Superconducting Magnets in CEPC MDI

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- **Status of MDI magnets in high luminosity scheme**
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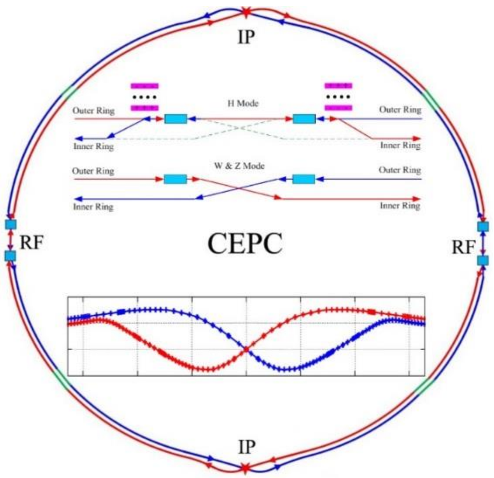
- **Summary**

Introduction

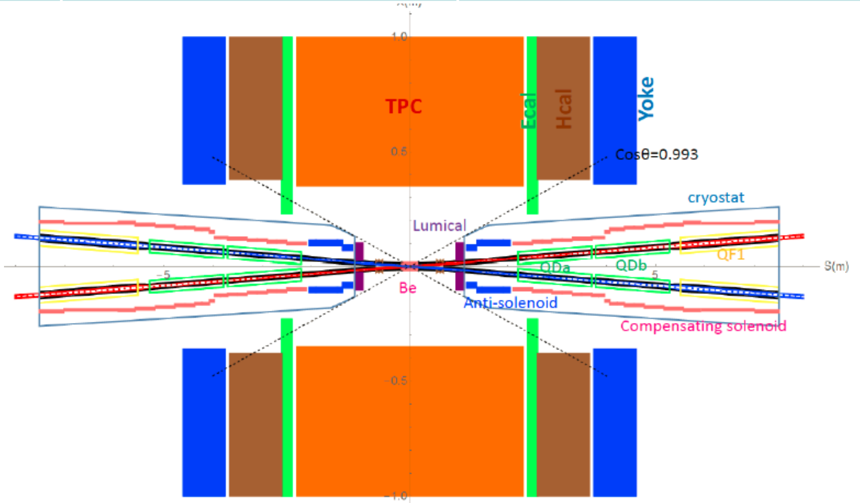
- To greatly squeeze the beam for high luminosity, compact high gradient final focus quadrupole magnets are required on both sides of IP points.
- The CDR requirements of Final Focus quadrupoles (QD0 and QF1) are based on L* of 2.2 m, beam crossing angle of 33 mrad.

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



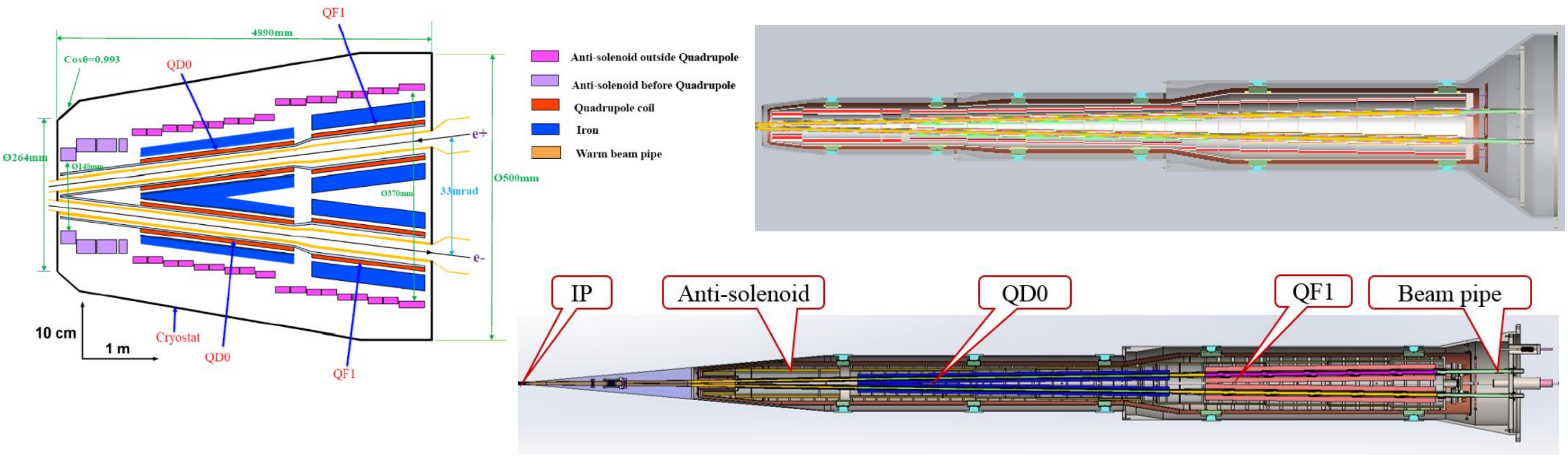
Sketch of CEPC Collider ring



CEPC MDI layout

Introduction

- 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 detector solenoid field on the beam, anti-solenoids before QD0, outside QD0 and QF1 are needed.
- QD0, QF1, and anti-solenoid coils are in the same cryostat.
- CEPC MDI SC Magnets start at z=1.13m, including: superconducting QD0, QF1, anti-solenoid on each side of the IP point.



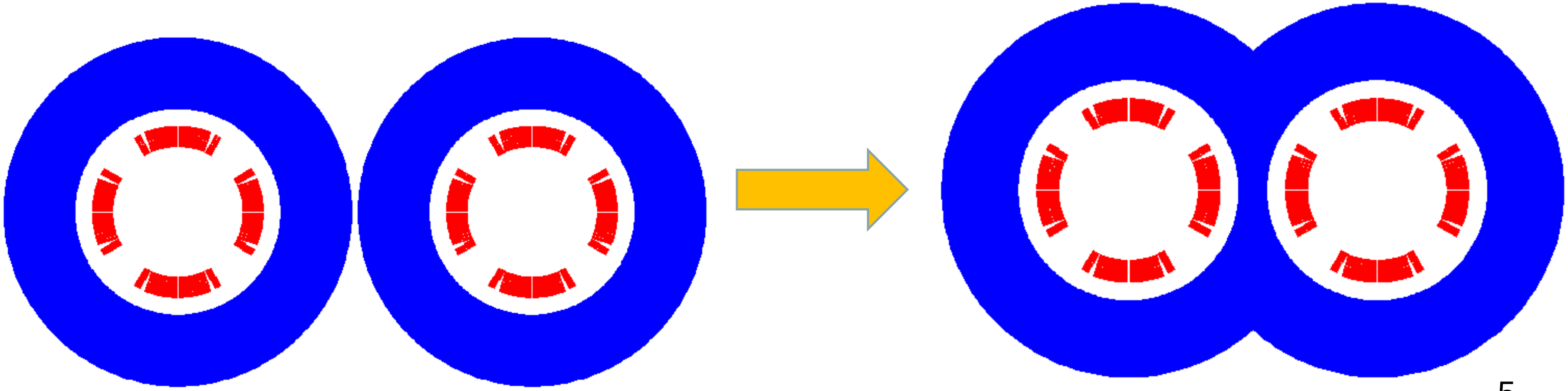
Schematic layout of QD0, QF1, and anti-solenoid

Status of MDI magnets in CDR scheme

- QD0 CDR: 136T/m, **inner diameter 40mm**, length 2m.
- Two options design: 1) with iron, 2) iron-free
- Inner radius of beam pipe:10 mm; Checked by HOM heating load calculation.

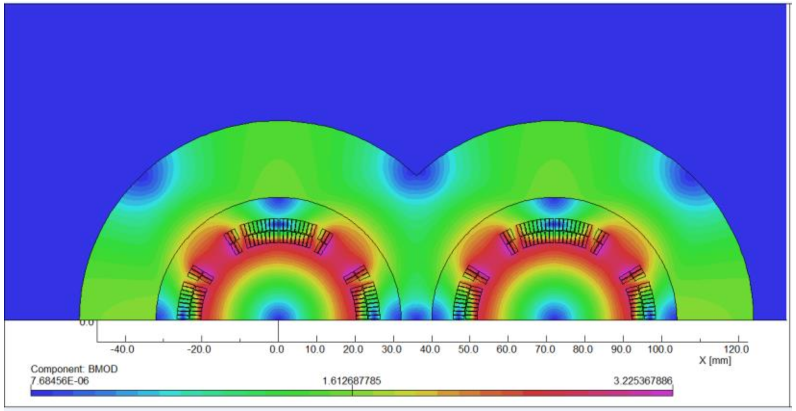
Baseline: **QD0 design with iron option**

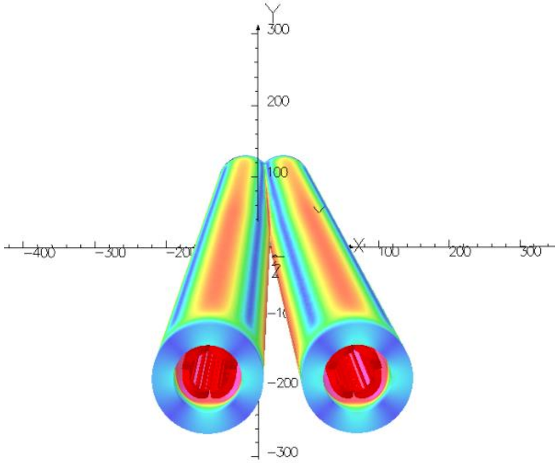
- Iron yoke: enhance field gradient, reduce coil excitation current, shield the field crosstalk.
- Not enough space to place two single apertures side by side, so a compact design is adopted. **Iron core in the middle part is shared by two apertures.**
- cos2θ quadrupole coil using NbTi Rutherford: highest magnetic efficiency and cooling capacity, good stability, no mandrel.

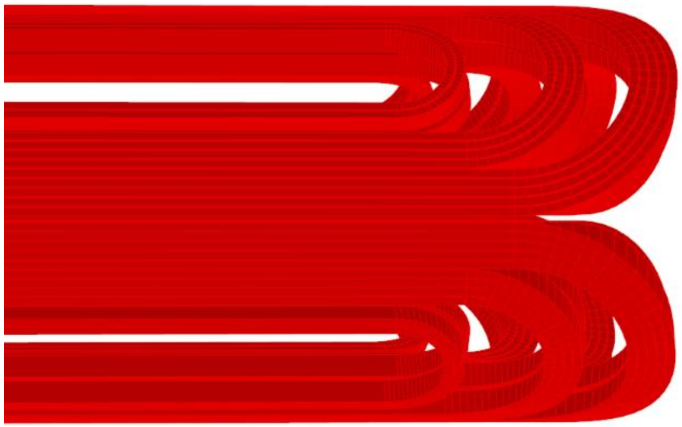


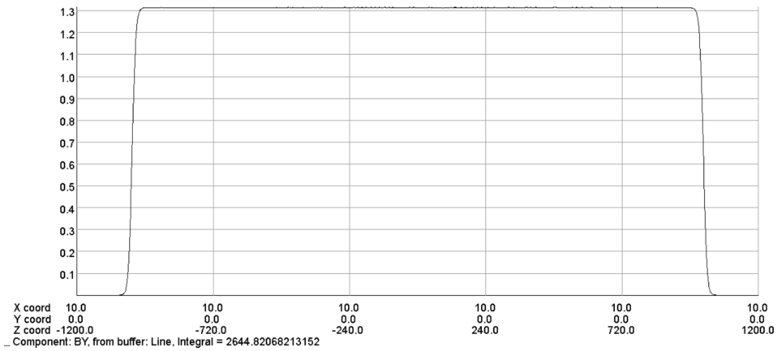
QD0 design with iron

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





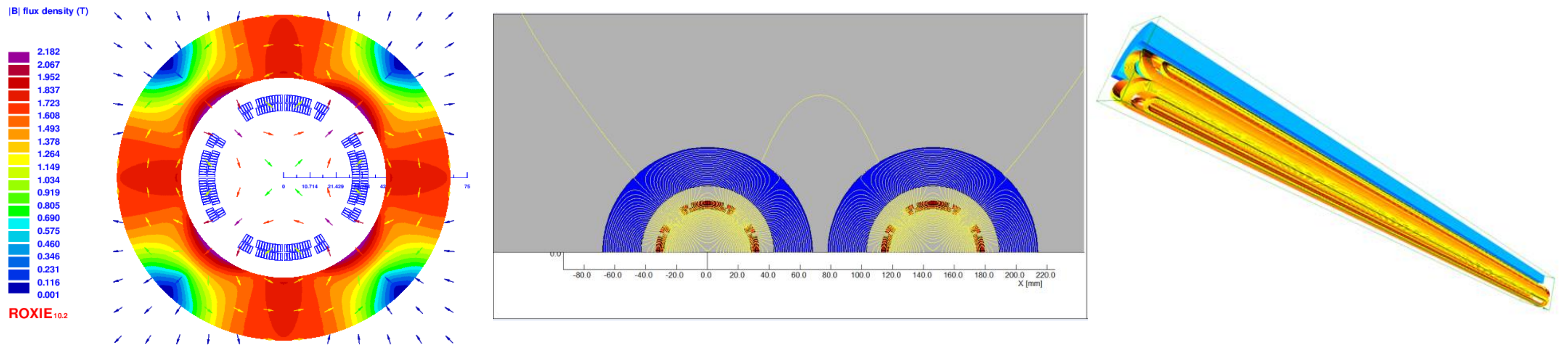




Opera

Design of superconducting quadrupole QF1

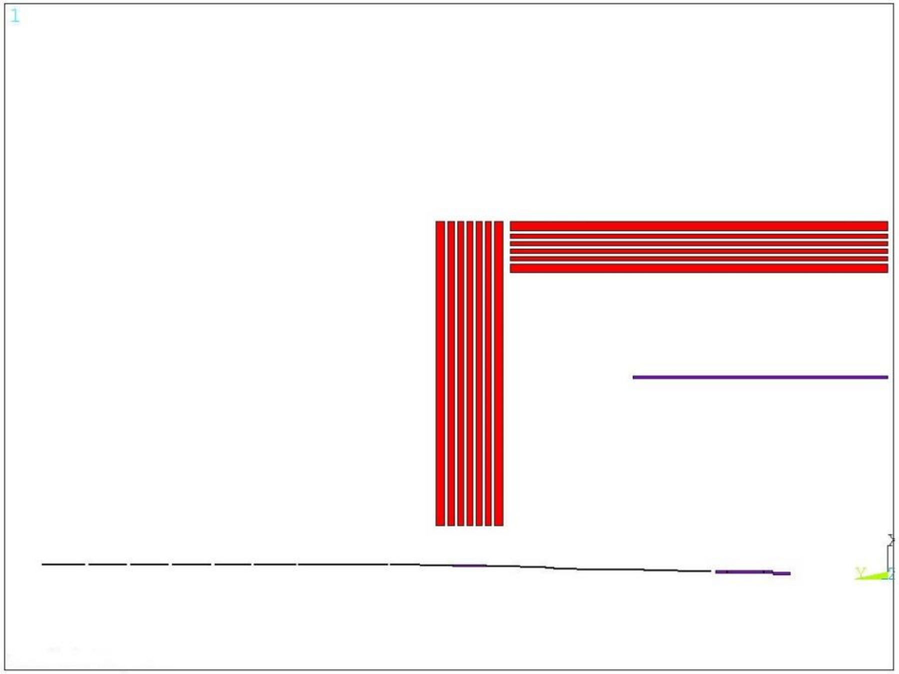
- Since the distance between the two apertures is much larger, the field cross talk between the two apertures of QF1 is not a problem using iron yoke.
- After optimization, QF1 coil consists of four coil blocks in two layers separated by wedges, and there are 28 turns in each pole.
- Current: 2280A. **The field gradient, magnetic length, field harmonics meet the design requirement.**
- Each systematic field harmonics is smaller than 1 unit (1×10^{-4}).
- Non-systematic field harmonics as a result of field cross talk can be neglected.



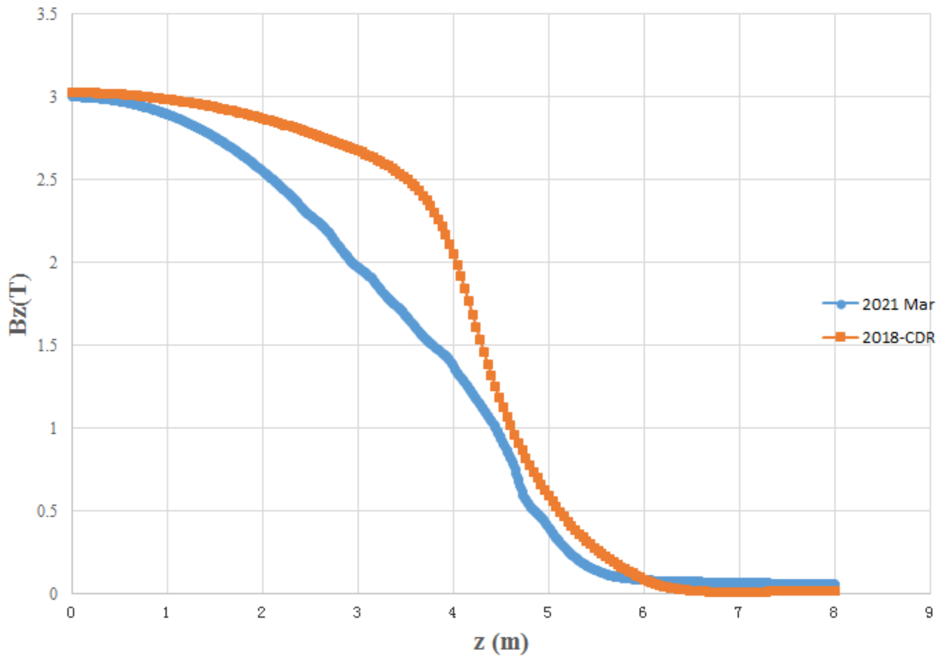
Field simulation of QF1

Design of superconducting anti-solenoid

- Recently, the design of Detector solenoid is modified (2021.3).
- The design of Accelerator anti-solenoid is updated.



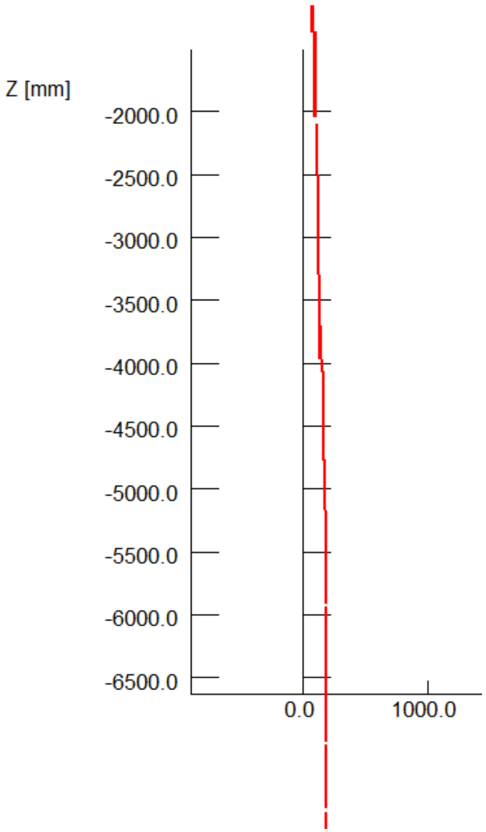
From F. Ning



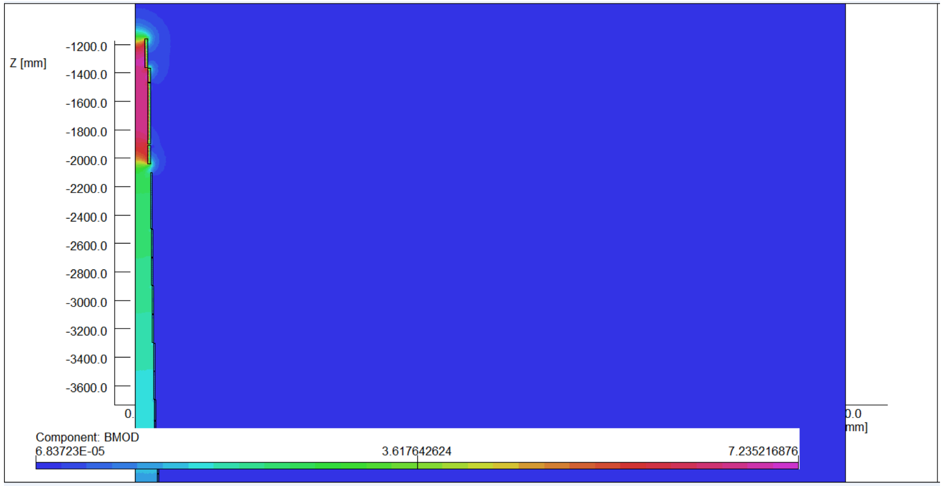
Field distribution comparison

- 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.
- Rectangular NbTi-Cu conductor.
- 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.

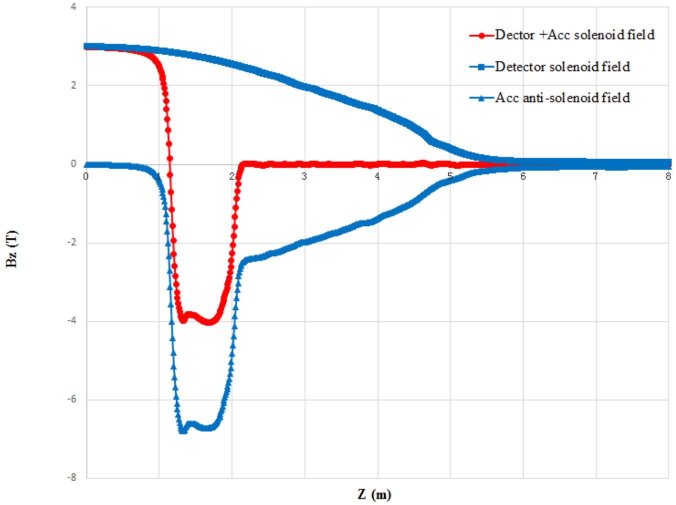
- The anti-solenoid along longitudinal direction:
  1) 4 sections, from IP point to QD0;
  2) 12 sections, QD0 region;
  3) 6 sections, QF1 region;
  4) 7 section, after QF1 region.



- Magnetic field calculation and optimization is performed using axi-symmetric model in OPERA-2D.
- The central field of the first section anti-solenoid is the strongest, with a peak value of 6.8T.



Magnetic flux density distribution

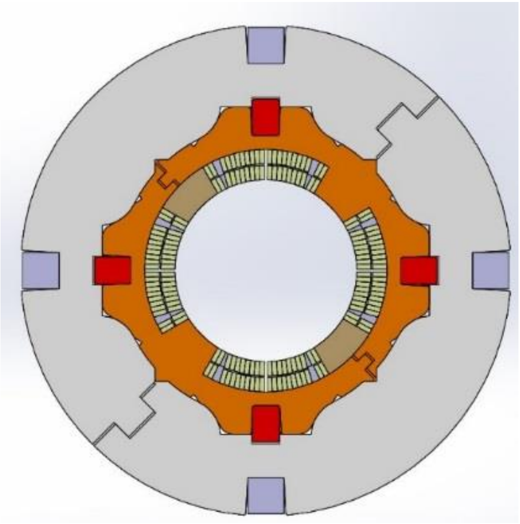


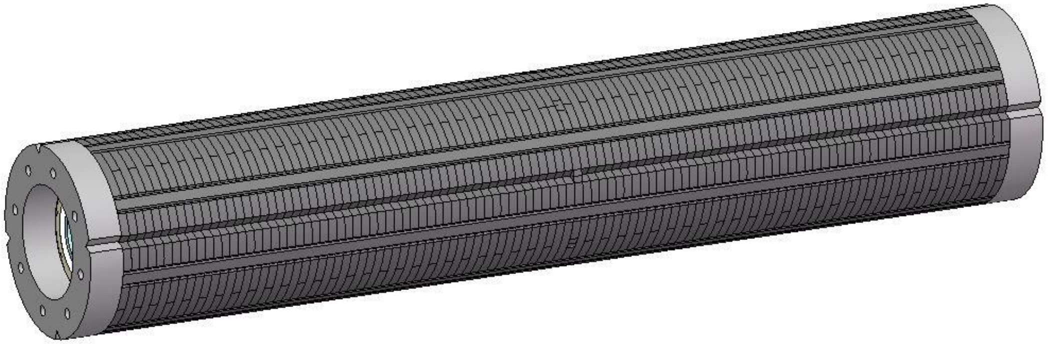
Magnetic field distribution

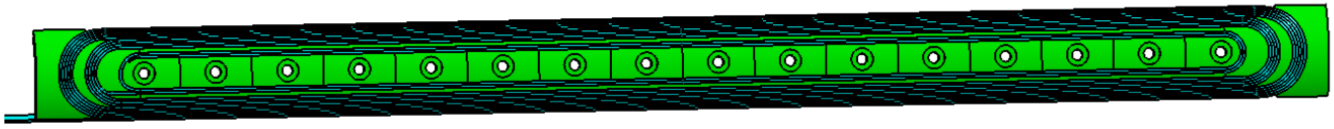
- The net solenoid field inside QD0 and QF1 at each longitudinal position is smaller than 300 Gs.
- The total integral solenoid field generated by the detector solenoid and anti-solenoid coils is zero.

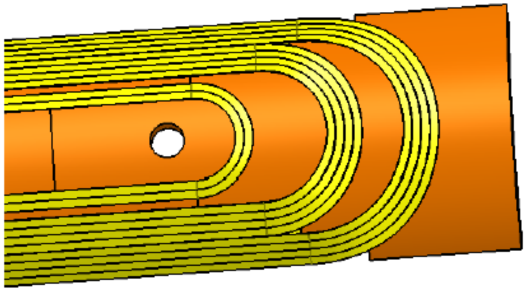
Status of 0.5m single aperture QD0 short model

- There is no cos2θ quadrupole magnet developed in China.
- Research on **key technologies** of 0.5m single aperture QD0 short model has started (NbTi, 136T/m), in collaboration with HeFei KEYE Company.
- Including: quadrupole mechanical design, coil winding technology, fabrication of quadrupole coil with small diameter, stress applying and monitoring, quadrupole magnet assembly, field measurement technology, etc.



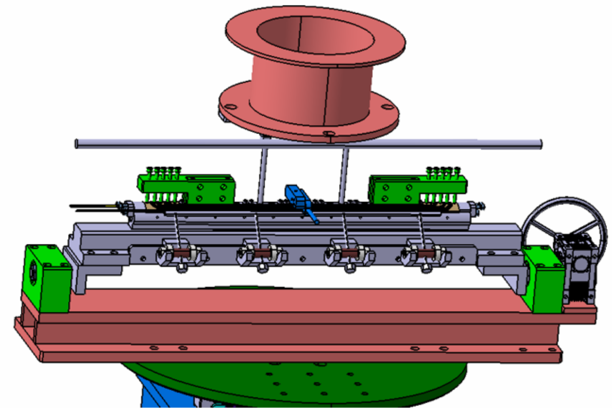




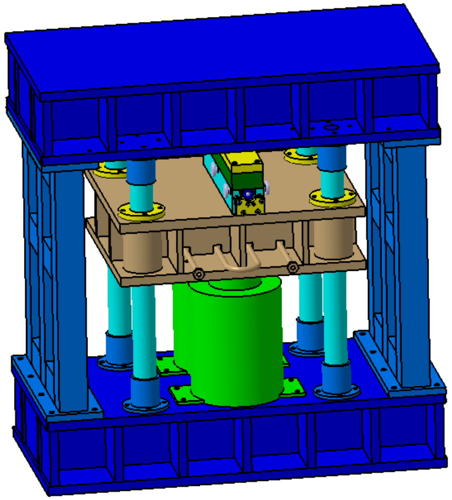


Fabrication of Rutherford cable

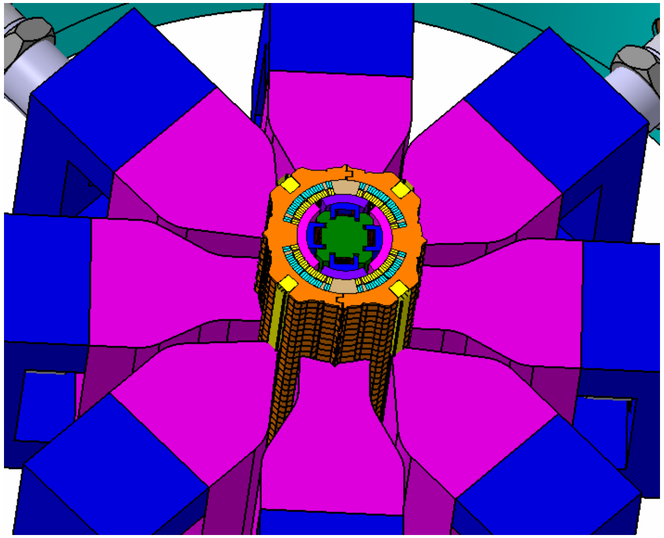
Winding machine



Coil heating and curing system

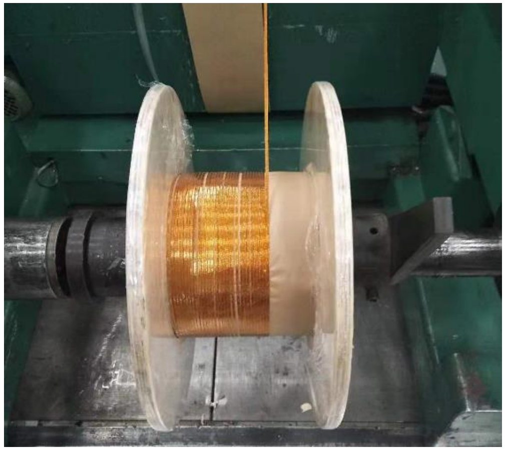


Coils assembly system



- **Progress:** Hardwares manufacturing is completed; fabrication of 0.5m single aperture QD0 model will be completed within half a year.

NbTi Rutherford cable (12 strands)



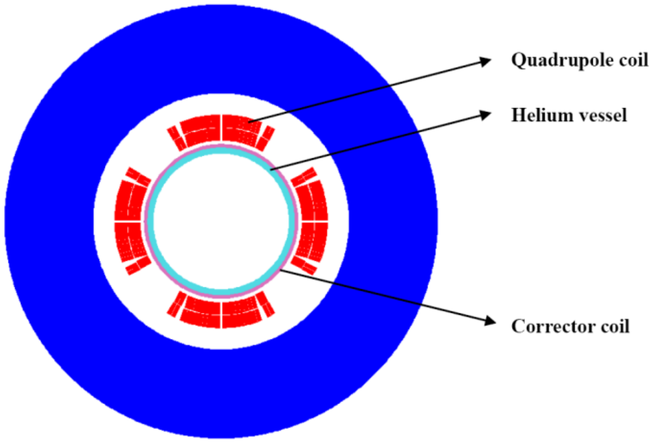
Winding machine

Coil heating and curing system

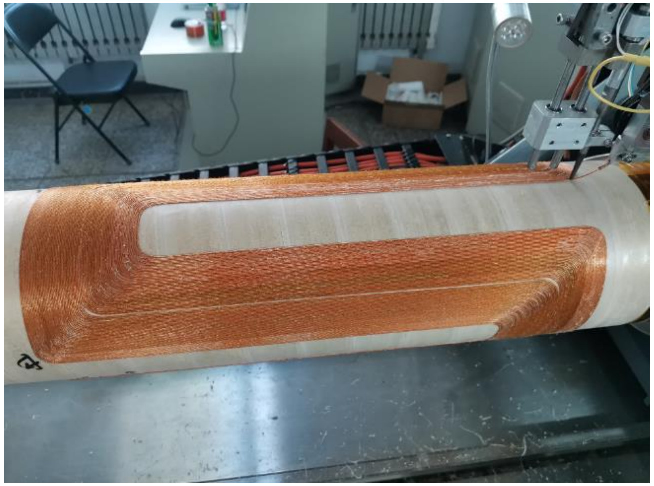
Coils assembly

Direct winding technology for corrector coils

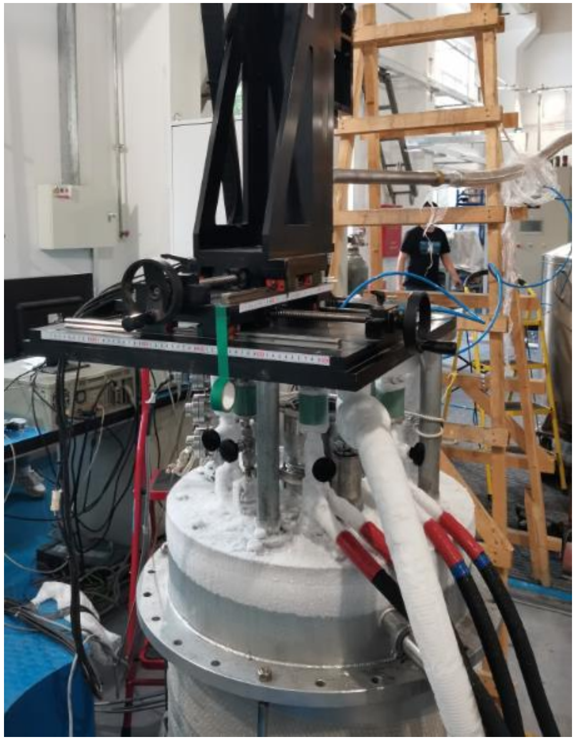
- Corrector magnets for CEPC final focus magnet are required.
- One or two layers corrector coils is added inside bore of QD0 quadrupole coil, using 0.33mm wire.
- Corrector coil will be wound using Direct winding technology.
- ◆ A model direct winding machine has been developed for BEPCII-U SC magnet.
- ✓ It can be modified and used for CEPC corrector coil winding.



CEPC corrector location



BEPCII-U coil



Status of MDI magnets in high luminosity scheme

- The requirement of CEPC Final Focus quadrupoles is updated for high luminosity with L*=1.9m in 2020.10.

Table 2: 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 quadrupole coil.
- Baseline: Iron yoke is used to eliminate field crosstalk of two apertures.

Conceptual design of HTS final focus quadrupole coils

- ***NbTi technology similar to that in CDR can be used for Q1a in high luminosity scheme.***

- In addition, feasibility of HTS SC magnet technology is being considered.

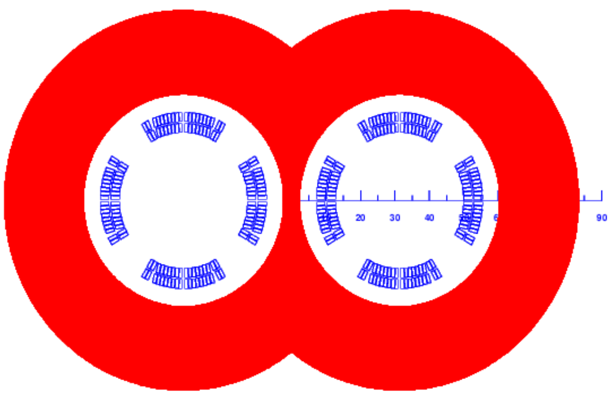
Advantage: Large critical current (expected), light weight of magnet
heat load resistant
High operating temperature

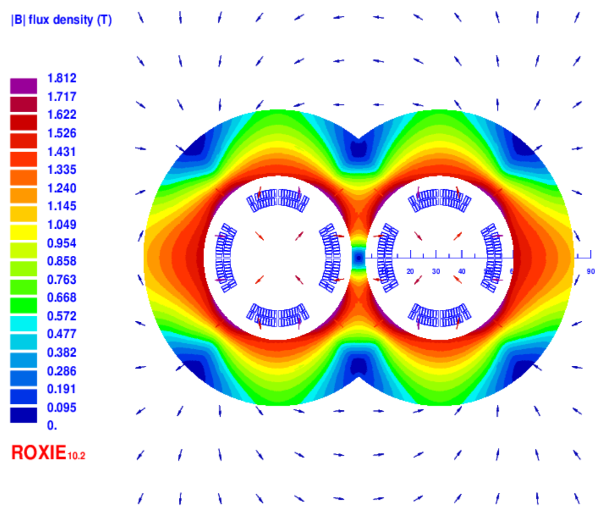
Disadvantage: HTS conductor not mature now, expensive
Poor mechanical properties
HTS coil manufacture needs heat treatment
Large diameter of superconductor filament or layer

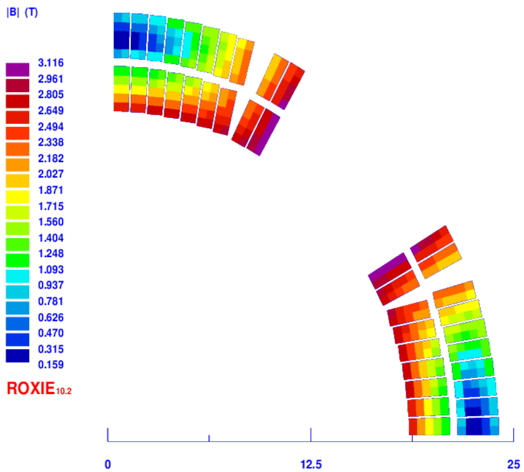
Conceptual design of Q1a for high luminosity

1) Cos2θ option of Q1a

- HTS Bi-2212 round 0.5mm wire or other conductor.
- Q1a: two layers cos2θ quadrupole coil using Rutherford cable with iron yoke. The inner diameter of the coil is 37mm.
- Single aperture cross section is optimized with four coil blocks in two layers.
- Width of the cable is 2.5mm, 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}.
- Magnetic field cross talk between two apertures is negligible.



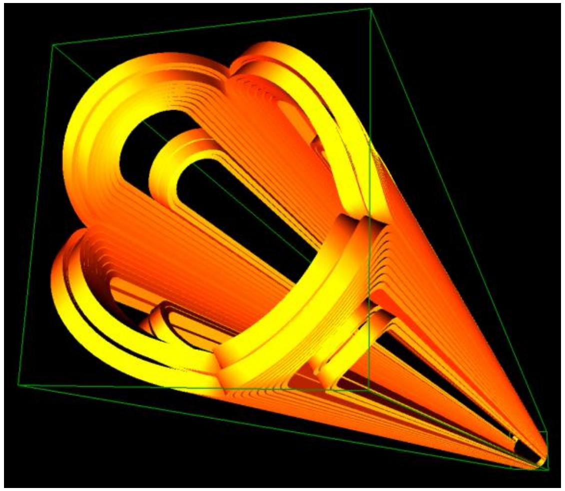


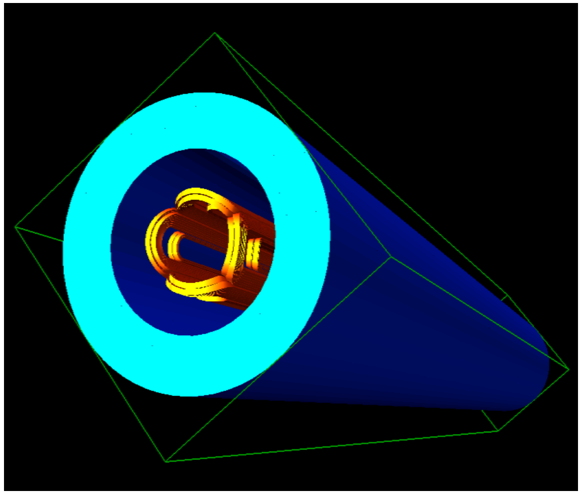


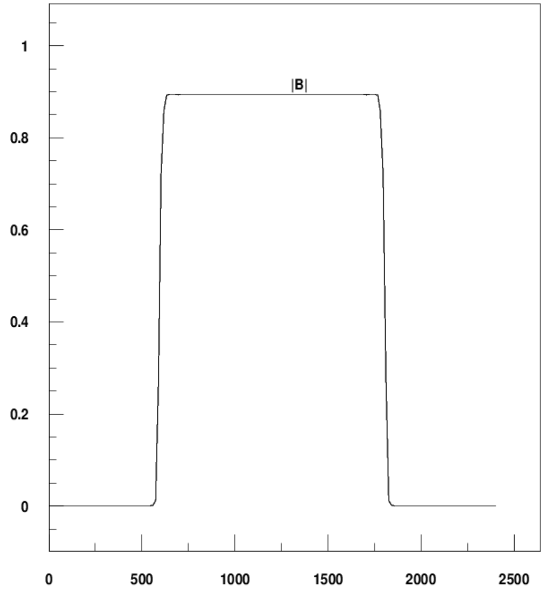
Cos2θ option of Q1a

3D design of Q1a

- 3D magnetic field is modeled and analysed using ROXIE.
- Coil end detailed shaped is optimized and determined.
- Field gradient 142T/m, each integrated field harmonics is smaller than 1×10^{-4}.
- The 3D magnetic field performance meets requirement.







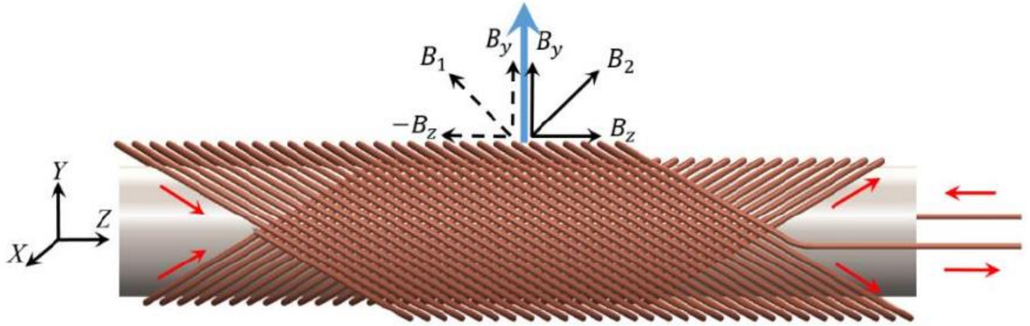
Single aperture model in 3D

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

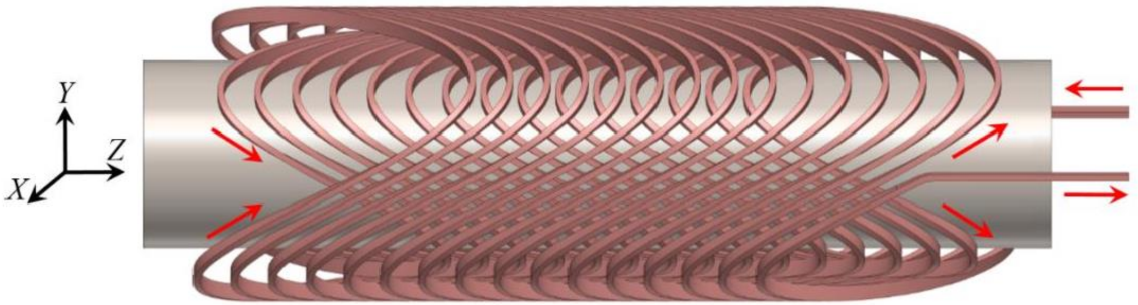
2) CCT option of Q1a

- CCT : Canted cosine theta
- CCT: based on a pair of conductors wound and powered such that their transverse field components sum up and their solenoid fields cancel.
- In practice, the conductor is wound on a pre-cut groove in a supporting cylinder.

CCT dipole



CCT quadrupole

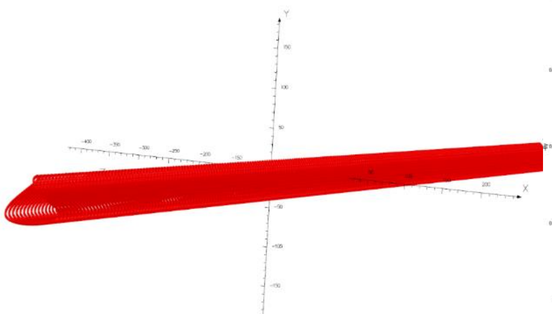


$$\vec{P}(\theta)=\begin{cases} r\cos\theta \\ r\sin\theta \\ A_n\sin(2\theta)+\dfrac{w\theta}{2\pi} \end{cases} \qquad -\pi N \le \theta \le \pi N$$

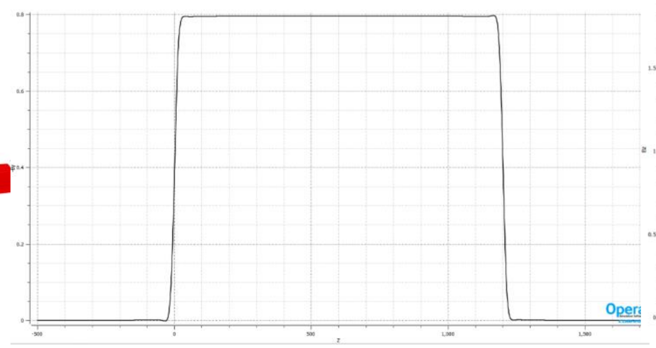
CCT option of Q1a, conceptual design

- HTS Bi-2212 0.8mm round wire or other conductor.
- Two layers CCT quadrupole coil. The inner radius of the spar is 18.5mm.
- Outer radius of single aperture coil: 29mm.
- Groove on the spar: 2×3mm; 6 wires in a groove.
- Conductor canted angle: 30 deg.
- Excitation current: 1342A.

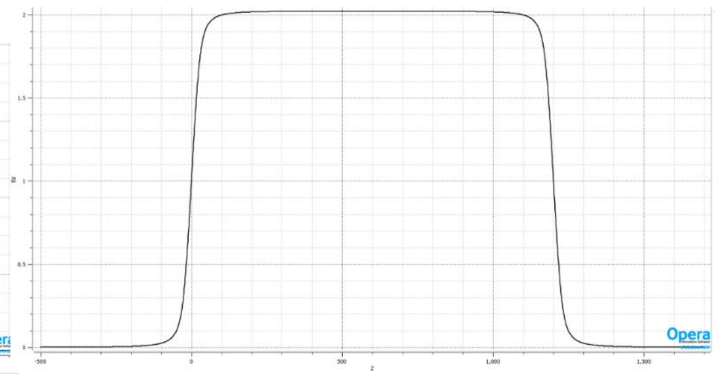
✓ Each integrated multipole field in single aperture is smaller than 1×10^{-4}.



1st layer CCT coil



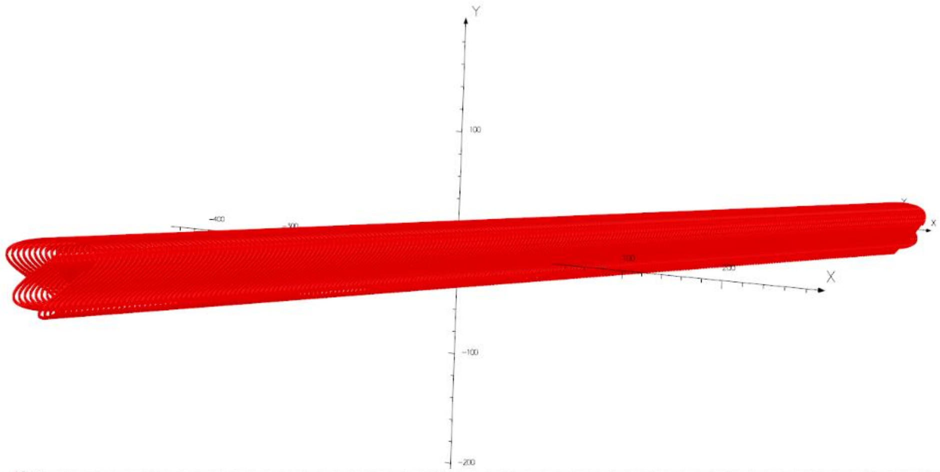
By along z

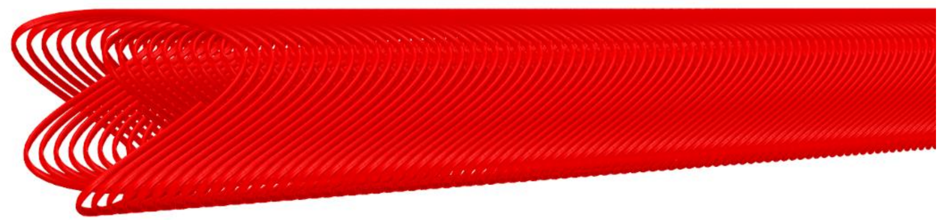


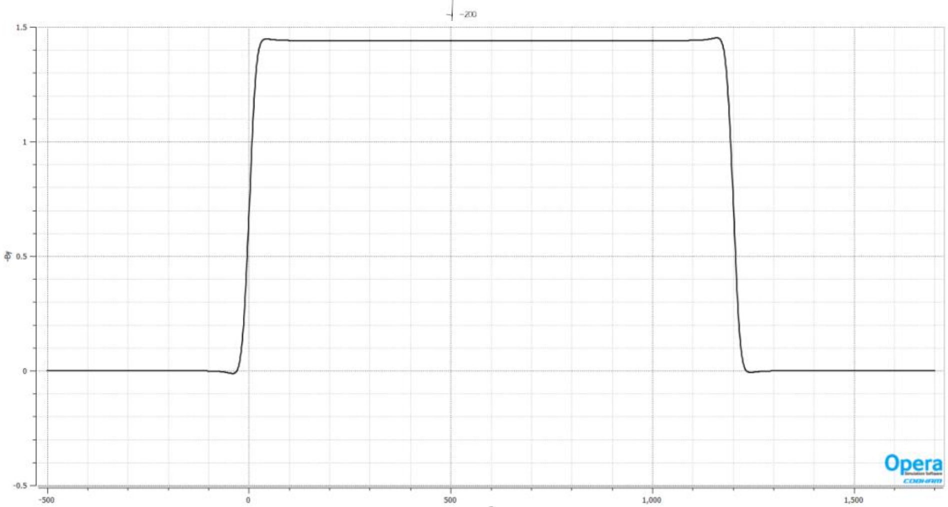
Solenoid field along z

CCT option of Q1a

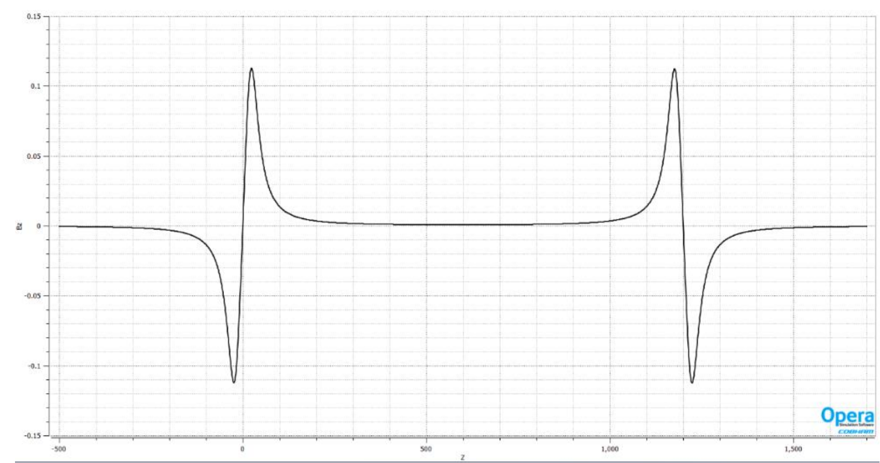
Double layer CCT coil of Q1a: Most solenoid field of two layers cancel out. Field gradient and field harmonics meets the requirement.







By along z



Solenoid field along z

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

Comparison of two HTS design options of Q1a (141T/m)

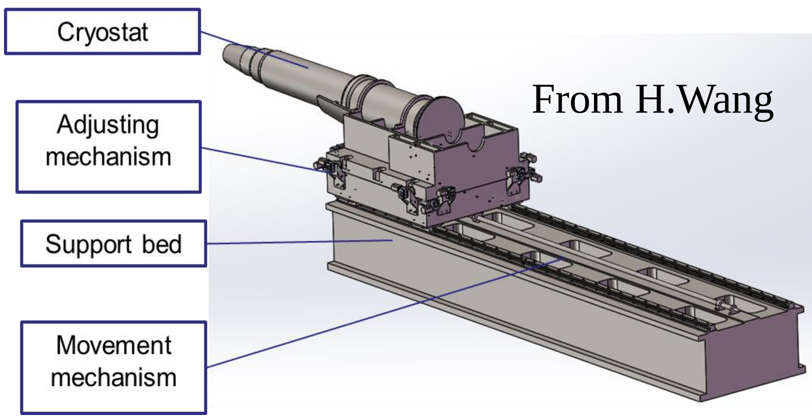
Option	Excitation current (A)	Needed Engineering current density J_E on wire (A/mm2)	Bmax on coil (T)	Possible Conductor
Cos2θ (with iron)	1970	1004	3.2	Bi-2212
CCT	1342 (940 with iron)	2670 (1870 with iron)	3.8	Bi-2212

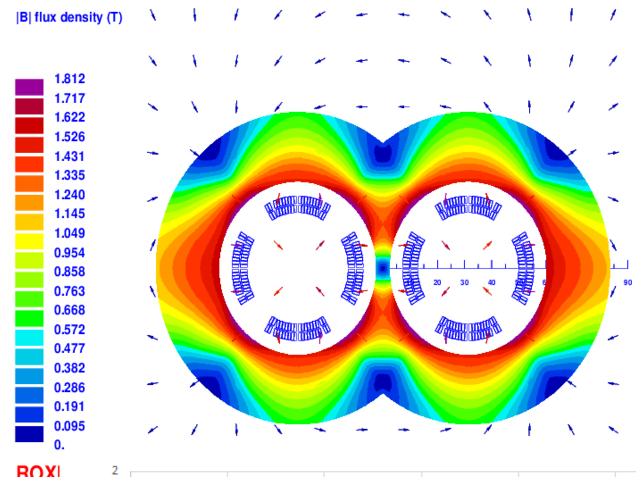
- From the comparison, Cos2θ coil has the higher magnetic efficiency, lower peak field, and Engineering current density;
- The current carrying capacity of Bi-2212 conductor is close to the requirement.
- Cos2θ coil as baseline design, CCT coil as alternative design.

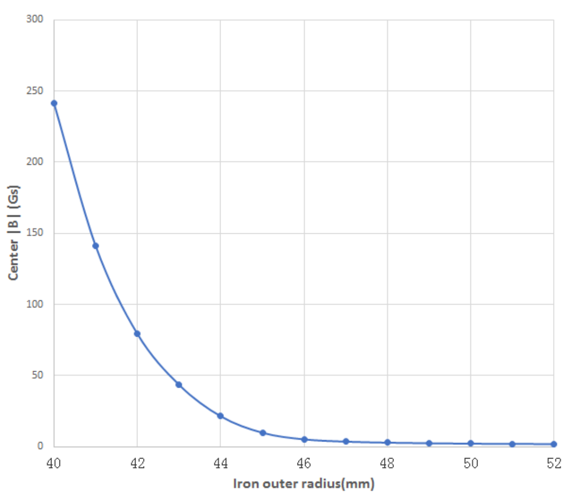
Optimization the weight of Q1a quadrupole magnet

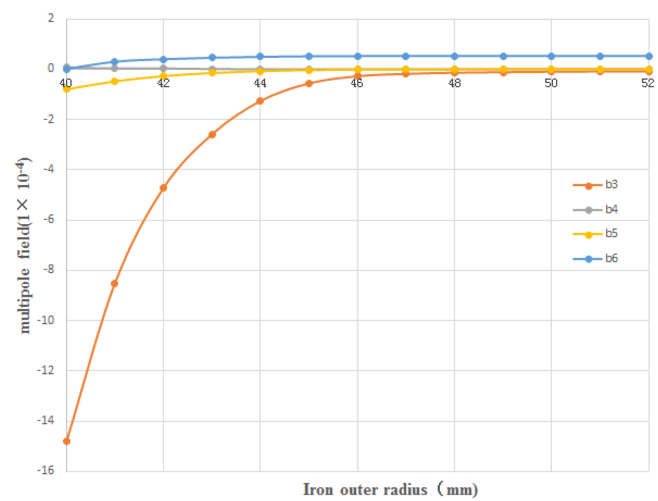
Option 1: Iron DT4, reduce weight. Reduce deformation for Cantilever support

- Field gradient: 141T/m. Relax the dipole field requirement to <30Gs
- 19 turns in each pole, excitation current 1970A.
- Dipole <30Gs, radius of the iron: 44mm, weight 96.9kg. (67% of r=52mm)





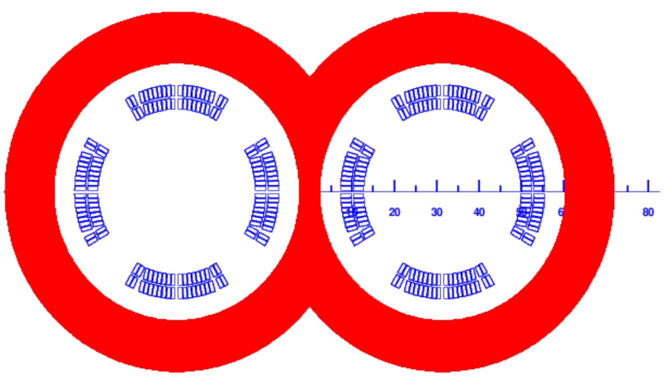


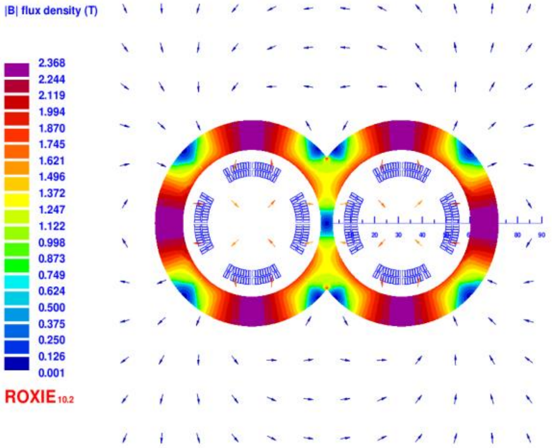


Option 2: Iron yoke FeCoV

Option 2: Iron FeCoV

- Saturation magnetic induction of FeCoV is about 2.35T, and the magnetic shielding effect is better.
- Compared with DT4, the thickness of the iron core can be reduced.
- Dipole field <30Gs, radius of the iron: 40.5mm. Weight: 78.9Kg (55% of r=52mm)



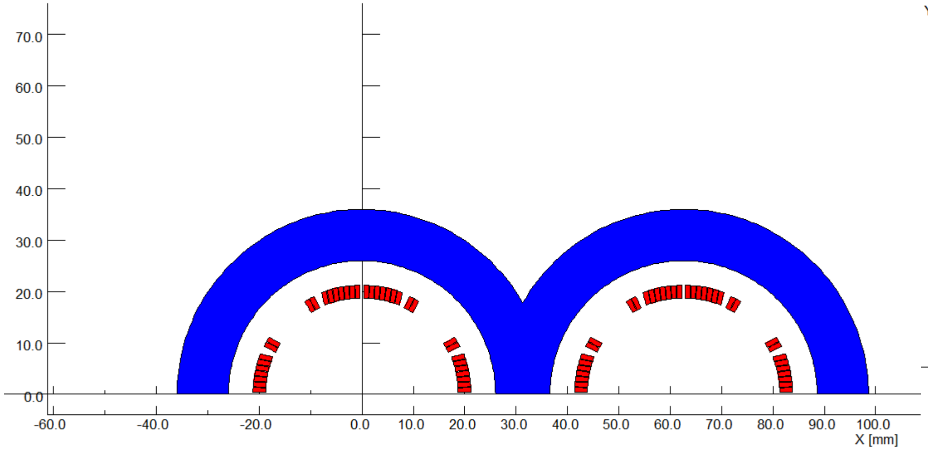


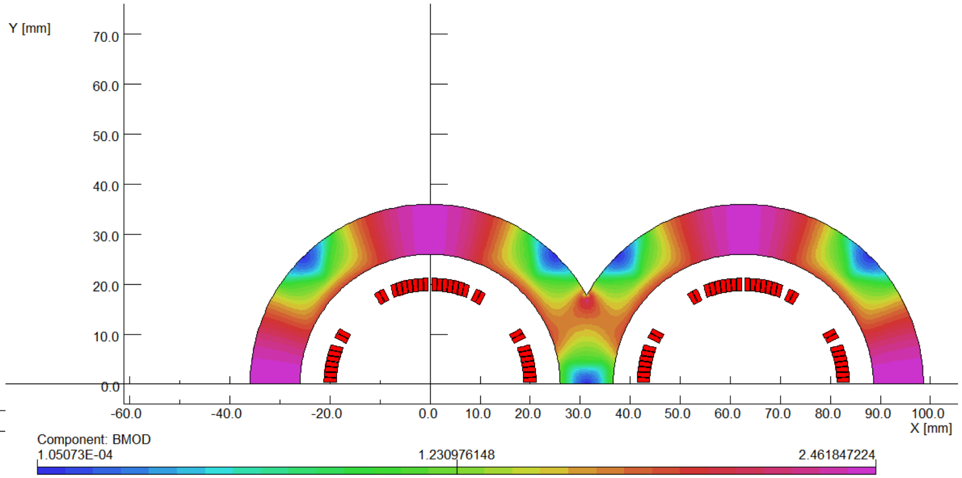
Iron outer radius (mm)	Center|B|(Gs)	b3(1×10-4)	b4	b5	b6	G(T/m)	Weight (Kg)
52	0.54021	-0.01825	0.00648	-0.0001	0.51924	141.8438	143.6445489
51	0.56295	-0.01863	0.00605	-0.00021	0.51931	141.8436	137.3799618
50	0.59658	-0.02238	0.00469	-0.0006	0.51925	141.8434	131.2370172
49	0.63944	-0.02528	0.00392	-0.00094	0.51916	141.8432	125.215715
48	0.72571	-0.02831	0.00291	-0.00122	0.51908	141.8426	119.3160554
47	0.85912	-0.03484	0.00256	-0.00206	0.51896	141.8418	113.5380381
46	1.0381	-0.04224	0.00245	-0.00251	0.51878	141.8409	107.8816634
45	1.2551	-0.05411	0.00147	-0.00337	0.51847	141.8395	102.3469311
44	1.5597	-0.06948	0.00182	-0.00415	0.5182	141.8375	96.93384133
43	2.1464	-0.11137	-0.00036	-0.00576	0.51746	141.834	91.64239399
42	3.0074	-0.16056	0.00056	-0.00961	0.51597	141.8285	86.47258912
41	6.392	-0.37045	-0.00758	-0.02326	0.51	141.8053	81.42442671
40.5	17.316	-1.04345	-0.00957	-0.06684	0.48809	141.731	78.94596144
40	55.258	-3.43489	-0.00163	-0.2194	0.4096	141.4705	76.49790678

Option 3: one layer coil

Option 3: one layer coil **possible for cos2θ coil**

- Iron yoke: FeCoV; one layer coil, HTS round 0.5mm Bi-2212.
- <30Gs Dipole field, radius of the iron: 36.5mm.
- Weight: 60.2Kg (42% of r=52mm)
- 9 turns in each pole, excitation current 3585A.
- Large current carrying capacity of conductor is required; working current doubled, the cryogenic system and power supply will be affected.
- *After five years, the current carrying performance of Bi-2212 may meet the requirement.*





Design options comparisons and recommendation

- HTS Bi-2212 0.5mm wire or other conductor; Field gradient 141T/m.

	Main features	Performance	Weight (kg)	Remark
Option 1	2 layers coil, DT4 iron	Meet all requirements (Dipole <30Gs)	96.9	Largest weight
Option 2	2 layers coil, FeCoV iron	Meet all requirements (Dipole <30Gs)	78.9	Manufacture cost increases slightly
Option 3	1 layer coil, FeCoV iron	Meet all requirements (Dipole <30Gs)	60.2	Double current carrying capacity, 5 years later

Recommendation

- Option 3 as baseline design, Option 2 as alternative design.

Summary

- MDI superconducting magnets are key devices for CEPC. The design of superconducting magnets meets the requirement.
- Despite of limited space, field crosstalk effect between two apertures in QD0 is negligible using iron yoke.
- **Study and research on key technologies** of 0.5m single aperture QD0 short model (LTS NbTi) is in progress, in collaboration with KEYE Company.

- Two HTS options have been studied for Q1a magnet using high luminosity parameters with L*=1.9m: **Cos2θ coil, CCT coil.** Both options are feasible; Cos2θ coil has higher magnetic efficiency, lower coil peak field.
- With relaxed dipole field and FeCoV yoke, the weight of Q1a magnet can be significantly reduced.

Thanks for your attention!