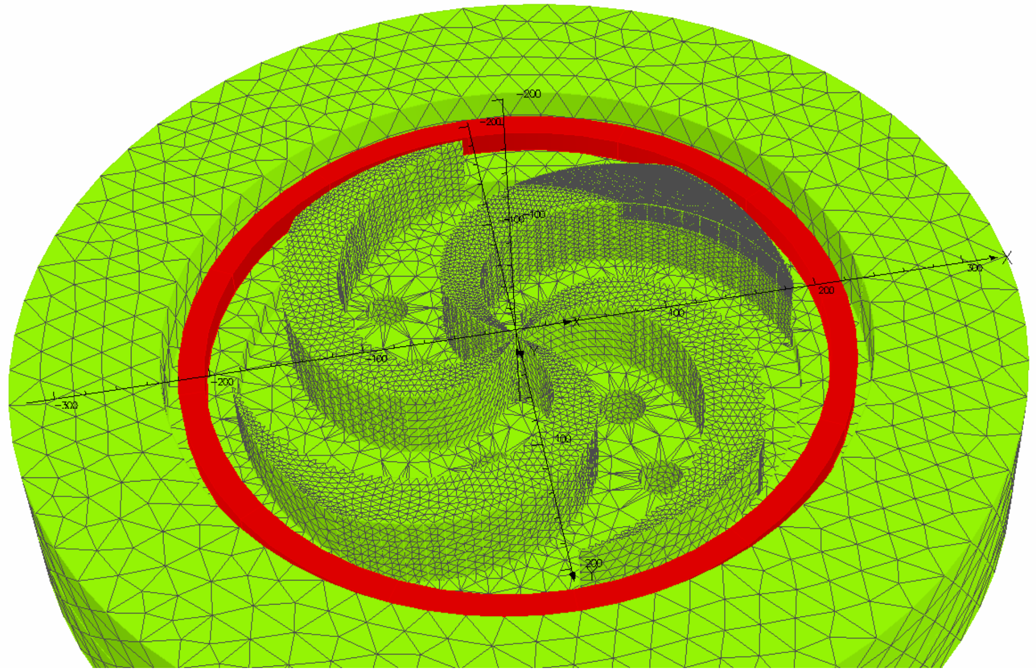
2D CYCLOTRON MODEL

MAGNETS
AND
BEAM
TRANSPORT



2D Cyclotron Model

Although the object is strongly 3D with its spiral hill and strong field difference between hills and valleys, 2D modelling can be used.



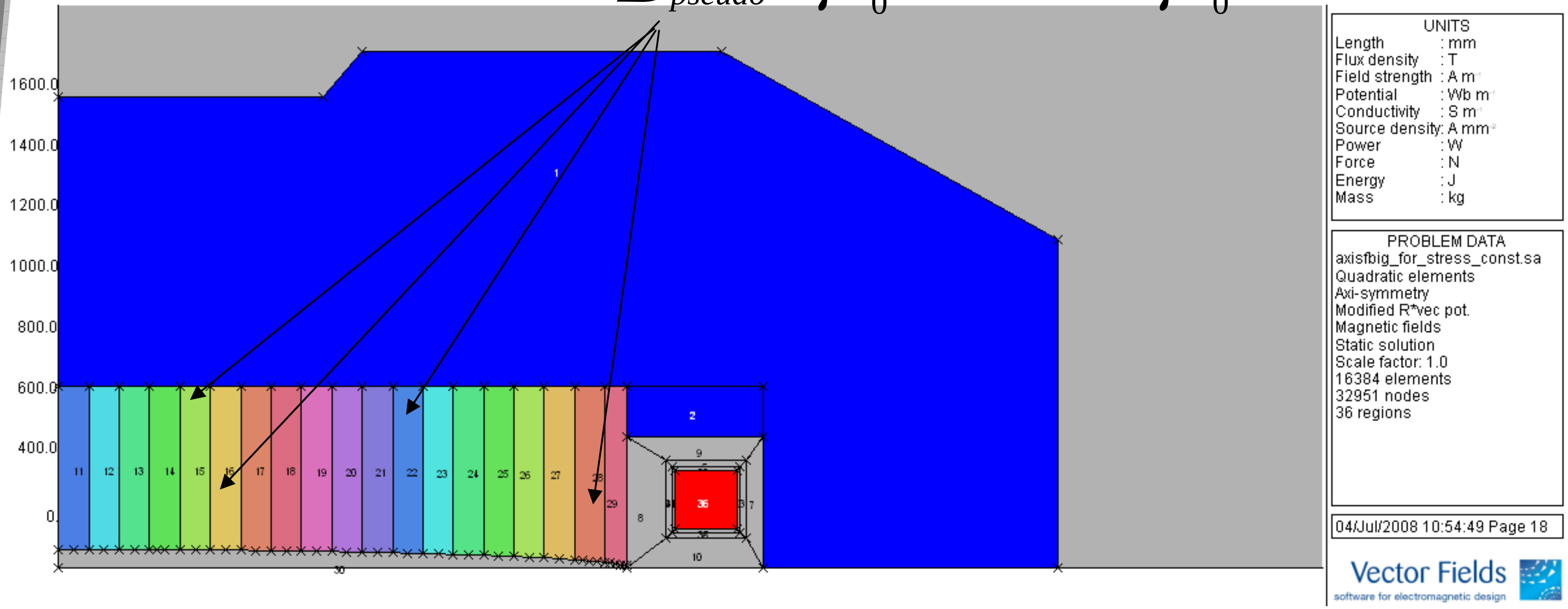
VECTOR FIELDS

2D CYCLOTRON MODEL

MAGNETS
AND
BEAM
TRANSPORT

The 3d geometry is modelled with a 2d code using pseudo-materials. The stacking factor is the proportion of the circle occupied by the real material. Each pseudo-material is defined by a modified B-H curve

$$B_{pseudo} = \mu_0 H + k \cdot (B - \mu_0 H)$$



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
axisfbig_for_stress_const.sa
Quadratic elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
16384 elements
32951 nodes
36 regions

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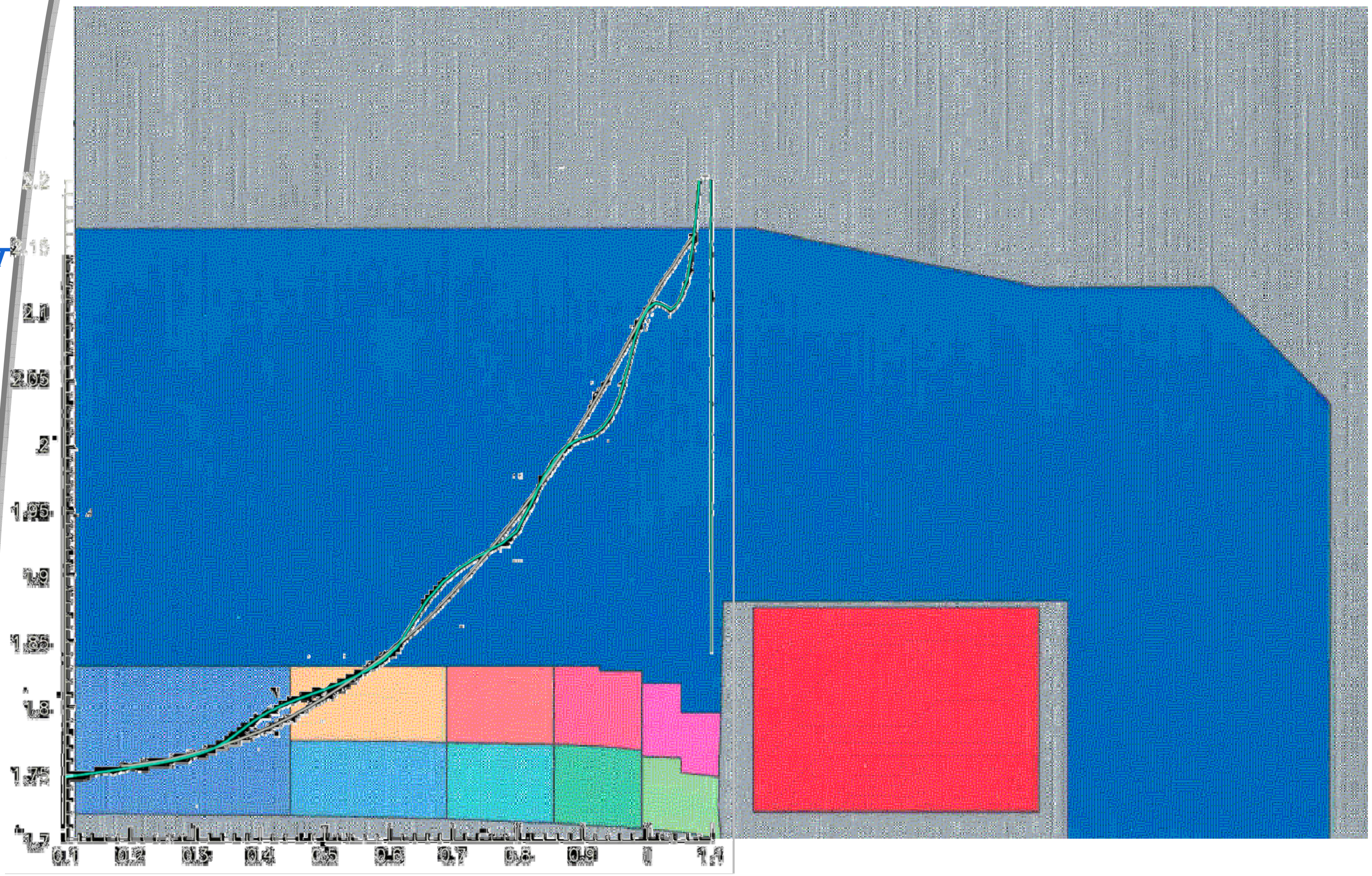
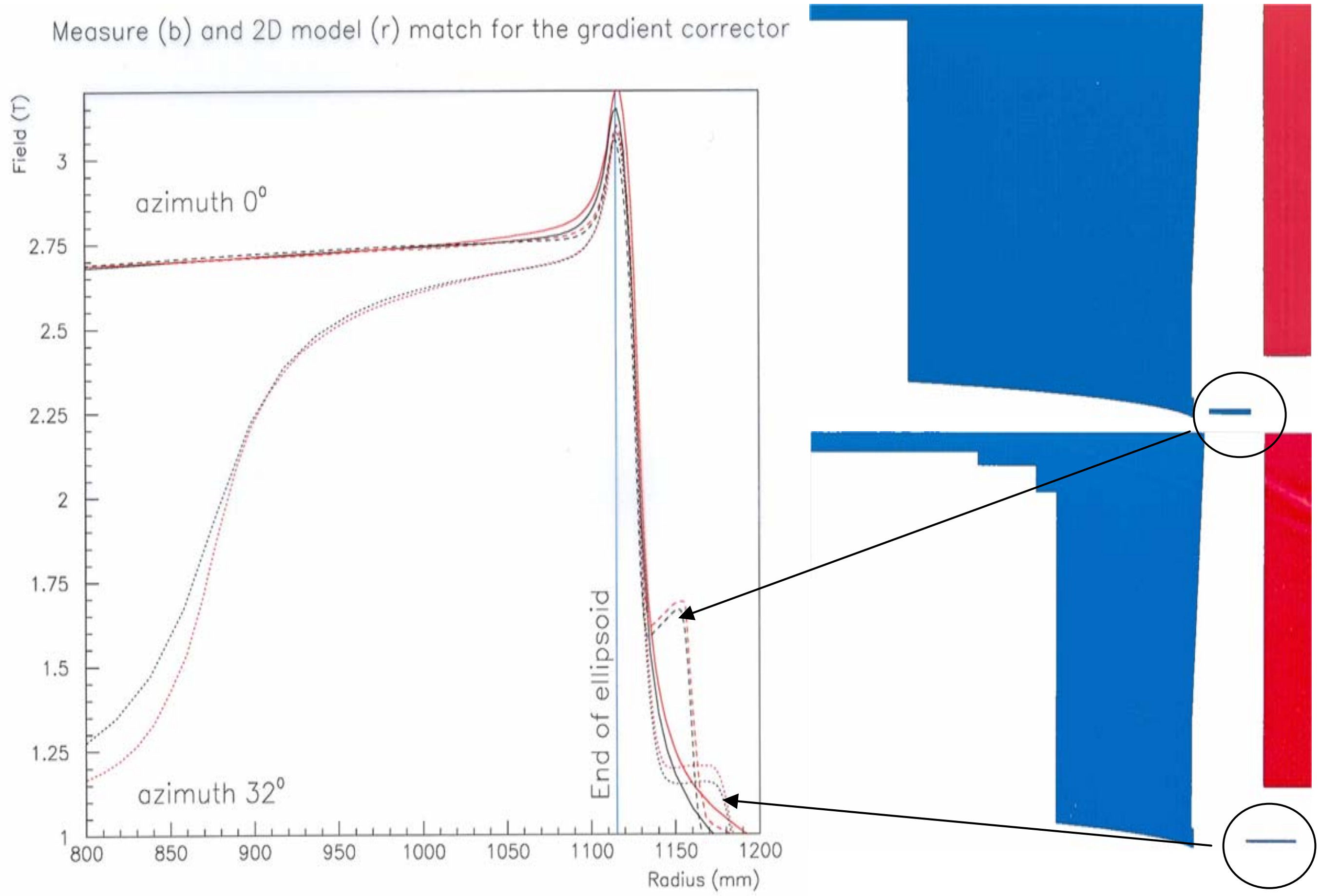
2D CYCLOTRON MODEL

MAGNETS
AND
BEAM
TRANSPORT



2D CYCLOTRON MODEL

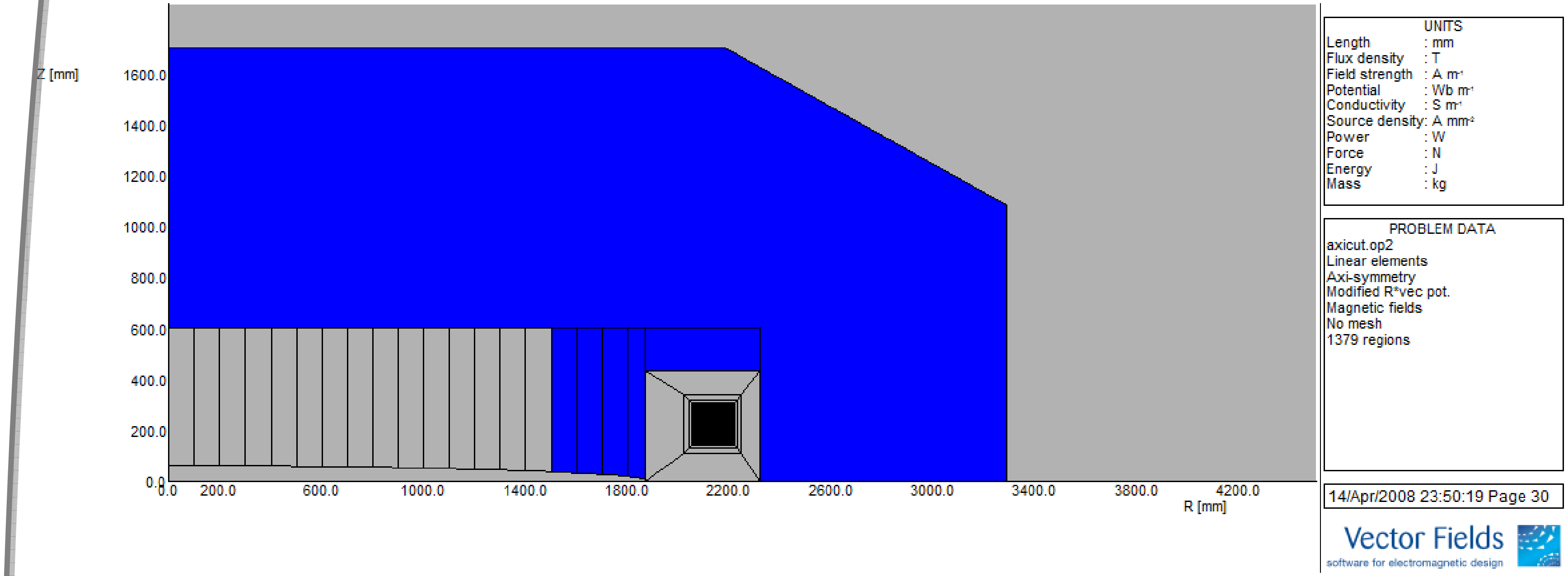
MAGNETS
AND
BEAM
TRANSPORT



Measure (b) and 2D model (r) match for the gradient corrector

2D CYCLOTRON MODEL

The 3d geometry is modelled with a 2d code representing a radial cut in the geometry at every angle. It works well for very saturated structures and is especially good in studying diferences in the geometry.



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Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
axicut.op2
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
No mesh
1379 regions

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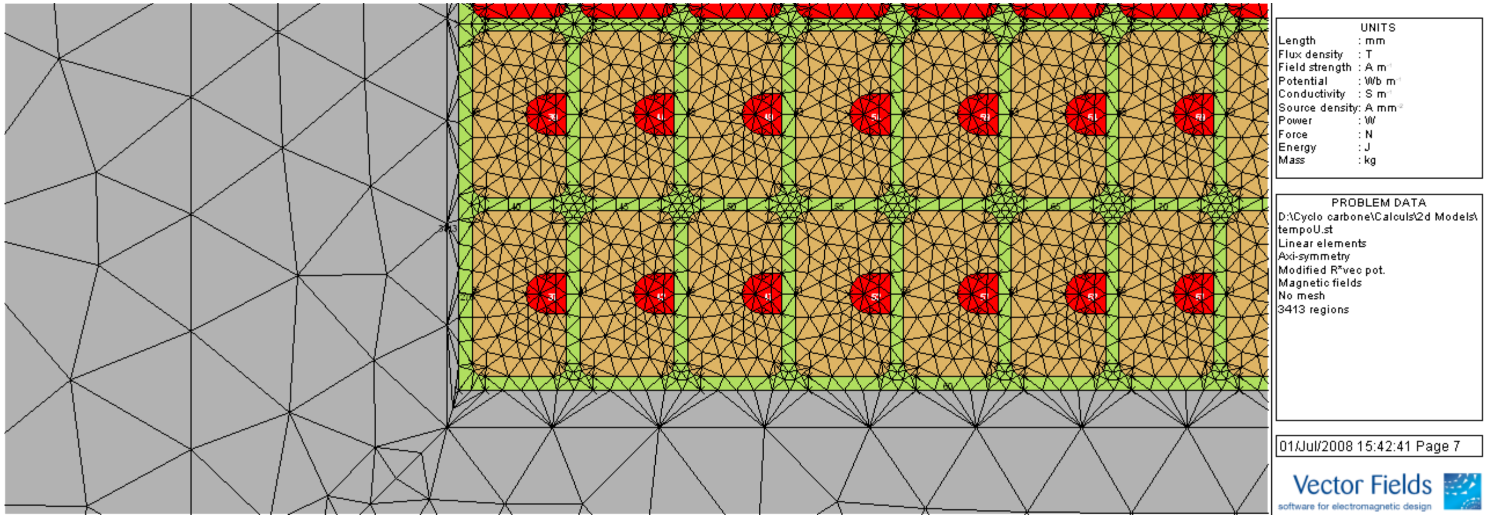
COIL MODEL FOR STRESS ANALYSIS

MAGNETS
AND
BEAM
TRANSPORT

The actual coil cross section should look a bit like this



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Conductivity : S m^{-1}
Source density: A mm^{-2}
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Force : N
Energy : J
Mass : kg

PROBLEM DATA
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Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
No mesh
3413 regions

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which is unfortunately rather difficult to model. For instance, one of the main concern is about resin behaviour and we can't expect a proper answer with just one layer of elements.

First turn to simpler problems

THE SIMPLEST DESCRIPTION (1)

Coil is 1 single homogeneous region

Mechanical properties given by the parallel mixtures rule

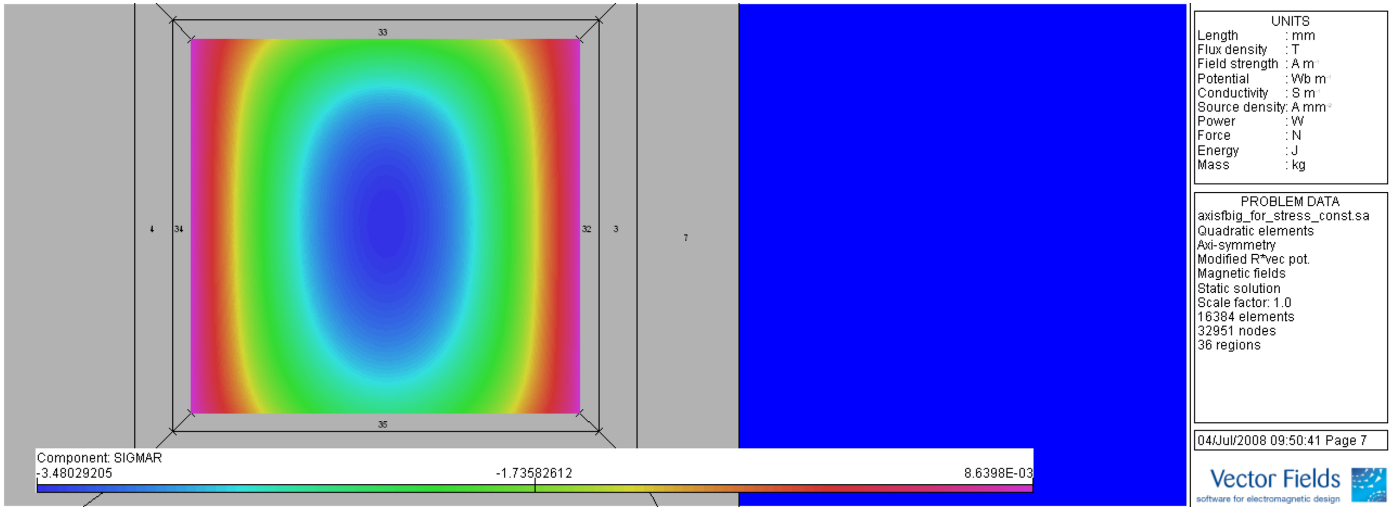
Young Modulus for the composite is the sum of the modulus for each component weighted by its fractional area

Cell area : 29.65 mm² - Metal area (CU+SC) : 23.86 mm² - Copper area : 23.37 mm²

	Fraction	Young (GPa)	Poisson
Cu	0.7889	150	0.3
SC	0.0165	160	0.3
G10	0.1946	20	0.28
Mixture	1	125	0.3

THE SIMPLEST DESCRIPTION (2)

Radial and axial stresses : the coil is indeed in compression



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PROBLEM DATA
axisfbig_for_stress_const.sa
Quadratic elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
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16384 elements
32951 nodes
36 regions

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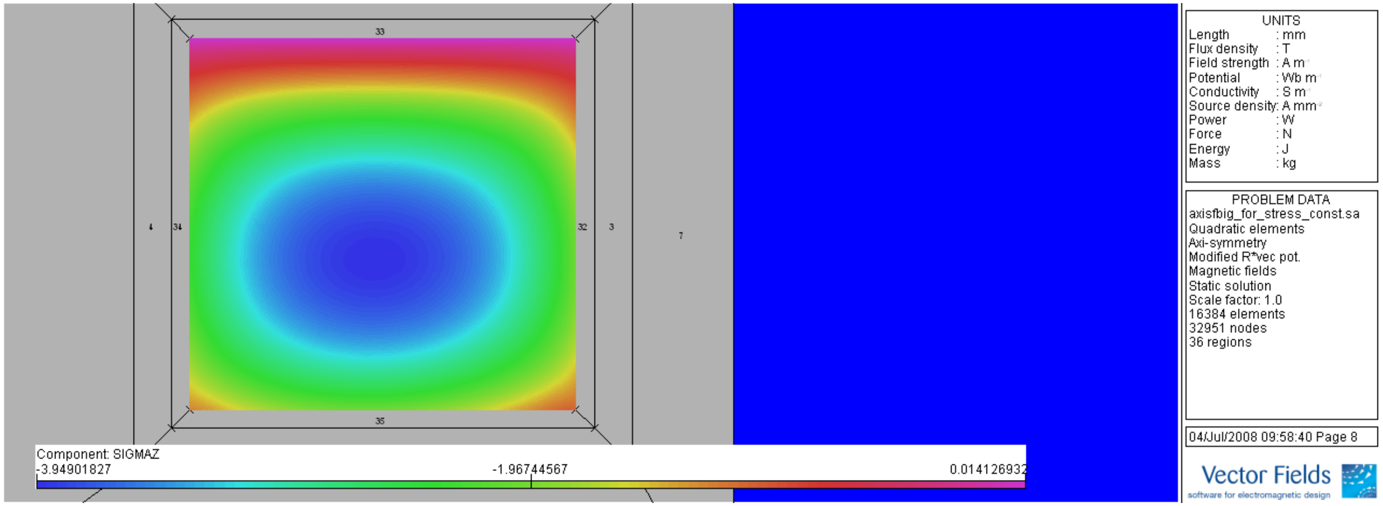

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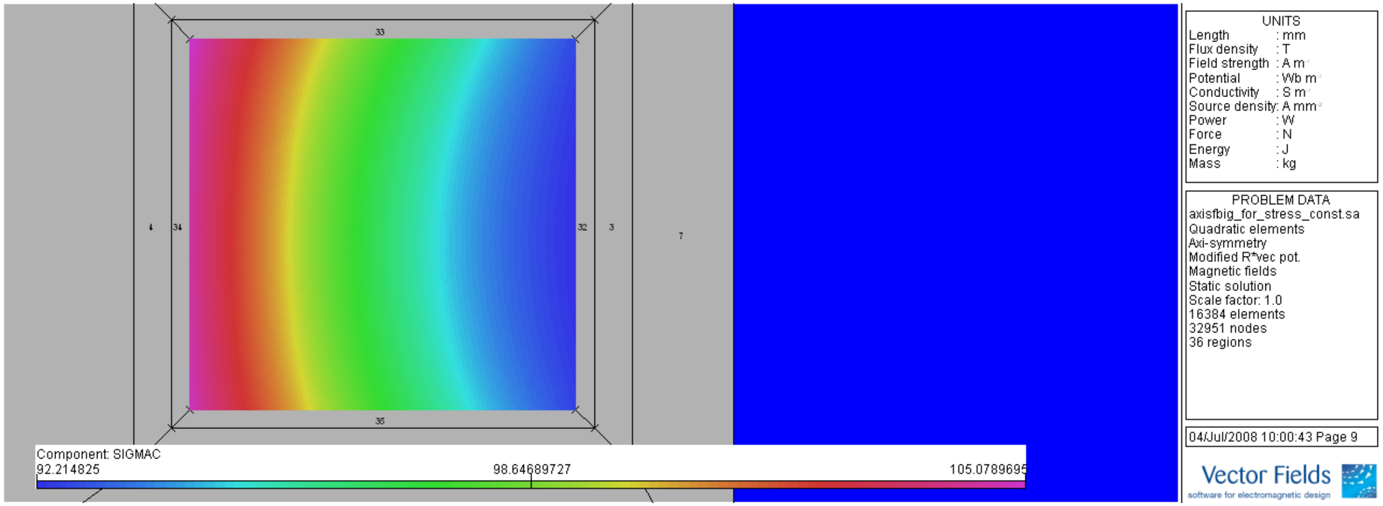
THE SIMPLEST DESCRIPTION (3)

MAGNETS
AND
BEAM
TRANSPORT

Hoop Stress and displacement : 105 MPa and 2 mm



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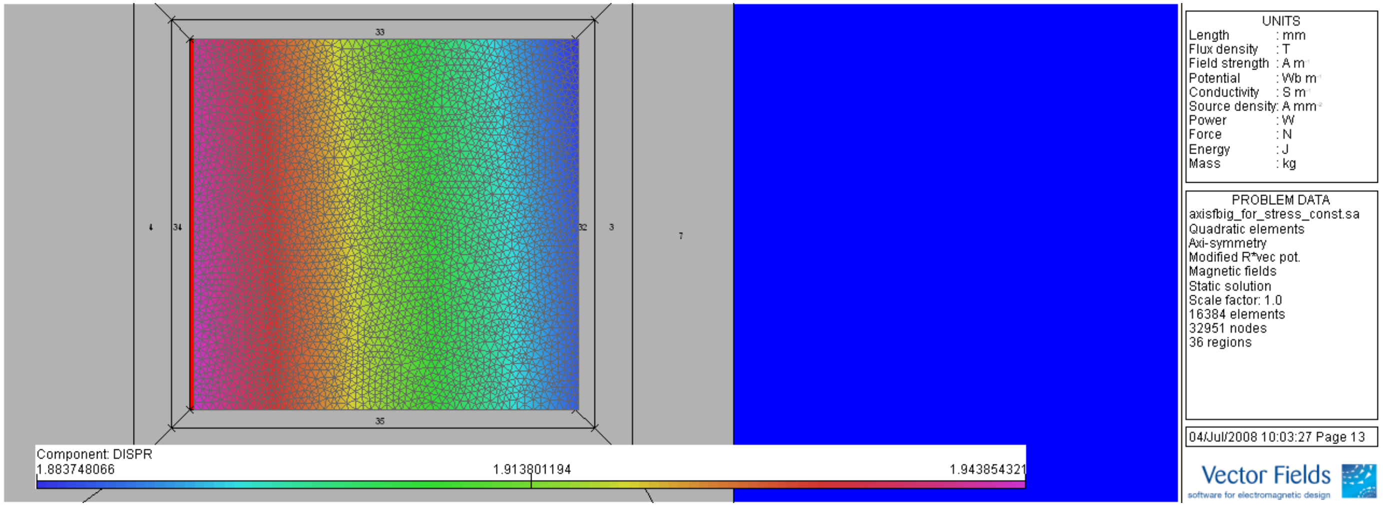

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COIL MODEL FOR STRESS ANALYSIS

Inadequate: 105 MPa instead of expected 140-150 Mpa

Unable to model curent density AND proper geometry.

Cross section considered to be filled with conductor and current density lowered wrt actual value to get same field

conductor filling factor ~78% → real stress ~ 105/0.78 = 135 MPa, much closer to the expected range of values.

Weak point: inability to describe the cross-section as it is while at the same time saving ~20% for the insulation.

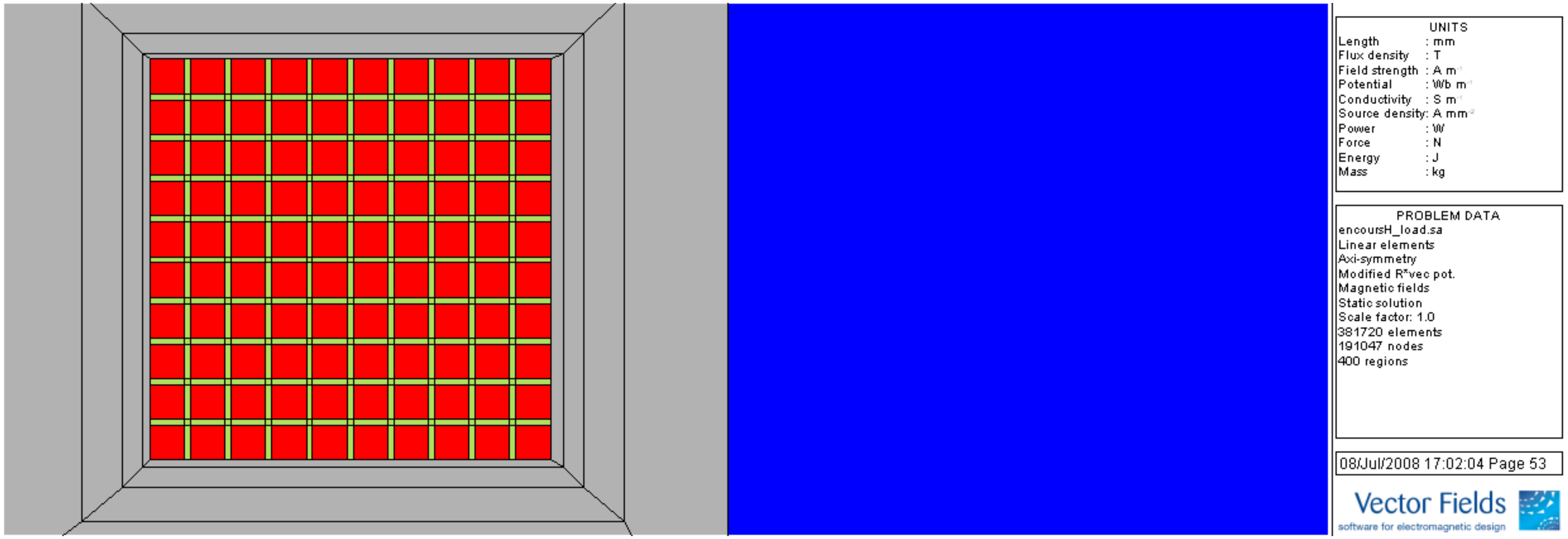
Must do something better

A BETTER MODEL - LAYOUT

Modelling all turns as they really are but insulation is only 0.5 mm making fine enough meshing very difficult.

Modelling the coil by a 10 x 10 turns grid, with square turns 17 mm x 17 mm and 3 mm insulation, allows inserting 22% insulation in the coil. Insulating material regions is large enough to accommodate many elements in all directions.

Adaptative meshing is used to improve the accuracy



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Source density: A mm^{-2}
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Energy : J
Mass : kg

PROBLEM DATA
encoursH_load.sa
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
381720 elements
191047 nodes
400 regions

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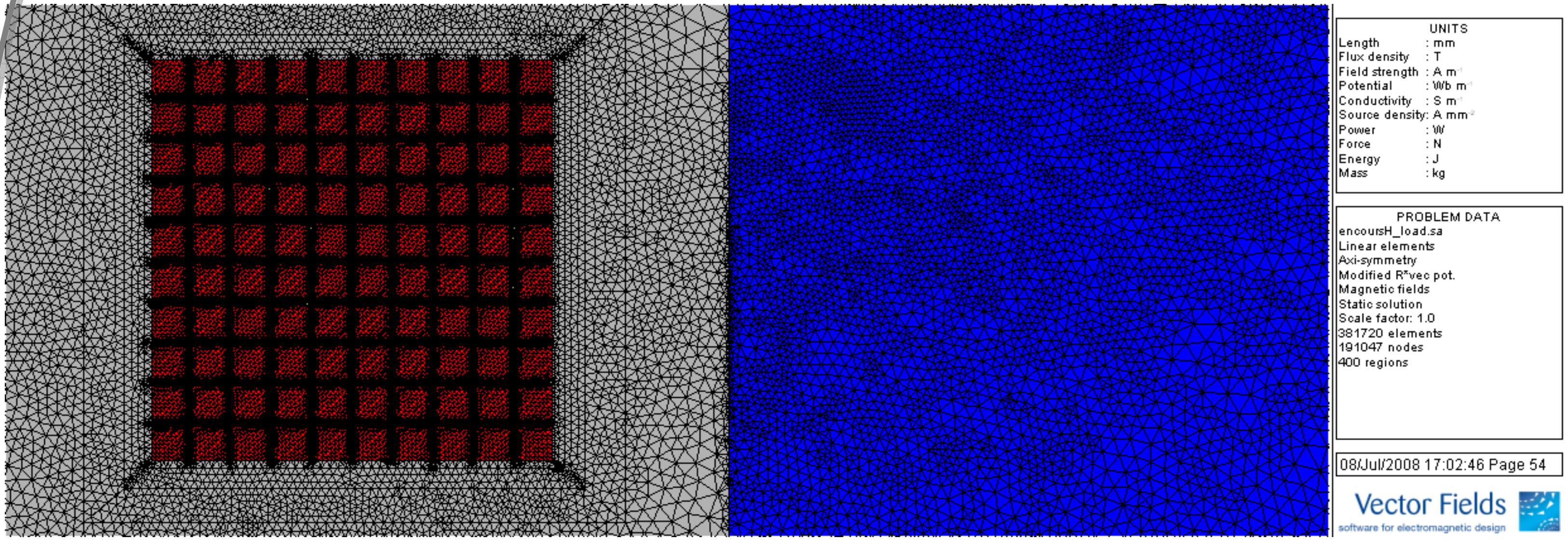
A BETTER MODEL - MESH

MAGNETS
AND
BEAM
TRANSPORT



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Linear elements
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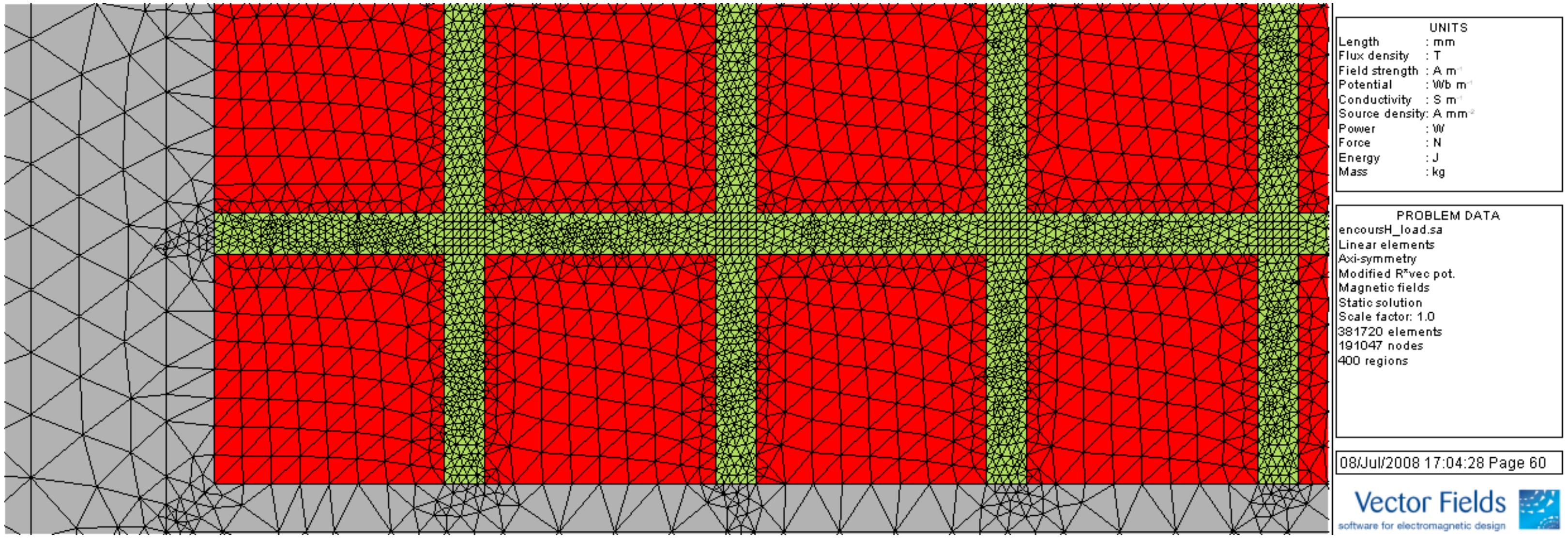

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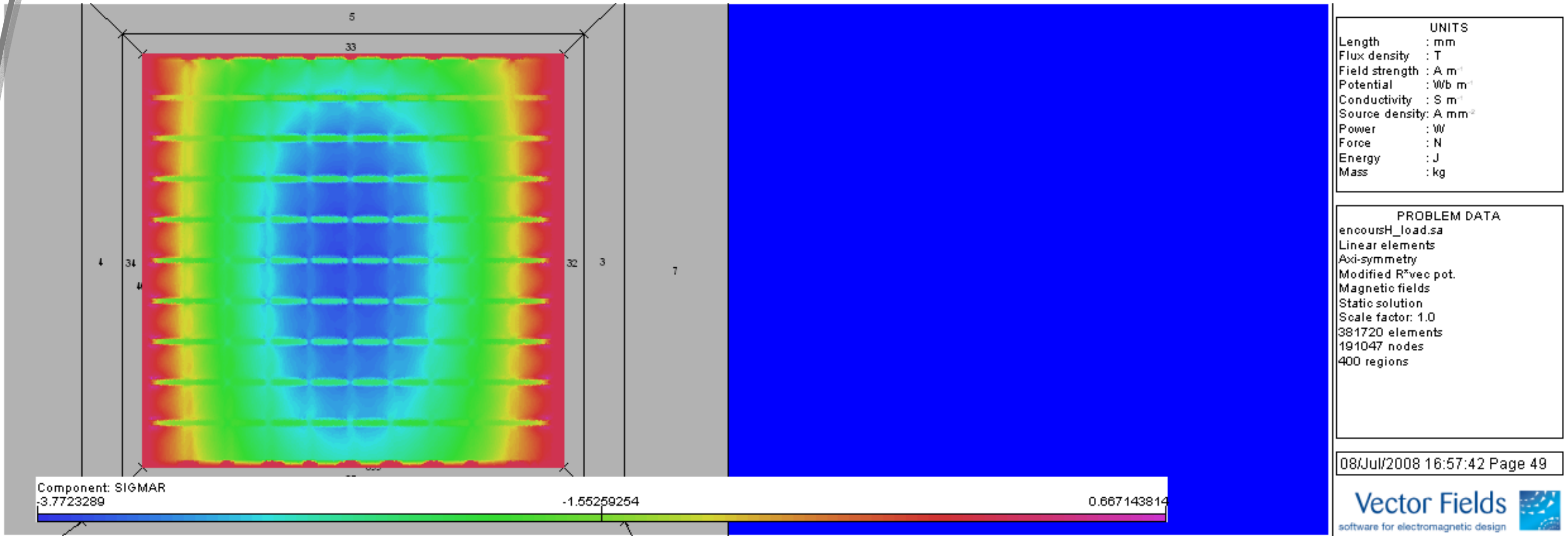
A better Model – R and Z Stresses



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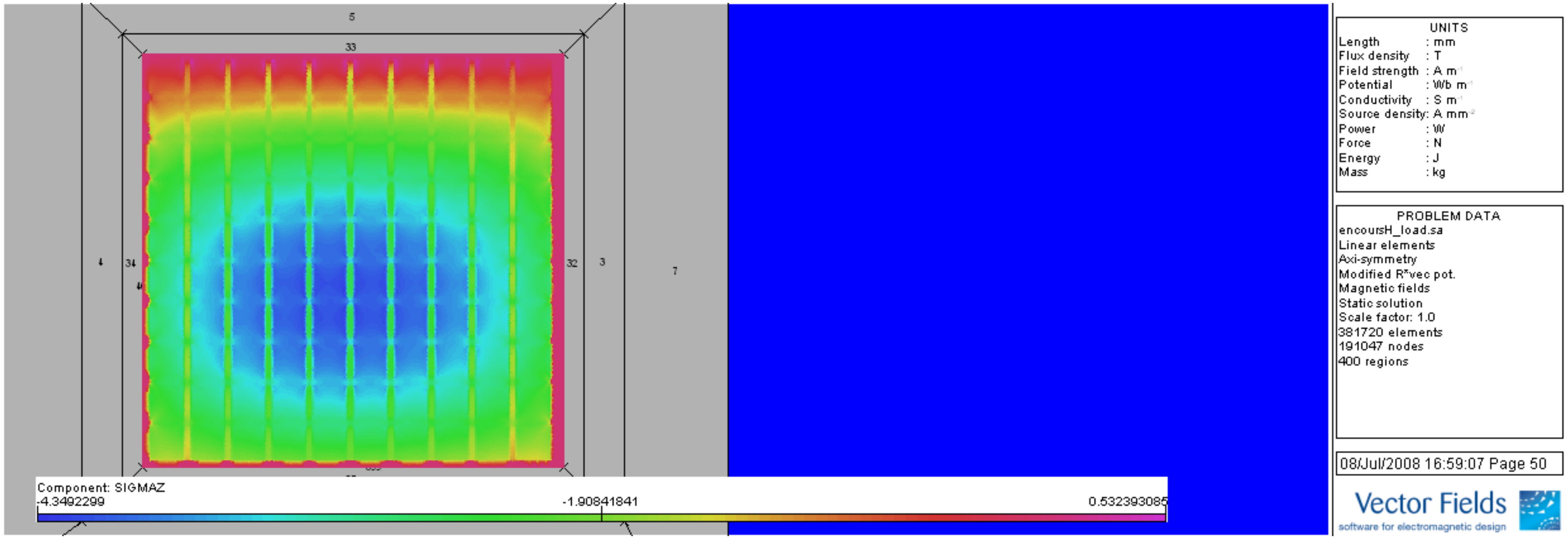

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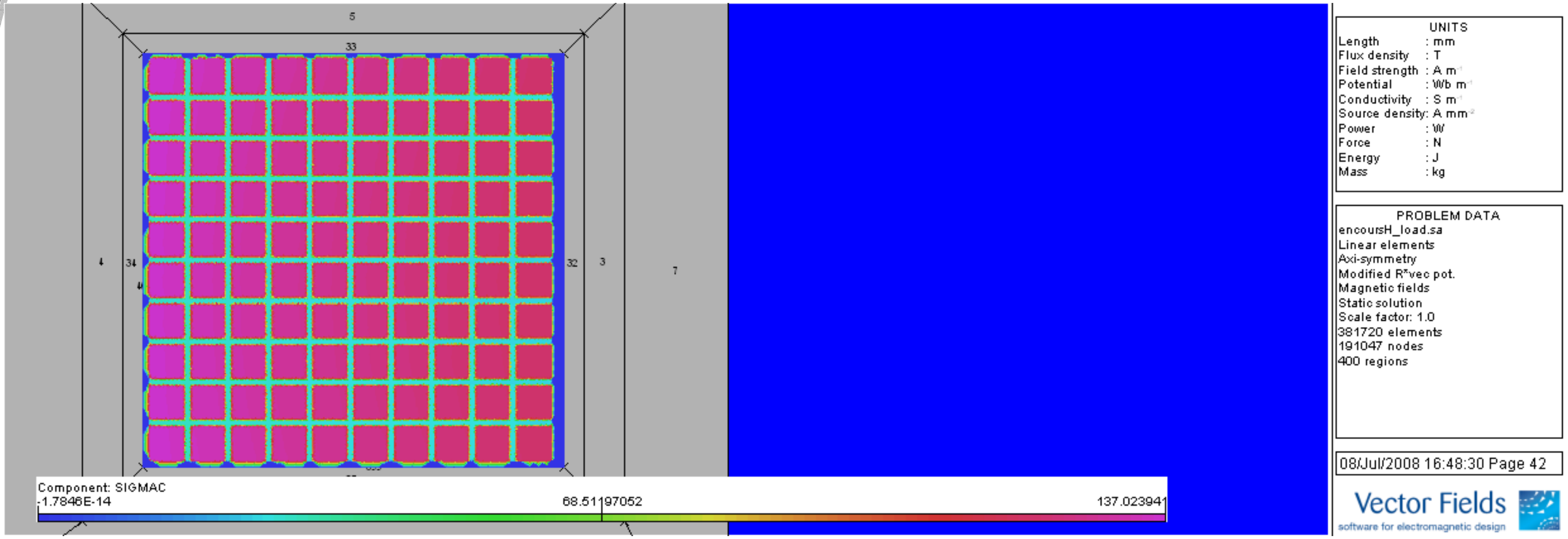
A BETTER MODEL – HOOP STRESS

MAGNETS
AND
BEAM
TRANSPORT



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Potential : Wb m^{-1}
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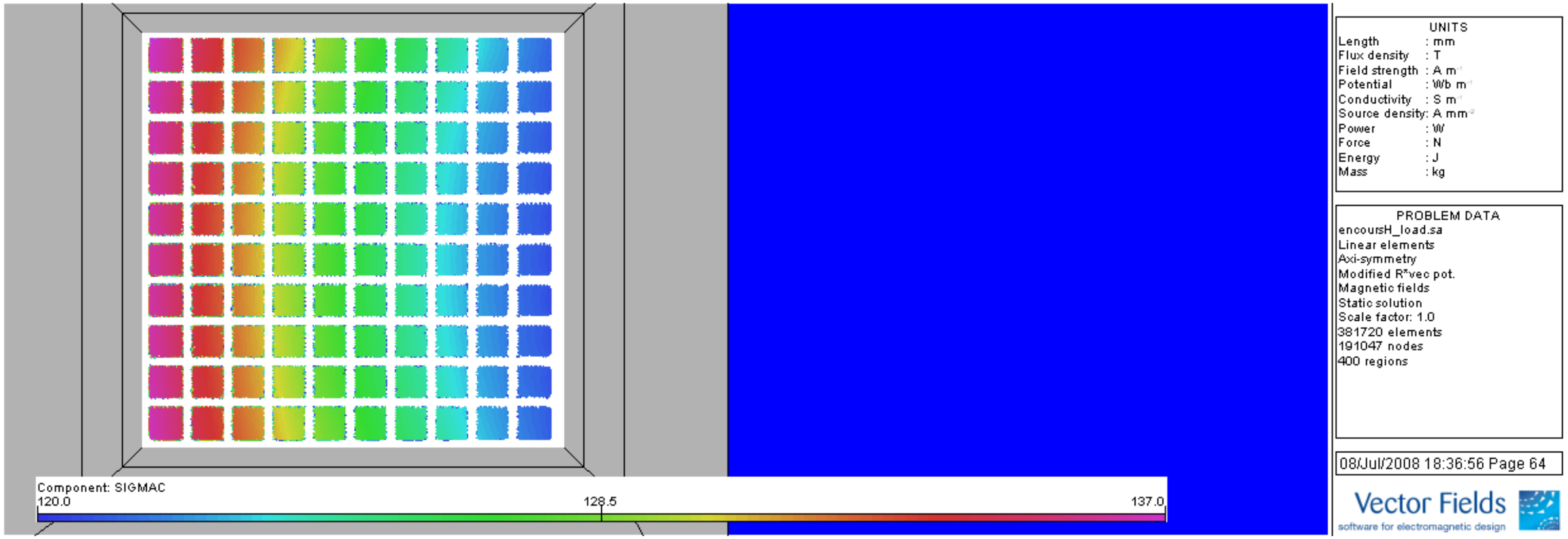

UNITS
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Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
encoursH_load.sa
Linear elements
Axi-symmetry
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Magnetic fields
Static solution
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191047 nodes
400 regions

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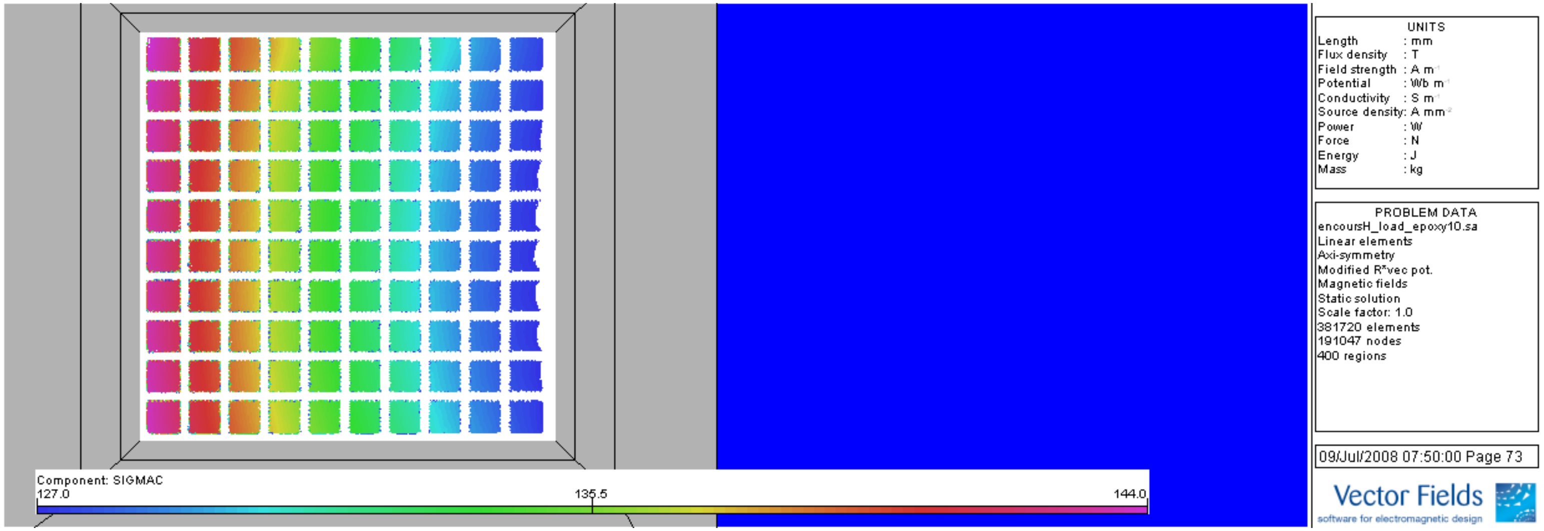
MODYFYING RESIN PROPERTIES



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Component: SIGMAC
127.0                    135.5                    144.0
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UNITS
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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
encoursH_load_epoxy10.sa
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
381720 elements
191047 nodes
400 regions

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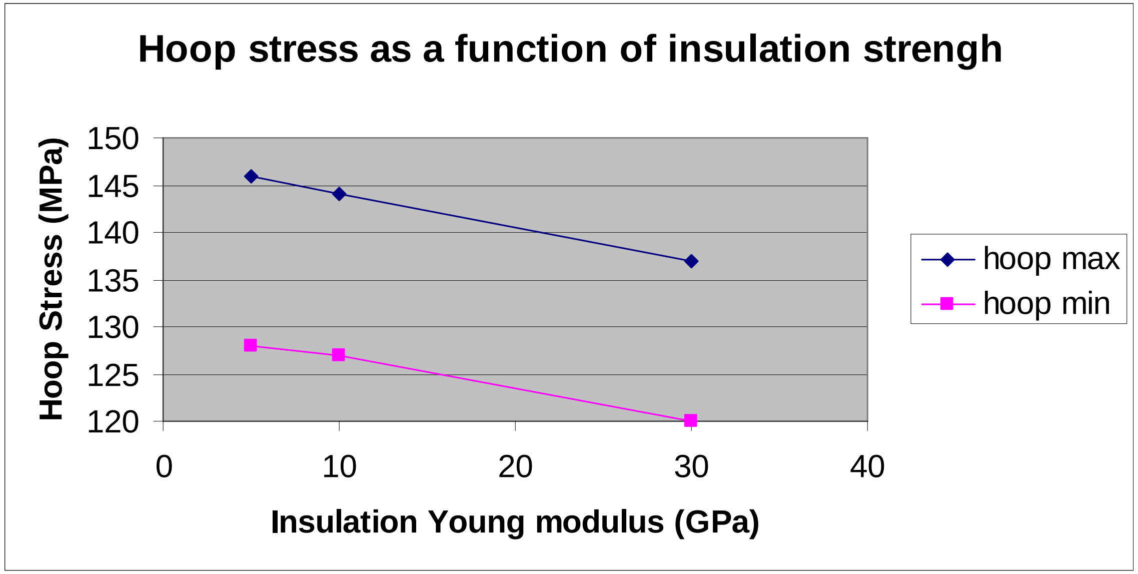
```



Hoop stress as a function of insulation strengh

FULL MODEL WITH SUPPORT

In previous models, the coil is prevented from drowning by boundary conditions.

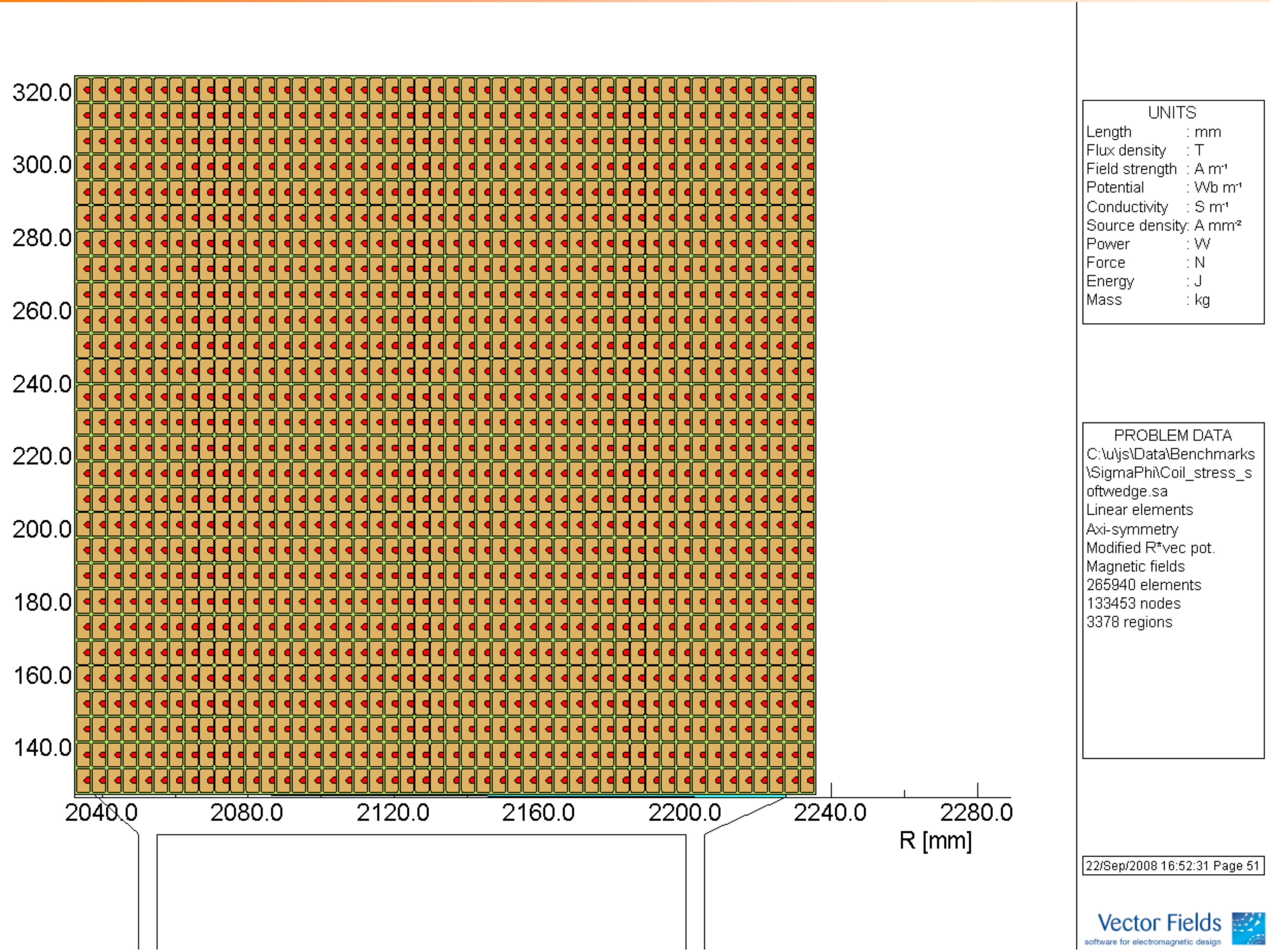
Unfortunately, the real world doesn't allow such a Harry Potter's feature and a real support must be taken into account, together with its interaction with the coil.

All the coil features are now described as accurately as possible. The support is studied with 2 geometries

- Flat horizontal
- Tilted

FULL MODEL - COIL

MAGNETS AND BEAM TRANSPORT



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:\u\js\Data\Benchmarks\SigmaPhi\Coil_stress_softwedge.sa
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
265940 elements
133453 nodes
3378 regions

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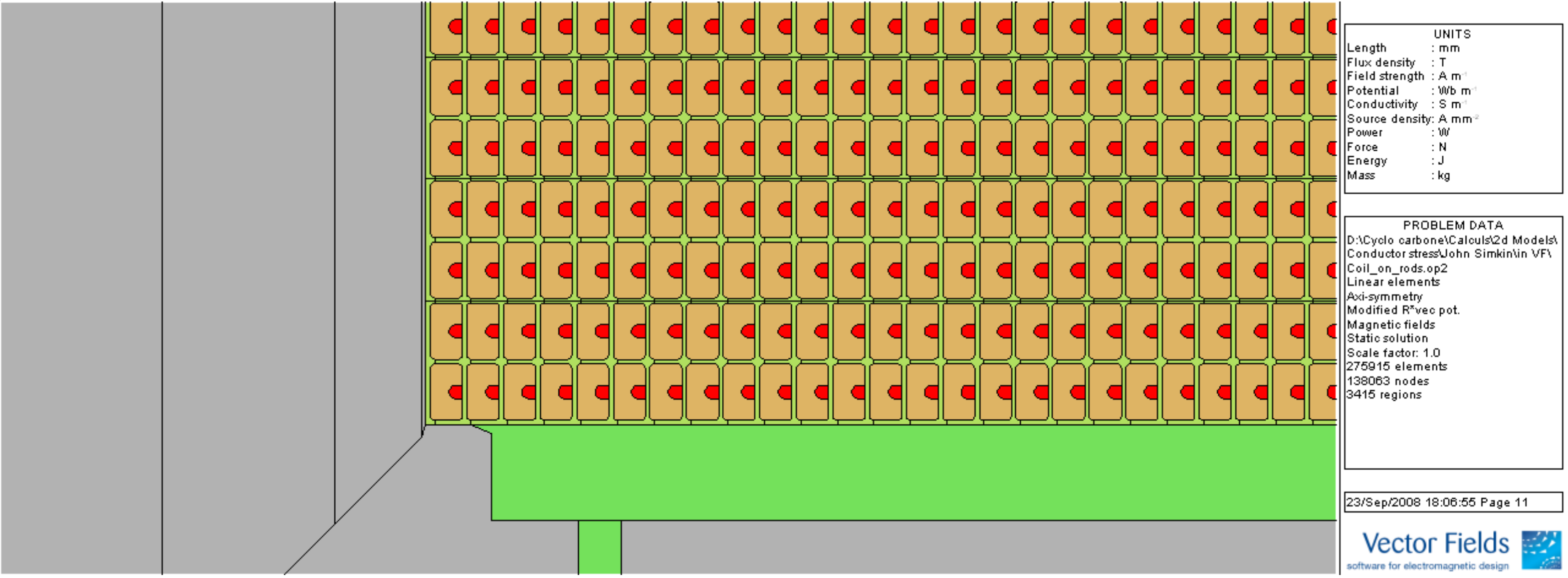
FULL MODEL – VERTICAL RESTRAINT



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
D:\Cyclo carbone\Calculs\2d Models\
Conductor stress\John Simkin\in VF\
Coil_on_rods.op2
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
275915 elements
138063 nodes
3415 regions

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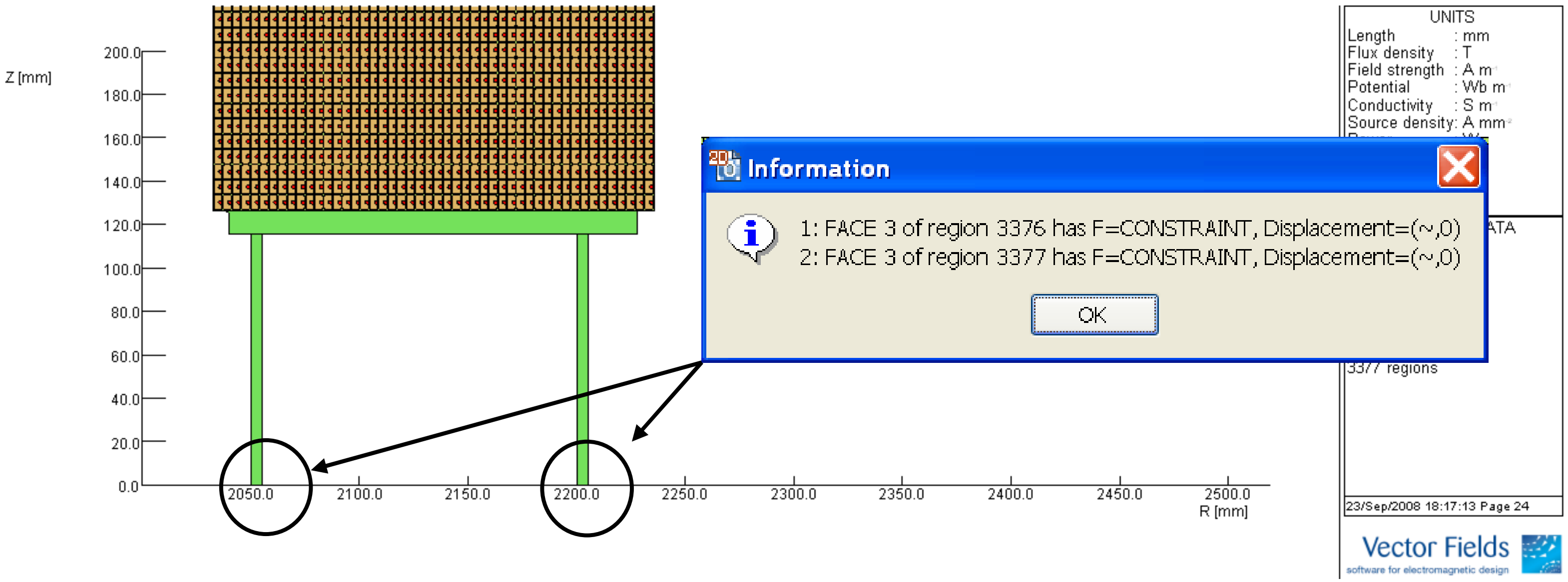

1: FACE 3 of region 3376 has F=CONSTRAINT, Displacement=(~,0)
2: FACE 3 of region 3377 has F=CONSTRAINT, Displacement=(~,0)

UNITS
Length : mm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}

ATA

3377 regions

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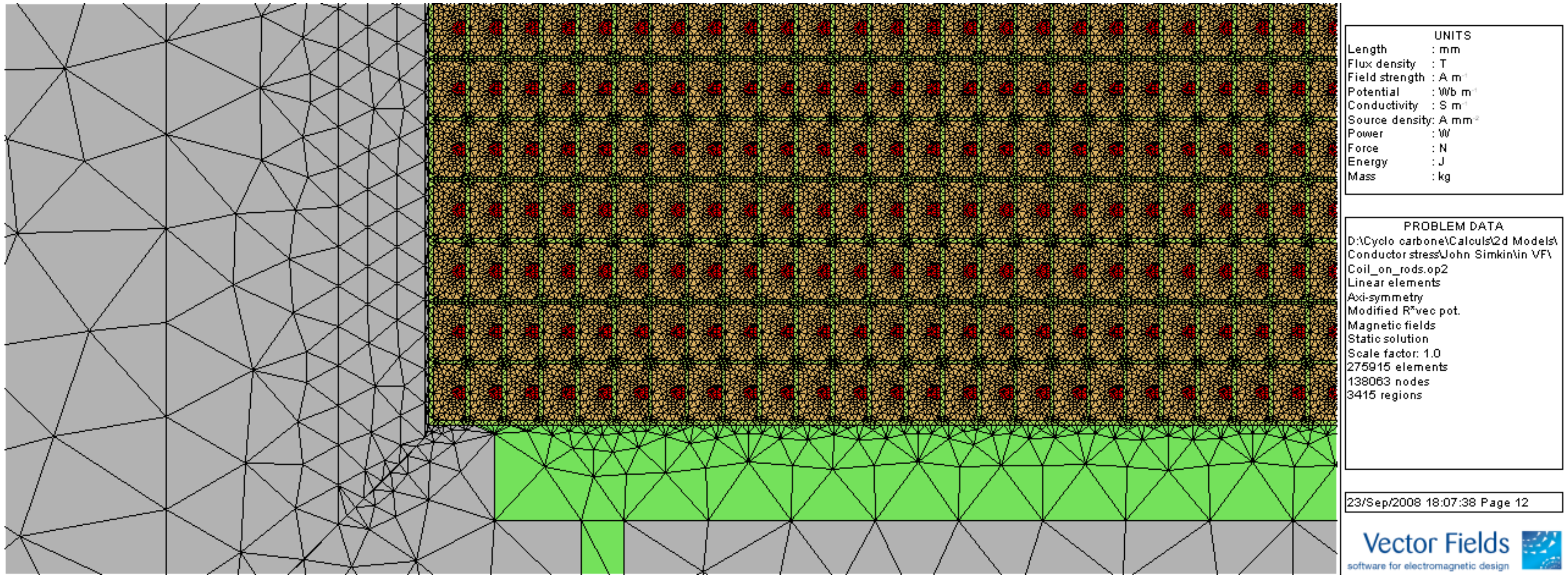
FULL MODEL - MESH



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
D:\Cyclo carbone\Calculs\2d Models\
Conductor stress\John Simkin\in VF\
Coil_on_rods.op2
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
275915 elements
138063 nodes
3415 regions

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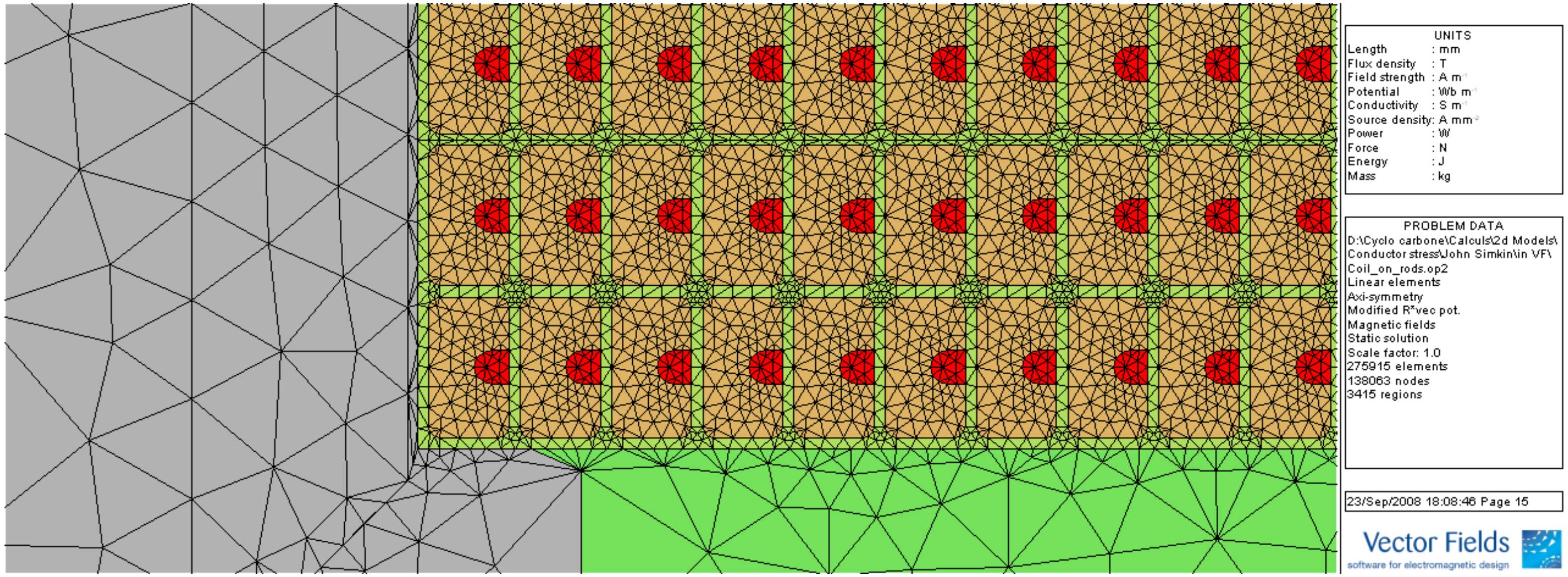

UNITS
Length : mm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
D:\Cyclo carbone\Calculs\2d Models\
Conductor stress\John Simkin\in VF\
Coil_on_rods.op2
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
275915 elements
138063 nodes
3415 regions

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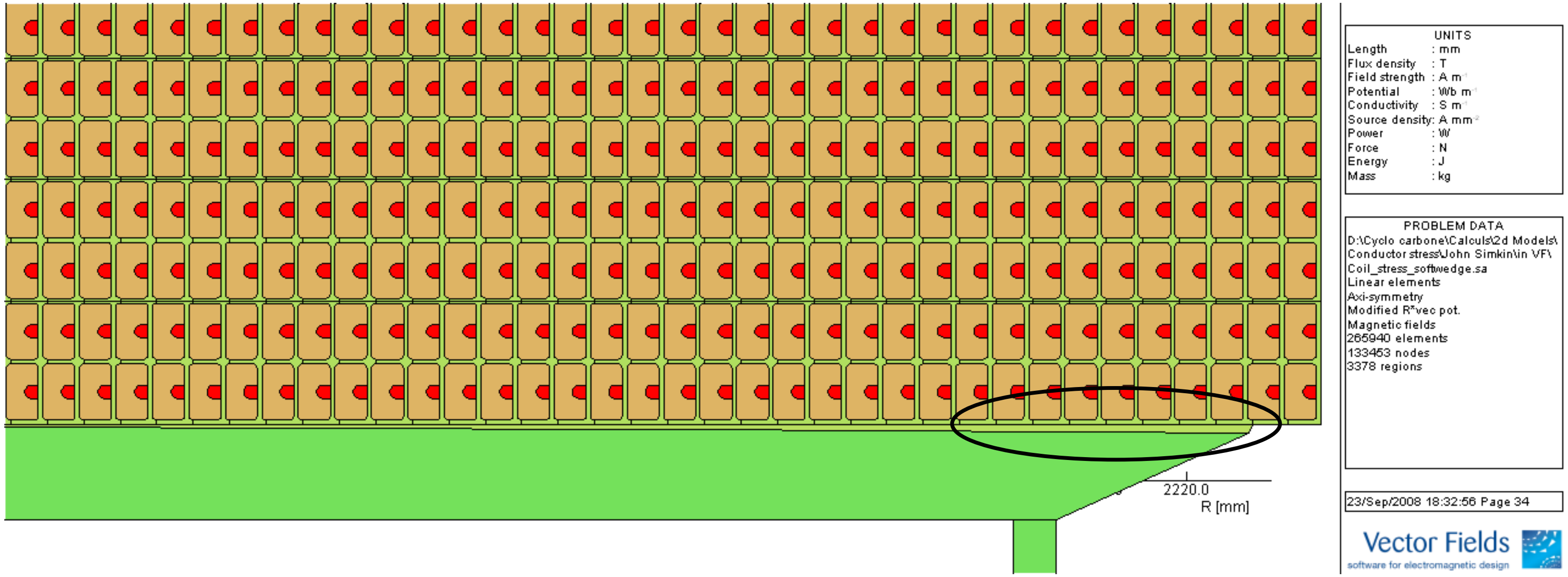
FULL MODEL – MATERIAL PROPERTIES

	Density (kg/dm^3)	**Young E (GPa)**	**Poisson ν**
Cu	8.933	150	0.33
SC	8.698	160	0.32
G10	1.100	20	0.28
Support	0.800	8	0.30
Buffer	8000	0.001	0.30

$$G = \frac{E}{2(1+\nu)}$$

TILTING THE COIL

Use a very soft buffer material that will squash. This allows nodes shared by the buffer and the coil to move while nodes shared by the buffer and the support stay fixed. Boundary conditions same as previously, i.e. imposed on the pillars of the support structure.



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
D:\Cyclo carbone\Calculs\2d Models\
Conductor stress\John Simkin\in VF\
Coil_stress_softwedge.sa
Linear elements
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Modified R*vec pot.
Magnetic fields
265940 elements
133453 nodes
3378 regions

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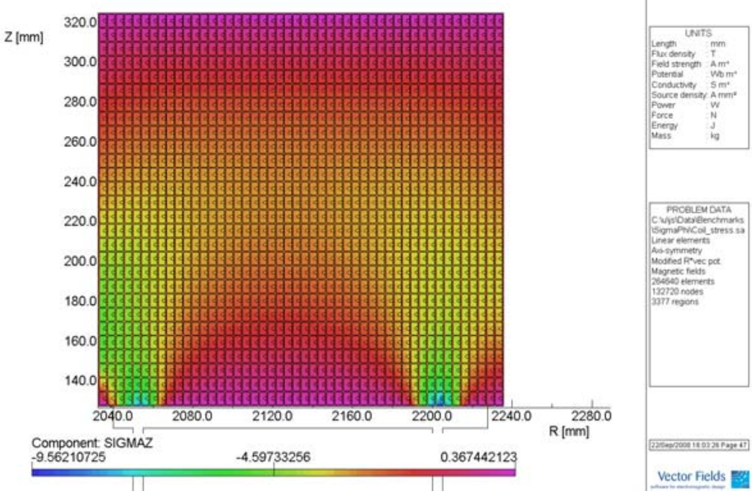
COMPARISON – R AND Z STRESSES



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:\u\js\Data\Benchmarks
\SigmaPhi\Coil_stress.sa
Linear elements
Axi-symmetry
Modified R*vec pot
Magnetic fields
264640 elements
132720 nodes
3377 regions

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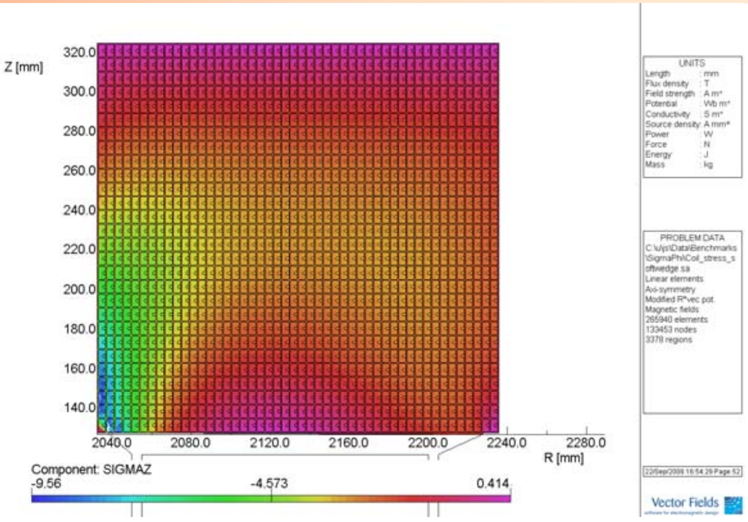

UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
C:\u\js\Data\Benchmarks
\SigmaPhi\Coil_stress_s
oftwedge.sa
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
265940 elements
133453 nodes
3378 regions

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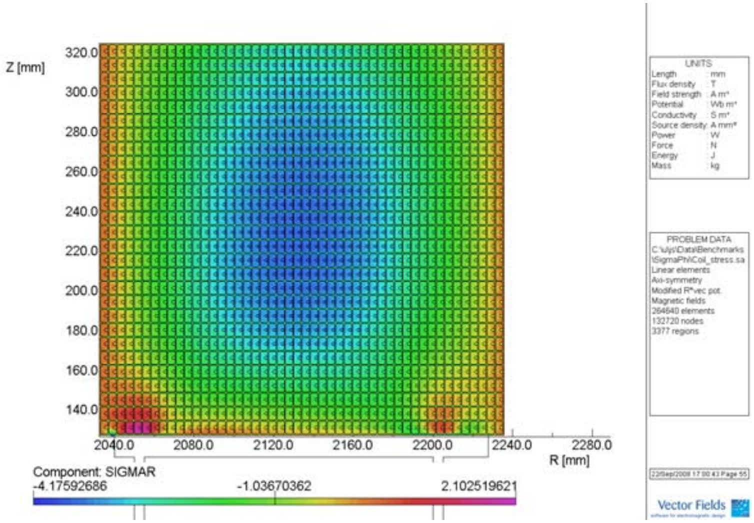

UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
C:\u\js\Data\Benchmarks
\SigmaPhi\Coil_stress.sa
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
264640 elements
132720 nodes
3377 regions

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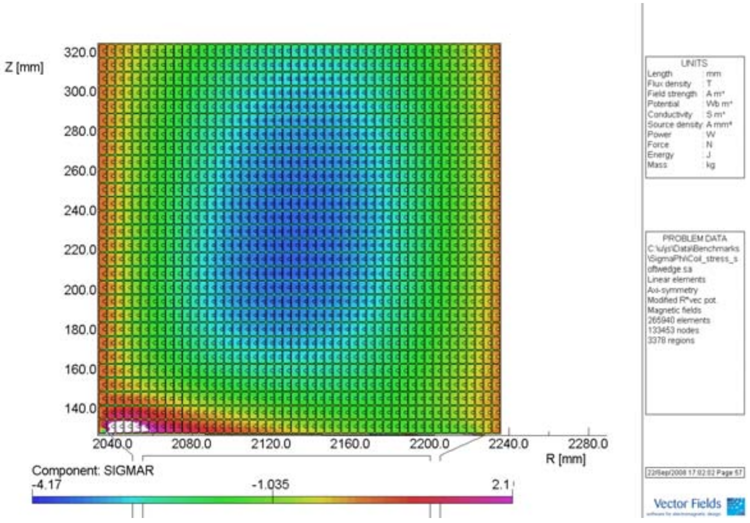

UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
C:\u\js\Data\Benchmarks
\SigmaPhi\Coil_stress_s
oftwedge.sa
Linear elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
265940 elements
133453 nodes
3378 regions

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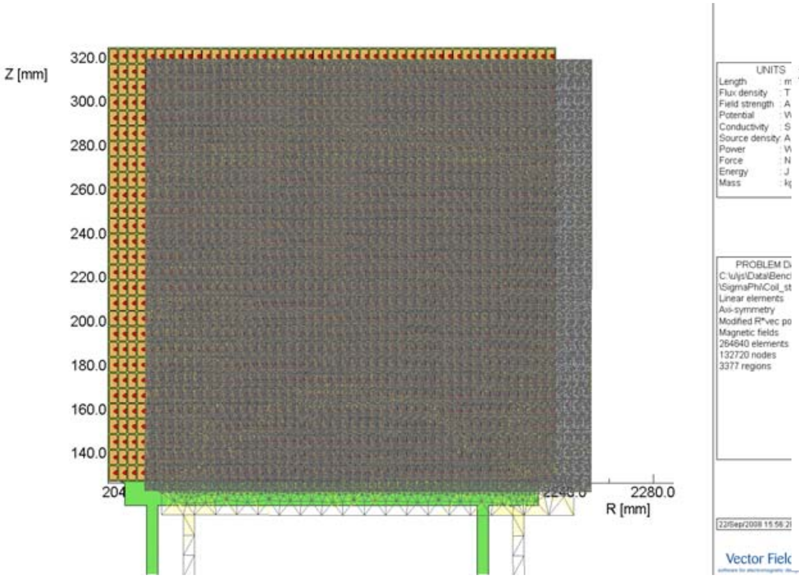
COMPARSION - DISPLACEMENT



UNITS
Length : m
Flux density : T
Field strength : A
Potential : W
Conductivity : S
Source density: A
Power : W
Force : N
Energy : J
Mass : k

PROBLEM D
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Linear elements
Axi-symmetry
Modified R*vec po
Magnetic fields
264640 elements
132720 nodes
3377 regions

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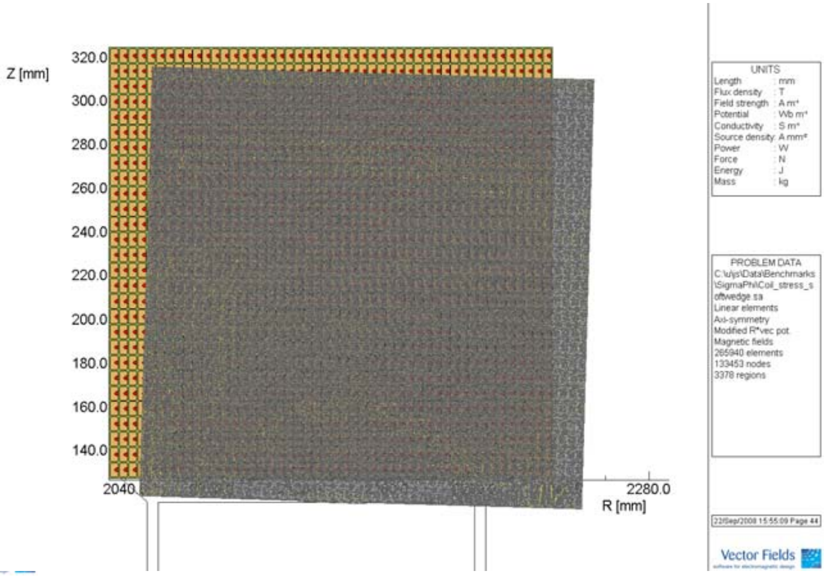
Vector Fielc



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:\u\js\Data\Benchmarks
\SigmaPhi\Coil_stress_s
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3378 regions

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Vector Fields

MAGNETS
AND
BEAM
TRANSPORT

THANK YOU