ELECTROMAGNETIC DESIGN

CONDUCTION COOLED SSR MAGNET ASSEMBLY FOR PIP-II (FDR – Phase I)

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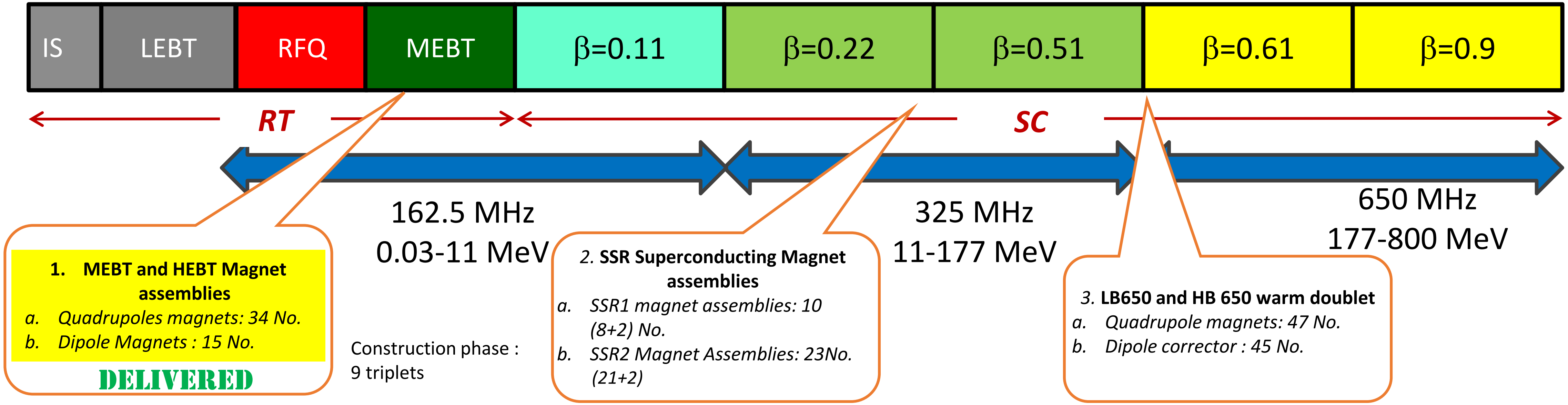
Outline

- **Introduction**
  - *BARC contribution for LINAC magnets in PIP-II technology map*

- **Electromagnetic Design of Conduction cooled magnet**
  - *Functional requirement specification*
  - *EM design for main solenoid*
  - *Corrector coil design*
  - *Fringe field on the cavity surface*
  - *Bucking coil optimization & tolerance studies on BC dimensions*
  - *Tolerance studies on bucking coil*
  - *Superconducting wire selection*
  - *Magnet load line & design operating margin*

- **Quench Studies**
  - *Quench initiated in main coil (variation in heat pulse, coil configuration & quench location)*
  - *Quench initiated in Bucking coil*
  - *Quench protection circuit*

Magnet Contribution- PIP-II LINAC Technology map



1. MEBT and HEBT Magnet assemblies

a. *Quadrupoles magnets: 34 No.*
b. *Dipole Magnets : 15 No.*

DELIVERED

Construction phase :
9 triplets

2. **SSR Superconducting Magnet assemblies**

a. *SSR1 magnet assemblies: 10 (8+2) No.*
b. *SSR2 Magnet Assemblies: 23No. (21+2)*

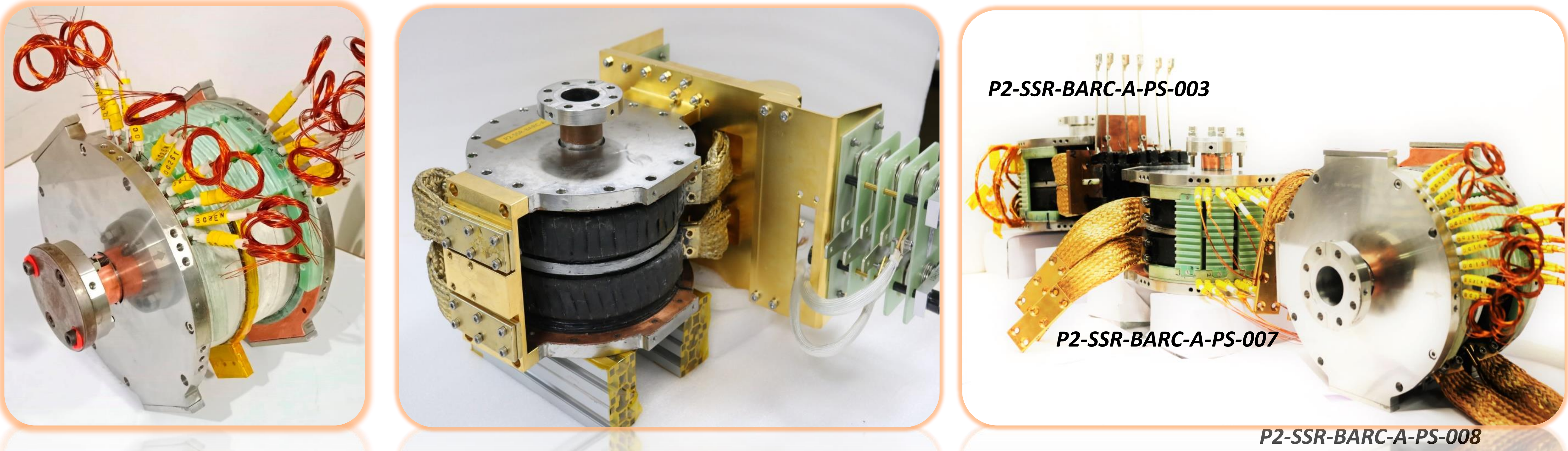
3. **LB650 and HB 650 warm doublet**

a. *Quadrupole magnets: 47 No.*
b. *Dipole corrector : 45 No.*

Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, **Solenoid**
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, **Solenoid**
LB 650 (β_G=0.61)	650	177-480	33/22/11	5-cell elliptical, **doublet***
HB 650 (β_G=0.9)	650	480-800	24/8/4	5-cell elliptical, **doublet***

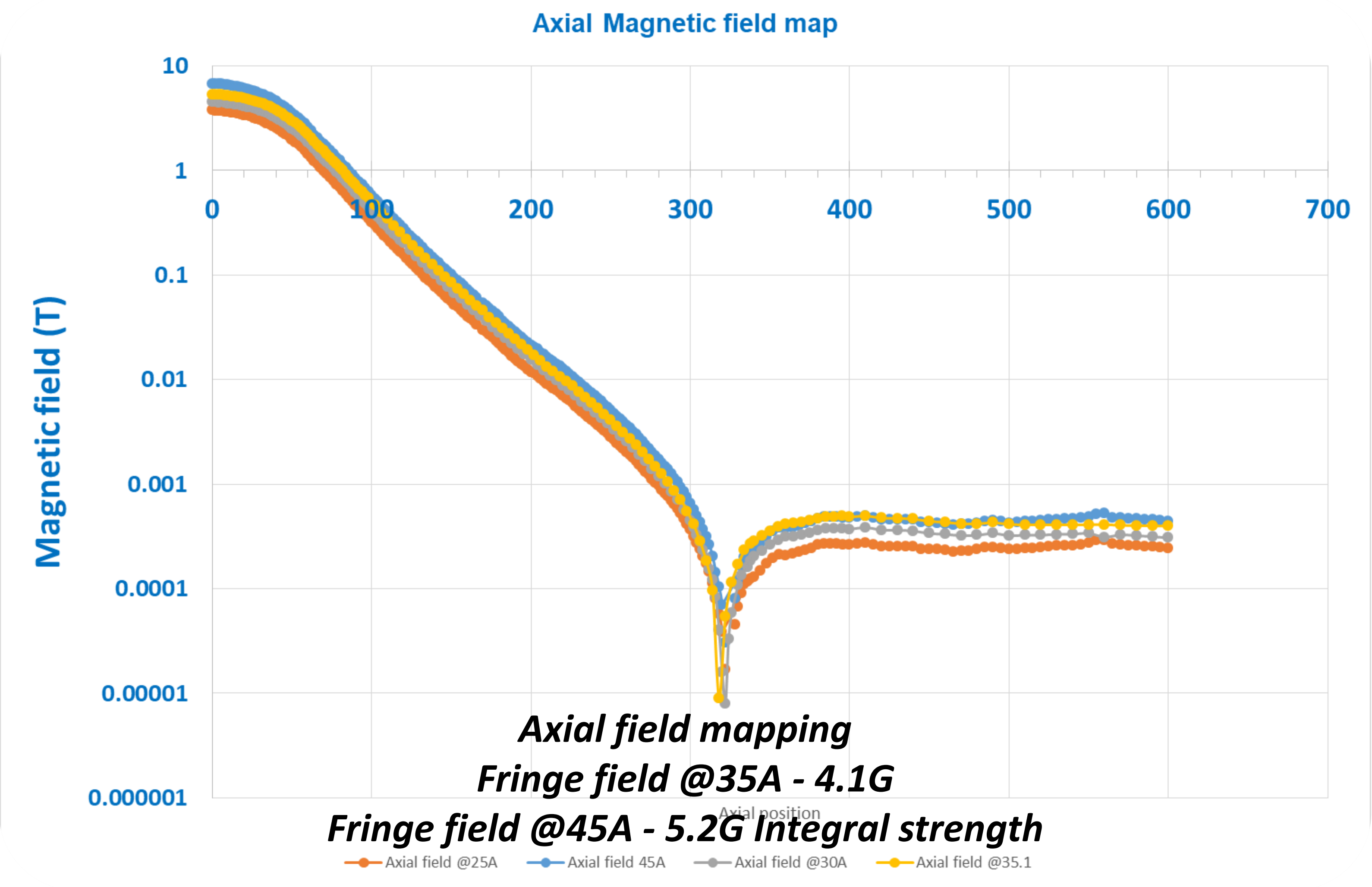
*Warm doublets external to cryomodules

Pre-series magnet development



Pre-series Magnet development was carried out with 0.4mm bare diameter SC wire

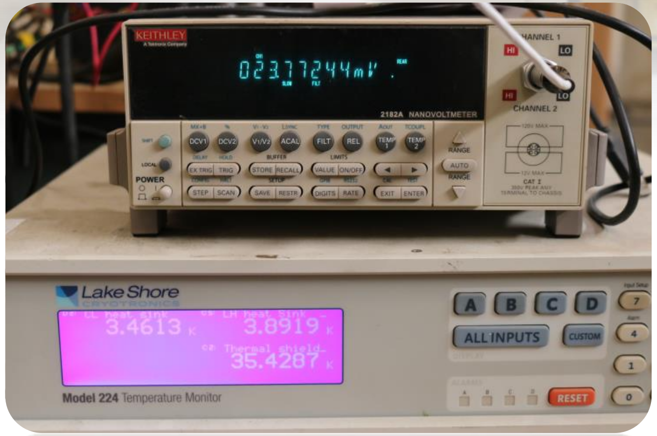
Pre-series magnet testing



Axial field mapping

Fringe field @35A - 4.1G

Fringe field @45A - 5.2G Integral strength



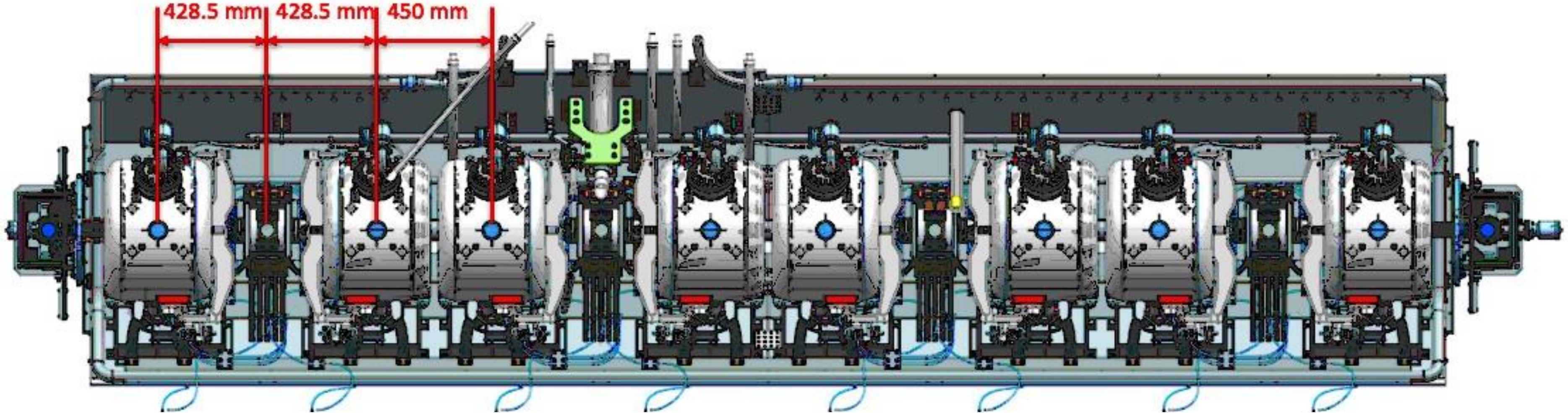
Functional Requirement Specifications (FRS)

Primary Design objectives:

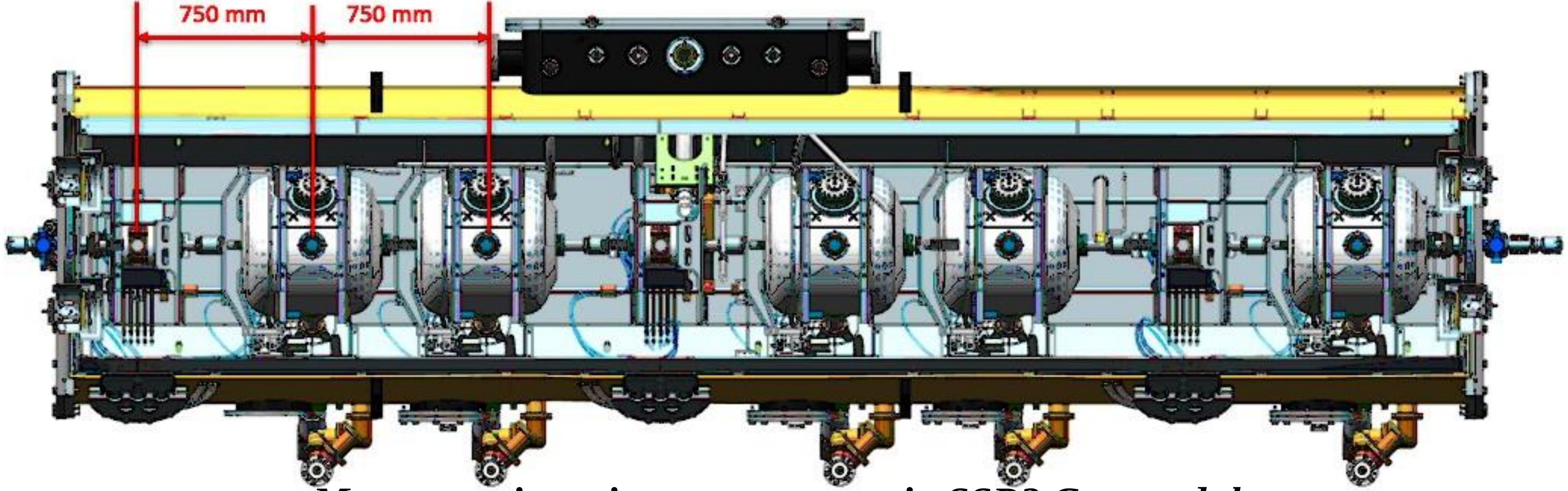
- ***High Field (focusing strength)***
- ***Low stray field as fringe field level on the adjacent spoke cavity surface is a major concern.***
- ***Dipole field and skew quadrupole field coils incorporated in the same magnet package.***

Parameters	SSR1/SSR2 New specification (Ver 2.)	SSR1/SSR2 New specification (Ver.3)
Focusing Strength	4.5 T^2m	4.5T^2m
Bending strength of Dipole correctors	5 mT-m	$\geq$6.0 (5.0) mT-m
Beam pipe aperture	40 mm	40 mm
Uncertainty in the location of magnetic axis w.r.t Reference points (Transverse and angular alignment)	<0.1mm RMS <0.5 mrad RMS	<0.1mm RMS <0.5 mrad RMS
Effective length of solenoid (FWHM)	<18cm	<18.5cm
Active magnetic shielding requirements	~ <10G	~<10G
Maximum current in the solenoid	100A	90 A
Maximum current in the dipole correctors	50 A	12 A

Arrangement of magnet assemblies in cryomodule

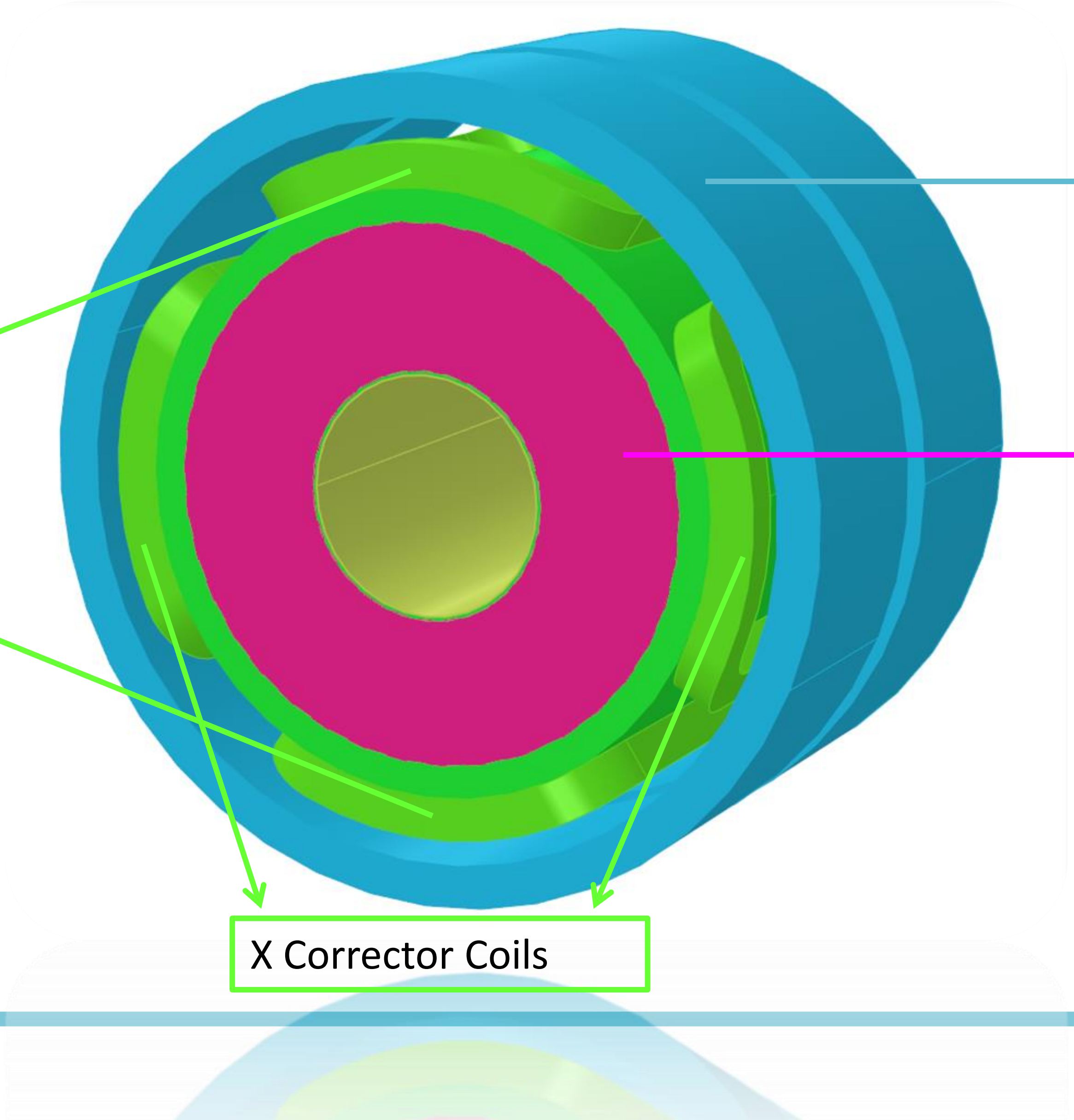


Magnet cavity string arrangement in SSR1 Cryomodule



Magnet cavity string arrangement in SSR2 Cryomodule

Electromagnetic Design



Active shielding coils

Main Coil

Y Corrector Coils

X Corrector Coils

Corrector Coils

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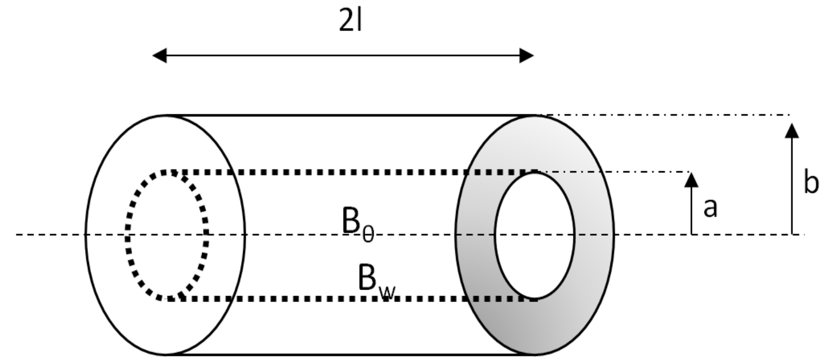
Magnetic Field Due to a Solenoid



- Peak magnetic Field is given by:-

$$B_0 = JaF(\alpha\beta)$$

Where

$$F(\alpha\beta) = \mu_0\beta\ln\left\{\frac{\alpha+(\alpha^2+\beta^2)^{\frac{1}{2}}}{1+(1+\beta^2)^{\frac{1}{2}}}\right\} \quad and \quad \alpha = \frac{b}{a} \quad , \quad \beta = \frac{l}{a}$$

- The magnetic field (B_w) responsible for determining critical current density is close to the winding is proportional to B_0 .

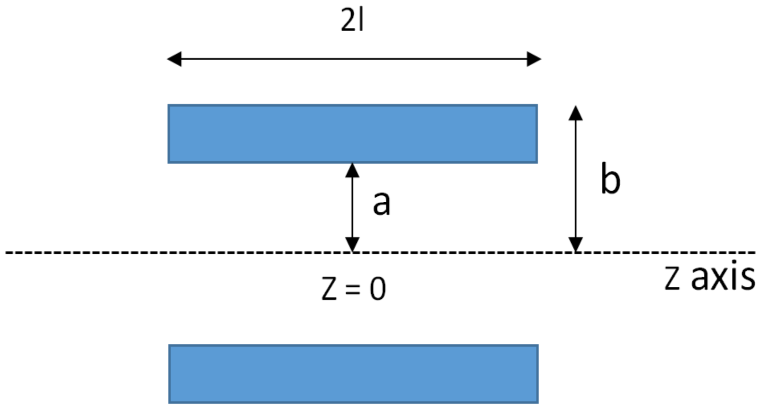
$B_w = c_0 B_0$, where c_0 is a function of shape factor α and β .

- The magnetic field on axis of the solenoid is given by:-

$$B_z = \frac{1}{2}Ja\,\{\,F(\alpha,\beta_1) + F(\alpha,\beta_2)\,\}$$

where

$$\beta_1 = \frac{(l - z)}{a} \quad \text{and} \quad \beta_2 = \frac{(l + z)}{a}$$



Focussing strength and spherical aberration

- Focussing strength:

$$k^2 = \left(\frac{qB}{2mc\gamma\beta}\right)^2$$

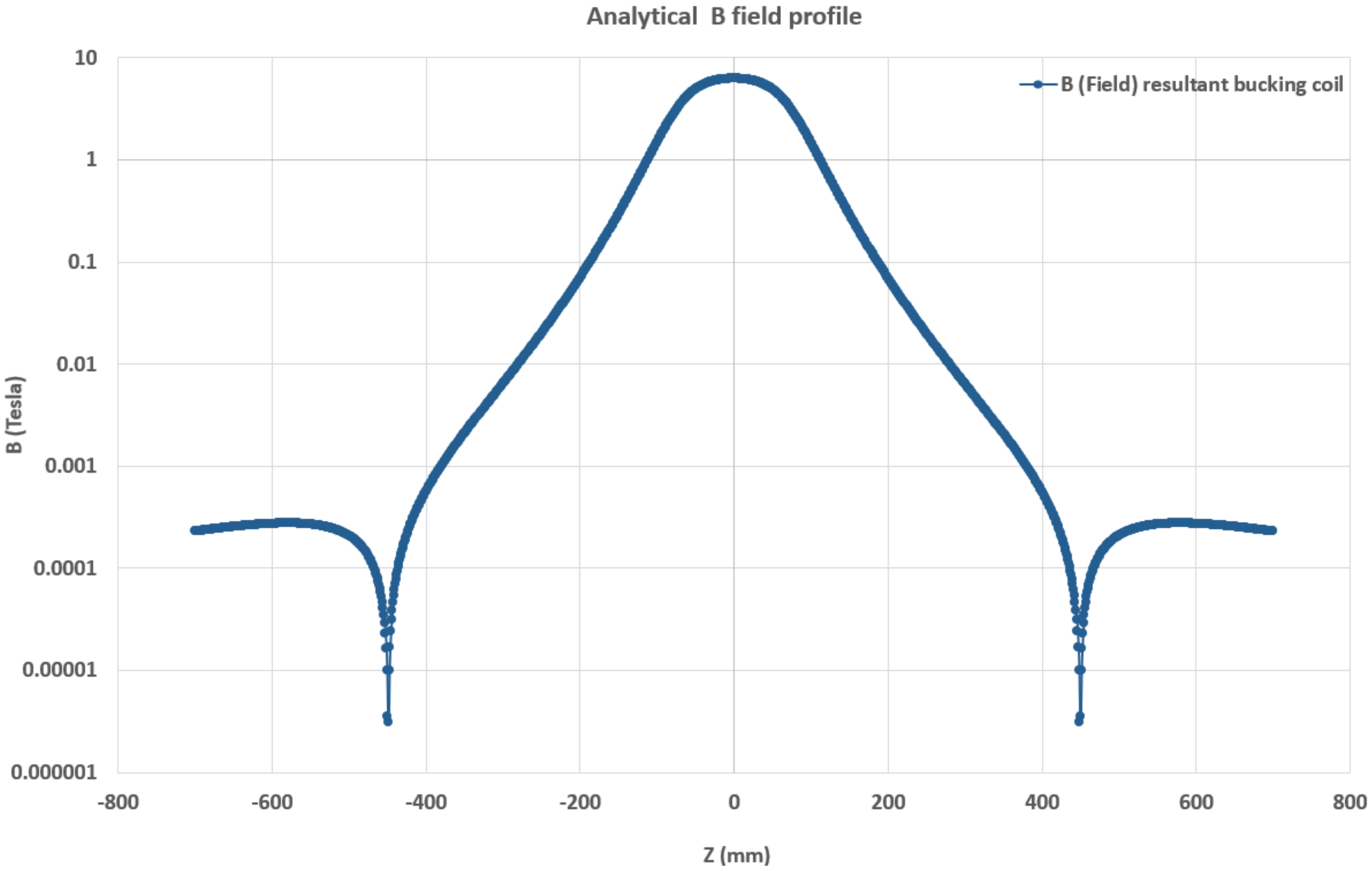
Focusing strength 4.42

- Effective length:

$$l = \frac{1}{B_0^2}\int_{-\infty}^{\infty} B^2(z)\,dz$$

- Spherical aberration:

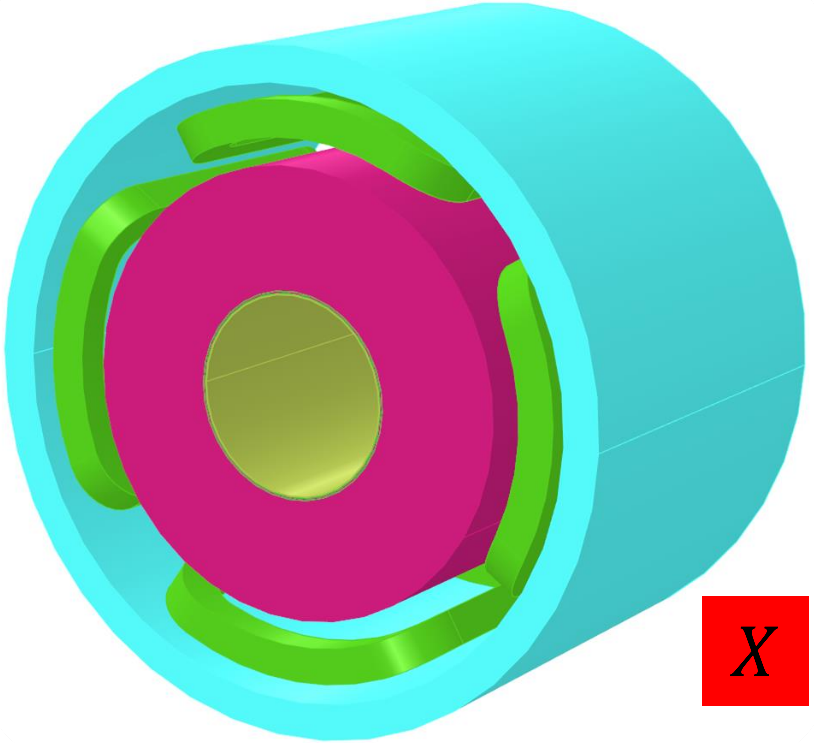
$$C_s = \frac{1}{2}\frac{\int \left(\frac{dB_z}{dz}\right)^2 dz}{\int B_Z^2 dz}$$



Spherical coil aberration 71.15982352

Electromagnetic Design

Configuration 1:
No extra benefit in spatial occupancy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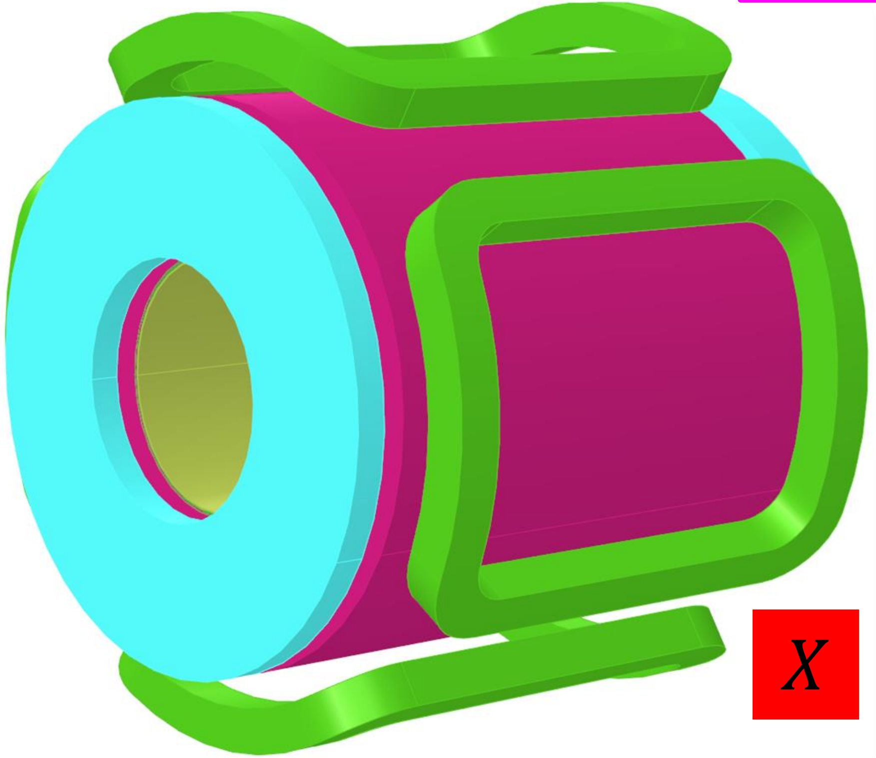
Configuration 2:
Less axial field uniformity
More longitudinal foot print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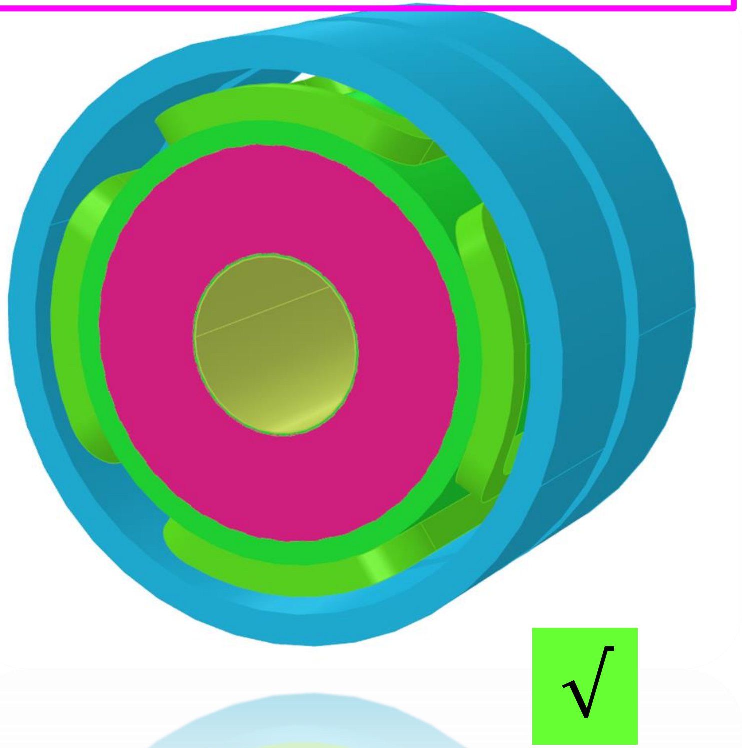
Configuration 3:
Good axial field uniformity
Optimized axial and longitudinal footprint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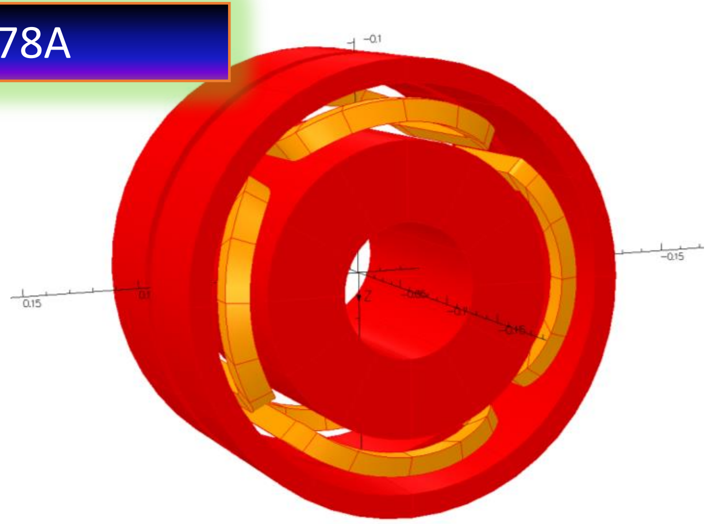
Electromagnetic Design

Sr. no	Parameter	Value	Unit
1.	Length of solenoid coils in the lens	140	mm
2.	Main coil inner radius	38	mm
3.	Main coil outer radius	75	mm
4.	Strand diameter bare (with insulation)	0.51(0.55)	mm
5.	Winding fill factor	0.85	
6.	Number of turns in the main coil	~14554	

Sr. no	Parameter	Value	Unit
1.	Length of Bucking Coils	64	mm
2.	Bucking coil inner radius	100	mm
3.	Bucking Coil outer radius	112.5	mm
4.	Strand diameter	0.51(0.55)	mm
5.	Bucking Coil Z location*	38	mm
6.	Winding fill factor	0.85	
7.	Number of turns in the Bucking coil	~2247	

Operating current 78A



Objective function :

$\int B_z^2 \,.\, dz \ \geq 4.5\ \mathrm{T^2m}$

Minimize $\int^{r=0.3} B.dl$ at z= 0.42m cavity location

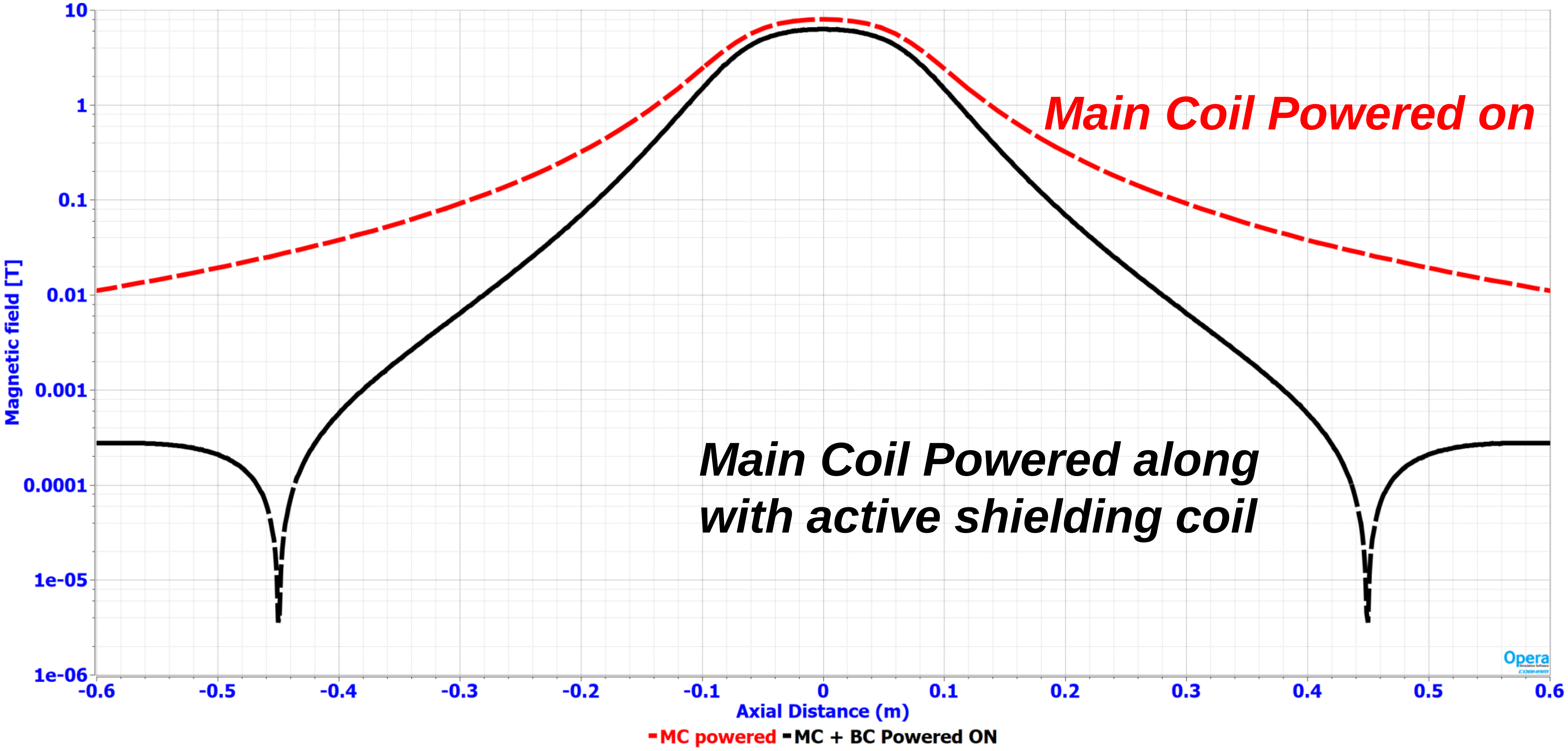
Constraints:

$Effective\ length \leq 185$ cm +/- 30mm ; $I_{exc} < 90$A

Optimization Parameters:

N_{main}, OR_{main}, IR_{main} , IR_{BC} , OR_{BC} L_{BC} , $Z_{center\text{-}BC}$

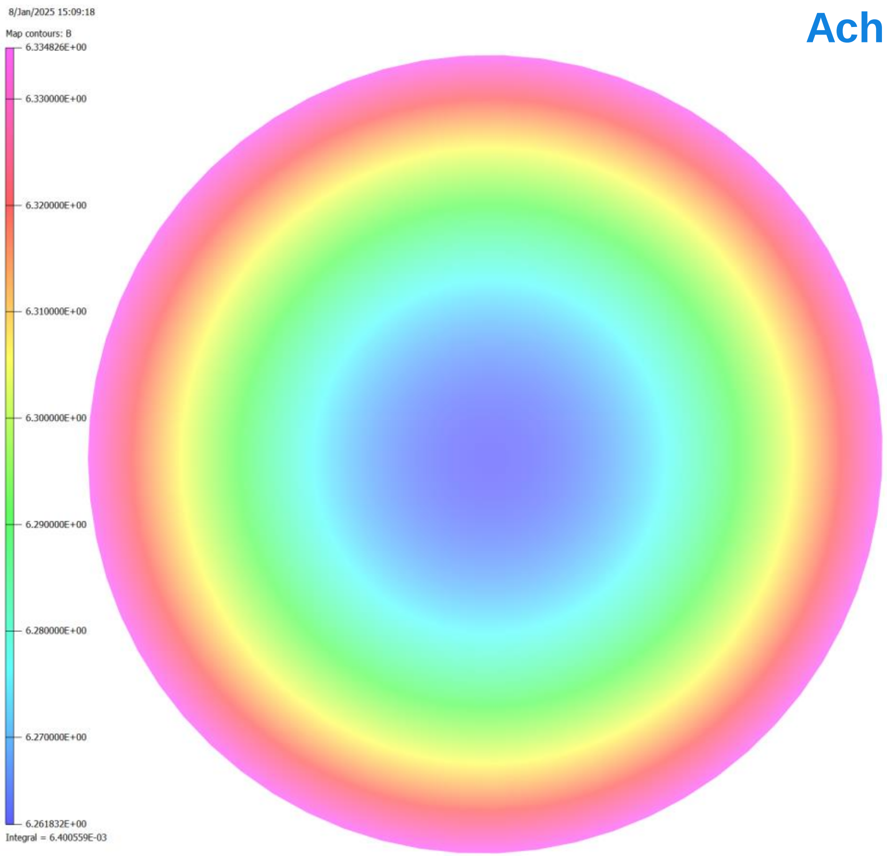
Electromagnetic Design… continued



B_{mod} field vs axial distance plot

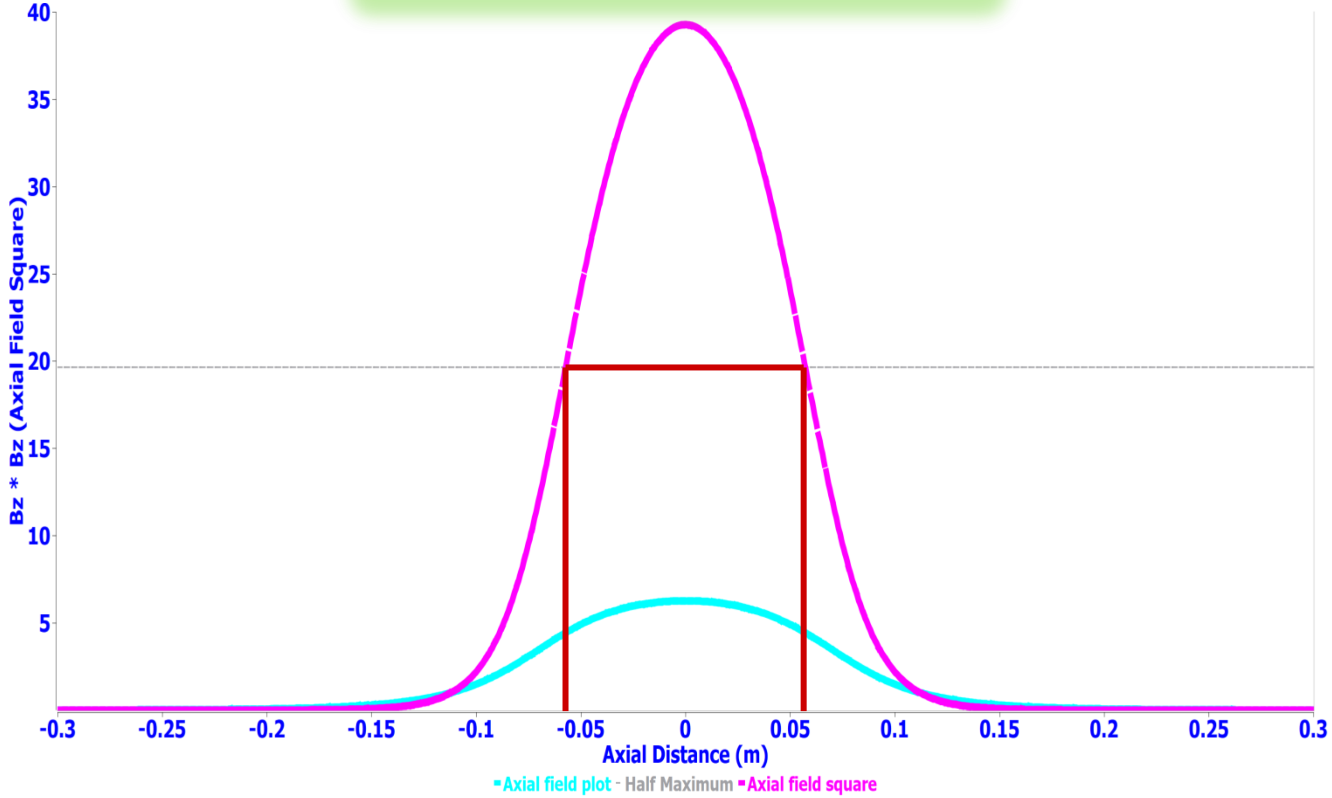
Electromagnetic design … continued

Focusing strength req. : 4.5 T^2m
Achieved : 4.57T^2m



Zonal plot of Magnetic field at the magnet center
(field homogeneity 1.1% @ r=18 mm)

Operating current 78A



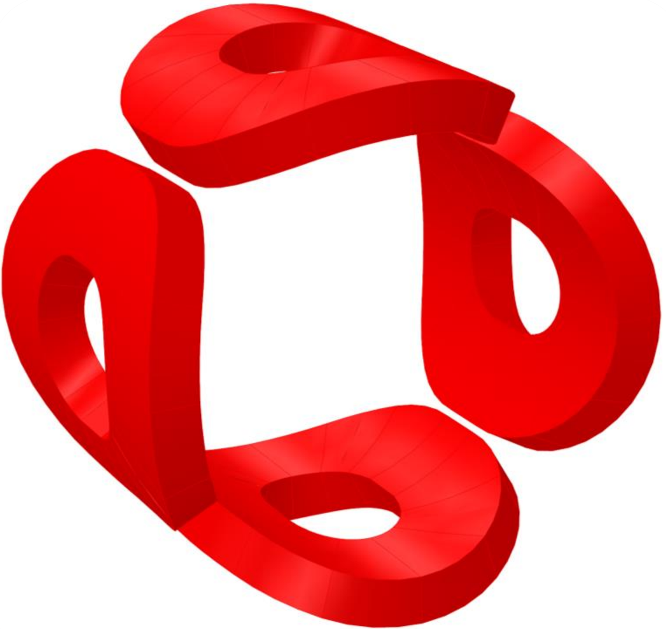
B field plot and B^2 Plot along the axial length
(Focusing strength of 4.57 T^2m)

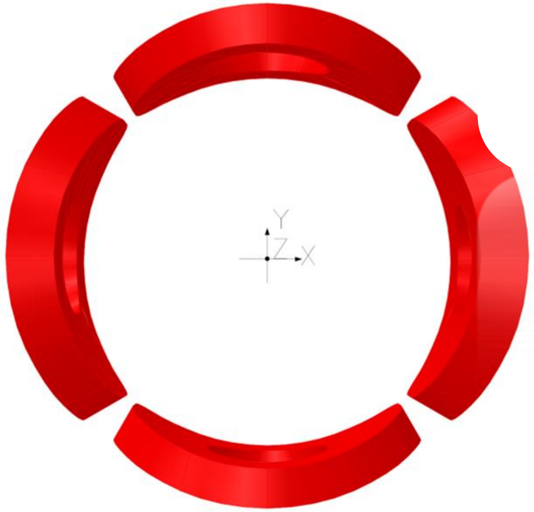
Dipole corrector design

Sr. no	Parameter	Value	Unit
1.	Straight Length of Dipole corrector coils (H1)	10	mm
2.	Width cross-Section in radial direction	15	mm
3.	Thickness cross-section in azimuthal direction	35	mm
4.	Radius of the Mandrel (R1)	80	mm
8.	Strand diameter (bare/insulated)	0.51/0.55	mm
9.	Number of turns in the dipole corrector coil	~1475	
10.	Operating current density at nominal bending strength	28	A/mm^2
11.	Winding fill factor	~0.85	

Sr. no	Parameter	Value	Unit
1.	Designed value of Bending strength of corrector coils	6.3	mT-m
2.	Peak Magnetic field on the corrector coil wire strand	2.8	T
3.	Quadrupole Gradient in skew Quadrupole mode	3.25	T/m
5.	Nominal current	~10	A
6.	Transfer function of the corrector coils	0.1525	mT/A

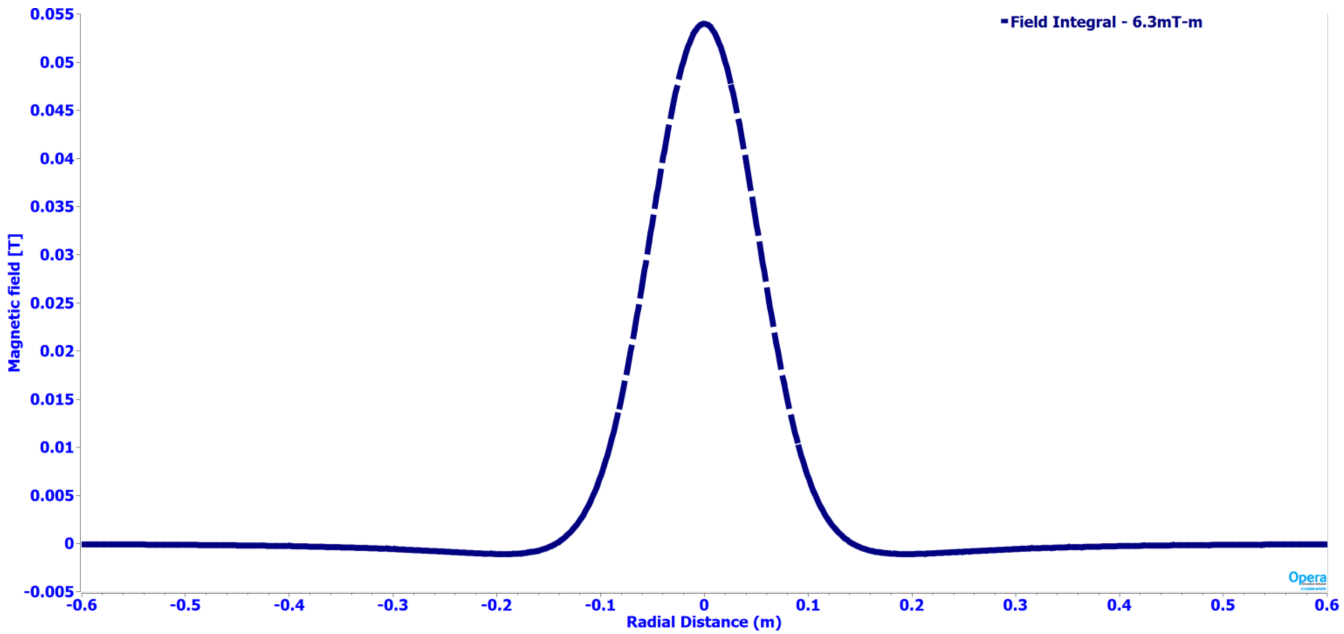
Corrector coils used in space between the main solenoid and active shielding coil to reduce the operating current requirement



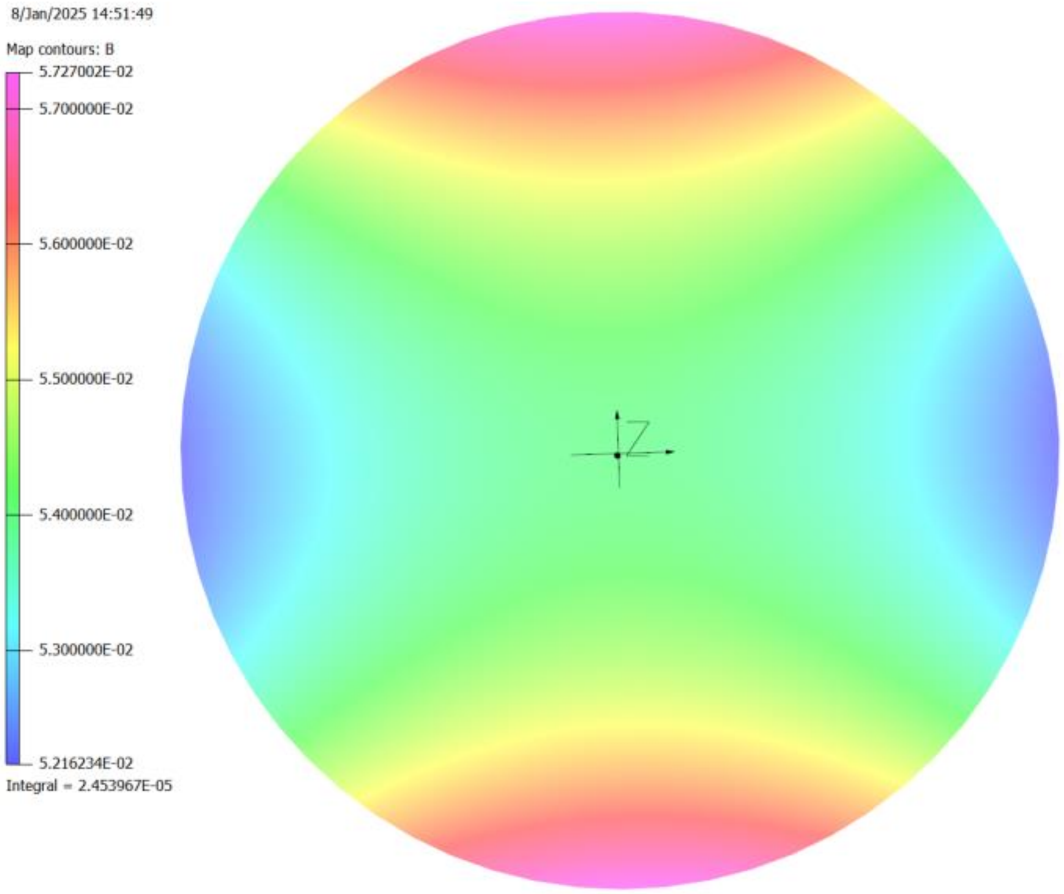


Dipole corrector design … continued

Bending strength req. : 6 mT-m
Achieved : 6.3 *mT-m*



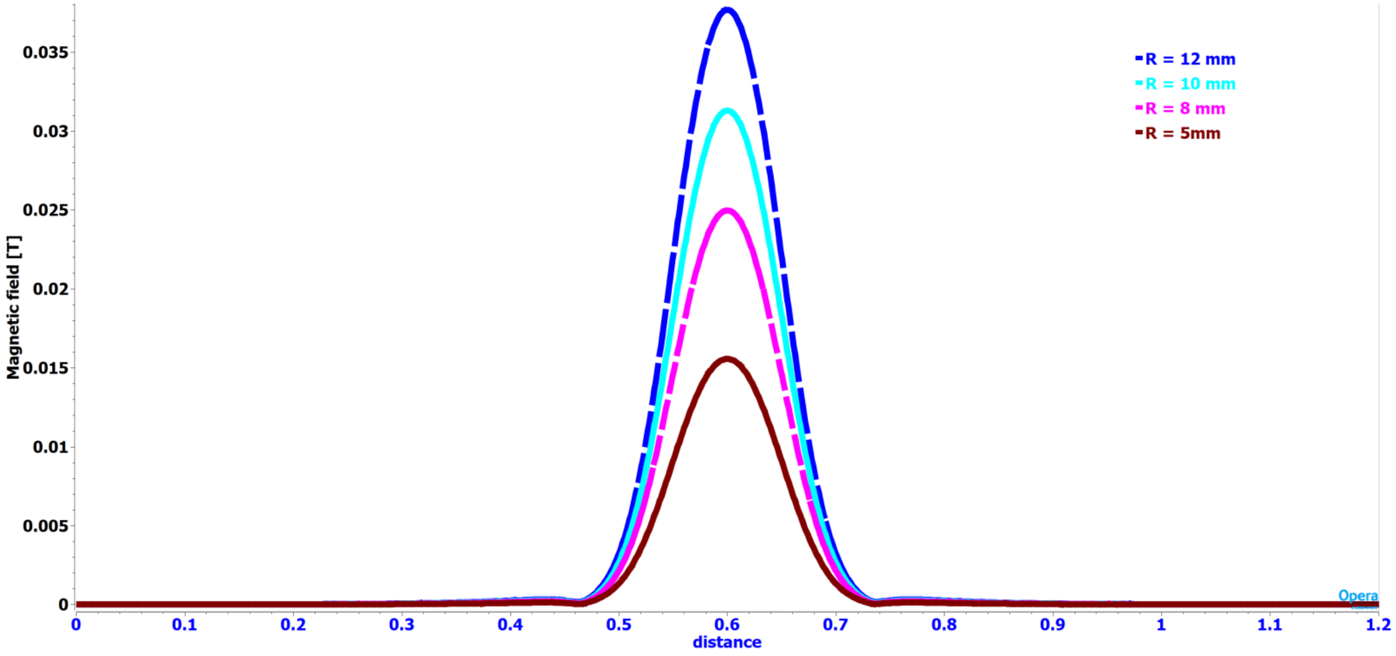
Magnetic Field plot for the dipole field (Dipole field Integral 6.3 mT-m)



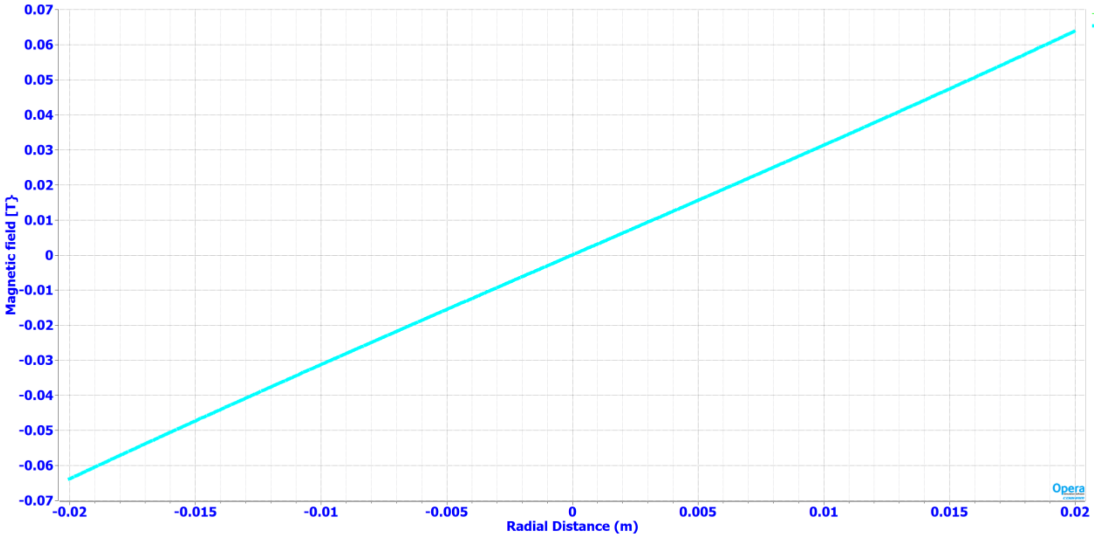
Zonal field plot of dipole field at the magnet center

Operating current ~10A

Dipole Corrector design (Quadrupole mode)



Magnetic Field (B_x or B_y) plot in the lens aperture at various radial locations when corrector coils are connected as skew quadrupole



Bx field plot vs radial distance in magnet aperture (Gradient = 3.25T/m)

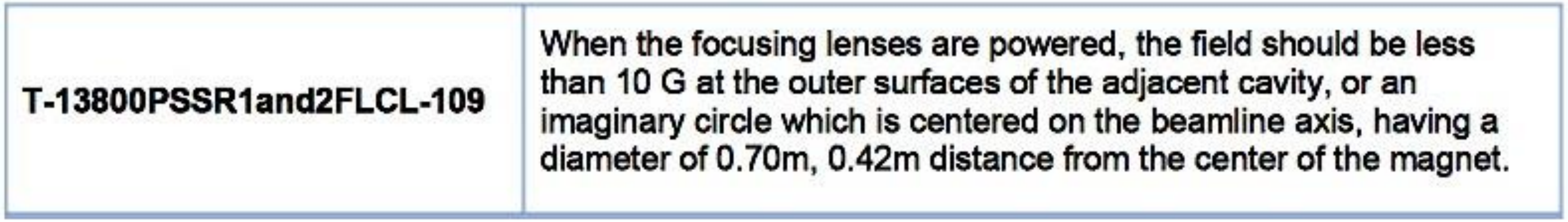
Fringe field on cavity surface

Completely defined by the properties of superconducting material

Cavity Specific

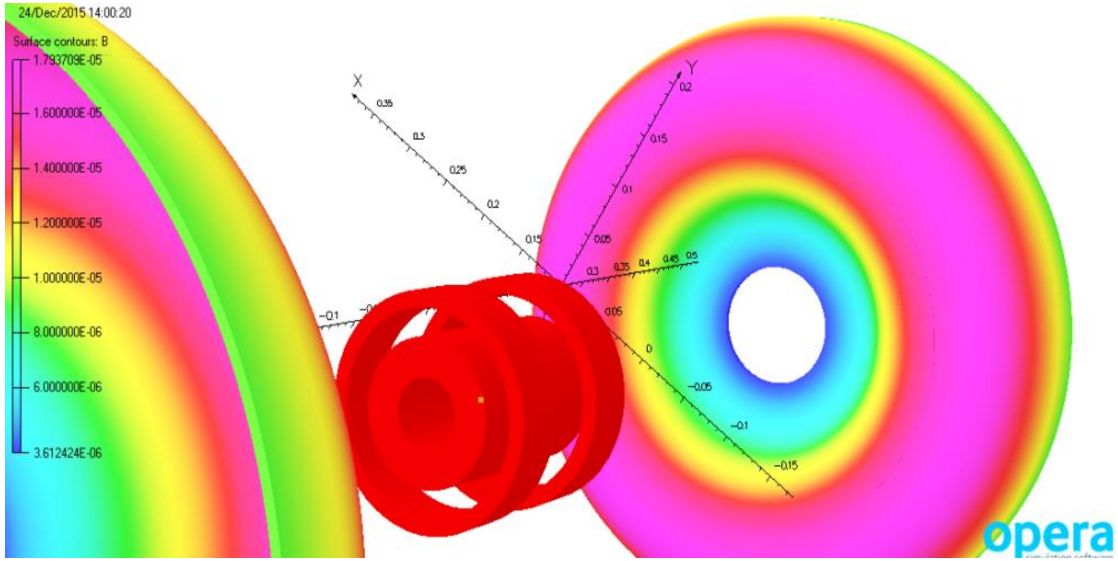
$$\Phi_{tr} = \frac{2\mu_0\Phi_0}{(Rs\cdot\xi_0^2)} * \frac{f\cdot V}{(\Lambda Q_0)} * \frac{(1-\eta)}{\eta}$$

Acceptable degree of degradation η with allowed amount of the trapped flux.



T-13800PSSR1and2FLCL-109	When the focusing lenses are powered, the field should be less than 10 G at the outer surfaces of the adjacent cavity, or an imaginary circle which is centered on the beamline axis, having a diameter of 0.70m, 0.42m distance from the center of the magnet.

Placement of a focusing lens inside the SSR cryomodule



$\mu_0 = 4\pi\cdot10^{-7}$H/m ; $\Phi_0 = 2\cdot10^{-15}$Wb

$\xi_0 = 3.9\cdot10^{-8}$ m is the coherent length in Nb, f is the frequency of the cavity,

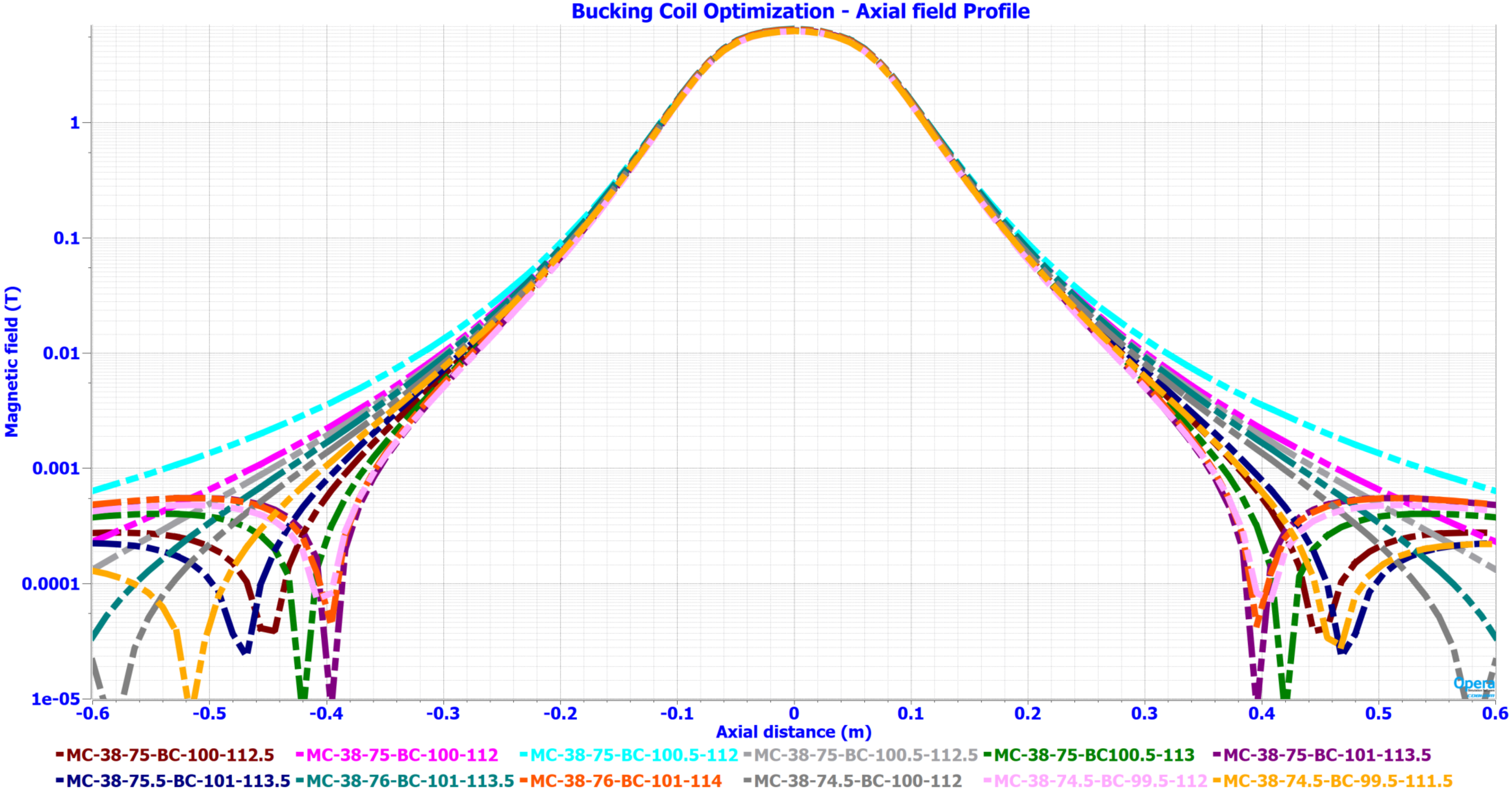
Rs is the surface resistance of Nb at this frequency,

V is the volume of the cavity,

$$\Lambda = \frac{\text{Magnetic energy density at the location of the quench}}{\text{Average energy density in the cavity}}$$

Surface integral / line integral at the maximum magnetic energy density location needs to be minimized during the design of bucking coil

Bucking coil optimization



B field vs axial distance plot for different cases of Bucking coil dimensions

Tolerance studies on bucking coil geometrical parameters

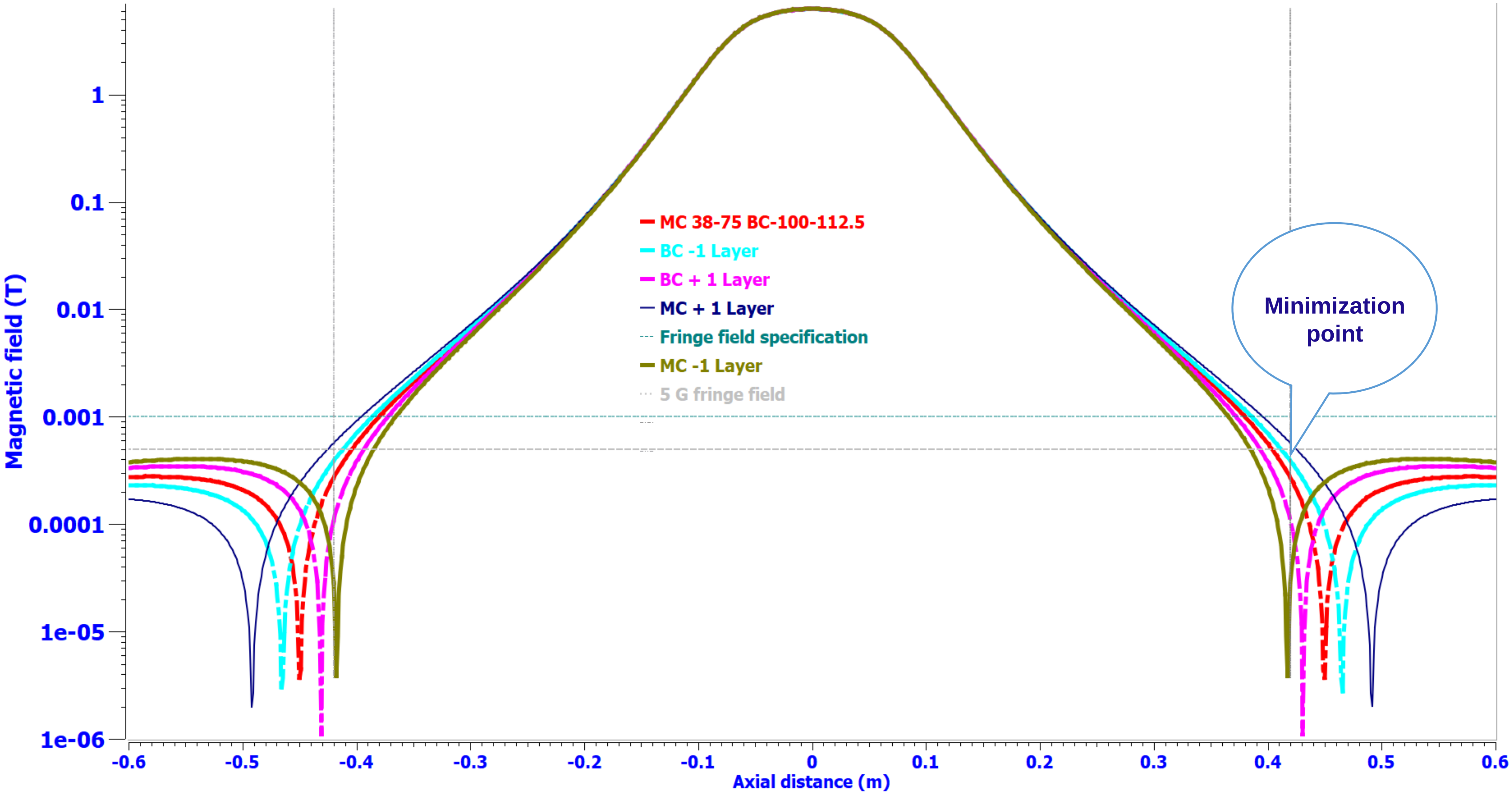
- Tight tolerance is required for the bucking coil winding dimensions and its placement w.r.t main coil.
- The positional inaccuracy of the Bucking coil effects the fringe magnetic field on the cavity surface.

Effect on fringe field level at different axial position of the Bucking coil w.r.t Main coil

Sr. no	BC-Coil IR	BC-Coil OR	BC-Coil L	BC-Coil Z center	B max On cavity surface	Field Surface Integral at Axial distance of 0.42 m)
	mm	mm	mm	mm	Gauss	G-m^2
1.	100	112.5	64	38	7.33	2.47
2.	101	113	64	38	11	1.908
3.	101	114	64	38	20	6.79
4.	99	112	64	38	12	6.018
5.	100.5	113	64	38	8.89	2.988
6.	102	115	64	38	25	8.42

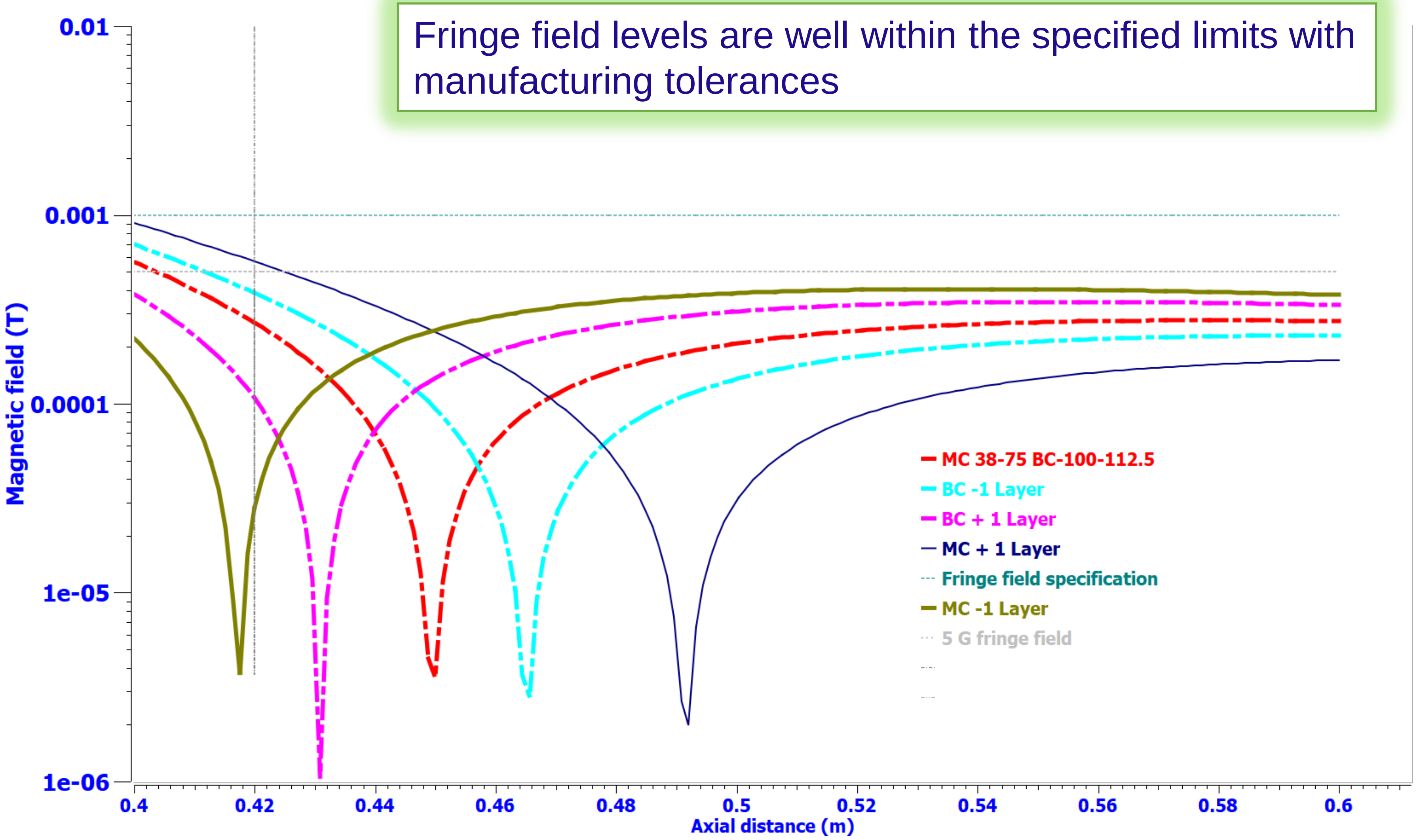
Two probable cases for detailed analysis

Error Sensitivity studies – Case (a)



B field vs axial distance plot for +/- one layer of bucking coil

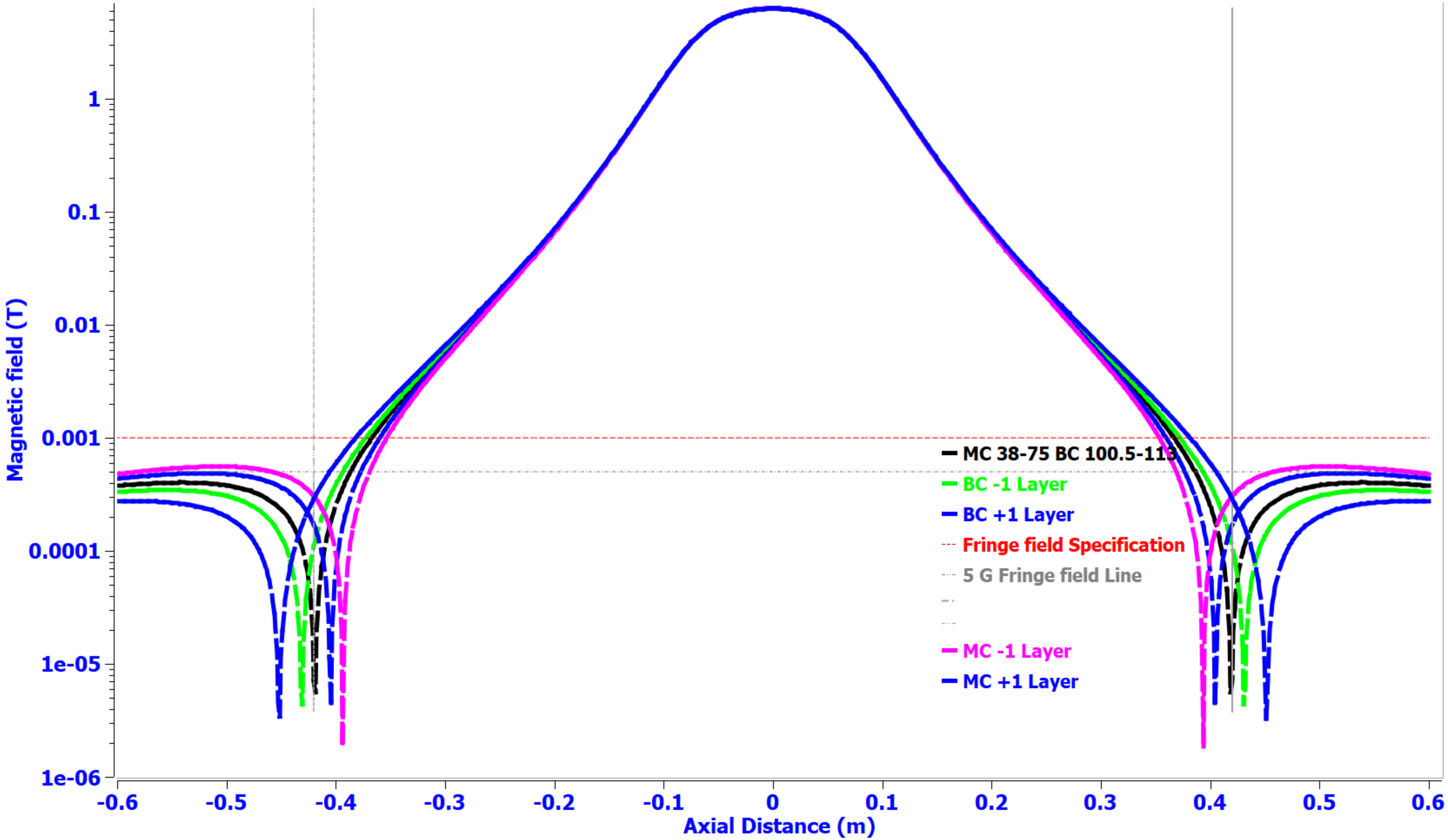
Error Sensitivity studies …continued Case (a)



Fringe field levels are well within the specified limits with manufacturing tolerances

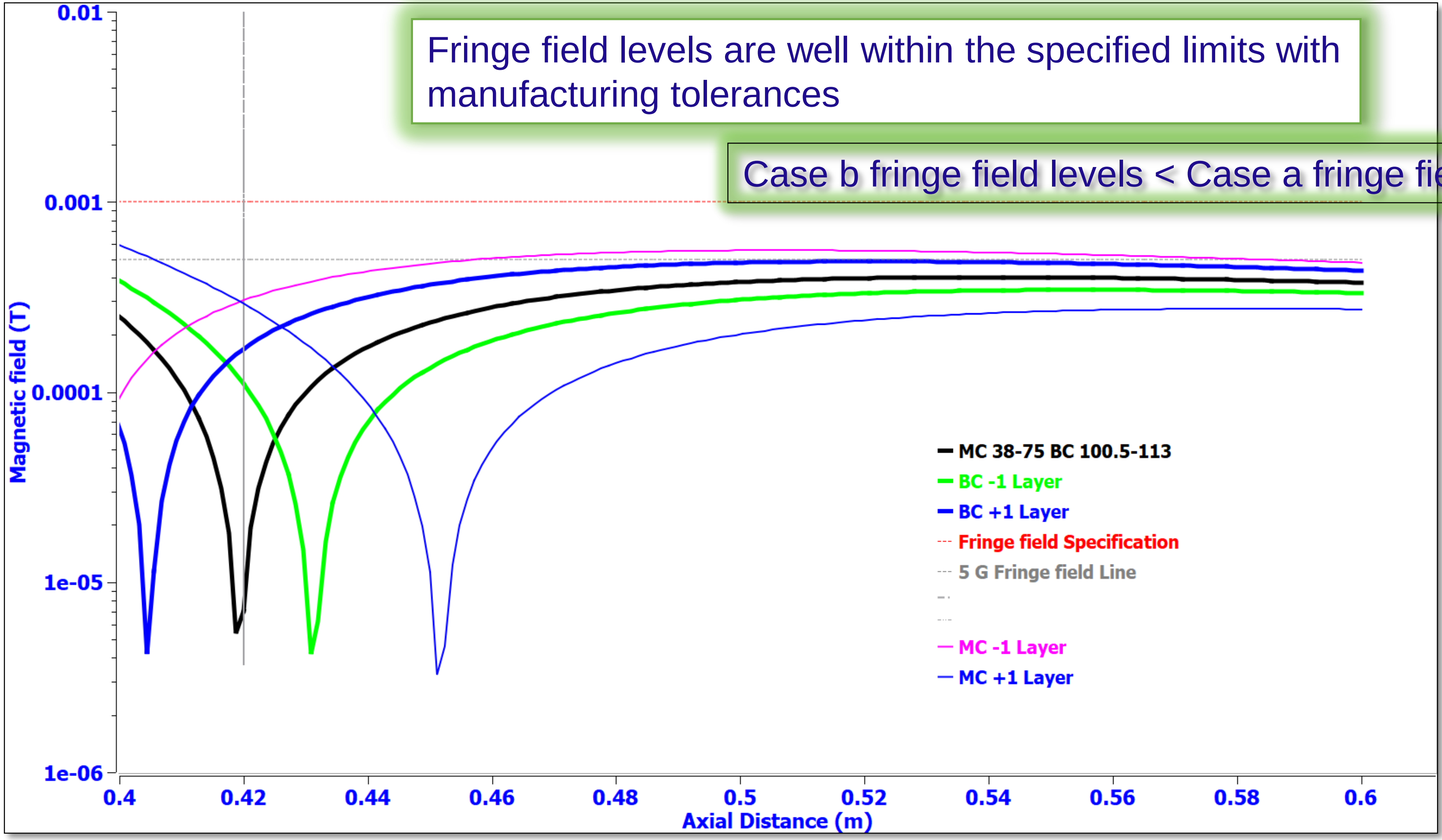
B field vs axial distance plot for +/- one layer of bucking coil

Error Sensitivity studies – Case (b)



B field vs axial distance plot for +/- one layer of bucking coil

Error Sensitivity studies … continued – Case (b)

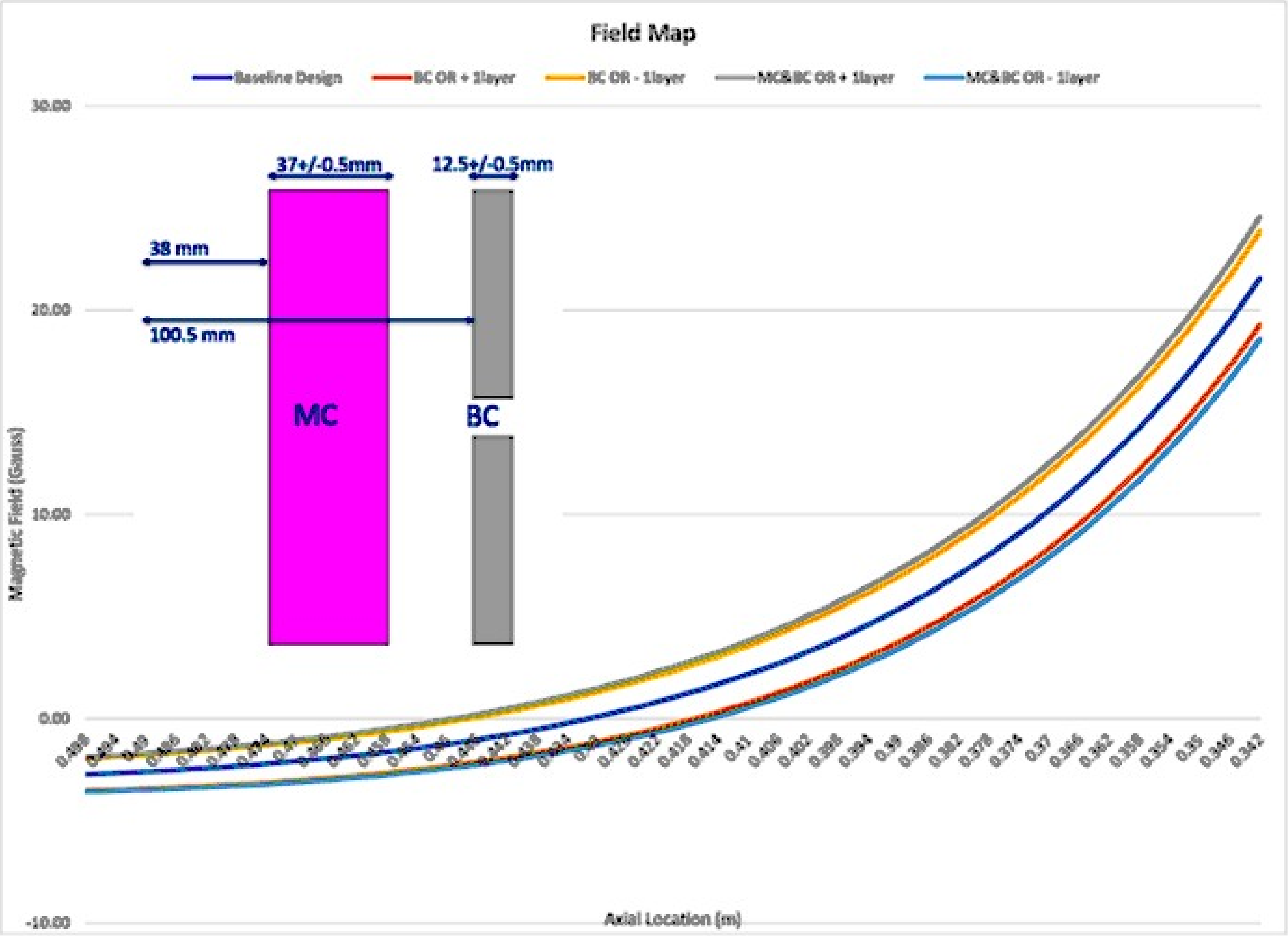


Fringe field levels are well within the specified limits with manufacturing tolerances

Case b fringe field levels < Case a fringe field levels

B field vs axial distance plot for +/- one layer of bucking coil

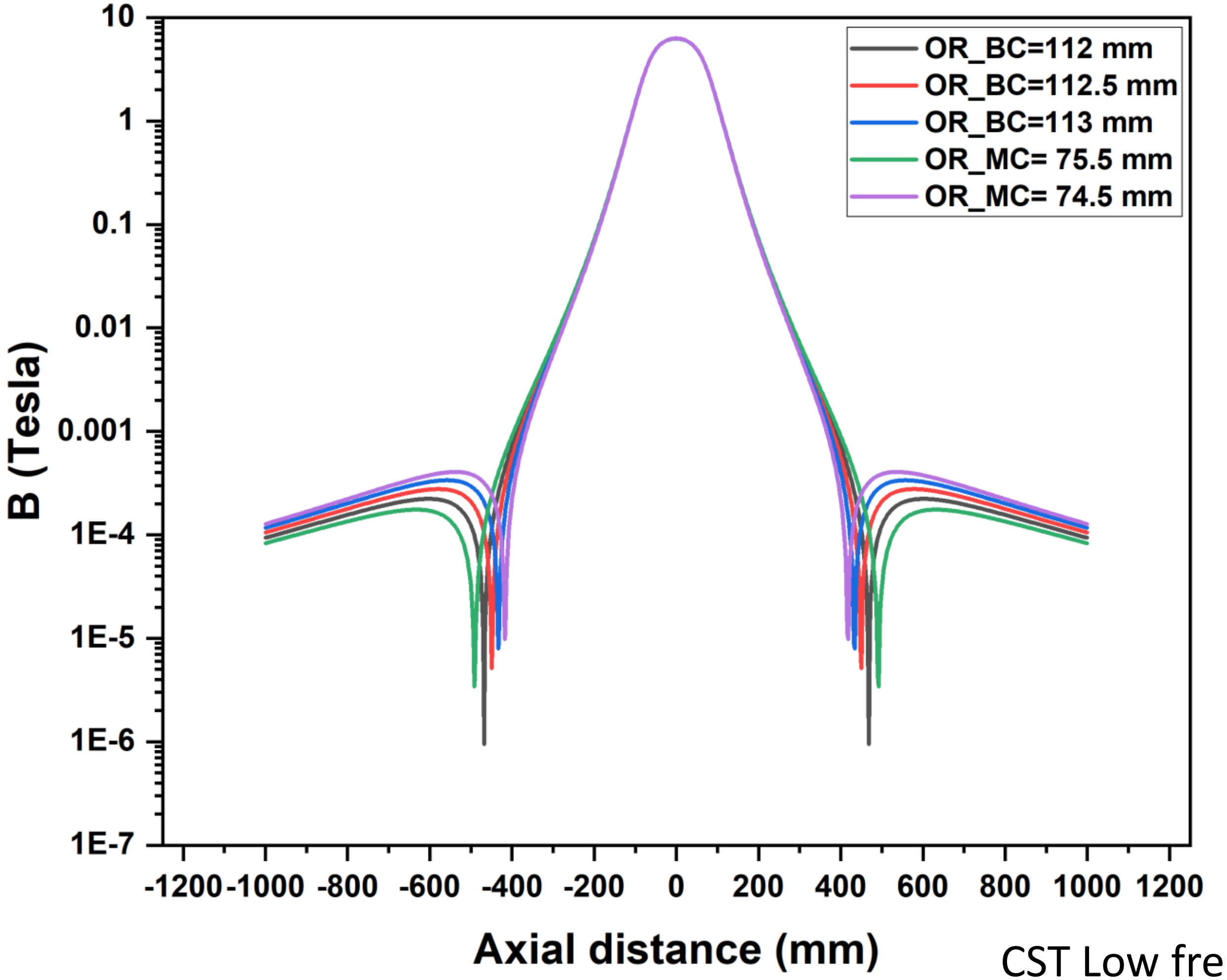
Validation with alternate solvers



Courtesy : Martin M Miao, FNAL

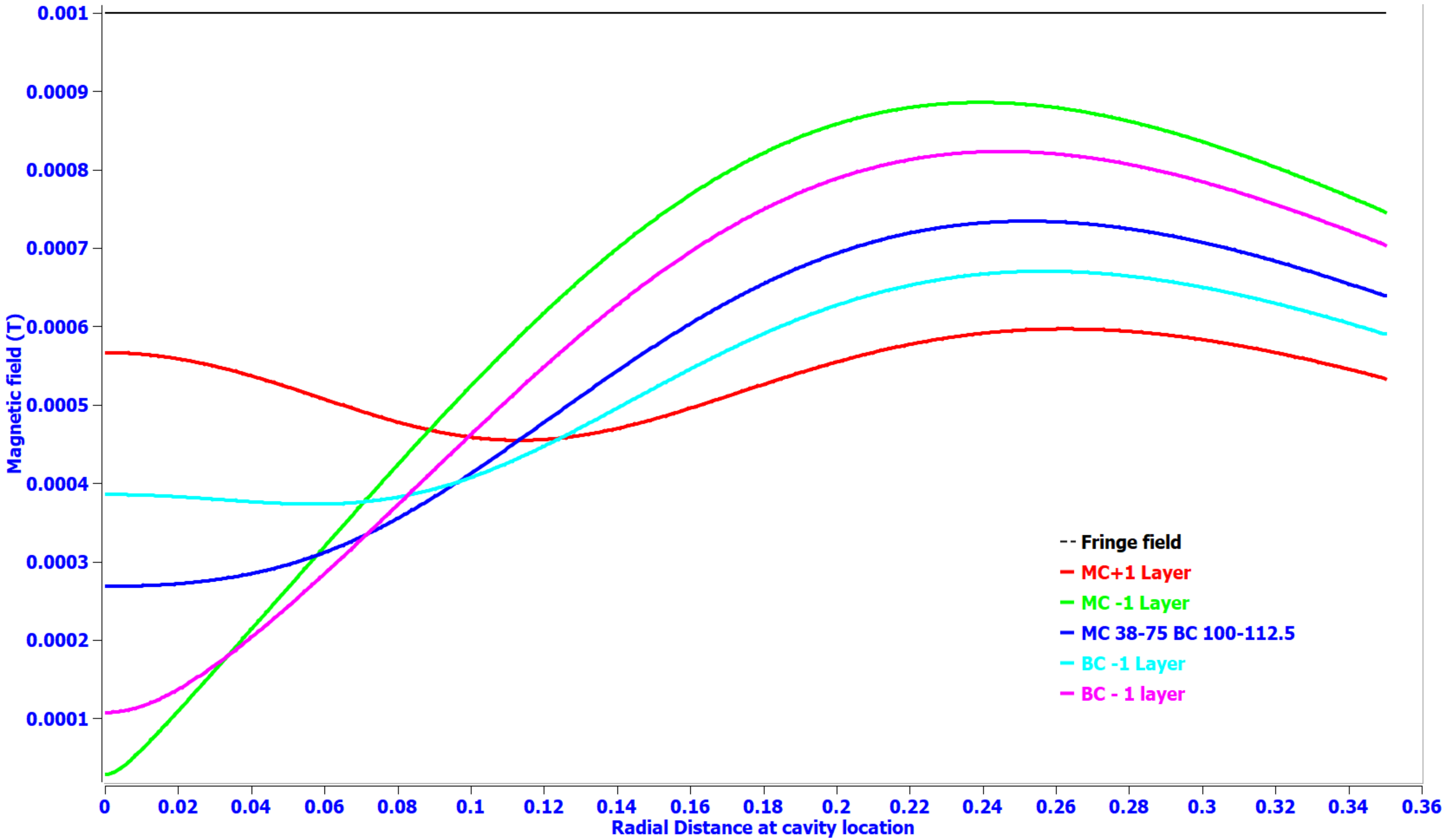
B field vs axial distance plot for +/- one layer of bucking coil

Validation with alternate solvers



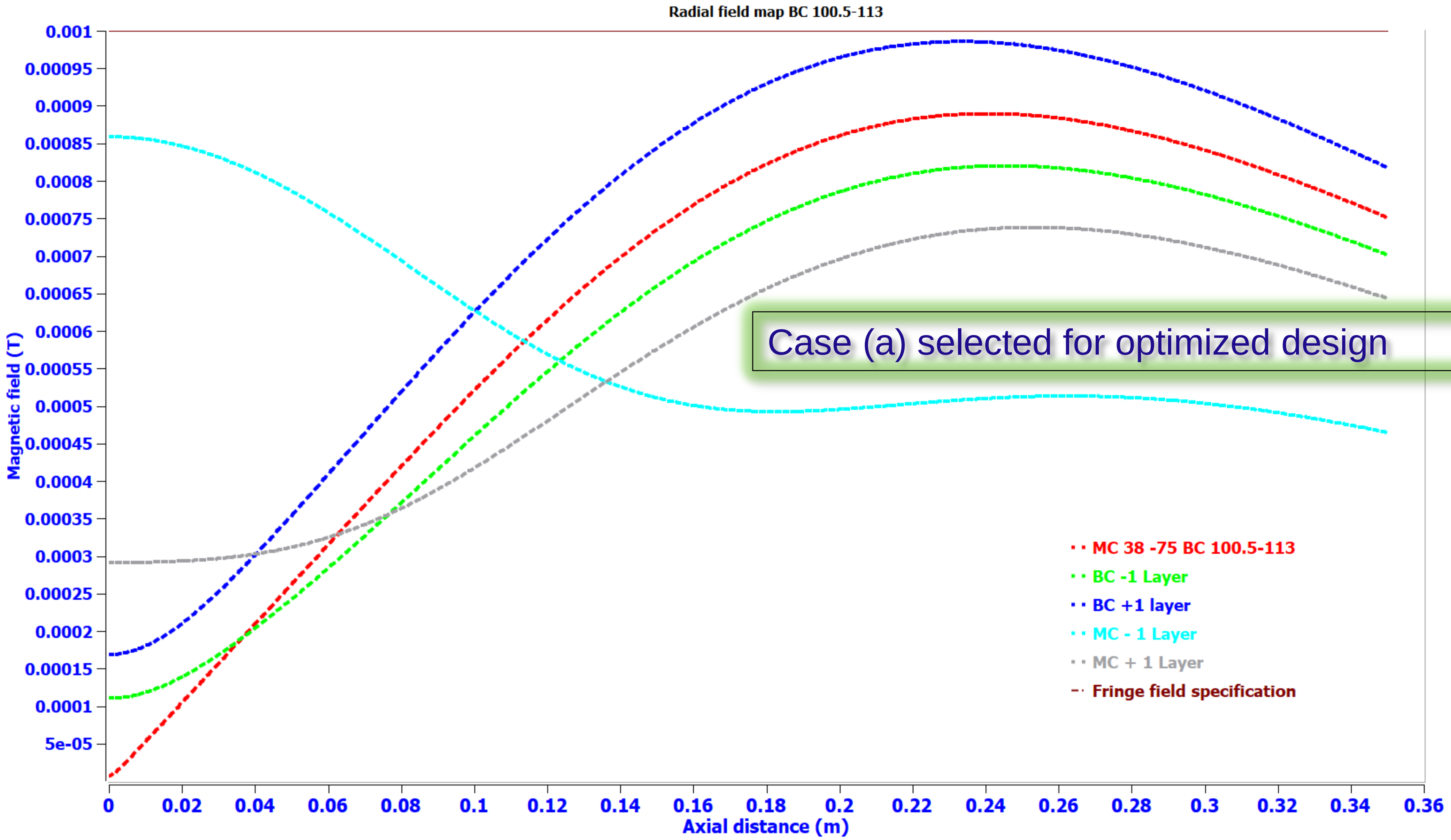
CST Low frequency Magnetostatic Solver

Radial field plot at cavity location for case (a)



B field vs axial distance plot for +/- one layer of bucking coil

Radial field plot at cavity location for case (b)

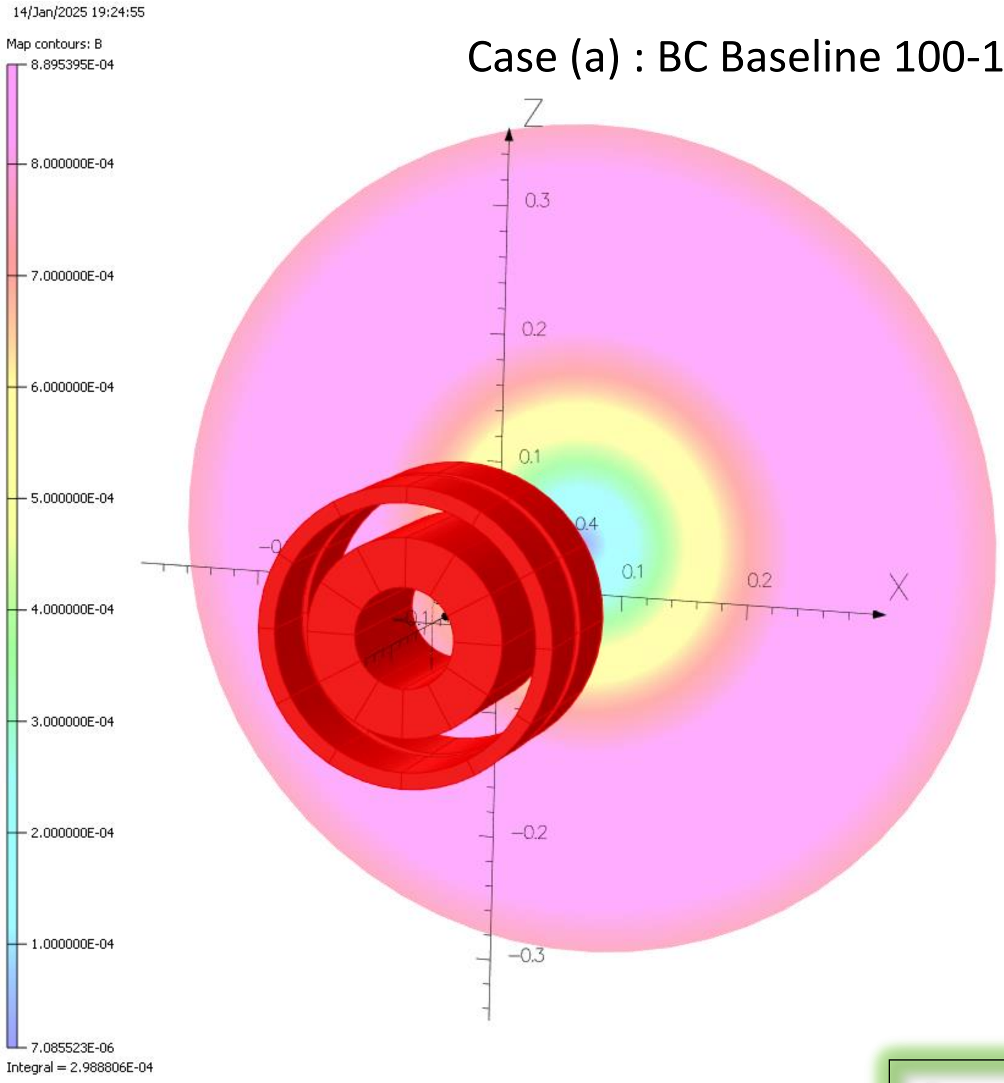


Case (a) selected for optimized design

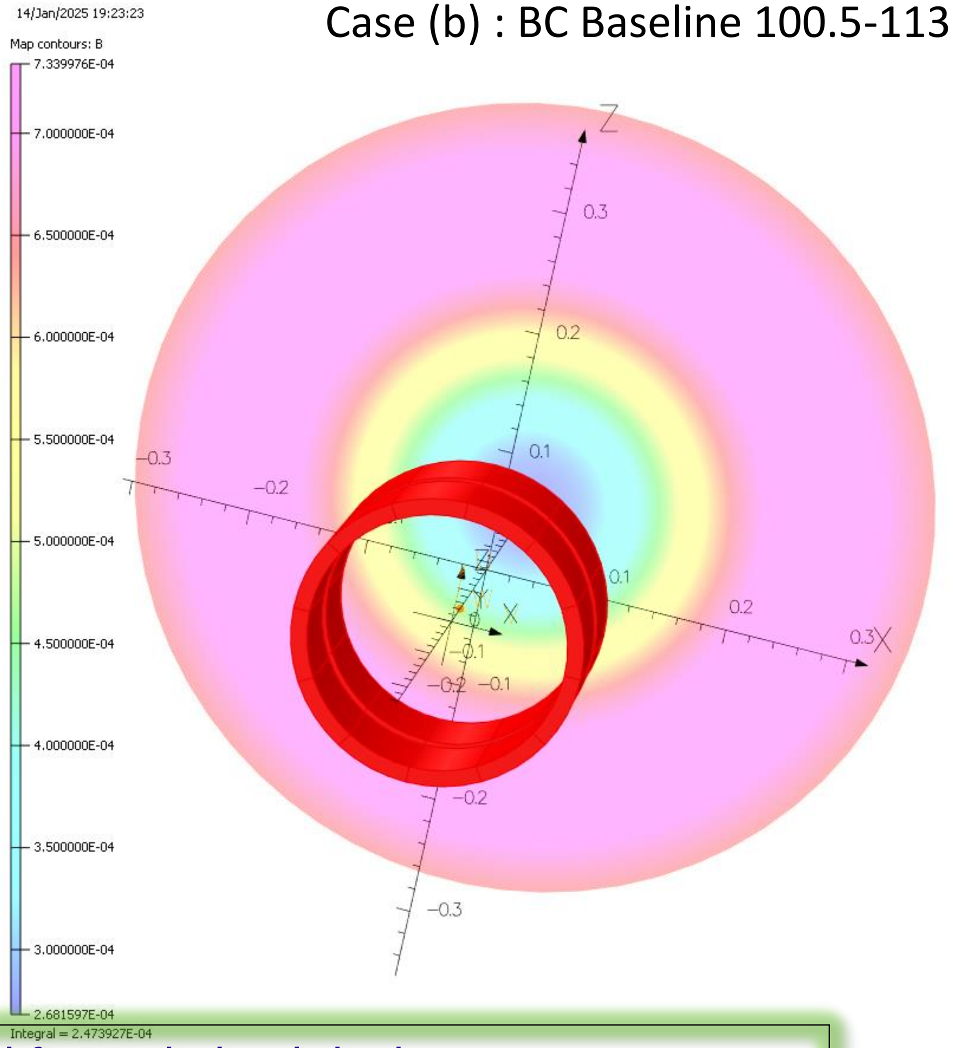
B field vs axial distance plot for +/- one layer of bucking coil

Surface plot at Cavity location

Case (a) : BC Baseline 100-112.5

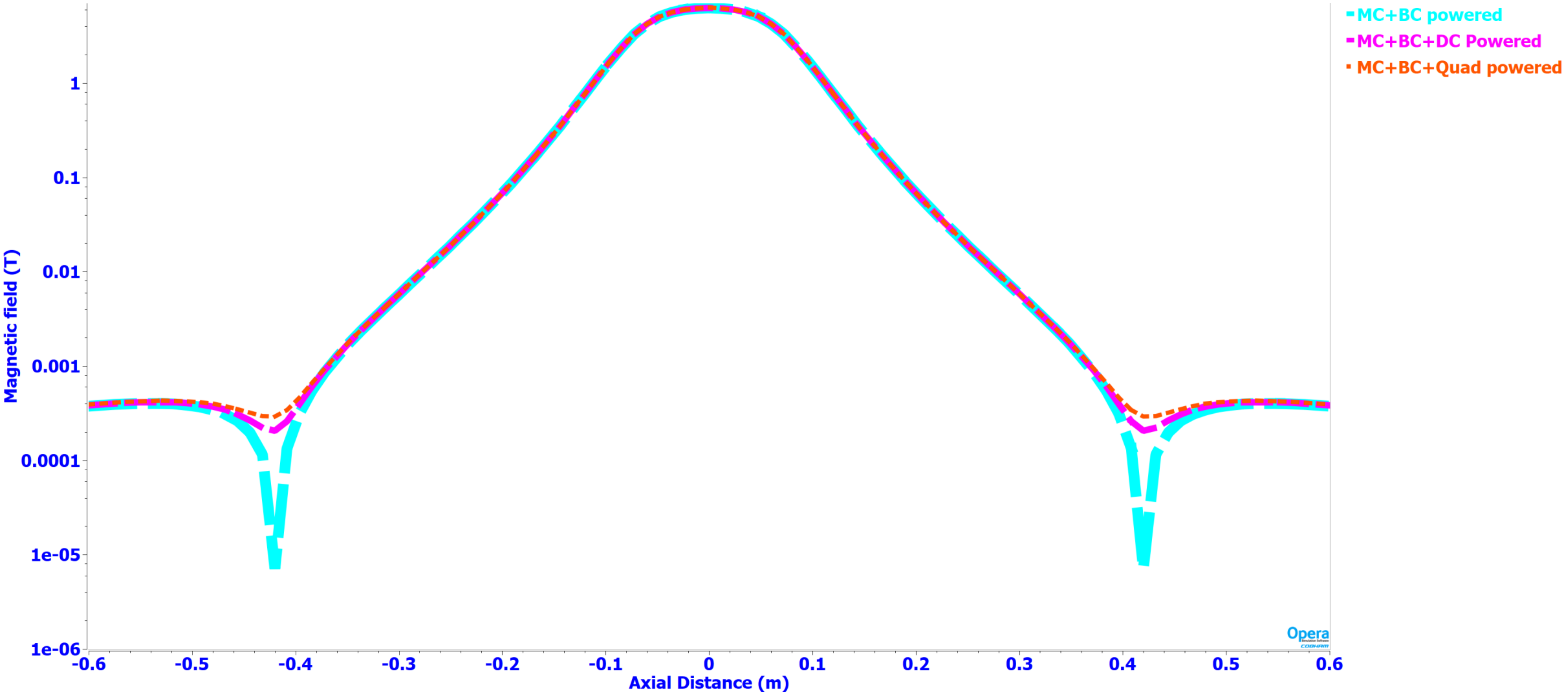


Case (b) : BC Baseline 100.5-113



Case (a) selected for optimized design

Combined-field-All coils-powered-on



Superconducting Wire strand material properties

- All conduction cooled magnets are proposed to be wound using round 0.5 bare diameter /0.54 mm insulated strand (NbTi/ copper matrix 1:2 Sc:Cu Ratio).

Bare Wire Dia	Filament Diameter	Cu/Sc Ratio	Filament twist pitch	RRR	Ic @ 3 T , 4.2K	Ic @ 5 T , 4.2K	Ic @ 7 T , 4.2K	Ic @ 9 T , 4.2K
0.51mm		2:1		70	240 A	140A	105A	32A

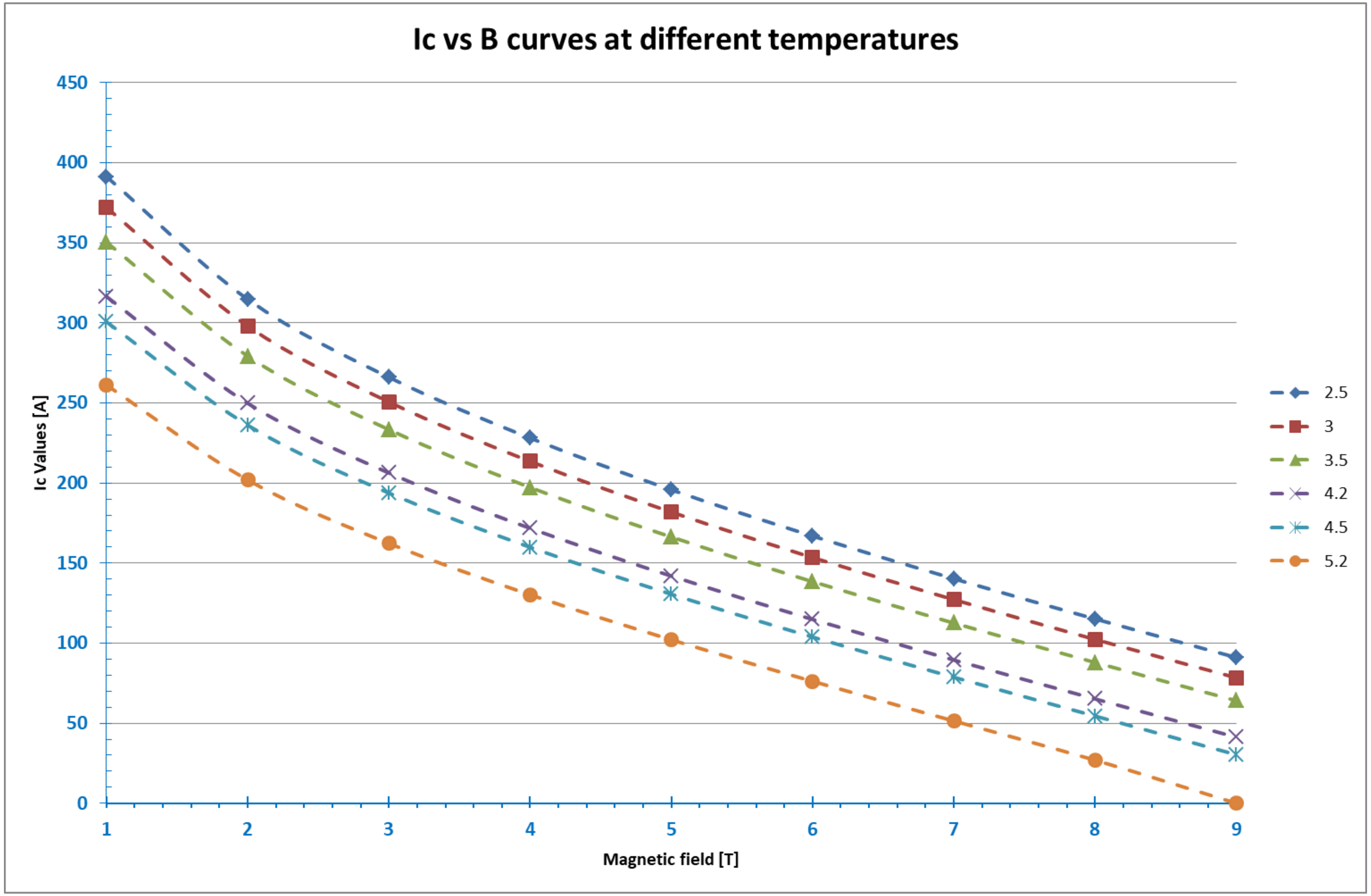
$$B_{CT} = B_{c0}\left(1-\left(\frac{T}{T_{c0}}\right)^{2}\right)$$

The ratio of the maximum current density in the superconductor at any magnetic field and temperature to that at B = 5 T and T = 4.2 K can be found using the expression given below:

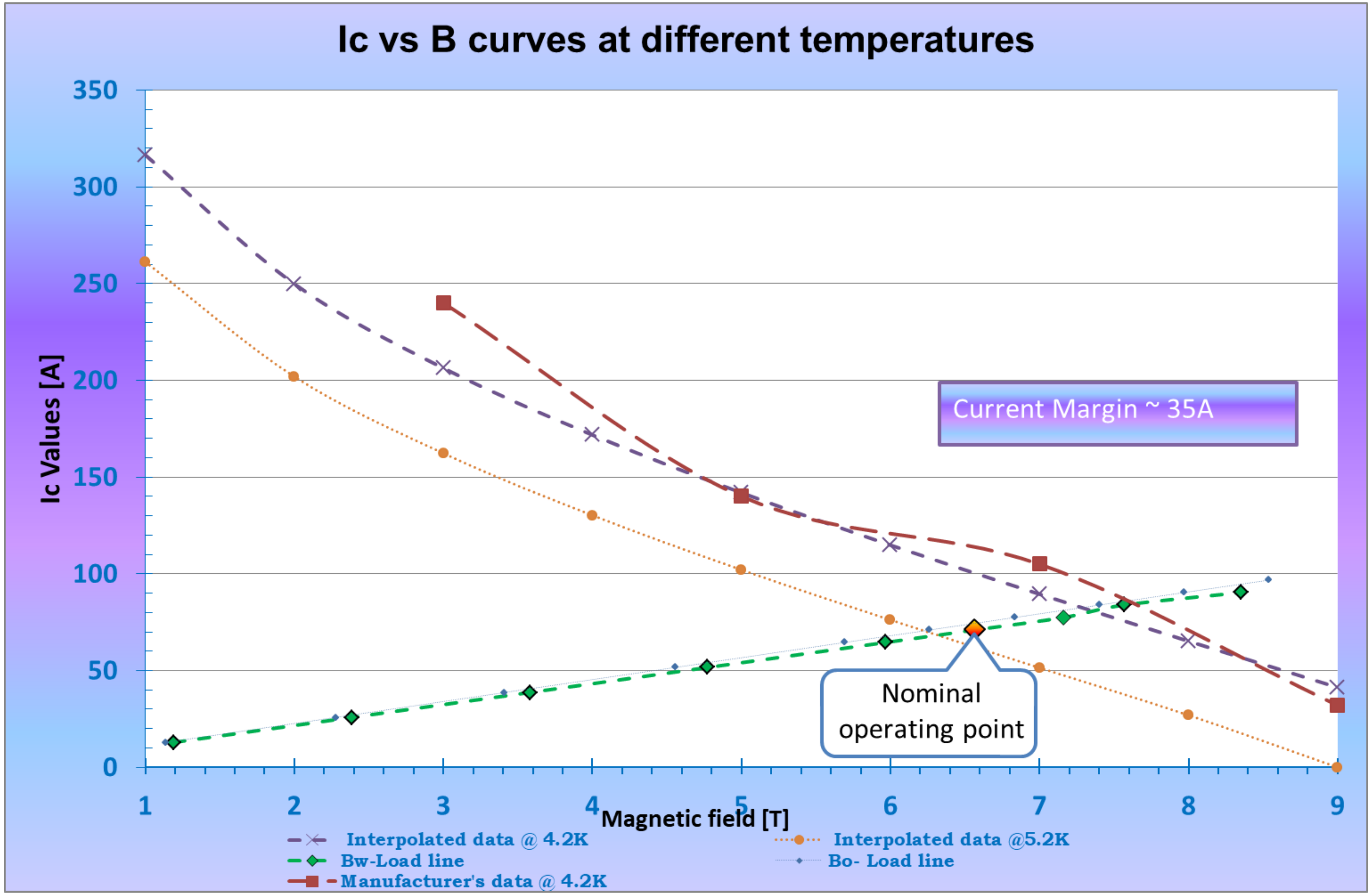
$$Jc(B,T) / Jc(5\ T, 4.2\ K) = C0/B \cdot b^{\alpha} \cdot (1-b)^{\beta} \cdot (1-tn)^{\gamma}$$

Where, $C_0 = 28.4$ T, $\alpha = 0.80$, $\beta = 0.89$, and $\gamma = 1.87$.

Superconducting Wire strand material properties

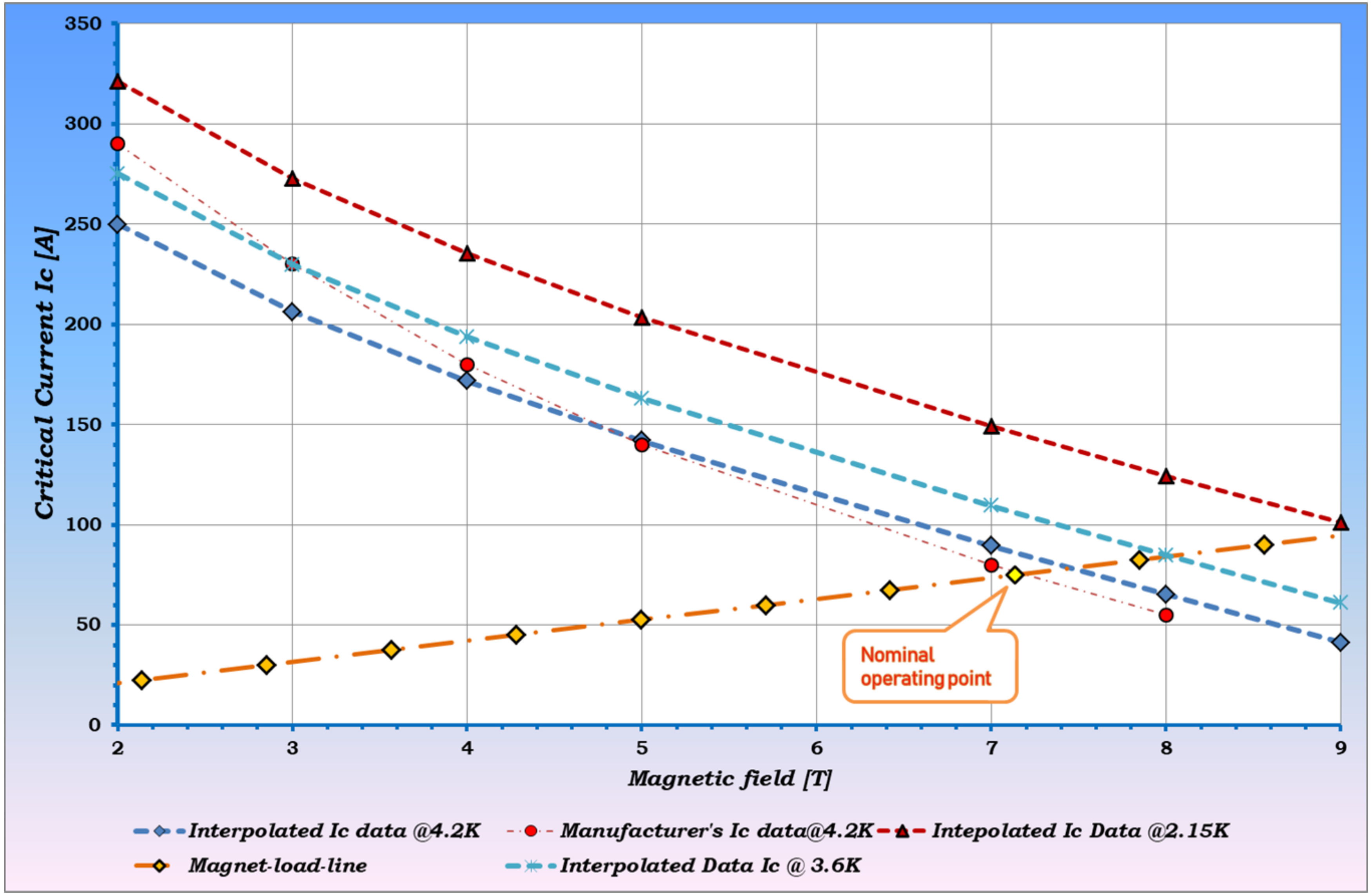


Magnet load line – New design



Comparing the manufacturer's data it is clear that practically there is a margin of ~ 35A @ 4.2K

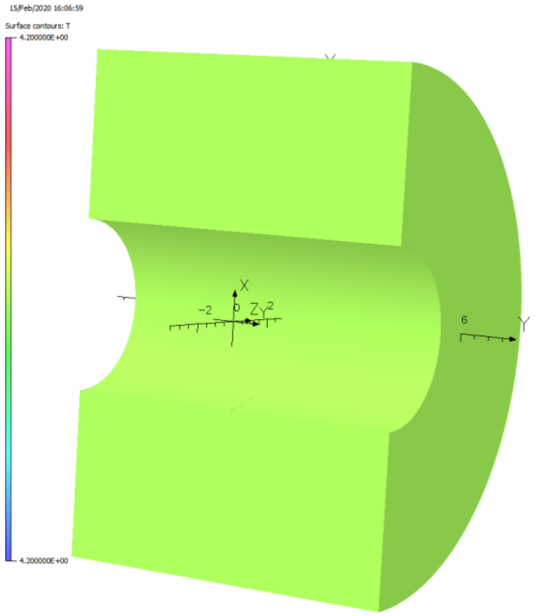
Magnet load line – Pre-series Magnet design (0.4mm bare dia wire)



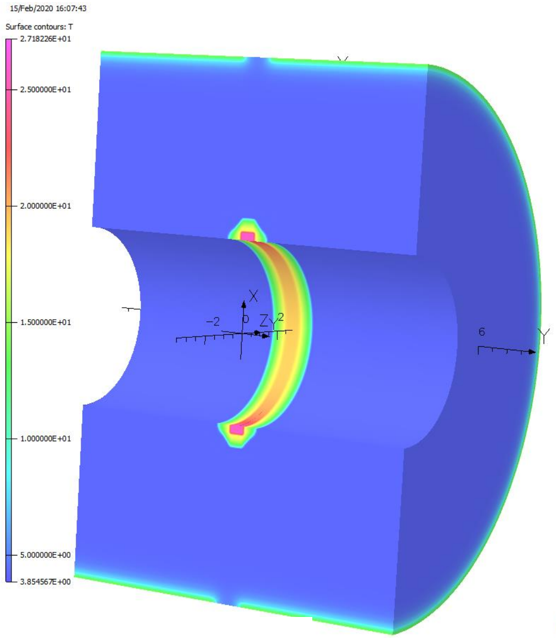
Practically no Margin @ 4.2K
~ 30A @ 2.15K

QUENCH STUDIES

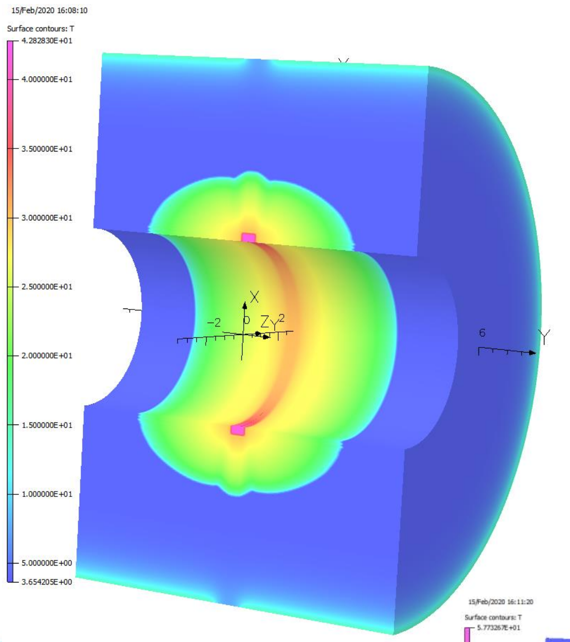
Quench Studies (Quench initiated in main coil)



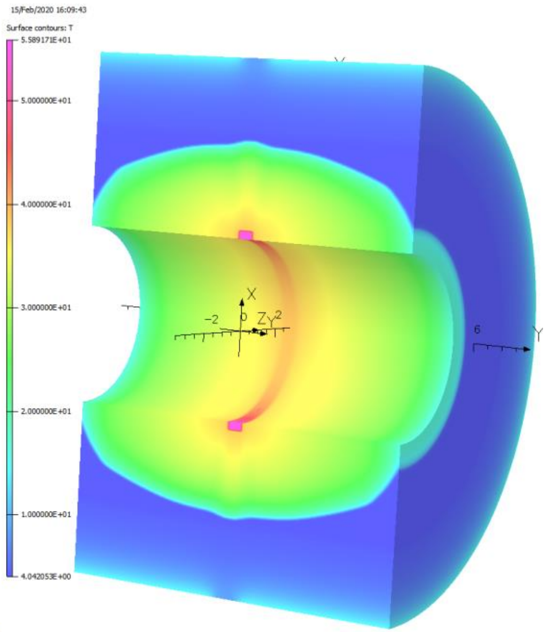
At t = 0s



At t = 0.01s



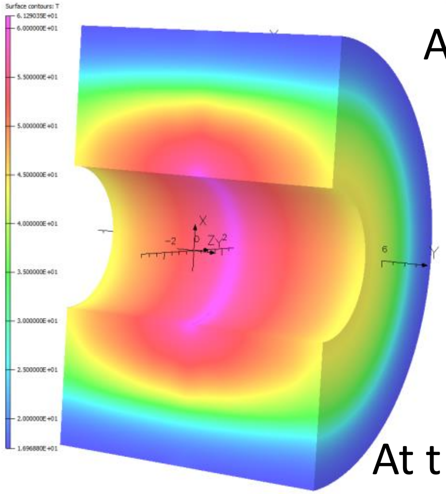
At t = 0.1s



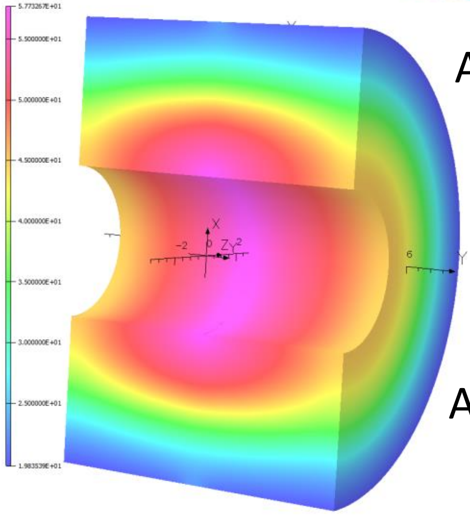
At t = 0.4s

Flux initiated by ~4W of heat deposition at peak B field location

To study peak temperature & peak coil voltages



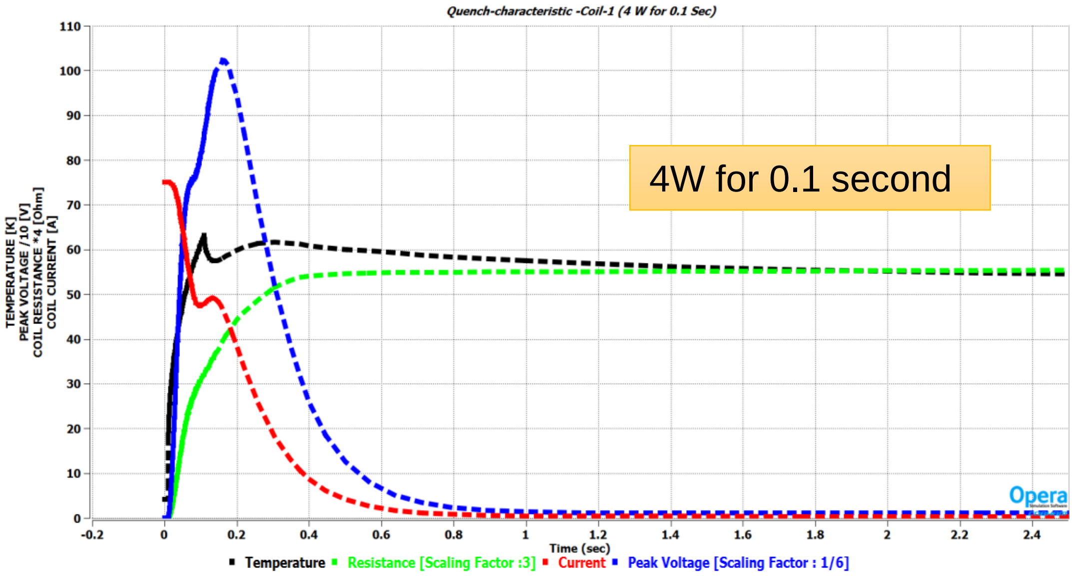
At t = 5s



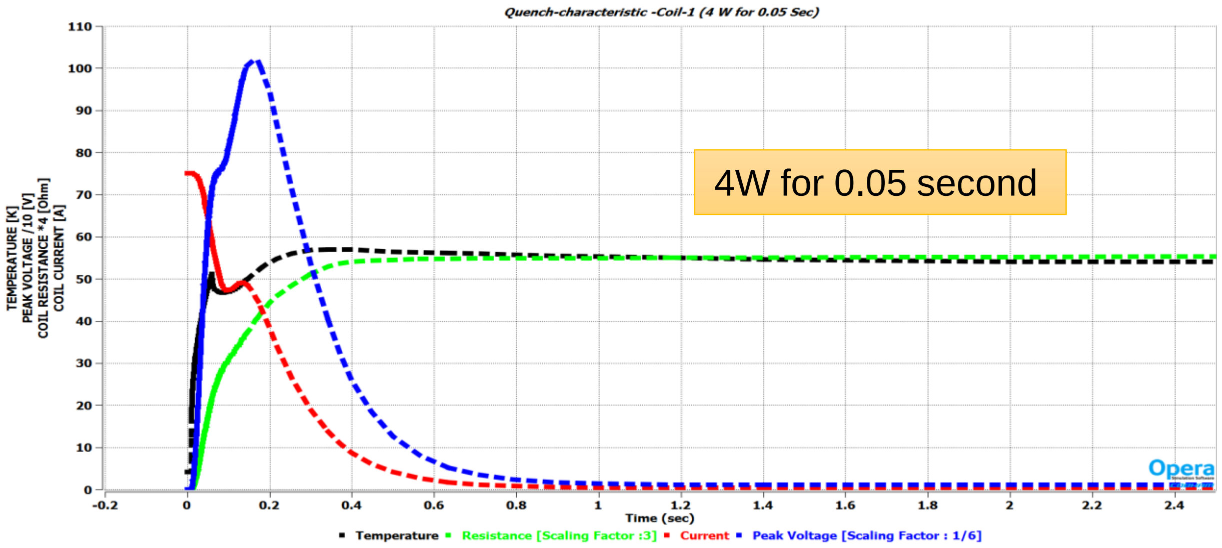
At t = 20s

Quench Design (Variation in heat pulse)

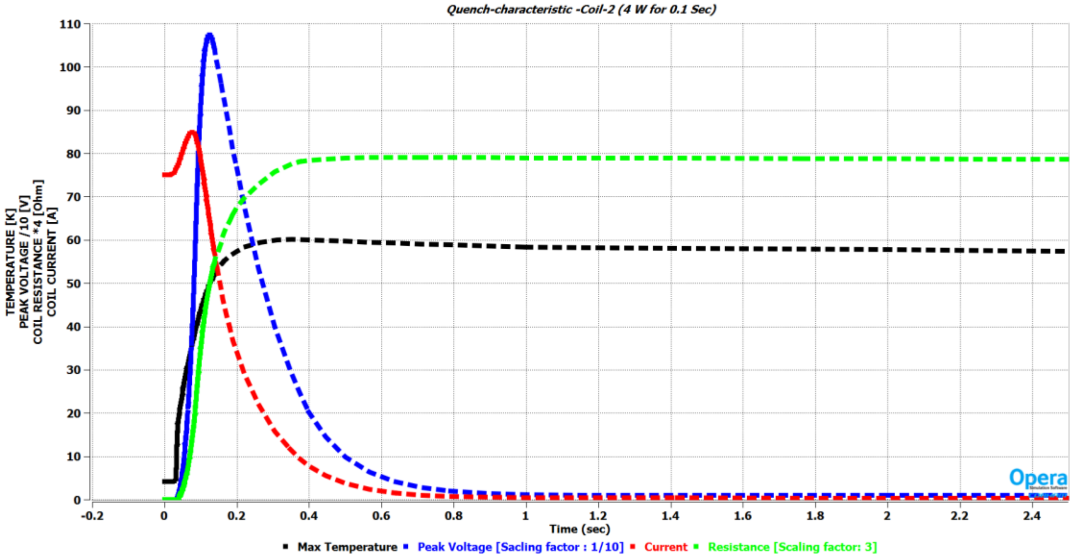
Quench Characteristic for two coils sub-sections of main coil

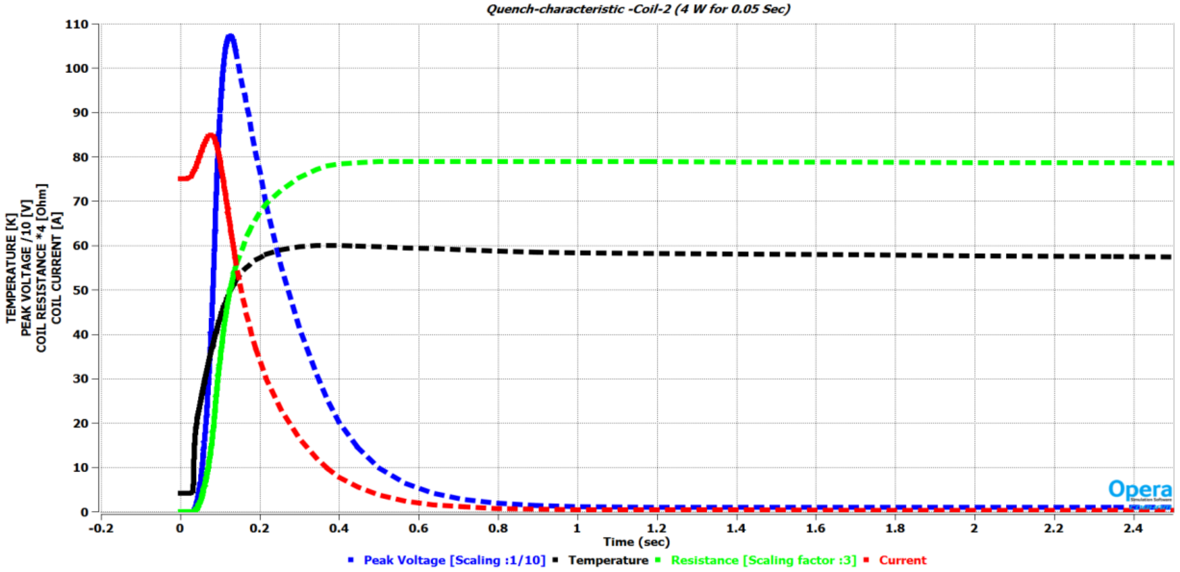

Quench-characteristic -Coil-1 (4 W for 0.1 Sec)

4W for 0.1 second

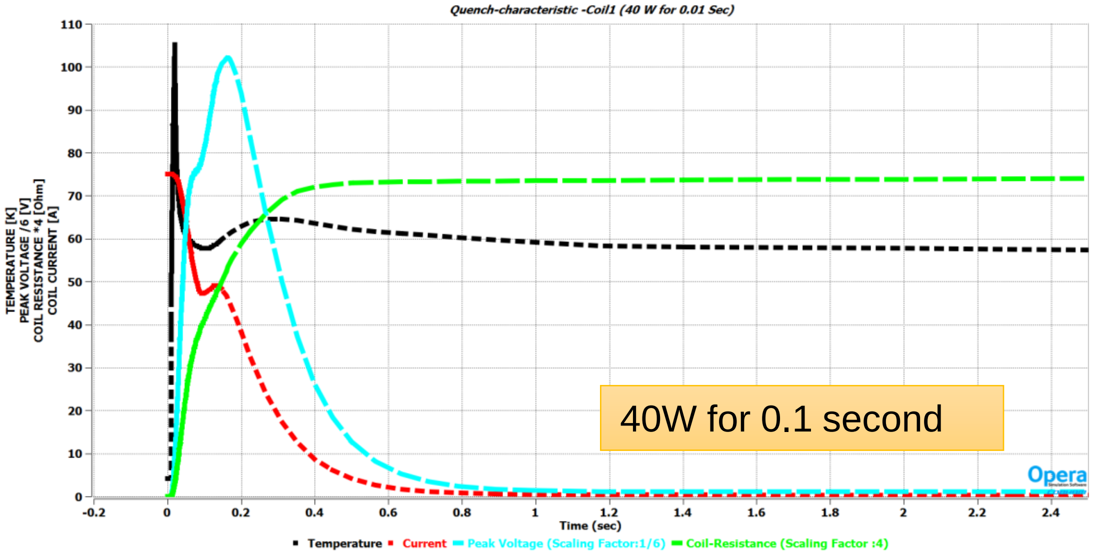

Quench-characteristic -Coil-1 (4 W for 0.05 Sec)

4W for 0.05 second

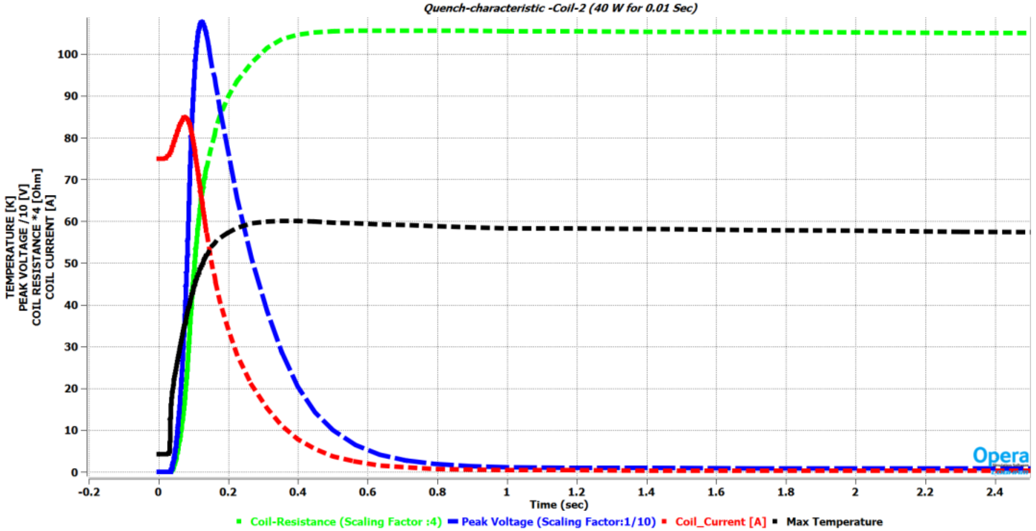

Quench-characteristic -Coil-2 (4 W for 0.1 Sec)


Quench-characteristic -Coil-2 (4 W for 0.05 Sec)

Quench Design (Variation in heat pulse)

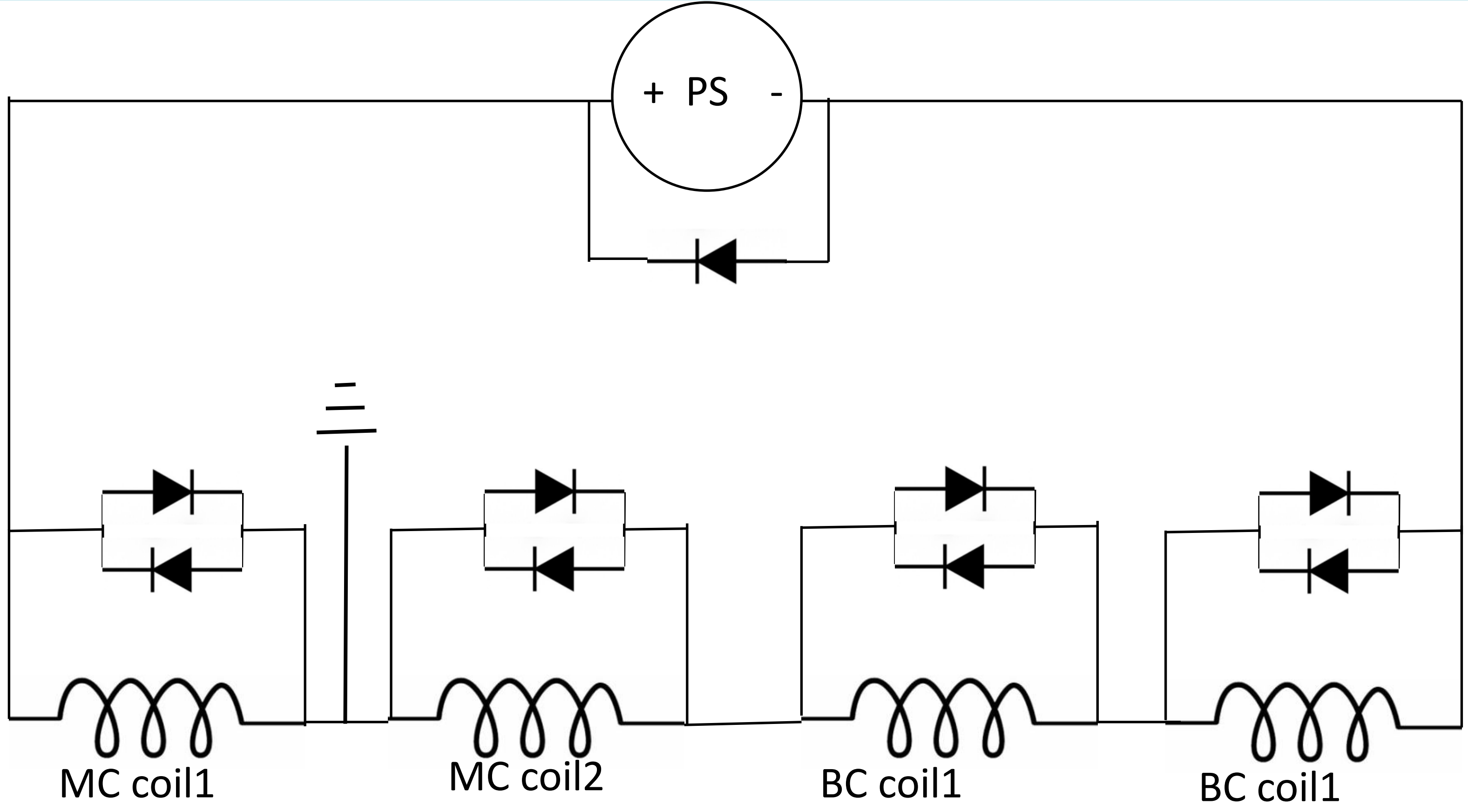


40W for 0.1 second



- ➢ The amount of input heat energy does not play very significant role in determining the coil temperature
- ➢ Once the quench has been initiated, by small amount of heat dissipation, the normal zone of the magnet will grow and decay the current
- ➢ However the initial peak temperature of the hot spot (location at which quench is initiated) does depend slightly on the heat pulse.

Quench protection circuit



Quench Protection by passive diodes

Differential Voltage sensed to detect Quench

Same Quench protection circuit for Dipole corrector coils

Quench detection

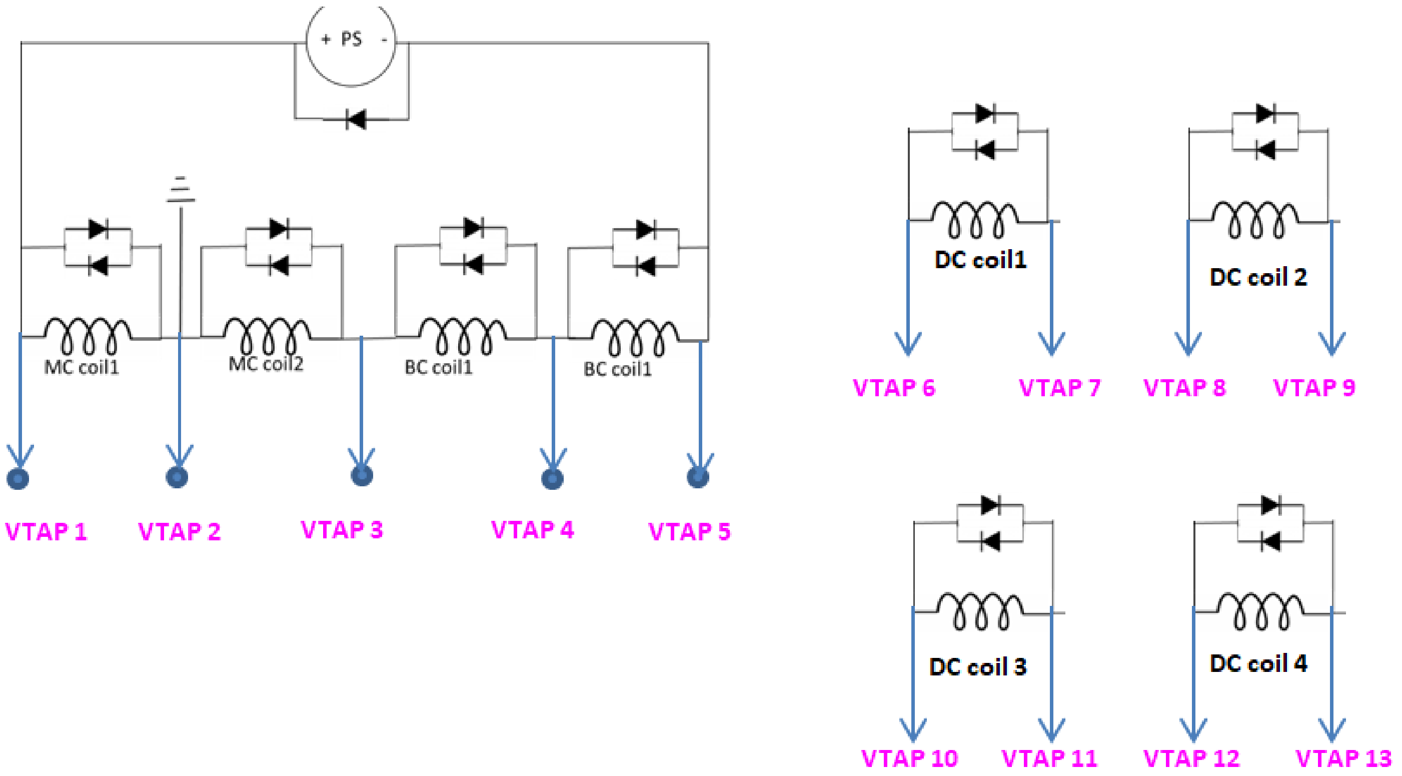


Fig.1 Electrical scheme showing location of the voltage taps and diodes for quench detection/protection

Voltage taps to monitor and record any event of quench

Based on the theoretical studies and pre-series magnet quench measurement the quench detection circuit is considered to be efficinet to detect and protect the magnet in event of quench.

Final Magnet parameters

	Coil1	Coil2	Coil3	Coil4
Coil1	5.82H	4.823H	-0.319H	-0.3191H
Coil2	4.823H	9.297H	-0.722H	-0.722H
Coil3	-0.319H	-0.722H	1.461H	0.521H
Coil4	-0.319H	-0.722H	0.521H	1.461H

Peak coil to ground voltage = 1.1kV

Peak temperature in case of quench = 65K

Magnet physical length = 140 mm

Engineering current density ~ 382 A/mm ^{2}	Excitation current 75A	Focusing strength 4.57 T^2m	Solenoid
Engineering current density ~ 50.995 A/mm ^{2}	Excitation current 10A	Focusing strength 6.3 mT-m	Dipole Corrector

Conclusion

Parameters	SSR1/SSR2 New specification (Ver.3)	Achieved	Remarks
Focusing Strength	$4.5 T^2 m$	$4.57 T^2 m$	√
Bending strength of Dipole correctors	≥6.0 (5.0) mT-m	6.3 mT-m	√
Beam pipe aperture	40 mm	40 mm	
Uncertainty in the location of magnetic axis w.r.t Reference points (Transverse and angular alignment)	<0.1mm RMS <0.5 mrad RMS	Majorly from the Mechanical design of magnet former and winding accuracy	
Active magnetic shielding requirements	~<10G	<10 G	√
Maximum current in the solenoid	90	75 A	√
Maximum current in the dipole correctors	12 (50)	10 A	√

- ✓ Electromagnetic design of the SSR solenoid has been carried out meet the specified requirements
- ✓ Predicted performance metrics and margins have been considered

In terms of (a) Operational margin (b) Manufacturing tolerance impact on performance (c) Fringe field on the cavity surface

Conclusion

- ✓ New design considerably has higher margin compared to pre-series magnets
- ✓ Dipole corrector current requirements have been reduced for reducing thermal load
- ✓ Based on the magnetic measurements and design performance of pre-series magnets predicted electromagnetic design will meet the design requirements
- ✓ Manufacturing tolerances has been accounted for during design and positioning accuracies of main coil and bucking coil shall be maintained to meet fringe field requirements under all conditions.

References

[1] PIP-II SSR2 CRYOMODULE FRS : ED0001829-D

[2] FOCUSING LENS FOR SSR1 AND SSR2 - Technical Requirements Specification (TRS)"

[3] BCR: SSR Solenoid design/validation test, PIP-II BCR

[4] “SSR1 Cavity Quenching in the Presence of Magnetic Field,” FNAL TD note TD-12-007, June 2012 , T. Khabiboulline, D. Sergatskov, and I. Terechkine,

[5] “Acceptable Level of Magnetic Field on the Surface of a Superconducting RF Cavity,” FNAL, TD note TD-12-008, June 2012T. Khabiboulline, T. Nicol, and I. Terechkine

[7] Electromagnetic design and performance of conduction cooled superconducting magnet for spoke resonator cryomodule for Proton Improvement Plan (PIP)-II, Kumud Singh, Janvin Itteera, Mahima , Vikas Tiwari , Himanshu Bisht , Sanjay Malhotra ,R.R. Singh , Rajesh Jalan , Sanjay Howal , Rajesh Chimurkar , Sunil Kumar , S. Stoynev ,M. Turenne , M. Yub, B. Hanna , J. Hayman , C. Boffo, July 2024 Elsevier, Superconductivity

Thank you for your kind attention

Back up slides

Summary of quench studies

With dump resistor in series with back to back diodes

Sr. no.	Series dump resistor value	Peak voltage in coil 1 Peak Voltage in coil 2	Voltage across Coil1 Voltage across Coil2	Coil 1 temperature Coil 2 temperature
1.	0 Ohms	600V 1100 V	4V 4V	60K 60K
2.	0.005 Ohms	60V 200V	~ 4.5V ~ 4.5V	45K 38K
3.	5 Ohms	100 V 120 V	~ 400 V ~128 V	38 K 27 K

With only back to back diodes in parallel with coil

Sr. no.	Configuration	Peak voltage in coil 1 Peak Voltage in coil 2	Voltage across Coil1 Voltage across Coil2	Coil 1 temperature Coil 2 temperature
1.	Radial Coil split (middle quench) No dump resistor 0.4J of energy deposition	600V 1100 V	~4V ~4V	65K 60K
2.	Axial Coil split (middle quench) No dump resistor 0.4J of energy deposition	~ 850V ~850V	~4V ~4V	75K 75K
3.	Axial Coil split (corner quench) No dump resistor 0.4J of energy deposition	~ 850V ~850V	~4V ~4V	75K 75K