
Initial Design of 200 mm, 6 T Superconducting Solenoid for e-lens

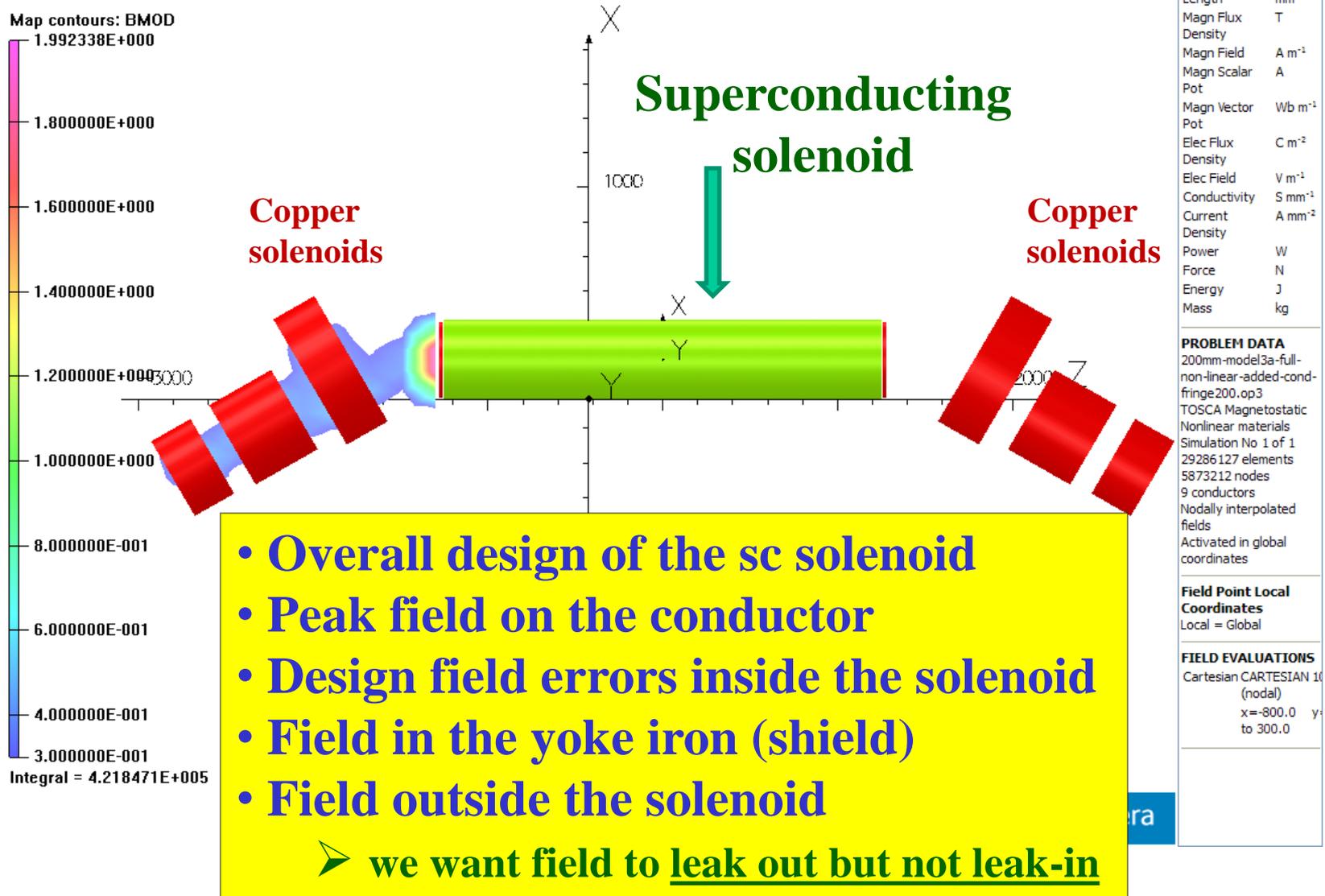
Ramesh Gupta
March 30, 2010

Main Features

- Dipole copper correctors that were previously inside the solenoid coil are now moved outside the solenoid coil and are made superconducting.
- This significantly reduces the aperture (~292 mm to ~200 mm).
- This reduces the stored energy and Lorentz forces and thus makes the smaller aperture superconducting solenoid less demanding.
- This also reduces the material cost - less superconductor, iron, etc.
- In addition, there are some cost saving specific to us because of
 - ❖ the use of existing stainless steel shell.
 - ❖ the use of RHIC cryostat.
 - ❖ the use of existing tooling.
- However, this makes corrector more complex in construction(?) and operation and increases the number of low current superconducting leads. We must make sure that there is net gain.

Overview of the Design Presentation

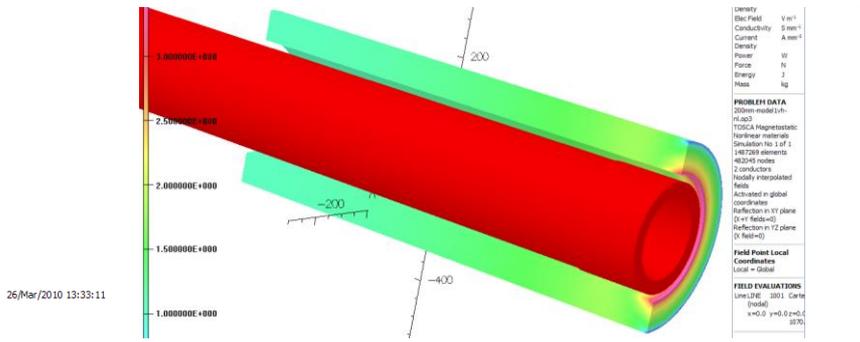
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Preliminary Parameter List for 6 T, 200 mm Superconducting Solenoid for e-lens (Rev 1)

Coil i.d.	200 mm
Coil length	2500 mm
Yoke length	2500 mm
Wire, bare	1.78 mm X 1.14 mm (70 mil X 45 mil)
Wire, insulated	1.91 mm X 1.27 mm (75 mil X 50 mil)
Turn-to-turn spacing (axial, radial)	2.03 mm X 1.42 mm (80 mil X 56 mil)
Number of layers (main, full length)	22 (11 double layers)
Number of layers for trimming end fields	2 (1 double layer)
Length of layers for trimming end fields	175 mm on each end
Coil o.d. (main coil only)	262.58 mm
Coil o.d. Trim coil (in series to the main coil)	268.28 mm
Coil o.d. with trim coil and over-wrap	270.86 mm
Number of turns per layer main coil	~1230
Number of turns per layer trim coil	~86 (on either end)
Total number of turns	~27,404
Current for 6 T	~442 A
Stored energy @ 6 T	~1.4 MJ
Inductance	~14 Henry
Yoke i.d.	~300 mm
Yoke o.d.	~450 mm
Yoke width (radial)	~75 mm
Field on the axis	6 T
Maximum computed error on axis	~3 X 10 ⁻³ (-1050 to 1050 mm and within 20 mm)
Peak Field on the conductor @ 6T	6.15 T (2.4% peak field enhancement)

3-d Calculations for on-axis field



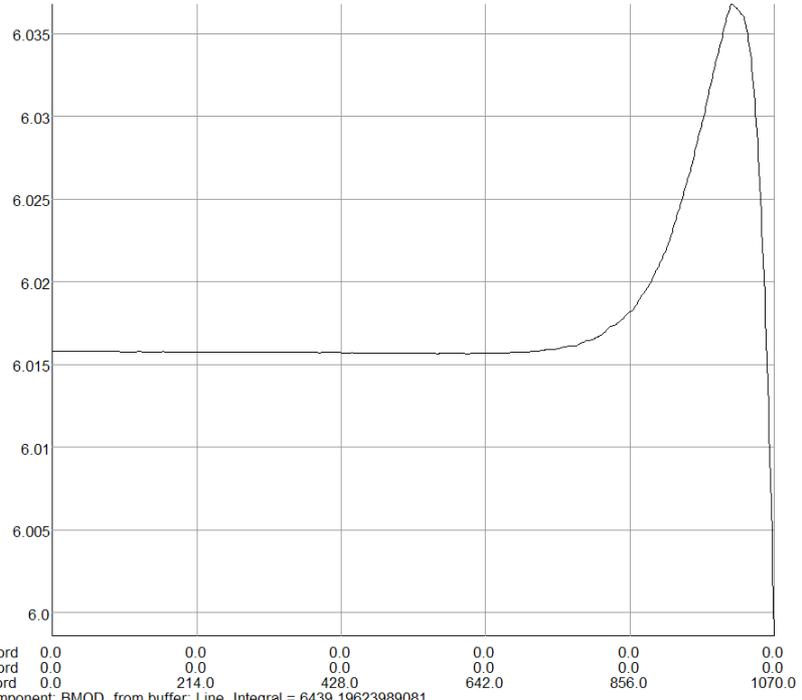
Density V m⁻³
 Elec Field S m⁻¹
 Conductivity A m⁻¹
 Current A m⁻²
 Density V m⁻³
 Power W
 Force N
 Energy J
 Mass kg

PROBLEM DATA
 200mm-model1vh-
 H1.a3f
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No 1 of 1
 1487269 elements
 482045 nodes
 2 conductors
 Nodally interpolated
 fields
 Activated in global
 coordinates
 Reflection in XY plane
 (X+Y fields=0)
 Reflection in YZ plane
 (X field=0)

**Field Point Local
 Coordinates**
 Local = Global

FIELD EVALUATIONS
 Line:LINE 1001 Carte
 (nodal)
 x=0.0 y=0.0 z=0.0
 1070.

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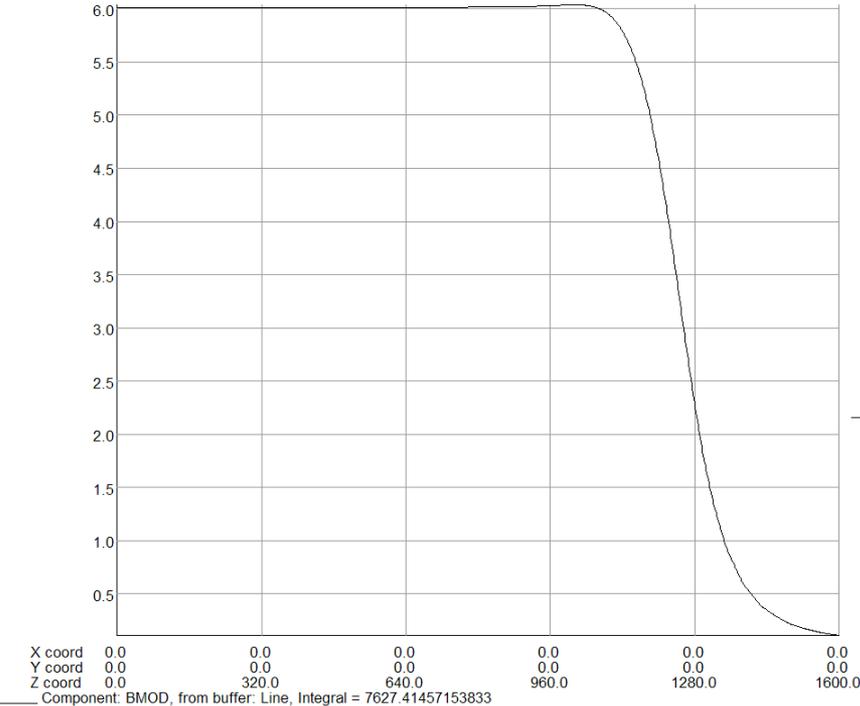


UNITS
 Length mm
 Magn Flux T
 Density T
 Magn Field A m⁻¹
 Magn Scalar A
 Pot Wb m⁻¹
 Magn Vector Wb m⁻¹
 Pot C m⁻²
 Elec Flux V m⁻¹
 Density S m⁻¹
 Elec Field A m⁻²
 Conductivity S mm⁻¹
 Current A mm⁻²
 Density W
 Force N
 Energy J
 Mass kg

PROBLEM DATA
 200mm-model1vh-
 r1.op3
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No 1 of 1
 1487269 elements
 482045 nodes
 2 conductors
 Nodally interpolated
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 Activated in global
 coordinates
 Reflection in XY plane
 (X+Y fields=0)
 Reflection in YZ plane
 (X field=0)

**Field Point Local
 Coordinates**
 Local = Global

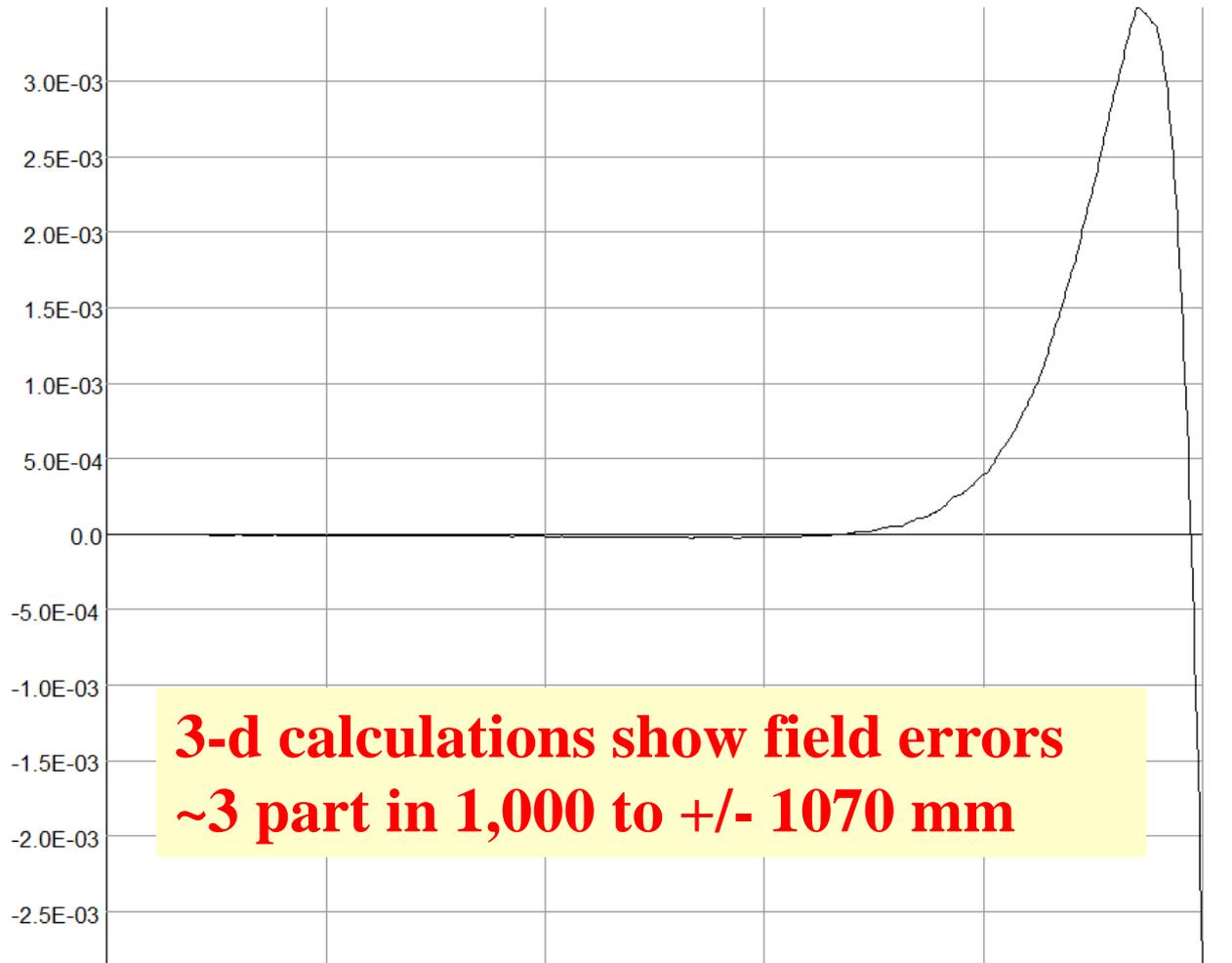
FIELD EVALUATIONS
 Line:LINE 1001 Carte
 (nodal)
 x=0.0 y=0.0 z=0.0
 1070.



Opera

Opera

Relative Field Errors



**3-d calculations show field errors
~3 part in 1,000 to +/- 1070 mm**

X coord 0.0 0.0 0.0 0.0 0.0 0.0
 Y coord 0.0 0.0 0.0 0.0 0.0 0.0
 Z coord 0.0 214.0 428.0 642.0 856.0 1070.0

Component: (BMOD-6.0158)/6.0158, from buffer: Line, Integral = 0.38070412759988

Density	
Magn Field	A m ⁻¹
Magn Scalar	A
Pot	
Magn Vector	Wb m ⁻¹
Pot	
Elec Flux	C m ⁻²
Density	
Elec Field	V m ⁻¹
Conductivity	S mm ⁻¹
Current	A mm ⁻²
Density	
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
 200mm-model1vh-nl.op3
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No 1 of 1
 1487269 elements
 482045 nodes
 2 conductors
 Nodally interpolated fields
 Activated in global coordinates
 Reflection in XY plane (X+Y fields=0)
 Reflection in YZ plane (X field=0)

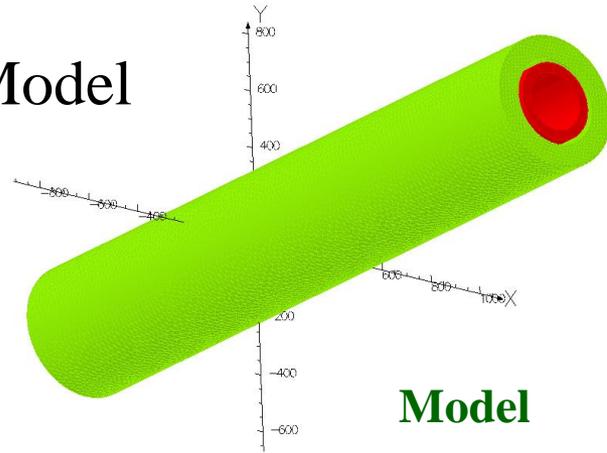
Field Point Local Coordinates
 Local = Global

FIELD EVALUATIONS
 Line LINE 1001 Carte (nodal)
 x=0.0 y=0.0 z=0.0
 1070.

Computer Models

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3d Model



Model

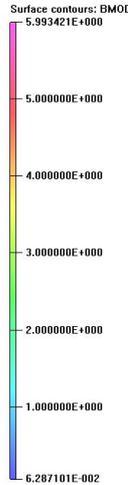
UNITS	
Length	mm
Magn Flux	T
Density	A m ⁻¹
Magn Field	A
Magn Scalar	A
Pot	Wb m ⁻¹
Magn Vector	Wb m ⁻¹
Pot	C m ⁻²
Elec Flux	C m ⁻²
Density	V m ⁻²
Elec Field	V m ⁻²
Conductivity	S mm ⁻¹
Current	A mm ⁻²
Density	W
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA	
200mm-model3a-full-non-linear.op3	
T102CA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
9532968 elements	
2380854 nodes	
2 conductors	
Nodally interpolated fields	
Activated in global coordinates	

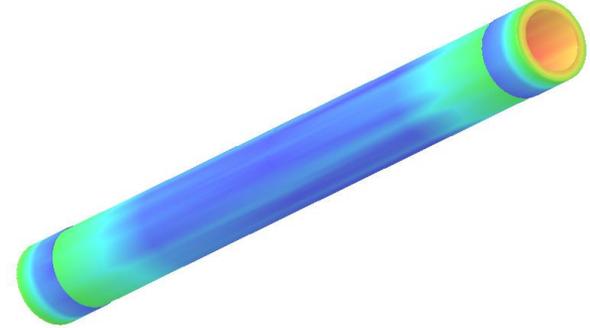
Field Point Local Coordinates	
Local = Global	

Opera

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Coil with field superimposed

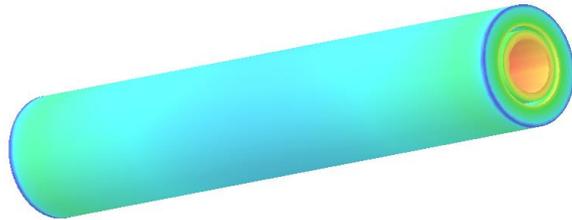
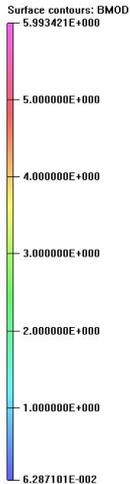


UNITS	
Length	mm
Magn Flux	T
Density	A m ⁻¹
Magn Field	A
Magn Scalar	A
Pot	Wb m ⁻¹
Magn Vector	Wb m ⁻¹
Pot	C m ⁻²
Elec Flux	C m ⁻²
Density	V m ⁻²
Elec Field	V m ⁻²
Conductivity	S mm ⁻¹
Current	A mm ⁻²
Density	W
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA	
200mm-model3a-full-non-linear.op3	
T102CA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
9532968 elements	
2380854 nodes	
2 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

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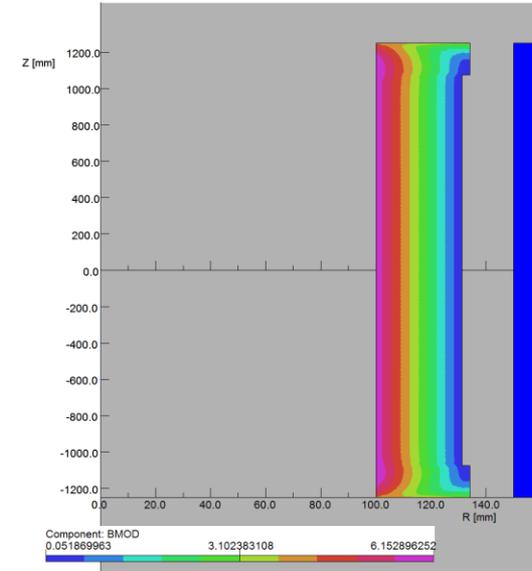
Field on iron and coil

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

PROBLEM DATA	
200mm-model3a-full-non-linear.op3	
T102CA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
9532968 elements	
2380854 nodes	
2 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

Opera



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

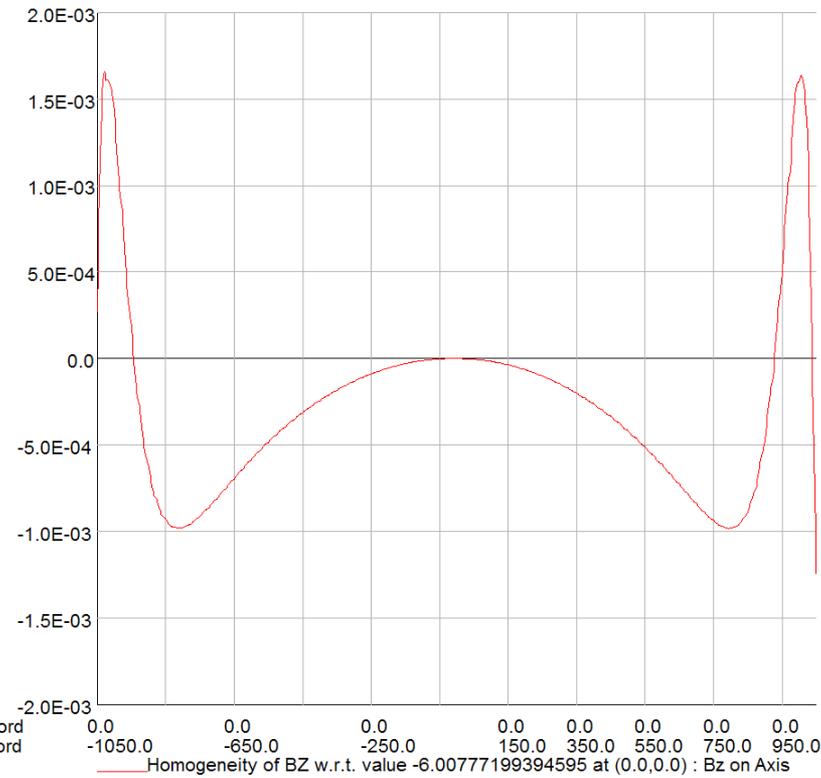
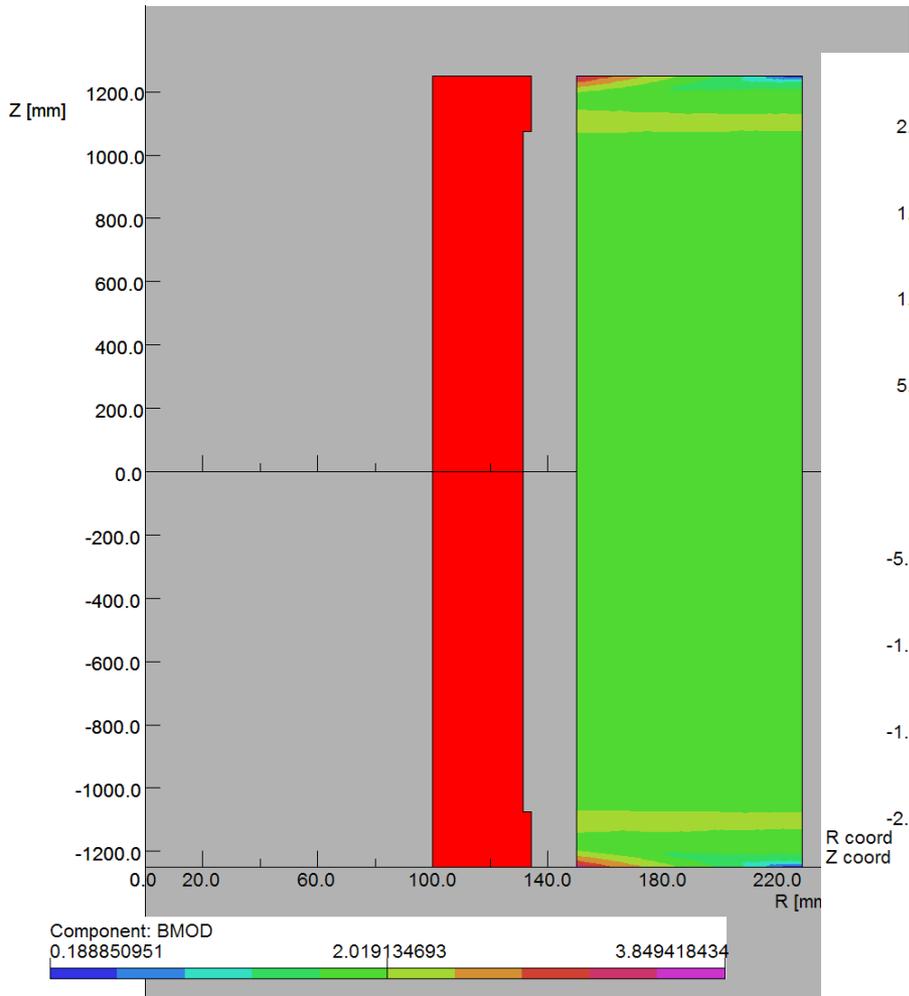
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Quadratic elements	
Axis-symmetry	
R/vector potential	
Magnetic fields	
Static solution	
Case 1 of 2	
Scale factor: 1.0	
14430 elements	
29430 nodes	
13 regions	

Opera

2d Model

(more accurate and faster calculations in many cases)

2-d Cylindrical Symmetric Model (more accurate and faster calculations)

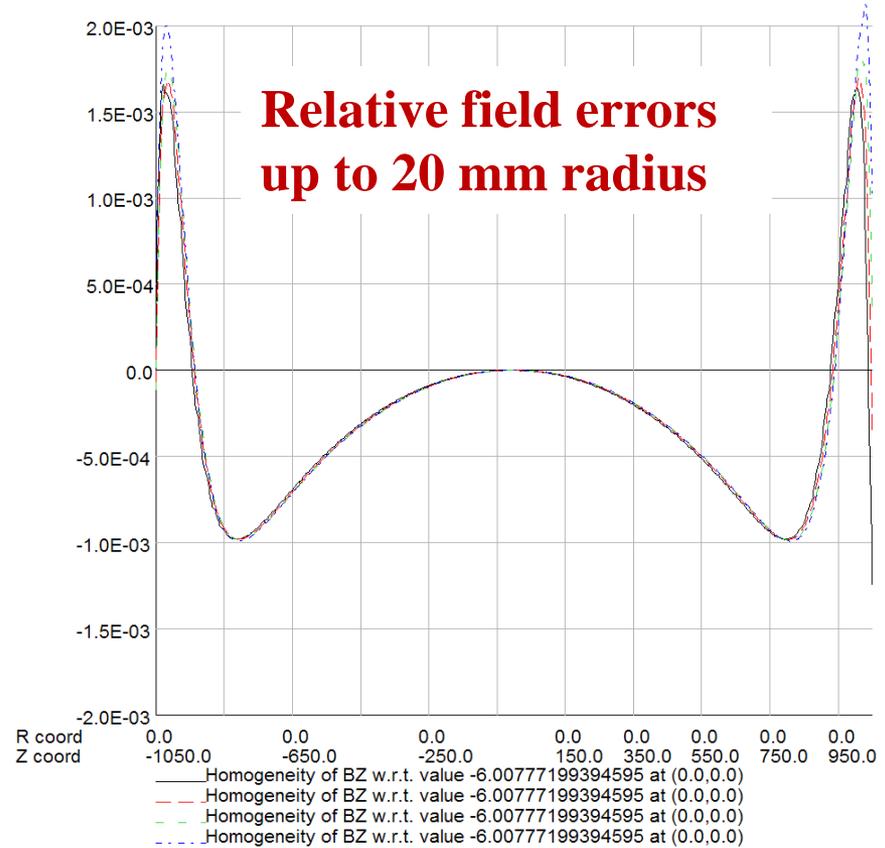
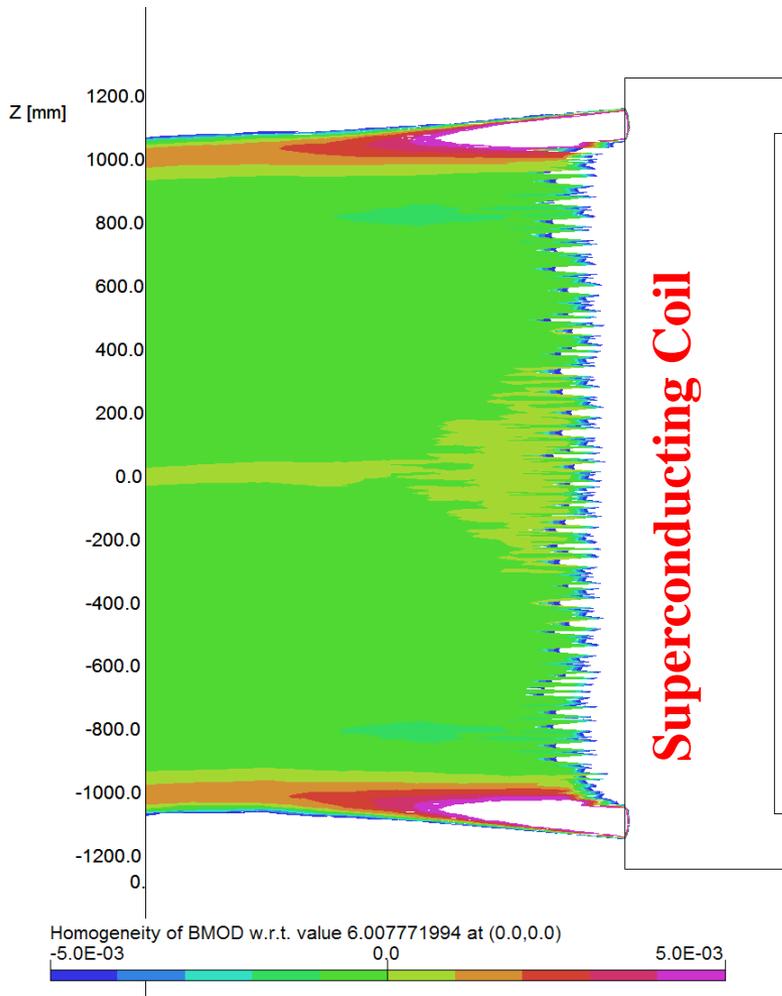


UNITS	
Length	: mm
Flux density	: T
Field strength	: A m ⁻¹
Potential	: Wb m ⁻¹
Conductivity	: S m ⁻¹
Source density	: A mm ⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA	
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Quadratic elements	
Axi-symmetry	
R^vector potential	
Magnetic fields	
Static solution	
Case 1 of 2	
Scale factor: 1.0	
14432 elements	
29435 nodes	
13 regions	



Off-axis field errors



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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 00_c45x70-22_2lyrs-fe4
 57.st
 Quadratic elements
 Axi-symmetry
 R*vector potential
 Magnetic fields
 Static solution
 Case 1 of 2
 Scale factor: 1.0
 14432 elements
 29435 nodes
 13 regions

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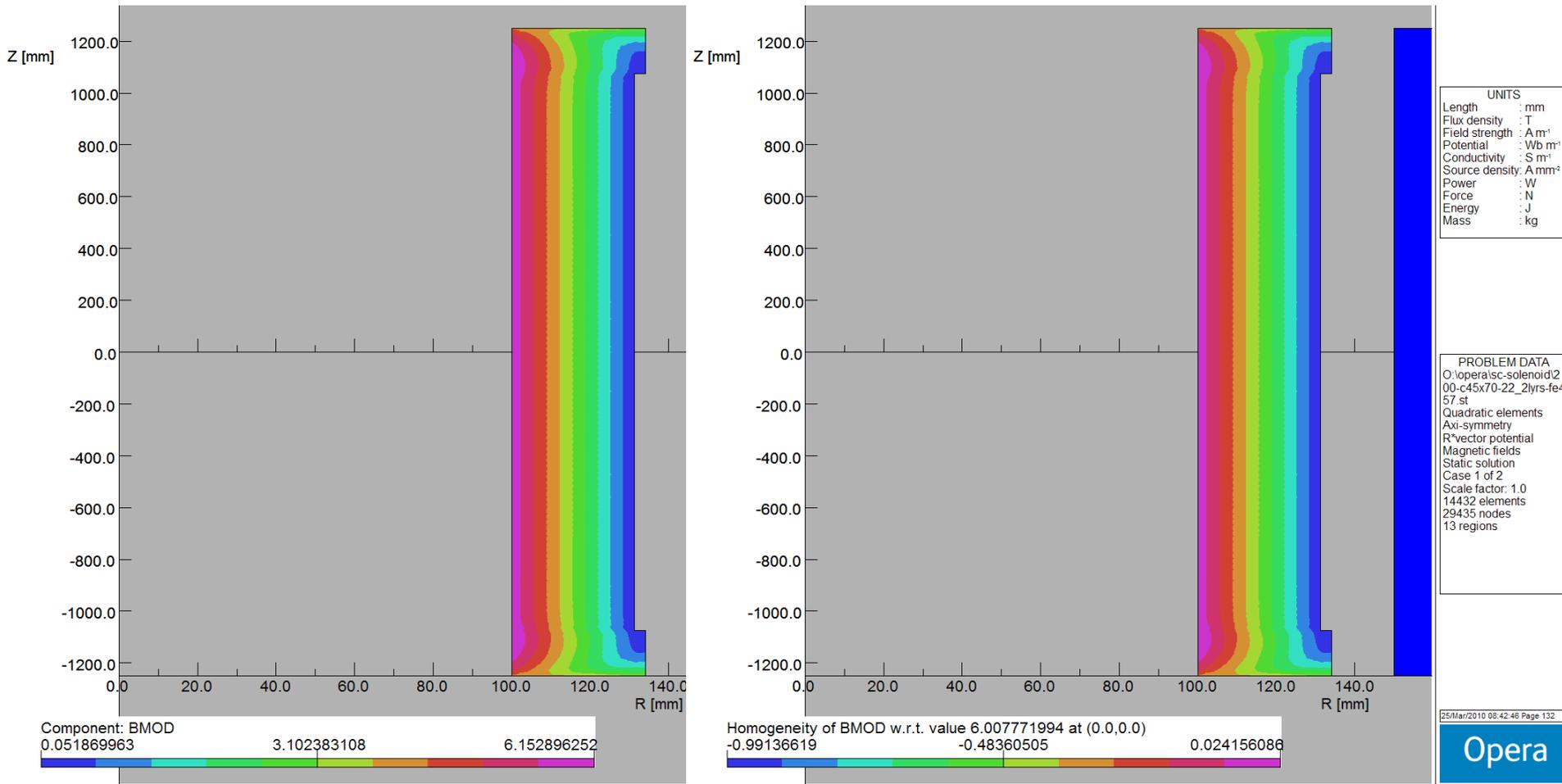


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Field on the Conductor

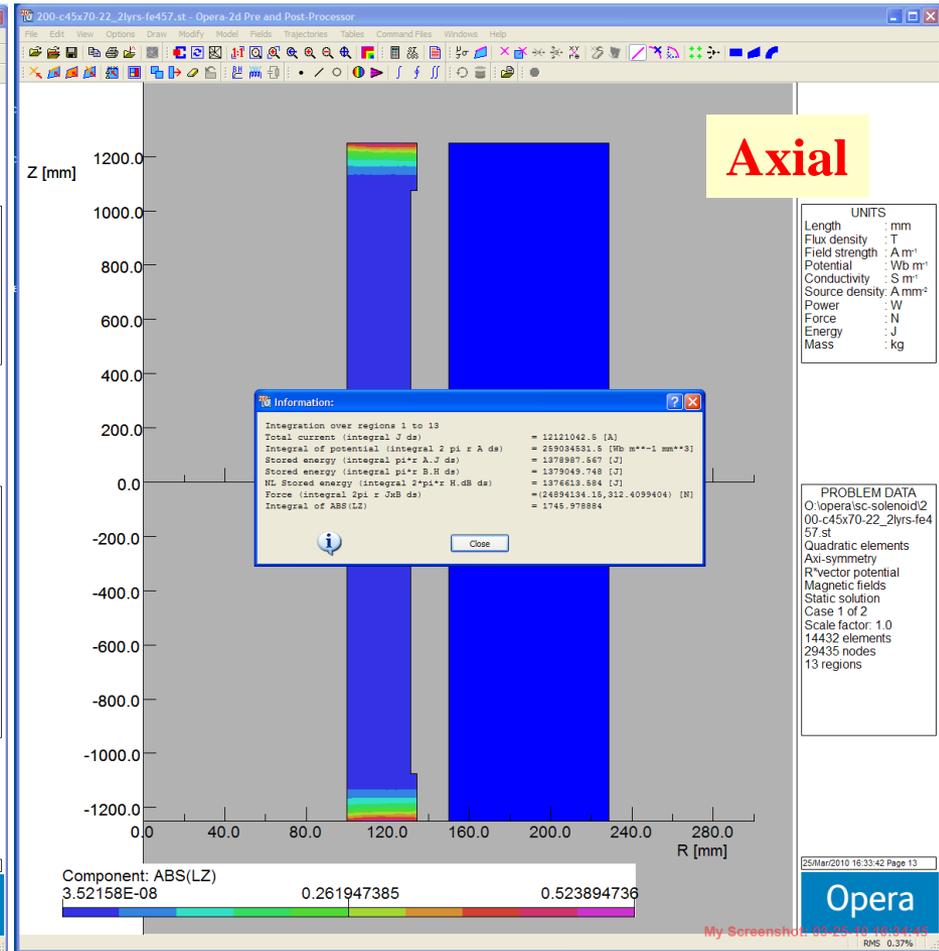
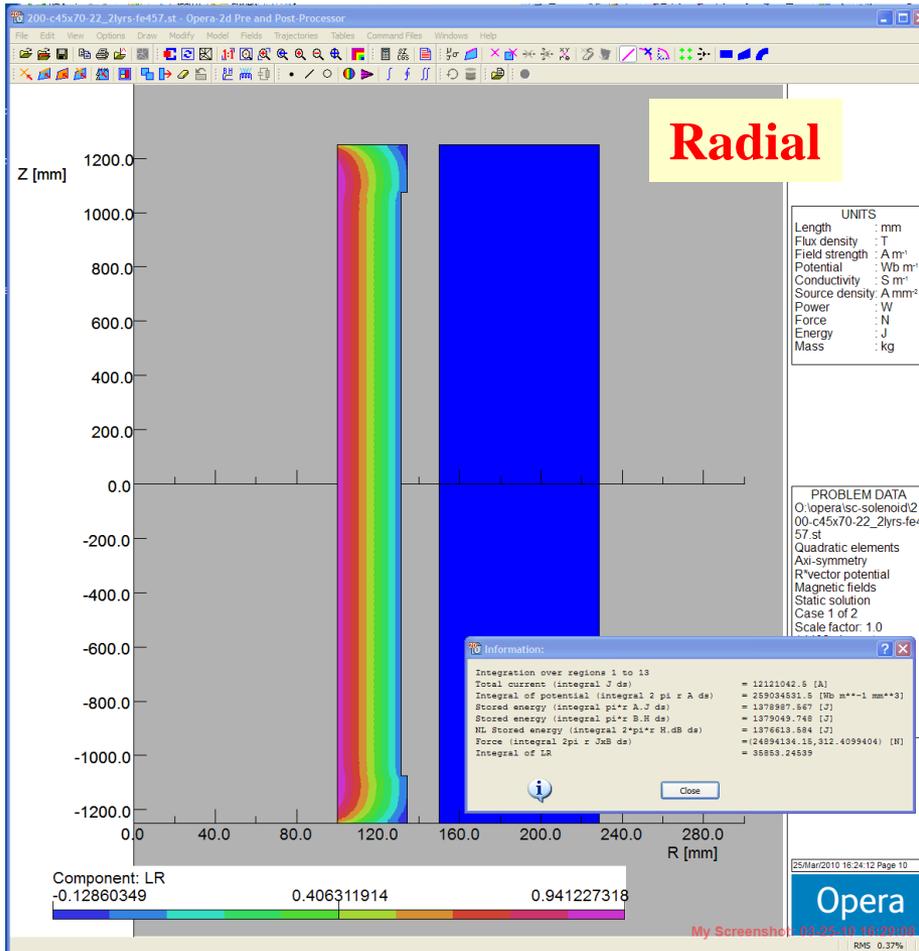
Small peak enhancement



only 2.4% enhancement of field on the conductor
[was about 2X in 292 mm solenoid]

Stored Energy and Lorentz Forces

Stored Energy ~ 1.4 MJ (was $\sim 2X$ in 292 mm solenoid); Inductance ~ 14 Henry



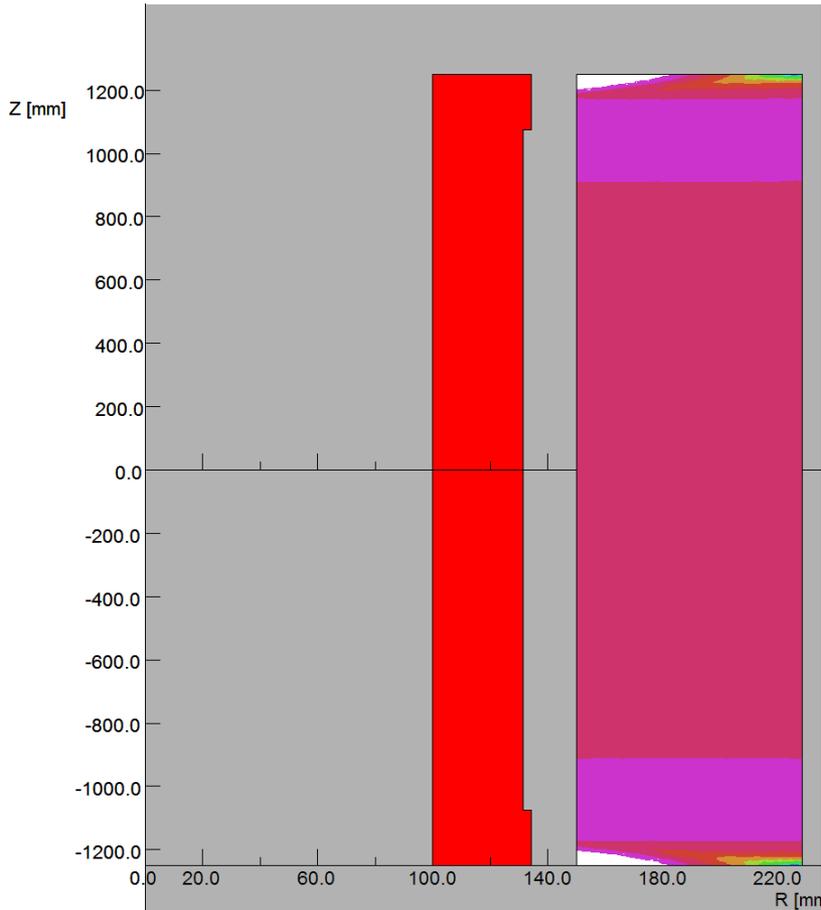
Radial Lorentz force (hoop stress) : ~ 24 MN

Axial force (inward, only at the ends): ~ 35 kN per side

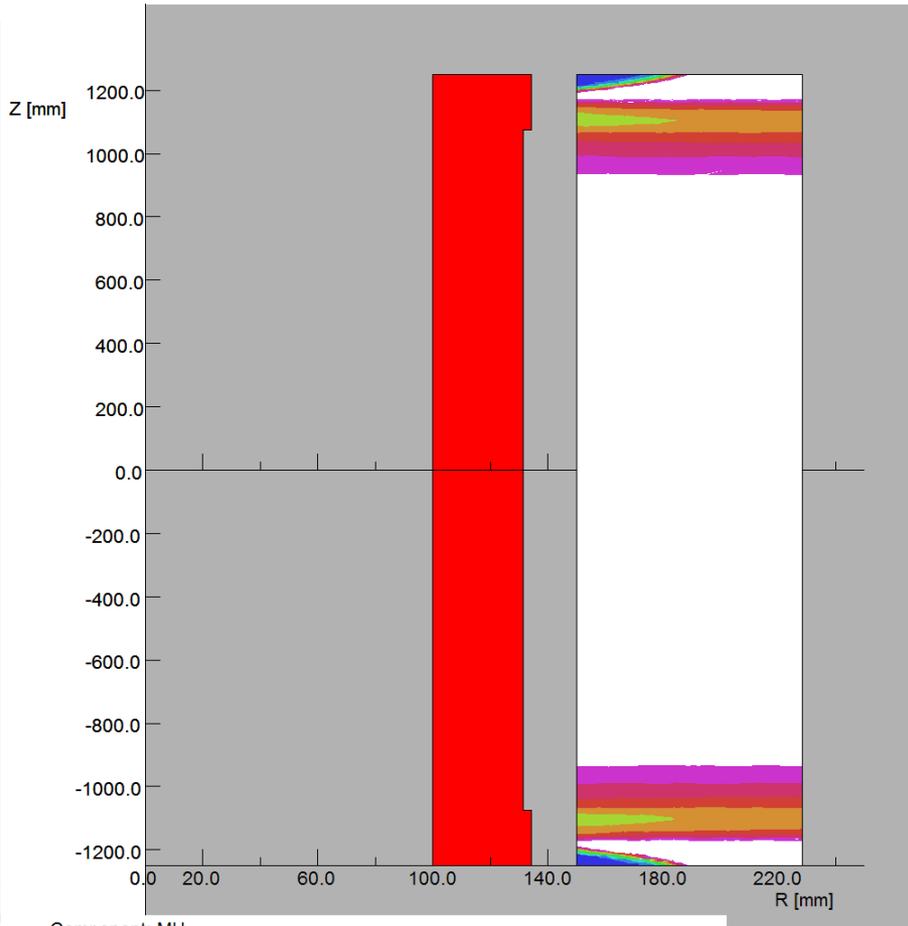
6 T @ ~ 442 A

Field and Permeability in Iron at 6 T (important for shielding from outside environment)

B in iron



mu in iron



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

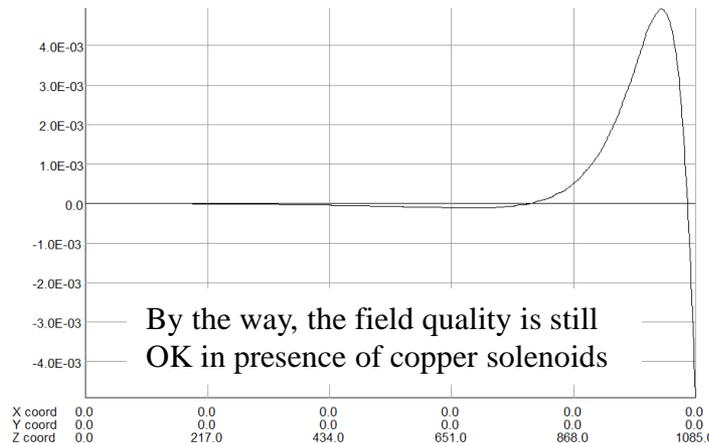
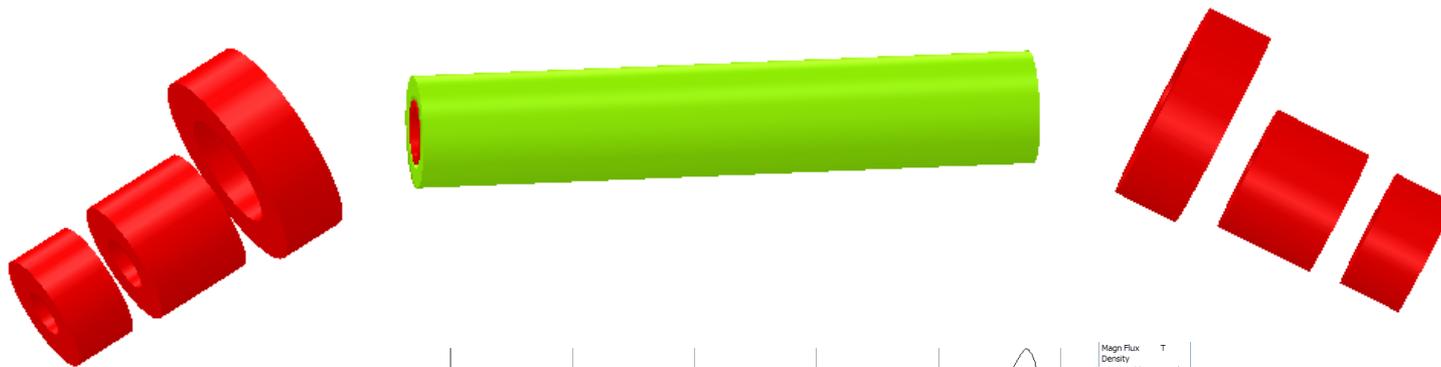
PROBLEM DATA

O:\opera\isc-solenoid\2
00-c45x70-22_2lyrs-fe4
57.st
Quadratic elements
Axi-symmetry
R^vector potential
Magnetic fields
Static solution
Case 1 of 2
Scale factor: 1.0
14432 elements
29435 nodes
13 regions

Model with Copper Solenoids

30/Mar/2010 09:57:47

- **0.3 T (3 kG) or so field is desired between copper solenoids and superconducting solenoid along the beam path**
- **One way to obtain that field is to benefit from the field leaking from superconducting solenoid**



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

PROBLEM DATA	
200mm-model1v1h-added-cond-rings.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
5151965 elements	
1126583 nodes	
8 conductors	
Nodally interpolated fields	
Activated in global coordinates	
Reflection in XY plane (0<+ field=0)	
Reflection in ZX plane (Y field=0)	
Field Point Local Coordinates	
Local = Global	

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

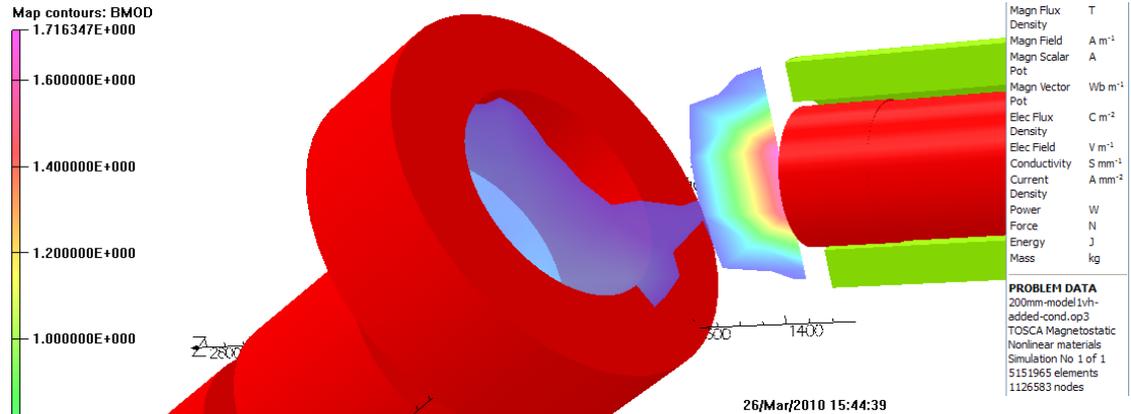
PROBLEM DATA	
200mm-model3a-full-non-linear-added-cond.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
29286127 elements	
5873212 nodes	
8 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

Note: The exact location of copper solenoid may not be up-to-date, but the general direction is correct



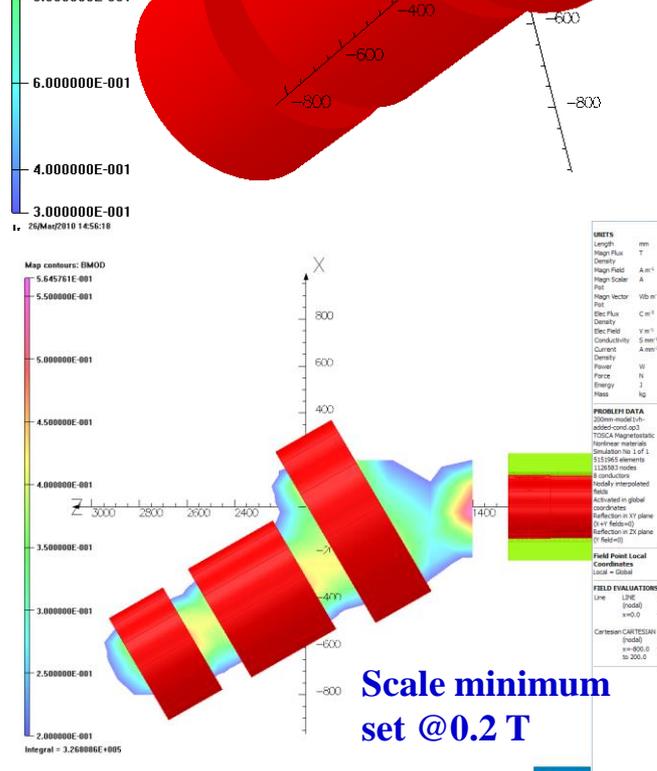
Field between Copper and Superconducting Solenoids



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

PROBLEM DATA
 200mm-model1vh-added-cond.op3
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No 1 of 1
 5151965 elements
 1126583 nodes

We don't get 0.3 T field...
 What can be done to help?



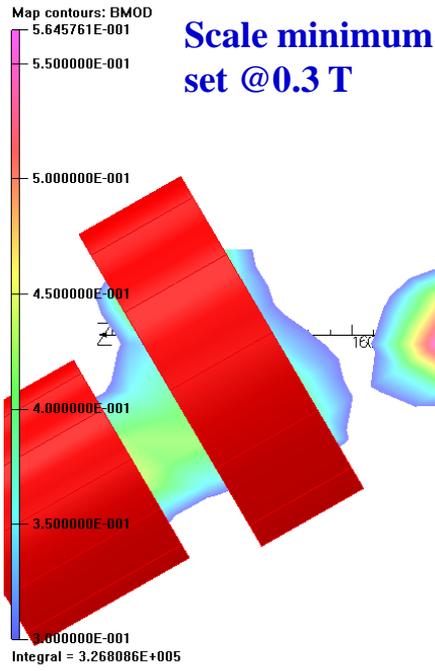
Length	mm
Magn Flux	T
Density	
Magn Field	A m ⁻¹
Magn Scalar	A
Pot	
Magn Vector	Wb m ⁻¹
Pot	
Elec Flux	C m ⁻²
Density	
Elec Field	V m ⁻¹
Density	
Conductivity	S mm ⁻¹
Current	A mm ⁻²
Density	
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
 200mm-model1vh-added-cond.op3
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No 1 of 1
 5151965 elements
 1126583 nodes
 8 conductors
 Nodally interpolated fields
 Activated in global coordinates
 Reflection in XY plane (X+Y fields=0)
 Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
 Local = Global

FIELD EVALUATIONS
 Local = Global
 Cartesian CARTESIAN (nodal)
 x=-800.0 y= to 200.0

Scale minimum set @0.2 T



Scale minimum set @0.3 T

Integral = 3.268086E+005

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

PROBLEM DATA
 200mm-model1vh-added-cond.op3
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No 1 of 1
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 1126583 nodes
 8 conductors
 Nodally interpolated fields
 Activated in global coordinates
 Reflection in XY plane (X+Y fields=0)
 Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
 Local = Global

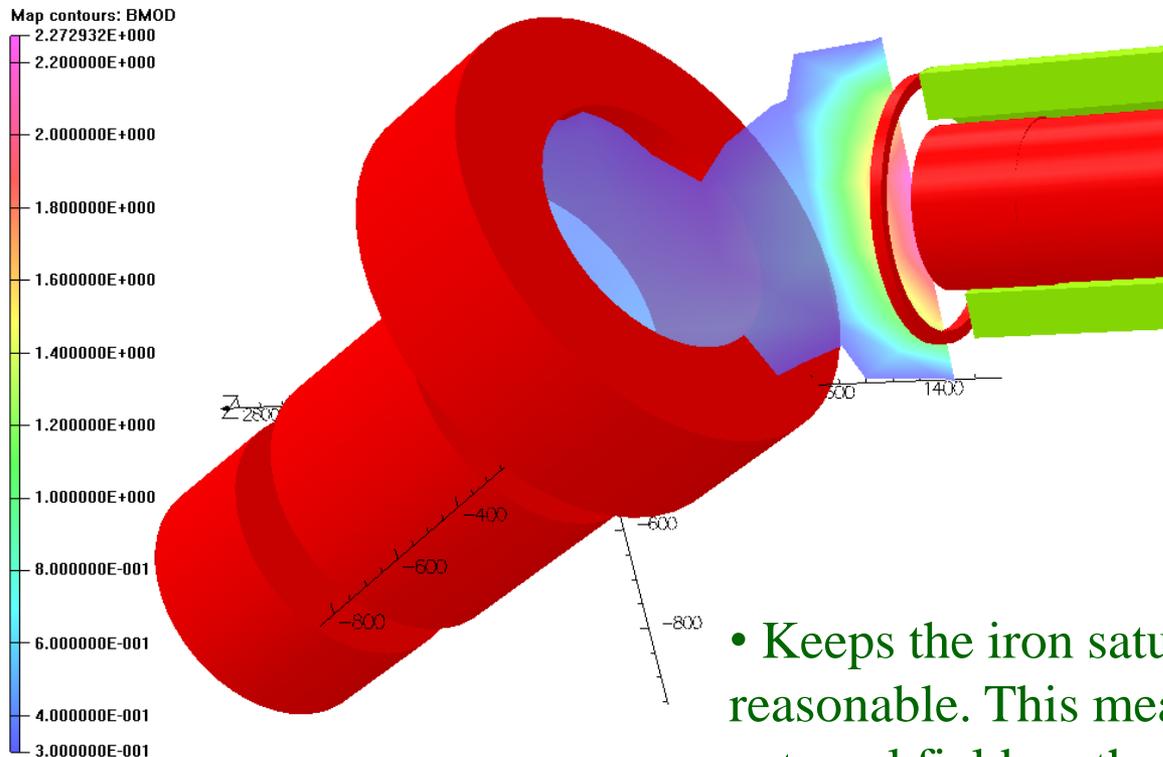
FIELD EVALUATIONS
 Cartesian CARTESIAN (nodal)
 x=-800.0 y= to 200.0

Opera

Small Superconducting Solenoid next to Main Solenoid (fringe field coil may be part of the same coldmass)

Size of the small sc solenoid : A few cm X a few cm - likely to be made of small corrector wire to keep current low.
(parameters are not yet optimized)

29/Mar/2010 15:07:42



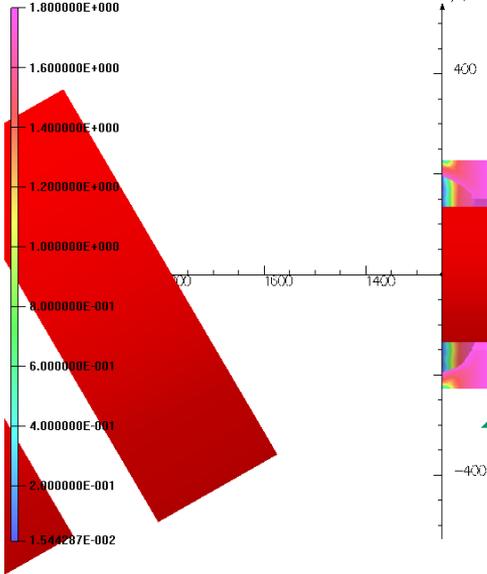
- There are several benefits of a separate solenoid to create field in the region between the superconducting and the copper solenoids.
- Provides an independent control (knob) to create the desired field, irrespective of what that desired field is, the field in the main solenoid and the field in the copper solenoid

• Keeps the iron saturation in the main solenoid reasonable. This means that the influence of the external field on the field inside the main solenoid is minimized (a major consideration in this design).

Field in Yoke Iron with Fringe Field Solenoid

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Surface contours: BMOD



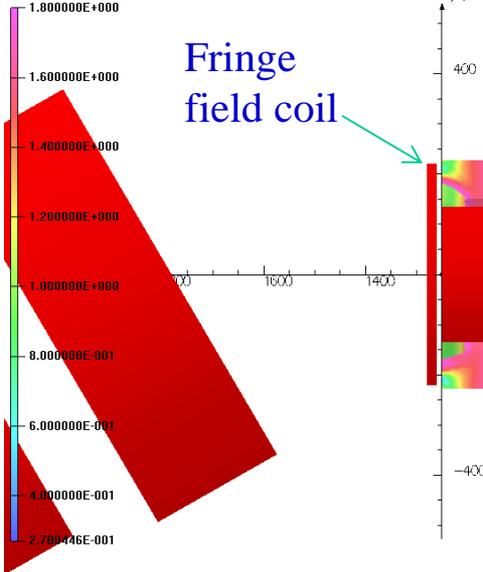
Field in the significant part of the solenoid iron is above 1.8 T in the absence of fringe field solenoid

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

PROBLEM DATA	
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TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
5151965 elements	
1126583 nodes	
8 conductors	
Nodally interpolated fields	
Activated in global coordinates	
Reflection in XY plane (X+Y fields=0)	

26/Mar/2010 15:50:25

Surface contours: BMOD



Fringe field coil

Field in the solenoid iron is below 1.8 T in the presence of fringe field solenoid.

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

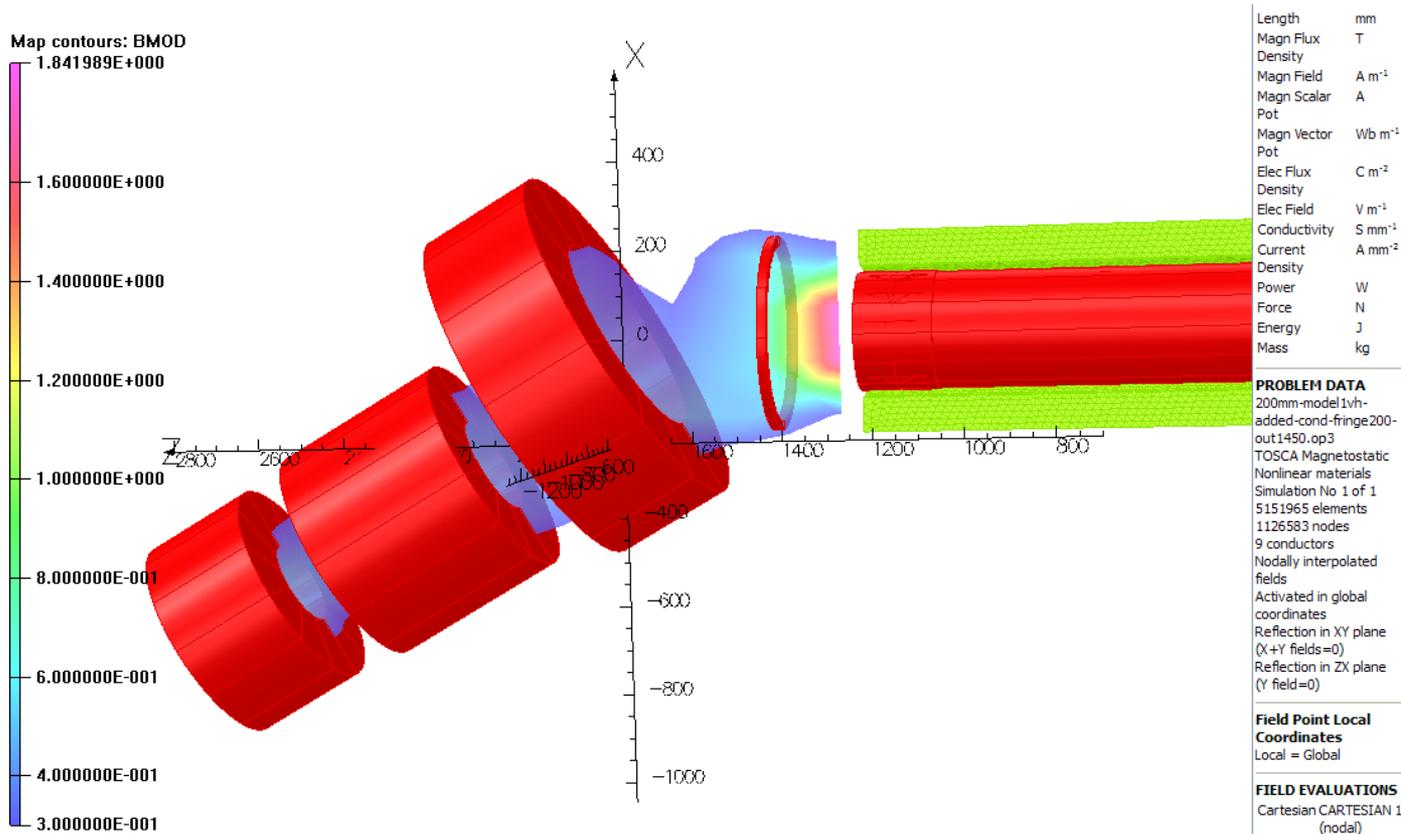
PROBLEM DATA	
200mm-model\1h-added-cond-fringe.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
5151965 elements	
1126583 nodes	
9 conductors	
Nodally interpolated fields	
Activated in global coordinates	
Reflection in XY plane (X+Y fields=0)	
Reflection in ZX plane (Y field=0)	

Field Point Local Coordinates	
Local = Global	

Opera

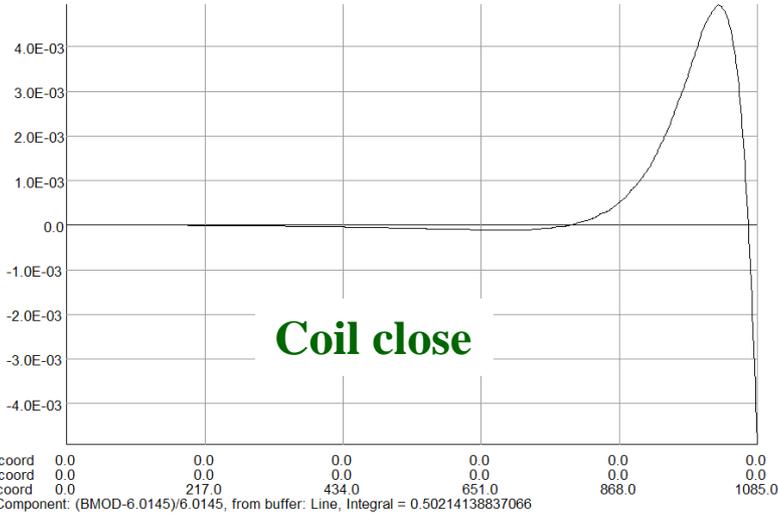
Another location of Fringe Field Solenoid

- Fringe field solenoid coil can be brought further out to make it more efficient.
- This reduces the size by a factor of two or more.
- Location of the coil as per Mike Anerella - leads to come out between main coil and fringe field solenoid coil.



A more efficient location of fringe field coil may be a bit off-axis.

Influence of fringe field coil on field errors



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

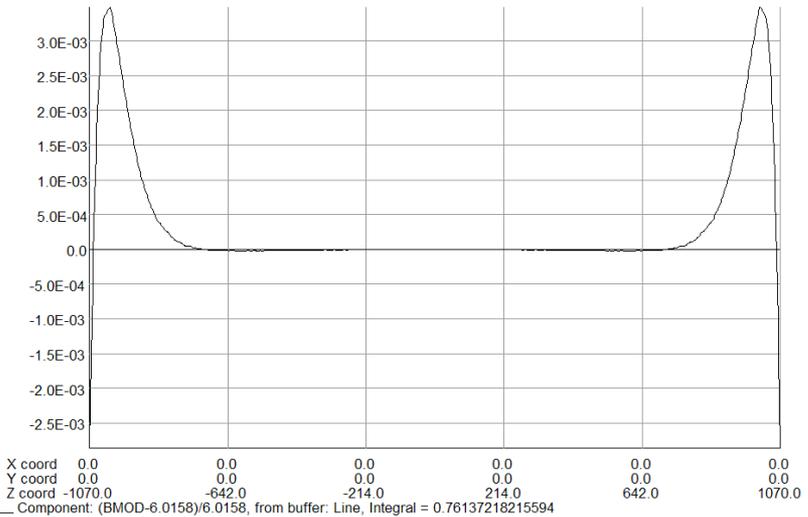
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PROBLEM DATA
 200mm-model1vh-added-cond-fringe.op
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No. 1 of 1
 5151965 elements
 1126583 nodes
 9 conductors
 Nodally interpolated fields
 Activated in global coordinates
 Reflection in XY plane (X+y field=0)
 Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
 Local = Global

FIELD EVALUATION
 Line:LINE 1001 Ca
 (nodal)
 x=0.0 y=0.0 z=

Field errors on axis without fringe field coil



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

PROBLEM DATA
 200mm-model1vh-added-cond-fringe200-out1450.op3
 TOSCA Magnetostatic
 Nonlinear materials
 Simulation No. 1 of 1
 5151965 elements
 1126583 nodes
 9 conductors
 Nodally interpolated fields
 Activated in global coordinates
 Reflection in XY plane (X+y field=0)
 Reflection in ZX plane (Y field=0)

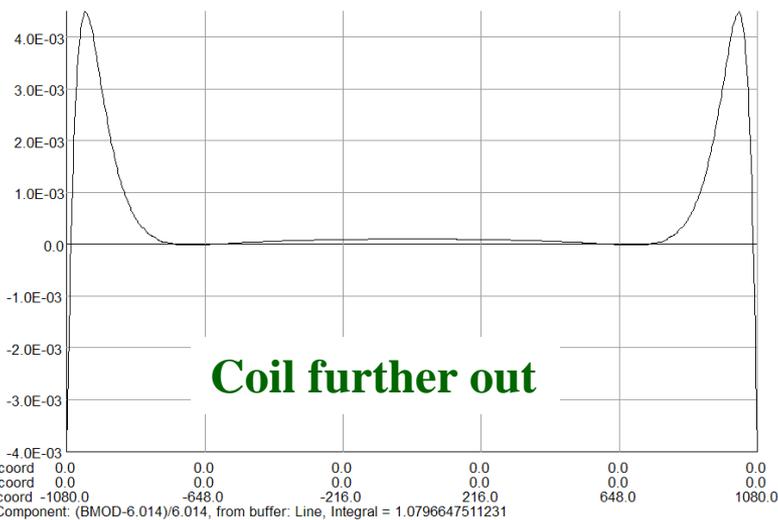
Field Point Local Coordinates
 Local = Global

FIELD EVALUATIONS

UNITS		
Length	mm	
Magn Flux	T	
Density	A m ⁻¹	
Magn Field	A	
Magn Scalar	A	
Pot	Wb m ⁻¹	
Magn Vector	Wb m ⁻¹	
Pot	C m ⁻²	
Elec Flux	C m ⁻²	
Density	V m ⁻¹	
Elec Field	S mm ⁻¹	
Conductivity	A mm ⁻²	
Current	W	
Density	N	
Power	J	
Force	kg	
Energy		
Mass		
PROBLEM DATA		
200mm-model1vh-nl.op3		
TOSCA Magnetostatic		
Nonlinear materials		
Simulation No. 1 of 1		
1487269 elements		
492045 nodes		
2 conductors		
Nodally interpolated fields		
Activated in global coordinates		
Reflection in XY plane (X+y field=0)		
Reflection in YZ plane (X field=0)		
Field Point Local Coordinates		
Local = Global		
FIELD EVALUATIONS		
Line:LINE 1001 Carte		
(nodal)		
x=0.0 y=0.0 z= 10		
to 10		

Opera

Field errors with fringe field coils



Conclusion:
Small influence

Summary

Work in progress

The design is in reasonable stage to move forward
– no showstoppers