CEPC Collider and Booster Magnets

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Outline

- CEPC collider magnets (F. Chen, M. Yang, X. Sun)
  - Overview
  - Design of the dual aperture dipole
  - Design of the dual aperture quadrupole
  - Design of the sextupole
  - Cost Estimation
- CEPC booster magnets (W. Kang)
  - Introduction
  - Dipole magnets
  - Quadrupole magnets
  - Sextupole magnets
  - Correcting magnets

CEPC Collider Magnets Overview

- Over 80% of collider ring is covered by conventional magnet.

<table>
<tr><th></th><th>Dipole</th><th>Quad.</th><th>Sext.</th><th>Corrector</th><th>Total</th></tr>
<tr><td>Dual aperture</td><td>2384</td><td>2392</td><td>-</td><td>-</td><td rowspan="2">13742</td></tr>
<tr><td>Single aperture</td><td>80*2+2</td><td>480*2+172</td><td>932*2</td><td>2904*2</td></tr>
<tr><td>Total length [km]</td><td>71.5</td><td>5.9</td><td>1.0</td><td>2.5</td><td>80.8</td></tr>
<tr><td>Power [MW]</td><td>7.0</td><td>20.2</td><td>4.6</td><td>2.2</td><td>34</td></tr>
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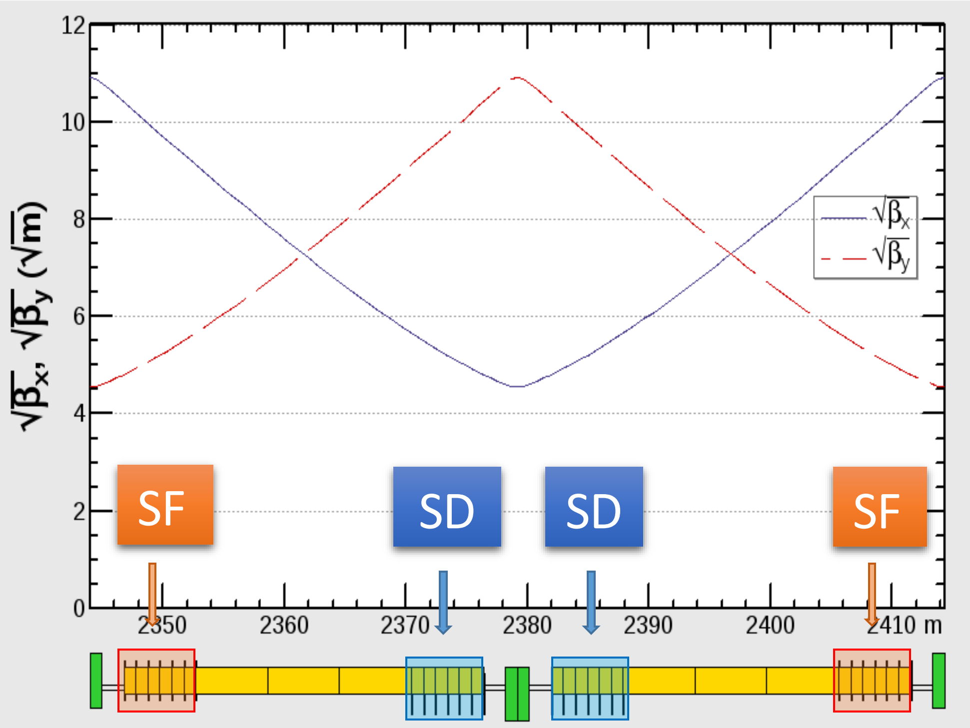
- The most important issues are Cost & Power Consumption.
  - Make the magnets compact and simple.
  - Use aluminum for the coils.
  - Dual aperture magnets save nearly 50% power.
  - Consider the combined function magnets.
  - Increase the coil cross section and decrease the operating current.

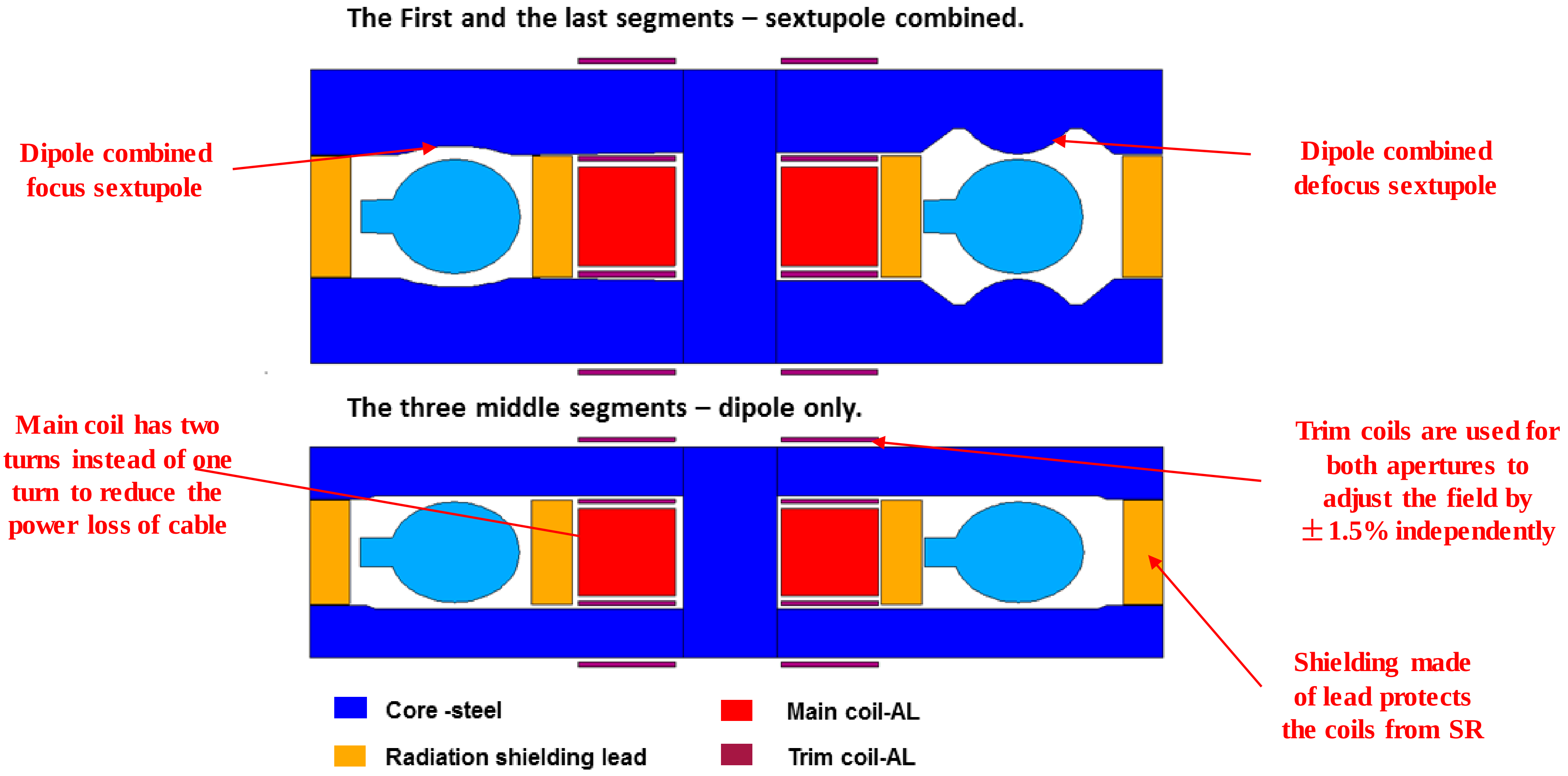
Dual Aperture Dipole Design

- Length: 28.7m, divided into 5 segments.
- Combine sextupoles in the first and last segments.
    - Different polarities in different apertures.
    - Reduce the strength of individual sextupoles.



Dual Aperture Dipole Design

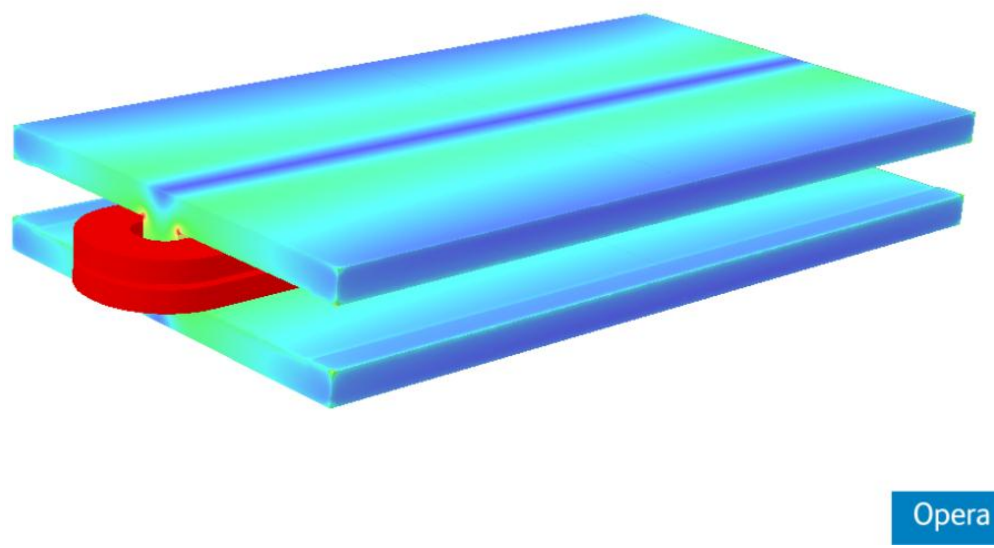
- The dual aperture dipole has ‘I’ shaped cross section.



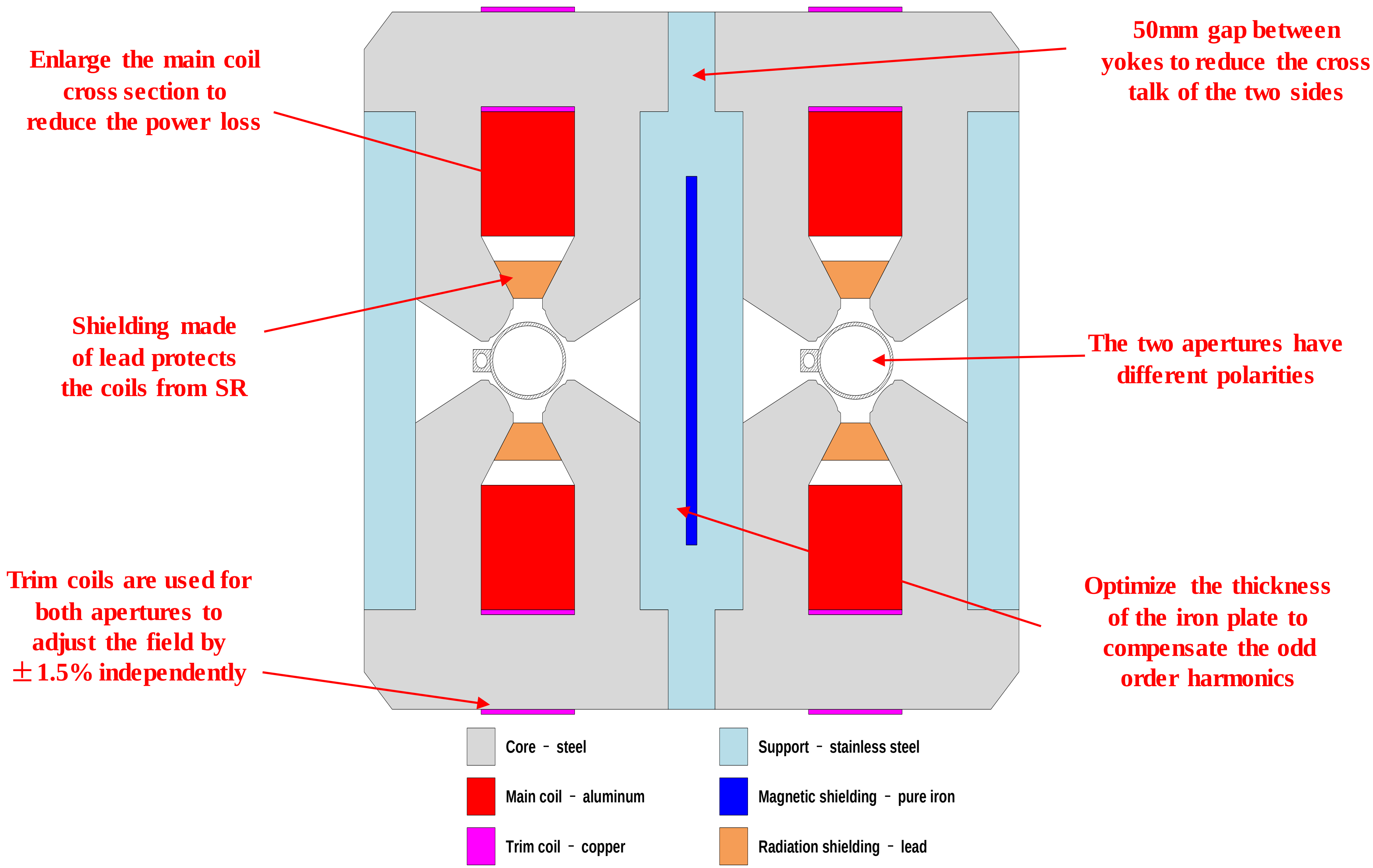
Dual Aperture Dipole Design

- Field optimization
  - Shim the pole to improve the field uniformity. → 3×10^{-4}@10mm
  - Tuning the profile to adjust the sextupole component.
  - The cross talk between the two apertures is not a problem.

Magnetic strength [T]		0.037
Aperture [mm]		70
Main coil	Turns	2
	Material	Aluminum
	Current [A]	1058
	Current density [A/mm²]	0.67
	Power consumption [kW]	2.73
Trim coil	Turns	1×4
	Material	Aluminum
	Current [A]	16.7
	Current density [A/mm²]	0.093
	Power consumption [kW]	0.006
Cooling water	Velocity [m/s]	1.75
	Flux [l/s]	0.138
	Temperature rise [°C]	4.7



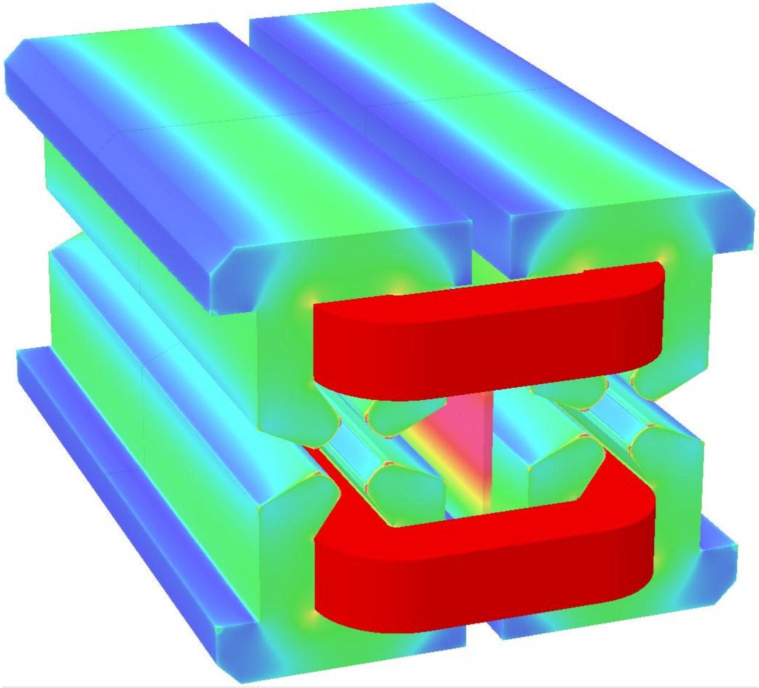
Dual Aperture Quadrupole Design



Dual Aperture Quadrupole Design

- 3D simulation
  - The iron plate can not compensate the b1 & b3 at once.
  - Prototype will be developed for further study.

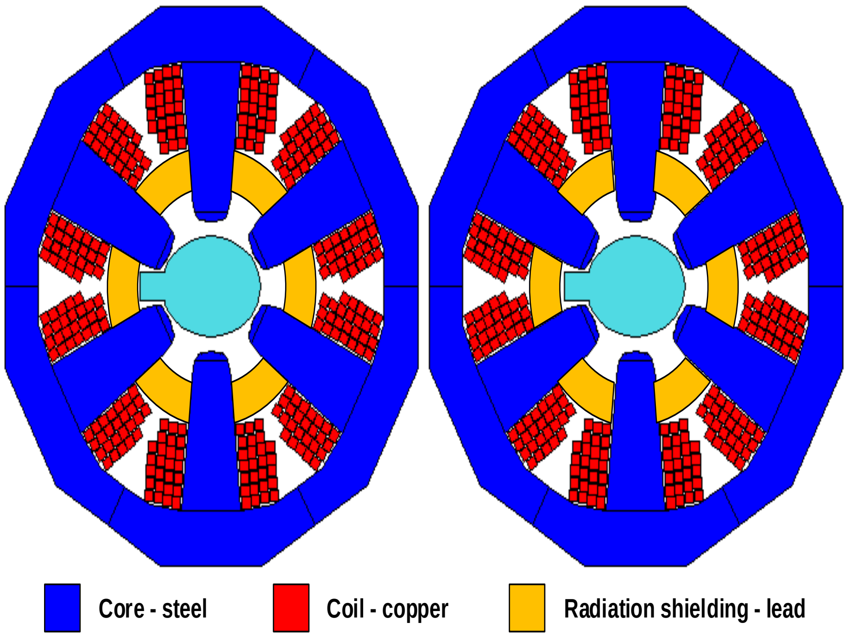
Gradient [T/m]		8.42
Aperture [mm]		76
Main coil	Turns	64 × 2
	Material	Aluminum
	Current [A]	154
	Current density [A/mm^2]	1.89
	Power consumption [kW]	5.3
Trim coil	Turns	20 × 4
	Material	copper
	Current [A]	7.2
	Current density [A/mm^2]	0.9
	Power consumption [kW]	0.04
Cooling water	Velocity [m/s]	1.3
	Flux [l/s]	0.201
	Temperature rise [°C]	6.3



Sextupole Design

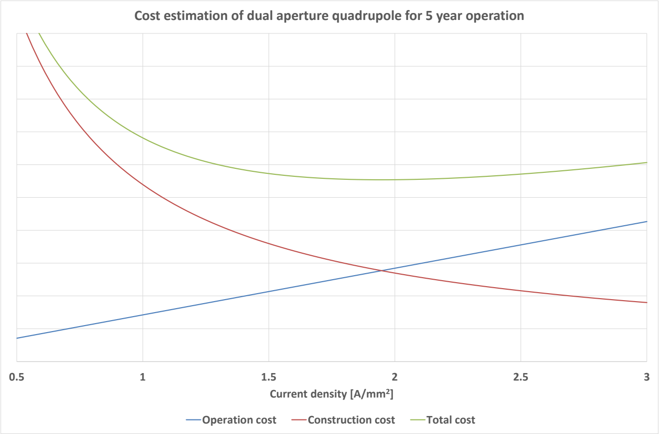
- Two single aperture sextupoles are installed side by side.
  - Core size is limited by the 350mm beam center separation.
  - Use copper for coils & enlarge the cross section as much as possible.
  - 10mm gap between two magnets but the cross talk can be ignored.

Type		SF	SD
Magnetic length [m]		0.7	1.4
Gradient [T/m²]		506	
Aperture [mm]		80	
Coil	Turns	26×6	
	Material	Copper	
	Current [A]	168.4	
	Current density [A/mm²]	4.1	4.7
	Power consumption [kW]	3.3	7.0
Cooling water	Velocity [m/s]	2.1	1.8
	Flux [l/s]	0.175	0.269
	Temperature rise [°C]	4.5	6.2



Cost Estimation

- Work breakdown structure (WBS) sheet is used to estimate the construction cost.
  - Includes the cost of materials, accessories, toolings, fabrication, test, package & delivery and some commercial costs.
- Total cost
  - Construction cost + Operation cost
  - Optimize the current density to minimize the total cost.

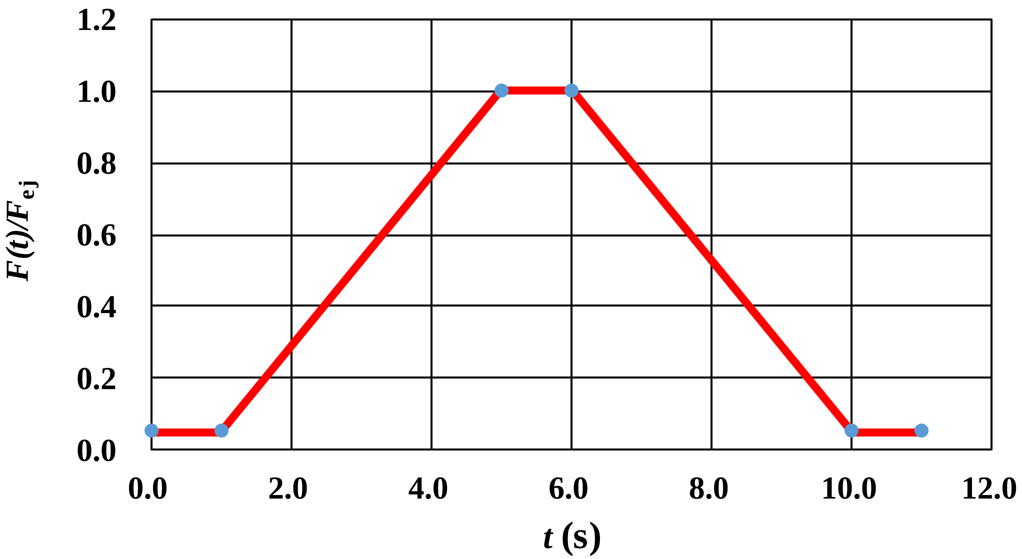


Magnet type	Coil material	Optimized density [A/mm²]		Design density [A/mm²]
		5 year operation	10 year operation	
Dual aperture Dipole	Aluminum	1.34	0.95	0.67
Dual aperture quad.	Aluminum	1.95	1.38	1.89
Sextupole	Copper	3.48	2.46	4.1

CEPC Booster Ring Magnets

Introduction

- **In the 100 km booster ring, there are 16320 dipoles, 2036 quadrupoles and 448 sextupoles.**
- **The most dipole and quadrupole magnets are 4.7 m and 1 m long, so the total length of all these magnets is nearly 77 km.**
- **The field of the booster magnets will change with beam energy, a typical field waveform is trapezoid.**
- **The cost is an important issue in design of the magnets, especially for the dipoles. The min working field of the dipoles is only 29 Gs, a high quality dipole magnet with such low field has never been developed in the world.**



Design of dipole magnets

➢ Specifications of dipole magnets for CEPCB

	BST-63B	BST-63B-Arc-Dis	BST-74B-IR
Quantity	15360	640	320
Max. field [Gs]	338	338	392
Min. field [Gs]	29	29	33
Gap (mm)	63	63	63
Magnetic Length (mm)	4711	2355.5	1682.5
Good field region (mm)	55	55	55
Field uniformity	0.1%	0.1%	0.1%

Challenges

- ✓ **Total length of the dipoles ~74km → how to reduce cost**
- ✓ **Field error <29Gs*0.1%=0.029Gs → how to design**
- ✓ **Field reproducibility<29Gs*0.05%=0.015Gs → how to measure**
- ✓ **Magnet length ~4711mm → how to fabricate**

Design of dipole magnets

- **Considerations of dipole magnets with iron core**

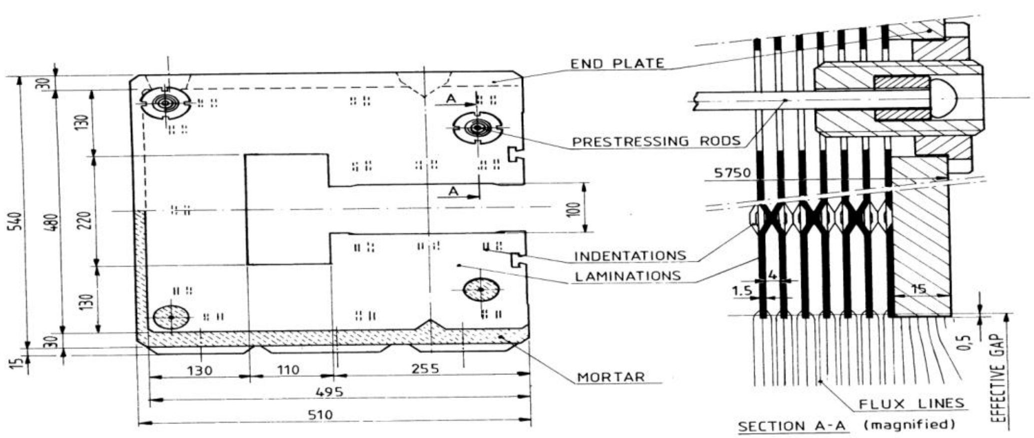
Remnant field in magnet gap due to the iron core is about 4-6 Gs, which is 13%-20% of the min working field.

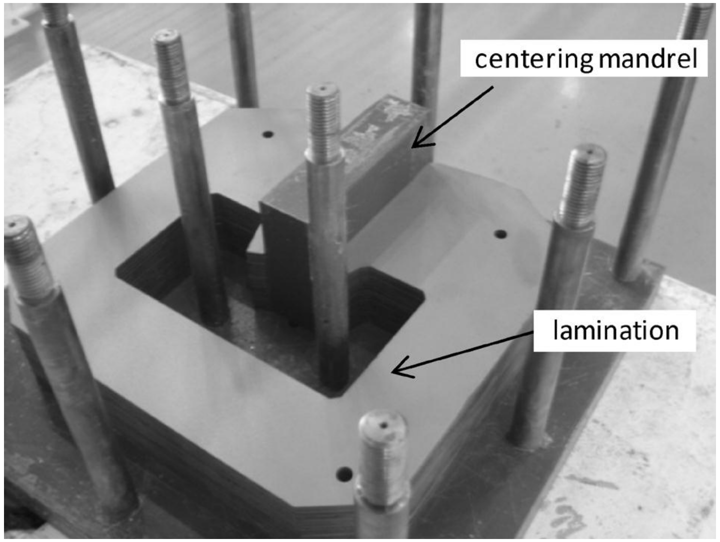
To reduce the influence of remnant field:

- ✓ The oriented low carbon silicon steel laminations with lower coercive force instead of non-oriented laminations will be used to stack the cores of the magnet.
- ✓ The technology of core dilution will be adopted to increase the field in the core material.
- ✓ The design of dipole magnet without core will be considered.

Design of dipole magnets

- ✓ Due to low working field, the technology of core dilution in longitudinal direction proposed by LEP will be used to reduce the weight and cost of the magnets.
- ✓ The cores of CEPCB dipole magnets will be stacked by silicon steel and aluminium laminations with ratio of 1:1.





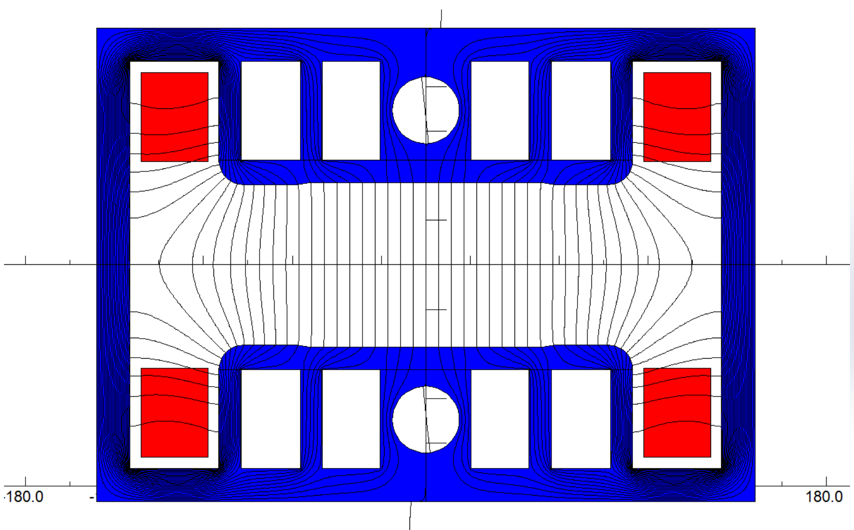
Design of dipole magnets

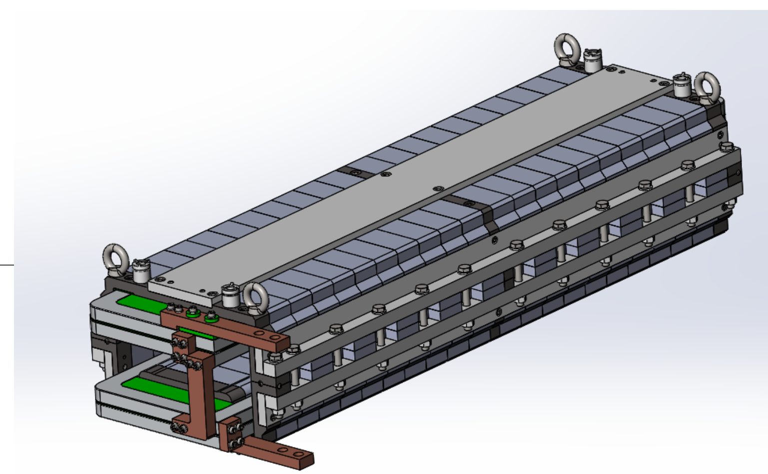
- To reduce weight and cost of the magnet further, the core dilution technology in transversal direction is proposed.

  1) The return yoke of the core will be made as thin as possible.

  2) In the pole areas of the laminations, some holes will be stamped.

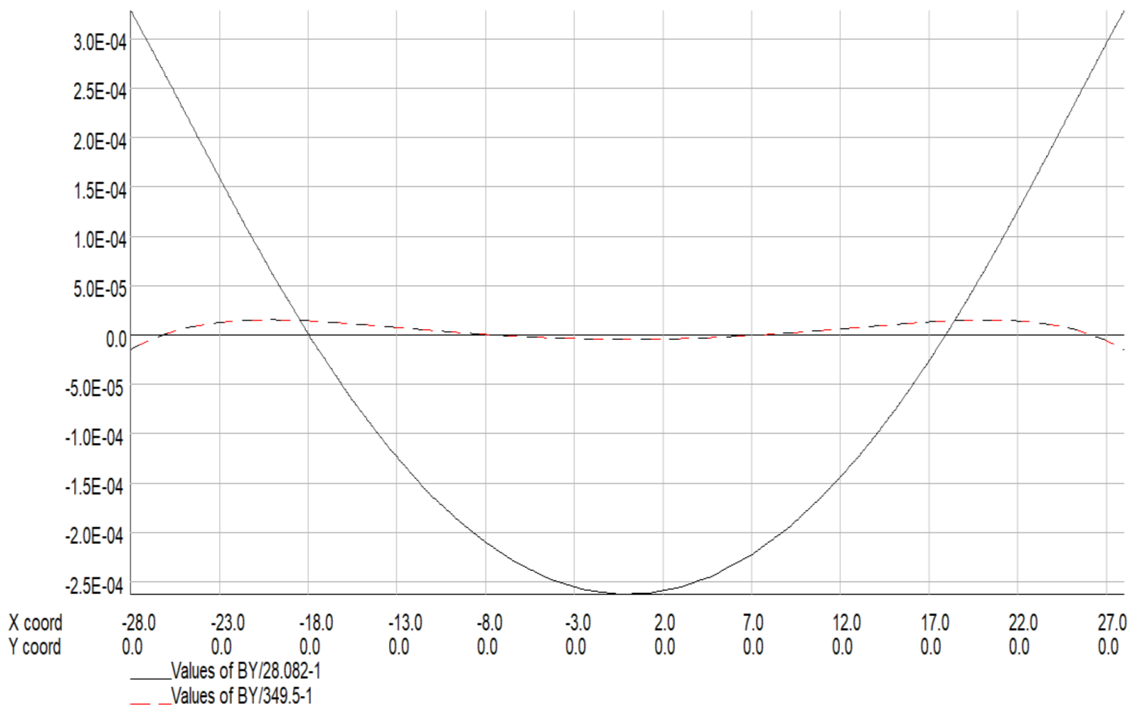
- The coil of the magnet is designed as simple as possible, which has only one turn and will be made by solid aluminum bars without water cooling.





Design of dipole magnets

- ✓ To compensate errors of the simulation modelization, the simulated field quality of the dipole magnet at high field level is optimized to be 10 time better than the requirements.
- ✓ It means that the field errors at low field level will probably meet the requirements even though it becomes 10 time worse than the simulated results.



Design of dipole magnets

Since the resolution of Hall probe is about 0.02 Gs, the field uniformity and reproducibility of the low field dipole magnet can not be precisely measured by Hall probe.

- ✓ To improve field measurement precision, NMR probe will be used to measure the field errors and reproducibility.
- ✓ To improve the efficiency of the field measurement, long search coil measurement system will be designed and developed.

Design of dipole magnets

The main designed parameters of the dipole magnets

	BST-63B-Arc	BST-63B-Arc-Dis	BST-74B-IR
Quantity	15360	640	320
Max. field [Gs]	338	338	392
Min. field [Gs]	28	28	33
Gap (mm)	63	63	63
Magnetic Length (mm)	4711	2355.5	1682.5
Turns per pole	1	1	1
Max. current[A]	856	856	992
Min. current[A]	71	71	84
Conductor size (mm)	30×40(Al)	30×40(Al)	30×40(Al)
Max. current density(A/mm^2)	1.04	1.04	1.21
Max. power loss (W)	407.7	212.5	210.8
Avg. power loss [W]	163.1	85.0	84.3
Core width/height（mm）	330/220	330/220	330/220
Core length (mm)	4650	2293	1620
Core weight (ton)	1.22	0.61	0.66
Conductor weight (ton)	0.18	0.09	0.1
Magnet weight (ton)	1.4	0.7	0.76

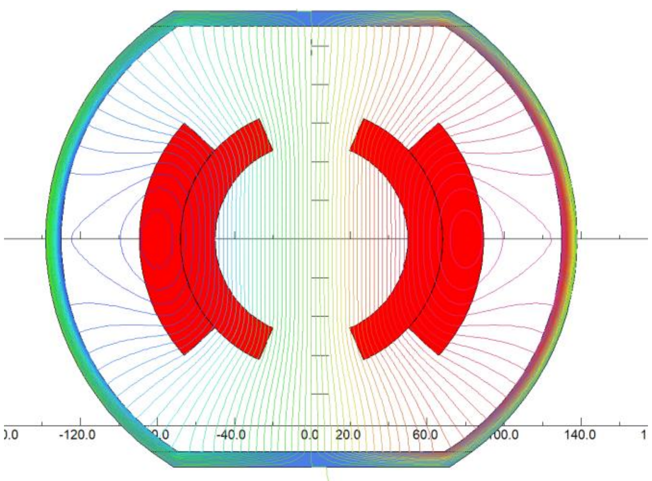
Design of dipole magnets

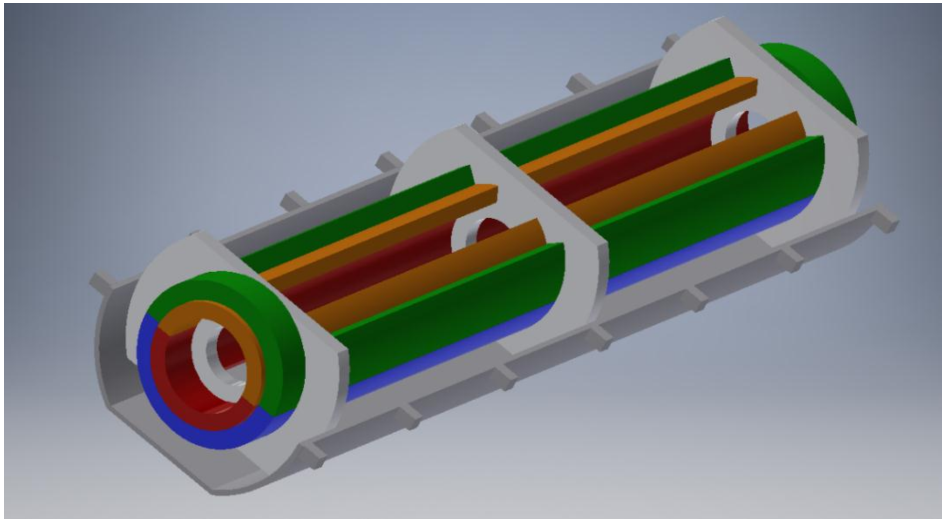
➢ Consideration of dipole magnet without iron core

- ✓ Because remnant field of the iron core is the key factor that destroy the quality of the low filed, a good design of dipole magnet without iron core can theoretically meet the high precision requirement at low field level of 29 Gs.
- ✓ The design of dipole magnets without iron core can referred to that of superconducting magnets, but because of the low field, the difficult problems of high vacuum, low temperature and large magnetic force do not exist.
- ✓ However, the main problems of the magnets without iron core are how to improve the excitation efficiency at high field level of 390Gs and how to control the mechanical tolerance of the coils.
- ✓ The cosθ and canted cosθ (CCT) dipole magnet without iron cores will be tried to design the booster dipole magnet.

Design of dipole magnets

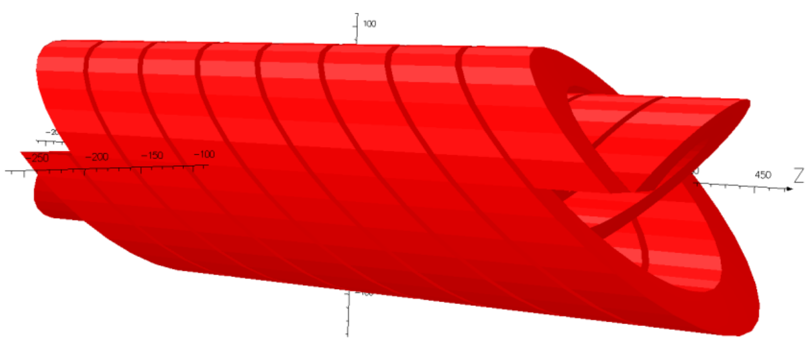
- ✓ To improve the excitation efficiency of the CT magnet, the top and bottom of the shielding cylinder can be flatted, the simulation result shows that it can increase by 5% of excitation efficiency.
- ✓ More importantly, to adjust the position of flat top and bottom of the cylinder can adjust the field distribution and improve field quality.
- ✓ Because of small magnetic force, the coils can be only supported and fixed on several fixtures in longitudinal direction.

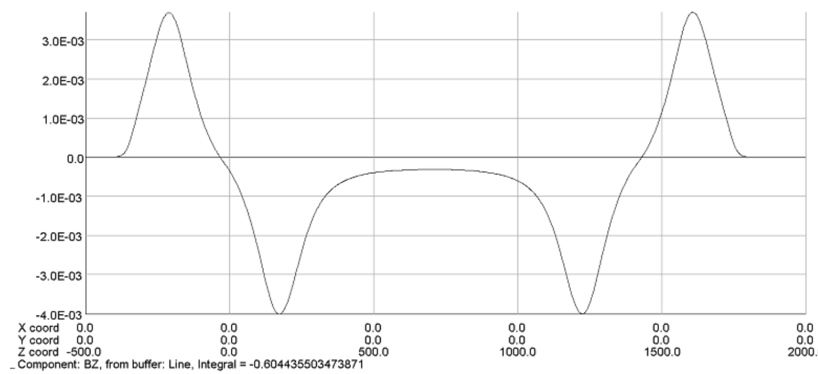




Design of dipole magnets

- ✓ The design of CCT coil dipole magnets is composed of two canted solenoids, of which the excited currents have different direction. The By field in the magnet center is By=μ0I/(w * tan(α)), the Bz field is compensated to nearly zero；
- ✓ The two canted solenoids can be manufactured by two aluminum cylinders with different diameters.
- ✓ As CT coil magnet, the coils CCT magnet can be also supported and fixed on several fixtures in longitudinal direction.





Design of dipole magnets

➢ Comparisons of the dipole magnet with and without iron core

- ✓ The advantage of the magnet with iron core are high efficiency, low power loss, but to meet the requirements of field quality at low field is very challengeable.
- ✓ The design of CT and CCT coil magnets can meet the requirements of field quality at low field, but the excitation efficiency at high field is not high.
- ✓ CCT coil seems have a little higher efficiency than that of CT coil, so the CCT coil dipole magnet will be designed and developed in this year.

	Iron Yoke	CT	CCT
Turns per magnet	2	4	264
Max.current (A)	856	1275	434
Min.current (A)	71	109	46.5
Conductor area (mm^2)	1200	1233	750
Max.current density(A/mm^2)	1.04	1.03	0.72
Max. power loss (W)	407.7	1496	862
Avg. power loss (W)	163.1	598	345
Inductance (mH)	0.09	0.36	1.5
Magnet size (mm)	330	300	280
Magnet length (mm)	4650	4632	4865
Magnet weight (ton)	1.4	0.45	0.5

Design of quadrupole magnets

➢ Specifications of quadrupole magnets for CEPCB

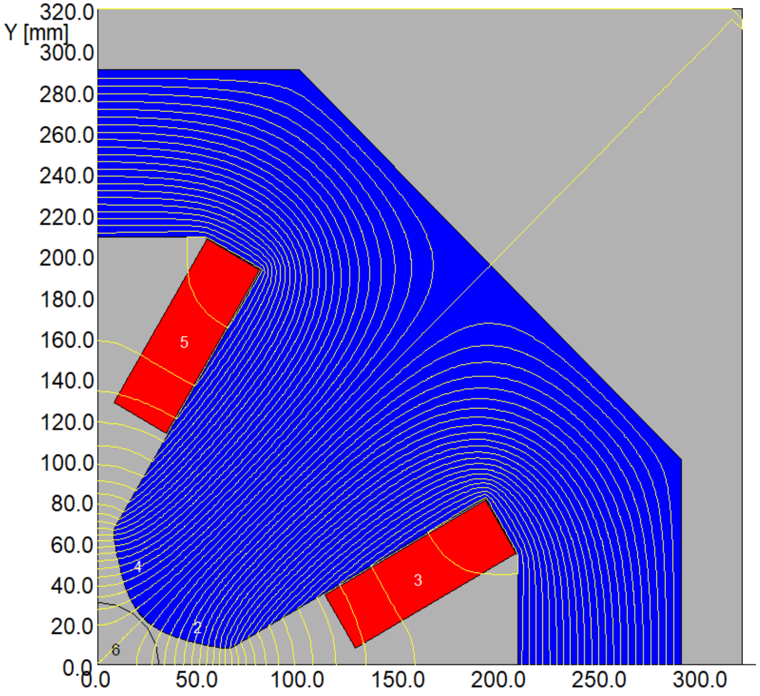
Magnet name	BST-QM	BST-QMRF	BST-QRF
Quantity	1910	8	118
Aperture diameter(mm)	64	64	64
Magnetic length（mm）	1000	1500	2200
Max. Field gradient（T/m）	12.18	15.29	16.61
Min. Field gradient（T/m）	0.99	1.03	1.38
GFR radius (mm)	28	28	28
Harmonic errors	5.0E-4	5.0E-4	5.0E-4

- ✓ All quadrupole magnets have the same aperture, which are categorized into 3 families according to their magnetic length.
- ✓ The field errors are required to be less than 5E-4.

Design of quadrupole magnets

➢ Key technologies of quadrupole magnets for CEPCB

- ✓ The magnet will be assembled from four identical quadrants, and can also be split into two halves for installation of the vacuum chamber.
- ✓ The iron core is stacked by low carbon silicon steel laminations.
- ✓ Hollow aluminum instead of copper conductor is selected for the coil winding, because of lower price and reduced weight.
- ✓ The coil windows leave a certain amount of space to place radiation shielding blocks.



Design of quadrupole magnets

➢ **The main designed parameters of the quadrupole magnets**

Magnet name	BST-QM	BST-QMRF	BST-QRF
Quantity	1910	8	118
Aperture diameter(mm)	64	64	64
Magnetic length（mm）	1000	1500	2200
Max. Field gradient（T/m）	12.18	15.29	16.61
Min. Field gradient（T/m）	0.99	1.03	1.38
GFR radius (mm)	28	28	28
Harmonic errors	5.0E-4	5.0E-4	5.0E-4
Coil turns per pole	16	20	20
Max. current（A）	313	316	344
Al conductor size（mm）	10×10D6	10×10D6	10×10D6
Max. current density（A/mm^2）	4.42	4.46	4.86
Max Power loss（kW）	6.14	11.11	18.74
Avg. Power loss (kW)	2.46	4.44	7.50
Conductor weight（kg）	29	51	73
Core length（mm）	940	1440	2140
Core width & height（mm）	600	622	622
Core weight（kg）	1478	2594	3855

Design of sextupole magnets

➢ Specifications of sextupole magnets for CEPCB

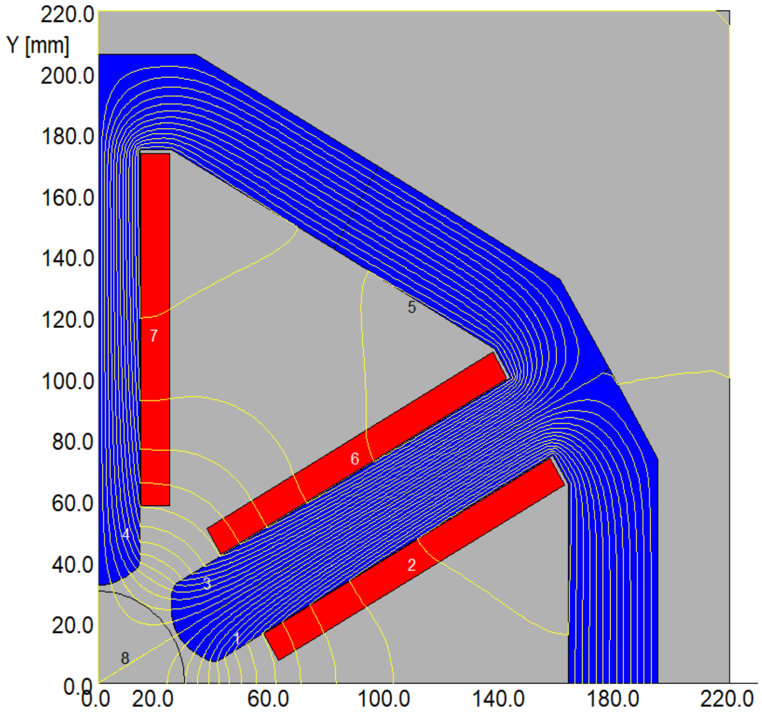
Magnet name	BST-64SF	BST-64SD
Quantity	224	224
Aperture diameter(mm)	64	64
Magnetic length（mm）	400	400
Max. sextupole field (T/m^2)	216.9	437.1
Min. sextupole field (T/m^2)	18.1	36.4

- ✓ The sextupole magnets are divided into two families, focusing or defocusing (horizontally).
- ✓ Both magnets have the same aperture and magnetic length but different working magnetic field.

Design of sextupole magnets

➢ Key technologies of sextupole magnets for CEPCB

- ✓ The cores of the magnets have a two-in-one structure, made of low-carbon silicon steel sheets.
- ✓ The coils of the magnets have a simple racetrack-shaped structure, which is wound by hollow copper conductors.
- ✓ The coil windows leave a certain amount of space to place radiation shielding blocks.



Design of sextupole magnets

➢ **The main designed parameters of the sextupole magnets**

Magnet name	BST-64SF	BST-64SD
Quantity	224	224
Aperture diameter(mm)	64	64
Magnetic length（mm）	400	400
Max. sextupole field (T/m^2)	216.9	437.1
Min. sextupole field (T/m^2)	18.1	36.4
Coil turns per pole	8	16
Max. current（A）	120.4	122.2
Cu conductor size（mm）	6×6D3	6×6D3
Max. current density（A/mm^2）	4.19	4.25
Max Power loss（kW）	0.40	0.81
Avg. Power loss (kW)	0.16	0.33
Core length（mm）	360	360
Core width & height（mm）	300	400
Magnet weight（kg）	120	200

Design of correcting magnets

➢ Specifications of correcting magnets for CEPCB

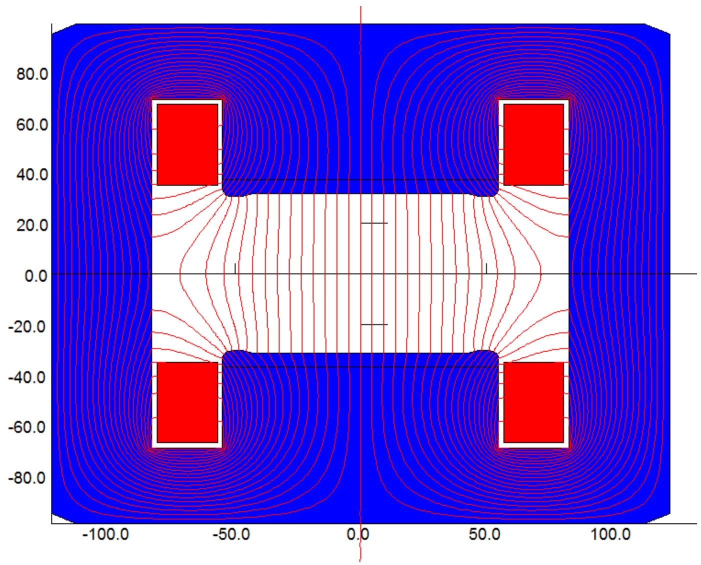
Magnet name	BST-63C
Quantity	350
Magnet gap (mm)	63
Magnetic field (T)	0.02
Effective length (mm)	583
Good field region (mm)	55
Field errors	0.1%

- ✓ Two types of correctors in the booster are used for vertical and horizontal correction of the closed-orbit.
- ✓ The field errors are required to be less than 1E-3.

Design of correcting magnets

➢ Key technologies of correcting magnets for CEPCB

- ✓ To meet the field quality requirements, the correctors have H-type structure cores so that the pole surfaces can be shimmed to optimize the field.
- ✓ The cores are stacked by silicon steel laminations.
- ✓ The racetrack shaped coils are wound from solid copper conductor.



Design of correcting magnets

➢ The main designed parameters of the correcting magnets

Magnet name	BST-63C
Quantity	350
Magnet gap (mm)	63
Magnetic field (T)	0.02
Effective length (mm)	583
Good field region (mm)	55
Field errors	0.1%
Maximum current (A)	22.5
Coil turns per pole	24
Conductor size （mm）	5.5×5
Current density（A/mm^2）	0.82
Voltage drop (V)	1.12
Power loss （W）	25
Core length (mm)	550
Core width/height(mm)	246/198
Magnet weight（kg）	240

Summary

- ✓ Conceptual design of CEPC Collider and Booster magnets has been finished.
- ✓ Prototypes magnets for CEPC Collider and Booster are proposed, and the R&D has started.

Thanks for your attention!