

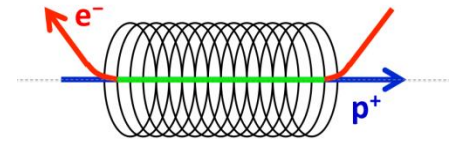
## Electron Lens Superconducting Solenoid

### Magnetic and Overall Design

Ramesh Gupta  
Superconducting Magnet Division

October 20, 2010

# Requirements

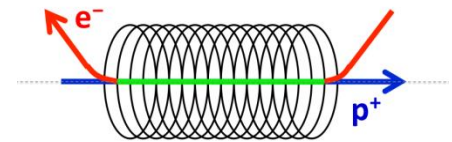


1. Design field : 6 T
  - Specified operating field range 1 T to 6 T
2. Good field ( $\sim 6 \times 10^{-3}$ ) region: 20 mm aperture along  $\sim 2100$  mm
3. Fringe field : significant field required outside along the beam path
  - Unique situation, unique solution
4. **Field straightness:  $\pm 100$  micron ( $\pm 50 \mu\text{m}$  desired) in  $\sim 2100$  mm**

**Field straightness** is the most critical and demanding requirement

- guides and determines the overall design
  - too risky for industry to take this job
- well beyond the normal construction errors
  - corrector magnets become integral part of the overall design
- must have enough magnetic shielding to limit the influence of surrounding

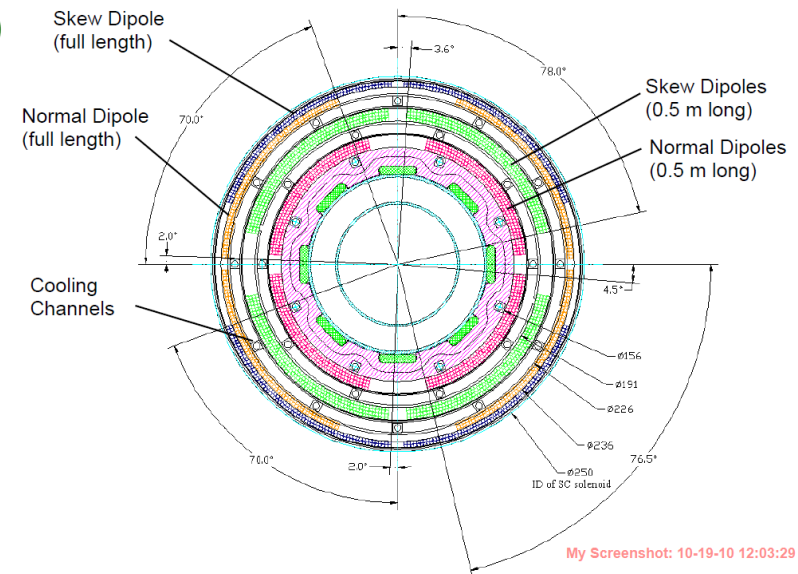
# Superconducting Solenoid with Superconducting Correctors



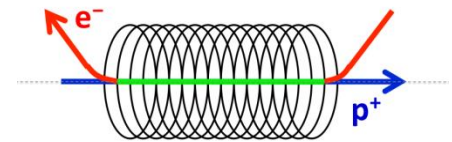
- Axial field straightness is achieved by compensating transverse field errors with horizontal and vertical dipole correctors.
- Corrector dipoles that were previously “inside” the solenoid and to be made of high current density copper coils are now moved “outside” and made superconducting.
- This reduces the solenoid aperture and increases the possible corrector strength.
- The current design consists of a number of superconducting corrector dipoles located outside the superconducting solenoidal coil but within the same yoke iron.
- Significant reduction in size (292mm to 200mm) reduces the stored energy, Lorentz forces and thus makes the solenoid a bit itself less risky.

Earlier design with warm corrector

Correctors shown here were placed inside the superconducting solenoid

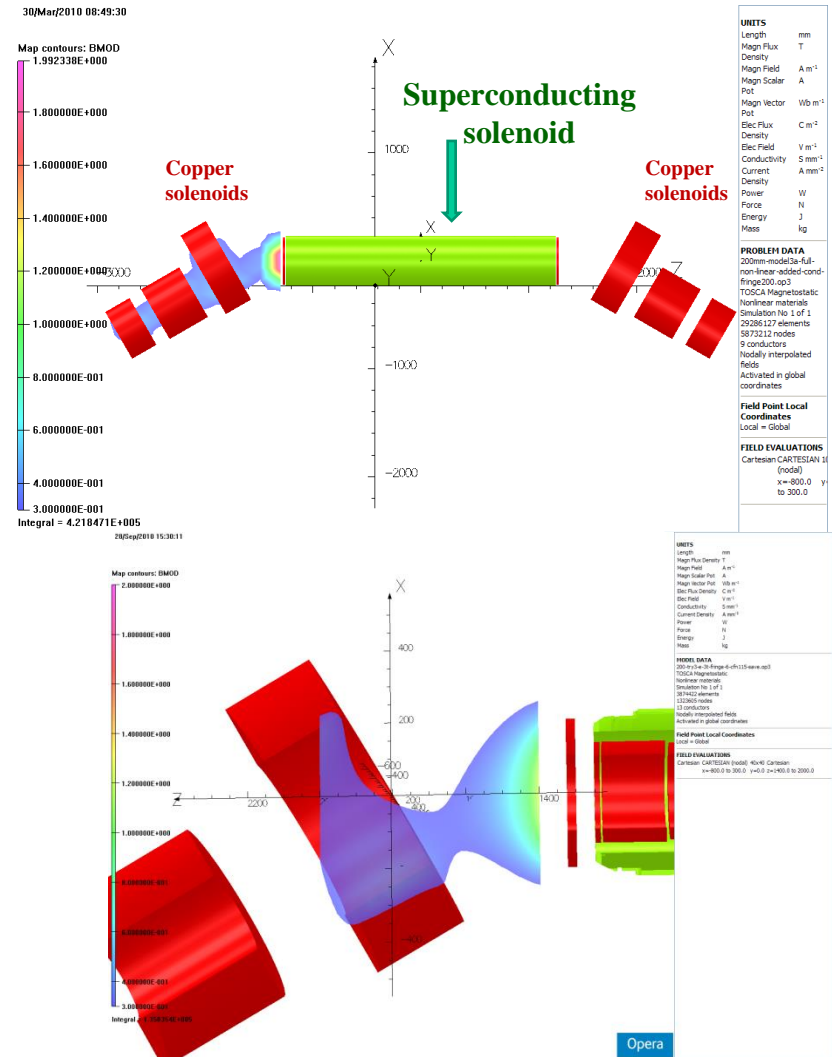


# Overall Magnetic System Design



## Overall magnetic system consists of:

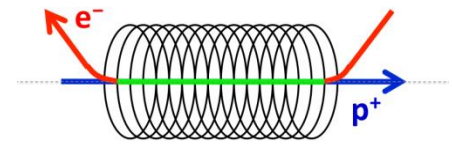
- Main solenoid
  - including end sections
- Correction coils
  - long and short
  - horizontal and vertical
- Fringe field coils
- Anti-fringe field coils
- Room temperature magnets



# Superconducting Solenoid System

## Cost and Schedule Consideration

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Additional important consideration in designing the system:  
use existing components to reduce cost (and schedule)

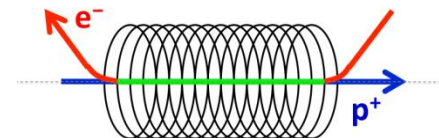
Opportunity for cost saving come from the use of existing:

- ❖ stainless steel shell
- ❖ RHIC cryostat
- ❖ tooling

This made the design a bit more restrictive.

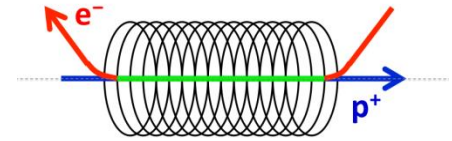
- However, we were able to use all of above without compromising the performance.

# Main Parameter List



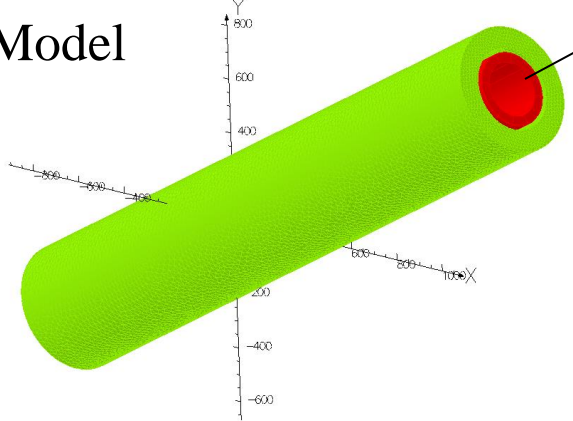
Coil i.d.	200 mm
Coil length (main)	2360 mm
Yoke length	2450 mm
Wire, bare	1.78 mm X 1.14 mm (70 mil X 45 mil)
Wire, insulated	1.91 mm X 1.27 mm (75 mil X 50 mil)
Wire $I_c$ specification (4.2 K, 7 T)	>700 A
Turn-to-turn spacing (axial, radial)	2.03 mm X 1.42 mm (80 mil X 56 mil)
Number of layers (main, full length)	22 (11 double layers)
Additional layers for trimming end fields (in series)	4 (2 double layer)
Length of layers for trimming end fields	173 mm on each end
Coil o.d. (without trim)	262.6 mm
Coil o.d. (with trim)	274 mm
Coil o.d. with trim coil and over-wrap	277 mm
<b>Maximum design field</b>	<b>6 T</b>
Current for 6 T	~460 A
<b>Peak Field on the conductor @ 6T</b>	<b>~6.5 T (~8% peak field enhancement)</b>
<b>Computed Short Sample @4.2 K</b>	<b>~7.0 T (6.6 T, specified)</b>
Stored energy @ 6 T	~1.4 MJ
Inductance	~14 Henry
Yoke i.d.	330 mm
Yoke o.d.	454 mm
Yoke width (radial)	62 mm
<b>Field on the axis</b>	<b>1 to 6 T</b>
Maximum computed error on axis	~6 X 10 <sup>-3</sup> (-1050 to 1050 mm and within 20 mm )

# Computer Models



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## 3d Model



UNITS	
Length	mm
Magn Flux	T
Density	A
Magn Field	A m <sup>-1</sup>
Magn Scalar	A
Pot	Vb m <sup>-1</sup>
Magn Vector	Vb m <sup>-1</sup>
Pot	C m <sup>2</sup>
Elec Flux	C m <sup>2</sup>
Density	V m <sup>-1</sup>
Elec Field	S mm <sup>-1</sup>
Conductivity	A mm <sup>-1</sup>
Current	W
Density	N
Power	J
Force	kg
Energy	
Mass	

PROBLEM DATA	
200mm-model3a-full-non-linear-op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
9852868 elements	
238054 nodes	
2 conductors	
Nodally interpolated fields	
Activated in global coordinates	

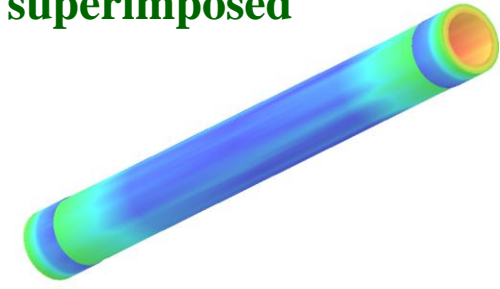
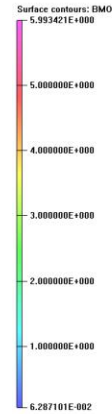
  

Field Point Local Coordinates	
Local = Global	

z-axis

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## Coil with field superimposed



UNITS	
Length	mm
Magn Flux	T
Density	A m <sup>-1</sup>
Magn Field	A m <sup>-1</sup>
Magn Scalar	A
Pot	Vb m <sup>-1</sup>
Magn Vector	Vb m <sup>-1</sup>
Pot	C m <sup>2</sup>
Elec Flux	C m <sup>2</sup>
Density	V m <sup>-1</sup>
Elec Field	S mm <sup>-1</sup>
Conductivity	A mm <sup>-1</sup>
Current	W
Density	N
Power	J
Force	kg
Energy	
Mass	

PROBLEM DATA	
200mm-model3a-full-non-linear-op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
9852868 elements	
238054 nodes	
2 conductors	
Nodally interpolated fields	
Activated in global coordinates	

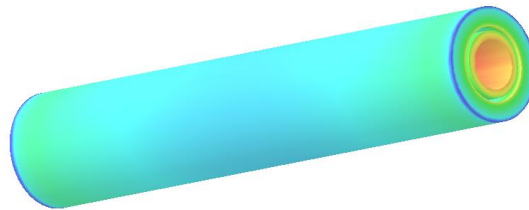
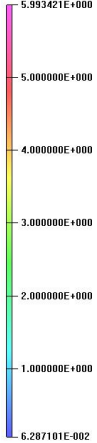
  

Field Point Local Coordinates	
Local = Global	

Opera

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Surface contours: BMOD



## Field on iron and coil

UNITS	
Length	mm
Magn Flux	T
Density	A
Magn Field	A m <sup>-1</sup>
Magn Scalar	A
Pot	Vb m <sup>-1</sup>
Magn Vector	Vb m <sup>-1</sup>
Pot	C m <sup>2</sup>
Elec Flux	C m <sup>2</sup>
Density	V m <sup>-1</sup>
Elec Field	S mm <sup>-1</sup>
Conductivity	A mm <sup>-1</sup>
Current	W
Density	N
Power	J
Force	kg
Energy	
Mass	

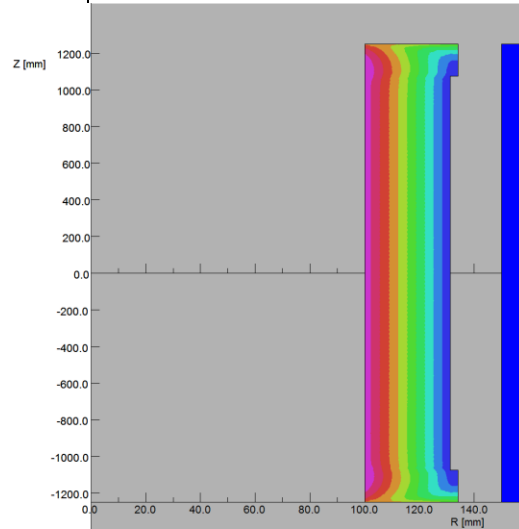
PROBLEM DATA	
200mm-model3a-full-non-linear-op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
9852868 elements	
238054 nodes	
2 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

Opera

z-axis



Component: BMOD  
0.051869963 3.102383108 6.152896252

UNITS	
Length	mm
Flux density	T
Field strength	A m <sup>-1</sup>
Potential	Vb m <sup>-1</sup>
Conductivity	S m <sup>-1</sup>
Source density	A mm <sup>-1</sup>
Power	W
Force	N
Energy	J
Mass	kg

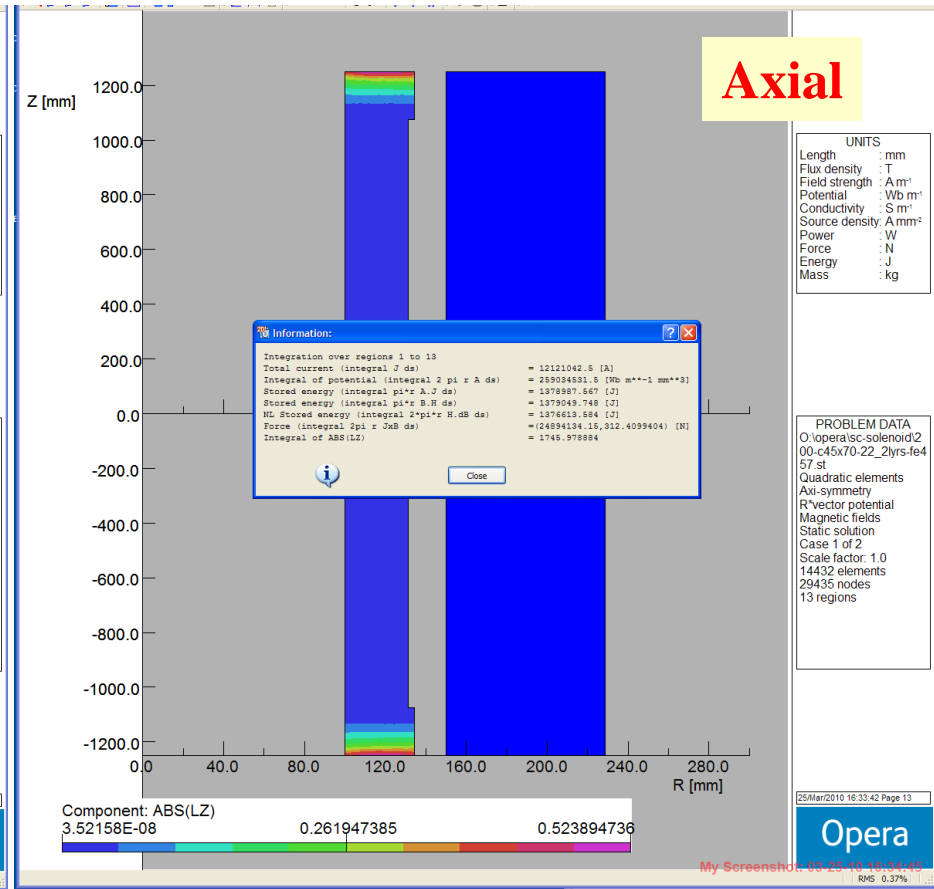
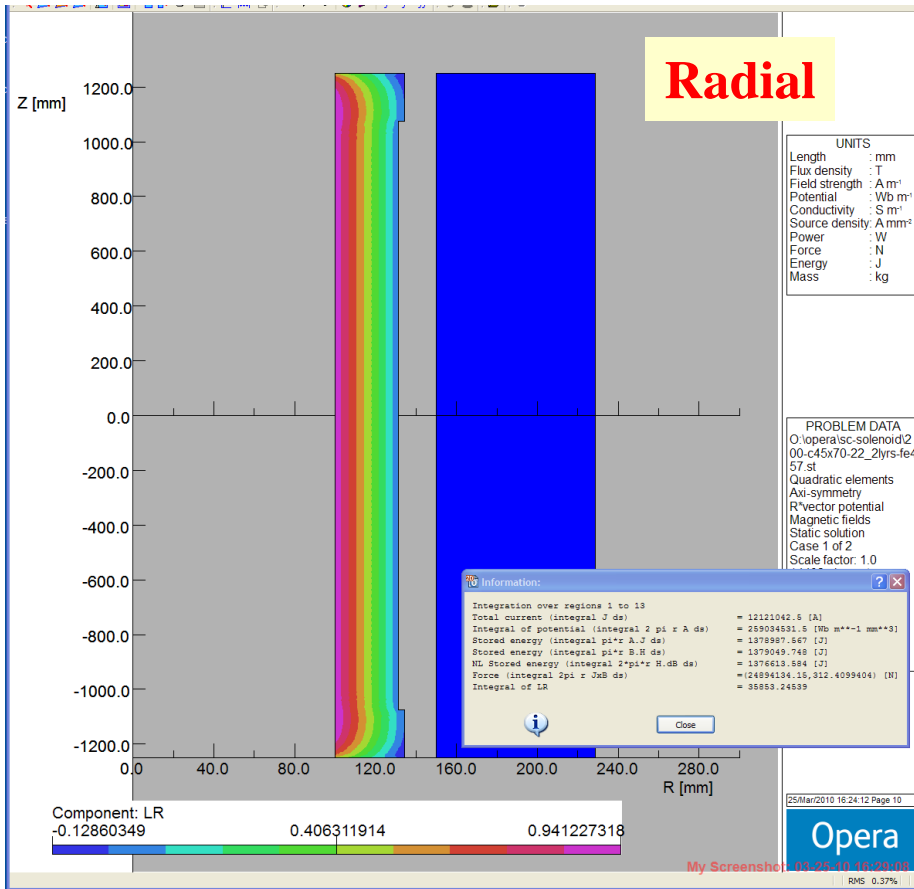
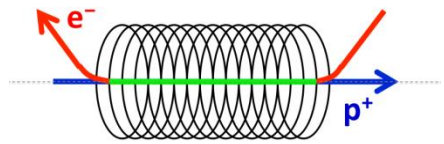
PROBLEM DATA	
0) geometric-elements2	
03-c45x70-22_2lrys-564	
57.8	
Quadratic elements	
Axis-symmetry	
V vector potential	
Magnetic fields	
Static isolation	
Case 1 of 2	
Scale factor: 1.0	
14432 elements	
29435 nodes	
13 regions	

Opera

## 2d Model

(more accurate and faster calculations in many cases)

# Lorentz Forces (simple design) Contour Plot of Force Density

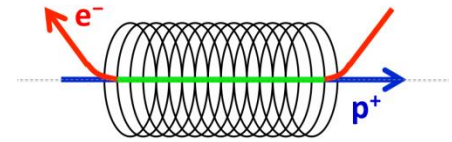


**Radial Lorentz force (hoop stress) : ~24 MN**  
- see A. Marone's presentation

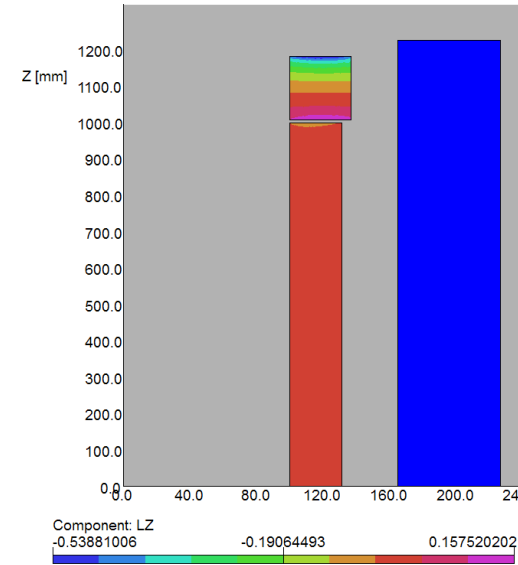
**Axial force: ~35 kN per side**  
- large axial forces, only in the ends



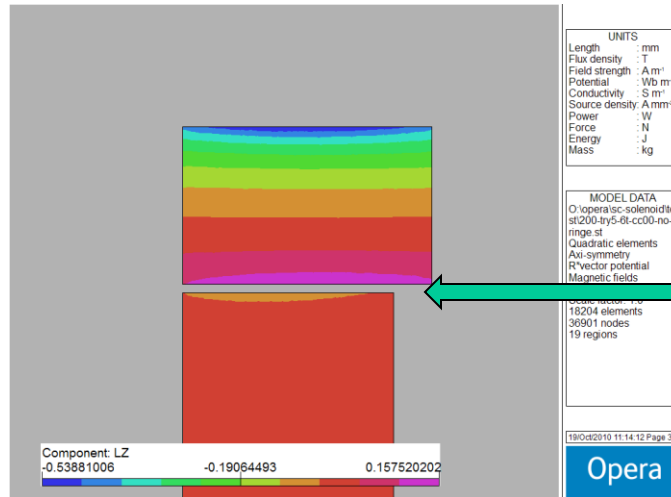
# Axial force containment



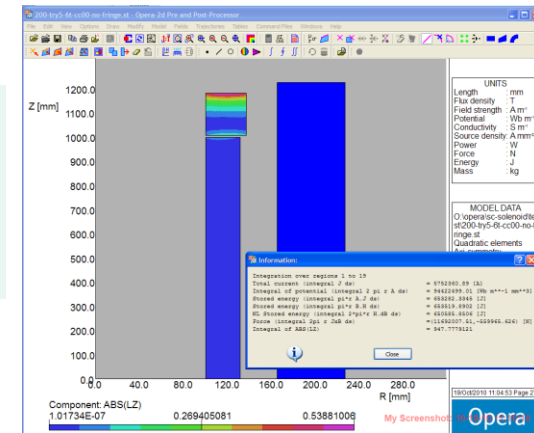
- Insert structure towards the end of the coil to contain forces
- Coil is wound continuously through the end structure to keep axial forces contained throughout (during quench).
- If the coils were separate and one in the end quenches then the end forces will no longer be balanced (not acceptable).
- Quench protection is such that the full length double layers are quenched



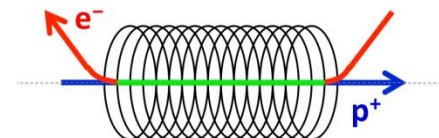
Stored Energy:  
~1.4 MJ;  
Inductance :  
~14 Henry



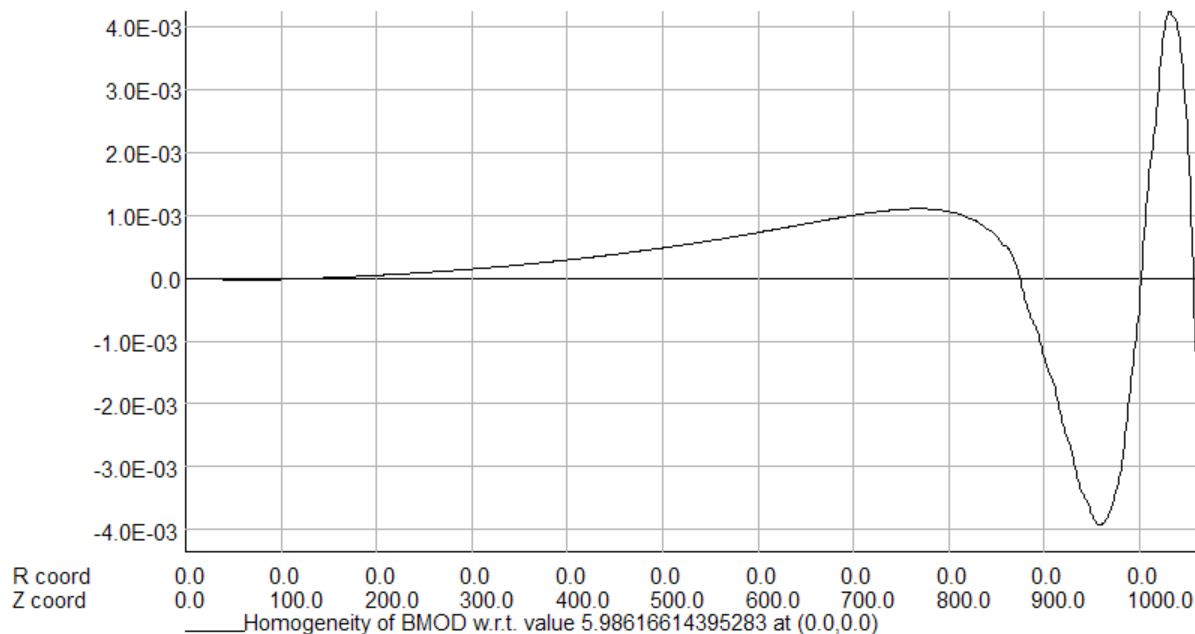
Structure  
for  
containing  
large axial  
force



# Relative Field Errors on the Axis



Relative field errors (computed) to 1075 mm  $< 5 \times 10^{-3}$



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

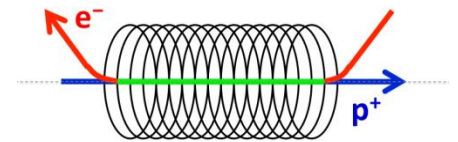
MODEL DATA	
O:\opera\sc-solenoid\test\20	
0-try5-6t-cc00.st	
Quadratic elements	
Axi-symmetry	
R*vector potential	
Magnetic fields	
Static solution	
Scale factor: 1.0	
18204 elements	
36901 nodes	
19 regions	

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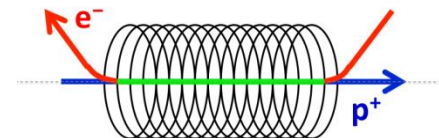
Initial specifications were for 1050 mm  $< 5 \times 10^{-3}$

However, the primary goal is to keep field straight rather than uniform.



# Corrector Design Considerations

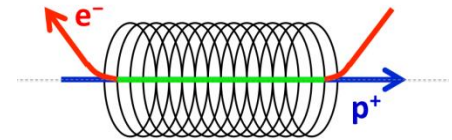
# Design Considerations for correctors (1)



- For cooling to work well, proton and electron beams must be aligned within  $\pm 100$  micron ( $\pm 50$  micron desired).
- Proton beam is aligned to the solenoid axis with long correctors (entire length).
- Electron field follows the solenoid magnetic axis. However, the tube on which the solenoid is wound can't be perfect and the coil winding can't be perfect either. Moreover, the weight of the coil will also cause some sag.
- One must also deal with the field from the material in surrounding.
- Therefore, many short correctors are needed to achieve the desired straightness magnetically.
- The number and strength of short correctors is chosen based on estimated errors (a reasonable cost to risk ratio).

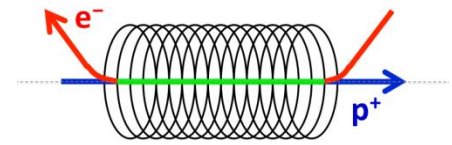
## Design Considerations for correctors (2)

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- Need both long and short correctors
- Need both horizontal and vertical correctors
- Short correctors must create a dipole field of 0.02 T and long correctors 0.006 T (estimated by A. Jain)
- Should have a minimum layers to minimize schedule and cost
- Slotted design to minimize schedule conflict with other projects
- Should have low operating current to minimize heat load

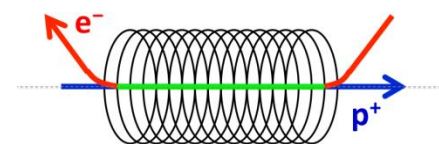
# Estimating Axis Correction (without a Corrector Design!)



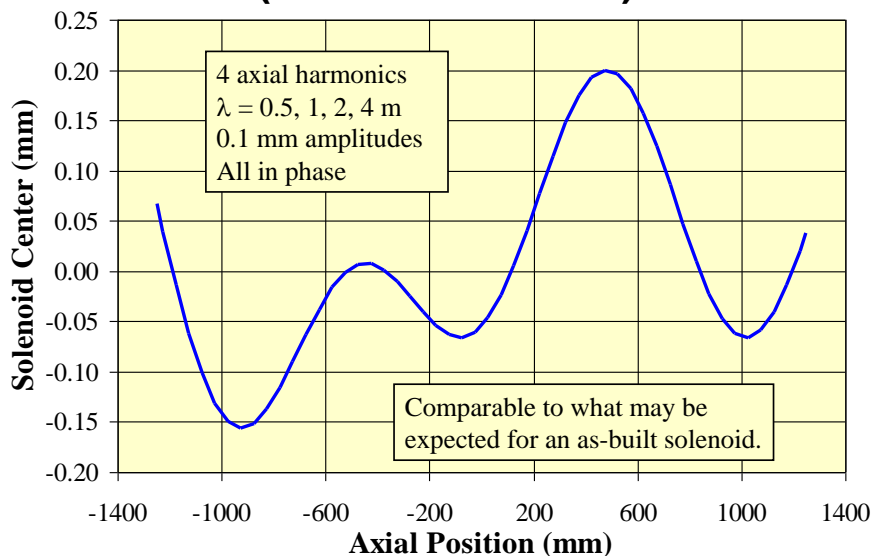
- Generate a hypothetical axial profile of vertical offset of solenoid axis:
  - 4 axial harmonics of wavelengths 0.5, 1.0, 2.0, and 4.0 meters
  - 0.100 mm amplitude for all modes; all modes add in phase.
- Break up solenoid into 50mm long segments, with each segment offset and tilted as per the profile generated.
- Compute the vertical field ( $B_y$ ) profile on-axis.
- Decompose  $B_y$  profile into spatial harmonics (40 terms).
- Assume  $\sim N/2$  strongest modes can be zeroed using  $N$  correctors.  
*(Only an approximation! Ideally, the resulting axis offsets should be minimized using real corrector transfer functions.)*
- Compute the residual  $B_y$  profile on-axis.
- Compute the residual axis offset profile.

Courtesy: Animesh Jain

# Estimation and correction of axis offset with 0.02 T correctors



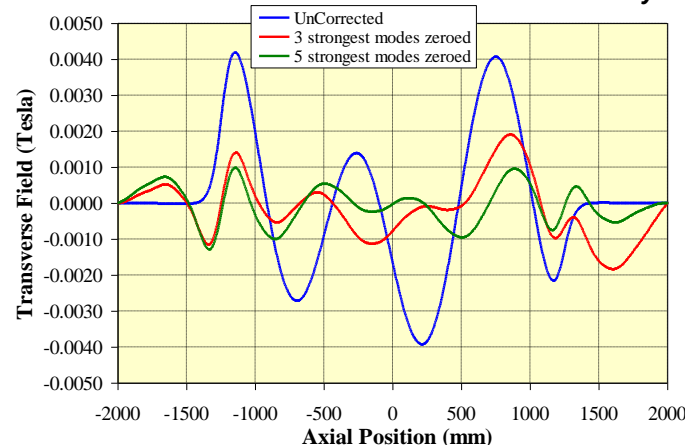
## Hypothetical Vertical Offset Profile (before correction)



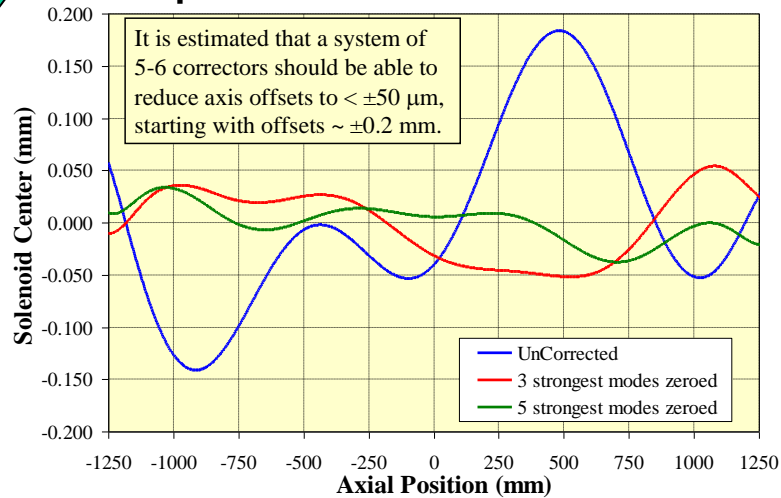
Courtesy: Animesh Jain

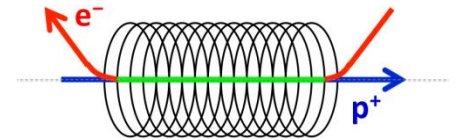
After correction

## Computed Profile of Vertical Field, $B_y$



## Computed Axis Offset Profile



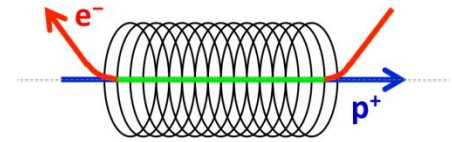


# Corrector Design

## Magnetic

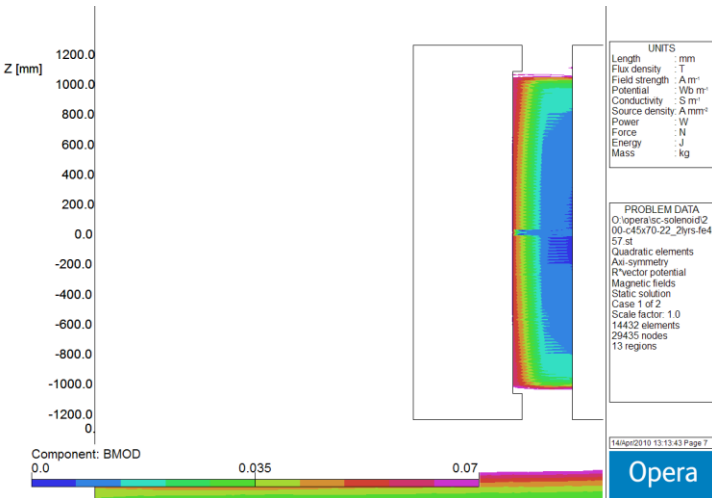
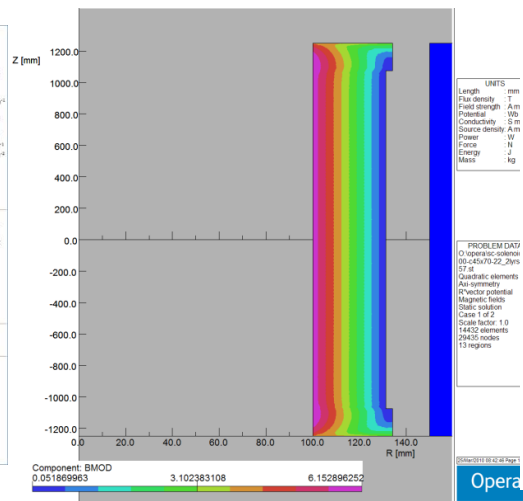
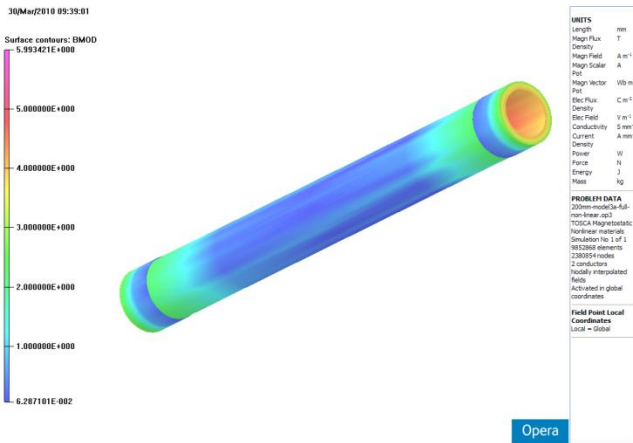
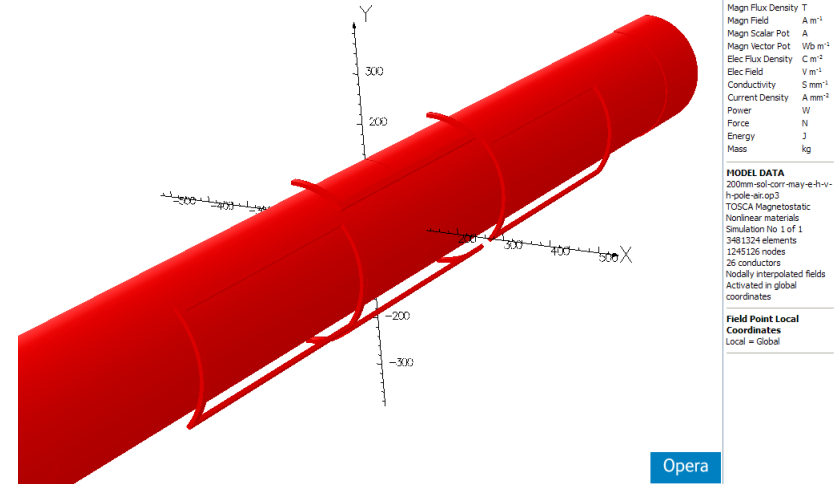


# Field on the Corrector

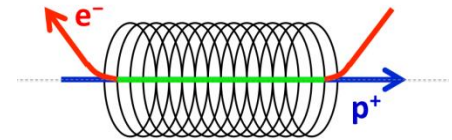


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- Correctors will be placed outside the solenoid
- They reside in a low field region (<1% of 6T)
- This helps significantly because:
  - Large margin for the same wire
  - Low Lorentz forces on the conductor

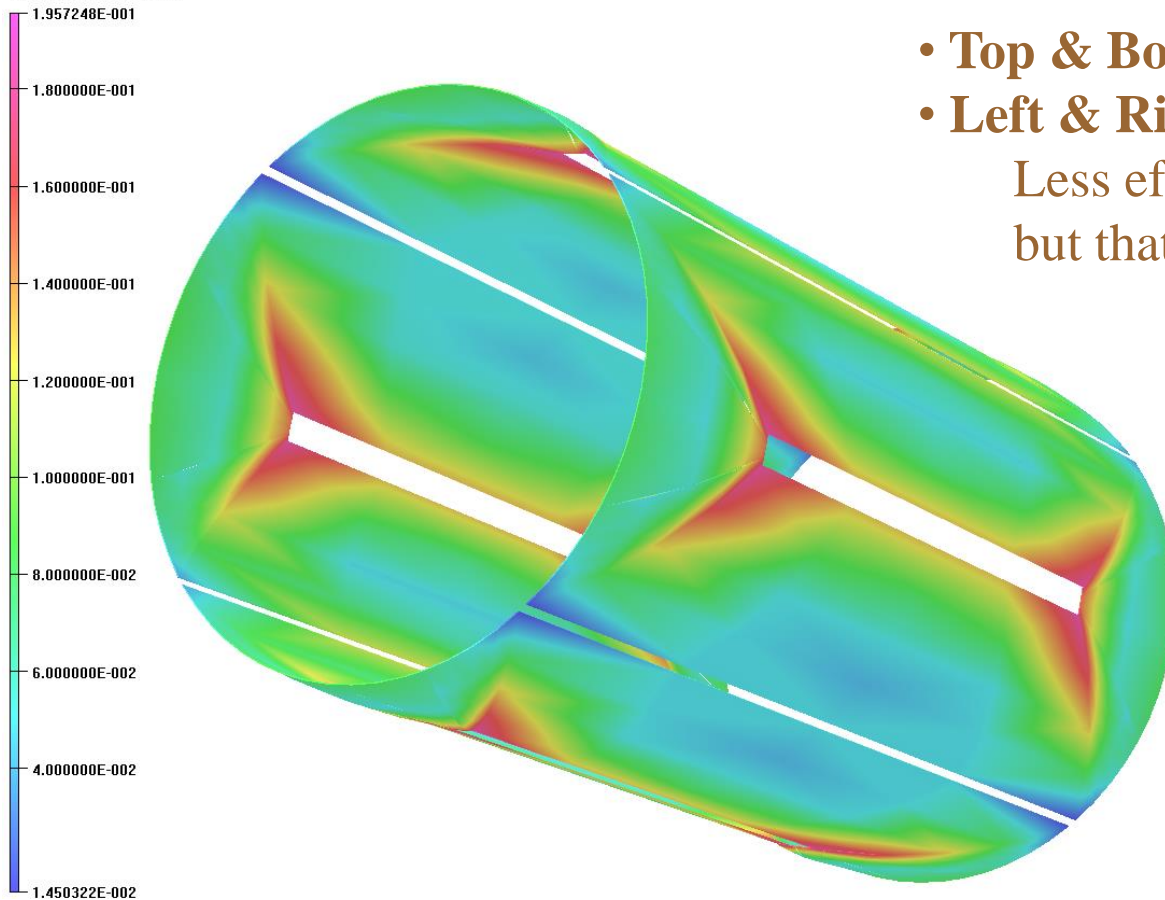


# Combined Corrector Design



Both horizontal and vertical dipole correctors are accommodated in a single layer

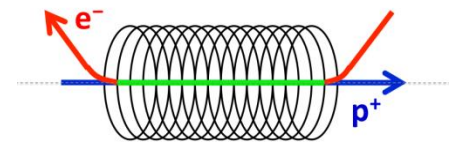
Surface contours: BMOD



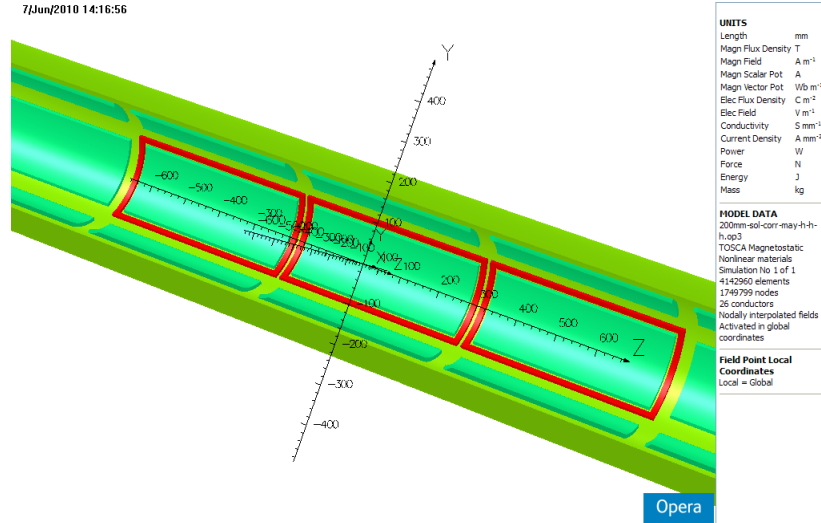
- Top & Bottom Windings for Vertical
  - Left & Right Windings for Horizontal
- Less efficient in terms of conductor use, but that is not a consideration here

- Significantly cuts down on the construction time and cost
- More optimization in geometry and construction (next slides)

# Slotted Corrector Design

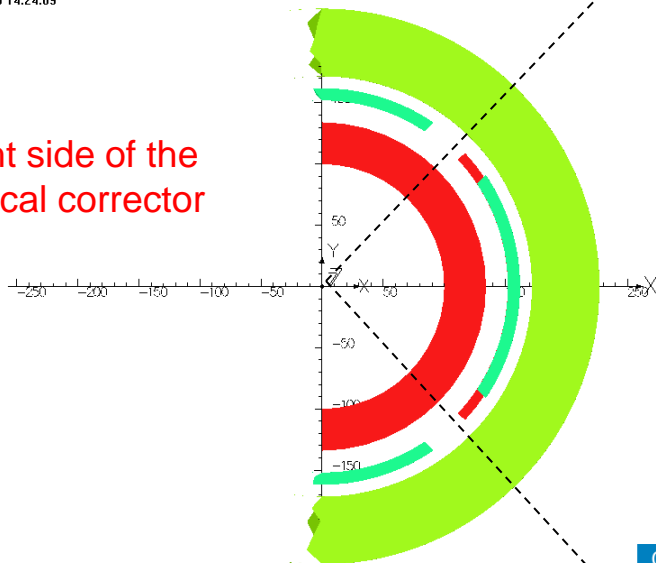


- Slot is machined in an aluminum tube (similar to that done in RHIC and AGS helical magnets).
- Superconducting corrector wires are placed in the slot (details in other presentations).
- Horizontal and vertical correctors are placed in the same radial location (saves on cost and on the radial space)



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Right side of the vertical corrector



+45 degree

UNITS	
Length	mm
Magn Flux Density T	A m <sup>-1</sup>
Magn Field	A m <sup>-1</sup>
Magn Scalar Pot	A
Magn Vector Pot	Vb m <sup>-1</sup>
Elec Flux Density	C m <sup>-2</sup>
Elec Field	V m <sup>-1</sup>
Conductivity	S mm <sup>-1</sup>
Current Density	A mm <sup>-2</sup>
Power	W
Force	N
Energy	J
Mass	kg

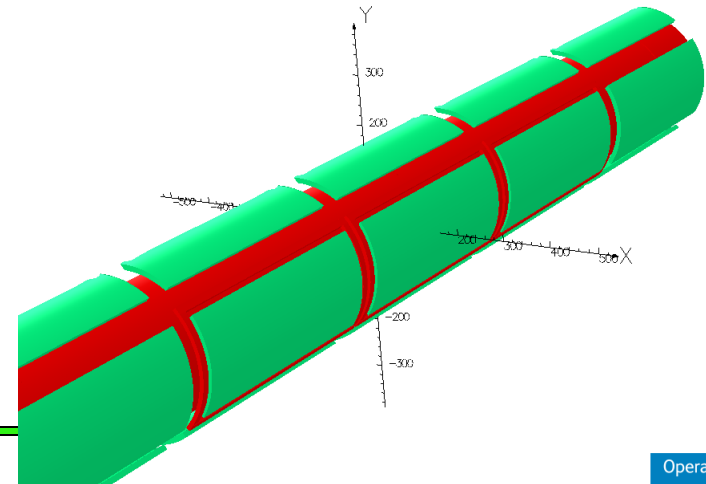
MODEL DATA	
200mm-sol-corr-may-h-h-op3	
TOSCA Magnetostatic	
Nonlinear materials:	
Simulation No. 1 of 1	
4142960 elements	
1749799 nodes	
26 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line	LINE 1001
Cartesi	an
(nodal	)
x=0.0	y=0.0
z=-10	00.0
to	1000.0

Opera

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UNITS	
Length	mm
Magn Flux Density T	A m <sup>-1</sup>
Magn Field	A m <sup>-1</sup>
Magn Scalar Pot	A
Magn Vector Pot	Vb m <sup>-1</sup>
Elec Flux Density	C m <sup>-2</sup>
Elec Field	V m <sup>-1</sup>
Conductivity	S mm <sup>-1</sup>
Current Density	A mm <sup>-2</sup>
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
200mm-sol-corr-may-h-h-op3	
TOSCA Magnetostatic	
Nonlinear materials:	
Simulation No. 1 of 1	
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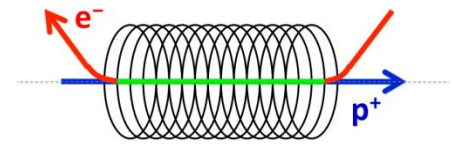
Field Point Local Coordinates	
Local = Global	

Opera



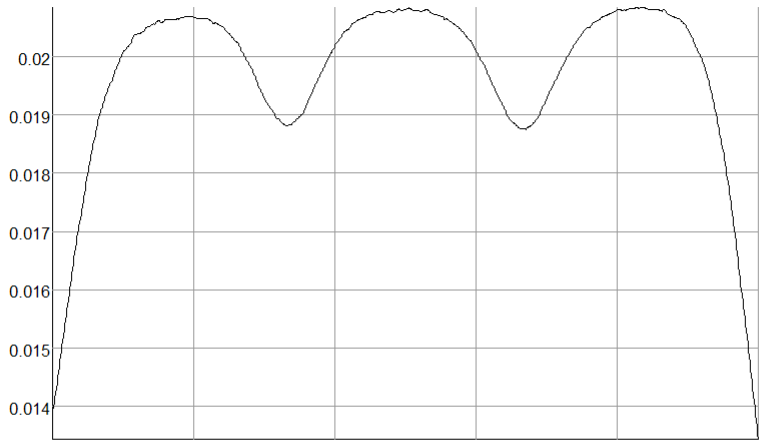
# Fields of Many Short Correctors

## Three Vertical correctors



- Seems to work OK
- Maximum ~10% drop between two corrector from a flat (peak) field

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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 -750.0 -450.0 -150.0 150.0 450.0 750.0

Component: BY, from buffer: Line, Integral = 29.5544880596964

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

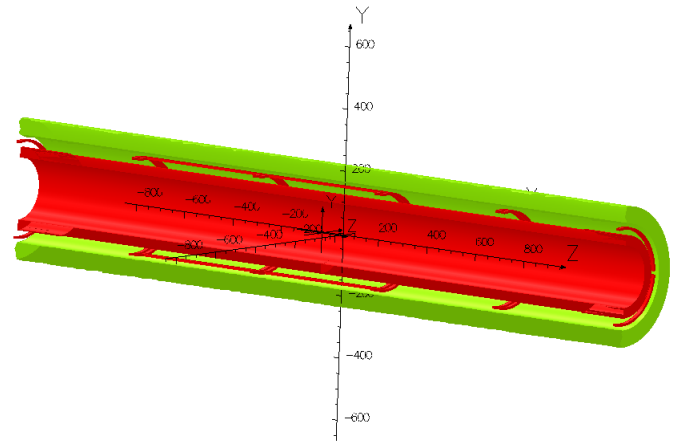
**MODEL DATA**  
 200mm-sol-corr-v-all-h-some-scale-6T.op3  
 TOSCA Magnetostatic  
 Nonlinear materials  
 Simulation No 1 of 1  
 3481324 elements  
 1245126 nodes  
 58 conductors  
 Nodally interpolated fields  
 Activated in global coordinates

**Field Point Local Coordinates**  
 Local = Global

**FIELD EVALUATIONS**  
 Line LINE 1001 Cartesi  
 (nodal an  
 )  
 x=0.0 y=0.0 z=-75  
 0.0 to 750.0

Opera

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

**MODEL DATA**  
 200mm-sol-corr-v-all-h-some-scale-6T.op3  
 TOSCA Magnetostatic  
 Nonlinear materials  
 Simulation No 1 of 1  
 3481324 elements  
 1245126 nodes  
 58 conductors  
 Nodally interpolated fields  
 Activated in global coordinates

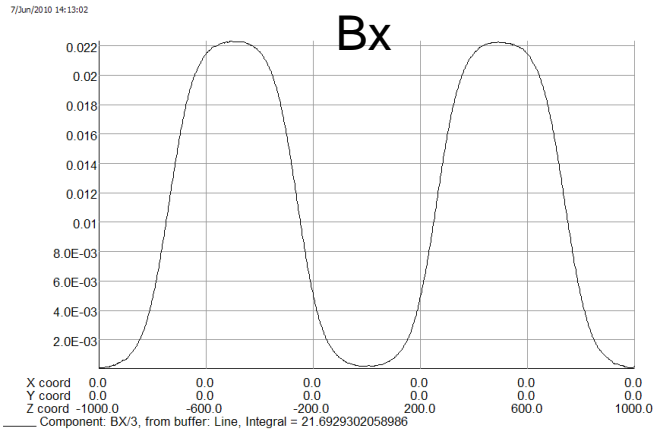
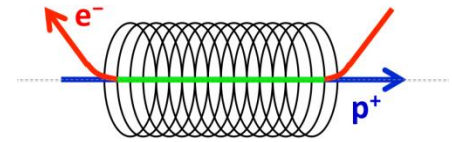
**Field Point Local Coordinates**  
 Local = Global

**FIELD EVALUATIONS**  
 Line LINE 1001 Cartesi  
 (nodal an  
 )  
 x=0.0 y=0.0 z=-10  
 00.0 to 750.0

Opera

# Fields of Many Short Correctors

## Two Horizontal and One Vertical



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

MODEL DATA	
200mm-sol-corr-may-e-h-v-h-pole-air-op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
3481324 elements	
1245126 nodes	
26 conductors	
Nodally interpolated fields	
Activated in global coordinates	

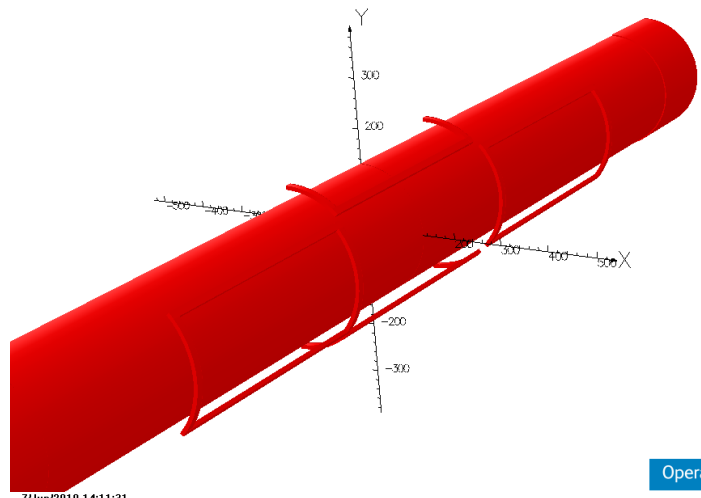
Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS		
Line	LINE 1001 Cartesi	
(nodal)	an	
)	)	
x=0.0	y=0.0	z=-10
		00.0
		to
		1000.0

Looks OK

Opera

7/Jun/2010 14:12:21

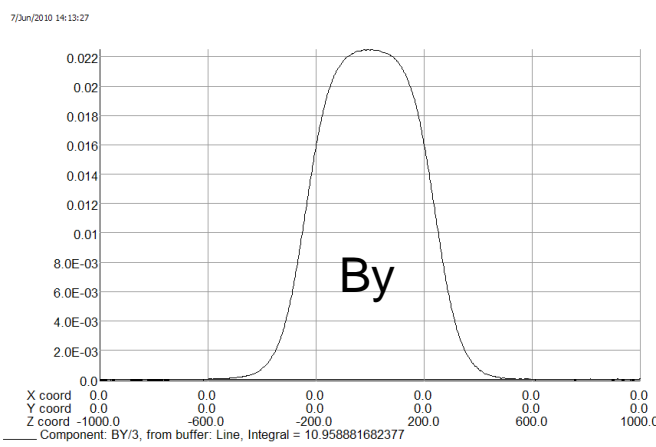


UNITS	
Length	mm
Magn Flux Density T	
Magn Field	A m <sup>-1</sup>
Magn Scalar Pot	A
Magn Vector Pot	Wb m <sup>-1</sup>
Elec Flux Density	C m <sup>-2</sup>
Elec Field	V m <sup>-1</sup>
Conductivity	S mm <sup>-1</sup>
Current Density	A mm <sup>-2</sup>
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
200mm-sol-corr-may-e-h-v-h-pole-air-op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
3481324 elements	
1245126 nodes	
26 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

Opera



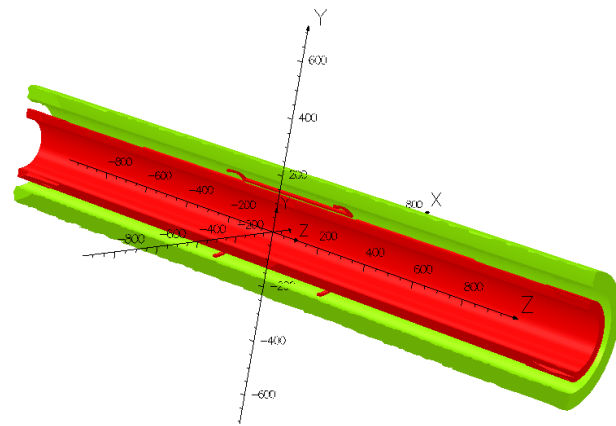
UNITS	
Length	mm
Magn Flux Density T	
Magn Field	A m <sup>-1</sup>
Magn Scalar Pot	A
Magn Vector Pot	Wb m <sup>-1</sup>
Elec Flux Density	C m <sup>-2</sup>
Elec Field	V m <sup>-1</sup>
Conductivity	S mm <sup>-1</sup>
Current Density	A mm <sup>-2</sup>
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
200mm-sol-corr-may-e-h-v-h-pole-air-op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
3481324 elements	
1245126 nodes	
26 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

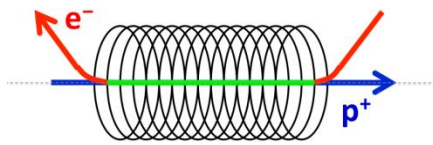
FIELD EVALUATIONS		
Line	LINE 1001 Cartesi	
(nodal)	an	
)	)	
x=0.0	y=0.0	z=-10
		00.0
		to
		1000.0

Opera

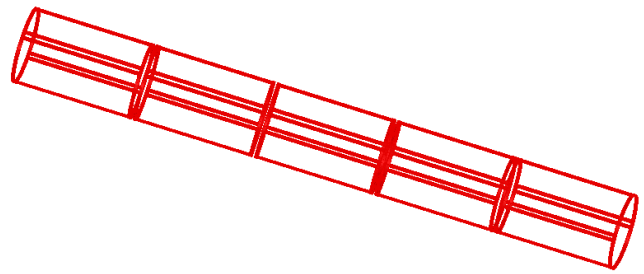


Opera

# Complex Configuration of Short Correctors



Jun/2010 14:36:15



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

MODEL DATA	
sol-corr-v3-short-3t.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
3623048 elements	
1307561 nodes	
82 conductors	
Fields by integration	
Activated in global coordinates	

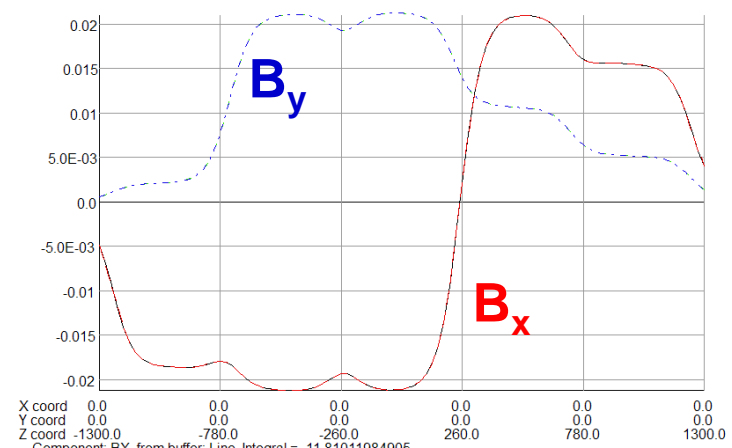
Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line	LINE 101 Cartesian
(Integral	)
x=0.0	y=0.0 z=-1300.0
	0 to
	1300.0

Opera

15/Jun/2010 14:31:03



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

MODEL DATA	
sol-corr-v3-short-6t.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No 1 of 1	
3623048 elements	
1307561 nodes	
82 conductors	
Fields by integration	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line	LINE 101 Cartesian
(Integral	)
x=0.0	y=0.0 z=-1300.0
	0 to
	1300.0

Opera

## Case examined

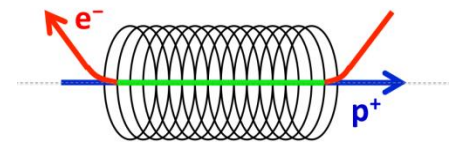
- Vertical: 1/8, 1/2, 1, 2, 4 of maximum 0.02 T
- Horizontal: -7/8H, -H, -H, +H, +3/4H of 0.02T

Actual error may not follow this physical pattern. e.g., there could be a change in sign in the middle of a short corrector.

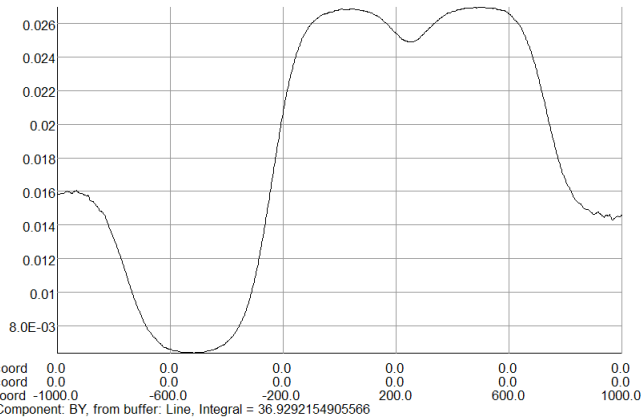
The error due to that could be much larger than the dip between two short correctors having the same strength.

However, correction does not have to be perfect. As long as the net error is <50 micron, it should be OK.

# Short and Long Correctors Together



7/Jun/2010 13:27:58



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

MODEL DATA	
200mm-sol-corr-all-scale-6T.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
348.1324 elements	
1245.126 nodes	
66 conductors	
Nodally interpolated fields	
Activated in global coordinates	

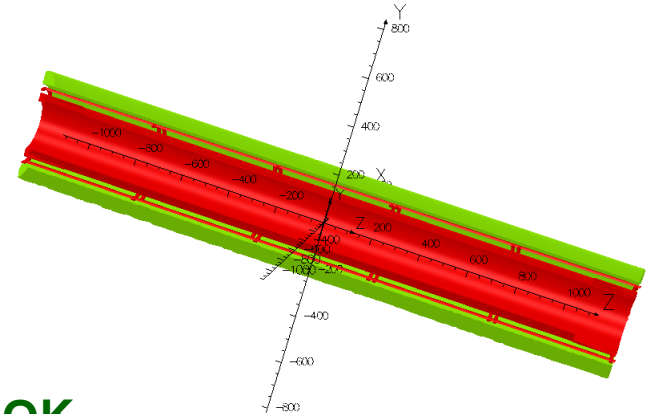
Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line LINE 1001 Cartesian (nodal) an	
x=0.0 y=0.0 z=-10.00.0 to 1000.0	

Opera

7/Jun/2010 13:23:05



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

MODEL DATA	
200mm-sol-corr-all-scale-6T.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
348.1324 elements	
1245.126 nodes	
66 conductors	
Nodally interpolated fields	
Activated in global coordinates	

Field Point Local Coordinates	
Local = Global	

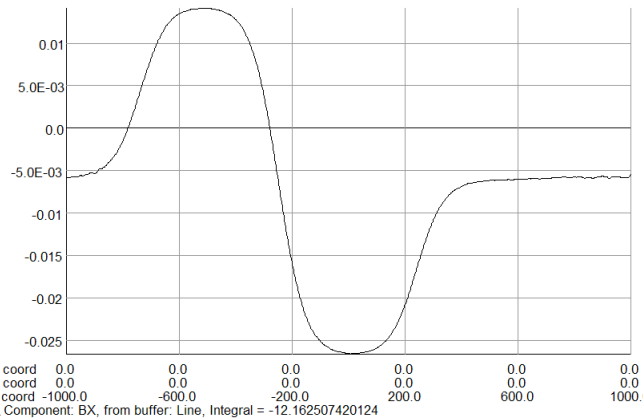
  

FIELD EVALUATIONS	
Line LINE 1001 Cartesian (nodal) an	
x=0.0 y=0.0 z=-10.00.0 to 1000.0	

Opera

Looks OK

7/Jun/2010 13:27:21



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

MODEL DATA	
200mm-sol-corr-all-scale-6T.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
348.1324 elements	
1245.126 nodes	
66 conductors	
Nodally interpolated fields	
Activated in global coordinates	

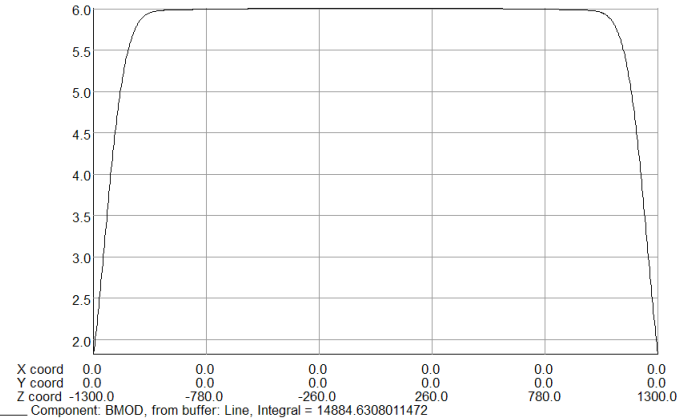
Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line LINE 1001 Cartesian (nodal) an	
x=0.0 y=0.0 z=-10.00.0 to 1000.0	

Opera

7/Jun/2010 13:26:01



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

MODEL DATA	
200mm-sol-corr-all-scale-6T.op3	
TOSCA Magnetostatic	
Nonlinear materials	
Simulation No. 1 of 1	
348.1324 elements	
1245.126 nodes	
66 conductors	
Nodally interpolated fields	
Activated in global coordinates	

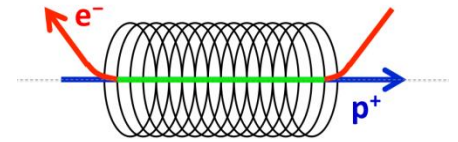
  

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line LINE 1001 Cartesian (nodal) an	
x=0.0 y=0.0 z=-15.00.0 to 1300.0	

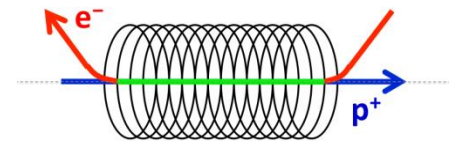
Opera



# Exterior Field Requirements



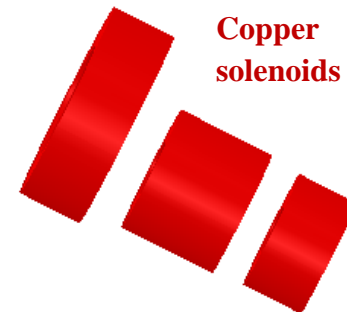
# Field between superconducting and copper solenoid



- 0.3 T (3 kG) field is desired between copper solenoids and superconducting solenoid along the beam path.
- This would be a very large fringe field in the axial direction. Removing or reducing the radial width of the iron will generate some. However, that would also allow outside components to create transverse field inside the solenoid and impact the field straightness.
- Copper solenoids are not able to generate that large field for the required spacing between the components.
- This requirement is satisfied by inserting additional superconducting coils inside the cryostat of the main superconducting solenoid. These coils create a large fringe field (and hence named fringe field coil/solenoid).



Superconducting solenoid

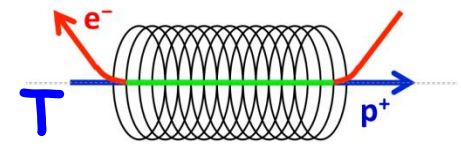


Density	
Power	W
Force	N
Energy	J
Mass	kg

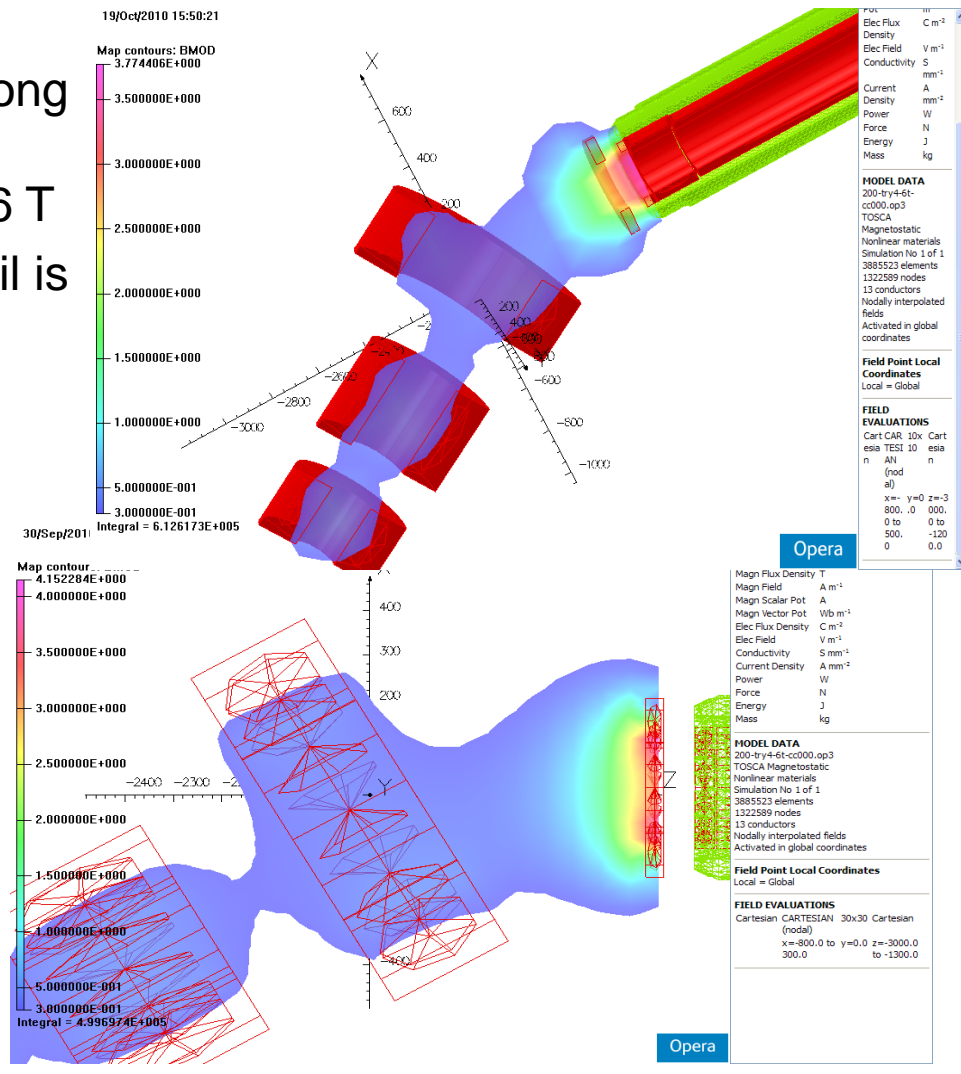
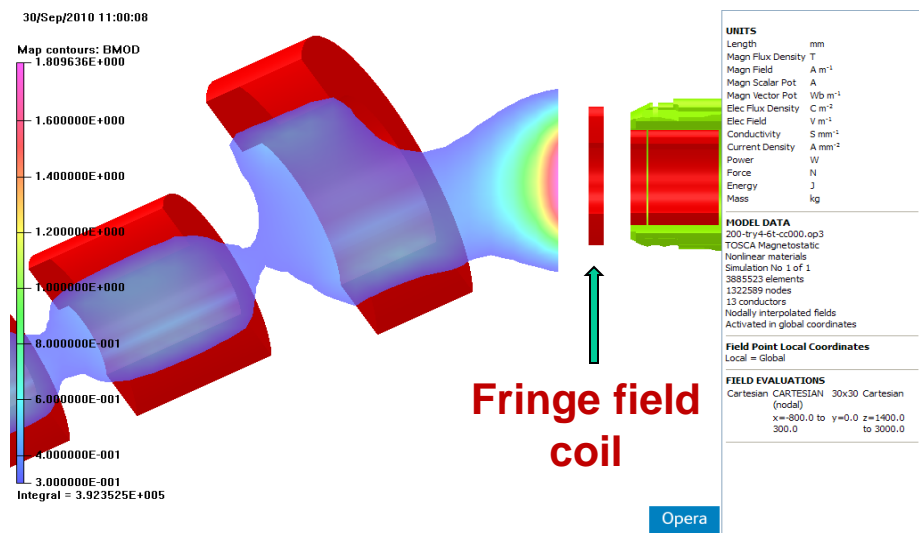
#### PROBLEM DATA

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

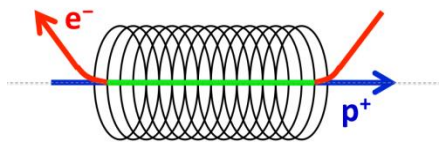
# Field between superconducting and copper solenoid with superconducting solenoid at 6 T



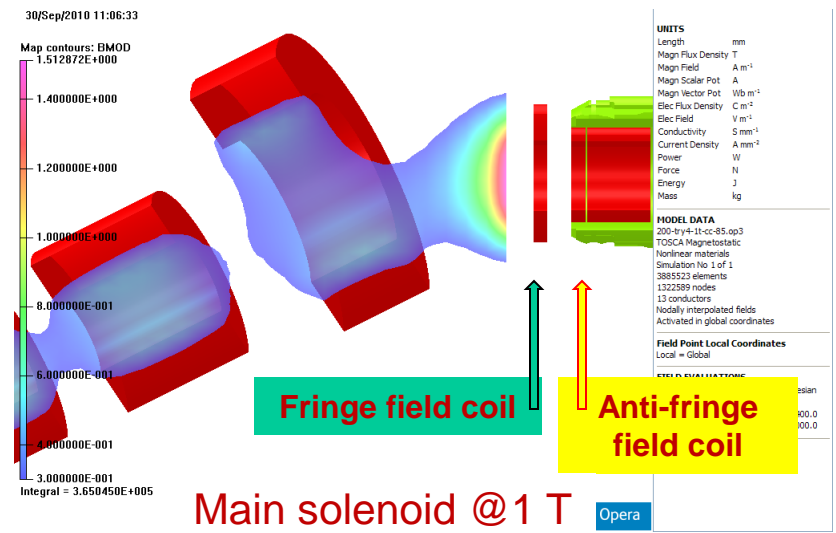
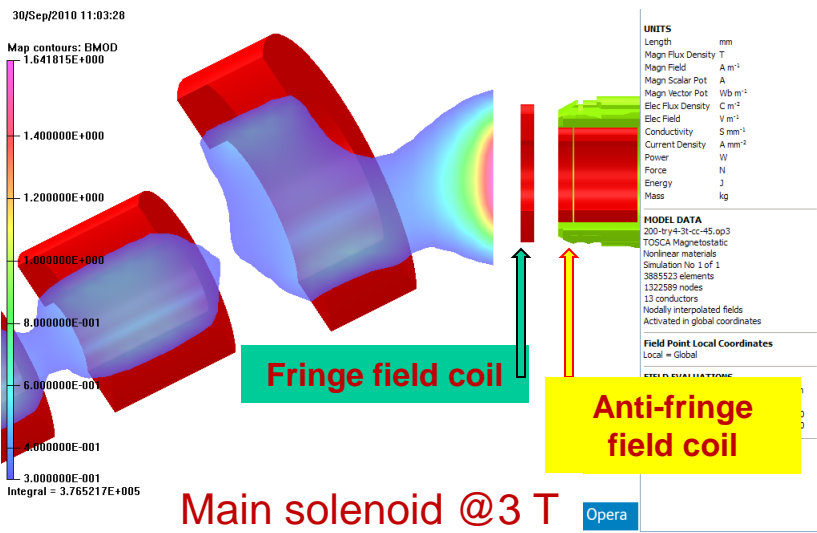
- The desired field (>0.3 T between copper solenoids and superconducting solenoid along the electron beam path) with a sufficiently sized fringe field coil and main solenoid at 6 T
- The size and location of the fringe field coil is optimized to minimize space usage
- Strong fringe field coils have a significant impact on the field inside the main solenoid



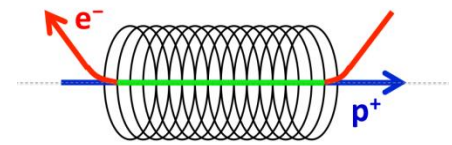
# Field between superconducting and copper solenoid with superconducting solenoid < 6 T



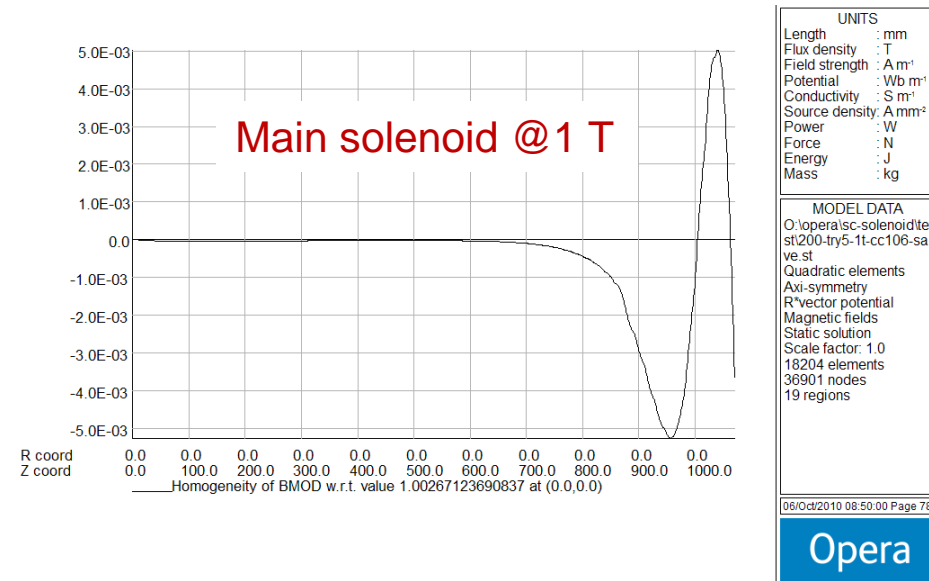
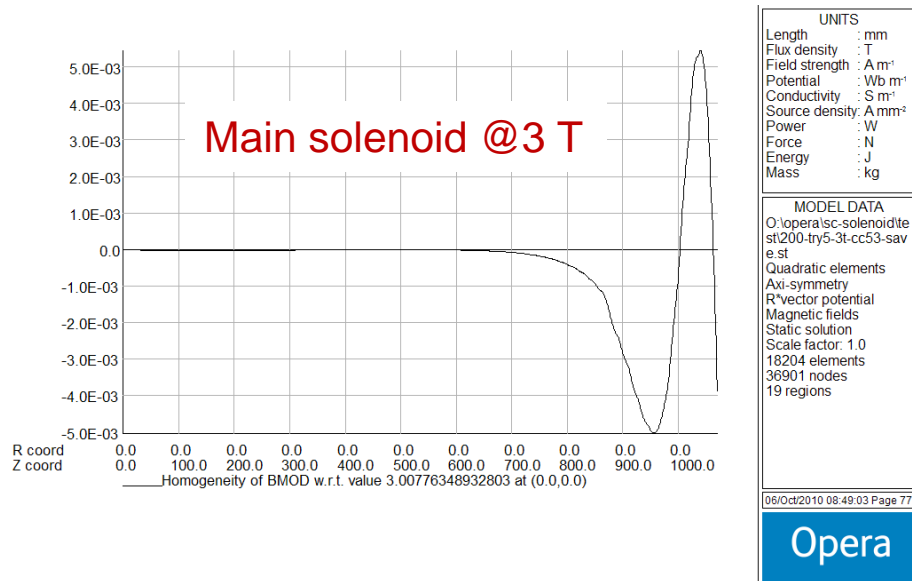
- Situation becomes more complicated when the main solenoid is operated at a field lower than 6 T – the desired range is field as low as 1 T.
- In this case the outside field becomes significantly smaller because (a) the leakage field from the main solenoid becomes lower and (b) exterior field from the fringe field coil also becomes lower if it scales with the main solenoid to maintain field quality.
- To obtain desired the desired (>0.3 T) field between copper solenoids and the superconducting solenoid, the fringe field must run at full power.
- To obtain the required field quality, an additional coil (anti-fringe field coil) is added and powered independently to adjusted field quality.



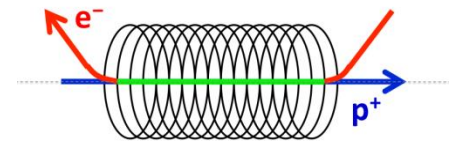
# Field Quality in Main Solenoid at 1T & 3T with the desired fringe field (>0.3 T)



- To obtain the desired (>0.3 T) field between copper solenoids and the superconducting solenoid, the fringe field must run at full power.
- To obtain the required field quality, the current in the anti-fringe field coil is adjusted.
- To minimize the amp-turn requirements, anti-fringe field coils have a nominal zero current when the main solenoid is at 6 T.
- The current in anti-fringe coil must be negative at 3T (~-16 A) and even more at 1T (~-33 A). These give the desired field quality (errors <math>6 \times 10^{-3}</math> from  $z=-1050</math> to  $+1050</math>).$$



# Summary



➤ This is a demanding magnet system with both traditional and unique challenges.

The following key steps have been taken to meet the requirements:

- Corrector magnets are made superconducting to reduce size, stored energy and Lorentz forces in the superconducting solenoid.
- Large axial forces in a relatively small end-section are contained by allowing space for plates within the coil. The coil is wound continuously on either side of the plate to avoid large asymmetric forces during the quench.
- A corrector design is developed that allows the same radial space to be shared between horizontal and vertical correctors. This design also minimizes cost and schedule conflict with other projects.
- Fringe field coil is added to obtain the large field ( $>0.3$  T) desired between the copper solenoids and the superconducting solenoid along the beam path.
- An additional (anti-)fringe field coil is incorporated to maintain the desired field quality in main solenoid over a large range (1 T to 6 T).

These design developments should help meet all requirements:

High field, large aperture, field uniformity, field straightness and fringe field.