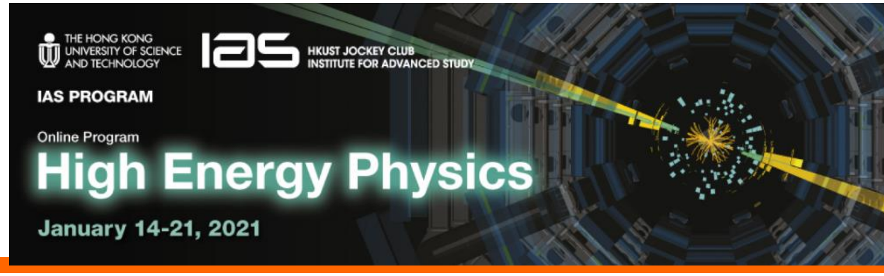

CEPC Superconducting Quadrupole in Interaction Region

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Outline

- **Introduction**
- **Overall design of CEPC Interaction Region Superconducting Quadrupole**
- **Conceptual design of HTS final focus quadrupole**

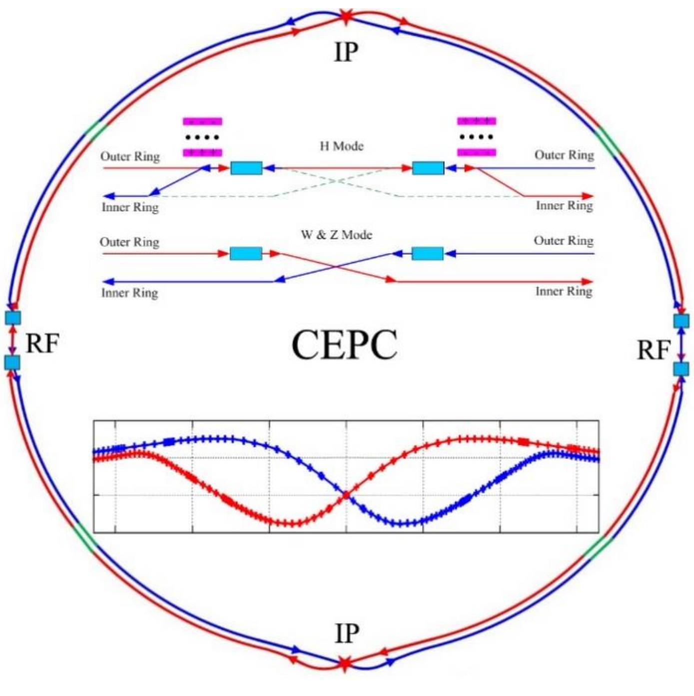
  1) Cos2θ coil

  2) CCT coil

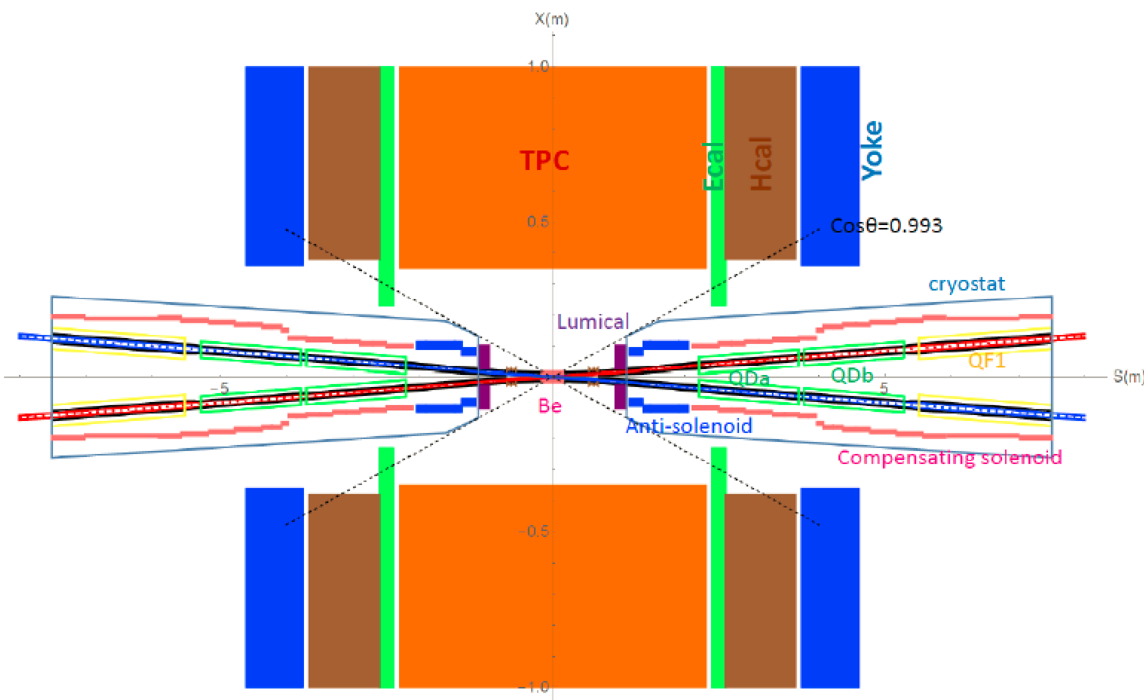
  3) Racetrack coil
- **Summary**

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 in 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

Introduction

- 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.

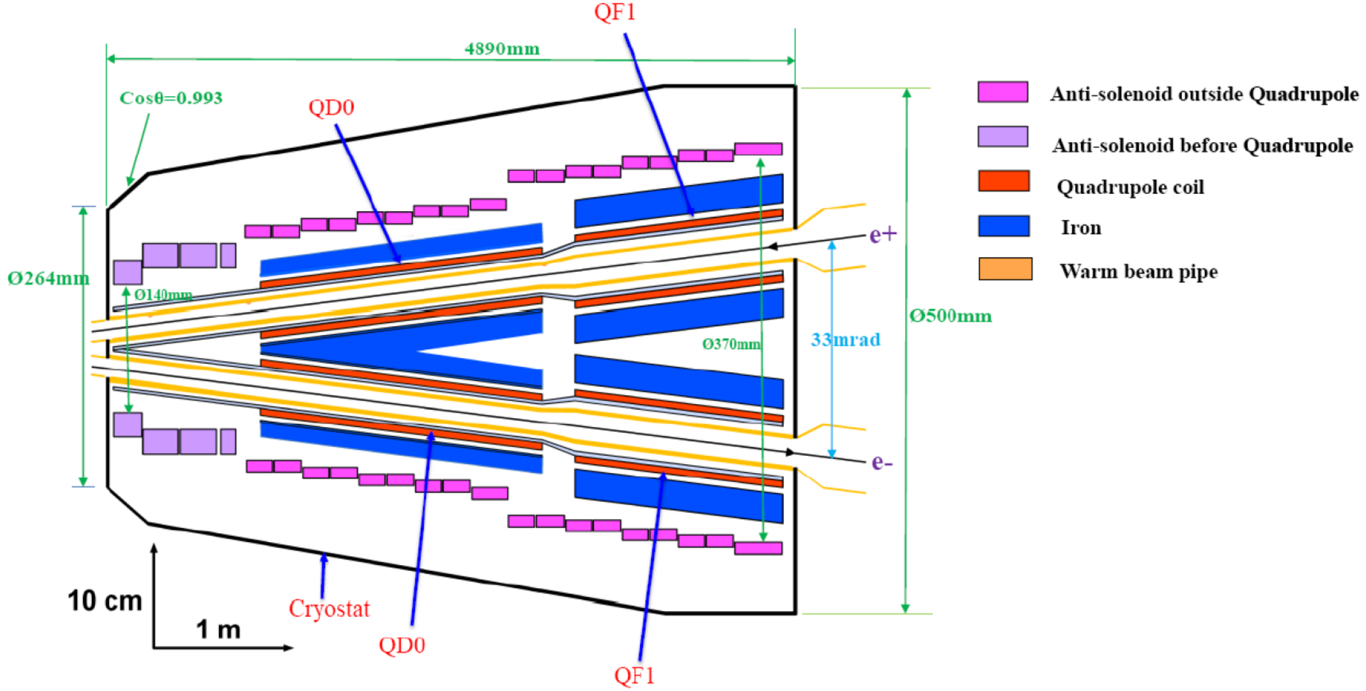
Table 1: CDR requirements of Interaction Region quadrupole magnets for Higgs

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

- 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.

Introduction

- 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.

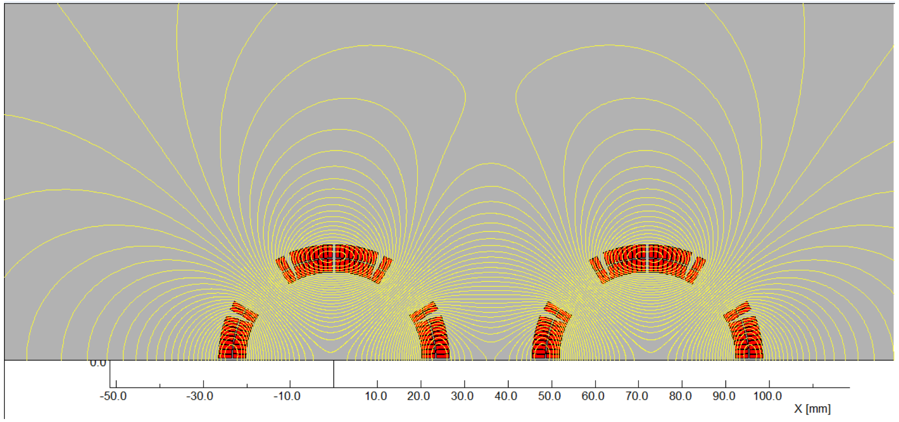


Schematic layout of QD0, QF1, and anti-solenoid

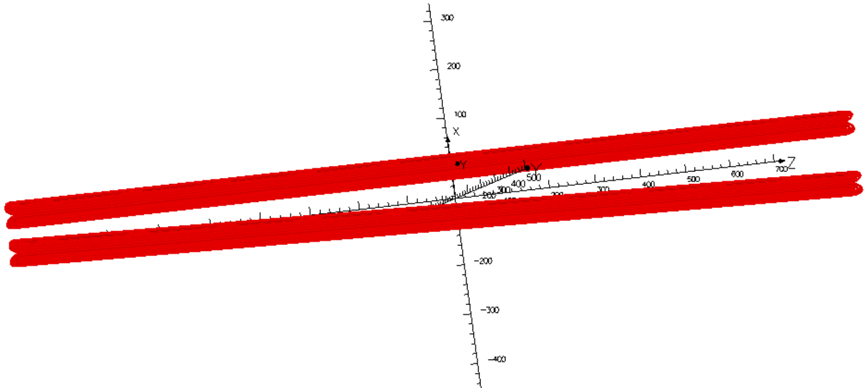
Overall design of QD0

Option1: Iron-free design of 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 2600A. the field crosstalk between the two apertures is very large. Integrated multipoles in 3D : b3 19 unit (1×10^{-4}), b4 3.6 unit.



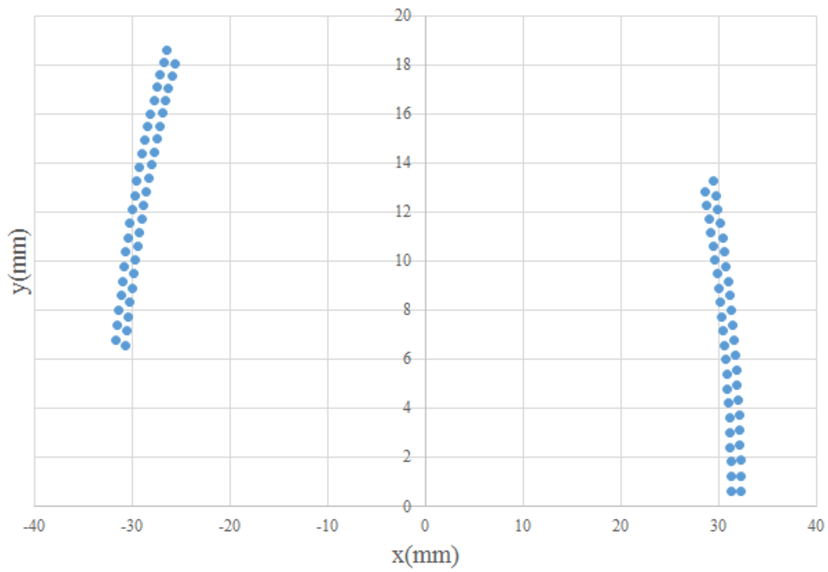
2D flux lines



3D model

Overall design of QD0

- 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})

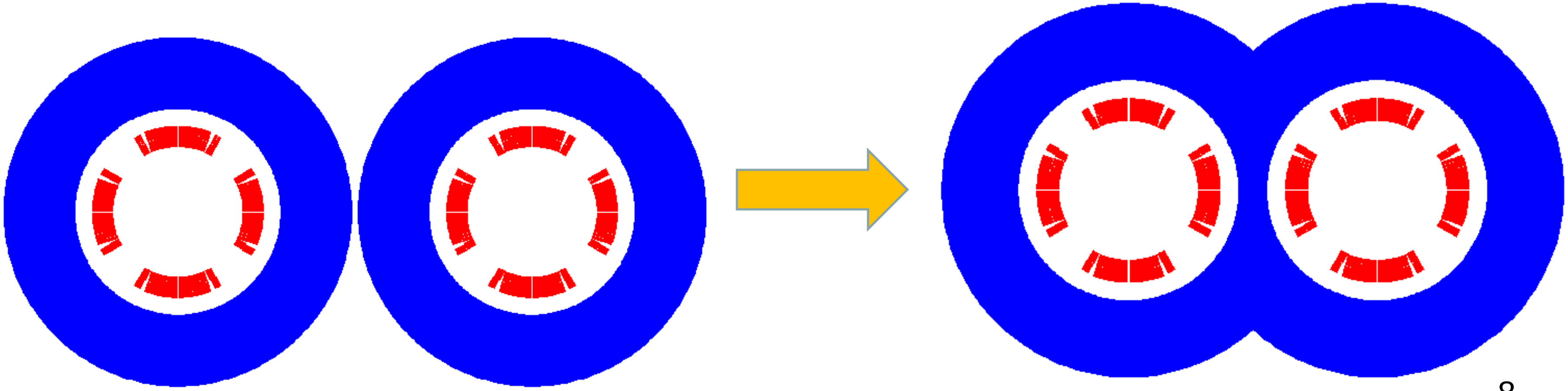
n	B_n/B_2@R=9.8 mm
2	10000.0
3	-0.57
4	1.53
5	0.38
6	-0.14
7	0.015
8	-0.031
9	-0.02
10	-0.058

Option2: QD0 design with iron

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

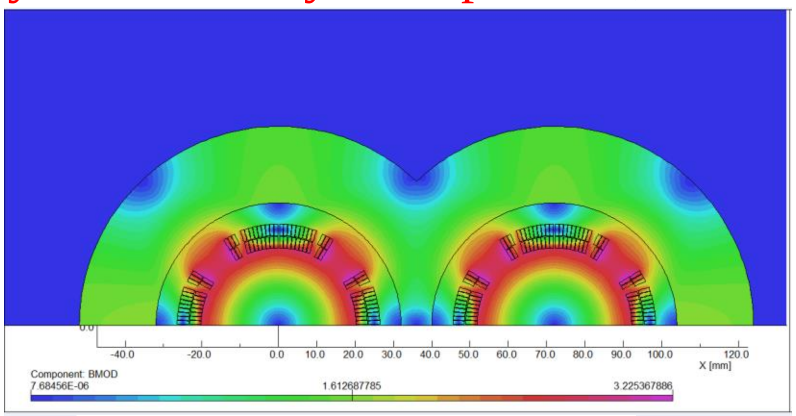
QD0 design of iron option

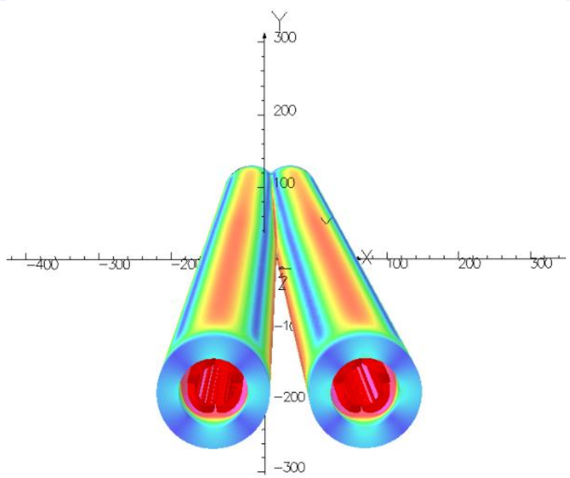
- Iron yoke is added outside the collar to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk.
- Not enough space to place two single apertures side by side, so a compact design is adopted.
- cos2θ quadrupole coil using NbTi Rutherford: highest magnetic efficiency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

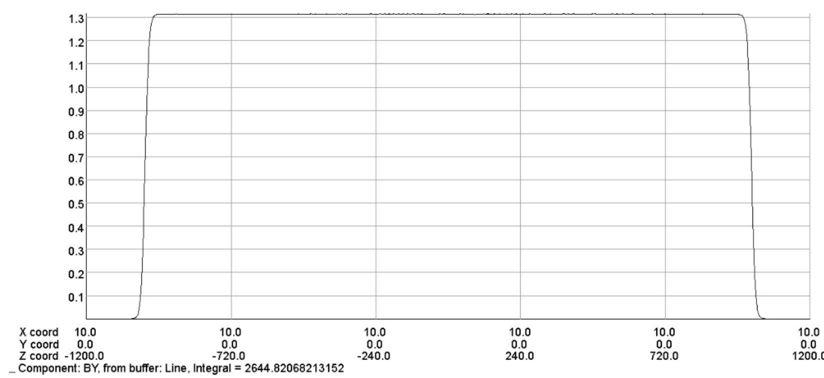


Option2: QD0 design with iron

- 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 the iron-free design, the excitation current can be reduced.
- Novel design: Double aperture quadrupole magnet using cos2θ coil with iron yoke shared by two apertures, with crossing angle between two apertures.



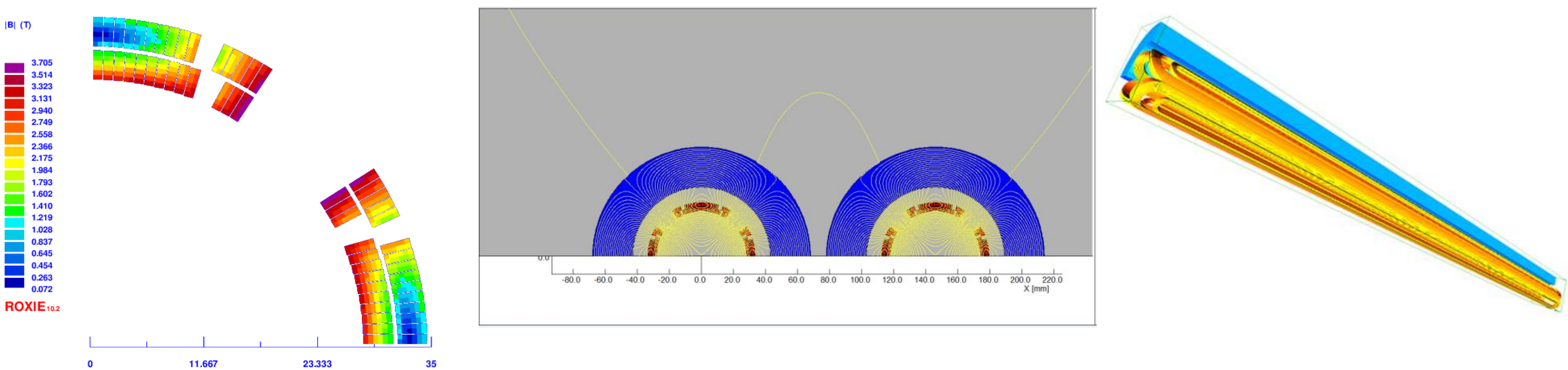




Opera

Overall design of superconducting quadrupole magnet QF1

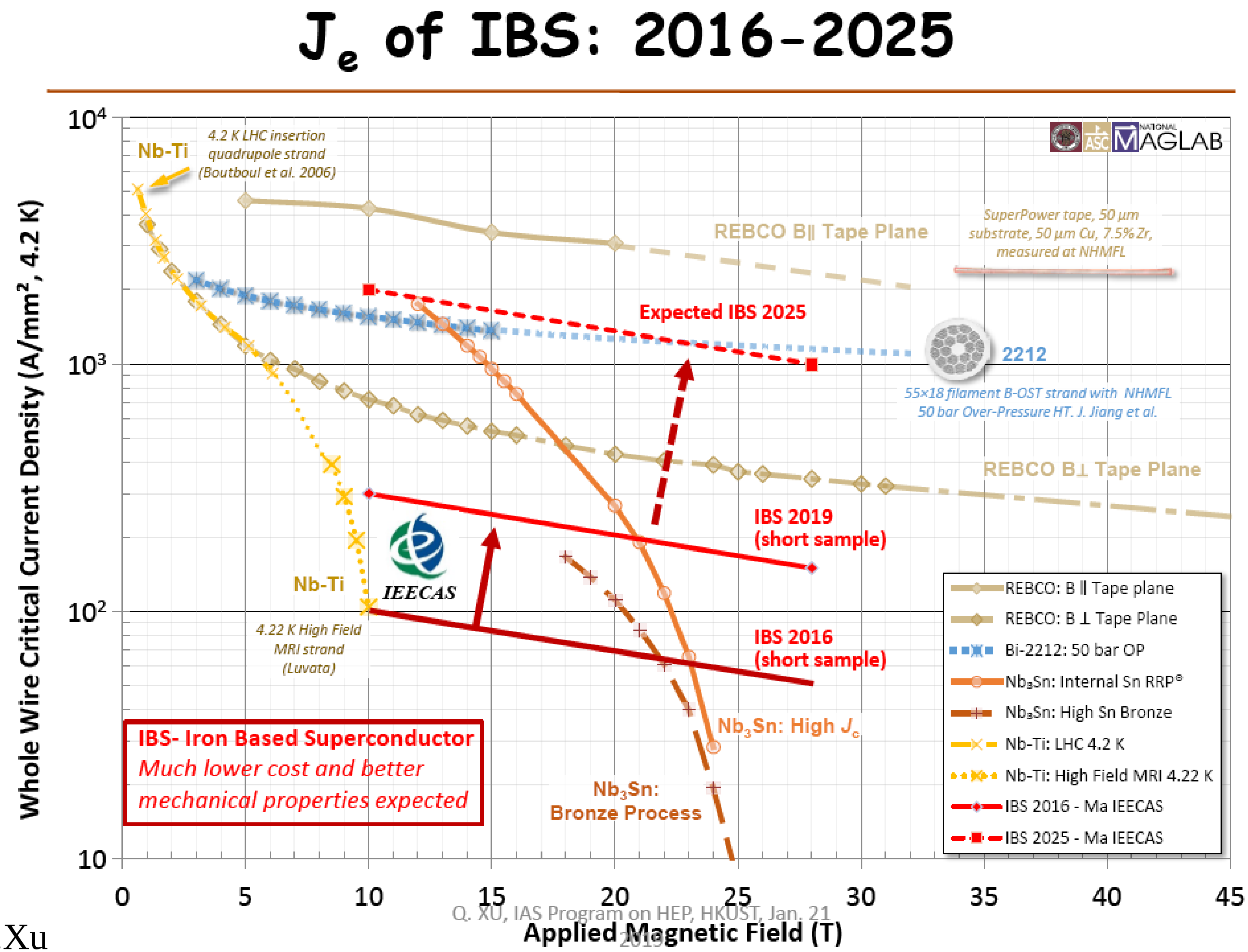
- Since the distance between the two apertures is much larger, the field cross talk between the two apertures of QF1 is not a problem using iron yoke.
- After optimization, the QF1 coil consists of four coil blocks in two layers separated by wedges, and there are 28 turns in each pole.
- Each systematic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



Field simulation of QF1

Conceptual design of HTS final focus quadrupole coils in CEPC IR

- HTS conductor: Bi-2212 (Tc 80K), Bi-2223, YBCO (Tc 92K), MgB2, IBS…



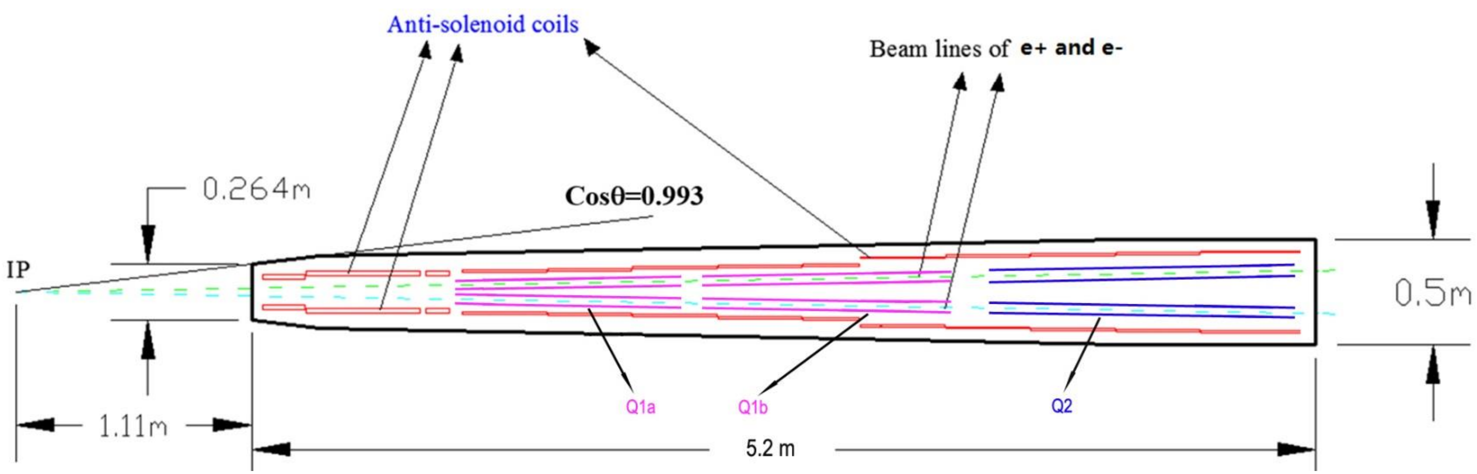
From Q.J.Xu

Conceptual design of HTS final focus quadrupole coils in CEPC IR

- The requirement of the CEPC double aperture Final Focus quadrupoles is recently updated for high luminosity with L*=1.9m.

Table 3: 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 Q1b and Q2 quadrupole coil.
- Iron yoke is used to eliminate the field crosstalk between the two apertures.
- Inside quadrupole, beam pipe diameter is around 17mm or 18 mm.

Conceptual design of HTS final focus quadrupole coils in CEPC IR

- Feasibility of HTS superconducting magnet technology is being considered for CEPC IR superconducting magnets.
- Both HTS round wire and tape are considered.

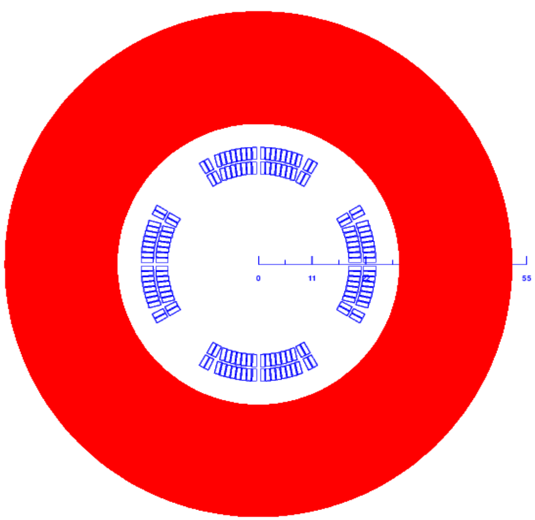
Advantage: Large critical current (expected), light weight of magnet
heat load resistant
Higher operating temperature.

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

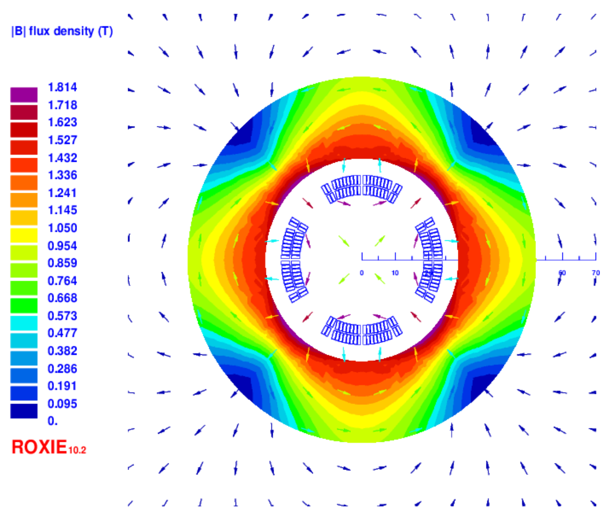
Conceptual design of Q1a for high luminosity with L*=1.9m

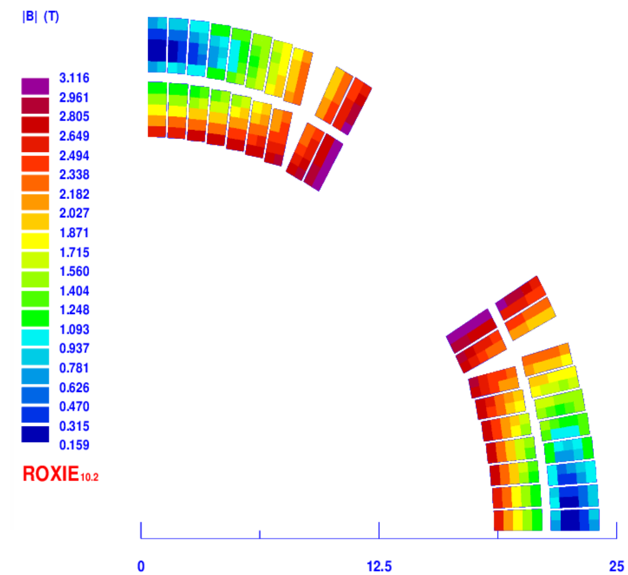
1) Cos2θ option of Q1a

- HTS Bi-2212 0.5mm wire or other conductor.
- The design of Q1a is based on 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 separated by wedges, using ROXIE.
- The width of the cable is 2.5mm, and there are 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}.



2D model (single aperture)



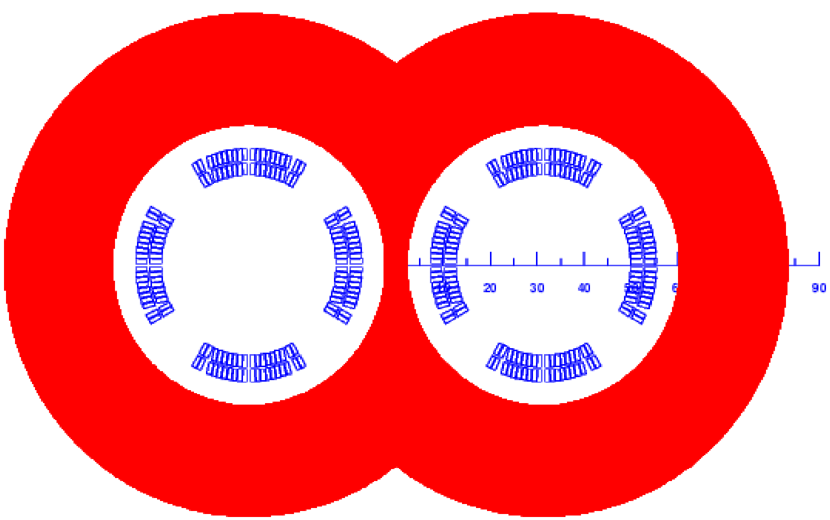


Magnetic flux density distribution

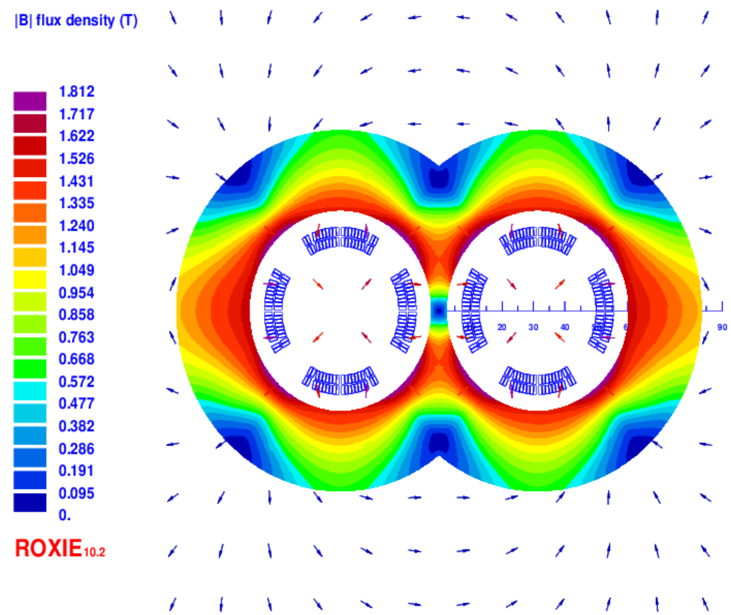
Cos2θ option of Q1a

Field cross talk of the two apertures

- 2D field cross talk of Q1a two apertures near the IP side, where the distance between two aperture centerlines is minimum.
- Iron yoke width in the middle is very limited; 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. Magnetic field cross talk between two apertures is negligible.



Double aperture model

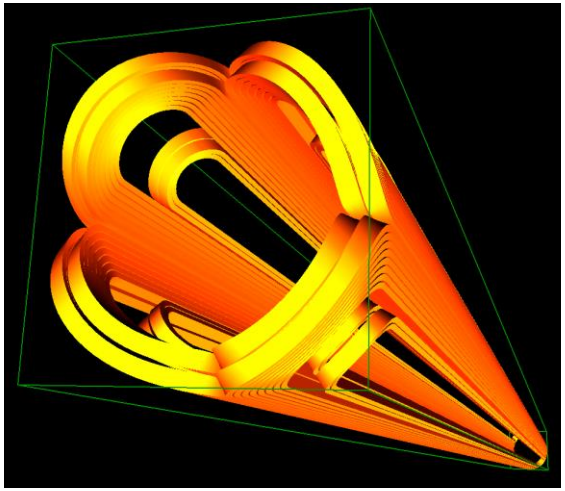
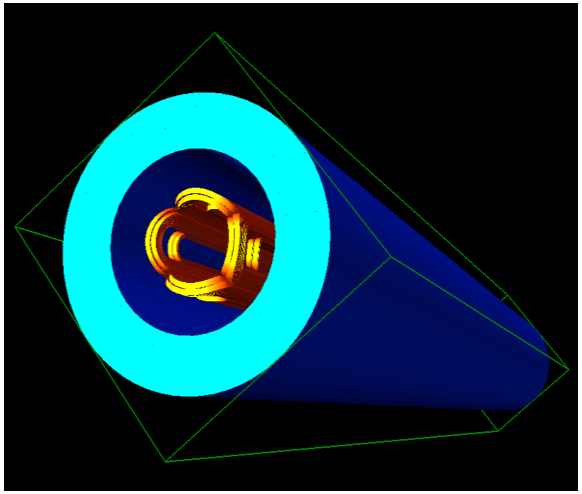
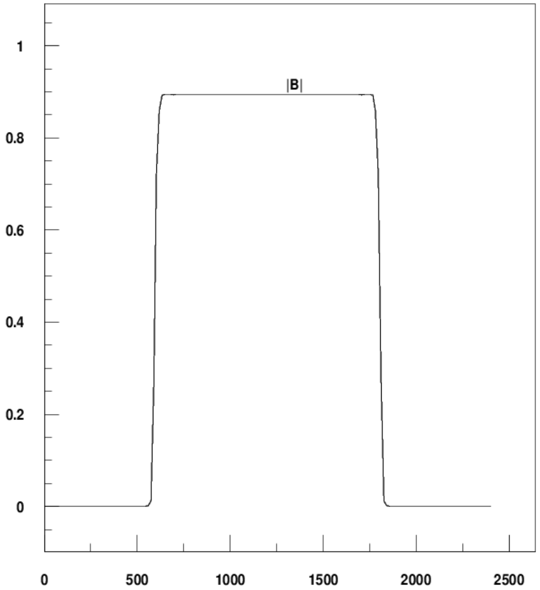


2D Flux lines

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.

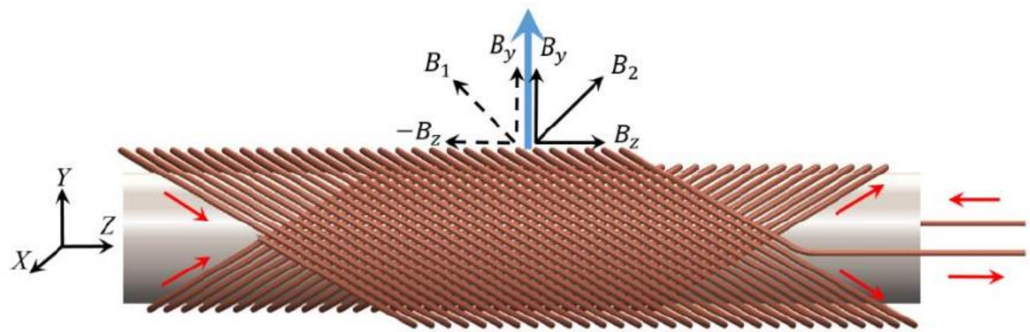
Single aperture model in 3D

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

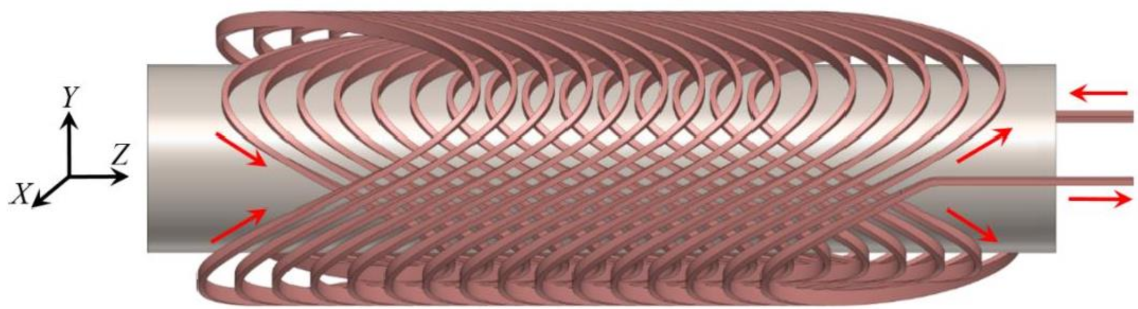
2) CCT option of Q1a

- CCT : Canted cosine theta
- The CCT design is 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 hollow cylinder or mandrel.

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

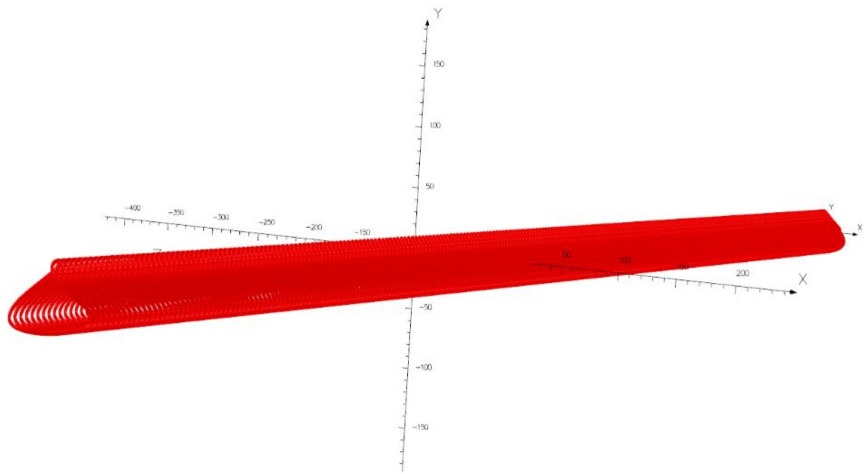
CCT option of Q1a, conceptual design

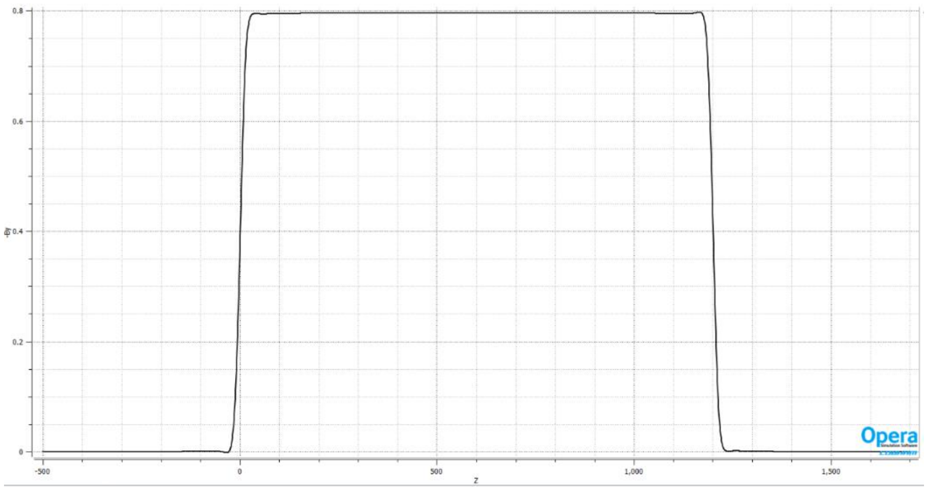
- HTS Bi-2212 0.8mm round wire or other conductor.
- The design of Q1a is based on two layers CCT quadrupole coil. The inner radius of the spar is 18.5mm.
- Outer radius of single aperture coil: 29mm.
- Groove on the spar: 2×3mm; 6 wires in a groove.
- Conductor canted angle: 30 deg
- The excitation current of Q1a is 1342A,

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

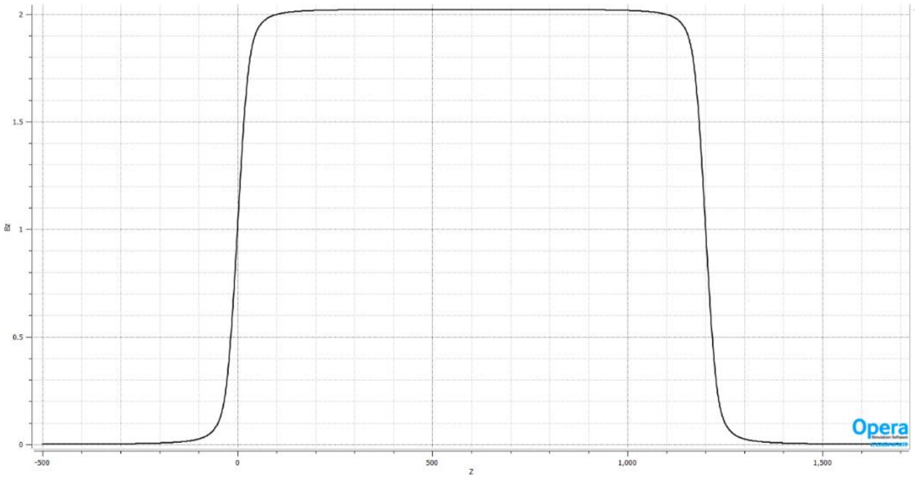
CCT option of Q1a

1st layer CCT coil of Q1a: consists of many small conductors



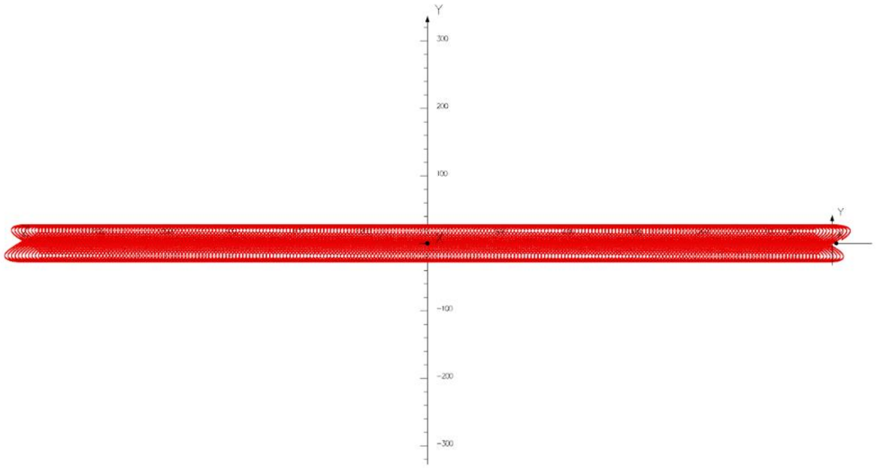


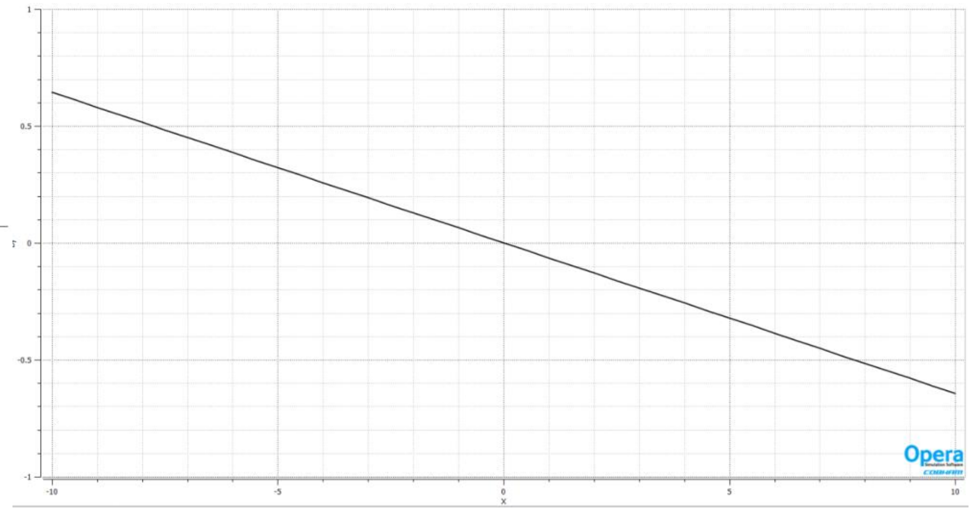
By along z

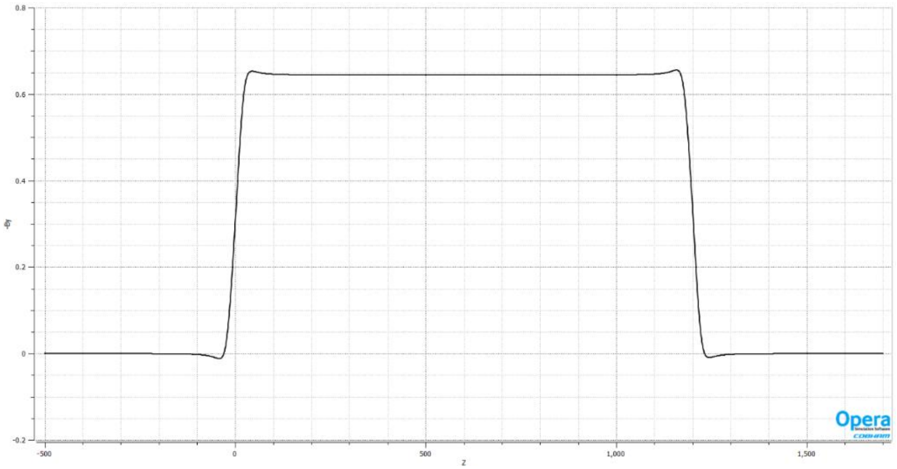


Solenoid field along z

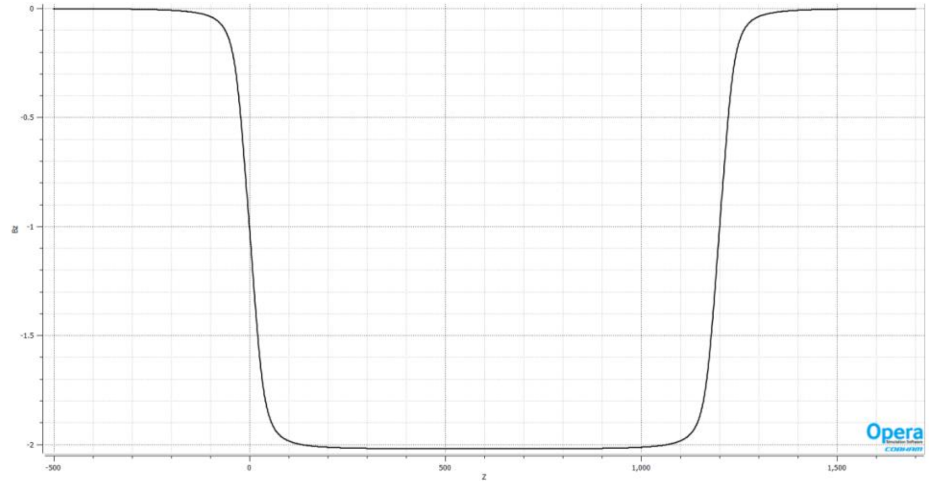
2nd layer CCT coil of Q1a







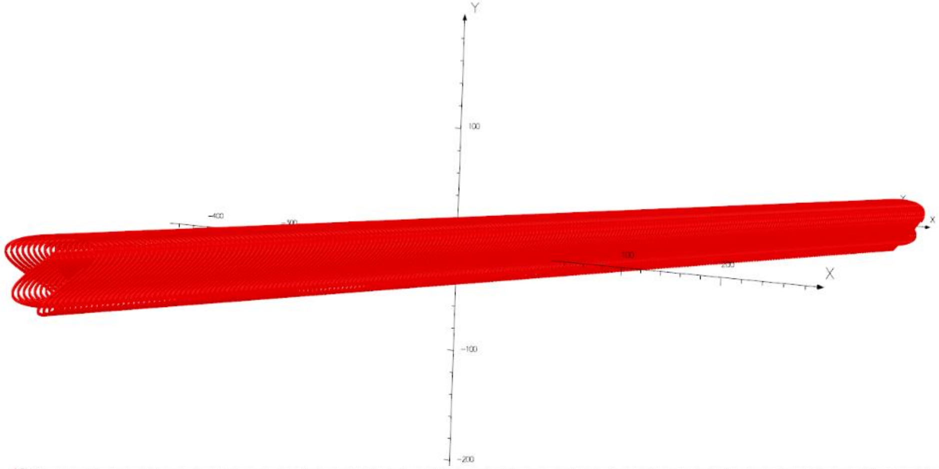
By along z

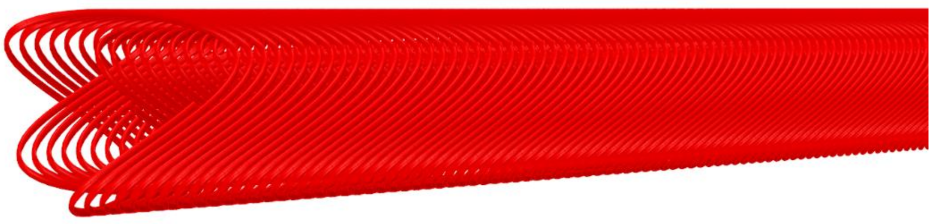


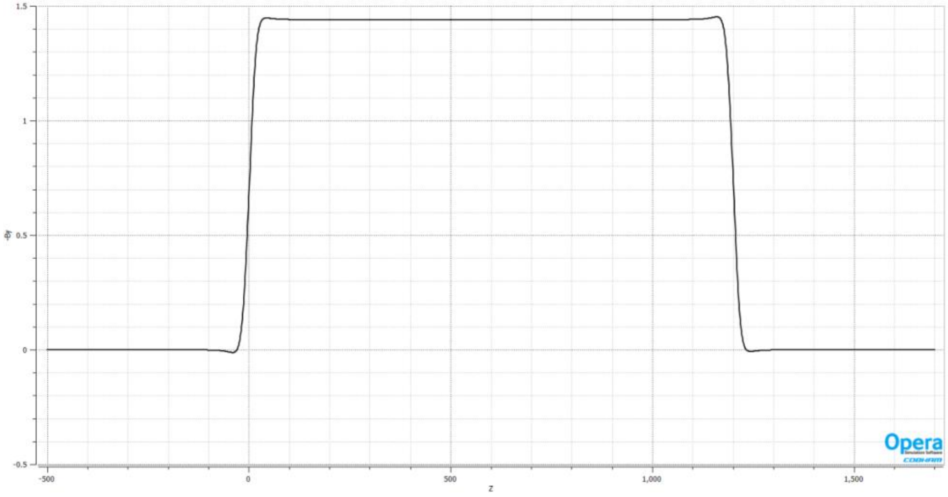
Solenoid field along z

CCT option of Q1a

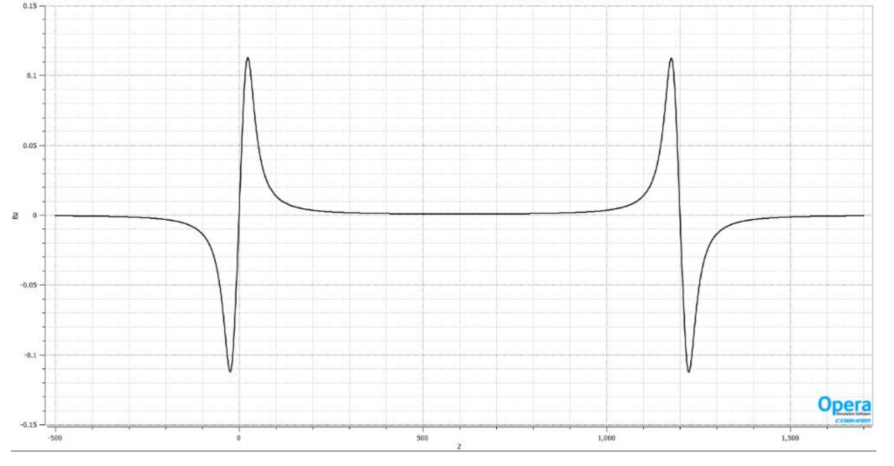
Double layer CCT coil of Q1a: Most of the solenoid fields of two layers cancel out. Field gradient and field harmonics meets the requirement.







By along z

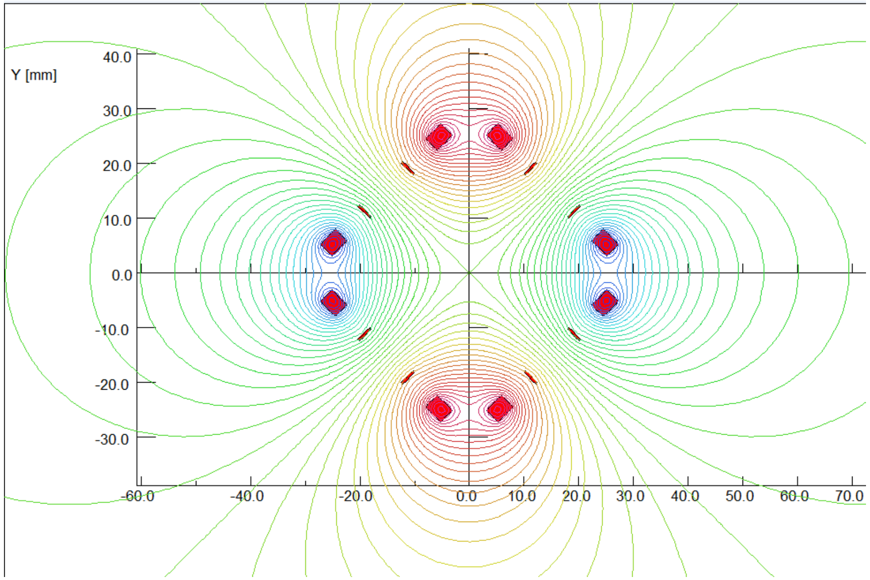


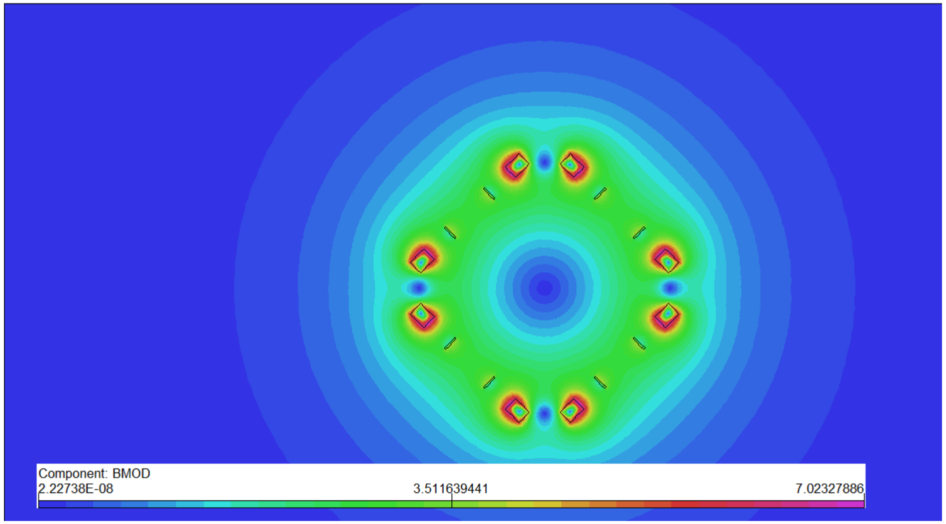
Solenoid field along z

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

3) Racetrack coil option of Q1a

- Iron-dominated HTS quadrupole magnet using racetrack coils has been studied and fabricated in the world.
- ***Can coil-dominated HTS quadrupole magnet using racetrack coils work?*** (field harmonics around 1×10^{-4}).
- ✓ Quadrupole coil using racetrack coils for Q1a is optimized. Each multipole field is smaller than 1×10^{-4} (b6: -0.5×10^{-4}; b10: -0.2×10^{-4}, R_{ref}=7.6mm).





Quadrupole racetrack coils

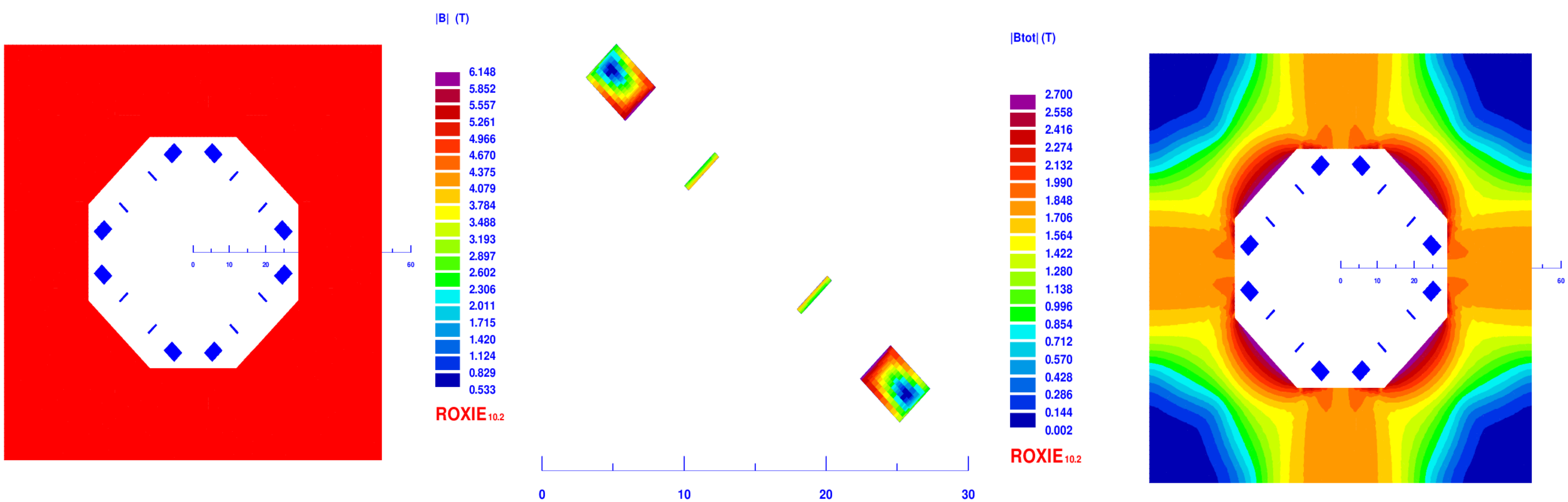
Racetrack coil option of Q1a

Racetrack coil option of Q1a, conceptual design

- HTS YBCO tape (width 3 mm, thickness 0.1 mm) or other conductor.

Single aperture field calculation of Racetrack coils with iron

- The excitation current of Q1a is 1020A; 43 turns for each pole
- Each multipole field in single aperture is smaller than 1×10^{-4} (Rref=7.6mm).

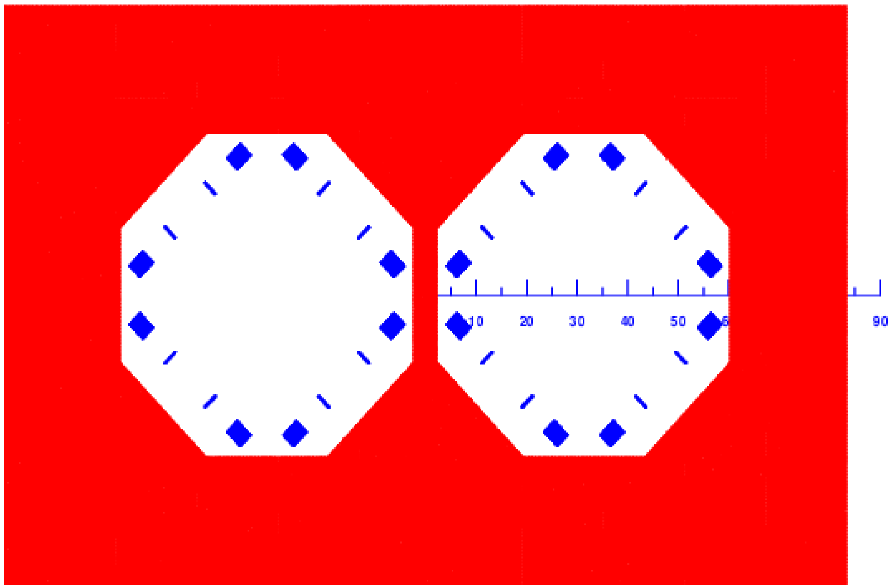


Quadrupole racetrack coils 2D field calculation

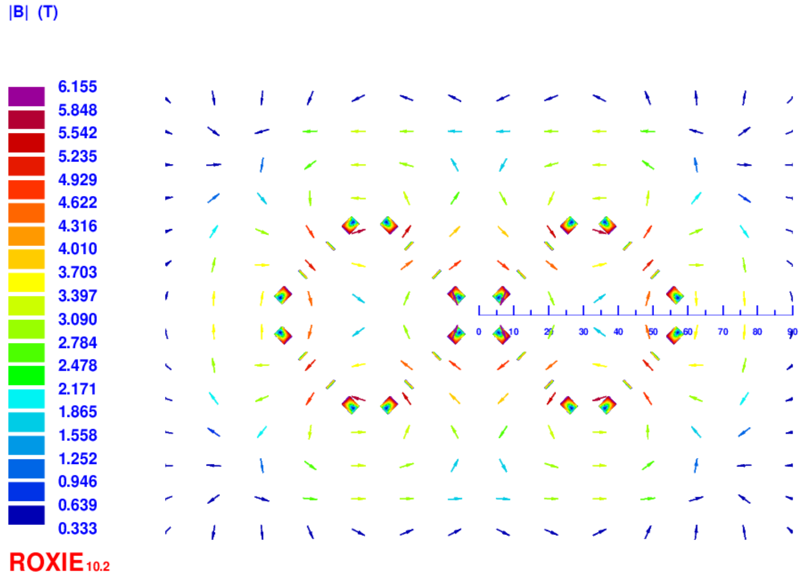
Racetrack coil option of Q1a

Field cross talk of the two apertures

- 2D field cross talk of Q1a two apertures near the IP side, where the distance between two aperture centerlines is minimum.
- The field gradient in each aperture reaches 141 T/m.
- Iron yoke width in the middle is very limited; the field harmonics as a result of field crosstalk is smaller than 2.0×10^{-4}.
- Magnetic field cross talk between two apertures is small.



Double aperture model

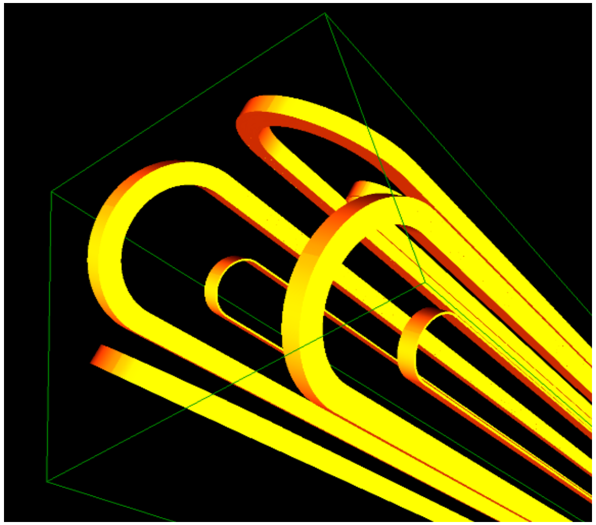


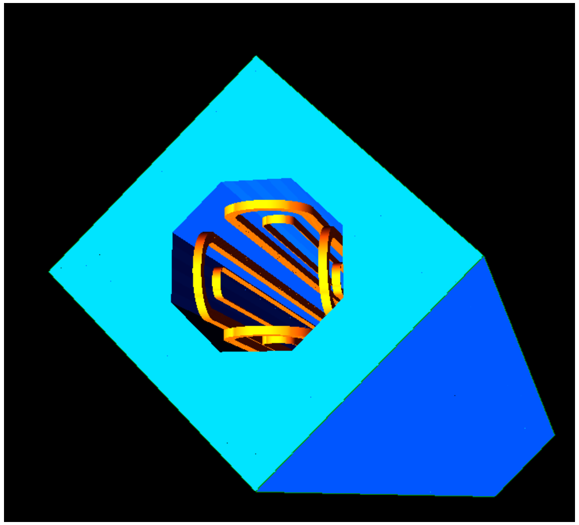
2D BMOD

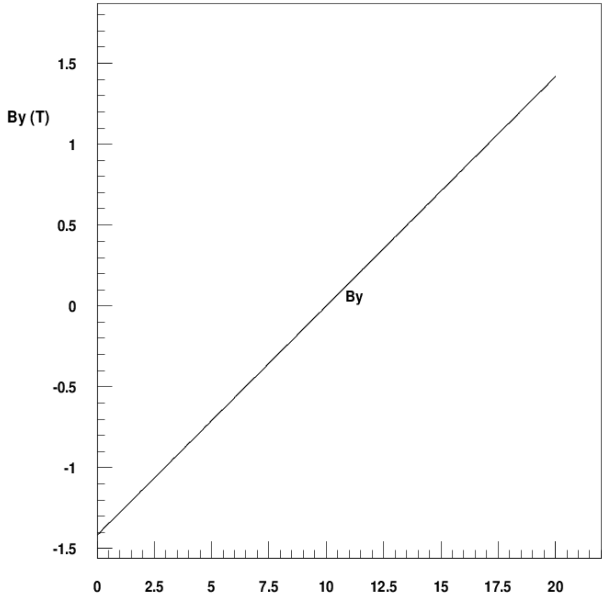
Racetrack coil option of Q1a

3D design of Q1a with Racetrack coils

- 3D magnetic field is modeled and analysed using ROXIE.
- Coil end detailed shaped is optimized and determined.
- Field gradient 141T/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

Comparison of three design HTS 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	1970	1004	3.2	Bi-2212
CCT	1342 (940 with iron)	2670 (1870 with iron)	3.8	Bi-2212
Racetrack coil	1020	3400	6.2	YBCO

- From the comparison, Cos2θ coil has the highest magnetic efficiency, lowest needed Engineering current density; the current carrying capacity of Bi-2212 conductor is close to it.

Summary

- Superconducting quadrupole magnets are key devices for CEPC. The design of quadrupole magnets with the CDR parameter meets the requirement.
- Despite limited space, field cross talk effect between two apertures in QD0 is negligible using iron yoke.
- **Coil-dominated HTS quadrupole magnet using racetrack coils** has been studied in the CEPC IR. Field quality of the coil layout $< 1 \times 10^{-4}$.
- Three HTS options have been studied for the Q1a magnet using high luminosity parameters with L*=1.9m: ***Cos2θ coil, CCT coil, Racetrack coil.***
- **Cos2θ coil has the highest magnetic efficiency**, and the current carrying capacity of Bi-2212 conductor is close to the requirements.

Thanks for your attention!