Harmonic Suppression Study on Twin Aperture CCT Type Superconducting Quadrupole for CEPC Interaction Region

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Abstract—Iron-free twin-aperture superconducting quadrupole in the interaction region is a key technology to increase the luminosity of high-energy future colliders, such as the circular electron-positron collider that China will build in the next ten years with a center-of-mass energy of 240 GeV and a small crossing angle of 33 mrad in the interaction region. The final focusing quadrupole QD0, which is 2.2 m away from the interaction point, only has a 72 mm beam separation distance at the front end of the magnet. Because of the tight space, canted cosine theta coil type is the best selection, where the coil can be wound directly on the coil former in a fixed inclination angle. For QD0, the superconducting quadrupole coils for the two apertures are nearly in contact; high-order harmonics will be produced by magnetic field crosstalk and should be canceled out at the design stage. This article will present the design study for a pair of 400 mm long QD0 prototype, where we deliberately introduce some opposite harmonics to optimize the coil configuration so as to cancel out the unwanted harmonics.

Index Terms—Coil former, field crosstalk, harmonic correction, twin aperture canted cosine theta (CCT) quadrupole magnet.

I. INTRODUCTION

A HIGH-ENERGY physics goal of the circular electron-positron collider (CEPC) is to provide $e^+e^-$ collisions at a beam energy of 120 GeV and to attain a luminosity of $3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ when operated in the Higgs mode; it can also run at the low energy as 80 or 45.5 GeV when operated in the W and Z modes [1]. At the present design, all the CEPC storage ring, booster ring, and the future superconducting RF cavities. In order to achieve the high luminosity, it requires multibunches, high-beam current, the small beam size and small crossing angle at IPs to realize the near head to head collision.

Fig. 1 shows the central part of the detector, where the horizontal crossing angle for the incoming electron and positron beams is only 33 mrad. The lattice design requires the first focusing quadrupole QD0 starts 2.2 m away from IP and has a length of 2.0 m, which gives very tight space to allow the quadrupole coils. A reliable solution is to build the quadrupoles in a twin-aperture pattern, where the space between the two beam pipes can be fully used.

Since the superconducting coils in each aperture are nearly in contact, it will give rise up to a strong crosstalk and should be reduced to an acceptable level. As shown in Fig. 1, QD0 and QF1 are all twin aperture quadrupoles, they are operated in the detector solenoidal field of 3.0 T.D. Similar as BEPCII [2], [3], a series of antisolenoids and shield solenoids are needed before QD0 and surrounding QD0 and QF1 to reduce the coupling effect that is coming from the particle detector.

In recent years, with the improvement of CNC lathe and 3-D printing technology, canted cosine theta (CCT) type coil that was proposed in the 1970s [4], are mentioned again in many laboratories and try to find applications in particle accelerator [4]–[7]. The advantages of using CCT coils include the following.

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1) CCT coils can reach an excellent integral field quality. A pure dipole or quadrupole field can be produced when the CCT coils are wound according to the standard spatial function, without special adjustments at the coil end.

2) Simplicity in engineering design. Compared with the superconducting magnet by using Rutherford cable, CCT magnet can operate at low current and low-electromagnetic force, no coil collars are needed. The CCT coils are embedded inside the premachined slots on the coil former, and the superconducting wires can withstand the electromagnetic forces just by epoxy impregnation.

3) An important application is that the CCT coils can also be designed with the combination of the several function magnets [8] or can be used for harmonic correction [9].

The disadvantage of using the CCT coil lies in: one CCT coil layer will produce a chosen multipole field plus an extra solenoid field, which needs an extra coil layer to cancel out the solenoid field and add up the wanted magnetic field. Compared with the conventional cosine theta coil design, it needs a more superconducting conductor.

Because the separation distance at the front part of the QD0 magnet is only 72 mm, the first 400 mm long coils can take only one double layer. Going from 2.6 to 4.2 m, when the beam separation space increasing, CCT coil in each aperture can take two double layers, so the total integral field can meet the physics requirements. This article will present the field calculation for the two 400 mm long CCT quadrupole coils, to study the coil design, field crosstalk, and harmonic suppression method.

II. COIL DESIGN FOR SINGLE APERTURE CCT QUADRUPOLE

If a single wire goes along the spatial function as (1), a pure quadrupole field plus a solenoid field can be produced. Here \( R \) is the mean radius of the coil, \( \theta \) is the space angle for each turn, \( \omega \) is the coil twist pitch, and \( \alpha \) is the coil inclination angle with respect to the coil axis. In order to produce a pure quadrupole field, we should put another layer with opposite current direction to the vicinity of QF0 will be revised when the total heat load calculation to that section of the beam pipe is finalized.

In 2-D space, the magnetic field inside the quadrupole aperture can be written as (2) [3]. Here \( a_n \) and \( b_n \) are, respectively, the shew and normal components, they are usually normalized with fundamental field \( B_2 \), with \( B_2 = \sqrt{a_2^2 + b_2^2} \); and expressed in units (one unit = \( 1 \times 10^{-4} \)). For the quadrupole field, we expected the scale of the high-order harmonics (from \( n = 3 \) to \( n = 10 \)) less than 10 units, here the dominant quadrupole field \( B_2 \) is set to 1 = 10 000 units. \( R_0 \) is the reference radius, and normally it is the two-third inner radius of the beam pipe. The fundamental and high-order harmonics in each cross section can be calculated by the fast Fourier transform (FFT). For a 3-D field, harmonic for each \( n \) order can be calculated by summing up the corresponding value in every cross section along the beamline and then normalized to the fundamental quadrupole \( B_2 \).

\[
B_x + iB_y = 10^{-4} B_2 \sum_{n=1}^{\infty} (a_n + ib_n) \left( \frac{x + iy}{R_0} \right)^{-n-1}.
\]

In order to wind the coil more easily, total eight NbTi wires with a diameter of 0.82 mm are previously bound up in a \( 2 \times 4 \) shape by a plastic mold, and gradually put each section into the machined slots on the coil former. The eight wires are connected in series at the end of the coil former. Table I illustrates the parameters for the 400 mm CCT quadrupole prototype.

| Symbol                                      | Unit   | Value   |
|---------------------------------------------|--------|---------|
| wire diameter                               | mm     | 0.825   |
| \( I_c(\text{@}5\text{T}, 4.2\text{K}) \)   | A      | 620     |
| Numbers of turns per slot                   |        | 2×4     |
| Slot size on the coil former                | mm     | 2.1×4.2 |
| Numbers of layers                           |        | 2       |
| Coil frame thickness                        | mm     | 5.2     |
| Canted coil angle                           | degrees| 30      |
| Axial pitch length \( \phi \)              | mm     | 5.2     |
| Design gradient \( G \)                     | T/m    | 67      |
| Beam pipe inner diameter                    | mm     | 40      |
| Inner diameter of the inner layer           | mm     | 46      |
| Inner diameter of the outer layer           | mm     | 58      |
| Peak field on the coil                      | T      | 2.3     |

For the real QF0 magnet, a cold beam pipe will be selected, where on its outer surface, several 2.5 mm in width, 0.4 mm in depth slots are machined to form the liquid helium channels to intercept the heat load from the beam pipe and keep the superconducting coils in liquid Helium temperature [11]. The beam pipe can pull through the first layer of the coil former, the assembly space between the beam pipe and the coil former is 0.1 mm. Similar to [12], connection below at the end of the magnet cryostat and an outer 80 K heat shield that covers the cold mass are used to intercept the heat load from the room temperature environment. The decision of a cold beam pipe in the vicinity of QF0 will be revised when the total heat load calculation to that section of the beam pipe is finalized.

Three 3-D software OPERA-3d [10] is used for the magnetic-field calculation; the cable is handled along with (1) as a cross section of 2×4 mm², and high-order field harmonics are taken out through FFT at the reference radius \( R_0 = 13 \) mm. With the operation current of 600 A in each wire, the calculated field gradient is 67 T/m, which is less than the required field gradient of 130 T/m. As it is only one double layer for the 400 mm prototype, summing up the following two double layers of 1.6 m long, the total integral field strength can meet the physics
requirements. The same idea had been reported in LBNL for an 18 T Hybrid CCT dipole [13].

Fig. 2 shows the coil configuration for the 400 mm CCT prototype. The coil winding direction can be seen clearly at the coil ends. From upper to lower, they are the inner coil layer (operation in a positive direction), the outer coil layer (operation in a negative direction), and a set of CCT coils.

Fig. 3 shows the harmonic distribution along the beamline, and they are already normalized to the quadrupole field at a reference radius of \( R_0 = 13 \) mm. The \( z \)-axis is along the beamline (coordinate starts from the IP, the next few figures are the same), and the \( y \) scale is in the unit.

### Table II

| Symbol | Value  | Unit   |
|--------|--------|--------|
| b3/B2  | -2.45E-06 | -0.025 |
| a3/B2  | 7.14E-06  | 0.071  |
| b4/B2  | 3.01E-05  | 0.30   |
| a4/B2  | 5.26E-06  | 0.053  |
| b5/B2  | -4.72E-05 | -0.47  |
| a5/B2  | -5.17E-06 | -0.052 |

Fig. 4 shows the harmonic distribution for the 400 mm pure quadrupole coil (@ \( R_0 = 13 \) mm). The \( z \)-axis is along the beamline (coordinate starts from the IP, the next few figures are the same), and the \( y \) scale is in the unit.

### III. Harmonic Generated by Field Crosstalk

If we put the two sets of CCT coils in closer, the magnetic field in each aperture will disturb another one and bring high-order harmonics. Fig. 4 shows the two sets of CCT quadrupole coils that are situated at a similar position as that of QD0. It is the model to study the crosstalk and harmonic suppression effects.

### IV. Introduced Opposite Harmonics in the CCT Coils

In order to cancel the newly generated harmonics, several extra \( z \) terms will be deliberately added in (1) and they are shown...
TABLE III
HIGH-ORDER HARMONICS BEFORE AND AFTER HARMONIC SUPPRESSION (UNIT: 10⁻⁴)

|       | AP1 Cross talk | Added harmonics | After correction | AP2 Cross talk | Added harmonics | After correction |
|-------|----------------|-----------------|------------------|----------------|-----------------|-----------------|
| b3    | -186           | 187             | -1.70            | 185            | -187            | 0.32            |
| a3    | 2.14           | ----            | 2.56             | -2.31          | ----            | -2.21           |
| b4    | 50             | -52             | -2.49            | 50             | -46             | 3.59            |
| a4    | -0.86          | ----            | -0.96            | -0.75          | ----            | -0.68           |
| b5    | -12            | 10.8            | -1.56            | 2.69           | ----            | 1.90            |
| a5    | 0.15           | ----            | 0.26             | -0.064         | ----            | -0.086          |
| b6    | 2.65           | ----            | 2.43             | 2.65           | ----            | 2.33            |
| a6    | -0.05          | ----            | -0.034           | 0.056          | ----            | 0.067           |

in (3) [9]. Here $C_m$ and $D_m$ are the cancelation factors, and they are, respectively, used to cancel the $m$ order of normal and skew harmonics.

\[
z = \sum_{m_b} \left( C_m \frac{R \sin (m_b \theta)}{m_b \tan \alpha} \right) + \sum_{m_a} \left( D_m \frac{R \cos (m_a \theta)}{m_a \tan \alpha} \right) \quad \text{(3)}
\]

As we know, when $m \neq n$, \[\int_{0}^{2\pi} \sin (m \theta) \sin (n \theta) d\theta = 0\] or \[\int_{0}^{2\pi} \sin (m \theta) \cos (n \theta) d\theta = 0\], the newly added $m$ order harmonics do not affect the scale of the fundamental quadrupole field and other order harmonics. The new coil configuration can be rebuilt according to (1) and (3). For AP1 CCT coils, we introduce the opposite $b_3$, $b_4$, and $b_5$ values with the same absolute values in the second column in Table III, and do the calculation again as in Fig. 2 for each aperture. The calculated results are shown in the third column, and the newly generated harmonics are almost as we introduced. For comparison, high-order harmonics with less than one unit are not presented in the table. The same method is used for AP2, and the calculated results are presented in the sixth column in Table III.

Figs. 7 and 8 show the harmonic distribution in each aperture after adding the opposite harmonics, respectively.

V. COMBINED FIELD CALCULATION AFTER HARMONICS CORRECTION

The combined field was calculated after putting the modified AP1 and AP2 coils in the same position, as shown in Fig. 4, the purpose is to check the harmonic suppression effects after adding the opposite harmonics in each aperture. Figs. 9 and 10 show the suppressed harmonic distribution in AP1 and AP2, respectively. Comparing with Figs. 5 and 6, the sextupole and octupole scales are greatly reduced. Their corresponding values are presented in the fourth column for AP1 and the seventh column for AP2 in Table III, although the $b_3$ components are still high, they are reduced to an acceptable level. The reason is the crosstalk between the two apertures, and the effects are reduced with the increase of the harmonic order $n$.

As QF0 is an iron-free quadrupole, if we do not care about the persistent current effect, the field harmonics can keep the same values with the increasing current. For a single aperture coil, AP1 or AP2, whatever it is in the room temperature or in 4.2 K state, the scale of the newly added harmonics can be checked by a long rotating coil. On the other hand, when putting the two modified coils in a similar position as that of QD0, their...
The harmonic cancelation effect can be checked out at both room temperature or in the cryogenic state.

VI. CONCLUSION AND PROSPECT

Two sets of 400 mm CCT quadrupole coils are designed to verify the possibility of fabricating a 2.0 m long twin aperture quadrupole for CEPC IR. Since the two sets of the CCT coils are very close, they will bring a strong crosstalk effect. By adding opposite harmonics in each modified coil configuration, the unwanted harmonics can be eventually canceled out in each aperture. In the future, two sets of 400 mm CCT coils will be fabricated and put them in the same relative position as that of QF0, then take the field measurement both at room temperature and at 4.2 K to test the reliability of the coil design and harmonic correction effect. Field-independent property will lead us to design a multifunction CCT magnet, which will save space and reduce the magnet cost.

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