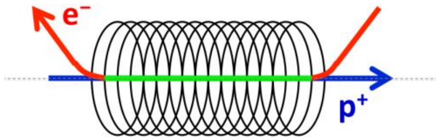


RHIC elens Solenoid Experience

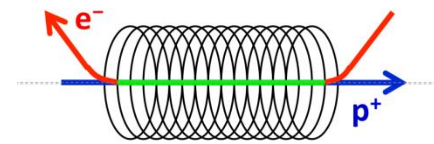
Magnetic and Overall Design

Ramesh Gupta
Superconducting Magnet Division

December 4, 2024

(based on the presentation on November 16, 2010, and before)

Design Requirements of elens Superconducting Solenoid



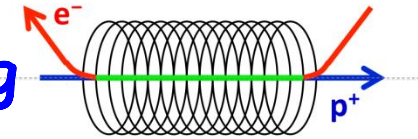
1. Maximum design field : 6 T (@ ~4.4 K) + margin
   – Specified operating field range 1 T to 6 T
2. Field errors, -1050 <z <1050 mm, 1-6 T : <6 x 10^{-3}
3. Required fringe field : field along the beam path till copper solenoid > 0.3T
   – Unique situation, unique solution (Note: spec is for “>”, not “<“)
4. Field straightness: ±50 μm, -1050<z<1050 mm (stringent requirement)

(NOTE: no hard spec on coil i.d.)

How one obtains the above straightness, has a large impact on the solenoid coil i.d. => on the stored energy => on the magnet cost.

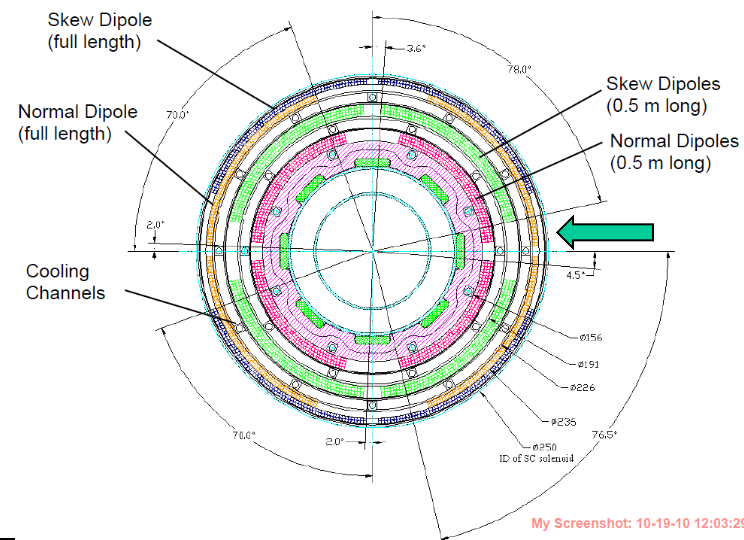
➢ *Therefore, it was worth having a second look on the approach.*

0^{th} Order Optimization for Value Engineering



Field straightness *was a critical* requirement. This required dipole correctors.
Original design had high current density copper correctors inside the solenoid

- Moving them outside significantly reduced the solenoid coil i.d. from 292 mm to 200 mm.
- That brought a large reduction in the stored energy and Lorentz forces. The solenoid became technically less demanding, in addition to significantly reducing the cost.
- Correctors become superconducting with a field strength very small for sc magnets.

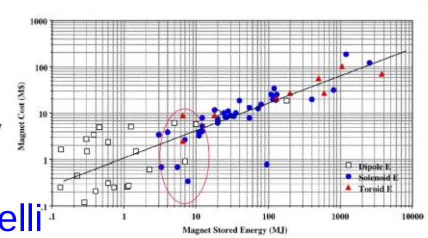


$(292/200)^2$ => 2.1

Green's law

For solenoids:

$C(M\$_{2007}) = 0.95\ E(MJ)^{0.67}$



$C(M\$_{2007}) = 0.95\ E(MJ)^{0.67}$

Slide from the last presentation of Calvelli

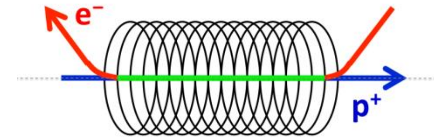
In the region of 2 ÷ 10 MJ there are large incertainties that needs to be estimated for our case

Nov 4, 2024

Earlier design was with warm correctors

(since the correctors were inside the superconducting solenoid, solenoid coil i.d. must be greater than last corrector)

Main Parameter List of the elens solenoid



Superconductor

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)

Computed Short Sample @2K: 9.1 T

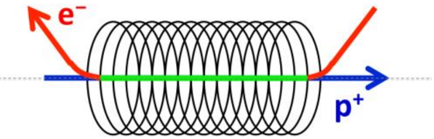
Spin Rotator Solenoid

	Short	Long
B(T)	7.42	8.19
L(m)	2-2.4	5.7-6.1

Bore diameter 100 mm

Coil i.d. ??? mm

Conductor for the elens Solenoid



Conductor Specifications for the Electron-Lens Solenoid

The conductor chosen for this magnet is a rectangular monolith insulated with a half-overlap wrap of Kapton film, 25 micron thick.

Bare conductor parameters

Dimension	1.78 mm x 1.14 mm ± 0.01 mm
Copper/Non-Cu ratio	3.0
Number of filaments	150
Ic at 7 T (4.22 K)	> 700 A
RRR	>100
Twist Pitch	20 mm ± 2 mm

Wire delivered

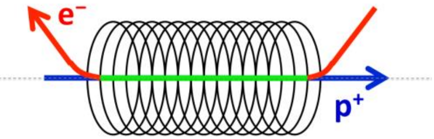
Spec limits					1.12 - 1.16	1.76 - 1.80
BilletNo	PieceNo	PartNo	POno	Length	Thickness	Width
52901	1	21286	167810	8290	1.146	1.790
52901	2	21286	167810	7590	1.145	1.789
52902	1	21286	167810	8500	1.147	1.790
52902	2	21286	167810	8075	1.148	1.791
52903	1	21286	167810	3092	1.154	1.793
52903	2	21286	167810	8100	1.152	1.791
52903	3	21286	167810	5505	1.153	1.792
52904	2	21286	167810	10961	1.148	1.791

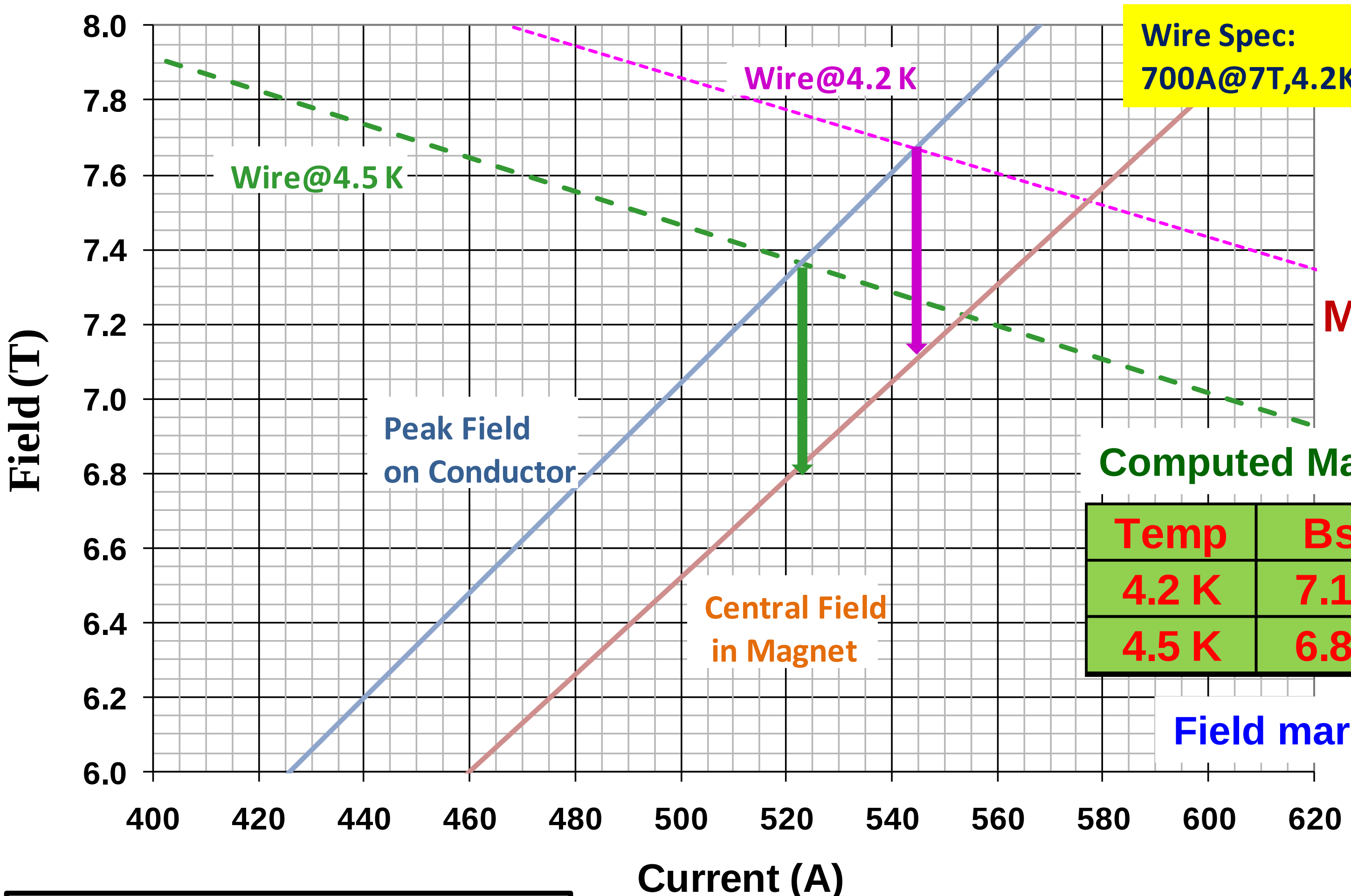
Spec limits			>100	2.70 - 3.30	>700	Reference
BilletNo	PieceNo	End	RRR	CuSc	Ic (7_0T)	nValue
52901	2	A	155	**3.04**	872	31.0
52902	2	A	167	**3.08**	858	31.0
52903	2	A	154	**3.11**	820	31.8
52904	2	A	167	**3.23**	815	30.0

A few specs for wire ordered

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)

E-lens Solenoid Wire and Magnet Performance





Max. Design Field: 6 Tesla

Computed Magnet Performance:

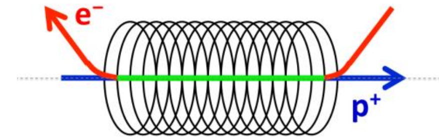
Temp	Bss	Bpk	I(A)
4.2 K	7.1 T	7.65 T	545 A
4.5 K	6.8 T	7.35 T	523 A

Field margin@4.5 K: ~13%

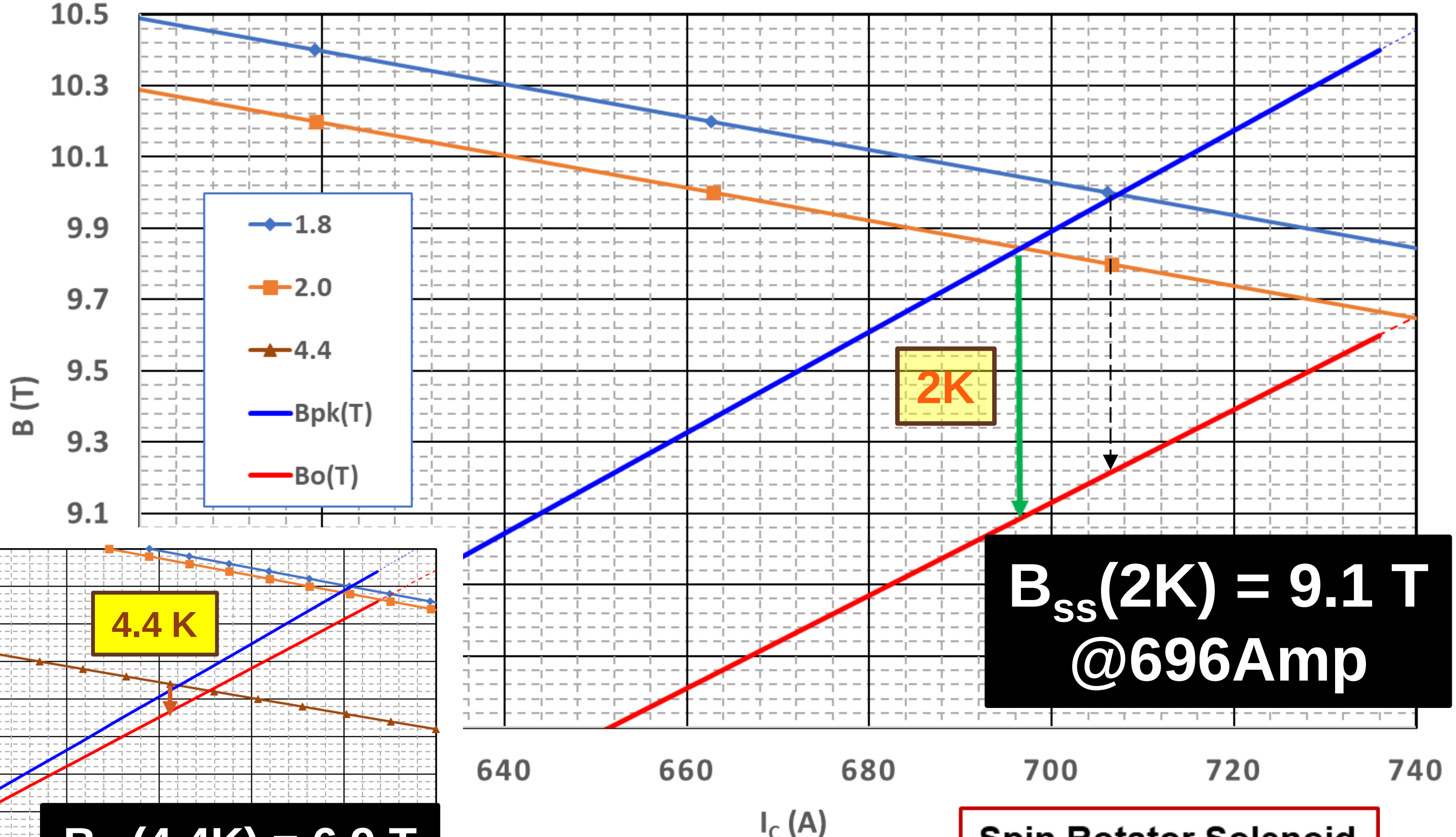
B_{ss}(2K) = 9.1 T@696Amp
(next slide)

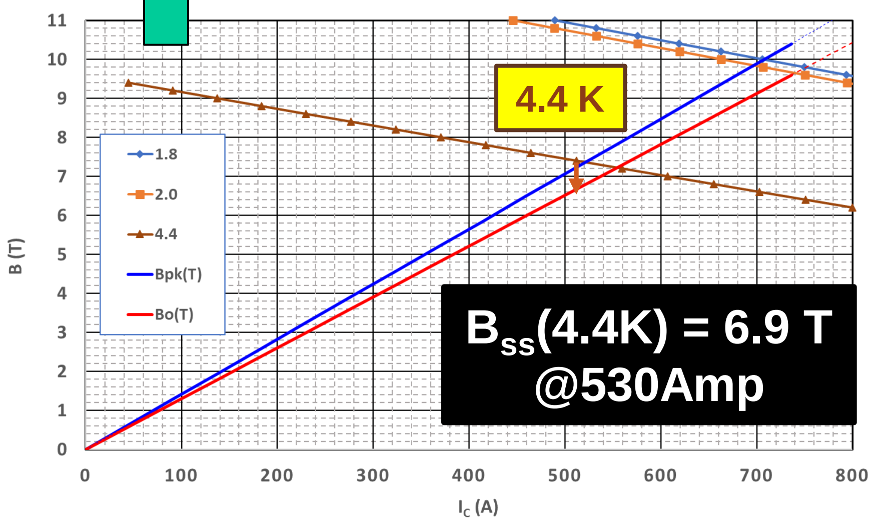
Stored Energy: ~1.4 MJ, Inductance:~14 Henry

E-lens Computed Magnet Performance @2K



Coil i.d. 200 mm





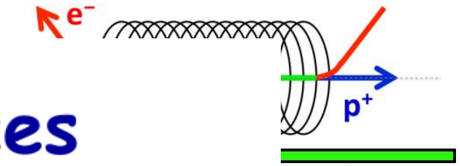
For comparison

Spin Rotator Solenoid

	Short	Long
B(T)	7.42	8.19
L(m)	2-2.4	5.7-6.1

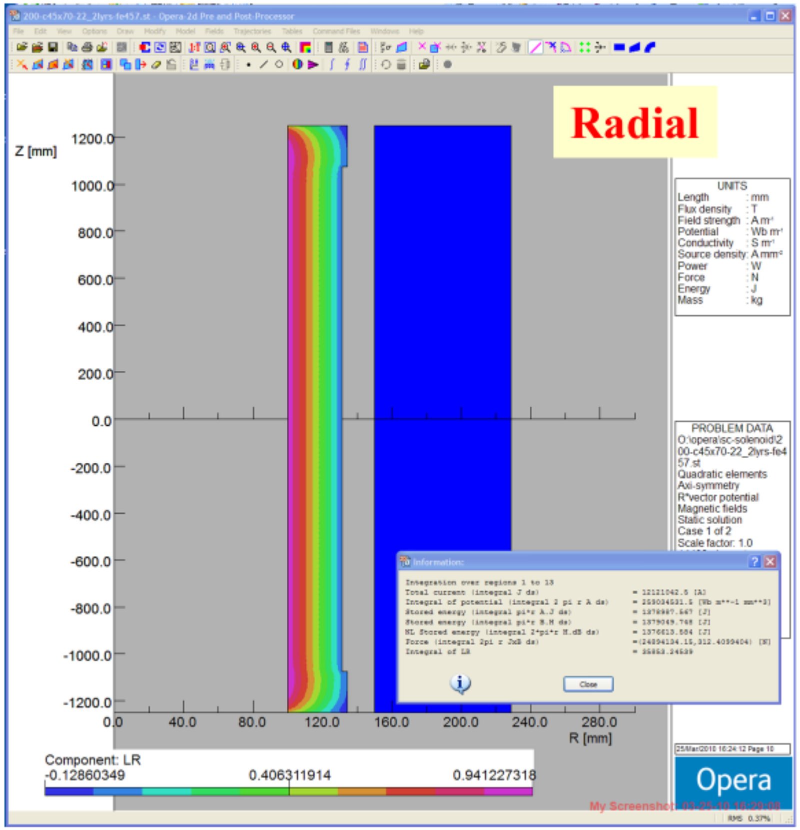
Bore diameter 100 mm

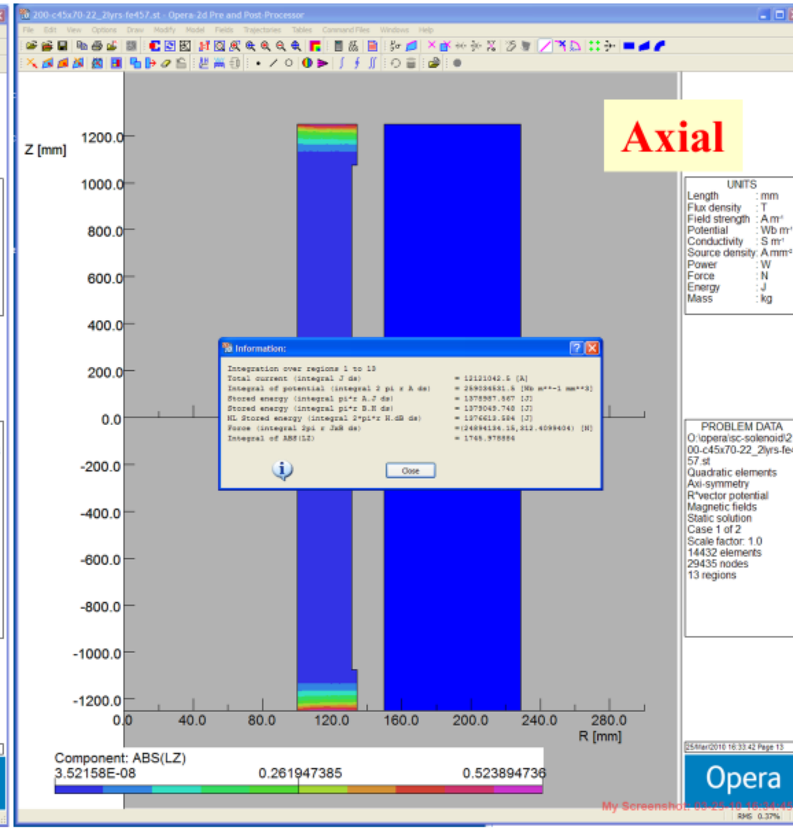
Coil i.d. ??? mm



Stored Energy and Lorentz Forces

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





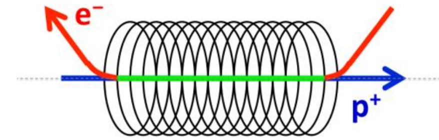
Radial Lorentz force (hoop stress) : ~24 MN

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

6 T @ ~442 A

Ramesh Gupta, March 30, 2010

Axial force containment (1)

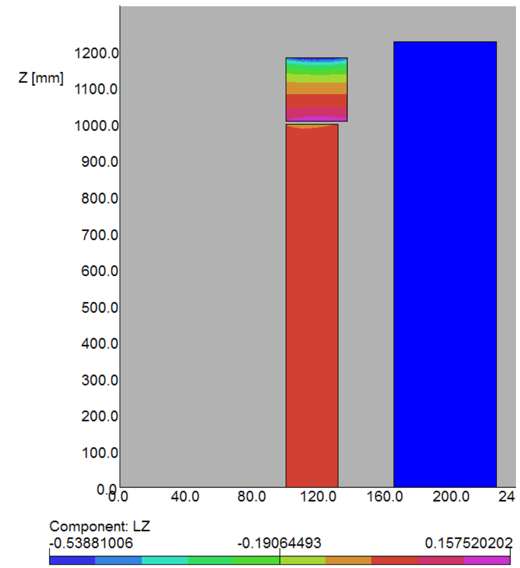


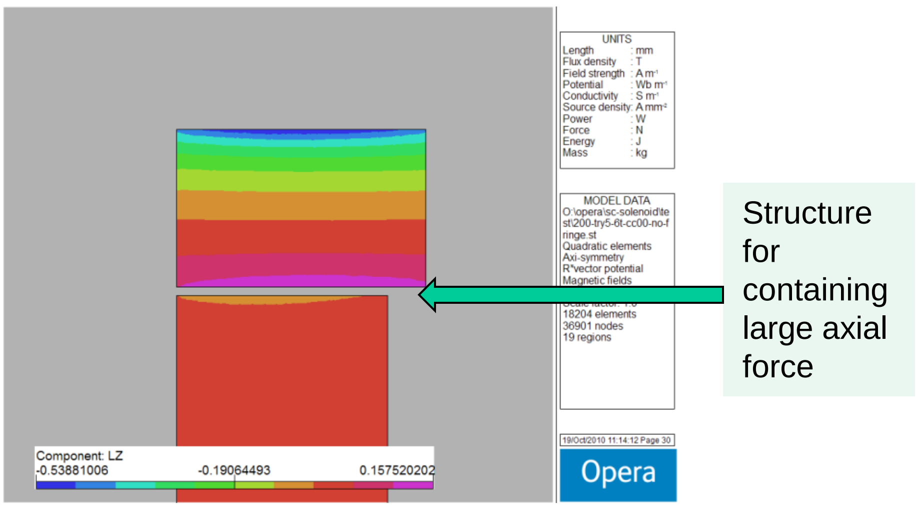
• Insert structure towards the end of the coil to contain forces

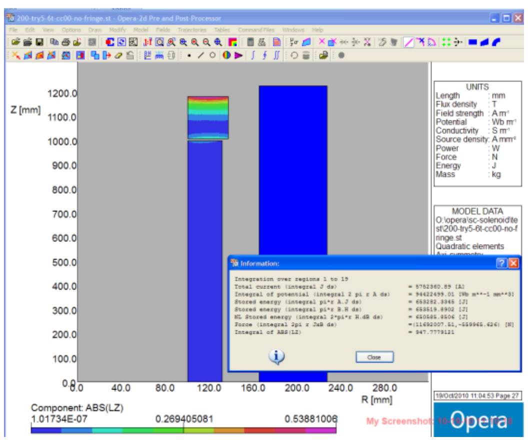
• Coil is wound continuously through the end structure to keep axial forces contained throughout (during quench).

• If coils were separate and one in the end was to quench. then the end forces will no longer be balanced (NOT ok).

• Quench protection is such that the full-length double layers are quenched



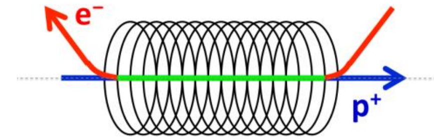




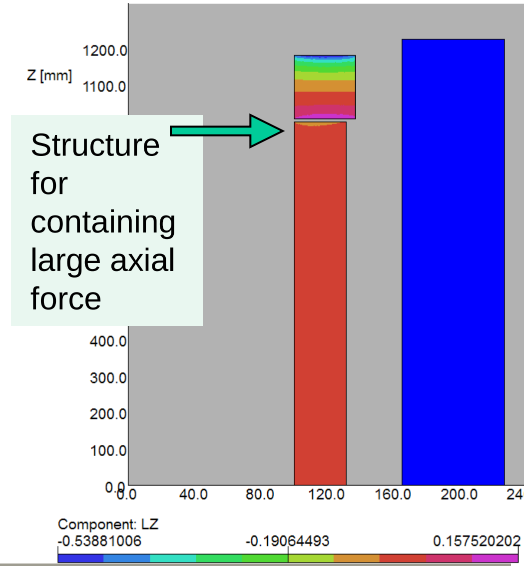
Stored Energy: ~1.4 MJ;

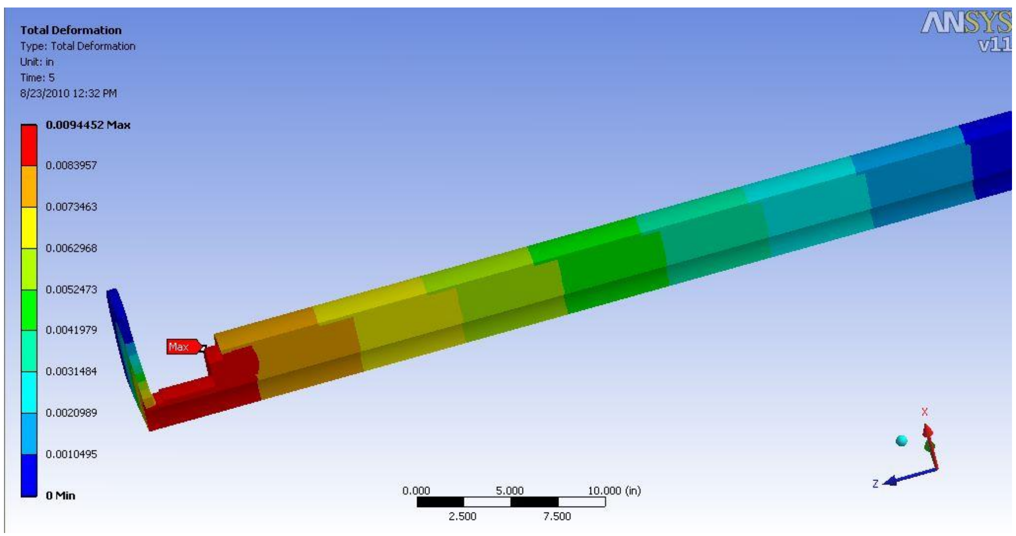
Inductance : ~14 Henry

Axial force containment (2)

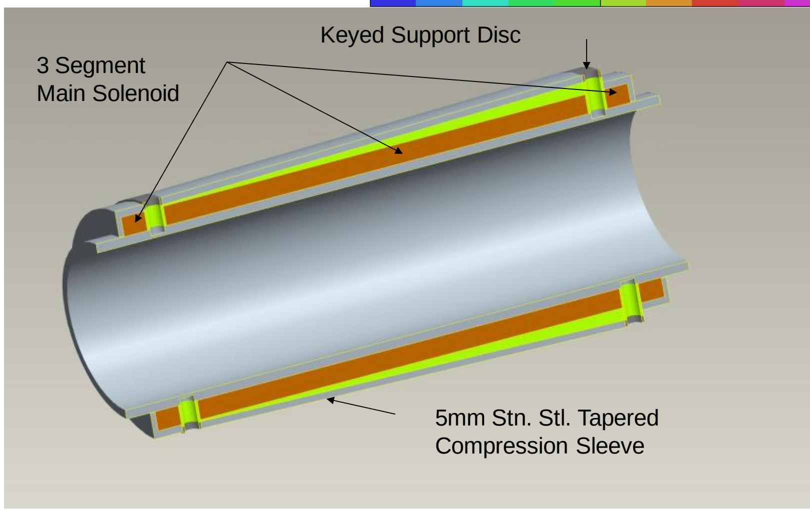


- Insert structure towards the end of the coil to contain forces
- Coil is wound continuously through the end structure to keep axial forces contained throughout (during quench).
- The axial forces exerted by the outer solenoid sections are transferred around (NOT on) the center section.
- The keyed support discs transfer the load to the support tube and the compression sleeve.

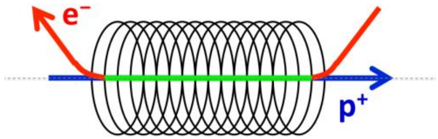




Courtesy: A. Marone



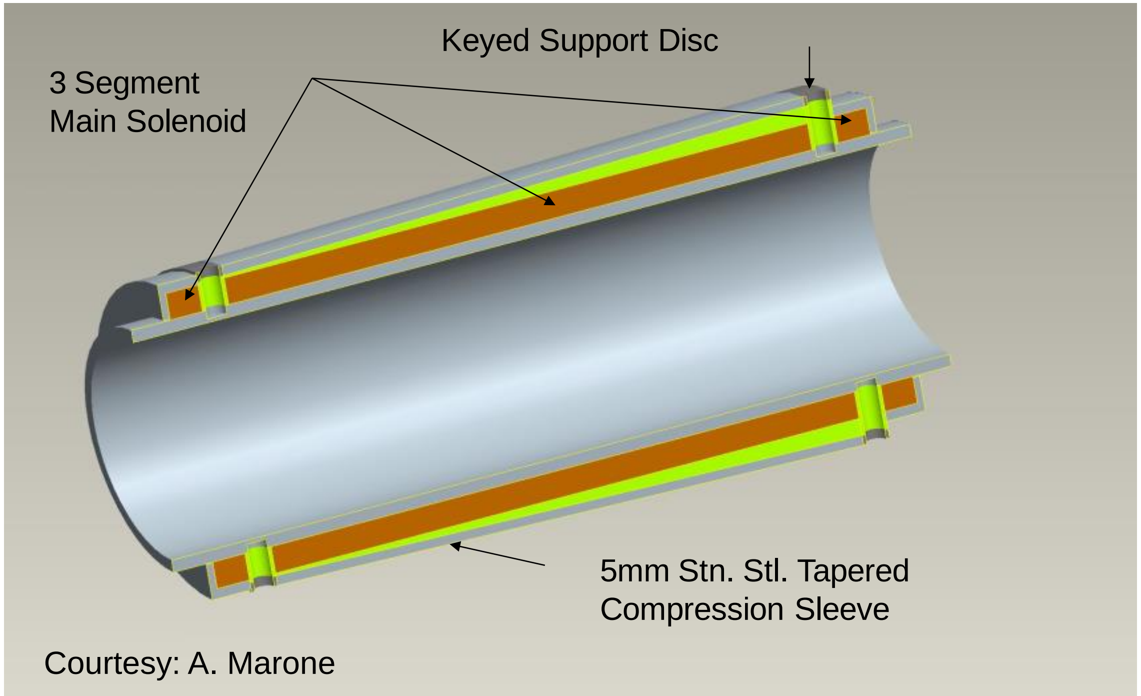
Radial Force Restraint



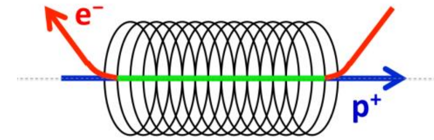
- Outward pressure (hoop stress) from 24 MN Lorentz forces.
- Radial forces can be restrained by 6 mm of material stressed (hoop) to 40,500 psi with coil energized.
- Resulting stress in support tube (pressure vessel) is 17,000 psi. Required strain for S.S. tube is 0.014.
- S.S. Tube heated to 80 degree C will give the required interference.
- Tube has 10 mm radial taper.

Engineering group should make a separate presentation as this was a major and a remarkable piece of work

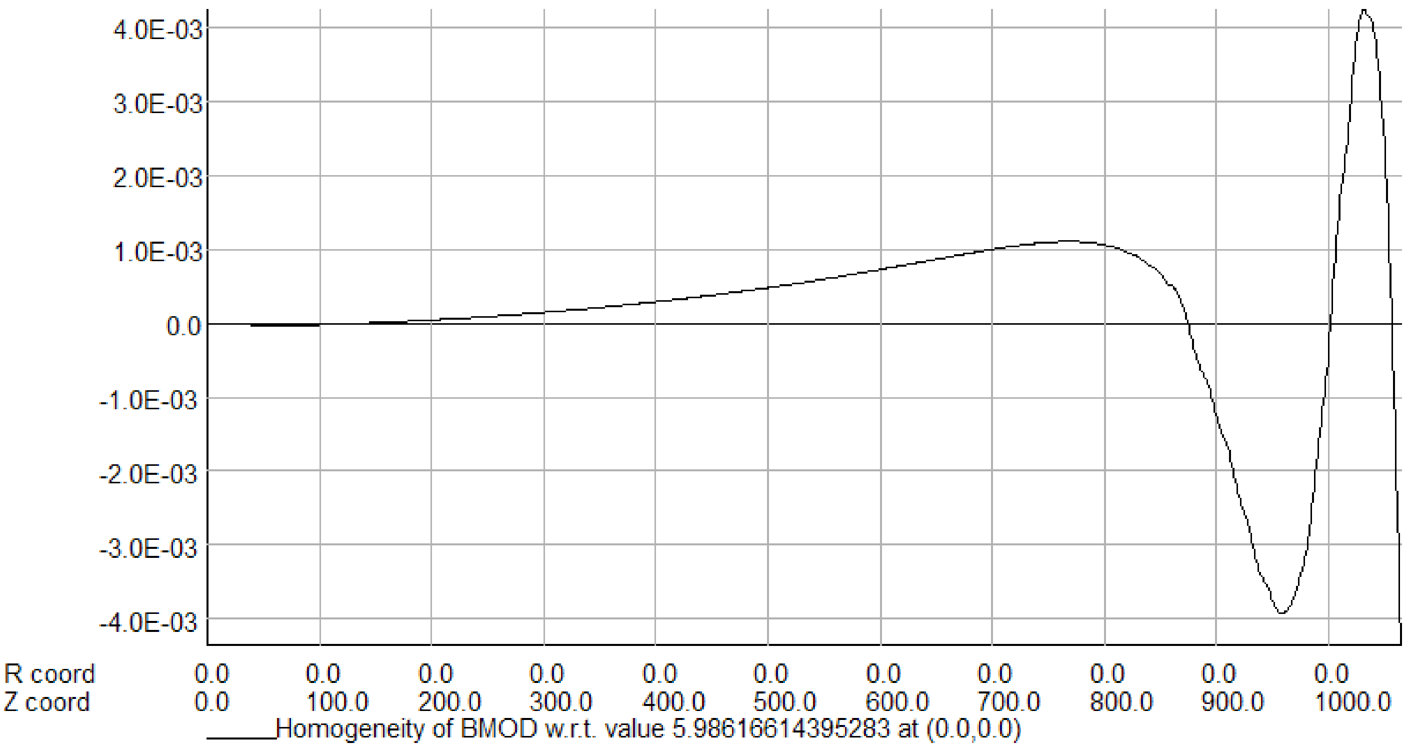
Would have needed thicker SS sleave for 2K (high field design)

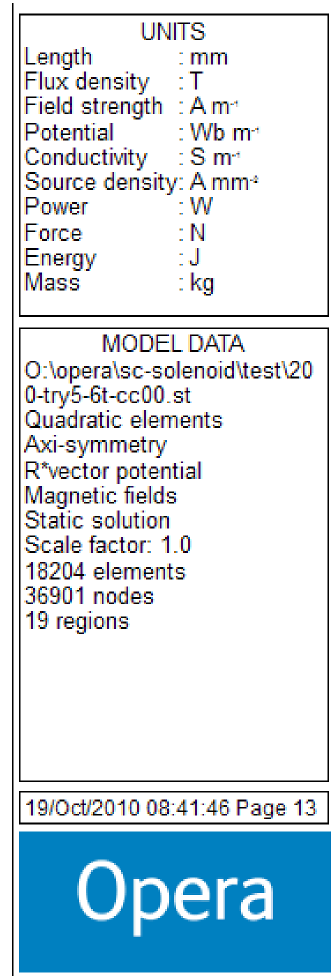


Relative Field Errors on the Axis



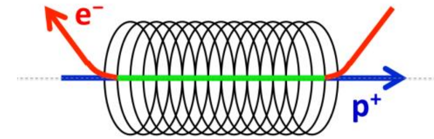
Relative field errors (computed) to 1075 mm < 6 x 10^{-3}





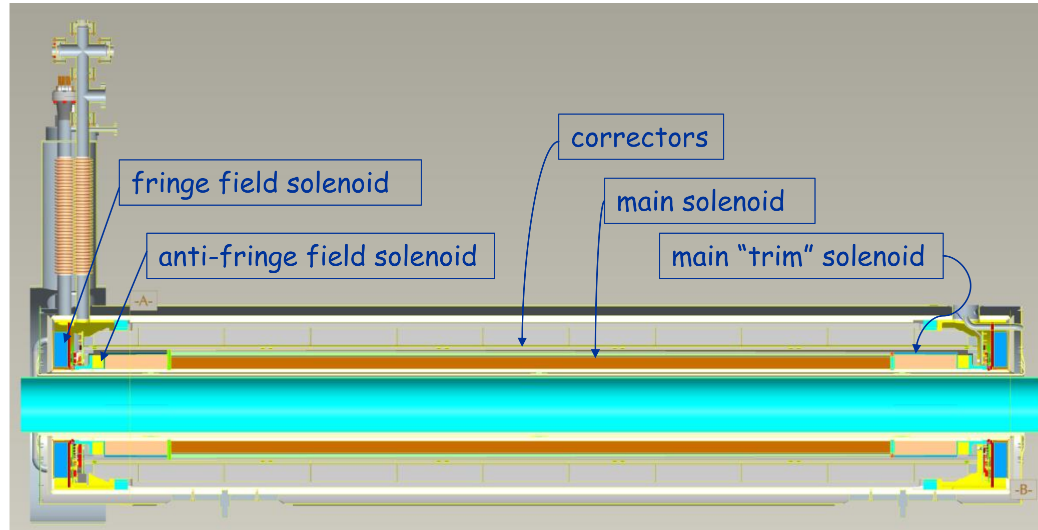
Specifications was to 1050 mm < 6 x 10^{-3}

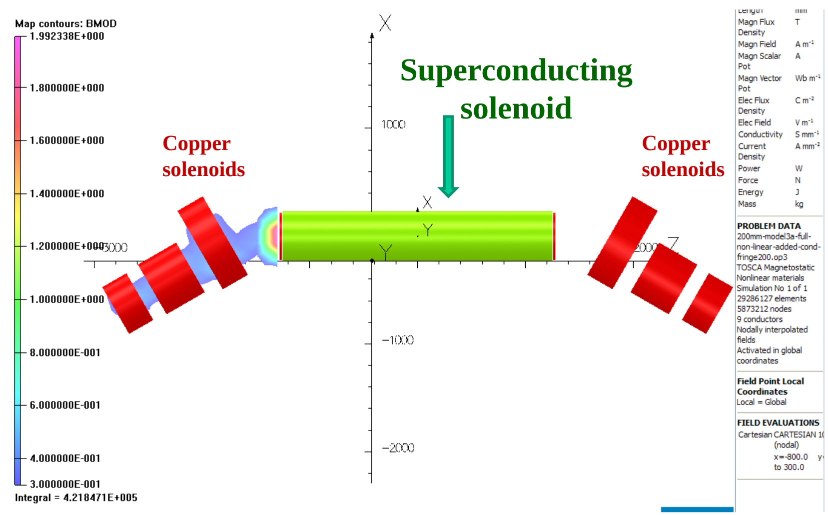
Overall Magnetic System Package

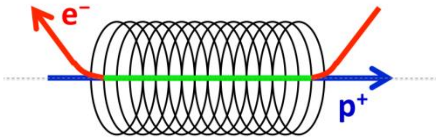


Overall magnetic system consists of:

- Main solenoid
  - including trim sections
- Correction coils
  - long and short
  - horizontal and vertical
- Fringe field coils
- Anti-fringe field coils
- Room temperature magnets in beamline (not part of the magnet division scope of work)

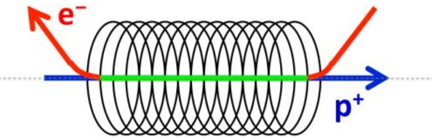




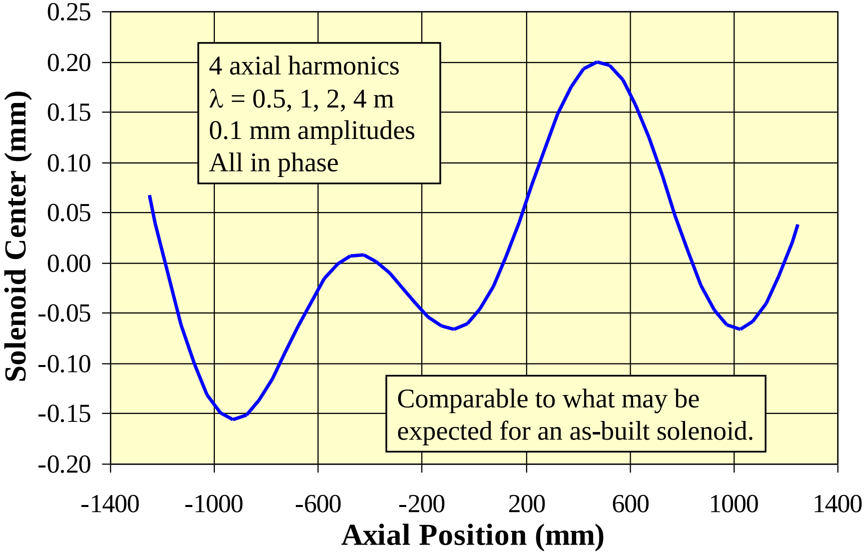


Dipole correctors within the same superconducting solenoid package

Estimation and correction of axis offset with 0.02 T correctors

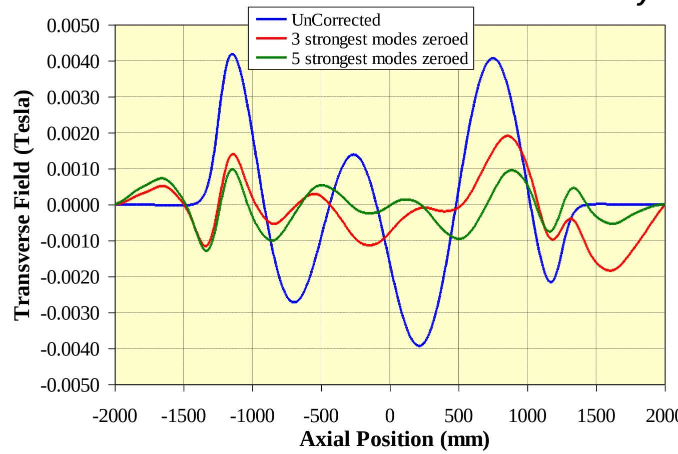


Hypothetical Vertical Offset Profile (before correction)

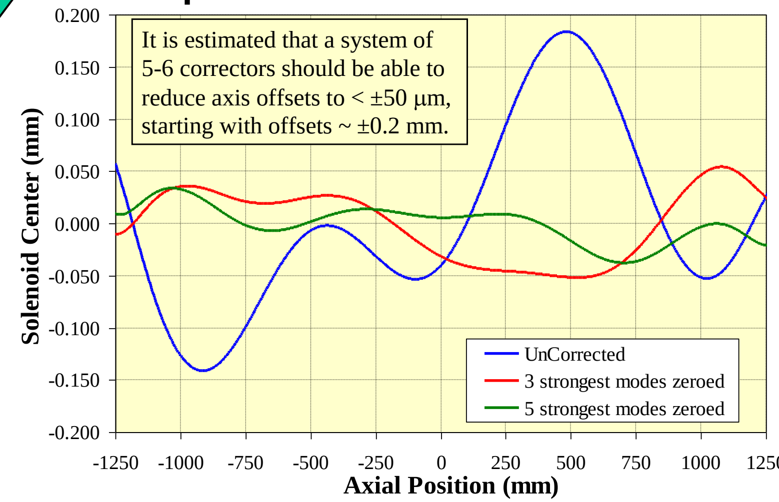


After correction

Computed Profile of Vertical Field, B_y

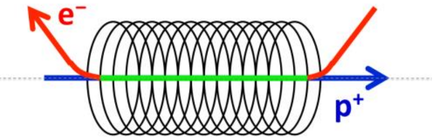


Computed Axis Offset Profile

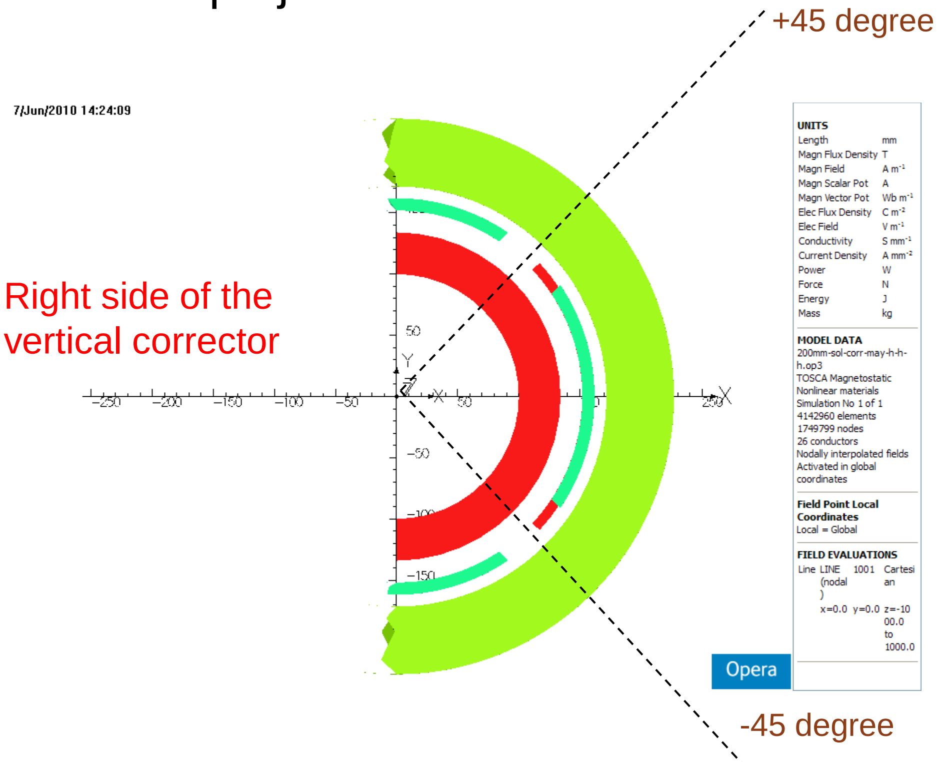


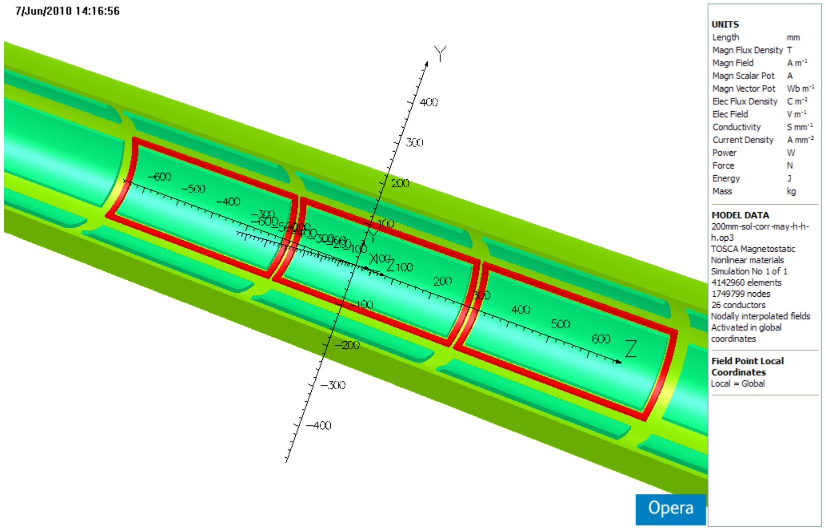
Courtesy: Animesh Jain

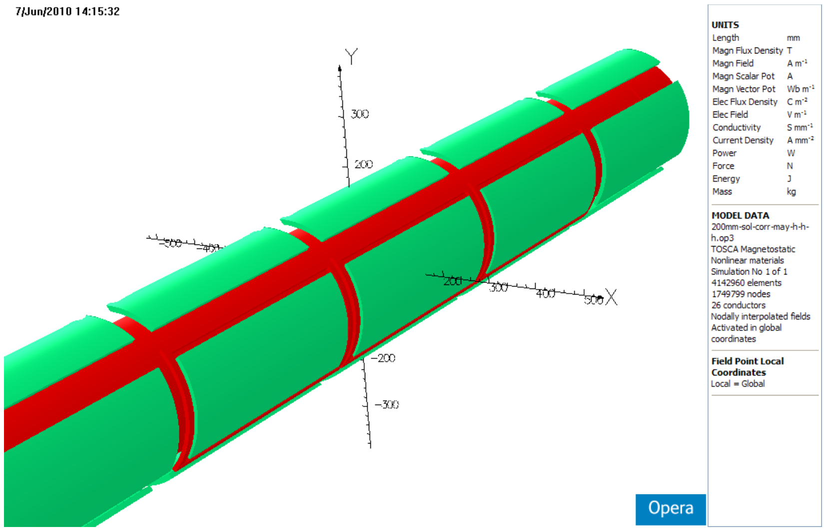
Slotted Corrector Design

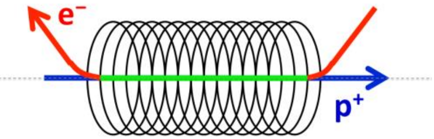


- Slots are machined in an aluminum tube and superconducting wires are place in the slots.
- Horizontal and vertical correctors are placed in the same radial location.
- Slotted design removes significant conflict with other projects in the use of certain machine



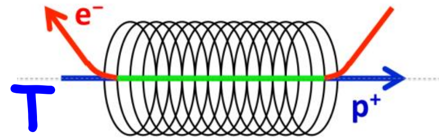






Exterior Field Requirements

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

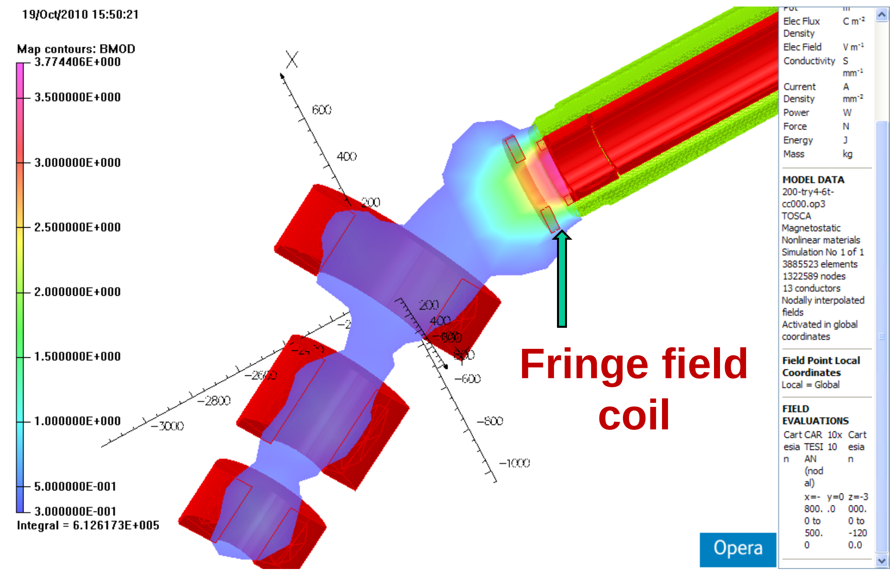


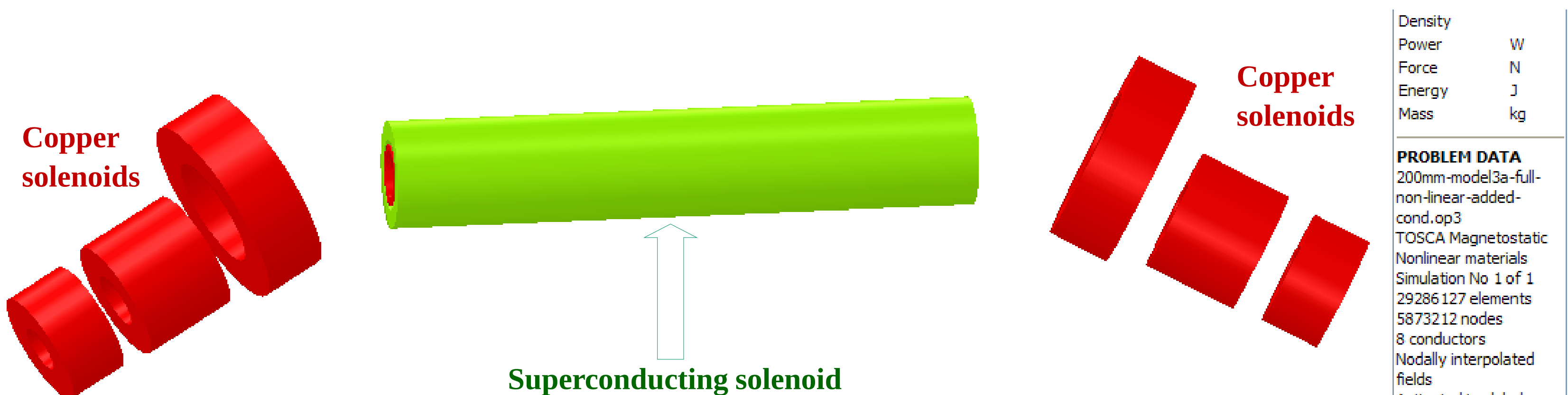
• The desired field (>0.3 T between copper solenoids and superconducting solenoid along the electron beam path) with desired spacing is not possible with copper solenoid alone.

• This requirement is satisfied by inserting superconducting coils inside the cryostat of the main superconducting solenoid.

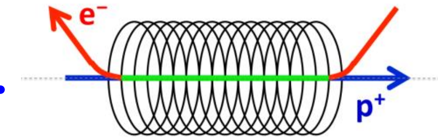
• The size and location of the fringe field coil is optimized to minimize space usage

• 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

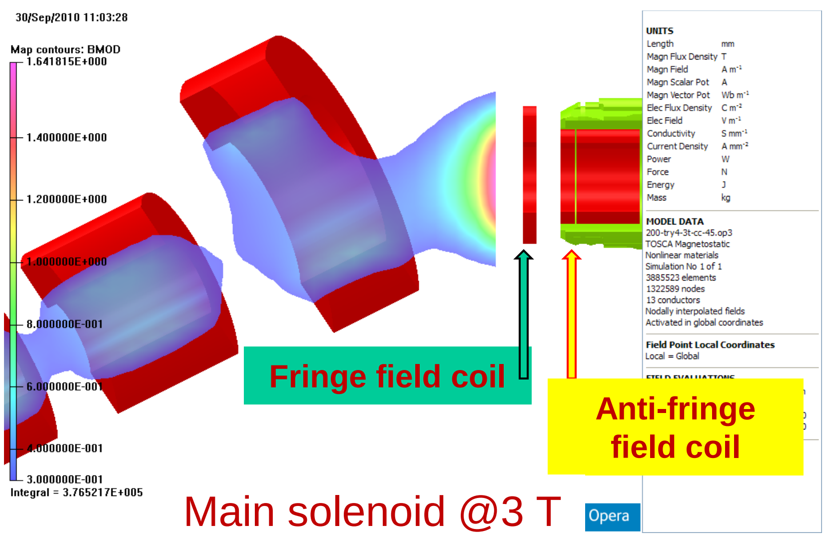


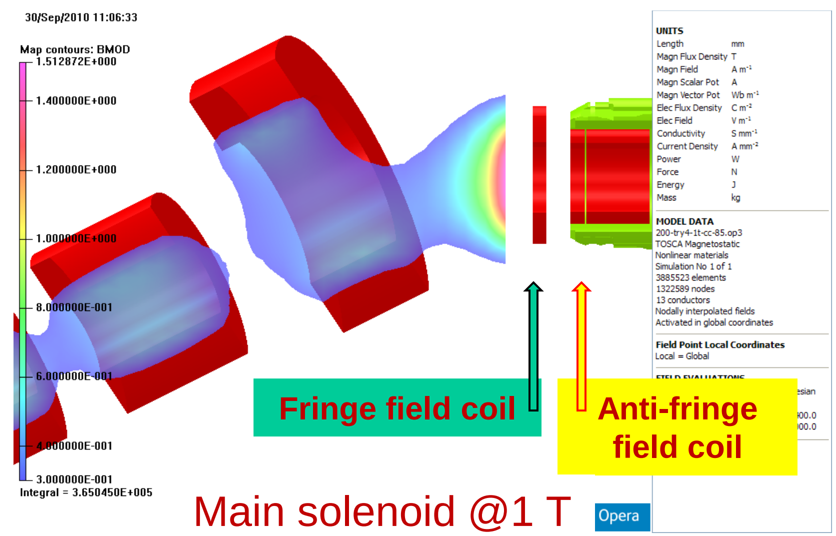
• However, the situation becomes complicated when the main solenoid is operated at a field lower than 6 T – the desired range is field as low as 1 T.

• 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.

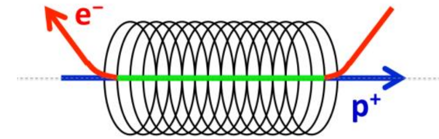
• To obtain desired the desired (>0.3 T) field between copper solenoids and the superconducting solenoid, the fringe field must run at full power.

• To obtain the required field quality, an additional coil (anti-fringe field coil) is added and powered independently to adjusted field quality.

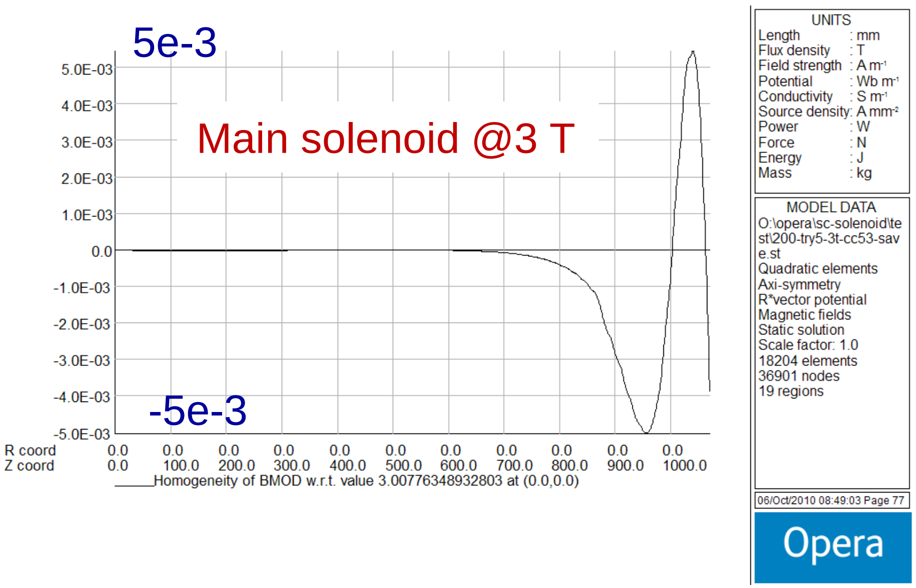


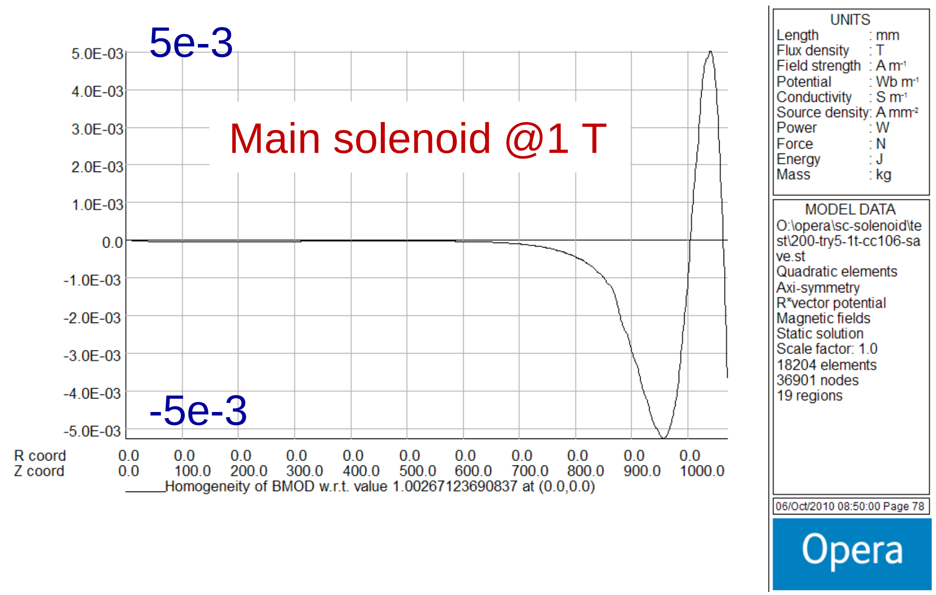


Field Quality in Main Solenoid at 1T & 3T with the desired fringe field (>0.3 T)

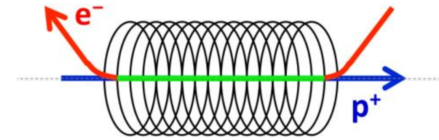


- To obtain the desired (>0.3 T) field between copper solenoids and the superconducting solenoid, the fringe field must run at full power.
- To obtain the required field quality, the current in the anti-fringe field coil is adjusted.
- To minimize the amp-turn requirements, anti-fringe field coils have 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 < 6 x 10^{-3} from z=-1050 to +1050).





Quench Protection



Total MIITs in the circuit:

$\int I^2\, dt$: ~1.5 MIITs

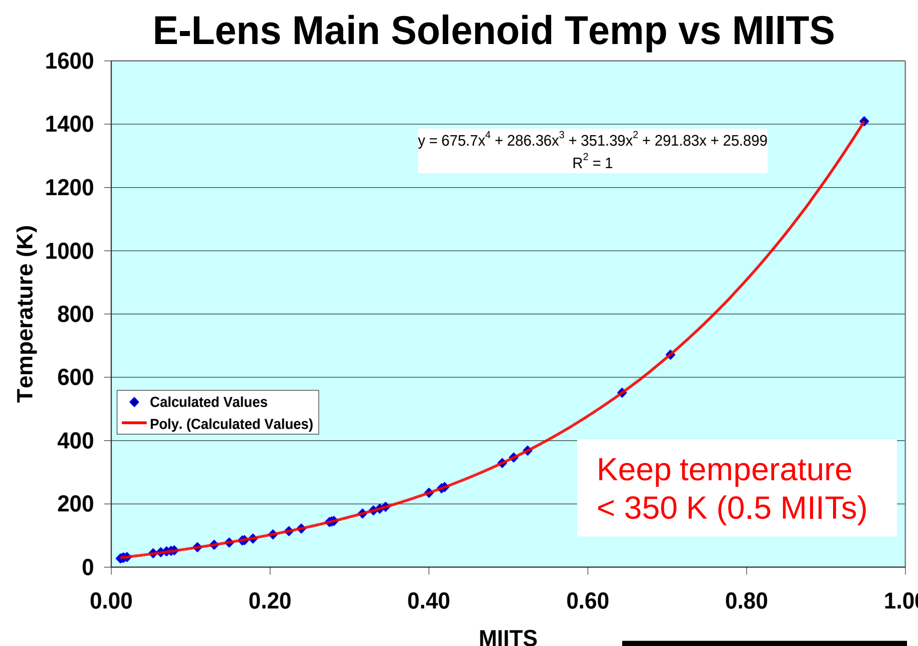
(for I=~500 A, L=~14 H, R_{dump}=~1.2 Ω; giving time constant: ~ τ= ~12 sec)

Diodes are across segments of the coil to limit the energy deposited in the coil segment (< 0.5 MIITs).

Bus & diodes are designed to handle a much higher MIITs than the coil conductor (> 1.5 MIITs).

Energy extraction is used to limit the maximum MIITs in the bus & diodes

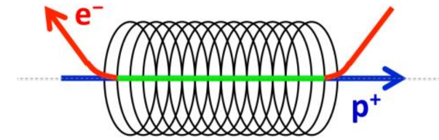
Energy extraction and quench protection diodes are used to control temperature rise in the coil in the event of a quench



Courtesy
Joe Muratore
George Ganetis

- ➢ **Should be safe as temperature remains well below 350 K**

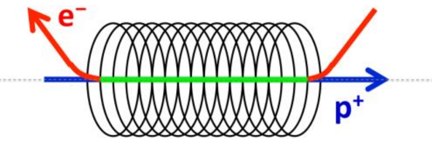
Value Engineering



- Use existing designs, materials, etc. wherever possible
  - Existing spare RHIC CQS cryostat
  - Surplus IsaBelle stainless steel helium vessels
  - Stock RHIC corrector superconducting wire
  - Stock RHIC Ultem support posts
- Use existing equipment, e.g.:
  - SMD direct wind machine, BEPC-II precision solenoid gantry
  - SMD automated take-up spools
  - C-AD curing oven
- Incorporation of Corrector Coils into superconducting magnet system:
  - Increased Solenoid costs, but reduced other eLens program costs (i.e. change is cost neutral) and improved eLens performance
- Development of fringe field solenoid coils:
  - Resolved previously unaddressed operational eLens issue

Courtesy: M. Anerella

Summary and Relevance to EIC Spin Rotator Solenoid



e-lens solenoid was a demanding magnet system with unique challenges

- Large magnet aperture with significant stored energy and Lorentz forces
- The field should be very straight inside the magnet and the field magnitude should be large outside the magnet
- In addition, significant effort was made to keep cost low and schedule accelerated

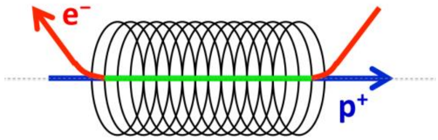
The following major steps were taken to meet various requirements:

- Novel and robust cryo-mechanical structure is developed (details not discussed)
- Corrector magnets made superconducting and compact (H&V together) to reduce size, stored energy and Lorentz forces in the superconducting solenoid
- A corrector design was developed to facilitate the required field straightness
- Significant work was done in magnetic measurement to assure straightness
- Superconducting fringe field and anti-fringe coils were added to obtain the large field outside while maintaining good field quality inside for 1 T to 6 T range.

Relevance to EIC spin rotator solenoid: <u>Significant field/aperture</u> (slides 4 & 7)

Extra slides

Project Scope

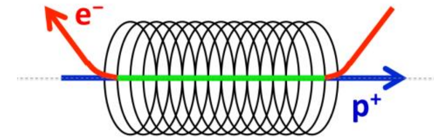


Design, Build and Test 2 eLens Solenoid Magnets:

- Magnetic, mechanical, electrical requirements as specified by C/AD
- Conduct ongoing communications & meetings to ***significantly*** clarify scope, improve design and performance
- Maintain cost control
- Deliver by April 2012

Courtesy: M. Anerella

Magnet Mechanical Design Overview



17 separate circuits / max. current:

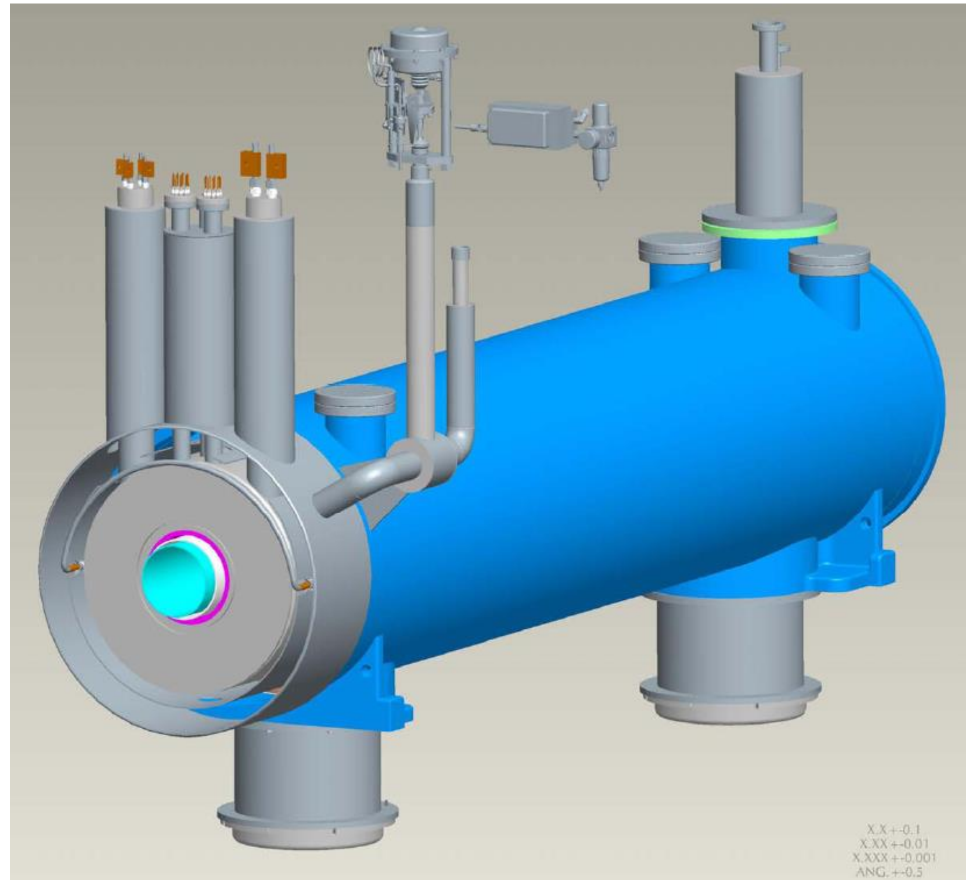
- 1 main solenoid / 460A
- 2 fringe field solenoids / 47A
- 2 anti-fringe field solenoids / 33A
- 5 0.5m vertical correctors / 26A
- 5 0.5m horizontal correctors / 26A
- 1 2.5m vertical corrector / 34A
- 1 2.5m horizontal corrector / 34A

Quench protection via cold diodes

Helium vessel cooled by liquid bath from RHIC supply

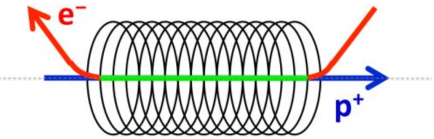
Outer heat shield actively cooled from 4K boil-off, inner shield conductively cooled

RHIC support posts / cryostat



Courtesy: M. Anerella

Dimensions



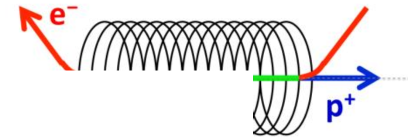
- Yoke length 96.5 inches (~2.5 m)
- Yoke OD 17.9 inches

- Cold mass length 104.7 inches
- Cold mass OD 19.5 inches

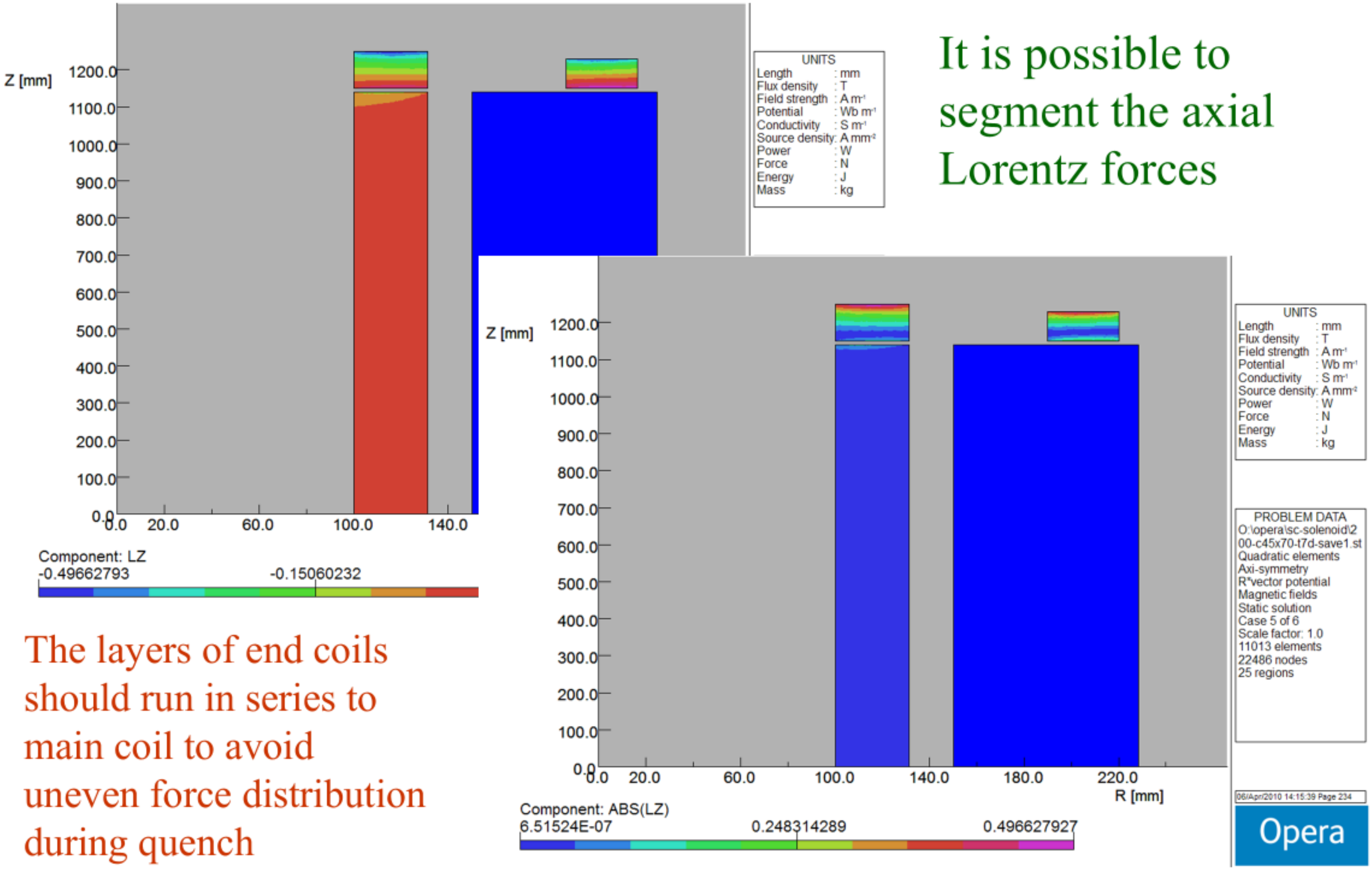
- Magnet OD 24.0 inches
- Magnet length 110.6 inches

- Magnet weight ~7000 lbs.

Courtesy: S. Plate



Axial Forces

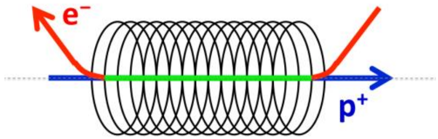


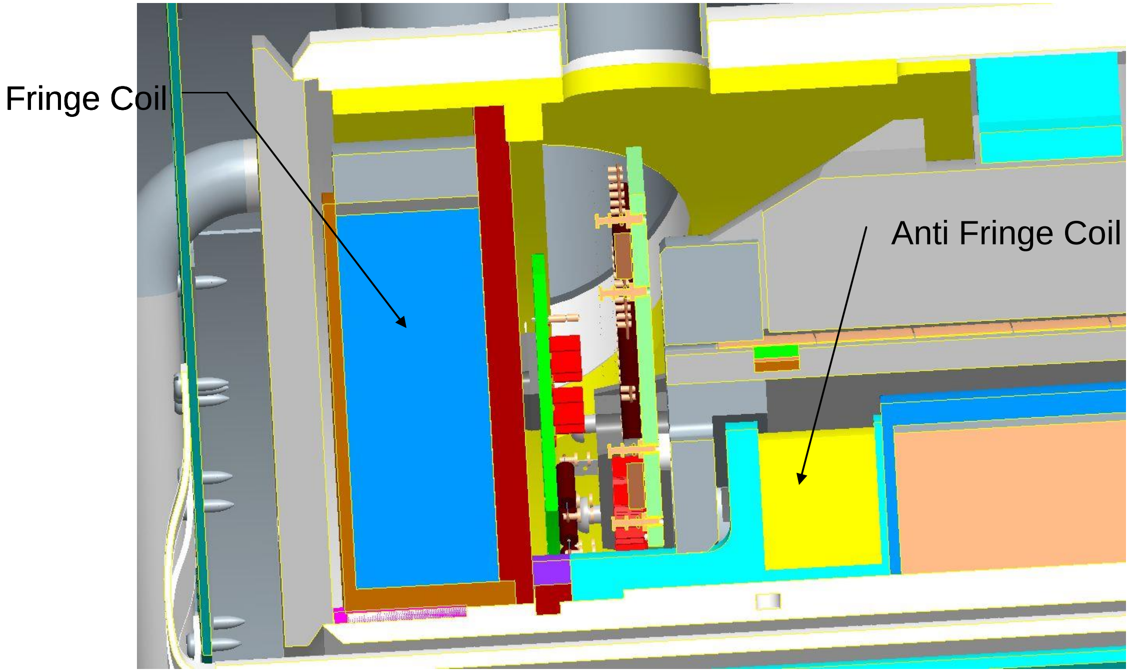
It is possible to segment the axial Lorentz forces

The layers of end coils should run in series to main coil to avoid uneven force distribution during quench

Ramesh Gupta, April 6, 2010

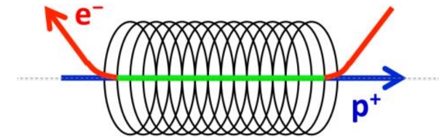
Fringe & Anti Fringe Coils

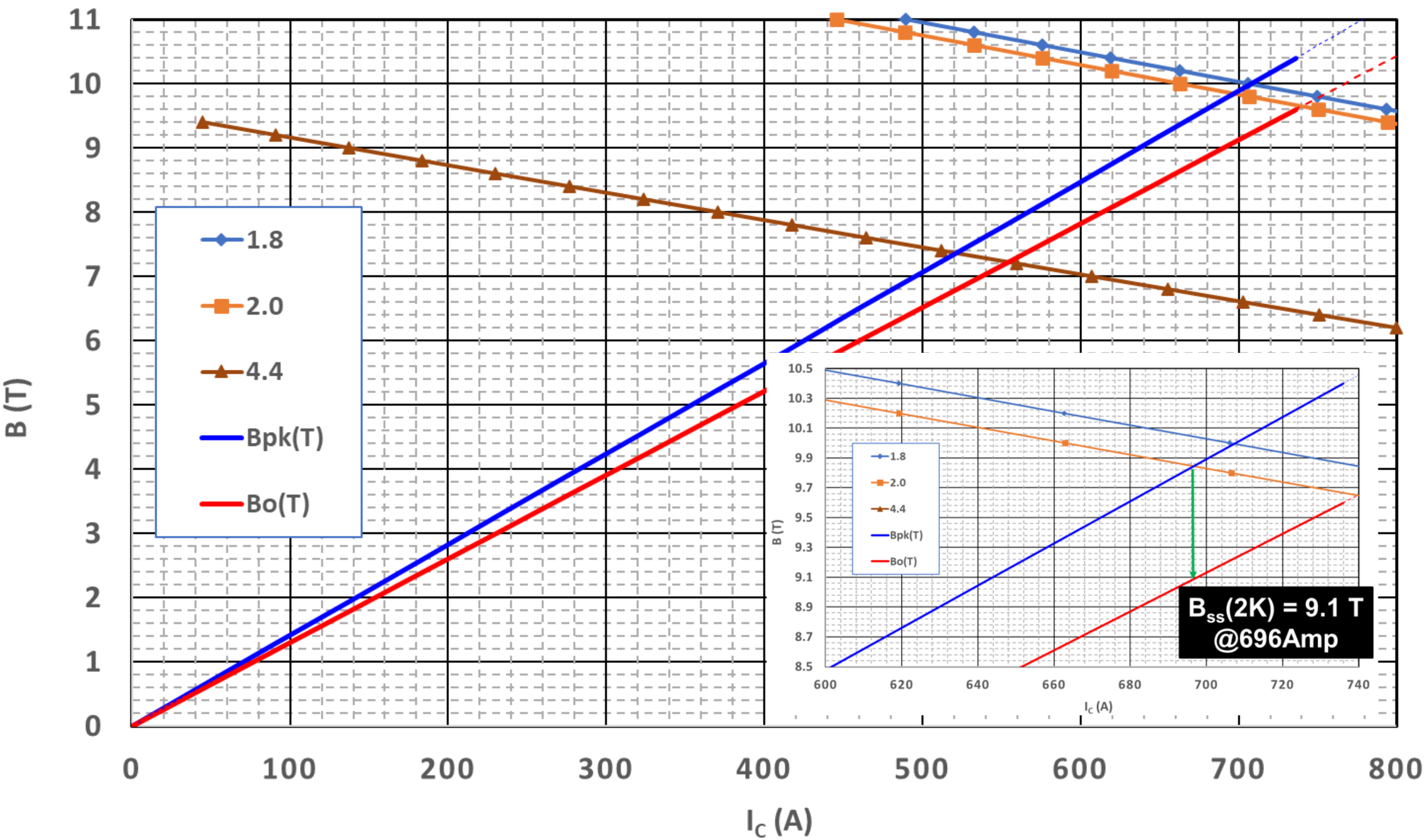




- Fringe
  - 40,000 lbs. axially inward (toward main Solenoid).
  - 2000 psi radially outward (@ O.D. of coil)
- Anti Fringe
  - 15,000 lbs. axially outward (toward fringe coil).
  - 225 psi radially inward

Courtesy: A. Marone


e⁻
p⁺


B (T)
I_C (A)
1.8
2.0
4.4
Bpk(T)
Bo(T)
B_{ss}(2K) = 9.1 T
@696Amp