Indian Institute Fermi Lab Collaboration

Project X and IIFC Status of MEBT Magnet

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MEBT Line Specifications

Input beam emittance :

- **Transverse: 0.16 pi.mm.mrad**
- **Longitudinal: 0.21 pi.mm/mrad**

Output beam emittance :

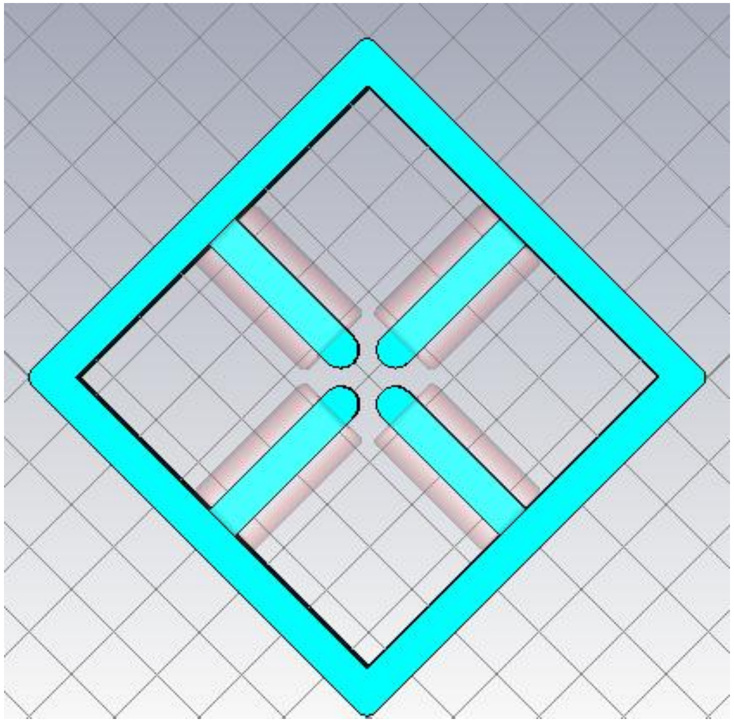
- **Transverse: 0.16 pi.mm.mrad**
- **Longitudinal: 0.2776 pi.mm/mrad**

- **The primary functions of the PXIE MEBT are to match optical functions between the RFQ and the superconducting HWR cryomodule and to generate arbitrary bunch patterns at 162.5 MHz using an integrated wide-band chopper and beam absorbers, capable of disposing of 4 mA average beam current. In addition, the MEBT will include beam diagnostics to measure the beam properties coming out of the RFQ and into the HWR cryomodule.**

Design requirements and boundary conditions

1. **The focusing lattice consists of two quadrupole doublets and seven triplets along with nine horizontal and nine vertical corrector dipole magnets. A dipole corrector assembly is mounted downstream of each triplet or doublet (total of 9). Each assembly includes two (H and V) dipole correctors. The lattice appears like : FF-FF-DFD-DFD-DFD-DFD-DFD-DFD-DFD. Details are tabulated below.**

S.No	Particulars	Value
1.	Number of Type F Quadrupoles	11
2.	Number of Type D Quadrupole	14
3.	Integrated Gradient of type F Quads	1.50 Tesla
4.	Integrated Gradient of type D Quads	0.85 Tesla
5.	Good Field Region	23 mm diameter
6.	Integrated gradient homogeneity in the good field region	1 %
7.	Dipole Horizontal and vertical correctors	9 each
8.	Integrated dipole field	2.1 mT-m
9.	Field homogeneity	1 %



Upright Quadrupole Magnet

Design Consideration

1. Selection of Magnetic steel is crucial and good material selection can aid in optimized design.
2. Pole shape is crucial in achieving good magnetic field uniformity, low undesirable systematic poles, low skew components and less MMF requirements.
3. Odd harmonics of Quadrupoles arise in quadrupole design, even-harmonics arise due to manufacturing tolerances.
4. Air cooled Coils are preferred as complexities involved are less when compared to the water cooled coils. Our design have taken these issues in consideration.
5. The coil design is carried out keeping the power supply in consideration (400 W, 10 A)- available at FNAL.
6. The quadrupoles should be removable and mountable without breaking the vacuum.

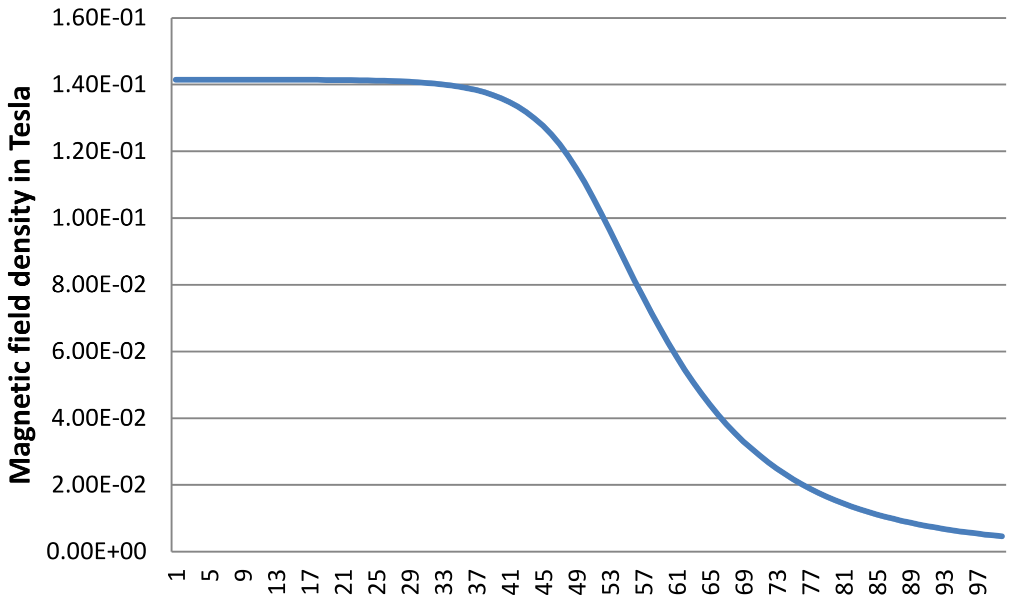
Manufacturing Approach

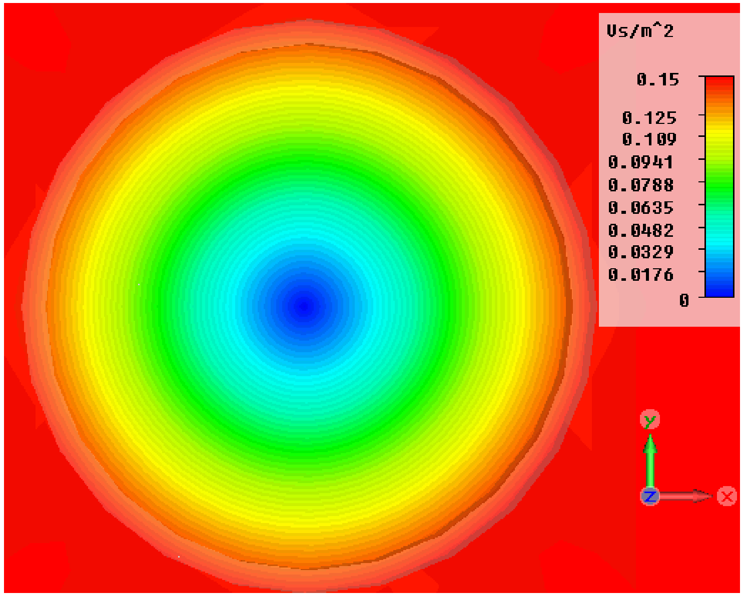
a. After freezing a joint design with Fermi Lab team, one prototype of each type of Quad (F & D) and Dipole correctors shall be undertaken in India and may be in USA.

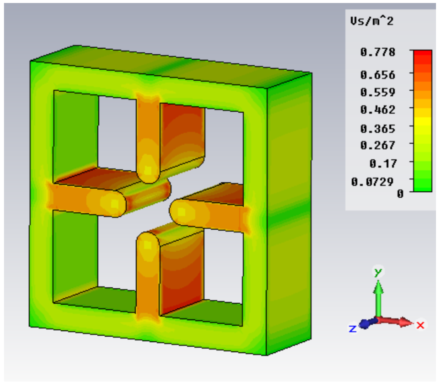
b. These Indian prototypes shall be qualified on Induction Coil Magnetometers at BARC before shipping them to Fermi Laboratory.

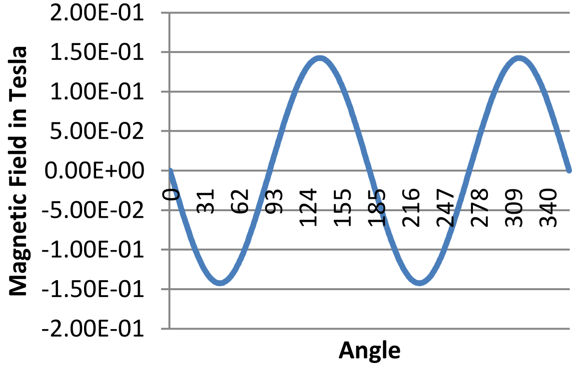
Type F Quadrupole design: Typical Field profiles

Quadrupolar field in longitudinal direction at periphery of GFR

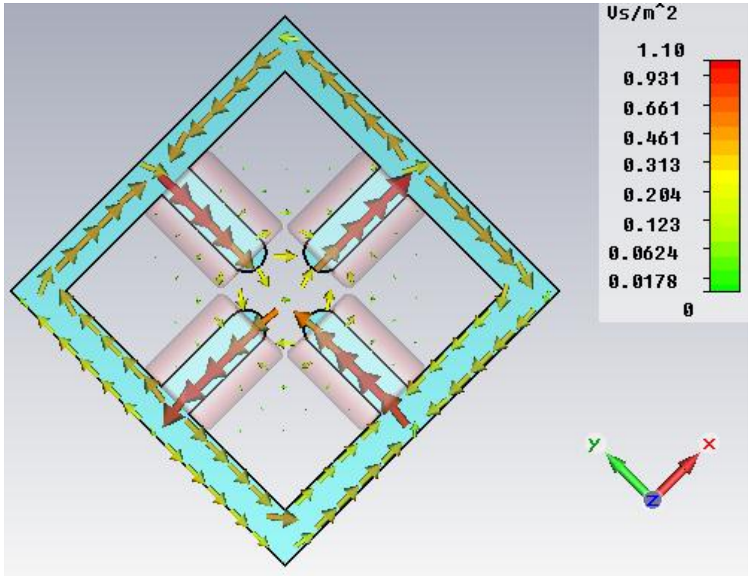




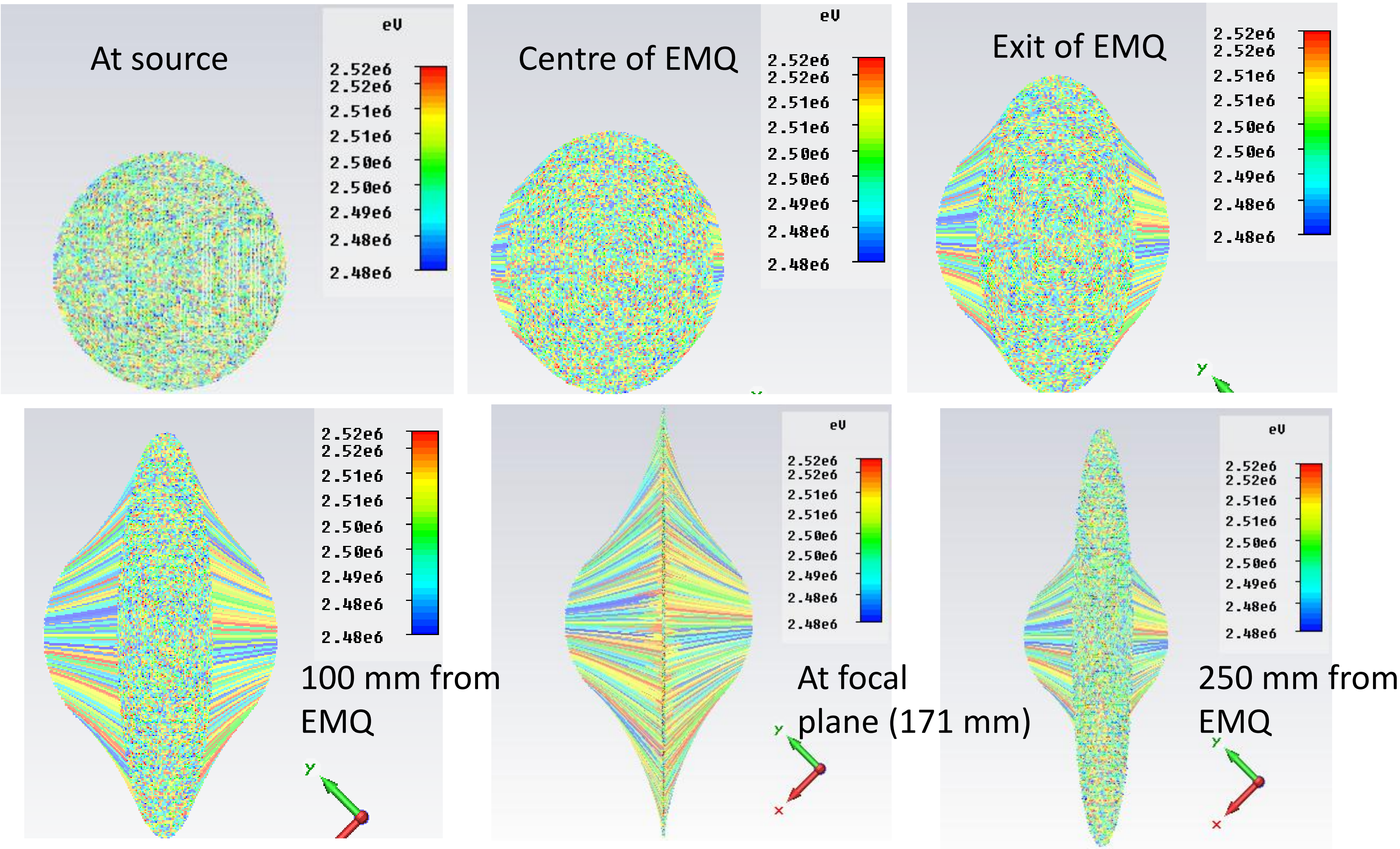




Tangential absolute magnetic field

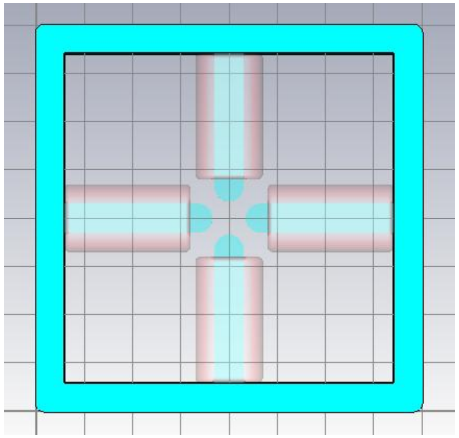


Proton Beam Focusing on different longitudinal planes: typical

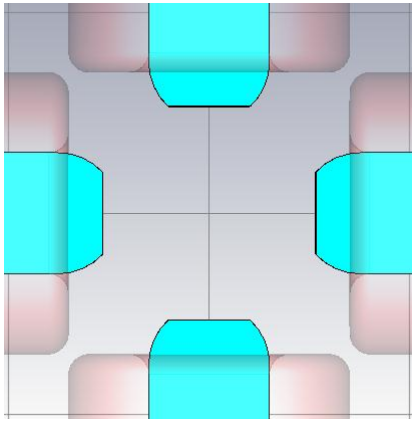


Type F Quadrupole design

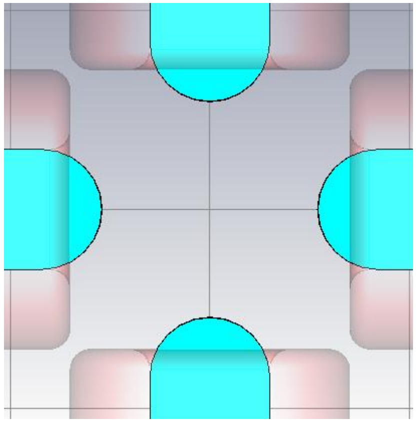
1. **Three EMQ-F Type designs are carried out with different pole width and pole shaping as detailed below.**
2. **The basic design is based on figure shown alongside.**



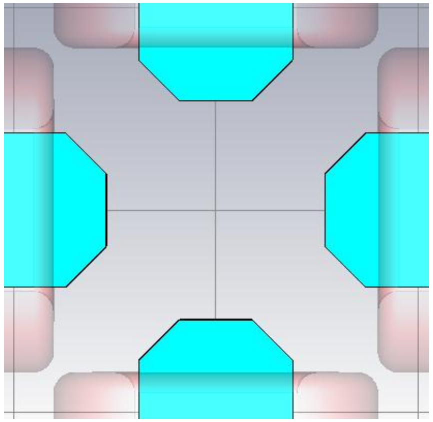
S.No.	Parameters	Design29	Design33	Design44
1.	Outer dimension of yoke	400	400	400
2.	Inner dimension of yoke	340	340	340
3.	Yoke depth	140	140	140
4.	Pole depth	100	100	100
5.	Pole width	30	30	38
6.	Pole Shape	15 mm fillet and copping at 4 mm depth	15 mm fillet	10 mm chamfer, 45 degree



Design 29



Design 33



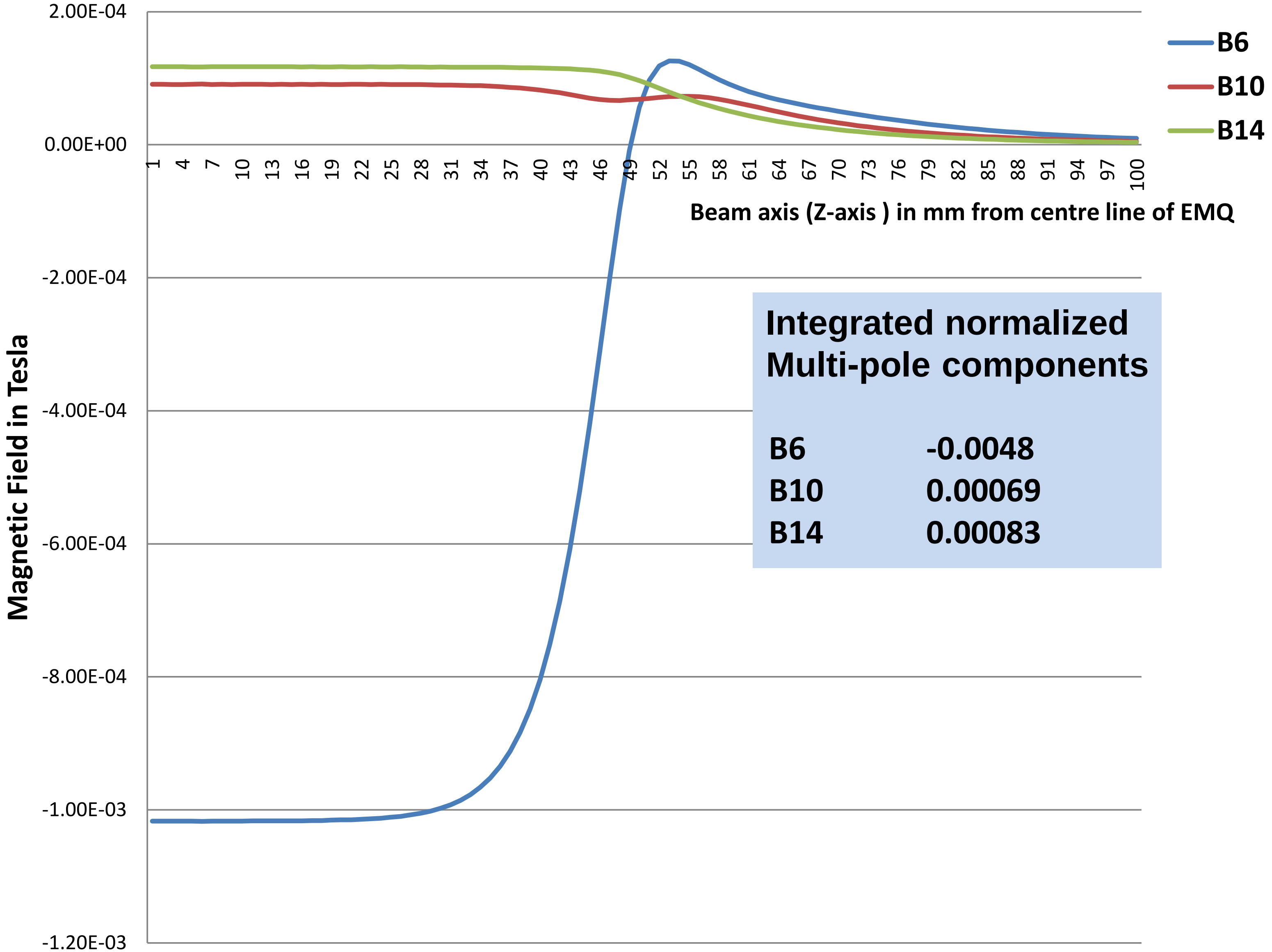
Design 44

Type F Quadrupole design : Comparison of results

1. Comparison of three EMQ designs are tabulated below

S.No.	Parameters	Design29	Design33	Design44
1.	Ampere Turns (AT)	2500	2700	3100
2.	Integrated magnetic field gradient (T)	1.52	1.46	1.48
3.	Magnetic field gradient (T/m)	12.2	11.5	11.71
4.	Magnetic length (mm)	100	100	100
5.	Effective magnetic length (mm)	124.6	126.1	126.4
6.	Pole Tip to Pole Tip gap (mm)	53	54	54
7.	Integrated gradient uniformity in GFR (%)	0.60	0.74	0.56
8.	Absolute Magnetic field uniformity (%)	0.93	0.42	0.10
9.	Integrated Normalized Dodecapole B6 (T)	-0.0048	0.00028	0.0016
10	Integrated Normalized B10 (T)	0.00069	0.00059	0.00091
11.	Integrated Normalized B14 (T)	0.00083	0.00083	0.00080

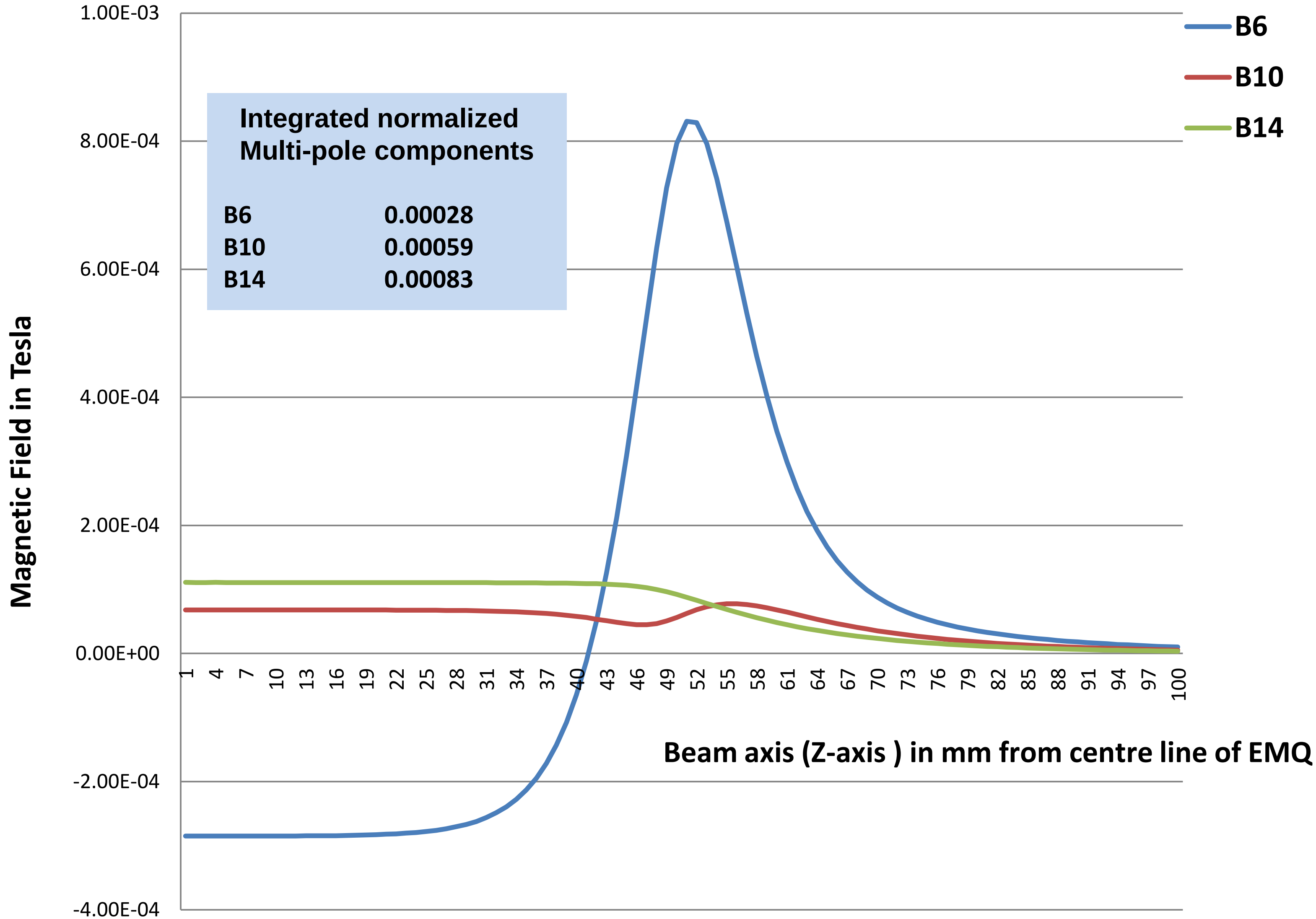
Systematic Multi-pole Components at periphery of GFR : Design29



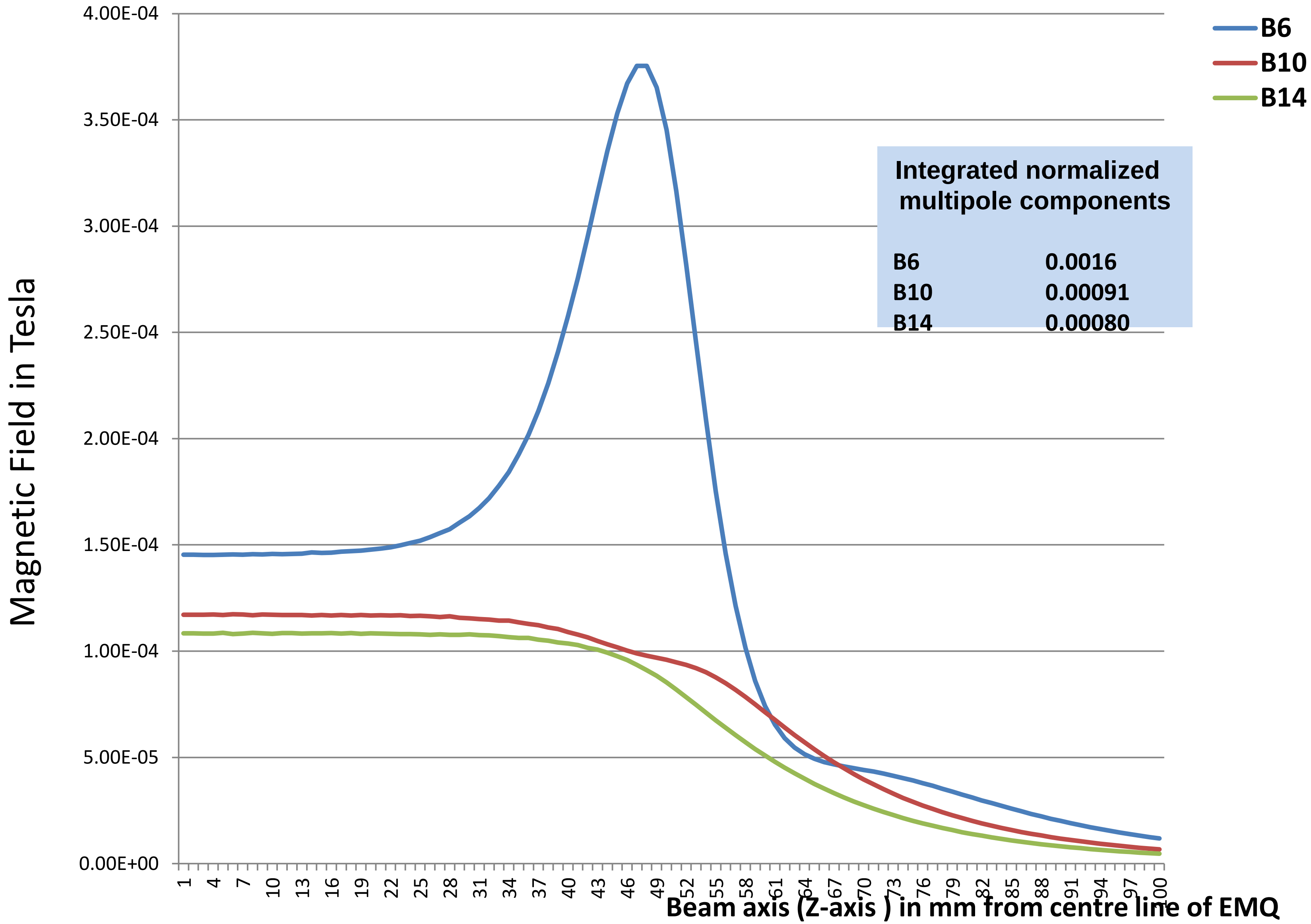
Integrated normalized Multi-pole components

B6	-0.0048
B10	0.00069
B14	0.00083

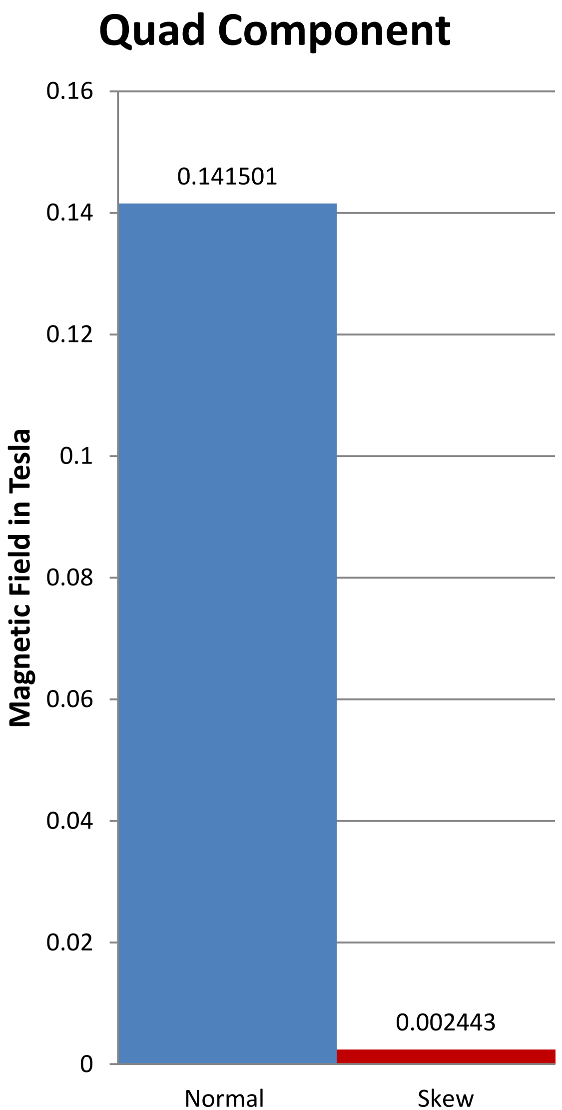
Systematic Multi-pole Components at periphery of GFR : Design33

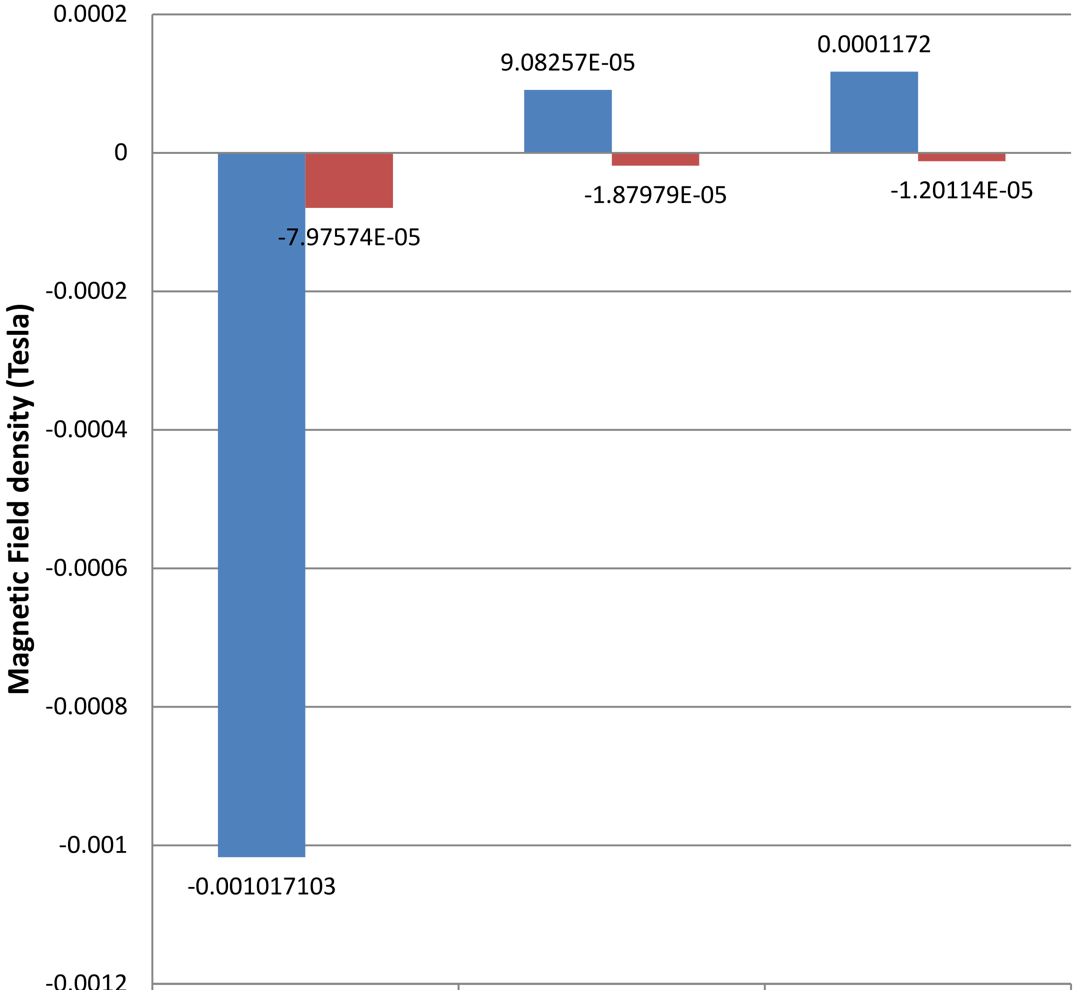


Systematic Multi-pole Components at periphery of GFR : Design44



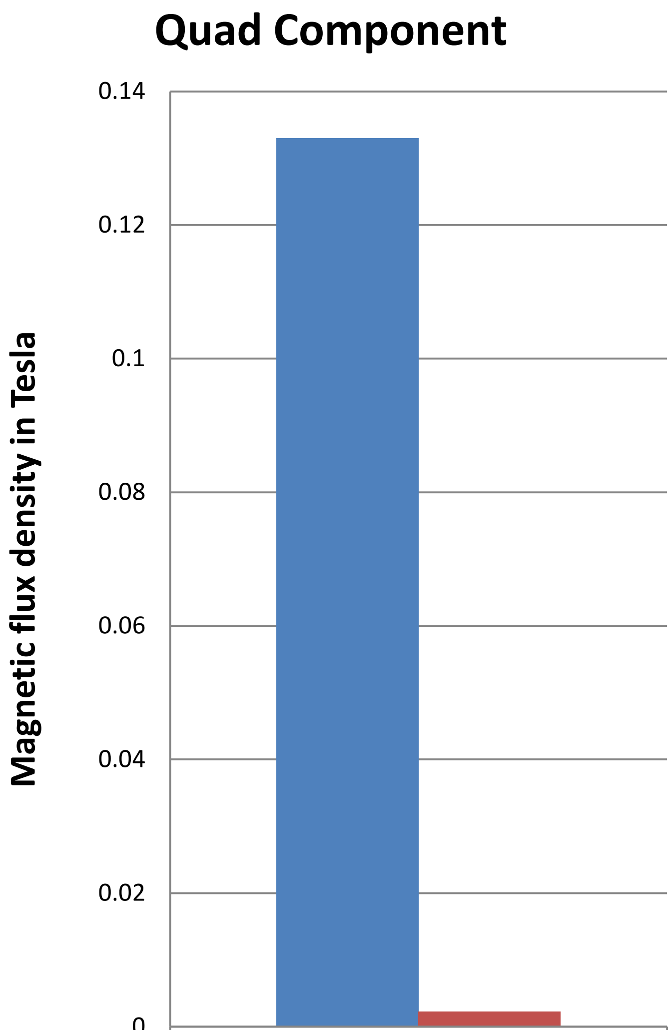
Normal and Skew components at periphery of GFR : Design29



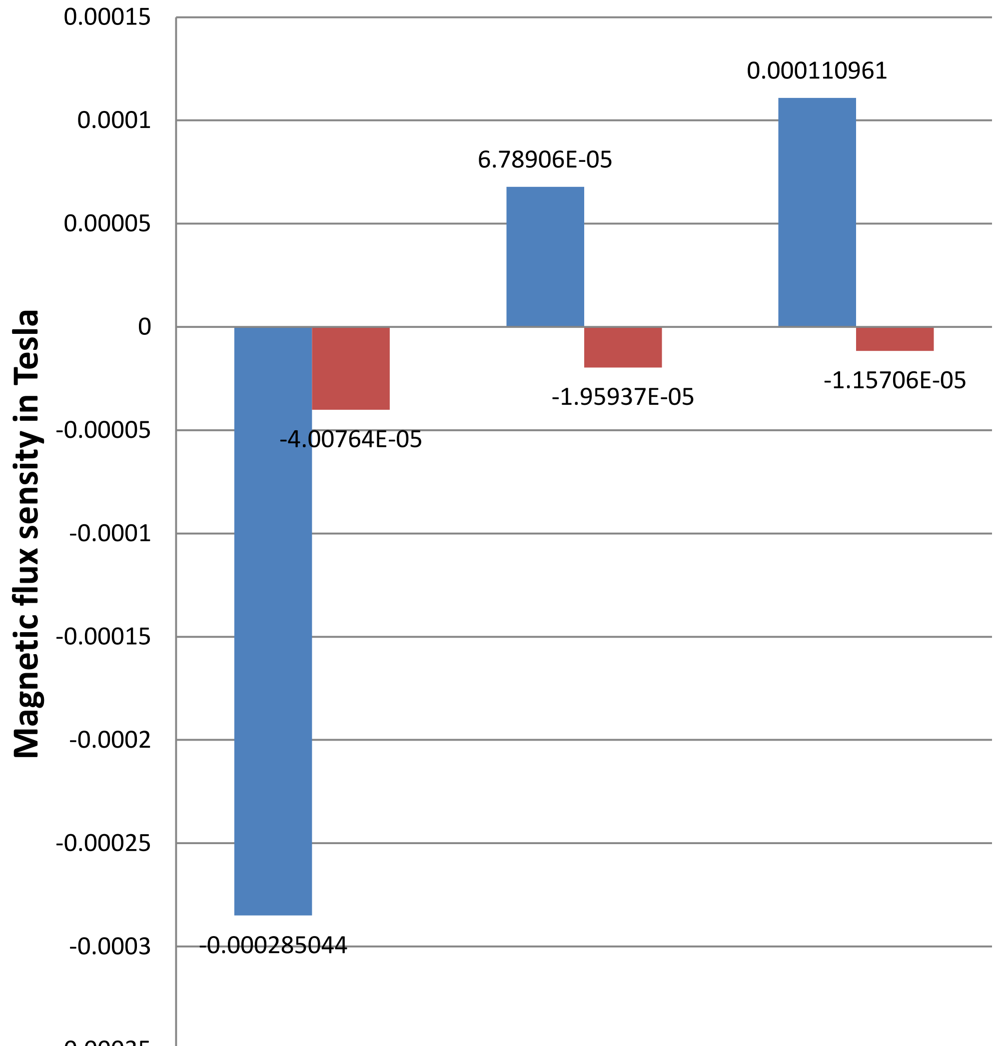


	B6	B10	B14
Normal	-0.001017103	9.08257E-05	0.0001172
Skew	-7.97574E-05	-1.87979E-05	-1.20114E-05

Normal and Skew components at periphery of GFR : Design33

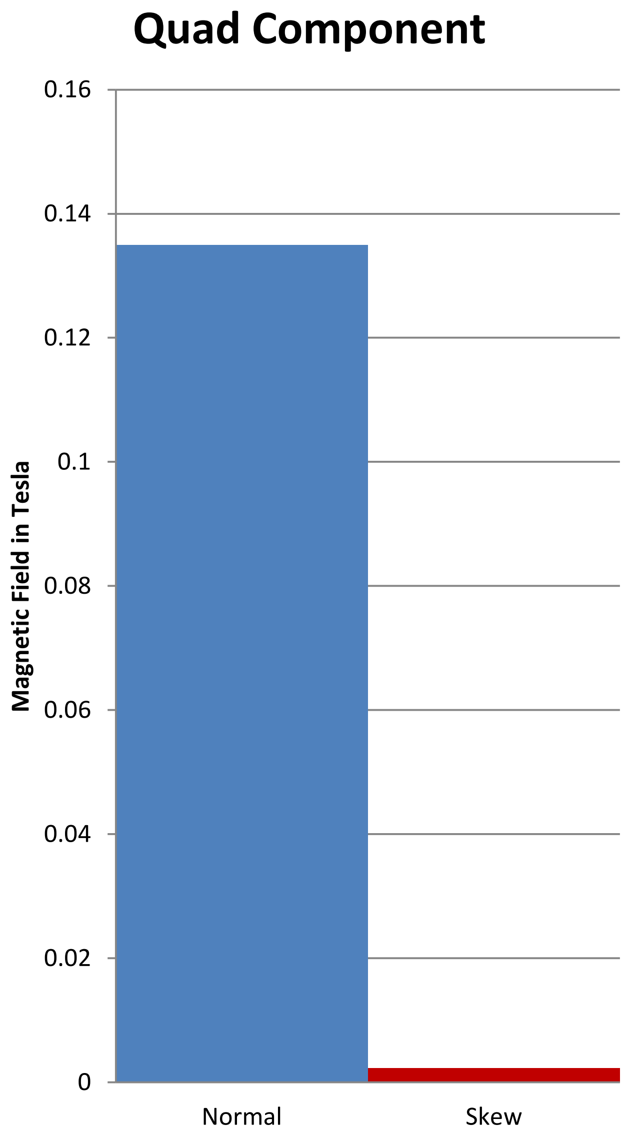


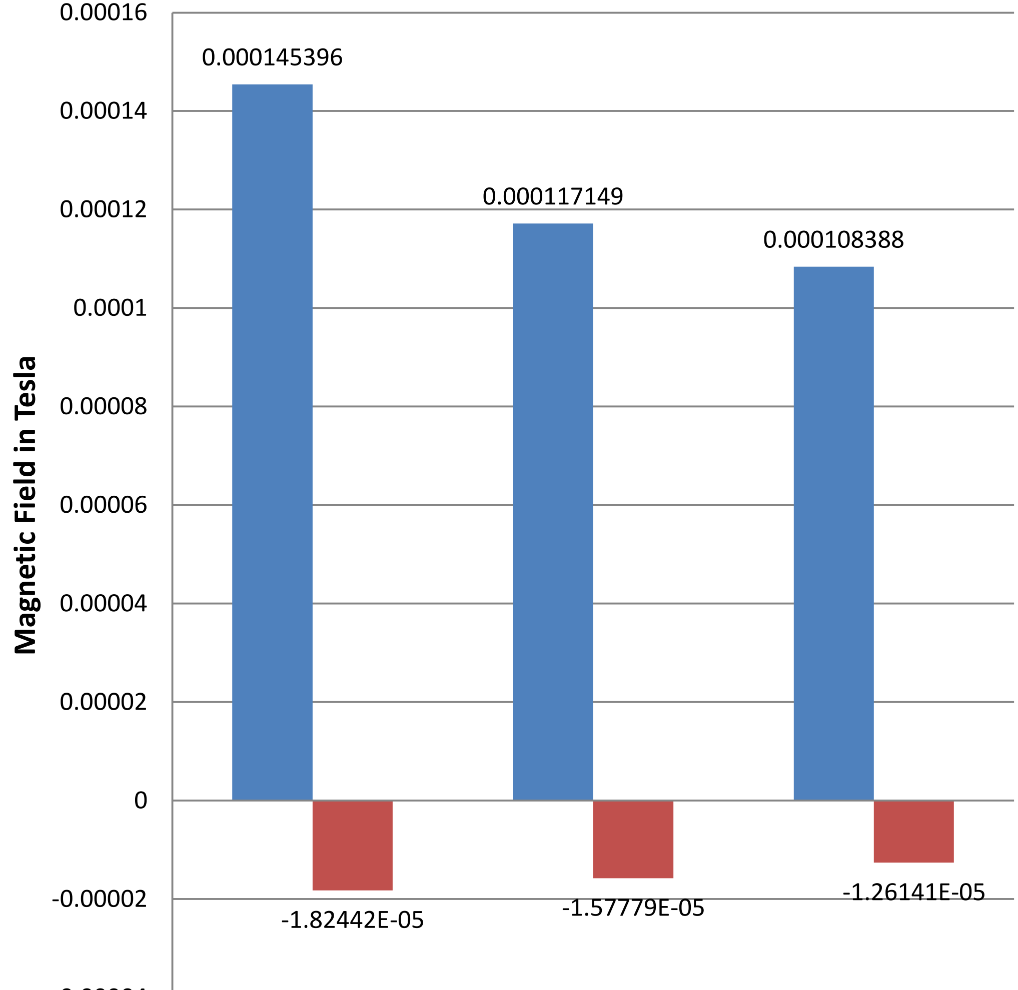
	B2
Normal	**0.133021057**
Skew	**0.002296114**



	B6	B10	B14
Normal	**-0.000285044**	**6.78906E-05**	**0.000110961**
Skew	**-4.00764E-05**	**-1.95937E-05**	**-1.15706E-05**

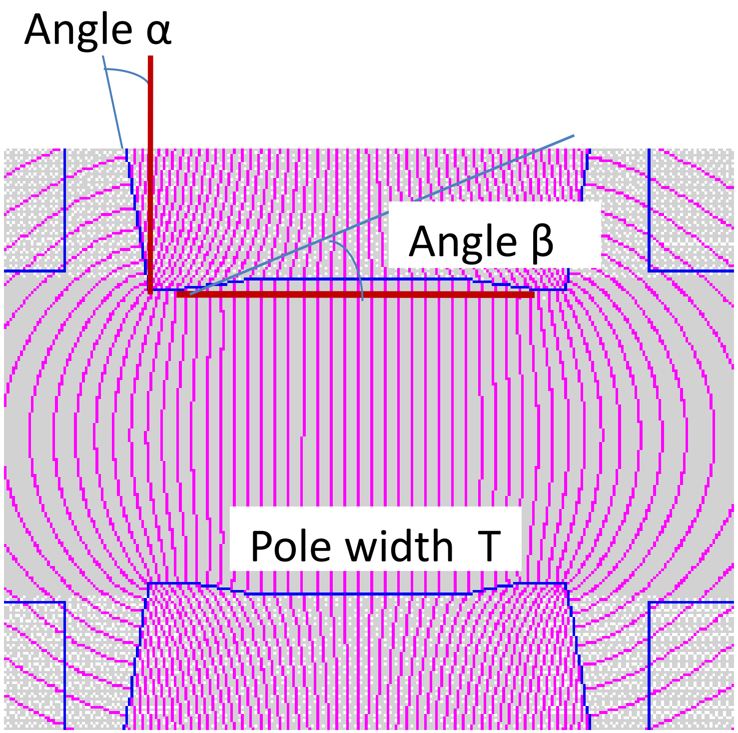
Normal and Skew components at periphery of GFR : Design44





	B6	B10	B14
Normal	**0.000145396**	**0.000117149**	**0.000108388**
Skew	**-1.82442E-05**	**-1.57779E-05**	**-1.26141E-05**

Dipole Corrector optimization



Objectives

To minimize iron for a given field uniformity

For un-optimized pole

$a/h = -0.36\ln(\Delta B/B)-0.95$

For optimized pole

$a/h = -0.14\ln(\Delta B/B)-0.14$

a is pole overhang beyond good field region

Rule of thumbs for dipole pole optimization

The dipole shim takes the form of a trapezoidal extension above the pole face. The area A of the shim has the primary influence on the edge correction that is produced. It is important to limit the height of the shim to prevent saturation in this region at high excitations.

On the other hand, if a very low, long shim is used, the nature of the field correction would change, with different harmonics being generated. The shim size and shape is therefore a compromise that depends on the field quality that is desired and on the peak induction in the gap.

Shim heights and shapes vary widely according to the magnet parameters and the quality of field that is required.

Dipole corrector coil design optimization

Corrector	Angle α (degree)	Angle β (degree)	Separation distance d	Pole width	B gap (Gauss)	ΔB in % of B field
1	9.66	0	0	100	1212	1.9
2	10.4	14.04	10	60	1217	0.57
3	10.4	14.04	5	70	1215	0.98
4	10.4	10.88	5	54	1218	0.65
5	15.25	12.789	0	54	1220	2.4

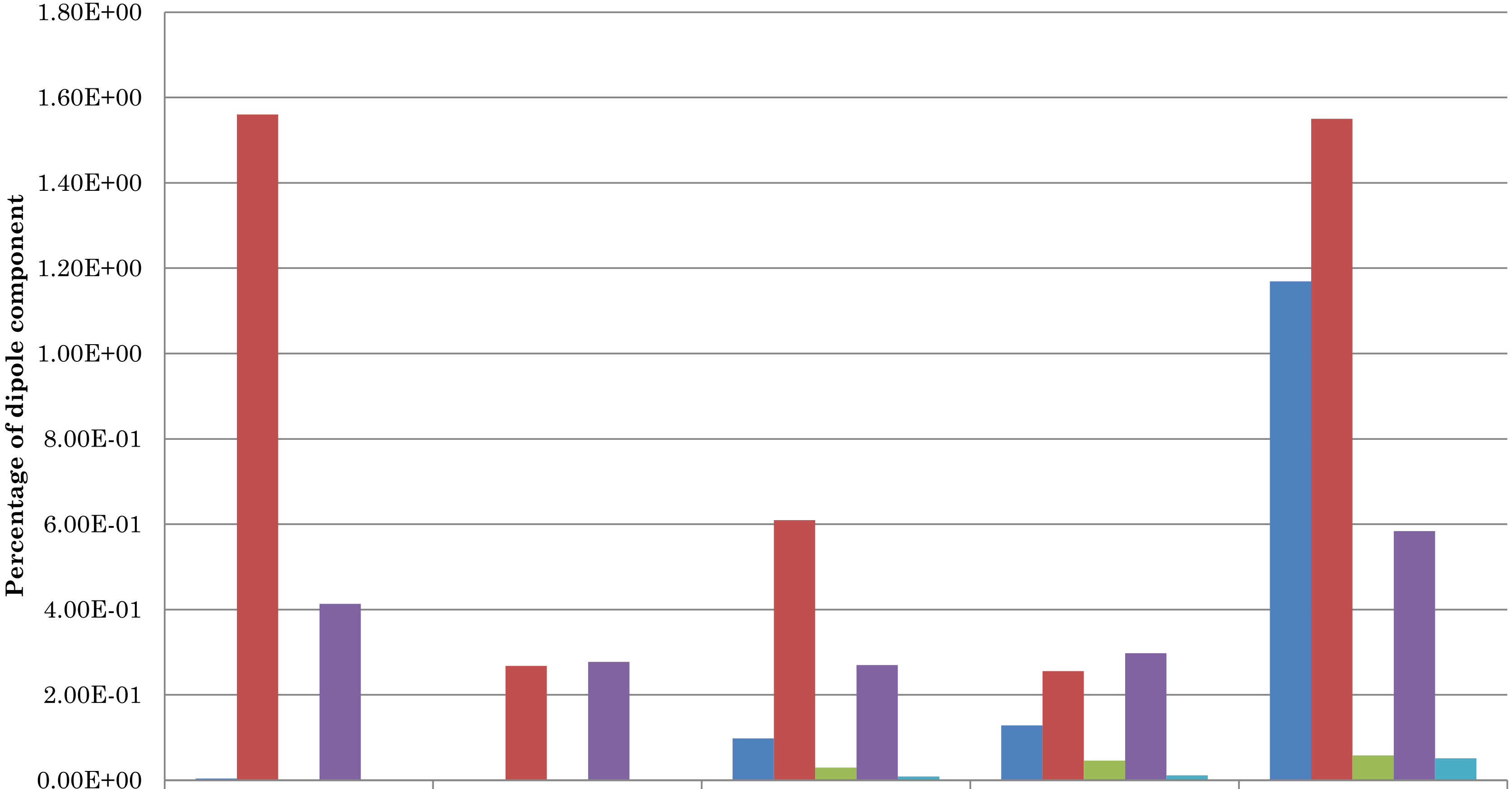
First one is the flat pole since angle β is zero.

All other four designs have trapezoidal shape at the pole tips which results in increase of field as well as uniformity.

Increasing Angle α when near optimum design results in increase of field but decrease in uniformity.

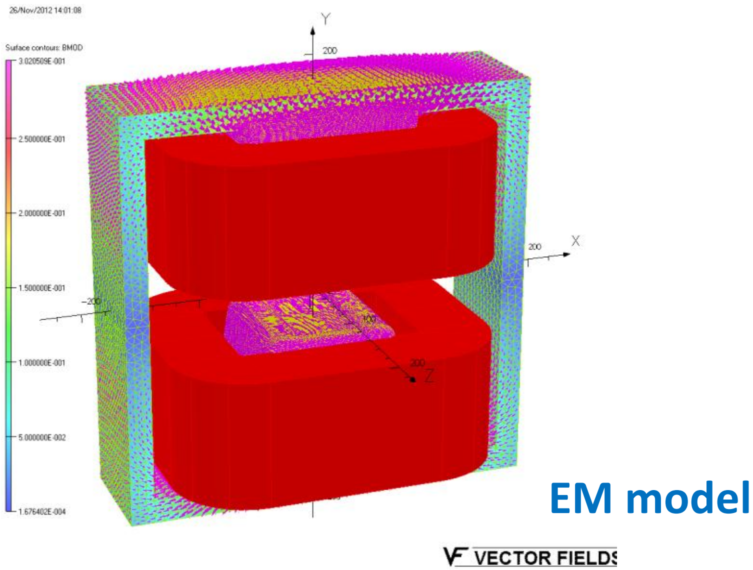
Pole shapes

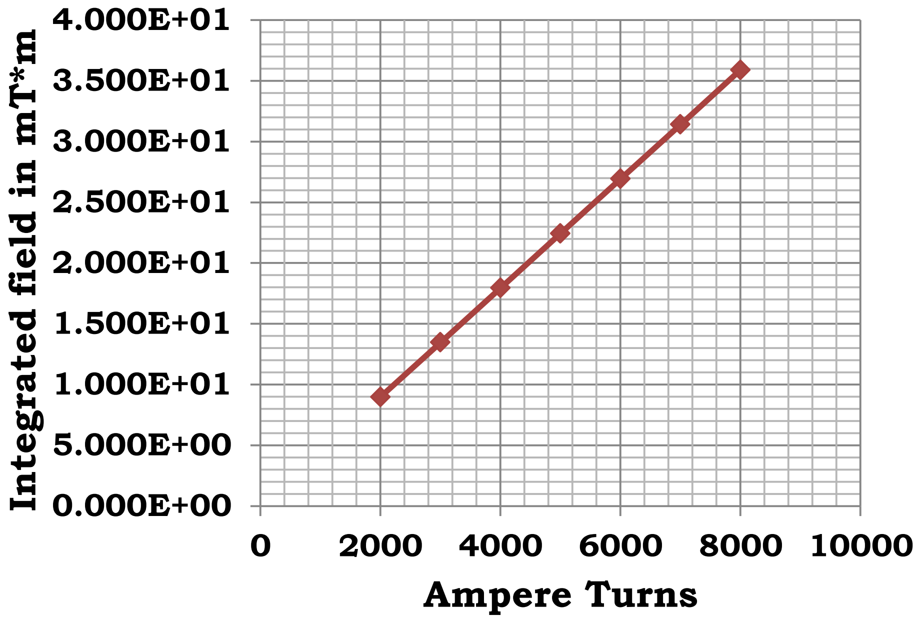
Multi-pole components in terms of percentage of dipole component

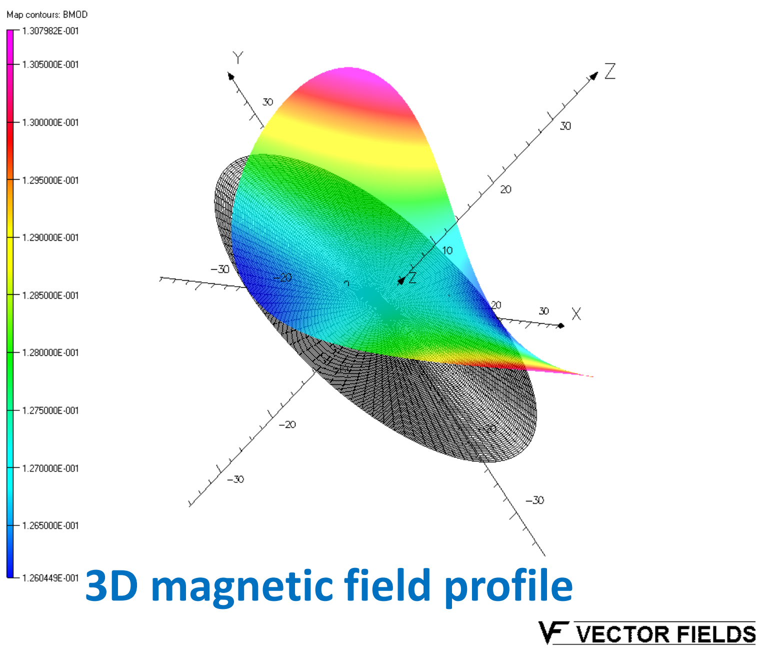


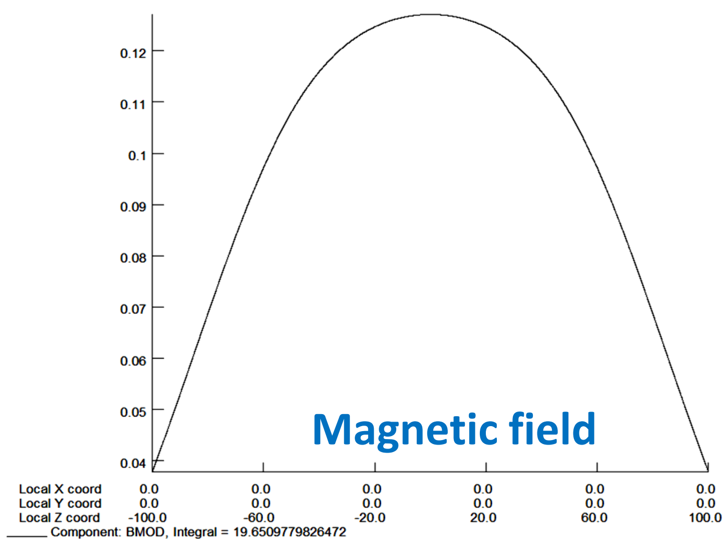
	corrector1	corrector2	corrector3	corrector4	corrector5
Quad	3.84E-03	1.28E-03	9.77E-02	1.28E-01	1.17E+00
Sextupole	1.56E+00	2.68E-01	6.10E-01	2.55E-01	1.55E+00
octapole	8.52E-04	1.19E-03	2.97E-02	4.59E-02	5.79E-02
decapole	4.14E-01	2.77E-01	2.70E-01	2.98E-01	5.84E-01
dodecapole	1.44E-04	3.59E-04	8.46E-03	1.13E-02	5.12E-02

Simulation model and magnetic field profile in dipole gap

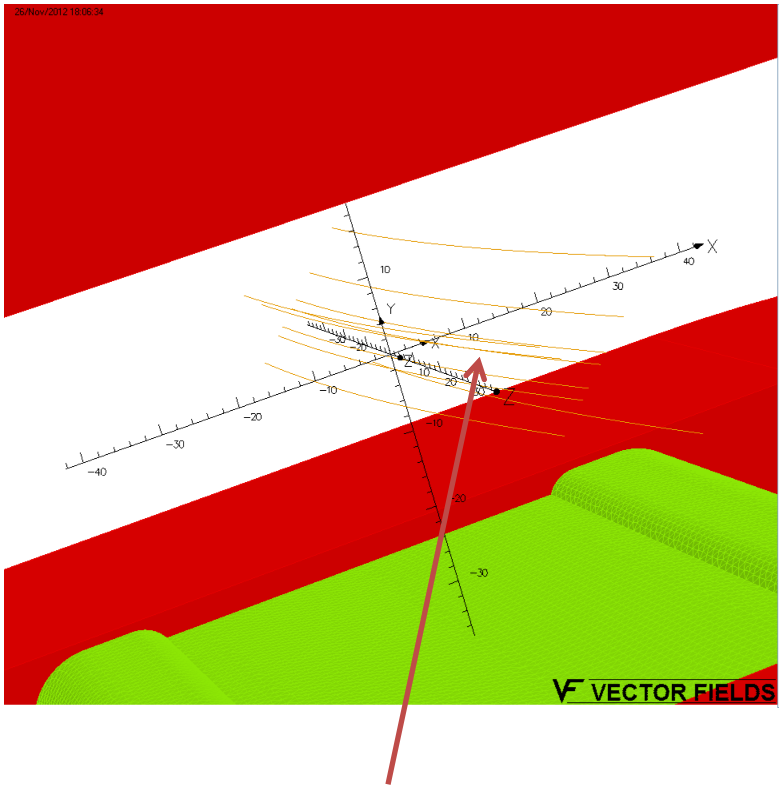








Particle Trajectory and bending angle of dipole



Particles bending trajectory in OPERA

The trajectory of a charged particle in a magnetic field (perpendicular to the trajectory) describes an arc of radius r given by

$$\frac{1}{r} = e \cdot \frac{B}{p}$$

Electrical design of Coil (Per Coil)

S.No.	Parameters	Quadrupole	Dipole
1.	MMF	3100	5120
2.	Current	8	8
3.	Turns	392	640
4.	Wire AWG	10	9
5.	Current density	1.51	1.21
6.	Resistance mΩ	461	942.5
7.	Power Consumption	30	60
8.	Coil cross section mm^2	20 X 130	30 X 100
9.	Coil cooling	AN	AN
10.	Expected temperature rise (first order)	60 °	70°

Coil Prototyping : Air cooled coils for both quadrupole and dipole are being given for prototyping for evaluating the thermal behaviour of the coils. Coils will be epoxy potted for mechanical strength and better thermal properties.

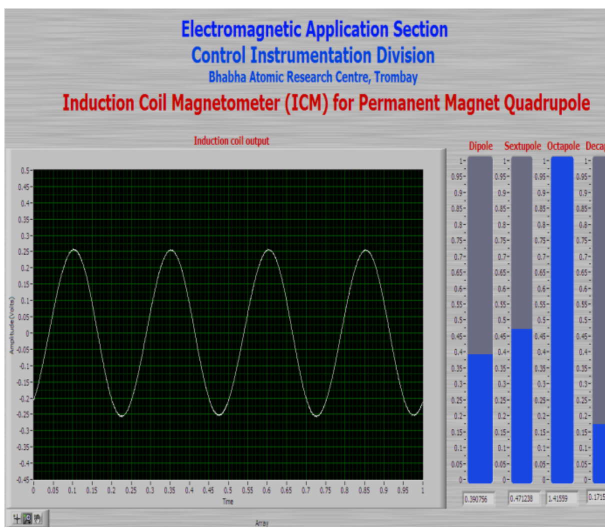
Magnetic Qualifications at BARC

1. Magnetic qualifications of Magnets shall be carried out using Induction Coil magnetometers (ICM) and Hall probe arrays.

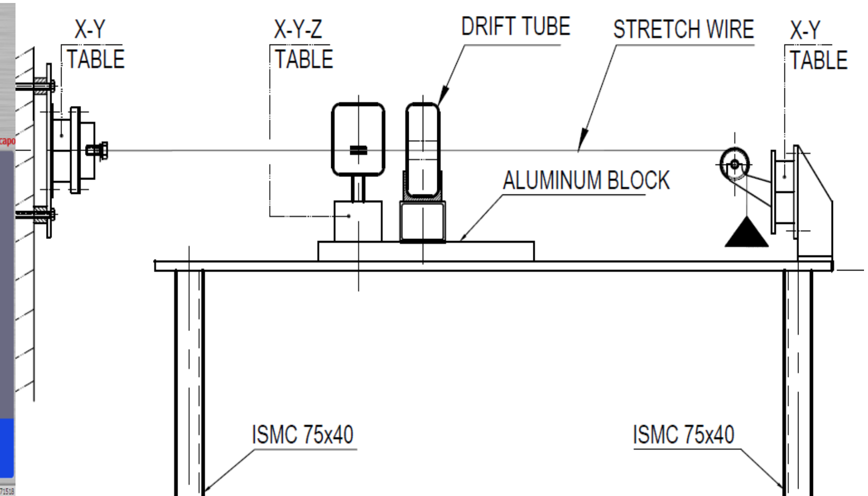
2. Induction coil magnetometer have been developed for qualification of PMQs and appropriate experience exists at BARC for development of ICM and other magnetic measurement benches.

3. The magnetic centre determination shall be carried using stretch wire benches, prototype of which are under fabrication for PMQs.

ICM close-up



ICM GUI



Stretch Wire set-up

Future Work

Design of 'D' type Quadrupole : The 'D ' type quadrupole design will be commenced on lines of 'F' type quadrupole.

Optimization of Quadrupole magnets : Quadrupole optimization for achieving the desired magnetic parameters shall be done for second order design optimization.

Proximity effect of magnets: Combined design and analysis of doublet, quadrupole with corrector magnets will be carried backed with beam dynamics in CST.

Prototyping the EM Coils : The quadrupole and dipole EM coils will be prototyped for accessing the thermal behaviour of the coils for designed current densities. This will include the study of epoxy potting of the coils.

Mechanical designs of Quadrupole magnets and corrector magnets: The mechanical design of the Quad and correctors magnets including ease of manufacturing, adjustability, assembly along with fiducials will be carried out.

Beam dynamics : Beam studies of MEBT in CST Particle studio and Trace 3D.

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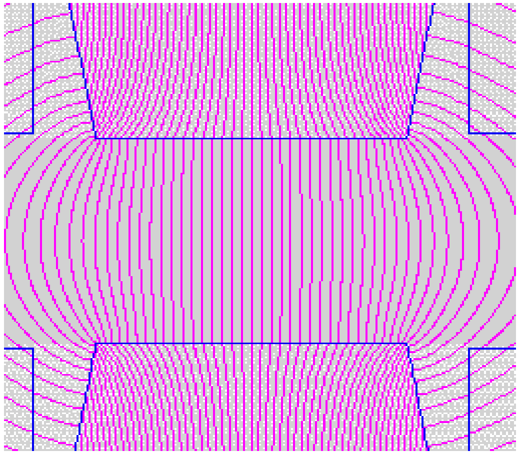
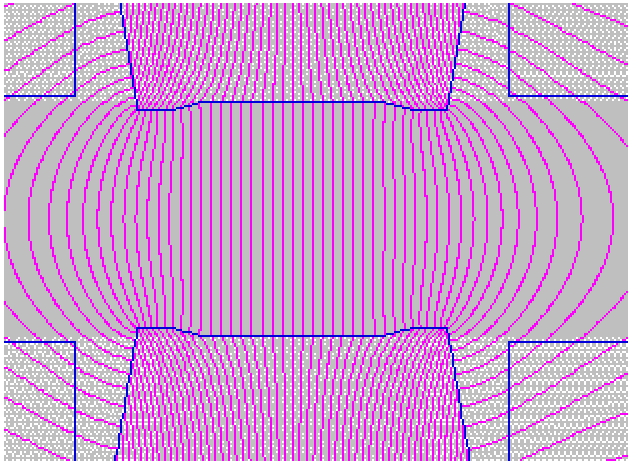
Dr. Arvind Jain

Thanks for your kind attention!

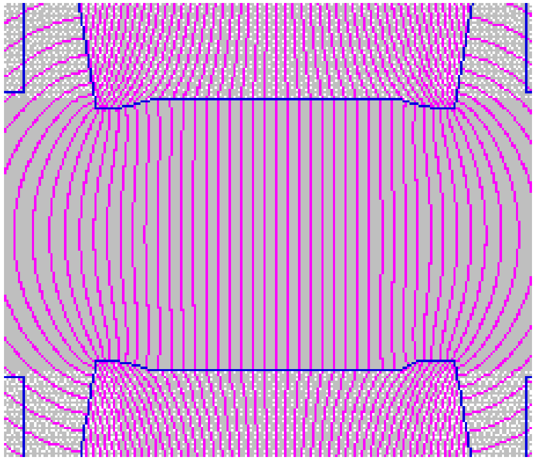
Additional slides



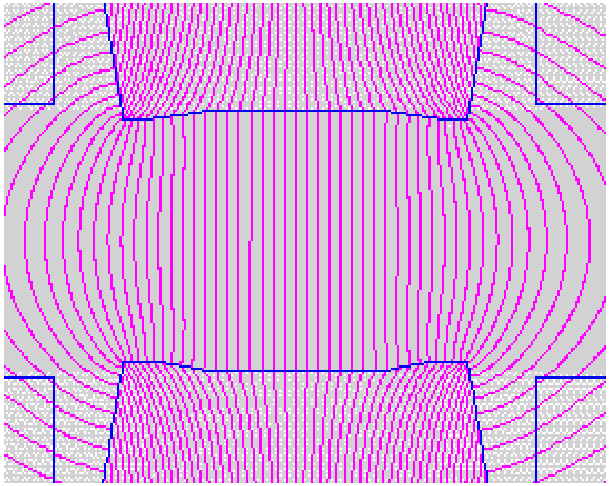
corrector1



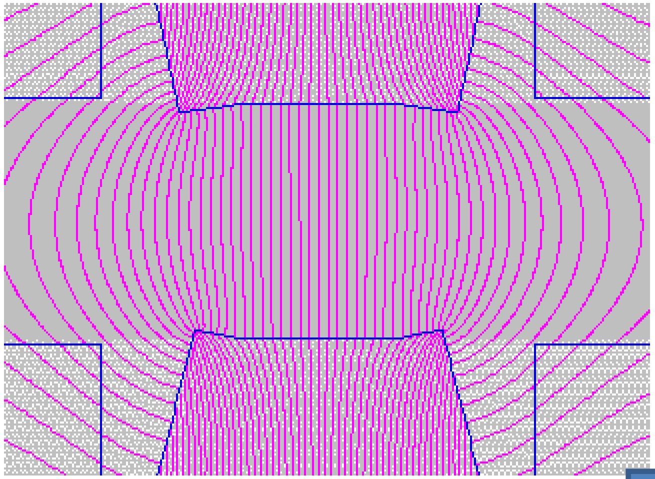
corrector2



corrector3



corrector4



corrector5

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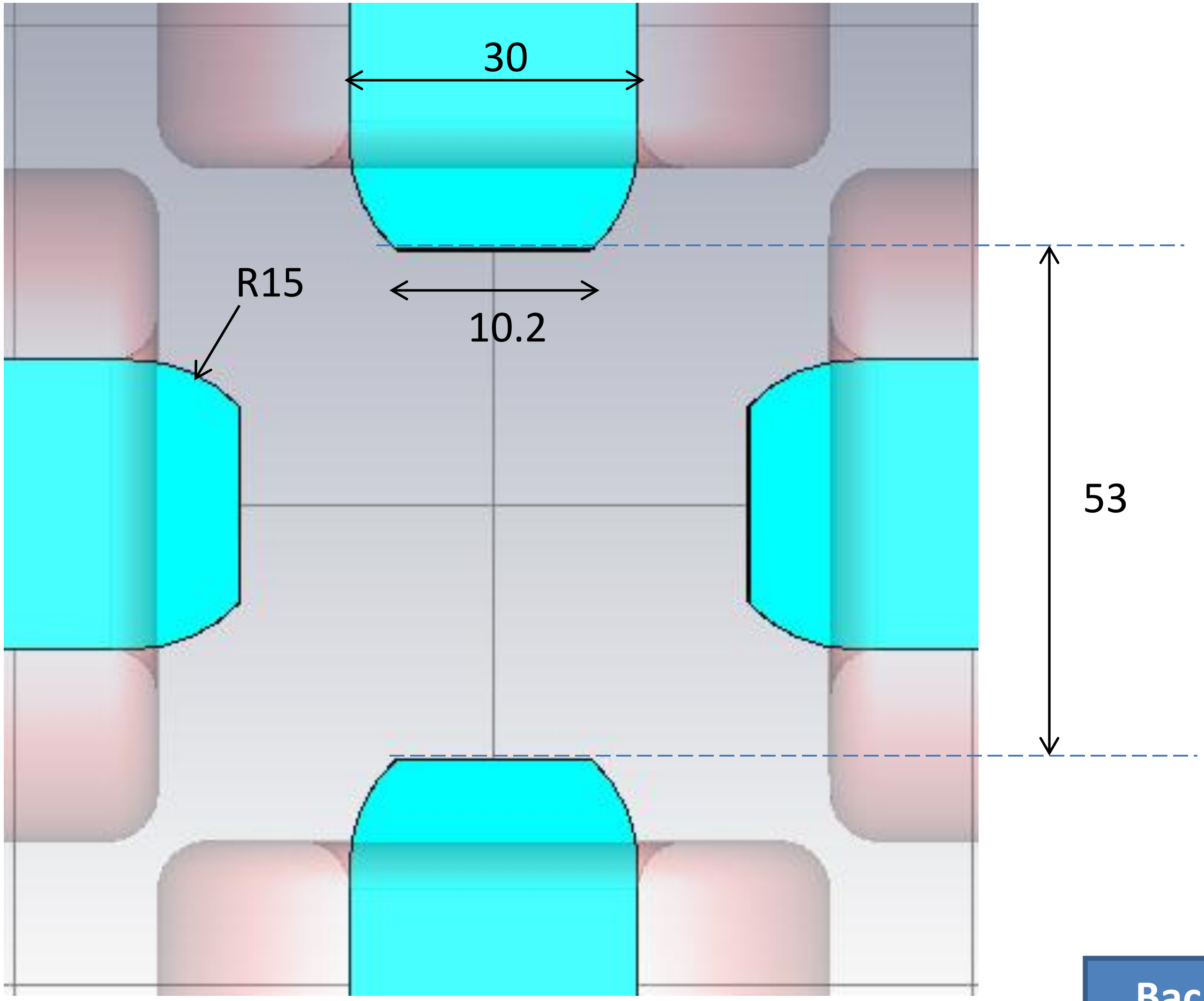
Type F Quadrupole : Design29 Pole Shape



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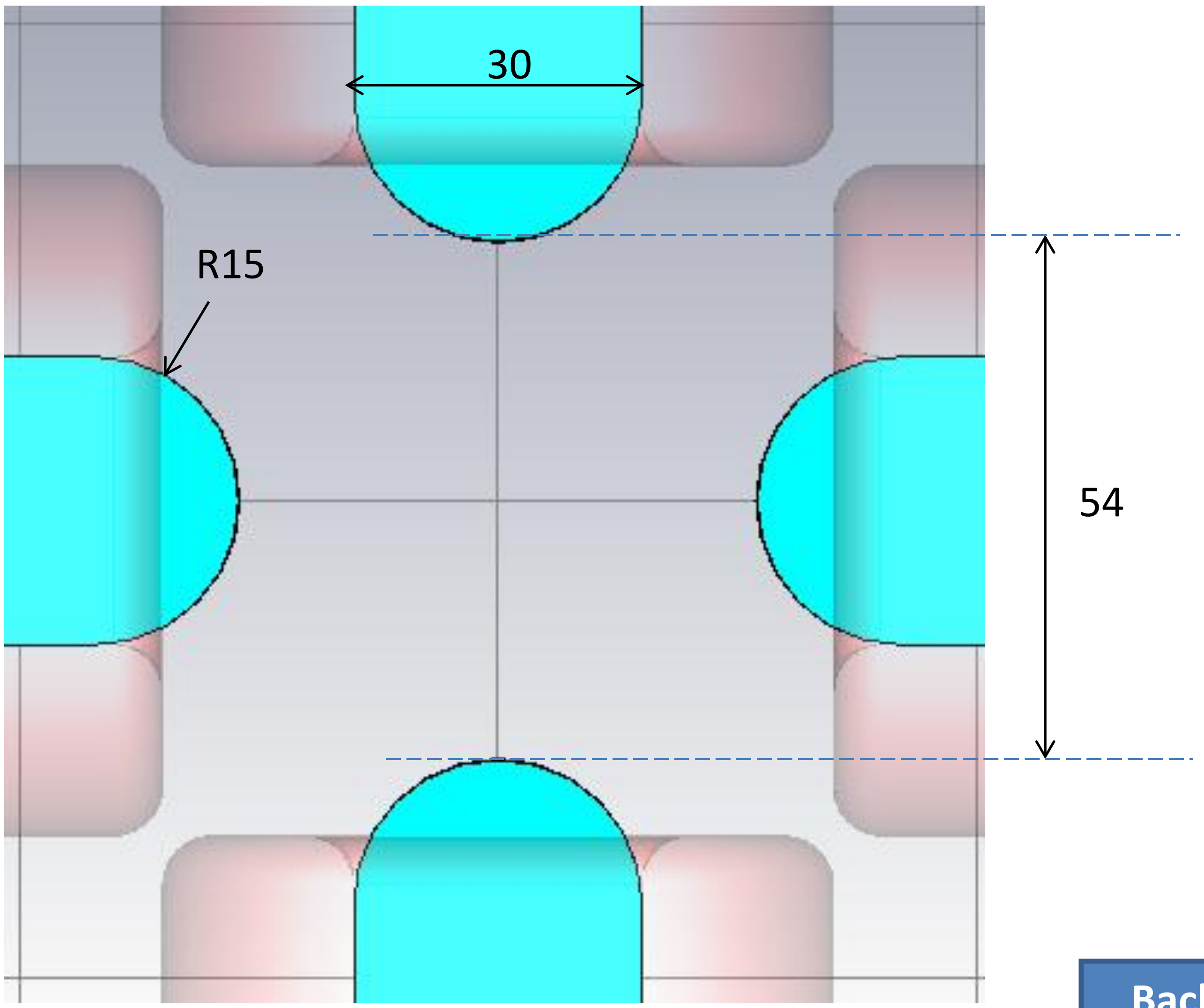
Type F Quadrupole : Design33Pole Shape



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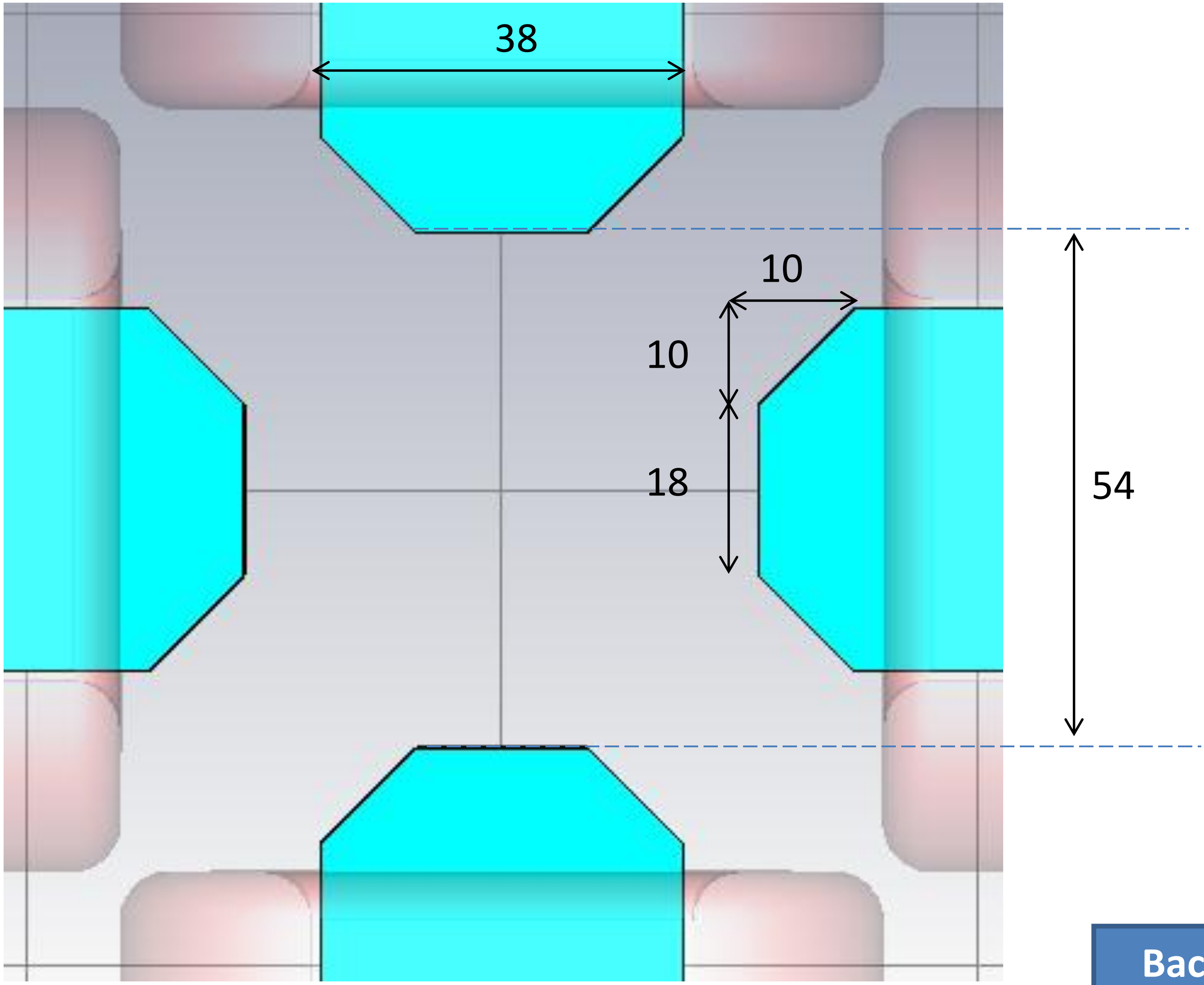
Type F Quadrupole : Design44 Pole Shape



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