Recent progress in CEPC final focus quadrupole magnet

Yingshun Zhu, Chuang Shen, Xiangchen Yang, Ran Liang

Institute of High Energy Physics, Chinese Academy of Sciences

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CEPC day

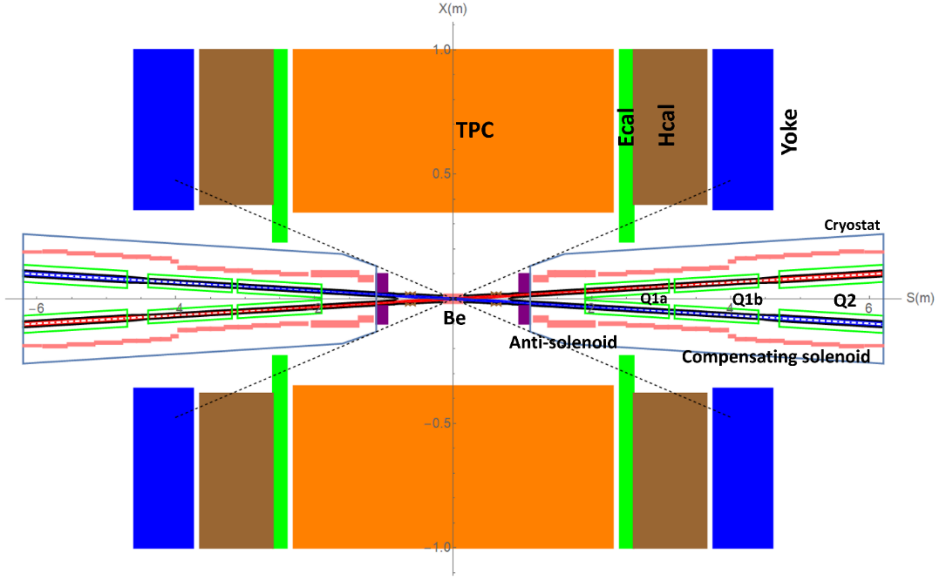
Outline

- Introduction
- Progress in final focus quadrupol magnet design in CEPC high luminosity scheme
- Progress of 0.5m single aperture short model quadrupole
- Summary

Introduction

- To squeeze the beam for **high luminosity**, compact high gradient final focus quadrupole magnets (Q1a, Q1b, Q2) are required on both sides of IP points.
- TDR requirements of CEPC Final Focus quadrupoles are based on L* of 1.9 m, beam crossing angle of 33 mrad.
- Preliminary design of quadrupole magnet in TDR stage is finished, considering various design options.

- Study and research on main key technologies of 0.5m single aperture quadrupole model is in progress, in collaboration with HeFei KEYE Company.
- Its manufacture is completed; cryogenic test at 4.2K in vertical Dewar is planned.



Progress in final focus quadrupol magnet design in CEPC high luminosity scheme

Table 1: TDR requirements of final focus quadrupole magnets for Higgs

Magnet	Central field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)	Outer diameter of beam pipe (mm)	Dipole field	Minimal distance between two aperture beam lines (mm)
Q1a	**142.3**	1.21	14.92	26 or 28	**<30 Gs**	**62.71**
Q1b	85.4	1.21	18.17	31	<30 Gs	105.28
Q2	96.7	1.5	24.48	40	<30 Gs	155.11

1 Design of Q1a

- Minimal distance between two aperture beam lines: **62.71 mm**
- Outer radius of beam pipe: **13 or 14 mm**
- Leaving space for helium vessel, **quadrupole coil inner radius: 20 mm**

■ It is challenging to meet stringent design requirement

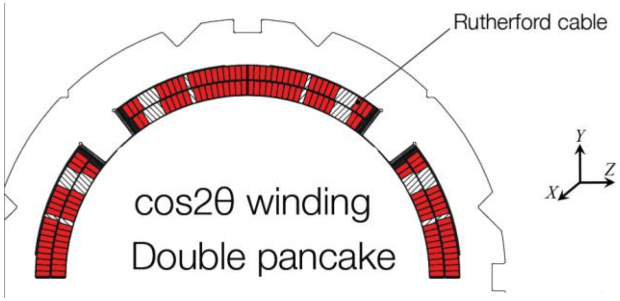
- High field gradient: **142.3 T/m** (FCC-ee 100T/m)
- Magnetic field crosstalk between two apertures:

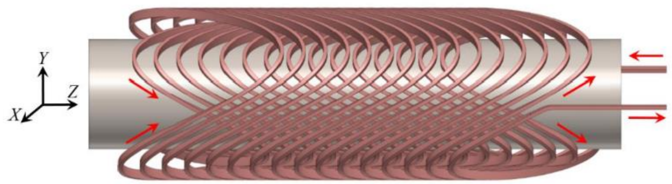
  Dipole field <30 Gs*, high order field harmonics* $<5\times10^{-4}$
- Limited radial space in the magnet middle:

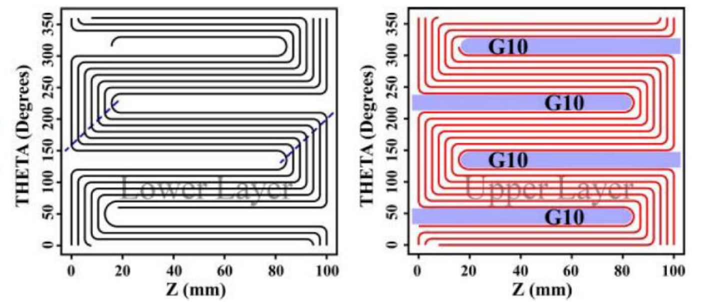
  R: [20mm, 31.36mm], **only 11.36mm available**

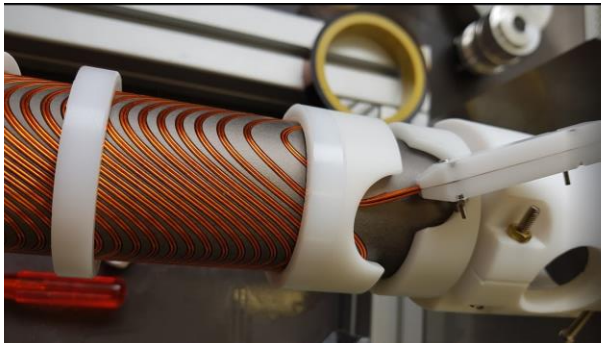
Design of Q1a

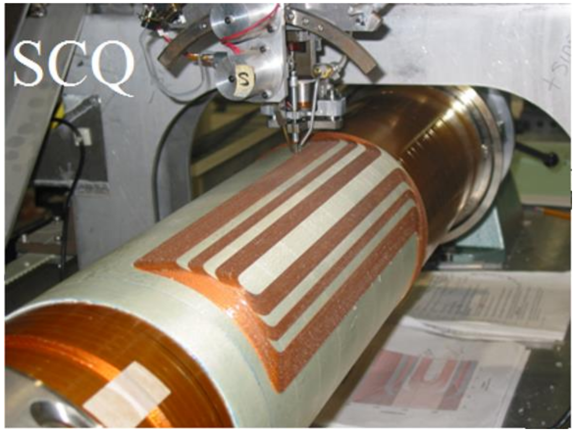
- Magnetic design of Q1a with 3 kinds of quadrupole coil structures, including **cos2θ coil, CCT coil, and Serpentine coil.**











Cos2θ coil
(SuperKEKB)

CCT coil
(FCC-ee)

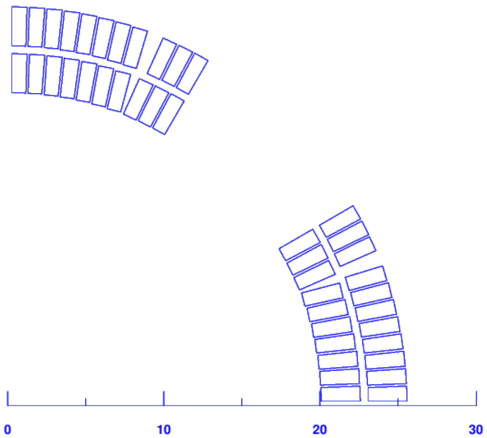
Serpentine coil
(BEPCII)

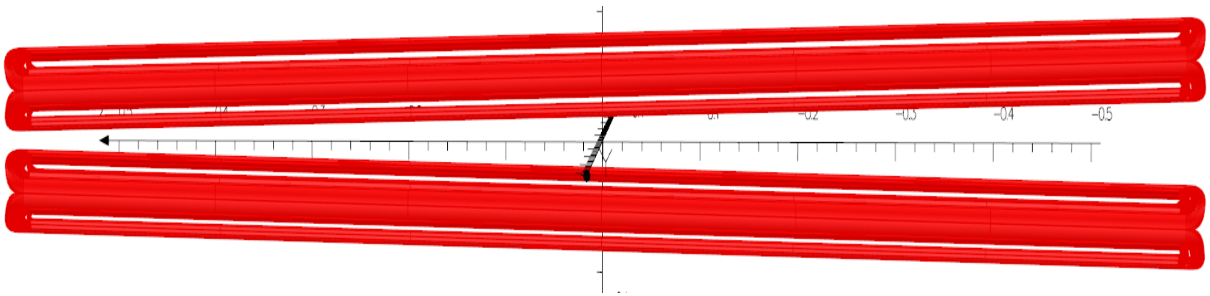
Design of Q1a

1) Cos2θ option of Q1a

- Round 0.5mm strand, HTS Bi-2212 or LTS NbTi
- Two layers cos2θ quadrupole coil using Rutherford, with 10 NbTi strands.
- The inner diameter of the coil is 40mm.
- Single aperture cross section is optimized with four coil blocks in two layers.
- Width of the cable is 2.5mm, 21 turns in each pole.

Option 1: Iron free design



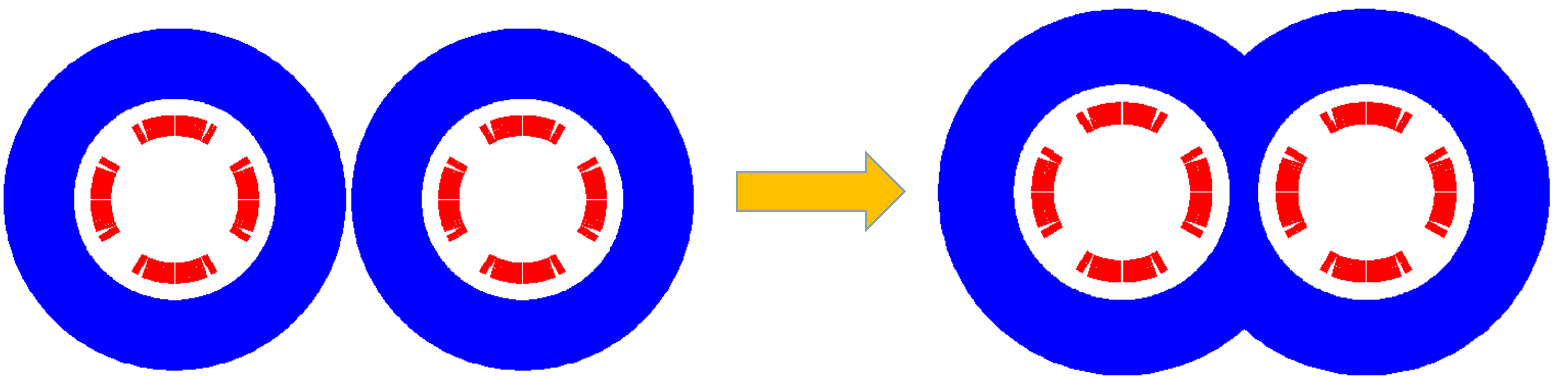


- Field crosstalk between two apertures introduces a dipole field, >1000 Gs; cannot meet design requirements. (anti-symmetric coil, add corrector coil, etc.)

Design of Q1a

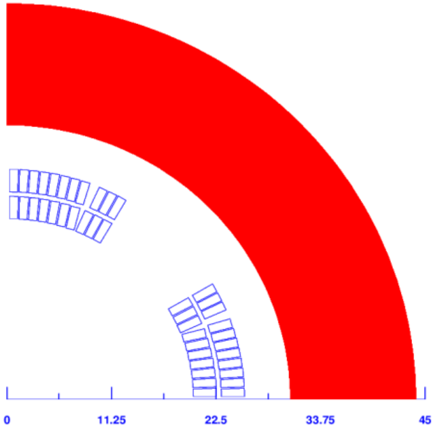
Option 2: With iron design

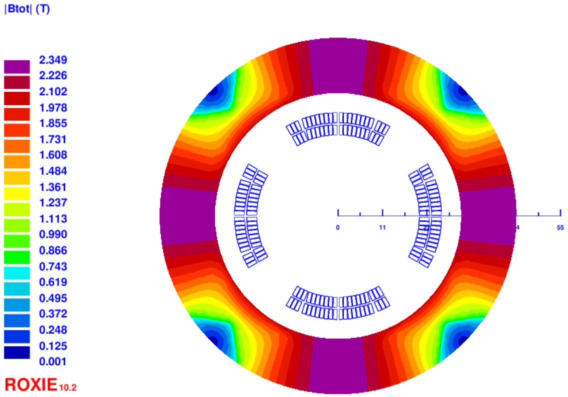
- Iron yoke FeCoV with high saturation field is added outside the coil, to enhance the field gradient, reduce the coil excitation current, and shield the field crosstalk
- Not enough space to place two single apertures side by side
- ➢ Compact design: Iron core in the middle part is shared by two apertures

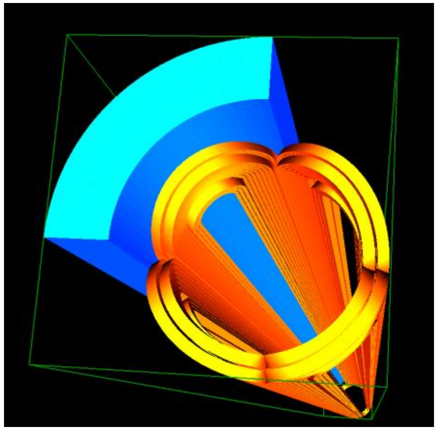


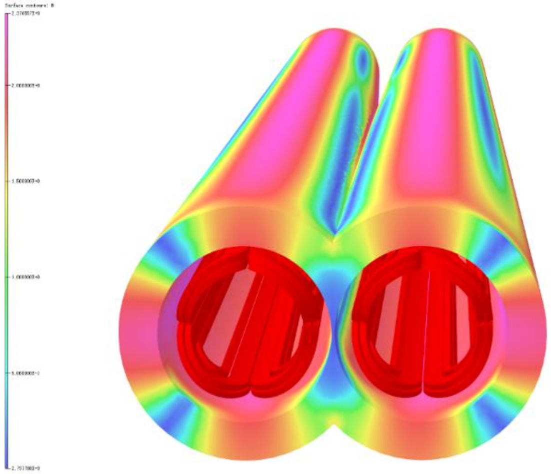
Q1a design with iron

- The field harmonics as a result of field crosstalk is smaller than 1×10^{-4}.
- **Dipole field at aperture center is smaller than 20 Gs.** Compared with iron-free design, the excitation current is reduced to 2020A @4.2K.
- Double aperture cos2θ quadrupole with iron yoke shared by two apertures, with crossing angle 33mrad of two apertures. **Meet all requirements.**



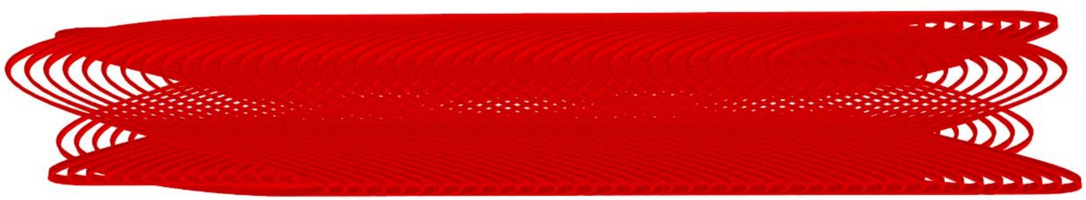


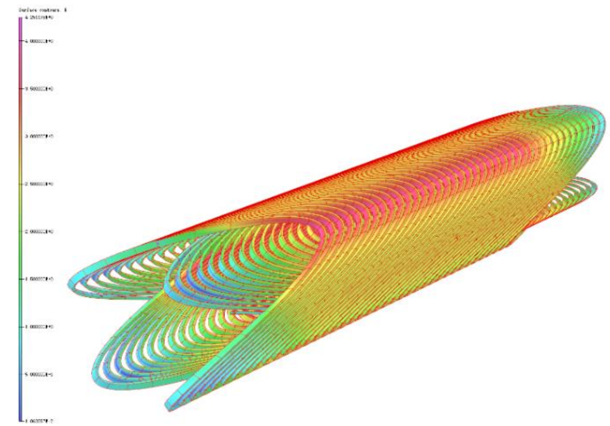


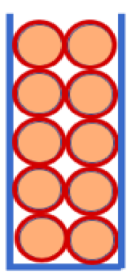


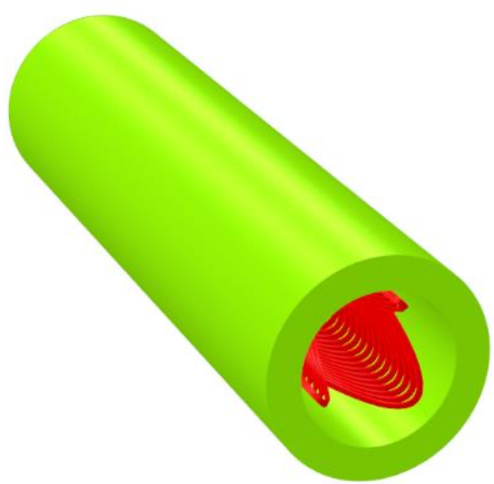
2) CCT option of Q1a

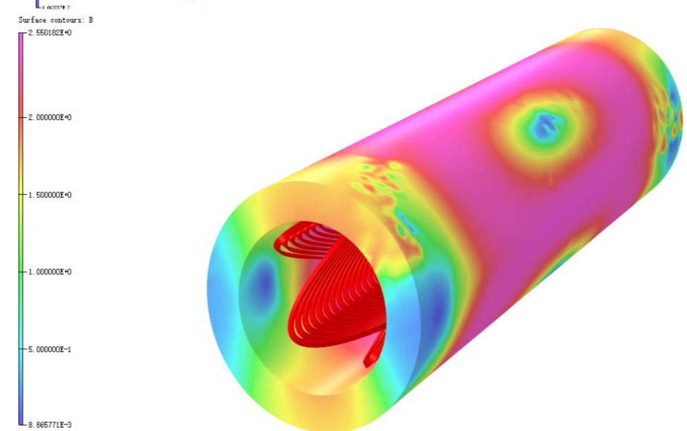
- 0.5mm round wire, HTS Bi-2212 or LTS NbTi.
- Two layers CCT quadrupole coil. The inner radius of the spar: 20mm.
- Groove on the spar: 1×2.5mm; 10 wires in a groove.
- Conductor canted angle: 30 deg. Excitation current: 324A.
- Field gradient is calculated using theoretical formula, and OPERA-3D.
- ✓ Each integrated multipole field in single aperture is smaller than 1×10^{-4}.





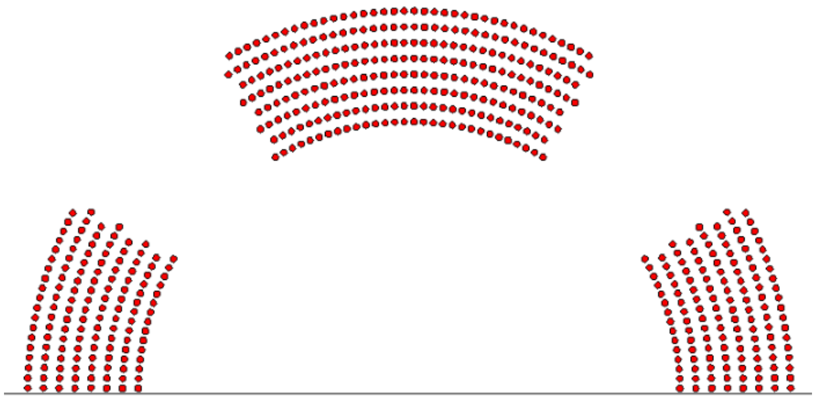


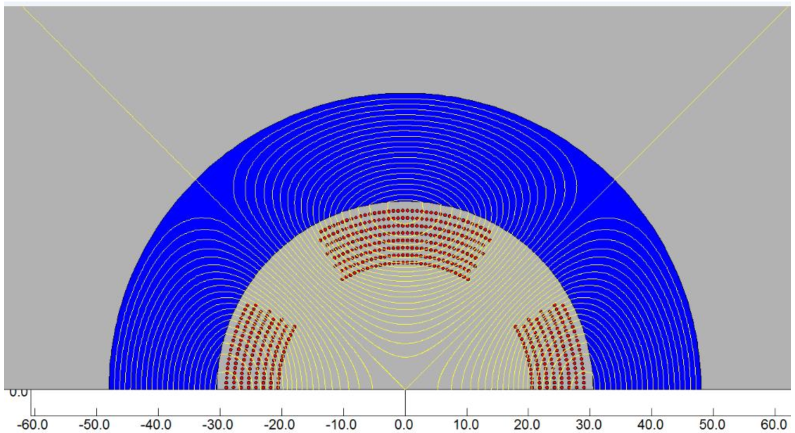


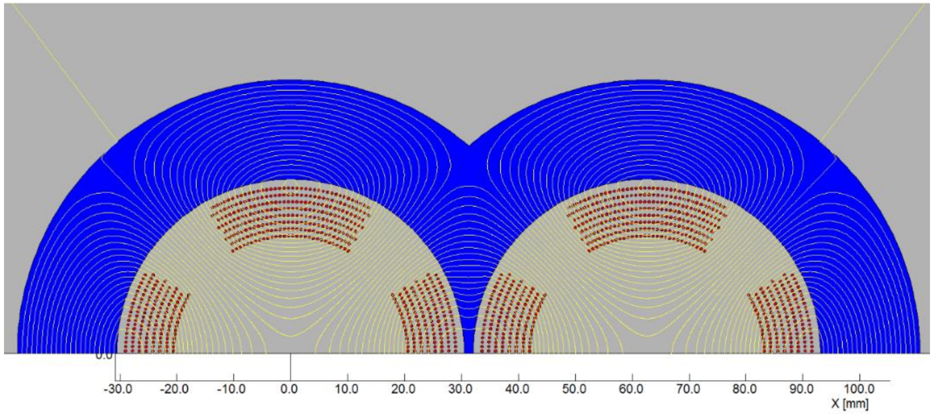


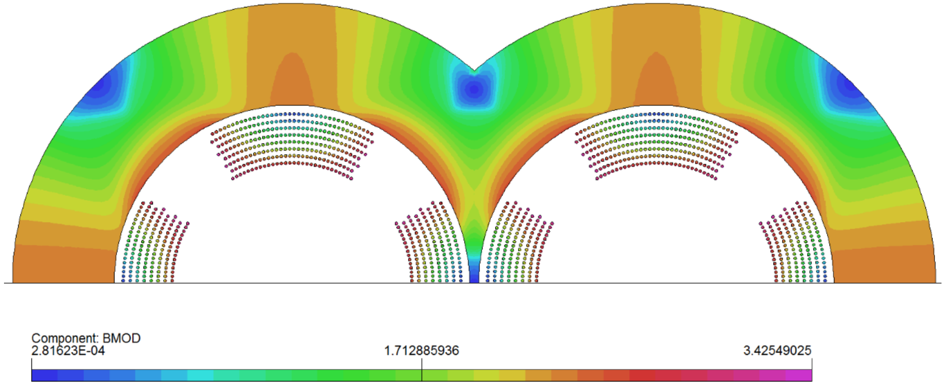
3) Serpentine option of Q1a

- 0.5mm round wire, HTS Bi-2212 or LTS NbTi.
- 8 layers Serpentine quadrupole coil. The inner radius of the coil: 20mm.
- 2D calculation, each multipole field in single aperture is smaller than 1×10^{-4}.
- Excitation current: 334A (with iron)









Comparison of three design options of Q1a

1) Comparison of three design options of Q1a (142.3T/m, no iron)

Q1a option	Cos2θ coil	CCT coil	Serpentine coil
Excitation current in strand (A)	265	472.5	480
Current density Je on wire (A/mm^2)	1350	2406	2445
Peak field in coil (T)	3.6	4.3	4.2

2) Comparison of three design options of Q1a (142.3T/m, with iron)

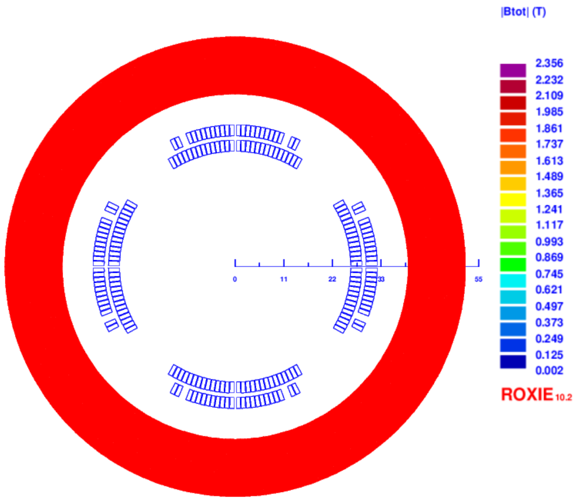
Q1a option	Cos2θ coil	CCT coil	Serpentine coil
Excitation current in strand (A)	202	324	334
Current density Je on wire (A/mm^2)	1029	1650	1701
Peak field in coil (T)	3.5	3.8	3.8

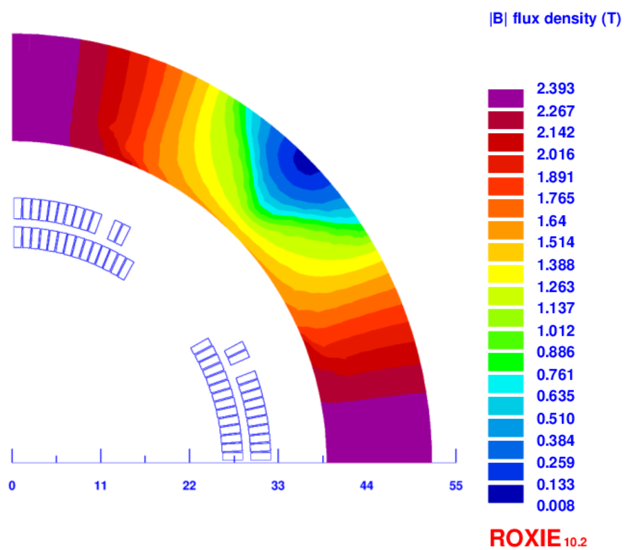
- From the comparison, Cos2θ coil has lower current, lower peak field, and lower current density.
- Cos2θ coil as baseline design, CCT and Serpentine coil as alternative design.

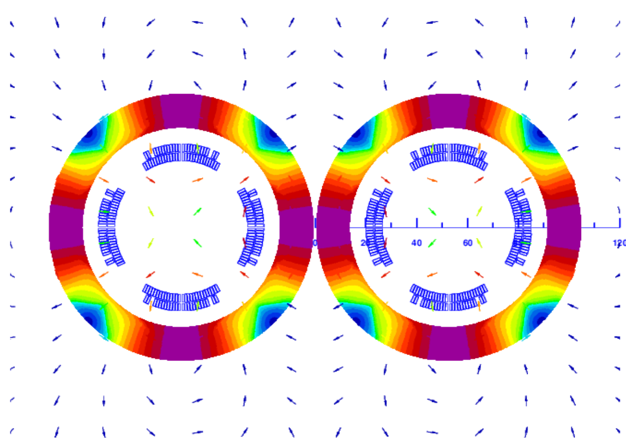
2 Design of Q1b

Baseline design: Cos2θ coil; CCT and Serpentine coil as alternative design

- Round 0.5mm strand, HTS Bi-2212 or LTS NbTi
- Q1b: two layers cos2θ quadrupole coil using Rutherford cable with iron yoke. The inner radius of the coil is 26 mm.
- Single aperture cross section is optimized with three coil blocks in two layers.
- Width of the cable is 3 mm, 26 turns in each pole.
- The excitation current of Q1a is 1590A.
- Two apertures do not need to share the iron yoke like Q1a.
- Two layers corrector coils will be added inside quadrupole coil, using 0.33mm wire.



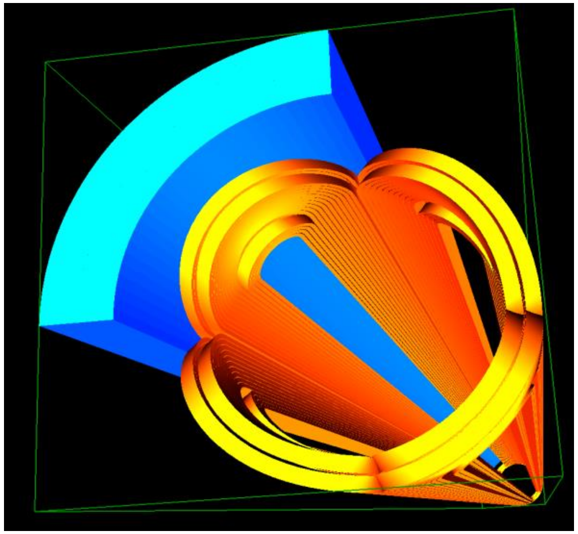


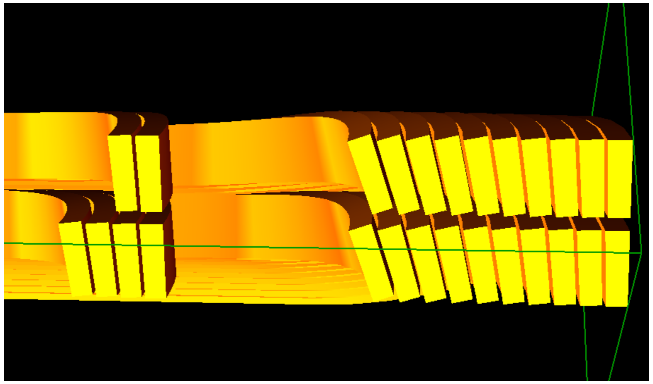


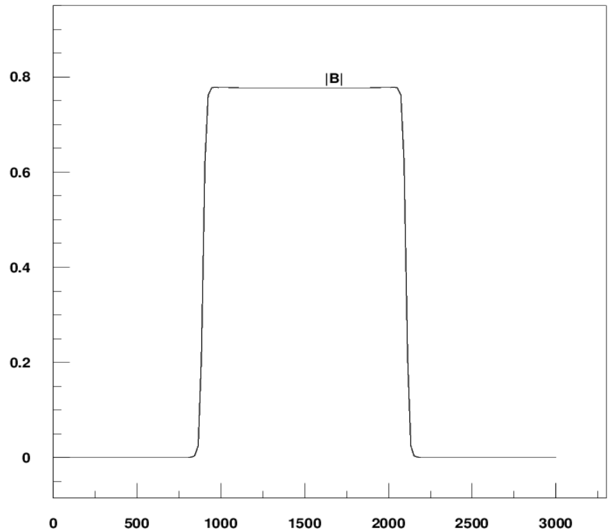
Design of Q1b

3D design of Q1b

- 3D magnetic field is modeled and analysed using ROXIE.
- Coil end detailed shaped is optimized and determined.
- Field gradient 85.4T/m, each integrated field harmonics is smaller than 1×10^{-4}.
- ◆ The 3D magnetic field performance meets requirement.





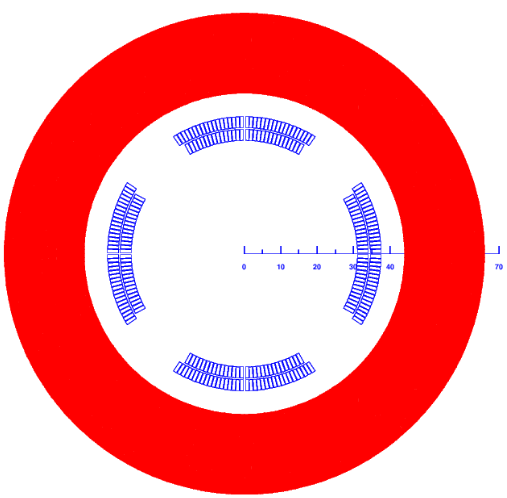


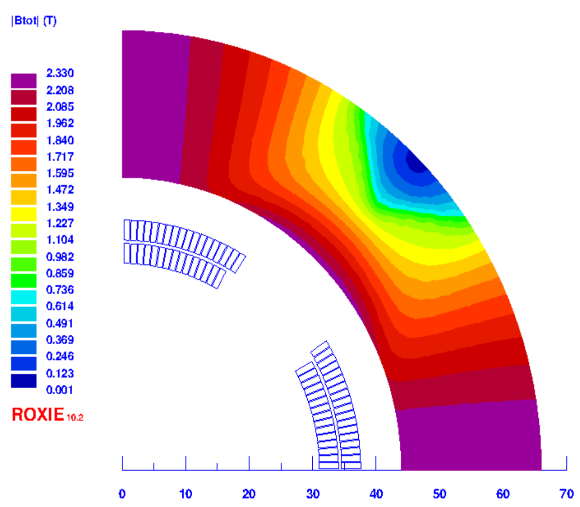
Single aperture model in 3D

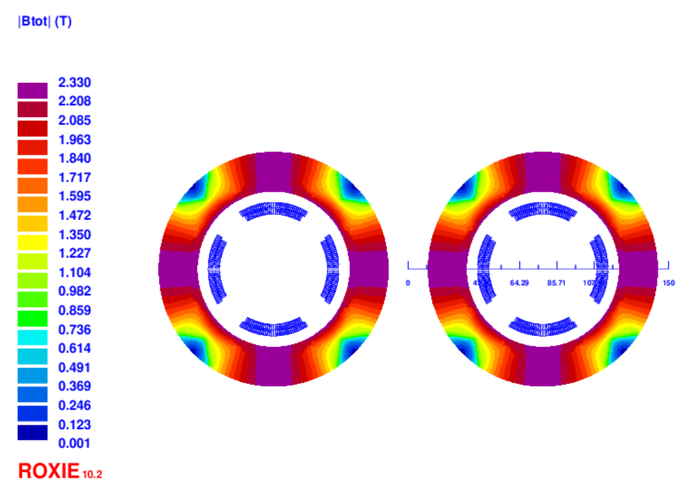
3 Design of Q2

Baseline design: Cos2θ coil; CCT and Serpentine coil as alternative design

- Round 0.5mm strand, HTS Bi-2212 or LTS NbTi
- Q2: two layers cos2θ quadrupole coil using Rutherford cable with iron yoke. The inner radius of the coil is 31mm.
- Single aperture cross section is optimized with two coil blocks in two layers.
- Width of the cable is 3mm, 33 turns in each pole.
- The excitation current of Q1a is 1925A, and each multipole field in single aperture is smaller than 1×10^{-4} in 2D.
- Two apertures do not need to share the iron yoke like Q1a.
- Two layers corrector coils will be added inside quadrupole coil, using 0.33mm wire.



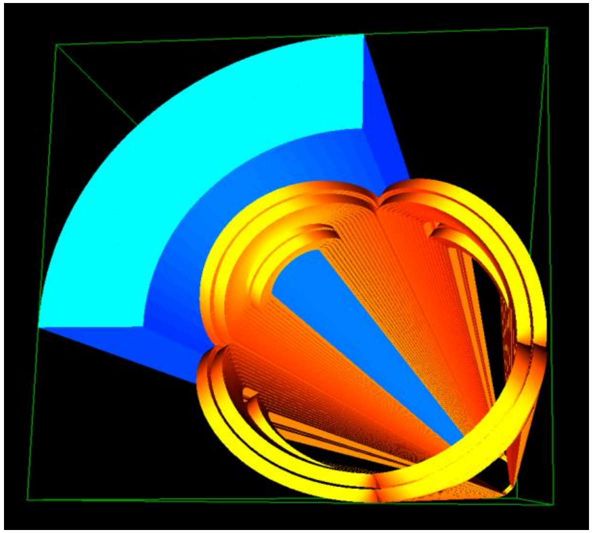


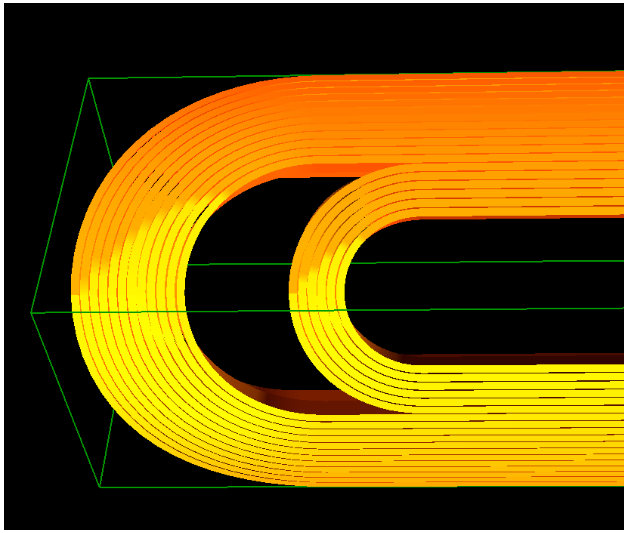


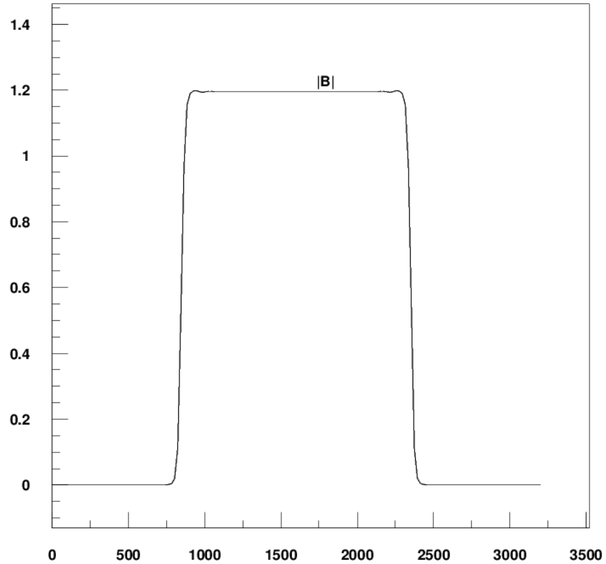
Design of Q2

3D design of Q2

- 3D magnetic field is modeled and analysed using ROXIE.
- Coil end detailed shaped is optimized and determined.
- Field gradient 85.4T/m, each integrated field harmonics is smaller than 1×10^{-4}.
- ◆ The 3D magnetic field performance meets requirement.







Single aperture model in 3D

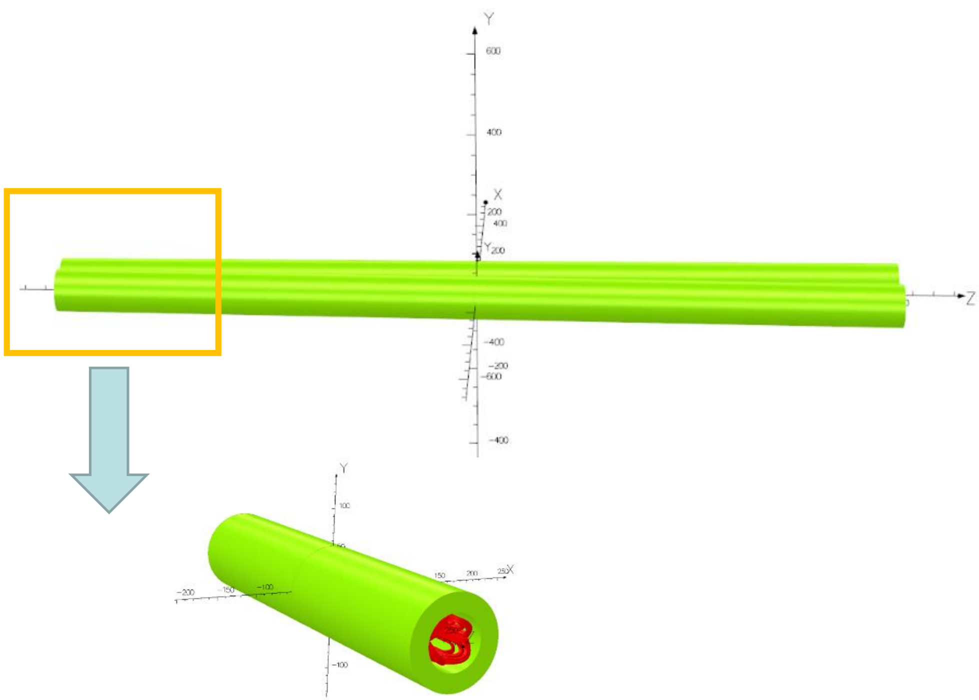
Progress of 0.5m single aperture short model quadrupole

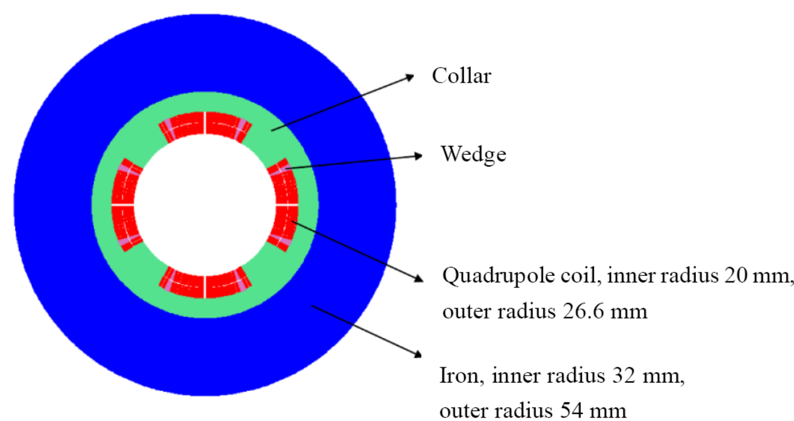
- Baseline design of quadrupole, there is no such magnet in the world:

  Collared cos2θ quadrupole magnet, with shared iron yoke and crossing angle between two apertures.

  In practice, can it be fabricated and really meet the requirement?

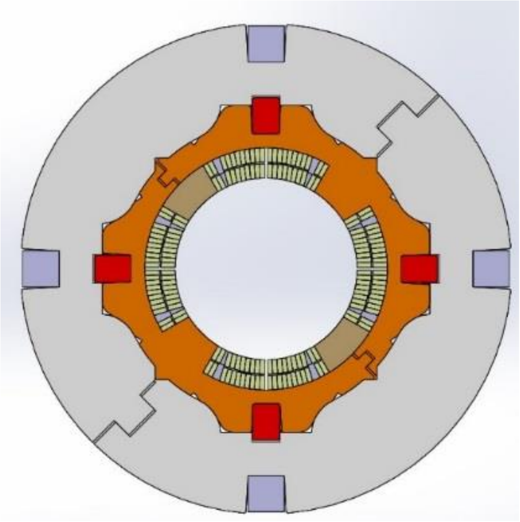
- So far, there is no cos2θ superconducting quadrupole magnet in China.
- The first step is to **study and master main key technologies of** superconducting quadrupole magnet by developing a short model magnet with **0.5m length**.

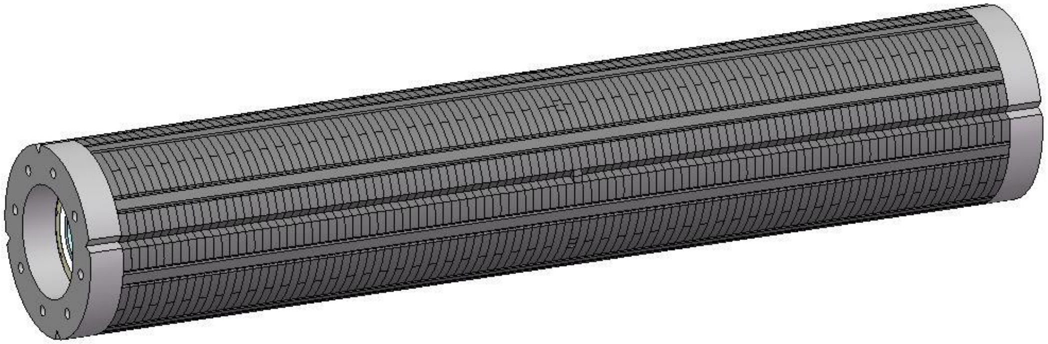


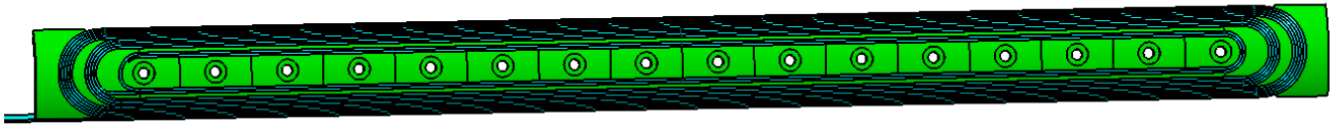


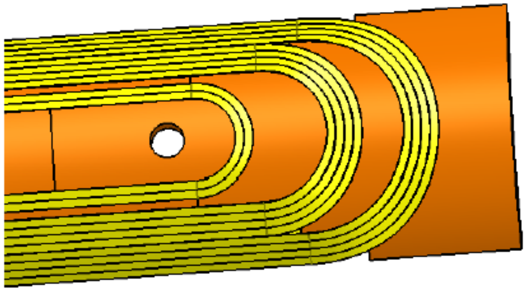
Progress of 0.5m single aperture short model quadrupole

- Research on main **key technologies** of 0.5m single aperture quadrupole model has started (NbTi, 136T/m), in collaboration with HeFei KEYE Company.
- Including: quadrupole coil winding technology, fabrication of quadrupole coil with small diameter, stress control, quadrupole magnet assembly, cryogenics vertical test and field measurement technology, etc.









Progress of 0.5m single aperture short model quadrupole

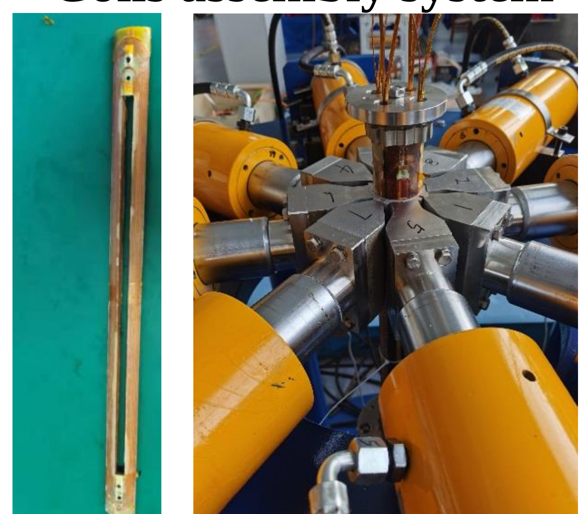
- **Progress:** Manufacture of all hardware is completed.

NbTi Rutherford cable (12 strands)

Winding machine

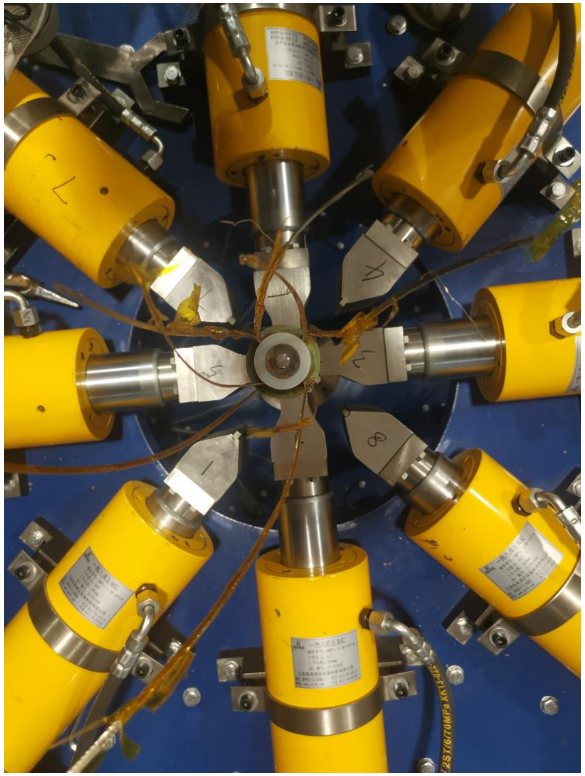
Coil heating and curing system

Coils assembly system



Progress of 0.5m single aperture short model quadrupole

- Many test on the winding and curing of quadrupole coils were performed.
- Four SC quadrupole coils have been fabricated, then they are assembled with stainless collar and iron yoke.
- Coil resistance and ground insulation voltage test have been performed.
- Manufacture of 0.5m single aperture short model quadrupole was completed in August 2022. Then, the magnet has been transported to IHEP.



Progress of 0.5m single aperture short model quadrupole

- Cryogenic excitation test at 4.2K is planned to be performed in future, to verify whether high magnetic field gradient can be achieved.
- Design current: 2115A

✓ Already available: vertical Dewar

- No additional cost required, if the following two hardware available:
  - Refrigerator (production of liquid helium, 1 or 2 days)
  - Power supply (~2500A)

  (Both in Superconducting magnet group)

Summary

- For CEPC IR superconducting quadrupole magnets, it is challenging to meet stringent design requirements, including limited space, magnetic field crosstalk between two apertures, field gradients up to 142T/m.
- Various design options are considered, including Iron-free option, with iron option, HTS option, LTS option.
- Three kinds of quadrupole coil structures have been studied for Q1a using high luminosity parameters: **Cos2θ coil, CCT coil, Serpentine coil.**
- Cos2θ coil has higher magnetic efficiency, lower current and low coil peak field. It is the baseline option.

- **Study and research on key technologies** of 0.5m single aperture quadrupole model (136T/m, NbTi) is in progress;
- Its manufacture is completed, and cryogenic test at 4.2K in vertical Dewar is planned; No additional cost required, if two hardware are available.

Thanks for your attention!