Superconducting magnets design in CEPC Interaction Region

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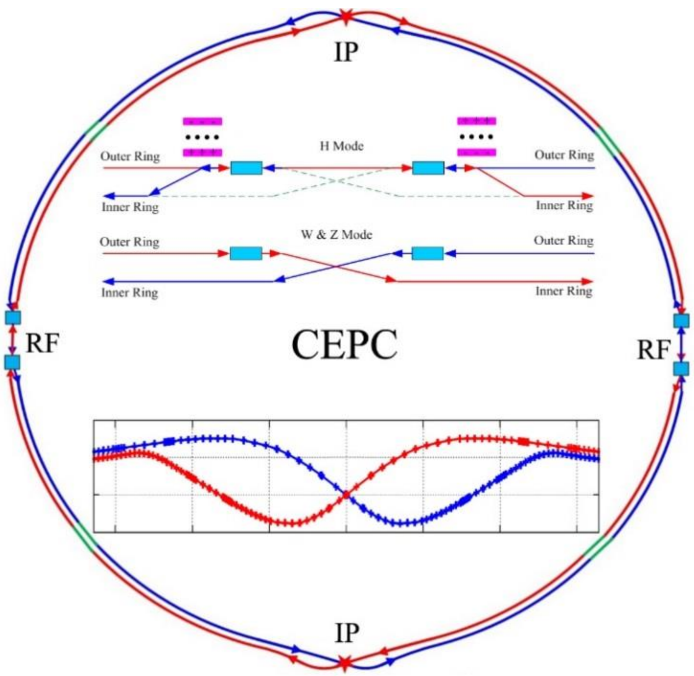
Outline

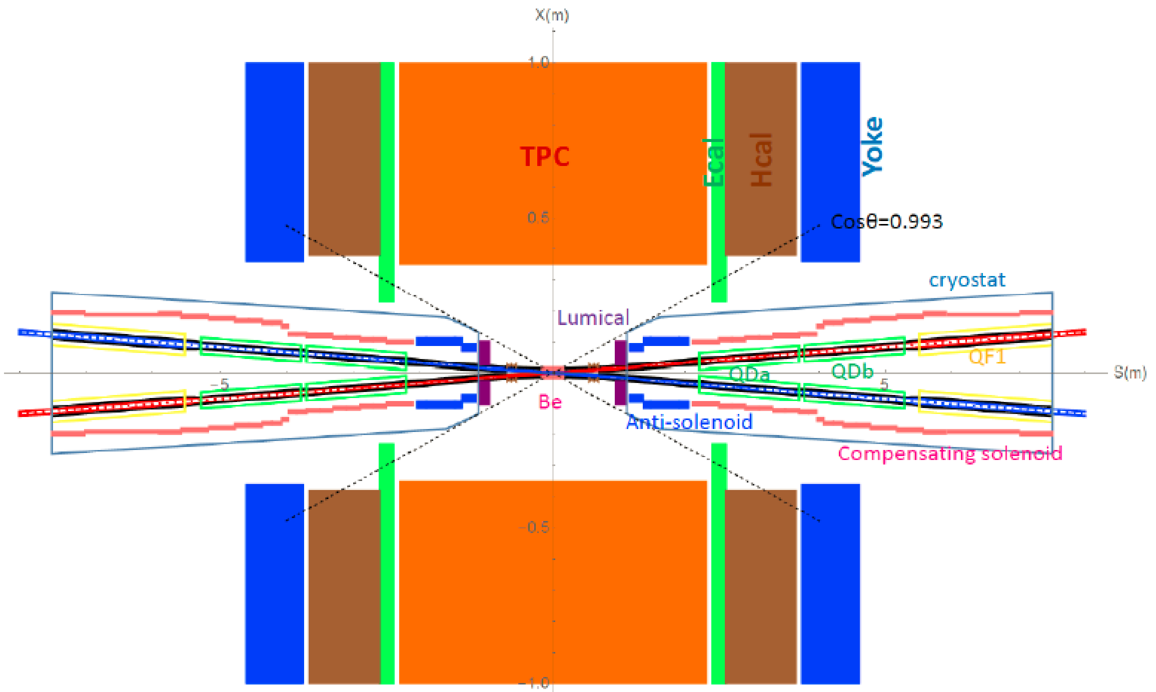
- Overall design of CEPC Interaction Region Superconducting magnets
- Design progress of CEPC Superconducting magnets
    1. Design of superconducting quadrupole magnet QF1
    2. Study the influence of solenoid field on superconducting quadrupole
    3. Conceptual design of QDa using HTS Bi-2212 conductor
    4. Conceptual design of Q1a for high luminosity with L*=1.9m
- Mechanical design progress of QD0 short model magnet
- Summary

Overall design of CEPC Interaction Region Superconducting magnets

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



Sketch of CEPC Collider ring



CEPC MDI layout

Overall design of CEPC Interaction Region Superconducting magnets

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

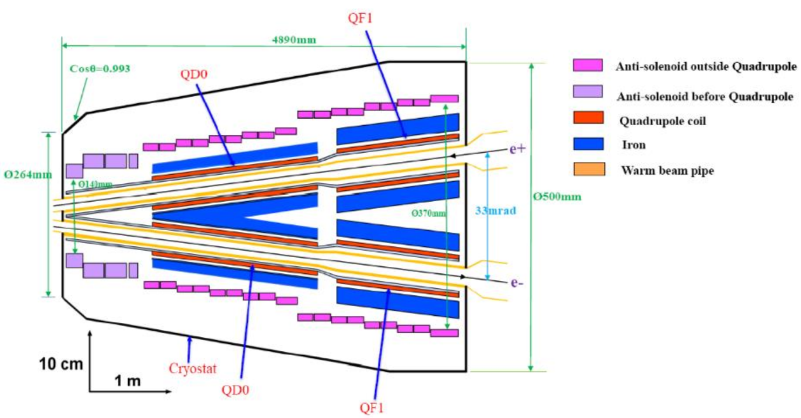
Table 1: CDR requirements of Interaction Region quadrupole magnets for Higgs

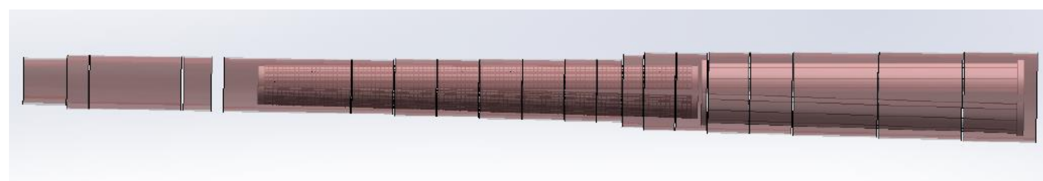
Magnet	Central field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
QD0	136	2.0	19.6	72.6
QF1	110	1.48	27.0	146.20

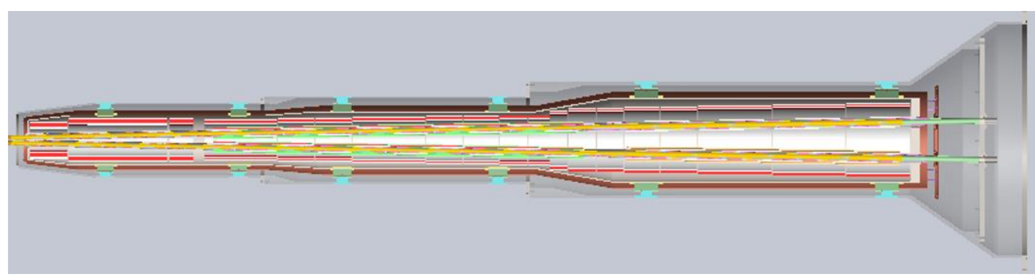
- QD0 and QF1 magnets are operated inside the field of Detector solenoid magnet with a central field of 3.0 T.
- To cancel the effect of the longitudinal detector solenoid field on the accelerator beam, anti-solenoids before QD0, outside QD0 and QF1 are needed.
- The total integral longitudinal field generated by the detector solenoid and accelerator anti-solenoid is zero; Local net solenoid field in the region of quadrupole is close to zero.

Overall design of CEPC Interaction Region Superconducting magnets

- CEPC MDI SC Magnets start at z=1.12m, including: superconducting QD0,QF1, anti-solenoid on each side of the IP point.
- Inner radius of beam pipe is 10 mm in CDR; Checked by HOM heating load calculation.
- QD0, QF1, and anti-solenoid coils are in the same cryostat.





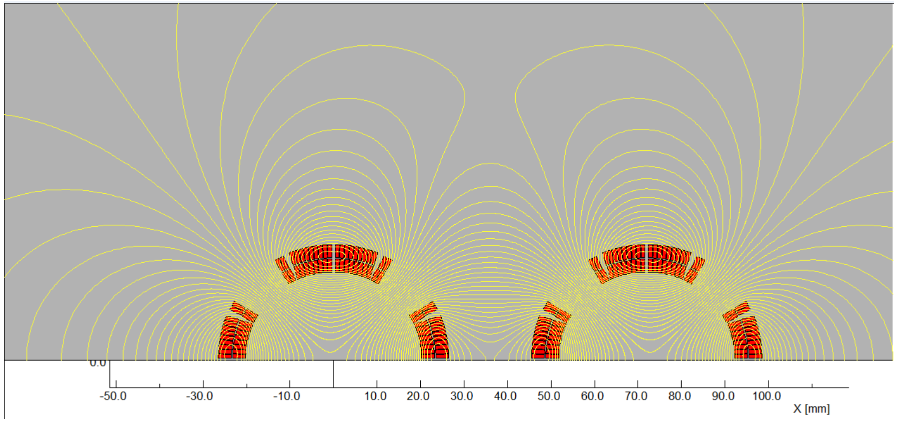


Schematic layout and mechanical design of QD0, QF1, and anti-solenoid

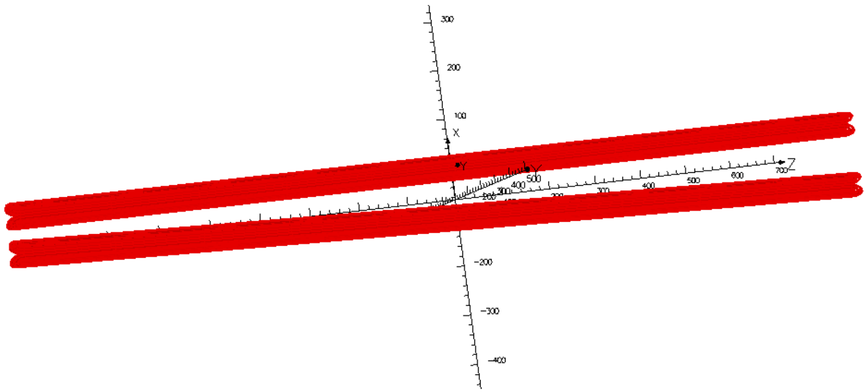
Overall design of QD0

Option1: Iron-free design of QD0 (CDR)

- ◆ Minimum distance between QD0 two aperture centerlines: 72.61 mm.
- ◆ The Iron-free design of QD0 is based on two layers cos2θ quadrupole coil using NbTi Rutherford cable without iron yoke.
- ● The QD0 single aperture coil cross section is optimized with four coil blocks in two layers separated by wedges, and there are 21 turns in each pole.
- ● The excitation current is 2680A. the field crosstalk between the two apertures is very large. Integrated multipoles in 3D : b3 19 unit (1×10^{-4}), b4 3.6 unit



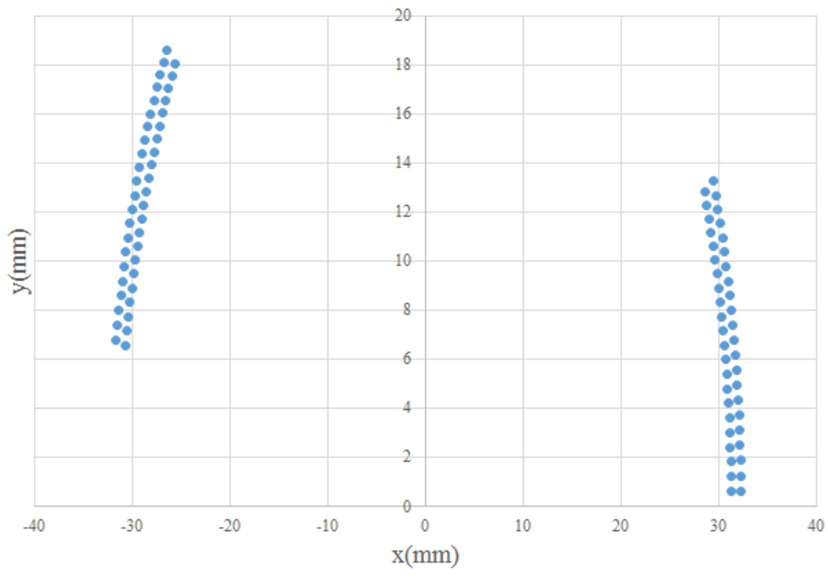
2D flux lines



3D model

Overall design of QD0

- Two layers of shield coil is introduced 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. The calculated integrated field quality and multipole fields at different longitudinal positions are all smaller than 3×10^{-4}.



Shield coil layout (half)

Table 2: Integrated field harmonics with shield coil (1×10^{-4})

n	B_n/B_2@R=9.8 mm
2	10000.0
3	-0.57
4	1.53
5	0.38
6	-0.14
7	0.015
8	-0.031
9	-0.02
10	-0.058

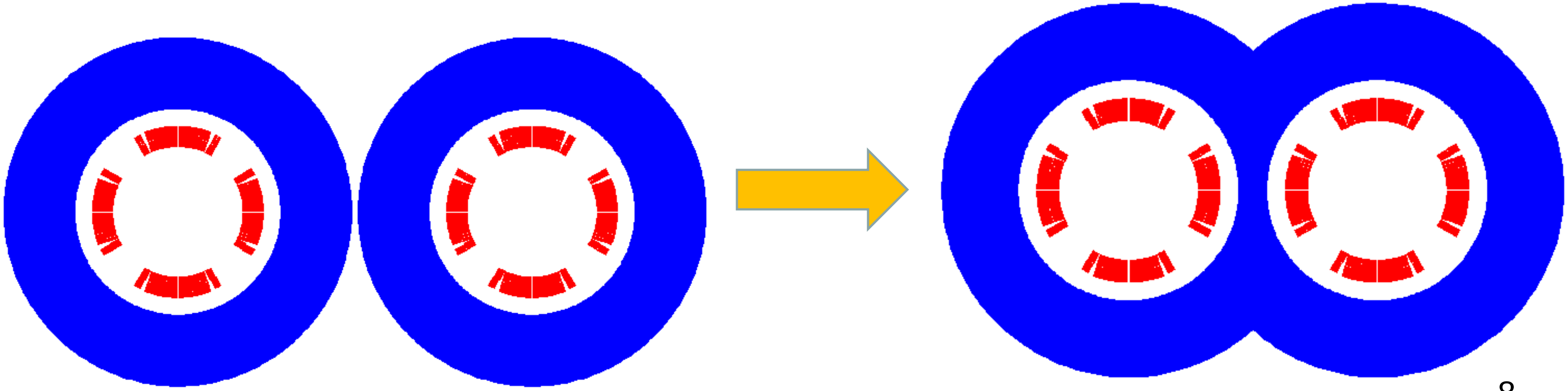
Option2: QD0 design with iron

- QD0 CDR: 136T/m, **inner diameter 40mm**, length 2m.

QD0 design of iron option

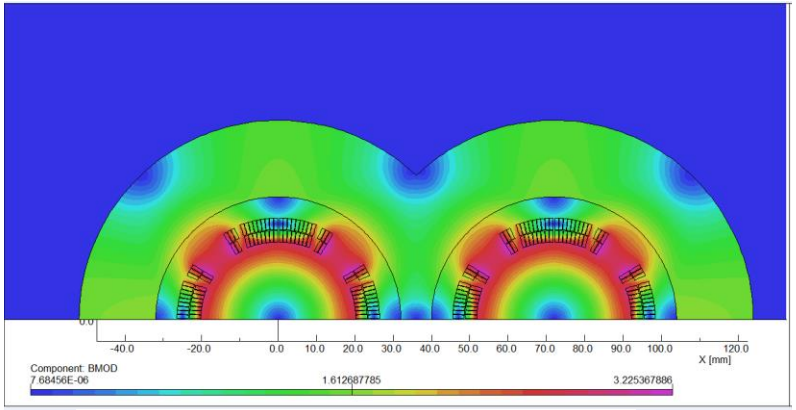
- Iron yoke is added outside the collar to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk.
- Not enough space to place two single apertures side by side, so a compact design is adopted.
- cos2θ quadrupole coil using NbTi Rutherford: highest magnetic efficiency and cooling capacity, good stability, elimination of field crosstalk.

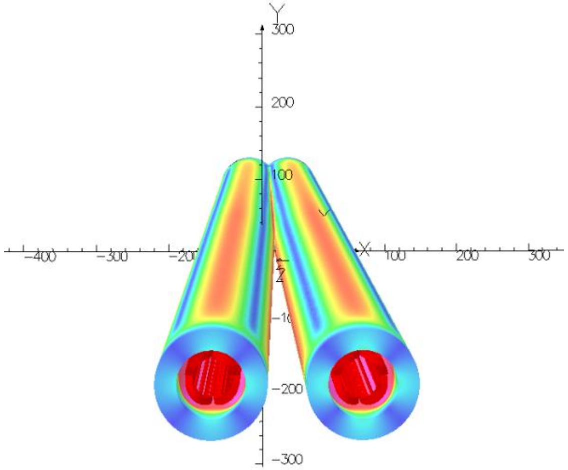
✓ **Iron core in the middle part is shared by the two apertures.**

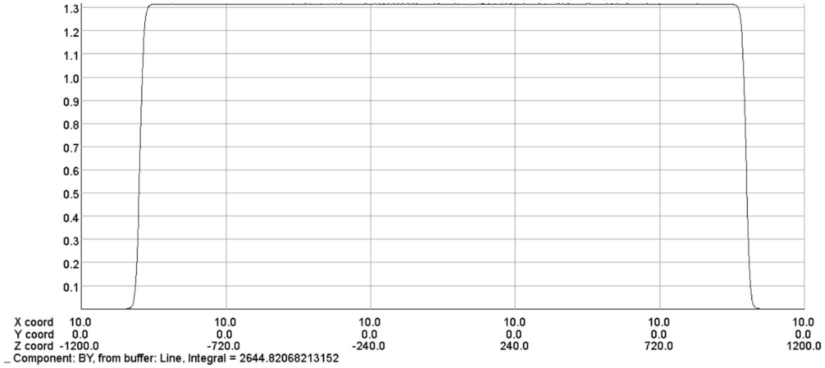


Option2: QD0 design with iron

- The excitation current is 2080A @4.2K or 1.9K.
- The field harmonics as a result of field crosstalk is smaller than 0.5×10^{-4}. Compared with the iron-free design, the excitation current can be reduced.
- Novel design: Double aperture quadrupole magnet using cos2θ coil with iron yoke shared by two apertures, with crossing angle between two apertures.

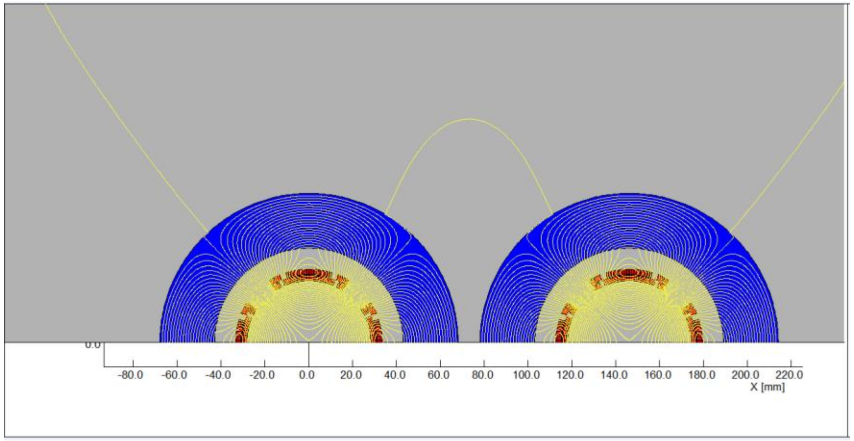


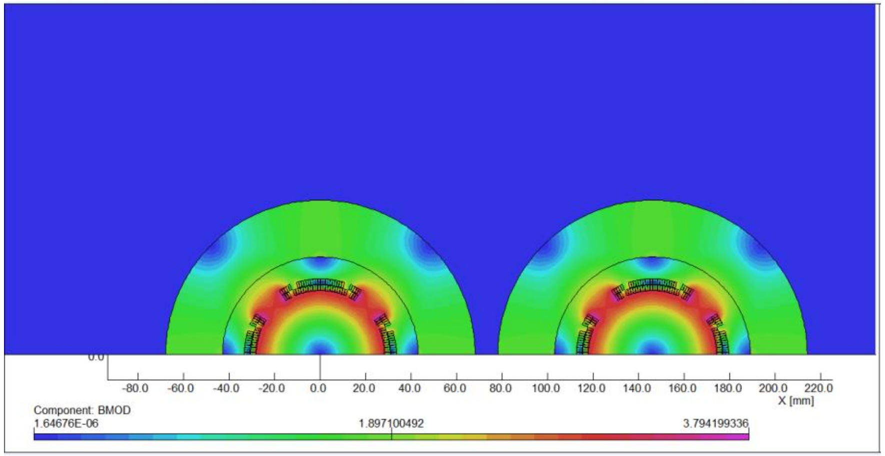




Overall design of superconducting quadrupole magnet QF1

- Since the distance between the two apertures is much larger, the field cross talk between the two apertures of QF1 is not a problem using iron yoke.
- After optimization, the QF1 coil consists of four coil blocks in two layers separated by wedges, and there are 29 turns in each pole.(by OPERA)
- Each systematic field harmonics is smaller than 1 unit (1×10^{-4}).
- The non-systematic field harmonics as a result of field cross talk can be neglected.



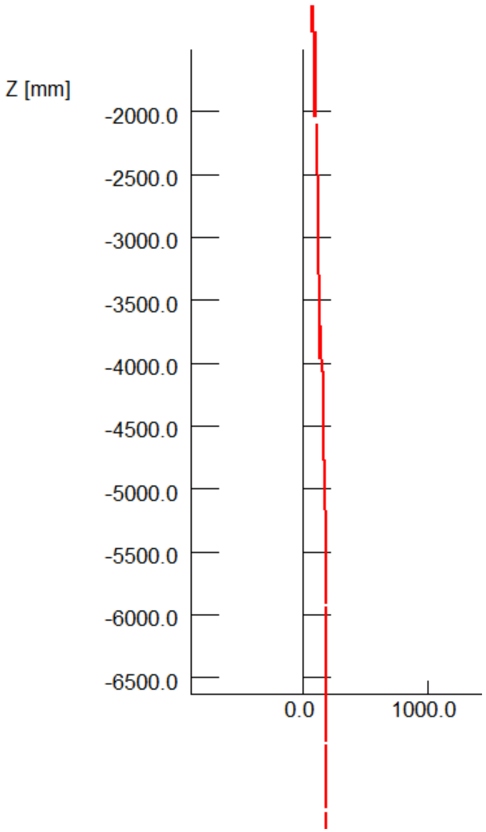


2D field simulation of QF1 in OPERA

Overall design of superconducting anti-solenoid

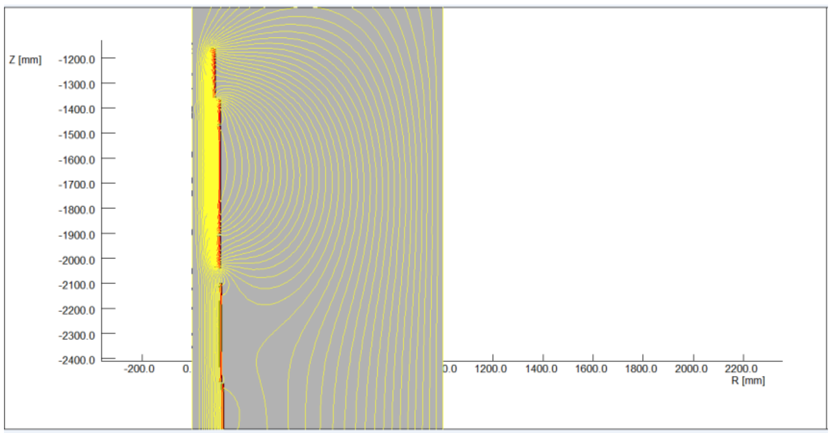
- The magnetic field of the Detector solenoid is not constant, and it decreases slowly along the longitudinal direction.
- In order to reduce the magnet size, energy and cost, the anti-solenoid is divided into a total of 29 sections with different inner coil diameters, using rectangular NbTi-Cu conductor.

- The anti-solenoid along longitudinal direction:
  1) 4 sections, from IP point to QD0;
  2) 12 sections, QD0 region;
  3) 6 sections, QF1 region;
  4) 7 section, after QF1 region.
- To reduce the length of the cryostat, the sections of anti-solenoid after QF1 region with low field will be operated at room-temperature.

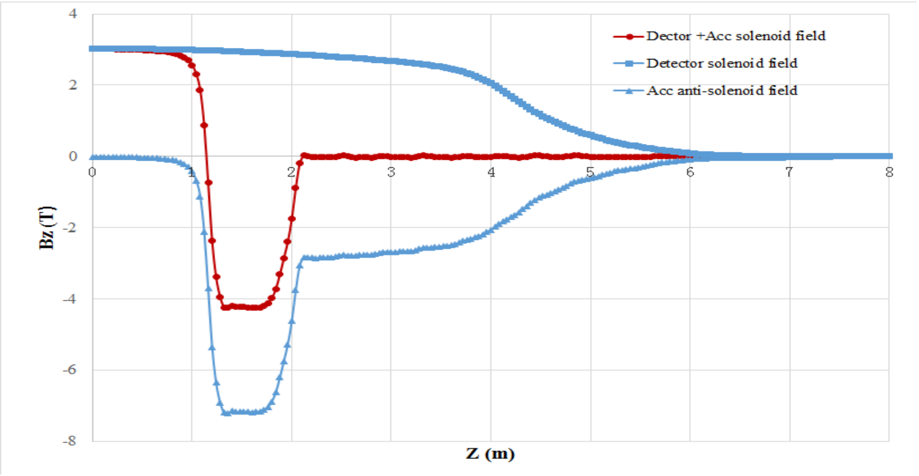


Overall design of superconducting anti-solenoid

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



2D flux lines



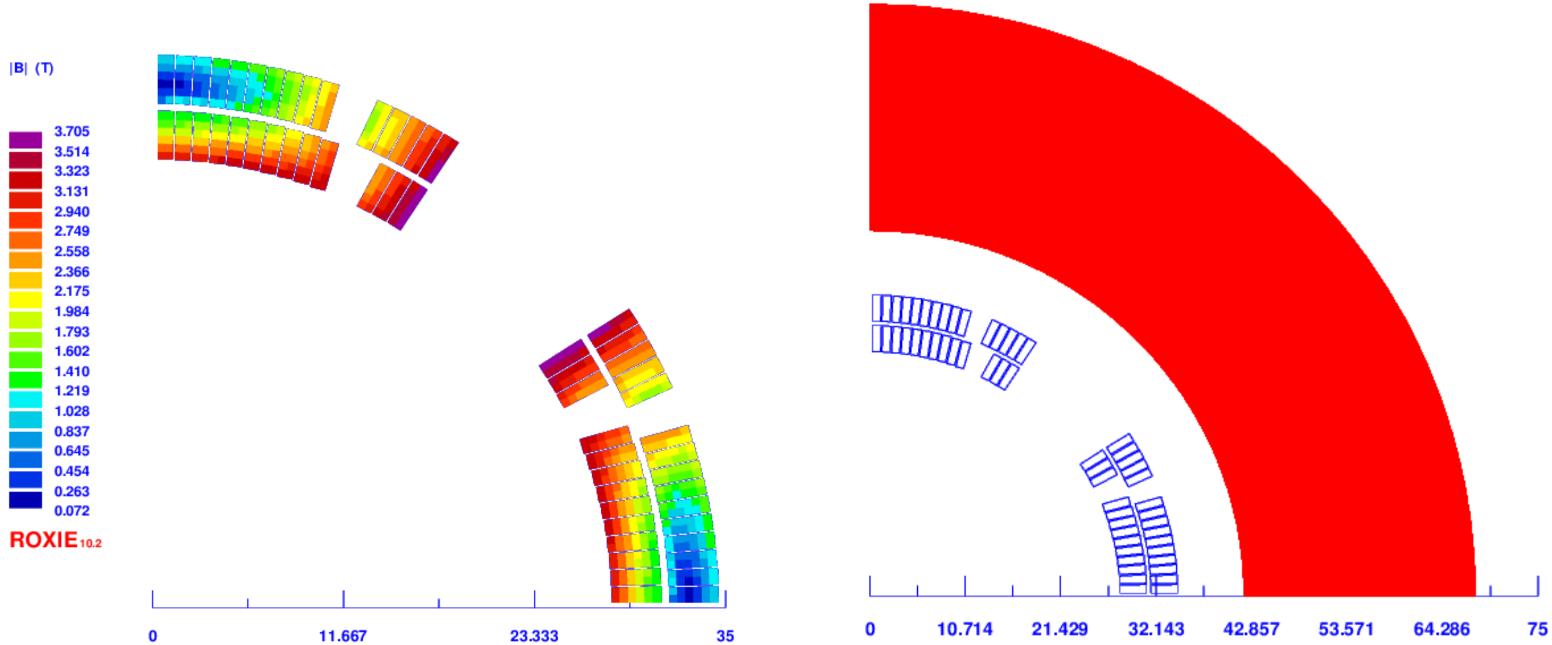
Combined field of Anti-solenoid and Detector solenoid

- The net solenoid field inside QD0 and QF1 at each longitudinal position is smaller than 300 Gs.
- In addition, there are 32 superconducting sextupole magnets in the CEPC interaction region, reported in the Conceptual Design Report.

Design progress of CEPC Superconducting magnets

1. Design of superconducting quadrupole magnet QF1

- The used NbTi Rutherford cable is similar to that of QD0. Since the distance between the two apertures is much larger, the field cross talk between the two apertures of QF1 is not a problem.
- After optimization by ROXIE, the QF1 coil consists of four coil blocks in two layers separated by wedges, and there are 28 turns in each pole. Current: 2280A.

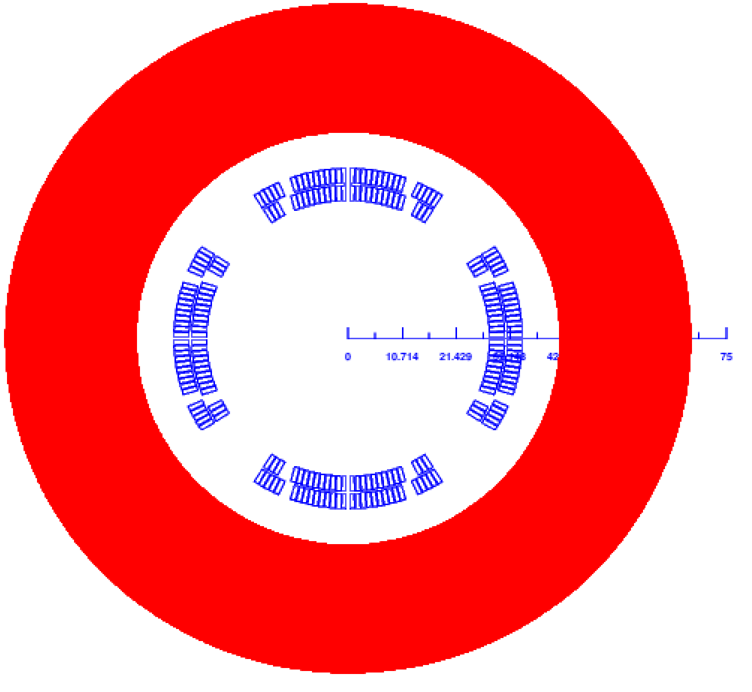


2D model (One quarter cross section) by ROXIE

Design progress of CEPC Superconducting magnets

Table 3: 2D field harmonics of QF1 (unit, 1×10^{-4})

n	B_n/B_2@R=13.5mm
2	10000
6	-0.32
10	-0.49
14	0.002

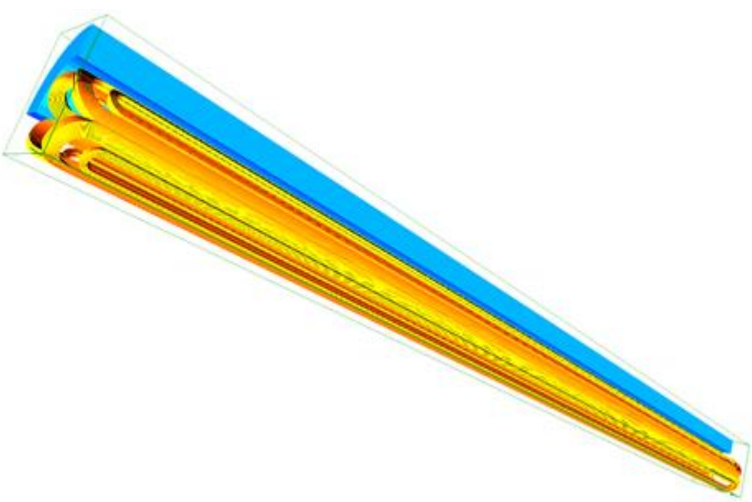


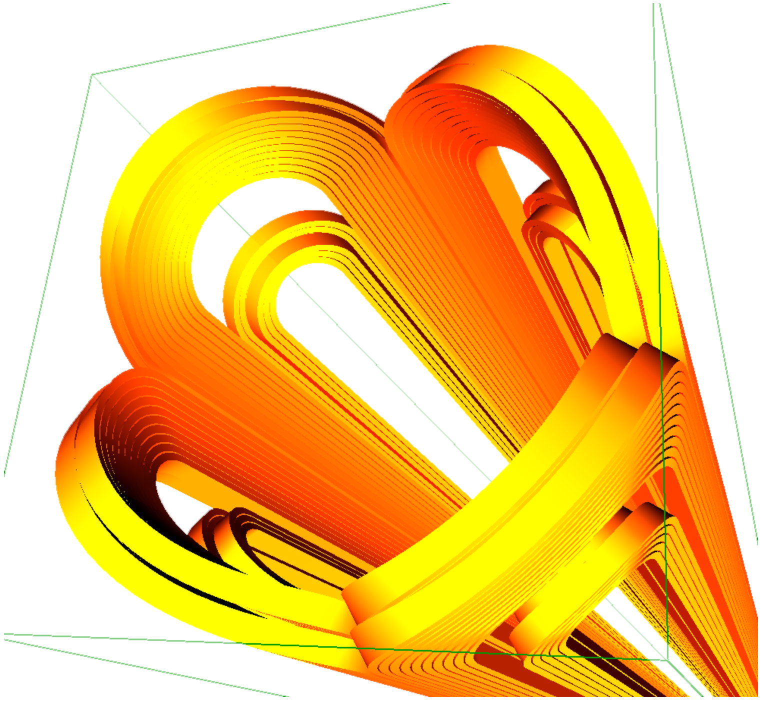
Coil cross section of single aperture QF1

Design progress of CEPC Superconducting magnets

3D magnetic field optimization

- The detailed coil end shape and conductors group is determined by field simulation using ROXIE.
- The field gradient, magnetic length meet the design requirement.
- Each systematic field harmonics is smaller than 1 unit (1×10^{-4}).



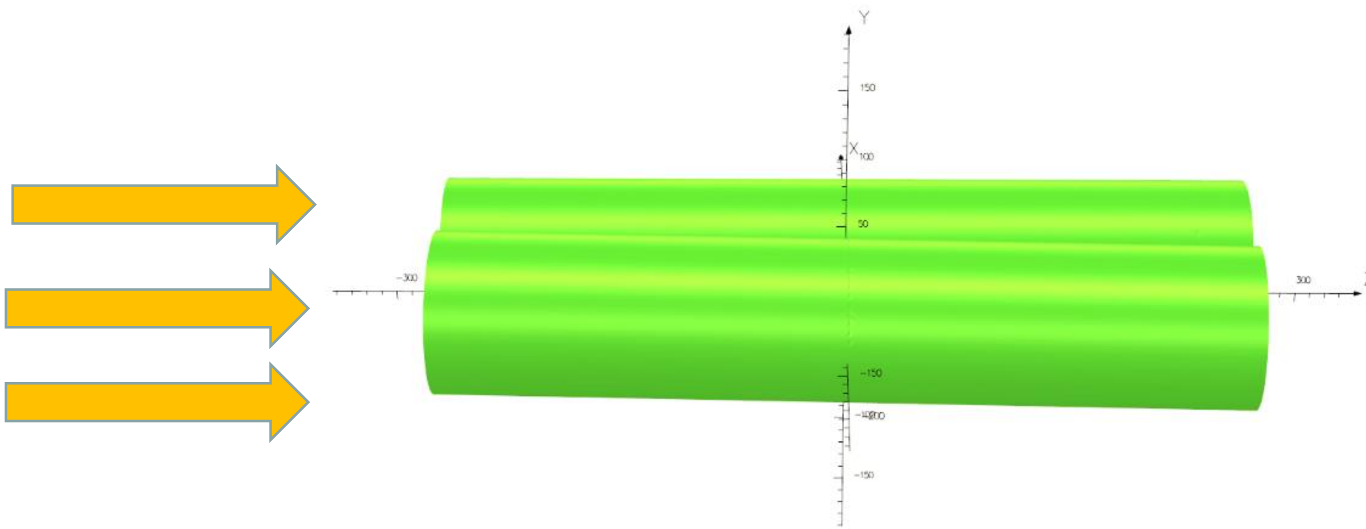


3D design of QF1

2. Study the influence of solenoid field on quadrupole

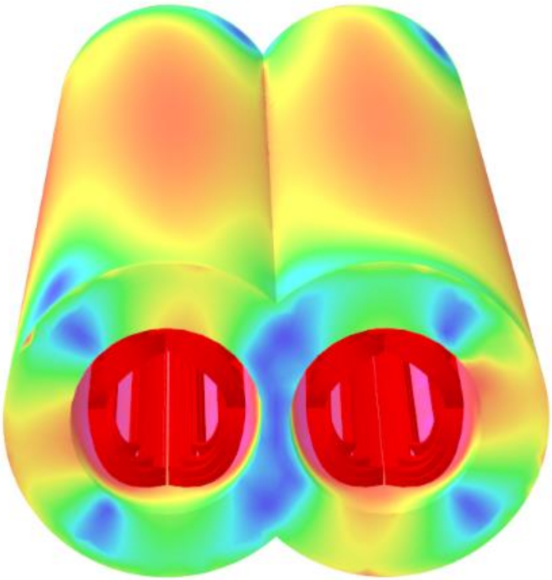
- Quadrupoles are located inside the bore of Accelerator anti-solenoid, which can cancel the field of Detector solenoid.
- The cancellation of solenoid is not perfect, and residual solenoid field exists. During optimization, the solenoid field is smaller than 300 Gs in the quadrupole region.
- 3D field simulation of 0.5m QD0 with 300 Gs background solenoid field is performed.

300 Gs solenoid

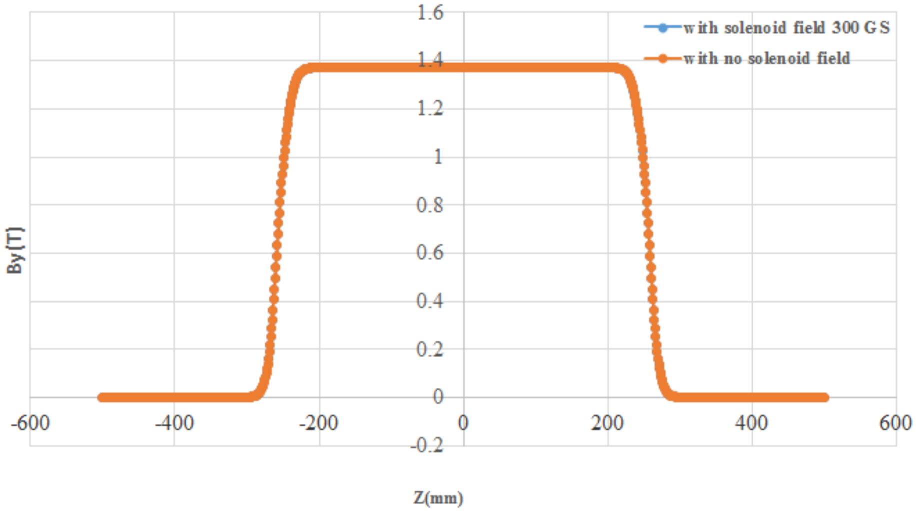


Design progress of CEPC Superconducting magnets

- 3D field simulation result shows that, the quadrupole magnet can work normally under 300Gs solenoid field.
- The maximum field in iron core increased by 0.1 T; magnetic field saturation is not serious.
- The change in the integrated field gradient is smaller than 3×10^{-4}; the change in the integrated multipole field is smaller than 0.2×10^{-4}.



3D model



Magnetic fled distribution

3. Conceptual design of QDa using HTS Bi-2212 conductor

◆ The updated requirement of the CEPC Final Focus quadrupoles:

Table 4: Updated Requirements of final focus quadrupole magnets for Higgs

Magnet	Central field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
QDa	77.5	1.5	19.2	72.61
QDb	77.5	1.5	22.0	124.75
QF1	63.4	2.0	30.9	181.85

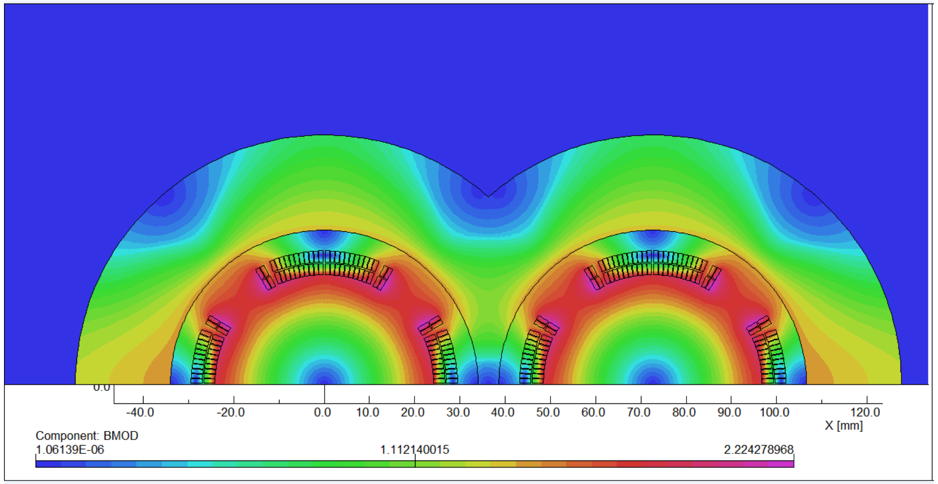
Design considerations

- The field gradient of quadrupoles is reduced compared to that in CDR; the development of QDa is the most challenging.
- Design of quadrupoles and anti-solenoid is similar to that in CDR.
- Space for the corrector coil is enough inside the bore of quadrupole coil.
- Iron yoke is used to eliminate the field crosstalk from the two apertures.

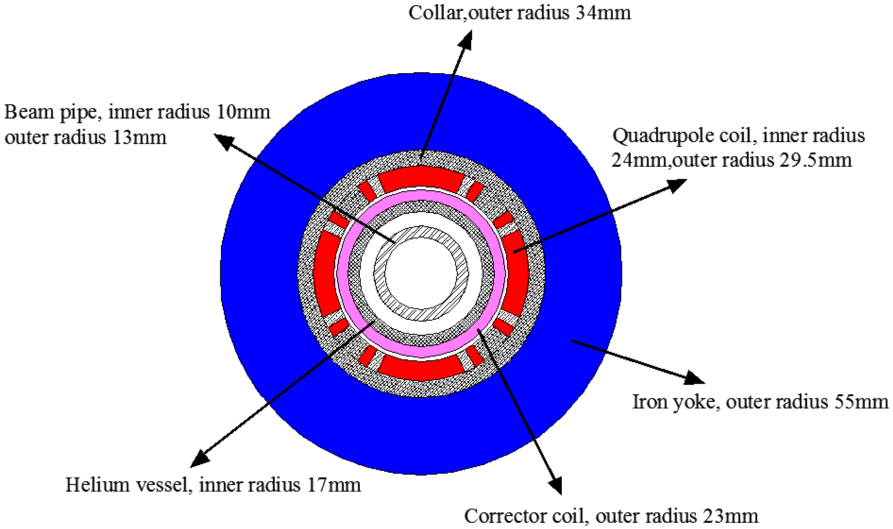
Design progress of CEPC Superconducting magnets

NbTi option of QDa (inner diameter 48mm)

- The QDa single aperture cross section is optimized with four coil blocks in two layers, and there are 25 turns in each pole.
- The excitation current of QDa is 1240A, and each multipole field in single aperture is smaller than 1×10^{-4}. The field harmonics as a result of field crosstalk is smaller than 0.5×10^{-4}.
- The dipole field in each single aperture as a result of field crosstalk is smaller than 5 Gs.



Magnetic flux density distribution



3. Conceptual design of QDa using HTS Bi-2212 conductor

- Feasibility of HTS superconducting magnet technology is being considered for CEPC IR superconducting magnets.

  Advantage: Large critical current, heat load resistant,
  High operating temperature.

  Disadvantage: Expensive, conductor and coil manufacture not mature,
  Large diameter of superconductor filament.

HTS Bi-2212 option for CEPC SC quadrupole

- Bi-2212: High current carrying capacity, isotropic properties, relatively mature production technology

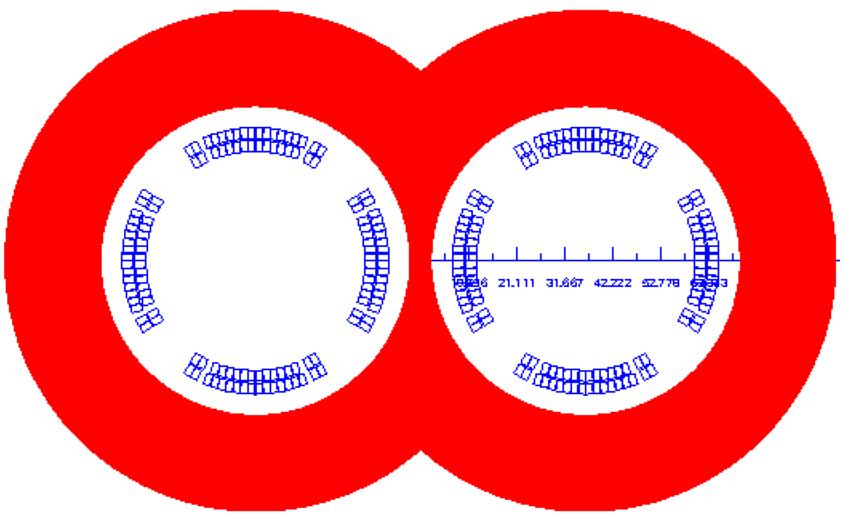
  Similar cross section as NbTi option;

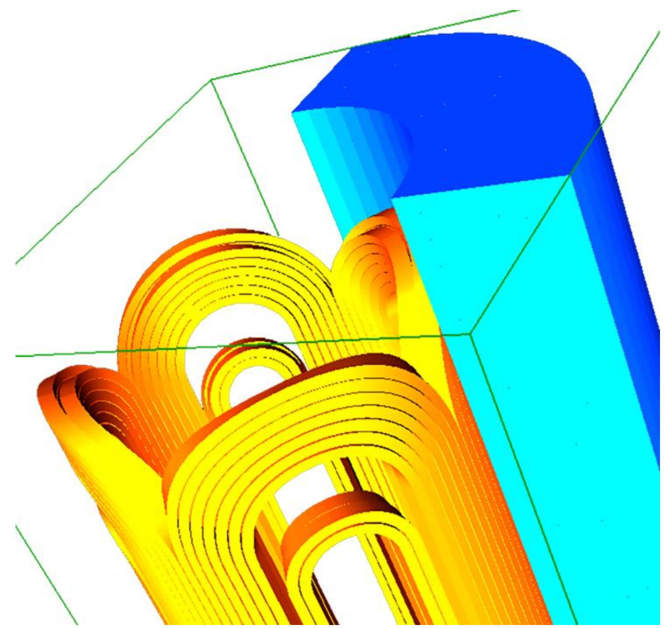
  Wind and react; or React and wind;

3. Conceptual design of QDa using HTS Bi-2212 conductor

Bi-2212 option of QDa

- Two layers cos2θ quadrupole coil using Rutherford cable with iron yoke.
- Inner diameter **48mm**, Bi-2212 strand diameter 0.8 mm.
- Rutherford Cable: Width 2.4mm, No of stands: 6, 17turns each pole.
- The excitation current of QDa is 1800A, and each multipole field as a result of field crosstalk is smaller than 0.5×10^{-4}.



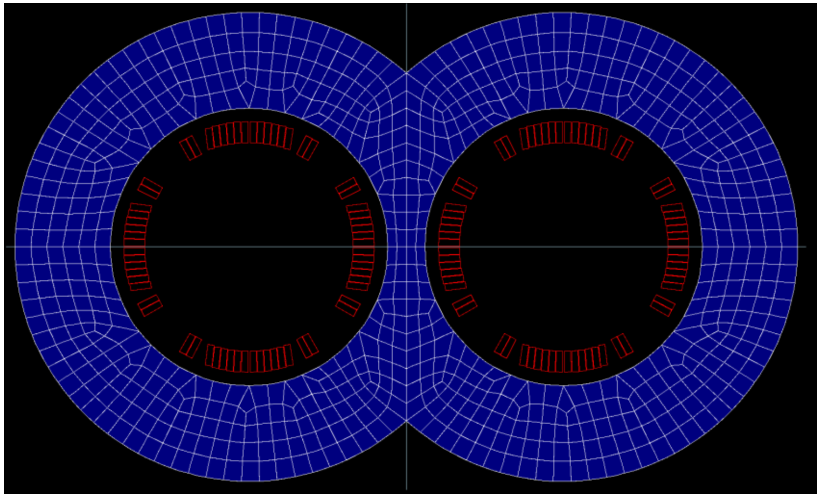


Field calculation model

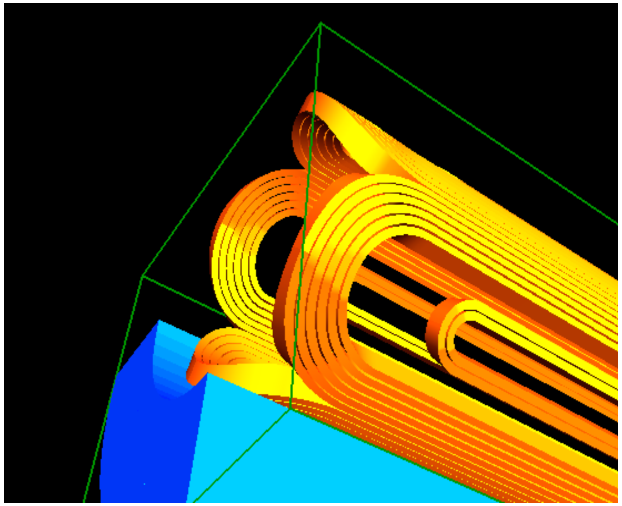
3. Conceptual design of QDa using HTS Bi-2212 conductor

Alternative Bi-2212 option of QDa

- One layer cos2θ quadrupole coil using Rutherford cable with iron yoke.
- Inner diameter **48mm**, Bi-2212 strand diameter 0.8 mm.
- Rutherford Cable: Width 4mm, No of stands: 10.
- 8 turns each pole.
- The excitation current of QDa is 3600A, and each multipole field in each aperture is smaller than 2×10^{-4}.



2D calculation model



3D calculation model

✓ As a first step, some test on Bi-2212 conductor is planned (Wind and react; React and wind).

4. Conceptual design of Q1a for high luminosity with L*=1.9m

- The requirement of the CEPC Final Focus quadrupoles is recently updated for high luminosity with L*=1.9m.

Table 5: Updated Requirements of final focus quadrupole magnets for Higgs

Magnet	Central field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
Q1a	141	1.21	15.21	62.71
Q1b	84.7	1.21	17.92	105.28
Q2	94.8	1.5	24.14	155.11

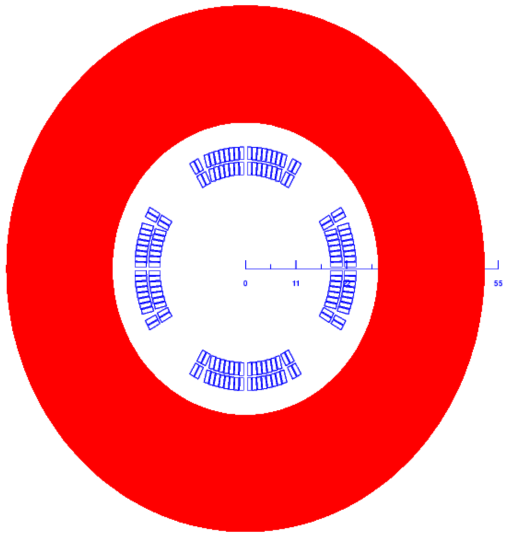
Design considerations

- The field gradient of quadrupoles is stronger compared to that in CDR, and the available bore space for the coil is smaller.
- The development of Q1a is the most challenging.
- Design of quadrupoles and anti-solenoid is similar to that in CDR.
- Corrector coils will be inside the bore of Q1b and Q2 quadrupole coil.
- Iron yoke is used to eliminate the field crosstalk between the two apertures.

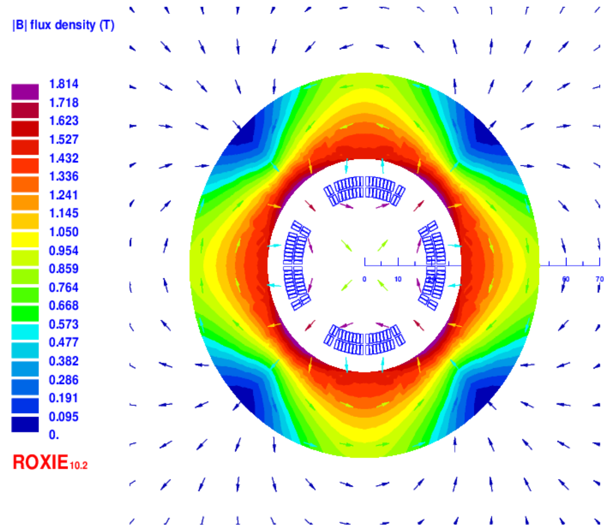
4. Conceptual design of Q1a for high luminosity with L*=1.9m

Design progress of Q1a

- The design of Q1a is based on two layers cos2θ quadrupole coil using Rutherford cable with iron yoke. The inner diameter of the coil is 37mm.
- The Q1a single aperture cross section is optimized with four coil blocks in two layers separated by wedges, using ROXIE.
- The width of the cable is 2.5mm, and there are 19 turns in each pole.
- The excitation current of Q1a is 1970A, and each multipole field in single aperture is smaller than 1×10^{-4}.



2D model (single aperture)

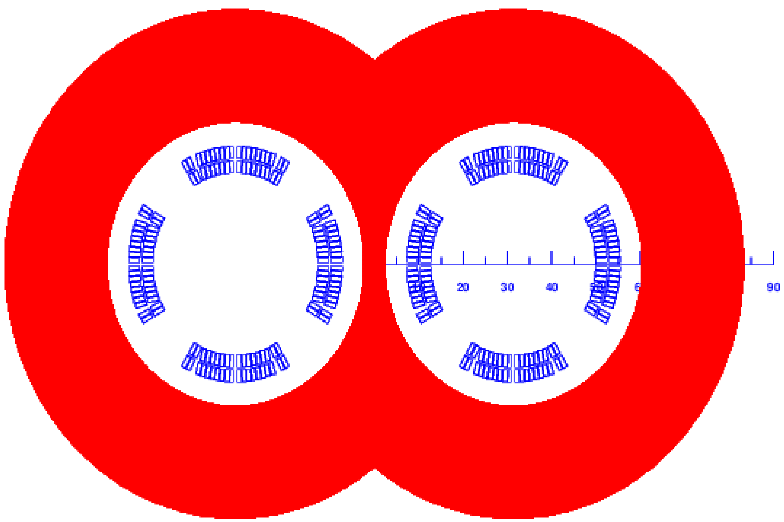


Magnetic flux density distribution

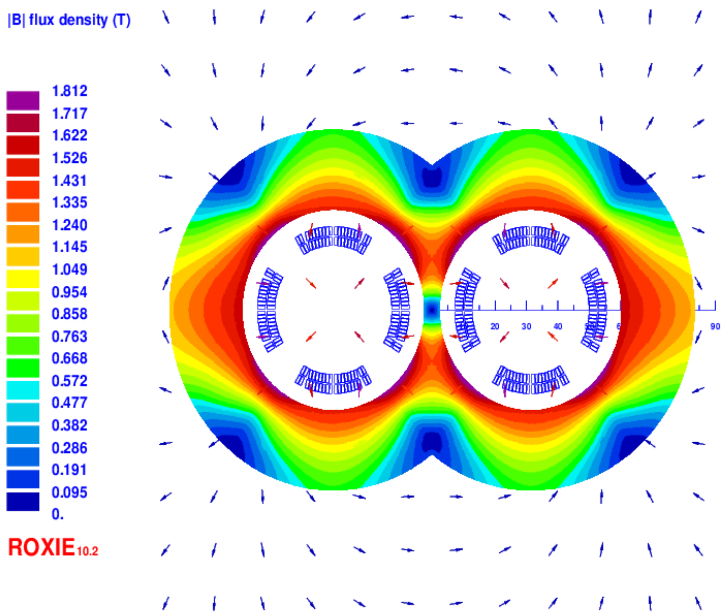
4. Conceptual design of Q1a for high luminosity with L*=1.9m

Field cross talk of the two apertures

- 2D field cross talk of Q1a two apertures near the IP side, where the distance between two aperture centerlines is minimum.
- Iron yoke width in the middle is very limited; the field harmonics as a result of field crosstalk is smaller than 0.5×10^{-4}.
- The dipole field in each single aperture as a result of field crosstalk is smaller than 5 Gs. Magnetic field cross talk between two apertures is negligible.



Double aperture model



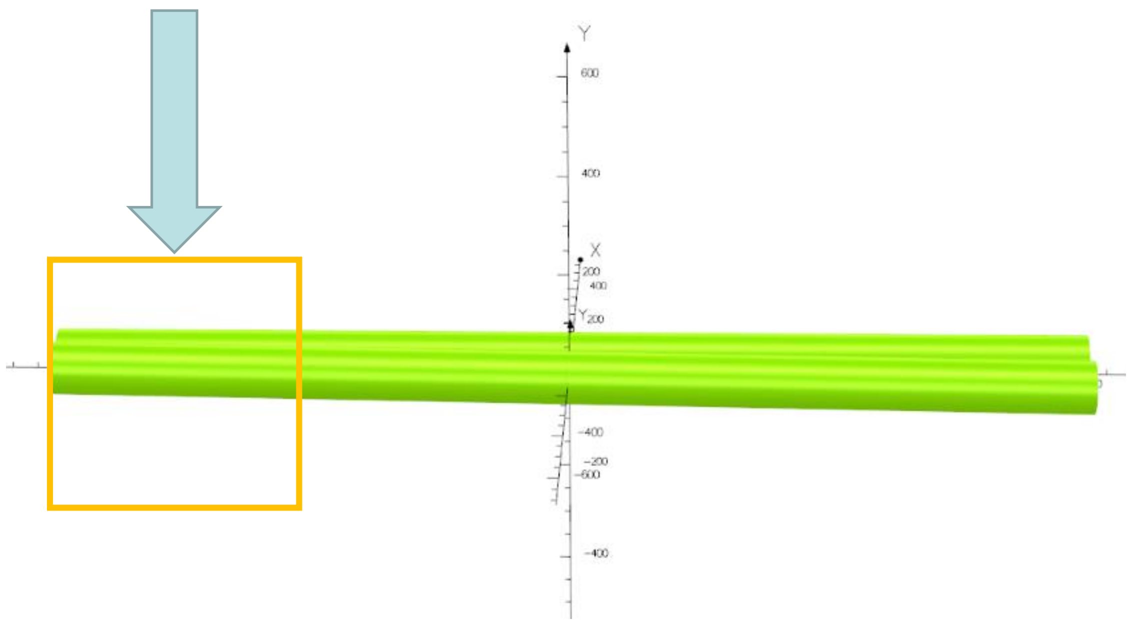
2D Flux lines

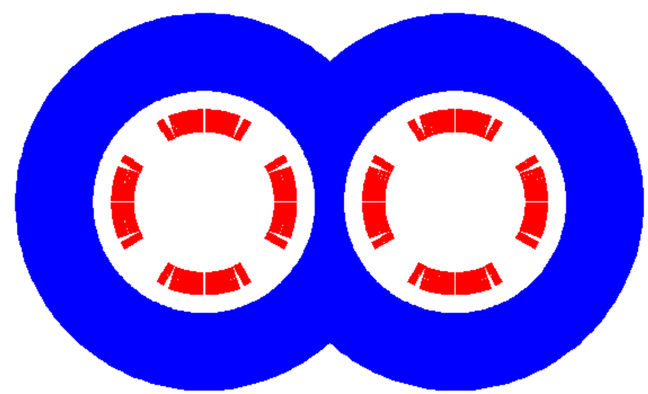
Mechanical design progress of QD0 short model magnet

- Novel design of QD0 iron option:

Collared cos2θ quadrupole magnet with shared iron yoke and crossing angle between two aperture centerlines. **In practice, can it be fabricated and really meet the requirement?**

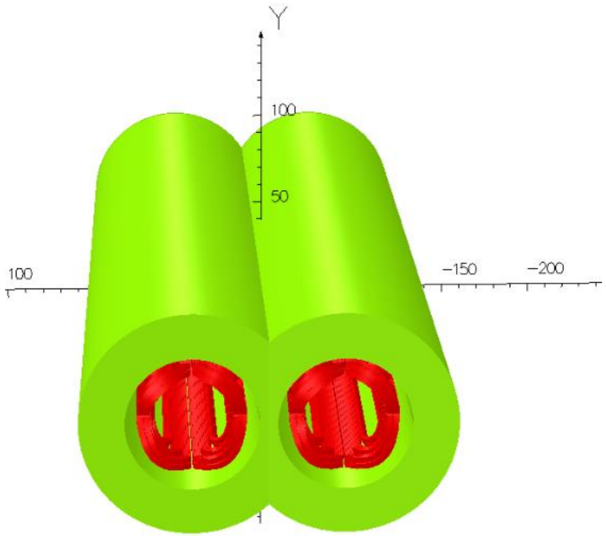
- So far, there is no cos2θ superconducting quadrupole magnet in China.
- In the R&D, the first step is to **study and master main key technologies of** superconducting quadrupole magnet by developing a short QD0 model magnet (短实验磁体) with 0.5m length (near IP side).

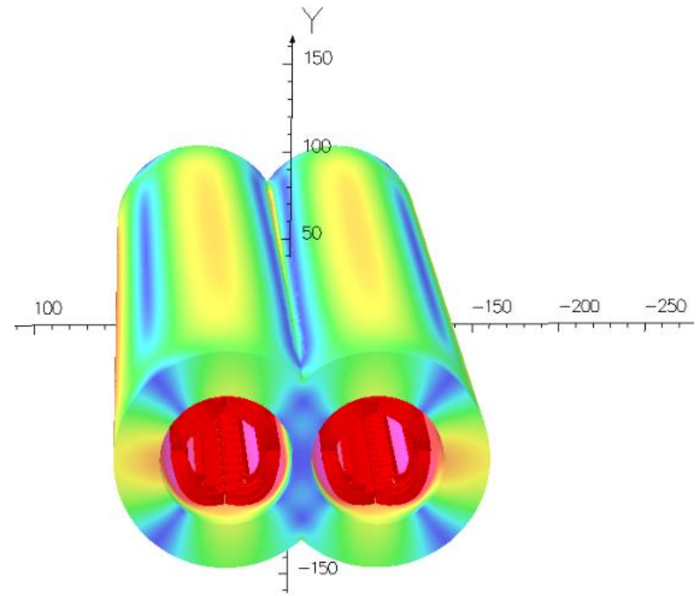


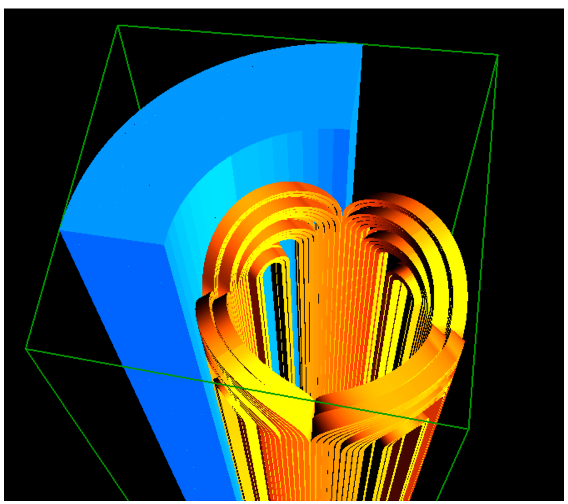


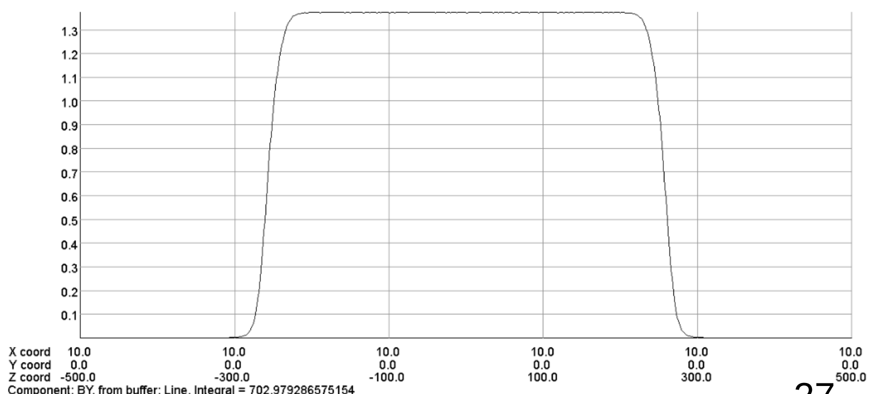
Mechanical design progress of QD0 short model magnet

- 3D field simulation and stress analysis of 0.5m QD0 is finished.
- The physical design of 0.5m QD0 short model magnet passed the experts review in July 2019.





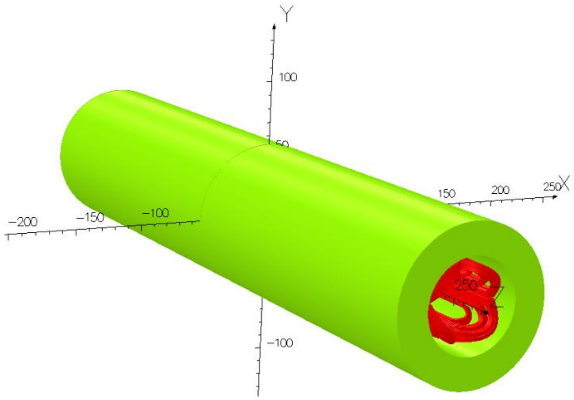


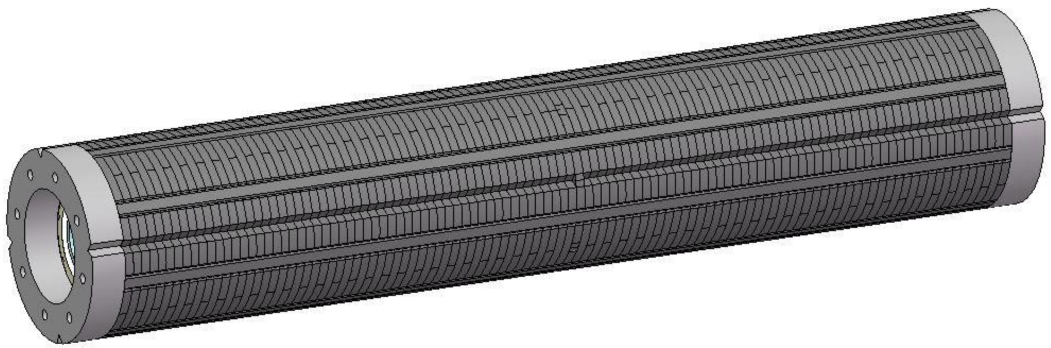


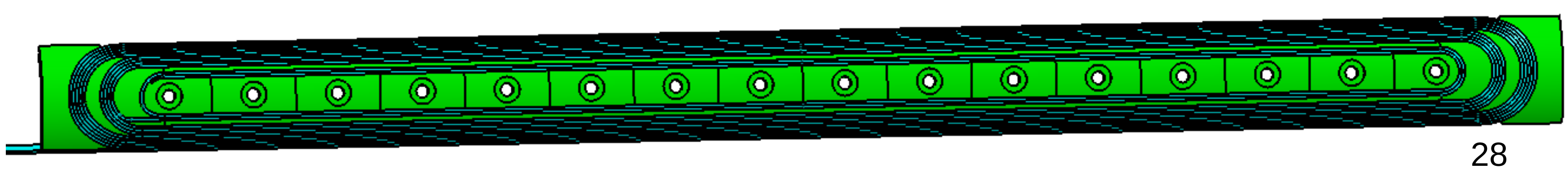
Opera

Mechanical design progress of QD0 short model magnet

- Research on some key technologies of superconducting quadrupole magnet in CEPC IR has started, in collaboration with HeFei KEYE Company.
- Including: quadrupole mechanical design, coil winding technology, fabrication procedure of quadrupole coil with small diameter, stress applying and monitoring, quadrupole magnet assembly and measurement technology, etc.

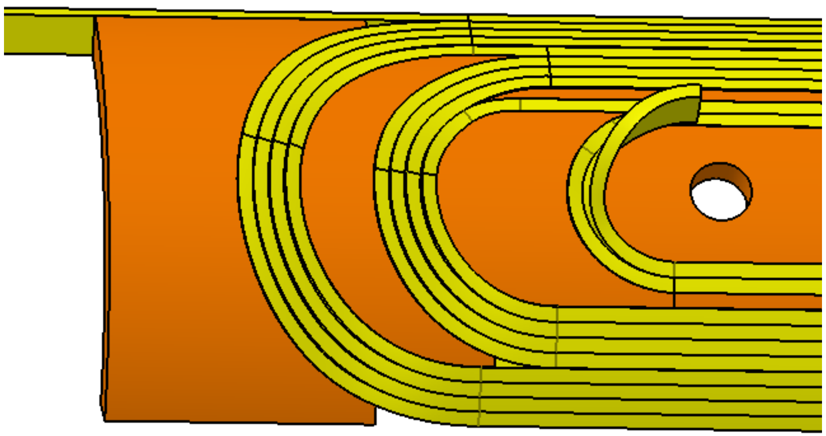


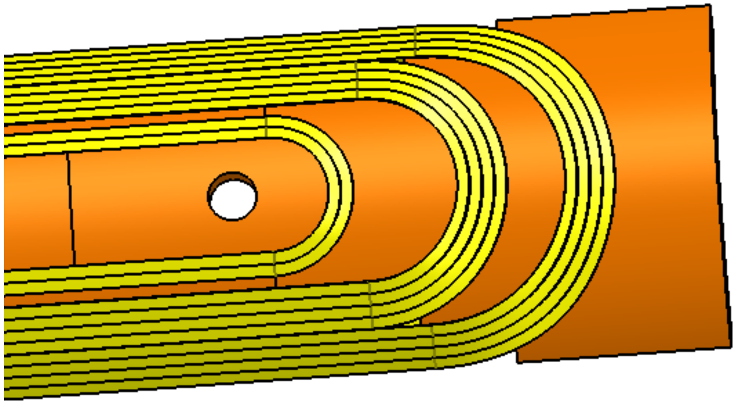




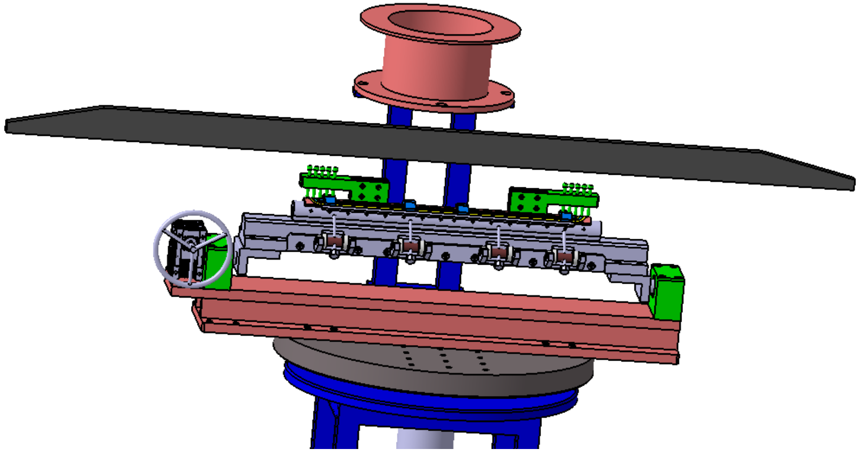
Mechanical design progress of QD0 short model magnet

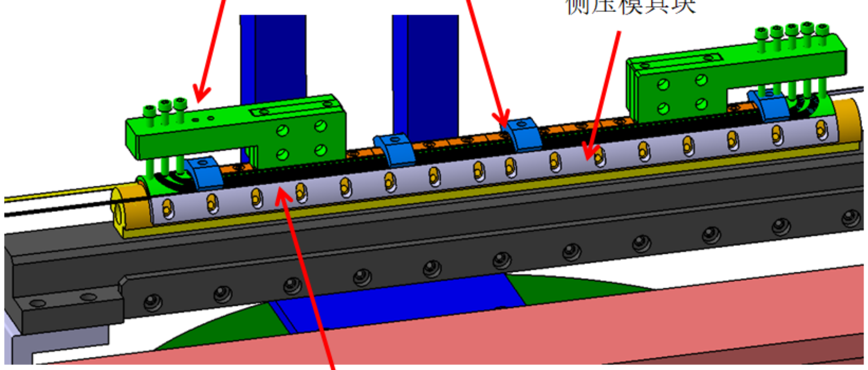
- Mechanical design of the 0.5m single aperture magnet and quadrupole coil winding machine has been finished.





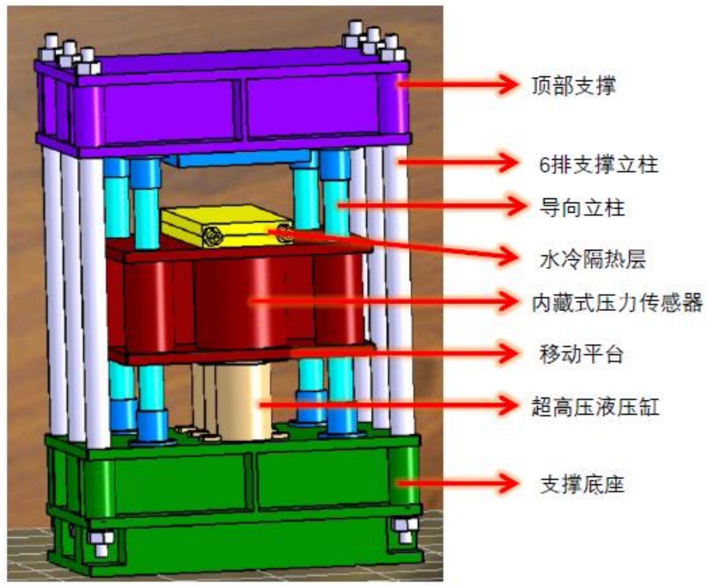
Coil winding machine

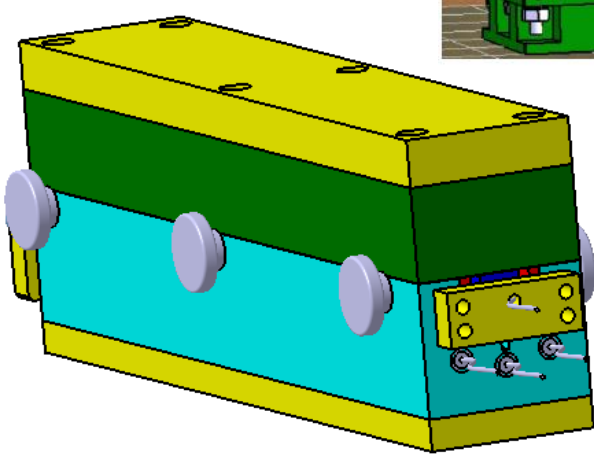


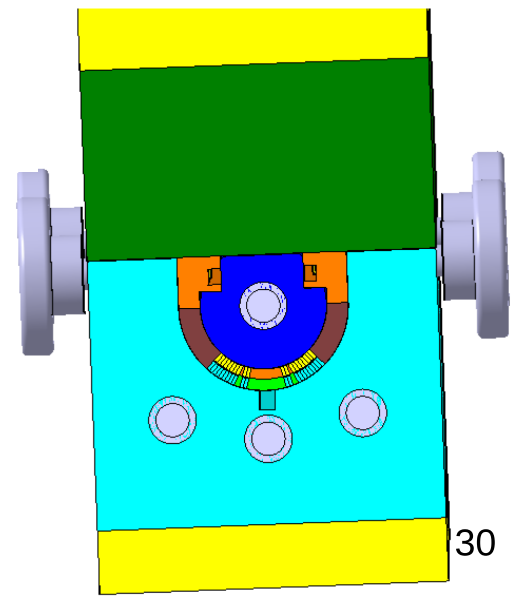


Mechanical design progress of QD0 short model magnet

- After the winding process, the quadrupole coil will be heated and cured inside a curing mold.
- Mechanical design of Superconducting quadrupole coil heating and curing system is completed.







Summary

- Superconducting magnets are key devices for CEPC. The design of superconducting magnets with the CDR parameter meets the requirement.
- **Novel design of QD0 with iron option is studied.** Despite limited space, field cross talk effect between two apertures is negligible using iron yoke.
- Conceptual design of superconducting quadrupole using HTS Bi-2212 conductor/ for high luminosity is performed.
- There is no cos2θ superconducting quadrupole in China. The first step of the R&D is to **study and master main key technologies** of superconducting quadrupole magnet by developing a 0.5m short QD0 model magnet.
- The physical and mechanical design of the 0.5m quadrupole model magnet are finished. Its fabrication is planned to be started **(depending on fund).**

Thanks for your attention!