

## Development of Short Prototype Dual-Aperture Quadrupole Magnet for CEPC Ring

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### Abstract

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### Full Text

## Development of a Short Prototype of Dual-Aperture Quadrupole Magnets for CEPC

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## Abstract

Main quadrupole magnets are critical components for the Circular Electron Positron Collider (CEPC) and are specifically designed as dual-aperture quadrupole (DAQ) magnets. However, field crosstalk between the two apertures presents significant challenges. Since the CEPC will operate at four beam energies corresponding to Z, W, Higgs, and  $t\bar{t}$  modes, the DAQ magnets must function across a wide range of field gradients from 3.18 to 12.63 T/m. The first short quadrupole magnet prototype, featuring a bore diameter of 76 mm and magnetic length of 1.0 m, revealed problems with large magnetic field harmonics and magnetic center shifts within the beam energy range. This work proposes a compensation method to address the field crosstalk effect. By adjusting the gap height at the midpoint between the two apertures, both field harmonics and magnetic center shifts are significantly reduced. Following optimization, the short prototype was modified using a new scheme. Field simulations were validated against magnetic measurement results, and the multipole field now meets requirements at all four beam energies. Detailed magnetic field optimization, field harmonics adjustment, and measurement results are presented herein.

**Keywords**— Dual aperture magnets, Field measurements, Crosstalk effect, Quadrupole magnet, Field harmonics, CEPC.

## 1. Introduction

The Circular Electron Positron Collider (CEPC) is a proposed facility for construction in China, primarily serving as a Higgs factory. With a circumference of approximately 100 km, the collider features a double-ring lattice, and more than 80 km of the CEPC tunnel will be occupied by magnets. Because the individual magnetic fields are relatively low, most magnets are designed as iron-dominated devices, which offer an economical and effective means of field shaping. The two rings require numerous dipole, quadrupole, sextupole, and corrector magnets [1-4]. These magnets are sorted and grouped into small batches for production.

Unlike conventional colliders that use single-aperture quadrupole magnets [5-7], the double-ring CEPC requires dipole and quadrupole magnets of similar length and strength. Therefore, a dual-aperture magnet scheme similar to that proposed for FCC-ee [8-10] has been adopted to reduce both magnet count and power consumption, achieving approximately 50% power savings compared to using two separate magnets.

Table 1 lists the main specifications of the dual-aperture quadrupole (DAQ) magnets. The collider operates in Z, W, Higgs, and  $t\bar{t}$  modes, corresponding to beam energies of 45.5, 80, 120, and 180 GeV, respectively. For different operating modes—except in the radio frequency (RF) region—compatible lattices

are obtained by scaling magnetic strength with energy. Consequently, the magnets must cover four different energies and exhibit a large dynamic range. The collider ring contains only two RF cavities [11,12], and significant synchrotron radiation occurs throughout the ring, leading to a corresponding energy sawtooth effect [13,14]. To compensate for this, trim coils are incorporated into the main dipole and quadrupole magnets. These individual trim coils in each aperture adjust the field strength or gradient in one aperture without affecting the magnetic field quality in the other aperture. The trim coils are gradually adjusted at different ring positions relative to their distance from the RF station. Additionally, these trim coils can accommodate dispersion in magnetic field strength between magnets.

The DAQ magnet features opposite polarities in its two apertures: one focusing and one defocusing. Furthermore, the magnet shares two pancake coils that excite both apertures, rather than requiring eight coils as would be needed for two separate quadrupole magnets [15,16]. These special requirements introduce several technical challenges in DAQ magnet design, with the key issue being magnetic crosstalk between the two apertures. The installation of shared coils necessitates dividing the yoke into several parts, adding mechanical complexity. Therefore, careful consideration must be given to magnetic design, mechanical design, fabrication cost, and power consumption.

**Table 1** The basic requirements of CEPC dual-aperture quadrupole (DAQ) magnets

Parameter	Value
Aperture diameter (mm)	76
Field gradient, 45.5 GeV ~ 180 GeV (T/m)	3.18 ~ 12.63
Magnetic length (mm)	1000
Reference radius (mm)	12.2
Multipole field content ( $1 \times 10^{-4}$ )	\$ \$1.5
Adjustment ability	\$ \$0.5%
Central field difference	

Section 2 summarizes the preliminary design and field measurement results of a 1-m-short DAQ magnet prototype. Section 3 describes the magnetic optimization process, including a novel scheme involving center shim adjustment to balance flux line distributions in individual apertures of the DAQ magnet. Different trim coil layouts are compared, and an optimized scheme is selected. Section 4 briefly introduces the modified short prototype. Section 5 describes magnetic center shift adjustment in the horizontal direction, reviews the principle of harmonic adjustment using magic fingers, and presents the final adjustment scheme along with field measurement results. Finally, Section 6 provides conclusions.

## 2. Preliminary Design and Field Measurement of the Short DAQ Magnet Prototype

The distance between electron and positron beams in the CEPC collider is 350 mm, determined by the excitation coil, vacuum chamber, cooling tube, and lead block in the dual-aperture dipole magnet. Quadrupole magnet field gradients range from 3.18 to 12.63 T/m, with a maximum pole-tip magnetic field of 0.48 T at 180 GeV. With approximately 2000 quadrupole magnets required for the CEPC, each 2 m long, several design aspects were considered to reduce construction costs and power consumption.

A laminated prototype was selected to ensure magnet consistency and ease of processing. Hollow aluminum conductors are used for excitation coils to reduce cost and weight. Low current density and high voltage were chosen to minimize power loss in both the magnet and the cables connecting it to the power supply. The preliminary cross-section of the 1-m-short DAQ magnet prototype is shown in Fig. 1 [Figure 1: see original paper]. The iron is divided into several pieces to facilitate coil installation [17]. To reduce magnetic coupling effects, a 50 mm stainless steel plate with a DT4 sheet inserted between them was used to decouple the two apertures. Trim coils were wound on the top and bottom yokes. Yellow lead blocks (Fig. 1) were placed between the poles to protect the excitation coil from synchrotron radiation.

The first short quadrupole magnet prototype was fabricated in 2019 with a bore diameter of 76 mm and length of 1.0 m. Magnetic field simulations of the DAQ magnet were performed using the electromagnetic software OPERA [18]. The 2D simulation in Higgs mode demonstrated that as the DT4 sheet thickness increases,  $b_1$  and  $b_3$  in one aperture increase, with a fixed and unidirectional change ratio of  $b_1$  to  $b_3$ . Using an appropriate DT4 sheet thickness,  $b_1$  and  $b_3$  can be reduced. Preliminary field measurements were conducted using a Hall probe measurement system (Fig. 2 [Figure 2: see original paper]). Results indicated a large and extended leakage field. As current increased from 58 to 234 A—corresponding to beam energies from 45.5 to 180 GeV—the magnetic center shifted. The overall offset of the magnetic center in the horizontal direction ( $X$ -axis) was approximately 1.7 mm and 2 mm in the two apertures, which is unacceptable for accelerator physics. This shift is due to the field crosstalk effect between the two apertures. When excitation current increased, the DT4 sheet in the middle quickly saturated, providing insufficient compensation capability. Additionally, the magnetic field was heavily influenced by the trim coils, which exacerbated the magnetic center shift. Furthermore, magnetic field simulations showed that in the preliminary design, compensation using the DT4 sheet was optimized only for Higgs mode. In other operating modes, the magnetic field harmonics in the two apertures could not satisfy design requirements. Therefore, the short DAQ magnet prototype required further optimization and modification.

In this paper,  $a$  and  $b$  denote the  $2n$ -th skew and normal multipole components,

respectively, normalized to the main quadrupole magnetic field in units of  $10^{-4}$  at the reference radius of 12.2 mm in CEPC quadrupole magnets.

The first quadrupole magnet prototype for FCC-ee exhibited similar problems. In the energy range of 45.5–180 GeV, the measured magnetic center shift in the horizontal direction was approximately 0.4 mm, and the sextupole field component was as large as 57 units in each aperture [19].

**Fig. 1** Preliminary cross-section of the first dual-aperture quadrupole (DAQ) magnet prototype

**Fig. 2** First short DAQ magnet prototype on a Hall probe measurement system

### 3. Optimization of the DAQ Magnet

In a normal-conducting quadrupole magnet, field quality depends primarily on the pole profile and symmetry of the iron yoke [20,21]. While such quadrupole magnets typically exhibit fourfold symmetry, the CEPC DAQ magnet is a type-II quadrupole magnet with figure-of-eight symmetry. Constrained by shared coils, the DAQ magnet has opposite polarities in its two apertures, and the outer yoke must be opened at the midplane, similar to a Collins quadrupole magnet [22]. Because the two apertures share one coil, they exhibit intrinsic magnetic coupling, which mainly affects the dipole and sextupole fields in both apertures.

Three key aspects were considered in the re-optimization of the DAQ magnet: (1) compensation for field crosstalk effects to reduce and stabilize the magnetic center in the horizontal direction across the energy range; (2) minimization of higher-order field harmonics; and (3) placement of trim coils at suitable positions to adjust only the field gradient in their respective aperture without generating additional field harmonics in either aperture.

#### 3.1 Two-Dimensional Optimization of the Quadrupole Magnetic Field

Various approaches were attempted to compensate for field crosstalk effects. The first approach involved increasing the beam separation from 350 to 500 mm, which reduced dipole field components from 2359 to 1624 units—still far from requirements. Moreover, this approach not only failed to completely resolve the problem but also increased magnet volume and power consumption.

The second approach involved adding local shims inside or outside the pole tip; however, this proved ineffective and adversely affected the field in the other aperture. Thus, local shims cannot resolve crosstalk effects between the two apertures.

In multipole magnets, the magnetic pole profile and yoke symmetry determine field quality. Unlike ordinary quadrupole magnets with fourfold symmetry, a single aperture of the DAQ magnet possesses only vertical symmetry in its cross-section. Due to the shared coil, the left and right aperture structures are balanced and symmetrical. However, for a single aperture, the left and right

sides of the yoke are asymmetrical because of the iron core in the other aperture. Therefore, this asymmetry must be counteracted through asymmetric shimming to achieve symmetrical magnetic flux distribution in a single aperture—this is the fundamental principle of compensation.

Two modification options were considered for the DAQ magnet: (a) a single upper or lower core for both apertures, and (b) separate cores for each aperture, as shown in Fig. 3 [Figure 3: see original paper]. The optimization scheme employs a center shim at the horizontal gap to ensure symmetry between the left and right apertures, as depicted in Fig. 4 [Figure 4: see original paper]. The magnetic properties of each DAQ magnet aperture become symmetric when the middle of the yoke protrudes.

Because the shared main coils exhibit properties similar to dipole coils, they generate a large dipole field. Meanwhile, the sextupole field  $b_3$  is a systematic high-order component of the dipole field  $b_1$ ; consequently,  $b_3$  and  $b_1$  are strongly correlated. In the 2D model, the change in  $b_3$  was linearly proportional to that in  $b_1$ , with a ratio of approximately 0.08, which was used to estimate the center shim size. After several iterations, the optimized center shim dimensions were 70 mm in width and 19.8 mm in height, yielding final multipole components of -0.5 units for  $b_1$  and -0.06 units for  $b_3$ .

The second scheme involves decoupling the iron into two yokes separated by a gap. Fig. 3(b) [Figure 3: see original paper] shows the modified cross-section of the DAQ magnet with separate iron cores, where the flux distribution in each aperture is symmetric. The gap between the two iron yokes is 80 mm, and the central yokes are wider than the outer yokes. Different yoke gaps can be optimized independently while considering mechanical properties and saturation effects.

Numerical simulations showed that both schemes met the DAQ magnet field specifications. The entire yoke scheme offers a more stable mechanical structure and lower magnetic saturation. The core structure is significantly simplified if a U-shaped copper-plate coil that can be inserted from one end of the magnet is used [23]. The entire iron core comprises two pieces of lamination—upper and lower halves—facilitating mass production. In contrast, the separated yoke scheme exhibits slightly higher iron saturation, particularly at maximum energy, along with greater mechanical complexity and more potential error sources. Therefore, the entire iron yoke scheme was selected as the baseline for DAQ magnet reconstruction, while the separated iron-core scheme was retained as an alternative.

### 3.2 Trim Coil Layouts

Because many arc quadrupole magnets with identical gradients are distributed throughout such a long collider, it is not economical to power each magnet with a separate power supply. Consequently, several quadrupole magnets are powered in series, resulting in integral field gradient dispersion among them.

Furthermore, with only two RF stations in the ring and very large synchrotron radiation, a substantial energy sawtooth effect occurs along the ring, particularly at high energies. Trim coils are therefore used to compensate for both the sawtooth effect and magnet dispersion, with a maximum field gradient tunability of  $\pm 1.5\%$ .

In iron-dominated magnets, field quality is determined primarily by the pole profile and assembly accuracy, while the magnetic circuit is defined by the magnetic length, iron core layout, and excitation source location.

Three trim coil layouts were analyzed for the DAQ magnet using 2D simulations, as illustrated in Fig. 5 [Figure 5: see original paper]. In the first configuration, trim coils were wound on the top and bottom of the return yokes; the second placed trim coils at the pole root region; and the third positioned them at the pole tip region. The first two layouts contained twice as many turns as the third layout, with four coils in each aperture.

The central aperture region experiences strong synchrotron radiation through which the beam passes. Since excitation coils contain insulation materials that are not resistant to this radiation, the exciting coils should be placed as far from this area as possible. The first trim coil option involves winding on the top and bottom yokes. Magnetic field simulations were performed for all three configurations, with corresponding flux lines plotted in Fig. 5. When only the correction coil of the left aperture is excited, flux lines appear in the right aperture, indicating that the trimming coil affects the field in the opposite aperture and creates a dipole field, as shown in Fig. 5(a). In Fig. 5(b), the trimmer coil is on the left arm, and flux lines penetrate the right aperture. Due to the very high magnetic permeability of iron compared to air, the reluctance in iron is much smaller than that in the central gap, causing flux lines to disperse between the two apertures. However, as depicted in Fig. 5(c), the magnetic circuit loop is almost closed within a single aperture.

In the separated iron yoke scheme, when trim coils are wound on the top and bottom yokes, fewer flux lines appear in the right aperture and the main field is a dipole field, as seen in Fig. 6(a) [Figure 6: see original paper]. This occurs because the gap between the two yokes introduces large magnetic reluctance. However, an extra dipole field still appears in the other aperture. As shown in Fig. 6(b) [Figure 6: see original paper], this configuration performs almost identically to that in Fig. 5(c).

The optimal location for trim coils is on the four poles, which produces minimal effect on field quality in the other aperture. Independent correction power supplies are used for the two apertures. This configuration generates the same flux distribution in the four poles as normal quadrupole magnetic coils. In Figs. 5(c) and 6(b), nearly no flux lines appear in the other aperture, demonstrating the best performance for magnetic gradient fine-tuning. An evident disadvantage of this configuration is the coils' proximity to the aperture region with intense synchrotron radiation, requiring shielding protection for all trim coils.

### 3.3 Three-Dimensional Optimization of the DAQ Magnet

A 3D simulation was performed to obtain the longitudinal dependence of fundamental and higher-harmonic field components. Typically, in long magnets, the magnetic field in the midplane of a 3D model is consistent with that in a 2D model. However, in the DAQ magnet, the shared main coil produces an extended dipole field with significant effects at the quadrupole magnet ends. Furthermore, in this Collins-type quadrupole magnet, fringe fields exist not only at the longitudinal ends but also at the horizontal opening side. Consequently, field harmonics in the 3D model differ from those in the 2D simulation. When the iron length is identical, the effective length of the dipole magnet is greater than that of the quadrupole magnet [24], so the dipole field must be reconsidered in 3D simulation. Additionally, the shim size should be reoptimized based on 3D simulation results, as accelerator physics requires evaluation of the three-dimensional integrated magnetic field quality of quadrupole magnets.

The short prototype was optimized based on the entire iron yoke scheme, with the final 3D model depicted in Fig. 7 [Figure 7: see original paper]. The resulting center shim dimensions were 70 mm in width  $\times$  41 mm in height, differing from the 2D simulation results.

**Fig. 7** 3D magnetic simulation model of the DAQ magnet with trim coils wound on poles

**Fig. 8** [Figure 8: see original paper] Distribution of dipole and quadrupole magnetic fields along the Z-axis @ 180 GeV

As shown in Fig. 8, the quadrupole magnetic field distribution is standard; however, the dipole field rises steeply and persists over a long distance. The DAQ magnet has an effective length of 1.053 m. Table 2 lists the calculated integrated multipole components of the DAQ magnet at different energies. The change in the  $b_3$  component is less than one unit, and multipole fields at different energies are smaller than five units, meeting requirements. The magnetic center on the X-axis varied by only 0.015 mm across the specified energy range. Trim coils wound on the poles had minimal effect on multipole fields.

**Table 2** Multipole field in the right aperture of the DAQ magnet at different energies ( $\times 10^{-4}$ )

n	$b$ @ 45.5 GeV	$b$ @ 120 GeV	$b$ @ 180 GeV
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## 4. Modification of the DAQ Magnet Prototype and Mechanical Measurements

The prototype was modified based on the 3D DAQ magnet simulation. The center stainless steel spacer was replaced with soft iron DT4 incorporating a center shim, as schematically shown in Fig. 9 [Figure 9: see original paper]; other magnet components remained unchanged. The DAQ magnet comprises

two main coils, each with 64 turns. The conductor consists of hollow square aluminum wire with 11 mm side length and a 7 mm diameter cooling hole. Operating currents were 50, 154, and 234 A, corresponding to energies of 45.5, 120, and 180 GeV, respectively.

To install the soft iron DT4 with a center shim, the DAQ magnet had to be disassembled. Because the mechanical structure was not optimally robust, re-assembly precision was poor. Mechanical measurement results in the magnet pole end region are presented in Fig. 10 [Figure 10: see original paper], showing that most gaps between adjacent poles are significantly out of tolerance. In this DAQ magnet, the aperture closest to the busbars is defined as aperture A, and the other as aperture B.

**Fig. 9** Schematic model and drawings of the modified DAQ magnet. Dark blue areas indicate DT4 material. The left aperture is aperture A, and the right aperture is aperture B

**Fig. 10** Adjacent pole gap tolerance of the modified DAQ magnet

## 5. Field Measurement Results

### 5.1 Initial Field Measurements

The modified DAQ magnet was examined using a high-precision rotating coil measurement system based on a coordinate measuring machine (CMM) [25]. A new rotating coil was fabricated using a compensation coil scheme [26-30] that bucks out dipole and quadrupole terms to increase system sensitivity to high-order field harmonics. The coil framework was made of  $\text{Al}_2\text{O}_3$  ceramic, which provides good mechanical stiffness and hardness. The shaft has an outer radius of 20 mm and length of 1.9 m, covering the entire magnetic field region. Fig. 11 [Figure 11: see original paper] shows the modified DAQ magnet prototype mounted on a rotating coil measurement bench.

**Fig. 11** Modified DAQ magnet prototype placed on a rotating coil measurement bench

After three standardization cycles with current ramping from 0 to 234 A and back to 0 A, field measurements were performed. The integral transfer functions of the two apertures are displayed in Fig. 12 [Figure 12: see original paper]. The curve shows approximately 97% excitation efficiency at 234 A, with no significant iron saturation. Transfer functions in the two apertures are very similar, with a maximum difference of about 0.2% at the low current of 20 A. With increasing current, this difference decreased to less than 0.1% at 234 A.

**Fig. 12** Integrated transfer functions in the two apertures

Measured normal and skew multipole field errors for both apertures at different currents are presented in Fig. 13 [Figure 13: see original paper]. Field harmonics were less than  $1 \times 10^{-4}$ , except for the sextupole component. The sextupole component is the first nonsystematic harmonic of the quadrupole

magnet and is easily affected by pole profile errors, gap height deviations, and magnet assembly errors. The magnetic center offset is approximately 0.5 mm in both apertures, and the magnetic center shift across the energy range is about 0.1 mm in aperture A and 0.075 mm in aperture B.

**Fig. 13** Measured field harmonics at different energies in the two apertures of the DAQ magnet

## 5.2 Magnetic Center Reduction

As discussed in Section 3, the field crosstalk effect introduces large  $b_1$  components in both apertures. In the modified DAQ magnet prototype, the center-protruding shim was 70 mm wide and 41 mm high, with a 24 mm gap height between the yoke centers. The second modification involved reducing the upper and lower shim blocks by 1 mm, resulting in a 26 mm gap height between the center yokes.

After adjusting the center gap height to 26 mm, field measurements were repeated, with results listed in Table 3. In Higgs mode, the magnetic center in the X-direction decreased from 0.51 to 0.162 mm in aperture A and from 0.505 to 0.177 mm in aperture B, corresponding to reductions of 0.348 mm and 0.328 mm, respectively. The normal sextupole component  $b_3$  increased by 22.9 units in aperture A and 25.4 units in aperture B. Changes in the magnetic center in the Y-direction were minimal, and skew sextupole components in both apertures remained almost unchanged. The similar  $b_3$  variation in both apertures indicates that adjusting the intermediate pad between the two apertures is largely symmetrical, consistent with simulation results. The ratio of  $b_3$  to  $b_1$  change remained around 0.08.

**Table 3** Magnetic center (mm) and sextupole component (units of  $1 \times 10^{-4}$ ) in the DAQ magnet before and after changing the center shim @ 120 GeV

Parameter	Before	After	Change
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## 5.3 Harmonics Compensation

A harmonics compensation method based on magic fingers was employed to reduce field harmonics. Old copper plates were replaced with stainless steel plates, as depicted in Fig. 14 [Figure 14: see original paper], to ensure pole rigidity and reduce lifting deformation.

**Fig. 14** Connecting plate replacement (top: new stainless steel plate with finger slots; bottom: old copper plate)

Magic finger adjustment technology compensates for high-order nonsystematic harmonics, such as sextupole and octupole components in quadrupole magnets [31]. A magic finger is made of pure solid iron (DT4) with a slender rectangular

shape: 11 mm wide, 8 mm thick, and 38 mm radial length. It fits into slots in the connecting plates at various angles and positions, with its centerline passing through the aperture center. The magic finger is tightly attached to the pole using screws. The desired multipole magnetic field is generated through symmetric and periodic arrangement of several fingers to cancel existing magnetic field harmonics. When the quadrupole magnet is energized, the magic finger installed at the pole becomes magnetized and generates a magnetic field that acts as a local current source. A magic finger generates various high-order components, including both normal and skewed terms, with the proportions differing according to the finger angle. As harmonic order increases, harmonic amplitude decreases. For a quadrupole magnet, the largest multipole field is typically the sextupole component.

**Fig. 15** [Figure 15: see original paper] (a) 3D model and (b) back view of connecting plates with magic finger slots

Each aperture has one upper and one lower connecting plate at each magnet end. Each plate contains four magic finger slots, totaling 16 magic finger slots at both ends of one aperture, positioned at angles of  $\pi/8$ ,  $3\pi/8$ ,  $5\pi/8$ ,  $7\pi/8$ ,  $9\pi/8$ ,  $11\pi/8$ ,  $13\pi/8$ , and  $15\pi/8$ . With multiple fingers, total harmonics are the algebraic sum of magnetic fields generated by each magic finger.

Specific harmonics can be produced by combining magic fingers at different angles. The desired higher-order field is obtained through symmetric field cancellation and finger enhancement at different angles. To cancel the normal sextupole component, two fingers are predominantly used at angles of  $5\pi/8$  and  $11\pi/8$ , which generate larger  $b_3$  and lower negative  $b_1$  without skewing the  $a_1$  and  $a_3$  components. Multipole field amplitude is determined by the magic finger size, material, and radial distance from the quadrupole magnet aperture center. The closer the magic finger is to the aperture center, the larger the generated magnetic field harmonics. As an auxiliary method, magic finger adjustment capability is limited.

As shown in Table 3, aperture A exhibits large  $b_3$  components and certain  $a_3$  components. Fig. 16 [Figure 16: see original paper] presents the magic finger layout in aperture A (five magic fingers on the left), where fingers 1–4 adjust the  $b_3$  component and finger 5 adjusts the  $a_3$  component. In aperture B, four symmetrical magic fingers are distributed similarly to aperture A, but without the finger at  $15\pi/8$  (location 5) because the skew sextupole component in aperture B is very small.

**Fig. 16** Magic fingers in the two apertures

The  $b_3$  component changed from positive to negative values when current increased, with a variation of approximately five units, as detailed in Table 4. Final measured field harmonics after compensation are shown in Fig. 17 [Figure 17: see original paper]. All harmonics are less than five units, meeting requirements.

**Fig. 17** Higher-order harmonics in the two apertures at four different energies

**Table 4** Measured magnetic centers (mm) and field harmonics (units of  $1 \times 10^{-4}$ ) at four currents

Energy (GeV) |  $y_0$  (aperture A) |  $b_3$  (aperture A) |  $a_3$  (aperture A) |

Across the four energy ranges, the magnetic center on the X-axis varies by 0.07 mm in aperture A and 0.131 mm in aperture B. The offset of the magnetic center in the X-direction was almost identical for center shim gaps of 24 mm and 26 mm, likely due to magnetic hysteresis. The magnetic center in the Y-direction varied by 0.029 mm for aperture A and only 0.006 mm for aperture B. Because the collider operates at one energy level for several years with long intervals between the four energy modes, the fixed offset of the magnetic center on the X-axis can be corrected using trim coils or dipole magnets, making the magnetic center shift acceptable for accelerator physics.

## 6. Summary

DAQ magnets are key components of the CEPC ring. The main challenges include field crosstalk between the two apertures, field adjustability with trim coils, and suppression of magnetic center shifts across the beam energy range.

This work proposed a novel method to compensate for crosstalk effects using a center shim to adjust flux distribution in the iron of each aperture. The entire iron yoke scheme was selected as the baseline for the DAQ magnet and used to reconstruct the prototype, with a separated iron core scheme retained as an alternative. Various trim coil layouts were simulated and compared, and the scheme with trim coils on the poles was chosen. This configuration provides minimum and balanced reluctance between the four poles in a single aperture while having almost no effect on field quality in the other aperture. Because the relationship between dipole and sextupole components differs between 2D and 3D models, final optimization should be based on 3D simulations. After optimization and modification of the short quadrupole magnet prototype, field performance met all requirements.

The development of the short DAQ magnet prototype for CEPC provides a valuable reference for optimization design and further development of DAQ magnets in various colliders.

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