CEPC Booster and Collider Ring Magnets R&D

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HongKong, Jan. 20-22, 2020

Contents

Specifications and Challenges of CEPCB dipole

	BST-63B
Quantity	16320
Minimum field (Gs)	28
Maximum field (Gs)	338
Gap (mm)	63
Magnetic Length (mm)	4700
Good field region (mm)	55
Field uniformity	0.1%
Field reproducibility	0.05%

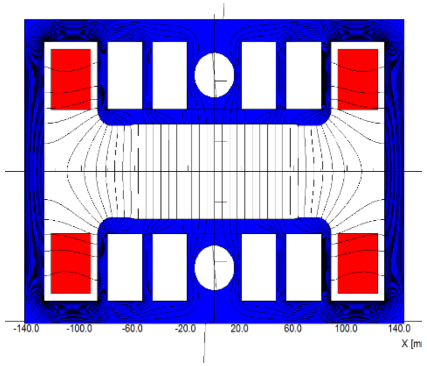
Challenges

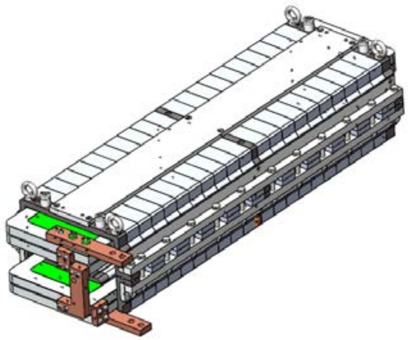
- Total length of the dipoles ~75km → how to reduce cost
- Field error <28Gs*0.1%=0.028Gs → how to design
- Field reproducibility<29Gs*0.05%=0.015Gs → how to measure
- Magnet length ~4700mm → how to fabricate

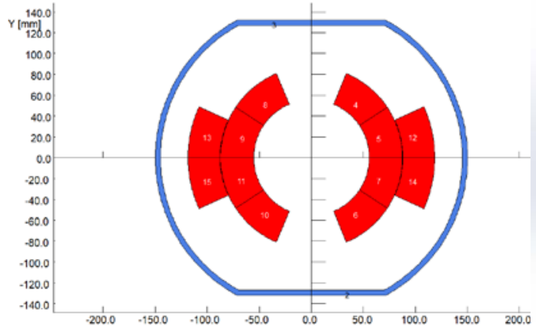
Development of the prototype dipole magnets

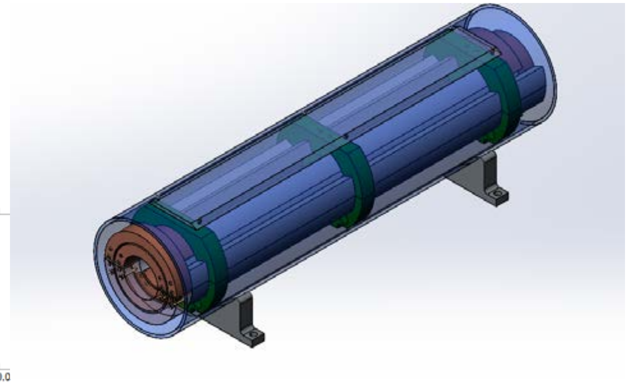
Since the high precision dipole magnet with the min. working field of 28 Gs has never been developed in the world, two kinds of new magnet designs with and without iron cores have been proposed and studied.

- **For the magnet with iron cores, the technology of core dilution was adopted and the grain-oriented silicon steel laminations were used to stack the magnet cores due to their low coercive and remnant.**
- **For the magnet without iron cores, the conventional Cosθ (CT) type coil was finally selected. Each coil was designed to have three turns to reduce the eddy current effect during the field ramping.**





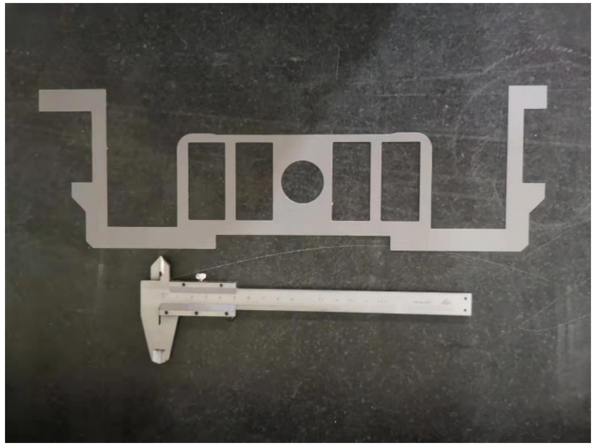


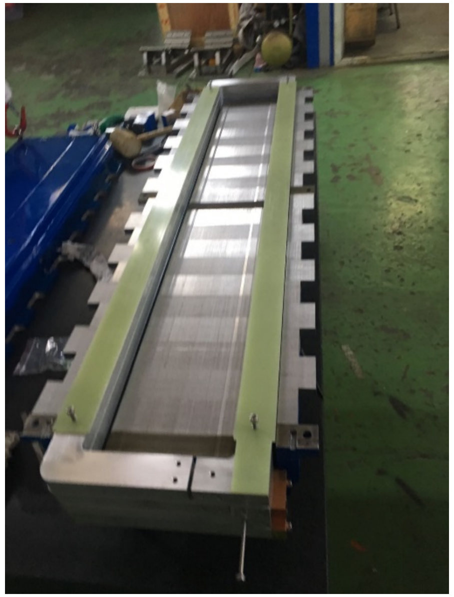


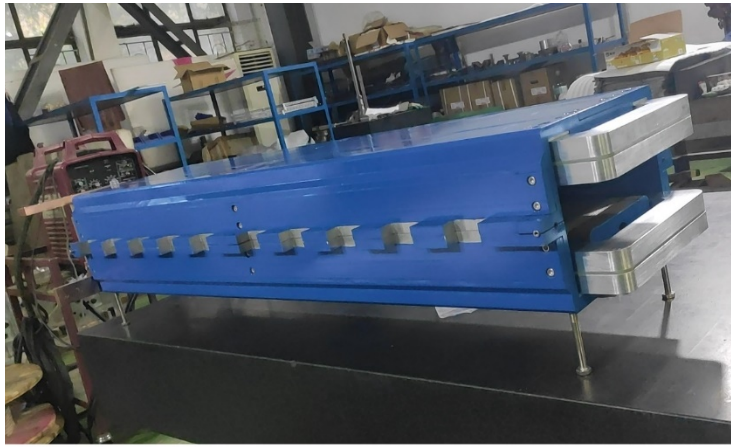
Development of the prototype dipole magnets

1) Fabrication of the subscale dipole magnet with diluted iron cores

- The magnet has the upper and lower cores, which are stacked by the grain-oriented silicon steel and aluminum laminations with the thickness ratio of 1:1.
- The magnet has two coils and each coil has two turns. The conductors of each turn are directly fabricated from the aluminum plates
- The G10 plates with thickness of 4mm are used for the insulation either from turn to turn or between the coils and cores.



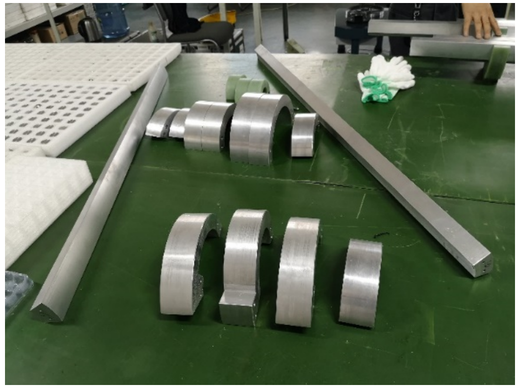
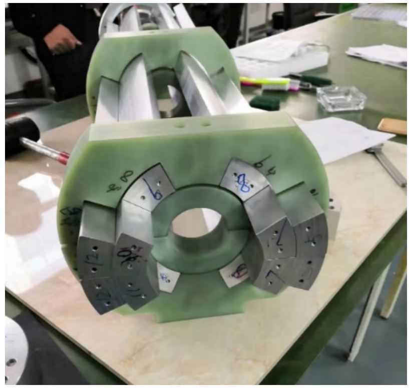


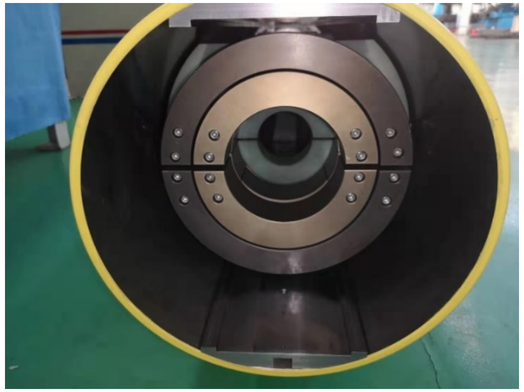


Development of the prototype dipole magnets

2) Fabrication of the subscale CT dipole magnet without iron cores

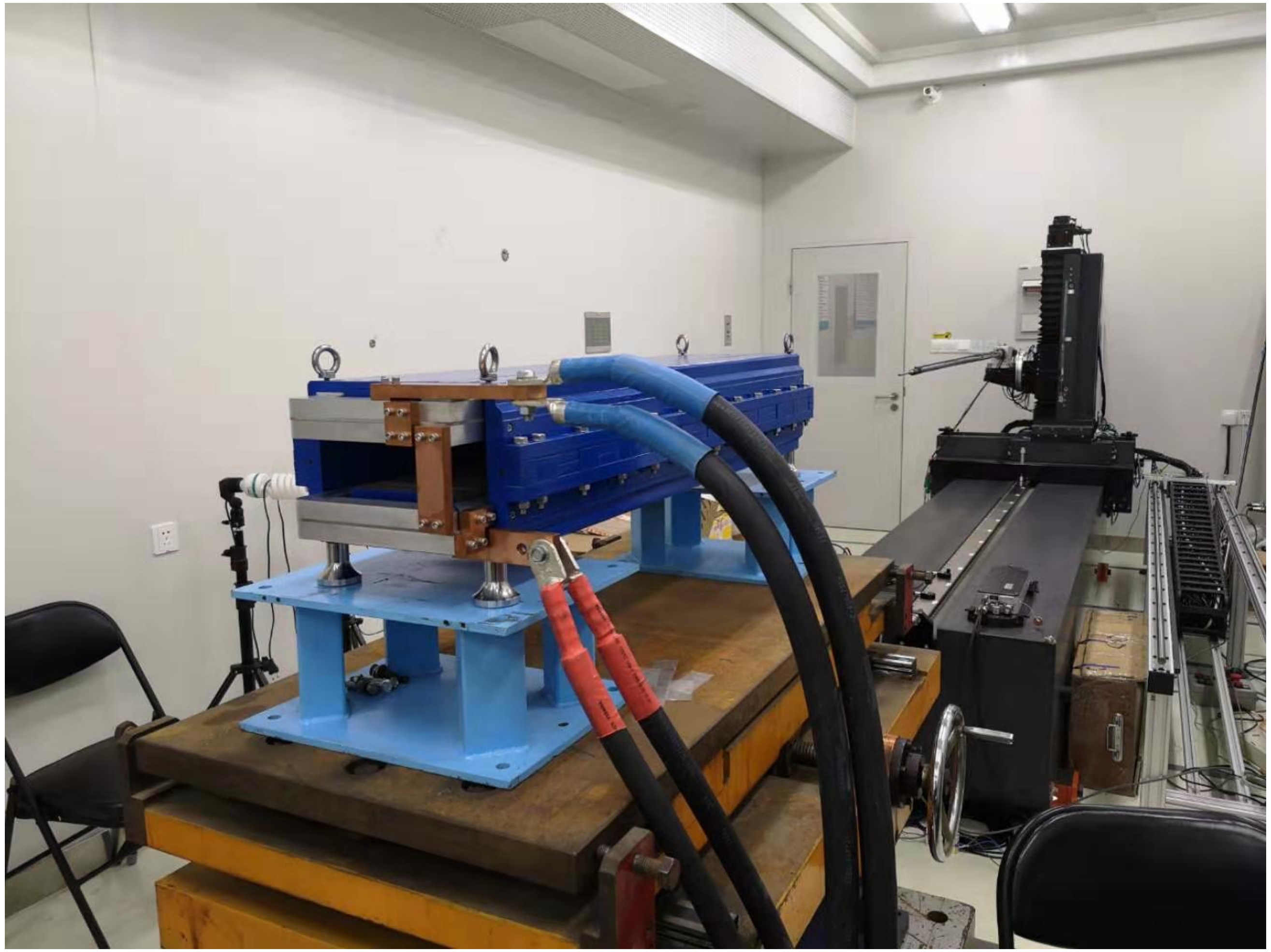
- In the structure, three turns of the upper and lower coils were formed by six aluminum arc bars with the same cross section areas, all bars were directly fabricated from two aluminum tubes with the right diameters.
- All the surfaces of the aluminum conductors were anodized for the insulation from turn to turn, the thickness of the anodized film is about 50 microns.
- The inner and outer conductors of the coils were connected by the by-pass circular conductors.
- Because the magnetic field force was not high, three supporters per meter in the longitudinal direction were strong enough to fix the bars of coils together.



Test of the subscale dipole magnets

1) Test of the dipole magnet with diluted iron core

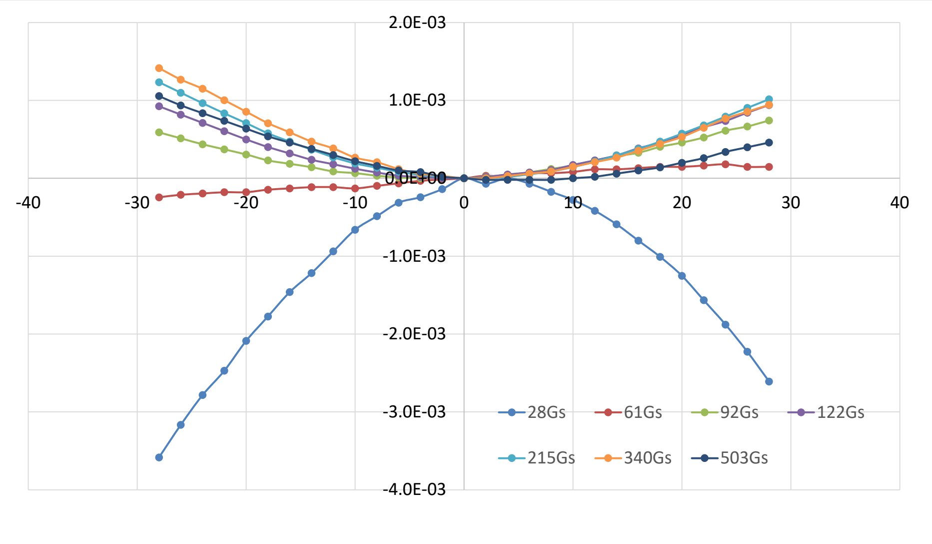


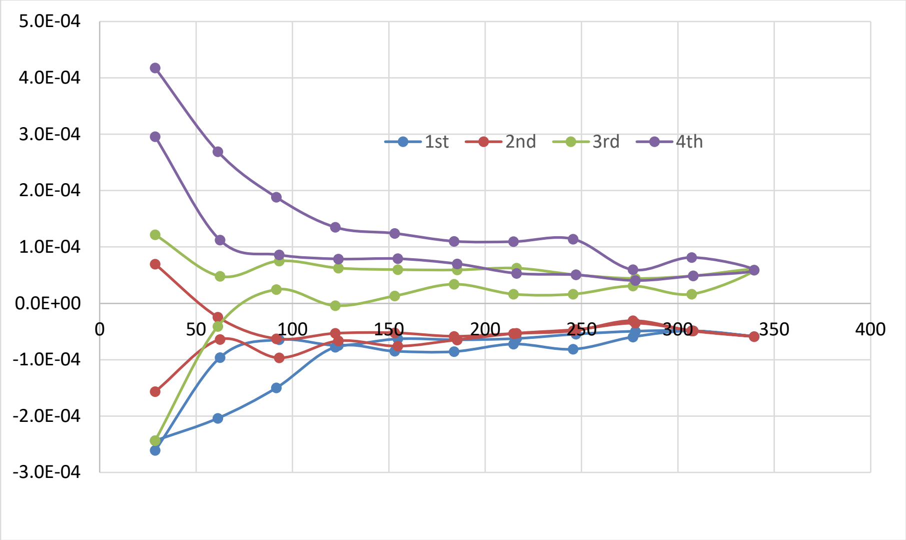
The dipole magnet with iron core was tested in the lab.

Test of the subscale dipole magnets

The measurement results show,

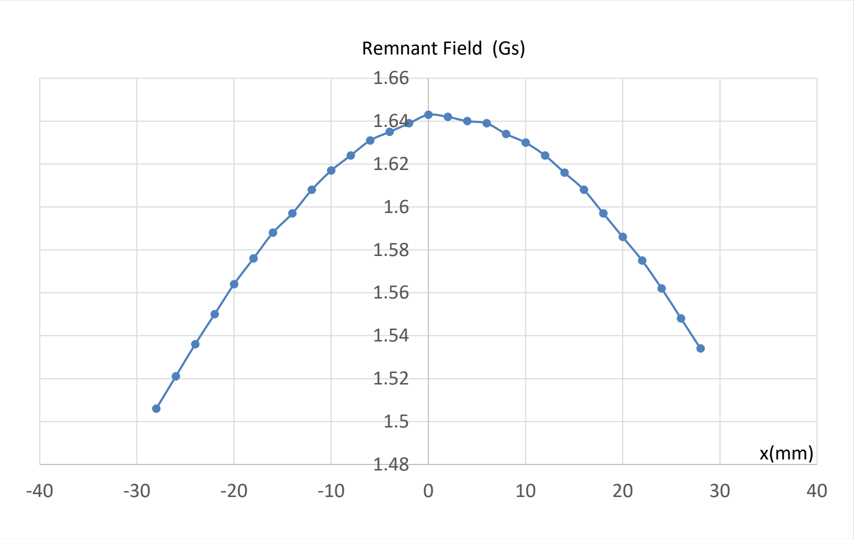
- The field uniformity in GFR is about 0.3% at low field level of 28Gs and 0.1% at high field level, which can not meet the requirements.
- The magnet is excited for 4 times from 28Gs to 338Gs then back to 28Gs, the field reproducibility at all level is better than the required value of 5E-4.

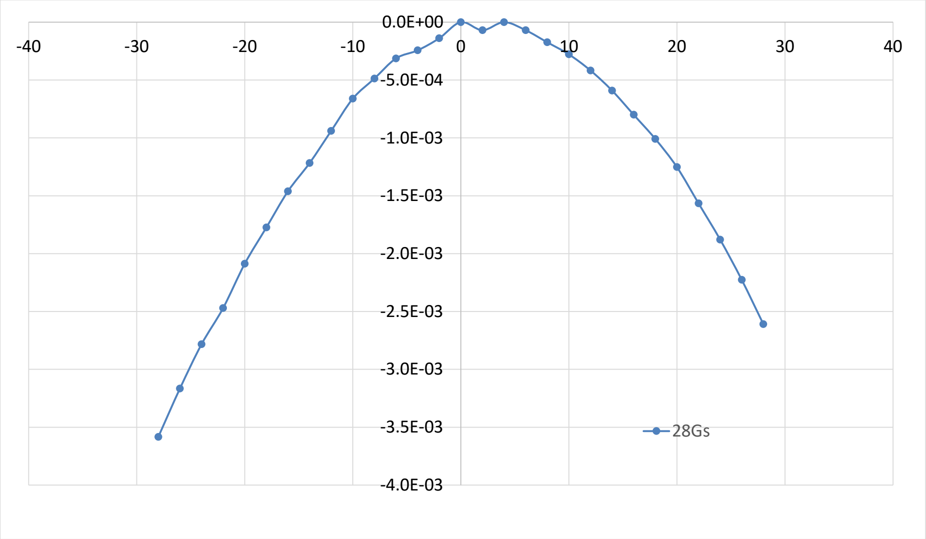




Test of the subscale dipole magnets

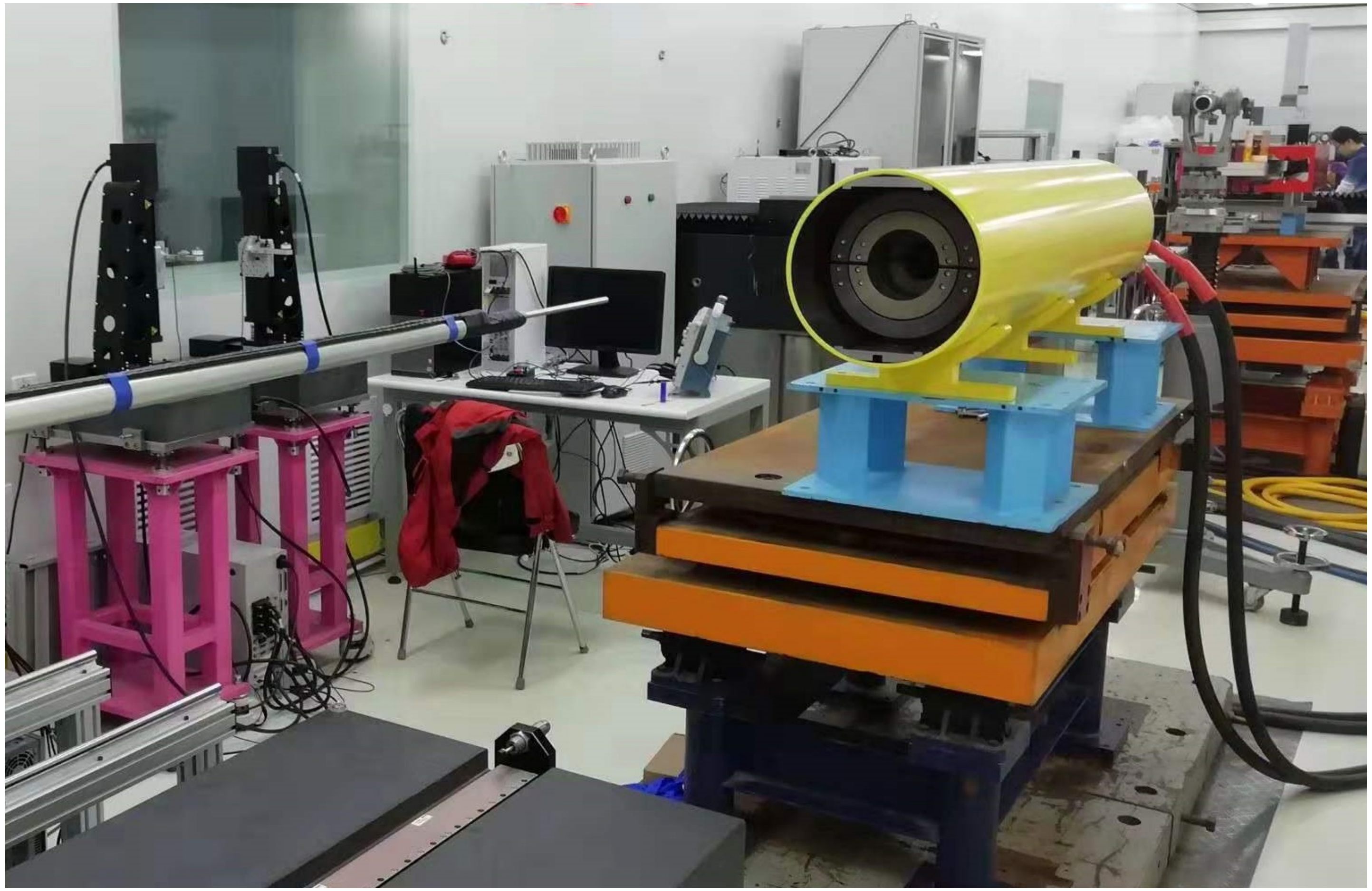
- ✓ The reason that the magnet performance at low field level is worse than that at high field level is the influence of remnant field in the magnet cores.
- ✓ The remnant field in the aperture of the magnet is only 1.6Gs as expected. But the difference of the remnant field in the GFR is 0.13Gs, which is 0.46% for 28Gs, nearly 5 time larger than the required value of 0.1%.





Test of the subscale dipole magnets

2) Test of the CT coil dipole magnet without iron core

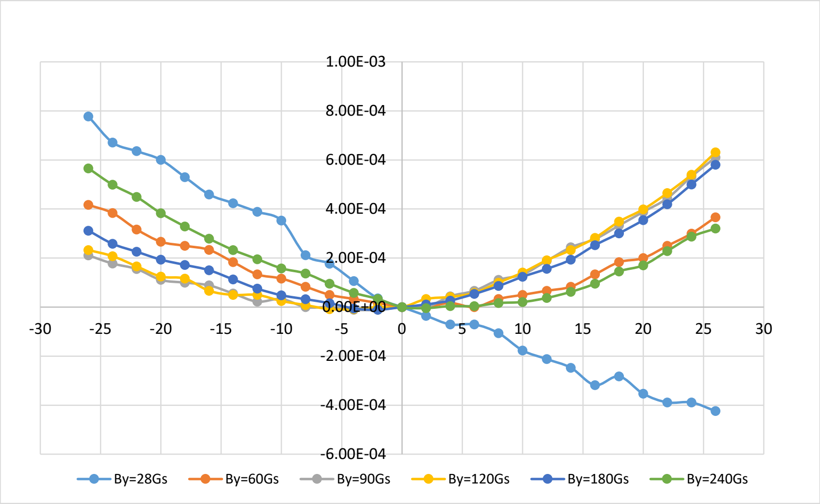


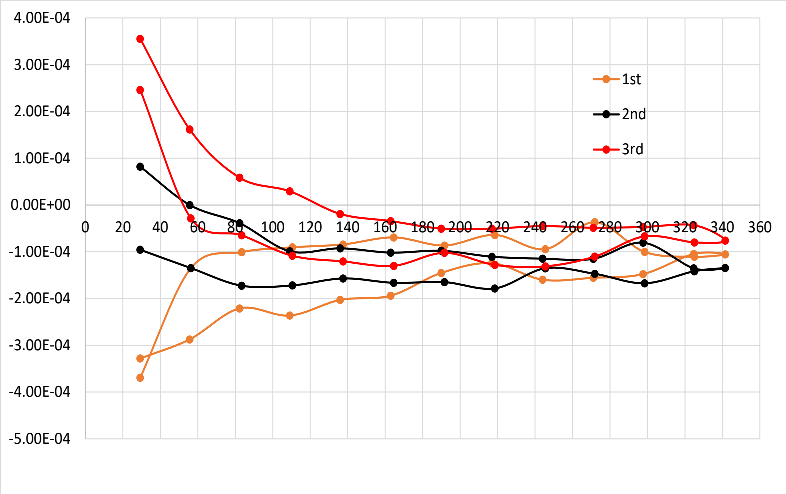
The CT coil dipole magnet was tested in the lab.

Test of the subscale dipole magnets

The measurement results show,

- ✓ The field precision at all level, especially at low field level of 28Gs, is better than the required value of 0.1%.
- ✓ The magnet is excited for 3 times from 28Gs to 338Gs then back to 28Gs, the field reproducibility at all level is better than the required value of 5E-4.





Main parameters of two dipole magnets

	Iron Yoke	CT
Max. field [Gs]	338	338
Min. field [Gs]	28	28
Good field region (mm)	55	55
Field uniformity	0.1%	0.1%
Coil turns of magnet	4	6
Max.current (A)	428	1000
Min.current (A)	37	80
Conductor area (mm^2)	1000	1348
Max.current density(A/mm^2)	0.43	0.73
Max. power loss (W)	245	1350
Avg. power loss (W)	98	540
Inductance (mH)	0.32	0.36
Magnet size（mm）	330	310
Magnet length (mm)	4650	4632
Magnet weight (ton)	1.4	1.1

Overview of collider magnets

- **Over 80% of collider ring is covered by conventional magnets. All these magnets work at DC mode.**

	Dipole	Quad.	Sext.	Corrector	Total
Dual aperture	2384	2392	-	-	13742
Single aperture	80*2+2	480*2+172	932*2	2904*2	
Total length [km]	71.5	5.9	1.0	2.5	80.8
Power [MW]	7.0	20.2	4.6	2.2	34

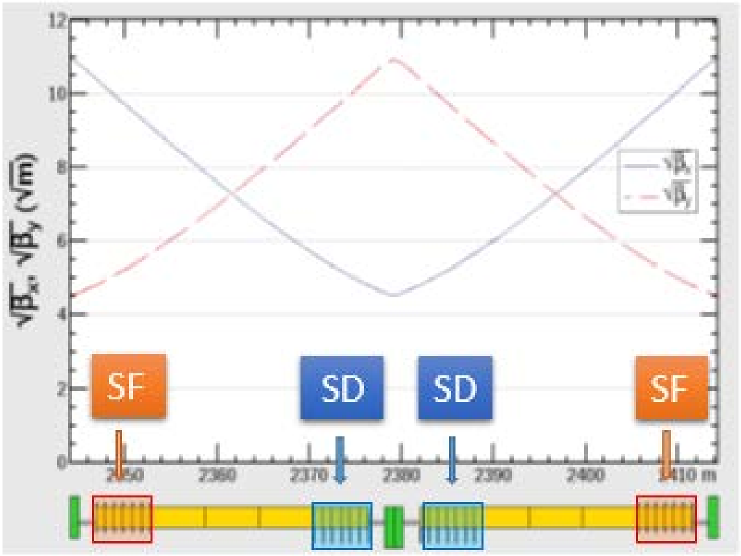
- The most important issues are Cost & Power Consumption.
  - **Make the magnets compact and simple.**
  - **Aluminum wire is used for the excitation coils.**
  - **Dual aperture magnets save nearly 50% power consumption.**
  - **Consider the combined function magnets.**
  - **Increase the coil cross section and decrease the operating current.**

Parameters of the DAD

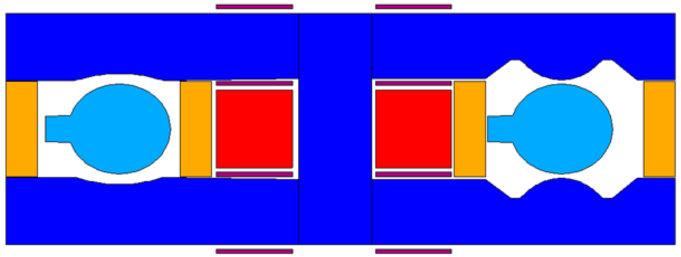
- Parameters of main dipole magnets.

Field strength(Gs)	140Gs~373Gs
Aperture(mm)	70
Effective length(m)	28.7m, 5 parts
GFR(mm)	13.5
Adjustment capability	±1.5%
Field quality	5×10^{-4}

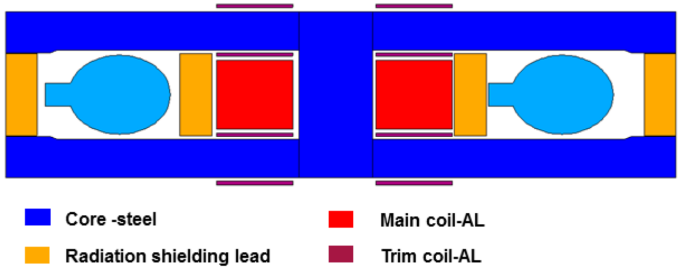
- Short prototype of DAD (1m in length)
  - **Central field： 140Gs@45GeV~373Gs @120GeV**
  - **Difference between the two aperture center fields <0.5%**
  - **High order harmonics<5×10^{-4} @R=13.5mm(except b3)**
  - **Trim coils in two apertures： ±1.5%**
  - **Size of vacuum chamber： (W*H) 99mm ×62mm**
  - **Thickness of radiation lead： 25mm**



The First and the last segments – sextupole combined.

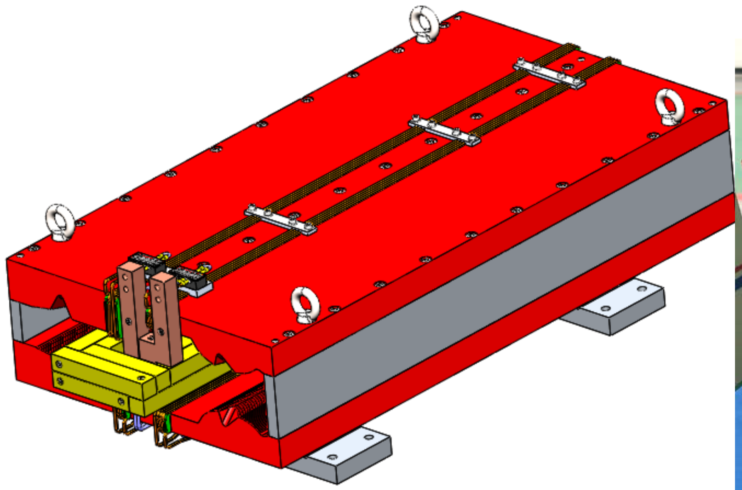


The three middle segments – dipole only.



Mechanical design of DAD prototype

- Liron=1m, solid yoke , three parts;
- Main coils: aluminum bus bars, 4 turns, air cooled, interconnect by screw;
- Trim coils: copper wire, 4 turns per pole, air cooled;
- Two stainless steel supporters to increase rigidity of the overall structure.



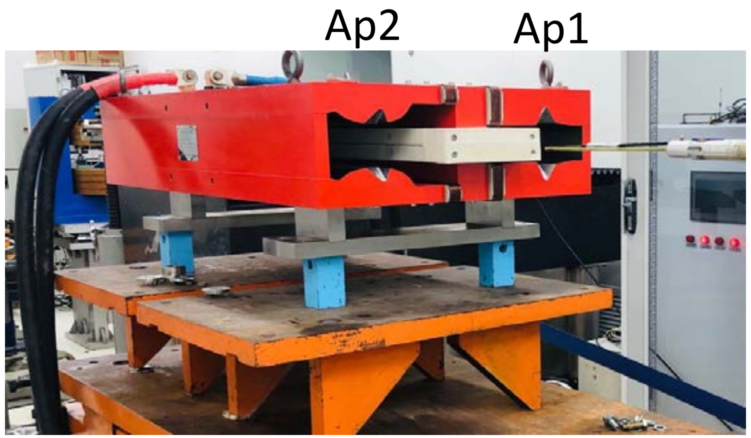
CAD model of dual aperture dipole

Dual aperture dipole prototype

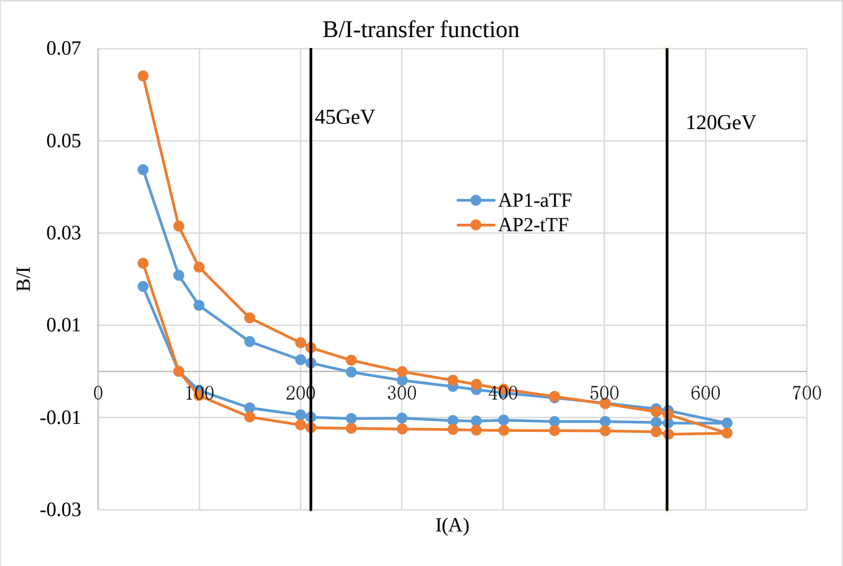
Magnetic strength [T]		0.0373
Aperture [mm]		70
Main coil	Turns	4
	Material	Aluminum
	Current [A]	563
	Current density [A/mm2]	0.7
	Power consumption [kW]	0.12
Trim coil	Turns	1×4
	Material	Copper
	Current [A]	16.7
	Current density [A/mm2]	0.093
	Power consumption [kW]	0.0005
Tot cross section(mm)		535*200
Iron length (mm)		1000
Iron weight(kg)		510
Al weight(kg)		22
Cu weight(kg)		0.3

Magnetic field measurements

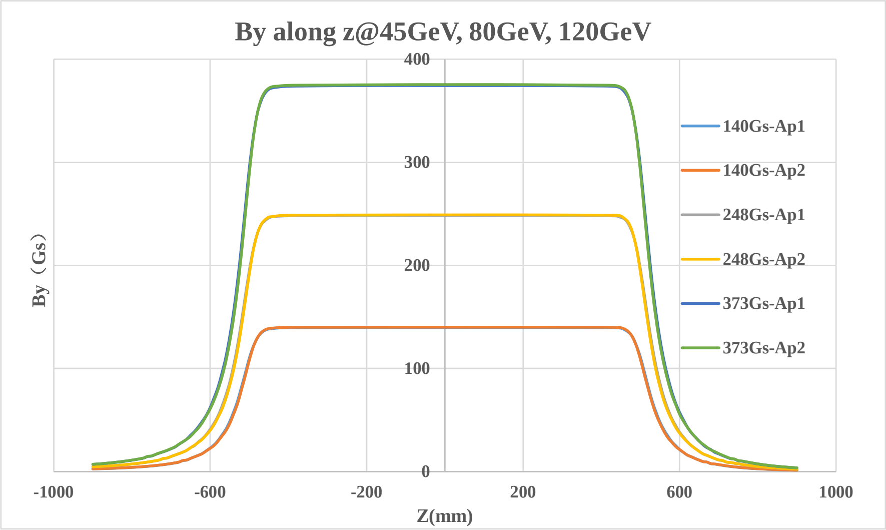
- The transfer function at two apertures:
  - Center field difference <0.3% in two apertures(residual field effect and different gaps at the two apertures).



Dipole measured by a hall probe system



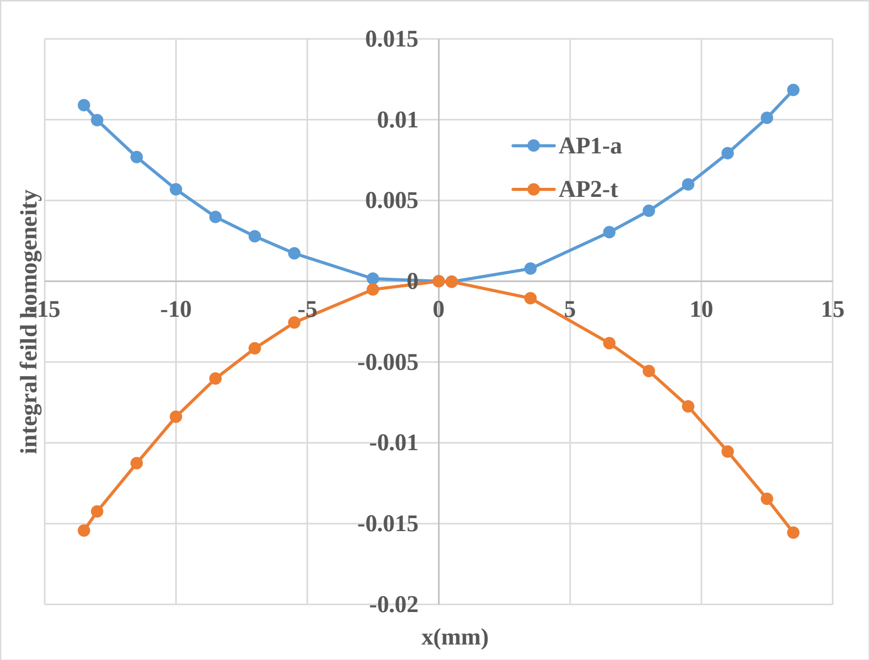
B/I Transfer function



By along z at different energy

Magnetic field measurements

- Integral field differences
  - Difference is less than 0.15%@45GeV.
- Harmonics@Rref=13.5mm



Measured integral field in the vertical midplane (y=0)

E(GeV)	Ap1 ByL(T.mm)	Ap2 ByL(T.mm)	Differ
45	15.3972	15.3765	-0.13%
80	27.3358	27.3199	-0.06%
120	41.2001	41.1810	-0.05%

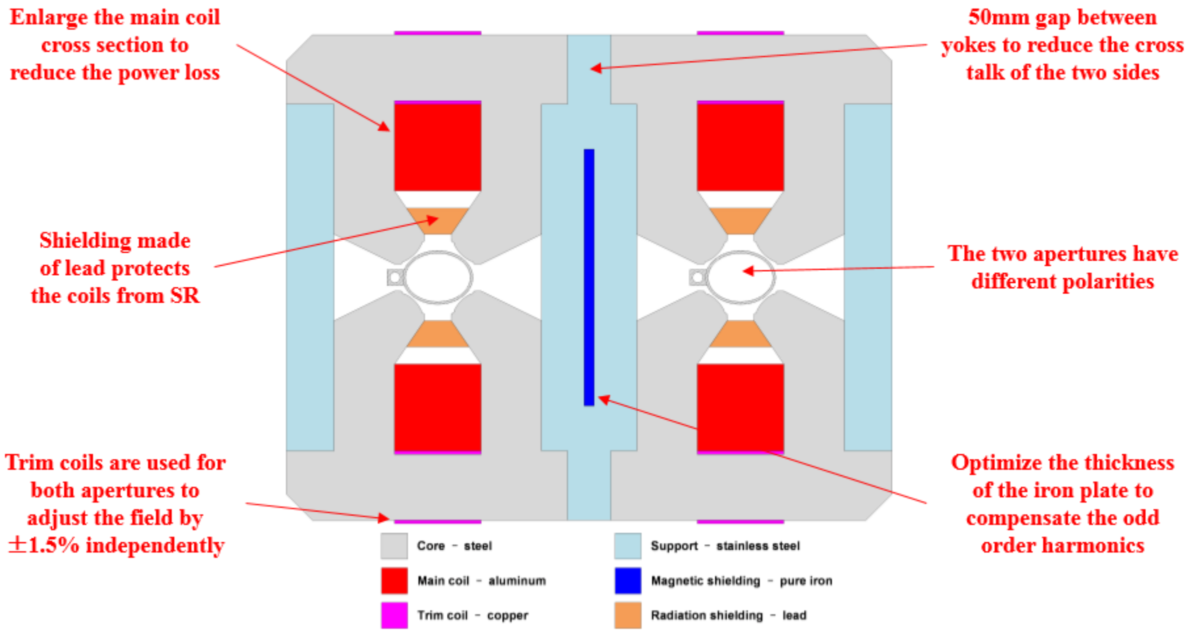
Harmonics at two apertures

n	Ap1@45GeV	Ap2@45GeV
2	5.38	-1.40
3	113.24	-157.23
4	4.49	-2.00
5	0.015	2.14
6	-5.29	2.60

Dual aperture quadrupole(DAQ)

- Requirements of DAQ

Gradient(T/m)	8.42
Aperture(mm)	76
Effective length(m)	1 or 2
GFR(mm)	12.2
Adjustment capability	$\pm$1.5%
Field quality	5×10^{-4}

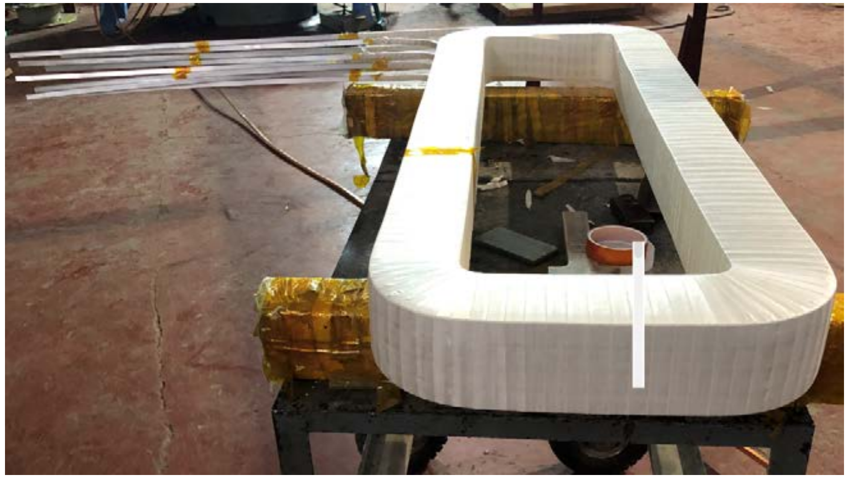


- Prototype study
  - **Complex structure to verify assembly tolerances and mechanical structure**
  - **Cross talk effect and compensation method study**
  - **Verify the hollow aluminum wires**
  - **Effect of trim coils on the main field**

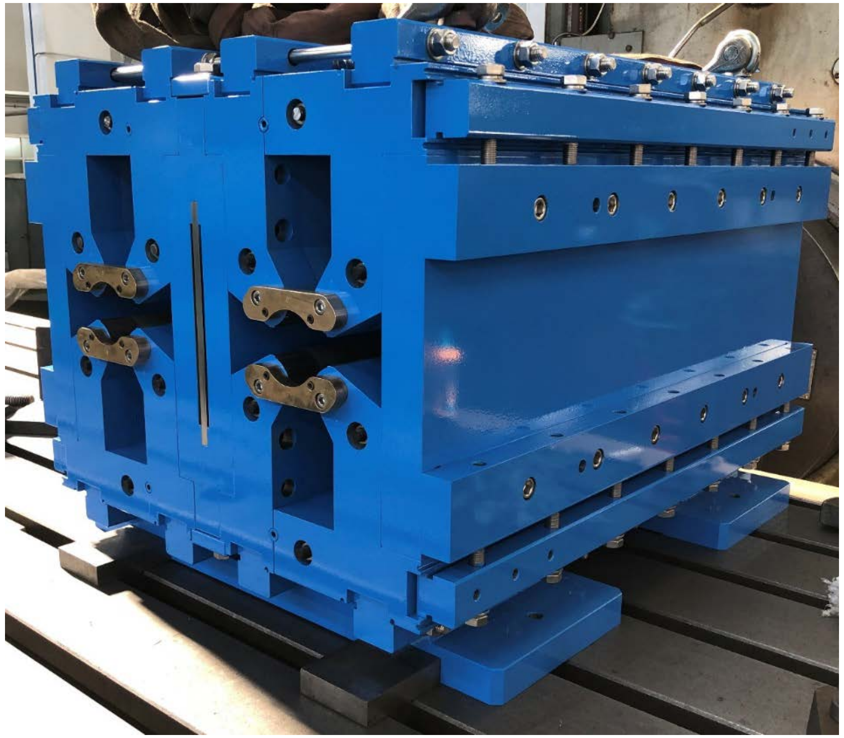
Dual aperture quadrupole prototype

- The DAQ prototype has been finished.

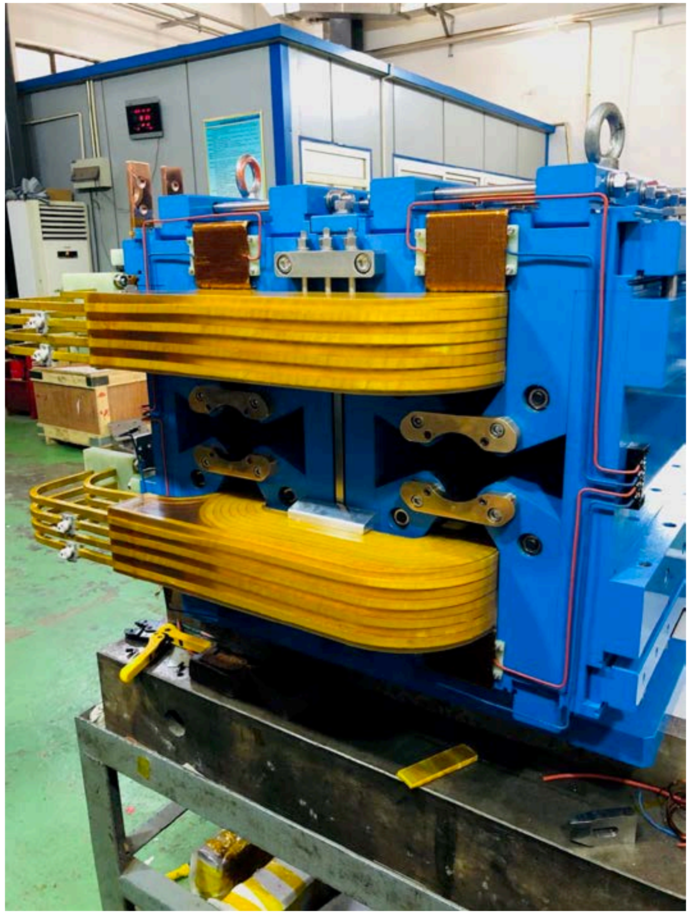
Hollow aluminum wire



Main coil



Iron of dual aperture quadrupole

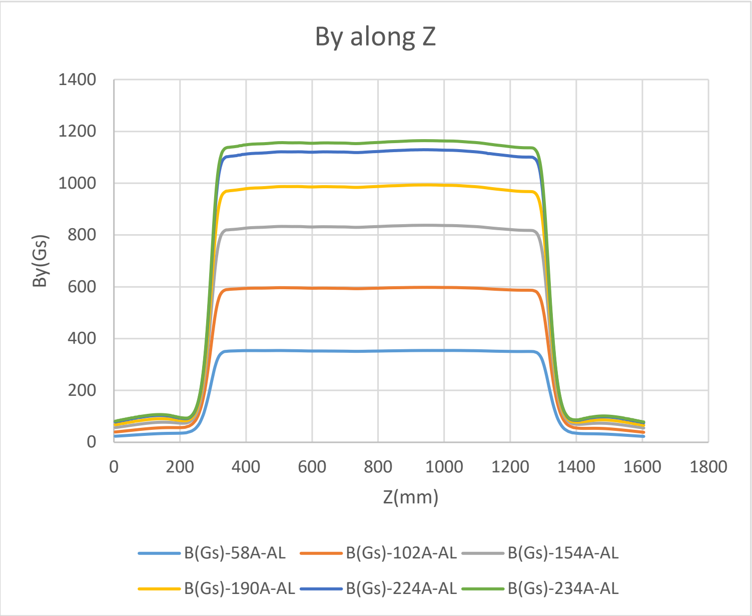


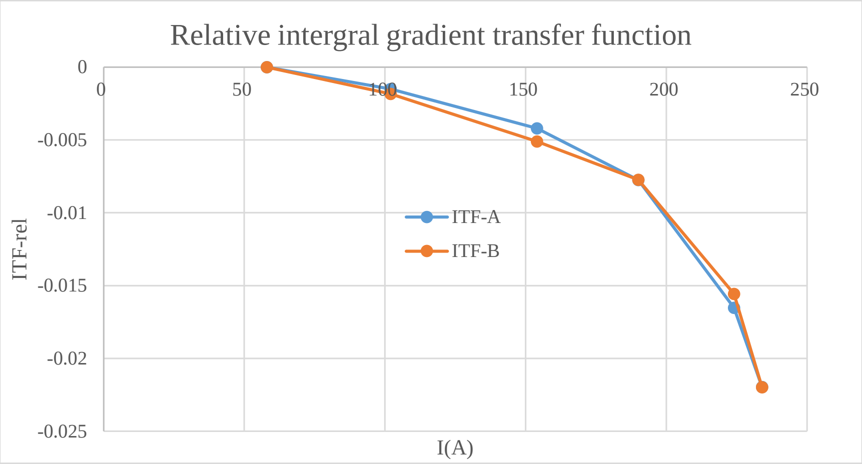
Dual aperture quadrupole prototype

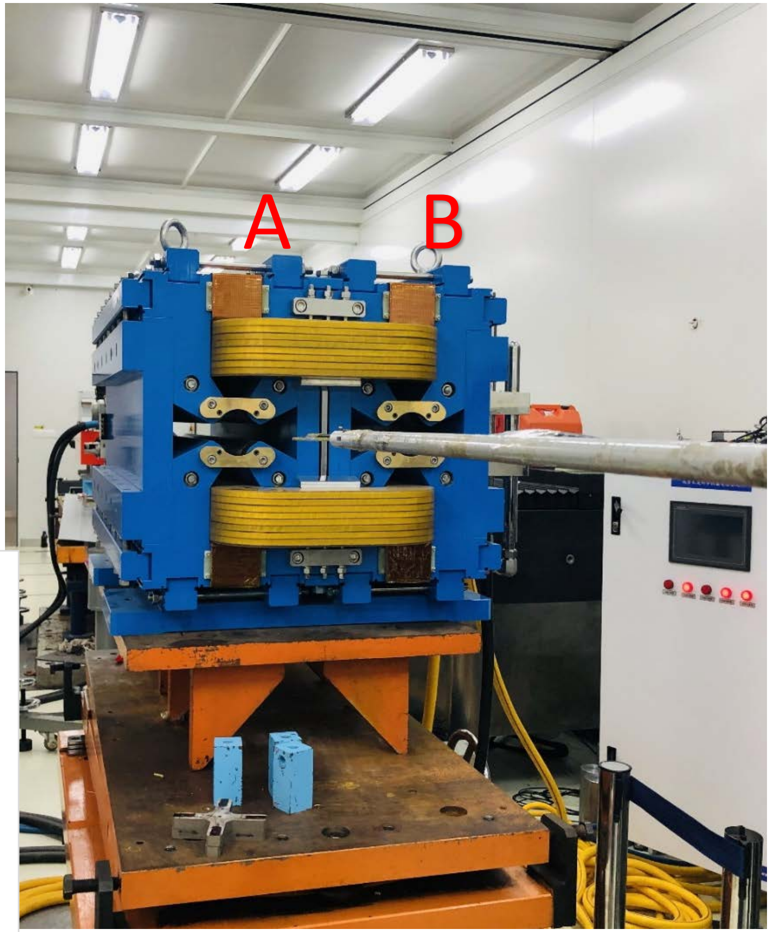
Primary field measurement results

Hall Probe measurement with the DT4 sheet.

- **Aperture A:Defocus G<0**
- **Aperture B:Focus   G>0**
- **GL is obtained by the integral field at x=-12.2mm and 12.2mm.**

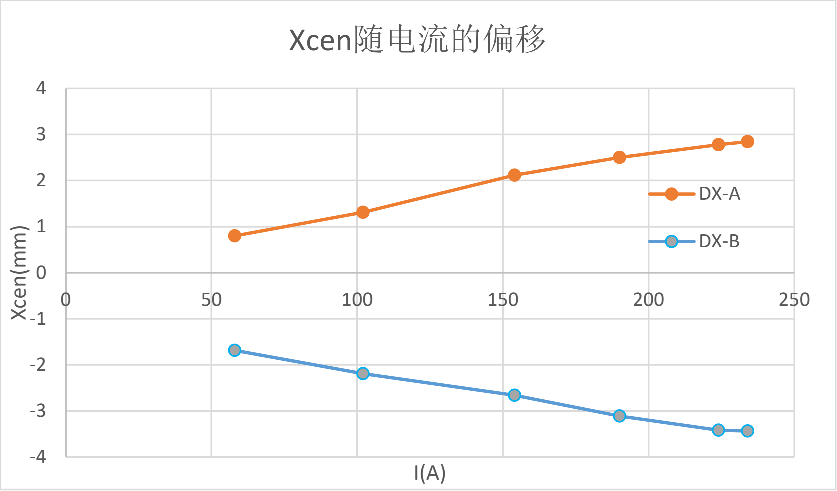


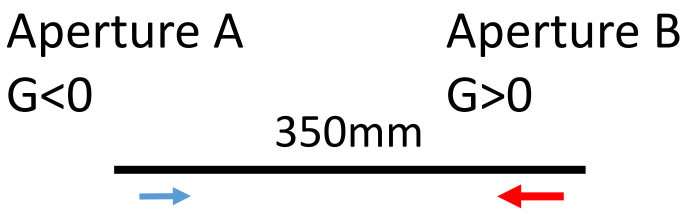




Primary field measurement results

- **The magnetic center at x direction shift by 2mm in aperture A and by -1.7mm in aperture B when the energy rises from 45GeV to 182.5GeV whereas the mechanical center distance between the two apertures is 350mm**





- **The gradient difference between the two apertures is about 0.5%.**

Summary

- ✓ Two kinds of subscale prototype dipole magnet with and without iron cores for the CEPCB were designed and fabricated.
- ✓ The test results showed that the field quality of CT coil dipole magnet without iron cores were satisfied with the requirements both at low and high field levels, whereas the dipole magnet with iron cores could not meet the requirements at low field level of 28 Gs due to the unavoidable difference of the remnant field.
- ✓ The prototype DAD and DAQ magnets for the Collider were designed and produced.
- ✓ The test results of the DAD magnet had a good consistent with the simulated ones and met the physical requirements.
- ✓ The integral field in two aperture of the DAQ magnet have been measured by the Hall probe measurement system. The field errors of the magnet will be measured the stretched wire or rotating coil measurement system.

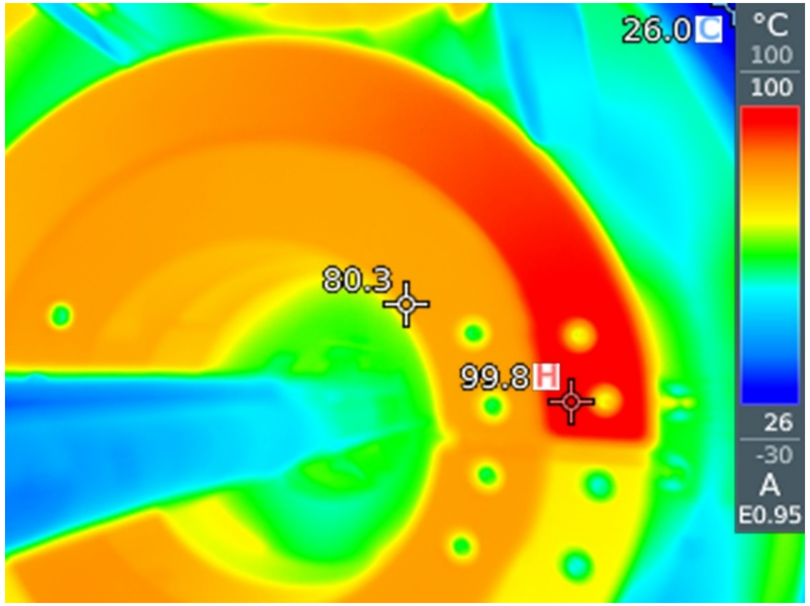
Thank you for your attention！

Backup slides

Problems of the CT coil dipole magnet

A serious problem is that the temperature of the coils increases to 80°C-100°C when the field increases to high level.

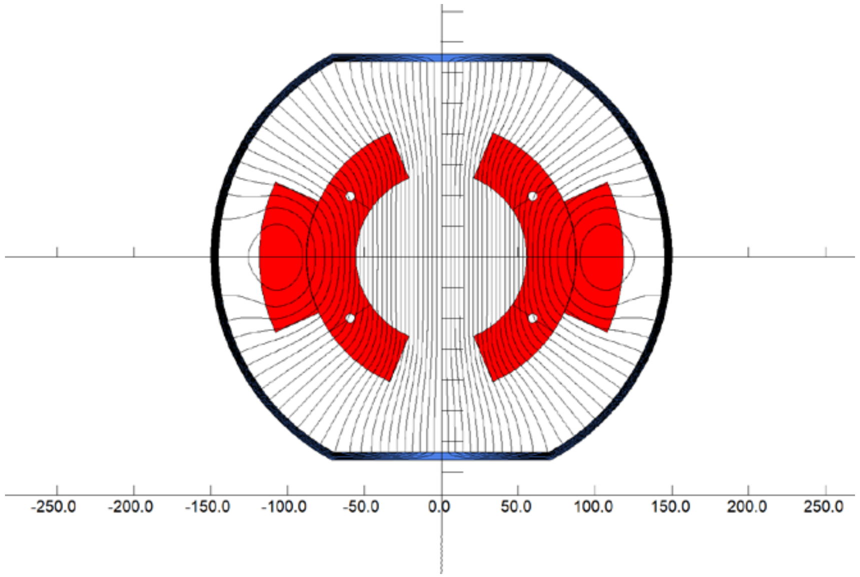
- The reason is that the aluminum alloy not the pure aluminum was selected as the material of the conductors because of its good mechanical properties.
- However, the resistivity of the aluminum alloy is 1.6 times larger than the pure aluminum.
- In addition, the touch resistance of the contacted surfaces of the conductors is larger than the expected one.

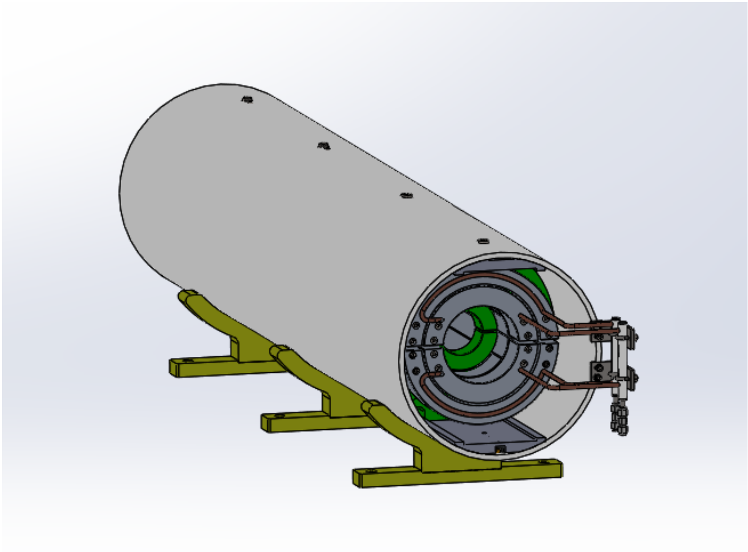


Problems of the CT coil dipole magnet

To decrease the temperature of the coils at high field level in future,

- ✓ **The pure aluminum not aluminum alloy will be selected as the material of the conductors.**
- ✓ **Increasing the cross section areas of the conductors or considering to insert water cooling tube into the coils.**
- ✓ **Coating the silver film on the touch surfaces of the connected conductors.**





Test of the subscale dipole magnets

- ✓ **The reason that the magnet performance at low field level is worse than that at high field level is probably the influence of remnant field in the shielding cylinder and field adjustment plates.**
- ✓ **The test results show that the remnant field in the aperture of the magnet is about 2.14Gs and the difference of the remnant field in the GFR is 0.066Gs, which causes the precision at low field level worse than high field level.**