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CEPC SUPERCONDUCTING MAGNETS*

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Abstract

A Circular Electron Positron Collider (CEPC) with a circumference about 100 km, a beam energy up to 120 GeV is proposed to be constructed in China. CEPC will be a double ring collider with two interaction points. Most magnets for CEPC accelerator are conventional magnets, but some superconducting magnets are required in the interaction region. Final focus superconducting high gradient quadrupoles are inside the solenoid field of Detector magnet, so superconducting anti-solenoid is need to minimize the effect of the solenoid field on the beam. In addition, high strength superconducting sextupole magnets are also required. In this paper, the layout and conceptual design of CEPC interaction region superconducting magnets are described, and the R&D plan is presented.

INTRODUCTION

A Circular Electron Positron Collider (CEPC) with a circumference about 100 km is proposed to be constructed in China. It is an important part of the world plan for high-energy physics research. The CEPC center-of-mass energy is 240 GeV, and at that collision energy it will serve as a Higgs factory. The design also allows operation at lower beam energy to be a Z or W factory. The accelerator complex of CEPC consists of a linear accelerator (Linac), a damping ring (DR), the Booster, the Collider and several transport lines [1]. The heart of the CEPC is a double-ring collider with two interaction points.

There are a large number of magnets in the CEPC collider ring, and the magnets occupy over 80% of the circumference. Most magnets for CEPC accelerator are conventional magnets, except some superconducting magnets are needed in the interaction region of CEPC collider ring. Compact high gradient superconducting quadrupole doublet magnets are usually required on both sides of the interaction point (IP) to final focus the beam to achieve high luminosity [2-4]. The CEPC final focus superconducting quadrupoles are inside the solenoid field of Detector magnet, so superconducting anti-solenoid is need to minimize the effect of the solenoid field on the beam. In addition, high strength superconducting sextupole magnets are also required in the CEPC interaction region.

SUPERCONDUCTING MAGNET SYSTEM

The requirements of the final focus quadrupole doublets QD0 and QF1 are based on the circumference 100 km of CEPC, L* of 2.2 m, and a beam crossing angle of 33 mrad in the CEPC interaction region. The requirements of the quadrupole magnets are listed in Table 1.

Table 1: Requirements of CEPC Interaction Region Quadrupole Magnets

Magnet	Field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)
QD0	136	2.0	19.51
QF1	110	1.48	27

The crossing angle between the electron and positron beams is 33 mrad in horizontal plane. The final focusing quadrupole is 2.2 m from the IP, and the QD0 and QF1 magnets are designed to be twin aperture quadrupole magnets. They are operated fullly inside the solenoid field of the Detector 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. Their magnetic field direction is opposite to the detector solenoid, and the total integral longitudinal field generated by the detector solenoid and anti-solenoid coils is zero. It is also required that the total solenoid field inside the QD0 and QF1 magnet should be close to zero.

The CEPC Machine Detector Interface (MDI) layout at one side of the interaction point is shown in Fig. 1, where QD0, QF1 and Anti-solenoid are the accelerator magnets.

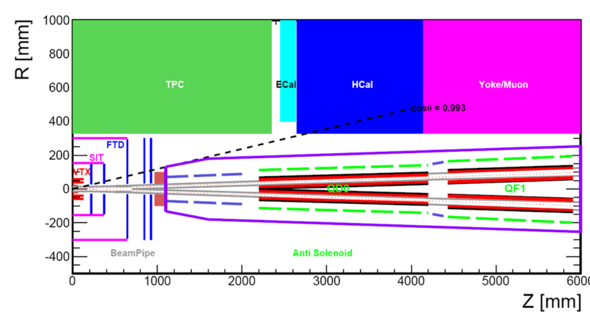

Figure 1: CEPC MDI layout.

According to the layout of the MDI, accelerator devices can only start after z=1.1 m along the longitudinal axis, so the available space for the anti-solenoid before QD0 is limited. In addition, the angle of the accelerator magnet seen from the IP point must be small and satisfy the requirement from the Detector. Taking into account the high field strength of twin aperture quadrupole magnet, high central field of anti-solenoid and the limited space, superconducting technology based on NbTi conductor will be used for these interaction region superconducting quadrupole magnets and anti-solenoids.

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Furthermore, there are also 32 superconducting sextupole magnets required in the CEPC interaction region. The requirements of superconducting sextupole magnets for Higgs operation are listed in Table 2.

Table 2: Requirements of CEPC Interaction Region Sextupole Magnets for Higgs

Magnet	Field strength (T/m^2)	Magnetic length (m)	Reference radius (mm)
VSIRD	1635	0.6	8.5
HSIRD	1882	0.8	15.0
VSIRU	1562	0.6	8.5
HSIRU	1999	0.6	15.5

CONCEPTUAL DESIGN

Superconducting Quadrupole Magnet QD0

The final focus QD0 is a double aperture superconducting magnet. The distance from QD0 to the interaction point is 2.2 m, and the minimum distance between two aperture centerlines is only 72.61 mm, so very tight radial space is available for QD0. The outer diameter of single aperture QD0 is determined by the separation of two beams at the IP side.

The design of QD0 is based on two layers cos2θ quadrupole coil using Rutherford cable without iron yoke. The four coils are clamped with the collars made of stainless steel or aluminium. The beam pipe at room temperature is held inside the helium vessel with a clearance gap of 4 mm. In the field calculation, it is assumed that the magnetic field harmonics in the good field region are required to be smaller than 3×10^{-4}.

2D Field Calculation The QD0 is an iron-free small-aperture long magnet. Its coils will be made of Rutherford cable with a width of 3 mm, a mid-thickness of 0.94 mm, and a keystone angle of 1.8 degrees. The QD0 coil cross section is optimized with four coil blocks in two layers, and there are 23 turns in each pole.

2D magnetic field calculation is performed using OPERA from Cobham Technical Services [5]. Firstly one aperture of QD0 magnet is included in the calculation, and only one quarter is modelled. After optimization, good field quality in the good field region is obtained. The excitation current is 2510A. The number of coil turns, the dimension of the coil and the excitation current are consistent with the expressions of Ampere-Turns for superconducting quadrupole magnets based on sector coils [6]. The magnetic flux lines and magnetic flux density distribution in single aperture are shown in Fig. 2 and Fig. 3, respectively.

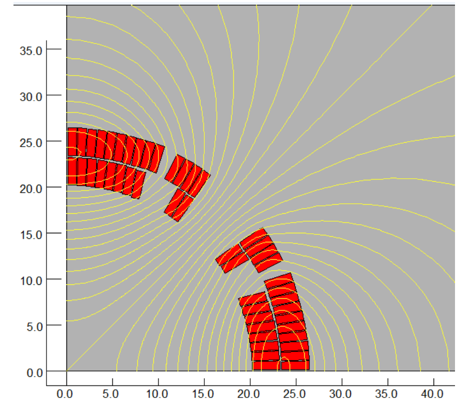

Figure 2: 2D flux lines (One quarter cross section).

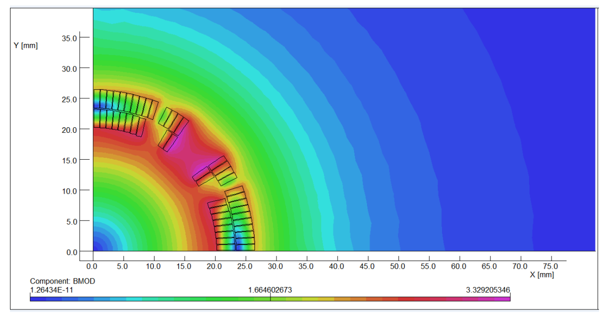

Figure 3: Magnetic flux density distribution.

The calculated relative multipole field contents normalized to the main quadrupole field are smaller than 1×10^{-4}.

The field in one aperture is affected due to the field generated by the coil in another aperture. Field crosstalk of the two apertures is modelled and studied in OPERA-2D. Figure 4 shows a typical case of flux lines in the two aperture coils.

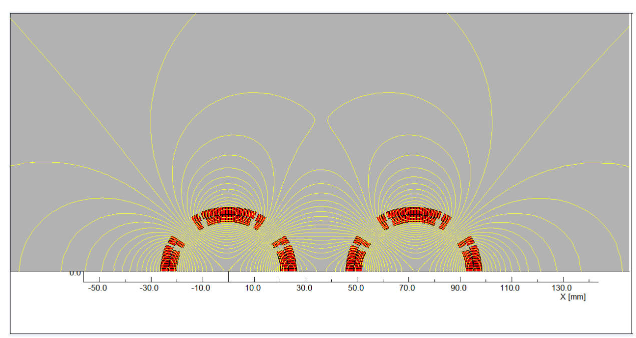

Figure 4: Flux lines of two aperture coils.

The calculated multipole field in one aperture as a function of aperture central distance is presented in Fig. 5 (unit, 1×10^{-4}).

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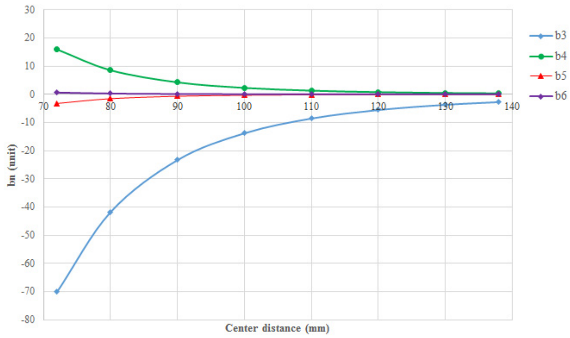

Figure 5: Multipole field in each aperture as a result of field crosstalk.

Since the small distance between the QD0 two apertures, the field crosstalk is serious. The largest multipole field is the sextupole field.

3D Field Calculation QD0 coils are simplified and modelled in OPERA-3D. Firstly the field quality in the single aperture is calculated, and then the multipole fields induced by the field crosstalk of the two apertures are obtained (Figure 6).

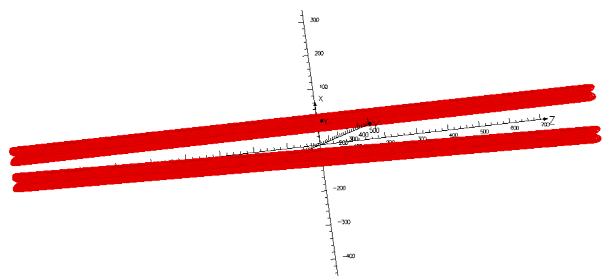

Figure 6: QD0 two aperture coils.

The calculated integrated multipole field contents in one aperture with the twin aperture layout are listed in [7]. The integrated sextupole and octupole field contents in the aperture are very large as a result of the field cross talk, especially the integrated sextupole component of 19×10^{-4}.

A two-layer 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 for each pole. After optimization, the shield coil in the left aperture is shown in Fig. 7, and each integrated multipole field in each aperture with a shield coil in the twin quadrupole coils layout is smaller than 2×10^{-4}.

To match the fall off of field harmonics caused by the field crosstalk when the distance of two beam lines increases, the conductor lengths of shield coil at each angular positions are different. Therefore, each multipole field is optimized to be smaller than 3×10^{-4} at different longitudinal positions in each aperture.

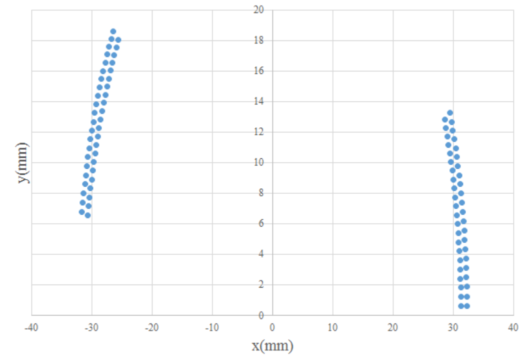

Figure 7: Shield coil in one aperture (half).

The schematic cross-section of single aperture QD0 magnet is shown in Fig. 8.

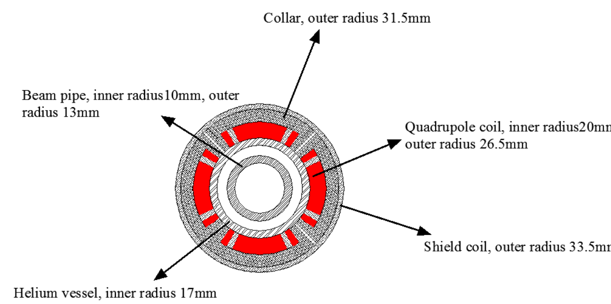

Figure 8: Single aperture QD0 magnet.

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. One quadrant of QF1 single aperture coil consists of four coil blocks in two layers separated by wedges, with 29 turns for each pole. 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 an issue as it is for QD0.

2D Field Calculation The QF1 cross section is optimized using OPERA-2D. Firstly, only one quarter of single aperture QF1 is modelled. After optimization, the field quality in each aperture is very good. The magnetic flux lines and magnetic flux density distribution are show in Fig. 9 and Fig. 10, respectively.

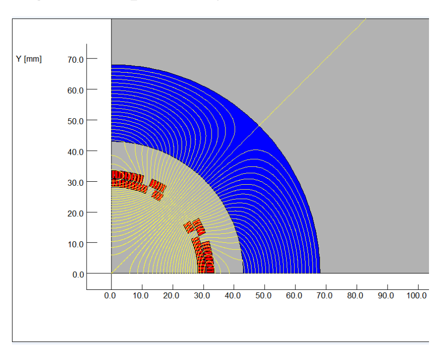

Figure 9: 2D flux lines of single aperture QF1 (One quarter cross section).

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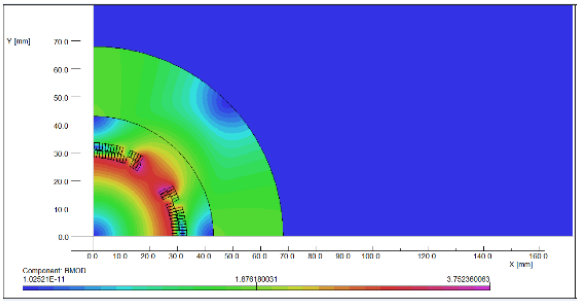

Figure 10: Magnetic flux density distribution of QF1.

Each calculated relative multipole field content in one aperture is smaller than $1{\times}10^{-4}$.

Then, field crosstalk of the two apertures in QF1 is modelled and studied in OPERA-2D. Figure 11 shows an example of flux lines in the two aperture coils. The field calculation results show that, the iron yoke can well shield the leakage field of each aperture. The field harmonics from field crosstalk between the two apertures is negligible.

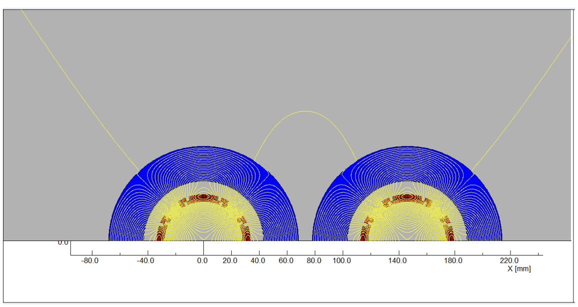

Figure 11: Flux lines of QF1 two aperture coils.

The schematic cross-section of single aperture QF1 magnet is shown in Figure 12.

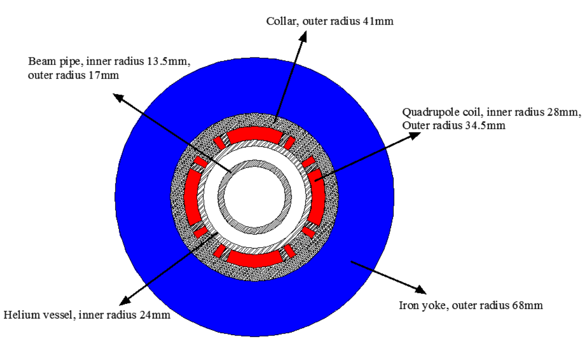

Figure 12: Single aperture QF1 magnet.

Design parameters and forces of QD0 and QF1 are listed in Table 3. The excitation current at W and Z model will decrease correspondingly.

Table 3: Design parameters of Quadrupoles QD0 and QF1

	QD0	QF1
Field gradient (T/m)	136	110
Magnetic length (m)	2.0	1.48
Coil turns per pole	23	29
Excitation current (A)	2510	2250
Coil layers	2	2
Conductor size (mm)	Rutherford NbTi-Cu Cable, width 3 mm, with keystone angle	
Stored energy (KJ)	25.0	30.5
Inductance (H)	0.008	0.012
Peak field in coil (T)	3.3	3.8
Coil inner diameter (mm)	40	56
Coil outer diameter (mm)	53	69
X direction Lorentz force/octant (kN)	68	110
Y direction Lorentz force/octant (kN)	-140	-120

Superconducting Anti-Solenoid

The requirements of the superconducting 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.

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 vertical 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. Since the magnetic field of the Detector solenoid is not constant, and it decreases slowly along the longitudinal direction, and also 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 in some sections of the anti-solenoid can be adjusted using auxiliary power supplies if necessary.

Magnetic field calculation is performed using axisymmetric model in OPERA-2D. Fig. 13 and Fig .14 show the flux lines and field distribution of anti-solenoids, respectively.

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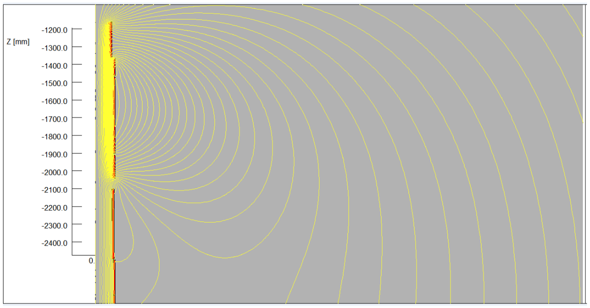

Figure 13: Flux lines of anti-solenoid.

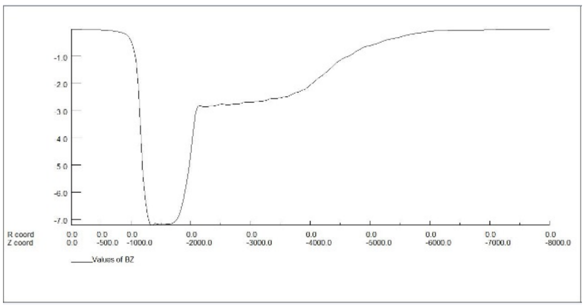

Figure 14: Field distribution of anti-solenoid.

The distribution of total field of Anti-solenoid and Detector solenoid magnet with linear superposition along the longitudinal direction is shown in Fig. 15.

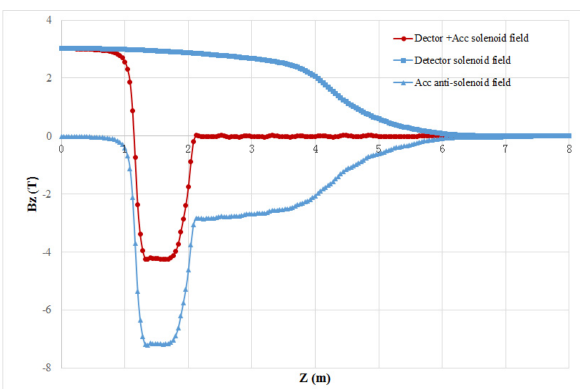

Figure 15: Combined field of Anti-solenoid and Detector solenoid magnet.

The central field of the first section in the anti-solenoid is the strongest, with a peak value of 7.2 T. The combined field distribution of anti-solenoid and Detector solenoid magnet meets the design requirements. Main design parameters of CEPC interaction region anti-solenoids can be found in [1, 7].

Since the field in the last section of anti-solenoid is very low, and to reduce the length of the cryostat, the last section of anti-solenoid will be operated at room-temperature. The superconducting QD0, QF1, and anti-solenoid coils (except the last section) at each side of interaction point are in the same cryostat, and the layout is shown in Fig. 16.

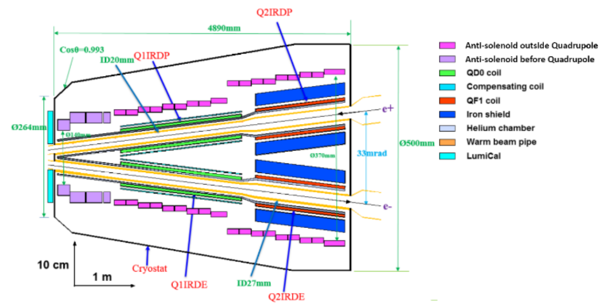

Figure 16: Layout of QD0, QF1, and anti-solenoid.

Preliminary combined field simulation of the Anti-solenoid and Detector solenoid magnet is performed to obtain the force of the Anti-solenoid [Fig. 17].

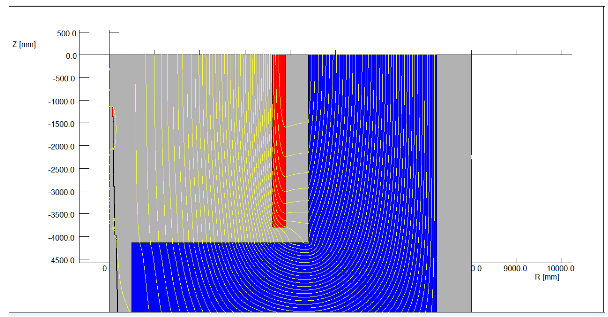

Figure 17: Combined field simulation of Anti-solenoid and Detector solenoid magnet.

QD0 Design Option with Iron Yoke An alternative design option for QD0 with iron yoke is under investigated. Field cross talk of the two apertures in QD0 is studied in OPERA-2D. Figure 18 shows an example of flux lines in the QD0 two aperture with iron yoke, in which the distance between the two aperture is the nearest and the field cross-talk is the most serious. The field calculation results show that, even the size of iron yoke is very limited, it 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 the case of Fig. 18. In other cases where the distance between the two apertures becomes larger, the field harmonics will also be smaller. So 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.

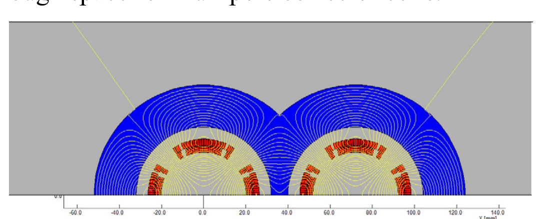

Figure 18: QD0 design option with iron yoke.

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Superconducting Sextupole Magnet

The superconducting sextupole magnets have an iron yoke around the coils 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.

The cross section of sextupole magnets is optimized using OPERA-2D. Only one quarter of cross section is modelled. After field optimization, the sextupole coil consists of two coil blocks in two layers, and there are 33 turns in each pole. The field quality in the good field region is very good. The magnetic flux lines and magnetic flux density distribution for type HSIRU sextupole magnet at Higgs operation are show in Fig. 19 and Fig. 20, respectively.

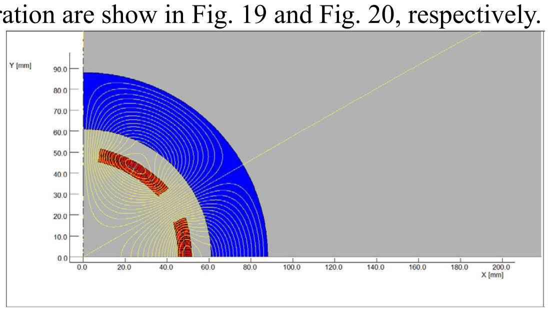

Figure 19: 2D flux lines of sextupole magnet (One quarter cross section).

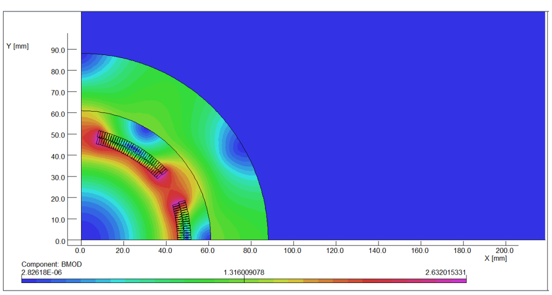

Figure 20: Magnetic flux density distribution.

The calculated relative multipole field contents are all smaller than 1×10^{-4}, and main design parameters of four type superconducting sextupole magnets at Higgs operation are reported in [1].

R&D PLAN

Prior to the construction of CEPC, there will be a five-year R&D period (2018-2022). During this period, prototypes of key technical components will be built.

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 combined function magnet including QD0, QF1 and anti-solenoids.

6) Development of the long cryostat for the combined function superconducting magnet.

7) Development of magnetic field measurement system for small aperture long superconducting magnet.

8) Development of quench protection system for combined function superconducting magnet.

9) Cryogenic test and field measurement of the small aperture long superconducting magnet.

CONCLUSION

Superconducting magnets in interaction region are key devices for CEPC. Conceptual design of superconducting magnets in CEPC interaction region has been finished. Field crosstalk 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 7.2T. Prototypes superconducting magnets in CEPC interaction region are proposed, and the R&D has started.

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