Superconducting Magnets in CEPC Interaction Region

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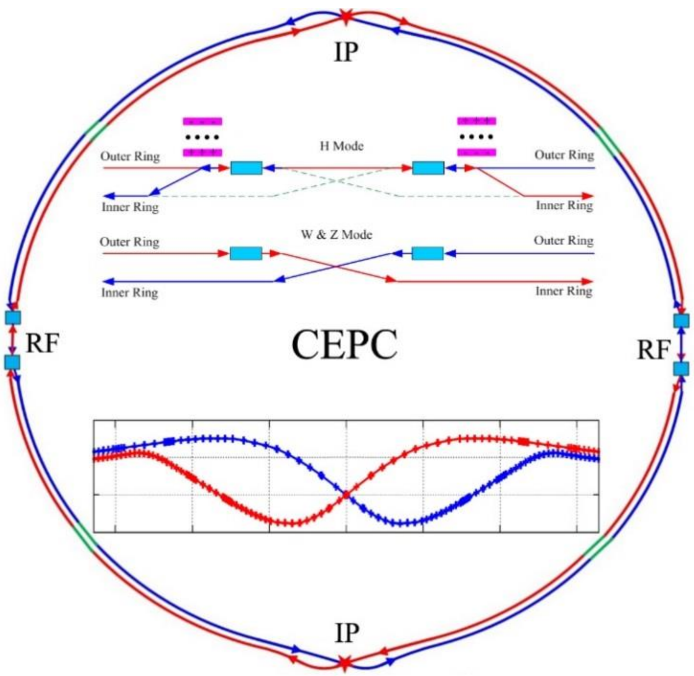
Outline

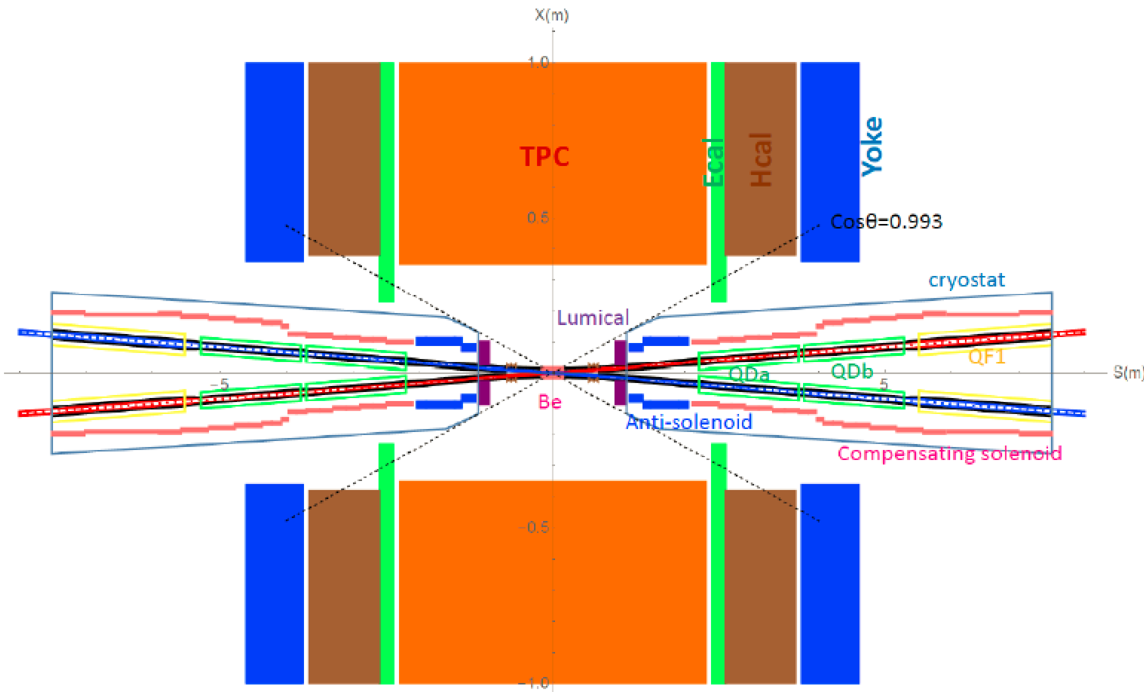
- Overview of CEPC MDI Superconducting magnets
- Design of MDI Superconducting magnets
- Mechanical design of QD0 short model magnet
- Summary

Overview of CEPC MDI SC 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 needed for 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

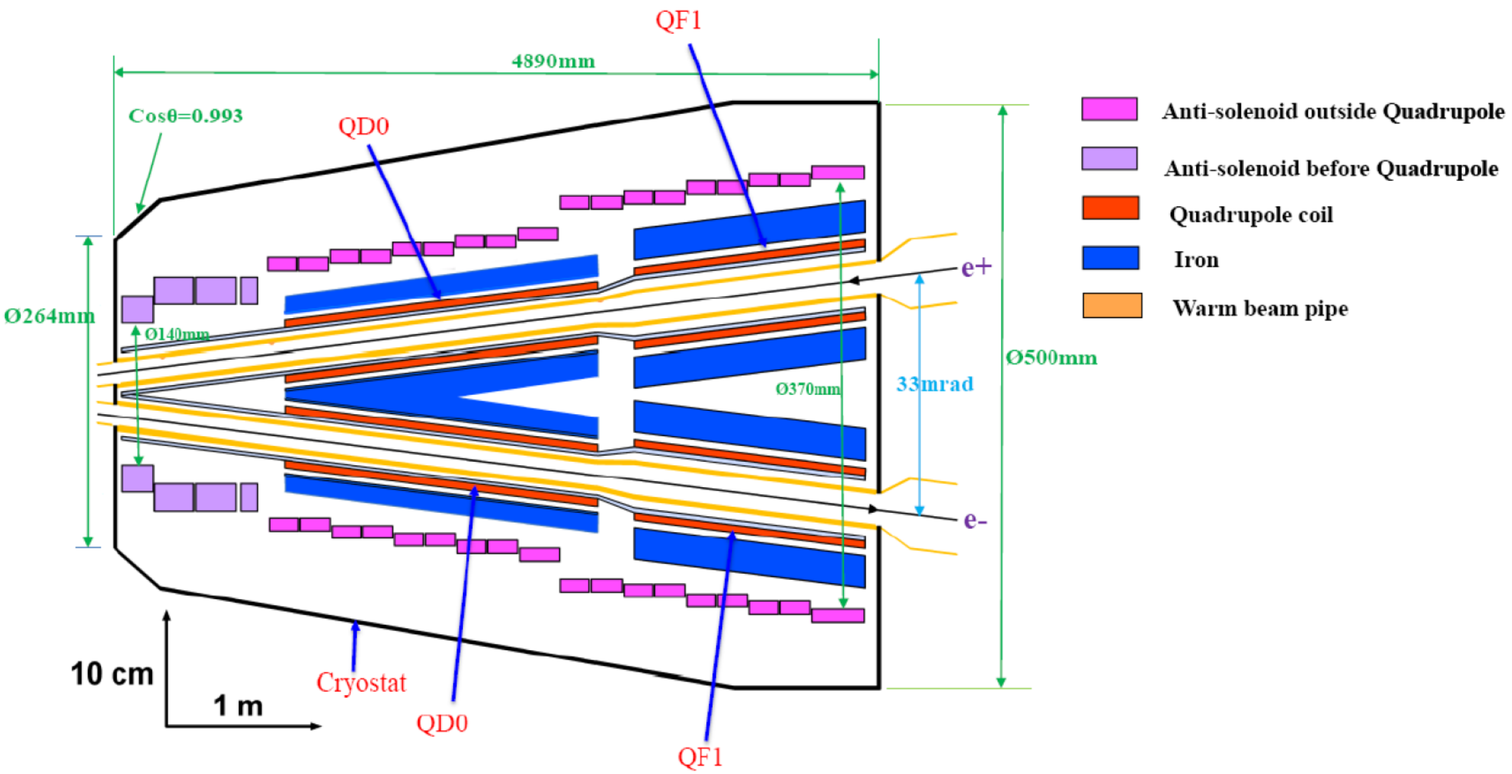
- The CDR requirements of the Final Focus quadrupoles (QD0 and QF1) are based on L* of 2.2 m, beam crossing angle of 33 mrad.

Table 1: 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.

- 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.

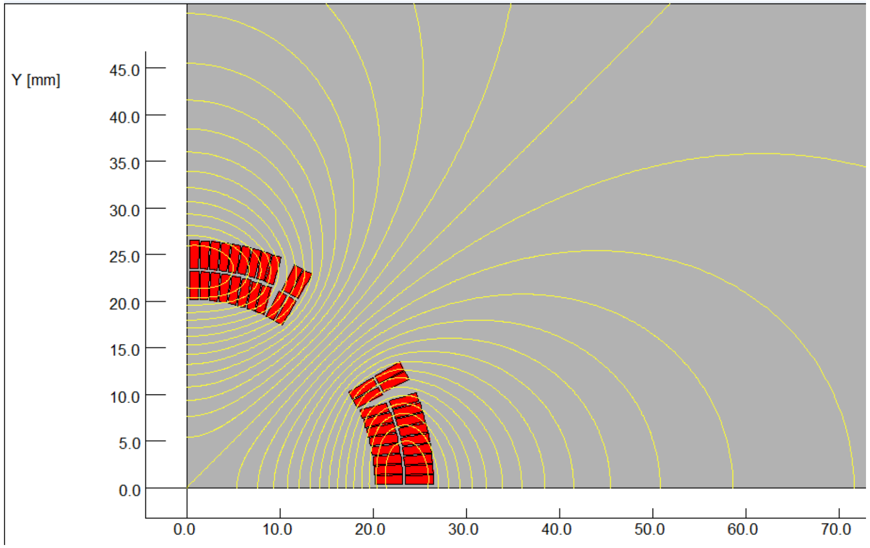


Schematic layout of QD0, QF1, and anti-solenoid

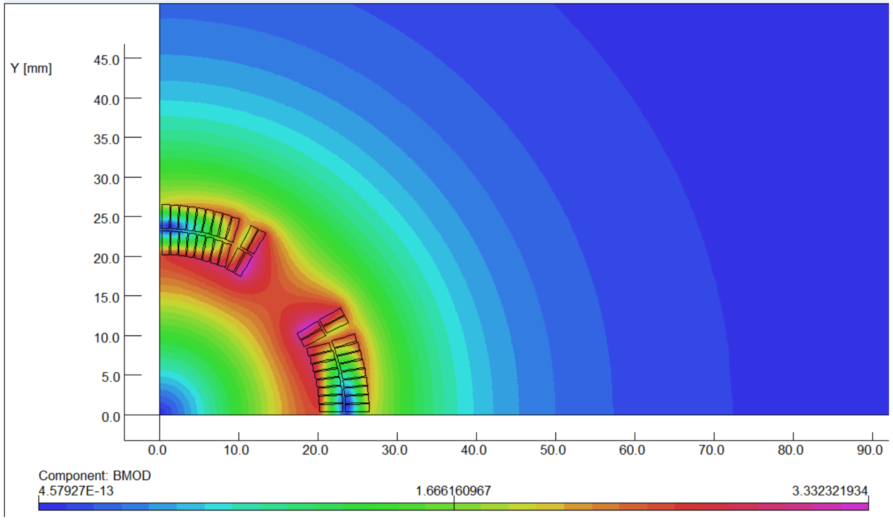
Design of MDI Superconducting magnets

Option1: Iron-free design of final focus 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.

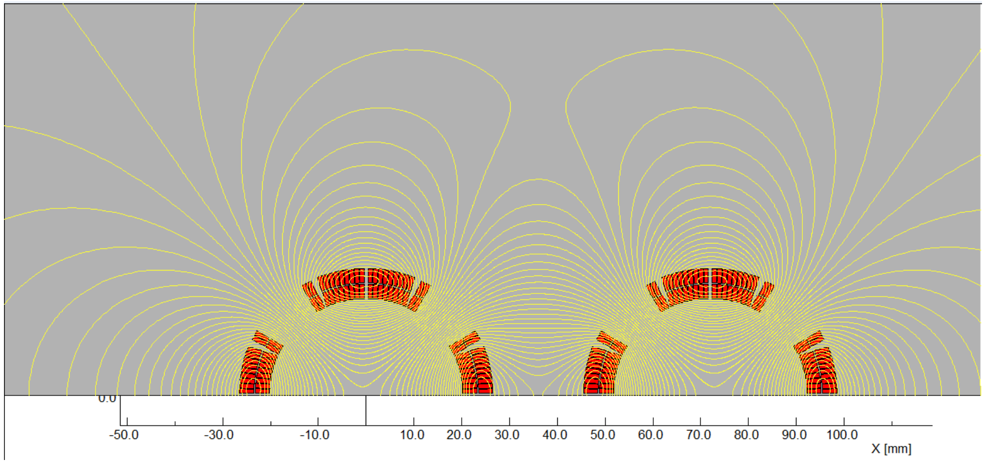


2D flux lines (1/4 cross section)

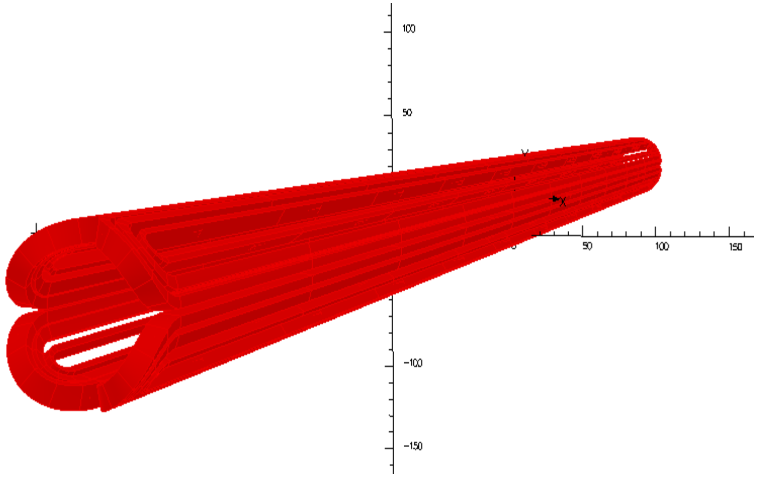


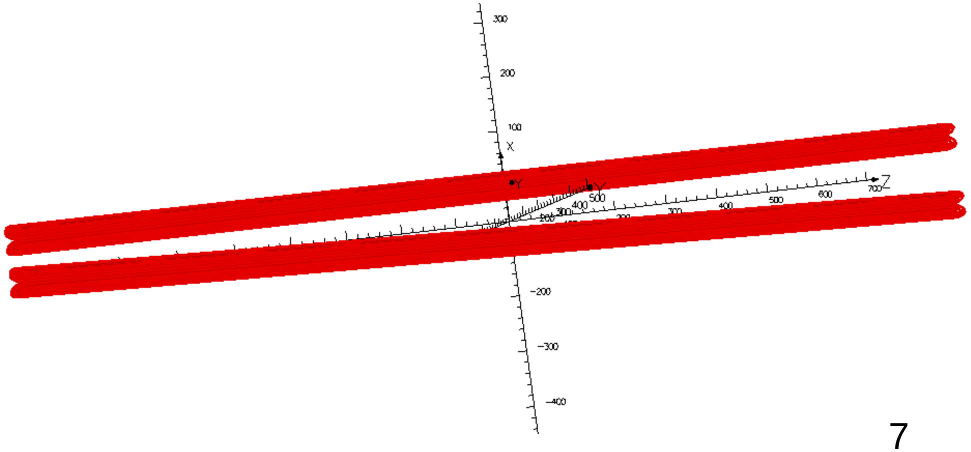
Magnetic flux density distribution

- For double aperture quadrupole magnets, the field crosstalk between the two apertures is one of the main difficulty. Field cross talk is very large.

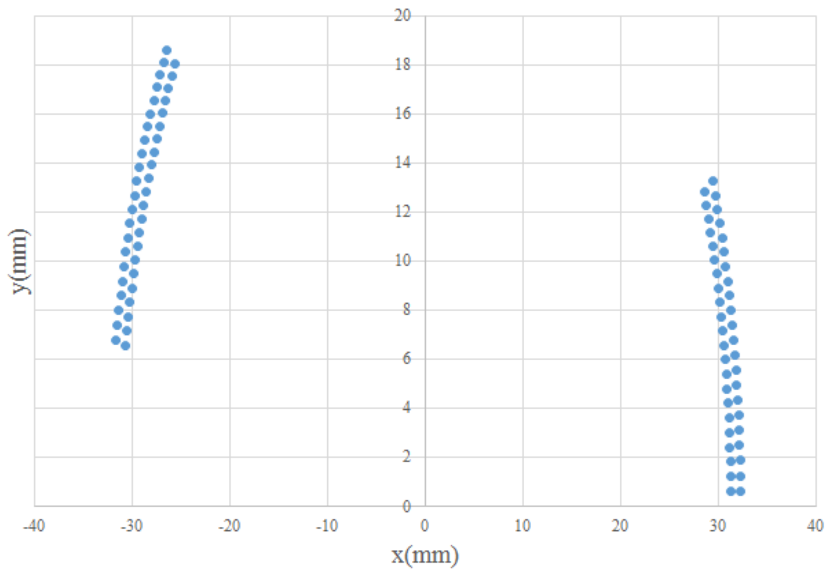


- Calculated integrated multipoles in 3D : b3 19 unit (1×10^{-4}), b4 3.6 unit.





- 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}.

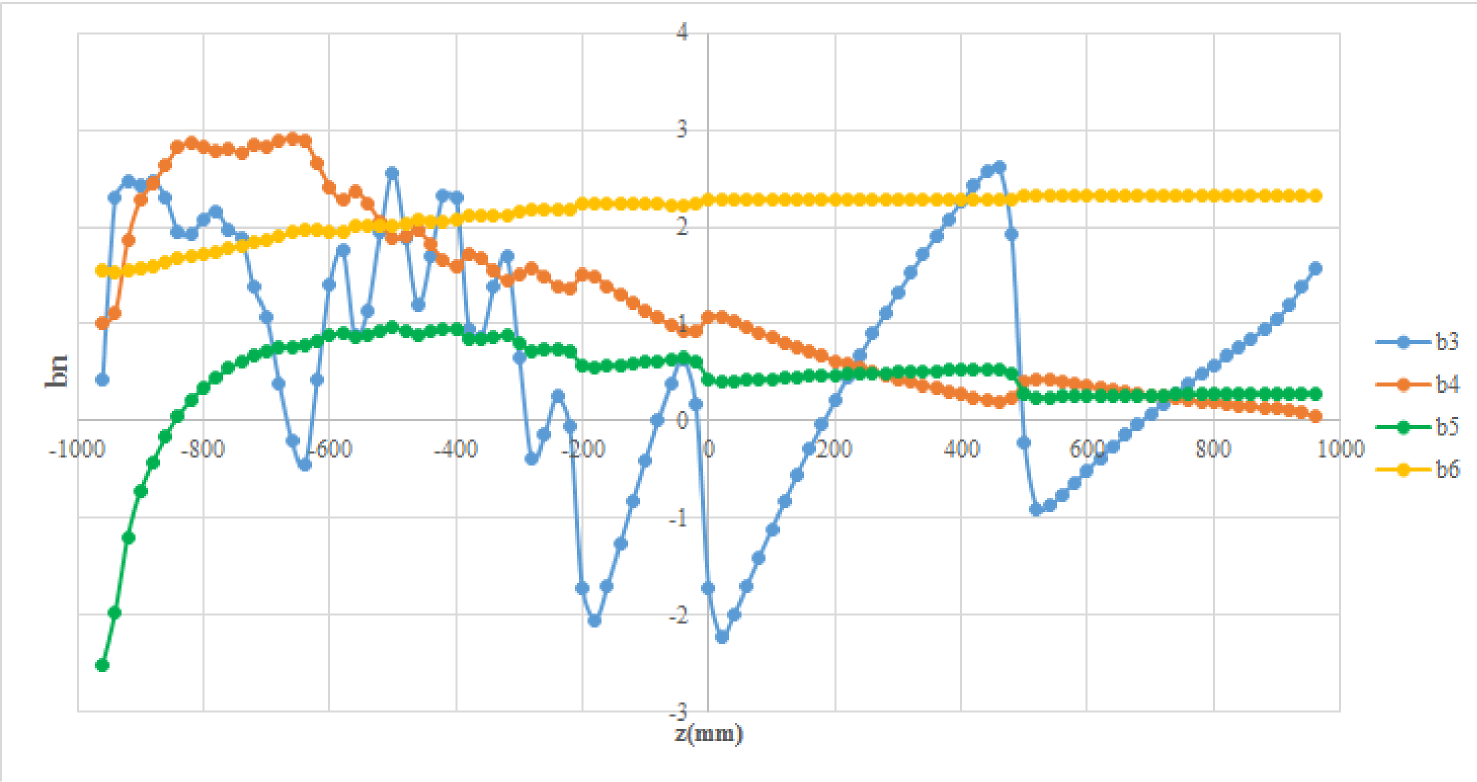


Shield coil layout (half)

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

n	B_n/B_2@R=9.8 mm
2	10000.0
3	-0.57419
4	1.525573
5	0.375555
6	-0.13735
7	0.015413
8	-0.03117
9	-1.7E-03
10	-0.05809

- To match the fall off of field harmonics caused by the field cross talk when the distance of two beam lines increases, the conductor length of shield coil at each angular position is different.

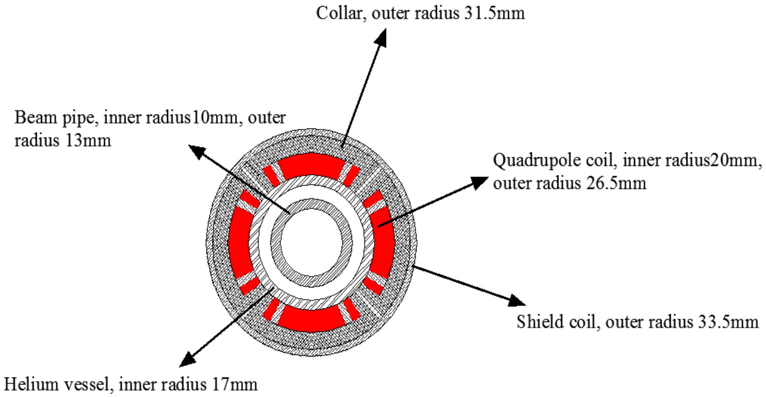


Field harmonics in one aperture along longitudinal position (1×10^{-4})

Design parameters and Layout of QD0:

Table 3: Design parameters of QD0 (Iron-free)

Magnet name	QD0
Field gradient (T/m)	136
Magnetic length (m)	2.0
Coil turns per pole	21
Excitation current (A）	2680
Shield coil turns per pole	44
Shield coil current (A）	135
Rutherford Cable	width 3 mm, mid thickness 0.94 mm, keystone angle 1.8 deg,Cu:Sc=1
Stored energy (KJ)	25.0
Inductance (H）	0.007
Peak field in coil (T)	3.3
Coil inner diameter (mm)	40
Coil outer diameter (mm)	53
X direction Lorentz force/octant (kN)	68
Y direction Lorentz force/octant (kN)	-140
Net weight (Kg)	75



Single aperture QD0

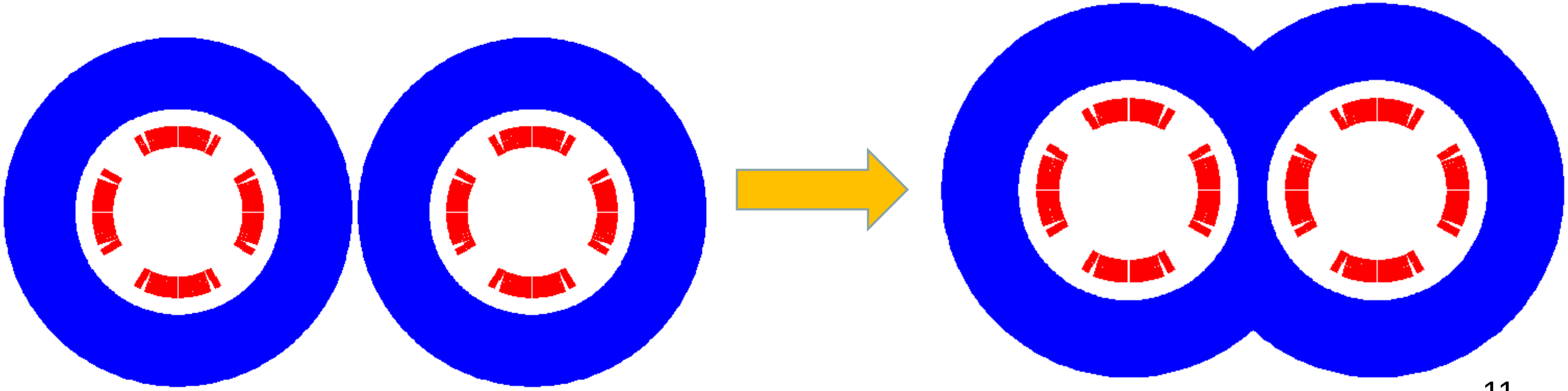
The current of QD0 at W and Z model will decrease.

Option2: QD0 design with iron

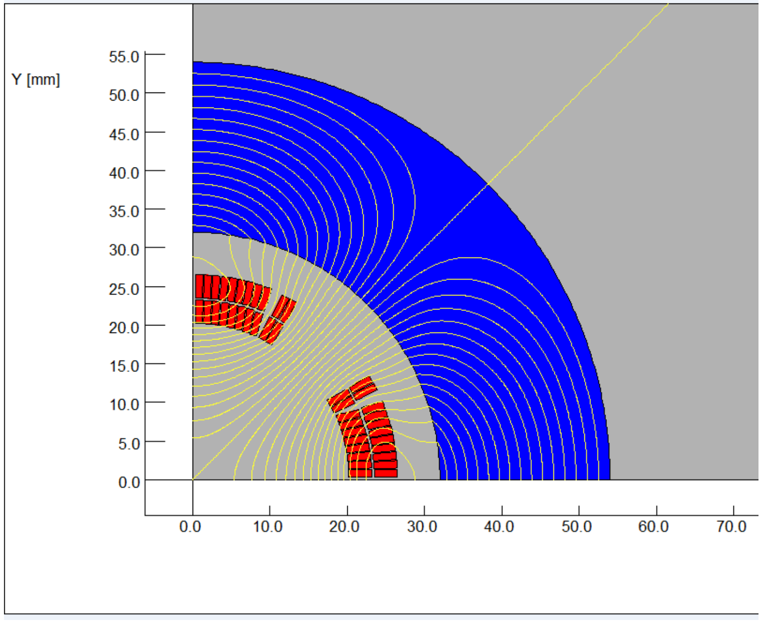
- QD0 CDR: 136T/m, **inner diameter 40mm**, length 2m.

QD0 design of iron option

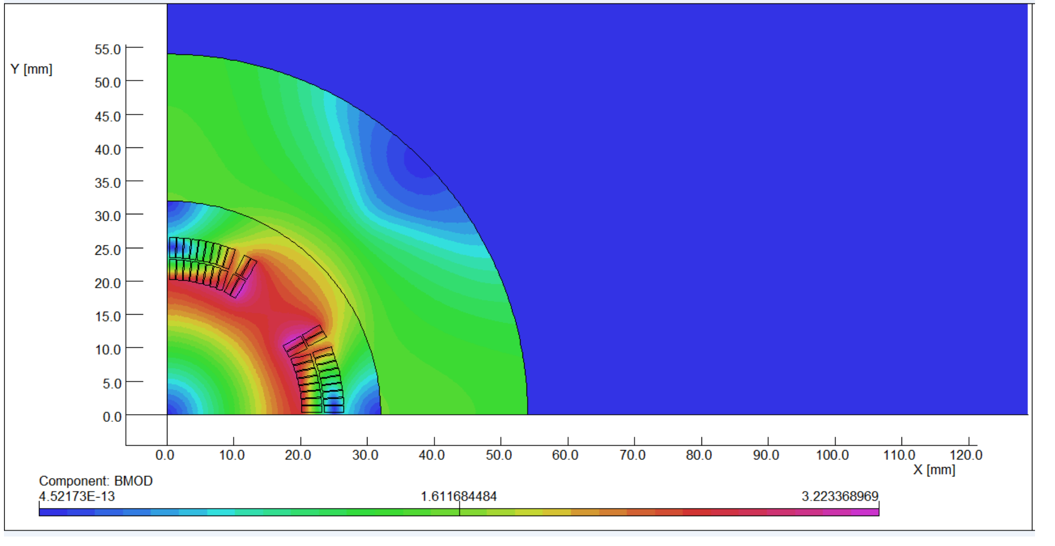
- Iron yoke is added outside the collar to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk.
- Not enough space to place two single apertures side by side, so a compact design is adopted.
- cos2θ quadrupole coil using NbTi Rutherford: highest magnetic efficiency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



- The design of QD0 is based on two layers cos2θ quadrupole coil using NbTi Rutherford cable with 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 2080A, and I_{op}/I_{c}<75% @4.2K.
- Actual insulation thickness and coil fabrication process are taken into account.



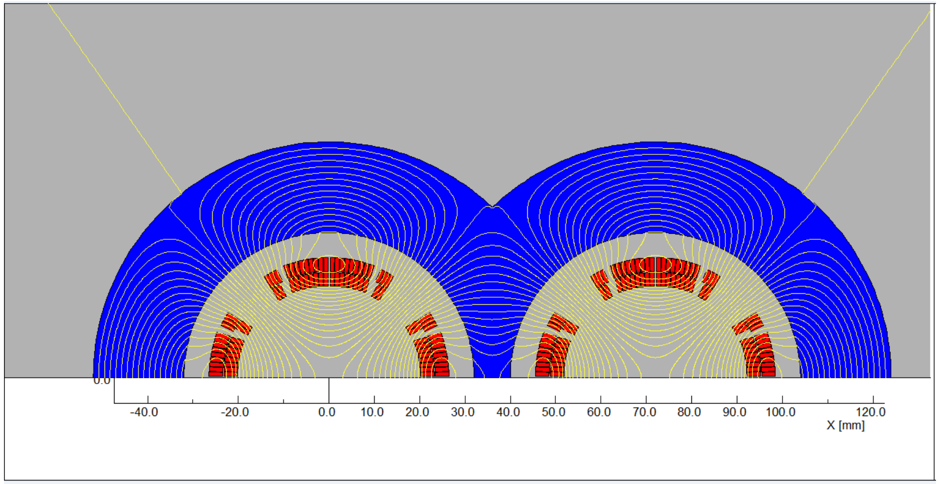
2D flux lines (1/4 cross section)



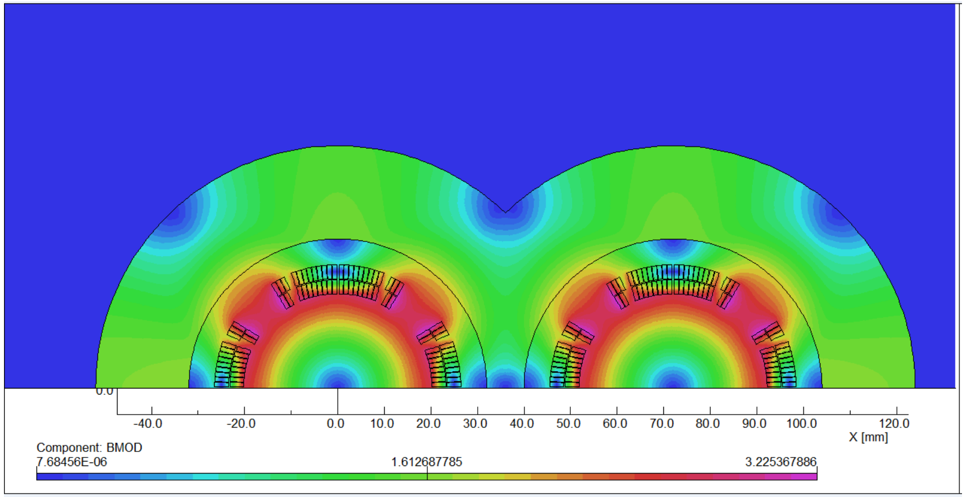
Magnetic flux density distribution

- 2D field cross talk of QD0 two apertures near the IP side.
- 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.

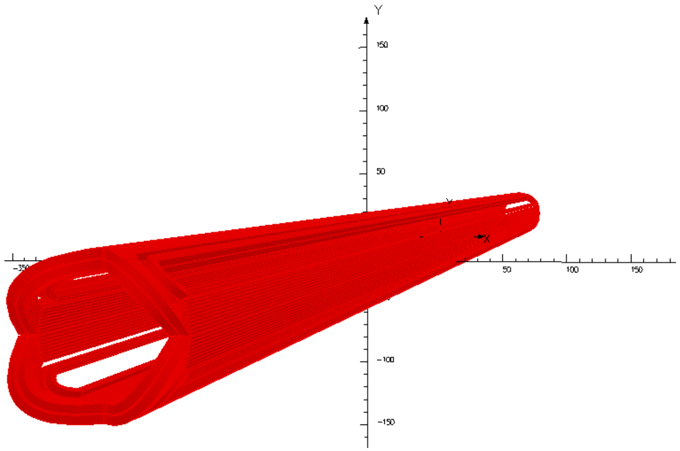
2D Flux lines

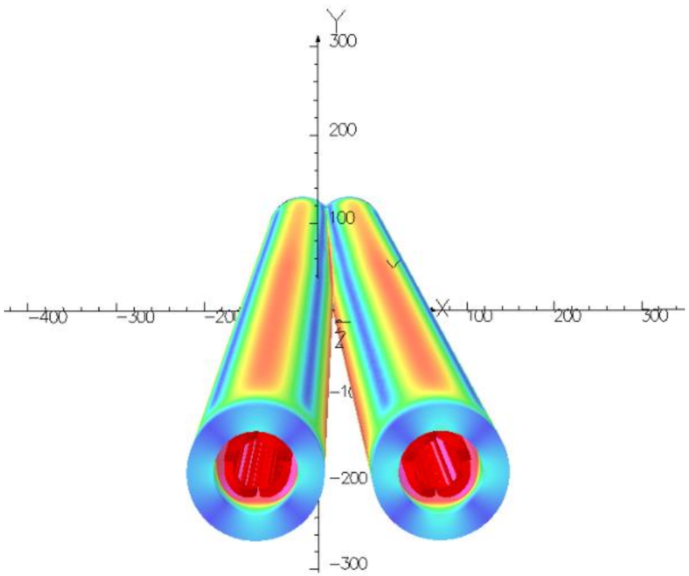


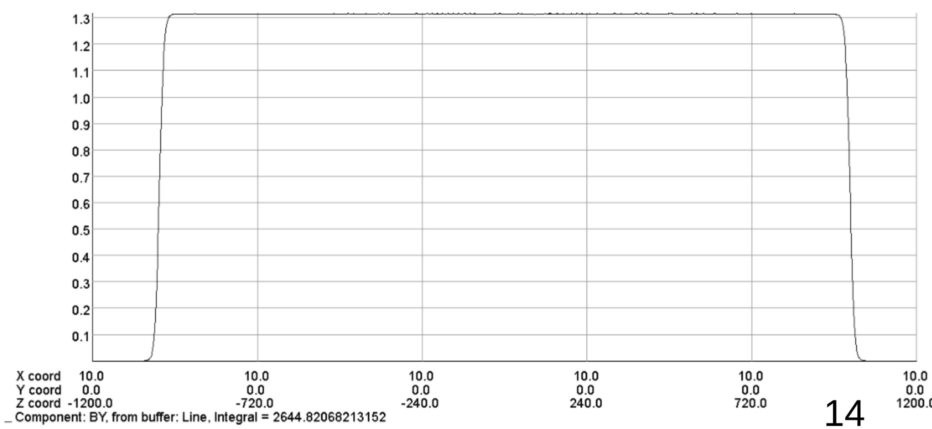
Bmod distribution



- ◆ QD0: Double aperture quadrupole magnet using cos2θ coil with iron yoke, with crossing angle between two apertures.
- ● Novel design, the first such magnet in the world.



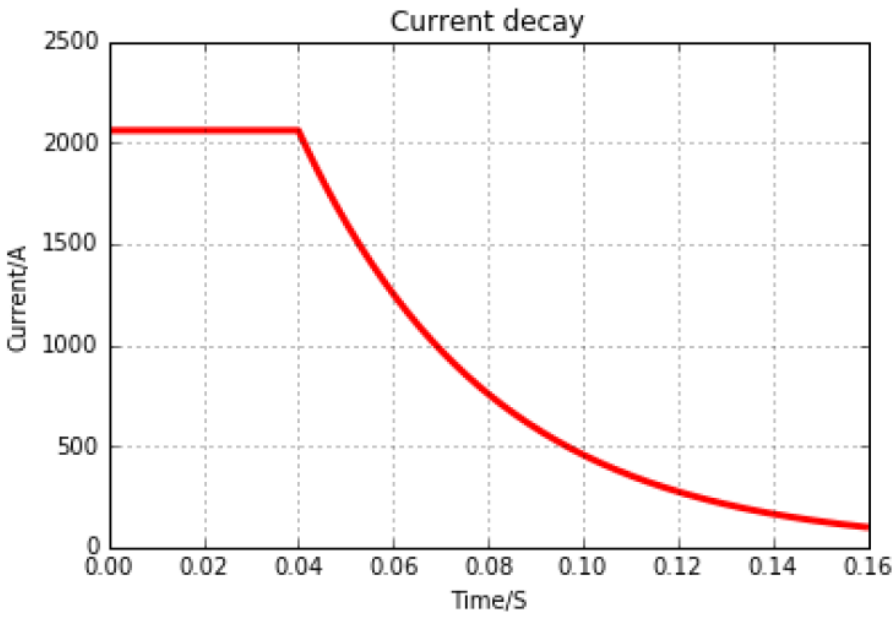


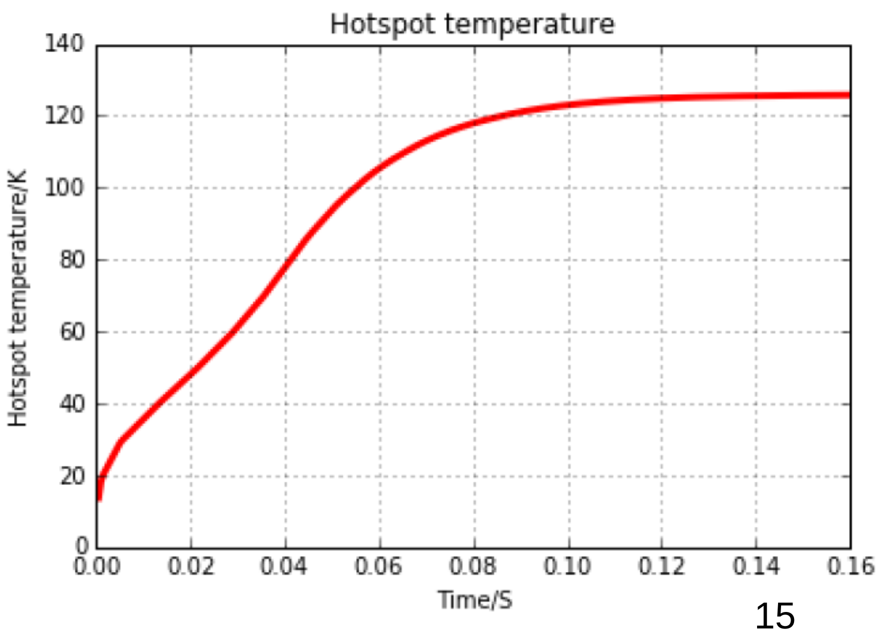


Opera

Quench simulation of QD0, safe

- ✓ Dump resistance=0.24Ω， Delay time= 40 ms.
- ✓ Hot spot temperature: 126K
- ✓ Magnet resistance: 0.009Ω
- ✓ Peak voltage : 500V

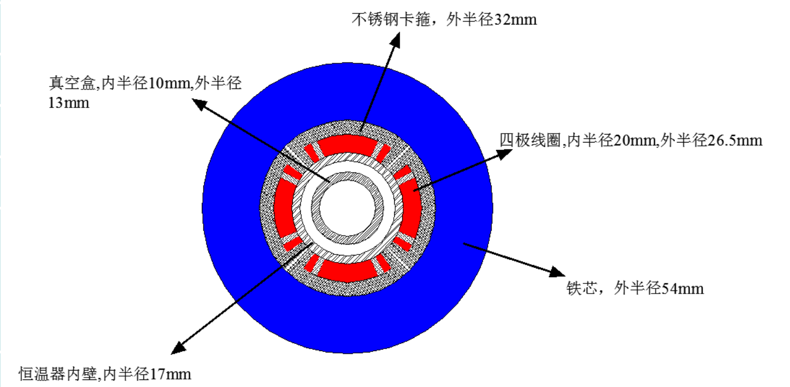




◆ Design parameters of QD0:

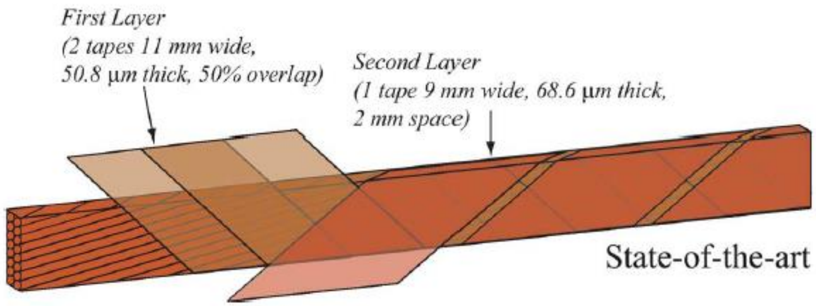
Table 4: Design parameters of QD0 (with iron core)

Magnet name	QD0
Field gradient (T/m)	136
Magnetic length (m)	2.0
Coil turns per pole	21
Excitation current (A）	2080
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
Stored energy (KJ) (Double aperture)	21.5
Inductance (H）	0.010
Peak field in coil (T)	3.3
Coil inner diameter (mm)	40
Coil outer diameter (mm)	53
X direction Lorentz force/octant (kN)	112
Y direction Lorentz force/octant (kN)	-108
Net weight (kg)	200

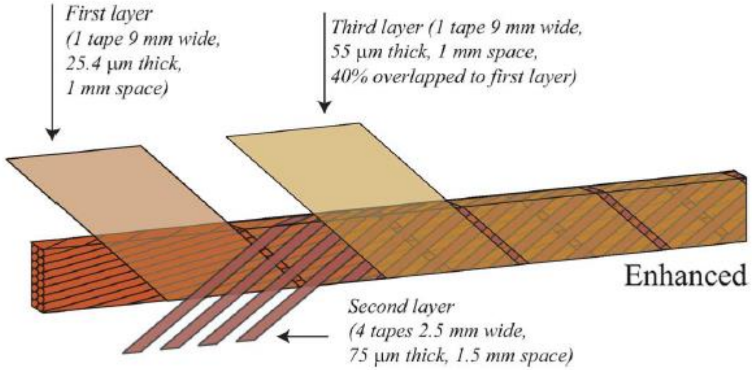


The current of QD0 at W and Z model will decrease.

- Literature survey of Cable insulation system for NbTi superconducting magnet



LHC insulation



Enhanced insulation

The most useful cooling method is liquid helium;
The most effective way to remove heat load is by superfluid helium at 1.9K.

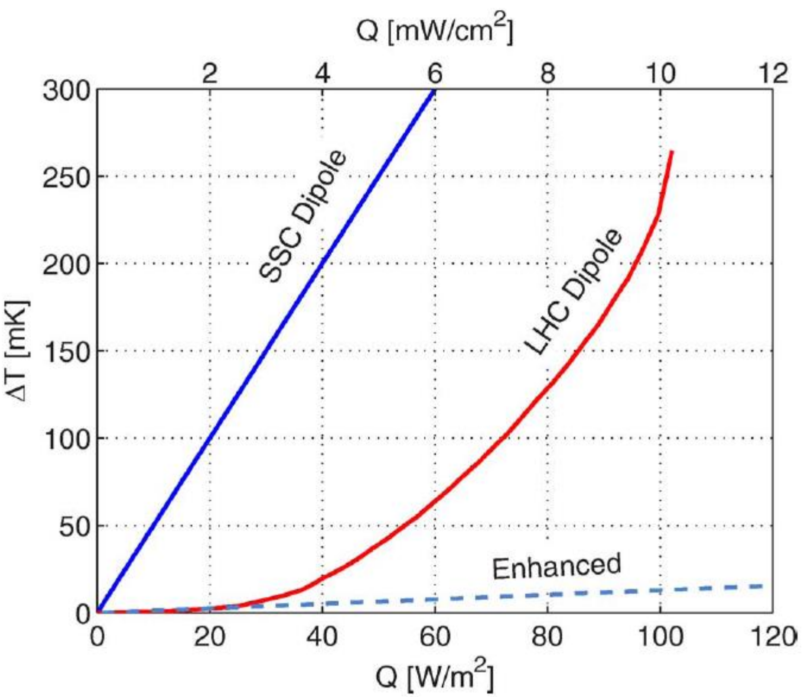


Fig. 3. Heat transfer curves for SSC and LHC insulations (measured [11]), and for enhanced insulation (estimated), all data refer to He II.

Enhanced insulation cable system will be used for CEPC superconducting quadrupole magnets.

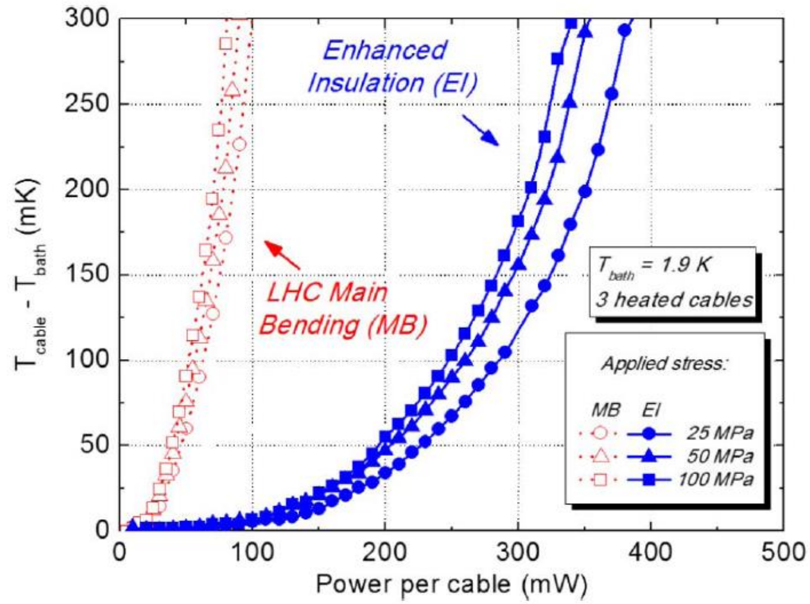


Fig. 2. Temperature rise of central cable vs. heat load for EI and MB insulation schemes at different pressure levels in 1.9 K He II bath (from [6]).

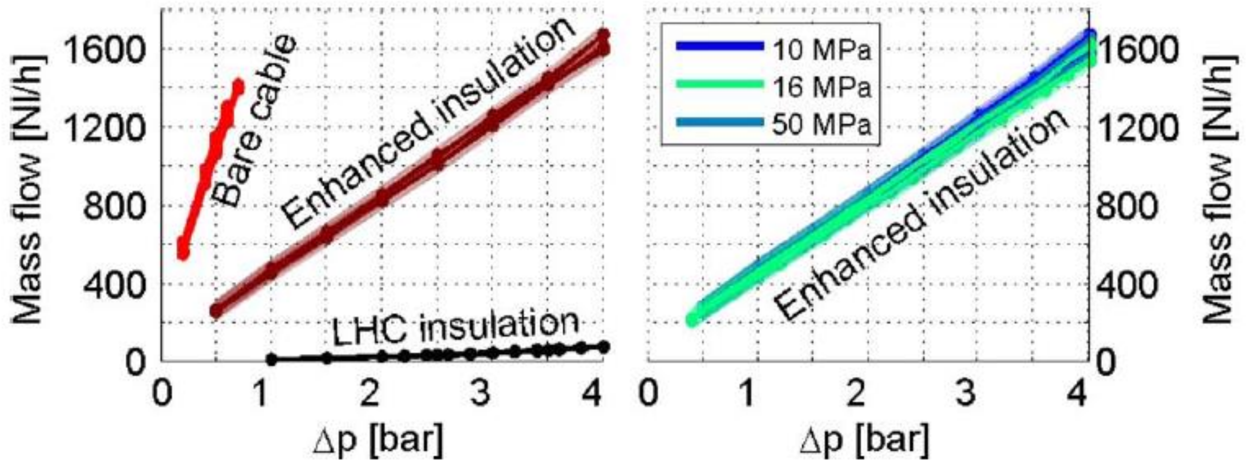
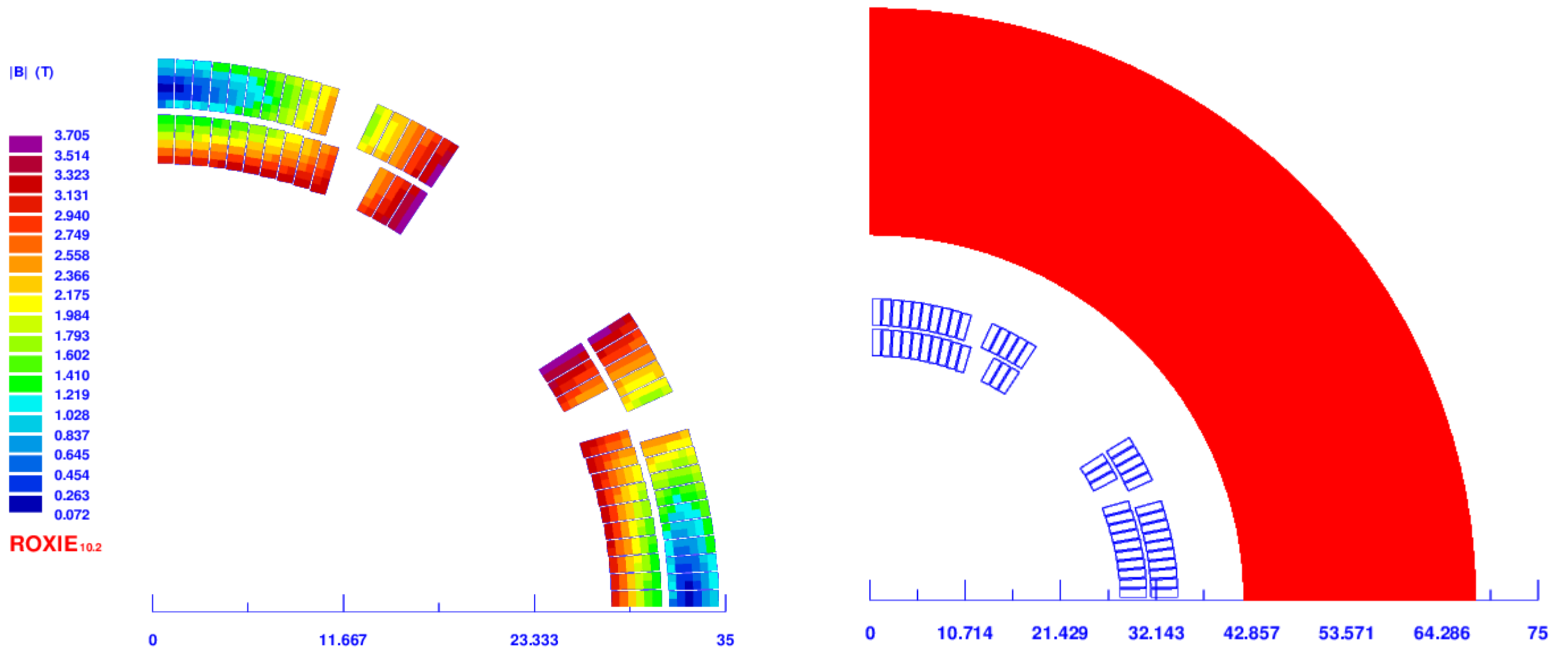


Fig. 8. Radial flow in cables with vertical compression of 10 MPa (left plot). Radial flow in cables with enhanced insulation, vertical compression of: 10, 16 and 50 MPa (right plot).

Design of superconducting quadrupole magnet QF1

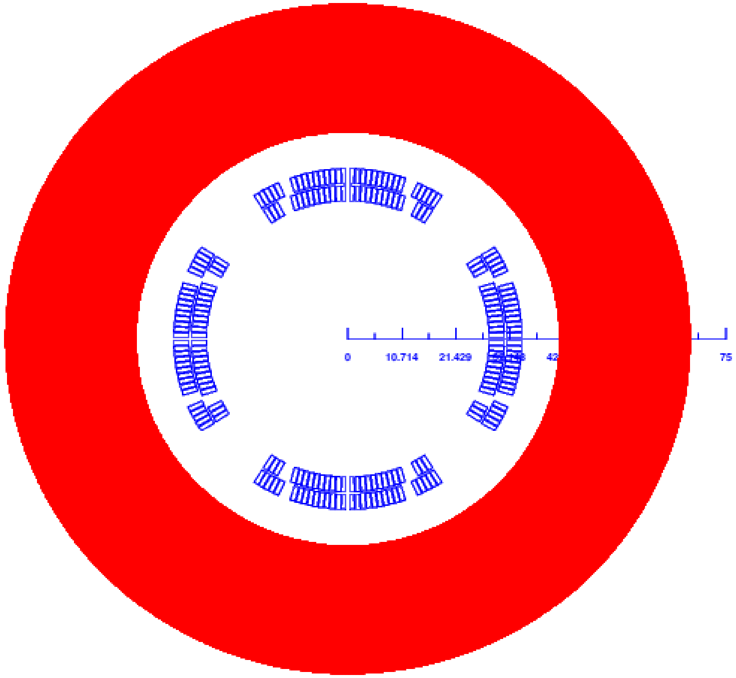
- The design of QF1 magnet is similar to the QD0 magnet, except that there is iron yoke around the quadrupole coil for QF1.
- The used Rutherford cable is similar to that of QD0. Since the distance between the two apertures is much larger and the usage of iron yoke, the field cross talk between the two apertures of QF1 is not 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.



2D model (One quarter cross section)

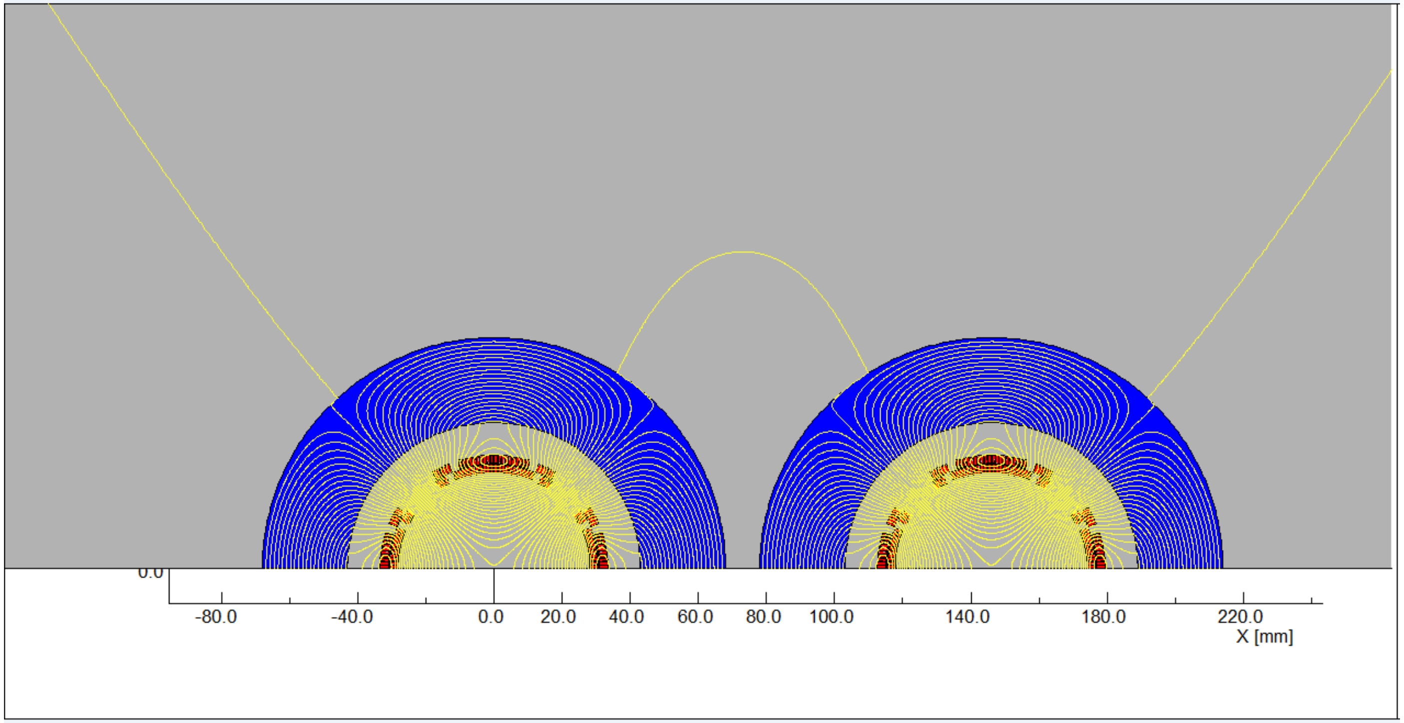
Table 5: 2D field harmonics of QF1 (unit, 1×10^{-4})

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

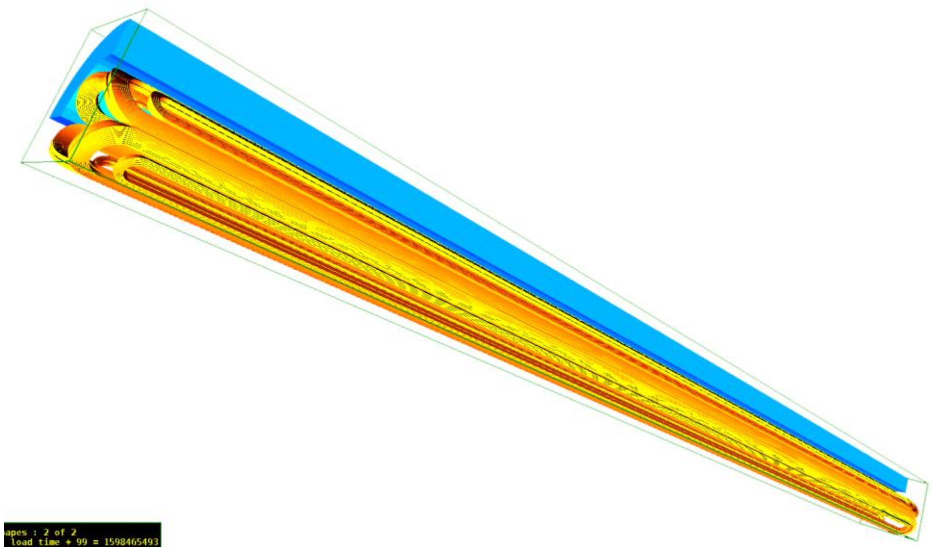
- Field cross talk of QF1 two apertures is modelled and studied in OPERA-2D.
- The calculation results show that, the iron yoke can well shield the leakage field of each aperture.
- Each systematic field harmonics is smaller than 1 unit (1×10-4).
- The non-systematic field harmonics as a result of field cross talk can be neglected.

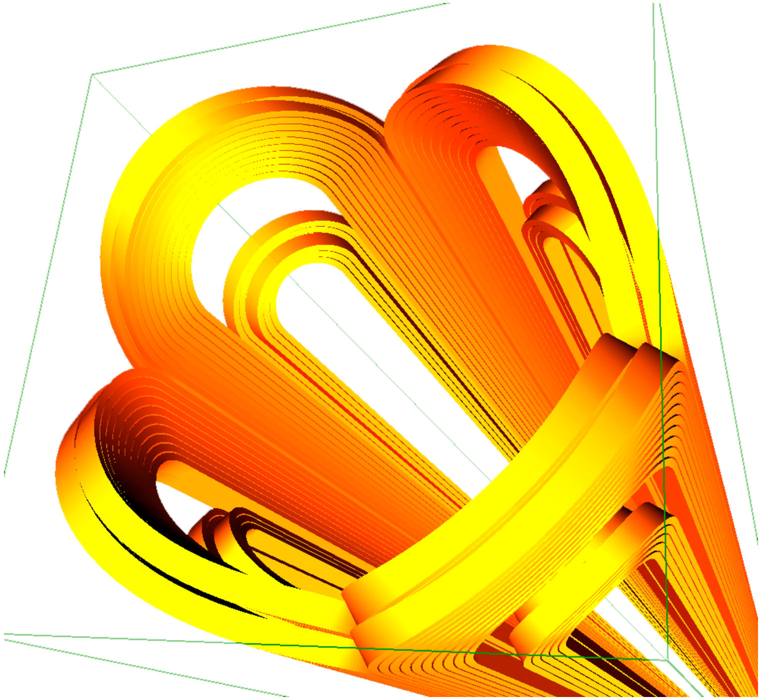


Two aperture Flux lines

3D magnetic field optimization

- ◆ Coil end shape is determined by ROXIE.
- ● The field gradient, magnetic length meet the design requirement.
- ● Each systematic field harmonics is smaller than 1 unit (1×10^{-4}).

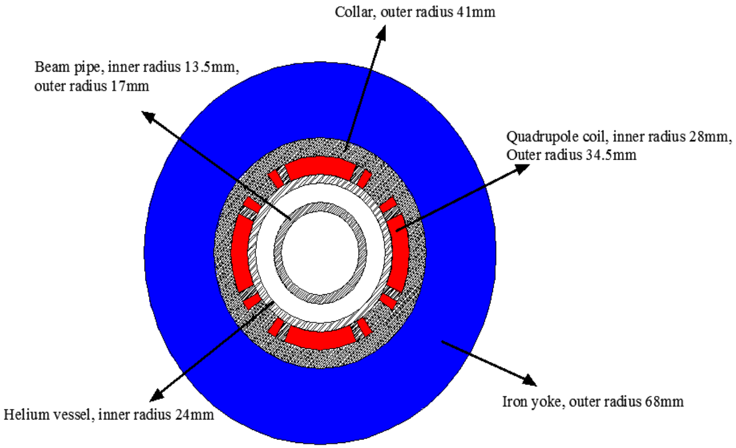




◆ Design parameters and magnet Layout of QF1:

Table 6: Design parameters of QF1

Magnet name	QF1
Field gradient (T/m)	110
Magnetic length (m)	1.48
Coil turns per pole	28
Excitation current (A）	2280
Coil layers	2
Conductor size (mm)	Rutherford Cable, width 3 mm, mid thickness 0.95 mm, 12 strands
Stored energy (KJ)	30.5
Inductance (H）	0.012
Peak field in coil (T)	3.8
Coil inner diameter (mm)	56
Coil outer diameter (mm)	69
X direction Lorentz force/octant (kN)	110
Y direction Lorentz force/octant (kN)	-120
Net weight (kg)	290



Single aperture QF1

The current of QF1 at W and Z model will decrease.

Design of superconducting anti-solenoid

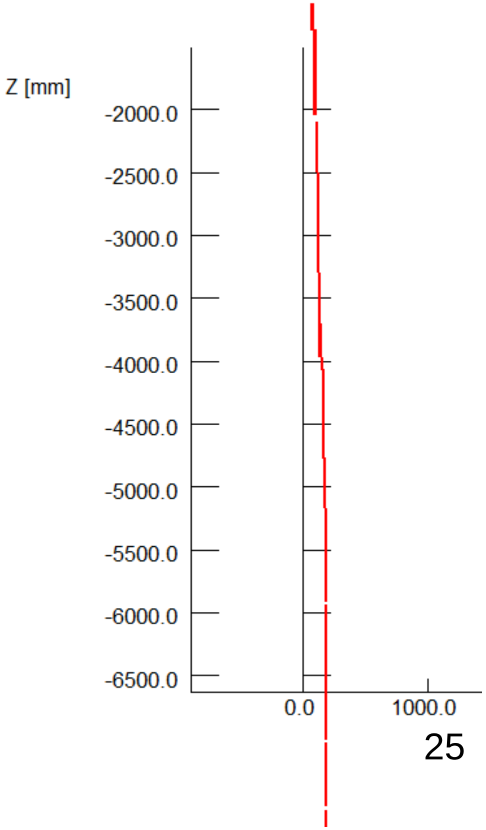
- The design requirements of the anti-solenoids in the CEPC Interaction Region are summarized below:

1) The total integral longitudinal field generated by the detector solenoid and anti-solenoid coils is zero. $\int B_z ds = 0$
2) The longitudinal field inside QD0 and QF1 should be smaller than a few hundred Gauss at each longitudinal position.
3) The distribution of the solenoid field along longitudinal direction should meet the requirement of the beam optics for emittance.
4) The angle of the anti-solenoid seen at the collision point satisfies the Detector requirements.

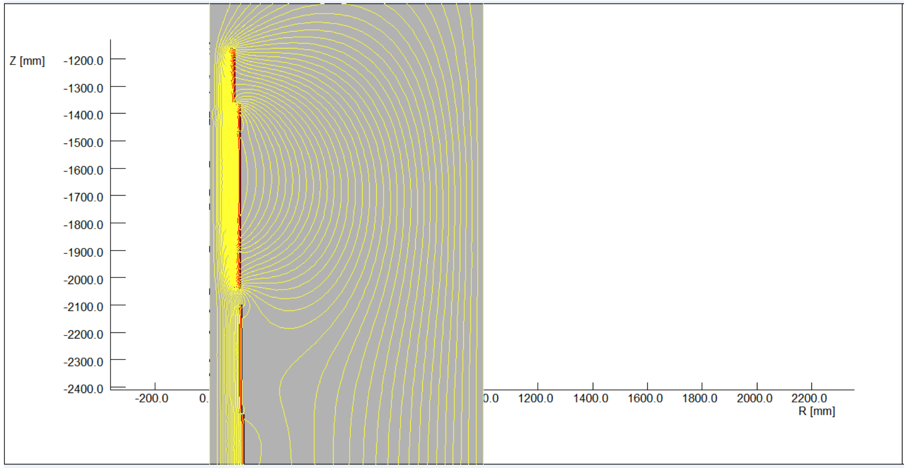
- The design of the anti-solenoid fully takes into account the above requirements. The anti-solenoid will be wound of rectangular NbTi-Cu conductor.

- 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.
- These sections are connected in series, but the current of some sections of the anti-solenoid can be adjusted using auxiliary power supplies if needed.

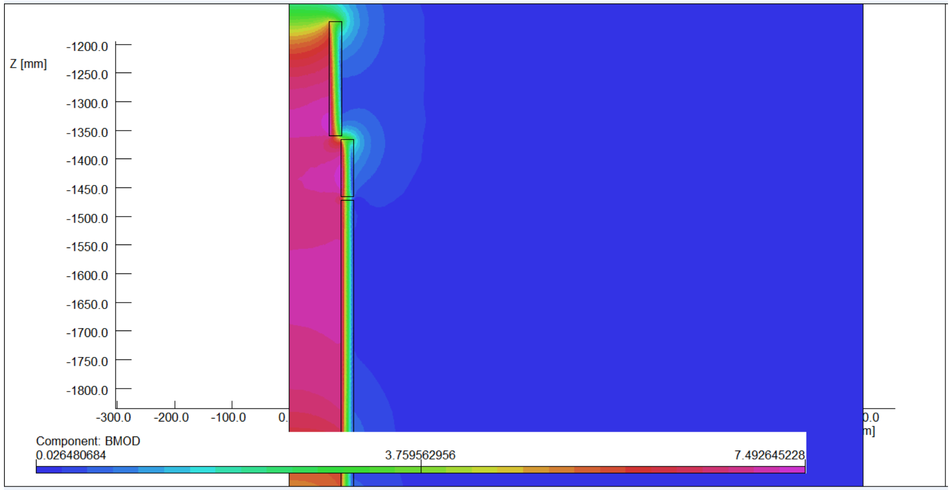
- The anti-solenoid along longitudinal direction:
  1) 4 sections, from IP point to QD0;
  2) 12 sections, QD0 region;
  3) 6 sections, QF1 region;
  4) 7 section, after QF1 region.
- To reduce the length of the cryostat, the sections of anti-solenoid after QF1 region with low field will be operated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



- 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 7.0T.

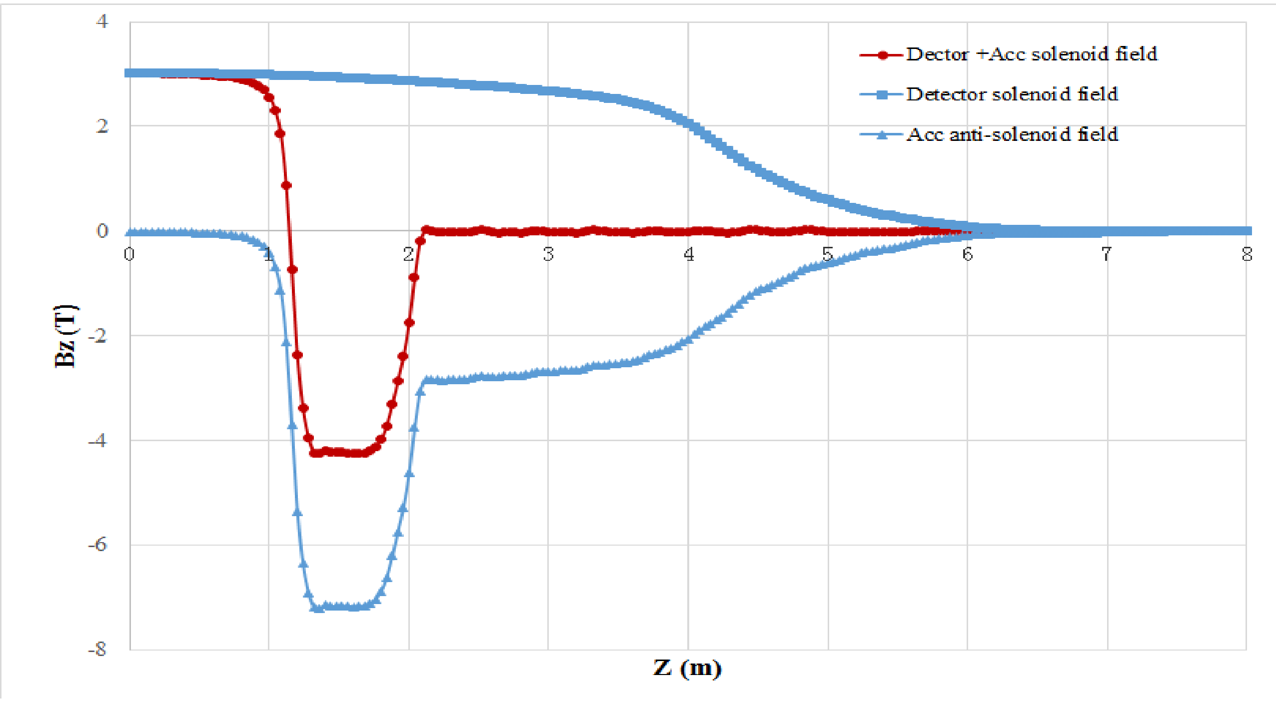


2D flux lines



Magnetic flux density distribution

◆ Combined field of Anti-solenoid and Detector solenoid.

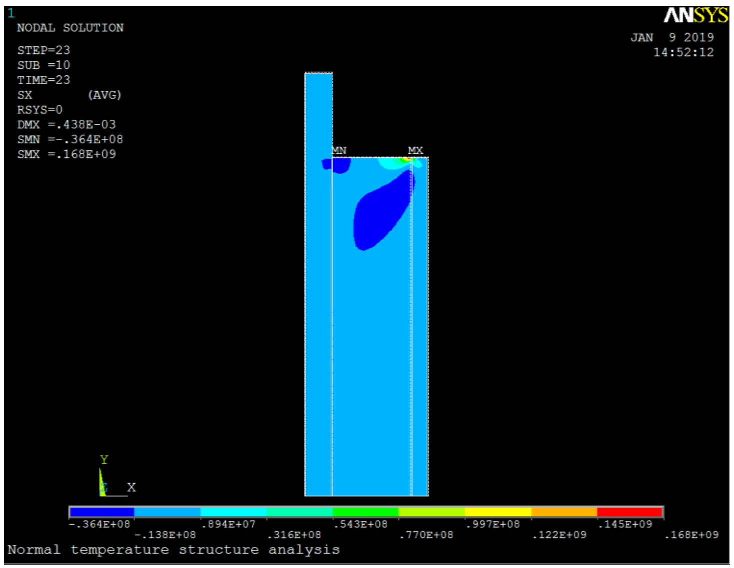


◆ The net solenoid field inside QD0 and QF1 at each longitudinal position is smaller than 300 Gs.

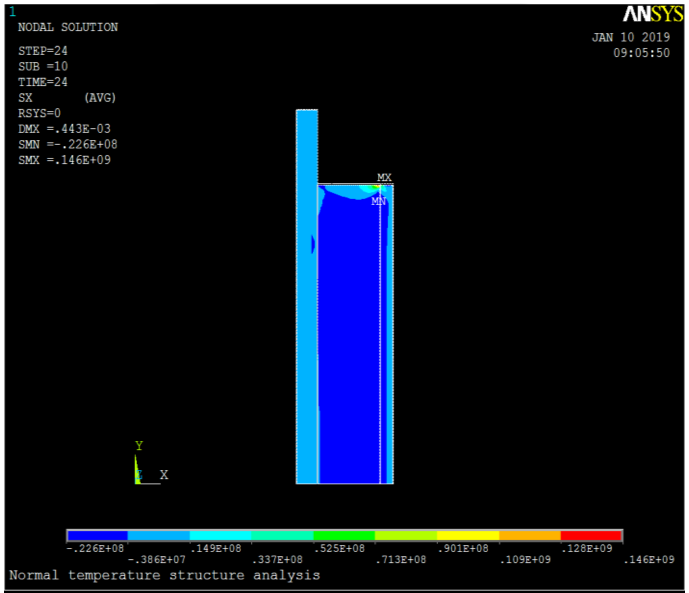
● The combined field distribution of anti-solenoid and Detector solenoid well meets the requirement of beam dynamics for emittance.

Stress analysis of first section of Anti-solenoid.

- A two-dimensional axisymmetric finite element model using ANSYS is established to model and analysis the stress of the first section of Anti-solenoid with a central field of 7T.



Stress after cool down to 4.2K



Stress after excitation

- The FEM analysis result shows that, the stress in each component of the Anti-solenoid during each operation step is safe, and the radial stress of the bottom coil to the support tube is still compressive stress when excited at 4.2K.

◆ Design parameters of Anti-solenoid:

Table 7: Design parameters of Anti-solenoid

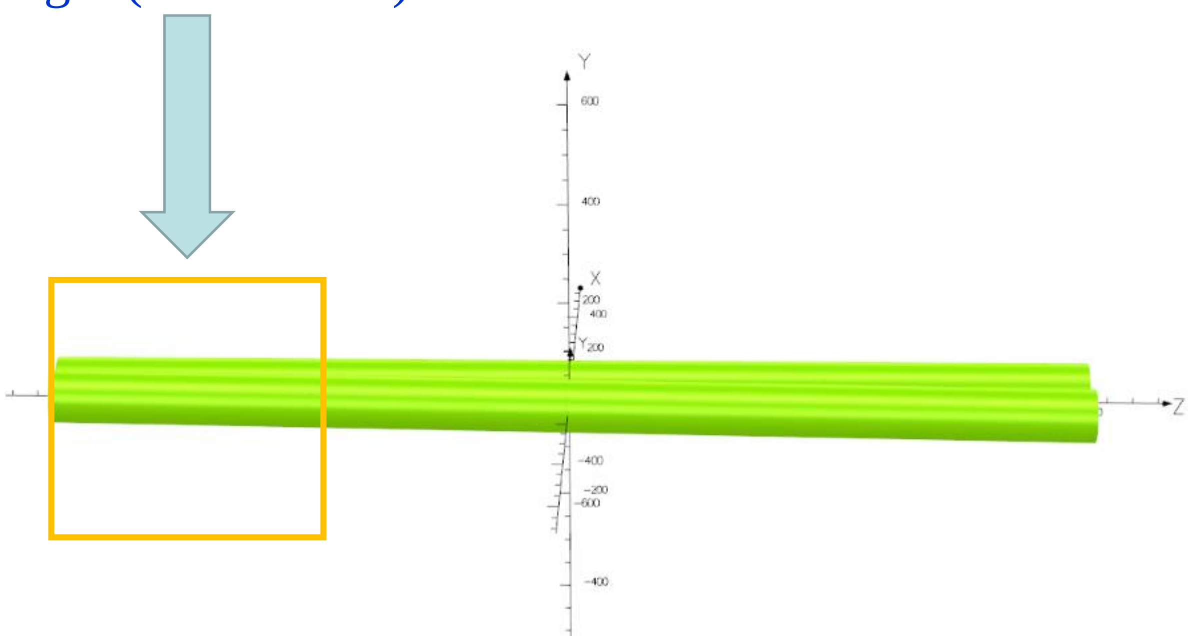
Magnet name	Anti-solenoid before QD0	Anti-solenoid QD0	Anti-solenoid after QD0
Central field（T）	7.0	2.8	1.8
Magnetic length（m）	1.1	2.0	1.7
Conductor (NbTi-Cu, mm)	2.5×1.5		
Coil layers	16	8	4/2
Excitation current（kA）	1.0		
Stored energy (KJ)	715		
Inductance（H）	1.4		
Peak field in coil (T)	7.7	3.0	1.9
Number of sections	4	11	7
Solenoid coil inner diameter (mm)	120		
Solenoid coil outer diameter (mm)	390		
Total Lorentz force F_z (kN)	-75	-13	88
Net weight (kg)	780		

Mechanical design of QD0 short model magnet

- Novel design of QD0:

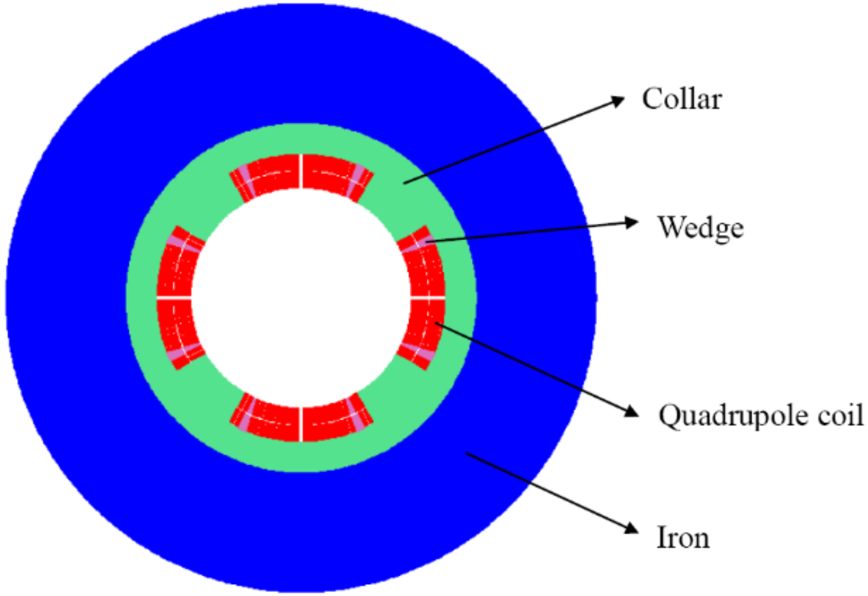
Collared cos2θ quadrupole magnet with shared iron yoke and crossing angle between two aperture centerlines. **In practice, can it be fabricated and really meet the requirement?**

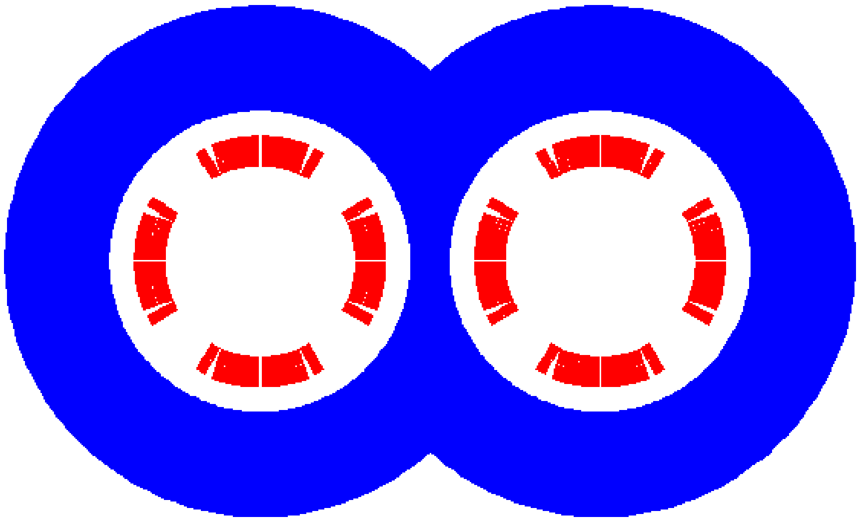
- So far, there is no cos2θ superconducting quadrupole magnet in China.
- In the R&D of CEPC interaction region superconducting magnets, the first step is to **study and master the main key technologies of** superconducting quadrupole magnet by developing a short QD0 model magnet (短实验磁体) with 0.5m length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



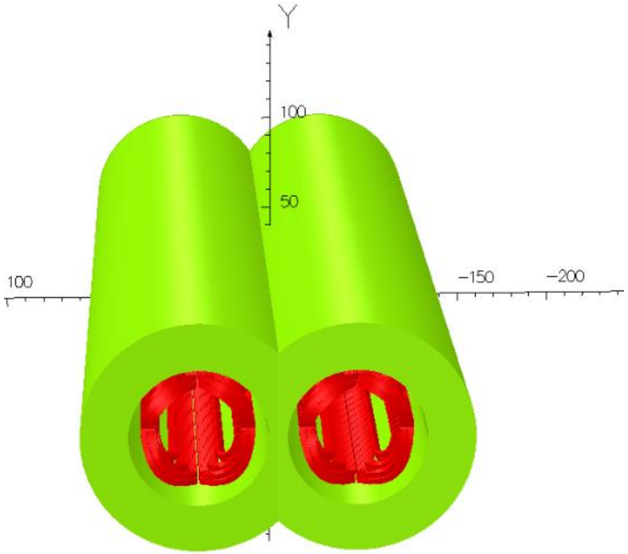
- The aim of QD0 short model magnet:

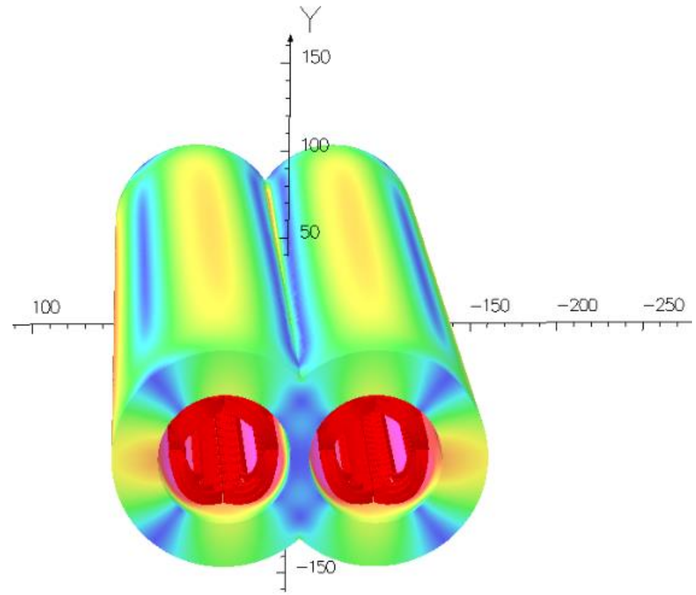
  Verify magnet design;
  Exploring magnet manufacturing technology;
  Master cryogenic testing Technology;
  Master the magnetic and quench performance of magnet;
  Lay the foundation for the development of long QD0 prototype.

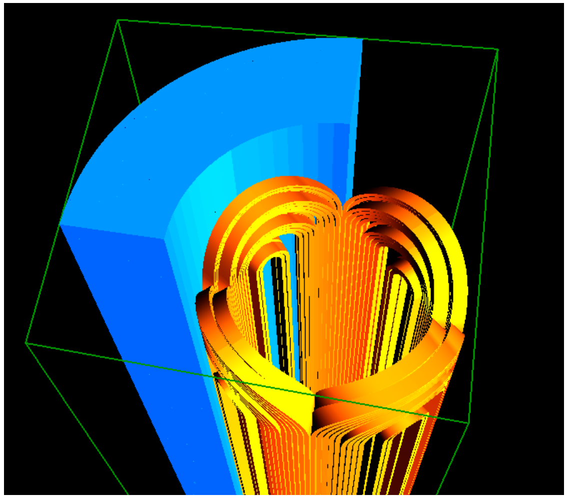


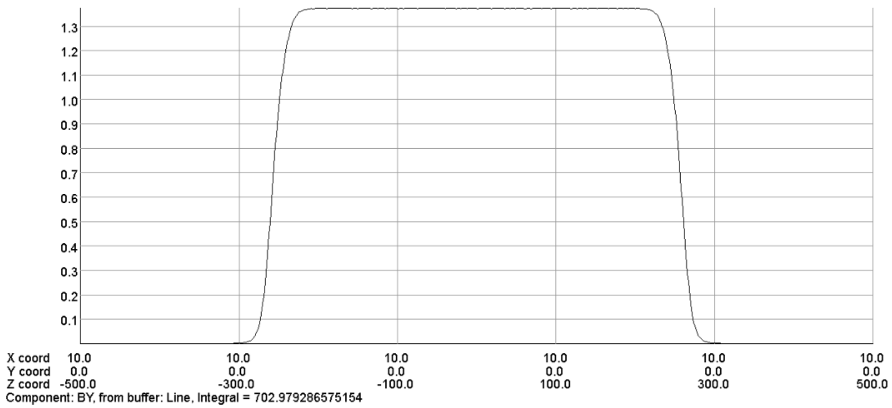


● 3D field simulation of two apertures 0.5m QD0.









- 3D field simulation result shows that, local field harmonic as a result of field cross talk is smaller than 0.5 unit (1×10^{-4}).
- Each integrated multipole field as a result of field crosstalk between the two apertures is smaller than 0.3 unit.
- The dipole field is smaller than 10 Gs at each longitudinal position.

Table 8: 3D integrated field harmonics（unit, 1×10^{-4}）

n	B_n/B_2@R=9.8 mm
2	10000.0
3	-0.28
4	0.017
5	-0.01
6	0.06
7	-0.02
8	0.022
9	0.012
10	-1.78
11	-0.02
12	0.015

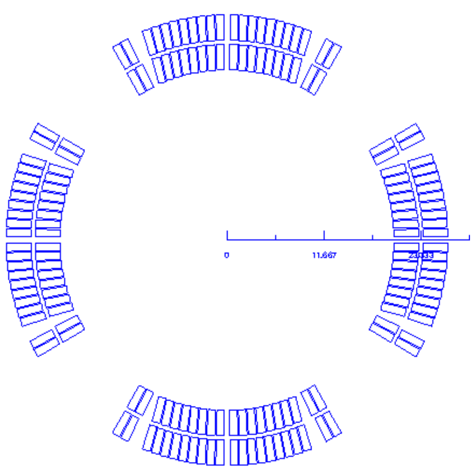
- The coil turns, the coil dimension and the excitation current of QD0 are consistent with the expressions of Ampere-Turns for superconducting quadrupole magnets based on sector coils.

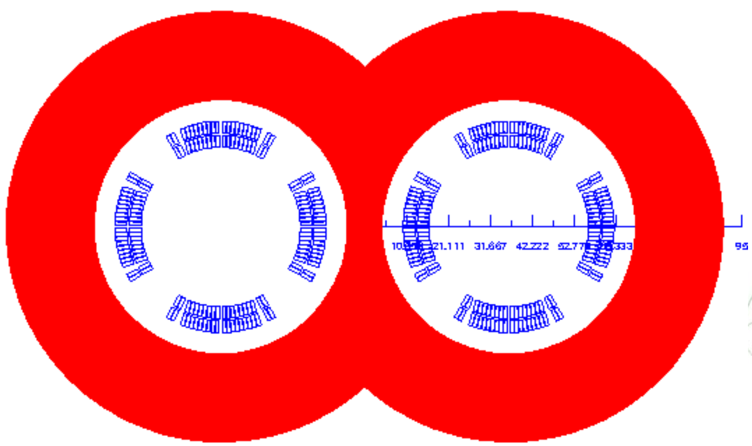
$$(NI)_{Quadrupole} \approx \frac{G\overline{R}^2}{\mu_0} \qquad \text{(no iron)}$$

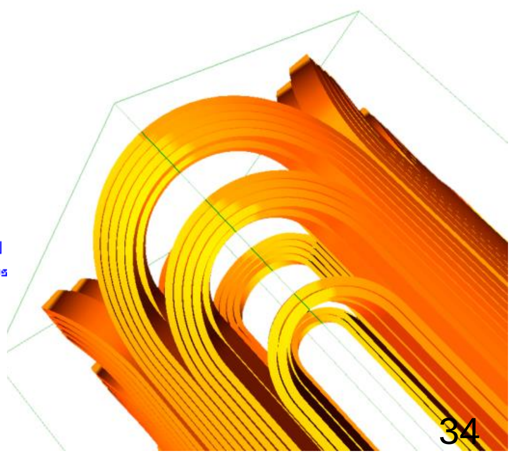
$$(NI)_{\text{Quadrupole}} \approx \frac{G\overline{R}^2}{\mu_0} / (1 + (\frac{\overline{R}}{R_y})^4) \qquad \text{(with iron)}$$

Yingshun Zhu, et al., Study on Ampere-Turns of Superconducting Dipole and Quadrupole Magnets Based on Sector Coils, *Nuclear Instruments and Methods in Physics Research A*, 2014, 741: 186-191.

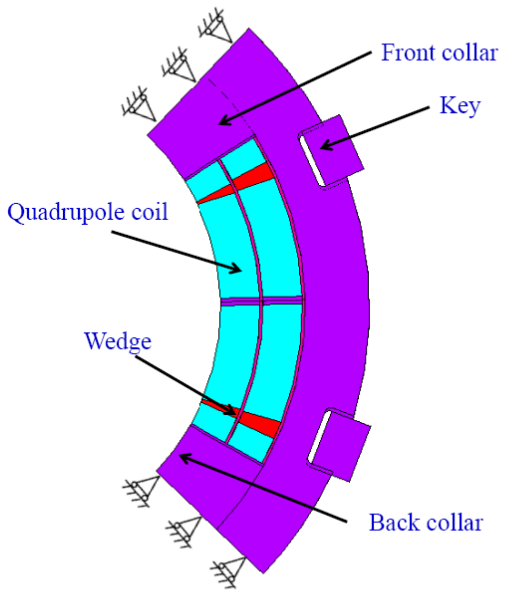
- The magnetic design is checked using ROXIE.



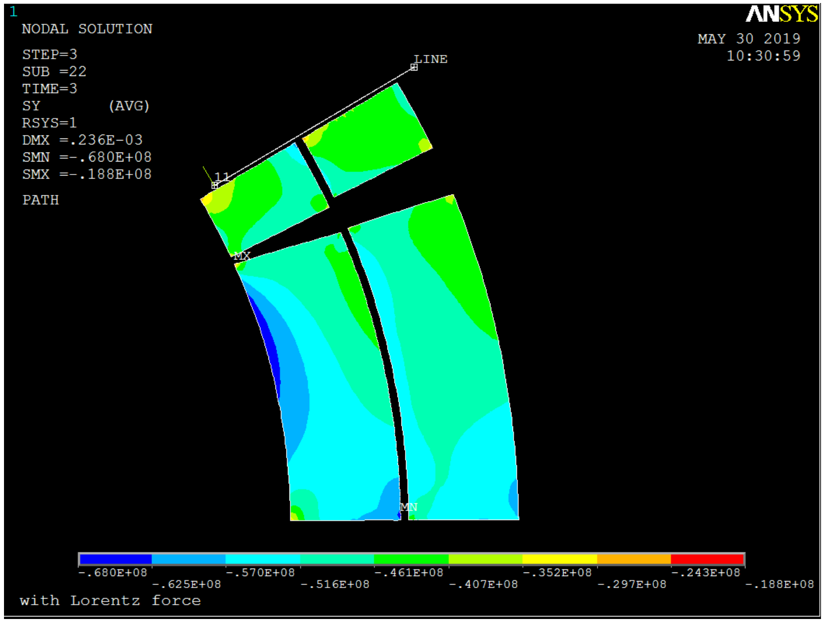




◆ Stress analysis of QD0 short model magnet:



Model



Stress in coil after excitation

- A total of 8 keys are used in the whole cross section.
- The FEM analysis result shows that, the stress in each component during each operation step is safe.
- **Collar material with high strength is required.**

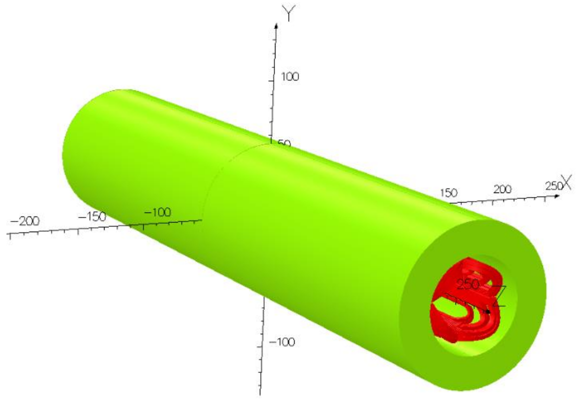
- ✓ **Cost inquiry for QD0 short model magnet fabrication has been completed.**
- The basic hardware necessary for prototype magnet was investigated.
- Winding machine for 0.5m QD0 quadrupole coil is available in IHEP Magnet Group (need some tooling).

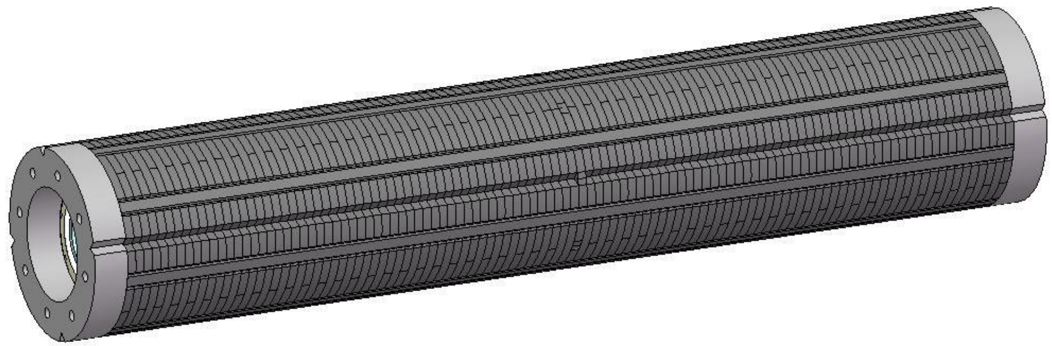
IHEP winding machine

Review meeting

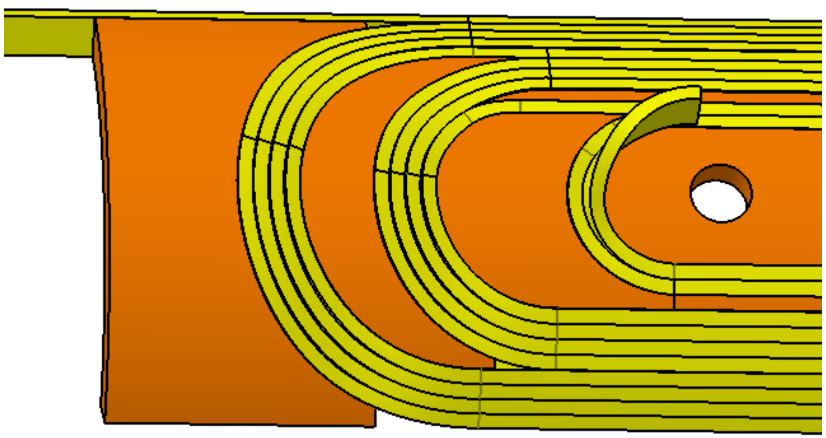
- The physical design of QD0 short model magnet passed the experts review in July 2019.

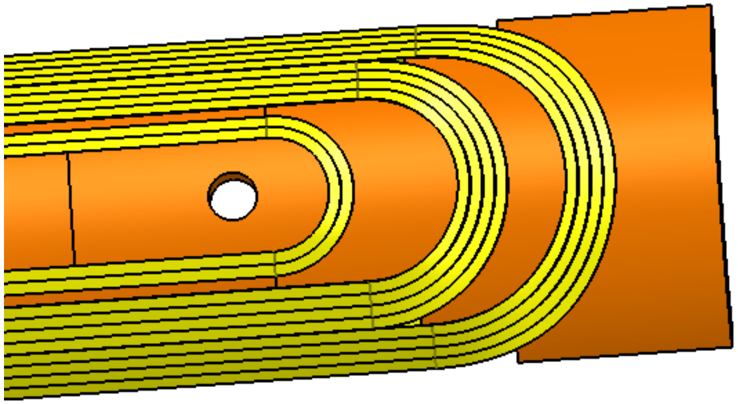
- Research on some key technologies of superconducting quadrupole magnet in CEPC IR has started, in collaboration with HeFei KEYE Company.
- Including: quadrupole mechanical design, coil winding technology, fabrication procedure study of quadrupole coil with small diameter, stress applying and monitoring,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



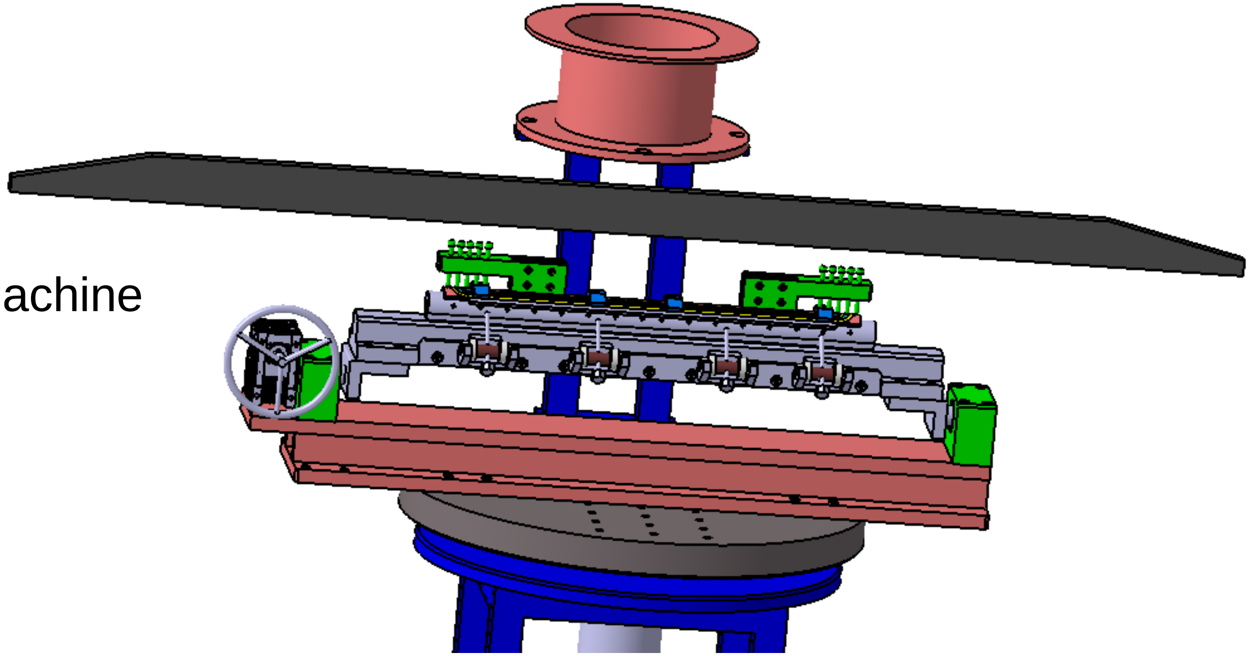


- Mechanical design of the quadrupole coil winding and support structure, winding machine has been finished.

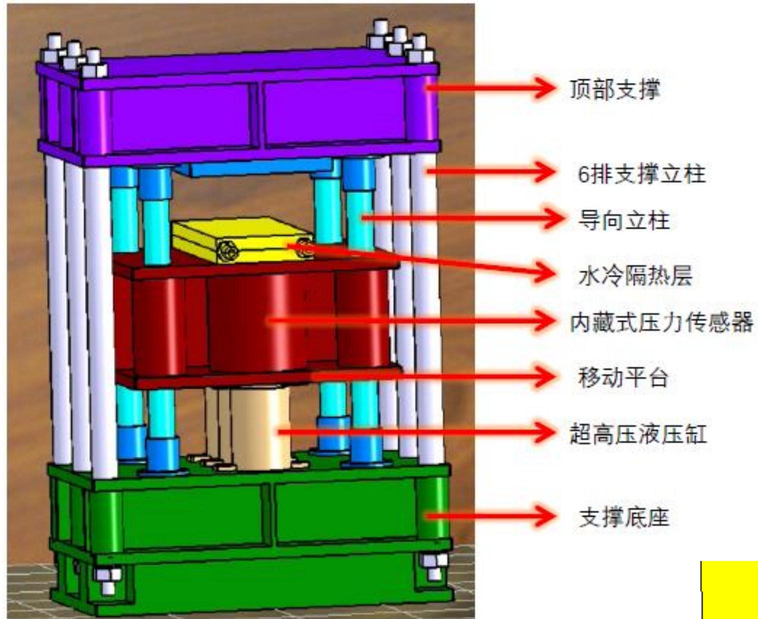


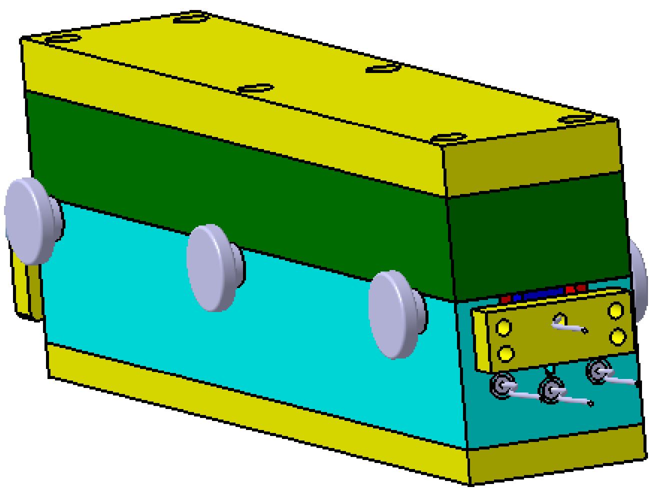


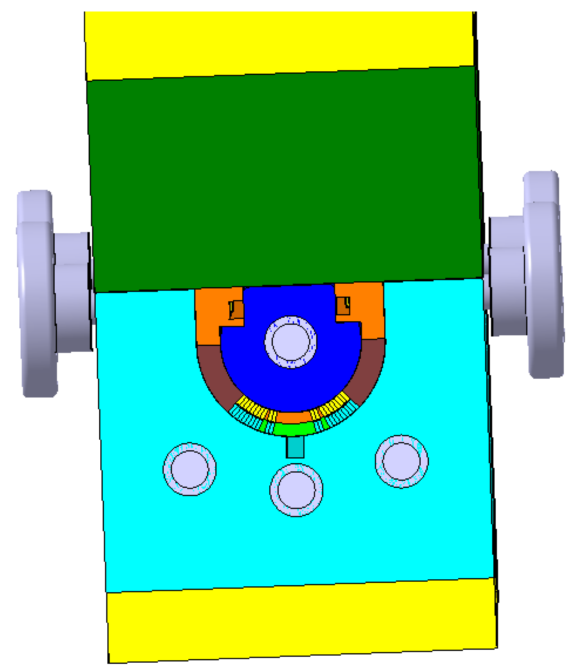
Coil winding machine



- Mechanical design of Superconducting quadrupole coil heating and curing system is completed.







Summary

- MDI superconducting magnets are key devices for CEPC. The design of superconducting magnets with the CDR parameter meets the requirement.
- **Novel design of QD0 is adopted.** Despite limited space, magnetic field cross talk effect between two apertures is negligible using iron yoke. Compared with the iron-free design of QD0, the excitation current with iron yoke can be substantially reduced.
- The anti-solenoid is divided into a total of 29 sections with different inner coil diameters, with a max central field of 7.0 T.
- So far, there is no cos2θ superconducting quadrupole magnet in China. The first step of the R&D is to **study and master main key technologies** of superconducting quadrupole magnet by developing a short QD0 model magnet with 0.5m length.
- **The physical design of the 0.5m model magnet has been finished and reviewed**. Its mechanical design is finished.

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Thanks for your attention!