
Superconducting Solenoid for e-lens with Fringe Field Coil

Ramesh Gupta
September 28, 2010

Overview

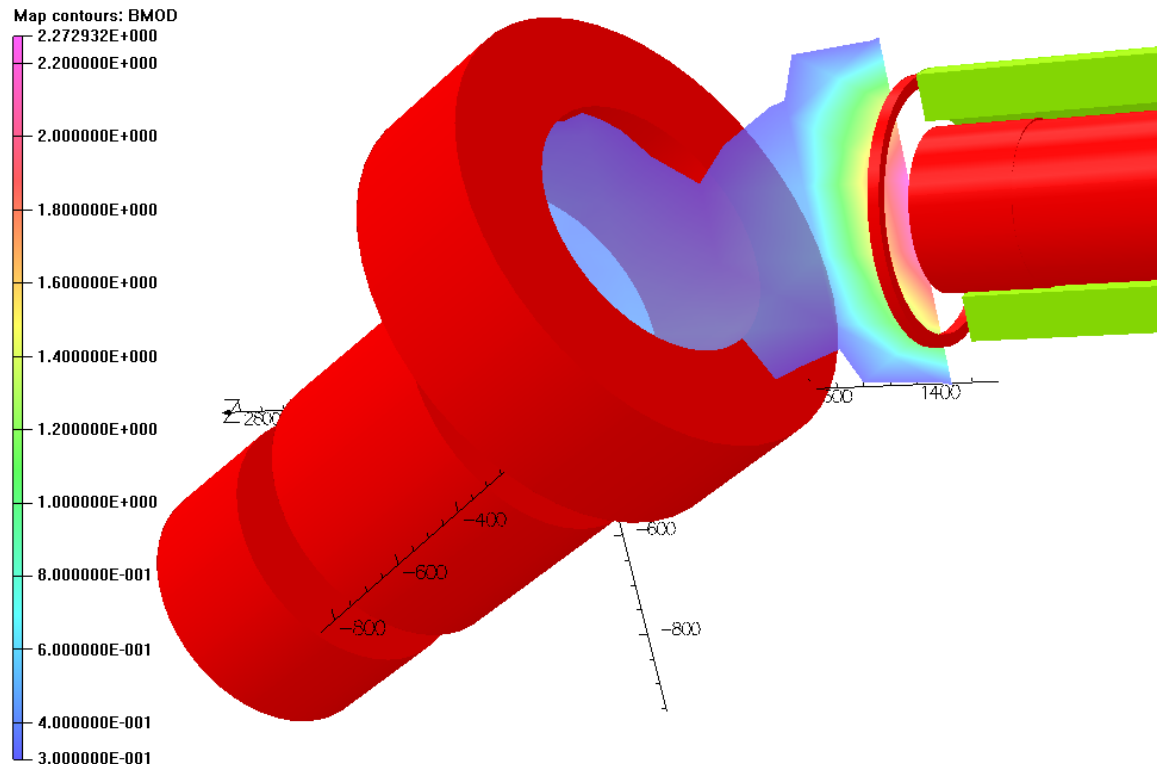
- Fringe field superconducting solenoidal coils (one on either side) have now become an integral part of the system design.
- They are designed to create a significant field outside the coldmass, in the interface region between the room temperature solenoid and superconducting solenoid (combined field should be greater than 0.3 T).
- Various iterations have made fringe field coils stronger and inner radius smaller.
- This means that now they not only create significant field outside the coldmass but also inside the solenoid. Therefore, the solenoid design to obtain a good field quality (on axis field errors $\sim 5 \times 10^{-3}$ within ± 1050 mm) needs to be re-optimized with the fringe field coils included in the calculations.
- This works well if current in main coil and fringe field coils scale linearly.
- However, it is desired that fringe field coils run stronger at lower fields (say 0.3 T or even 0.1 T) as higher contribution is needed in those cases to overcome the lower field in interface region.
- A solution is proposed that seems to do all above plus extend the good field region beyond ± 1050 mm).

Quick Review of the Previous Designs

Design #1

(fringe field coil - large radius and close to iron)

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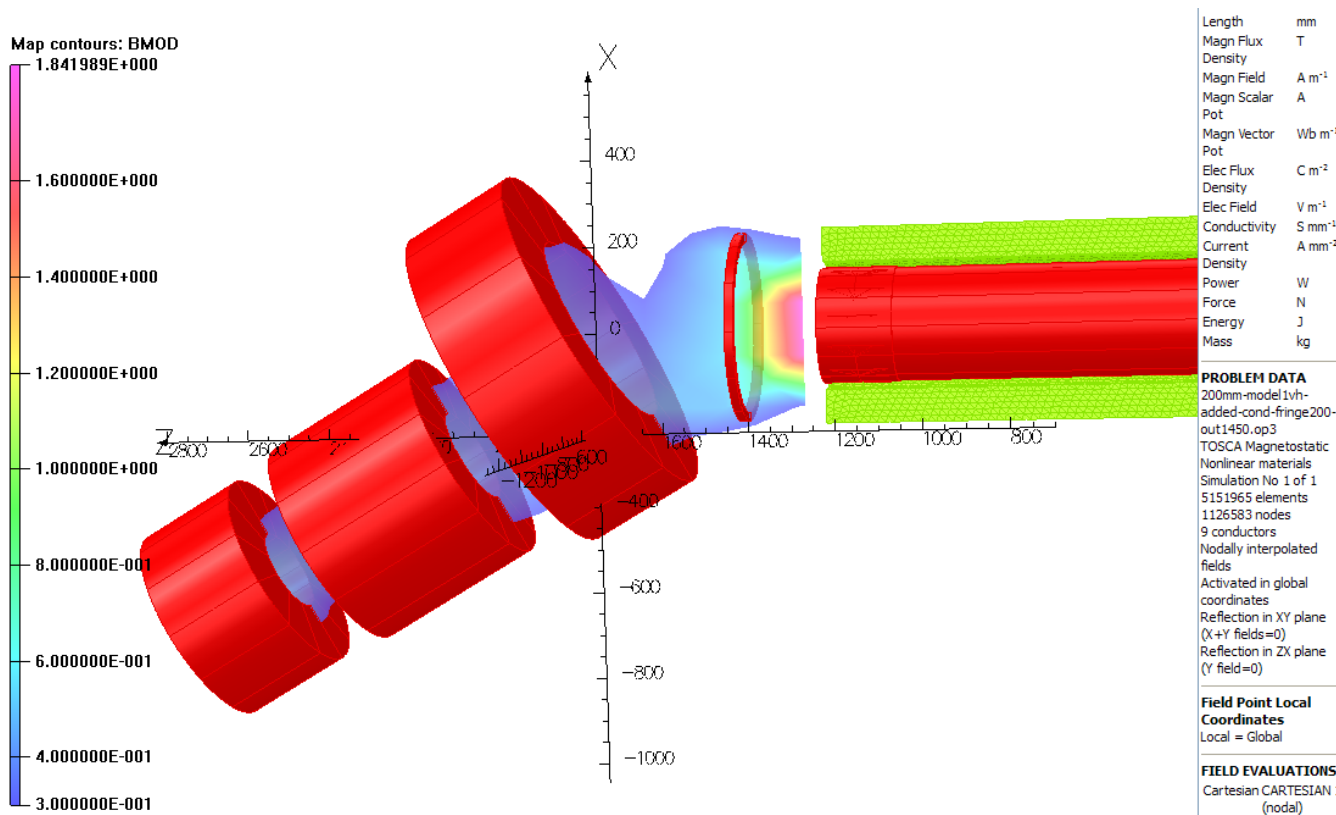


- **Worked well**
- **Benefits sold too well and users requested even more.**
- **But larger radius creates concern in cooling of the top part of the coil.**
- **Also some concern on field interaction between main and fringe field coil**

Design #2

(fringe field coil moved out axially)

- Request to increase power of fringe field (or exterior field coil).
- Moving it out creates larger fringe field.

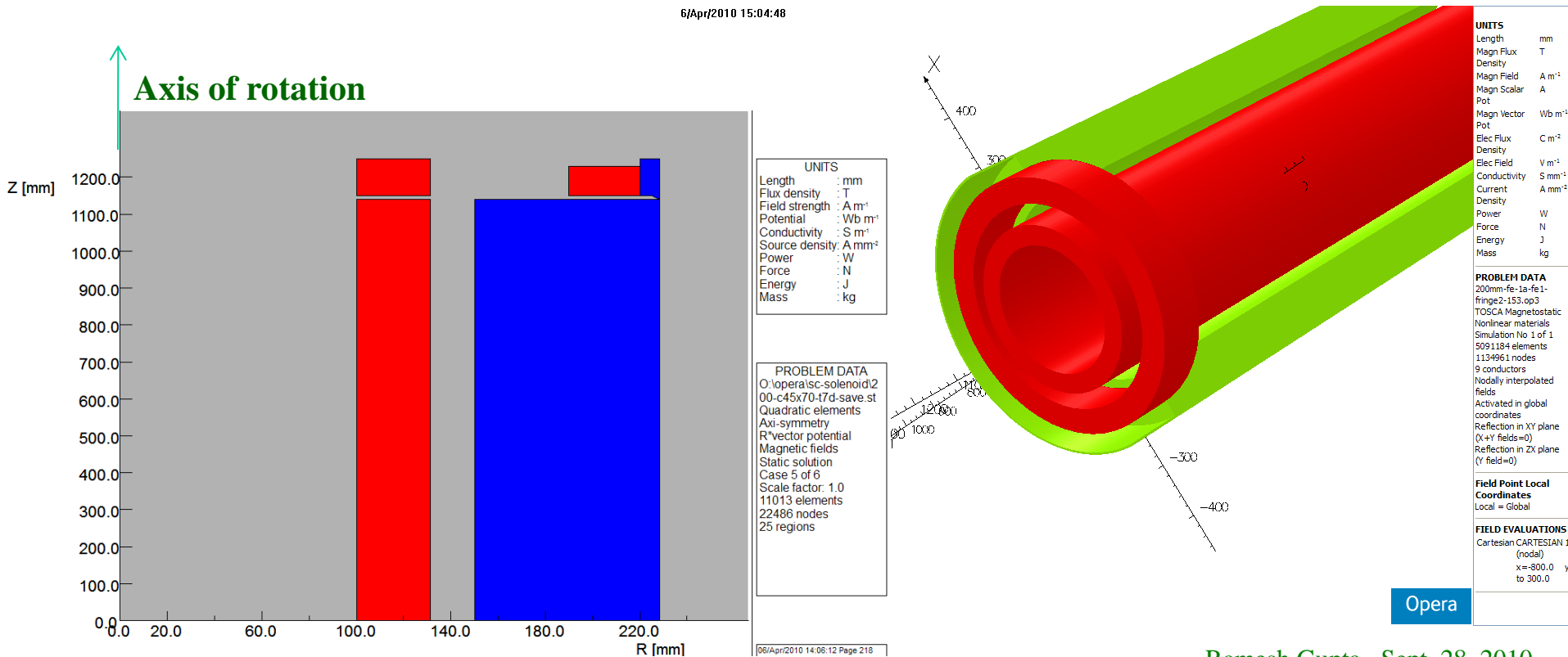


However, detailed design found that there is not enough space to move this far out.

Design #3

(fringe field coil inside the iron)

- Magnetic interaction between the main coil and fringe field coil is minimized for on-axis field quality inside the main solenoid.
- This is the design that is widely used by CAD in their review presentations.
- However, the concern remain on the cooling of the top part of the coil as that part is not submerged in liquid helium.

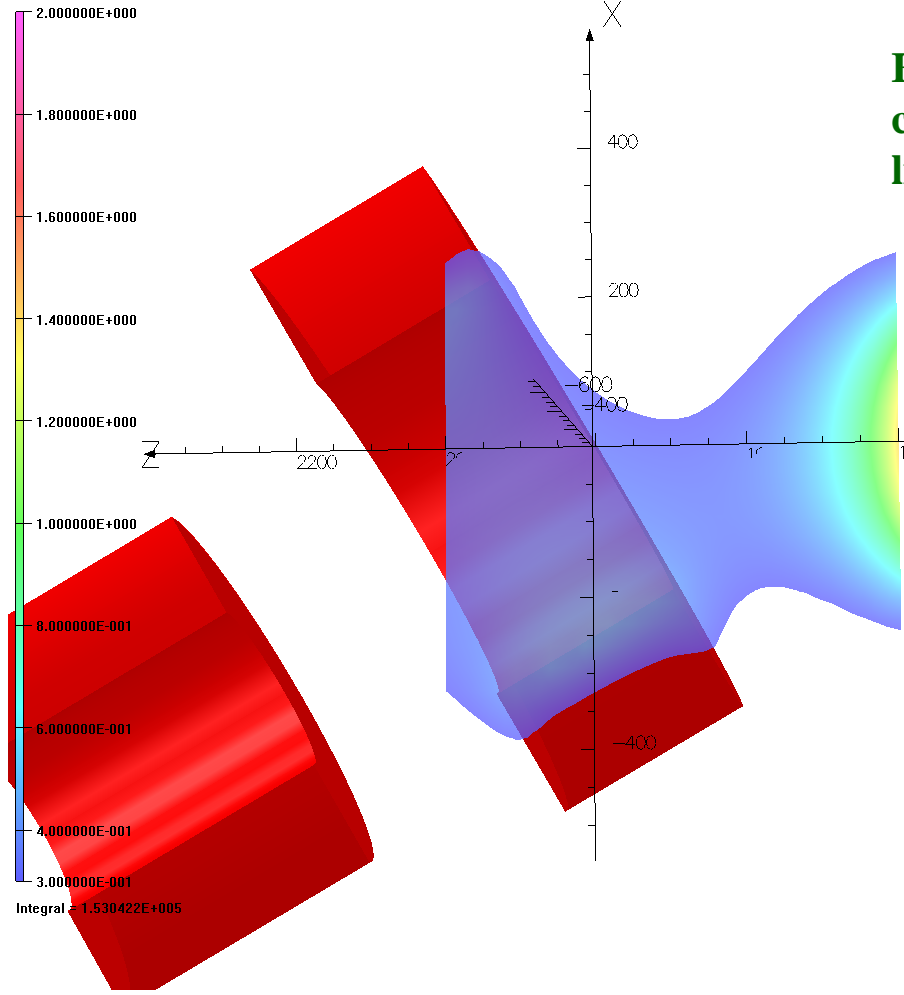


Current Design with Engineering (Design #4)

(one before the now being proposed)

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Map contours: BMOD



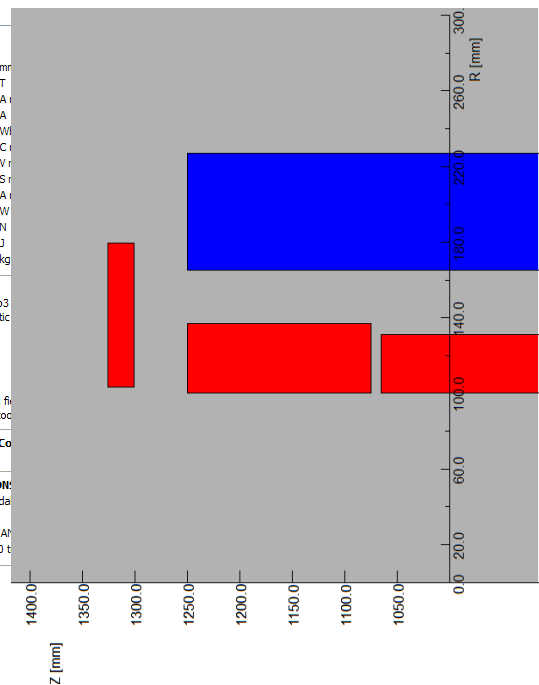
Fringe field coil inside the liquid helium

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

MODEL DATA	
test-new-opt-coil.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
3874422 elements	
1323605 nodes	
11 conductors	
Nodally interpolated fields	
Activated in global coordinate system	

Field Point Local Coordinate System	
Local = Global	

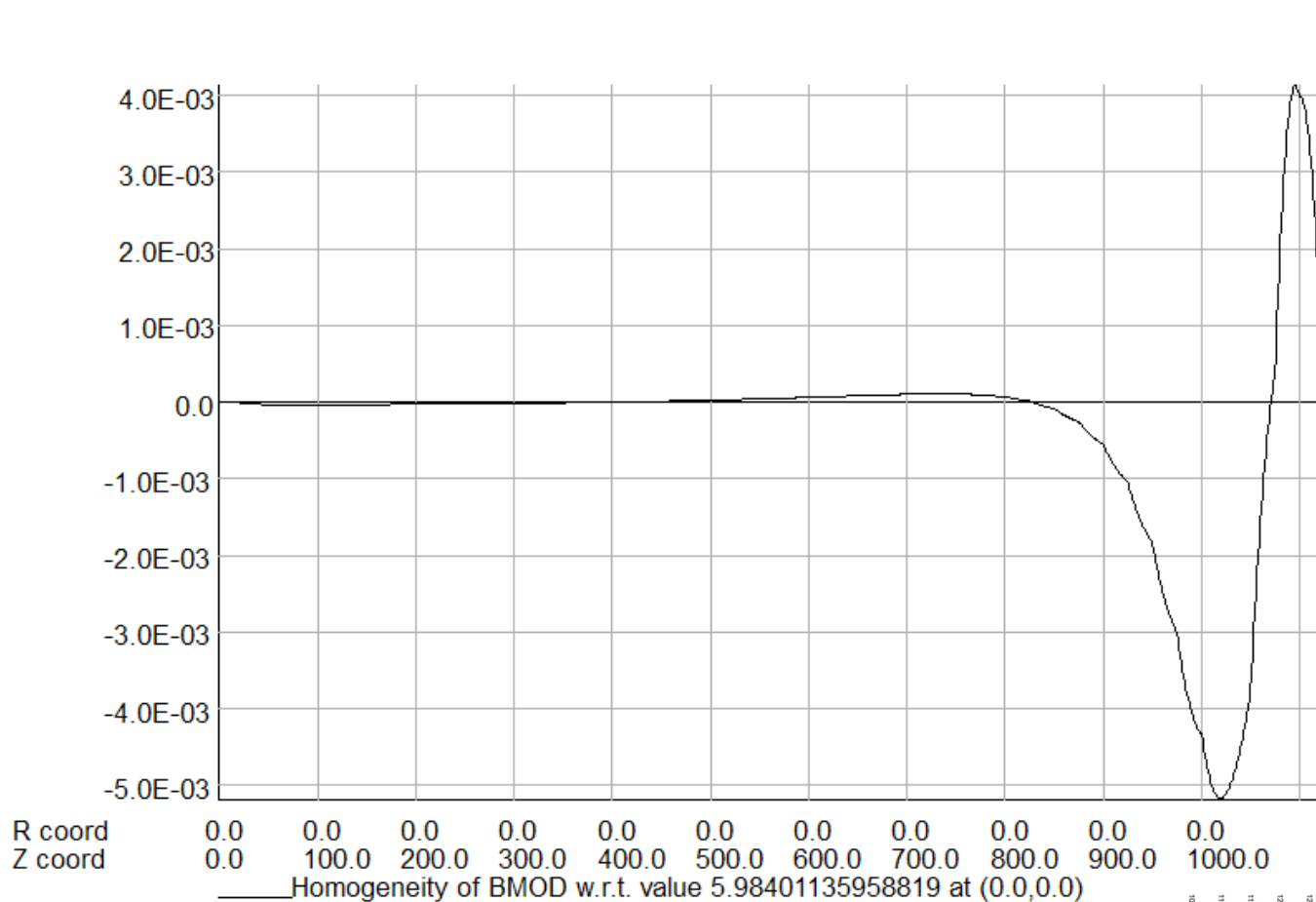
FIELD EVALUATION	
Line LINE (nodal)	
x=0.0	
Cartesian CARTESIAN	
x=-800.0	



- However, it is @6T main field.
- If one wants >0.3 T independent of the main field, then the fringe field coils have to be independently powered.
- What happens to on-axis field quality inside the solenoid?

Opera

On-axis field quality inside the Solenoid

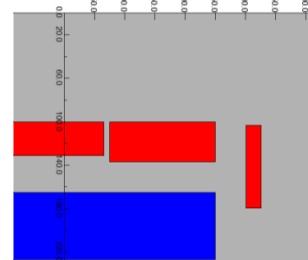


UNITS	
Length	: mm
Flux density	: T
Field strength	: A m ⁻¹
Potential	: Wb m ⁻¹
Conductivity	: S m ⁻¹
Source density	: A mm ⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

MODEL DATA	
O:\opera\sc-solenoid\ite	
st\200-new-yoke-new-c	
oil-save1.st	
Quadratic elements	
Axi-symmetry	
R*vector potential	
Magnetic fields	
Static solution	
Case 7 of 9	
Scale factor: 1.0	
16707 elements	
33872 nodes	
18 regions	

Construction errors not included

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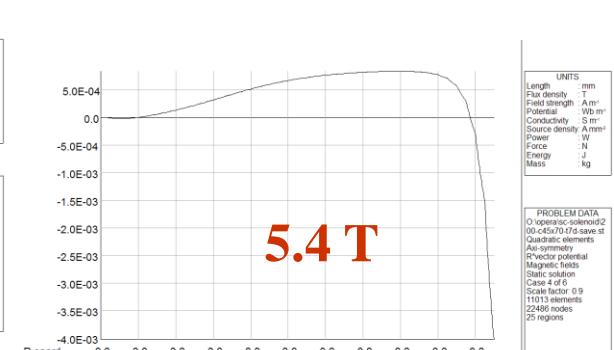
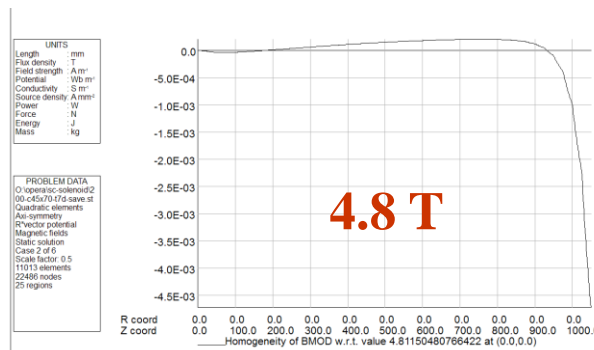
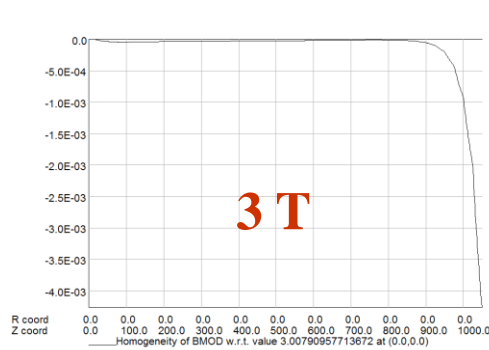


- The request was to make field errors $\sim 10^{-3}$ within ± 1050 mm
- SMD and fringe field coils are your friends
 - field quality is made good to ± 1130 mm

Field Errors at Different Fields

(earlier design)

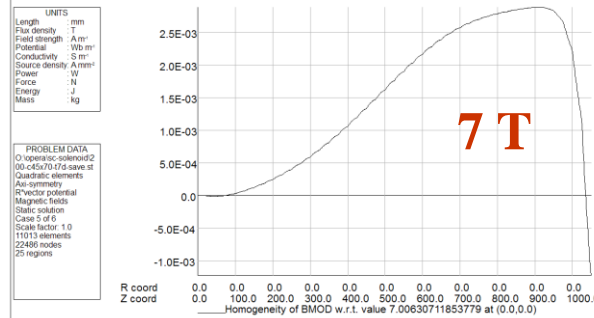
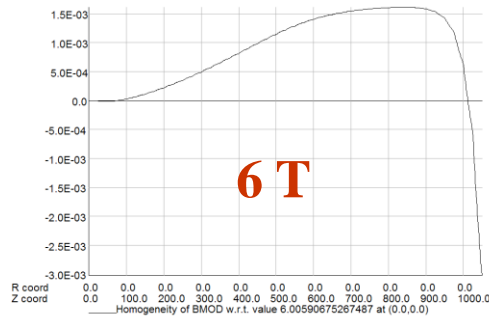
- Proof of principle design to show relative errors $\sim 5 \times 10^{-3}$
- Relative field errors are plotted from center to 1050 mm axially



Opera

Opera

Opera

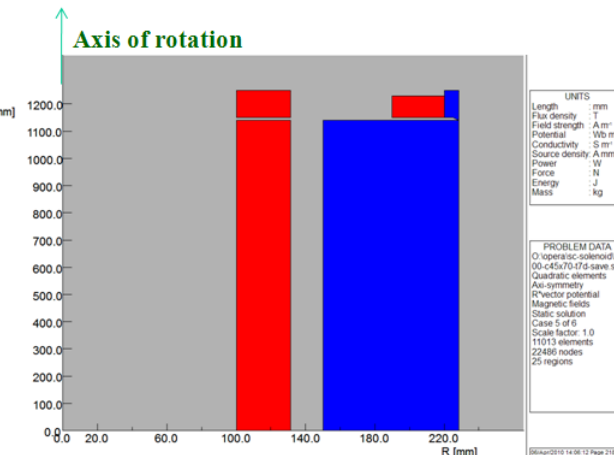


Opera

Opera

Opera

Opera

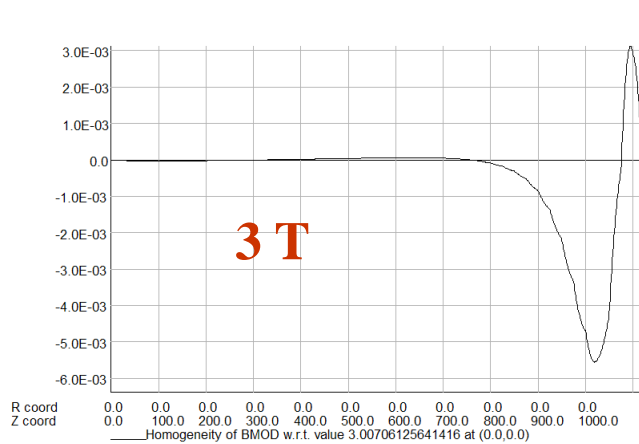


Opera

Field Errors at Different Fields

(Current design)

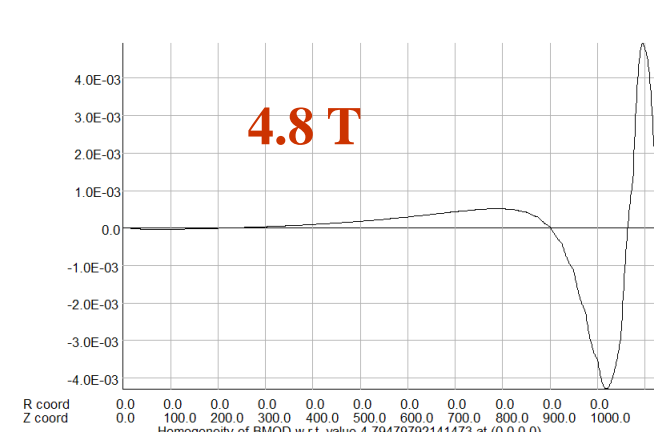
- All coils (main coil and fringe field coils) are powered in series
- Relative field errors remain $\sim 5 \times 10^{-3}$ to ± 1130 mm from 0.6 T to 7 T ---- wow!



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

MODEL DATA
 O:\opera\isc-solenoid\ite
 st200-new-yoke-new-c
 oil-save1.st
 Quadratic elements
 Axi-symmetry
 R'vector potential
 Magnetic fields
 Static solution
 Case 2 of 9
 Scale factor: 0.5
 16707 elements
 33872 nodes
 18 regions

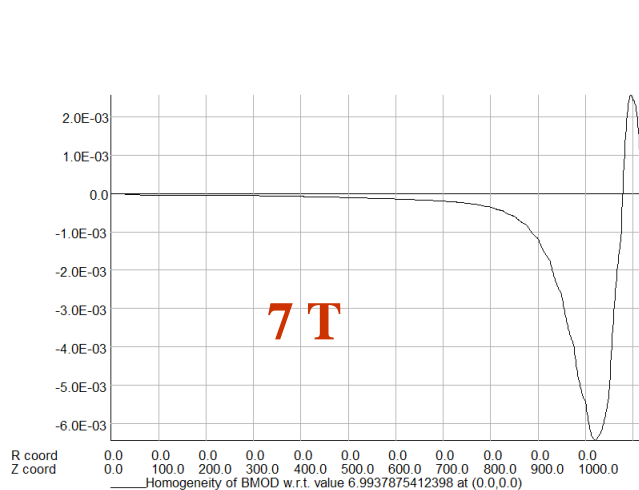
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UNITS
 Length : mm
 Flux density : T
 Field strength : A m⁻¹
 Potential : Wb m⁻¹
 Conductivity : S m⁻¹
 Source density: A mm⁻²
 Power : W
 Force : N
 Energy : J
 Mass : kg

MODEL DATA
 O:\opera\isc-solenoid\ite
 st200-new-yoke-new-c
 oil-save1.st
 Quadratic elements
 Axi-symmetry
 R'vector potential
 Magnetic fields
 Static solution
 Case 5 of 9
 Scale factor: 0.8
 16707 elements
 33872 nodes
 18 regions

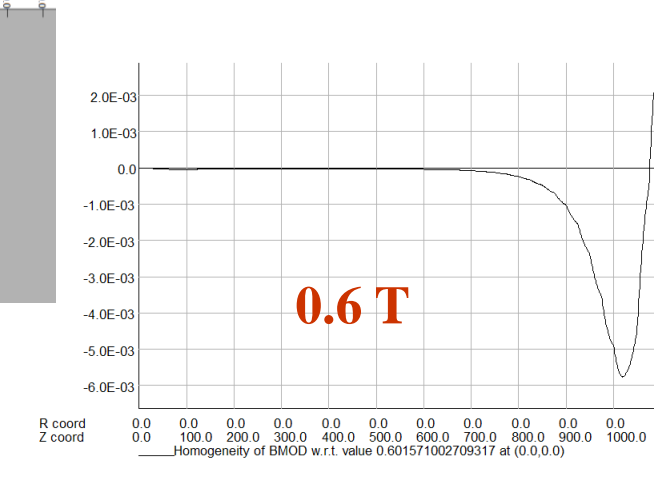
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UNITS
 Length : mm
 Flux density : T
 Field strength : A m⁻¹
 Potential : Wb m⁻¹
 Conductivity : S m⁻¹
 Source density: A mm⁻²
 Power : W
 Force : N
 Energy : J
 Mass : kg

MODEL DATA
 O:\opera\isc-solenoid\ite
 st200-new-yoke-new-c
 oil-save1.st
 Quadratic elements
 Axi-symmetry
 R'vector potential
 Magnetic fields
 Static solution
 Case 9 of 9
 Scale factor: 1.17
 16707 elements
 33872 nodes
 18 regions

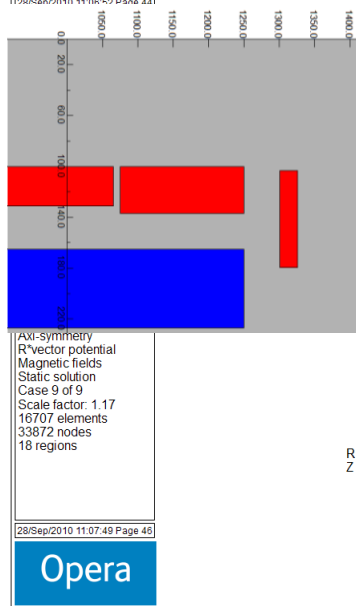
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UNITS
 Length : mm
 Flux density : T
 Field strength : A m⁻¹
 Potential : Wb m⁻¹
 Conductivity : S m⁻¹
 Source density: A mm⁻²
 Power : W
 Force : N
 Energy : J
 Mass : kg

MODEL DATA
 O:\opera\isc-solenoid\ite
 st200-new-yoke-new-c
 oil-save1.st
 Quadratic elements
 Axi-symmetry
 R'vector potential
 Magnetic fields
 Static solution
 Case 1 of 9
 Scale factor: 0.1
 16707 elements
 33872 nodes
 18 regions

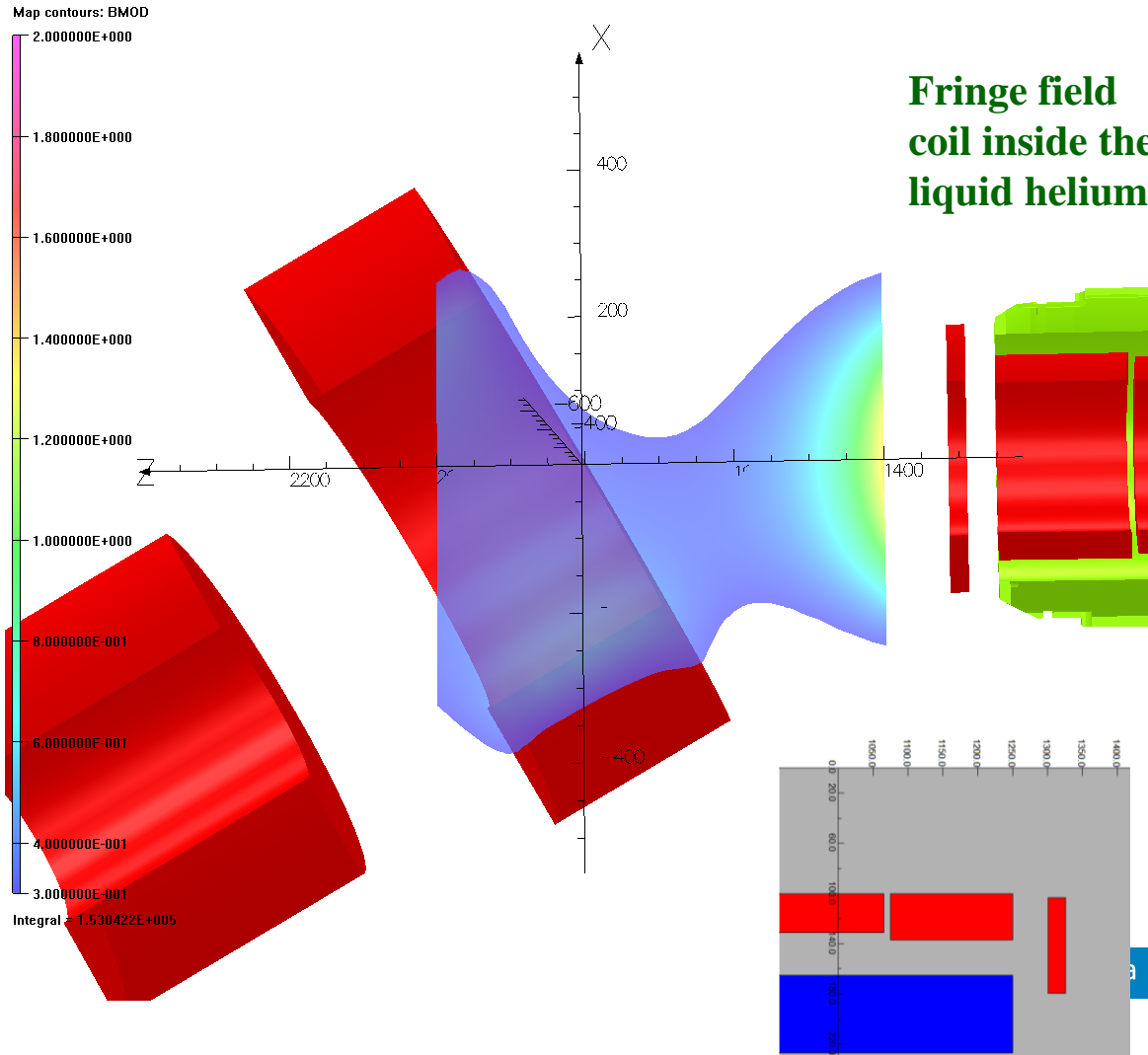
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Opera

Current Design (magnitude of the field)

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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

MODEL DATA	
test-new-opt-coil.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
3874422 elements	
1323605 nodes	
11 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line LINE (nodal) 1001 Cartesian	
x=0.0 y=0.0 z=0.0 to 1150.0	
Cartesian CARTESIAN (nodal) 40x40 Cartesian	
x=-800.0 to 300.0 y=0.0 z=1400.0 to 2000.0	

- @6T main field is barely above 0.3 T.
- Situation would be worse at lower field.

- Fringe field coil parameters: inner radius 103.19mm, outer radius 179.19 mm, thickness 25 mm

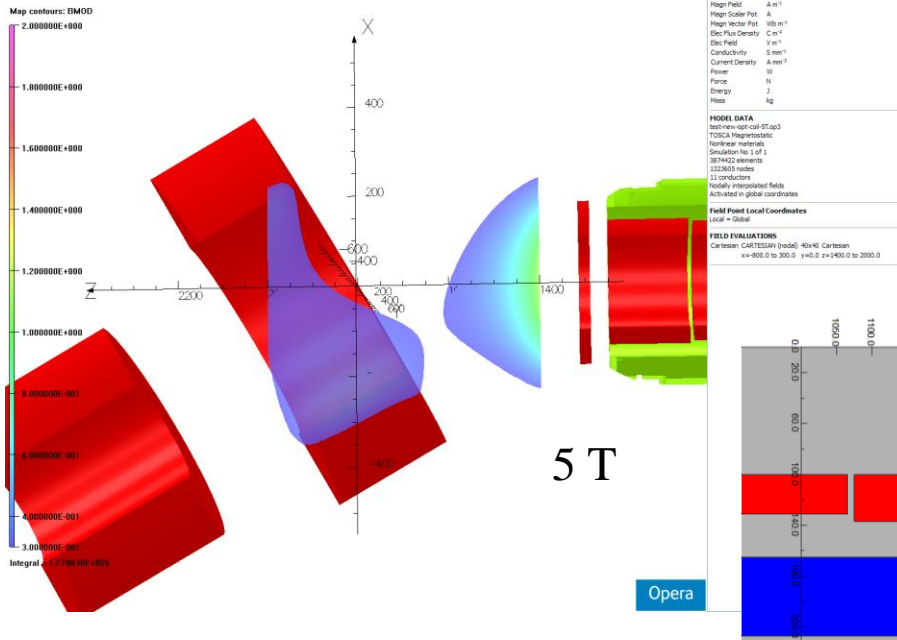
(coil o.d. can be slightly increased)

Current Design

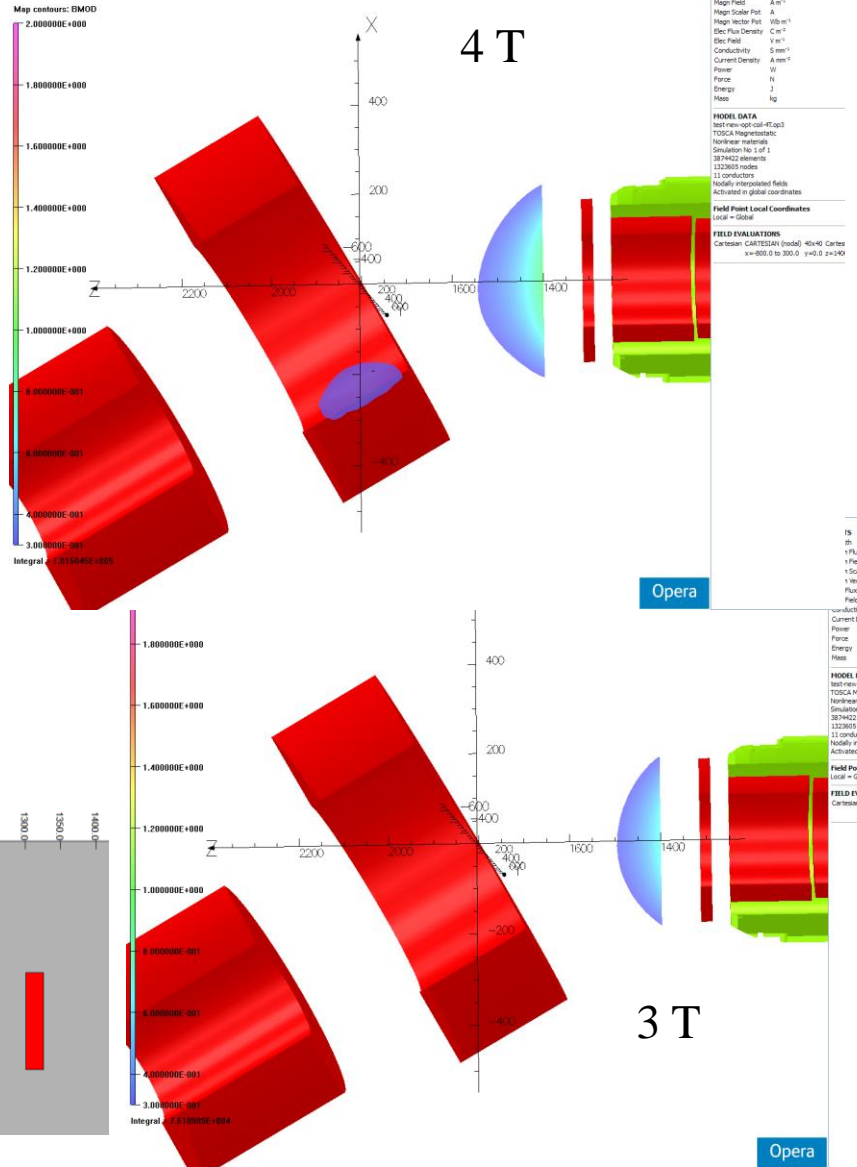
(magnitude of the field at lower main field)

- Obviously there is not enough power in the fringe field coil to generate >0.3 T at lower fields.
- Solution: increase the size
- Also see if we can power the fringe field coil independently while maintaining good field quality

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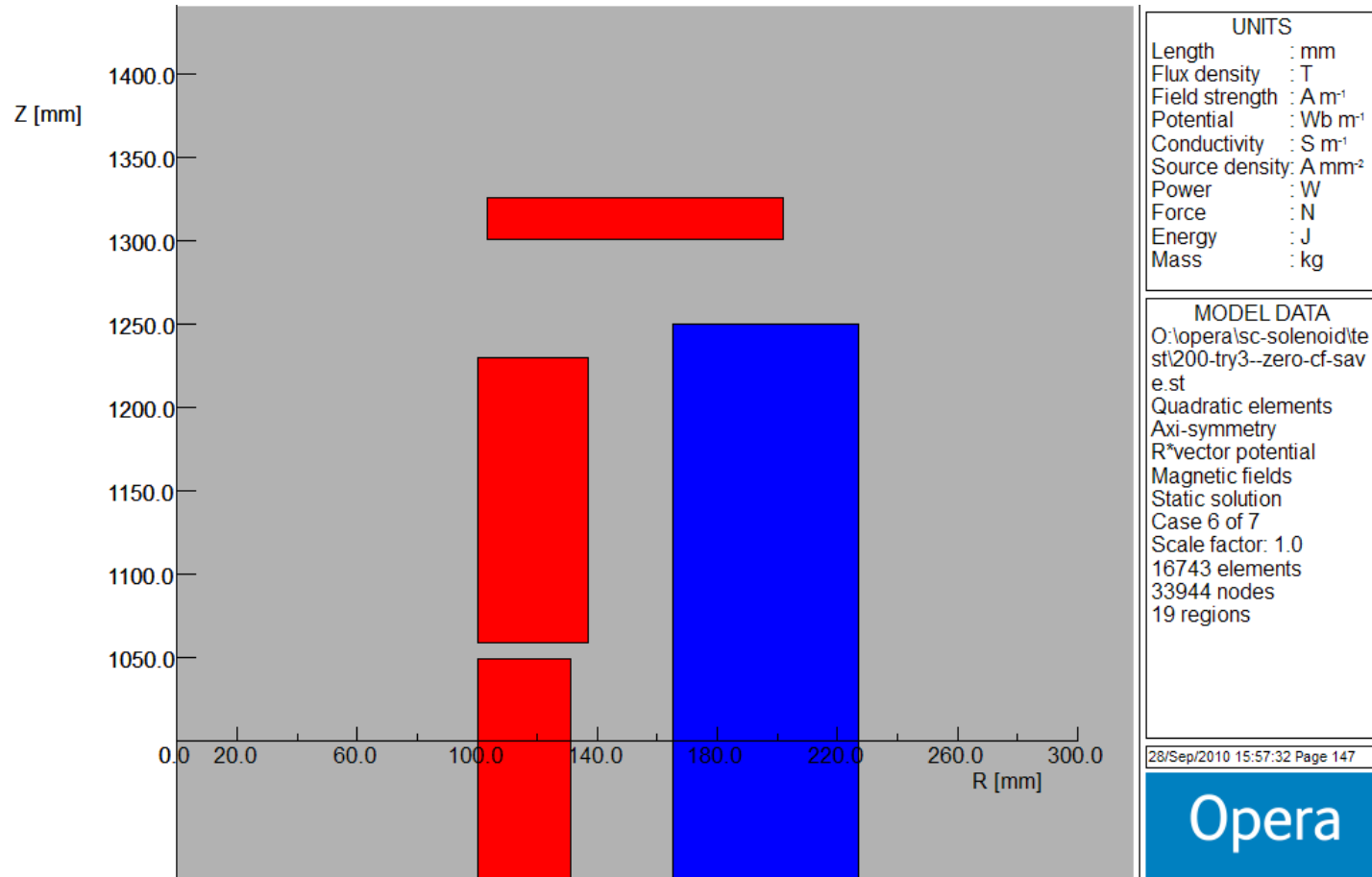
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Proposed Design

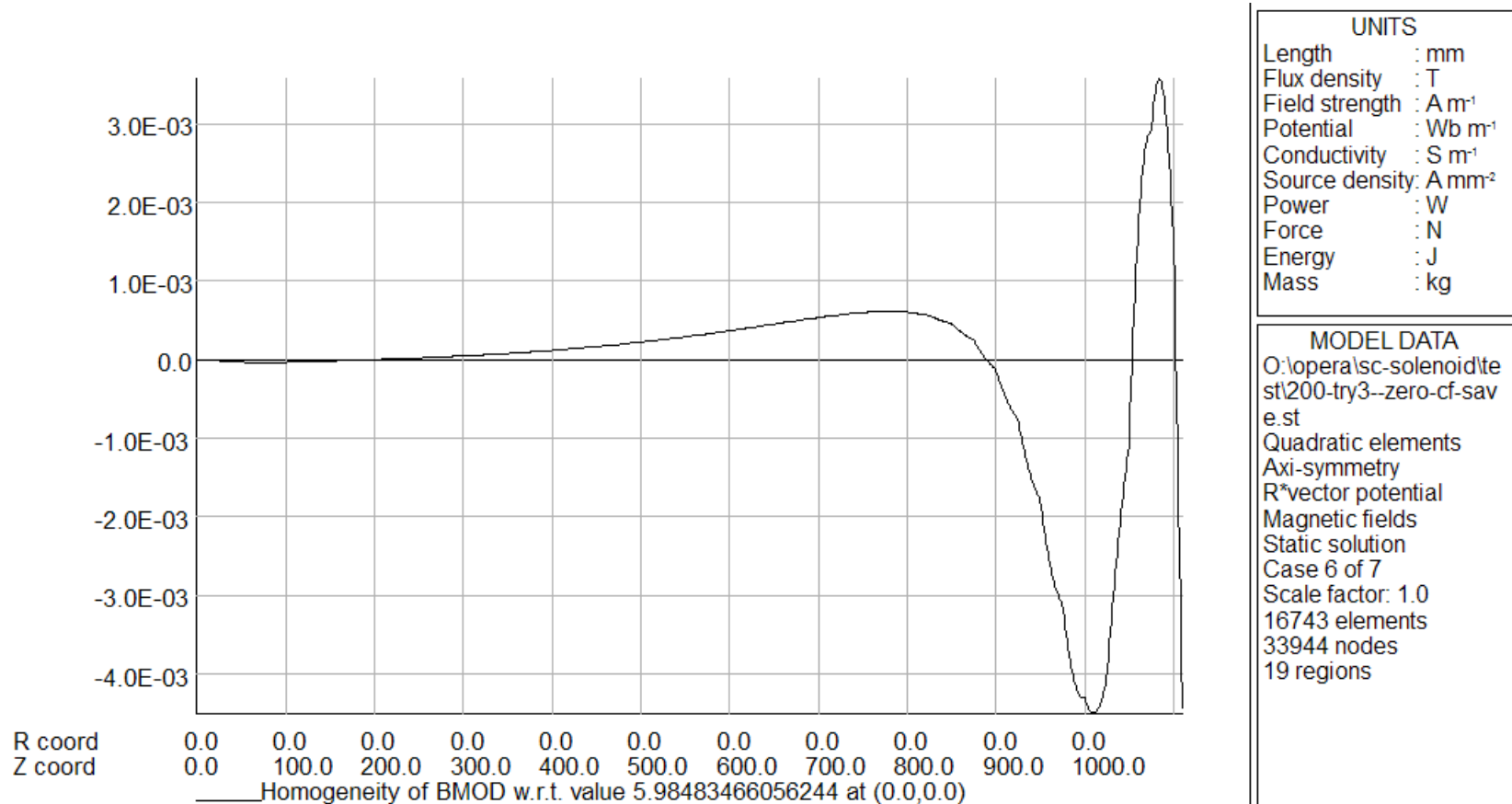
- Power fringe field coil separately from main coil
- Don't scale fringe field coil with the main coil and power the fringe field coil near the design current when main coils are running at lower field
- To obtain good field quality inside the solenoid, insert a correction coil within the tube of the main solenoid.
- Let's see if it works?

Field errors at 6 T with correction coil (correction coil not powered at 6T)



Additional correction coil not powered and not shown above

Field errors at 6 T with correction coil (correction coil not powered at 6T)

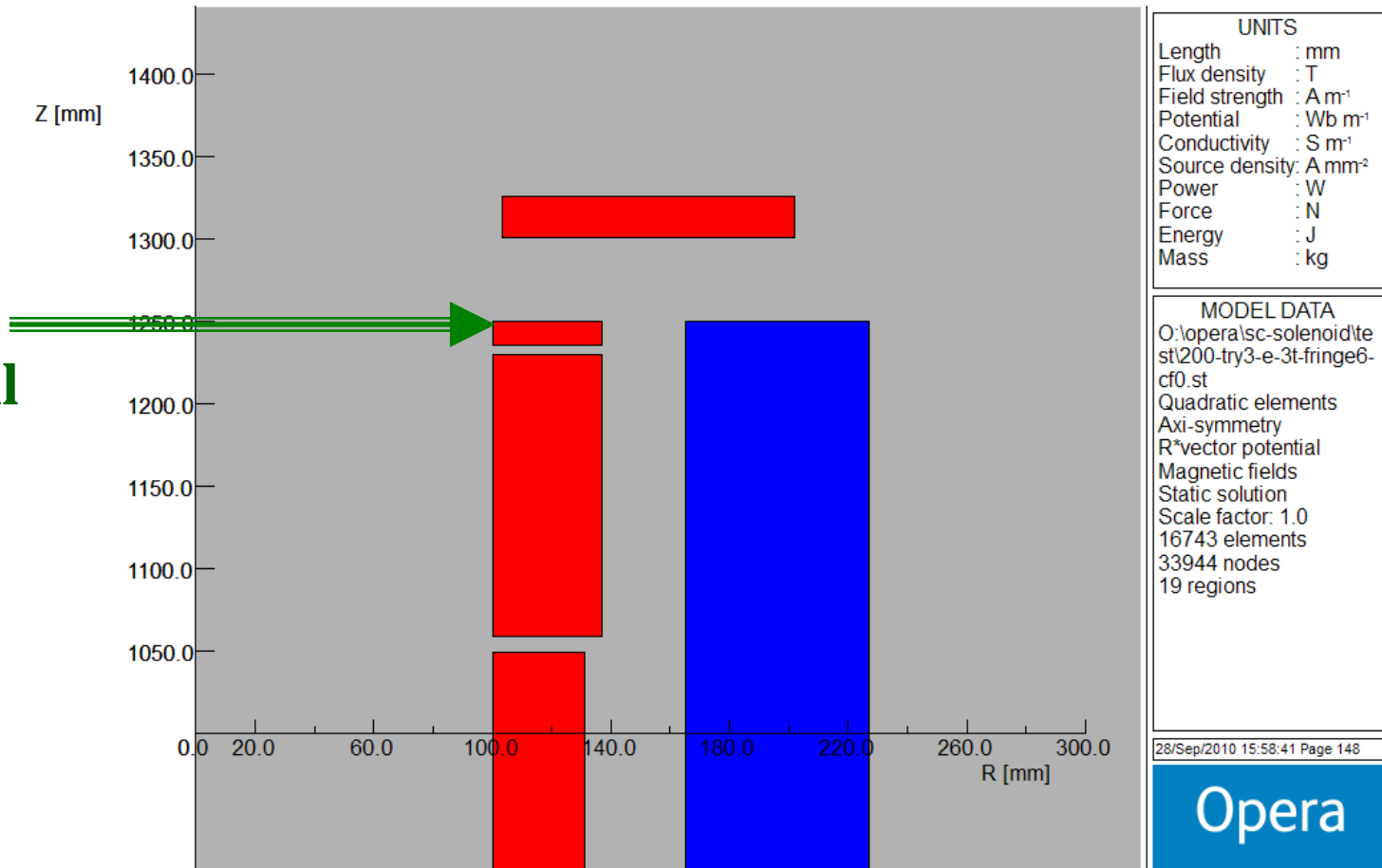


A good field quality is maintained to 1120 mm

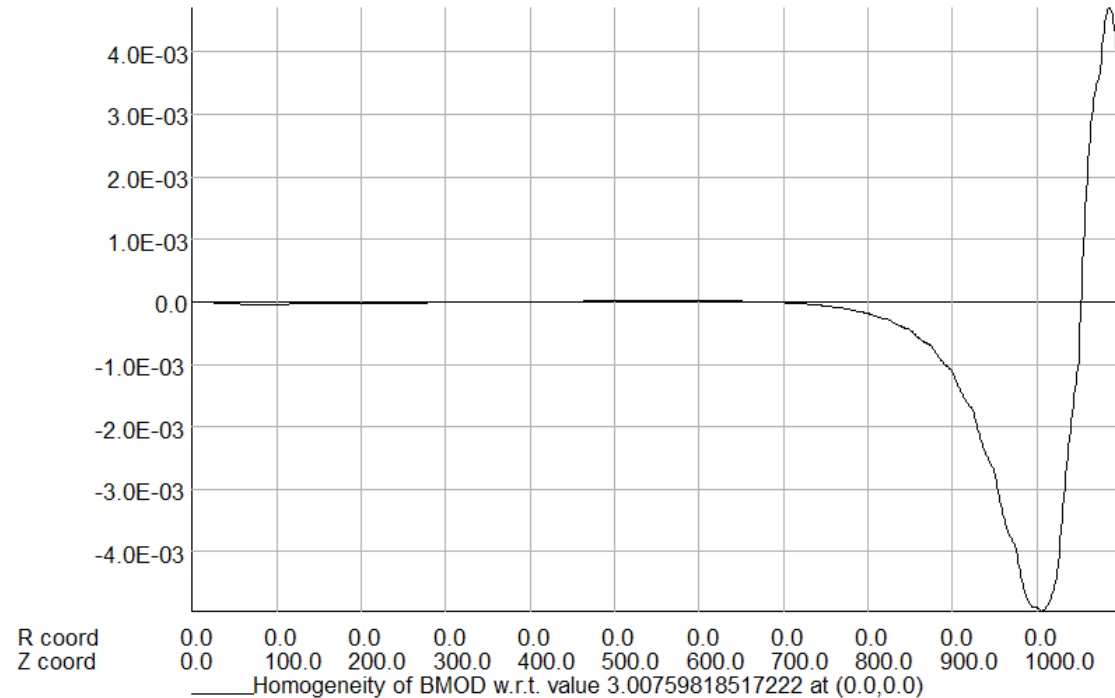
Opera

Design to Reduce Field errors at 3 T with additional correction coil

**Additional
correction coil**



Field errors at 3 T with correction coil



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

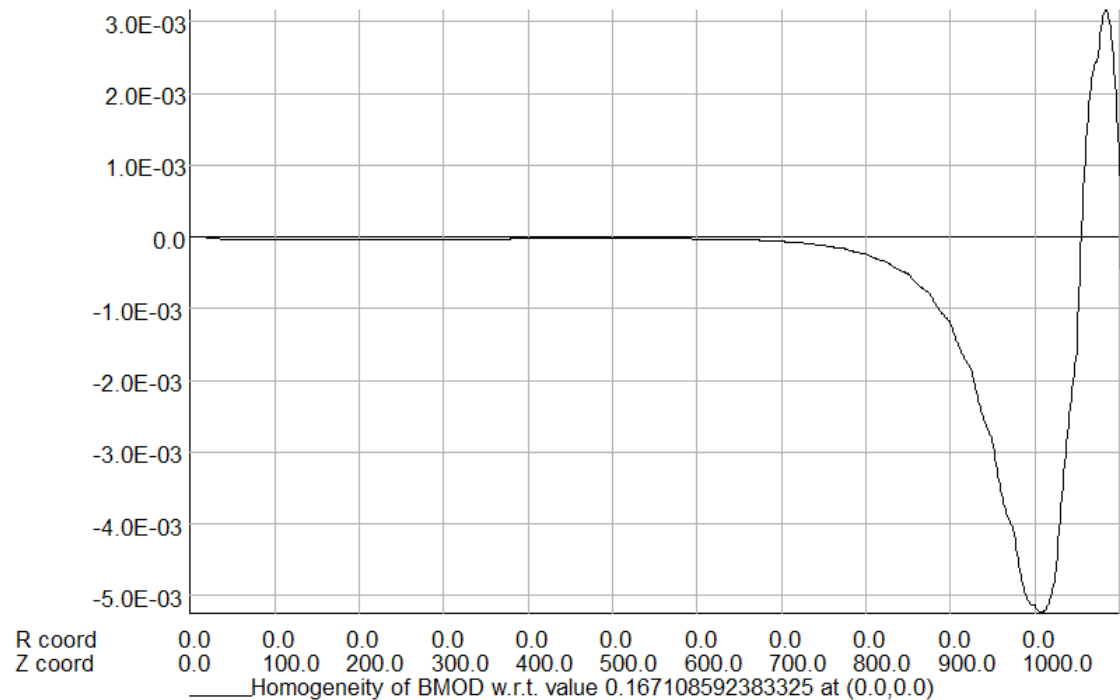
MODEL DATA
O:\opera\sc-solenoid\test200-try3-e-3t-fringe6-cfn115-save.st
Quadratic elements
Axi-symmetry
R*vector potential
Magnetic fields
Static solution
Scale factor: 1.0
16743 elements
33944 nodes
19 regions

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A good field quality is maintained to 1120 mm down to 3 T

Field errors below 1 T with correction coil



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

MODEL DATA
O:\opera\sc-solenoid\te
st200-try3-e-1t-fringe6-
cfn215-save.st
Quadratic elements
Axi-symmetry
R*vector potential
Magnetic fields
Static solution
Case 1 of 4
Scale factor: 0.1666666
16743 elements
33944 nodes
19 regions

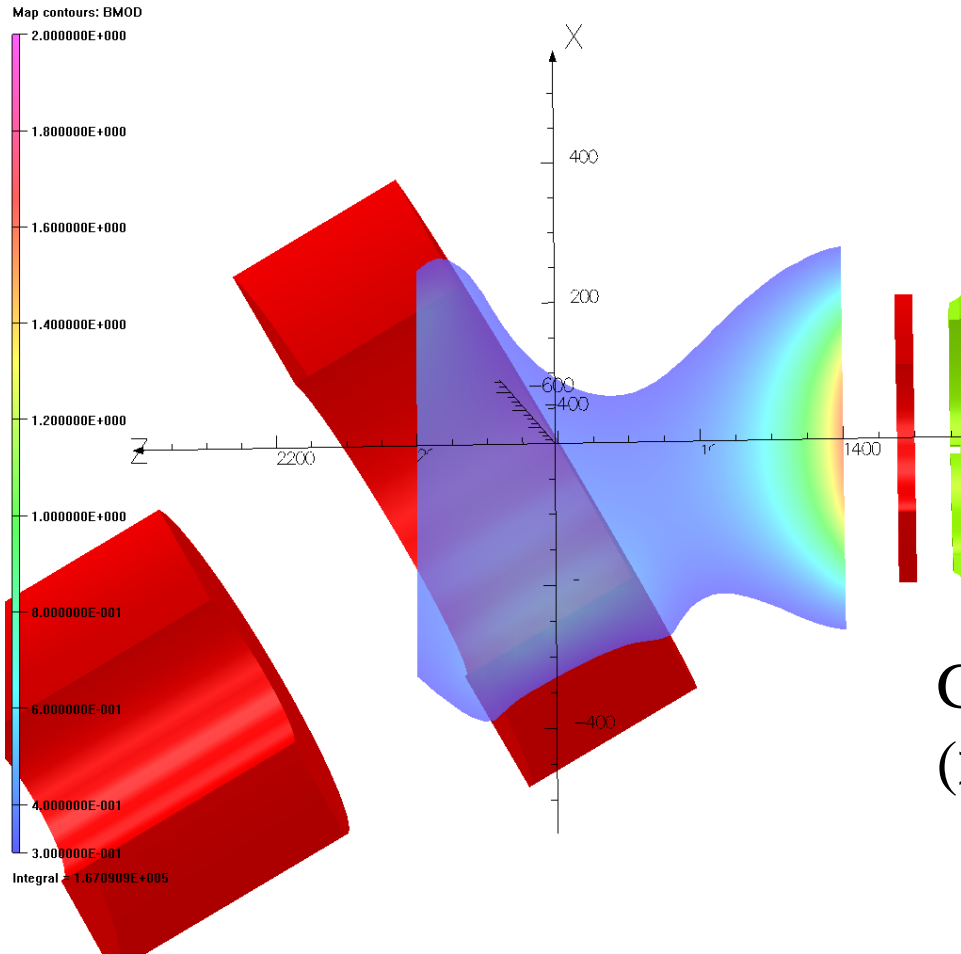
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Opera

A good field quality is maintained to 1110 mm even at very low fields (as low as 0.17 T in case above)

New Design at 6 T

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UNITS	
Length	mm
Magn Flux Density T	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

MODEL DATA	
200-try3-zero-cf-save-6T.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
3874422 elements	
1323605 nodes	
11 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Cartesian CARTESIAN (nodal) 40x40 Cartesian	
x=-800.0 to 300.0 y=0.0 z=1400.0 to 2000.0	

Radial increase in fringe field coil (to r= 202 mm, 25 mm less than the yoke)

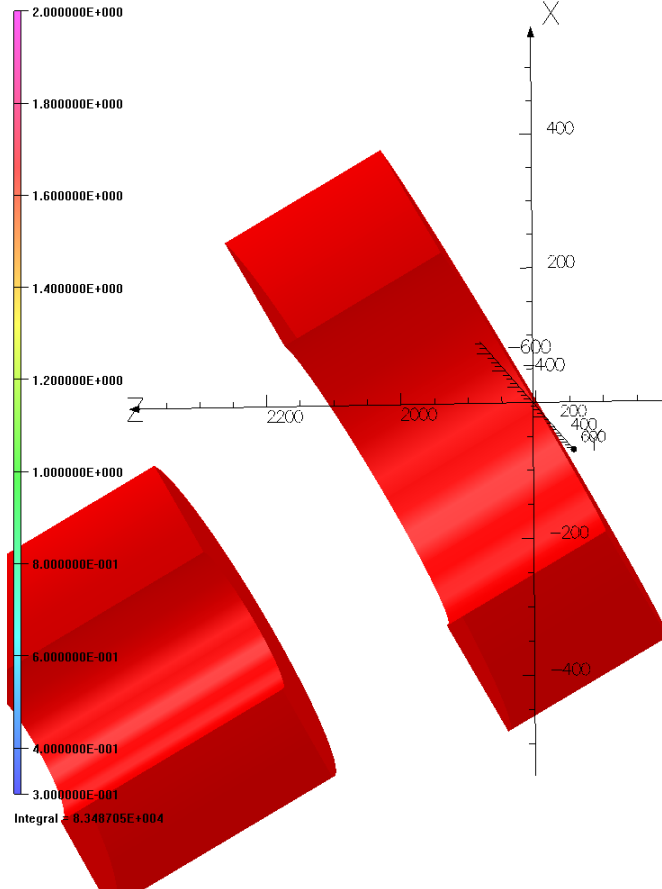
Generate sufficient fringe field (>0.3 T) with main solenoid at 6 T

Opera

New Design at 3 T

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Map contours: BMOD



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

MODEL DATA	
200-try3-zero-cf-save-3T.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
3874422 elements	
1323605 nodes	
11 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

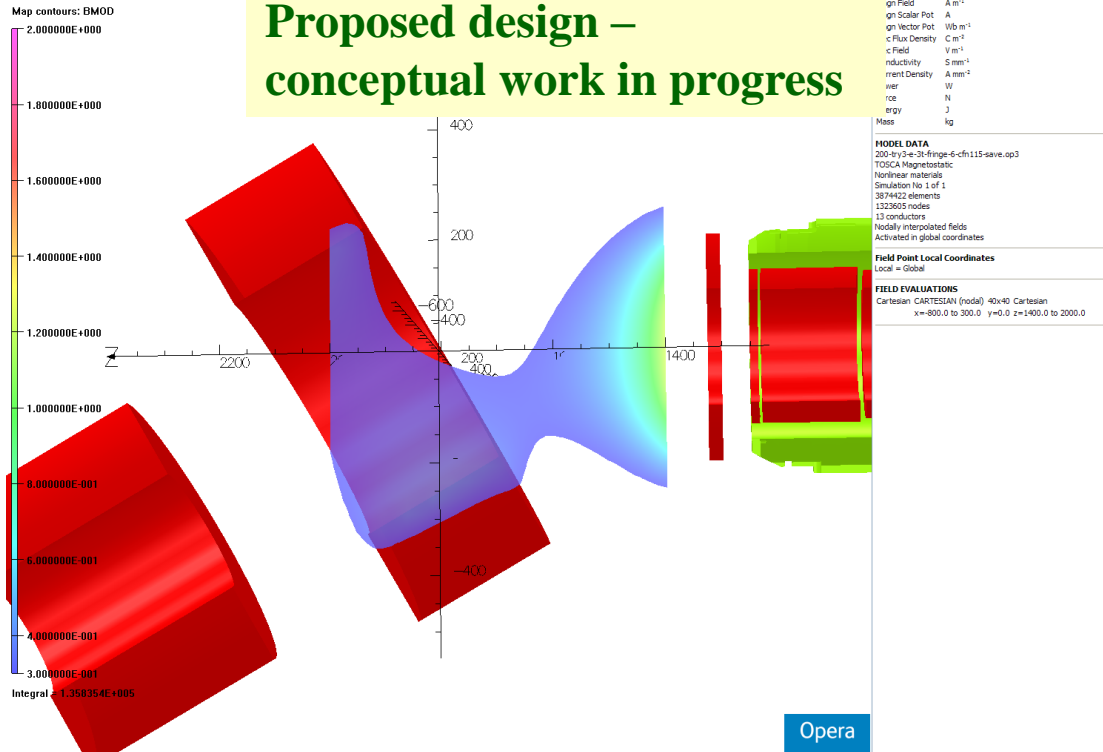
FIELD EVALUATIONS	
Cartesian CARTESIAN (nodal) 40x40 Cartesian	
x=-800.0 to 300.0 y=0.0 z=1400.0 to 2000.0	

However not sufficient fringe field (>0.3 T) with main solenoid at 3 T and fringe field coils running in series (amp-turns scaled down linearly)

•Next: Get extra field from fringe field coil by powering it to full current

New Design at 3 T (with fringe field and trim field coils)

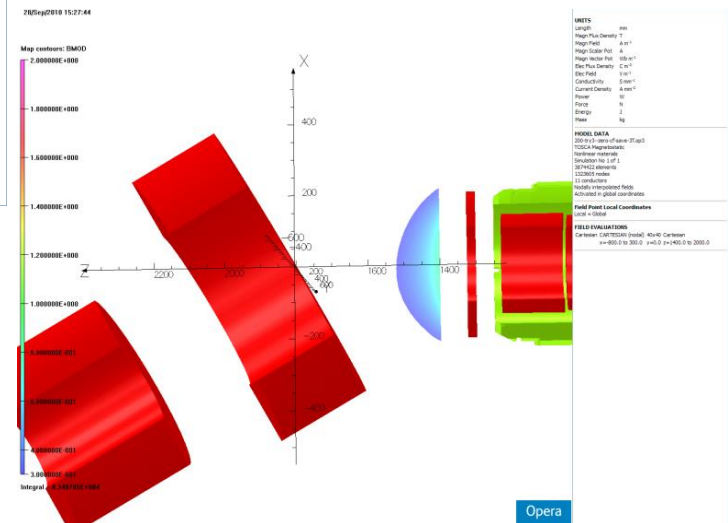
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- Fringe field coils are powered at the limit of current leads (50 A)
- Trim coils near the main coil powered to maintain good field quality.
- Situation is significantly improved but not enough

Solution under consideration:

- Increase the width of fringe field coil
- Obtain extra space by cutting size of the main solenoid as smaller length can still produce good field quality to +/-1050 mm



Summary

- It is possible to maintain good field quality inside the solenoid
 - Relative field errors can be kept at $\sim 5 \times 10^{-3}$ to $> \pm 1050$ mm (even longer length with fringe field coils playing a helping role) at all fields in main solenoid (1T to 6T).
 - This has been already demonstrated in the cases examined.
- With fringe field coil running independently, it should be possible to obtain > 0.3 T in the region between superconducting solenoid and room temperature solenoids provided enough amp-turns are allowed in the fringe field solenoid
 - In this case, additional correction coils running on a separate power supply will be required to maintain good field quality inside the main solenoid.
 - It may be necessary to reduce the length of the main solenoid (estimated by 25 mm on each side) to allow enough space for enough-amp turns in the fringe field coil.
 - Higher amp-turns in fringe field coils are needed when the main solenoid is running at lower field (say 3 T, or even 1T) as the leakage field becomes smaller when the main solenoid and room temperature solenoids are running at lower fields.
- We need to demonstrate that we can maintain both good field quality and required fringe field for 3 T (1T?) to 6T in main solenoid. It appears possible in principle but we need a consistent design meeting all magnetic, mechanical, electrical and cryogenic requirements. We need it soon.