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

Ramesh Gupta

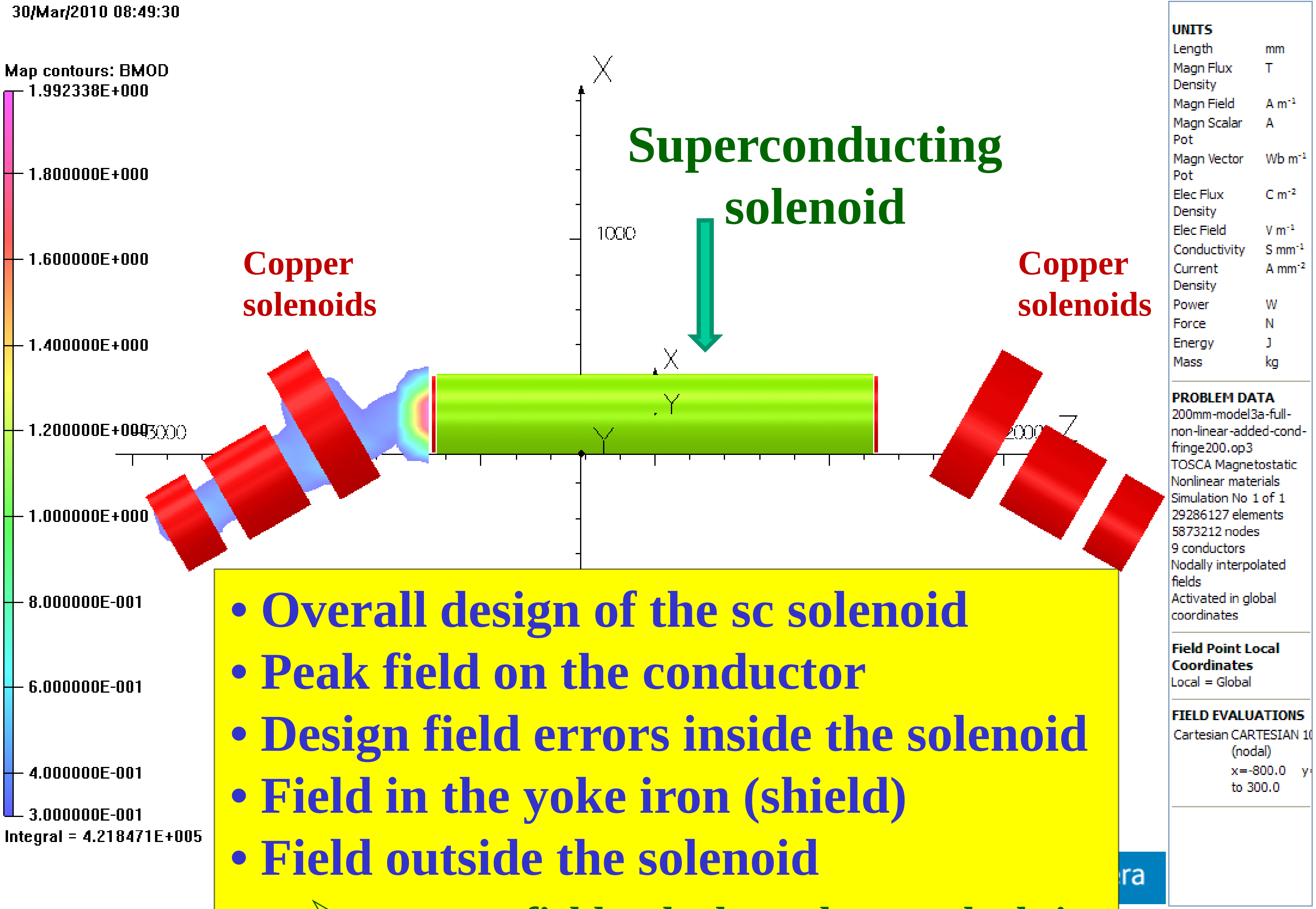
March 30, 2010

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



Superconducting solenoid

Copper solenoids

Copper solenoids

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
200mm-model3a-full-non-linear-added-cond-fringe200.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
29286127 elements
5873212 nodes
9 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

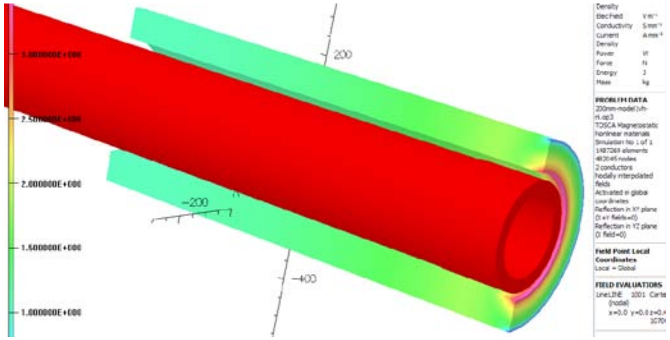
FIELD EVALUATIONS
Cartesian CARTESIAN 1
(nodal)
x=-800.0 y
to 300.0

- Overall design of the sc solenoid
- Peak field on the conductor
- Design field errors inside the solenoid
- Field in the yoke iron (shield)
- Field outside the solenoid
  - ➢ we want field to leak out but not leak-in

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



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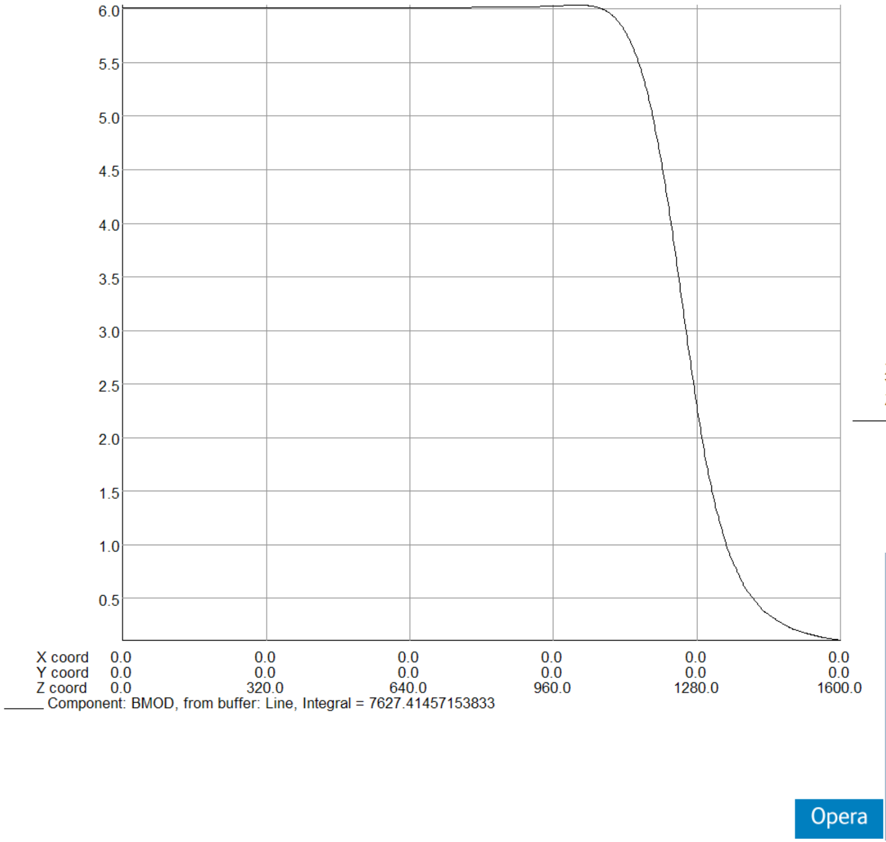

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1600.

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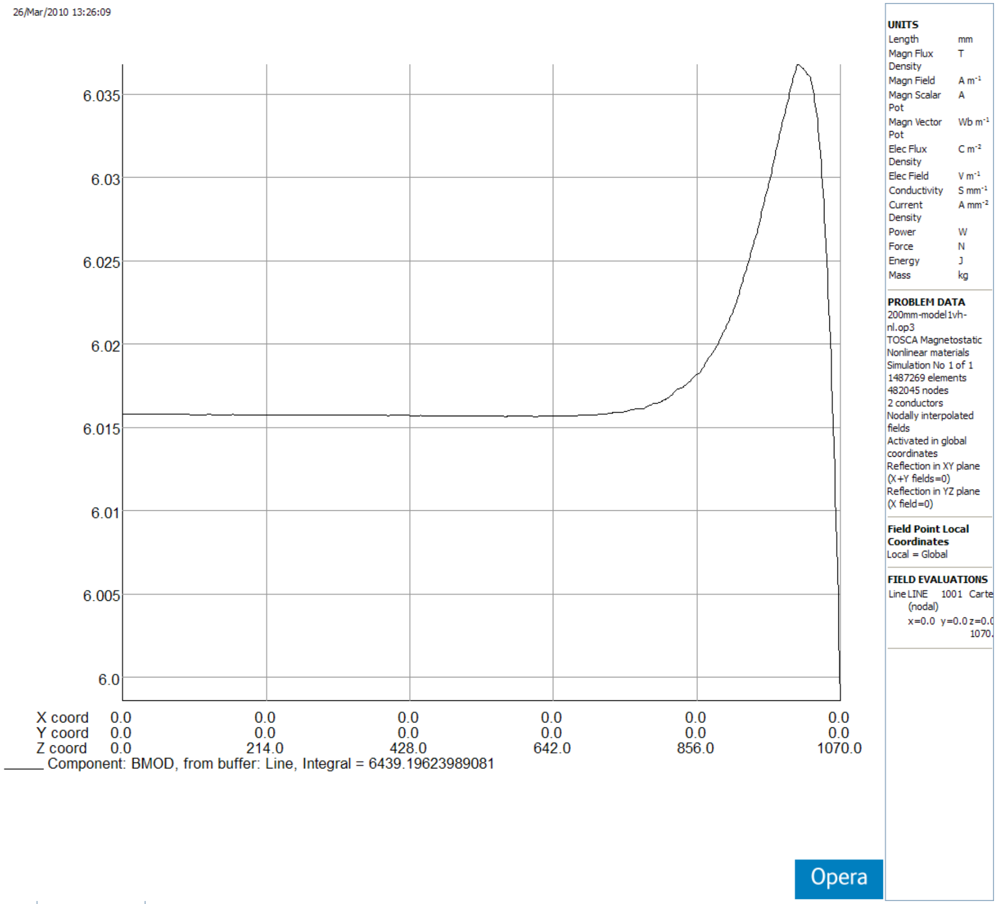

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UNITS

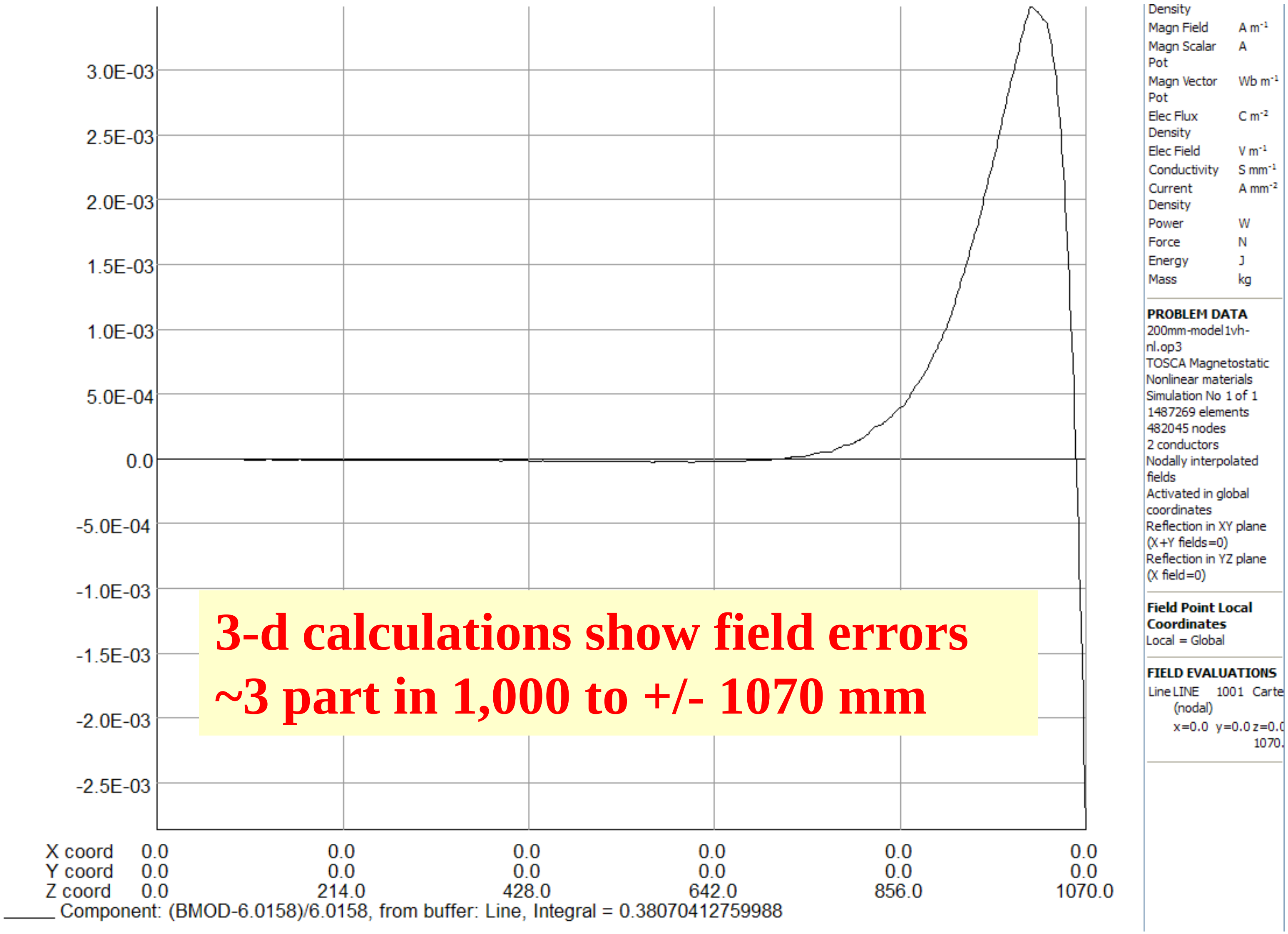
Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S mm^{-1}
Current Density	A mm^{-2}
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
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.

Relative Field Errors



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Density	
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
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Mass	kg

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200mm-model1vh-nl.op3
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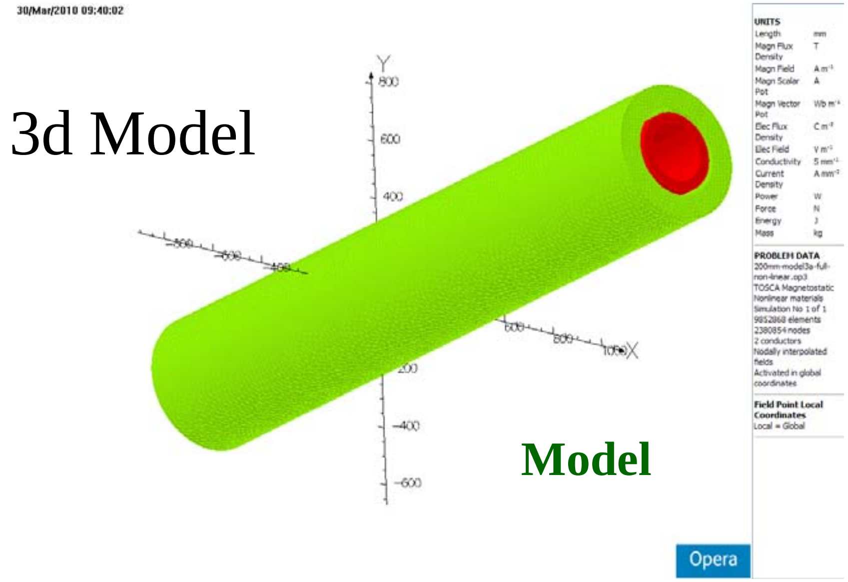
Field Point Local Coordinates
Local = Global

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

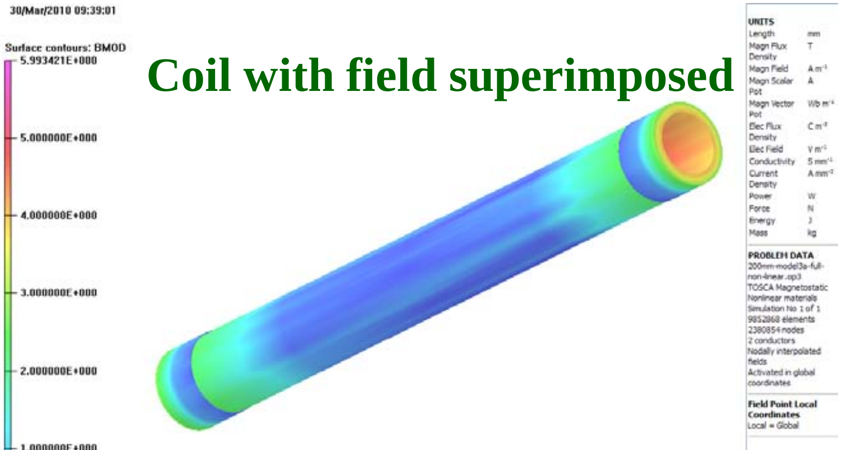
3-d calculations show field errors ~3 part in 1,000 to +/- 1070 mm

Computer Models

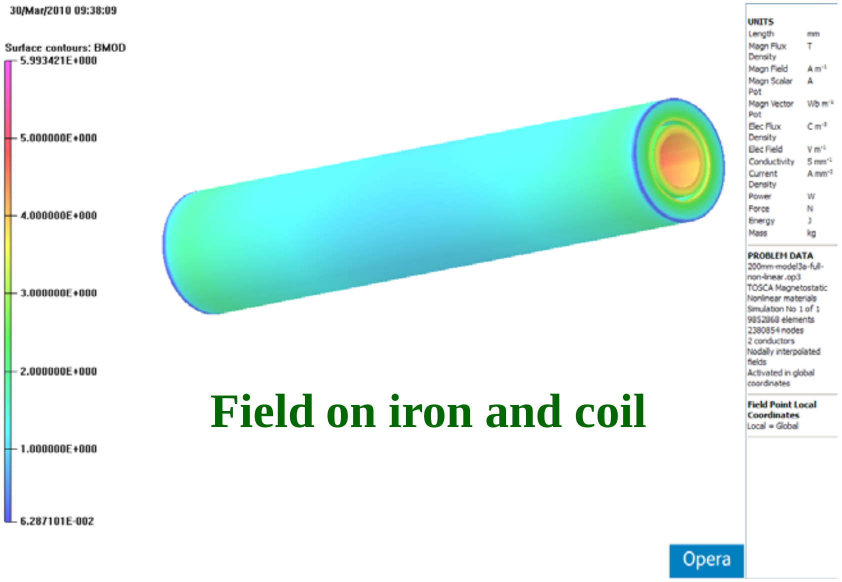


3d Model

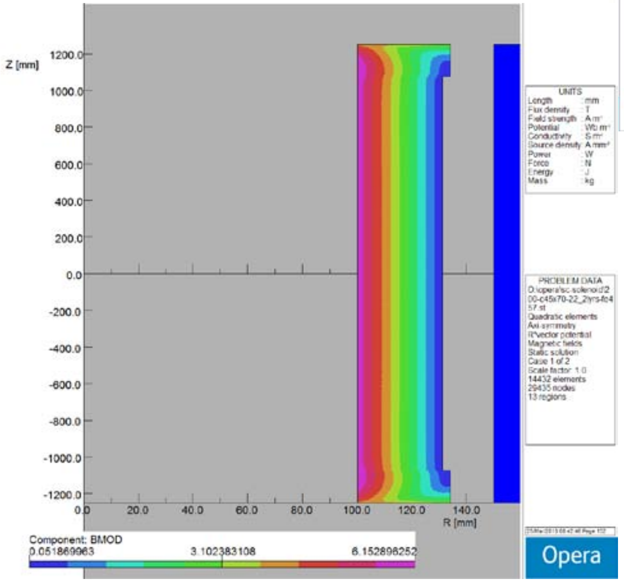
Model



Coil with field superimposed



Field on iron and coil

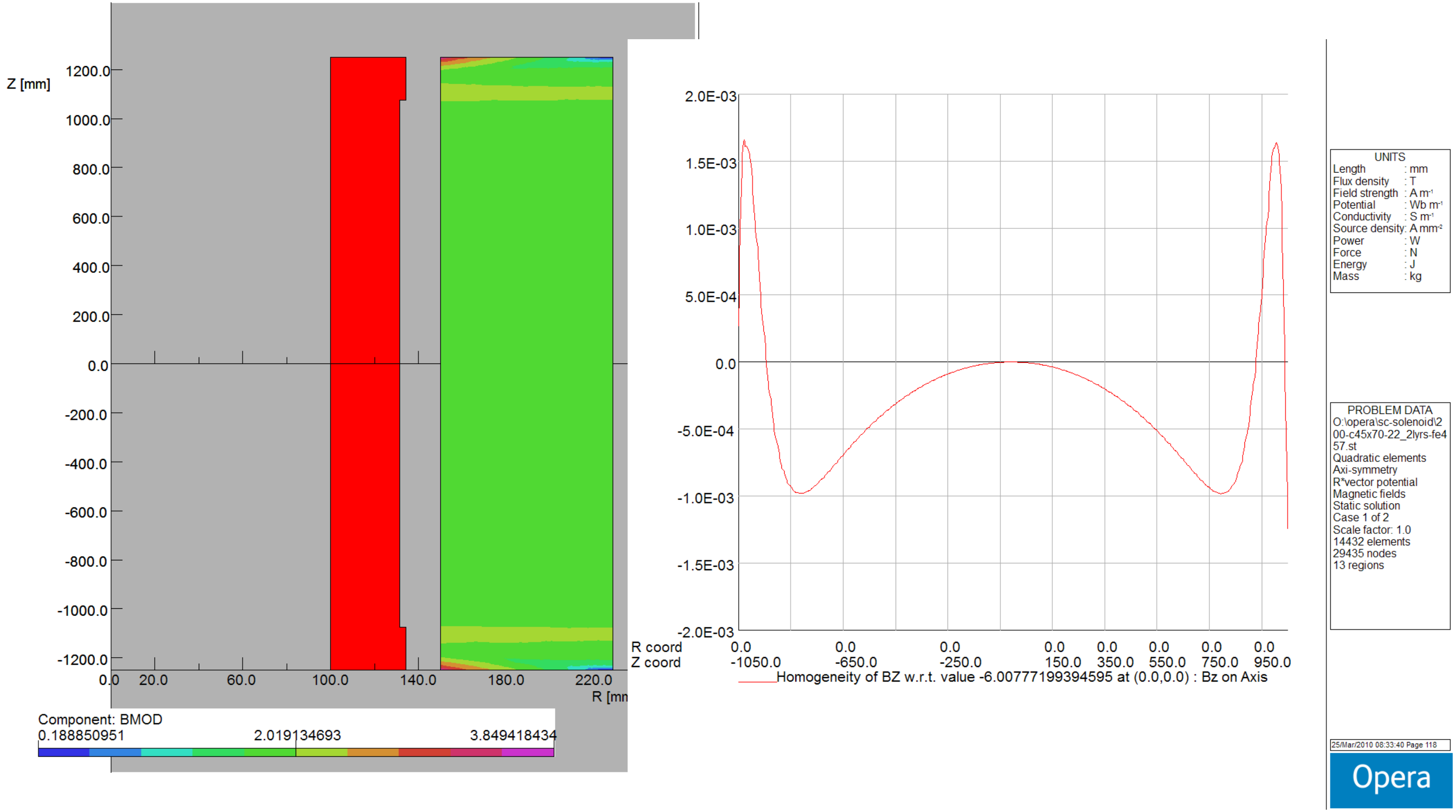


2d Model

(more accurate and faster calculations in many cases)

Ramesh Gupta, March 30, 2010

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
O:\opera\sc-solenoid\200-c45x70-22_2lyrs-fe457.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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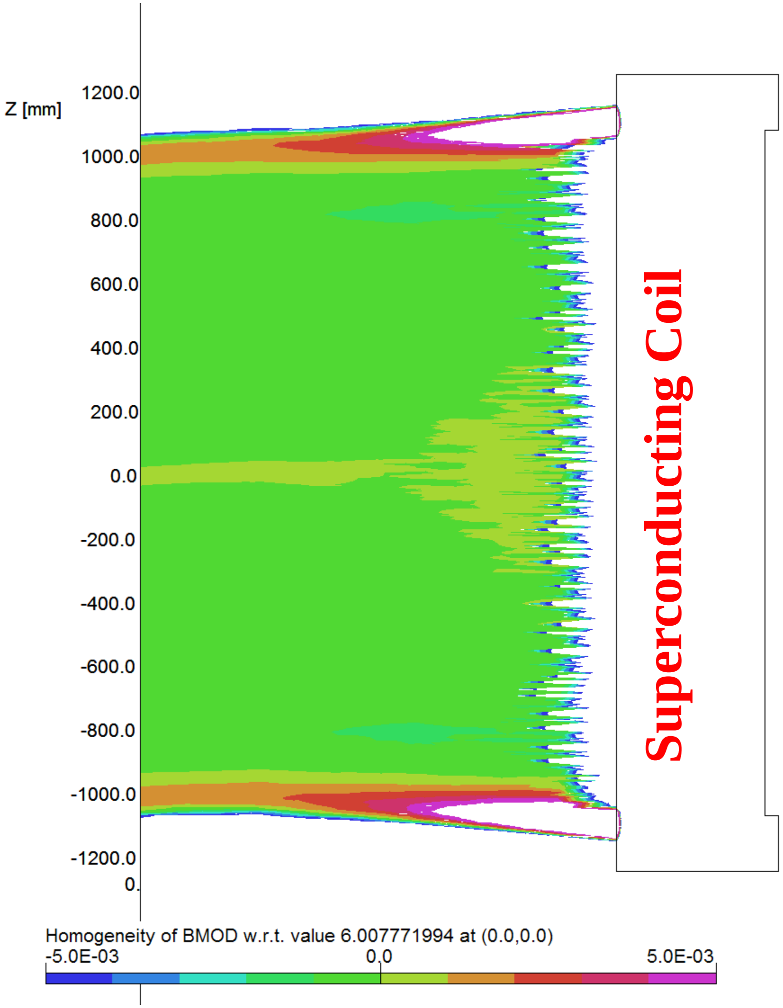
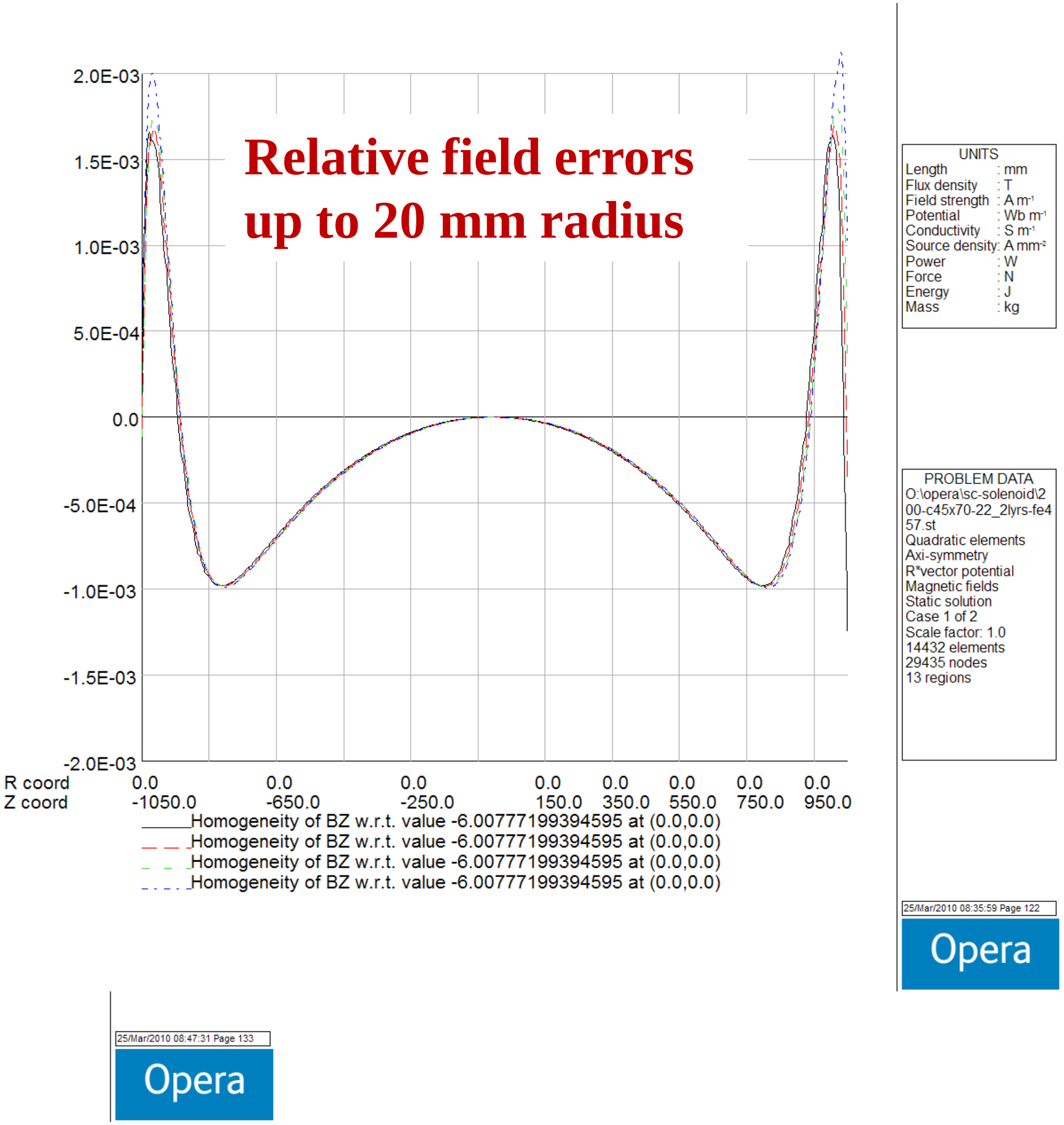
Off-axis field errors



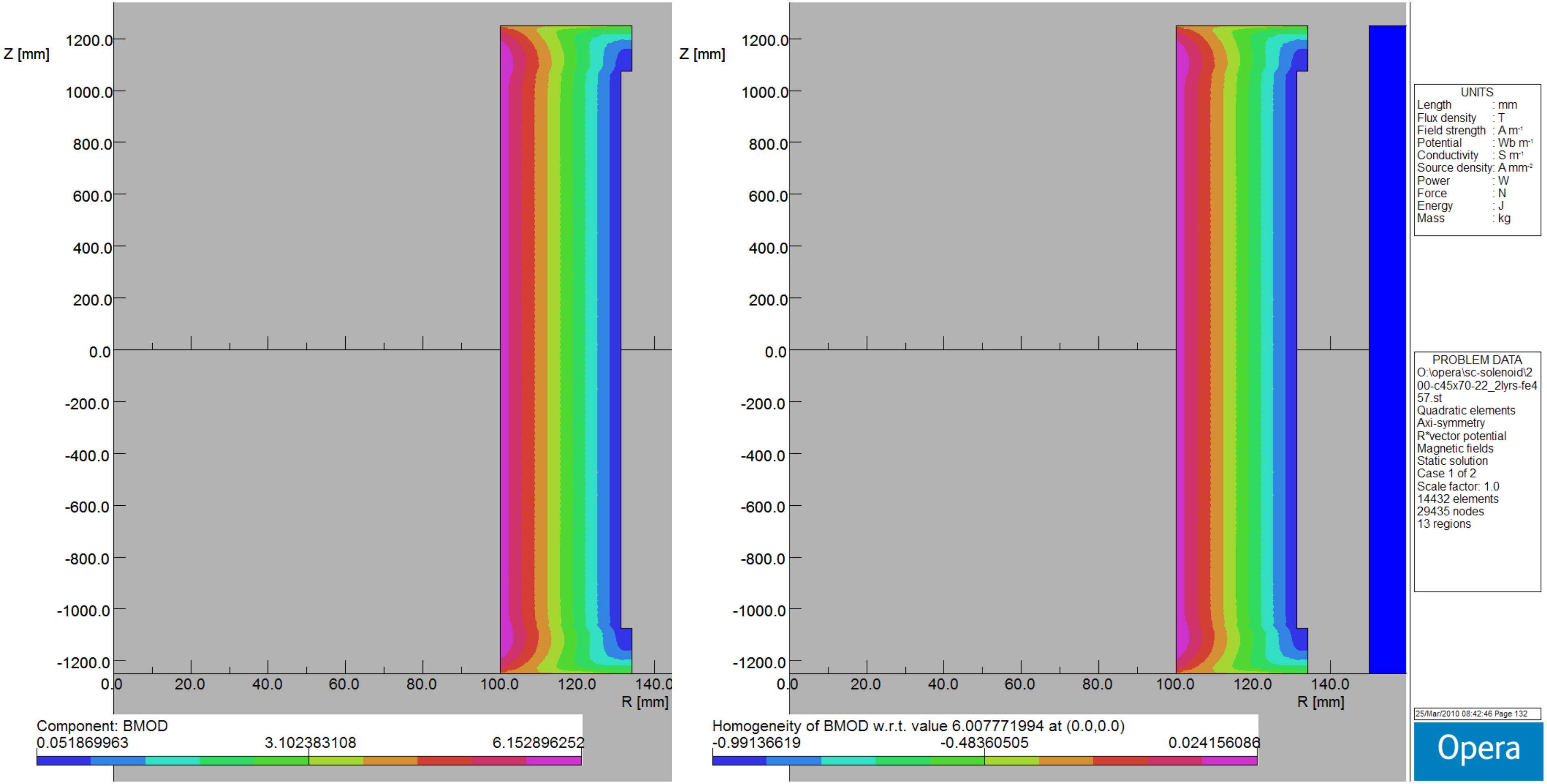
Superconducting Coil



Relative field errors up to 20 mm radius

Field on the Conductor

Small peak enhancement



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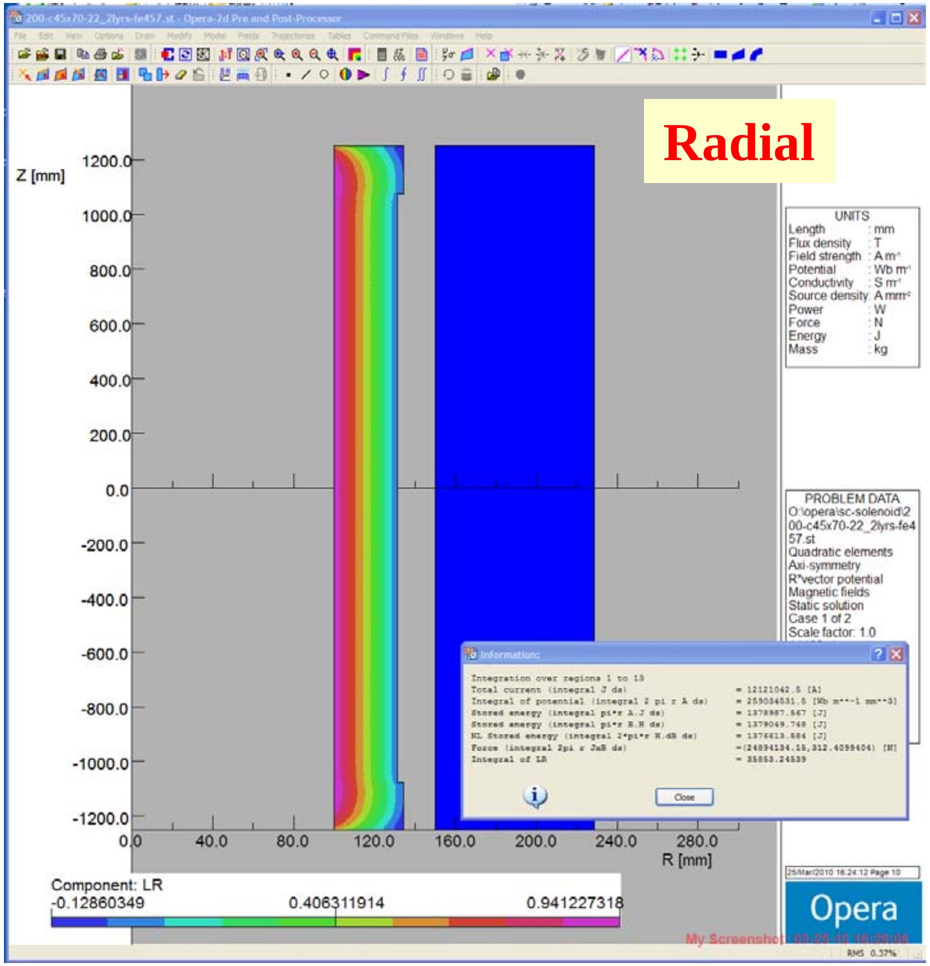
Quadratic elements
Axi-symmetry
R*vector potential
Magnetic fields
Static solution
Case 1 of 2
Scale factor: 1.0
14432 elements
29435 nodes
13 regions

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 ~2X in 292 mm solenoid); Inductance ~14 Henry

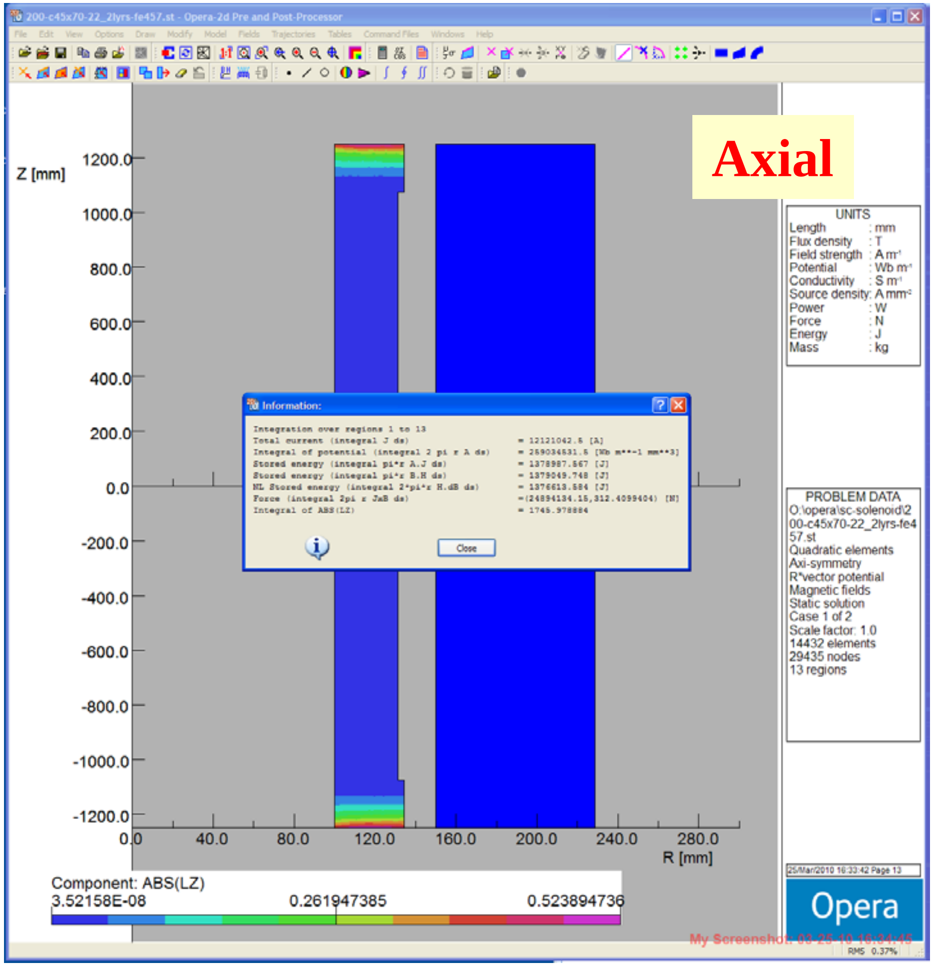


UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
O:\opera\sc-solenoid\200-c45x70-22_2lyrs-fe457.st
Quadratic elements
Axi-symmetry
R*vector potential
Magnetic fields
Static solution
Case 1 of 2
Scale factor: 1.0

Information:

```
Integration over regions 1 to 13
Total current (integral J ds)                        = 12121042.5 [A]
Integral of potential (integral 2 pi r A ds)         = 259034531.5 [Wb m**-1 mm**3]
Stored energy (integral pi*r A.J ds)                 = 1378987.567 [J]
Stored energy (integral pi*r B.H ds)                 = 1379049.748 [J]
NL Stored energy (integral 2*pi*r H.dB ds)           = 1376613.584 [J]
Force (integral 2pi r JxB ds)                        =(24894134.15,312.4099404) [N]
Integral of LR                                       = 35853.24539
```



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
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Stored energy (integral pi*r B.H ds)                 = 1379049.748 [J]
NL Stored energy (integral 2*pi*r H.dB ds)           = 1376613.584 [J]
Force (integral 2pi r JxB ds)                        =(24894134.15,312.4099404) [N]
Integral of ABS(LZ)                                  = 1745.978884
```

Radial Lorentz force (hoop stress) : ~24 MN

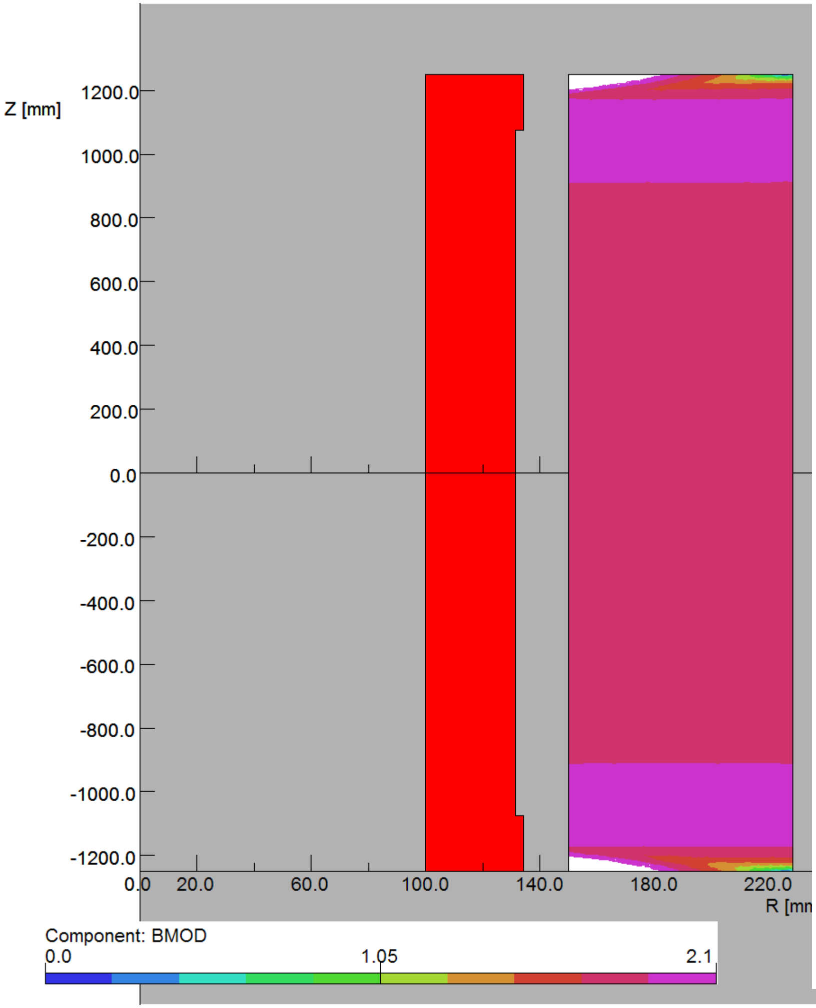
Axial force (inward, only at the ends): ~35 kN per side

6 T @ ~442 A

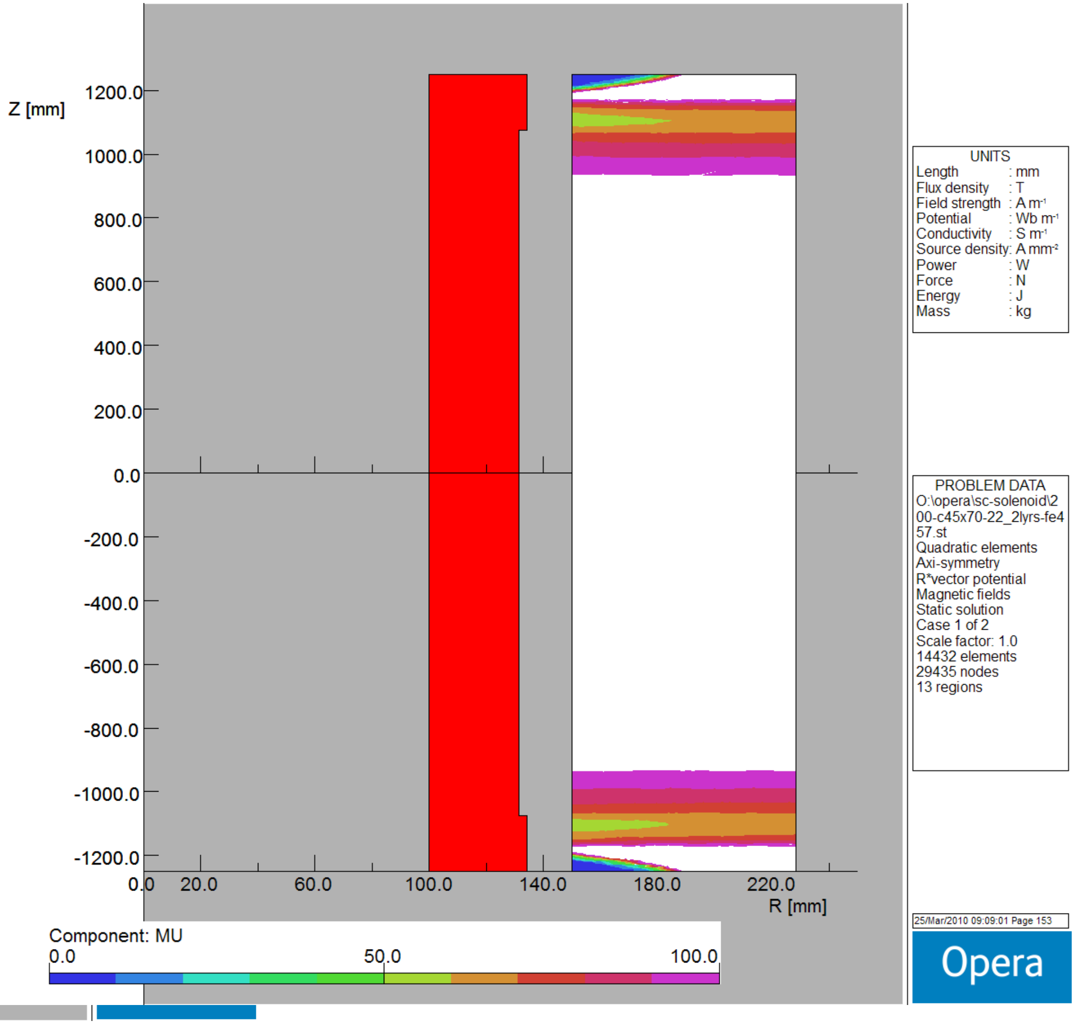
Ramesh Gupta, March 30, 2010

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

B in iron



mu in iron



Model with Copper Solenoids

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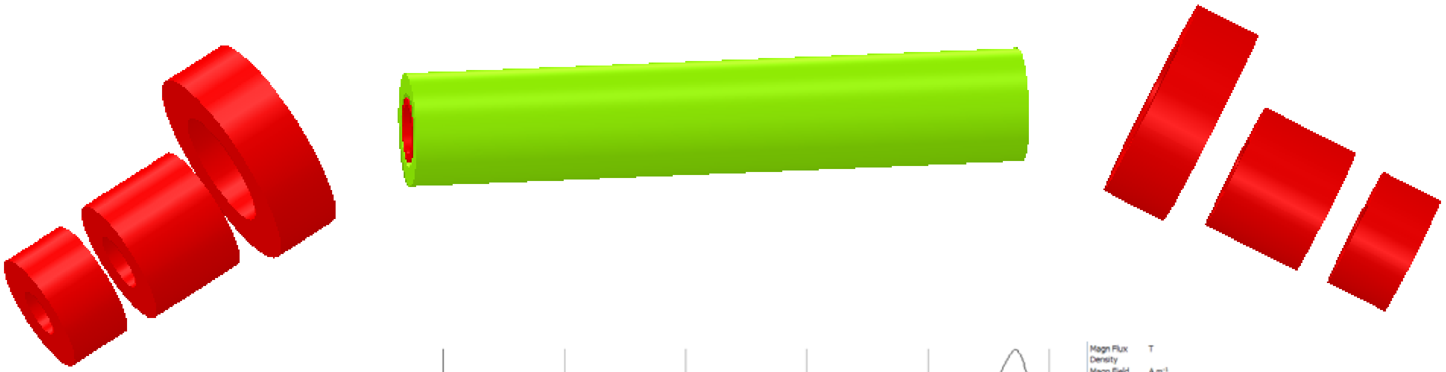
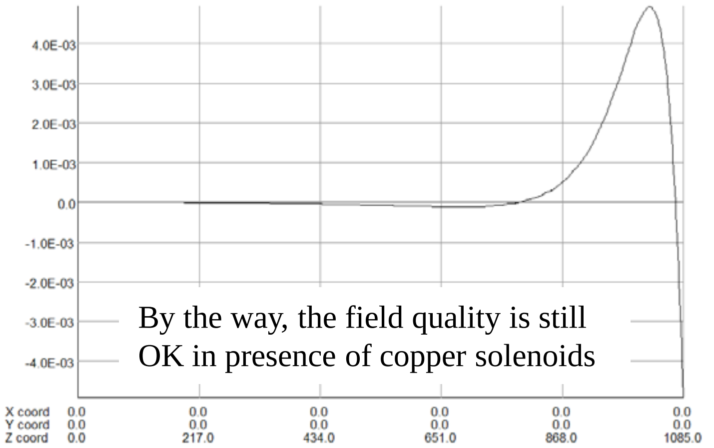
- 0.3 T (3 kG) or so field is desired between copper solenoids and superconducting solenoid along the beam path
- One way to obtain that field is to benefit from the field leaking from superconducting solenoid



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
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



By the way, the field quality is still OK in presence of copper solenoids

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

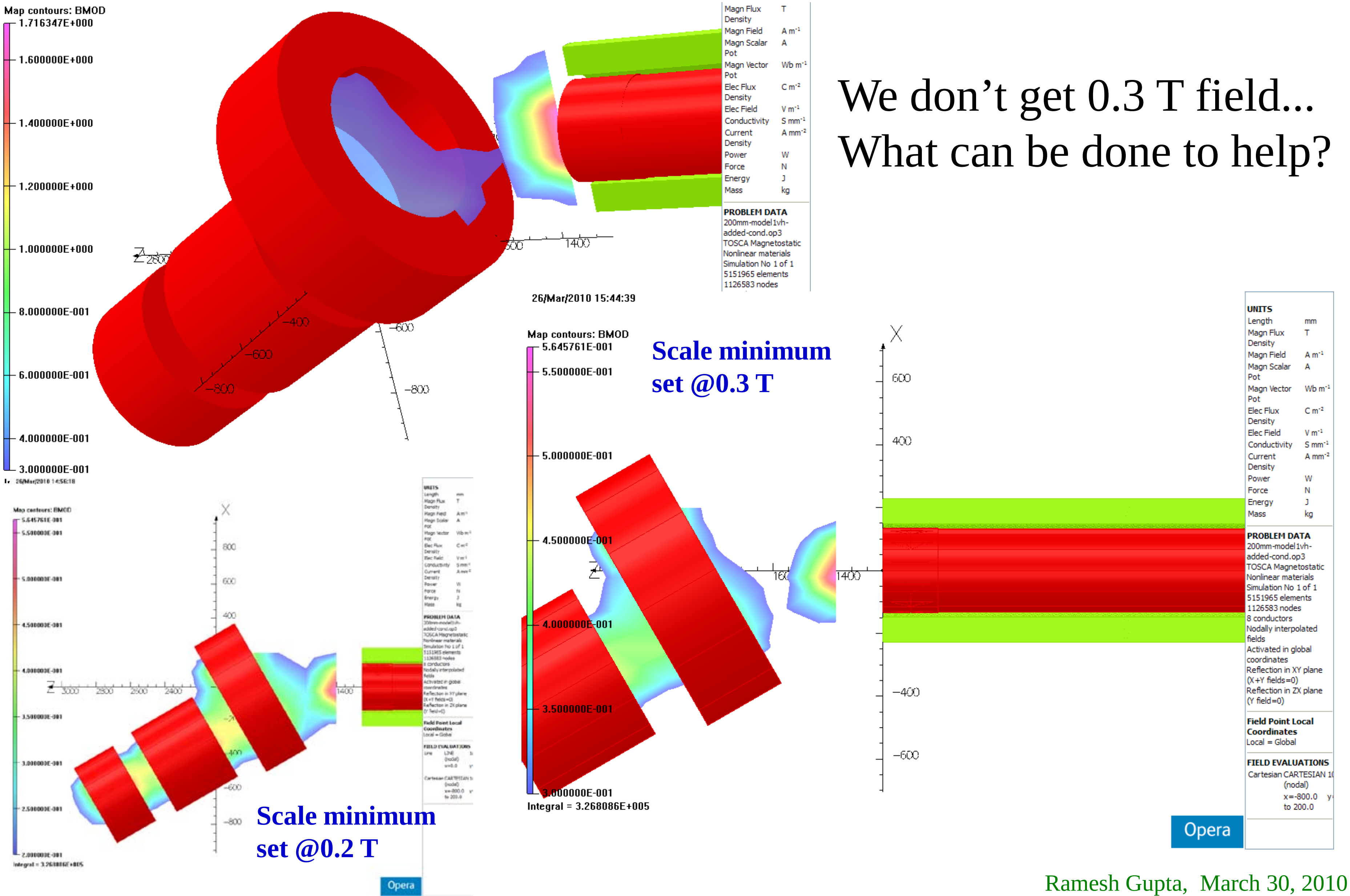
PROBLEM DATA
200mm-model1vh-added-cond-fringe.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
5151965 elements
1126583 nodes
9 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (X+Y fields=0)
Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
Local = Global

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

Opera

Field between Copper and Superconducting Solenoids



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
200mm-model1vh-added-cond.op3
TOSCA Magnetostatic
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Simulation No 1 of 1
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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 1
(nodal)
x=-800.0
to 200.0

We don’t get 0.3 T field…
What can be done to help?

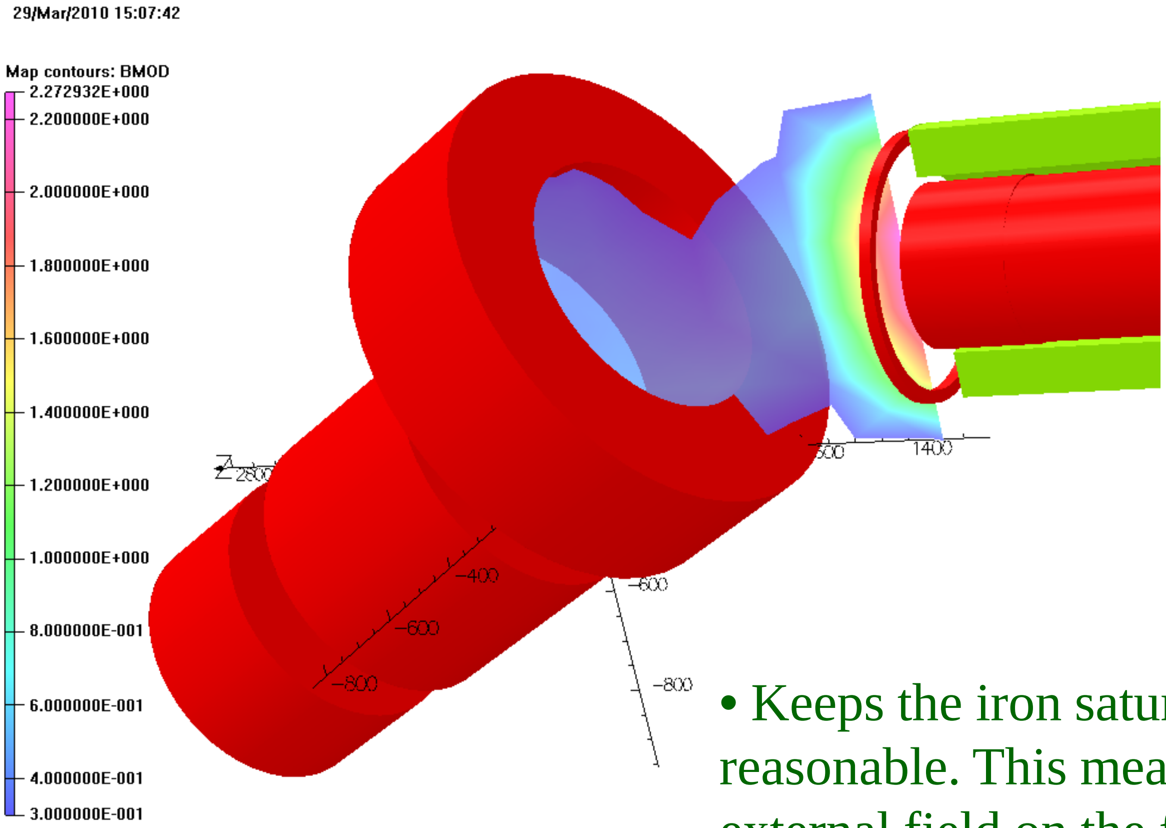
Scale minimum set @0.3 T

Scale minimum set @0.2 T

Ramesh Gupta, March 30, 2010

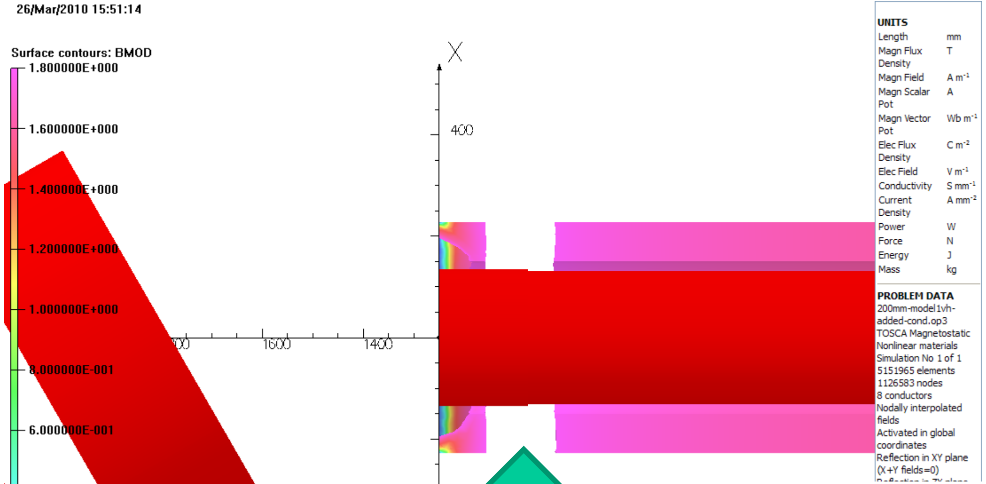
Small Superconducting Solenoid next to Main Solenoid
(fringe field coil may be part of the same coldmass)

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)



- 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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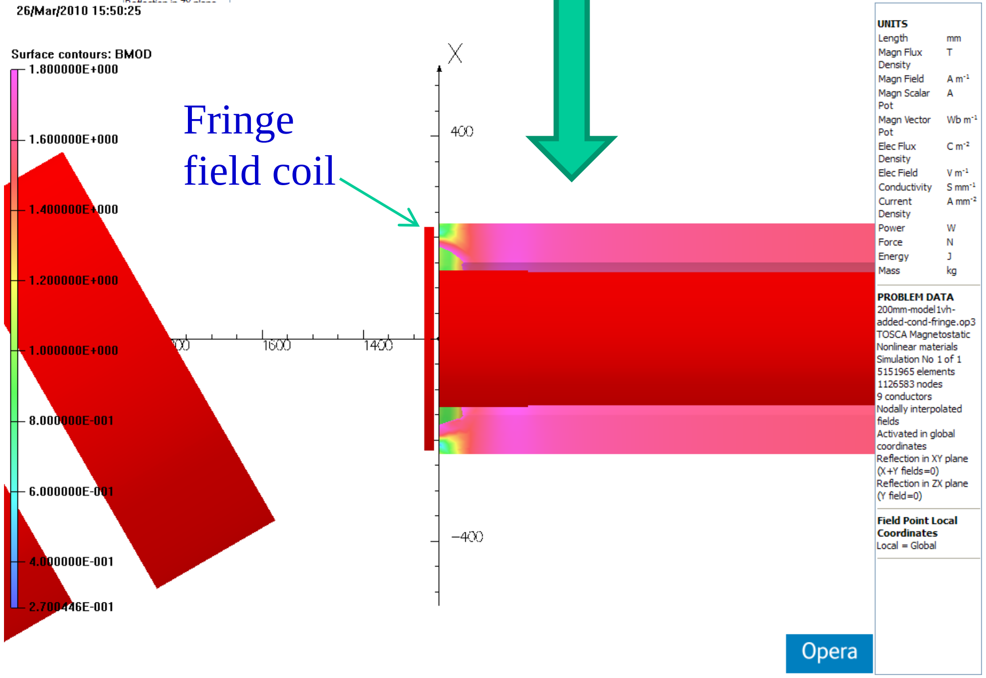
Surface contours: BMOD

```
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-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)
```

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



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Surface contours: BMOD

Fringe field coil

```
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

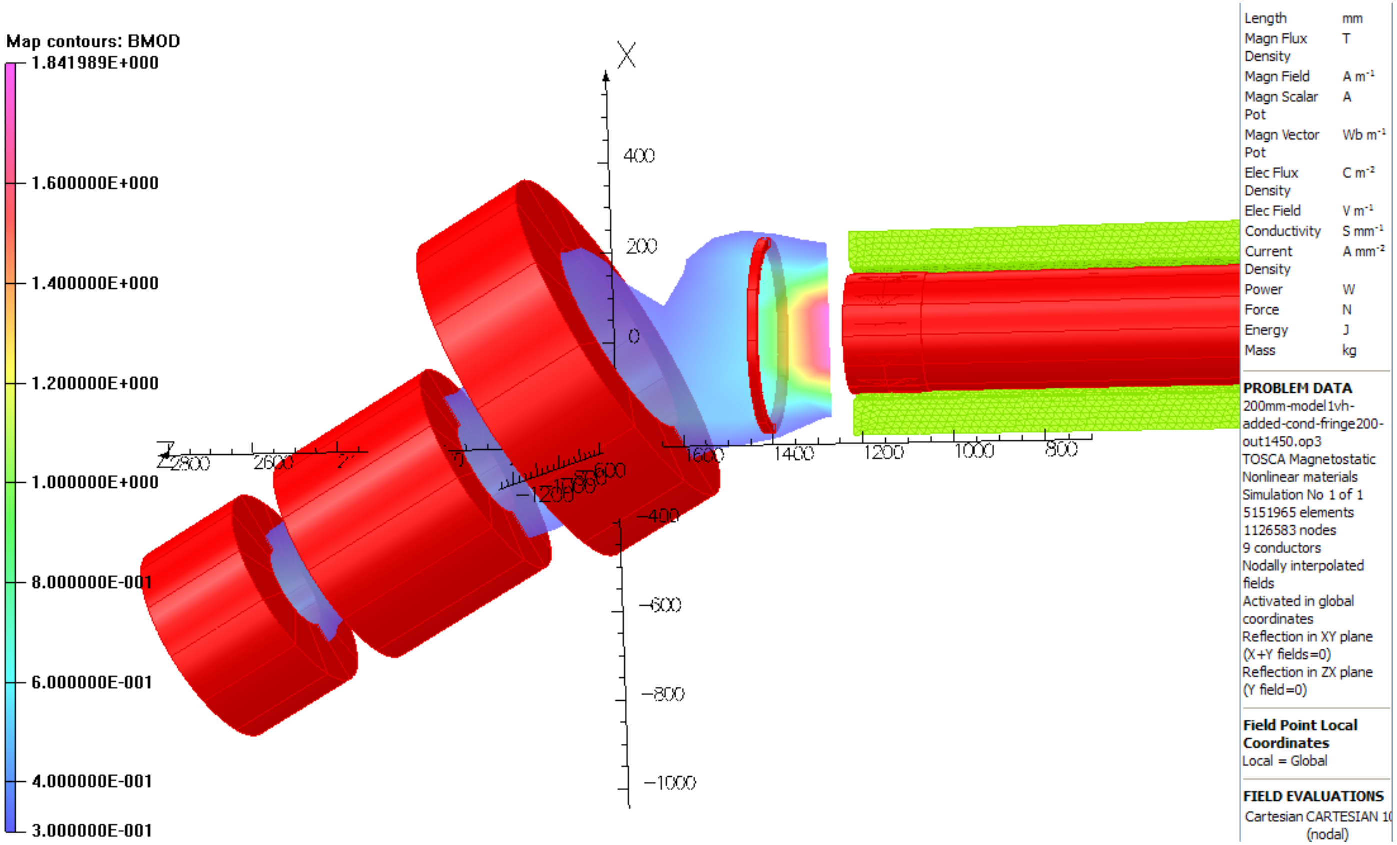
PROBLEM DATA
200mm-model1vh-
added-cond-fringe.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
5151965 elements
1126583 nodes
9 conductors
Nodally interpolated
fields
Activated in global
coordinates
Reflection in XY plane
(X+Y fields=0)
Reflection in ZX plane
(Y field=0)

Field Point Local
Coordinates
Local = Global
```

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

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.



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

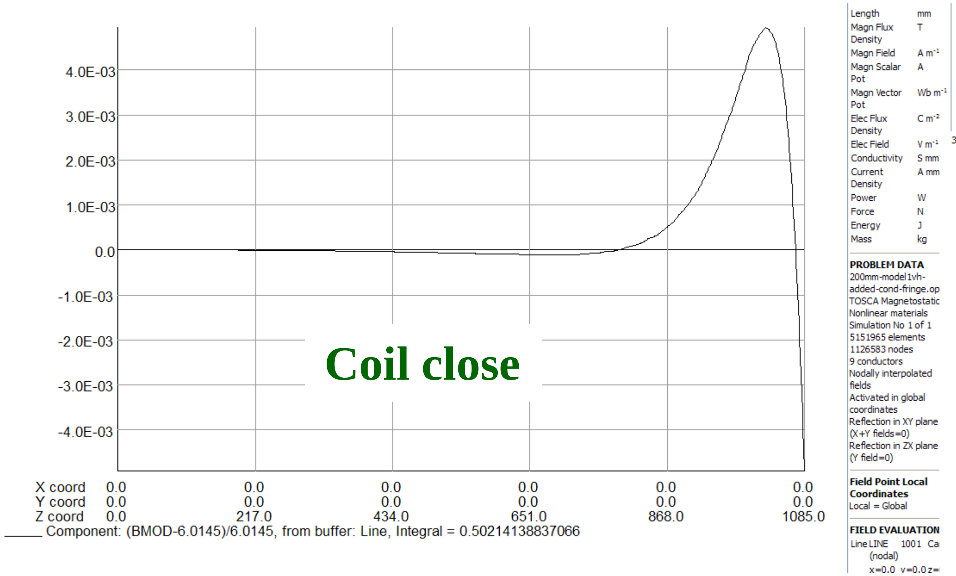
PROBLEM DATA
200mm-model1vh-added-cond-fringe200-out1450.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
5151965 elements
1126583 nodes
9 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (X+Y fields=0)
Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Cartesian CARTESIAN 1
(nodal)

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

Influence of fringe field coil on field errors



Coil close

Component: (BMOD-6.0145)/6.0145, from buffer: Line, Integral = 0.50214138837066

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
Current Density	A mm
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
200mm-model1vh-added-cond-fringe.op
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Nonlinear materials
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5151965 elements
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9 conductors
Nodally interpolated fields
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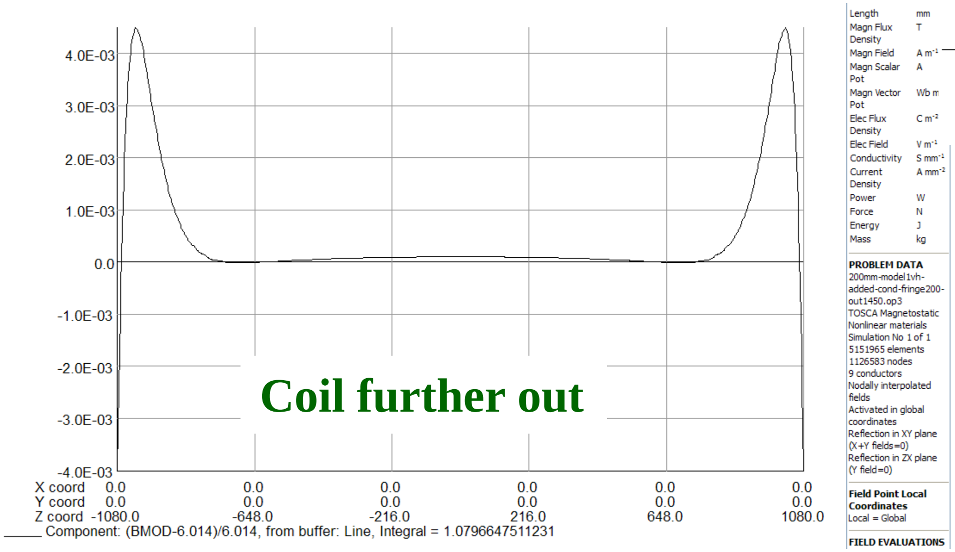
Reflection in XY plane (X+Y fields=0)
Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
Local = Global

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

Field errors with fringe field coils



Coil further out

Component: (BMOD-6.014)/6.014, from buffer: Line, Integral = 1.0796647511231

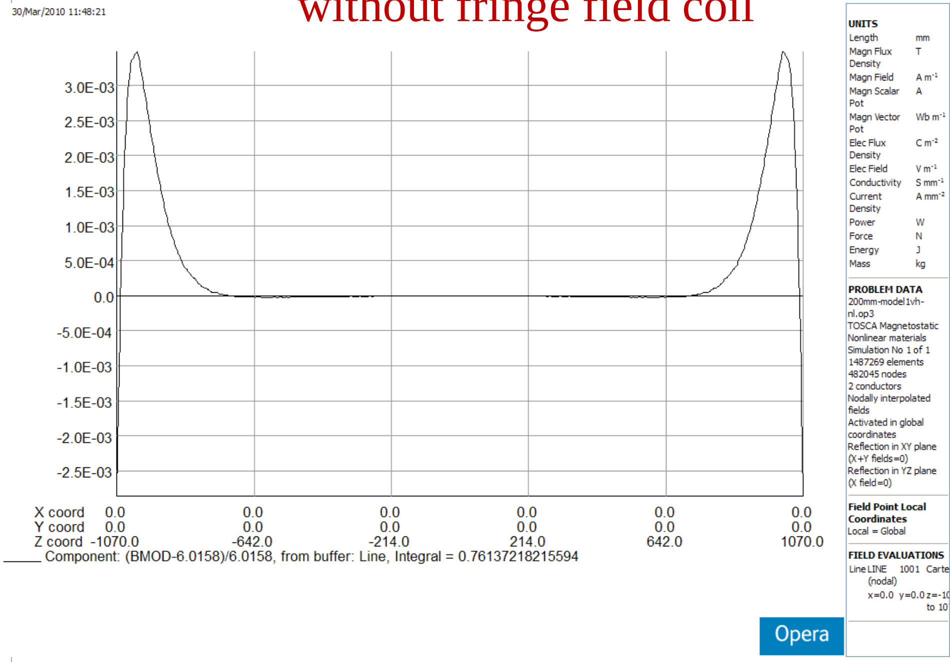
Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S mm^{-1}
Current Density	A mm^{-2}
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
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 fields=0)
Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Field errors on axis
without fringe field coil



Component: (BMOD-6.0158)/6.0158, from buffer: Line, Integral = 0.76137218215594

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
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=-10
to 10

Conclusion:
Small influence

Summary

Work in progress

The design is in reasonable stage to move forward
– no show stoppers