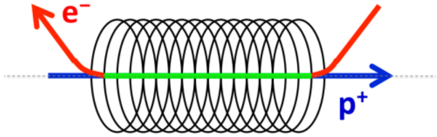


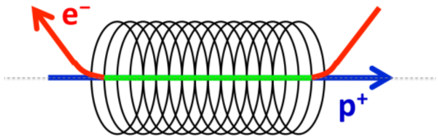
Electron Lens Superconducting Solenoid

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 (~6 x 10^{-3}) region: 20 mm aperture along ~2100 mm
3. Fringe field : significant field required outside along the beam path
   - Unique situation, unique solution
4. **Field straightness: ±100 micron** (± 50 µm desired) in ~2100 mm

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

☐ guides and determines the overall design

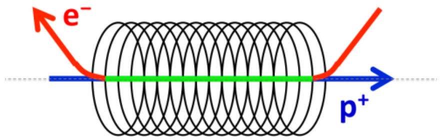
too risky for industry to take this job

☐ well beyond the normal construction errors

corrector magnets become integral part of the overall design

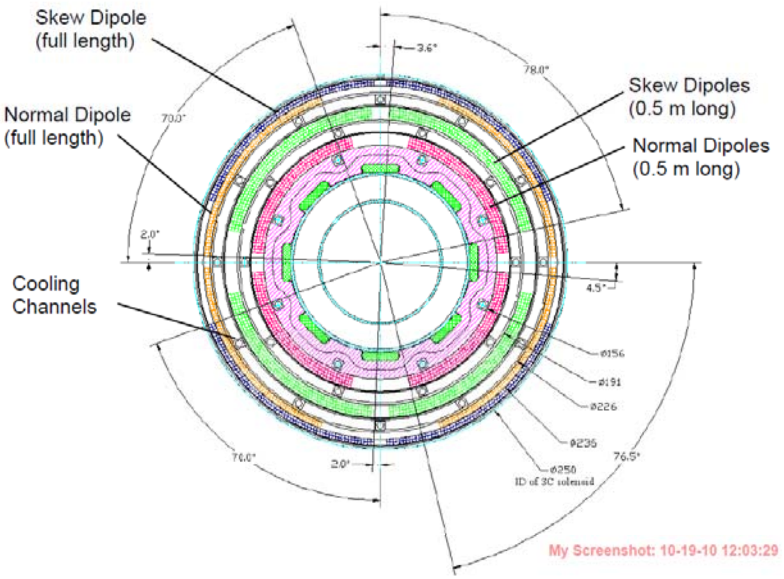
☐ must have enough magnetic shielding to limit the influence of surrounding

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.

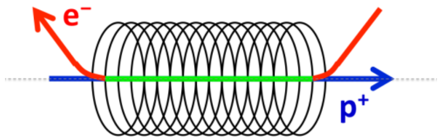
- Significant reduction in size (292mm to 200mm) reduces the stored energy, Lorentz forces and thus makes the solenoid a bit itself less risky.



Earlier design with warm corrector

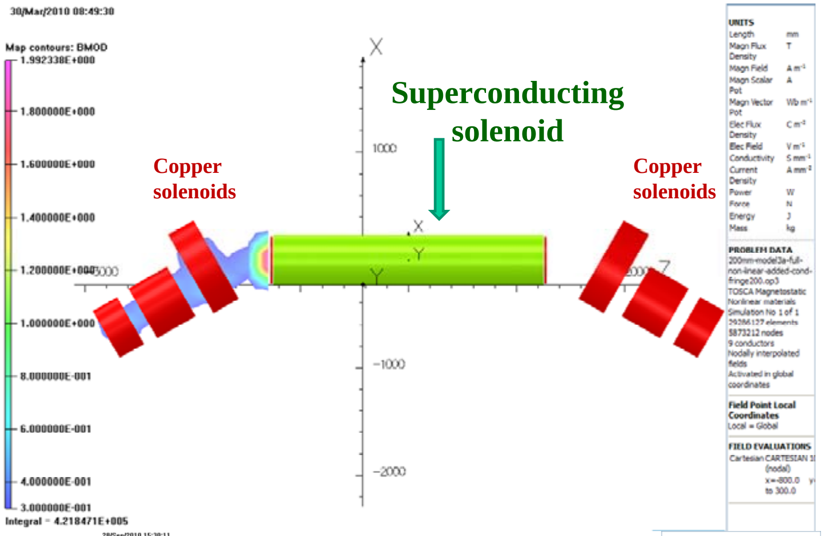
Correctors shown here were placed inside the superconducting solenoid

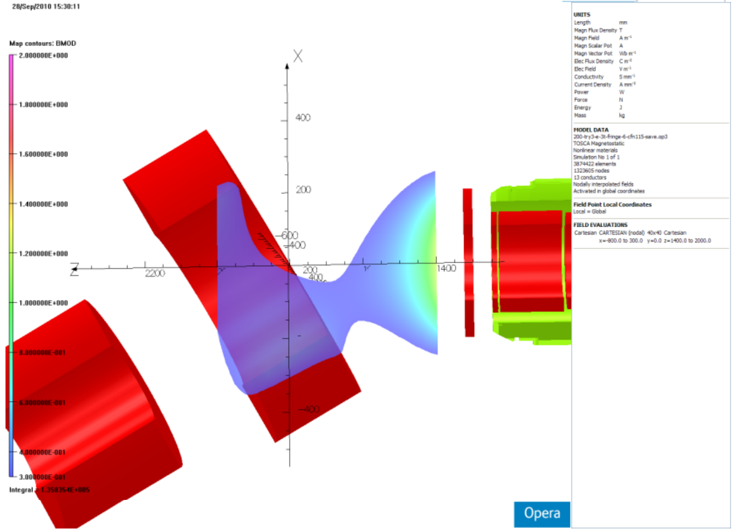
Overall Magnetic System Design



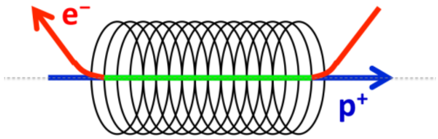
Overall magnetic system consists of:

- 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



Additional important consideration in designing the system:

use existing components to reduce cost (and schedule)

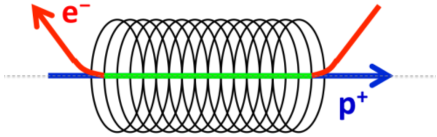
Opportunity for cost saving come from the use of existing:

- stainless steel shell
- RHIC cryostat
- tooling

This made the design a bit more restrictive.

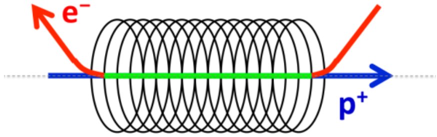
- However, we were able to use all of above without compromising the performance.

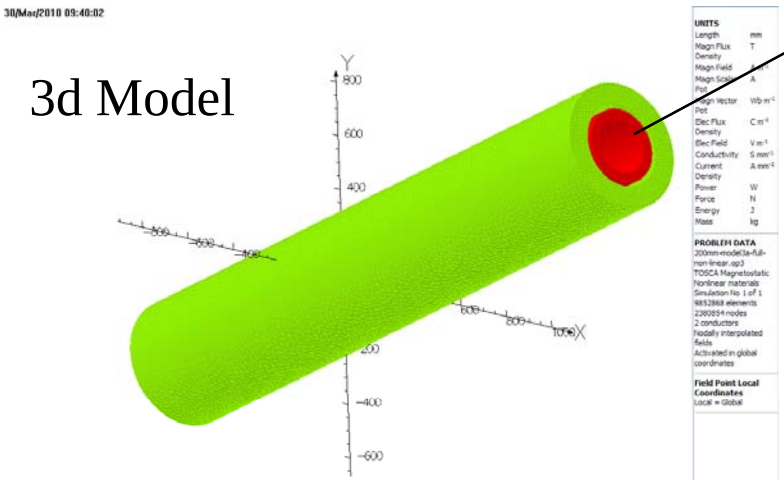
Main Parameter List



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
Maximum design field	**6 T**
Current for 6 T	~460 A
Peak Field on the conductor @ 6T	**~6.5 T (~8% peak field enhancement)**
Computed Short Sample @4.2 K	**~7.0 T (6.6 T, specified)**
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
Field on the axis	**1 to 6 T**
Maximum computed error on axis	~6 X 10^{-3} (-1050 to 1050 mm and within 20 mm)

Computer Models

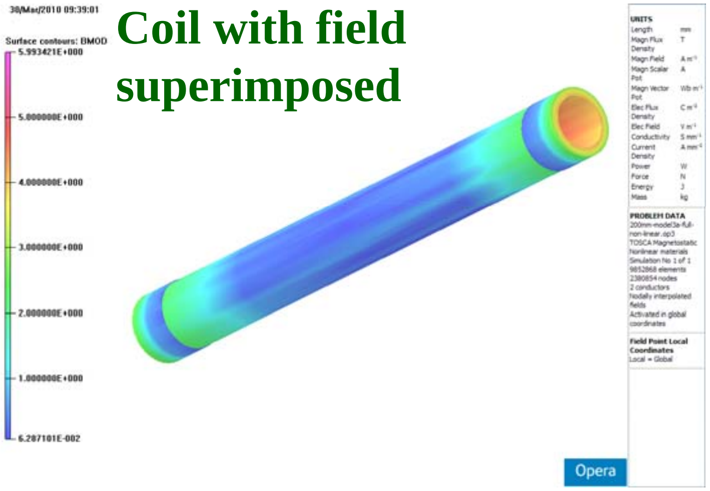




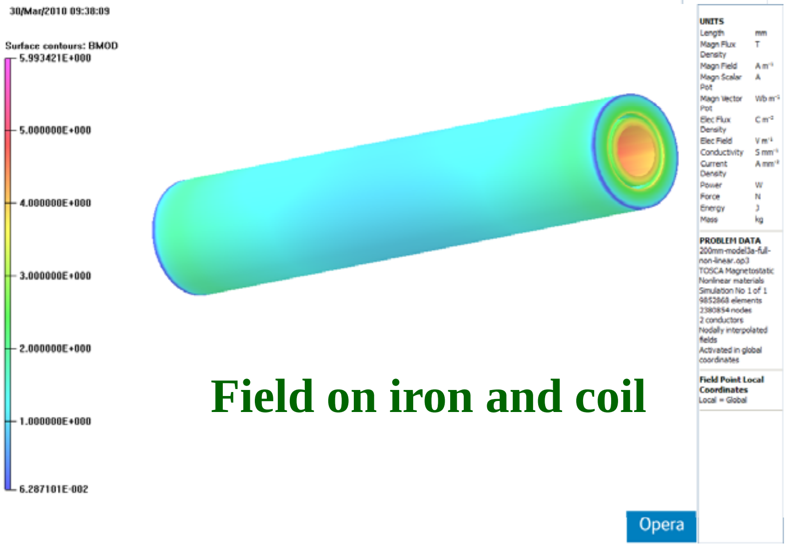
3d Model

z-axis

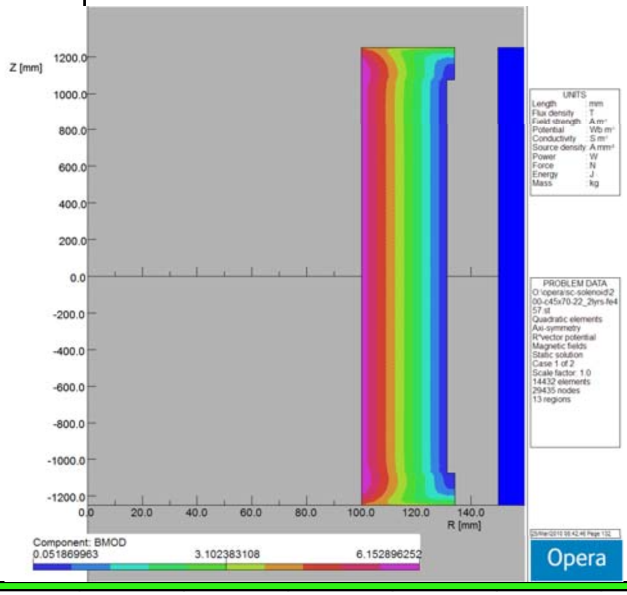
Coil with field superimposed



z-axis



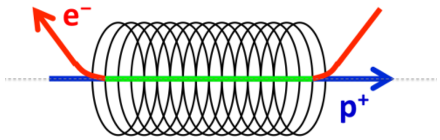
Field on iron and coil

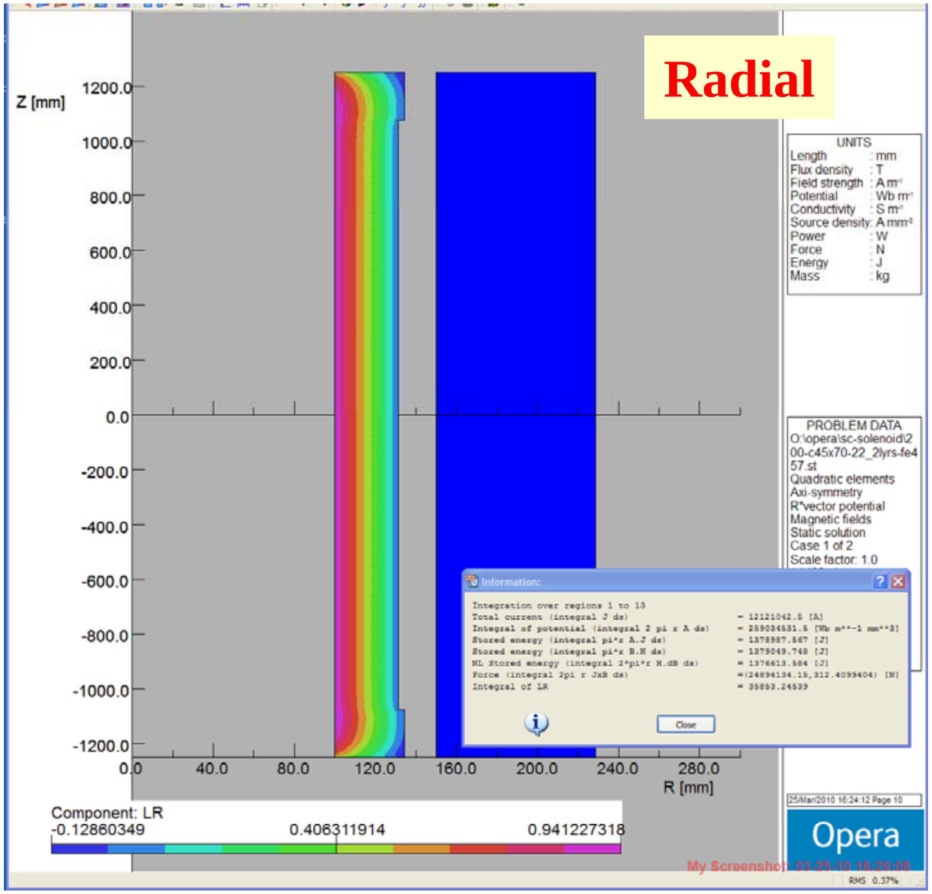


2d Model

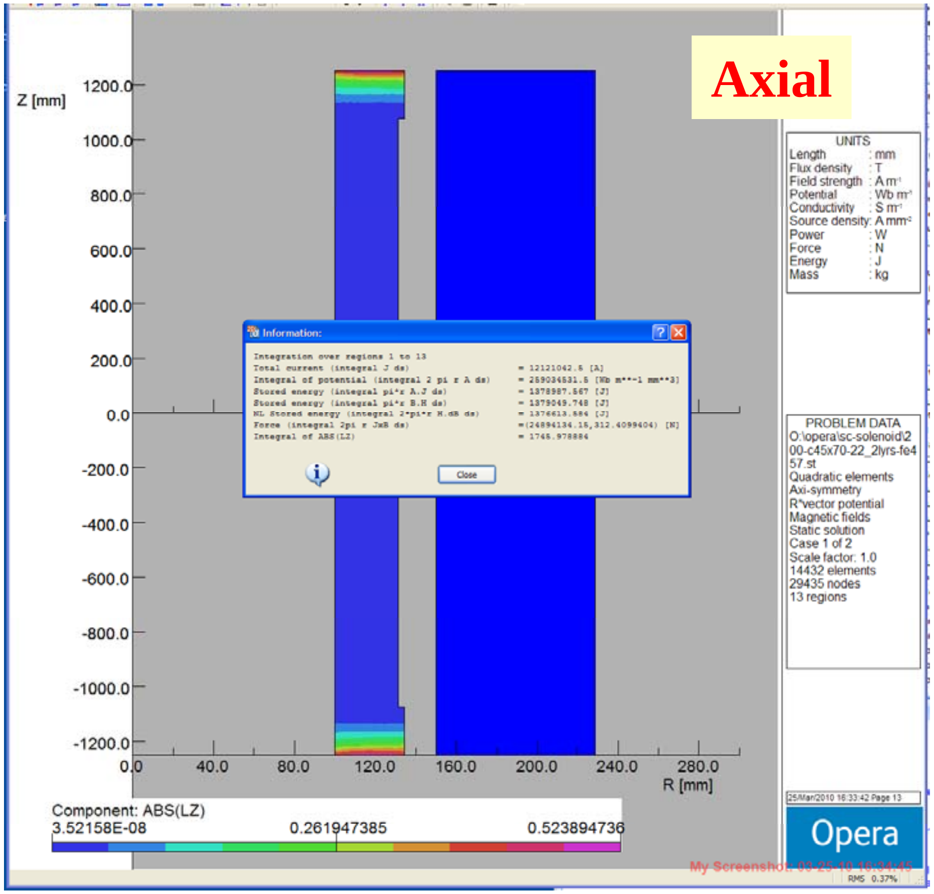
(more accurate and faster calculations in many cases)

Lorentz Forces (simple design)
Contour Plot of Force Density





```
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
```



```
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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
```
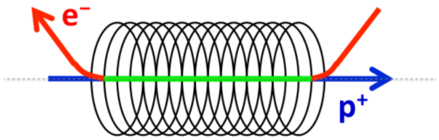
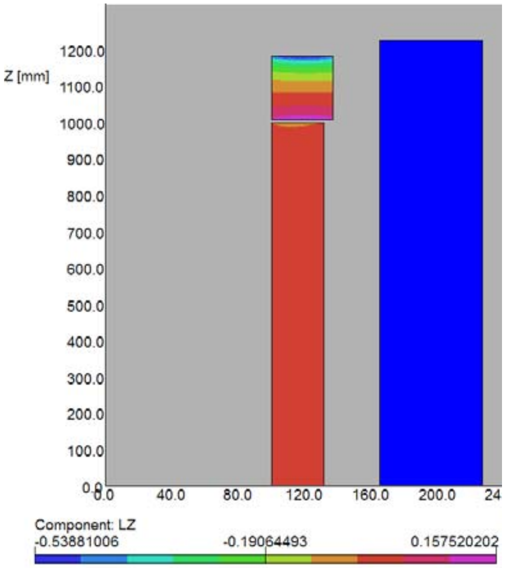

Radial Lorentz force (hoop stress) : ~24 MN
- see A. Marone's presentation

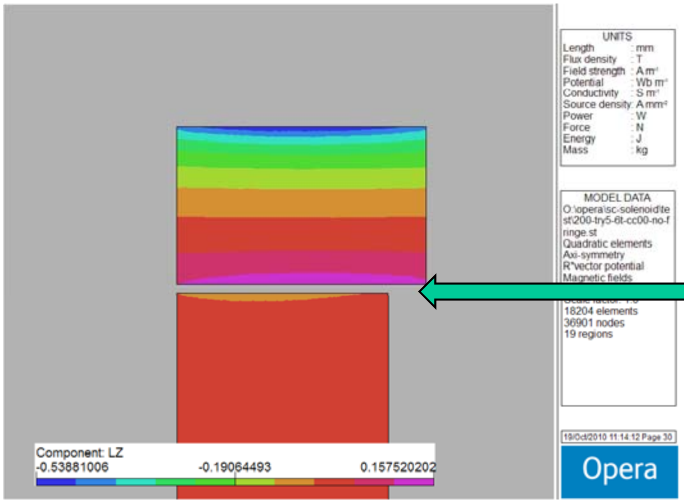
Axial force: ~35 kN per side
- large axial forces, only in the ends

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 quneches then the end forces will no longer be balanced (not acceptable).
- Quench protection is such that the full length double layers are quenched





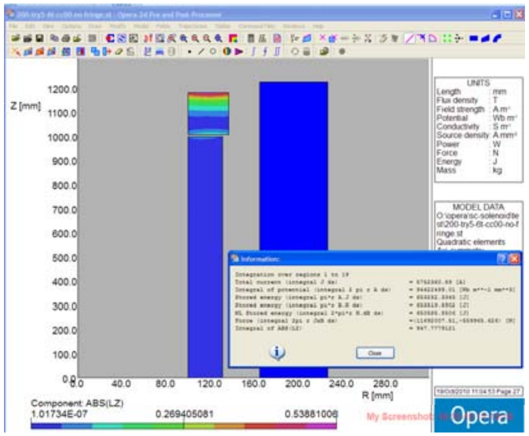
UNITS
Length : mm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

MODEL DATA
O:\opera\sc-solenoid\test\200-try5-6t-cc00-no-fringe.st
Quadratic elements
Axi-symmetry
R*vector potential
Magnetic fields
18204 elements
36901 nodes
19 regions

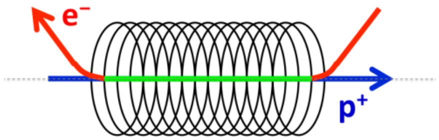
19/Oct/2010 11:14:12 Page 30

Structure for containing large axial force

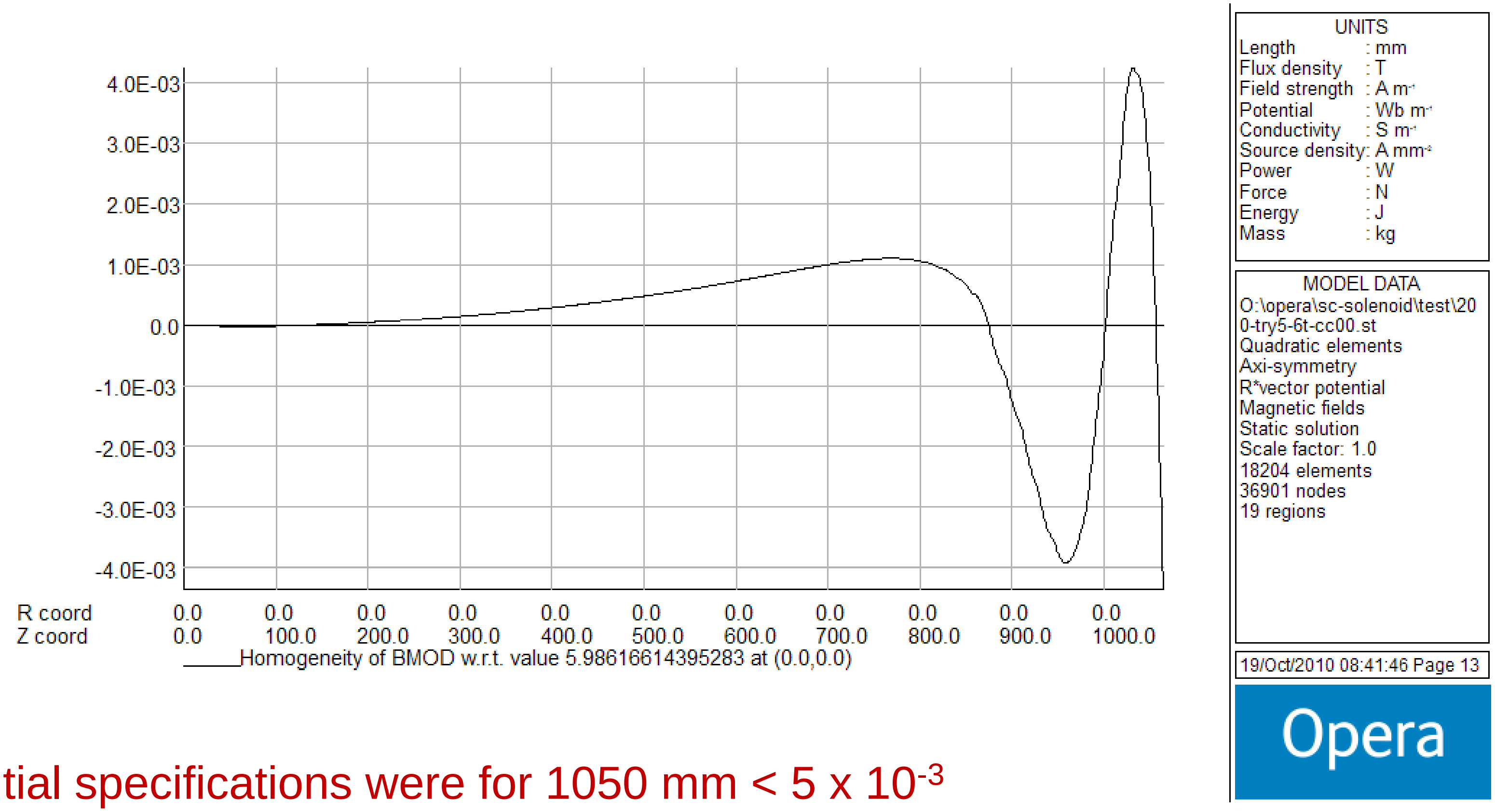
Stored Energy:
~1.4 MJ;
Inductance :
~14 Henry



Relative Field Errors on the Axis



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



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

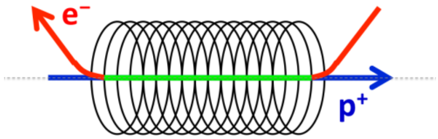
MODEL DATA
O:\opera\sc-solenoid\test\20
0-try5-6t-cc00.st
Quadratic elements
Axi-symmetry
R*vector potential
Magnetic fields
Static solution
Scale factor: 1.0
18204 elements
36901 nodes
19 regions

19/Oct/2010 08:41:46 Page 13

Opera

Initial specifications were for 1050 mm < 5 x 10^{-3}

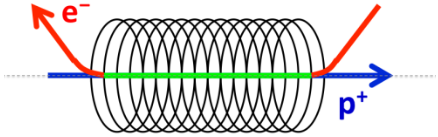
However, the primary goal is to keep field straight rather than uniform.



Corrector Design

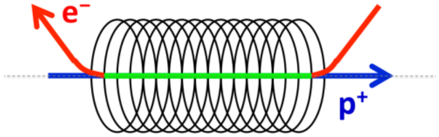
Considerations

Design Considerations for correctors (1)



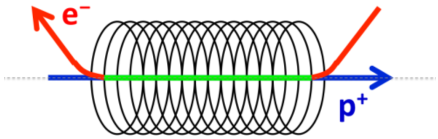
- For cooling to work well, proton and electron beams must be aligned within ±100 micron (±50 micron desired).
- Proton beam is aligned to the solenoid axis with long correctors (entire length).
- Electron field follows the solenoid magnetic axis. However, the tube on which the solenoid is wound can't 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)



- 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!)

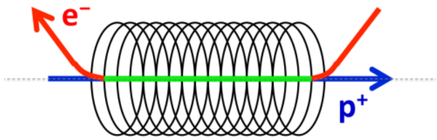


- Generate a hypothetical axial profile of vertical offset of solenoid axis:
  - 4 axial harmonics of wavelengths 0.5, 1.0, 2.0, and 4.0 meters
  - 0.100 mm amplitude for all modes; all modes add in phase.
- Break up solenoid into 50mm long segments, with each segment offset and tilted as per the profile generated.
- Compute the vertical field (B_y) profile on-axis.
- Decompose By profile into spatial harmonics (40 terms).
- Assume ~*N*/2 strongest modes can be zeroed using *N* correctors.

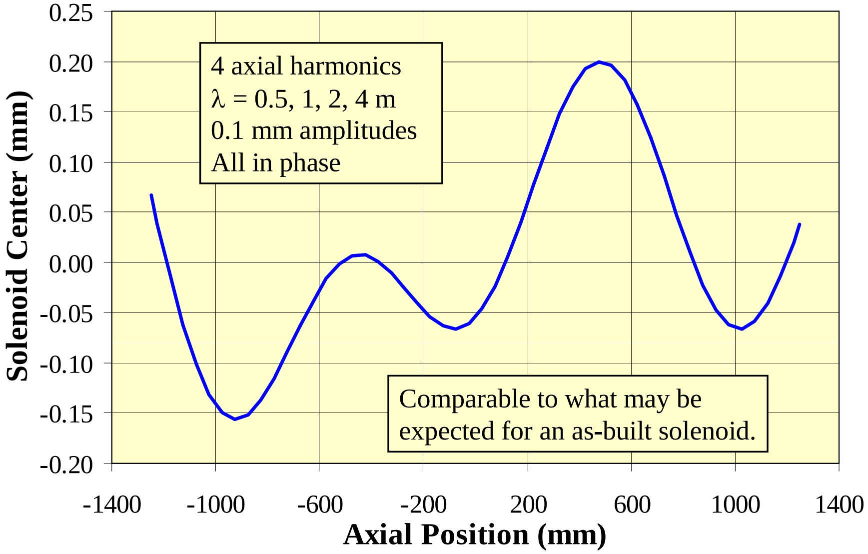
  (*Only an approximation! Ideally, the resulting axis offsets should be minimized using real corrector transfer functions.*)
- Compute the residual B_y profile on-axis.
- Compute the residual axis offset profile.

Courtesy: Animesh Jain

Estimation and correction of axis offset with 0.02 T correctors



Hypothetical Vertical Offset Profile (before correction)

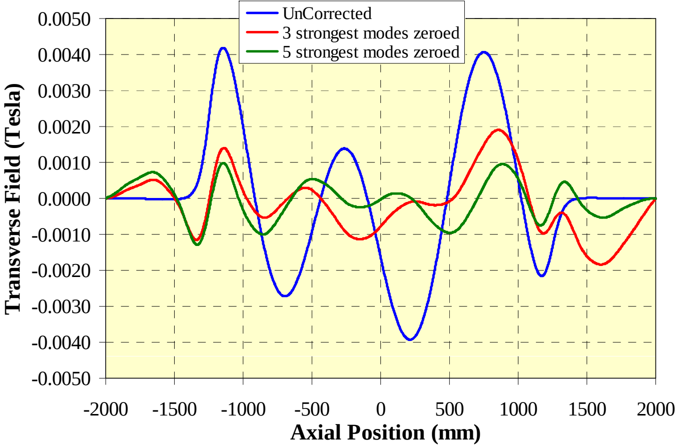


4 axial harmonics
λ = 0.5, 1, 2, 4 m
0.1 mm amplitudes
All in phase

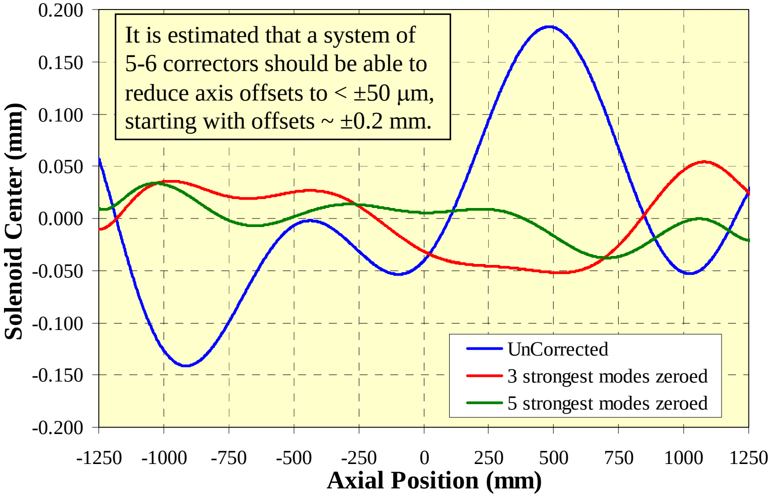
Comparable to what may be expected for an as-built solenoid.

After correction

Computed Profile of Vertical Field, B_y

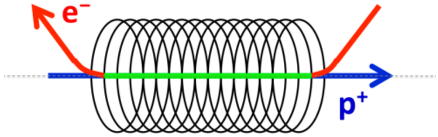


Computed Axis Offset Profile



It is estimated that a system of 5-6 correctors should be able to reduce axis offsets to < ±50 µm, starting with offsets ~ ±0.2 mm.

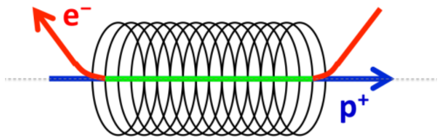
Courtesy: Animesh Jain



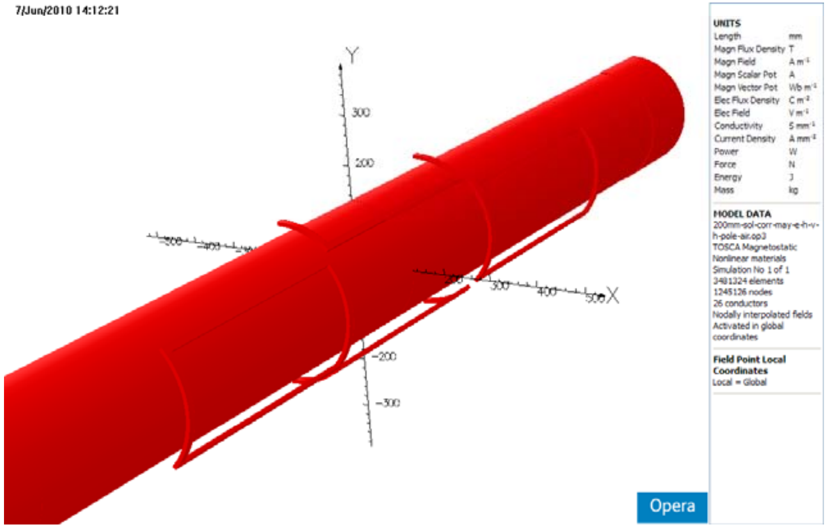
Corrector Design

Magnetic

Field on the Corrector



- 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

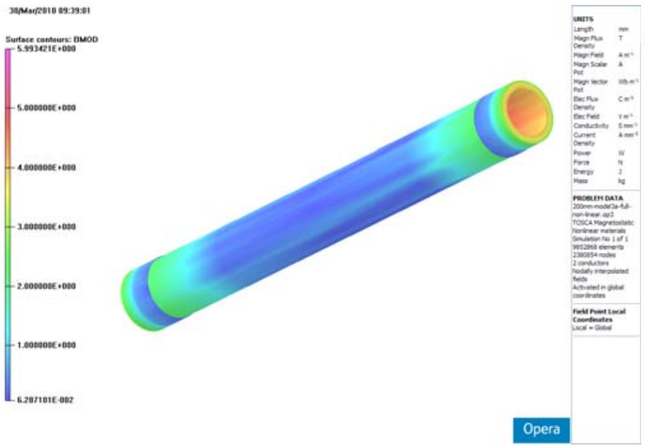


UNITS

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
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

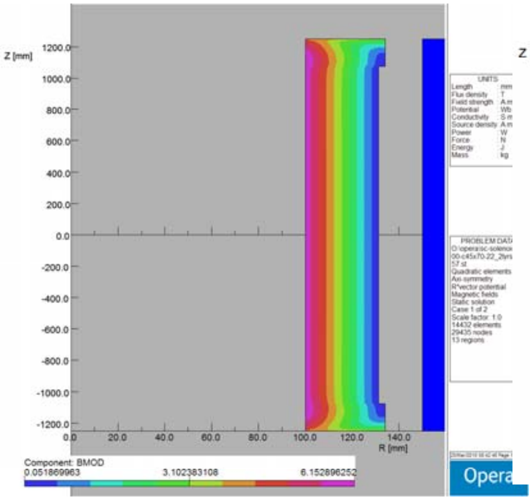


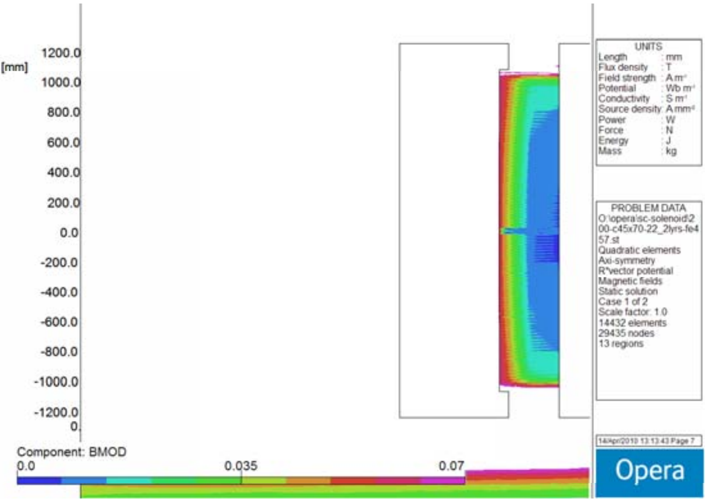
UNITS

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.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
9852868 elements
2380854 nodes
2 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global



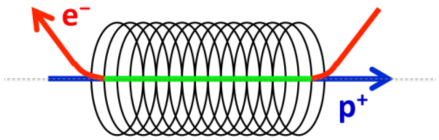


UNITS

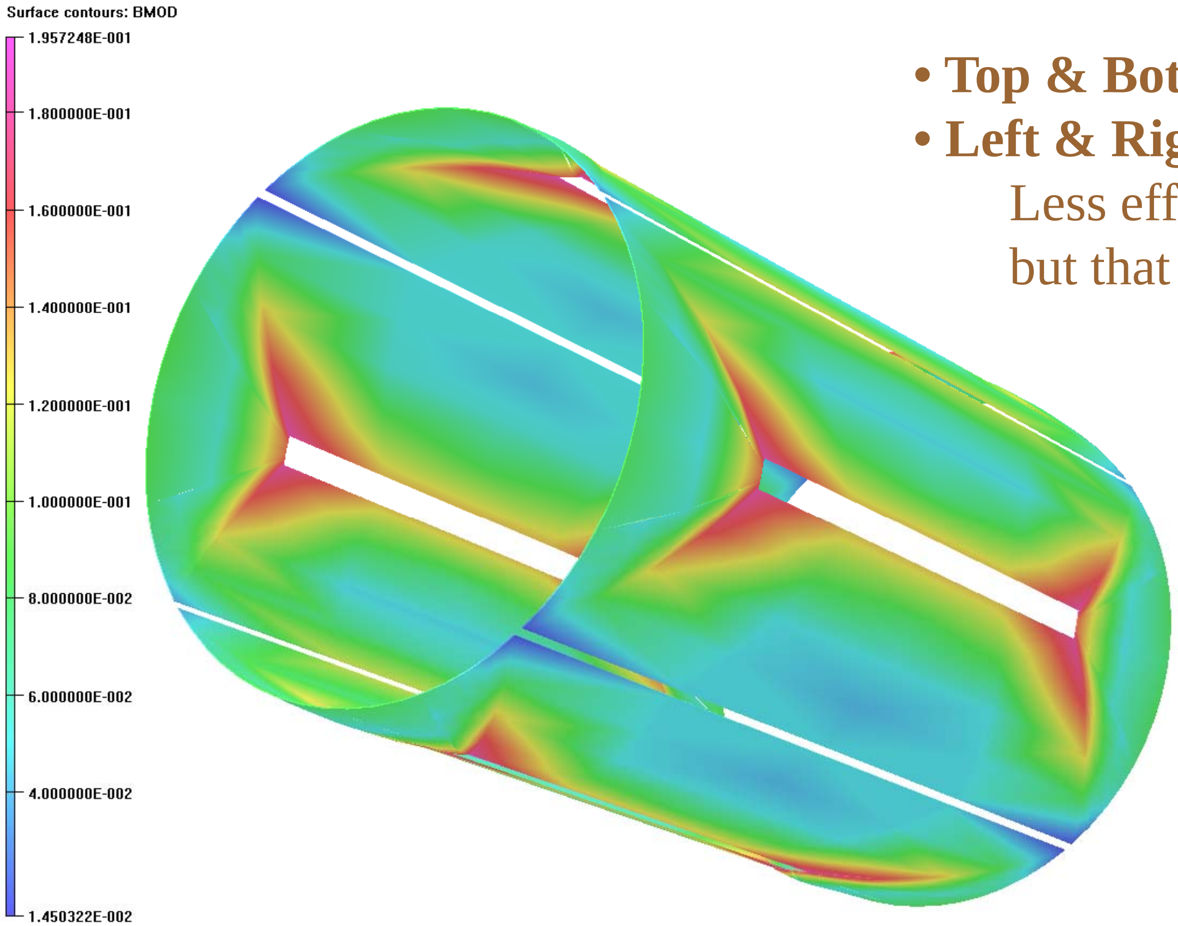
Length	: mm
Flux density	: T
Field strength	: A m⁻¹
Potential	: Wb m⁻¹
Conductivity	: S m⁻¹
Source density	: A mm⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

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

Combined Corrector Design



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

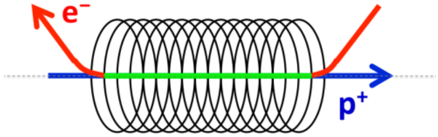


- **Top & Bottom Windings for Vertical**
- **Left & Right Windings for Horizontal**

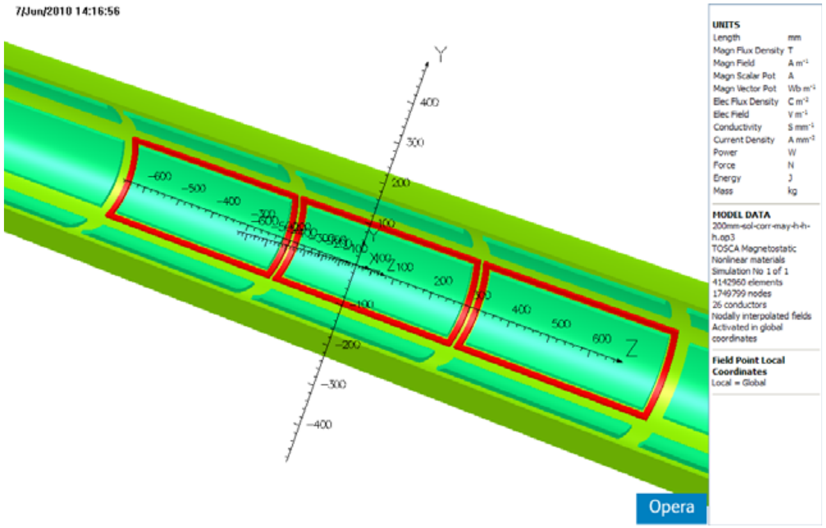
  Less efficient in terms of conductor use, but that is not a consideration here

- **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 place 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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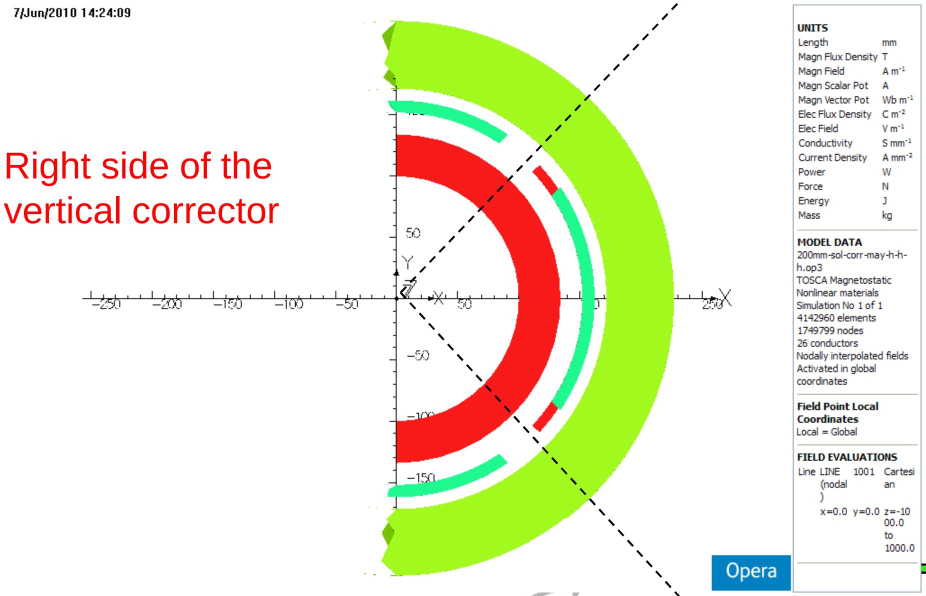
UNITS

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
200mm-sol-corr-may-h-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



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Right side of the vertical corrector

+45 degree

-45 degree

UNITS

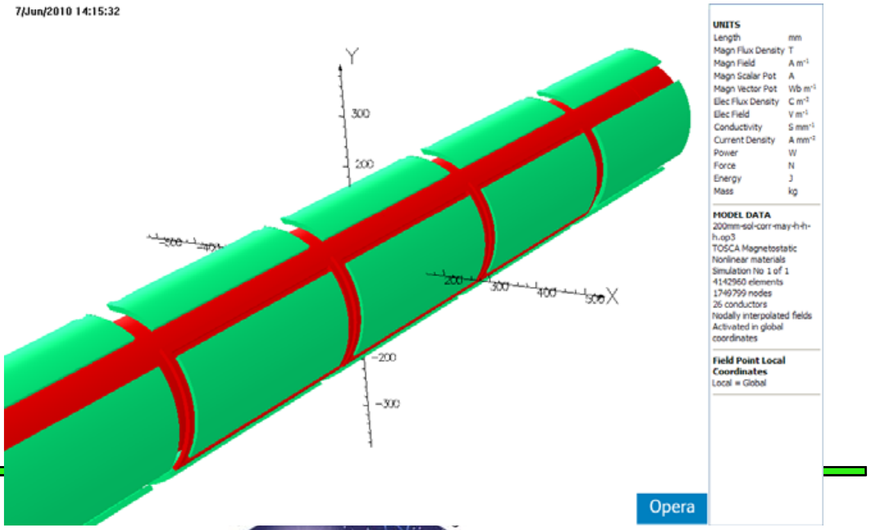
Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S mm^{-1}
Current Density	A mm^{-2}
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
200mm-sol-corr-may-h-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 (nodal)	1001	Cartesian
	x=0.0	y=0.0	z=-1000.0 to 1000.0



7/Jun/2010 14:15:32

UNITS

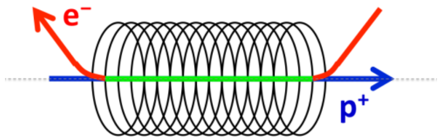
Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S mm^{-1}
Current Density	A mm^{-2}
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
200mm-sol-corr-may-h-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

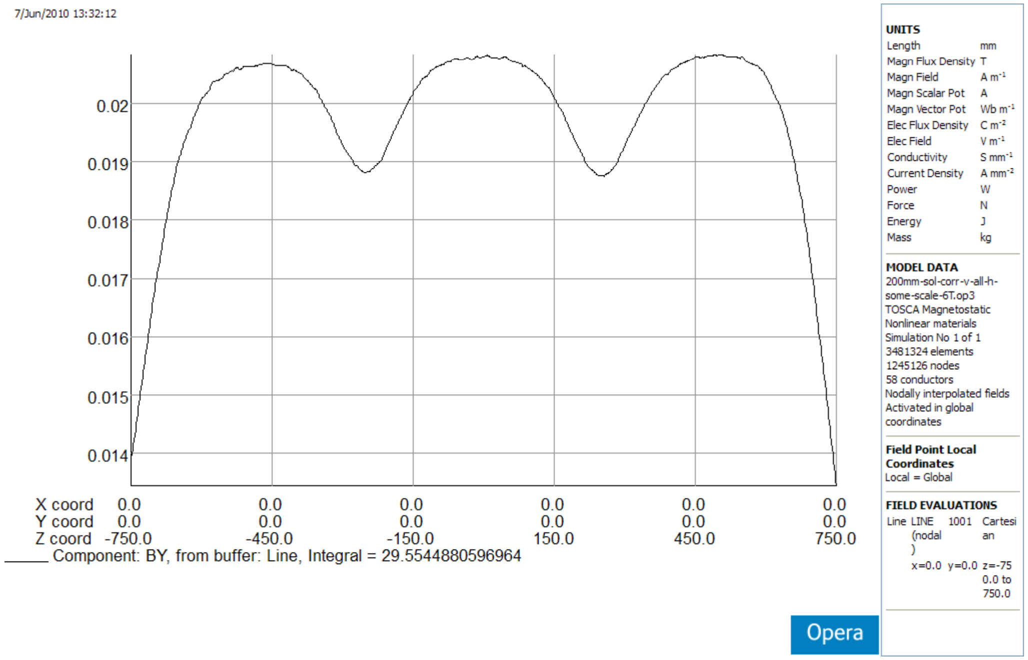
Fields of Many Short Correctors

Three Vertical correctors



- Seems to work OK

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



7/Jun/2010 13:32:12

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

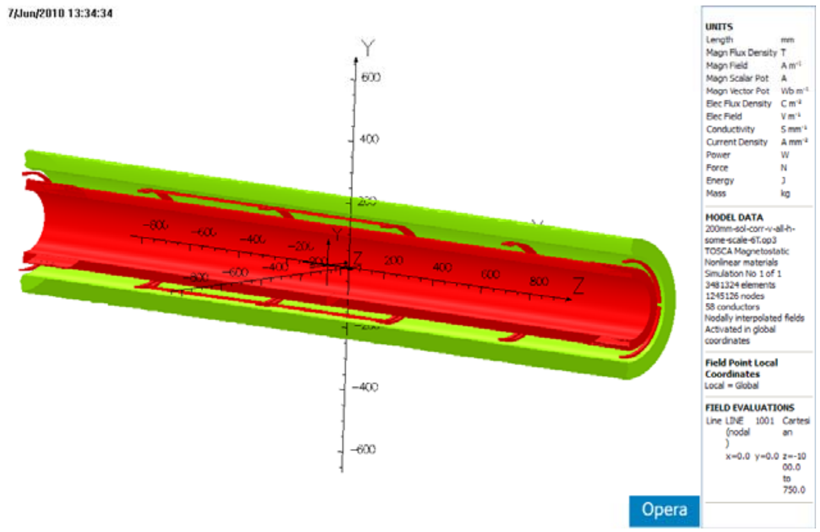
UNITS

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
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 (nodal) 1001 Cartesian
x=0.0 y=0.0 z=-750.0 to 750.0



7/Jun/2010 13:34:34

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

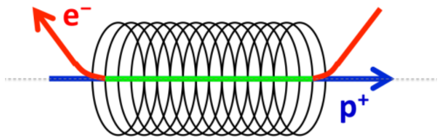
MODEL DATA
200mm-sol-corr-v-all-h-some-scale-6T.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3481324 elements
1245126 nodes
58 conductors
Nodally interpolated fields
Activated in global coordinates

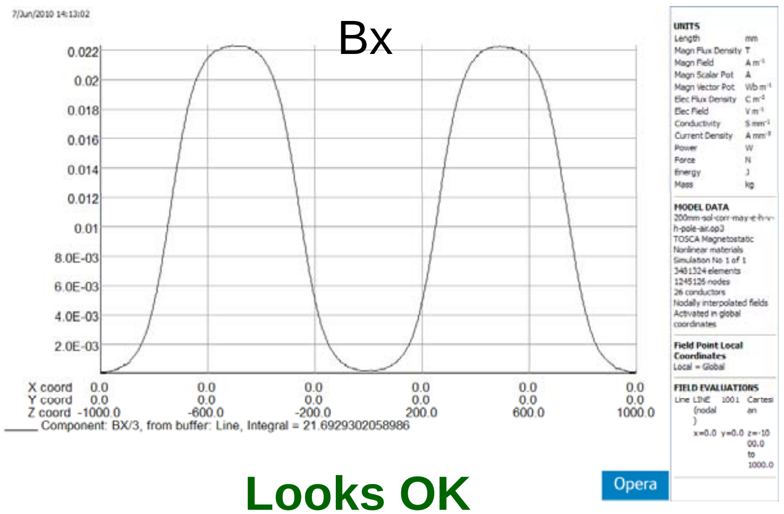
Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Line LINE (nodal) 1001 Cartesian
x=0.0 y=0.0 z=-1000.0 to 750.0

Fields of Many Short Correctors

Two Horizontal and One Vertical





Component: BX/3, from buffer: Line, Integral = 21.6929302058986

UNITS

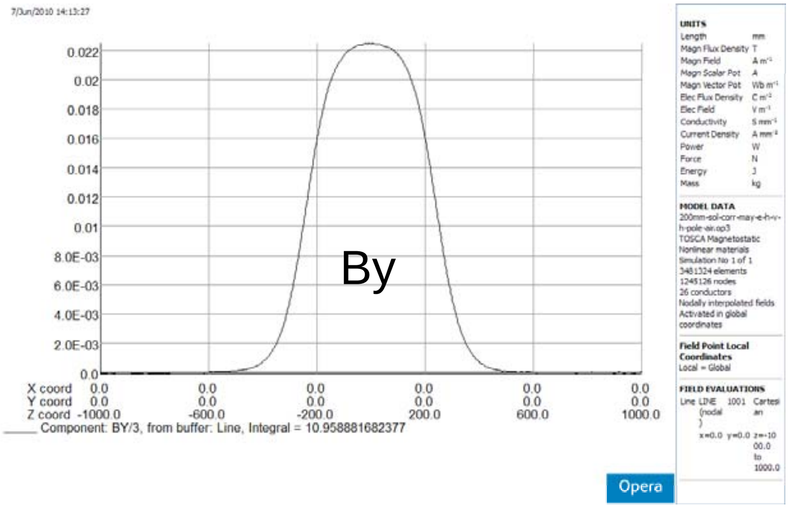
Length	mm
Magn Flux Density	T
Magn Field	A m⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m⁻¹
Elec Flux Density	C m⁻²
Elec Field	V m⁻¹
Conductivity	S mm⁻¹
Current Density	A mm⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
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 (nodal) 1001 Cartesian
x=0.0 y=0.0 z=-1000.0 to 1000.0

Looks OK



Component: BY/3, from buffer: Line, Integral = 10.958881682377

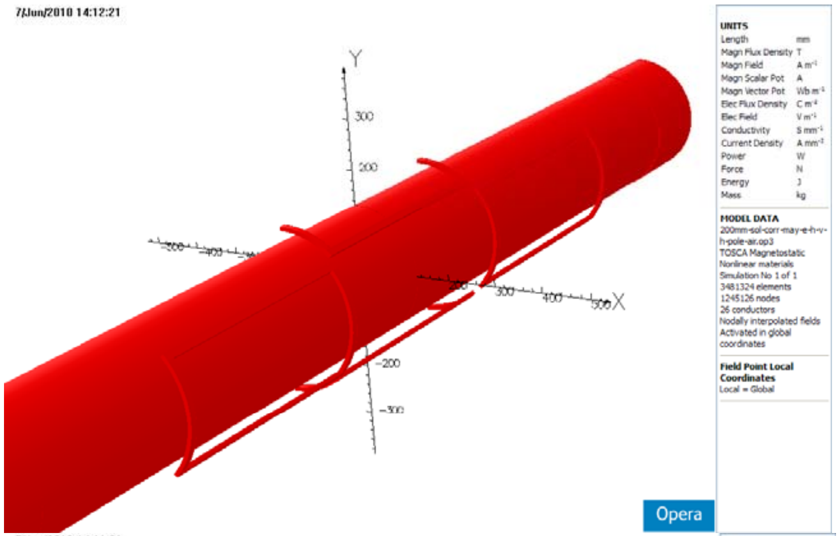
UNITS

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
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 (nodal) 1001 Cartesian
x=0.0 y=0.0 z=-1000.0 to 1000.0

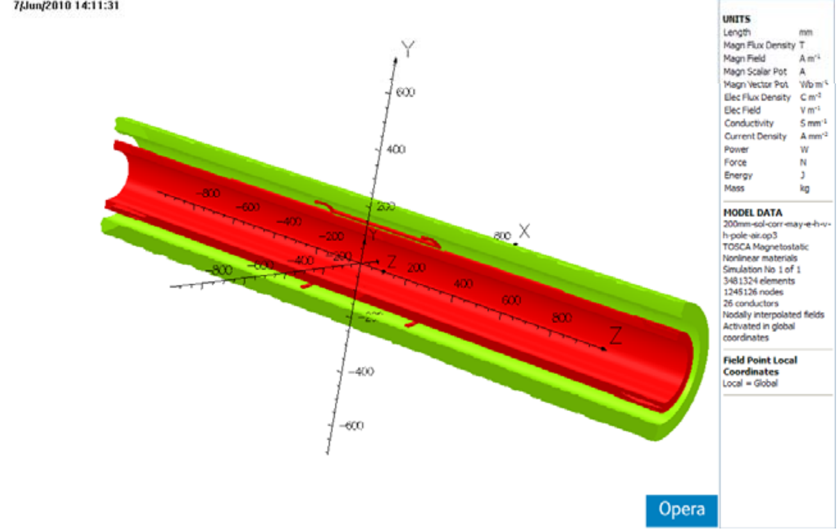


UNITS

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
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



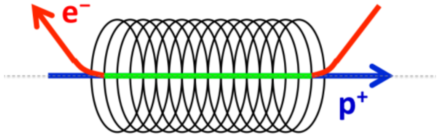
UNITS

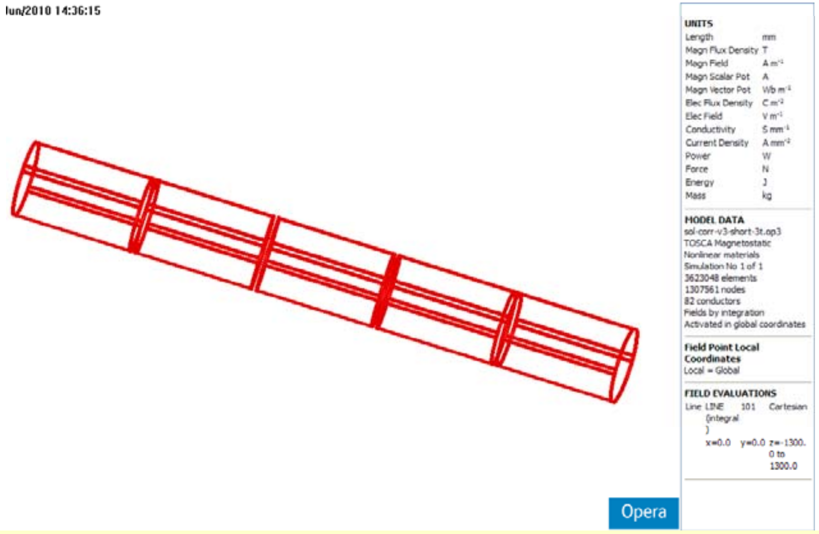
Length	mm
Magn Flux Density	T
Magn Field	A m⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m⁻¹
Elec Flux Density	C m⁻²
Elec Field	V m⁻¹
Conductivity	S mm⁻¹
Current Density	A mm⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
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

Complex Configuration of Short Correctors



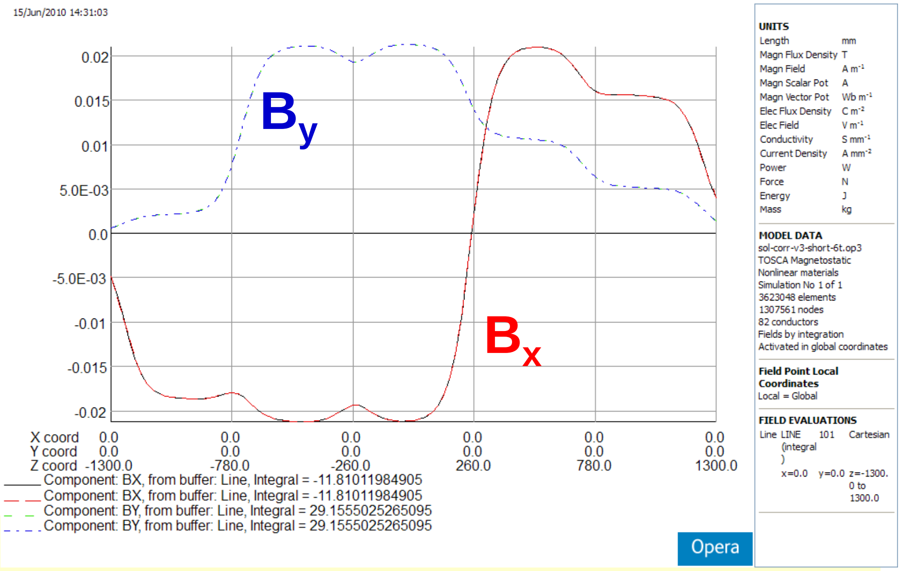


```
UNITS
Length               mm
Magn Flux Density    T
Magn Field           A m-1
Magn Scalar Pot      A
Magn Vector Pot      Wb m-1
Elec Flux Density    C m-2
Elec Field           V m-1
Conductivity         S mm-1
Current Density      A mm-2
Power                W
Force                N
Energy   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

MODEL DATA
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 to
                    1300.0
```



```
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 -1300.0   -780.0   -260.0    260.0   780.0  1300.0
______ Component: BX, from buffer: Line, Integral = -11.81011984905
_ _ _  Component: BX, from buffer: Line, Integral = -11.81011984905
_ _ _  Component: BY, from buffer: Line, Integral = 29.1555025265095
_ . _  Component: BY, from buffer: Line, Integral = 29.1555025265095
```

```
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
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 to
                    1300.0
```

Case examined

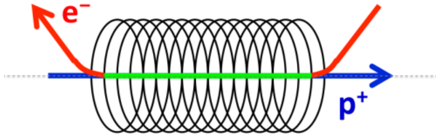
- Vertical: V/8, V, V, V/2, V/4 of maximum 0.02 T
- Horizontal: -7/8H, -H, -H, +H, +3/4H of 0.02T

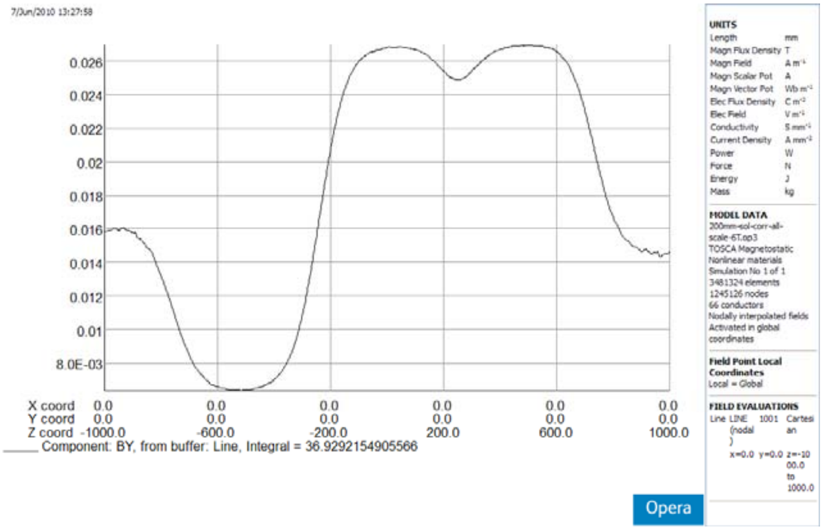
Actual error may not follow this physical pattern. e.g., there could be a change in sign in the middle of a short corrector.

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





Component: BY, from buffer: Line, Integral = 36.9292154905566

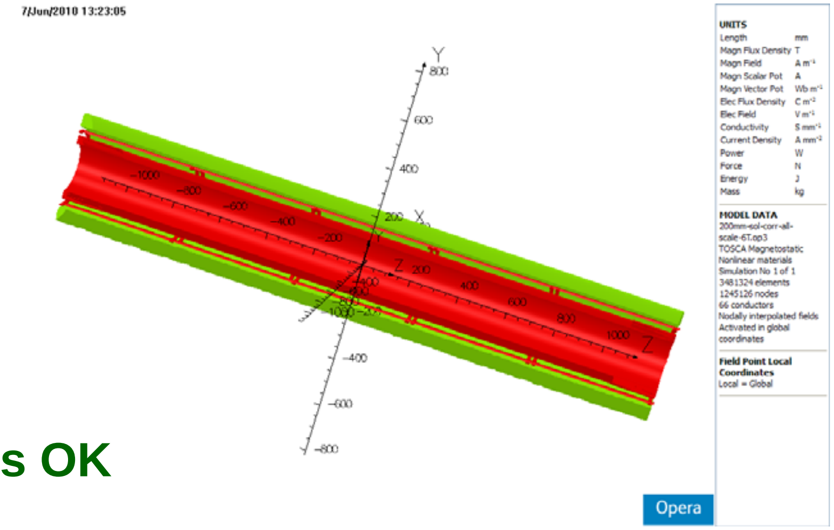
UNITS

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
200mm-sol-corr-all-scale-6T.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3481324 elements
1245126 nodes
66 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=-1000.0 to 1000.0



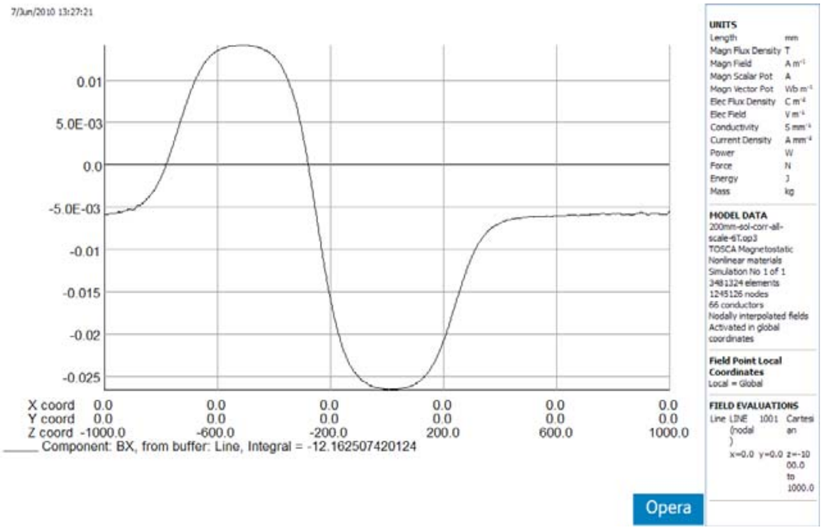
UNITS

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
200mm-sol-corr-all-scale-6T.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3481324 elements
1245126 nodes
66 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

Looks OK



Component: BX, from buffer: Line, Integral = -12.162507420124

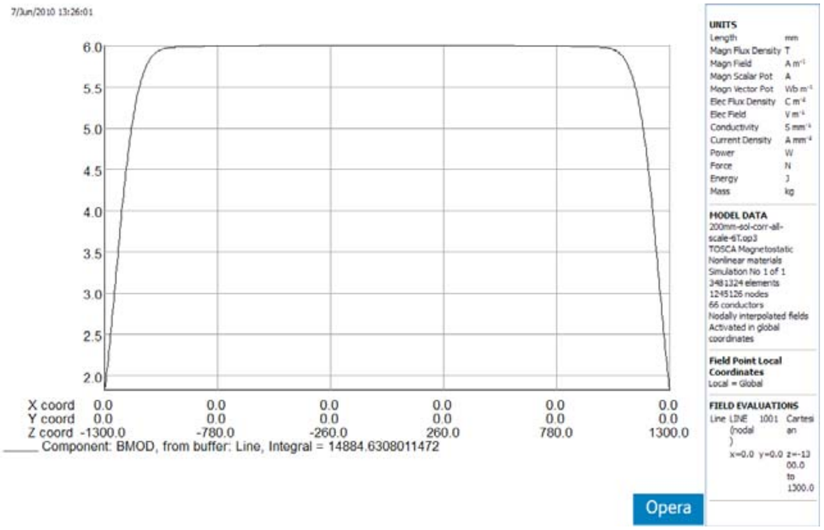
UNITS

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
200mm-sol-corr-all-scale-6T.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3481324 elements
1245126 nodes
66 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=-1000.0 to 1000.0



Component: BMOD, from buffer: Line, Integral = 14884.6308011472

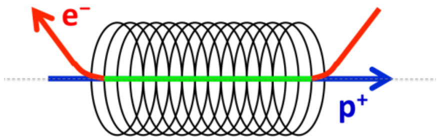
UNITS

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
200mm-sol-corr-all-scale-6T.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3481324 elements
1245126 nodes
66 conductors
Nodally interpolated fields
Activated in global coordinates

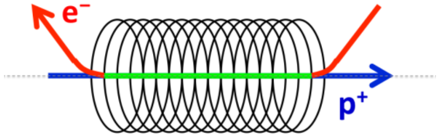
Field Point Local Coordinates
Local = Global

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

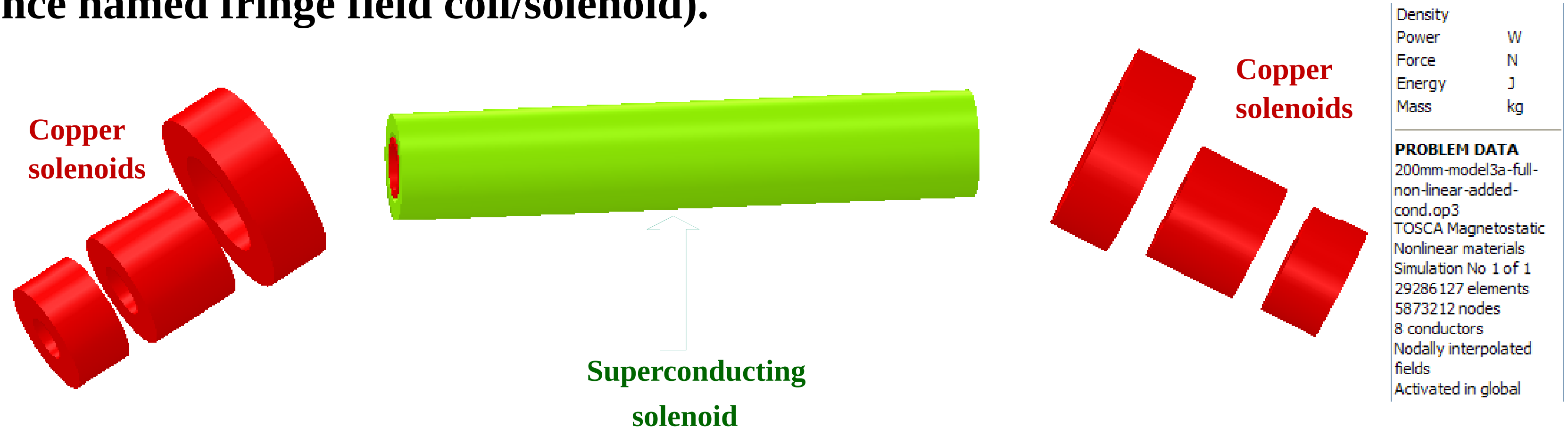


Exterior Field Requirements

Field between superconducting and copper solenoid



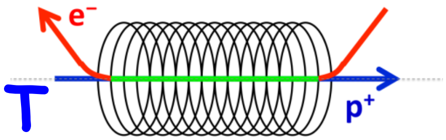
- **0.3 T (3 kG) field is desired between copper solenoids and superconducting solenoid along the beam path.**
- **This would be a very large fringe field in the axial direction. Removing or reducing the radial width of the iron will generate some. However, that would also allow outside components to 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).**



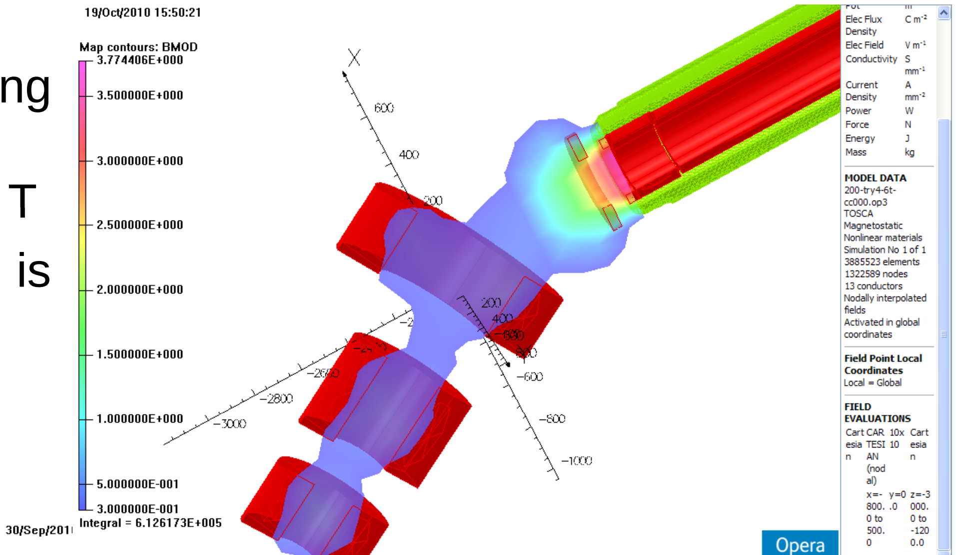
Density	
Power	W
Force	N
Energy	J
Mass	kg

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



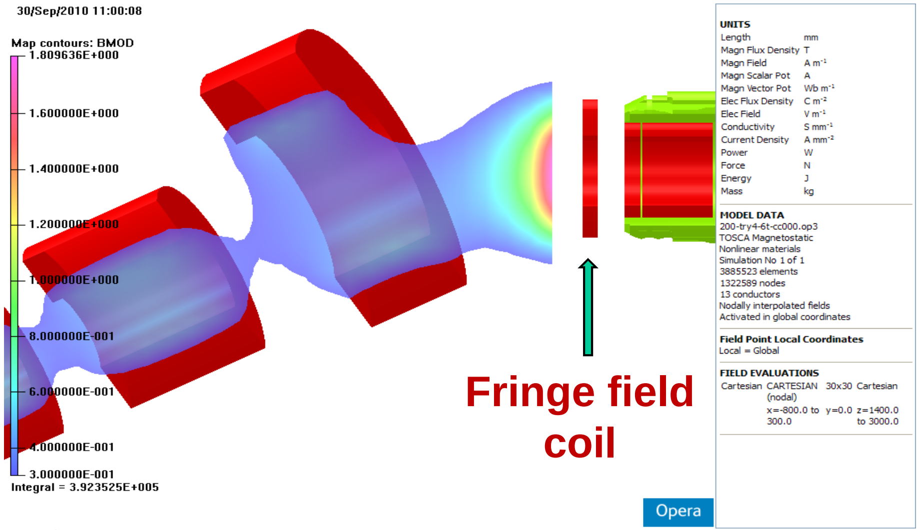
Elec Flux Density	C m⁻²
Elec Field	V m⁻¹
Conductivity	S mm⁻¹
Current Density	A mm⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
200-try4-6t-cc000.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3885523 elements
1322589 nodes
13 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal)	10x10	Cartesian
	x=-800.0 to 500.0	y=0.0	z=-3000.0 to -1200.0



Fringe field coil

UNITS

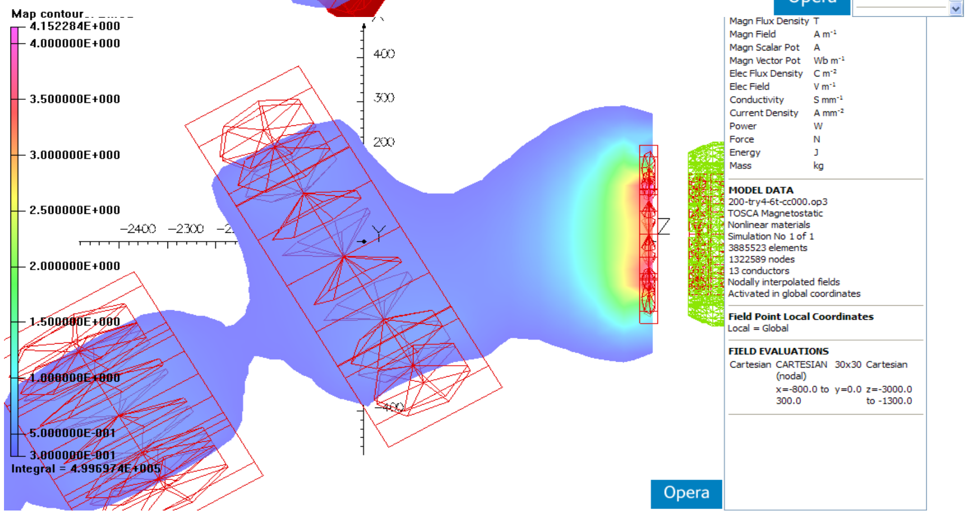
Length	mm
Magn Flux Density	T
Magn Field	A m⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m⁻¹
Elec Flux Density	C m⁻²
Elec Field	V m⁻¹
Conductivity	S mm⁻¹
Current Density	A mm⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
200-try4-6t-cc000.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3885523 elements
1322589 nodes
13 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal)	30x30	Cartesian
	x=-800.0 to 300.0	y=0.0	z=1400.0 to 3000.0



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

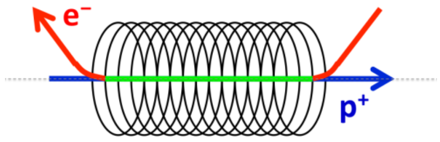
MODEL DATA
200-try4-6t-cc000.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3885523 elements
1322589 nodes
13 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

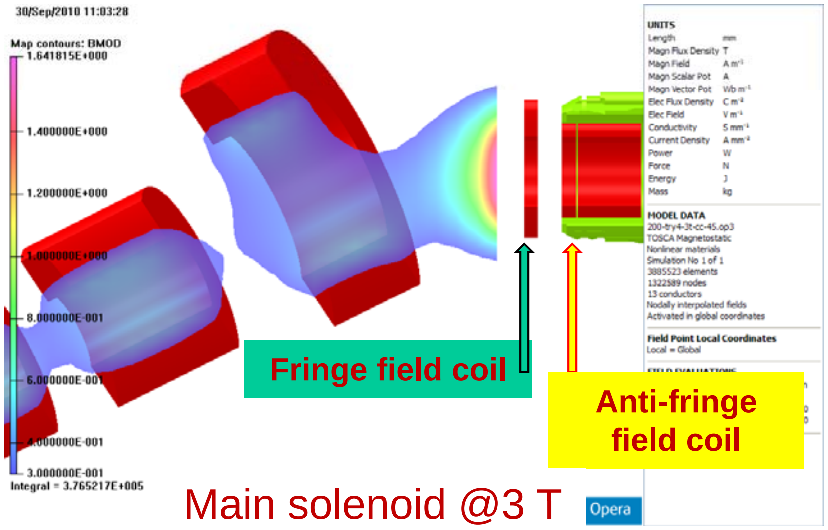
FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal)	30x30	Cartesian
	x=-800.0 to 300.0	y=0.0	z=-3000.0 to -1300.0

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.



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

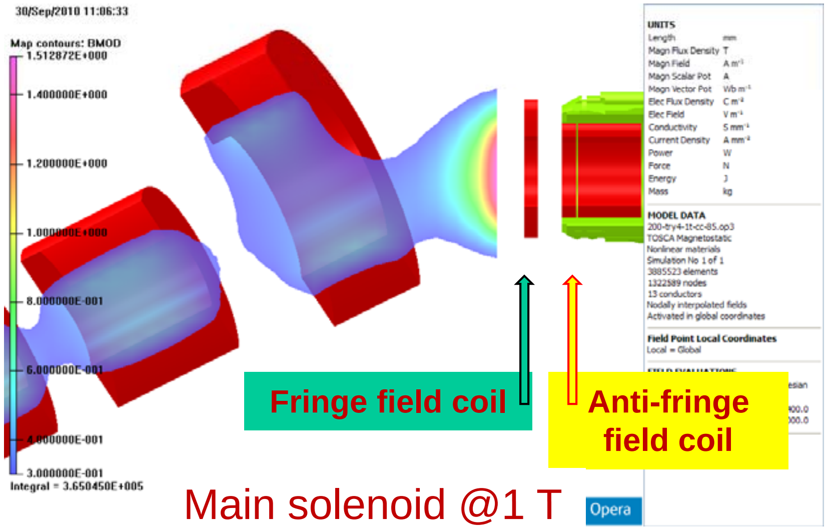
MODEL DATA
200-try4-3t-cc-45.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3885523 elements
1322589 nodes
13 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

Fringe field coil

Anti-fringe field coil

Main solenoid @3 T



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-try4-1t-cc-85.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
3885523 elements
1322589 nodes
13 conductors
Nodally interpolated fields
Activated in global coordinates

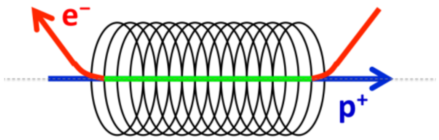
Field Point Local Coordinates
Local = Global

Fringe field coil

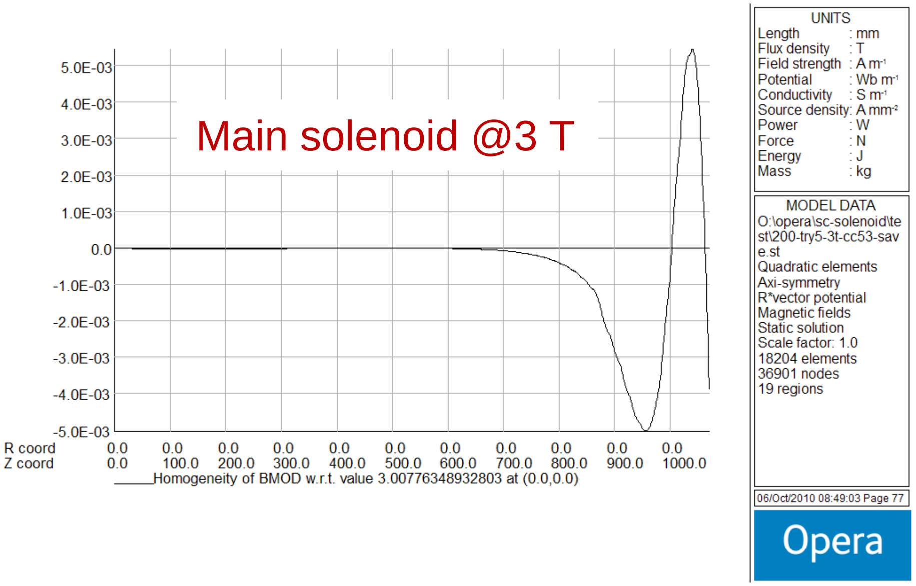
Anti-fringe field coil

Main solenoid @1 T

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 < 6 x 10^{-3} from z=-1050 to +1050).



Homogeneity of BMOD w.r.t. value 3.00776348932803 at (0.0,0.0)

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

MODEL DATA
O:\opera\sc-solenoid\test\200-try5-3t-cc53-save.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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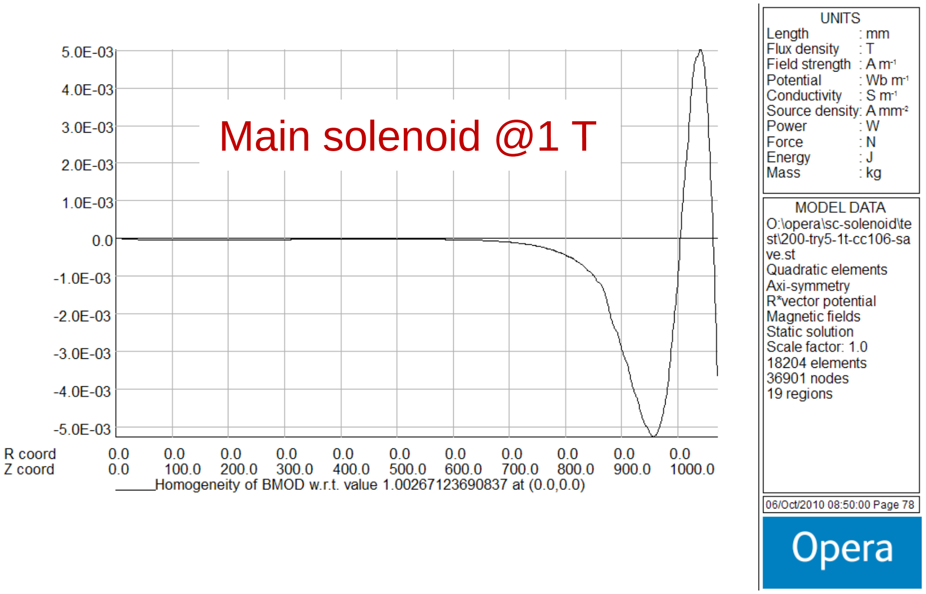

Homogeneity of BMOD w.r.t. value 1.00267123690837 at (0.0,0.0)

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

MODEL DATA
O:\opera\sc-solenoid\test\200-try5-1t-cc106-save.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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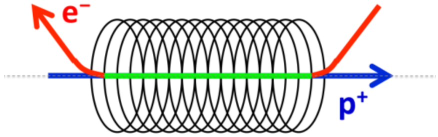
Summary



- 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.