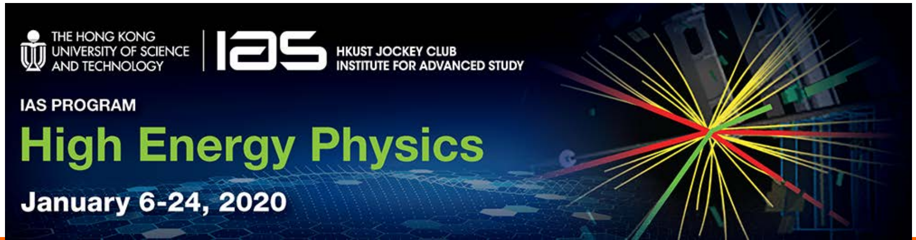

CEPC MDI SC Magnet System

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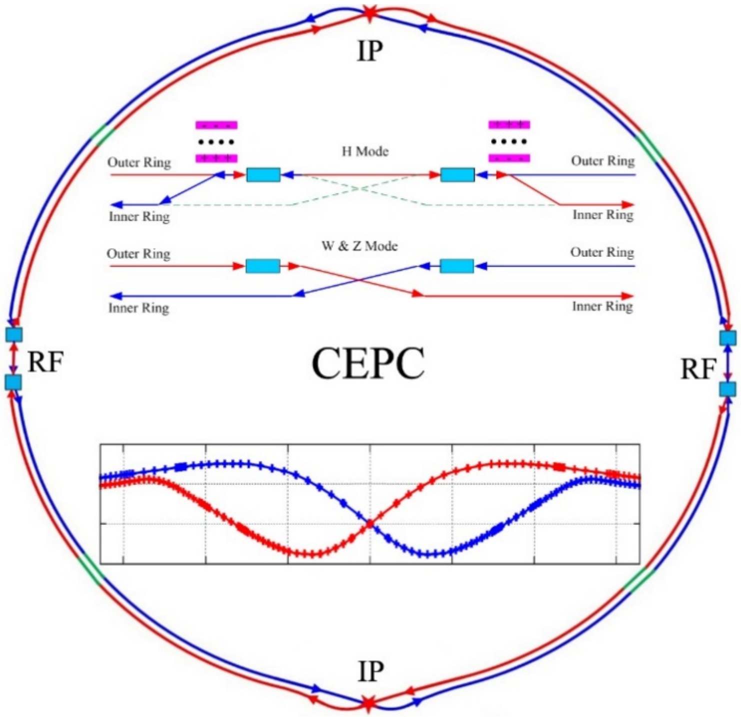
Outline

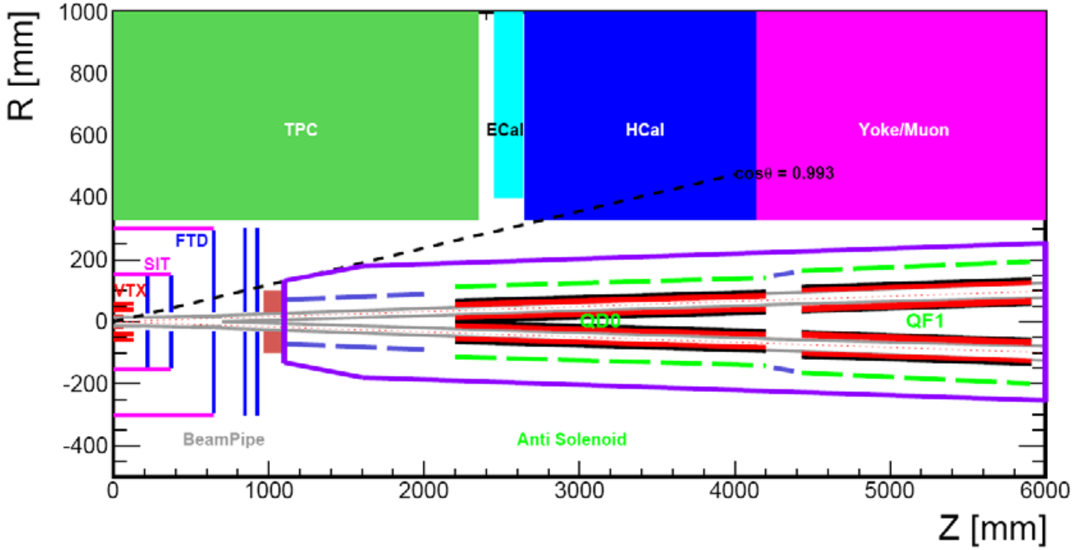
- Overview of CEPC MDI SC magnets
- Iron-free design of final focus QD0
- QD0 design with iron core
- Design of QD0 short model magnet
- Design of superconducting quadrupole magnet QF1
- Design of superconducting anti-solenoid
- Summary

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

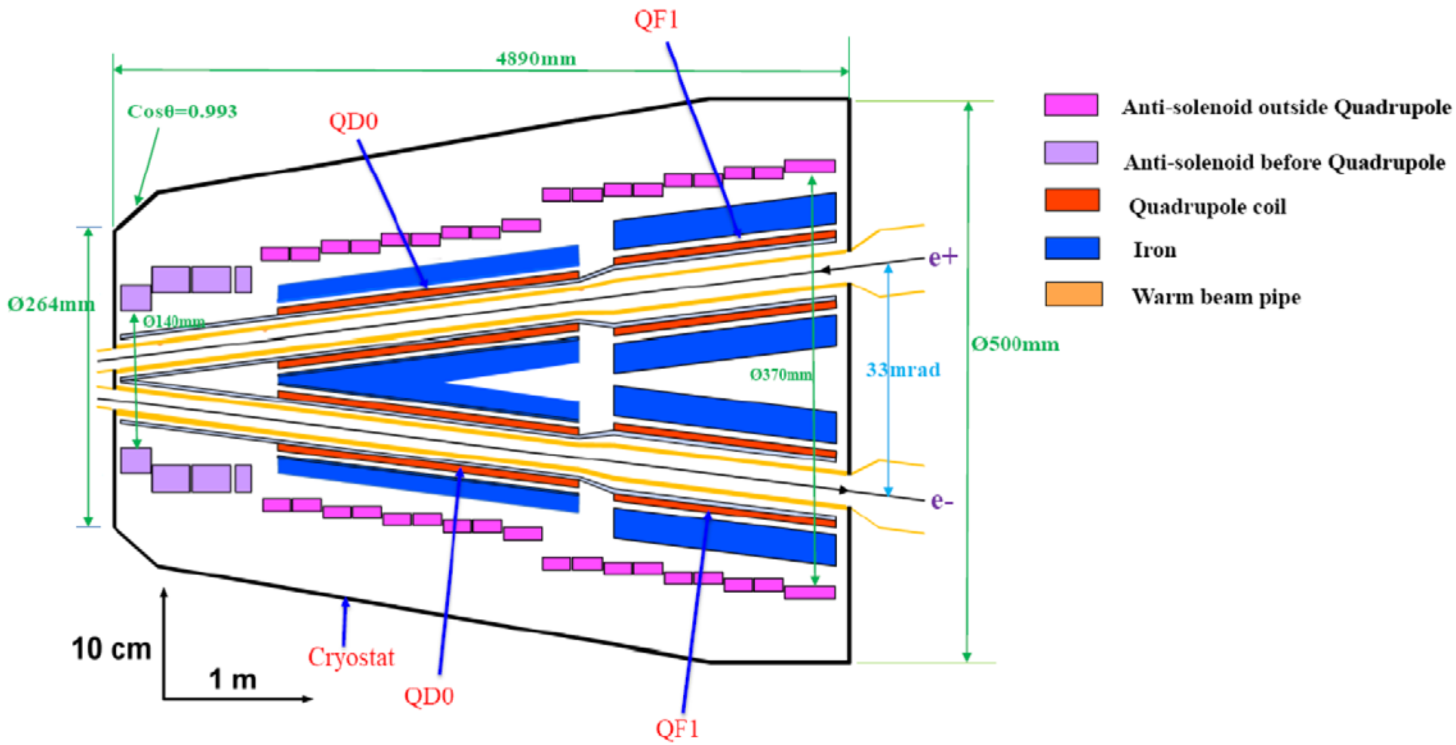
- The CDR requirements of the Final Focus quadrupoles (QD0 and QF1) are based on L* of 2.2 m, beam crossing angle of 33 mrad.

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.

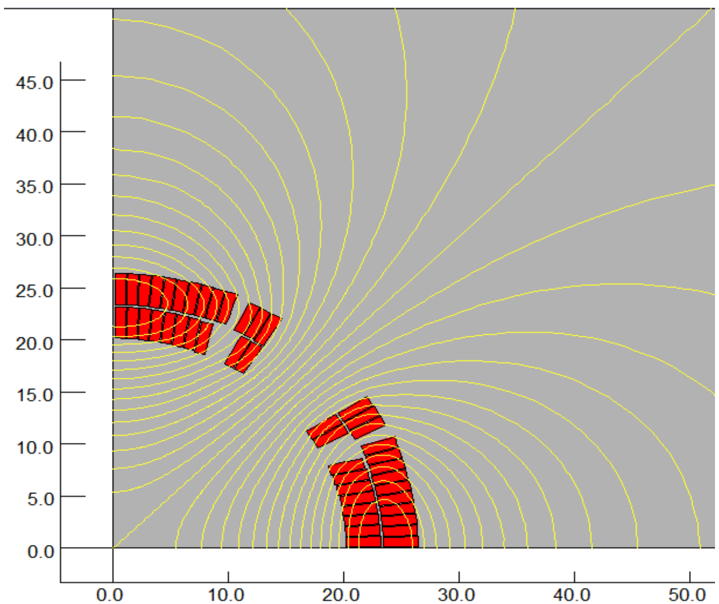
- CEPC MDI SC Magnets including: superconducting QD0,QF1, anti-solenoid on each side of the IP point.
- QD0, QF1, and anti-solenoid coils are in the same cryostat.



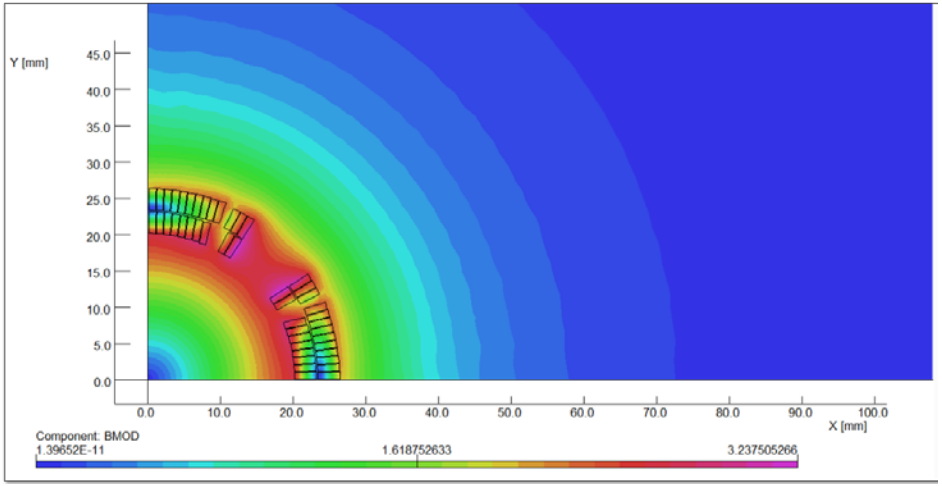
Schematic layout of QD0, QF1, and anti-solenoid

Iron-free design of final focus QD0 (CDR)

- The minimum distance between QD0 two aperture centerlines is only 72.61 mm, so very tight radial space is available.
- 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 23 turns in each pole.
- The excitation current is 2510A @4.2K.



2D flux lines (1/4 cross section)



Magnetic flux density distribution

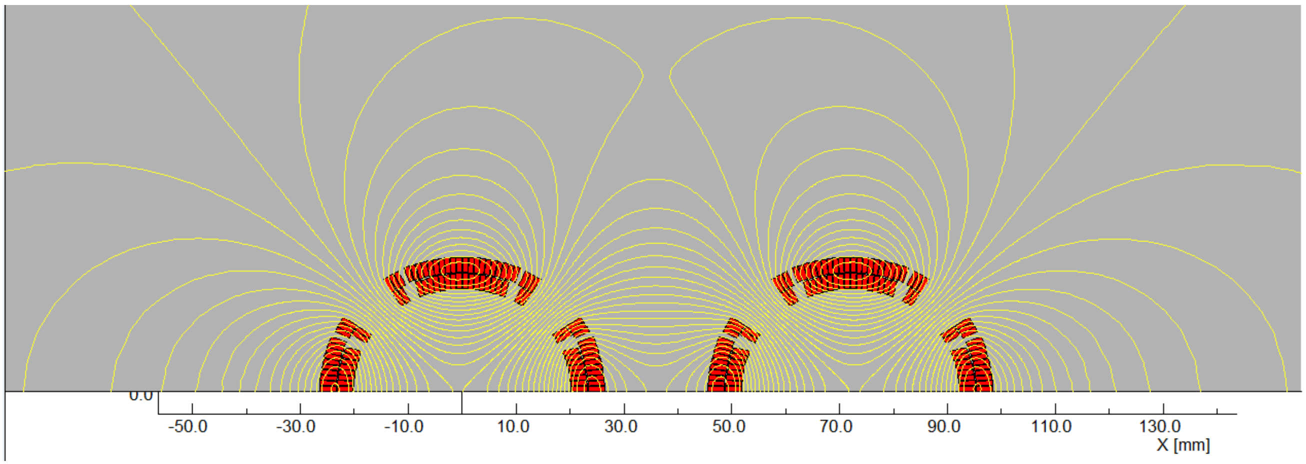
- The coil turns, the coil dimension and the excitation current of QD0 are consistent with the expressions of Ampere-Turns for superconducting quadrupole magnets based on sector coils.

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

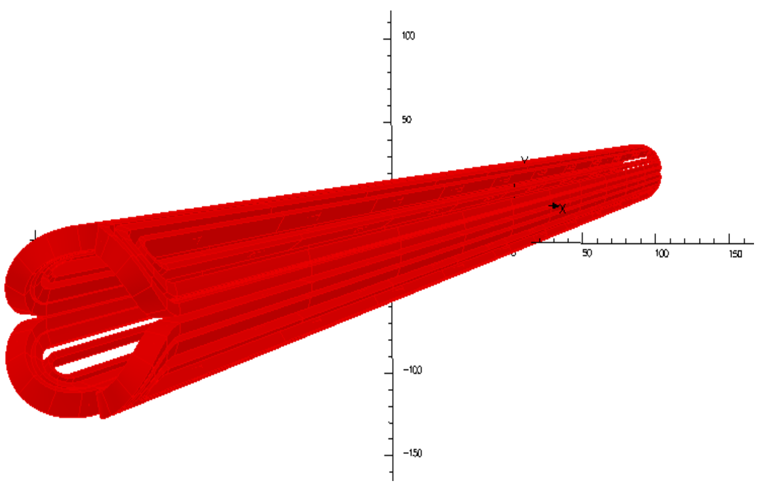
$$(NI)_{Quadrupole} \approx 2\frac{G\overline{R}^2}{2\mu_0} / \left(1 + \left(\frac{\overline{R}}{R_y}\right)^4\right) \qquad \text{(with iron)}$$

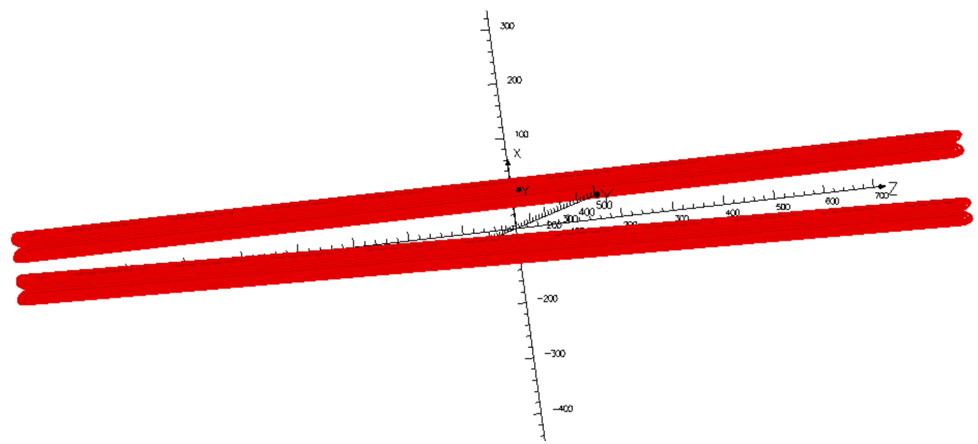
Yingshun Zhu, et al., Study on Ampere-Turns of Superconducting Dipole and Quadrupole Magnets Based on Sector Coils, *Nuclear Instruments and Methods in Physics Research A*, 2014, 741: 186-191.

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

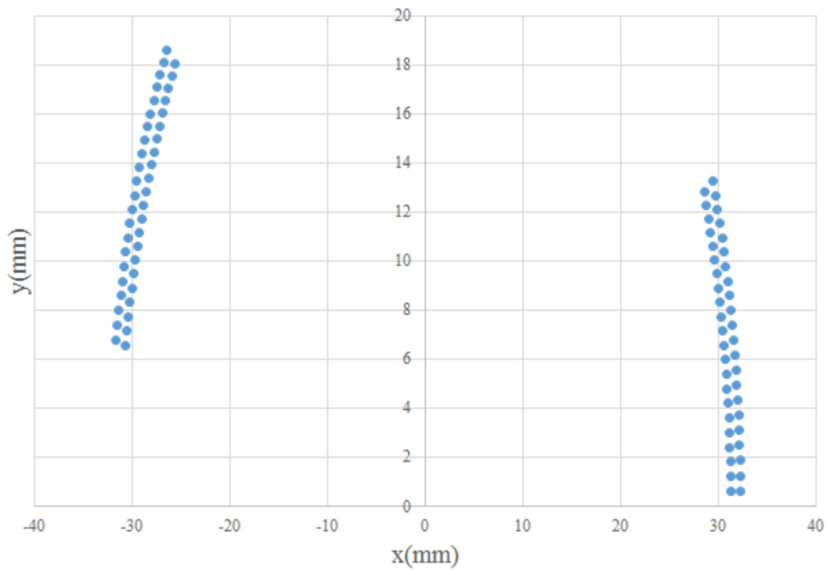


● Calculated integrated multipoles in 3D : b3 19 unit (1×10^{-4}), b4 3.6 unit.





- 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)

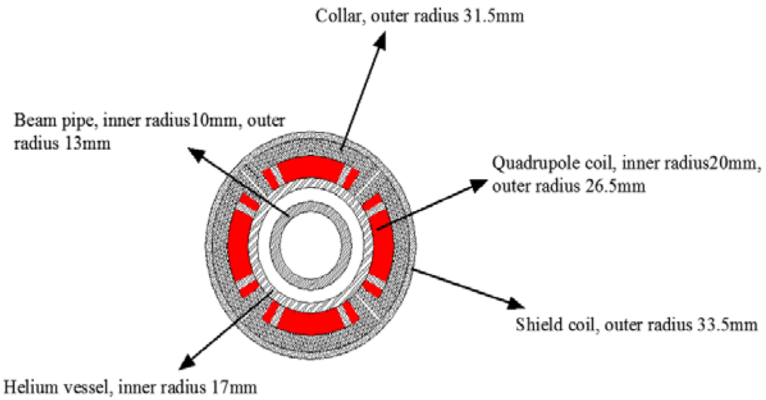
Table 2: Integrated field harmonics with shield coil (1×10^{-4})

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

◆ 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	23
Excitation current (A）	2510
Shield coil turns per pole	44
Shield coil current (A）	135
Coil layers	2
Conductor	Rutherford Cable, width 3 mm, mid thickness 0.94 mm, keystone angle 1.8 deg,Cu:Sc=1, 12 strands
Stored energy (KJ)	25.0
Inductance (H）	0.008
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

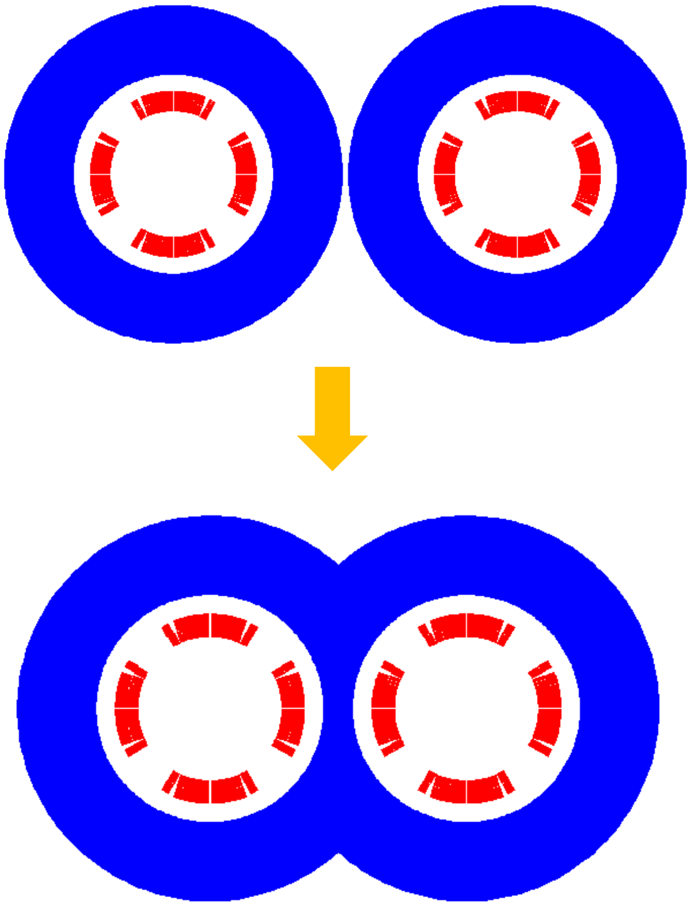


Single aperture QD0

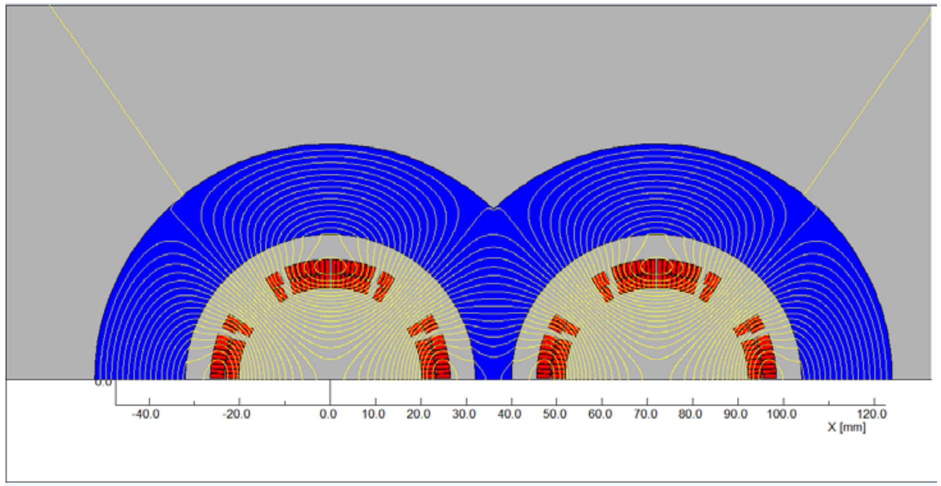
The current of QD0 at W and Z model will decrease.

QD0 design with iron core

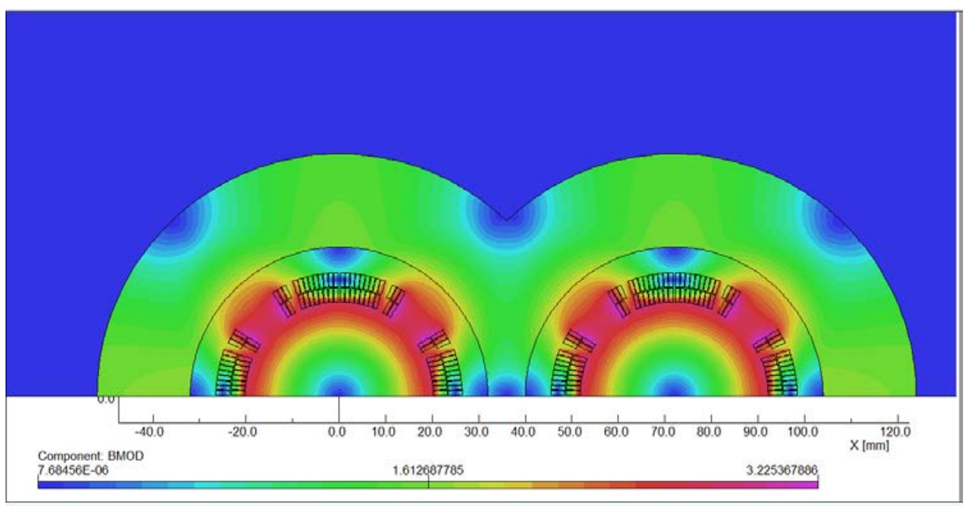
- Iron yoke is added outside the collar to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk.
- The radial space is limited, so a compact design is adopted. **Iron core in the middle part is shared by the two apertures.**



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

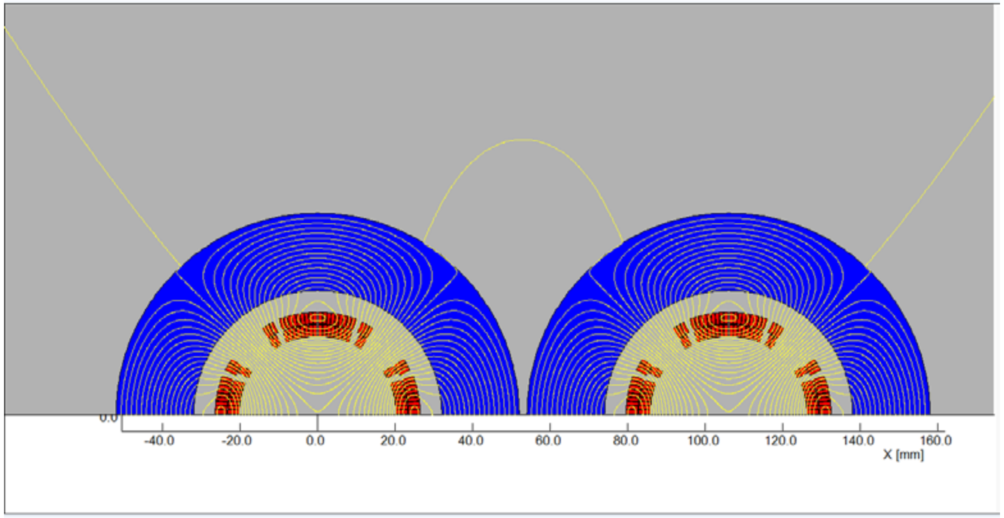


2D Flux lines

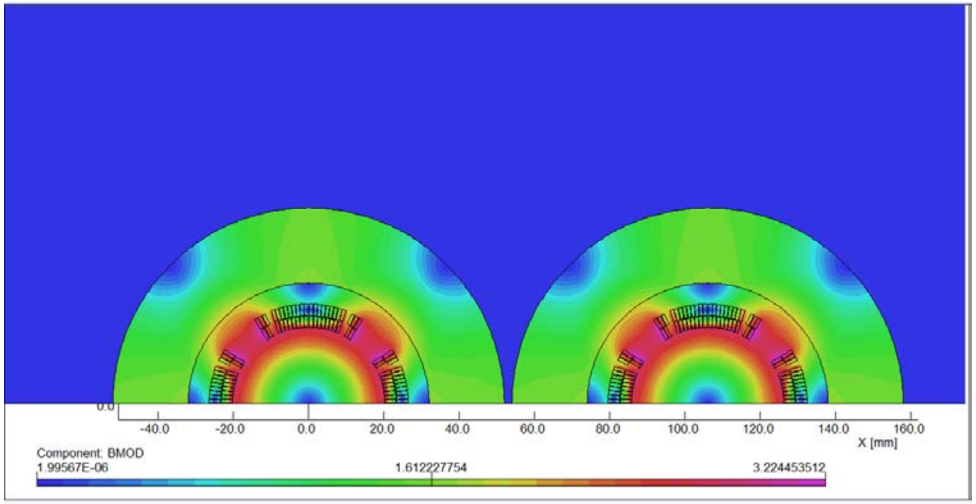


Bmod distribution

- 2D field cross talk of QD0 when the distance between two aperture is larger.



2D Flux lines



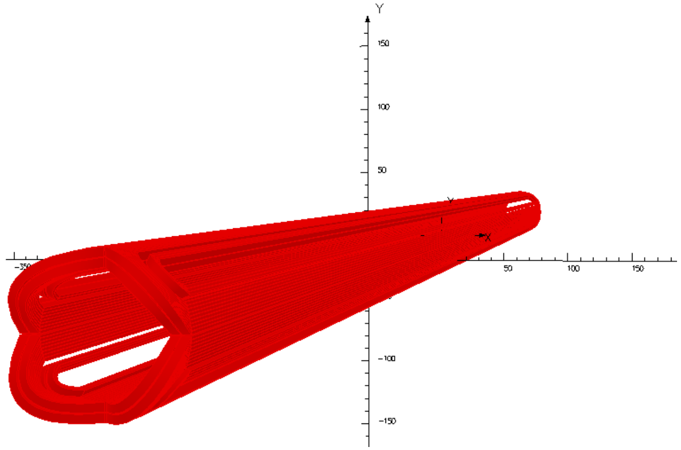
Bmod distribution

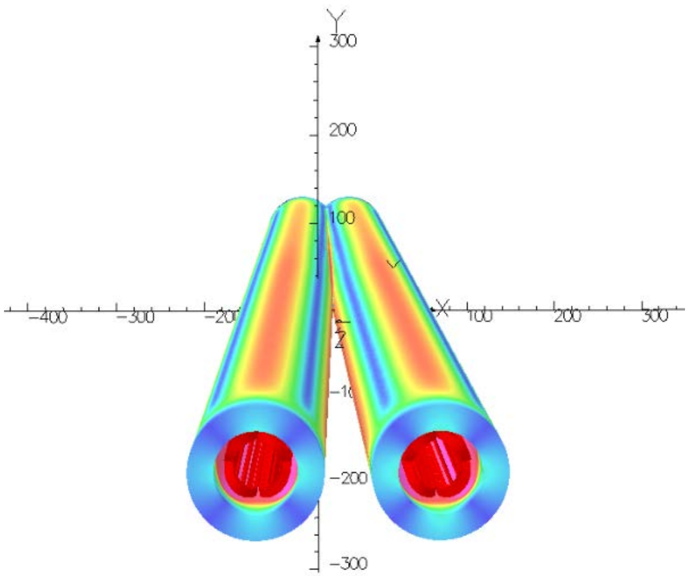
- In 2D case where the distance between the two aperture is the smallest and the field crosstalk is the most serious, iron yoke can well shield the leakage field of each aperture, and the field harmonics as a result of field crosstalk between the two apertures is smaller than 0.5×10^{-4}.
- In other cases where the distance between the two apertures becomes larger, the field harmonics as a result of field crosstalk will be smaller.

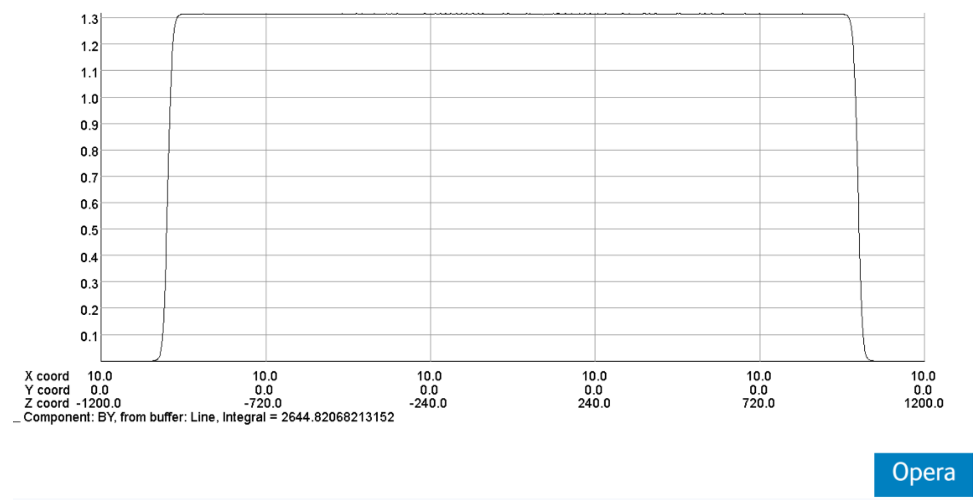
✓ Using the iron yoke, the field harmonics as a result of the field crosstalk is not a problem.

✓ In addition, compared with the iron-free design of QD0, the excitation current can be reduced.

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

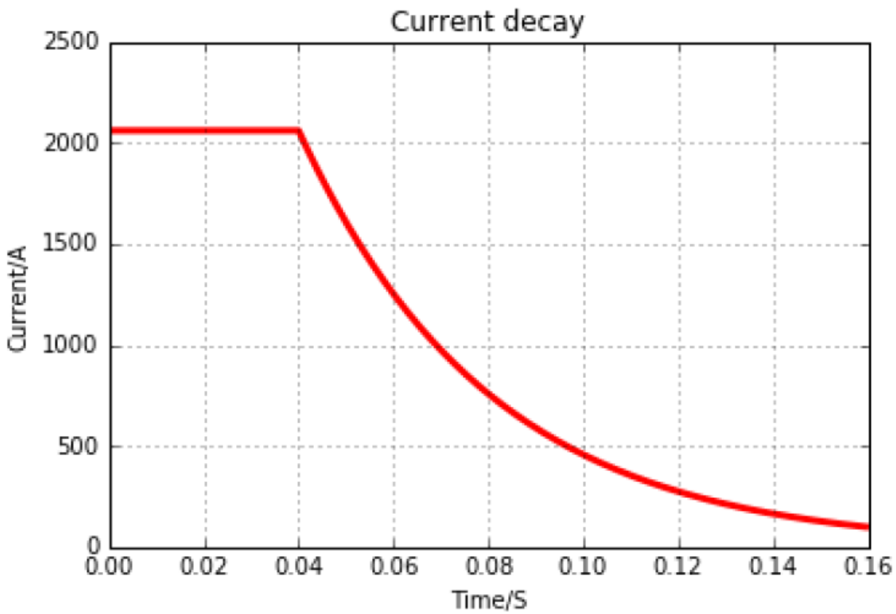


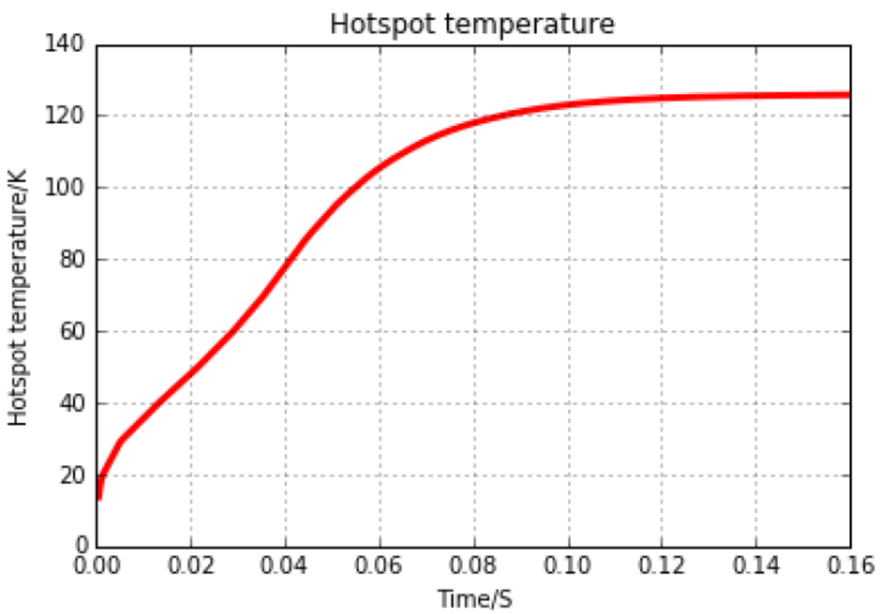




Quench simulation of QD0

- ✓ 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)

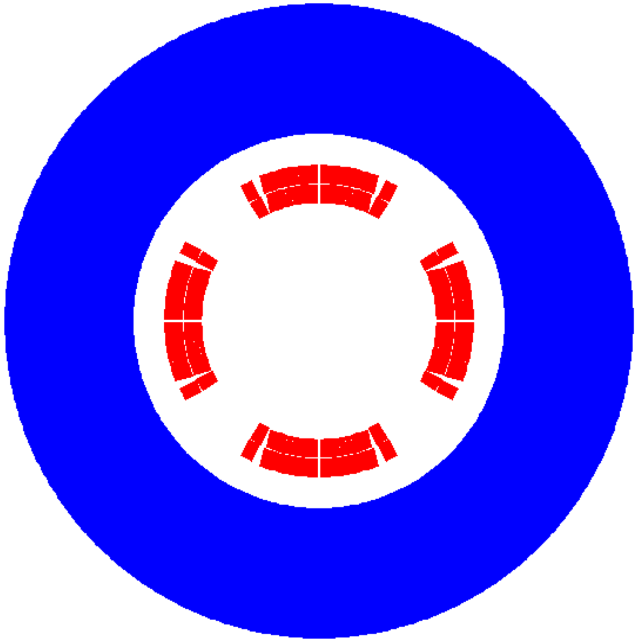
Magnet name	QD0
Field gradient (T/m)	136
Magnetic length (m)	2.0
Coil turns per pole	22
Excitation current (A）	2060
Coil layers	2
Conductor	Rutherford Cable, width 3 mm, mid thickness 0.93 mm, keystone angle 1.9 deg, Cu:Sc=1.3, 12 strands
Stored energy (KJ) (Double aperture)	21.5
Inductance (H）	0.010
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

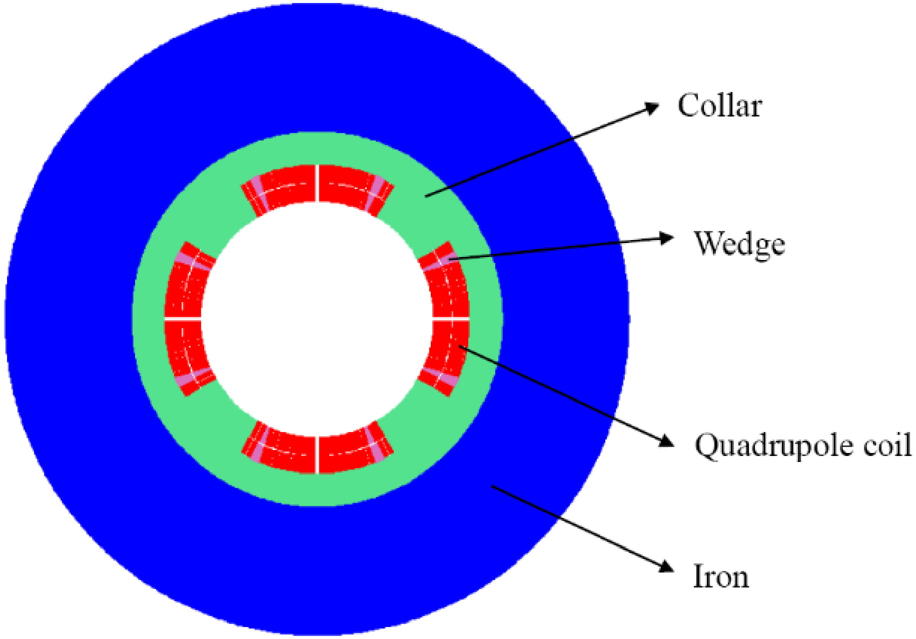
The current of QD0 at W and Z model will decrease.

Design of QD0 short model magnet

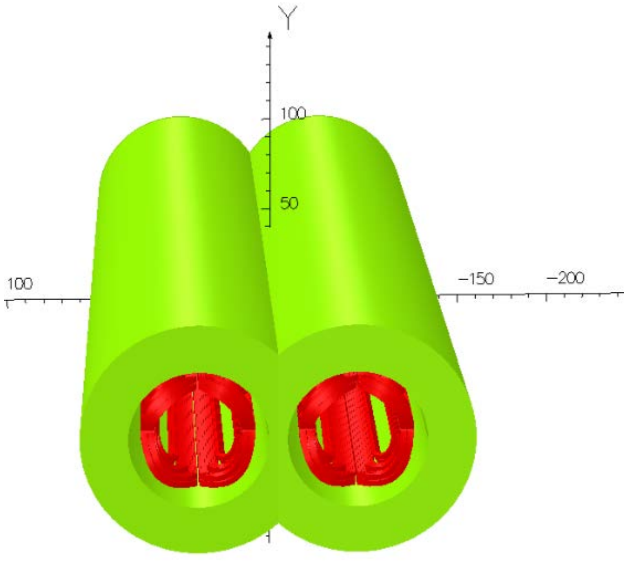
- In the R&D of CEPC interaction region superconducting magnets, the first step is to **develop a short QD0 model magnet with 0.5m length (near IP side).**
- So far, there is no cos2θ superconducting quadrupole magnet developed in China.
- The aim of QD0 short model magnet:

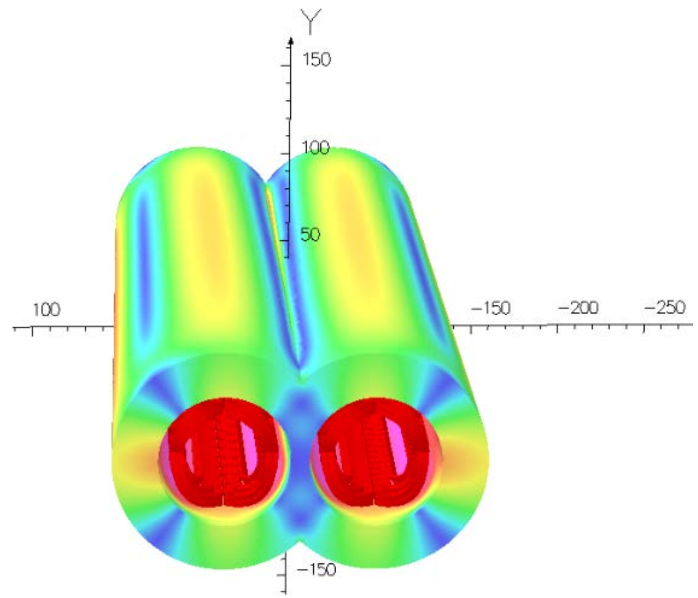
  Verify magnet design; Exploring magnet manufacturing technology;
  Master cryogenic testing Technology;
  Lay the foundation for the development of long QD0 prototype.

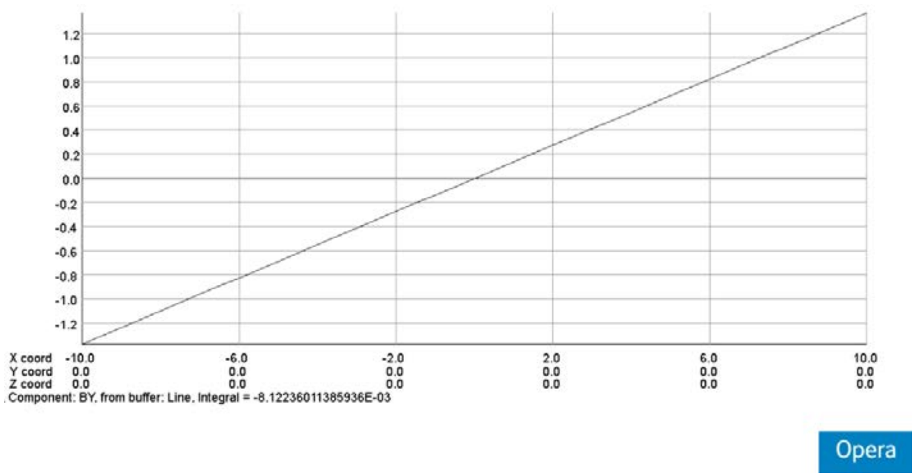


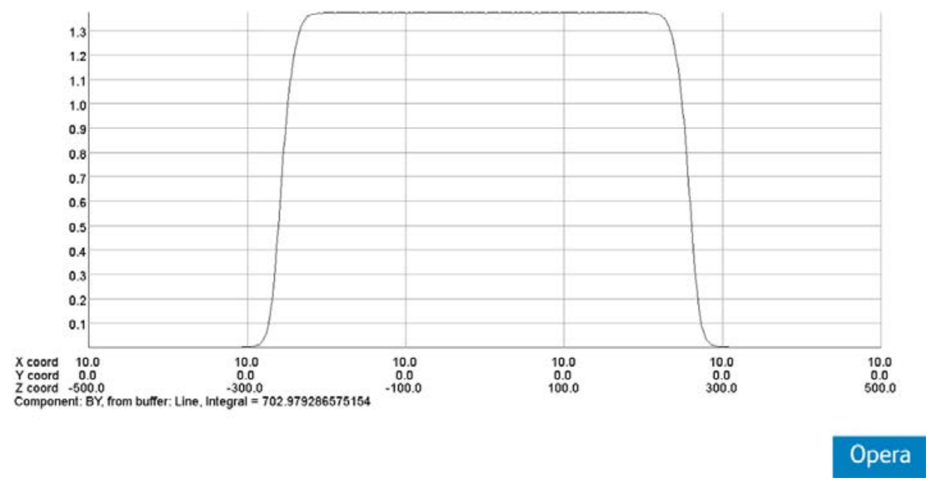


- 3D field simulation of two apertures 0.5m QD0.







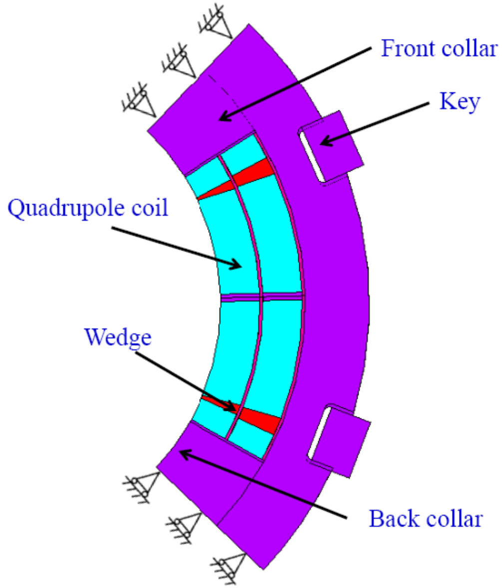


- 3D field simulation result shows that, local field harmonic as a result of field cross talk is smaller than 0.5 unit.
- Each integrated multipole field as a result of field crosstalk between the two apertures is smaller than 0.3 unit.
- The dipole field is smaller than 10 Gs at each longitudinal position.

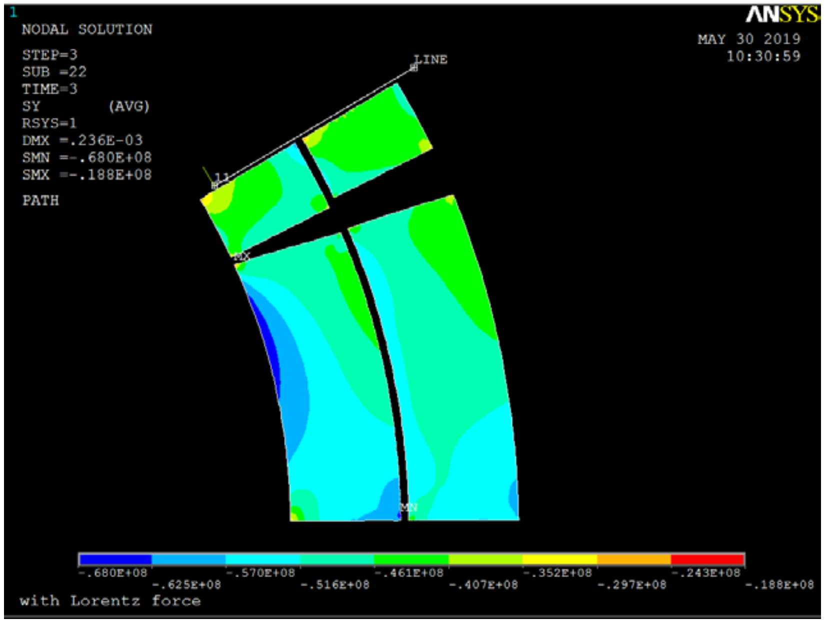
Table 5: 3D integrated field harmonics（unit, 1×10^{-4}）

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

◆ Stress analysis of QD0 short model magnet:



Model



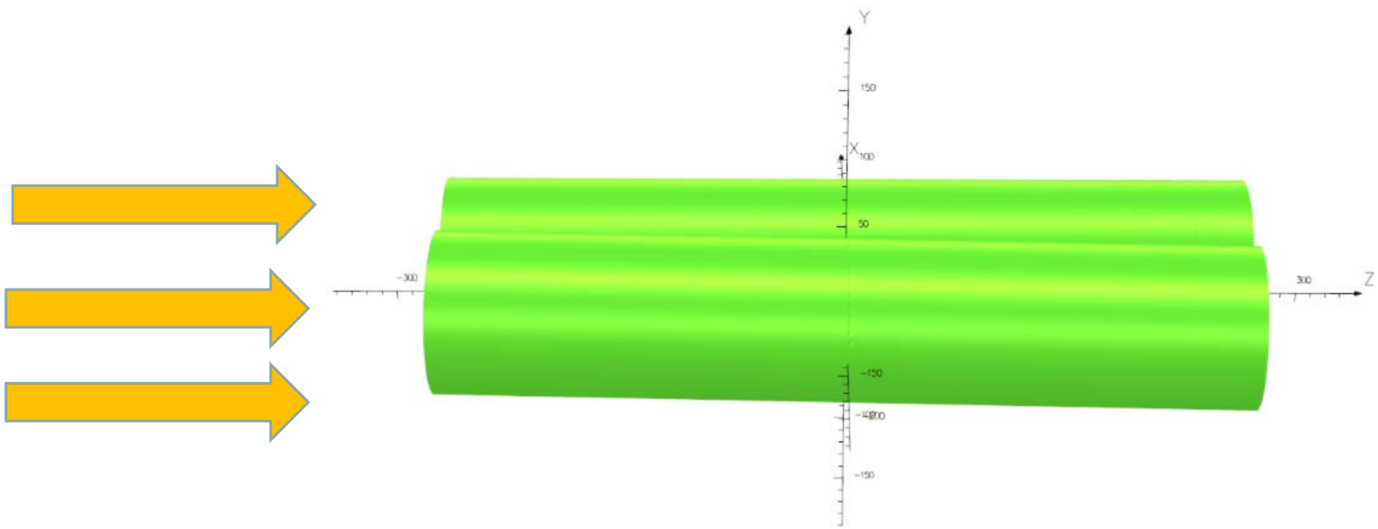
Stress in coil after excitation

- The FEM analysis result shows that, the stress in each component during each operation step is safe.
- Collar material with high strength is required.

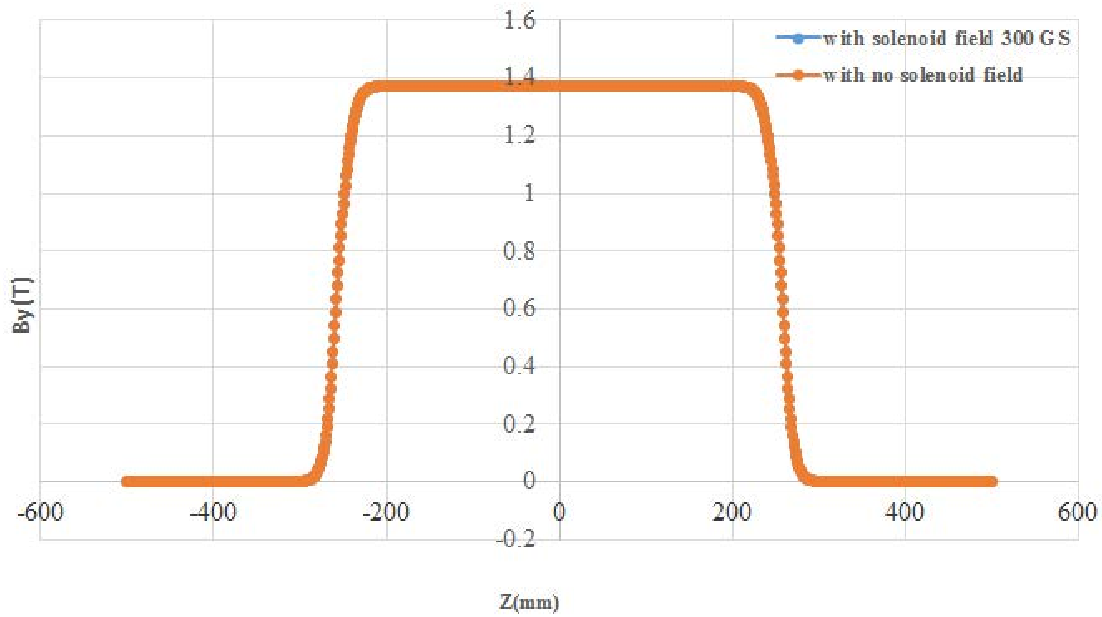
Influence of solenoid field on the quadrupole

- 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 exist. 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:

300 Gs solenoid

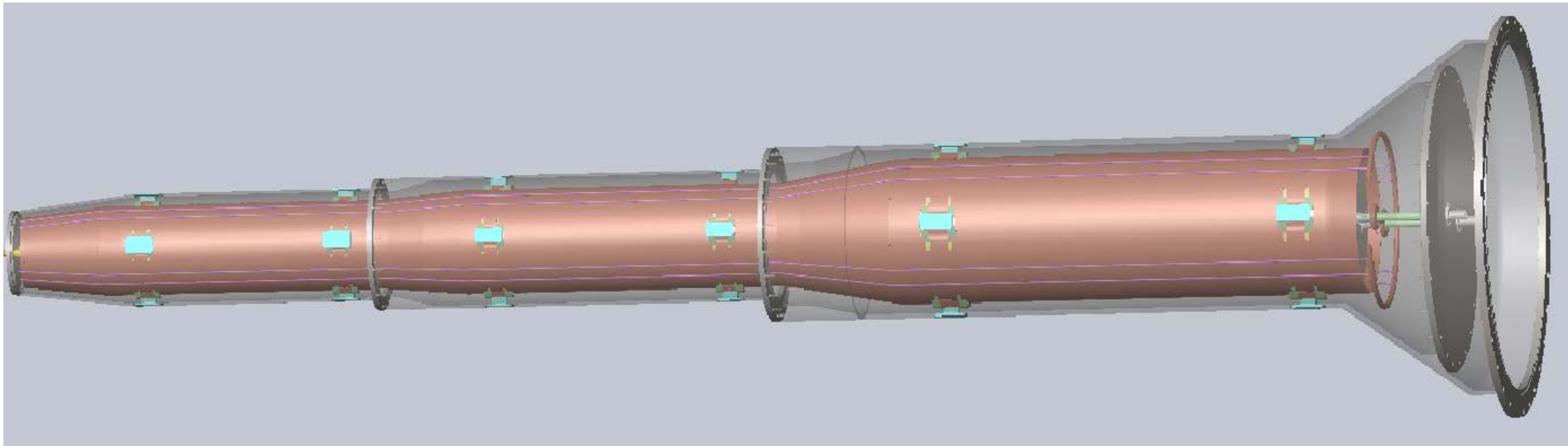


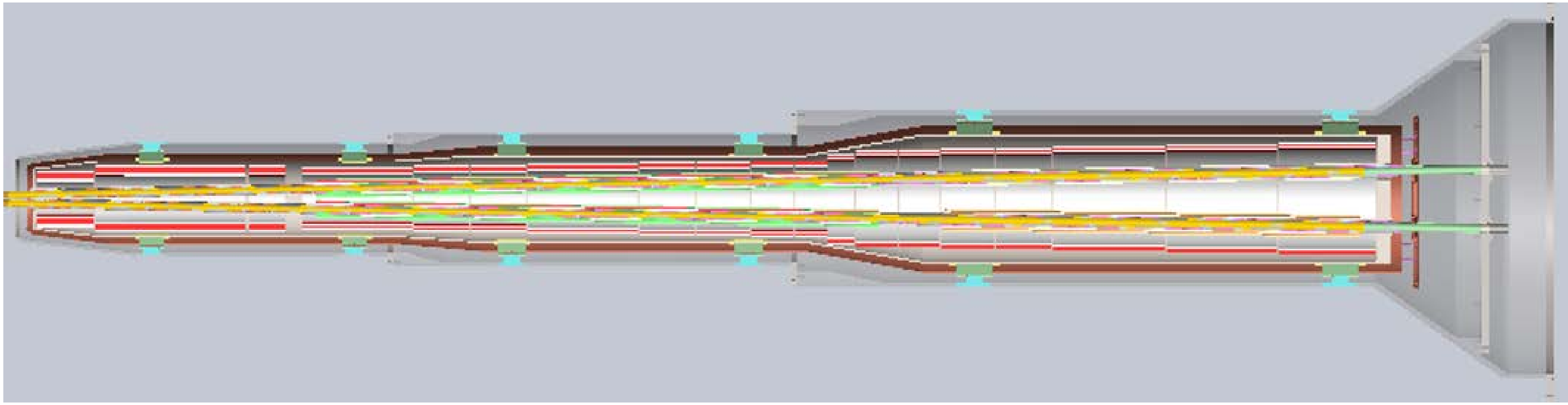
- 3D field simulation result shows that, the quadrupole magnet can work normally under 300Gs solenoid field.
- The magnetic field in the iron core increases, but magnetic field saturation is not serious.
- The integrated field gradient and multipole fields remain almost unchanged.



Magnetic fled distribution along longitudinal direction

◆ Design status of MDI SC magnet cryostat:





Specifications on NbTi/Cu Strand and keystoned Rutherford Cable:

- ✓ **Strand:**

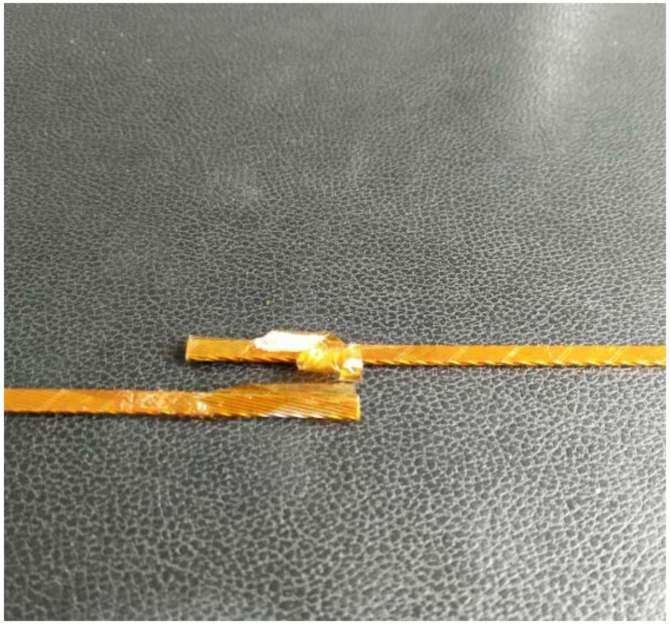
  NbTi/Cu, 0.5mm in diameter,

  Cu/Sc=1.3, Filament diameter < 8μm,

  @4.2K, Ic≥340A@3T， Ic≥280A@4T， Ic≥230A@5T.

- ✓ **Rutherford Cable:**

  Width: 3mm, mid thickness: 0.93 mm, keystone angle: 1.9 deg, No of stands: 12.



Cu Rutherford cable sample

- ✓ **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).

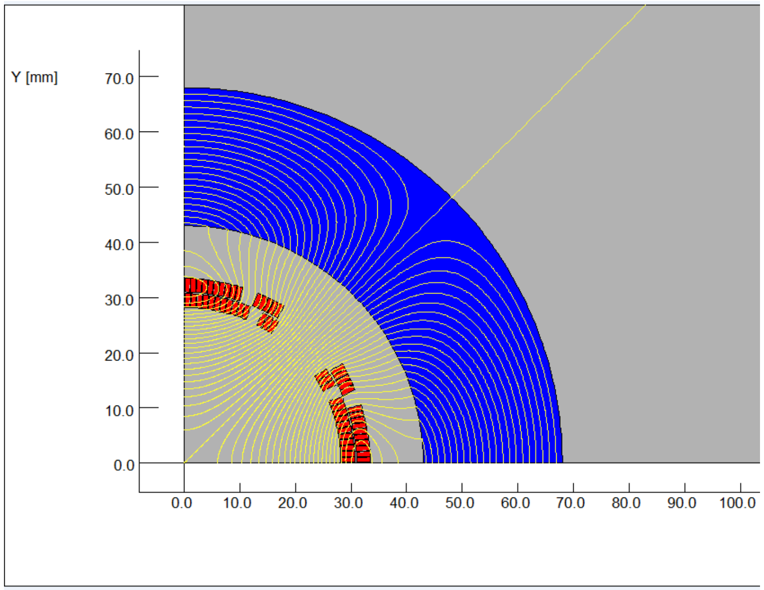
IHEP winding machine

Review meeting

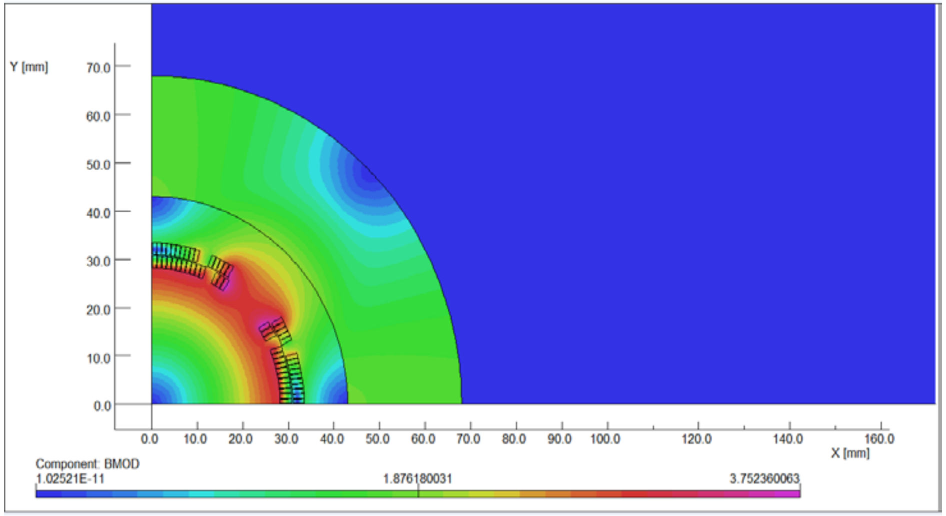
- The physical design of QD0 short model magnet passed the experts review in July 2019.

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, the QF1 coil consists of four coil blocks in two layers separated by wedges, and there are 29 turns in each pole.



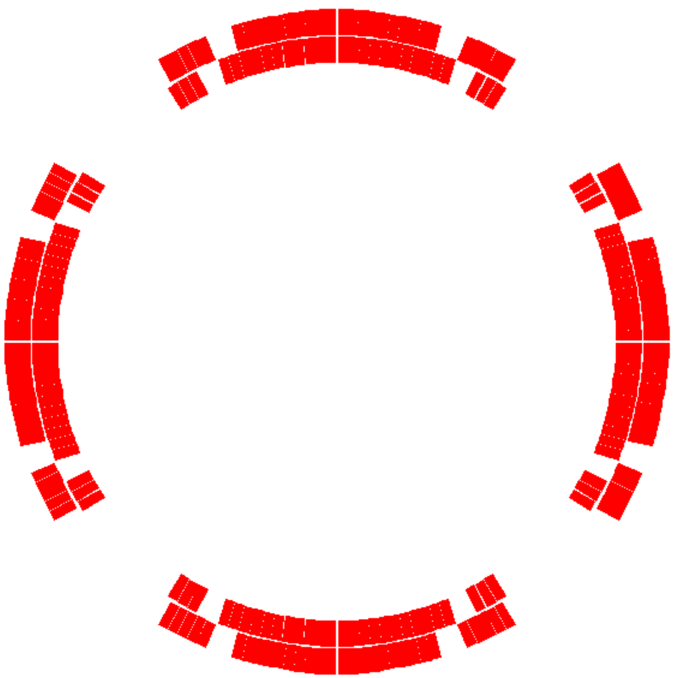
2D flux lines (One quarter cross section)



Magnetic flux density distribution

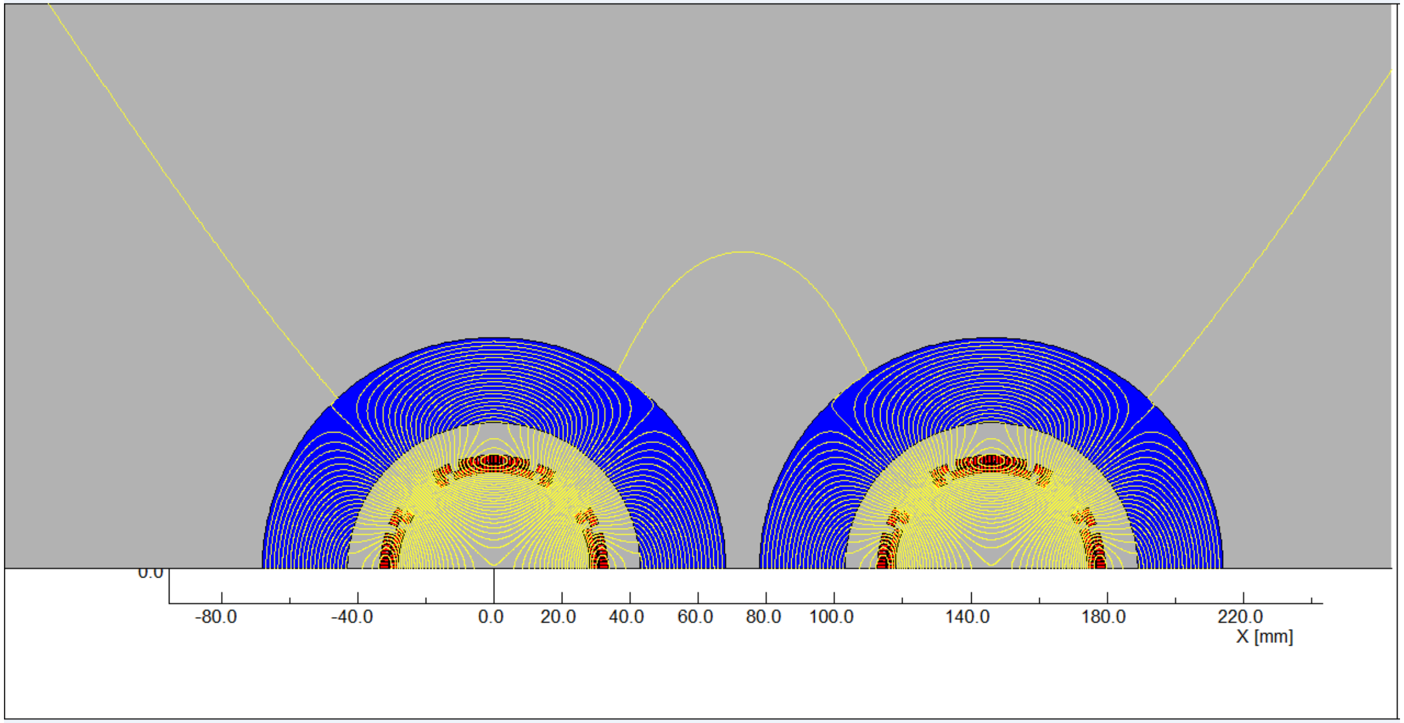
Table 5: 2D field harmonics of QF1 (unit, 1×10^{-4})

n	B_n/B_2@R=13.5mm
2	10000
6	1.08
10	-0.34
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, the field harmonics as a result of field cross talk between the two apertures can be neglected.

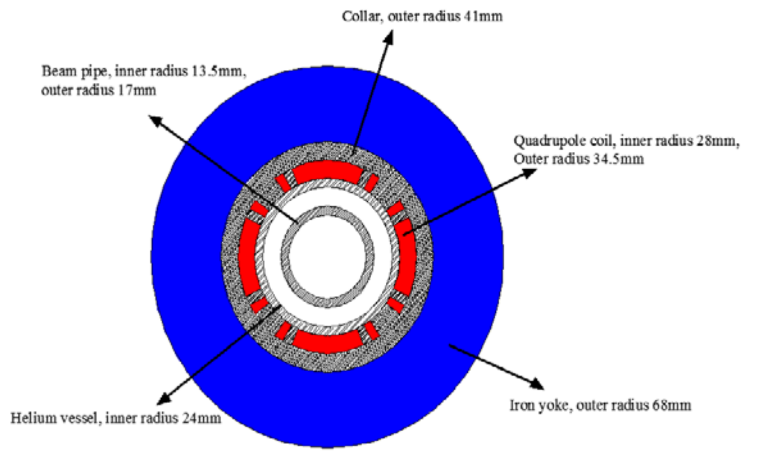


Two aperture Flux lines

◆ 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	29
Excitation current (A）	2250
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



Single aperture QF1

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

Design of superconducting anti-solenoid

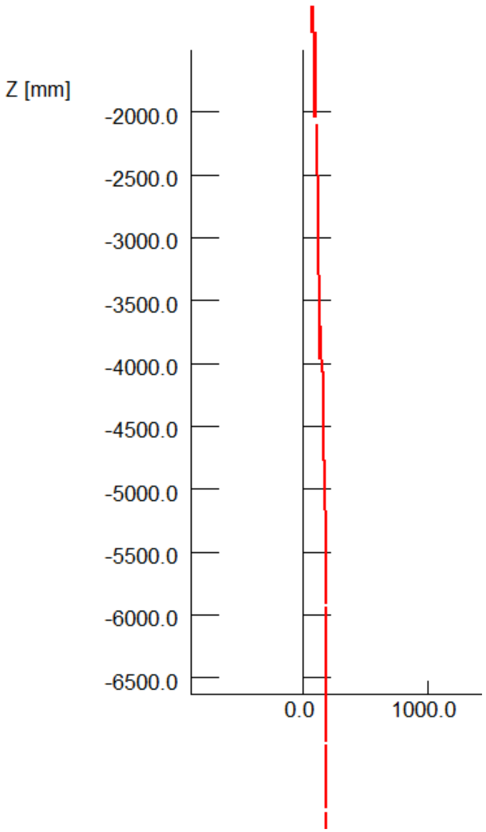
- The design requirements of the anti-solenoids in the CEPC Interaction Region are summarized below:

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.

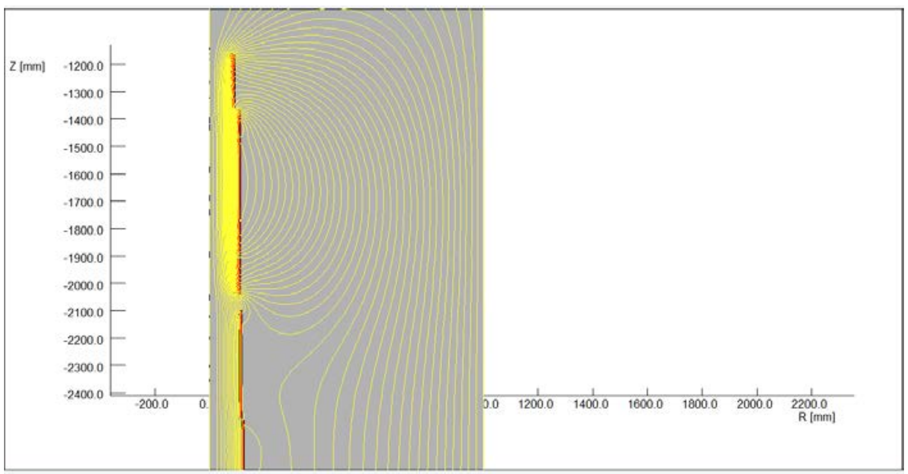
- The design of the anti-solenoid fully takes into account the above requirements. The anti-solenoid will be wound of rectangular NbTi-Cu conductor.

- 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.

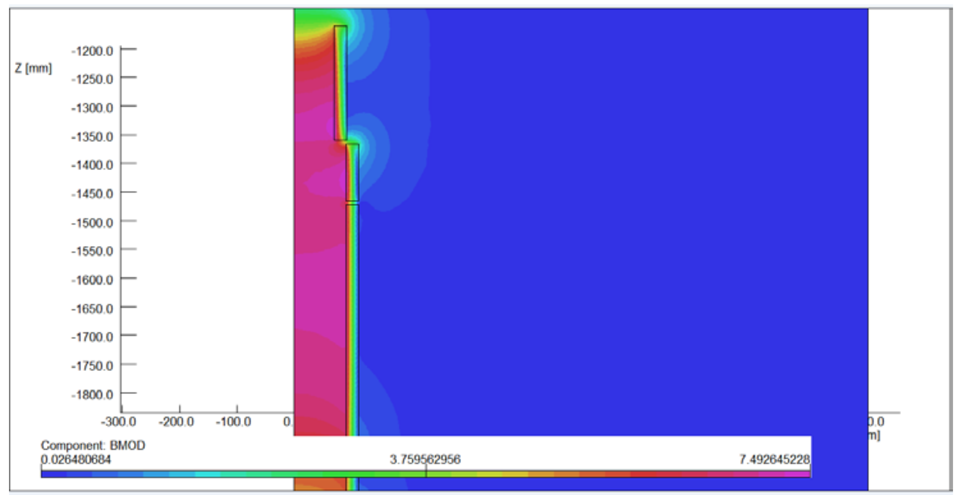
- The anti-solenoid along longitudinal direction:
  1) 4 sections, from IP point to QD0;
  2) 12 sections, QD0 region;
  3) 6 sections, QF1 region;
  4) 7 section, after QF1 region.
- To reduce the length of the cryostat, the sections of anti-solenoid after QF1 region with low field will be operated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

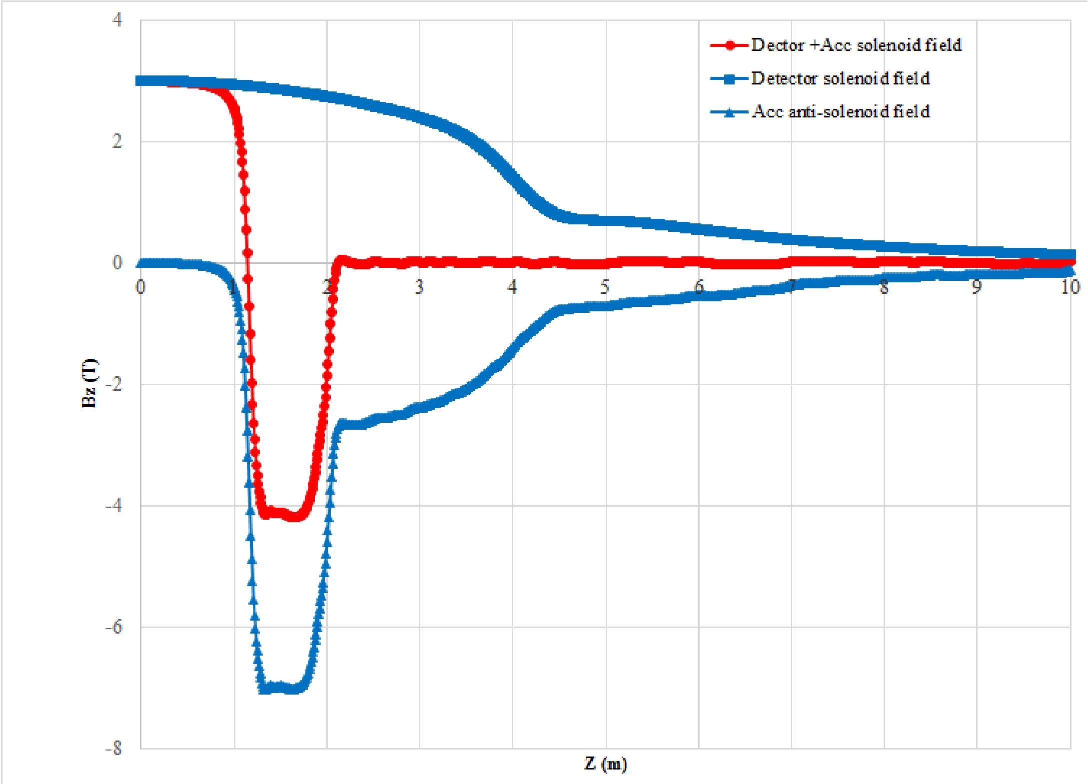


2D flux lines



Magnetic flux density distribution

◆ Combined field of Anti-solenoid and Detector solenoid with linear superposition.



◆ 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.

Summary

- MDI superconducting quadrupole magnets are key devices for CEPC.
- The width of iron core in the middle part of the QD0 two apertures is very limited, but it is effective in shielding magnetic field crosstalk..
- 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.
- **Physical design of 0.5m QD0 short model magnet has been finished**, and all the design requirements have been met.
- The fabrication of the QD0 short model magnet is planned to be started **(depending on fund)**.

Thanks for your attention!