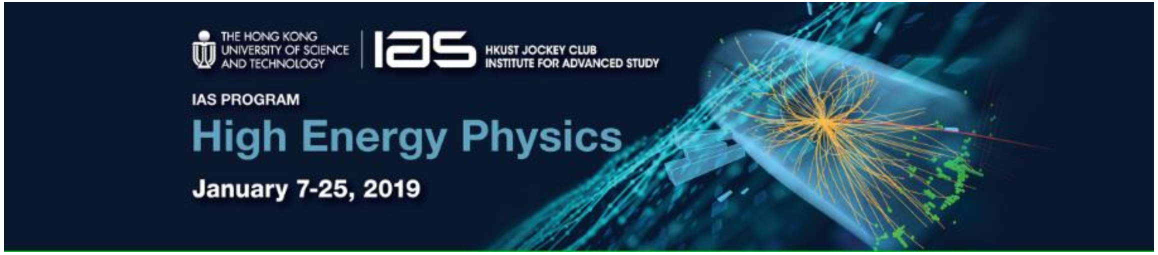

CEPC MDI SC Magnets R&D

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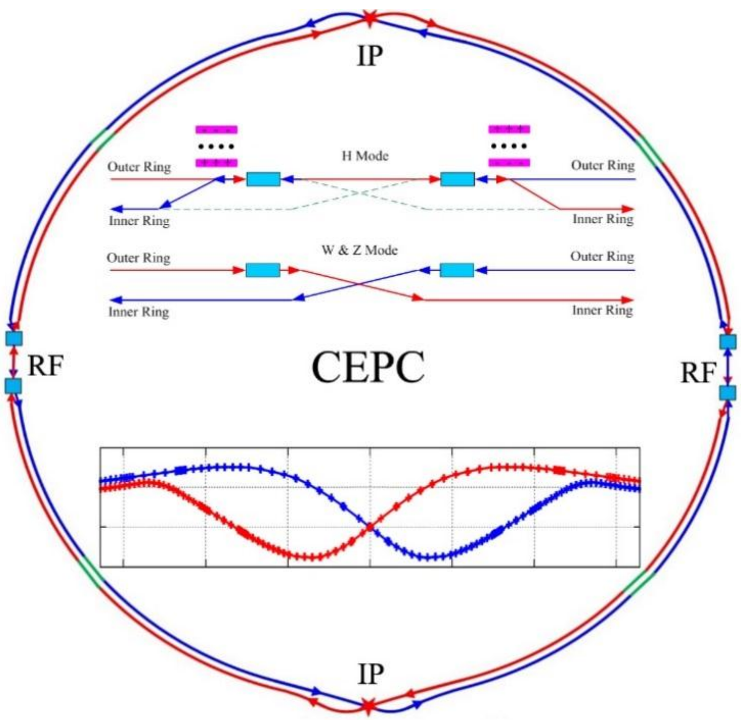
Outline

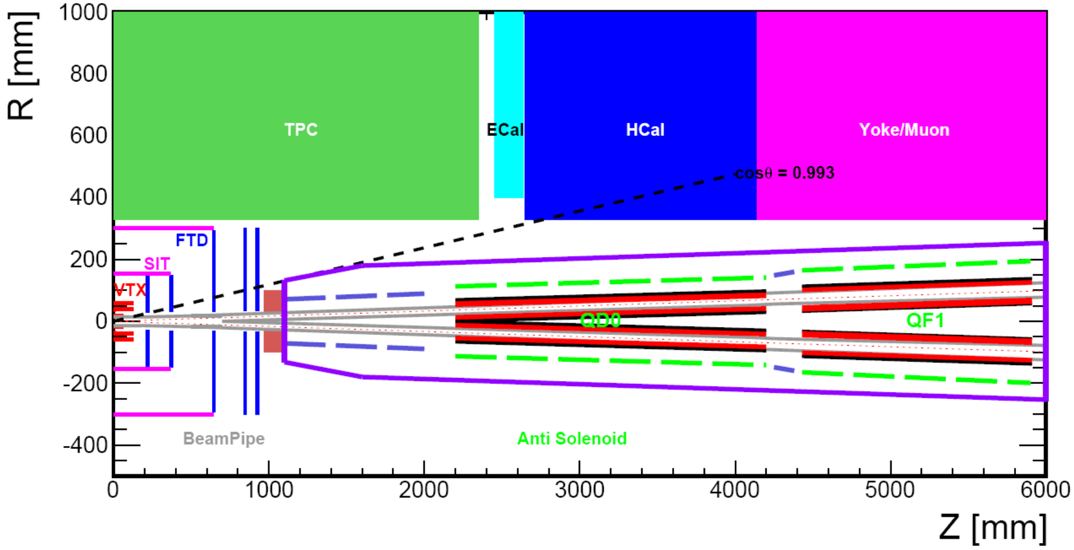
- Introduction
- Design progress of CEPC MDI SC Magnets
- TDR plan
- R&D status
- Summary

Introduction

- 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.
- Compact high gradient final focus quadrupole magnets are required on both sides of the collision points in interaction region of CEPC collider ring.



Sketch of CEPC Collider ring



CEPC MDI layout

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

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	19.51	72.61
QF1	110	1.48	27.0	146.20

- QD0 and QF1 magnets are operated full inside the field of the Detector solenoid magnet with a central field of 3.0 T.
- To minimize the effect of the longitudinal detector solenoid field on the accelerator beam, anti-solenoids before QD0, outside QD0 and QF1, after QF1 are needed, so that the total integral longitudinal field generated by the detector solenoid and accelerator anti-solenoid is zero.

CEPC MDI SC Magnets including: superconducting QD0,QF1, anti-solenoid on each side of the IP points.

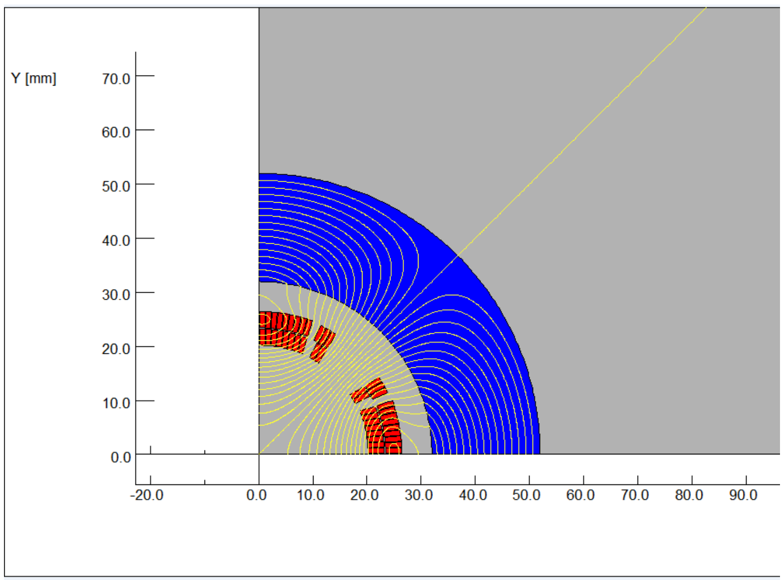
- The field distribution of net solenoid field should also meet the requirements from the accelerator beam dynamics.
- The MDI layout imposes strict boundary conditions on the longitudinal and transerve dimensions of the accelerator magnets.

- Taking into account the high field strength of twin aperture quadrupole magnet, high central field of anti-solenoid, and the limited space, superconducting technology base on NbTi conductor will be used for Interaction Region superconducting quadrupole magnets and anti-solenoids.

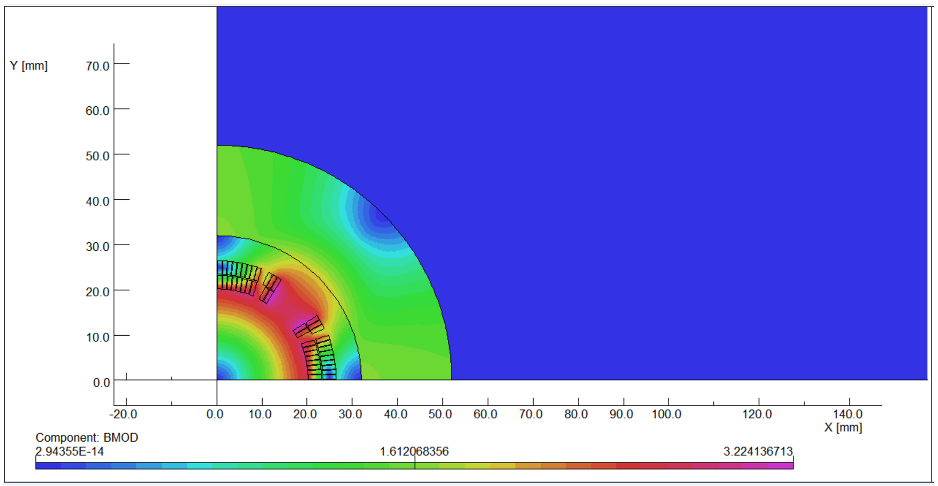
Design progress of CEPC MDI SC Magnets

Design progress of QD0

- The minimum distance between QD0 two aperture centerlines is only 72.61 mm, so very tight radial space is available.
- The design of QD0 based on two layers cos2θ quadrupole coil using Rutherford cable with iron yoke is in progress.
- The QD0 single aperture coil cross section is optimized with four coil blocks in two layers separated by wedges, and there are 22 turns in each pole.



2D flux lines (1/4 cross section)



Magnetic flux density distribution

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

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

(no iron)

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

(with iron)

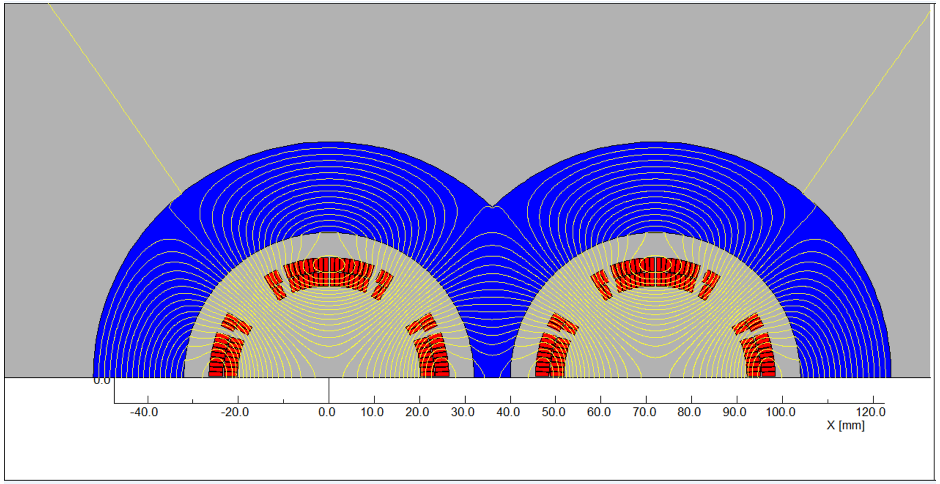
Yingshun Zhu, et al., Study on Ampere-Turns of Superconducting Dipole and Quadrupole Magnets Based on Sector Coils, *Nuclear Instruments and Methods in Physics Research A*, 2014, 741: 186-191.

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

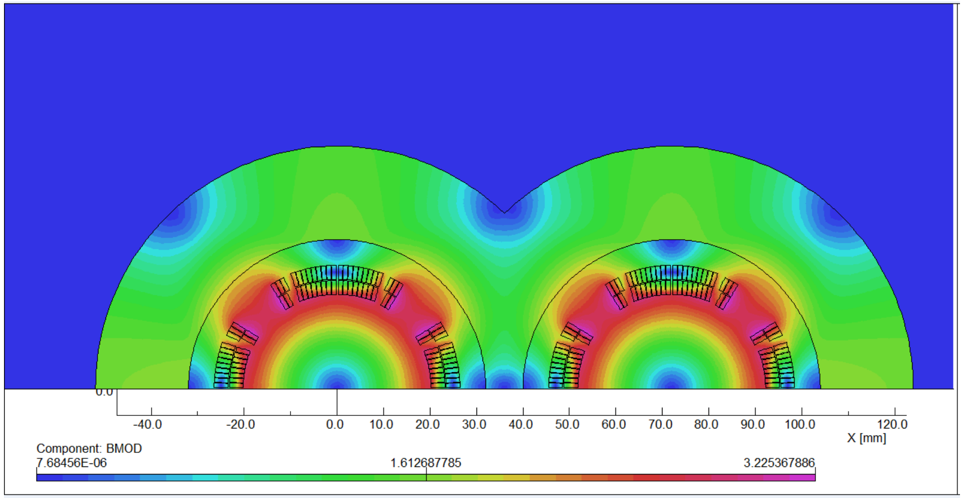
n	B_n/B_2@R=9.8mm
2	10000
6	0.005
10	-0.6
14	-0.005

- ◆ The excitation current of QD0 is 2060A.
- ◆ Field quality in single aperture is good.
- However, the field in one aperture is affected due to the field generated by the coil in another aperture.
- Field cross talk of the two apertures is studied.

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

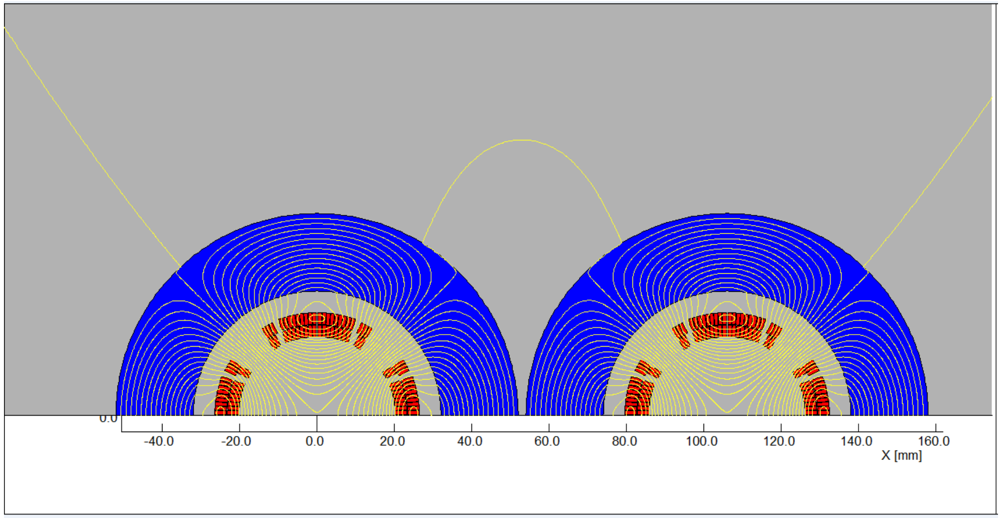


2D Flux lines

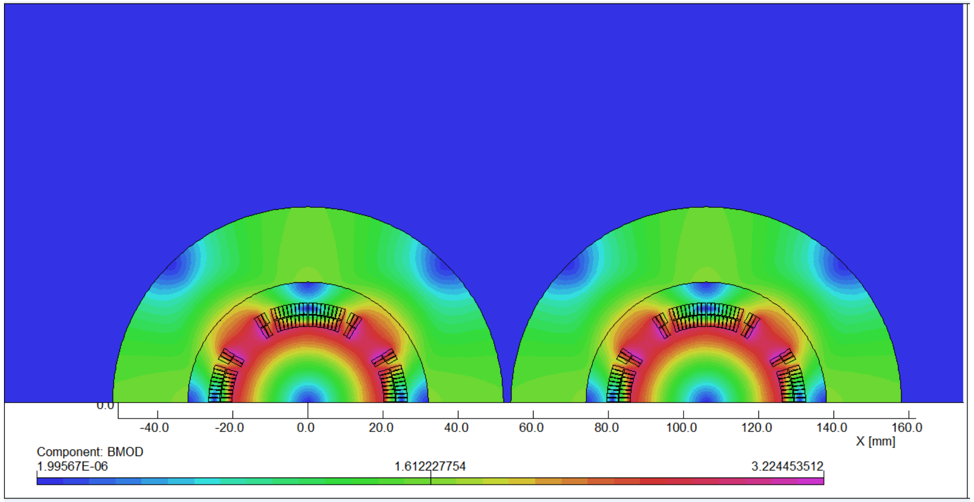


Bmod distribution

- 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 0.6×10^{-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.

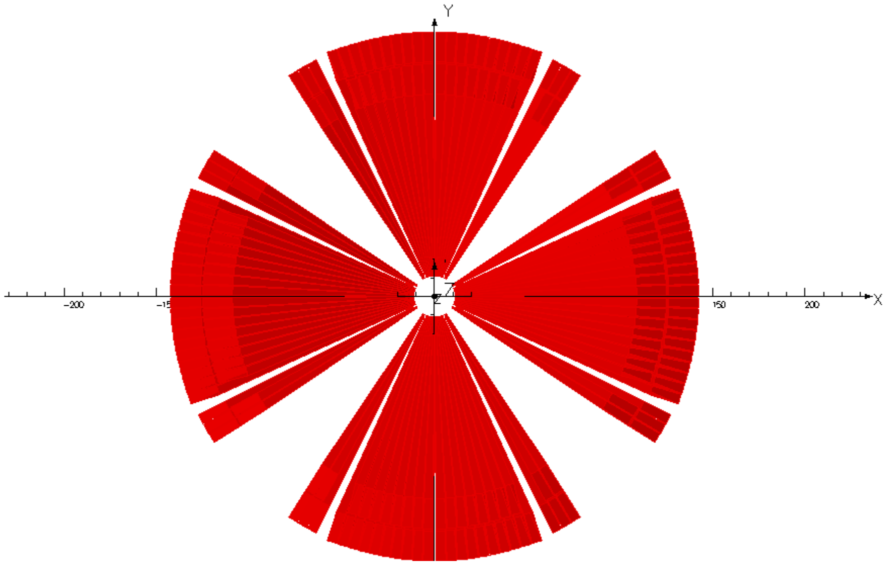
✓ Using the iron yoke, the field harmonics as a result of the field crosstalk is not a problem.

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

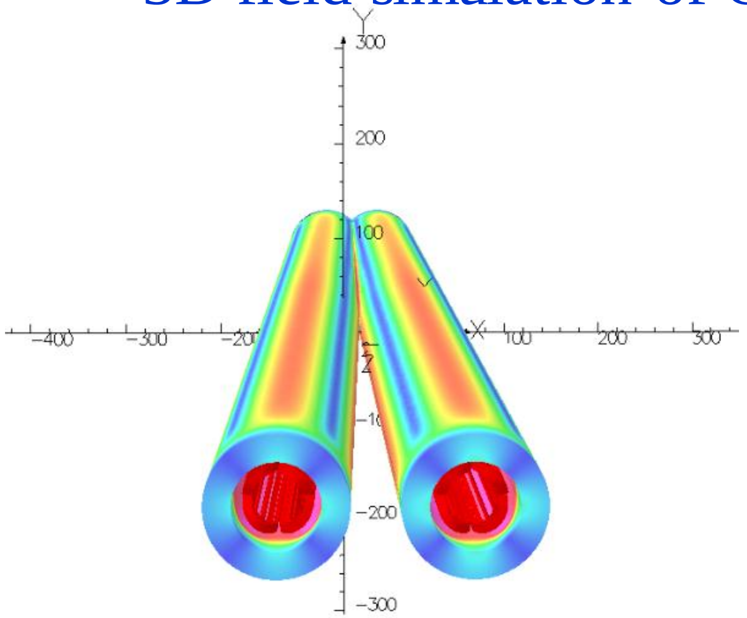
✓ The main disadvantage of the iron option is that the diameter of QD0 will be larger, and there will be not enough space for multipole corrector coils.

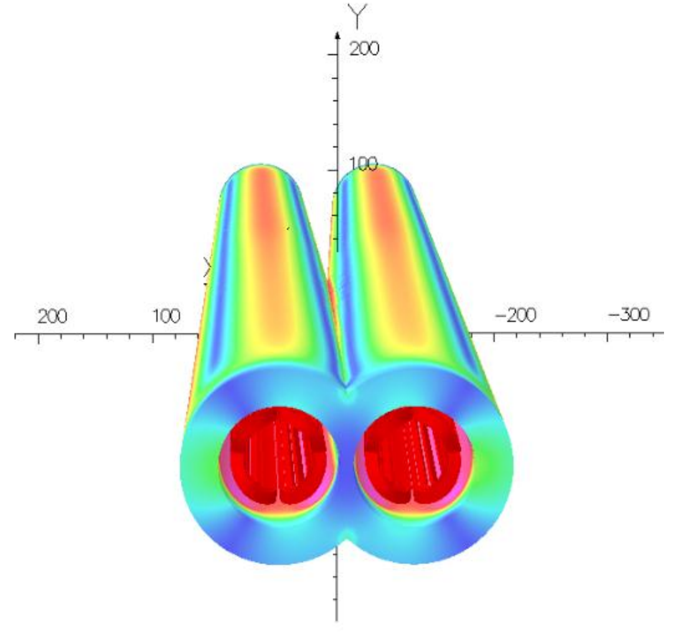
QD0 are modelled in OPERA-3D.

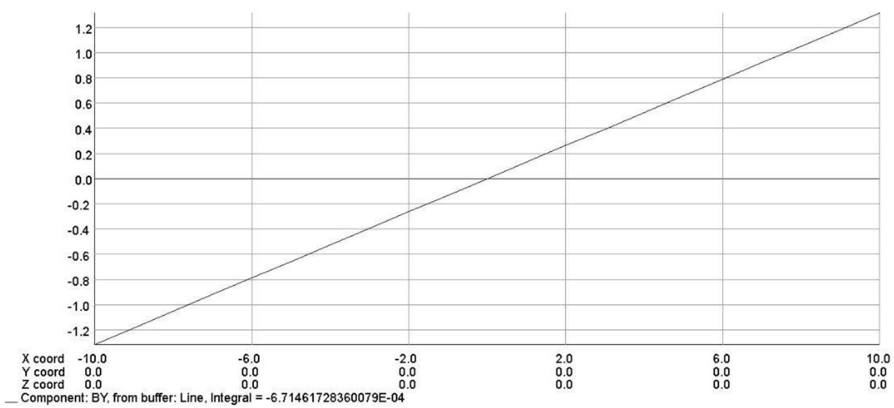
- Firstly one single aperture QD0 is modelled, the field gradient exceeds 136 T/m, and field quality is good.
- Then two aperture QD0 are modelled, the multipole fields induced by the field cross talk of the two apertures are obtained.

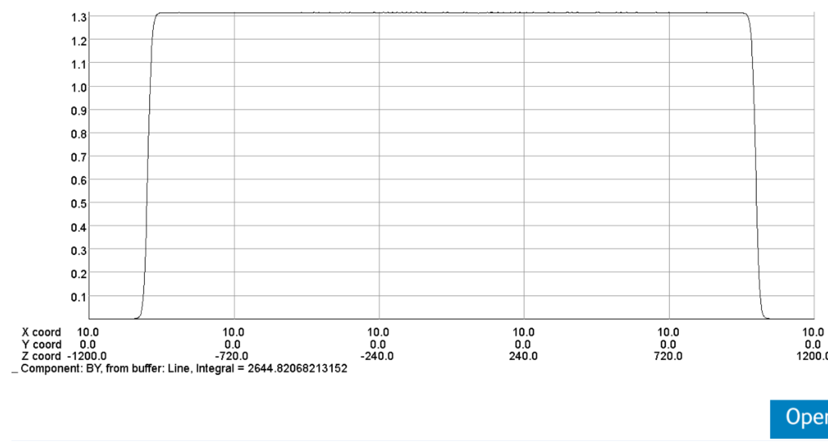


- 3D field simulation of QD0.





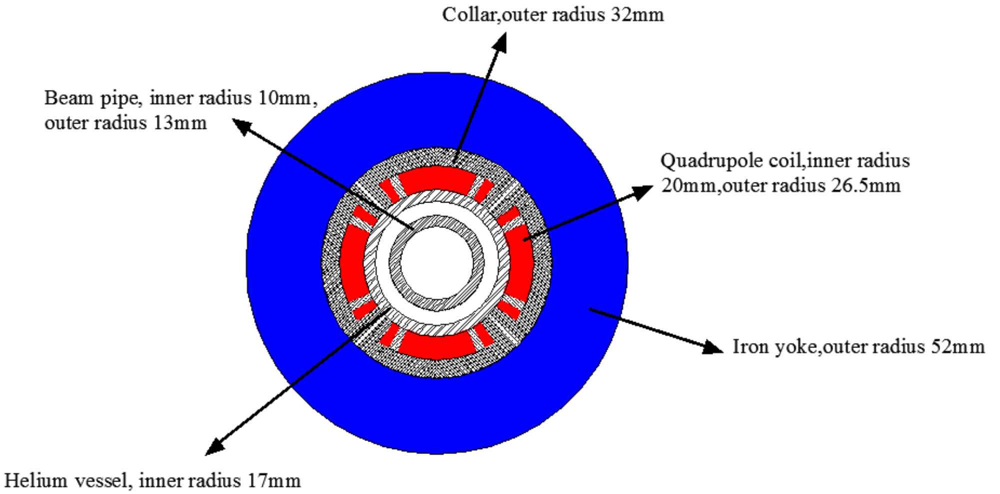


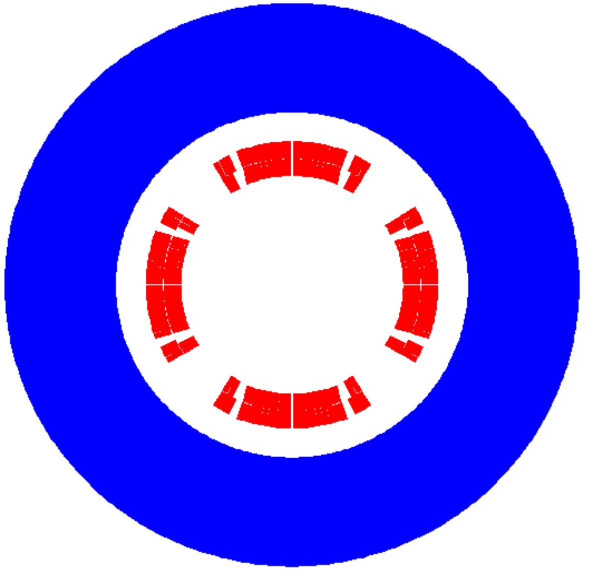


Opera

- 3D field simulation result shows that, iron yoke can well shield the leakage field of each aperture, so field cross talk is not a problem.
- Each integrated multipole field as a result of field crosstalk between the two apertures is smaller than 1×10^{-4}.

◆ QD0 single aperture cross section.





◆ The beam pipe at room temperature is held inside the helium vessel with a clearance gap of 4 mm.

◆ Design parameters of QD0:

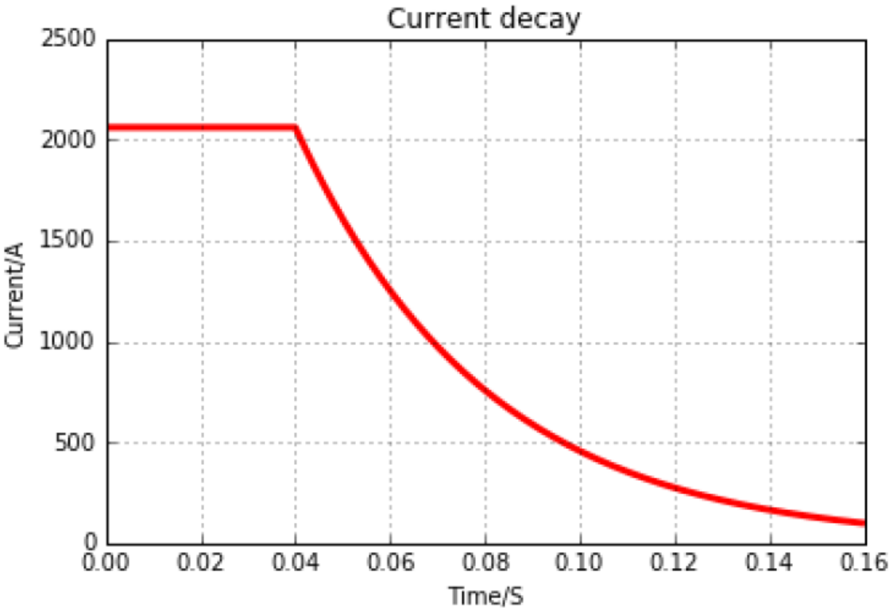
Table 3: Design parameters of QD0

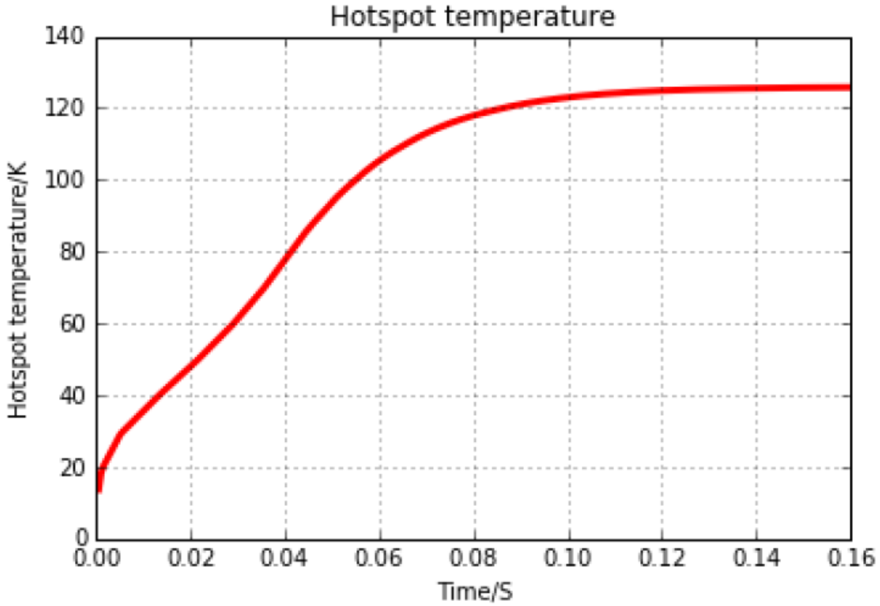
Magnet name	QD0
Field gradient (T/m)	136
Magnetic length (m)	2.0
Coil turns per pole	22
Excitation current (A）	2060
Coil layers	2
Conductor	Rutherford Cable, width 3 mm, mid thickness 0.93 mm, keystone angle 1.9 deg, Cu:Sc=1.3, 12 strands
Stored energy (KJ) (Double aperture)	21.5
Inductance (H）	0.010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

Quench simulation of QD0

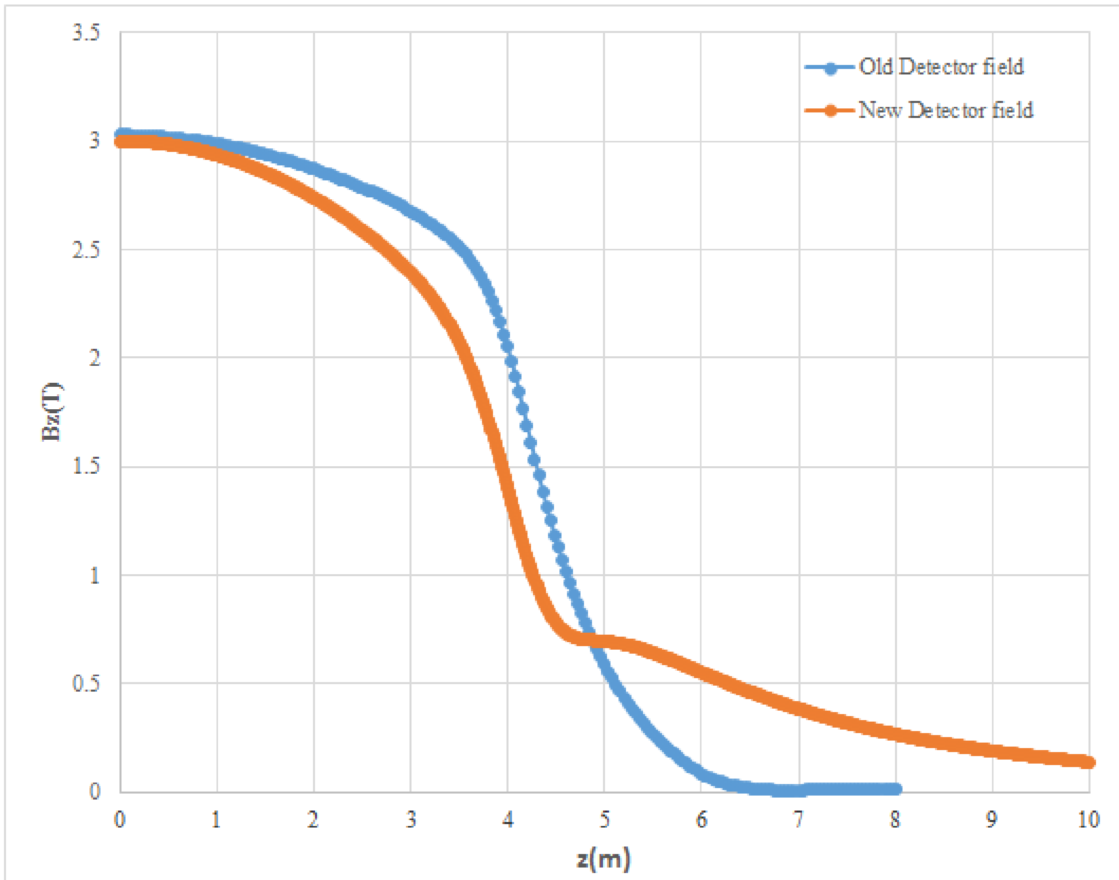
- ✓ Dump resistance=0.24Ω，Delay time= 40 ms.
- ✓ Hot spot temperature: 126K
- ✓ Magnet resistance: 0.009Ω
- ✓ Peak voltage : 500V





Design progress of superconducting anti-solenoid

- Recently, the design of Detector solenoid is modified, so the design of Accelerator anti-solenoid is updated.



Old vs new Detector solenoid field distribution

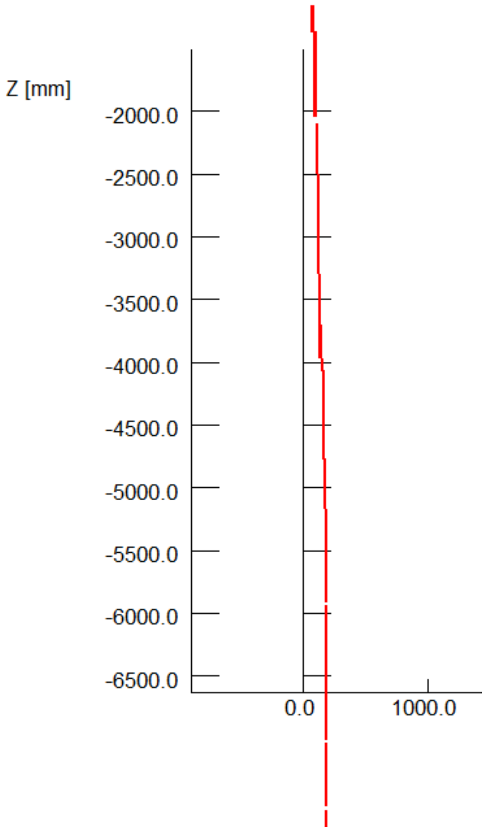
- The design requirements of the anti-solenoids in the CEPC Interaction Region are summarized below:

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.

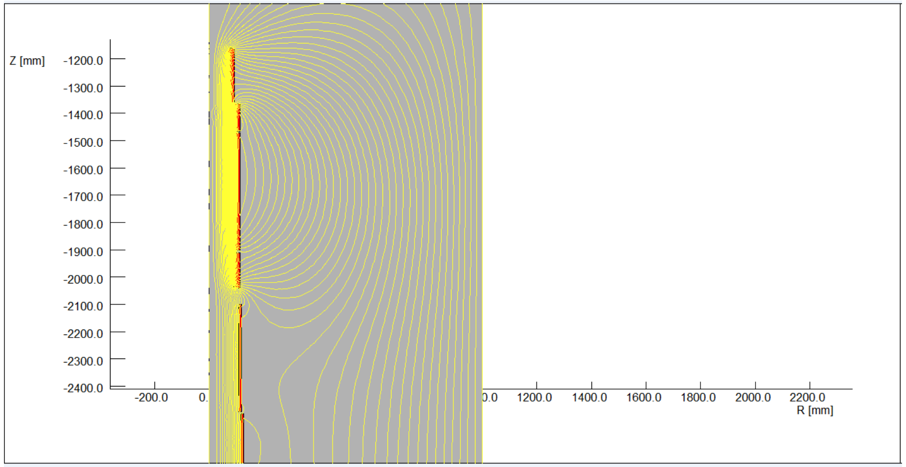
- The design of the anti-solenoid fully takes into account the above requirements. The anti-solenoid will be wound of rectangular NbTi-Cu conductor.

- 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.

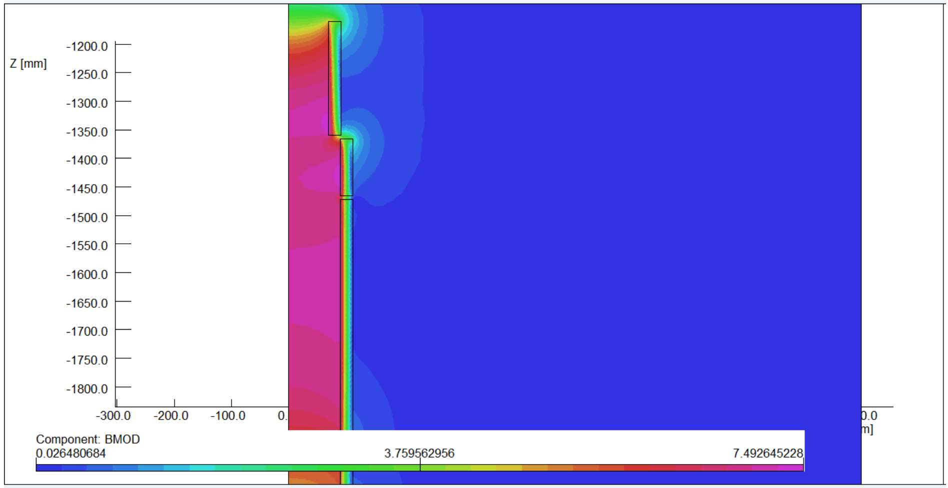
- The anti-solenoid along longitudinal direction:
  1) 4 sections, from IP point to QD0;
  2) 12 sections, QD0 region;
  3) 6 sections, QF1 region;
  4) 7 section, after QF1 region.
- To reduce the length of the cryostat, the sections of anti-solenoid after QF1 region with low field will be operated 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 (The old one is 7.2T).

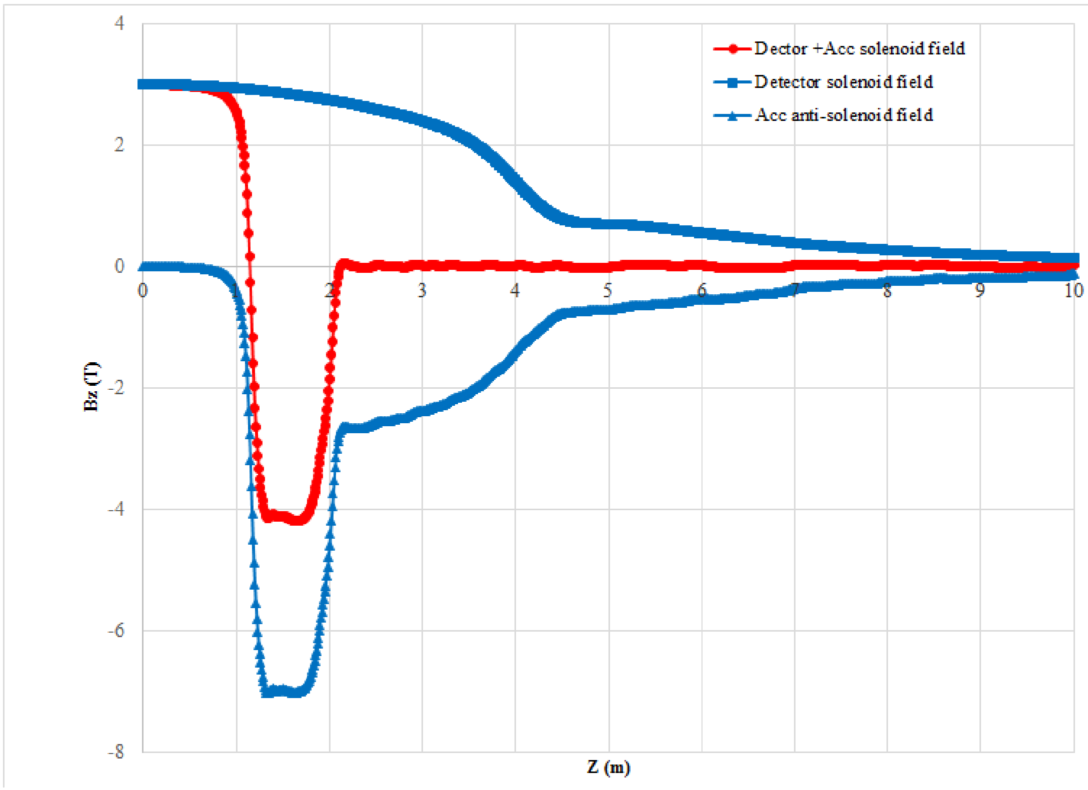


2D flux lines



Magnetic flux density distribution

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

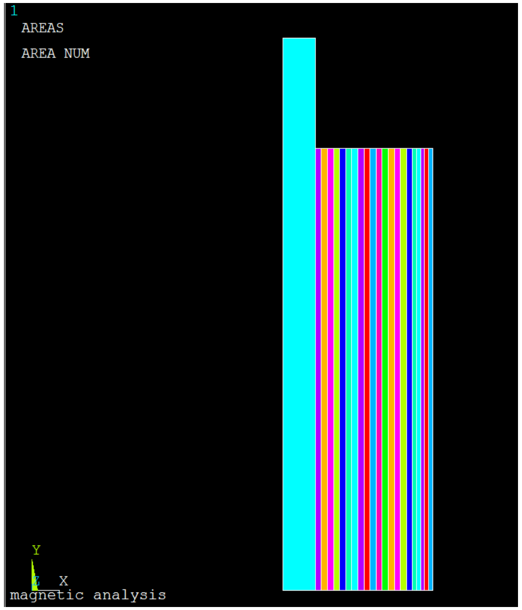


◆ The net solenoid field inside QD0 and QF1 at each longitudinal position is smaller than 300 Gs.

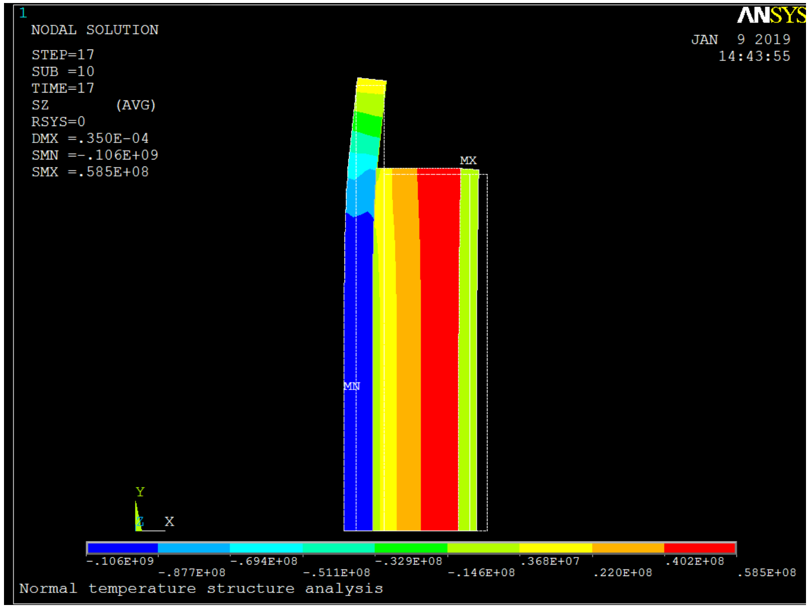
● The combined field distribution of anti-solenoid and Detector solenoid well meets the requirement of beam dynamics.

Stress analysis of first section of Anti-solenoid.

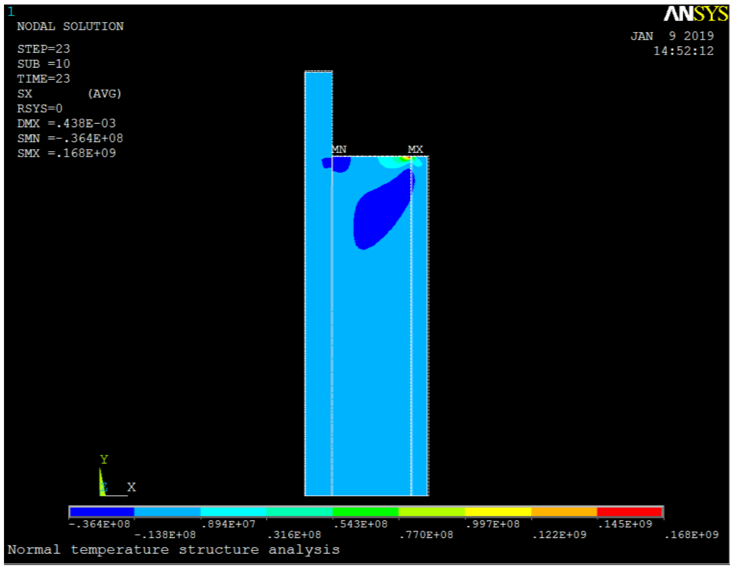
- A two-dimensional axisymmetric finite element model using ANSYS is established to model and analysis the stress of the first section of Anti-solenoid with a central field of 7T.
- The FEM model contains the superconducting coil, support tube, and Aluminum alloy bandage outside the coil.



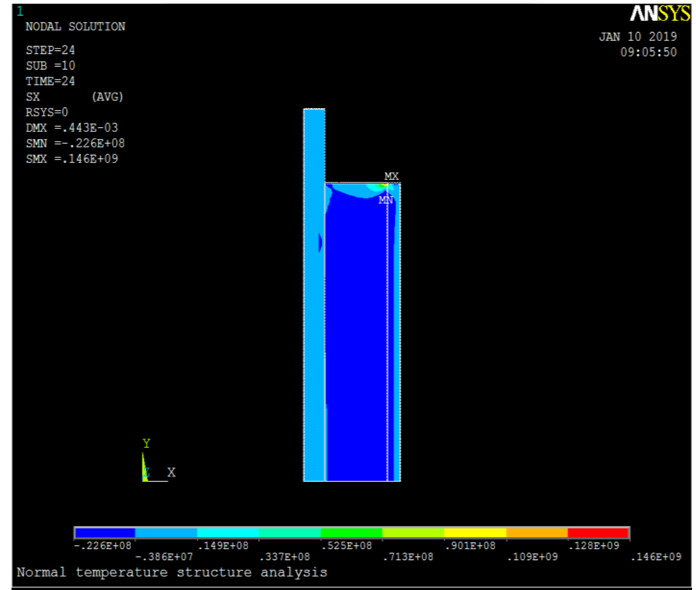
Model



Stress after winding



Stress after cool down to 4.2K

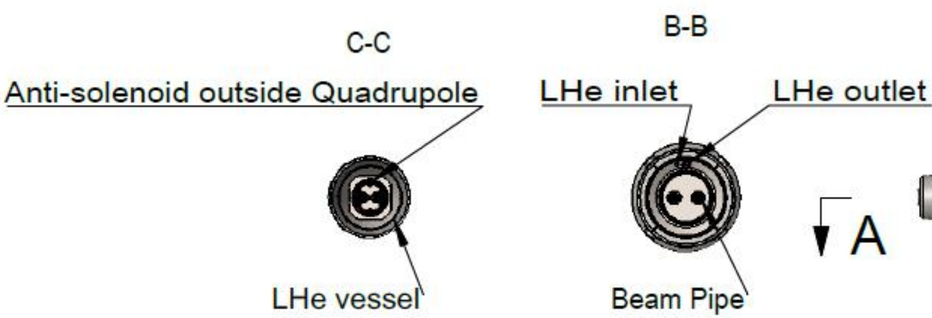


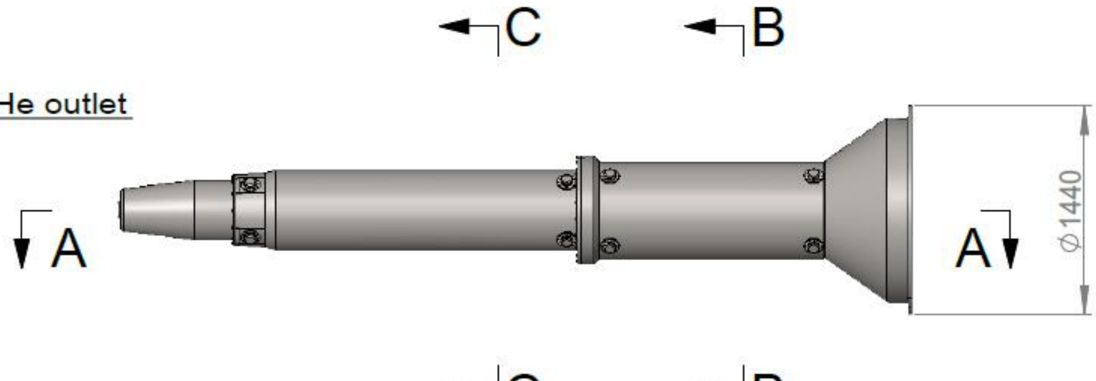
Stress after excitation

- 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 progress of magnet cryostat

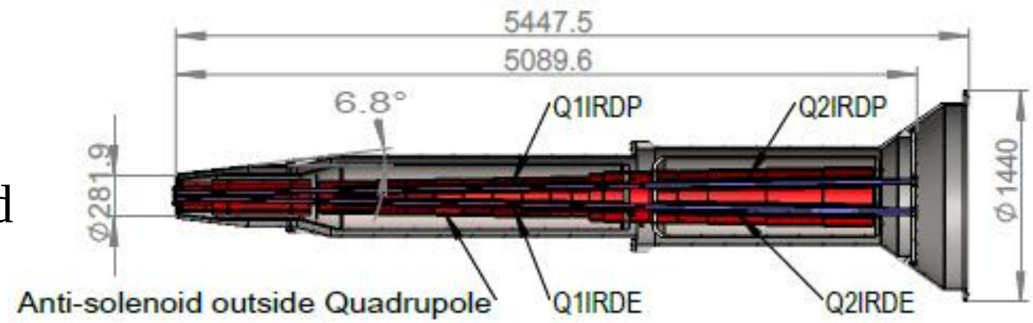
The Structure of Cryostat

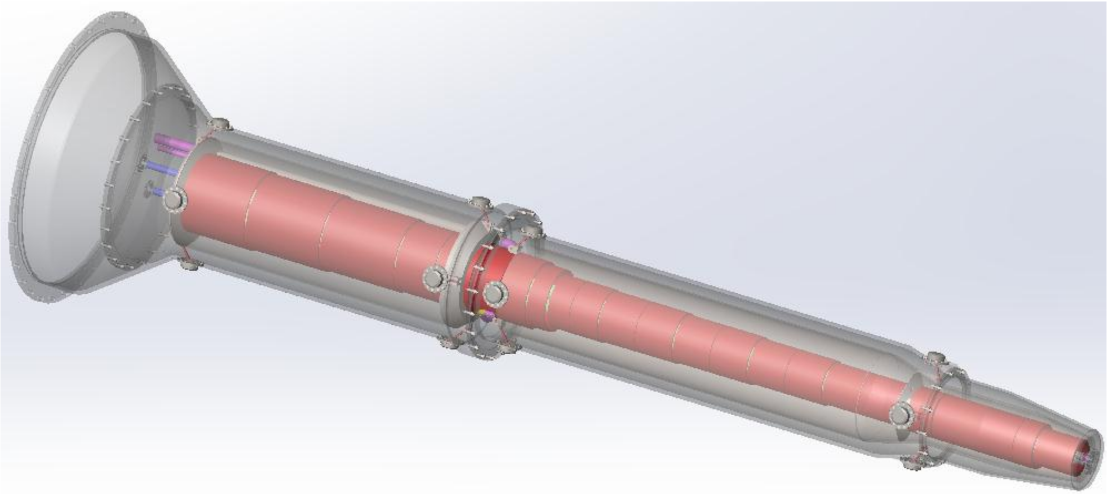




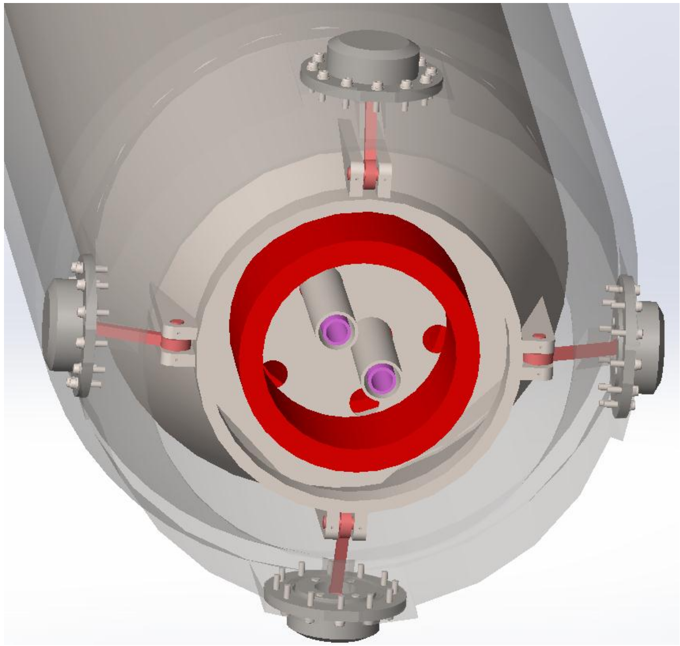
Magnet-cryostat design:

- superconducting magnets are assembled in the helium vessel.
- Two beam pipes at room temperature pass completely through the helium vessel at 4.2K.
- Self-centered supports are designed to make the magnet positions after cool-down to be the nominal positon for the beam operation.





- The helium vessels, in which the SC magnets are assembled, are supported by 8 rods from the vacuum vessel.
- The rods to be made of non-metallic materials such as Carbon fiber.
- The multilayer insulation material is very important to decrease the heat load.



The heat leakage of room temperature beam pipe is estimated.

1) Radiation Leakage of 300K beam pipe in QD0 Region to the Inner Wall of 4.2K Liquid Helium vessel:

$Q_{11}=\sigma\varepsilon_{1-2}A_1(T_2^4-T_1^4)$

$T_1=4.2K$ $T_2=300K$ $A_1=0.42m^2$ $A_2=0.32m^2$

$\sigma=5.67\times10^{-8}W\cdot m^{-2}\cdot K^{-4}$

$\varepsilon_{1-2}=[1/\varepsilon_1+A_1/A_2(1/\varepsilon_2-1)]^{-1}$

- It is assumed that the outer surface of the beam pipe and the inner wall of the helium vessel are coated specially,

  $Q_{11}=4.3$ W

2) Similarly, Radiation Leakage of 300K beam pipe in QF1 Region to the Inner Wall of 4.2K Liquid Helium vessel $Q_{22}=5.82W$.

- So the total heat leakage of room temperature beam pipes is roughly 10W.

TDR Plan

TDR plan for CEPC MDI superconducting magnets

2018

- Complete the conceptual design of superconducting magnets in CEPC Interaction Region
- Preliminary design of the short prototype of double aperture quadrupole QD0

2019

- Complete the physical design, mechanical design, stress and quench analysis of the short prototype double aperture quadrupole QD0
- Fabrication of short prototype of double aperture quadrupole QD0
- Development of rotating coil magnetic field measurement system
- Development of quench protection system
- Preliminary design of the cryostat for combined function magnet

2020

- Finish the physical design, mechanical design, stress and quench analysis of superconducting quadrupole magnet QD0, QF1 and anti-solenoid.
- Complete the cryogenic vertical test of short prototype of QD0
- Fabrication of short combined function superconducting magnet prototype
- Complete the design of cryostat for combined function superconducting magnet

2021

- Complete the cryogenic vertical test of short prototype of combined superconducting magnet
- Complete the fabrication of cryostat for combined function superconducting magnet prototype
- Fabrication of long prototype of combined function superconducting magnet

2022

- Complete the cryogenic test of long prototype of combined superconducting magnet
- Summary of the R&D prototype magnets.
- Complete the Technical Design Report (TDR) of CEPC MDI superconducting magnets.

R&D status

- In the R&D stage of CEPC project, superconducting prototype magnets for the MDI will be developed in three consecutive steps:

1) Development of double aperture superconducting quadrupole prototype magnet QD0.
2) Development of short combined function superconducting prototype magnet including QD0 and anti-solenoid.
3) Development of long combined function superconducting prototype magnet including QD0, QF1 and anti-solenoid.

- Supported by “Wang Yifang scientist studio”, **the Step 1 of the R&D has started:** Development of double aperture superconducting quadrupole prototype magnet QD0.

◆ The key technical issues of the prototype superconducting magnets to be studied and solved in the R&D are listed below:

1) Magnetic and mechanical design of the superconducting quadrupole magnet and anti-solenoids with very high field strength and limited space.
2) Fabrication technology of small size Rutherford cable with keystone angle.
3) Fabrication procedure of the twin aperture quadrupole coil with small diameter.
4) Fabrication procedure of the anti-solenoids with many sections and different diameters.
5) Assembly of the several coils including QD0, QF1 and anti-solenoids.
6) Development of the long cryostat for the combined function SC magnet.
7) Development of magnetic field measurement system for small aperture long superconducting magnet.
8) Development of quench protection system for combined function SC magnet.
9) Cryogenic test and field measurement of the small aperture long SC magnet.

- Technical discussions on superconductor wire, cable manufacturer and magnet fabrication company were performed.
- Literature survey of fabrication process of superconducting quadrupole:

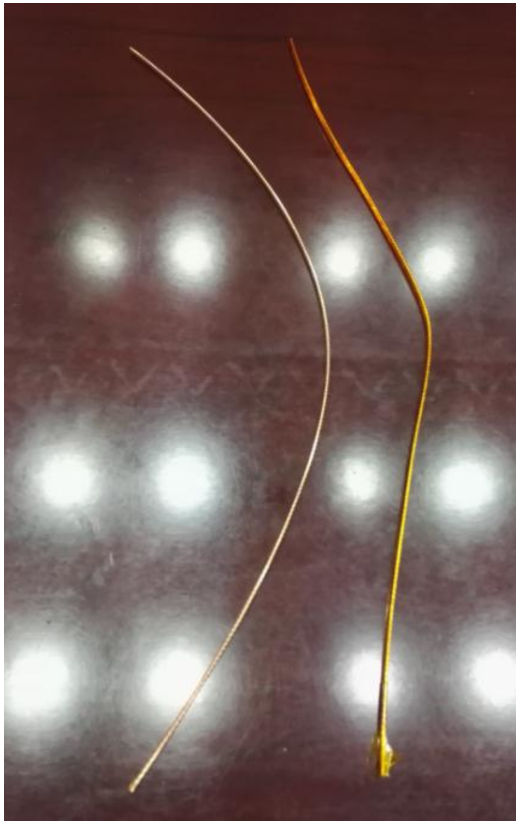
Superconducting strand → Rutherford Cable → Coil winding →
Coil curing → Magnet components fabrication →
Single aperture magnet assembly → Double aperture magnet assembly →
Room temperature field measurement → Cryogenic test and field measurement

- Specifications on strand and cable are obtained for procurement.

◆ The technical route for the development of QD0 prototype is determined.

Ordered: NbTi/Cu Strand, 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, two layers.
  The critical current loss during cabling: less than 5%.



Cu Rutherford cable sample

- ➢ Short prototype magnet of double aperture QD0 (0.5m long) will be fabricated in 2019; the detailed technical design is on going.

Summary

- MDI superconducting magnets are key devices for CEPC. Conceptual design of superconducting magnets in CEPC MDI has been finished.
- Field cross talk effect between two apertures of QD0 can be reduced to be acceptable using iron yoke.
- 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.
- TDR plan of superconducting magnets in CEPC MDI is formed.
- Prototypes superconducting magnets are proposed, and the R&D has started .

Thanks for your attention!