



CEPC Superconducting Quadrupole Magnet

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On behalf of CEPC IR SC magnet system



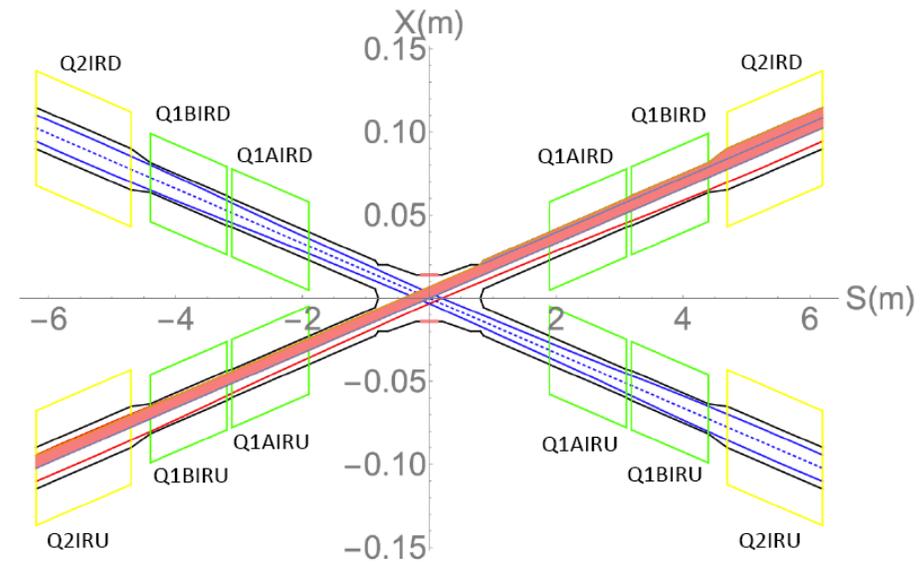
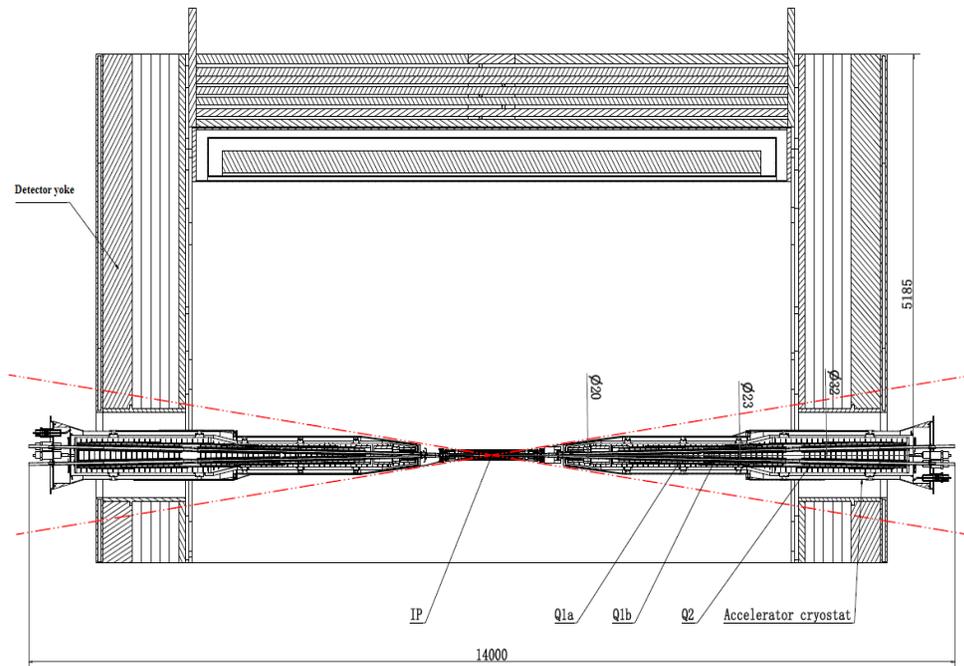
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Content

- **Introduction**
- **EDR plan of superconducting quadrupole magnets**
- **EDR status**
 - **Magnetic field design**
 - **Quench protection and simulation**
 - **Direct winding CCT quadrupole short model status**
- **Conclusion**

Introduction

- There are 2 interaction points in CEPC collider ring
- To final focus the beams for high luminosity, compact high gradient double aperture quadrupole magnets (Q1a, Q1b, Q2) are required on both sides of IP point
- To cancel the effect of the detector solenoid field (3T) on the beam, anti-solenoids before Quadrupoles and outside Quadrupoles are needed
- EDR requirements of CEPC Final Focus quadrupoles are based on L^* of 1.9 m, beam crossing angle of 33 mrad



Introduction

- Design requirement of CEPC Interaction Region quadrupole magnets:

- 1) Basic requirement of CEPC Interaction Region quadrupole magnets

Magnet	Field gradient (T/m)				Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
	tt	Higgs	W	Z			
Q1a	140.7	142.3	94.9	109.7	1.21	14.92	62.71 →
Q1b	58.9	85.4	57.0	64.8	1.21	18.17	105.28
Q2	51.3	96.7	64.5	0.0087	1.5	24.48	155.11

Field crosstalk will introduce Dipole field, sextupole, etc

- 2) Ratio of multipole field to quadrupole field $\leq 3 \times 10^{-4}$
- 3) Integral dipole field at the center of quadrupole aperture is zero
Local dipole field at each longitudinal position ≤ 300 Gs

EDR plan of superconducting quadrupole magnets

EDR goal of SC quadrupoles

Optimize and finish good magnet design, innovative, technically achievable

Complete the Engineering Design Report

EDR plan of SC quadrupoles

Year	Work plan	Status
2024	Iteration and finalize design requirements for SC quadrupole magnets Choose a good magnet design option	Finished
2025	Optimization of SC quadrupole, detailed magnetic field analysis, quench analysis Finish magnet design , summarize magnet parameters Complete 2025 CEPC proposal of SC quadrupoles Start direct winding experiments of CCT quadrupole coil	Finished
2026	Key technologies study, magnet engineering design Manufacture a direct winding CCT Q1a short model	To be done
2027	Cryogenic test of CCT Q1a short model Complete Engineering design report	To be done

Magnetic field design of superconducting CCT quadrupoles

The design requirement of Q1a is the most challenging

- Minimal distance between two aperture beam lines: **62.71 mm**
Radius of single aperture <31.36mm
- Leaving space for beam pipe, inner helium vessel, coil support
- **Quadrupole coil inner radius: 20 mm**

■ Challenging to meet stringent design requirements for Q1a

1) High field gradient: **142.3 T/m**

2) Limited magnet radial space

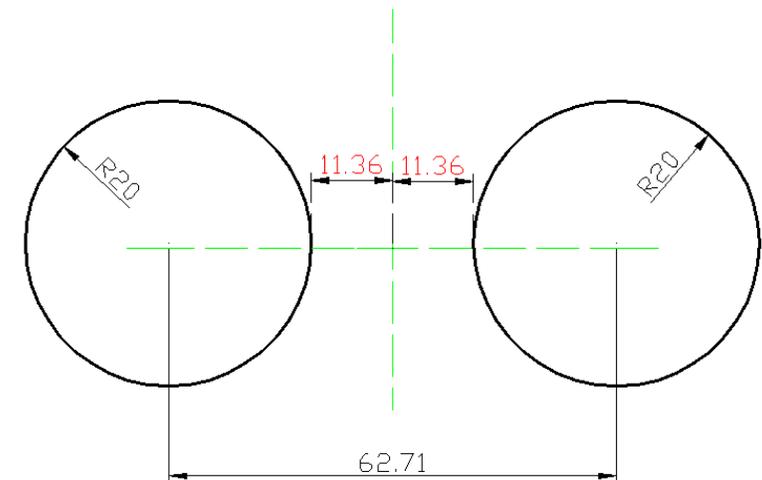
R: [20mm, 31.36mm], **11.36mm**

3) Magnetic field crosstalk between two apertures

High order field harmonics $\leq 3 \times 10^{-4}$

Local dipole field: ≤ 300 Gs

FCC-ee FFQ: 100 T/m



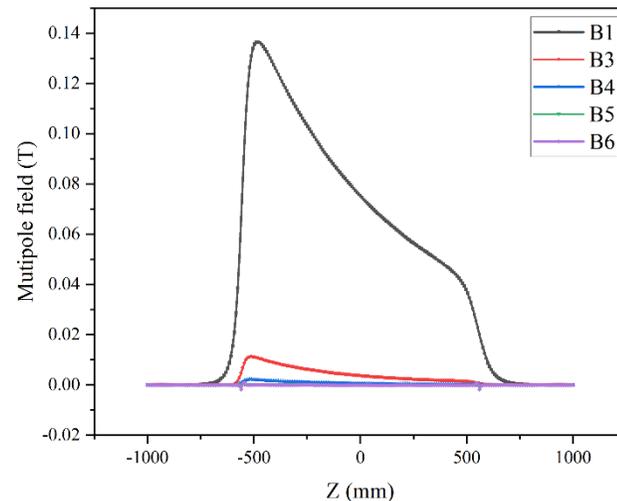
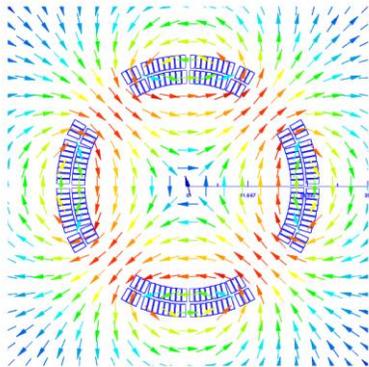
Field crosstalk in double aperture iron-free quadrupole

- In EDR, requirement on **local dipole field** in each aperture is relaxed to ≤ 300 Gs
- To reduce magnet weight, **iron-free structure** is selected for CEPC SC quadrupoles
- The two apertures of Q1a is in close proximity, distance between two beams changes
- Field crosstalk generates **multipole fields that vary longitudinally** and should be solved
- Using anti-symmetric coil, dipole field can not meet the design requirement

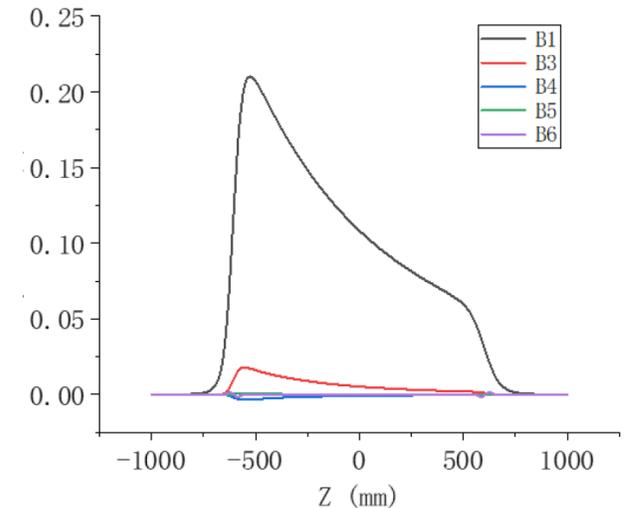


|B| (T)

3.570
3.382
3.194
3.006
2.818
2.630
2.442
2.254
2.067
1.879
1.691
1.503
1.315
1.127
0.939
0.751
0.563
0.375
0.187
0



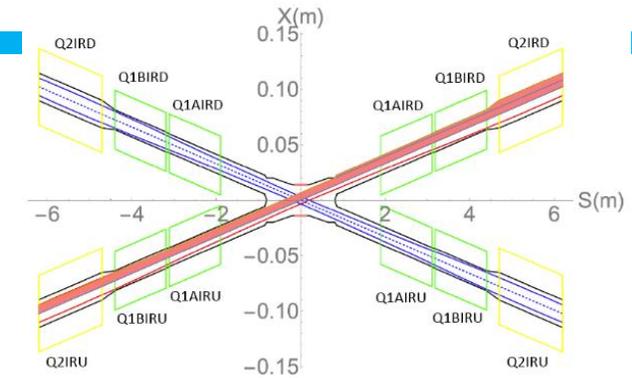
Cos2θ coil



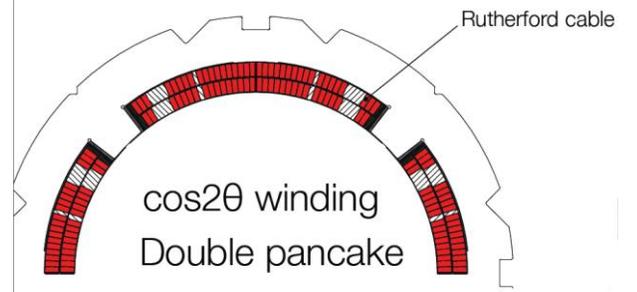
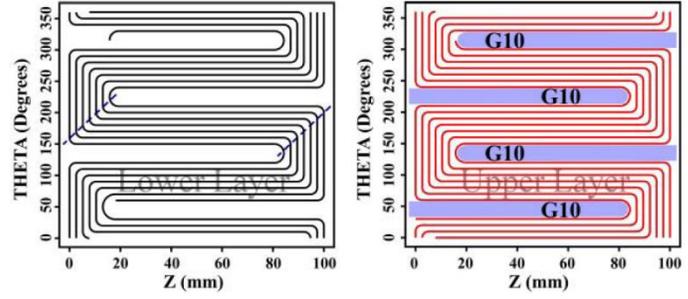
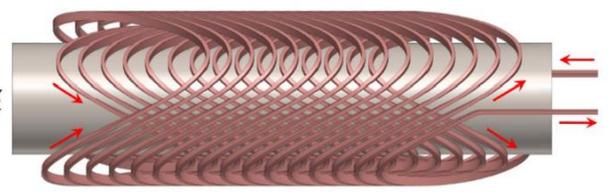
CCT coil

CCT option to solve field crosstalk in iron-free quadrupole

- Field crosstalk varies with longitudinal position
- Three kinds of quadrupole coil structures are studied
- Cos2θ and Serpentine coil: hard to locally adjust field distribution**
- CCT (Canted cosine theta) coil can locally adjust field distribution**
- CCT quadrupole coil is the selected option** (Iron-free, coil self correction)



$$\begin{cases} x = R\cos\theta \\ y = R\sin\theta \\ z = \frac{R\sin(n\theta)}{n\tan\alpha} + \frac{\omega\theta}{2\pi} \end{cases}$$

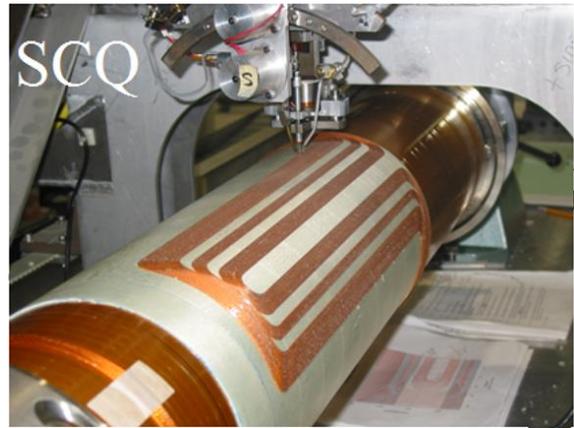


$$z' = \sum \left(C_m \frac{R\sin(n_1\theta)}{n_1\tan\alpha} \right) + \sum \left(D_m \frac{R\cos(n_2\theta)}{n_2\tan\alpha} \right)$$

CCT Coil with self correction



CCT coil



Direct winding Serpentine coil



Cos2θ coil

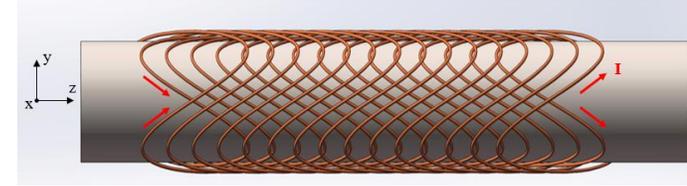
CCT option to solve field crosstalk in iron-free quadrupole

- Besides quadrupole coil, several corrector coils are needed in CEPC IR
Dipole corrector coil, Skew quadrupole coil
- **Direct winding CCT coil is preferred. Baseline design**
Wind CCT coil **layer by layer on tube surface** using Direct winding technology

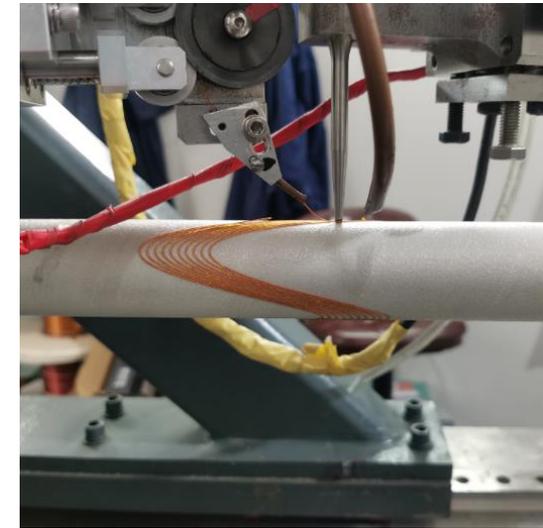
- Traditional CCT coil is alternative option
Conductors in groove, each layer requires a skeleton

Advantages of Direct winding CCT coil:

- **Accurate wire position** and high magnetic field precision
- **No gap** between adjacent layers or coils
- **Compact structure** for SC magnets with multiple coils
- **Coil self correction** is used to solve magnetic field crosstalk
- **Pre-stress can be applied** by wrapping fiberglass on coil layers
- **Magnetic field harmonics can be corrected** during multi-layer winding process



Direct winding CCT

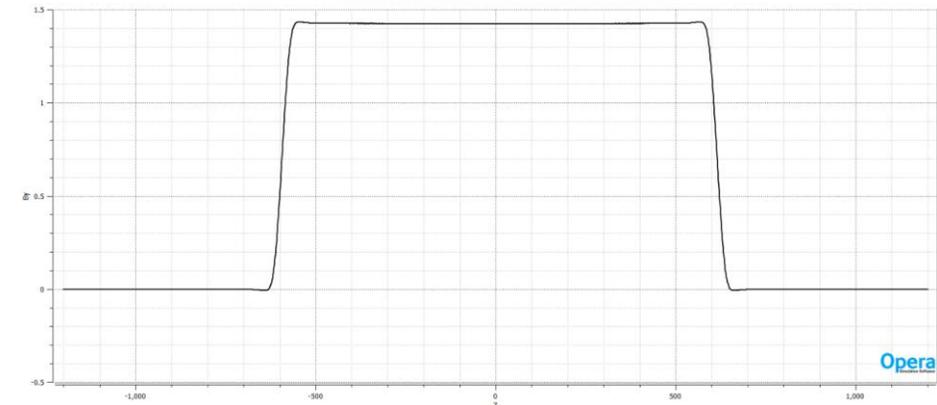
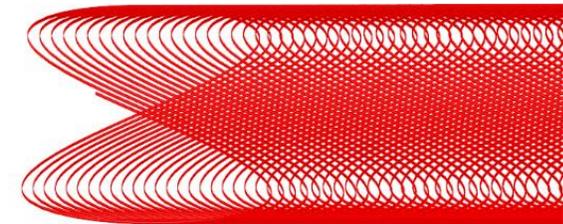


Magnetic field design of superconducting CCT quadrupoles

Q1a Direct winding CCT coil

Radius of single aperture <31mm

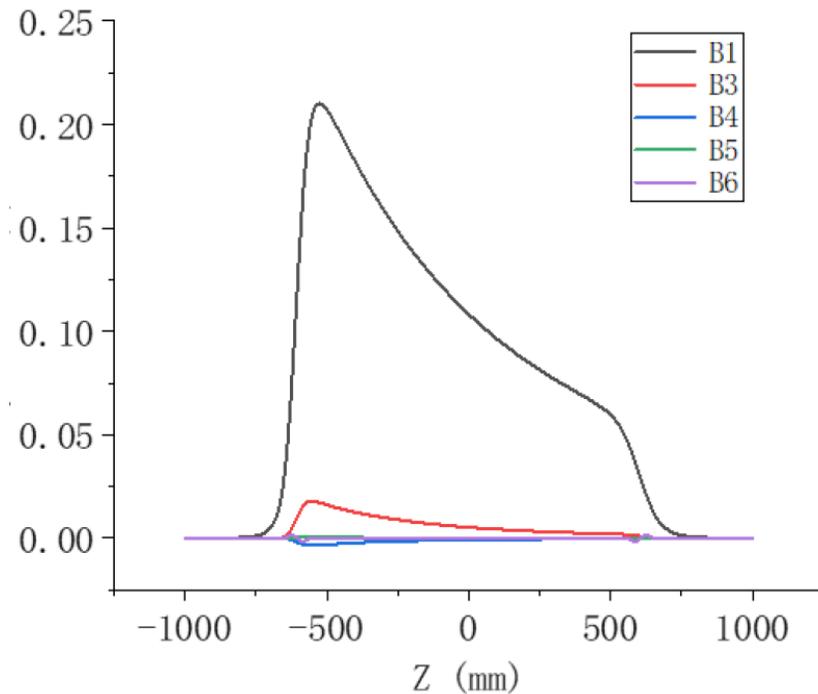
- 142.3T/m, Coil thickness 11mm
- **Baseline:** Round 0.75mm NbTi conductor, Cu:SC=1, Temperature 2K
- Canted angle: 24 deg, pitch: 2.3 mm
- **8 layers CCT quadrupole coil:** inner radius 20mm
- Excitation current: **720A**
- 3D field calculation in OPERA-3D



Magnetic field design of superconducting CCT quadrupoles

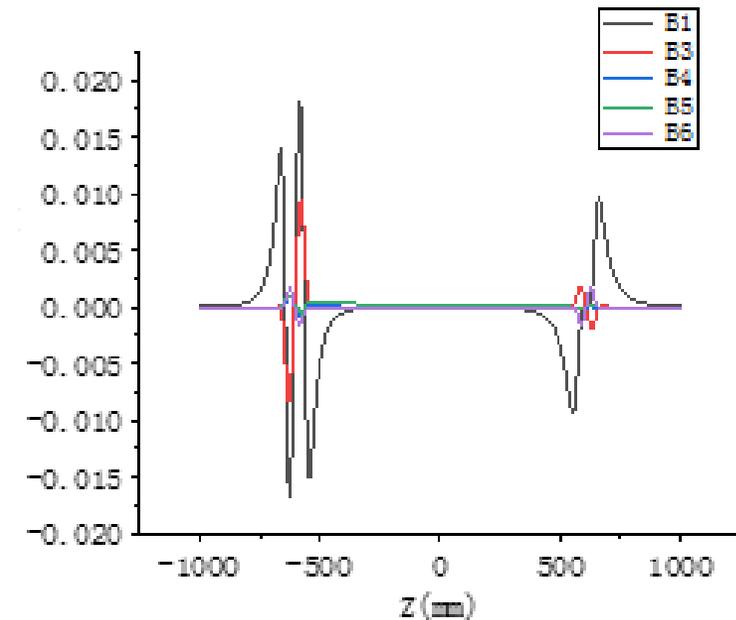
Q1a Direct winding CCT coil

- In 3D calculation, large number of conductor segments
- Coil self correction technology is used to solve magnetic field crosstalk
- After correction, local dipole field decreases to less than 300Gs (Higgs)



Before correction

Requirement: Local dipole field ≤ 300 Gs



Dipole field after correction

Magnetic field design of superconducting CCT quadrupoles

- Q1a: integrated multipole field **before coil self correction** (Higgs) $R_{ref}=7.46\text{mm}$

n	$b_n (B_n/B_2)$	$a_n (A_n/B_2)$	Required integrated field harmonics
2	10000		$B_n/B_2 \leq 3 \times 10^{-4}$
3	-65.0	-0.1	
4	10.3	0.1	
5	-1.7	-0.06	
6	0.2	0.01	
7	-0.03	<0.01	

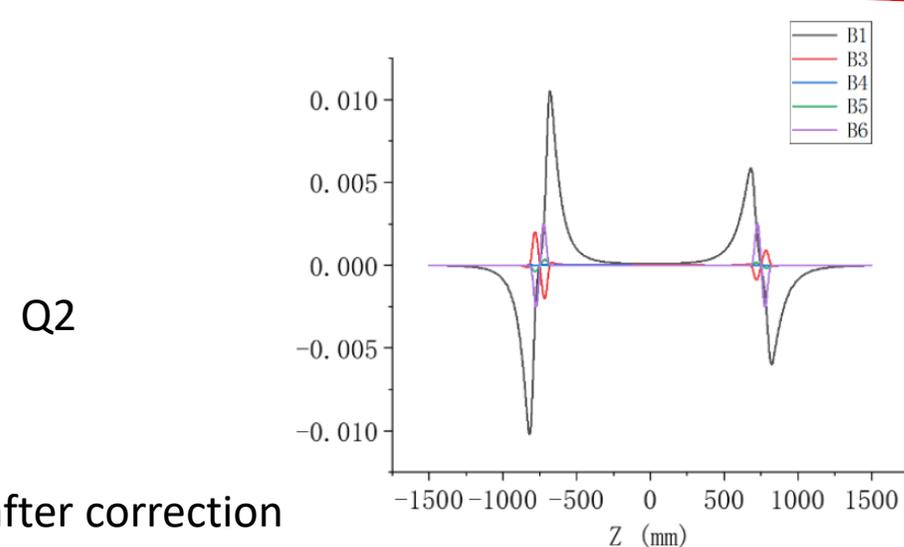
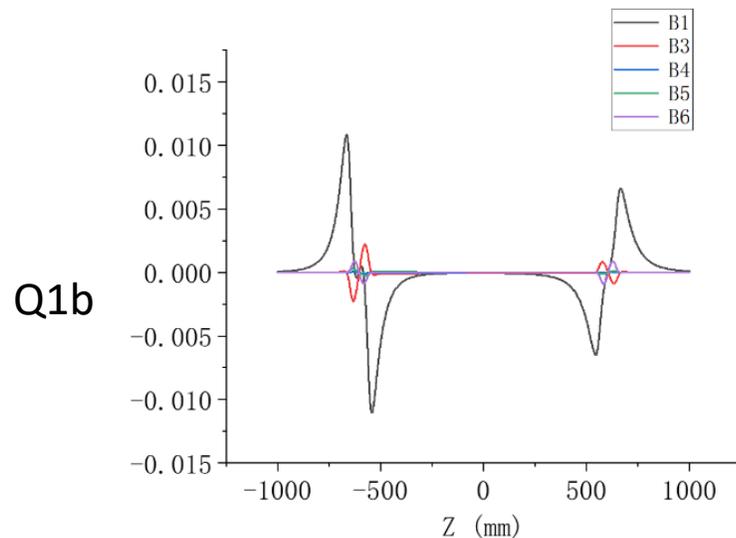
- Q1a: **After coil self correction**, integrated multipole field $< 2 \times 10^{-4}$ (Higgs)

n	$b_n (B_n/B_2)$	$a_n (A_n/B_2)$	Required integrated field harmonics
2	10000		$B_n/B_2 \leq 3 \times 10^{-4}$
3	-0.78	-0.1	
4	0.27	0.1	
5	-1.5	-0.06	
6	0.16	0.01	
7	-0.03	<0.01	

Magnetic field design of superconducting CCT quadrupoles

Q1b Q2 Direct winding CCT coil

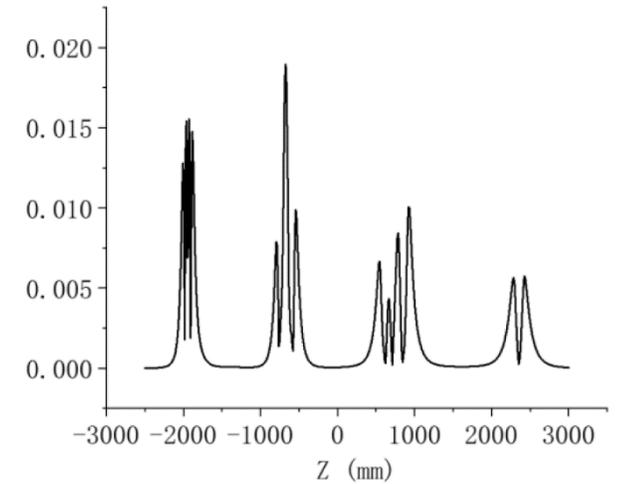
- Baseline: \varnothing 0.85mm NbTi conductor, canted angle: 24 deg (Q1b), 22 deg (Q2)
- 8 layers CCT quadrupole coil
- Coil thickness 12mm
- After correction, local dipole field decreases to less than 150Gs (Higgs)
- Calculated integrated field harmonics are smaller than 2×10^{-4}



Magnetic field design of superconducting CCT quadrupoles

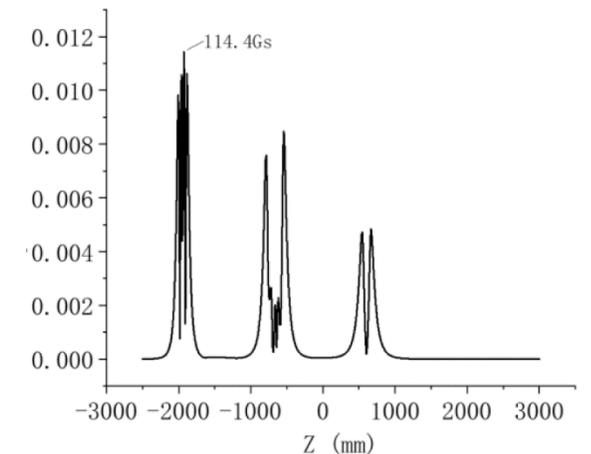
- Combined 3D magnetic field simulation of Q1a, Q1b, Q2 (Direct winding CCT)
- Local dipole field at each position <300Gs, meet the requirement

Higgs mode
Dipole field distribution



Requirement: Local dipole field ≤ 300 Gs

Z mode
Dipole field distribution



Design parameters of SC quadrupoles with CCT coil

■ Design parameters of Q1a, Q1b, Q2 with iron-free CCT coil @ Higgs

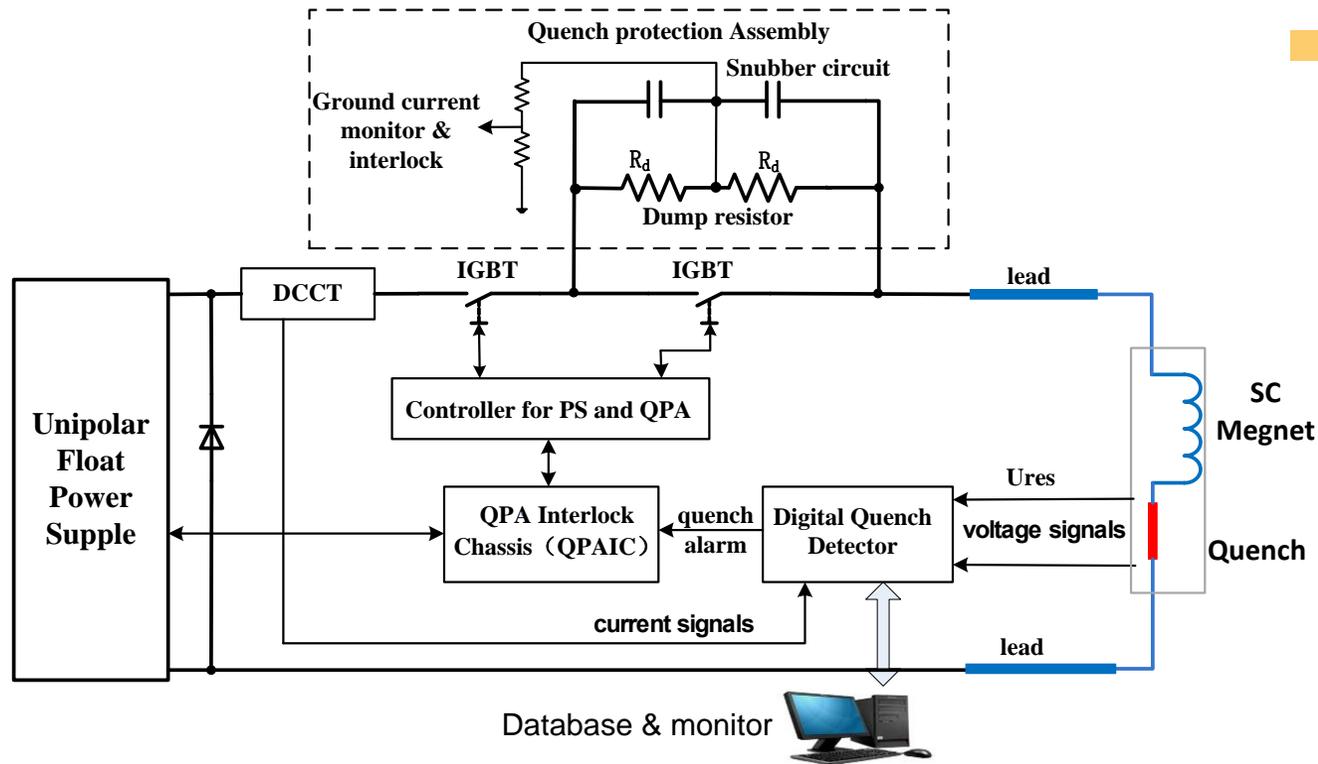
Baseline: Direct winding CCT coil

	Q1a	Q1b	Q2
Field gradient (T/m)	142.3	85.4	96.7
Magnetic length (m)	1.21	1.21	1.5
Excitation current (A)	720	640	760
Conductor diameter (NbTi, mm)	0.75	0.85	0.85
Current density (A/mm ²)	1630	1128	1340
Maximum dipole field in aperture (Gs)	193	134	107
Stored energy (KJ)	16.7	15.2	36.1
Peak field in coil (T)	4.0	3.7	4.1
Integrated field harmonics	$<2 \times 10^{-4}$		
Load line @2K	75%	63%	71%
Single aperture inner radius (mm)	19	26	31
Single aperture outer radius (mm)	30.8	39	44
Magnet mechanical length (m)	1.23	1.23	1.53
Net weight (kg)	25	32	43
Total weight of Q1a, Q1b, Q2 (kg)	100		

Quench protection and simulation

Protection Strategy:

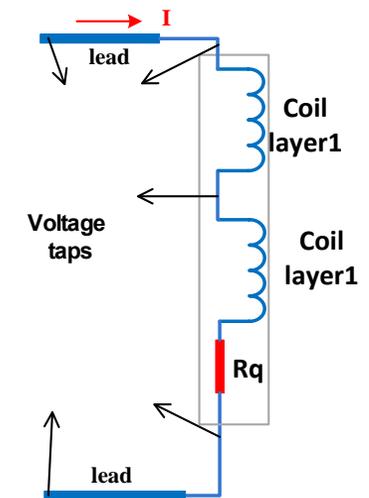
- First, Detect a quench as quickly as possible → the Quench Detector(QD)
- Then switch off the power supplies and trigger QPA (Quench Protection Assembly)
- Extract the stored energy by external dump resistors circuit



Structure of the Quench Protection System

How do we detect a quench?

- Measurement through voltage taps from coil and lead
- Resistive voltage reaches threshold U_{th} + validation delay



Quench protection and simulation

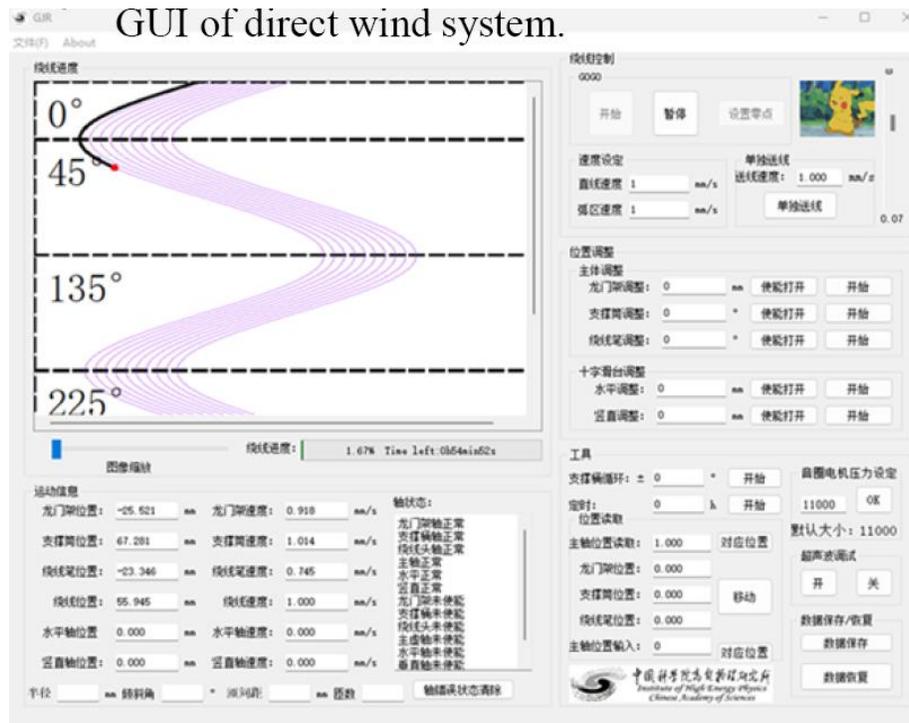
- The growth of the resistive region in a magnet is a complex process
- 1-D model: thermal links between turns and layers are not accounted for
 - 20ms total protection time delay between a quench and the dump resistor activation
 - Dump resistor 1.2Ω

Quadrupole	Conductor parameter	Current	Inductance	Stored energy	Protection time delay	Dump resistor	KIITs	Hot temperature	Maximum voltage
Q1a	diameter:0.75mm	720A	65mH	16.7KJ	20ms	1.2 Ω	23.6	271K	864V
	$S_{Cu}:S_{SC}=1$								
Q1b	diameter:0.85mm	640A	74mH	15.2KJ	20ms	1.2 Ω	18.9	139K	768V
	$S_{Cu}:S_{SC}=1.3$								
Q2	diameter:0.85mm	760A	125mH	36.1KJ	20ms	1.2 Ω	39.5	329K	912V
	$S_{Cu}:S_{SC}=1.3$								

- First quench analysis for CEPC IR SC magnets has been performed
- Results support that **an active protection system with an external energy dissipation resistor is feasible**
 - Assuming a 20ms protection time delay , the dump resistor 1.2Ω
- Simulated hot temperature $< 330K$, maximum voltage $< 1000V$

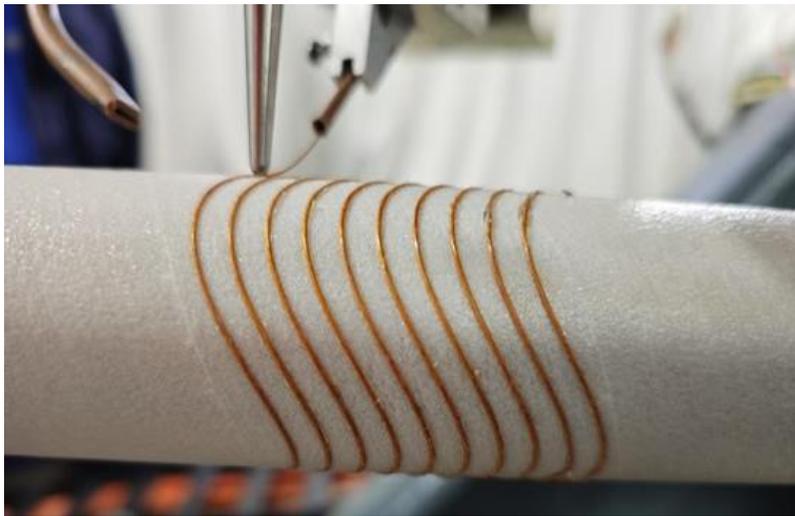
Direct winding CCT quadrupole short model status

- SC quadrupole design was reviewed in Mini-Review of CEPC MDI in June 2025
“The committee fully endorses the plan to build a prototype of a direct wind Q1a CCT quadrupole”
- Direct winding experiments of CCT coil has started
- According to the quadrupole coil design, **data file of CCT coil winding path** suitable for the winding machine has been generated
- **Control system software of winding machine** has been developed

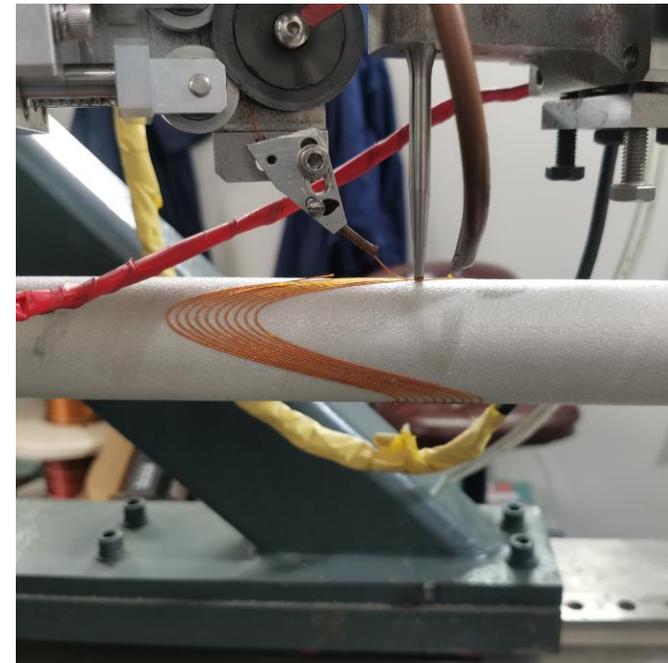


Direct winding CCT quadrupole short model status

- Direct winding experiment of CCT coil has been performed
- Use NbTi wire with 0.33mm diameter
- Direct winding test:
 - Pure CCT quadrupole
 - CCT quadrupole coil with self correction
- The shape of the test CCT winding looks good



Pure CCT quadrupole

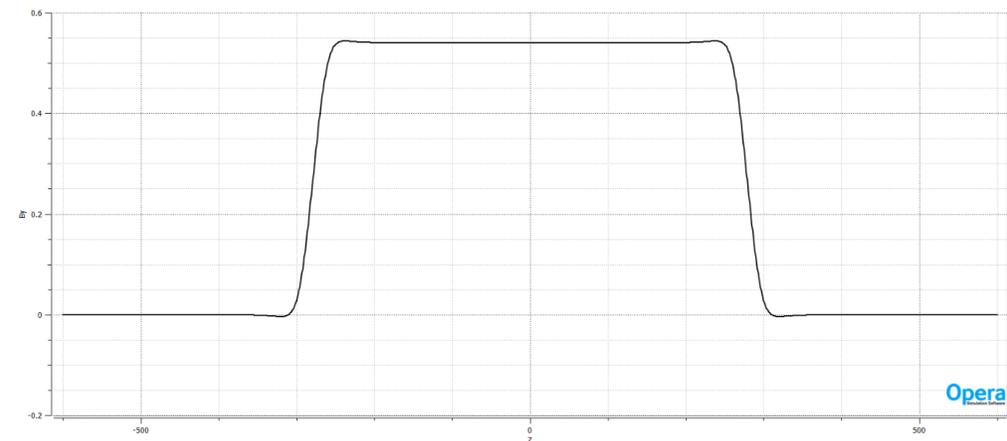
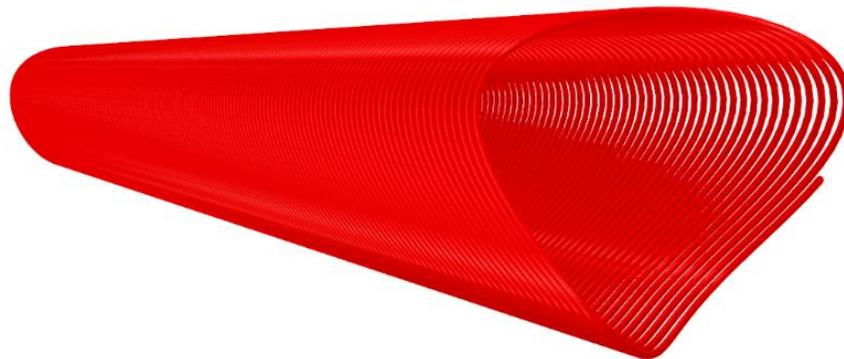


CCT quadrupole coil with self correction

Direct winding CCT quadrupole short model status

- In EDR, the 1st step: **develop a single aperture Direct winding CCT quadrupole model**
the 2nd step: **double aperture CCT quadrupole model with self correction**
- **Main purpose:** research and master key technologies of Direct winding CCT quadrupole
Coil aperture: \varnothing 40mm, Field gradient: >40 T/m @4.2K, mechanical length: 0.6m
- Not enough fund; use existing NbTi wire in the laboratory
Diameter 1mm or 0.6mm (not CEPC specification)
- A total of 6 layers Direct winding CCT coil
- Canted angle: 30 deg, pitch: 3.3 mm

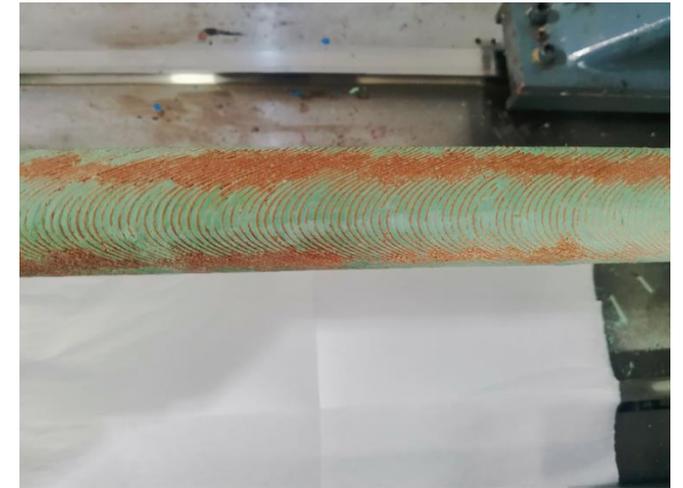
Single aperture
quadrupole



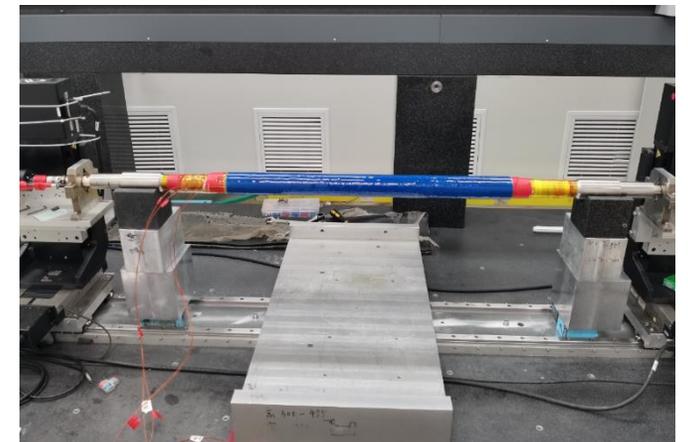
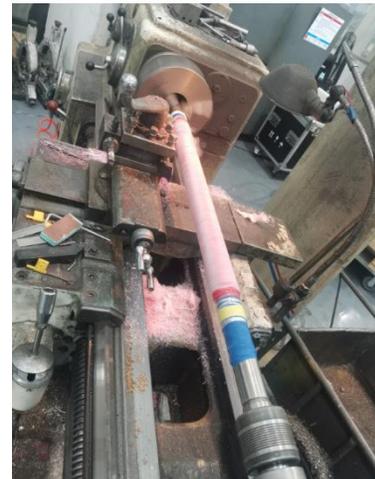
Direct winding CCT quadrupole short model status

- Main fabrication process of one double-layer CCT using direct winding technology:

Wrap substrate → coil winding → apply epoxy → apply pre-stress → surface machining
→ room temperature magnetic field measurement



4 layers CCT coils
have been wound



Direct winding CCT quadrupole short model status

- The single aperture direct winding CCT quadrupole model will be tested at 4.2K, using cryogenic vertical test facility at IHEP
- The **update of rotation coil and Hall probe measurement system** located in the middle of the Dewar is in progress
- To measure the variation of field harmonics along longitudinal direction, **short PCB rotating coil** will be fabricated
- Vertical test will be performed in the first half of 2026



Conclusion

- For CEPC superconducting quadrupole magnets, it is challenging to meet stringent design requirements
 - 1) High field gradient 142.3T/m
 - 2) Limited radial space ~11mm
 - 3) Field crosstalk of two apertures
- With updated design requirement, **Iron free coil** is selected
- **Direct winding CCT quadrupole coil option is the baseline design**
- Basic magnet design of CCT quadrupoles is finished and reviewed
- Direct winding experiment of CCT coil has been performed
- Study on key technologies of **Direct winding CCT 0.6m quadrupole model** in progress
- The first single aperture quadrupole short model will be cold tested at 4.2K

The logo for the Circular Electron-Positron Collider (CEPC), featuring the letters 'CEPC' in a stylized font with a blue and orange color scheme.

Thanks for your attention!



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