CEPC Superconducting Magnets

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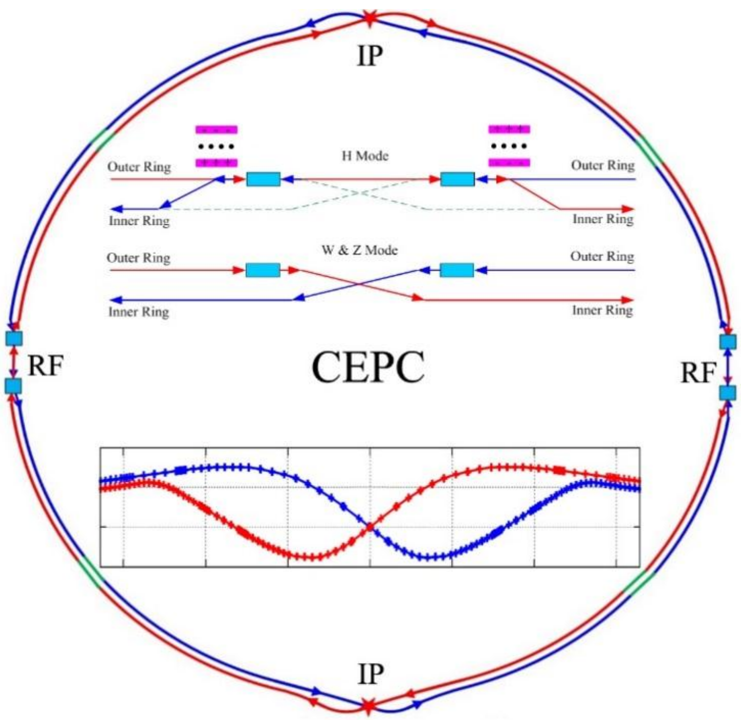
Outline

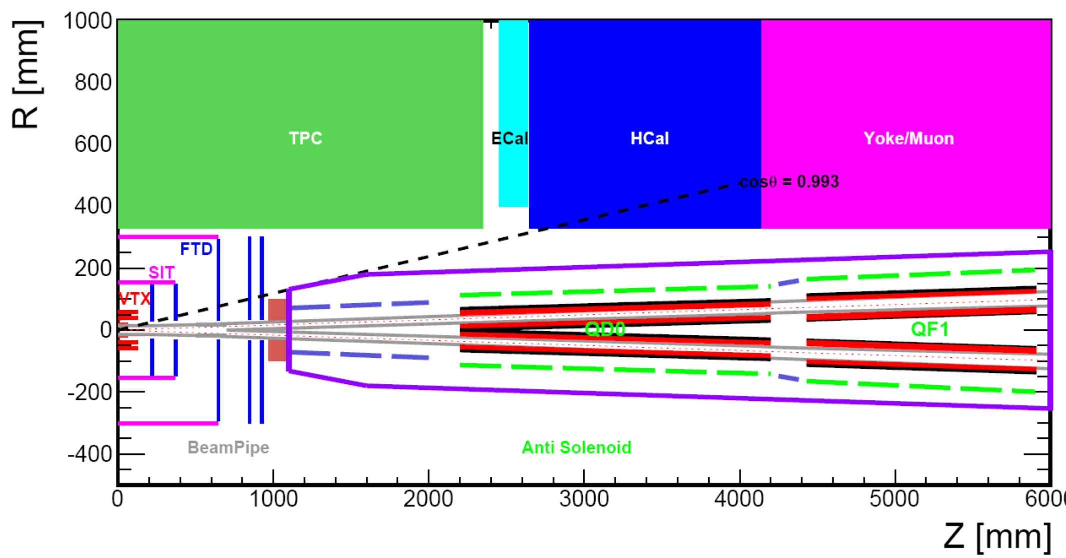
- Introduction
- Conceptual design of final focus quadrupole magnets and anti-solenoid
- Conceptual design of superconducting sextupole magnets
- R&D plan
- Summary

Introduction

- CEPC is a Circular Electron Positron Collider with a circumference about 100 km, beam energy up to 120 GeV proposed by IHEP.
- Most magnets needed for CEPC Accelerator are conventional magnets.
- Compact high gradient final focus quadrupole magnets are required on both sides of the collision points in interaction region of CEPC collider ring.



Sketch of CEPC Collider ring



CEPC MDI layout

- The requirements of the Final Focus quadrupoles (QD0 and QF1) are based on the L* of 2.2 m, beam crossing angle of 33 mrad in the interaction region.

Table 1: Requirements of Interaction Region quadrupole magnets for Higgs

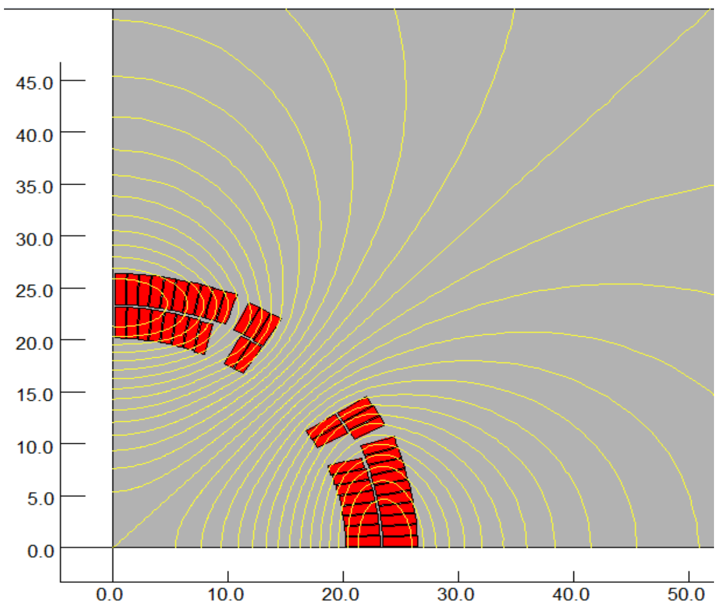
Magnet	Central field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
QD0	136	2.0	19.51	72.61
QF1	110	1.48	27.0	146.20

- QD0 and QF1 magnets are operated full inside the field of the Detector solenoid magnet with a central field of 3.0 T.
- To minimize the effect of the longitudinal detector solenoid field on the accelerator beam, anti-solenoids before QD0, outside QD0 and QF1 are needed, so that the total integral longitudinal field generated by the detector solenoid and accelerator anti-solenoid is zero.

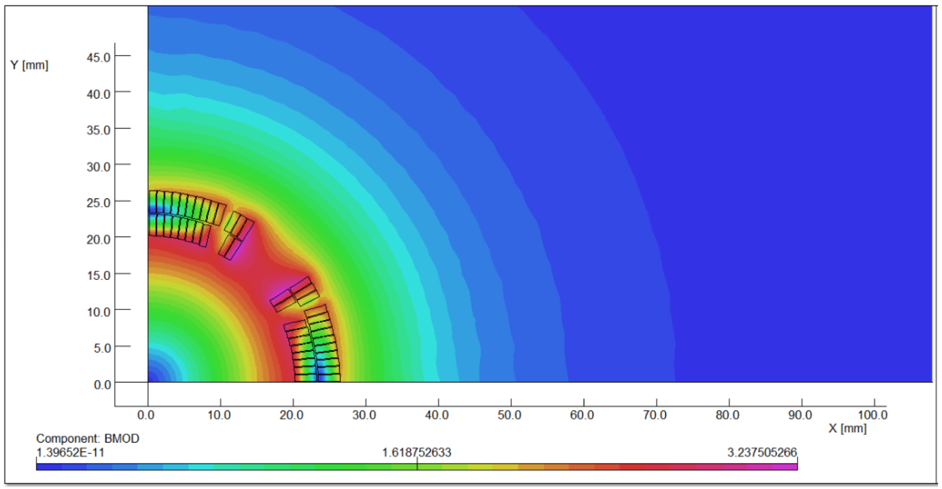
- The field distribution of net solenoid field should also meet the requirements from the accelerator beam dynamics.
- Furthermore, the MDI layout imposes strict boundary conditions on the longitudinal and transerve dimensions of the accelerator magnets.
- Taking into account the high field strength of twin aperture quadrupole magnet, high central field of anti-solenoid, and the limited space, superconducting technology base on NbTi conductor will be used for Interaction Region superconducting quadrupole magnets and anti-solenoids.
- In addition, there are 32 superconducting sextupole magnets required in the CEPC interaction region.

Conceptual Design of superconducting quadrupole magnet QD0

- The minimum distance between QD0 two aperture centerlines is only 72.61 mm, so very tight radial space is available.
- The design of QD0 is based on two layers cos2θ quadrupole coil using Rutherford cable without iron yoke.
- The QD0 single aperture coil cross section is optimized with four coil blocks in two layers separated by wedges, and there are 23 turns in each pole.
- The excitation current is 2510A, and I_{op}/I_{c}<75% @4.2K.



2D flux lines (1/4 cross section)



Magnetic flux density distribution

◆ The coil turns, the coil dimension and the excitation current of QD0 are consistent with the expressions of Ampere-Turns for superconducting quadrupole magnets based on sector coils.

$$(NI)_{Quadrupole} \approx \frac{G\overline{R}^2}{\mu_0}$$

(no iron)

$$(NI)_{Quadrupole} \approx 2\frac{G\overline{R}^2}{2\mu_0} \Big/ \left(1 + \left(\frac{\overline{R}}{R_y}\right)^4\right)$$

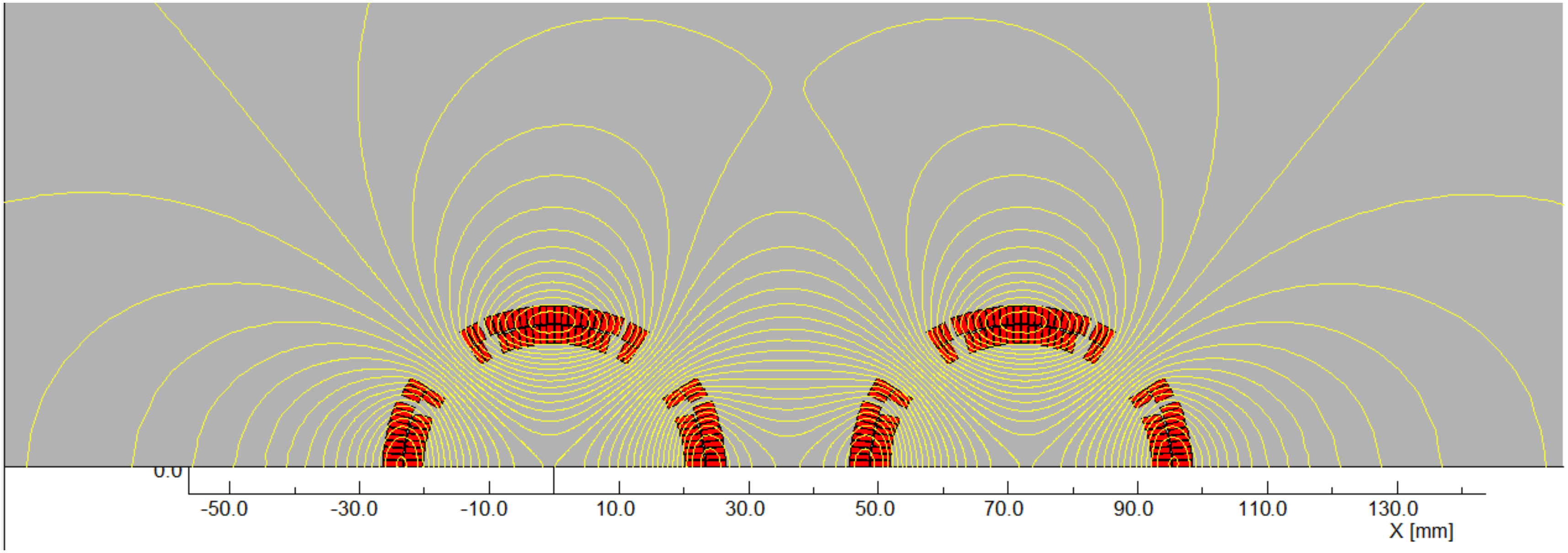
(with iron)

Yingshun Zhu, et al., Study on Ampere-Turns of Superconducting Dipole and Quadrupole Magnets Based on Sector Coils, *Nuclear Instruments and Methods in Physics Research A*, 2014, 741: 186-191.

Table 2: 2D field harmonics (unit, 1×10^{-4})

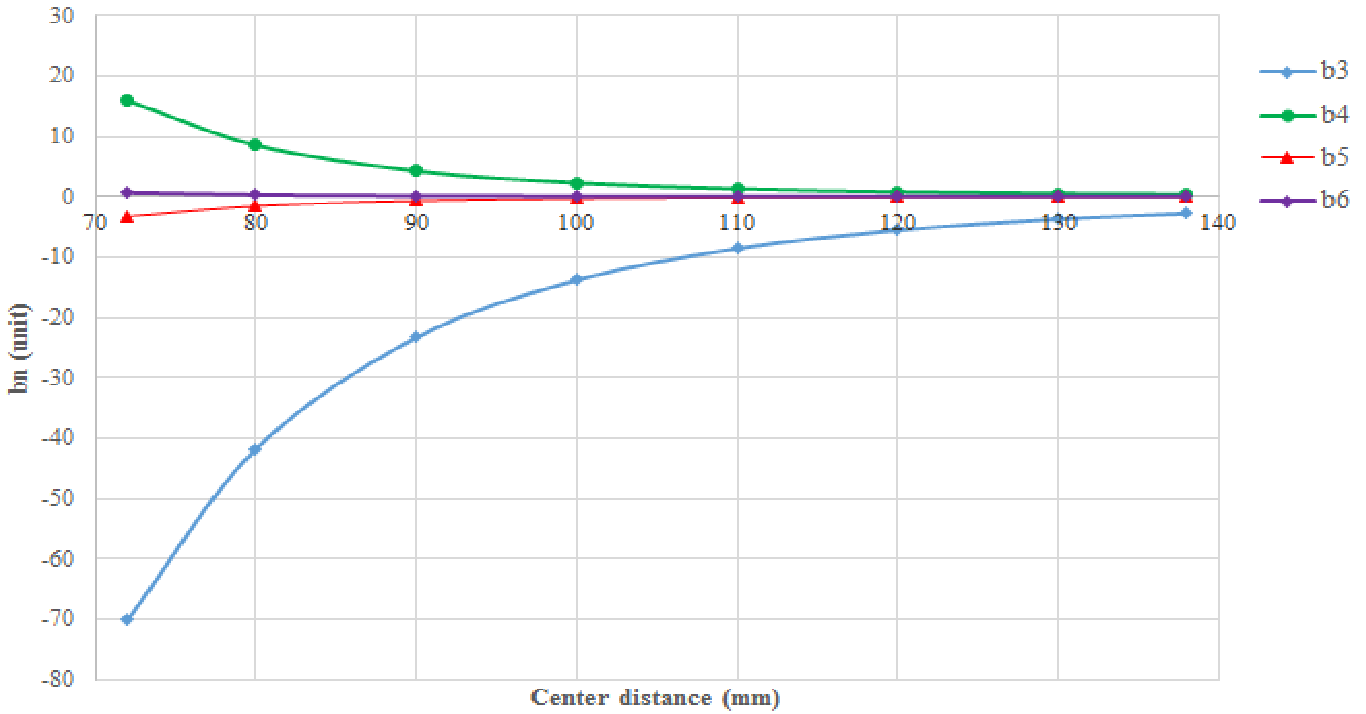
n	B_n/B_2@R=9.8mm
2	10000
6	-0.77
10	-0.45
14	-0.098

- The field in one aperture is affected due to the field generated by the coil in another aperture. Field cross talk of the two apertures is studied.



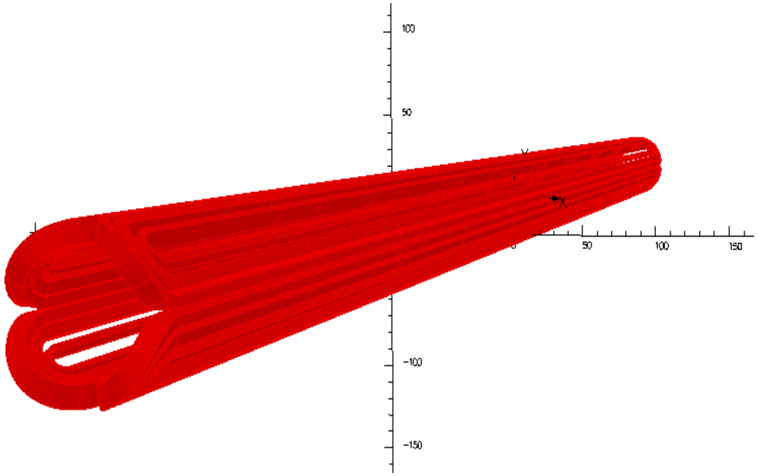
Flux lines of two aperture coils

- Multipole field in one aperture as a function of aperture central distance is shown below (2D calculation, unit, 1×10^{-4}):

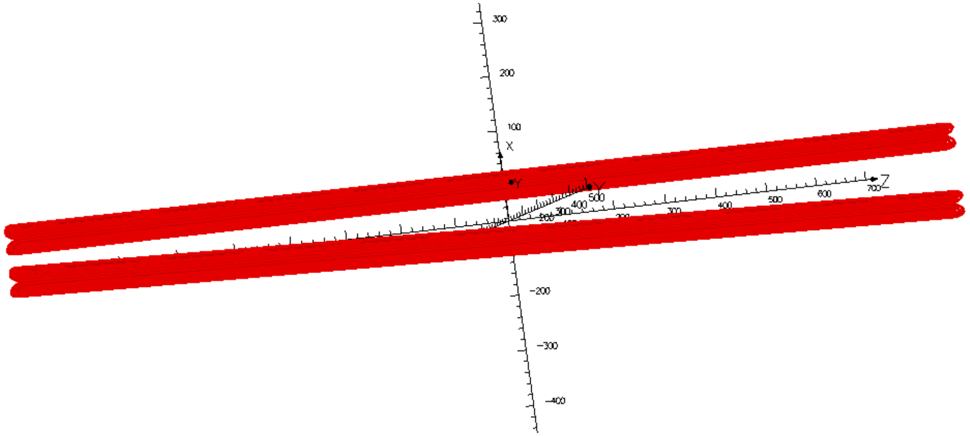


Multipole field in one aperture as a result of field cross-talk

- QD0 coils are simplified and modelled in OPERA-3D.
- Firstly one single aperture coil is modelled, the field gradient exceeds 136 T/m, and field quality is good.
- Then two aperture coils are modelled, the multipole fields induced by the field cross talk of the two apertures are obtained.



Single aperture coil



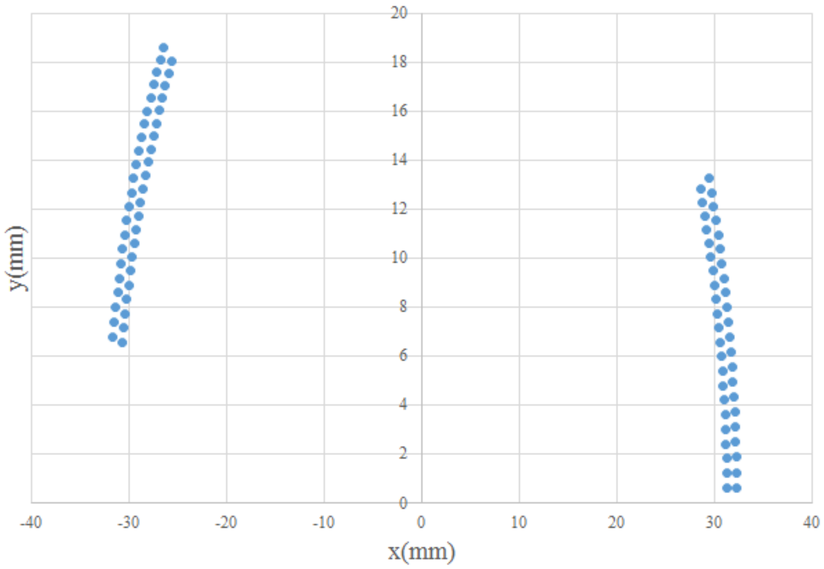
Two aperture coils

- The calculated multipole field contents in one aperture with the twin aperture layout:

Table 3: 3D field harmonics（unit, 1×10^{-4}）

n	B_n/B_2@R=9.8 mm
2	10000.0
3	-19.0015
4	3.574183
5	-0.61921
6	0.153909
7	-0.01883
8	2.19E-03
9	-4.7E-04
10	-0.05702
11	9.48E-04
12	3.63E-04

- Two layers of shield coil is introduced just outside the quadrupole coil to improve the field quality. The shield coil is not symmetric within each aperture, but the shield coils for two apertures are symmetric.
- The conductor for the shield coil is round NbTi wire with 0.5 mm diameter, and there are 44 turns in each pole. The calculated integrated field quality and multipole fields at different longitudinal positions are smaller than 3×10^{-4}.

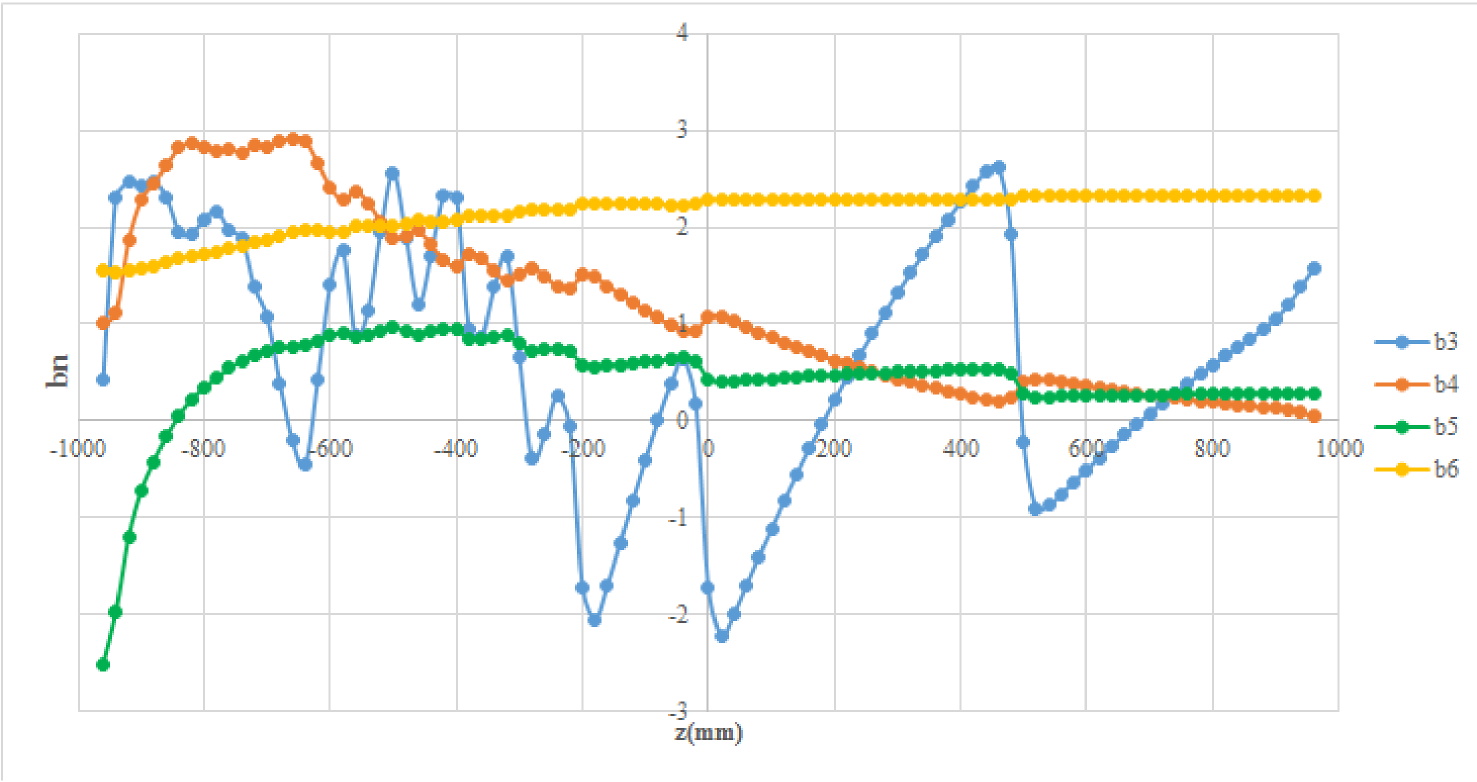


Shield coil layout (half)

Table 4: Integrated field harmonics with shield coil (1×10^{-4})

n	B_n/B_2@R=9.8 mm
2	10000.0
3	-0.57419
4	1.525573
5	0.375555
6	-0.13735
7	0.015413
8	-0.03117
9	-1.7E-03
10	-0.05809

◆ To match the fall off of field harmonics caused by the field cross talk when the distance of two beam lines increases, the conductor length of shield coil at each angular position is different.

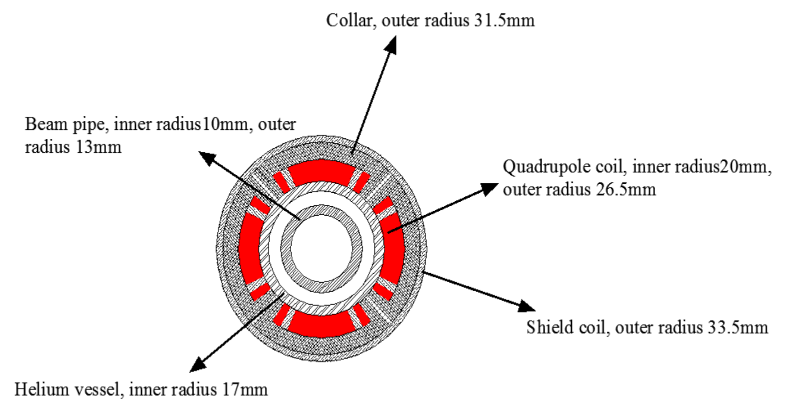


Field harmonics in one aperture along longitudinal position (1×10^{-4})

◆ Design parameters and magnet Layout of QD0:

Table 5: Design parameters of QD0

Magnet name	QD0
Field gradient (T/m)	136
Magnetic length (m)	2.0
Coil turns per pole	23
Excitation current (A）	2510
Shield coil turns per pole	44
Shield coil current (A）	135
Coil layers	2
Conductor	Rutherford Cable, width 3 mm, mid thickness 0.94 mm, keystone angle 1.8 deg,Cu:Sc=1, 12 strands
Stored energy (KJ)	25.0
Inductance (H）	0.008
Peak field in coil (T)	3.3
Coil inner diameter (mm)	40
Coil outer diameter (mm)	53
X direction Lorentz force/octant (kN)	68
Y direction Lorentz force/octant (kN)	-140

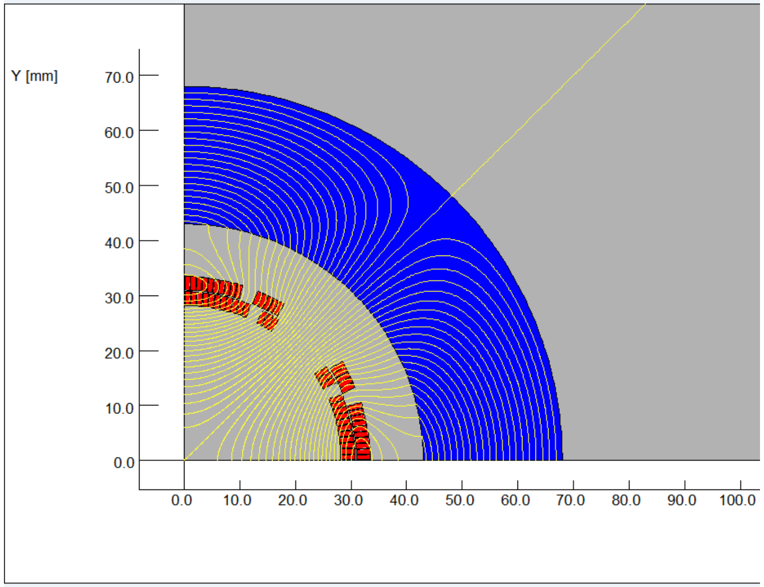


Single aperture QD0

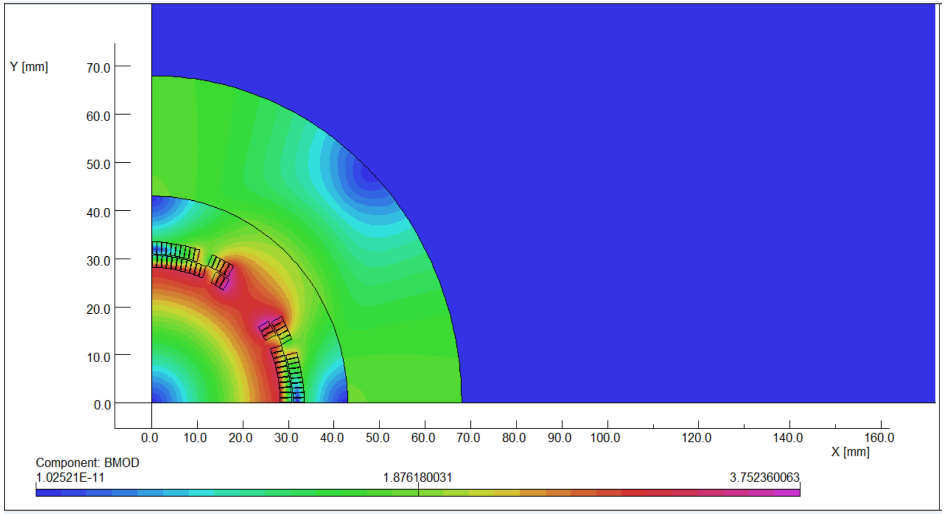
The current of QD0 at W and Z model will decrease.

Conceptual design of superconducting quadrupole magnet QF1

- The design of QF1 magnet is similar to the QD0 magnet, except that there is iron yoke around the quadrupole coil for QF1.
- The used Rutherford cable is similar to that of QD0. Since the distance between the two apertures is much larger and the usage of iron yoke, the field cross talk between the two apertures of QF1 is not a problem.
- After optimization, the QF1 coil consists of four coil blocks in two layers separated by wedges, and there are 29 turns in each pole.



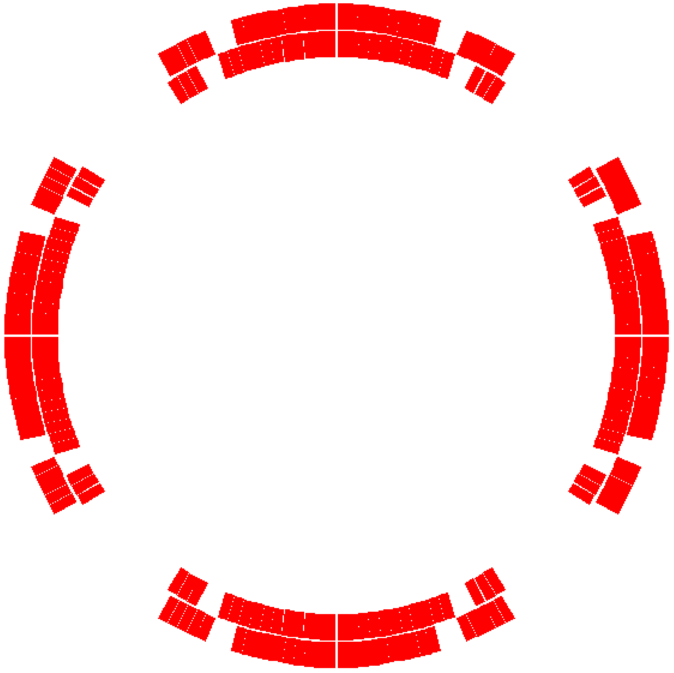
2D flux lines (One quarter cross section)



Magnetic flux density distribution

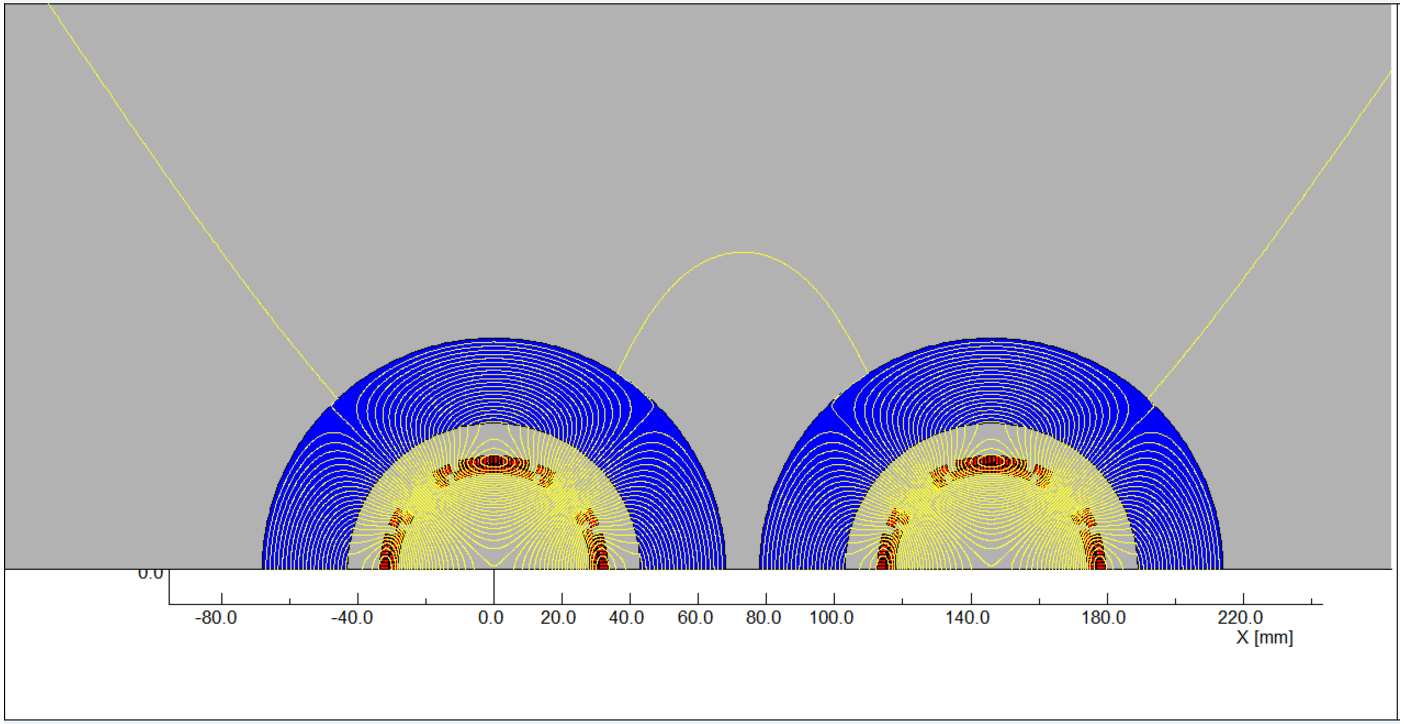
Table 6: 2D field harmonics of QF1 (unit, 1×10^{-4})

n	B_n/B_2@R=13.5mm
2	10000
6	1.08
10	-0.34
14	0.002



Coil cross section of single aperture QF1

- Field cross talk of QF1 two apertures is modelled and studied in OPERA-2D.
- The calculation results show that, the iron yoke can well shield the leakage field of each aperture, the field harmonics as a result of field cross talk between the two apertures can be neglected.

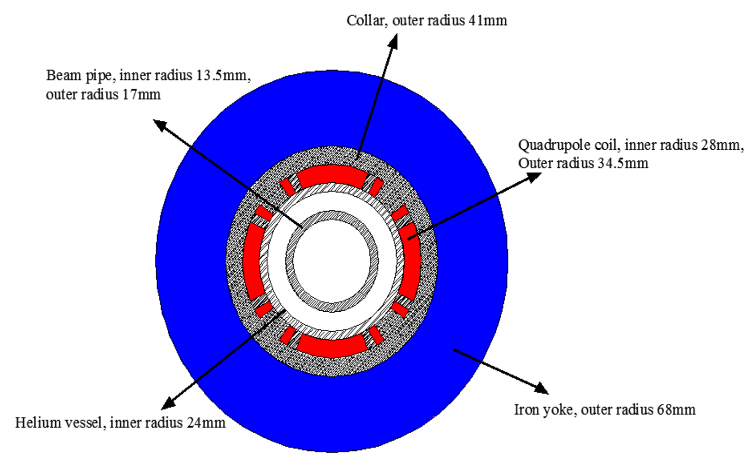


Two aperture Flux lines

◆ Design parameters and magnet Layout of QF1:

Table 7: Design parameters of QF1

Magnet name	QF1
Field gradient (T/m)	110
Magnetic length (m)	1.48
Coil turns per pole	29
Excitation current (A）	2250
Coil layers	2
Conductor size (mm)	Rutherford Cable, width 3 mm, mid thickness 0.95 mm, 12 strands
Stored energy (KJ)	30.5
Inductance (H）	0.012
Peak field in coil (T)	3.8
Coil inner diameter (mm)	56
Coil outer diameter (mm)	69
X direction Lorentz force/octant (kN)	110
Y direction Lorentz force/octant (kN)	-120



Single aperture QF1

The current of QF1 at W and Z model will decrease.

Conceptual design of superconducting anti-solenoid

- The design requirements of the anti-solenoids in the CEPC Interaction Region are summarized below:

1) The total integral longitudinal field generated by the detector solenoid and anti-solenoid coils is zero. $\int B_z ds = 0$
2) The longitudinal field inside QD0 and QF1 should be smaller than a few hundred Gauss at each longitudinal position.
3) The distribution of the solenoid field along longitudinal direction should meet the requirement of the beam optics for emittance.
4) The angle of the anti-solenoid seen at the collision point satisfies the Detector requirements.

- The design of the anti-solenoid fully takes into account the above requirements. The anti-solenoid will be wound of rectangular NbTi-Cu conductor.

- The magnetic field of the Detector solenoid is not constant, and it decreases slowly along the longitudinal direction.
- In order to reduce the magnet size, energy and cost, the anti-solenoid is divided into a total of 22 sections with different inner coil diameters.
- These sections are connected in series, but the current of some sections of the anti-solenoid can be adjusted using auxiliary power supplies if needed.

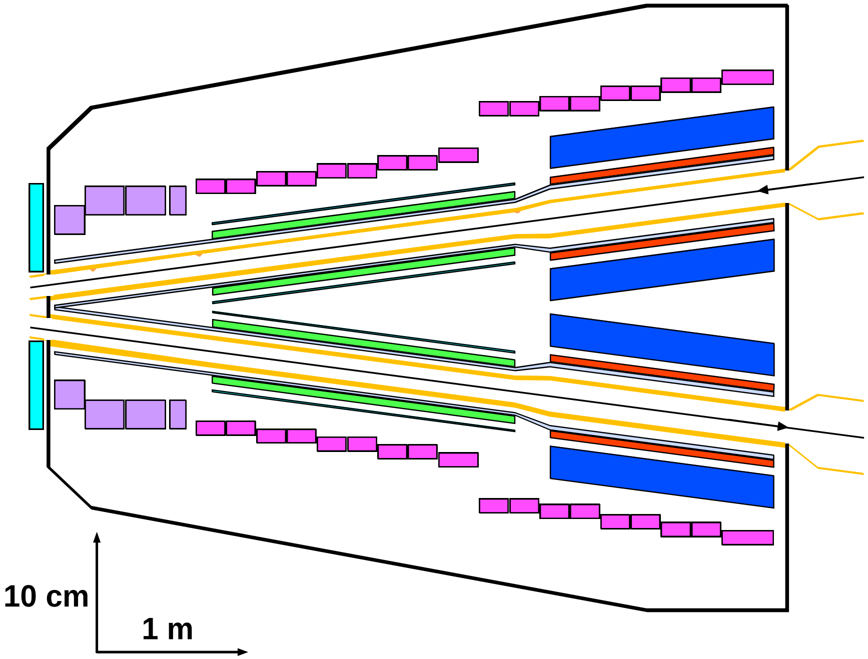
- The anti-solenoid along longitudinal direction:

  1) 4 sections, from IP point to QD0;

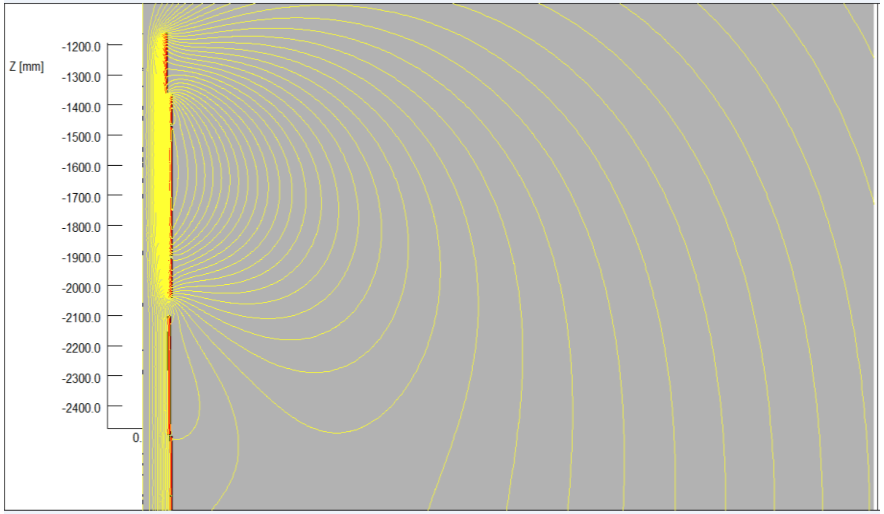
  2) 11 sections, QD0 region;

  3) 6 sections, QF1 region;

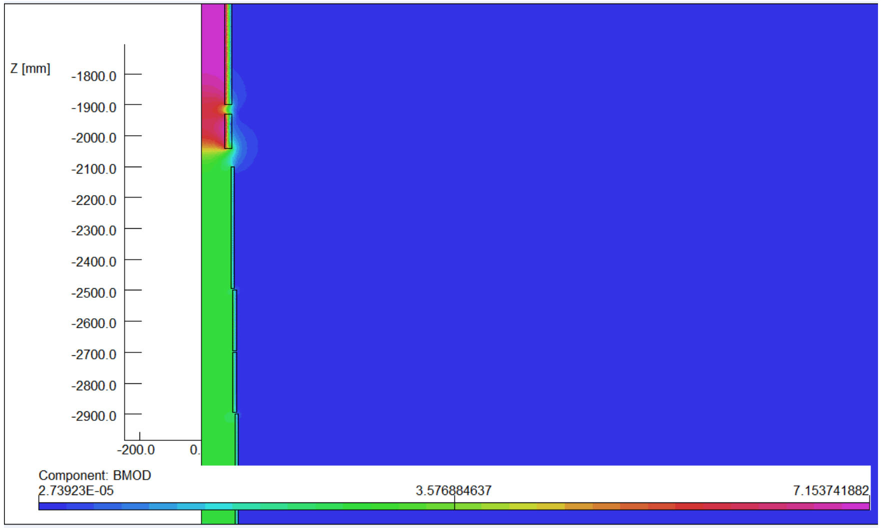
  4) 1 section, after QF1 region.



- Magnetic field calculation and optimization is performed using axi-symmetric model in OPERA-2D.
- The central field of the first section of the anti-solenoid is the strongest, with a peak value of 7.2T.

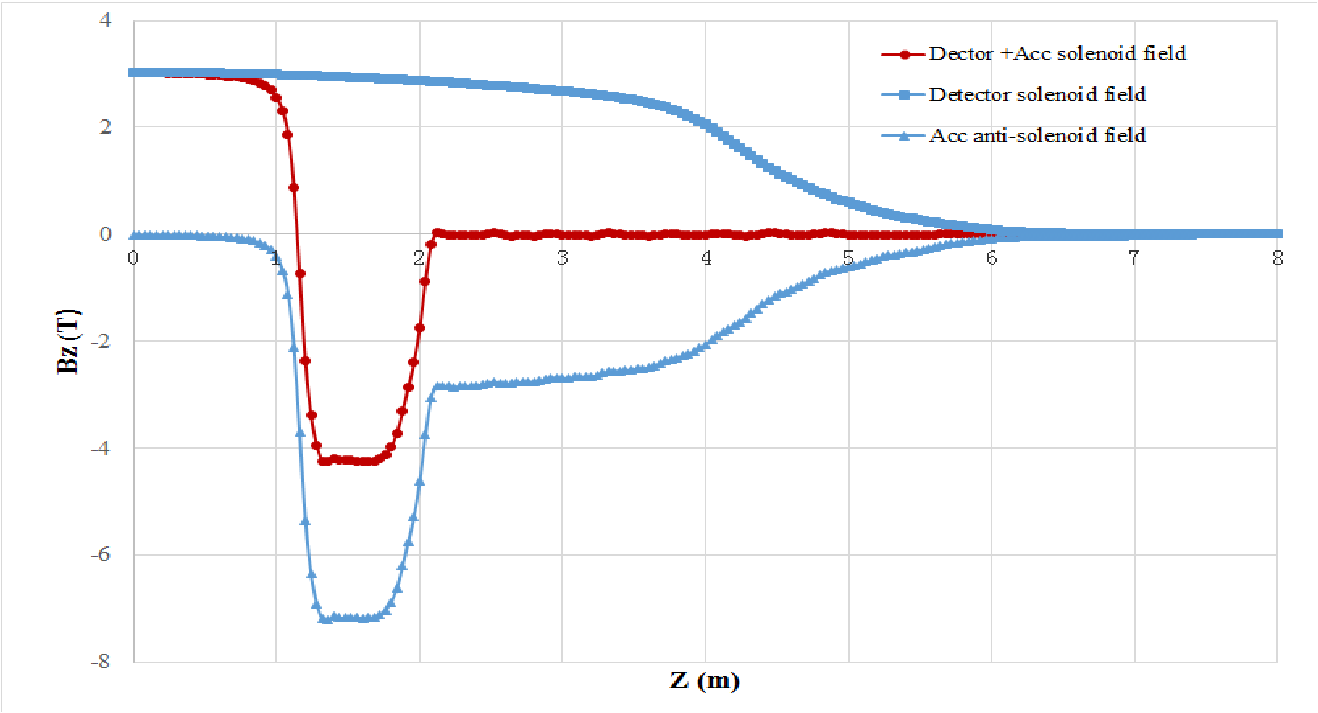


2D flux lines



Magnetic flux density distribution

- Combined field of Anti-solenoid and Detector solenoid with linear superposition.



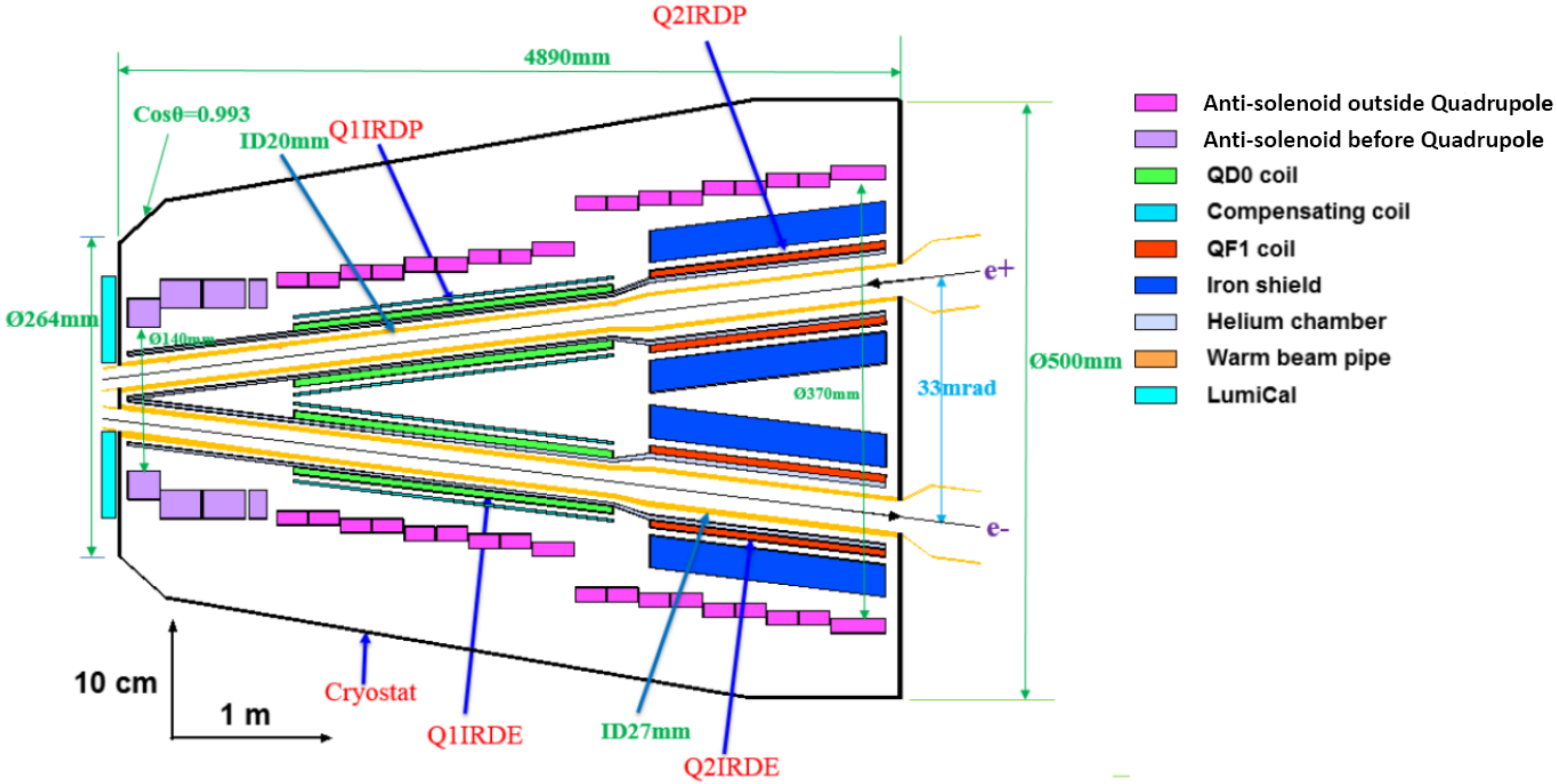
- The net solenoid field inside QD0 and QF1 at each longitudinal position is smaller than 300 Gs.
- The combined field distribution of anti-solenoid and Detector solenoid well meets the requirement of beam dynamics.

◆ Design parameters of Anti-solenoid:

Table 8: Design parameters of Anti-solenoid

Magnet name	Anti-solenoid before QD0	Anti-solenoid QD0	Anti-solenoid after QD0
Central field（T）	7.2	2.8	1.8
Magnetic length（m）	1.1	2.0	1.7
Conductor (NbTi-Cu, mm)	2.5×1.5		
Coil layers	16	8	4/2
Excitation current（kA）	1.0		
Stored energy (KJ)	715		
Inductance（H）	1.4		
Peak field in coil (T)	7.7	3.0	1.9
Number of sections	4	11	7
Solenoid coil inner diameter (mm)	120		
Solenoid coil outer diameter (mm)	390		
Total Lorentz force F_z (kN)	-75	-13	88
Cryostat diameter (mm)	500		

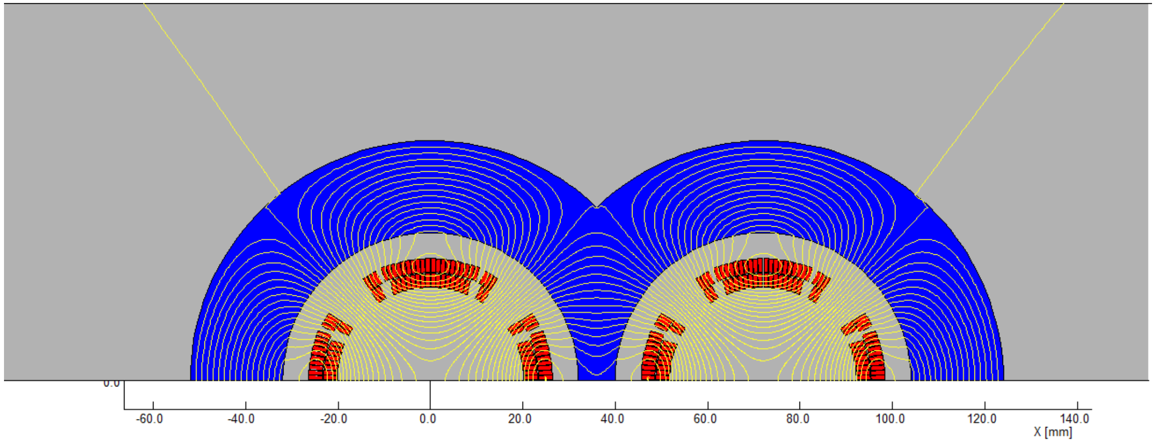
- To reduce the length of the cryostat, the last section of anti-solenoid with low field will be operated at room-temperature.
- The superconducting QD0, QF1, and anti-solenoid coils are in the same cryostat, and the schematic layout is shown below (tungsten not included):

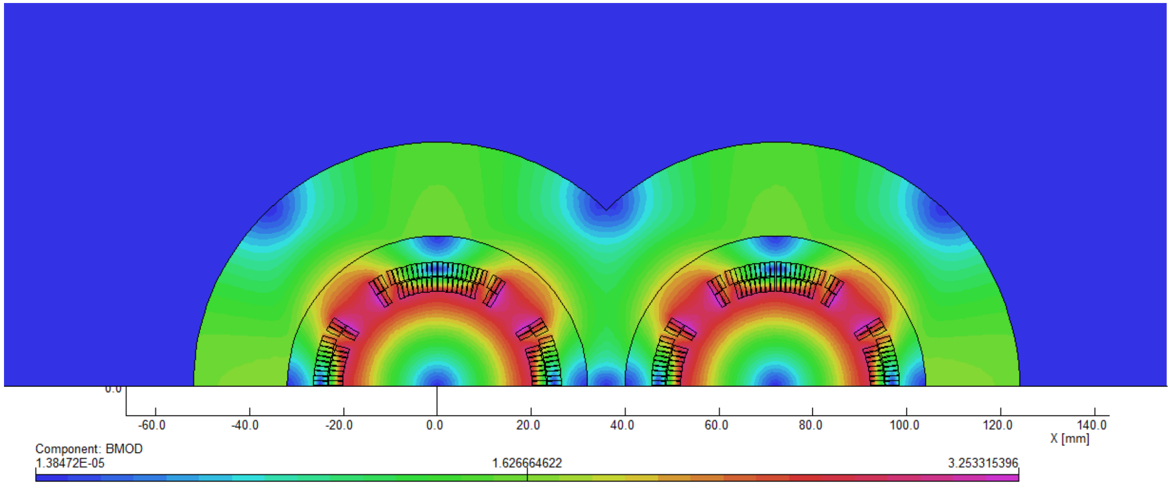


Schematic layout of QD0, QF1, and anti-solenoid

QD0 design option with iron yoke

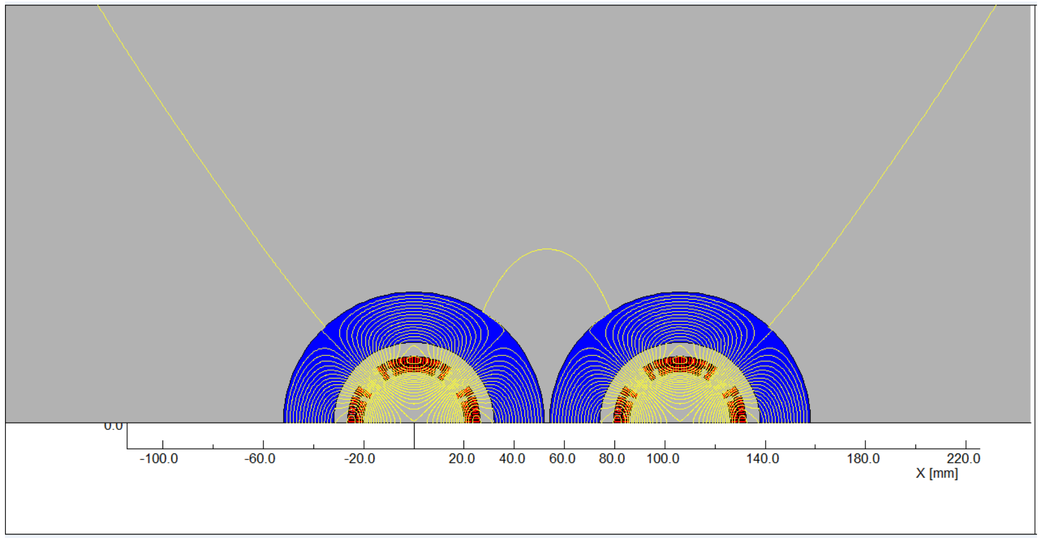
- An alternative design option for QD0 with iron yoke is under investigated.

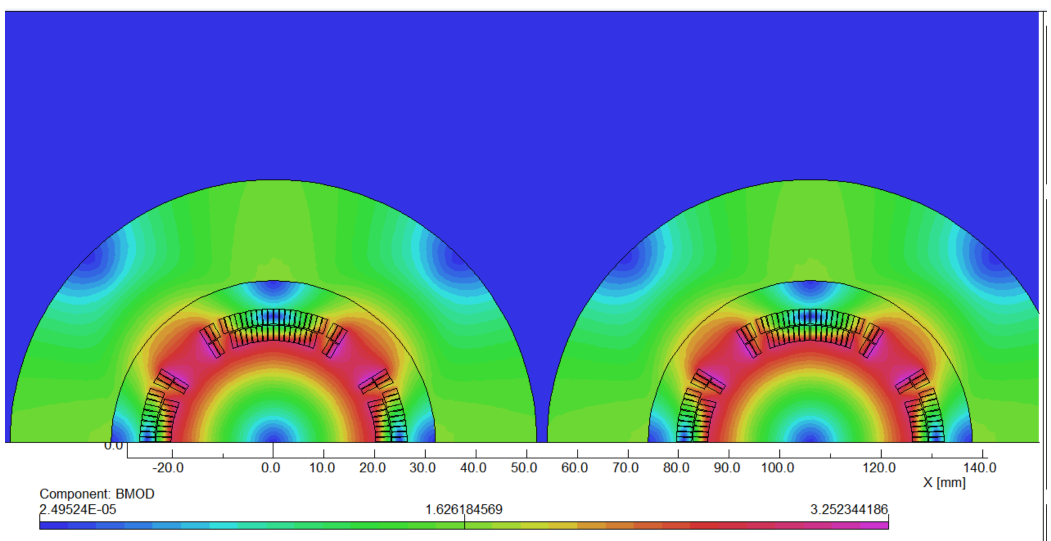




Nearest to the IP point

- Intermediate case





- In the case where the distance between the two aperture is the nearest and the field crosstalk is the most serious, iron yoke can well shield the leakage field of each aperture, and the field harmonics as a result of field crosstalk between the two apertures is smaller than 1×10^{-4}.
- In other cases where the distance between the two apertures becomes larger, the field harmonics will also be smaller.

- Using the iron yoke, the field harmonics as a result of the field crosstalk is not a problem. In addition, compared with the iron-free design of QD0, the excitation current can be reduced.

✓ The main disadvantage of the iron option is that the diameter of QD0 will be larger, and there will be not enough space for multipole corrector coils.

Conceptual design of superconducting sextupole magnets

◆ The requirements of superconducting sextupole magnets for Higgs operation:

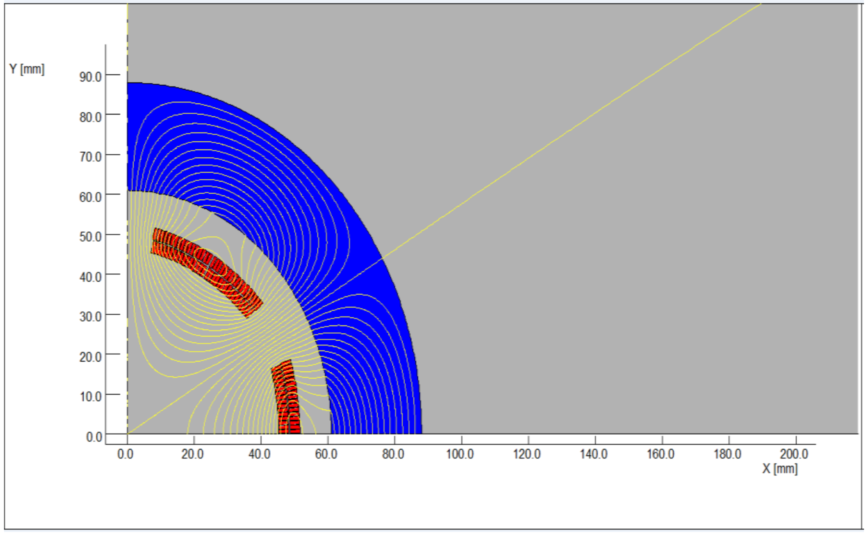
Table 9: Requirements of CEPC Interaction Region sextupole magnets for Higgs

Magnet	Number	Central field strength (T/m^2, for Higgs)	Magnetic length (m)	Aperture diameter (mm)	Rref (mm)
VSIRD	8	1635	0.6	66	8.5
HSIRD	8	1882	0.8	66	15.0
VSIRU	8	1562	0.6	66	8.5
HSIRU	8	1999	0.6	66	15.5

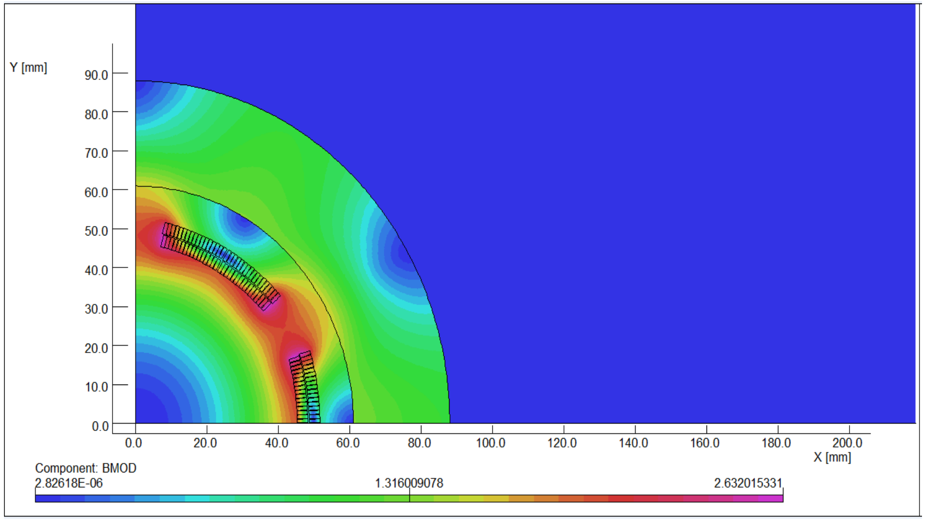
- Iron yoke around the sextupole coils is used to enhance the field strength and reduce the operating current.
- The four type sextupole magnets are designed to have the same cross section.
- The used Rutherford cable is similar to that of QD0.

Conceptual design of superconducting sextupole magnets

- The cross section of sextupole magnets is optimized using OPERA-2D.
- After optimization, the sextupole coil consists of two coil blocks in two layers, and there are 33 turns in each pole.



HSIRU 2D flux lines (One quarter cross section)



HSIRU Magnetic flux density distribution

Table 10: 2D field harmonics of HSIRU (unit, 1×10^{-4})

n	B_n/B_3@R=15.5mm
3	10000
9	-0.4
15	-0.01
21	0.01

Table 11: Design parameters of sextupole magnets at Higgs operation

Magnet name	VSIRD	HSIRD	VSIRU	HSIRU
Field strength (T/m^2)	1635	1882	1562	1999
Magnetic length (m)	0.6	0.8	0.6	0.6
Coil turns per pole	33			
Excitation current (A)	1200	1380	1150	1470
Coil layers	2			
Conductor size (mm)	Rutherford NbTi-Cu Cable, width 3 mm, mid thickness 0.95 mm			
Stored energy (KJ)	3.4	6.0	3.1	5.1
Inductance (H)	0.005	0.006	0.005	0.005
Peak field in coil (T)	2.2	2.55	2.1	2.7
Coil inner diameter (mm)	90			
Coil outer diameter (mm)	104			
Cryostat diameter (mm)	300			
Total magnet number	8	8	8	8

The current of sextupole magnets at W and Z model will decrease.

R&D plan

- In the R&D stage of CEPC project, superconducting prototype magnets for the Interaction Region will be developed in three consecutive steps:

1) Double aperture superconducting quadrupole prototype magnet QD0;
2) Short combined function superconducting prototype magnet including QD0 and anti-solenoid;
3) Long combined function superconducting prototype magnet including QD0, QF1 and anti-solenoid.

◆ The key technical issues of the prototype superconducting magnets to be studied and solved in the R&D are listed below:

1) Magnetic and mechanical design of the superconducting quadrupole magnet and anti-solenoids with very high field strength and limited space.
2) Fabrication technology of small size Rutherford cable with keystone angle.
3) Fabrication procedure of the twin aperture quadrupole coil with small diameter.
4) Fabrication procedure of the anti-solenoids with many sections and different diameters.
5) Assembly of the several coils including QD0, QF1 and anti-solenoids.
6) Development of the long cryostat for the combined function SC magnet.
7) Development of magnetic field measurement system for small aperture long superconducting magnet.
8) Development of quench protection system for combined function SC magnet.
9) Cryogenic test and field measurement of the small aperture long SC magnet.

Summary

- Superconducting magnets in interaction region are key devices for CEPC. Conceptual design of superconducting magnets in CEPC interaction region has been finished.
- Field cross talk effect between two apertures in QD0 and QF1 can be reduced to be acceptable.
- The anti-solenoid is divided into a total of 22 sections with different inner coil diameters, with a max central field of 7.2 T.
- It is challenging to develop high strength compact superconducting magnets in CEPC Interaction Region.
- Prototypes superconducting magnets in CEPC Interaction Region are proposed, and the R&D has started .

Thanks for your attention!