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Design of warm magnets for PIP-II

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PIP-II meeting

Fermilab

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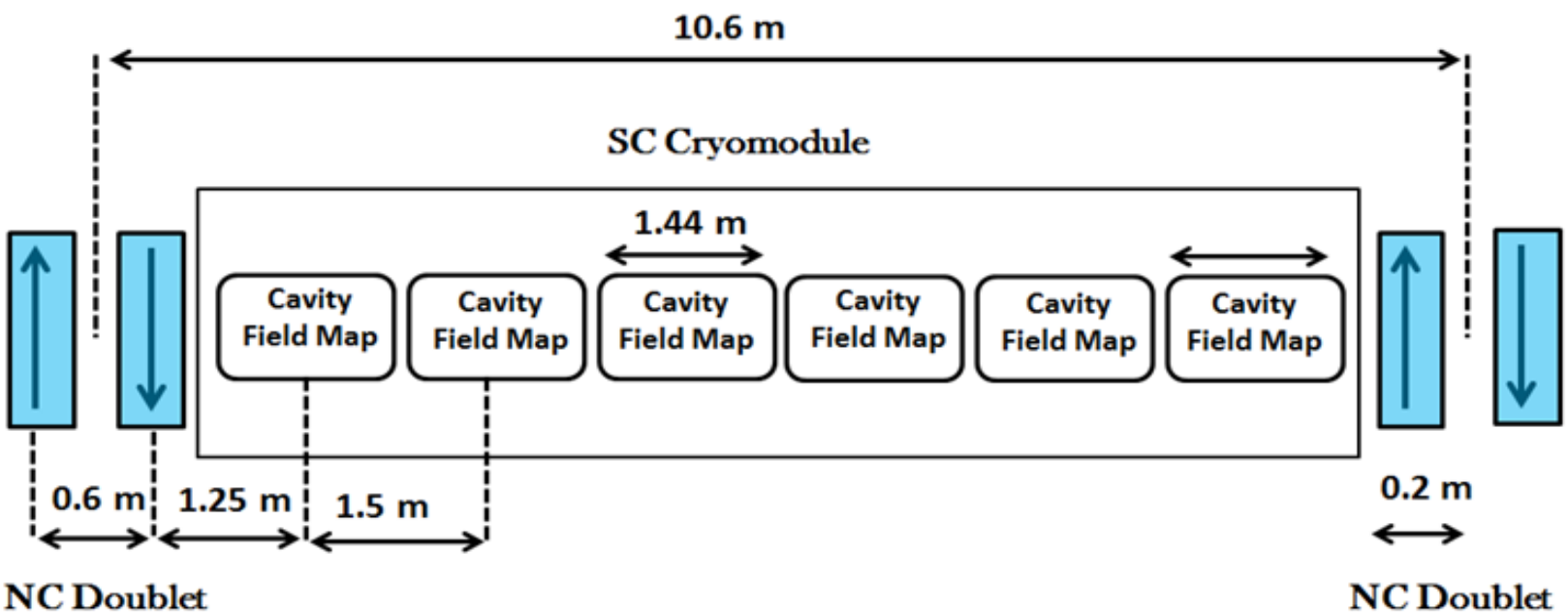
Introduction

- The Low beta (LB) and high beta (HB) sections of PIP-II consists of Warm magnets for transverse focusing and orbit corrections.
- The configuration of magnets and cavities in LB and HB sections are as follows.

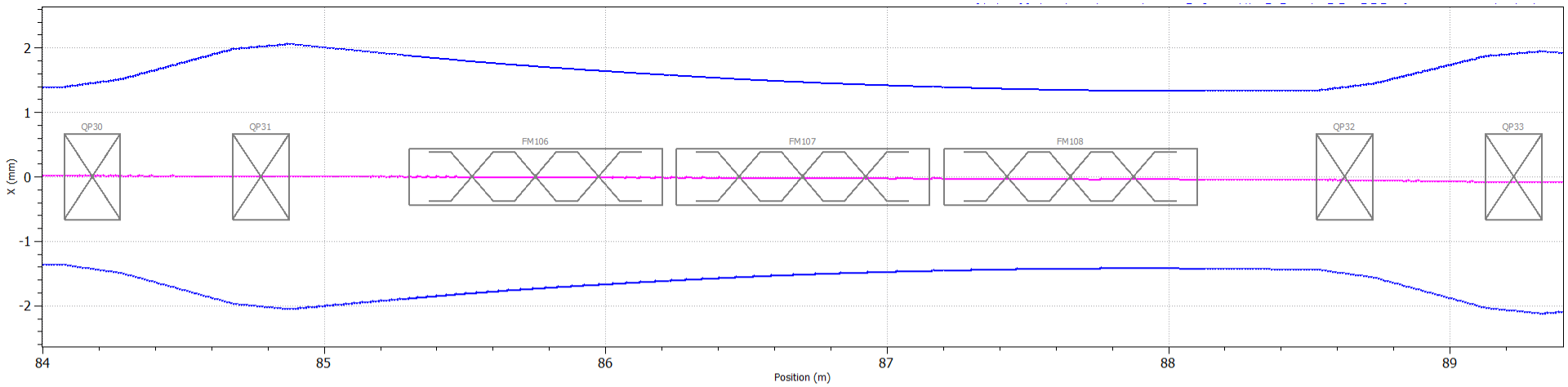
Low Beta : **QDQ** CCC **QDQ** ……. : 11 CM

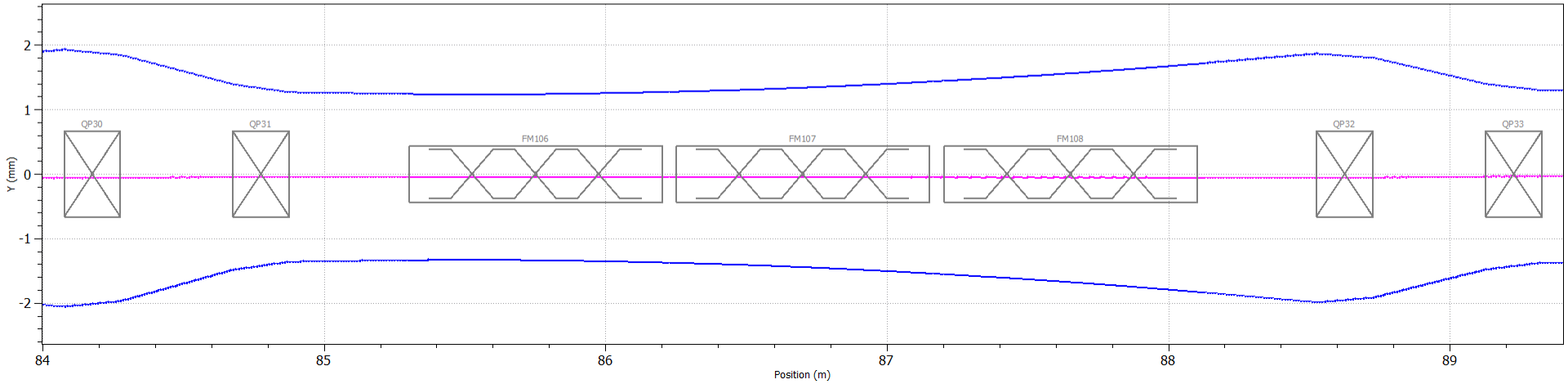
High Beta : **QDQ** CCCCCC **QDQ** ….. : 04 CM

Legend : Q : Quadrupole Magnet; D : Dipole Corrector; C : Cavity

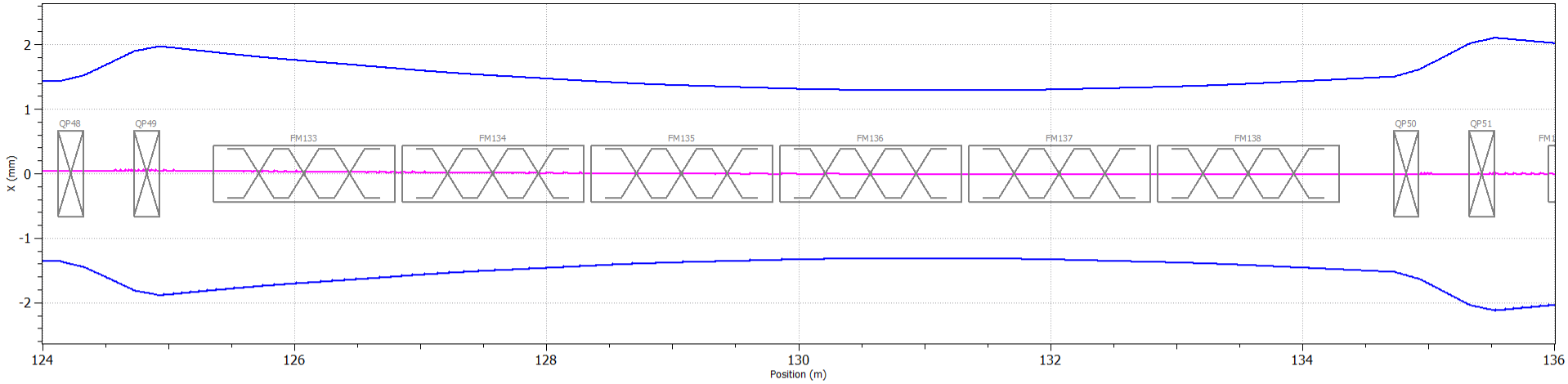


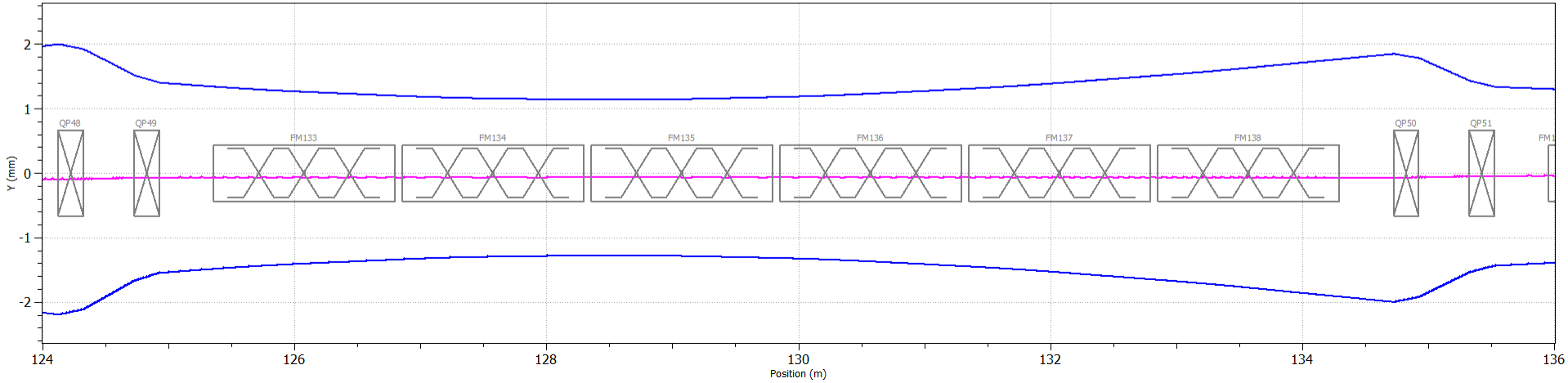
Beam dynamics in LB 650 MHz section





Beam dynamics in HB 650 MHz section





Specifications of Quadrupole

S.N.	Parameters	Value	Unit
1.	Integral Magnetic field gradient	3.0	Tesla
2.	Magnetic field gradient	13.5	T/m
3.	Pole tip to pole tip gap	48	mm
4.	Good Field region (diameter)	24	mm
5.	Uniformity of ∫G.dz in GFR	0.1	%
6.	Separation between Quad centre	600	mm
7.	Advised physical length	200	mm
8.	Maximum transverse dimensions	600	mm
9.	Maximum longitudinal dimensions (including coils)	300	mm
10.	Power supply preferences	<15	A
		<30	V

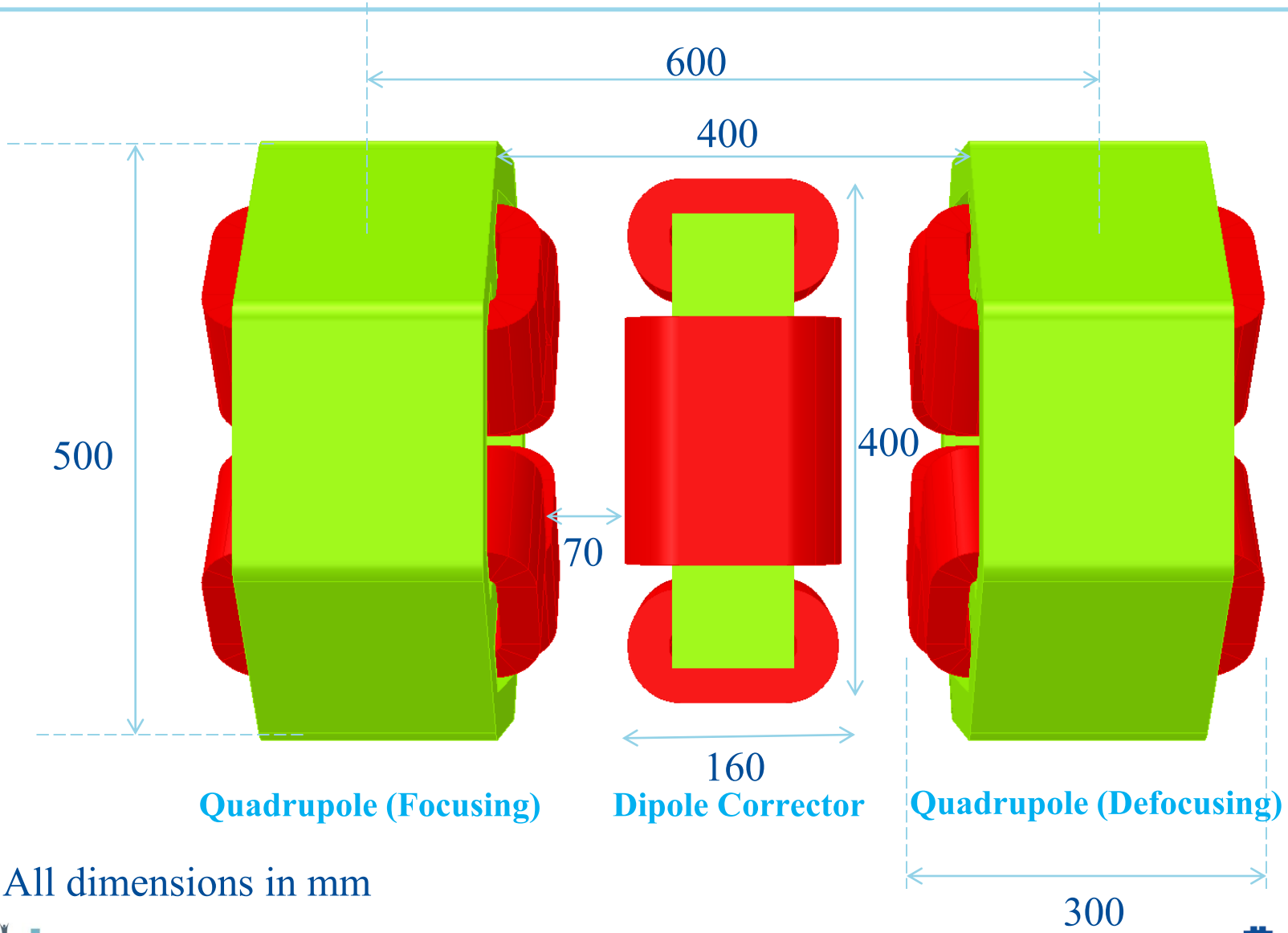
Specifications of Dipole Corrector

S.N.	Parameters	Value	Unit
1.	Integral Magnetic field	10	mT.m
2.	Pole tip to pole tip gap (Minimum)	48	mm
3.	Good Field region (diameter)	24	mm
4.	Uniformity in GFR	1	%
5.	Advised physical length	100	mm
6.	Maximum transverse dimensions	600	mm
7.	Maximum longitudinal dimensions (including coils)	160	mm
8.	Power supply preferences	<15	A
		<30	V

Proposed design (obtained from analytical model)

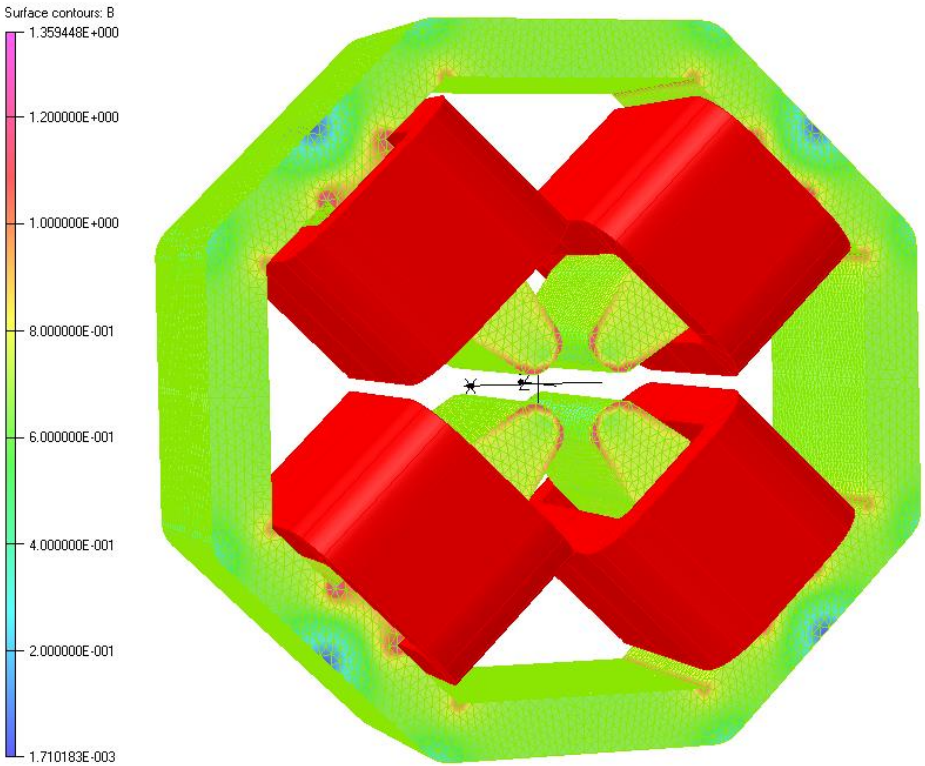
SN	Parameter	Value	SN	Parameter	Value
1.	∫G.dl	3 Tesla	11.	Resistance	0.39 Ω
2.	Pole to pole gap	48 mm	12.	Voltage	4.7 Volts
3.	Gradient	13.5 T/m	13.	Power consumption/coil	56 Watts
4.	MMF Required	3110 Ampere	14.	Estimated temperature rise in coils	30° C
5.	Magnetic length	222 mm	15.	Magnets longitudinal foot print	287 mm
6.	Physical length	198 mm	16.	Magnets Transverse foot print	492 mm
7.	Copper conductor	4 mm X 2 mm	17.	Total Magnet Weight (including poles, yokes and Coils)	217 Kg
8.	Current density	1.5 A/mm^2	18.	Coil window factor	0.5
9.	Turns	260	19.	Bobbin clearance (one side)	6 mm
10.	Current	12 Ampere			

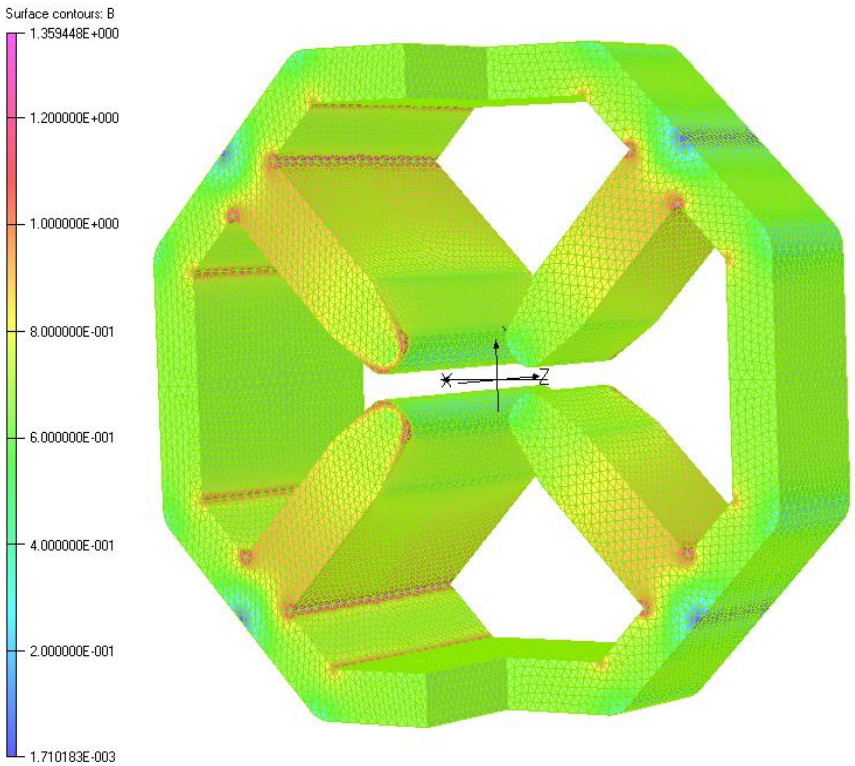
HB/LB650 Doublet configuration



All dimensions in mm

Magneto static Analysis using OPERA 3D

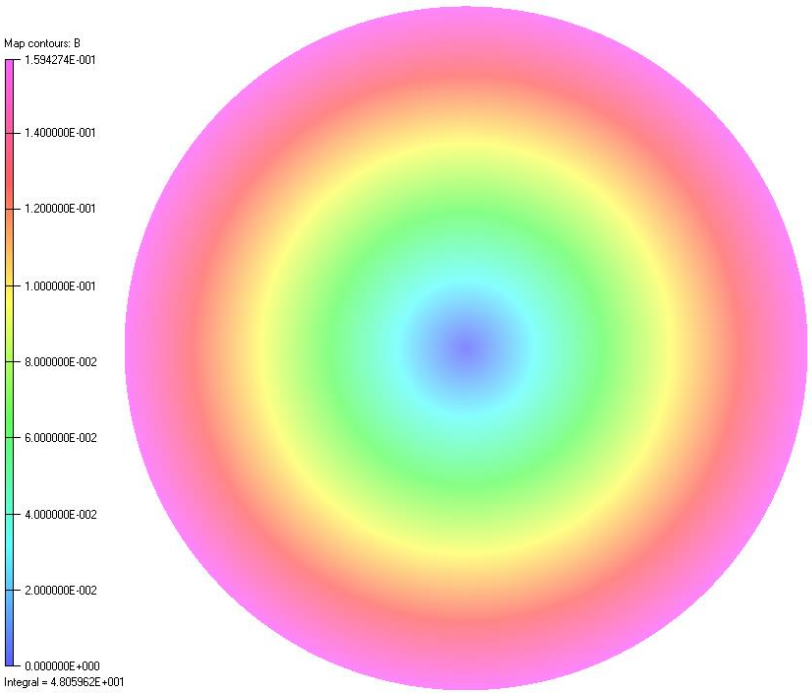




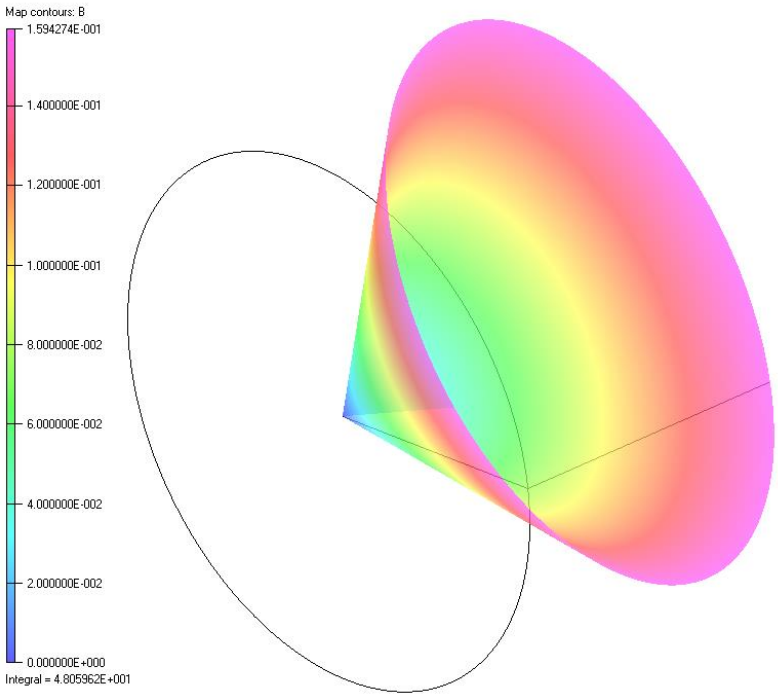
3-D Model and Magnetic field Distribution in the yoke

Magnetic field in the yokes (yoke is at 0.35 Tesla)

Magnetic field profile in the beam aperture

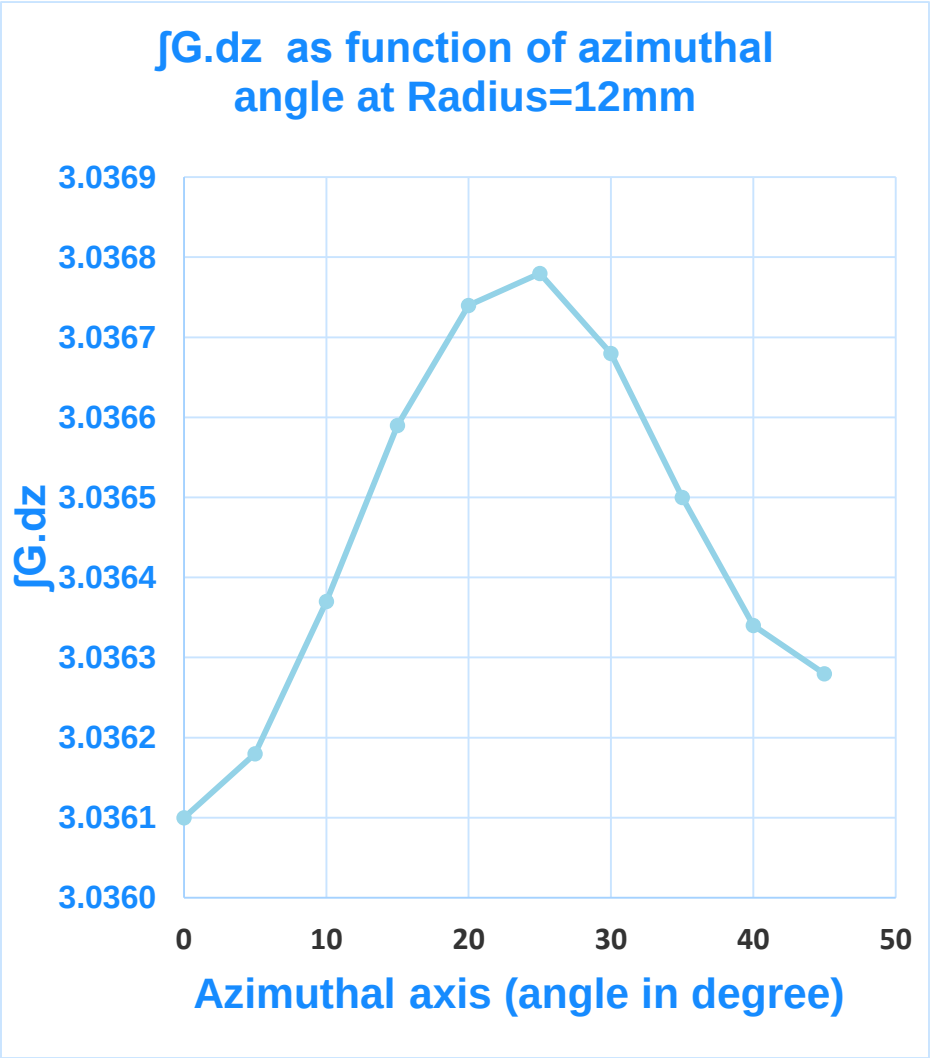


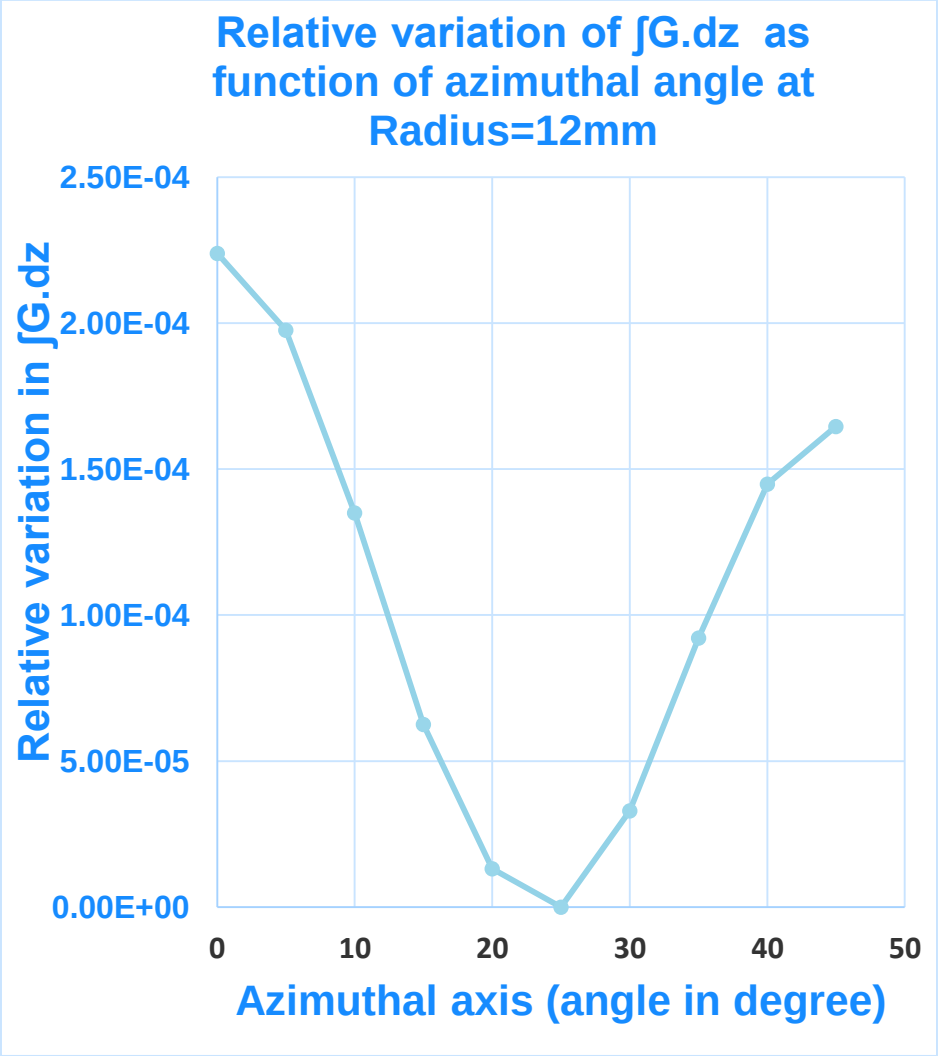
Magnetic field strength in the beam aperture



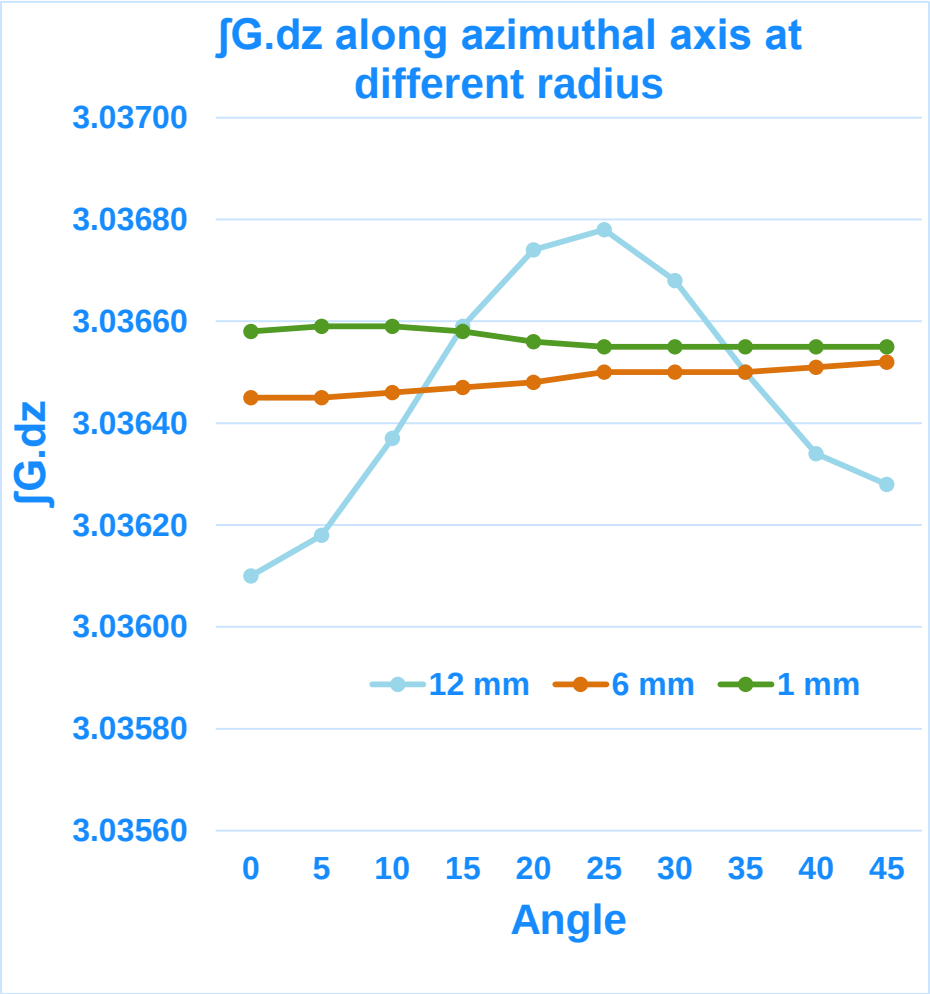
Histogram view of magnetic field in the beam aperture

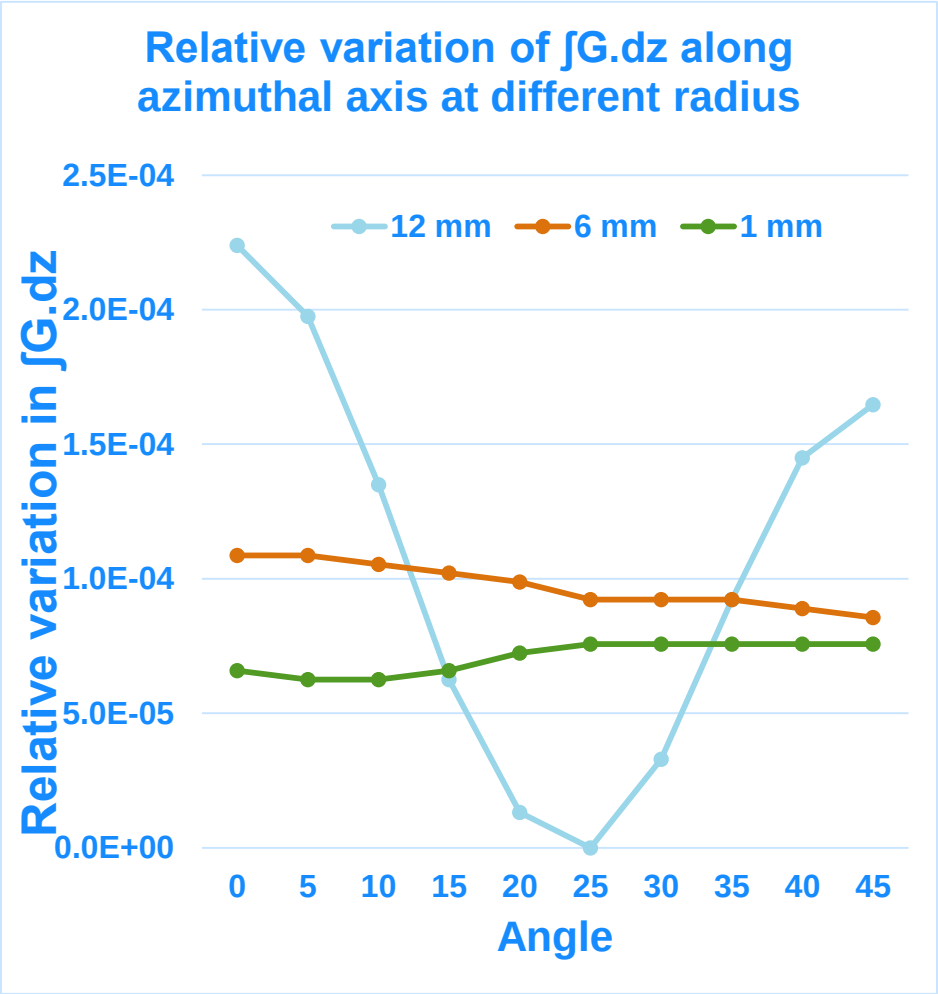
Uniformity of ∫G.dz @ 12 mm



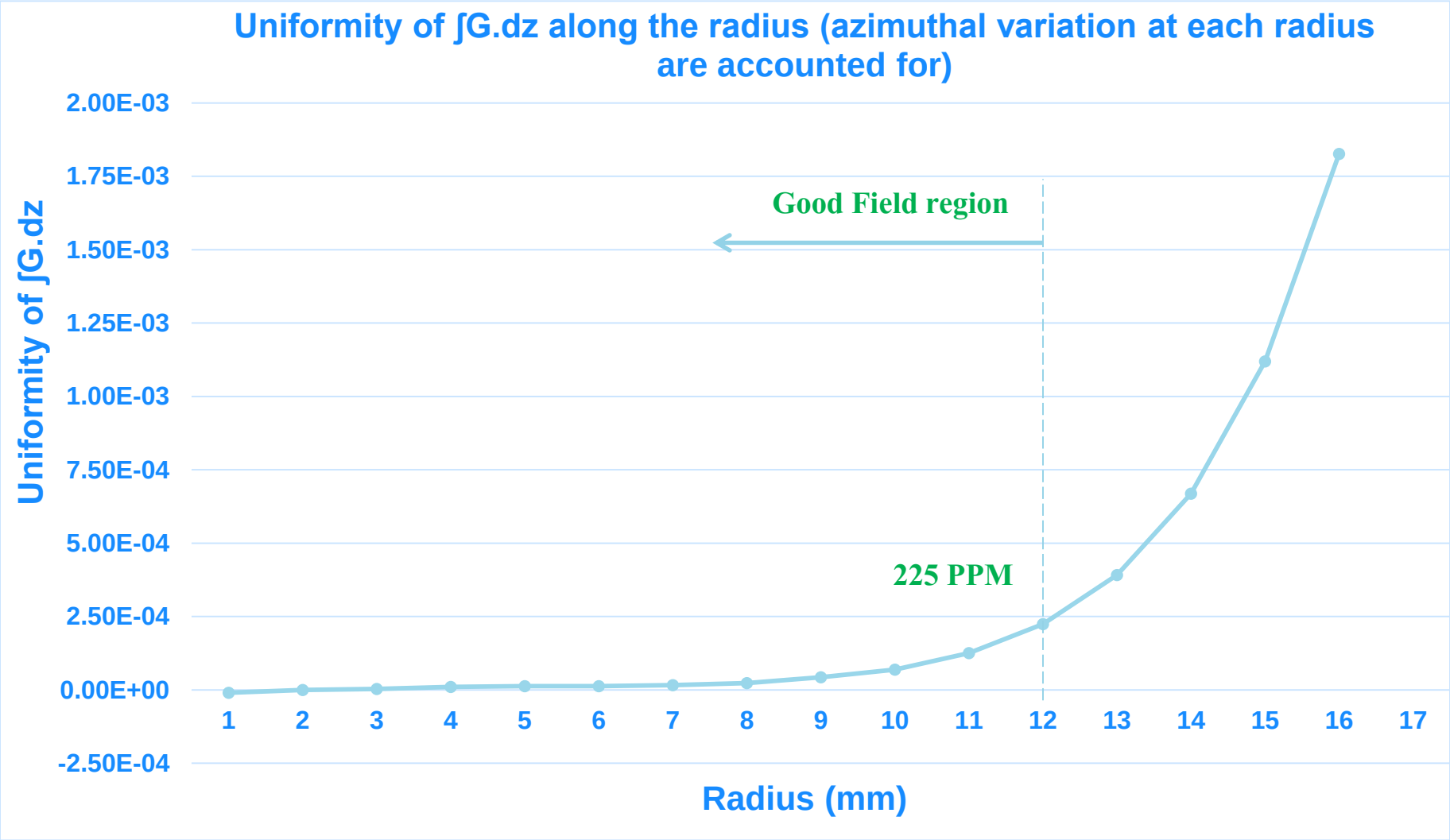


Uniformity of ∫G.dz @ 12 mm, 6 mm & 1mm

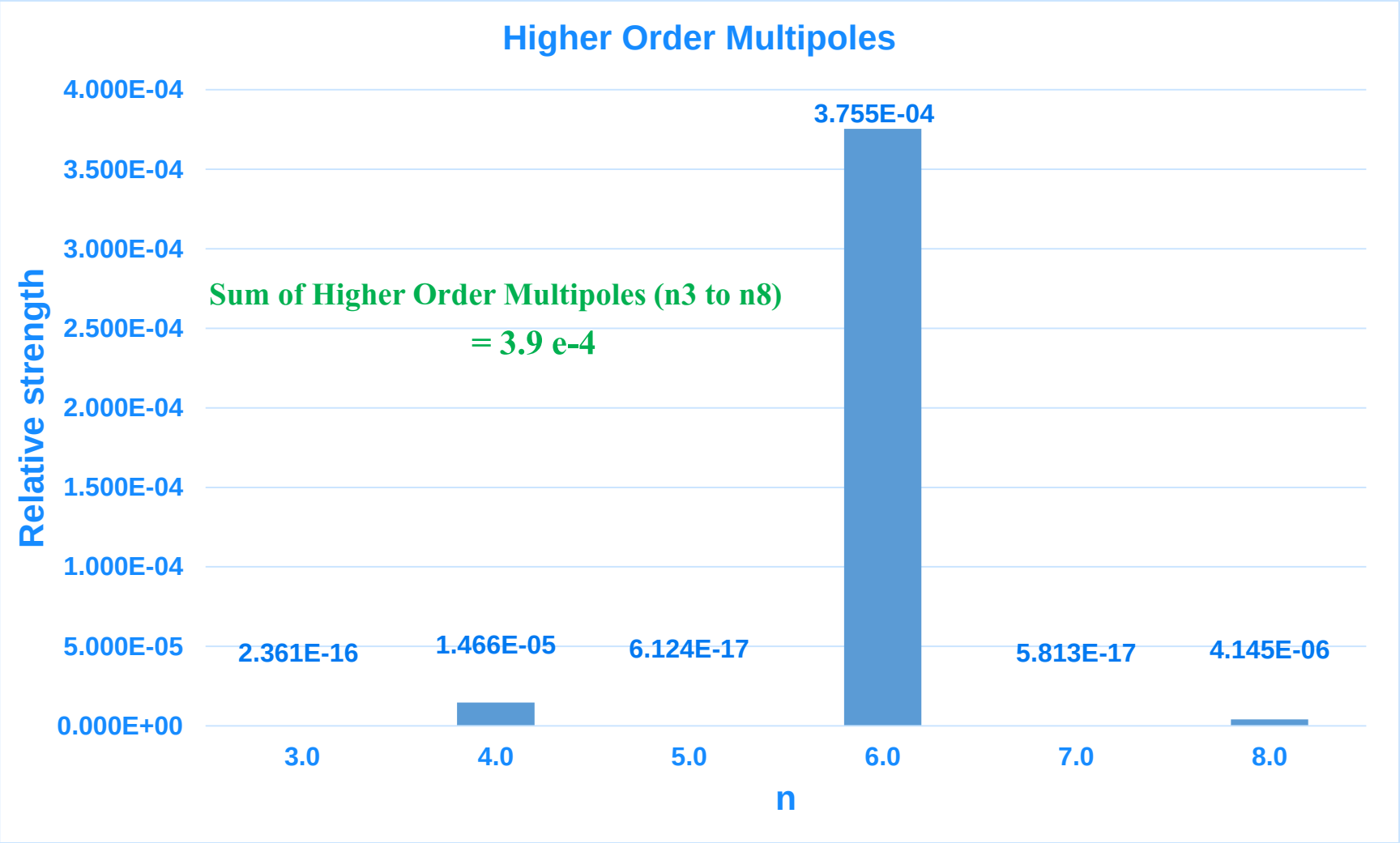




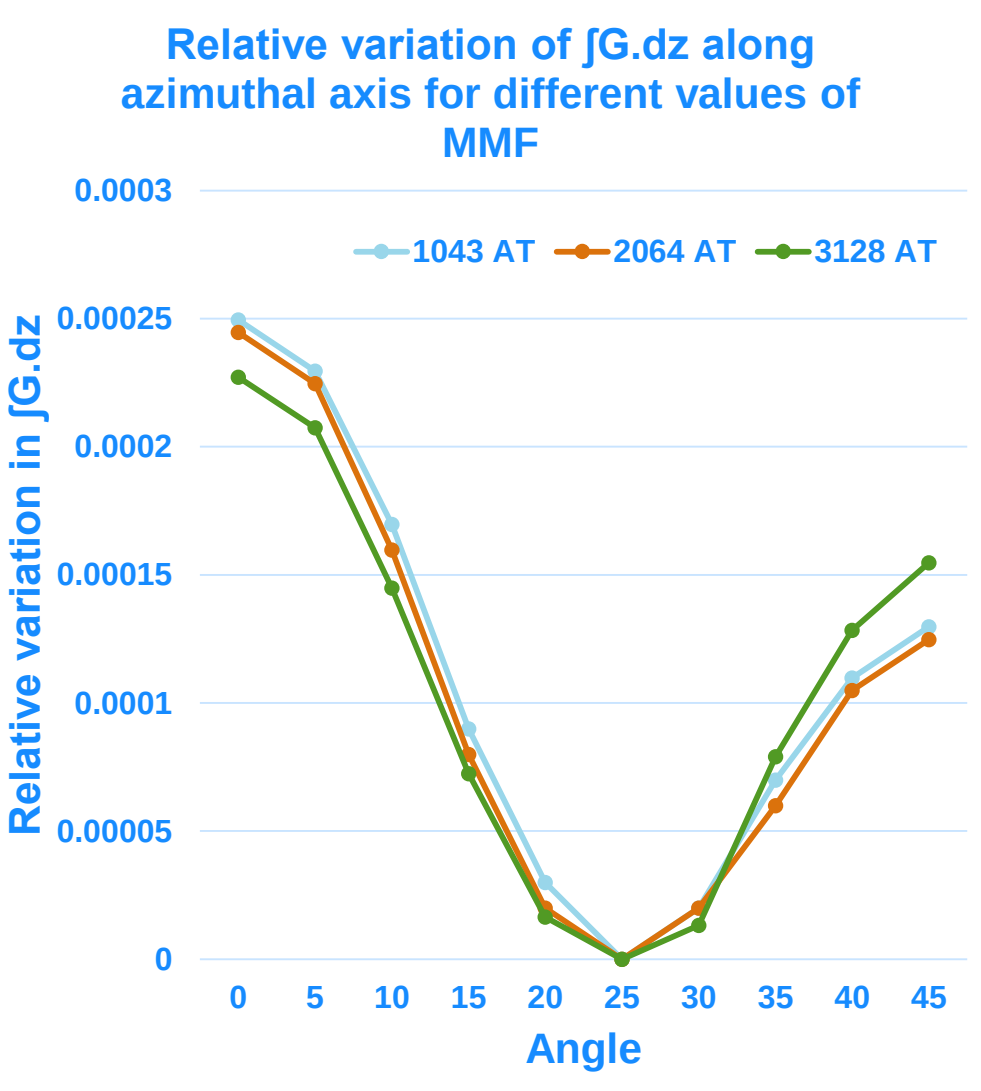
Uniformity of ∫G.dz along the radius

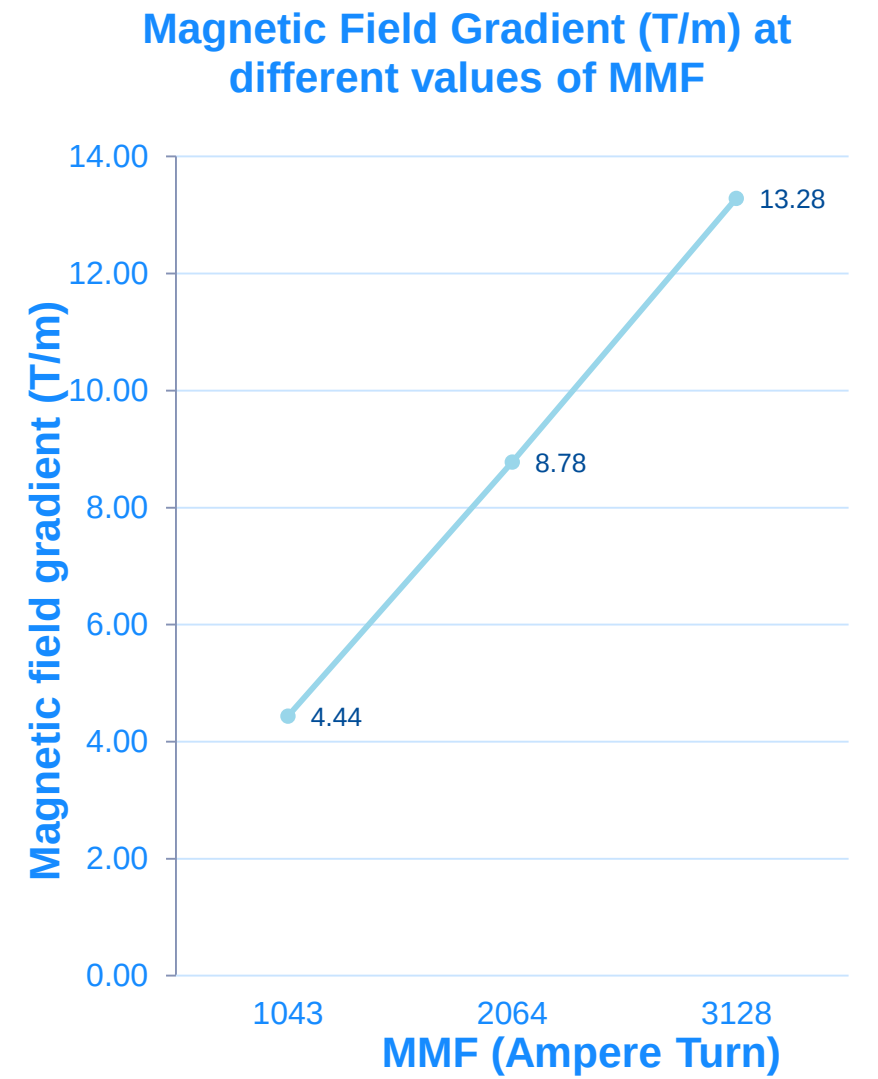


Higher order multipole components



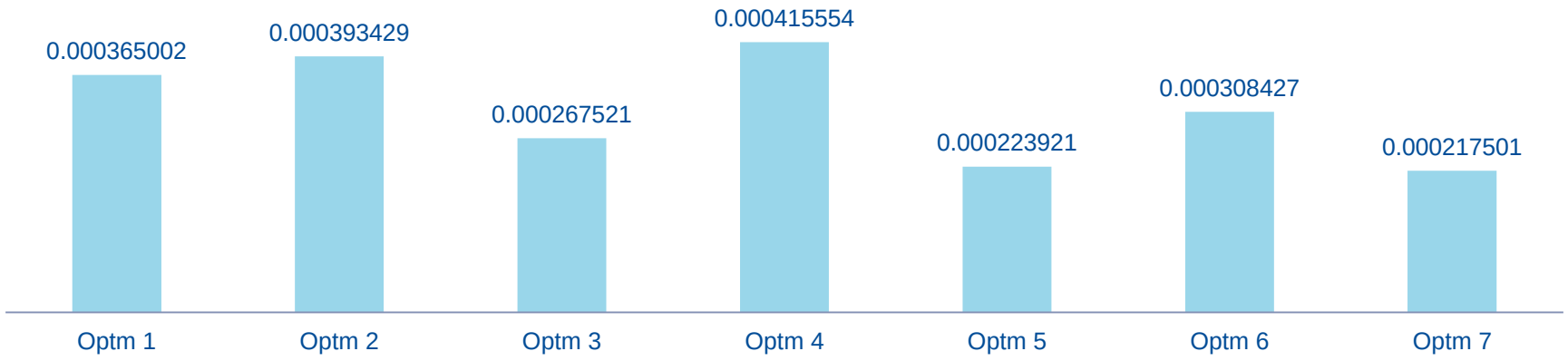
Variation in Uniformity of ∫G.dz with MMF

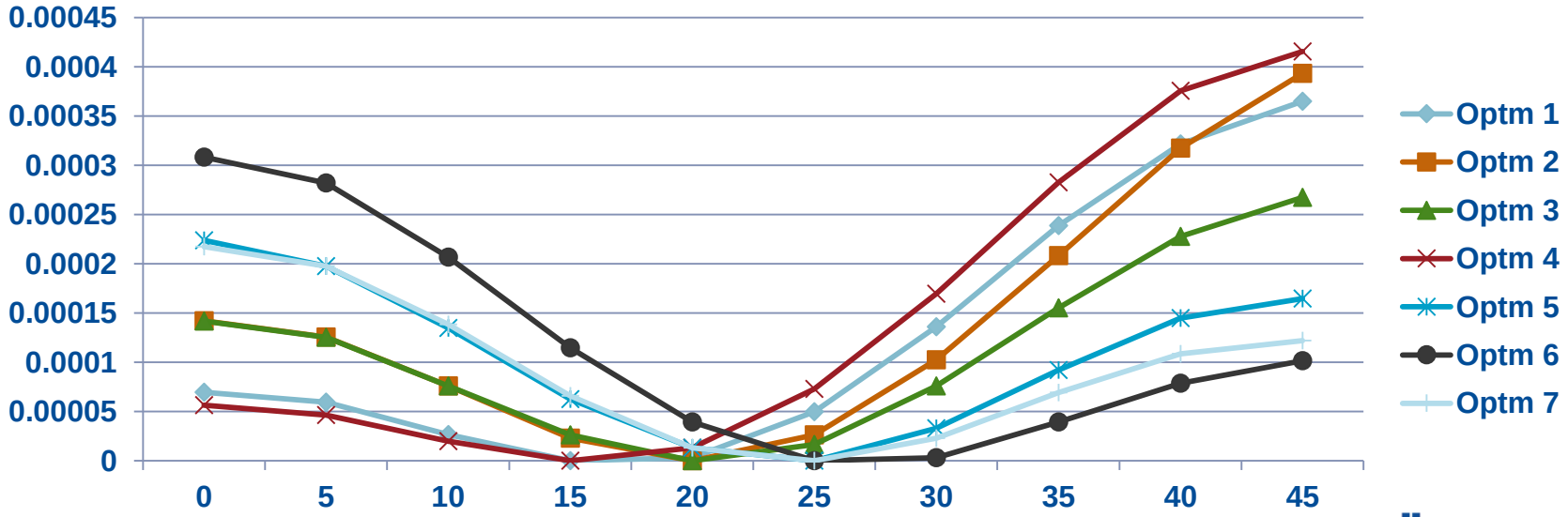




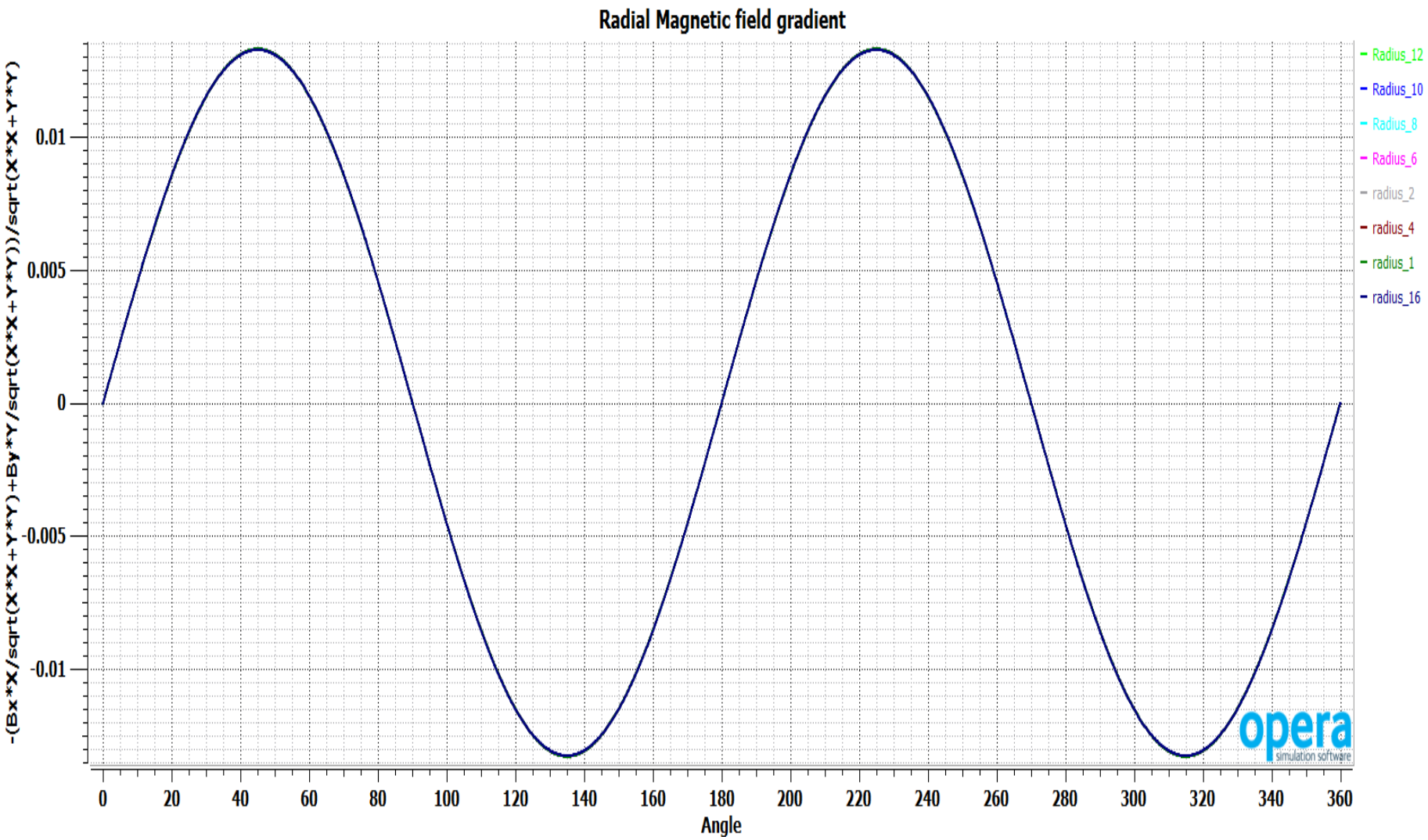
Optimization of the Pole shape (different optimization curves)

Optimization of poles (Uniformity of ∫G.dz)

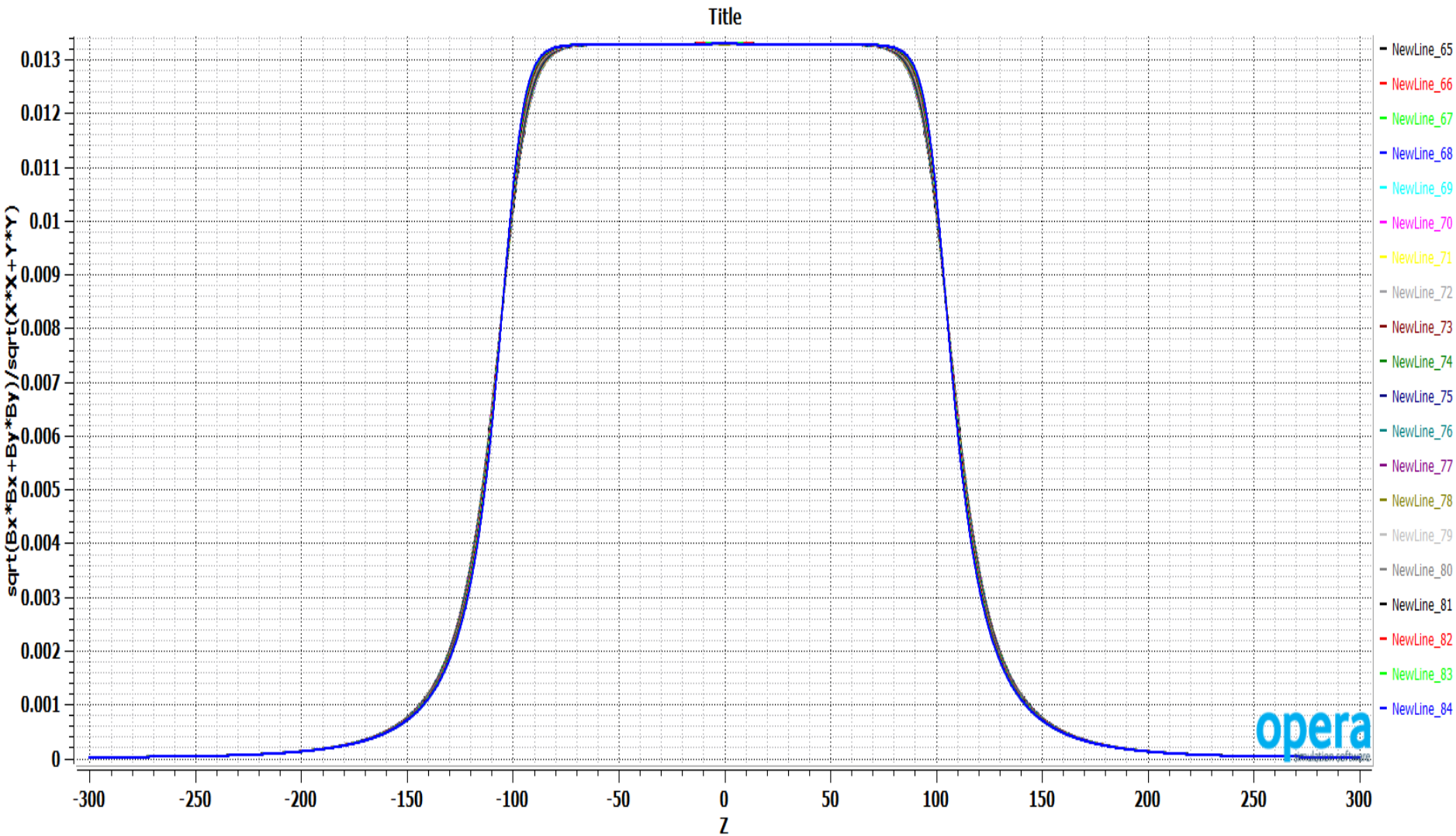




Radial component of magnetic field grad for various r, Ø points



Magnetic field gradient along the axis for various r, Ø points



Thermal Issues

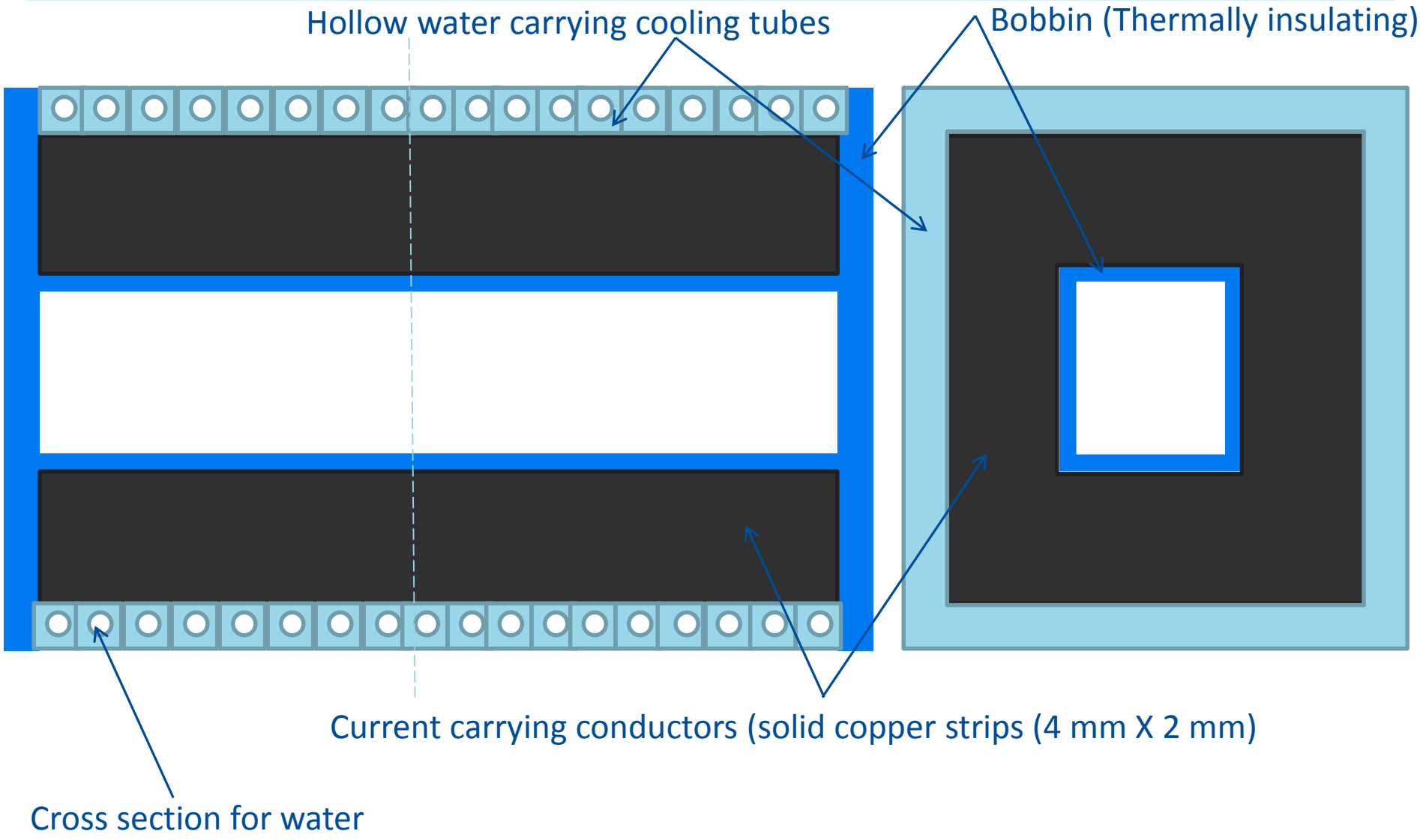
- Total 45 Magnets (Including Quadrupoles and Dipole correctors).
- Thermal dissipation of each Magnet is of the order of 300 Watts.
- Total heat load in the accelerator cave will be about 12 kW.
- This will put burden on air conditioning requirement of the cave. (Decision to be taken by project management)

In case above do not work out, two options can be considered.

1. Solid copper strips as current carrying conductors and heat carried out from internals of the coils with help of heat sinks and removed with help of water cooled hollow conductors.

2. Hollow water cooled copper current carrying conductors can be used for providing required MMF and heat can be removed adiabatically from the cave. (This will demand for high current/low voltage power supply and further form factor of the coil will be large). **Option 1 is more preferable**

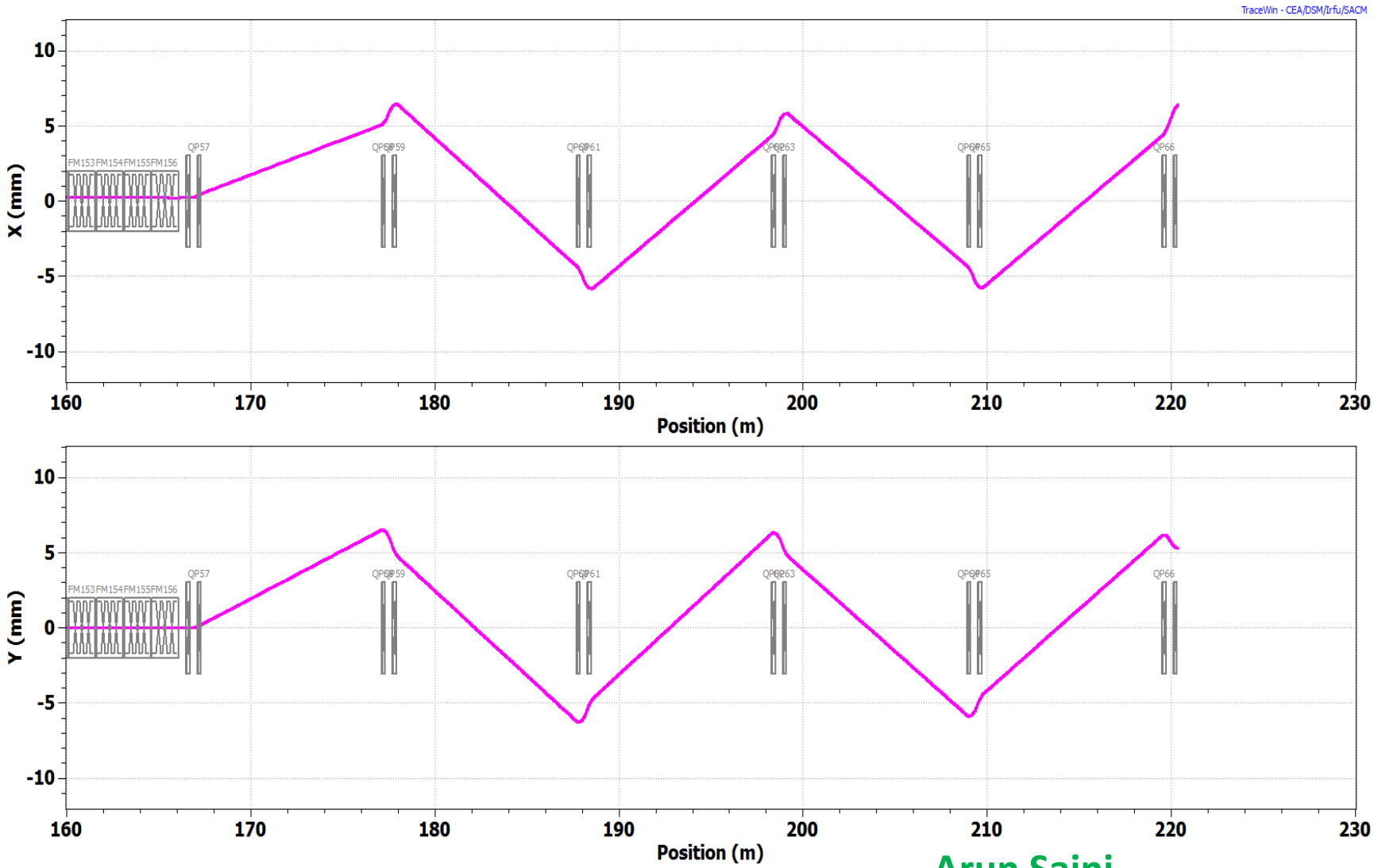
Thermal design of Coil



Summary of the Magnetic design of Quadrupole

SN	Parameter	Required	Obtained Value	Unit
1.	MMF	-	3128	Ampere-Turn
2.	Pole tip to pole tip distance	48	48	mm
3.	Good field region (diameter)	24	24	mm
4.	Magnetic field gradient	~13.5	13.28	Tesla/meter
5.	∫G.dl	3.00	3.037	Tesla
6.	Uniformity of ∫G.dl in GFR	1000	225	ppm
7.	Physical length	200	200	mm
8.	Magnetic length	-	228.7	mm
9.	Longitudinal footprint of magnets (yokes)	<600	500	mm
10.	Transverse footprint of Quad	<300	270	mm
11.	Power consumption per coil	<75	65	Watts
12.	Power supply	< 15, <30	12, 22	A, V
11.	Electrical coils	Solid copper strips, separately cooled by water carrying tubes.		

Centroid trajectory corrections by Dipole Correctors



Arun Saini

Dipole Corrector Strength

- Maximum integral corrector field @ 800 MeV = 0.008 T-m
- Corresponding deflection angle = 1.6 mrad

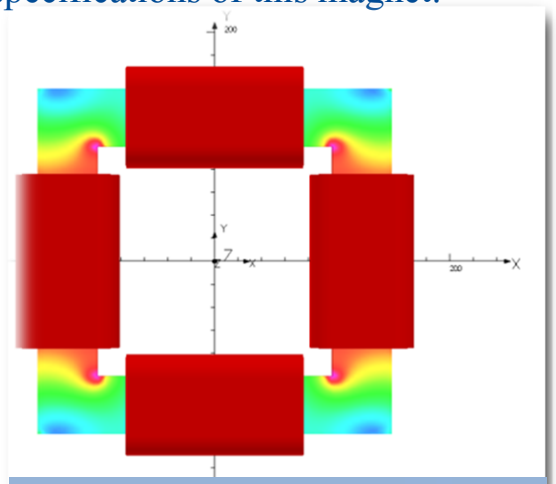
- Assuming corrector length 80 mm, corrector field is = 0.1 T

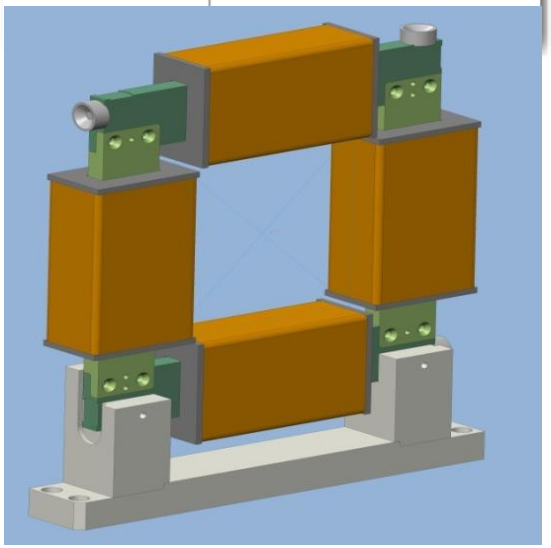
- Maximum integral corrector field @ 1GeV for same deflecting angle is = 0.010 T-m.
- Corrector Field is 0.125 Tesla

Arun Saini

Dipole corrector- Electromagnetic Design for PXIE MEBT

BARC has designed, prototyped and Qualified Dipole Corrector magnets for MEBT of PXIE. Following are specifications of this magnet.





SN	Parameter	Value	Unit
1.	Integral B field	2.4	mT-m
2.	Peak B field	9.5	mT
3.	Current density	1.2	A/mm^2
4.	Clear Aperture	150 x 150	mm^2
5.	Ampere turns	2400	AT
6.	Good Field region	ø25	mm
7.	Field uniformity	1	%
8.	Total Power consumption	112	Watts

The dipole correctors of PIP-II can be magnet of same specifications but a different physical length. The yoke thickness can be increased from 16 mm to 100 mm, keeping input current and form factor of the magnet same.

- The Dipole Corrector for PIP-II may be 4 A /10 Volts (each coil) with total power consumption less than **225 Watts**
- The coil cooling may be same as that of Quadrupole. Solid current carrying copper strips, separately cooled by water carrying tubes.

Decisions to be taken

Issues needed to be resolved to freeze the design of warm magnets

1. **The requirements related to BPM: Specifications of BPMs, Number of BPMs, their location and other engineering details.**

2. **The heat management : To select one of the two following issues**

a) **Heat to be dumped in ambient, or**

b) **Heat to removed using water carrying passive (no current) tubes**

3. **Position of the dipole corrector : between the Quad magnets (as shown in this presentation) or down stream (after the Quad pair).**

Summary

- Magnetic design of the Quadrupole Magnets is complete and required accuracy is achieved. The dipole corrector may be similar to MEBT one with increase in the physical length.
- Key engineering parameters like size of copper conductors, current density, number of turns, size and cooling solutions are worked out and may need minor modifications during engineering design.
- Sufficient data is available for initiating the Engineering Design Report. This will essentially consists of engineering drawings, assembly procedures, design of cooling circuit (backed by CFD analysis for optimization), coil design, Bill of material, traveler and inspection format etc.
- The detailed report will be shared with FNAL and after mutual consent on the final design, prototyping will be initialed with Indian Industry.
- Issues mentioned in last slide need to be addressed to finalize the design.

Acknowledgements

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Thanks for your attention!

Back-up slide : Calculation of temperature rise in Coils

1.The temperature rise in coil is calculated using the heat transfer coefficient (HTC) which is dependent on the geometry of the heat dissipating body and the ambient condition. For natural convection, HTC is about 4-5 W/ m^2K.

2.In present calculation, HTC as determined experimentally from EM coils of MEBT Quads is used. (During the reverse calculation of HTC from power dissipation and measured temperature rise, Area of the coil was taken instead of the area of the complete coil plus yoke, this has resulted in large HTC (about 17 W/ m^2K)

3.The temperature rise for coil having W watts heat dissipation and effective area of the coils (area of yokes not taken in consideration) exposed to ambient as A ; is given by $\Delta T = WHTC \times A$

4.For Quadrupole magnets Following calculation is carried out : W = 65 Watts, A= 0.10 m^2 , HTC=17 W/ m^2K.

5.Using information given in 4 and 5 above, $\Delta T = 38^\circ$ C (temperature rise over ambient).

6.The HTC taken is the effective HTC which includes the heat loss through the magnet.

7.For the present case the effective HTC may be even larger and actual temperature rise may be less. However the correct figure can be obtained after carrying out thermal simulations/prototyping.