STATUS OF INTERACTION REGION MAGNETS FOR CEPC*

Chuang Shen[1,2], Yingshun Zhu[†,1,2], Xiangchen Yang[1], Ran Liang[1], Fusan Chen[1,2], Wei Zou[3],
Yi Wan[3], Xinlian Wu[3]
[1] Key Laboratory of Particle Acceleration Physics and Technology,
Institute of High Energy Physics, Chinese Academy of Science, Beijing, China
[2] University of Chinese Academy of Sciences, Beijing, China
[3] Hefei Keye Electrical Physical Equipment Manufacturing Co., Ltd, Hefei, China

Abstract

High gradient quadrupole magnets are required on both sides of the interaction points in the proposed Circular Electron Positron Collider (CEPC). There are three double aperture superconducting quadrupoles with a crossing angle between two aperture centerlines of 33 mrad. It is challenging to meet stringent design requirements, including limited space, magnetic field crosstalk between two apertures, magnetic field gradients up to 142 T/m, etc. In this paper, status of superconducting magnets in CEPC interaction region in the technical design stage is described. Magnetic design of superconducting quadrupole magnet with three kinds of quadrupole coil structures, including cos2θ coil, CCT coil, and Serpentine coil is presented and compared. In addition, the development status of a single aperture short model quadrupole magnet with a magnetic length of 0.5 m is presented.

INTRODUCTION

To further study Higgs particles, Chinese physicists put forward a plan to build a Circular Electron Positron Collider (CEPC). Since the publication of CEPC conceptual design report (CDR) in 2018 [1], related research is going on. To pursue higher collision luminosity, accelerator physicists proposed a CEPC technical design report (TDR) based on the CEPC CDR study [2]. The superconducting quadrupole magnet QD0 is divided into two superconducting quadrupole magnets Q1a and Q1b. As shown in Fig. 1, compact high gradient quadrupole Q1a, Q1b and Q2 are required on both sides of the collision points. Q1a, Q1b and Q2 are double aperture quadrupoles and are operated fully inside the solenoid field of the detector magnet which has a central field of 3.0 T. To minimize the effect of the longitudinal solenoid field on the accelerator beam, anti-solenoids before Q1a and compensating solenoid outside Q1a, Q1b and Q2 are needed [3]. 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 Q1a, Q1b and Q2 magnet aperture be close to zero.

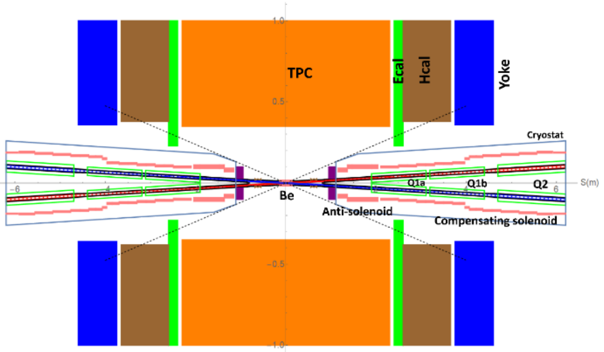

Figure 1: Layout of CEPC TDR interaction region (TPC = Time Projection Chamber, Ecal = Electromagnetic Calorimeter, Hcal = Hadronic Calorimeter, Be = beam tube near the IP. The dotted line refers to the included angle of the outer contour of cryostat).

SUPERCONDUCTING MAGNET ELECTROMAGNETIC DESIGN

Quadrupole Magnet Q1a Design

The first double-aperture quadrupole magnet Q1a was moved forward to a position 1.9 m from the interaction point (IP). The minimum distance between two aperture centerlines is only 62.71 mm, so a very limited radial space is available. The gradient of superconducting magnet Q1a is required to be 142 T/m, and the magnetic length is 1.21 m. The magnetic field harmonics in the good field region are required to be less than 5×10^{-4}. The field crosstalk of the two apertures in Q1a with such a small aperture separation distance is serious, and the dipole field at the center of each aperture is required to be less than 3 mT. The design requirements of the double aperture superconducting quadrupole magnet Q1a are listed in Table 1.

Table 1: Design requirements of the double aperture superconducting quadrupole magnet Q1a.

Item	Value	Unit
Field gradient	142.3	T/m
Magnetic length	1210	mm
Reference radius	7.46	mm
Minimum distance between two aperture centerlines	62.71	mm
High order field harmonics	$\leq5\times10^{-4}$	
Dipole field at the center of each aperture	≤3	mT

---

*Work supported by the National Natural Science Foundation of China under contract 11875272.
† yszhu@ihep.ac.cn

In the layout of CEPC TDR interaction region, the combined superconducting magnet is placed on a cantilever support, and then goes deep into the Detector. Such a magnet fixing method places strict requirements on the weight of superconducting magnets. It is most desirable to remove all iron yoke and keep only coils, so that the weight of the superconducting magnet can be minimized. Two electromagnetic design schemes are studied, one is a pure coil magnet structure without iron yoke, and the other is a magnet structure with iron yoke outside the coil.

Cos2θ Quadrupole Coil

In the cos2θ quadrupole coil, Rutherford cable made of 0.5 mm NbTi strand is used. The establishment of the 2D model and the magnetic field calculation are performed by ROXIE [4]. The design of magnet Q1a is based on two-layer cos2θ quadrupole coil and the two blocks in each layer are separated by wedge. The Rutherford cable with a trapezoidal angle of 2.1 degrees is twisted by 10 NbTi strands. The two-dimensional simulation model of the single-aperture model Q1a is shown in Fig. 2. The inner and outer radius of the coil are 20 mm and 25.65 mm, and the distance between the two layers is 0.35mm. The design current in Rutherford cable is 2650 pA and the peak field in coil is 3.572 T.

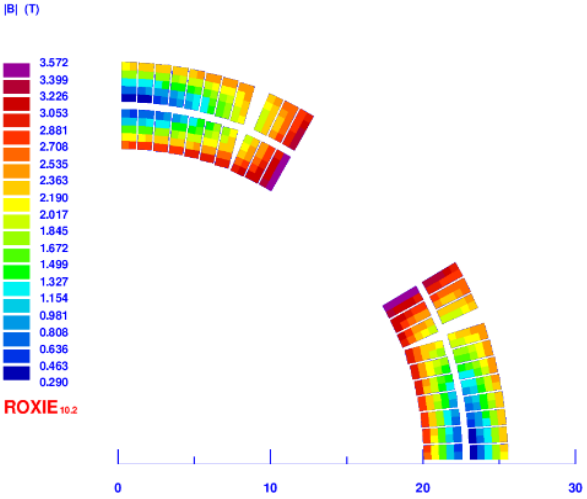

Figure 2: Layout of 2D cos2θ quadrupole coils without iron yoke.

As shown in Fig. 3, under the condition that the coil layout is unchanged, the iron yoke made of FeCoV is added outside the coil to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk. The inner and outer radius of the iron yoke are 30.5 mm and 44 mm. After adding the iron yoke, the exciting current in Rutherford cable is 2020 A and the peak field in coil is 3.413 T.

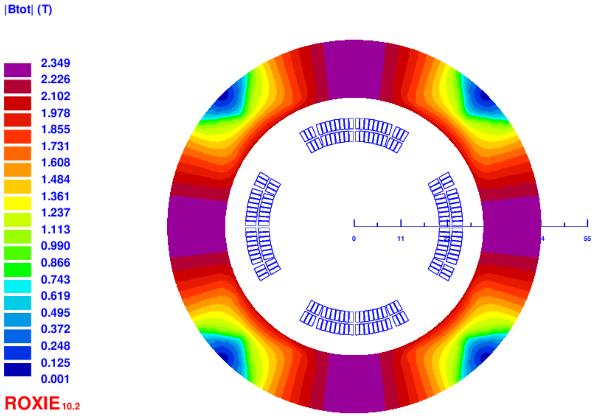

Figure 3: Layout of 2D cos2θ quadrupole coils with iron yoke.

CCT Quadrupole Coil

In CCT quadrupole coil option, the coil is wound by 10 NbTi strands in the form of 2×5, and the diameter of a single NbTi strand is 0.5 mm. In order to save the calculation time in 3D, the model is simplified, and one rectangular conductor is used instead of 10 strands. The cross-sectional size of the coil is 1 mm × 2.5 mm, and the electrical characteristic parameter is the average effect of 10 strands on the cross-section [5]. The inner radius of first layer coil is 22 mm and the inner radius of second layer coil is 25.5 mm. The single-aperture magnet consists of two layers of coils and its OPERA coil simulation results is shown in Fig. 4 [8]. The design current in each strand is 472.5 A and the peak field in the coil is 4.25 T.

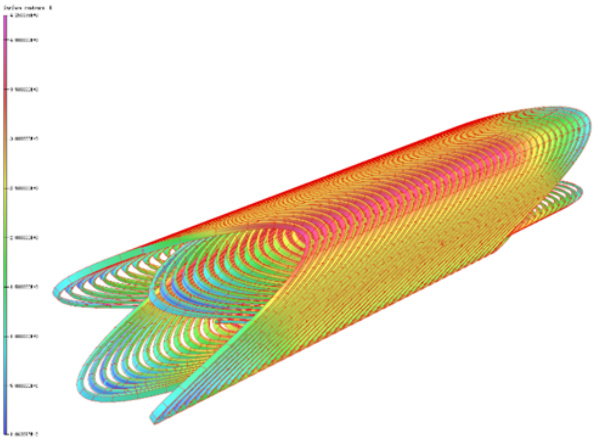

Figure 4: Simulation model of CCT quadrupole coil without iron yoke.

As shown in Fig. 5, the iron yoke made of FeCoV is added outside the coil. The inner radius and outer radius of the iron yoke are 30.5 mm and 44 mm, respectively. The exciting current in each strand drops to 324 A and the peak field in the coil is 3.783 T.

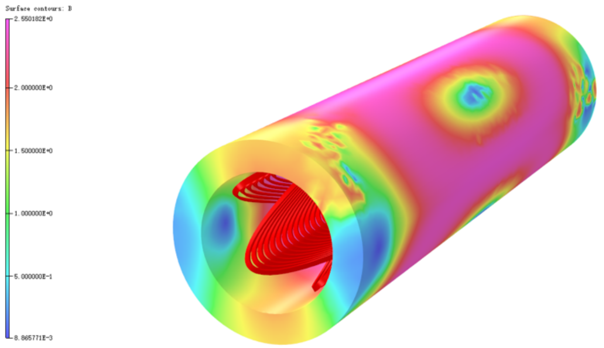

Figure 5: Simulation model of CCT coil with iron yoke.

Serpentine Quadrupole Coil

The serpentine quadrupole coil consists of eight layers of coils. The coil is directly wound by superconducting NbTi strands with a diameter of 0.5 mm [7]. The coil section arrangement is shown in Fig. 6. The design current in each strand is 480 A and the peak field in the coil is 4.2 T.

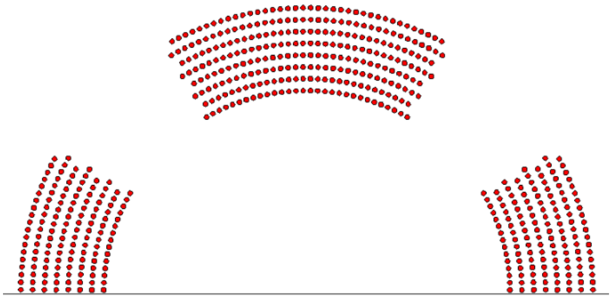

Figure 6: Layout of serpentine coil without iron yoke.

As shown in Fig. 7, the iron yoke made of FeCoV is added outside the coil. The inner radius and outer radius of the iron yoke are 30.5 mm and 44 mm. The exciting current in each strand drops to 334 A and the peak field in the coil is 3.8 T.

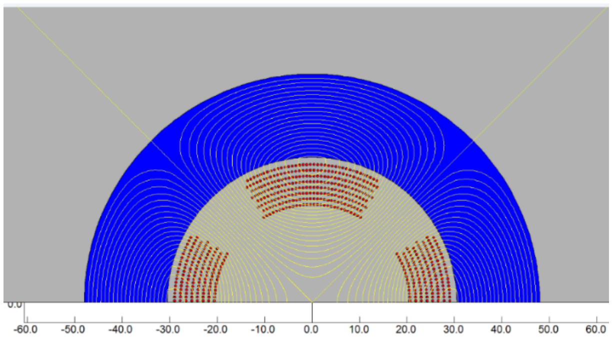

Figure 7: Layout of serpentine coil with iron yoke.

Table 2 lists the key performance parameters of the three coils. Based on the physical requirements of Q1a, all three coil structures were designed using 0.5 mm diameter NbTi strand. Under the same physical requirements, the operation current in the strand of cos2θ quadrupole coil is the smallest and the peak field in the cos2θ coil is the smallest. Therefore, cos2θ quadrupole coil is used as the baseline scheme of superconducting quadrupole magnet in CEPC interaction region, while racetrack coil and CCT coil are two alternative schemes.

Table 2: Electromagnetic performance comparison of three kinds of quadrupole coils

Coil type	**Cos2θ coil**	**CCT coil**	**Serpentine coil**
Gradient (T/m)	142.17	142.75	142.5
I_strand (A)	265	472.5	480
Peak field in coil (T)	3.572	4.251	4.2
After adding FeCoV iron yoke outside coil:			
Gradient (T/m)	142.4	140.8	142.3
I_strand (A)	202	324	334
Peak field in coil (T)	3.413	3.783	3.8

Crosstalk Between Two Apertures

Two single aperture quadrupole magnets are distributed at an angle of 33 mrad, 1.9 meters away from the interaction point. The field crosstalk between the two apertures will introduce a dipole field at the center of each aperture, which is far greater than 3 mT, reaching about 100 mT. The dipole field at the center of the aperture along the longitudinal direction is shown in Fig. 8. Not only cos2θ quadrupole coil has cross talk problems, but also CCT quadrupole coil and serpentine quadrupole coil have similar situation.

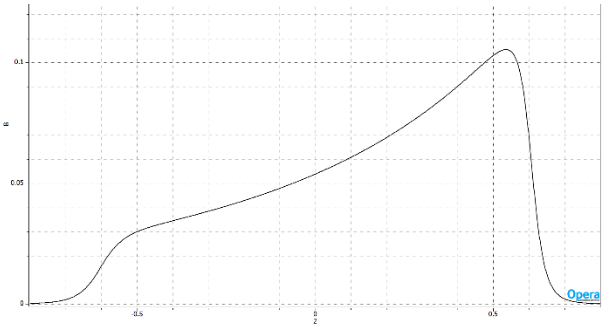

Figure 8: Dipole field along the centerline of each aperture in 3D calculation.

Therefore, in our baseline design, iron yoke is added outside the coil to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk. The two apertures of Q1a magnet are designed according to the same polarity, magnetic field gradient and field quality requirements in each aperture. There is not enough space to place two single apertures side by side, so a compact double aperture magnet design is adopted in Fig. 9. The two single apertures intersect in the middle part and the iron yoke made of FeCoV is shared by the two apertures. At the end closed to IP of magnet Q1a, the maximum dipole field at the center of each aperture is 2 mT, which meets the design requirement.

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAT0204

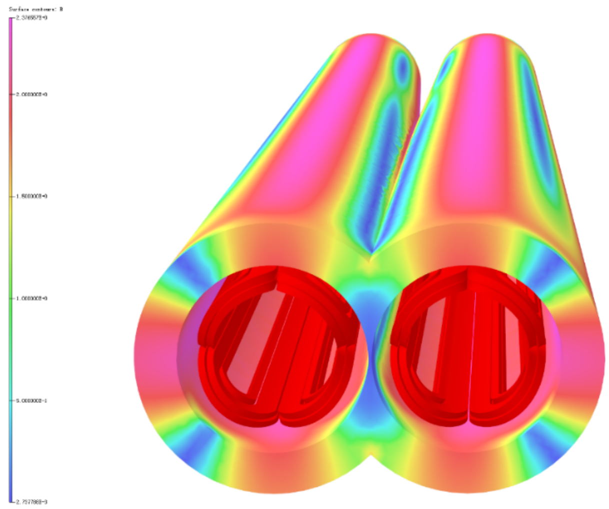

Figure 9: Simulation model of double aperture magnet Q1a.

The important design parameters including the mechanical size parameters, the electromagnetic parameters and the force analysis of the double aperture magnet Q1a are listed in Table 3.

Table 3: Electromagnetic design results of the double aperture superconducting quadrupole magnet Q1a

Magnet name	Q1a-double aperture
Field gradient (T/m)	142.41
Magnetic length (m)	1211.80
Coil turns per pole	21
Excitation current (A）	2020
Coil layers	2
Conductor	Rutherford Cable, width 2.5 mm, mid thickness 0.93 mm, keystone angle 2.1 deg, Cu:Sc=1.3, 10 strands
Maximum dipole field at the center of each aperture (mT)	2.497
Stored energy (KJ) (double aperture)	11.5
Inductance (mH）	5.64
Peak field in coil (T)	3.413
Load line	78.79%
Integrated field harmonics	b_6 = -0.61 b_{10} = -0.24
Coil inner diameter (mm)	40
Coil outer diameter (mm)	51.3
Yoke outer diameter (mm)	88
X direction Lorentz force/octant (kN)	62.33
Y direction Lorentz force/octant (kN)	-58.59
Net weight (kg)	93

Quadrupole Magnet Q1b Design

The double-aperture quadrupole magnet Q1b was moved forward to a position 3.19 m from the interaction point (IP). The minimum distance between the centerlines of two apertures is 105.28 mm. The gradient of superconducting magnet Q1b is required to be 85.4 T/m, and the magnetic length is 1.21 m. The magnetic field harmonics in the good field region are required to be less than 5×10^{-4}. The dipole field at the center of each aperture is required to be less than 3 mT. The design requirements of the double aperture superconducting quadrupole magnet Q1b are list in Table 4.

Table 4: Design requirements of the double aperture superconducting quadrupole magnet Q1b

Item	Value	Unit
Field gradient	85.4	T/m
Magnetic length	1210	mm
Reference radius	9.085	mm
Minimum distance between two aperture centerlines	105.28	mm
High order field harmonics	$\leq5\times10^{-4}$	
Dipole field at the center of each aperture	≤3	mT

In the cos2θ quadrupole coil structure, Rutherford cable made of 0.5 mm NbTi strand is used. The baseline design of magnet Q1b is based on two-layer cos2θ quadrupole coil. The first layer coil consists of one block and the two blocks of second layer are separated by wedge. The Rutherford cable with a trapezoidal angle of 1.9 degrees is twisted by 12 NbTi strands. The two-dimensional simulation model of the single-aperture model Q1b is shown in Fig. 10. The inner and outer radius of the coil are 26 mm and 32.15 mm, and the distance between the two layers is 0.35 mm. The design current of Rutherford cable is 1590 A and the peak field in coil is 2.675 T. The iron yoke made of FeCoV is added outside the collar to enhance the field gradient, reduce the coil excitation current and shield the field crosstalk. The inner and outer radius of iron yoke are 39 mm and 51.7 mm.

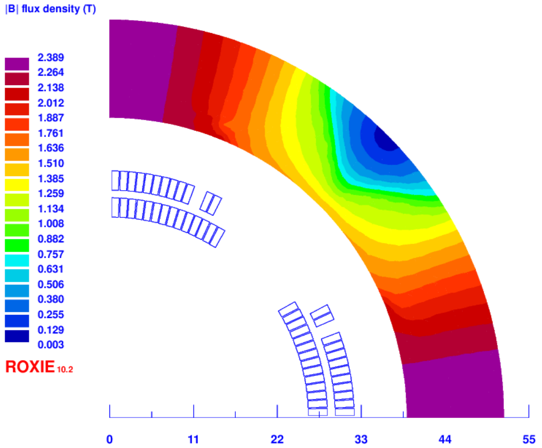

Figure 10: Layout of Q1b cos2θ quadrupole coils with iron yoke.

As shown in Fig. 11, the two apertures of Q1b magnet are designed according to the same polarity, magnetic field gradient and field quality requirements in each aperture. The minimum distance between the two apertures of the superconducting magnet Q1b is 105.28 mm, while the outer radius of the iron yoke is 51.7 mm, so the coils of two apertures do not need to share the iron yoke like Q1a. The maximum dipole magnetic field at the center of each aperture is 2.3 mT.

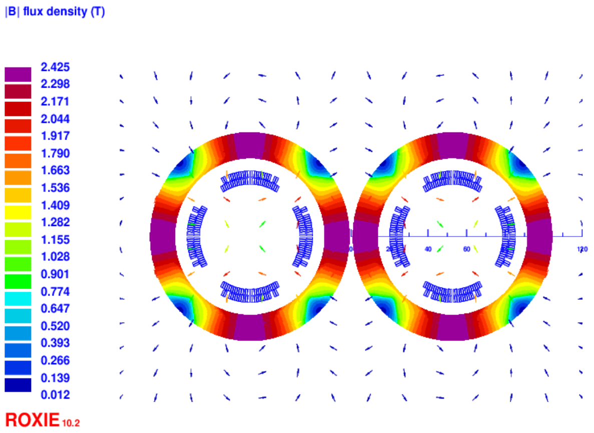

Figure 11: 2D layout of double aperture magnet Q1b near IP side.

The important design parameters including the mechanical size parameters, the electromagnetic parameters and the force analysis of the double aperture magnet Q1b are listed in Table 5.

Table 5: Electromagnetic design results of the double aperture superconducting quadrupole magnet Q1b

Magnet name	**Q1b-double aperture**
Field gradient (T/m)	85.5
Magnetic length (m)	1211.84
Coil turns per pole	26
Excitation current (A)	1590
Coil layers	2
Conductor	Rutherford Cable, width 3 mm, mid thickness 0.93 mm, keystone angle 1.9 deg, Cu:Sc=1.3, 12 strands
Maximum dipole field at the center of each aperture (mT)	2.301
Stored energy (KJ) (double aperture)	11.03
Inductance (mH)	8.75
Peak field in coil (T)	2.675
Load line	55.93%
Integrated field harmonics	$b_6 = 0.25$ $b_{10} = -0.14$
Coil inner diameter (mm)	52
Coil outer diameter (mm)	64.3
Yoke outer diameter (mm)	104
X direction Lorentz force/octant (kN)	45.86
Y direction Lorentz force/octant (kN)	-44.69
Net weight (kg)	124

Quadrupole Magnet Q2 Design

The double-aperture quadrupole magnet Q2 was moved forward to a position 4.7 m from the interaction point (IP). The minimum distance between two aperture centerlines is 155.11 mm. The gradient of superconducting magnet Q2 is required to be 96.7 T/m and the magnetic length is 1.5 m. The magnetic field harmonics in the good field region are required to be less than 5×10^{-4}. Considering the field crosstalk of the two apertures, the dipole field at the center of each aperture is required to be less than 3 mT. The design requirements of the double aperture superconducting quadrupole magnet Q2 are list in Table 6.

Table 6: Design requirements of the double aperture superconducting quadrupole magnet Q2

Item	**Value**	**Unit**
Field gradient	96.7	T/m
Magnetic length	1500	mm
Reference radius	12.24	mm
Minimum distance between two aperture centerlines	155.11	mm
High order field harmonics	$\leq5\times10^{-4}$	
Dipole field at the center of each aperture	≤3	mT

In the cos2θ quadrupole coil structure, Rutherford cable made of 0.5 mm NbTi strand is used. The design of magnet Q2 is based on two-layer cos2θ quadrupole coil. Each layer of coil has only one block. The Rutherford cable with a trapezoidal angle of 1.9 degrees is twisted by 12 NbTi strands. The two-dimensional simulation model of the single-aperture model Q2 is shown in Fig. 12. The inner and outer radius of the coil are 31 mm and 37.65 mm, and the distance between the two layers is 0.35mm. The design current in Rutherford cable is 1925 A and the peak field in coil is 3.656 T. The iron yoke made of FeCoV is added outside the collar to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk. The inner radius and outer radius of iron yoke are 44 mm and 63.2 mm.

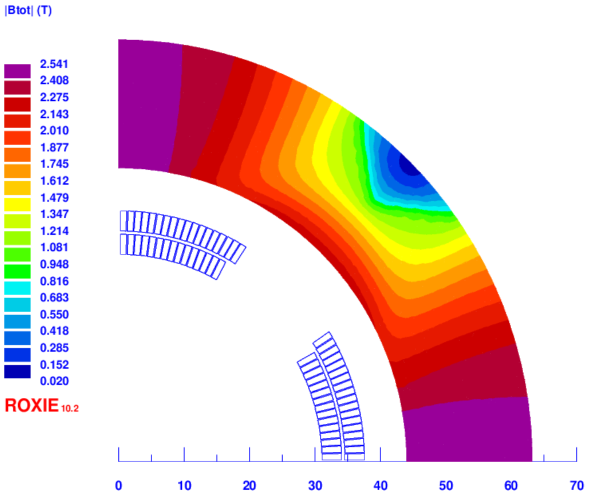

Figure 12: Layout of Q2 cos2θ quadrupole coil with iron yoke.

As shown in Fig. 13, the two apertures of Q2 magnet are designed according to the same polarity, magnetic field gradient and field quality requirements in each aperture. The minimum distance between the two apertures of the

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAT0204

superconducting magnet Q2 is 155.11mm, while the outer radius of the iron yoke is 63.2 mm, so the coils of two apertures do not need to share the iron yoke. The maximum dipole field at the center of each aperture is 2.54 mT.

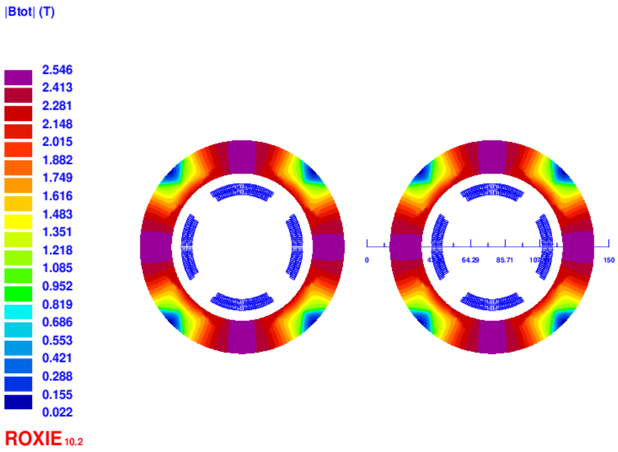

Figure 13: 2D Layout of double aperture magnet Q1b near IP side.

The important design parameters including the mechanical size parameters, the electromagnetic parameters and the force analysis of the double aperture magnet Q1b are listed in Table 7.

Table 7: Electromagnetic design results of the double aperture superconducting quadrupole magnet Q2

Magnet name	Q2-double aperture
Field gradient (T/m)	97.7
Magnetic length (m)	1502.08
Coil turns per pole	33
Excitation current (A)	1925
Coil layers	2
Conductor	Rutherford Cable, width 3 mm, mid thickness 0.93 mm, keystone angle 1.9 deg, Cu:Sc=1.3, 12 strands
Maximum dipole field at the center of each aperture (mT)	2.5401
Stored energy (KJ) (double aperture)	33.28
Inductance (mH)	18.19
Peak field in coil (T)	3.656
Load line	72.05 %
Integrated field harmonics	b_6 = -0.52 b_{10} = -0.49
Coil inner diameter (mm)	62
Coil outer diameter (mm)	75.30
Yoke outer diameter (mm)	126.4
X direction Lorentz force/octant (kN)	126.94
Y direction Lorentz force/octant (kN)	-112.68
Net weight (kg)	235

Anti-solenoid Design

The design of anti-solenoid is basically the same as in CDR [1]. The anti-solenoid is divided into a total of 29 sections with different inner coil diameters. The central field of the first section anti-solenoid is the strongest, with a peak value of 6.8 T. The net solenoid field inside quadrupole at each longitudinal position is smaller than 300 Gs [9]. As shown in Fig. 14, the total integral solenoid field generated by the detector solenoid and anti- solenoid coils is zero.

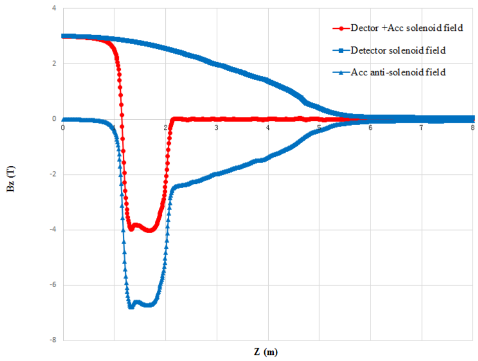

Figure 14: Magnetic field distribution of solenoid field.

Status of 0.5 m Single Aperture Short Model Quadrupole

In the R&D, the first step is to study and master main key technologies of superconducting quadrupole magnet by developing a short model magnet with 0.5 m length (near IP side). Research on main key technologies of 0.5 m single aperture quadrupole model has started (NbTi, 136 T/m), in collaboration with HeFei KEYE Company, including quadrupole coil winding technology, fabrication of quadrupole coil with small diameter, stress control, quadrupole magnet assembly, cryogenics vertical test and field measurement technology, etc.

Manufacture of 0.5 m single aperture short model quadrupole has been completed in HeFei KEYE in August 2022. Then, the magnet has been transported to IHEP. Rotating coil magnetic field measurement has been done with 4 A current at room temperature. Cryogenic excitation test at 4.2 K in the vertical Dewar will be performed in future, to verify whether high magnetic field gradient can be achieved.

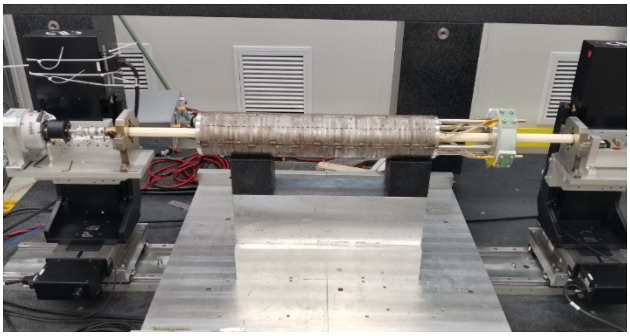

Figure 15: 0.5 m single aperture short model magnet.

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEZAT0204

CONCLUSION

Superconducting magnets in interaction region are key devices for CEPC. Despite of limited space and high field gradient, field crosstalk effect between two apertures is negligible using iron yoke. According to the physical design requirements of double aperture superconducting magnet Q1a, the electromagnetic design of three alternative coil schemes is completed. Under the condition that the superconducting strands are identical, the electromagnetic performances of cos2θ coil, CCT coil and serpentine coil are compared. From the comparison results, cos2θ quadrupole coil has a lower excitation current and a smaller peak field in the coil. Therefore, the superconducting quadrupole magnets in CEPC TDR interaction region adopt cos2θ coil with iron yoke as the baseline. The high-order field harmonics in superconducting quadrupole magnets Q1a, Q1b and Q2 are less than 5×10^{-4}. The calculated dipole field at the center of the aperture is less than 3 mT. Manufacture of 0.5 m single aperture short model quadrupole has been completed, and cryogenic excitation test will be performed in the future.

REFERENCES

[1] The CEPC Study Group, "CEPC Conceptual Design Report: Voume 1 - Accelerator," *arxiv:1809.00285*, 2018. doi:10.48550/arxiv.1809.00285

[2] Gao Jie, “CEPC and SppC Status—From the completion of CDR towards TDR,” *Int. J. Mod. Phys. A*, vol. 36, no. 22, p. 2142005, 2021. doi:10.1142/S0217751X21420057

[3] C. Shen, Y. Zhu, and F. Chen, "Design and Optimization of the Superconducting Quadrupole Magnet Q1a in CEPC Interaction Region", *IEEE Trans. Appl. Supercond.*, vol. 30, no. 6, p. 4004804, 2022. doi:10.1109/TASC.2022.3163684

[4] B. Auchmann, "ROXIE 10.2," 2010. https://espace.cern.ch/roxie/Lists/New%20in%20Version%2010/AllItems.aspx

[5] S. Caspi *et al.*, "Canted–Cosine–Theta Magnet (CCT) - A Concept for High Field Accelerator Magnets," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, p. 4001804, 2014. doi:10.1109/TASC.2013.2284722

[6] W. Wu *et al.*, "Multipole magnets for the HIAF fragment separator using the Canted-Cosine-Theta (CCT) geometry," *Journal of Physics: Conference Series*, vol. 1401, no. 1, p. 012015, 2020. doi:10.1088/1742-6596/1401/1/012015

[7] B. Parker and J. Escallier, "Serpentine Coil Topology for BNL Direct Wind Superconducting Magnets," in *Proc. of PAC’05*, pp. 737-739, 2005. doi:10.1109/PAC.2005.1590546

[8] Dassault systems, "Opera 2020," 2020. https://www.3ds.com/products-services/simulia/products/opera/

[9] Y. Zhu *et al.*, “Final Focus Superconducting Magnets for CEPC,” *IEEE Trans. Appl. Supercond.*, vol. 30, no. 4, p. 4002105, 2020. doi:10.1109/TASC.2020.2973110