



# CEPC Superconducting Quadrupole Magnet

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On behalf of CEPC IR SC magnet system



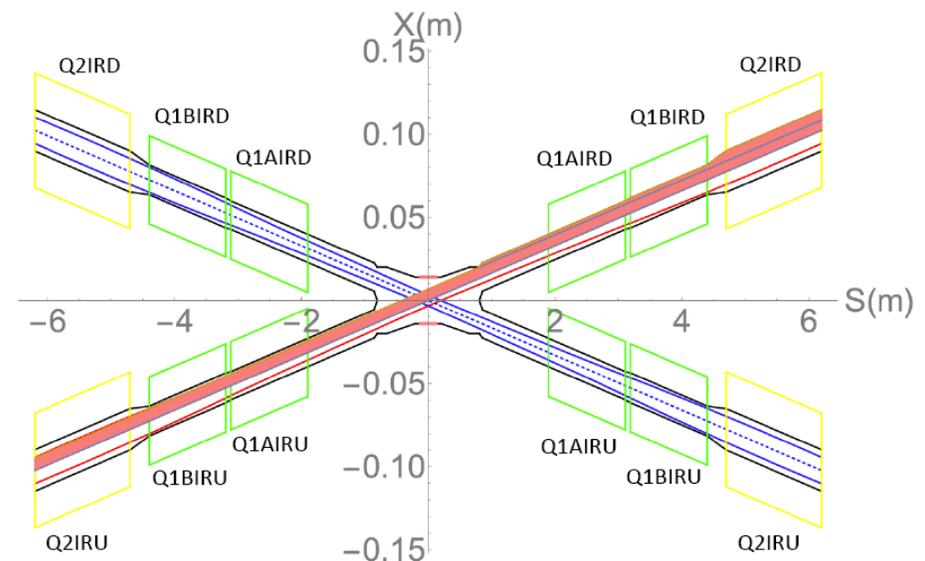
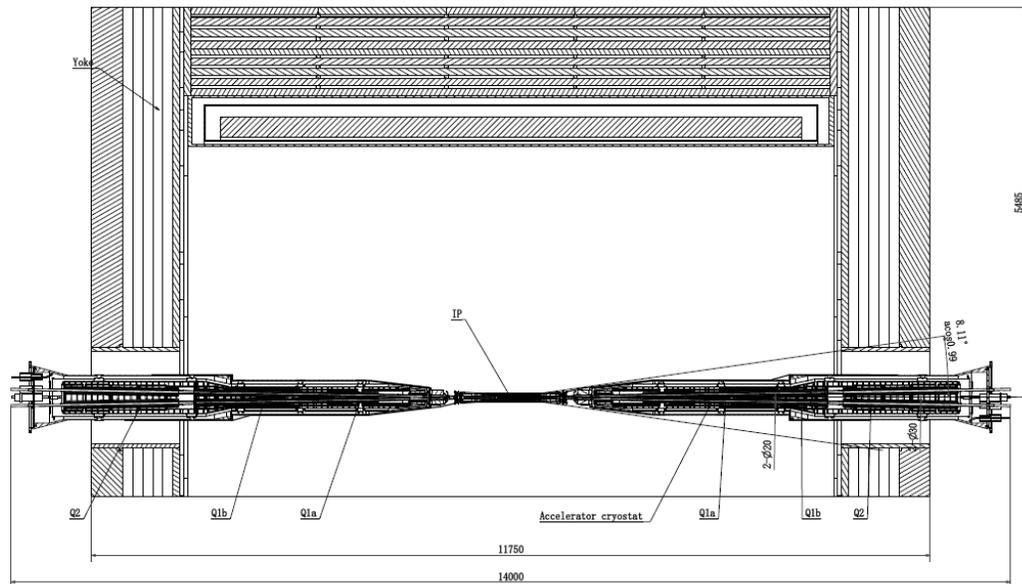
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# Introduction

- In CEPC interaction region, to final focus the beam for high luminosity, compact **high gradient double aperture quadrupole magnets** (Q1a, Q1b, Q2) are required on both sides of IP points
- To cancel the effect of the detector solenoid field on the beam, anti-solenoids before Quadrupoles and outside Quadrupoles are needed
- There are a total of 4 combined-function SC magnets in CEPC interaction region
- **One combined-function magnet includes: quadrupole Q1a, Q1b, Q2, and Anti-solenoid**



# Introduction

- EDR requirements of CEPC Final Focus quadrupoles are based on  $L^*$  of 1.9 m, beam crossing angle of 33 mrad between two apertures
- Design requirement of CEPC Interaction Region quadrupole magnets:
  - 1) Basic requirement of CEPC Interaction Region quadrupole magnets

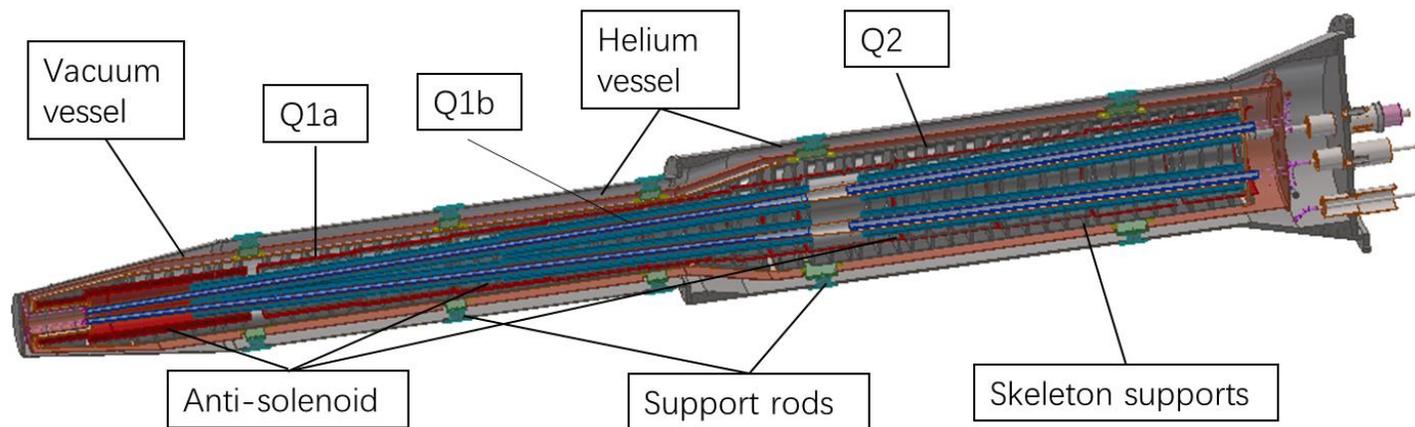
Magnet	Field gradient (T/m)				Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
	tt	Higs	W	Z			
Q1a	140.7	<b>142.3</b>	94.9	109.7	1.21	14.92	<b>62.71</b> 
Q1b	58.9	85.4	57.0	64.8	1.21	18.17	105.28
Q2	51.3	96.7	64.5	0.0087	1.5	24.48	155.11

Field crosstalk will introduce Dipole field, sextupole, etc

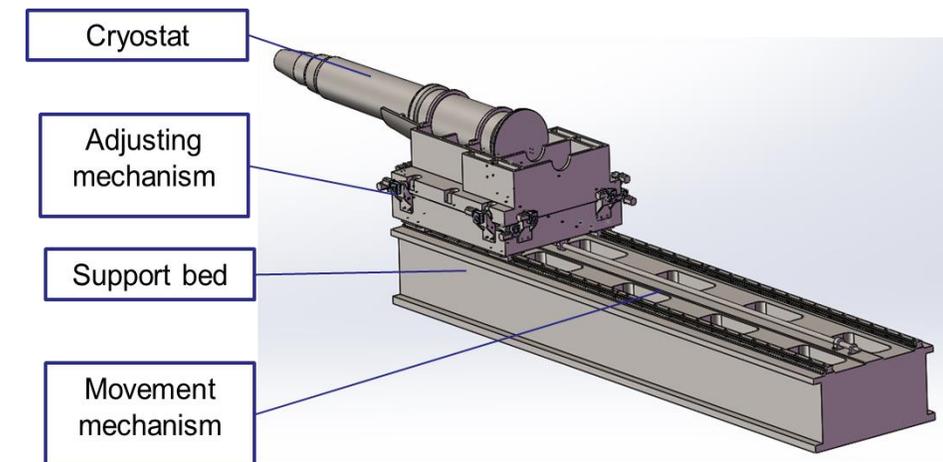
- 2) Ratio of multipole field to quadrupole field  $\leq 3 \times 10^{-4}$
- 3) Integral dipole field at the center of quadrupole aperture is zero  
 Local dipole field at each longitudinal position  $\leq 300$  Gs

# Introduction

- Quadrupole magnets and anti-solenoids on one side of IP are in a same cryostat, placed on a cantilever support system
- Compact magnet structure should be used to reduce weight and deformation
- In TDR: Different options have been studied
  - Iron free and with iron, Cos2 $\theta$  coil, CCT coil, Serpentine coil
  - Requirement on **local dipole field** in each aperture  $\leq 30$  Gs (challenging)
- In EDR, requirement on **local dipole field** in each aperture is relaxed to  $\leq 300$  Gs
- **Iron-free structure is selected for CEPC IR SC magnets**



From X.Z Zhang and H.J Wang



# CEPC superconducting quadrupole design status in EDR

## Design and optimization of IR SC magnets is on going

The design 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( $R_{in}$  10mm), helium vessel, **quadrupole coil inner radius: 20 mm**

### It is challenging to meet stringent design requirements for Q1a

1) High field gradient: 142.3T/m

2) Limited magnet radial space

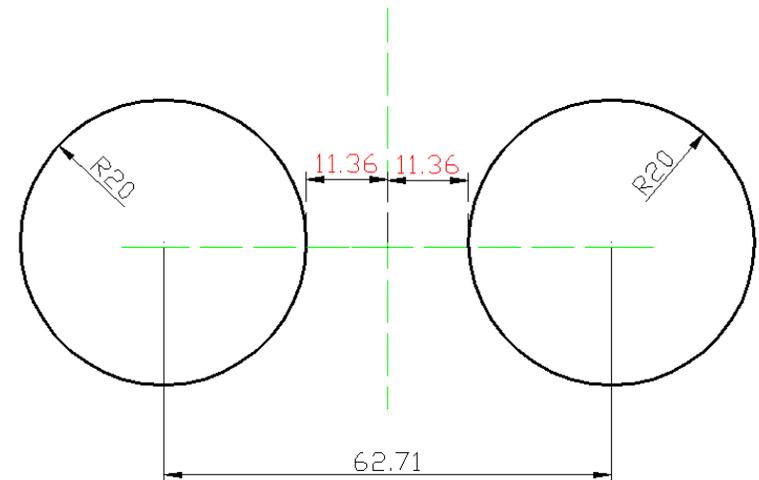
Limited radial space in the magnet middle:

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

3) Magnetic field crosstalk between two apertures

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

**Local dipole field:  $\leq 300$  Gs**

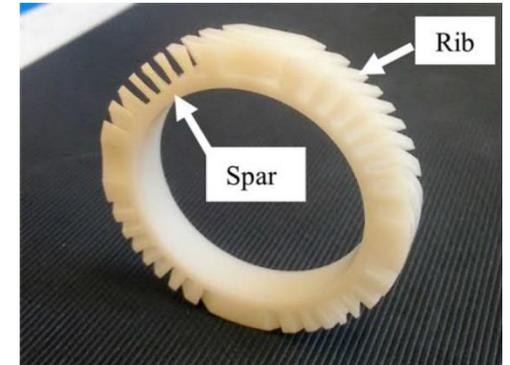
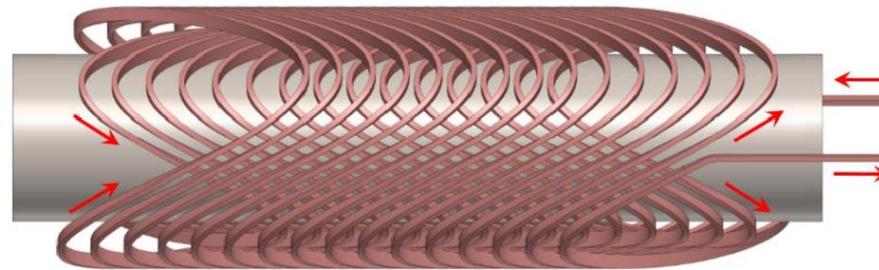


# CCT quadrupole

- The CCT (Canted Cosine Theta) coil is based on a pair of conductors wound and powered such that their **transverse field sum up** and **solenoid fields cancel**
- **Usually, the conductor is wound on a pre-cut groove** in a supporting cylinder
- The theoretical position of each conductor is given by equations
- **Self field correction**: Change each turn conductor path, multipole fields can be added

CCT quadrupole (n=2)  
Ideal conductor path

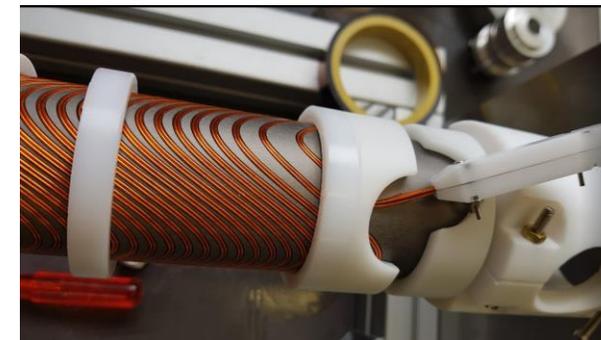
$$\begin{cases} x = R\cos\theta \\ y = R\sin\theta \\ z = \frac{R\sin(n\theta)}{n\tan\alpha} + \frac{\omega\theta x}{2\pi} \end{cases}$$



**Integrated field harmonics=0**

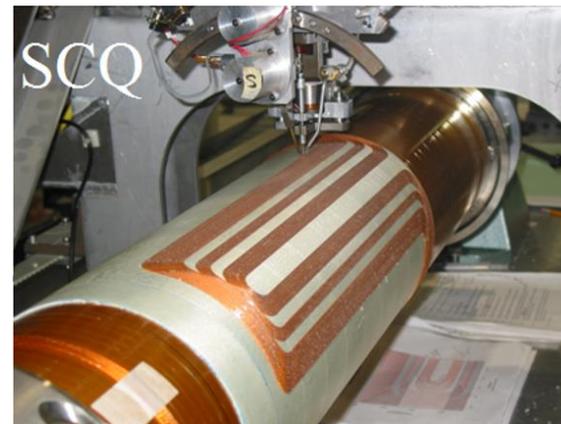
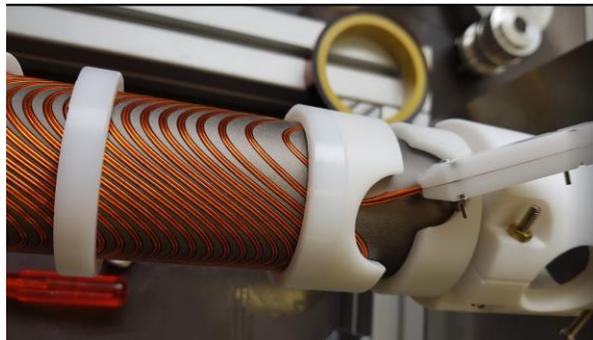
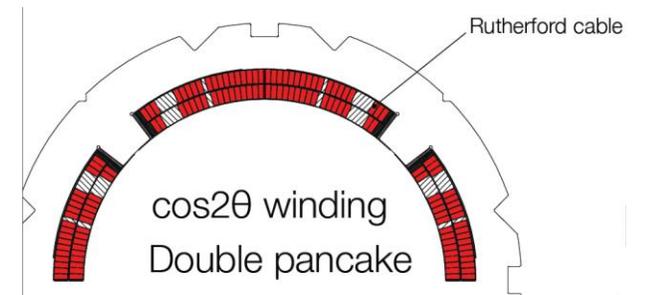
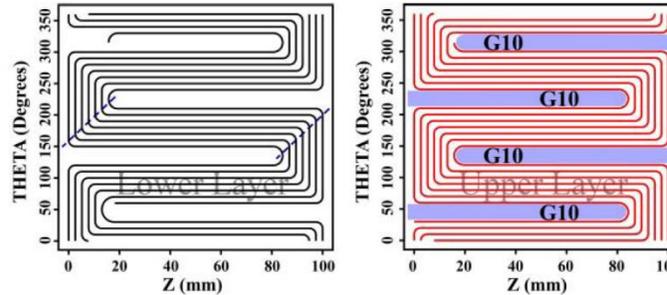
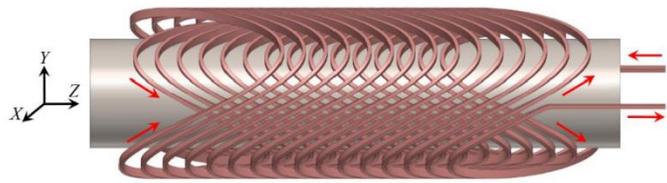
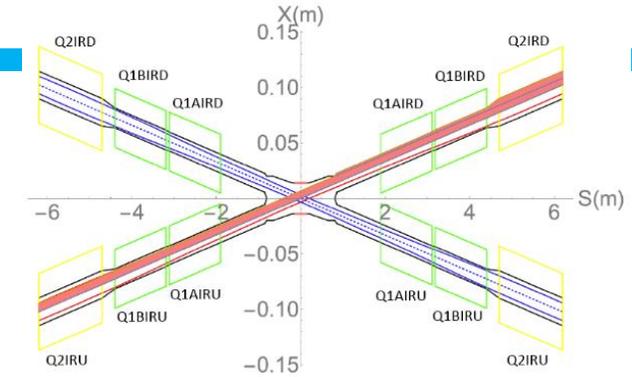
Correction on coil path  
n=1 dipole; n=3 sextupole

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



# CCT quadrupole

- EDR requirement on local dipole field is relaxed to  $\leq 300\text{Gs}$
- Compact magnet structure, reduce weight and deformation
- Field crosstalk varies with longitudinal position
- Three kinds of quadrupole coil structures are studied
- **CCT quadrupole coil is the selected option** (Iron-free, coil self correction)



- 1) CCT coil with conductors in groove
- 2) Direct winding CCT coil

CCT coil

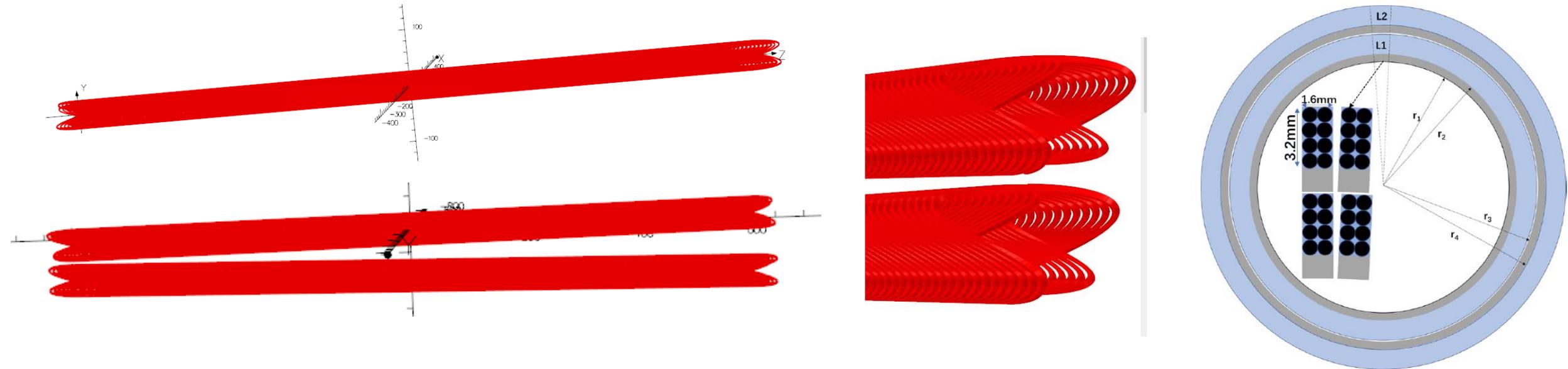
CCT generate magnetic field that varies longitudinally

Direct winding Serpentine coil

Cos2θ coil

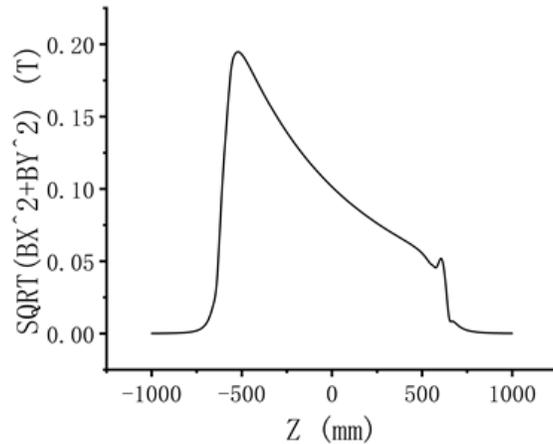
# CCT coil with conductors in groove design status

- Magnetic design of Q1a, Q1b, Q2 with CCT coil is performed
- **0.7mm round wire for Q1a**, HTS or LTS conductor (Bi-2212, Nb<sub>3</sub>Sn, NbTi, etc)
- Two layers CCT quadrupole coil. **The inner radius of the skeleton is 20mm**
- 8 wires in a groove
- Q1a Conductor canted angle: **17 deg**, pitch: 7.2 mm
- Excitation current: **780 A @ 4.2 K** (2K is also under study)
- Field gradient is calculated using theoretical formula, and OPERA-3D



# CCT coil with conductors in groove design status

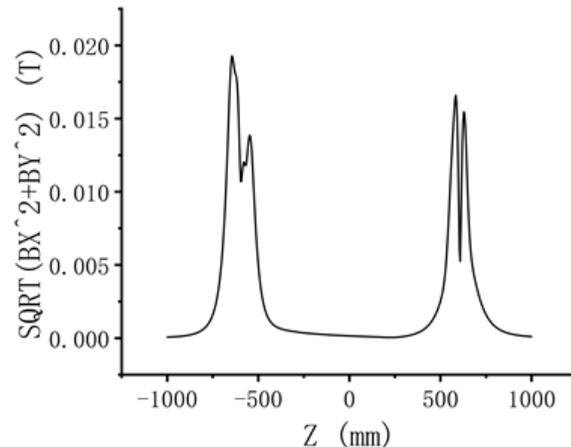
- Q1a: Dipole and multipole field **before coil self correction** (Higgs)  $R_{ref}=7.46\text{mm}$



n	$b_n$ (Bn/B2)	$a_n$ (An/B2)	Required integrated field harmonics
2	10000		Bn/B2 $\leq 3 \times 10^{-4}$
3	-61.0	-0.8	
4	10.3	0.2	
5	-1.6	-0.04	
6	0.2	0.01	
7	-0.03	<0.01	

- Q1a: **After coil self correction**, dipole <300Gs, multipole field < $2 \times 10^{-4}$  (Higgs)

Requirement: Local dipole field  $\leq 300$  Gs

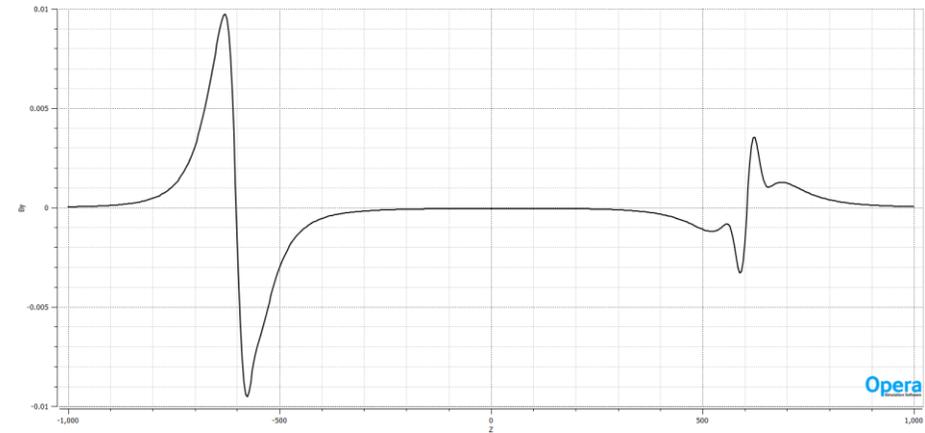
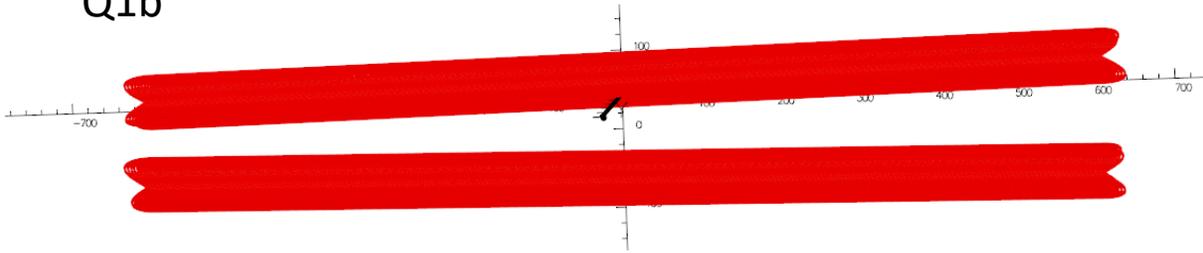


n	$b_n$ (Bn/B2)	$a_n$ (An/B2)	Required integrated field harmonics
2	10000		Bn/B2 $\leq 3 \times 10^{-4}$
3	0.17	-0.80	
4	-0.27	0.13	
5	-1.4	-0.06	
6	0.16	0.01	
7	-0.03	<0.01	

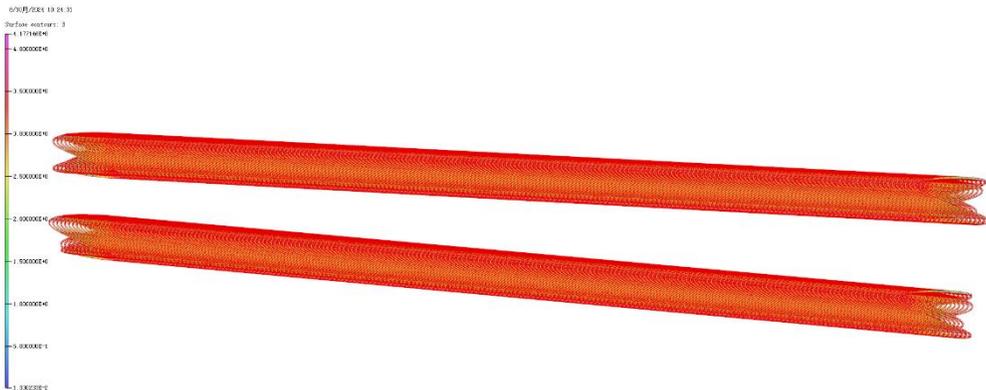
# CCT coil with conductors in groove design status

- Q1b, Q2 quadrupoles: Two layers coil, 8 wires in a groove, 0.8 mm diameter
- Q1b: Canted angle: 30 deg pitch 4.2 mm
- Q2: Canted angle: 17 deg pitch 7.2 mm
- Coil self correction technology is used to solve magnetic field crosstalk

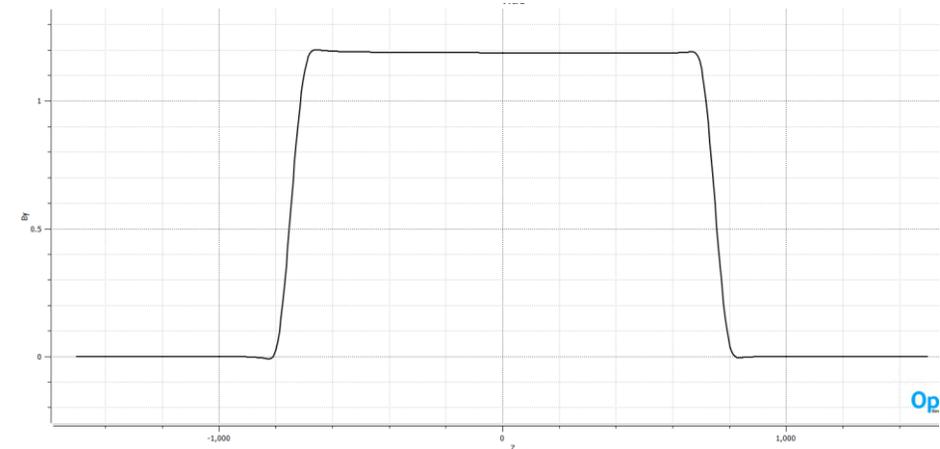
Q1b



Q2



Opera



Op

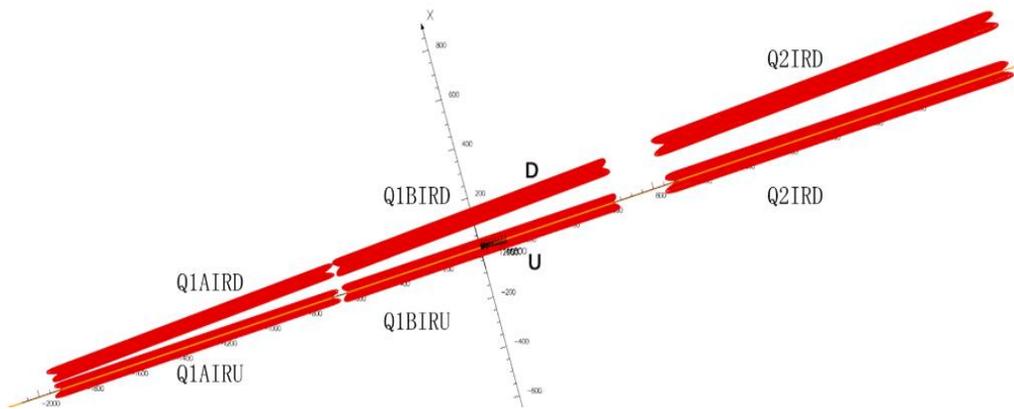
# CCT coil with conductors in groove design status

- Q1b Q2 Calculated integrated field harmonics meet the requirements (Higgs mode)

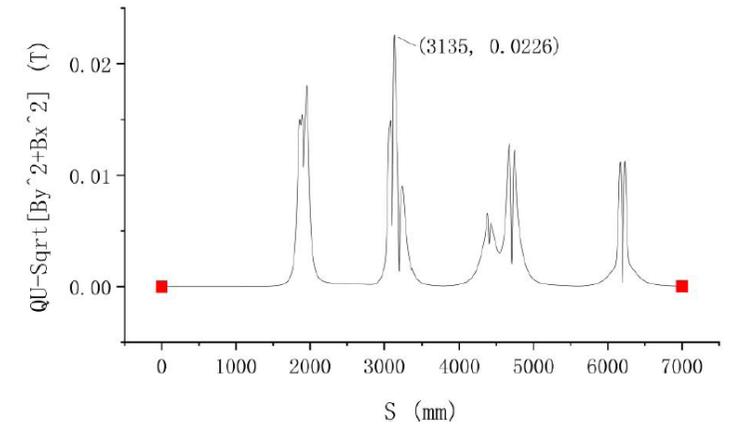
	$B_n/B_2$ (unit, $1 \times 10^{-4}$ )		Requirement
	Q1b	Q2	
2	10000	10000	$B_n/B_2 \leq 3 \times 10^{-4}$
3	-0.22	-1.2	
4	-0.05	0.13	
5	0.26	0.1	
6	0.01	0.03	
7	0.01	0.01	

# CCT coil with conductors in groove design status

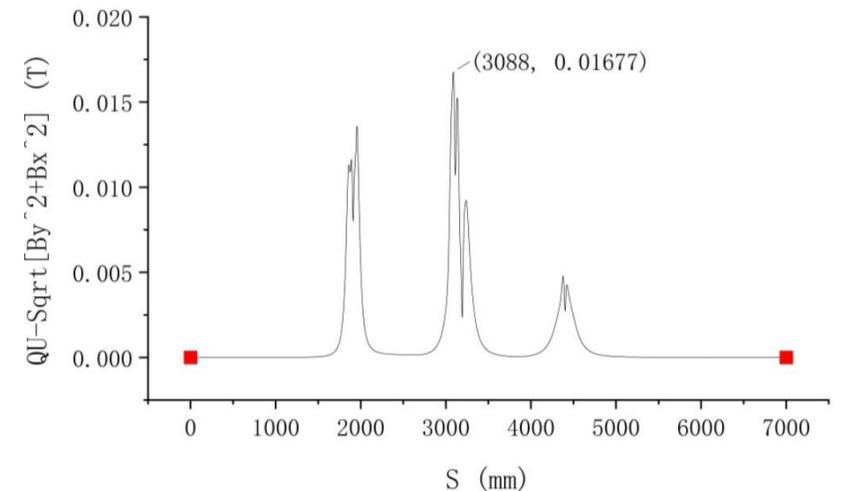
- Combined 3D magnetic field simulation of Q1a, Q1b, Q2
- Many optimizations have been made
- **local dipole field <300Gs, meet the requirement**



Higgs mode  
Dipole field distribution



Z mode  
Dipole field distribution

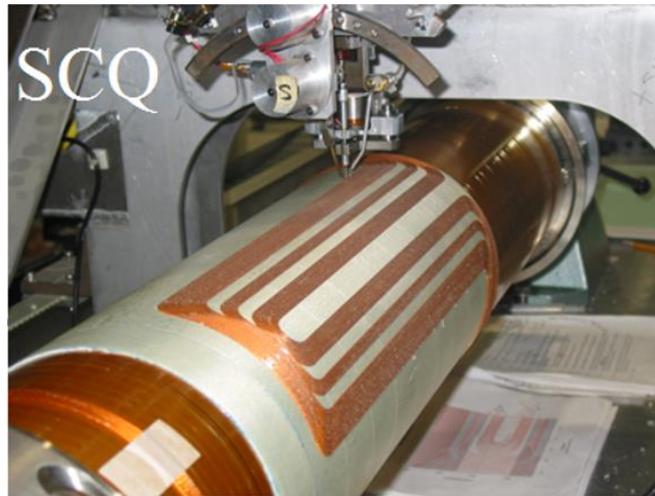


Requirement: Local dipole field  $\leq 300$  Gs

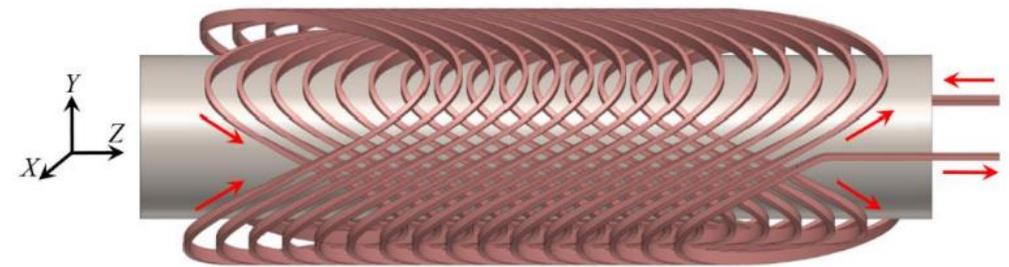
# Direct winding CCT coil

## Direct winding CCT coil

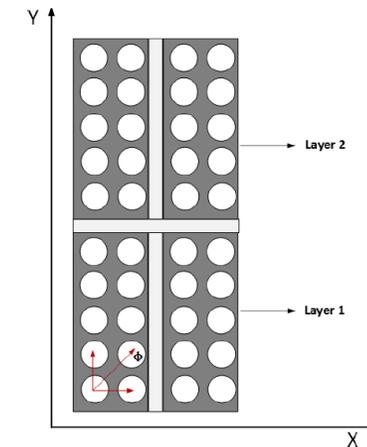
- Combine **Direct winding technology** and **CCT coils**, a new design is obtained
- Divide the CCT coil into many layers
- **Wind CCT coil layer by layer** using **Direct winding machine** (On surface of cylinder)
- Adjacent layers of coils are separated by epoxy and insulation material
- Winding machine directly winds the coil based on **theoretical position of each conductor**



Direct winding technology



CCT Coil



# Direct winding CCT coil

- Traditional CCT coil

Conductors in groove, each layer requires a skeleton

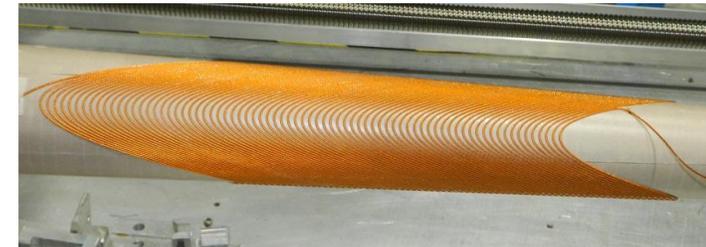
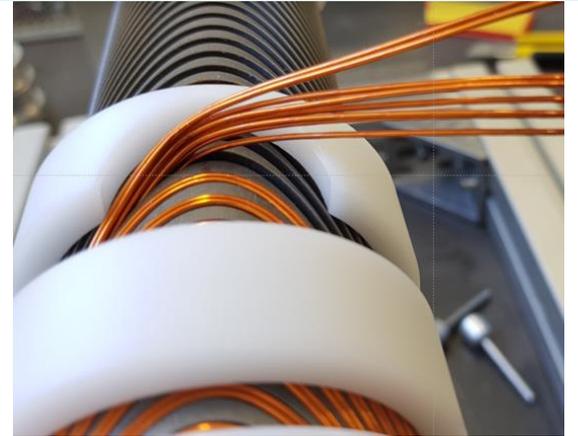
- Besides quadrupole coil, multiple sets of corrector coils are needed in CEPC IR

- **Direct winding CCT coil is preferred**

## 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**  
(field measurement at room temperature )

FCC-ee



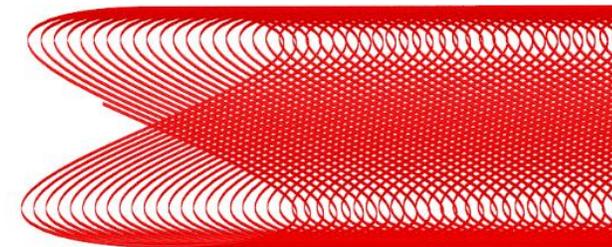
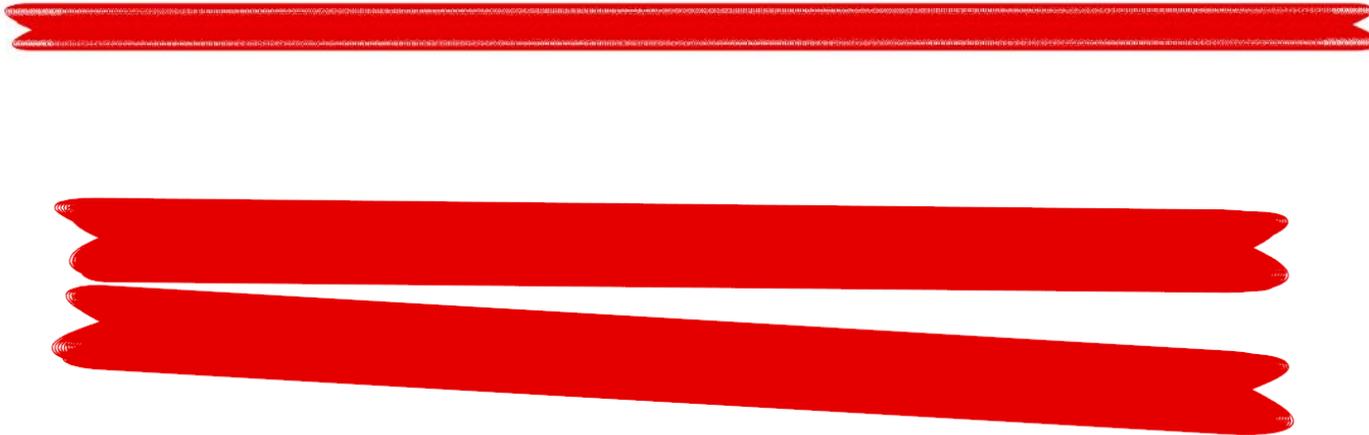
BNL

# Direct winding CCT quadrupole design status

## Q1a Direct winding CCT coil

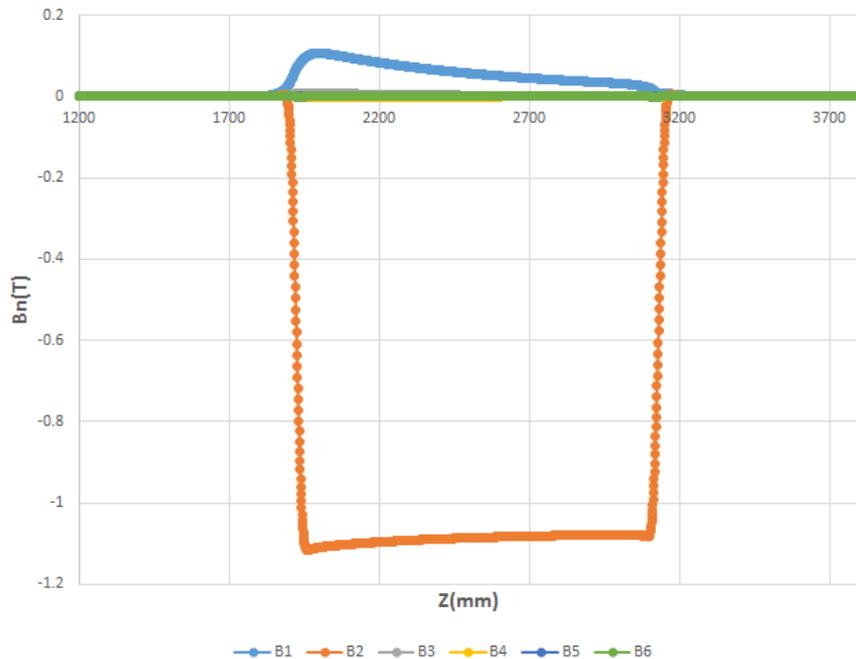
Radius of single aperture <31mm

- Preliminary design
- Round 0.7mm conductor, canted angle: 24 deg
- **8 layers CCT quadrupole coil**. The inner radius of the coil is 20mm
- Excitation current: **730A @4.2K** (2K is also under study)
- 3D calculation in OPERA-3D

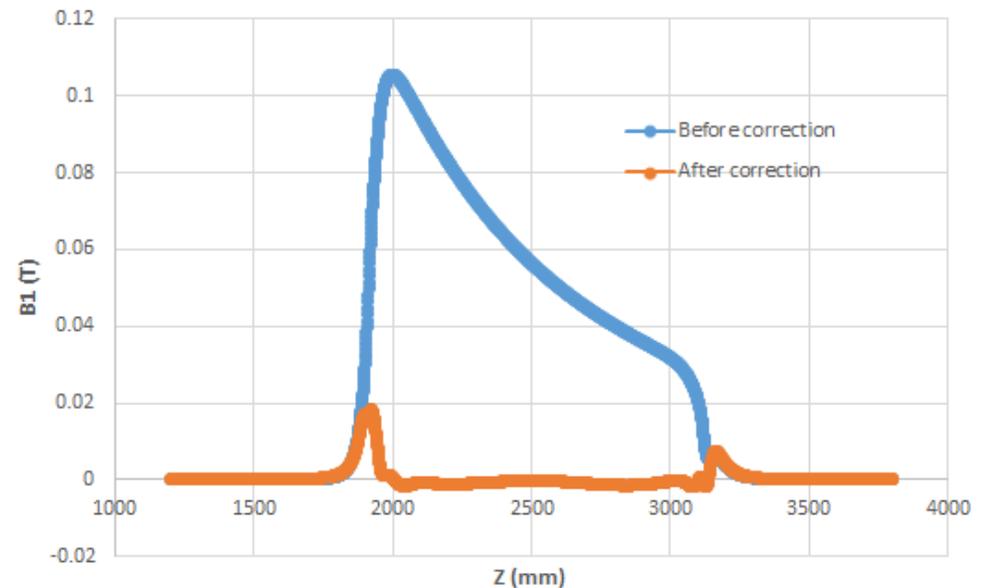


# Direct winding CCT quadrupole design status

- 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

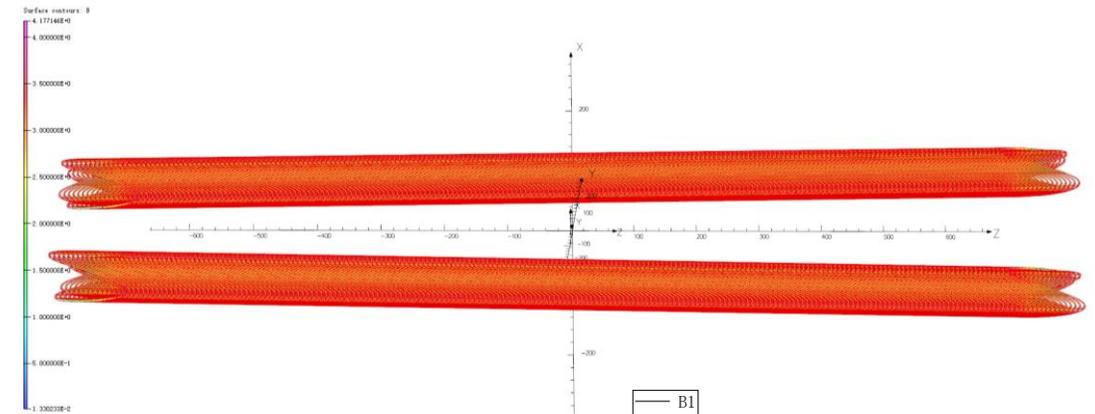


Dipole field before and after correction

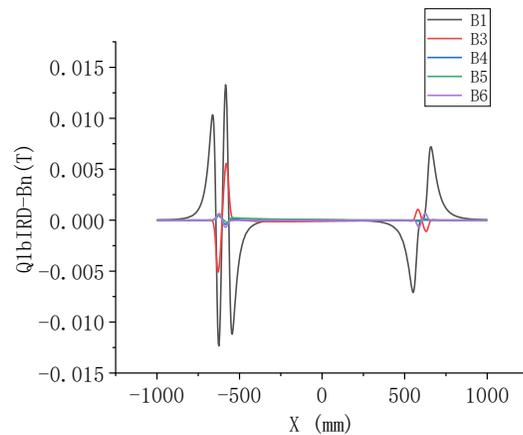
# Direct winding CCT quadrupole design status

## Q1b Q2 Direct winding CCT coil

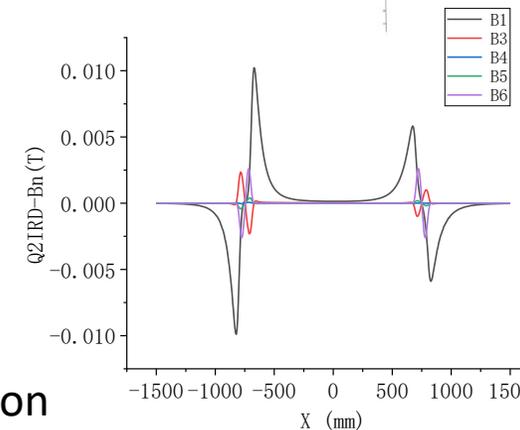
- Round 0.8mm conductor, canted angle: 24 deg
- 8 layers CCT quadrupole coil.
- After correction, local dipole field decreases to less than 150Gs (Higgs)
- Calculated integrated field harmonics are smaller than  $2 \times 10^{-4}$



Q1b



Q2



Multipole field after correction

# Direct winding CCT quadrupole design status

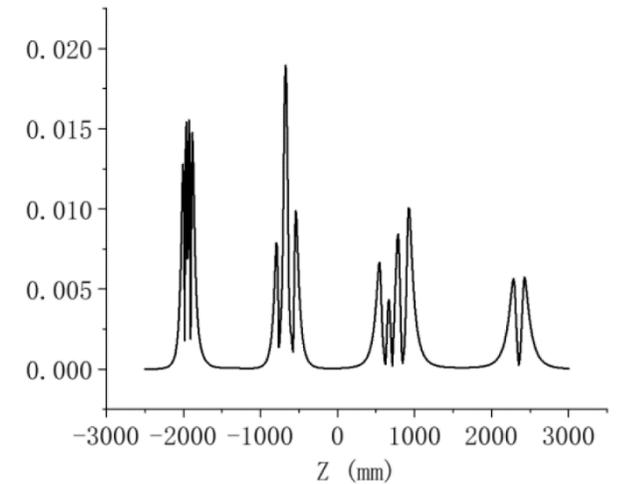
- Q1a, Q1b, Q2 Calculated integrated field harmonics meet the requirements (Higgs mode)

	$B_n/B_2$ (unit, $1 \times 10^{-4}$ )			Requirement
	Q1a	Q1b	Q2	
2	10000	10000	10000	$B_n/B_2 \leq 3 \times 10^{-4}$
3	-0.78	-0.58	-0.16	
4	0.08	0.17	0.08	
5	1.4	0.27	0.10	
6	0.02	0.03	0.01	
7	< 0.01	< 0.01	< 0.01	

# Direct winding CCT quadrupole design status

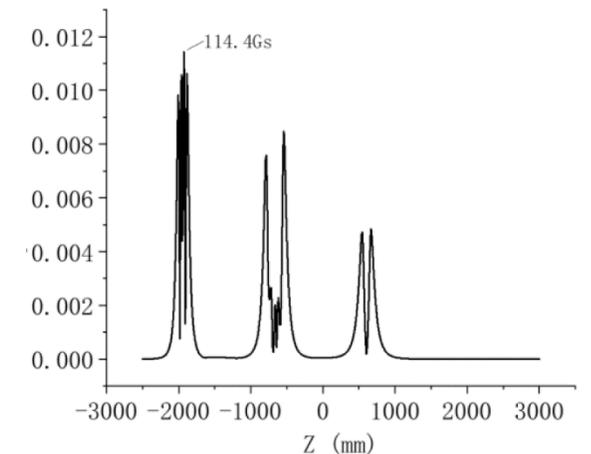
- Combined 3D magnetic field simulation of Q1a, Q1b, Q2 (Direct winding CCT)
- Many optimizations to reduce the field crosstalk
- Local dipole field at each position <300Gs, meet the requirement

Higgs mode  
Dipole field distribution



Requirement: Local dipole field  $\leq 300$  Gs

Z mode  
Dipole field distribution



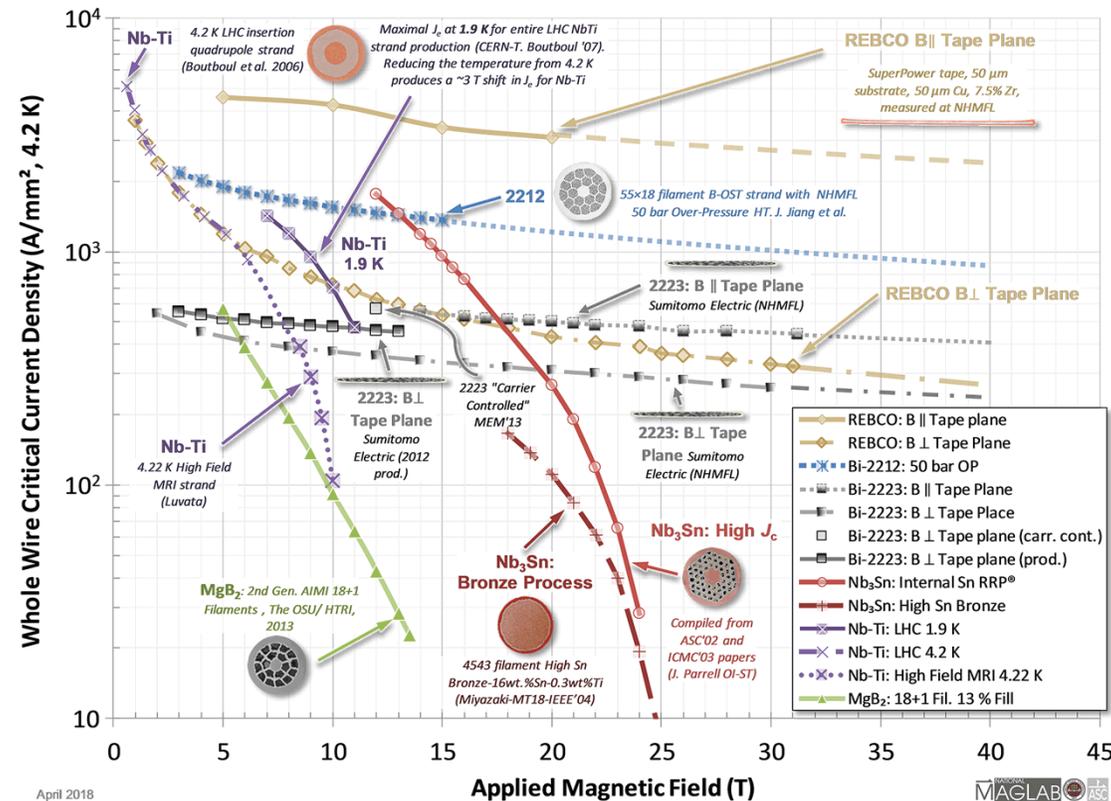
# Design parameters of SC quadrupoles with CCT coil

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

	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)	780 (Traditional) 730 (Direct winding)	640	760
Conductor diameter (HTS or LTS, mm)	0.7	0.8	0.8
<b>Current density</b> (A/mm <sup>2</sup> )	<b>2030 / 1900</b>	1270	1510
Maximum dipole field in aperture (Gs)	226	124	127
Stored energy (KJ)	16.7	15.2	36.1
Peak field in coil (T)	4.3	3.8	4.2
Integrated field harmonics	<math>2 \times 10^{-4}</math>		
(Single aperture) Coil inner radius (mm)	20	26	31
(Single aperture) Coil outer radius (mm)	30.5	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		
For comparison, old net weight with iron option (kg)	Q1a: 93, Q1b:124, Q2: 235 Total weight of Q1a, Q1b, Q2: 452		

# Superconductor Critical current density VS magnetic field

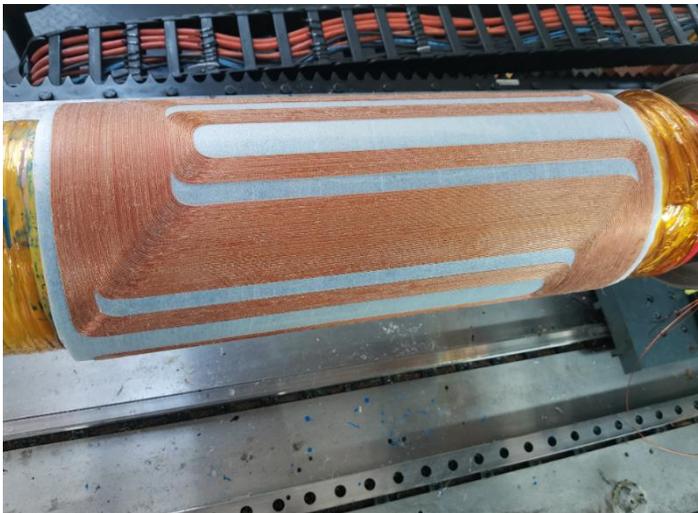
- One disadvantage of CCT coil: **Low magnetic efficiency**
- To meet high field gradient, superconductor with high current carrying performance is required ( $>2000\text{A}/\text{mm}^2$  around 4T) **will discuss and study with superconductor company**
- Working temperature for CEPC IR quadrupole: 4.2K and 2K both considered
- Temperature 2K is under study, helps to get more robust and stable design of quadrupole



From USPAS  
2018 and 2022

# Can maximum field in Q1a coil reaches 4.3 T ?

- In 3D calculation, maximum field in Q1a coil reaches 4.3 T @ 142.3T/m
- Can it be realized using Direct winding CCT quadrupole?
- BEPCII-U SC Quadrupole (Direct winding Serpentine)
  - 3.6 T in coil @ 530A (2.8GeV)
  - 4.3 T in coil @ 630A
  - Max stable current 630A in Cryogenic test



- **Estimation:** CEPC Q1a can reach the design field gradient

# Next step plan

## Next step plan

2025

- Further iteration and optimization of SC quadrupoles
- Study the feasibility of superconductor with high current carrying performance
- Perform Direct winding experiments of CCT coil with self correction
- Detailed magnetic field analysis, mechanical and quench analysis of each magnet
- Summary of magnet design, calculation results, Preliminary cost estimation

2026

- Research and determine magnet manufacturing technology route
- Magnet engineering design
- Study on Key technologies of CCT type short model quadrupole
- Cost evaluation of SC quadrupoles

2027

- Draft and revise Engineering design report of SC quadrupole magnets

# Conclusion

- With updated design requirement, **Iron free CCT quadrupole coil** is selected in EDR SC quadrupoles design
- Two CCT options are used:
  - Direct winding CCT coil, and CCT coil with conductors in groove
- **Preliminary design of CCT quadrupole coil is obtained**
- **In calculation, magnetic design requirements can be met at four modes**
- Detailed magnet design optimization, mechanical and quench analysis, and engineering design will be performed
- Winding experiment and study on key technologies on **Direct winding CCT quadrupole coil with self correction** are planned

**Thanks for your attention!**