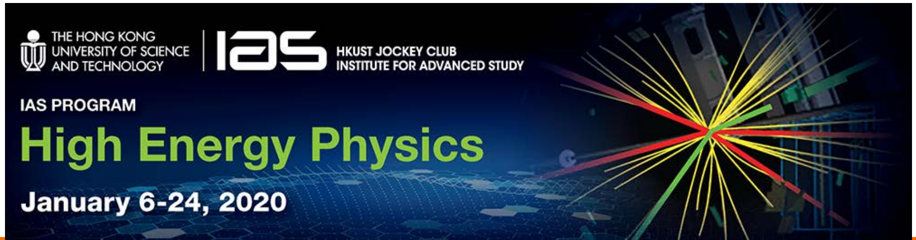


CEPC MDI SC Magnet R&D

Yingshun Zhu*, Xiangchen Yang, Ran Liang, Chuang Shen, Miaofu Xu

Institute of High Energy Physics, Chinese Academy of Sciences

HKUST January 20, 2019

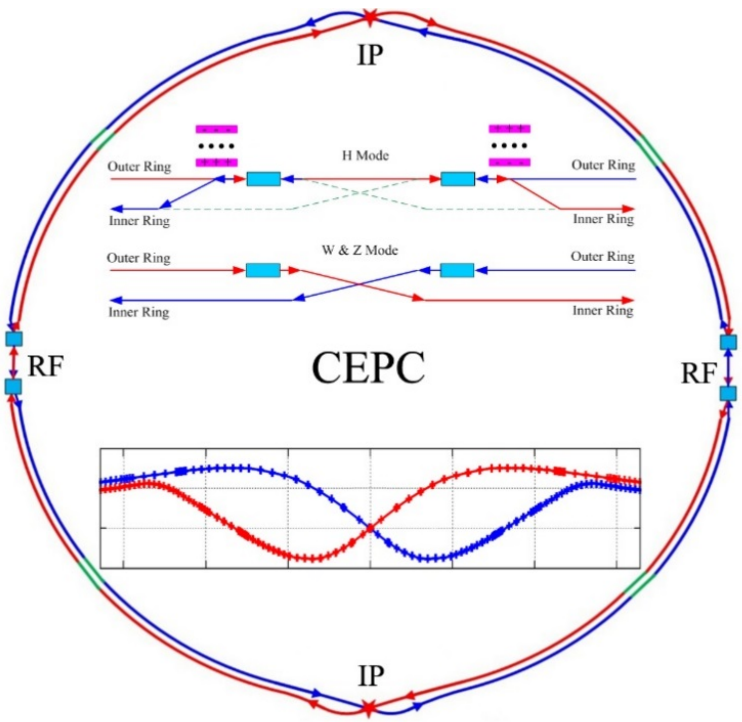
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Outline

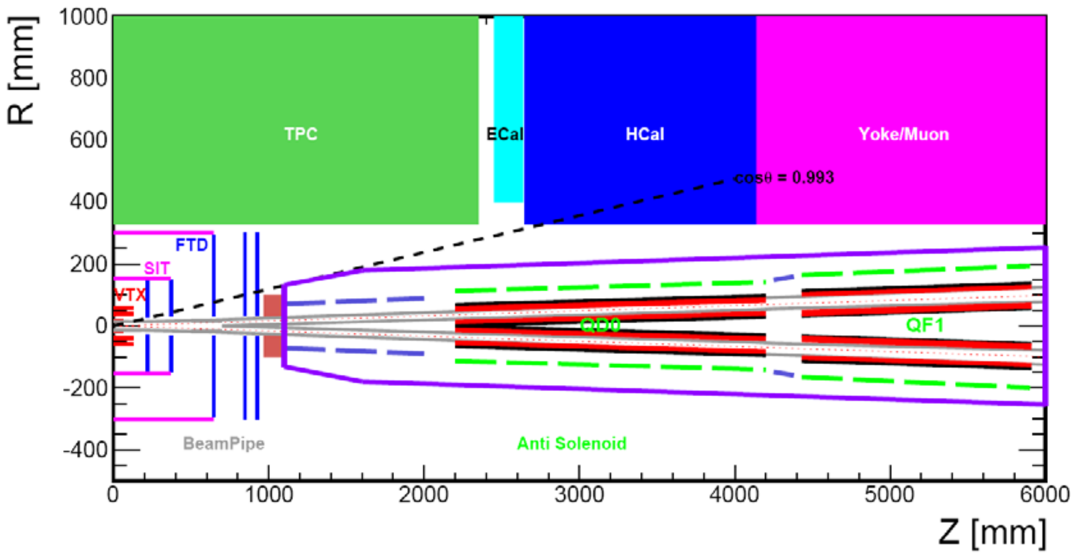
- Overview of CEPC MDI SC magnets
- QD0 design with iron core
- Design of QD0 short model magnet
- QD0 design with updated requirement
- Summary

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

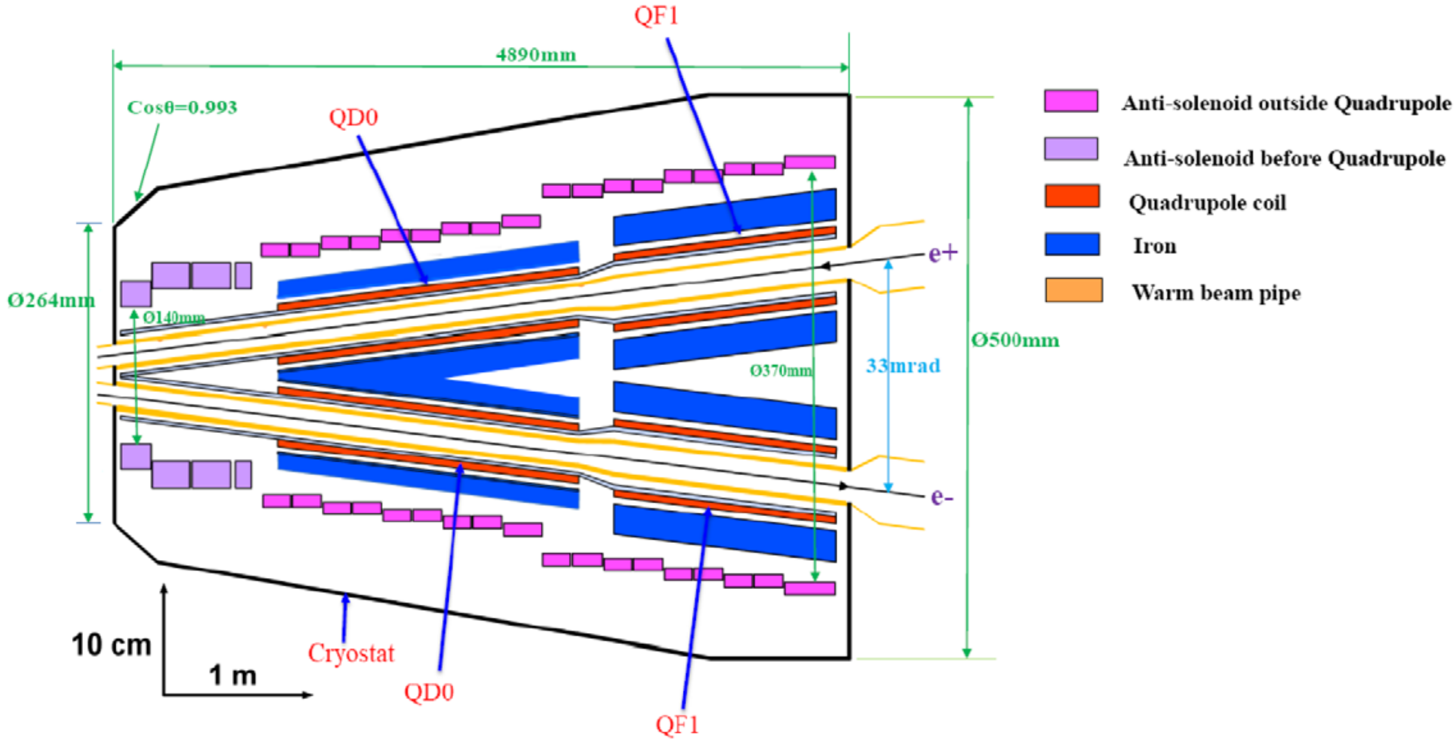
- The CDR requirements of the Final Focus quadrupoles (QD0 and QF1) are based on L* of 2.2 m, beam crossing angle of 33 mrad.

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.

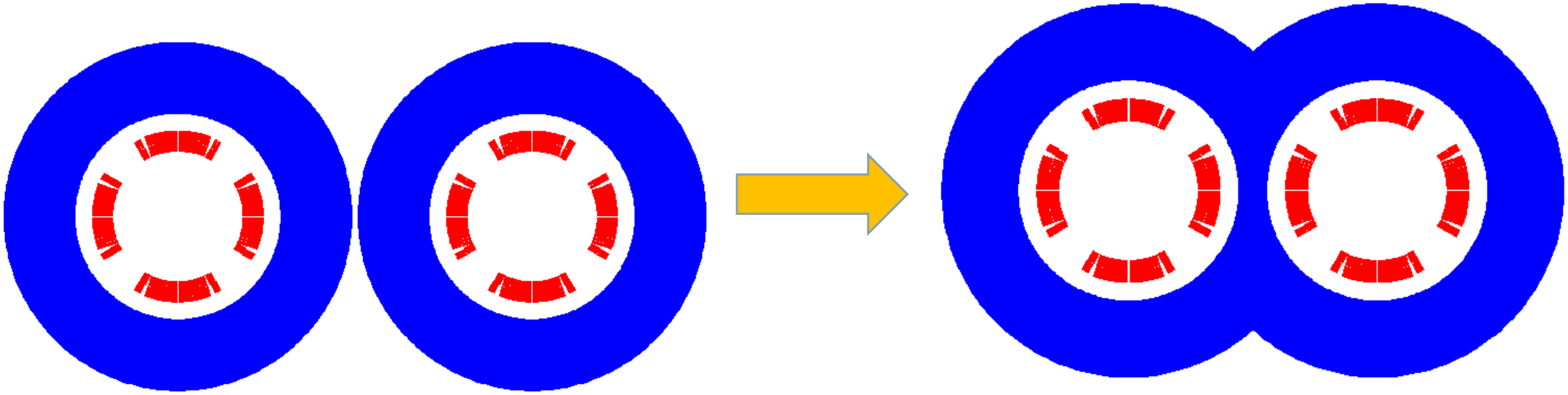
- CEPC MDI SC Magnets including: superconducting QD0,QF1, anti-solenoid on each side of the IP point.
- QD0, QF1, and anti-solenoid coils are in the same cryostat.



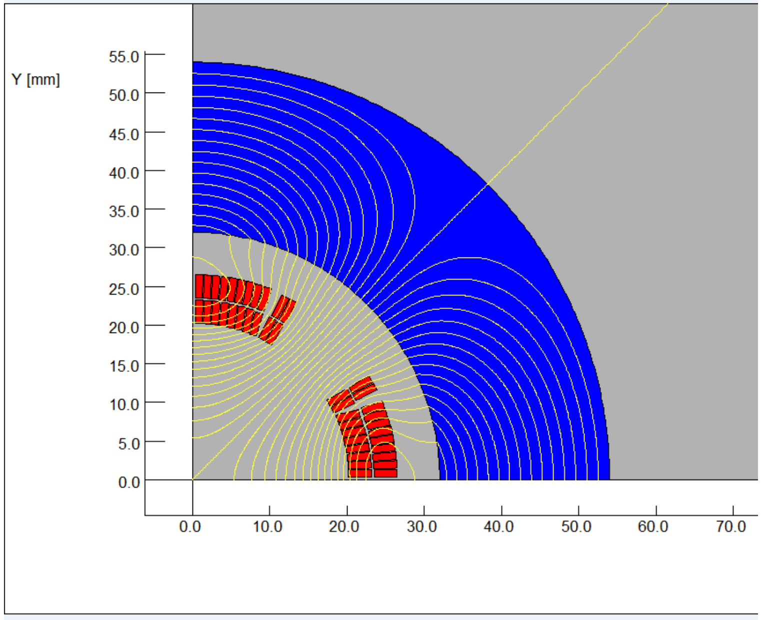
Schematic layout of QD0, QF1, and anti-solenoid

QD0 design with iron core

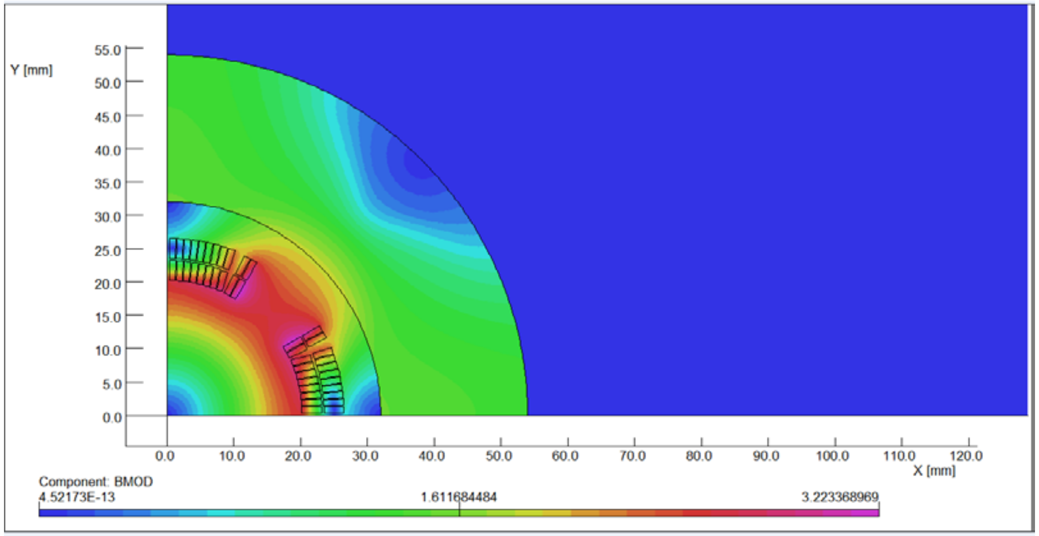
- Iron-free design of QD0 is presented in the CDR report.
- Iron option: Iron yoke is added outside the collar to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk.
- The radial space is limited, so a compact design is adopted.
- ✓ **Iron core in the middle part is shared by the two apertures.**



- 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.
- 2D magnetic field calculation is performed using OPERA.
- Actual insulation thickness and coil fabrication process are taken into account.

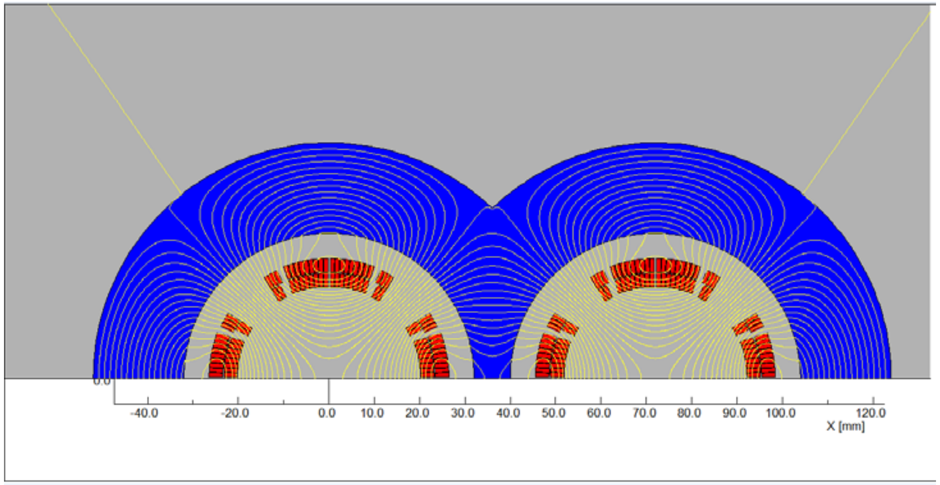


2D flux lines (1/4 cross section)

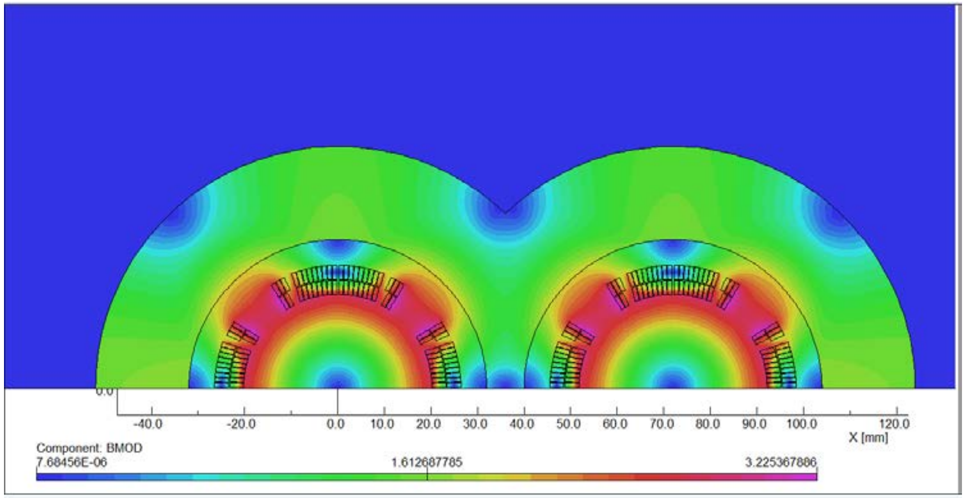


Magnetic flux density distribution

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

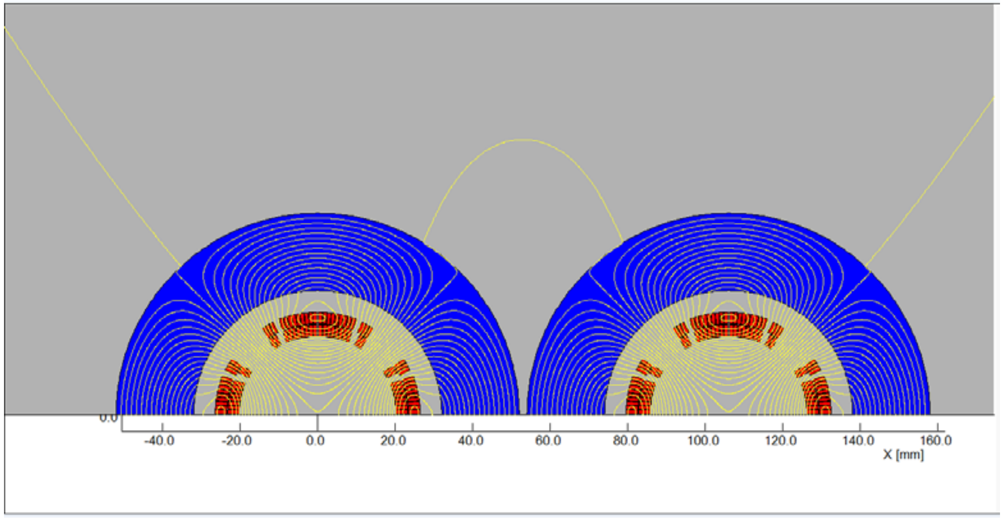


2D Flux lines

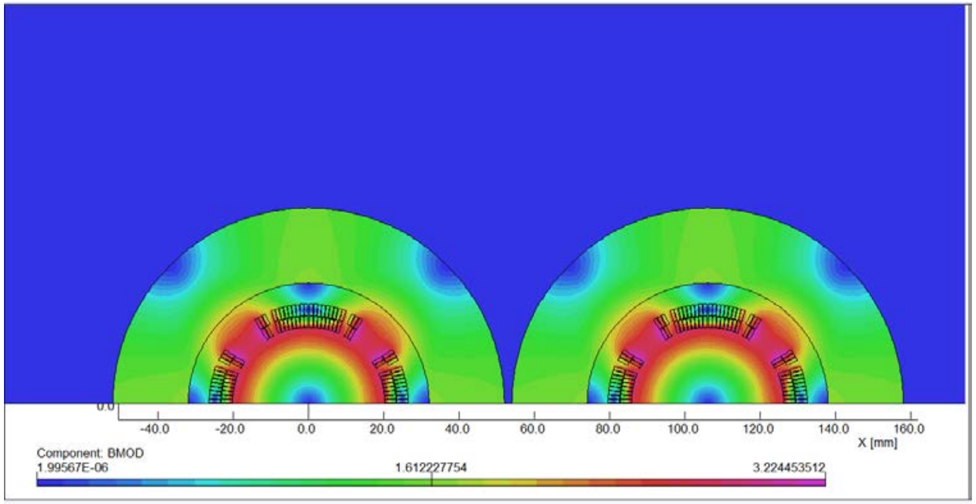


Bmod distribution

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



2D Flux lines



Bmod distribution

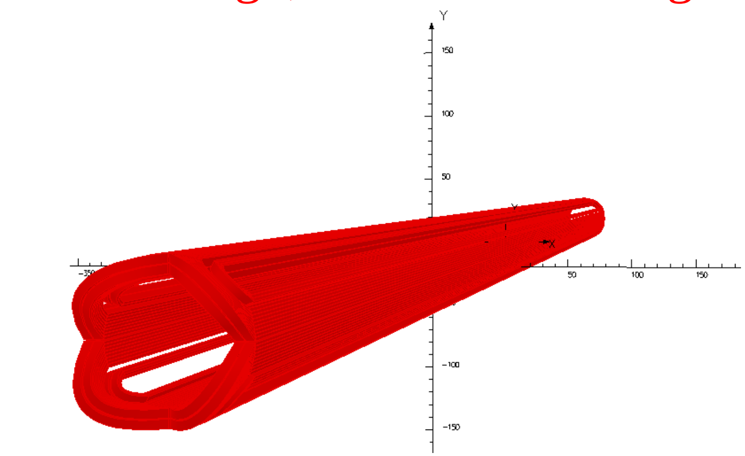
- In 2D case where the distance between the two aperture is the smallest and the field crosstalk is the most serious, iron yoke can well shield the leakage field of each aperture, and the field harmonics as a result of field crosstalk between the two apertures is smaller than 0.5×10^{-4}.
- In other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

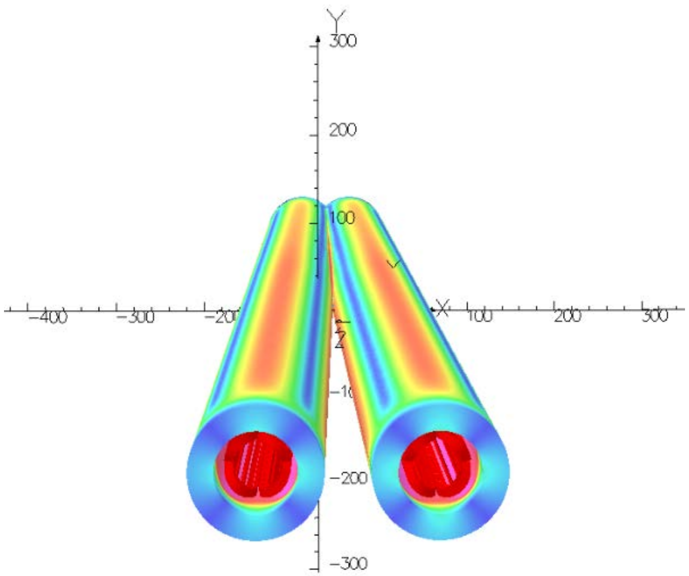
✓ Using the iron yoke, the field harmonics as a result of the field crosstalk is not a problem.

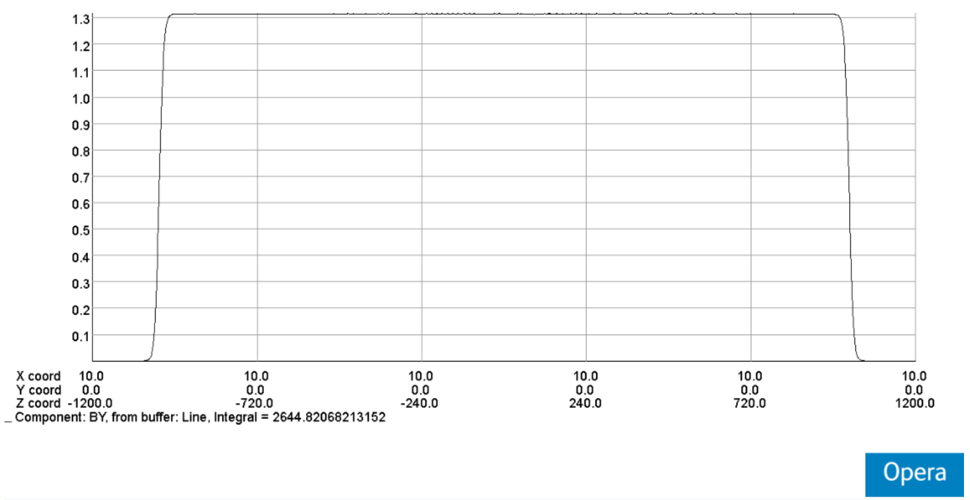
✓ No additional cancel coil for the field crosstalk compensation is needed.

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

- 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.

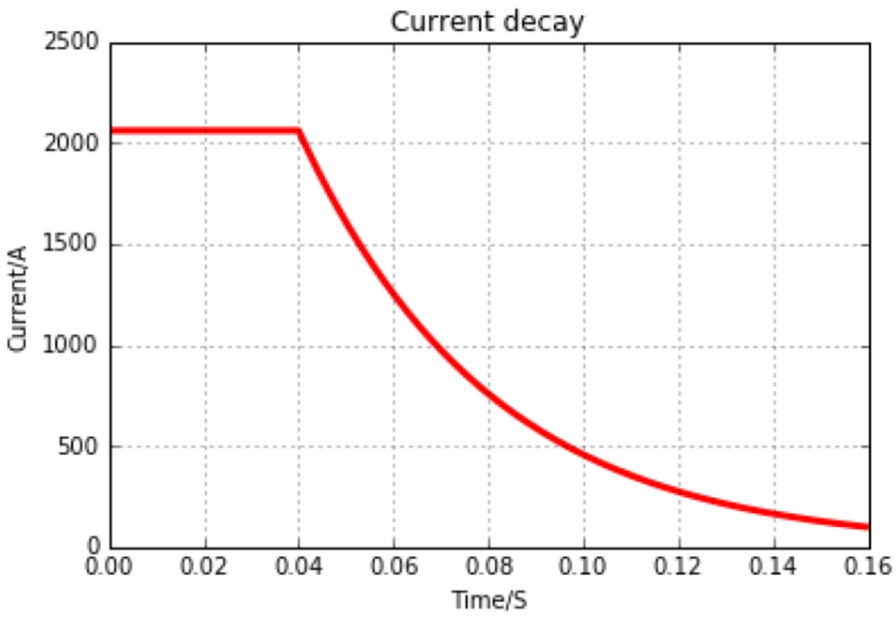


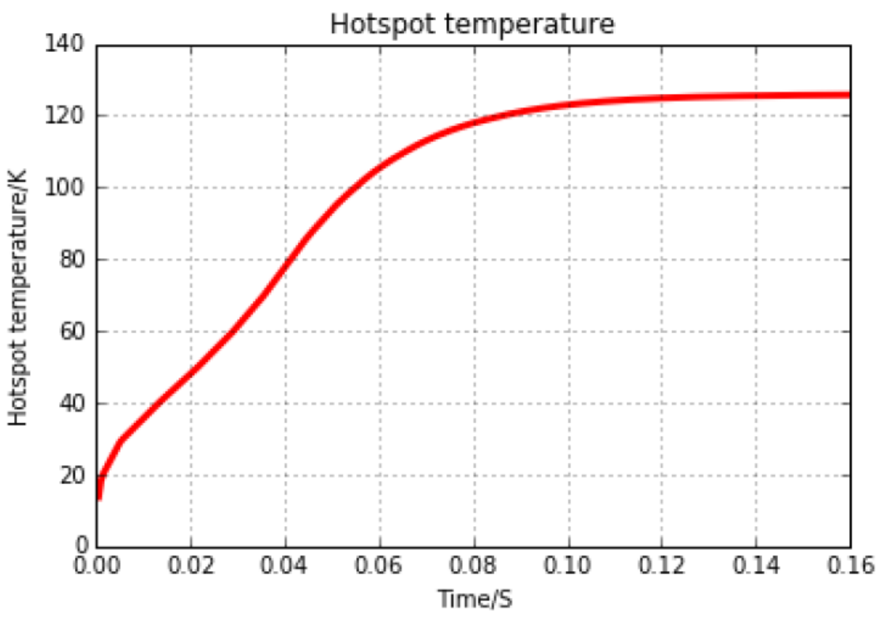




Quench simulation of QD0, safe

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





◆ Design parameters of QD0:

Table 2: 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

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

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

$$(NI)_{Quadrupole} \approx \frac{G\overline{R}^2}{\mu_0}$$

(no iron)

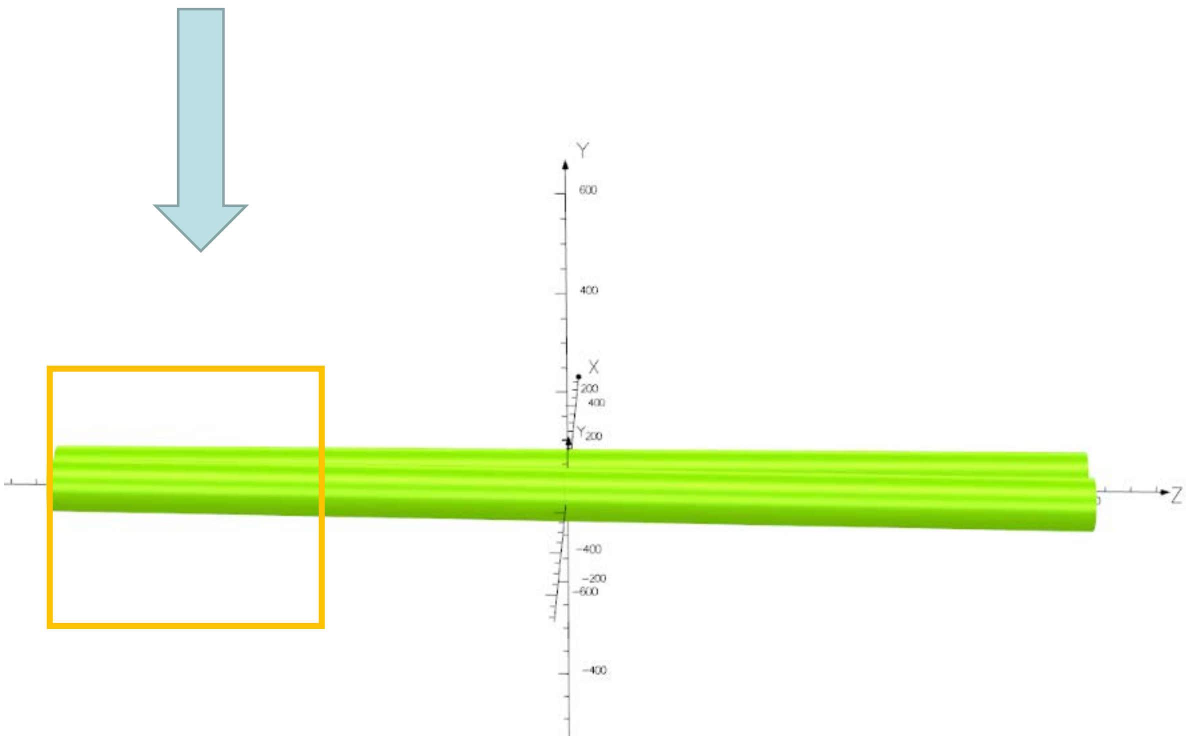
$$(NI)_{Quadrupole} \approx 2\frac{G\overline{R}^2}{2\mu_0} \Big/ \left(1 + \left(\frac{\overline{R}}{R_y}\right)^4\right)$$

(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.

Design of QD0 short model magnet

- Novel design of QD0 in the world:
  Collared cos2θ quadrupole magnet with shared iron yoke and crossing angle between two aperture centerlines.
- So far, there is no cos2θ superconducting quadrupole magnet developed in China.
- 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).**



- The aim of QD0 short model magnet:

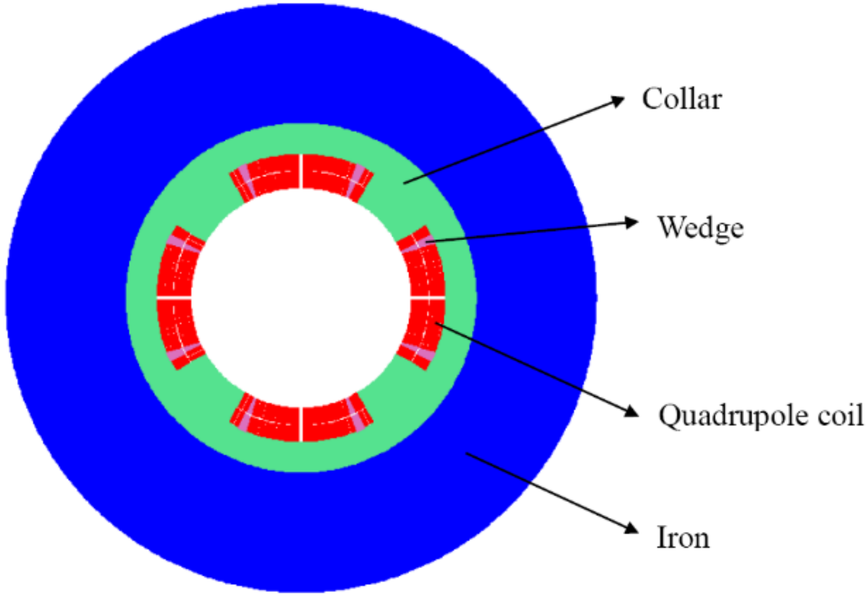
  Verify magnet design;

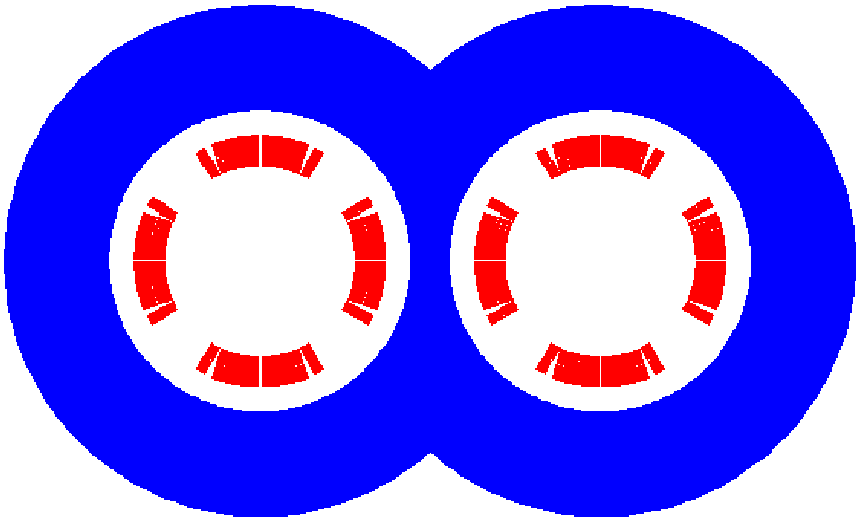
  Exploring magnet manufacturing technology;

  Master cryogenic testing Technology;

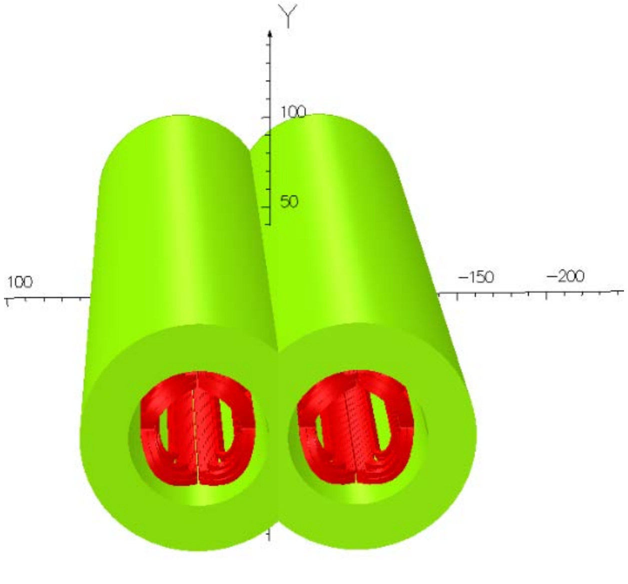
  Master the excitation and quench performance of magnet;

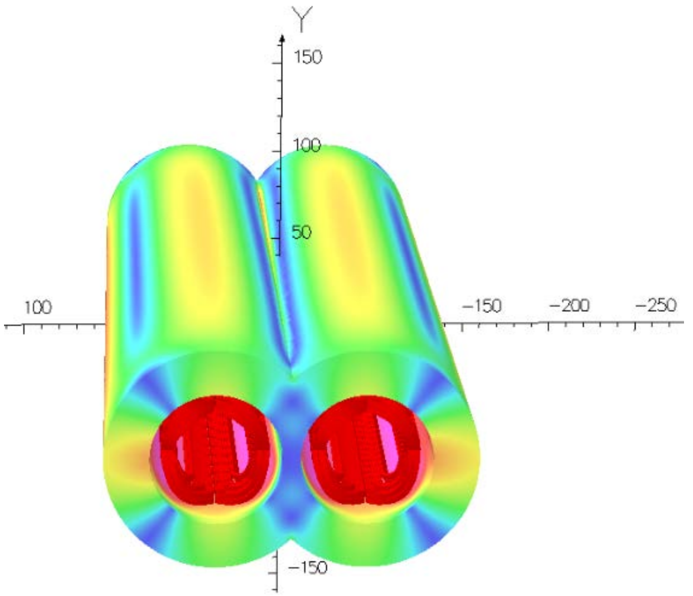
  Lay the foundation for the development of long QD0 prototype.

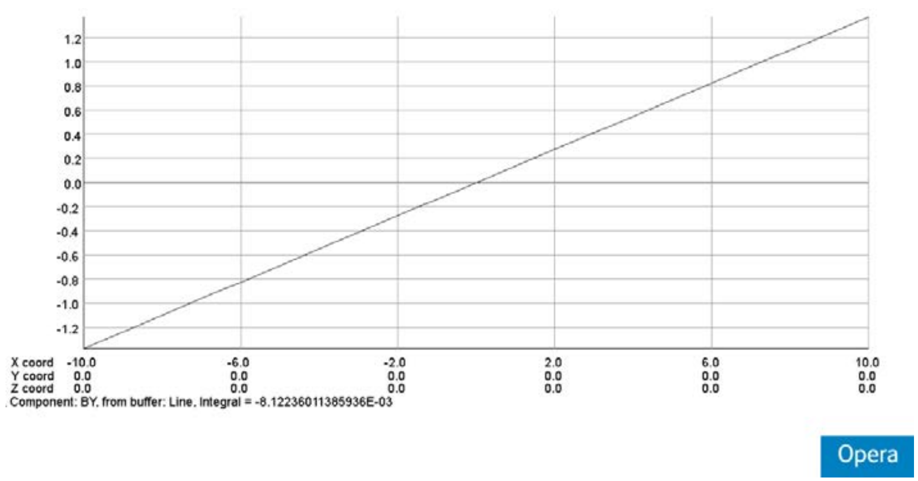


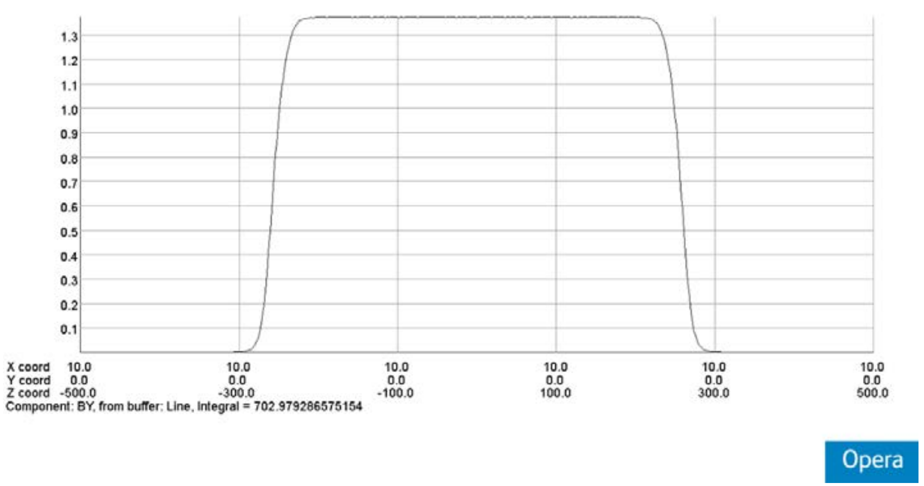


- 3D field simulation of two apertures 0.5m QD0.







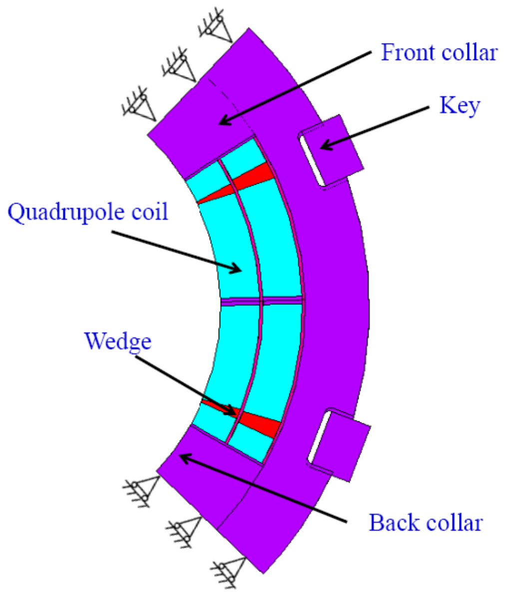


- 3D field simulation result shows that, local field harmonic as a result of field cross talk is smaller than 0.5 unit (1×10^{-4}).
- Each integrated multipole field as a result of field crosstalk between the two apertures is smaller than 0.3 unit.
- The dipole field is smaller than 10 Gs at each longitudinal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

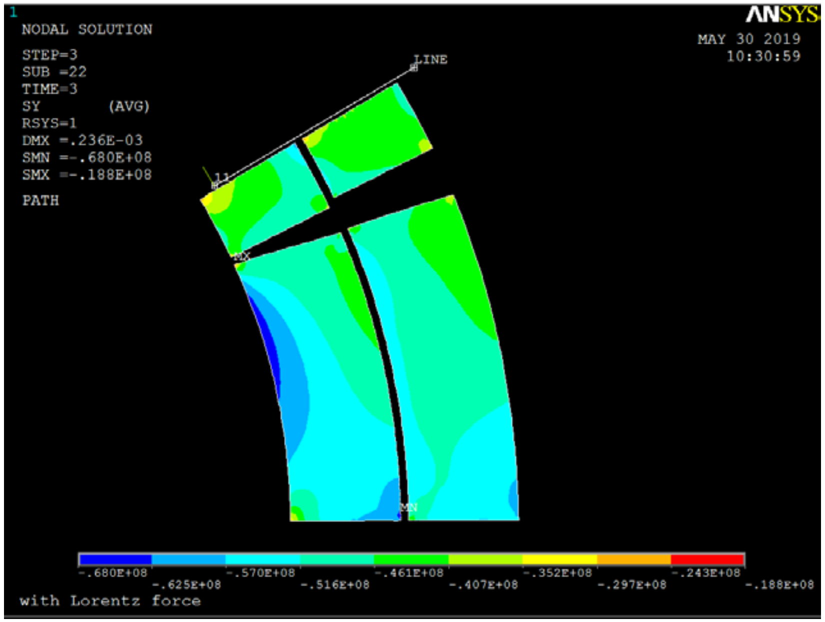
Table 3: 3D integrated field harmonics（unit, 1×10^{-4}）

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

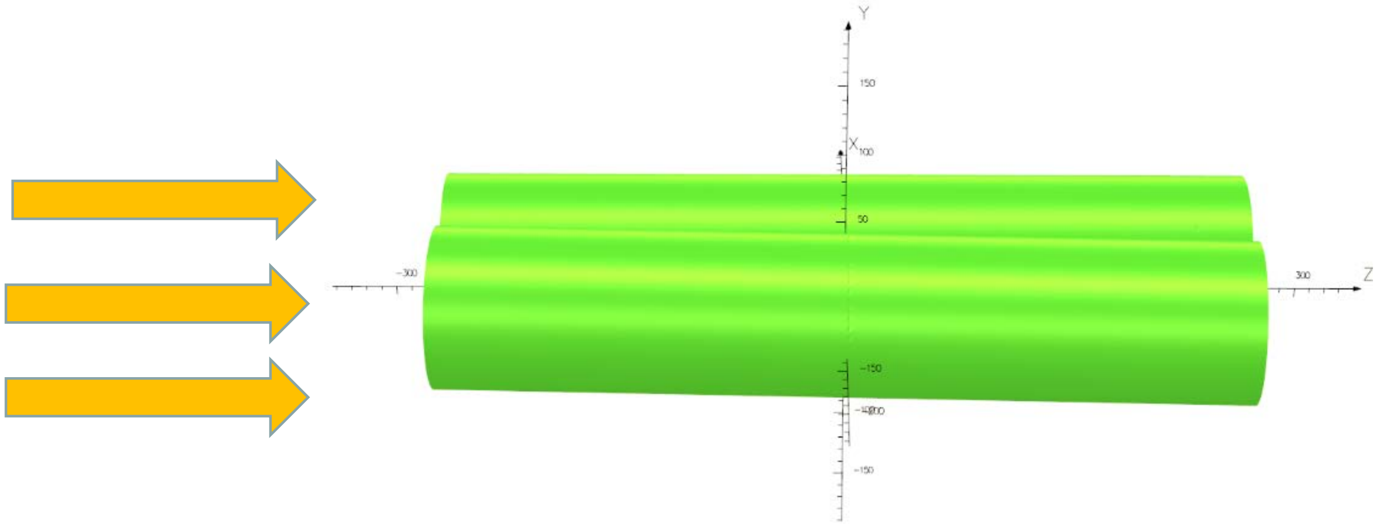
- A total of 8 keys are used in the whole cross section.
- The FEM analysis result shows that, the stress in each component during each operation step is safe.
- Collar material with high strength is required.

Influence of solenoid field on the quadrupole

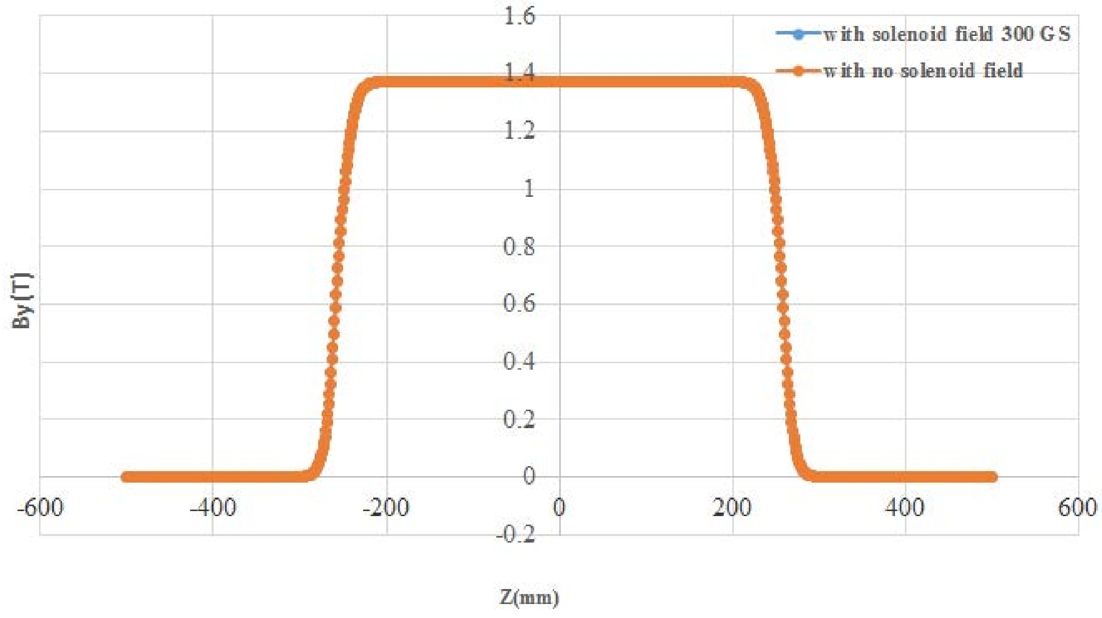
- Quadrupoles are located inside the bore of Accelerator anti-solenoid, which can cancel the field of Detector solenoid.
- The cancellation of solenoid is not perfect, and residual solenoid field exists. During optimization, the solenoid field is smaller than 300 Gs in the quadrupole region.

■ 3D field simulation of 0.5m QD0 with 300 Gs background solenoid field:

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 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}.



Magnetic fled distribution along longitudinal direction

Specifications on NbTi/Cu Strand and keystoned Rutherford Cable:

- ✓ **Strand:**

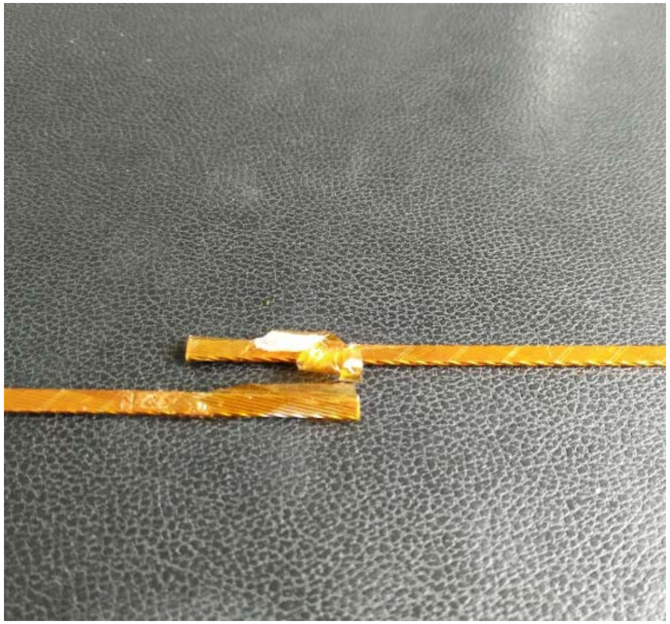
  NbTi/Cu, 0.5mm in diameter,

  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.

QD0 design with updated requirement

◆ The requirement of the Final Focus quadrupoles is recently updated.

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

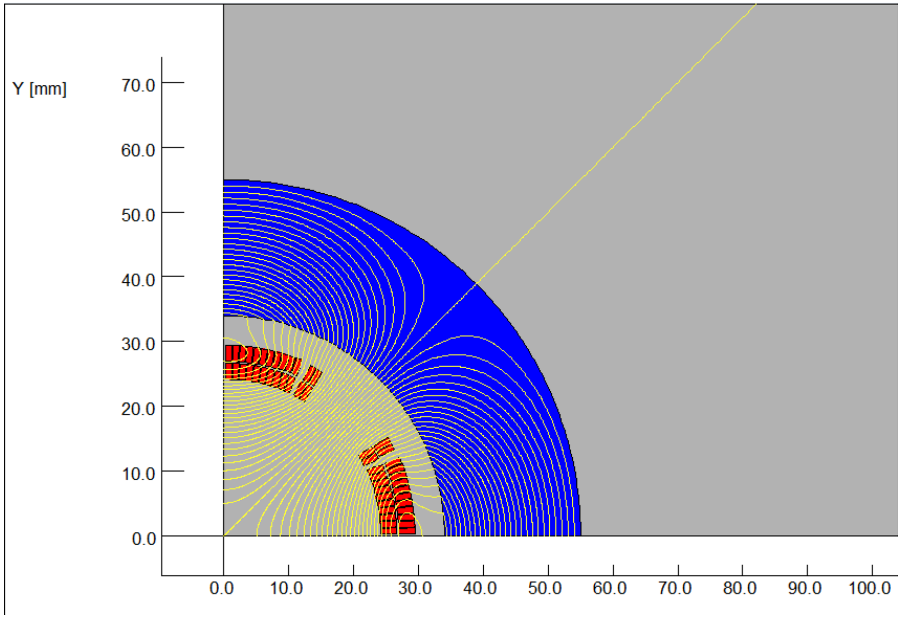
Magnet	Central field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
QDa	77.5	1.5	19.2	72.61
QDb	77.5	1.5	22.0	124.75
QF1	63.4	2.0	30.9	181.85

Design considerations

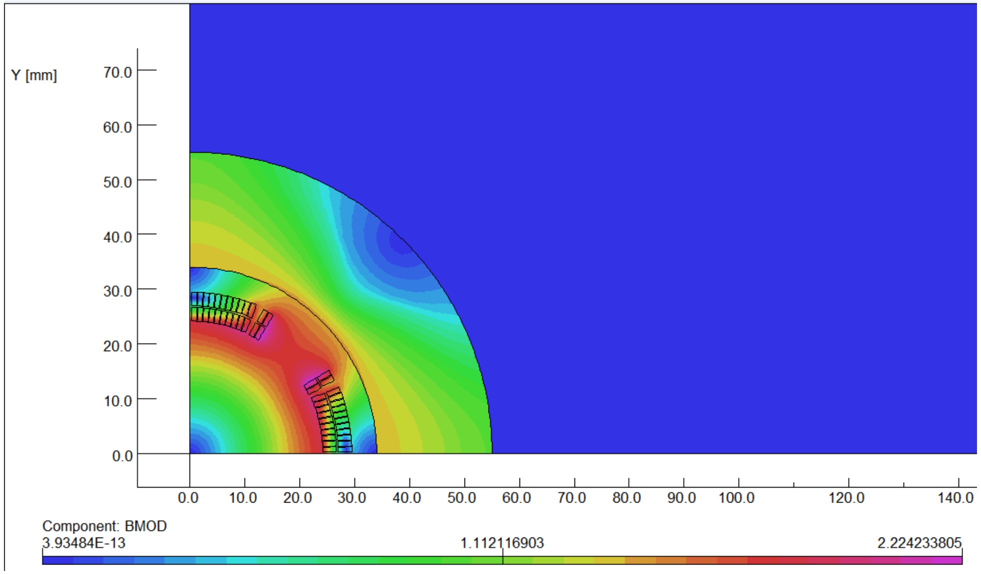
- The field gradient of quadrupoles is reduced compared to that in CDR; the development of QDa is the most challenging.
- Design of quadrupoles and anti-solenoid is similar to that in CDR.
- Space for the corrector coil is enough inside the bore of quadrupole.
- Iron yoke is used to eliminate the field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

Design progress of QDa

- The design of QDa is based on two layers cos2θ quadrupole coil using Rutherford cable with iron yoke.
- The QDa single aperture cross section is optimized with four coil blocks in two layers separated by wedges, 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}.



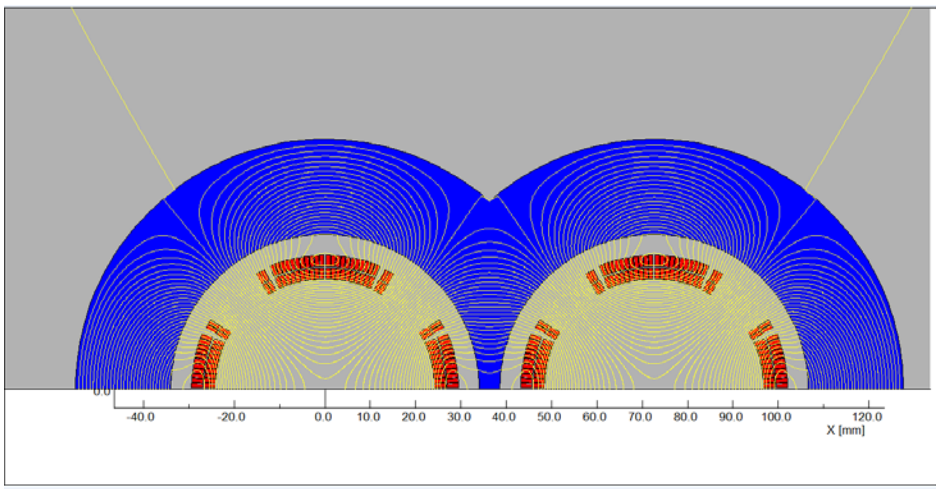
2D flux lines (1/4 cross section)



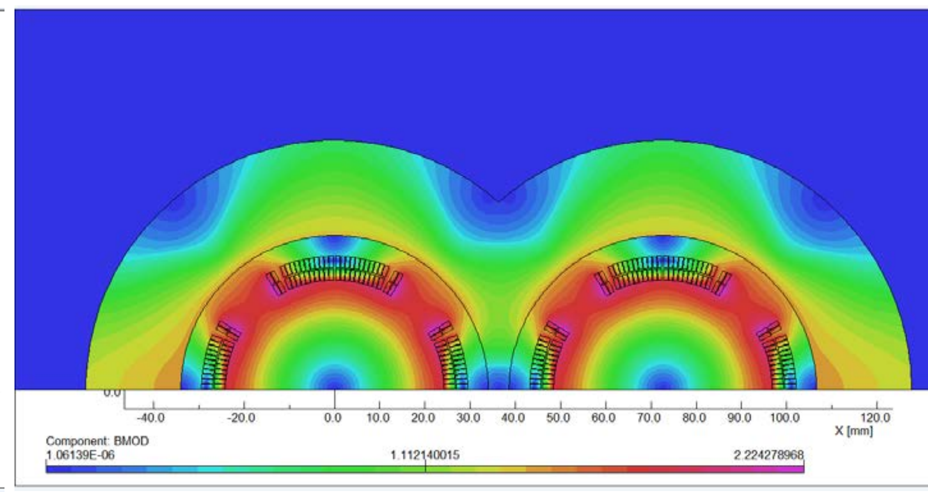
Magnetic flux density distribution

Field cross talk of the two apertures:

- 2D field cross talk of QDa two apertures near the IP side, where the distance between two aperture centerlines is minimum.
- Iron yoke can well shield the leakage field of each aperture. 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.



2D Flux lines

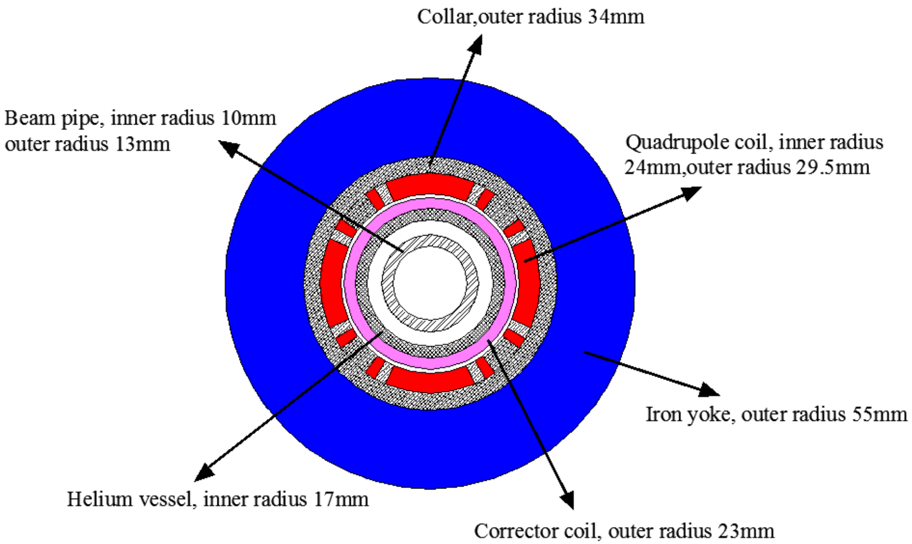


Bmod distribution

◆ Design parameters and single aperture cross section of QDa:

Table 5: Design parameters of QDa for Higgs

Magnet name	QDa
Field gradient (T/m)	77.5
Magnetic length (m)	1.5
Coil turns per pole	25
Excitation current (A）	1240
Coil layers	2
Conductor	Rutherford Cable, width 2.5 mm, mid thickness 0.93 mm, keystone angle 1.9 deg
Stored energy (KJ) (Double aperture)	8.0
Inductance (H）	0.010
Peak field in coil (T)	2.4
Coil inner diameter (mm)	48
Coil outer diameter (mm)	59
X direction Lorentz force/octant (kN)	39
Y direction Lorentz force/octant (kN)	-34



To minimize the quench caused by beam loss, a thin layer of liquid helium will be introduced inside superconducting corrector coils.

- 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
  Similar cross section as NbTi option;
  Wind and react; or React and wind;
  Firstly some tests on Bi-2212 conductor is needed.
- HTS YBCO option for CEPC SC sextupole.

Summary

- MDI superconducting quadrupole magnets are key devices for CEPC.
- 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 reduced about 20%.
- The first step of the R&D is to develop a QD0 short model magnet with a magnetic length of 0.5 m.
- **Physical design of 0.5m QD0 short model magnet has been finished**, and all the design requirements have been met. The fabrication is planned to be started **(depending on fund)**.
- With the reduced field gradient in the updated design, both the NbTi option and HTS option for CEPC superconducting magnets will be considered.

Thanks for your attention!