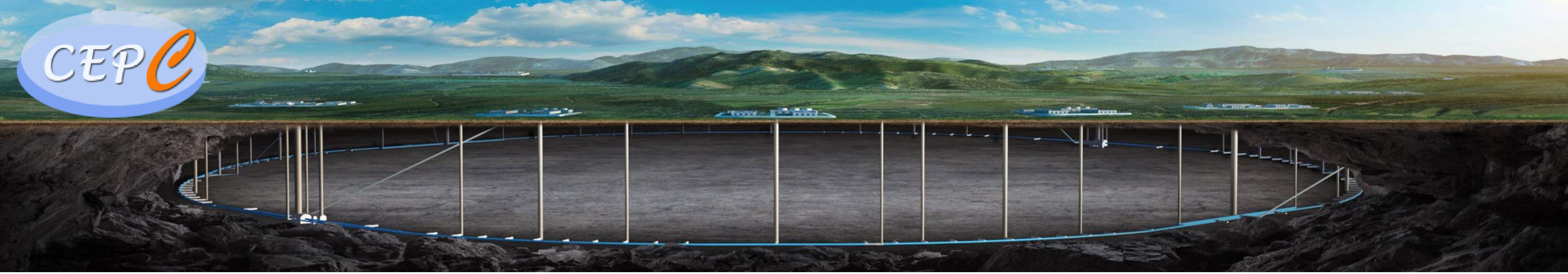


Magnet Design and R&D Status in CEPC Collider Ring

Mei Yang

On behalf of CEPC Magnet Group

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Content

- Overview of CEPC Collider ring magnets
- Dual Aperture Dipole (DAD) design
  - Short DAD prototype with sextupole component
  - Long DAD prototype and field measurement results
- Dual Aperture Quadrupole(DAQ) design
  - First prototype
  - Optimization design and prototype modification
  - Field measurement results
- Summary

Overview of CEPC collider magnet system

- Over 80% of collider ring is covered by conventional magnets, except some in IR region. All these magnets work at DC mode. (CEPC TDR)

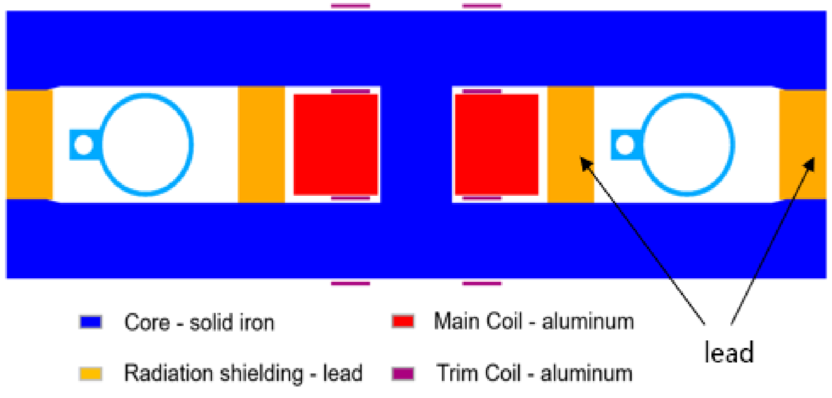
	Dipole	Quad.	Sext.	Corrector	Total
Dual aperture	3008	3008	-	-	17562
Single aperture	162	1120	3176	3544*2	
Total length [km]	68.71	9.95	2.17	3.1	83.9
Power[MW]@120GeV	6	17.5	8.91	0.28	32.7

- 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.
  - Increase the coil cross section and decrease the operating current.

Parameters of Dual Aperture Dipole(DAD)

- Dual aperture dipole parameters (TDR)

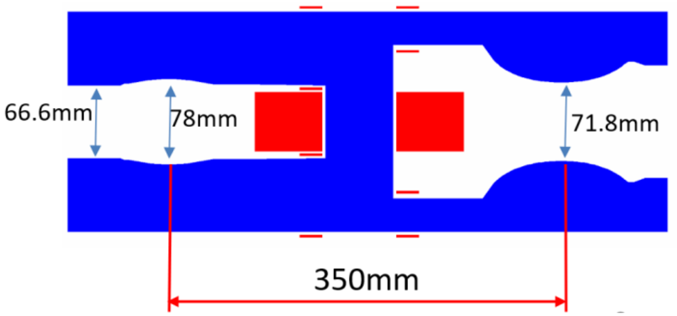
Field strength(Gs)	151~597
Aperture(mm)	**66**
Effective length(m)	19.7~23, 4 parts
GFR(mm)	11.6
Adjustment capability	±2.5%
Field quality	3×10^{-4}
Field difference in two apertures	<0.5%



- DAD design considerations
  - Low field with pure iron, in DC mode at four energies(45.5, 80, 120, 180 GeV)
  - Separate trim coils in two apertures with ±2.5% adjustability
  - Aluminum busbar coils, 2 turns, cost effective
  - Thickness of lead for radiation protection： 25mm
  - Beam separation: 350mm (vacuum chamber, lead, coil)

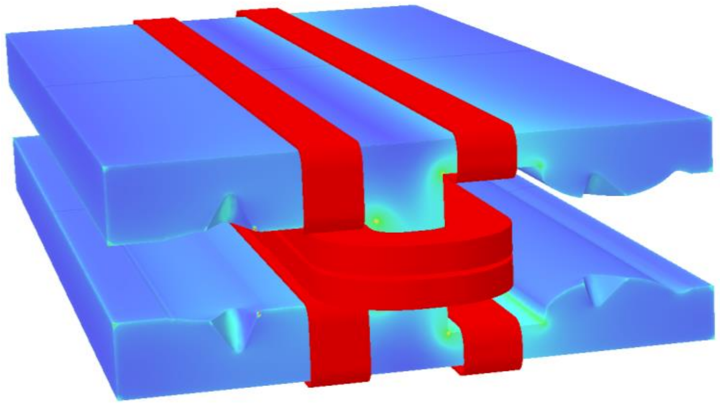
Short DAD prototype with sextupole component

- First short prototype of 1m （CEPC CDR)
  - Dual aperture dipole with sextupole component
  - Simple, pure solid iron, worked at DC mode
  - Low field range from 141Gs to 540Gs
  - Aluminum busbar coils of 4 turns (compatible with PS)
  - Opposite polarities of sextupole component in two apertures



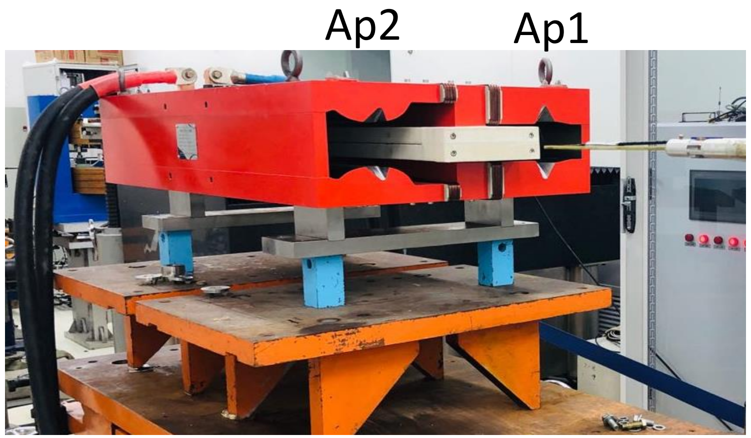
Ap1:Field adjustment@120GeV

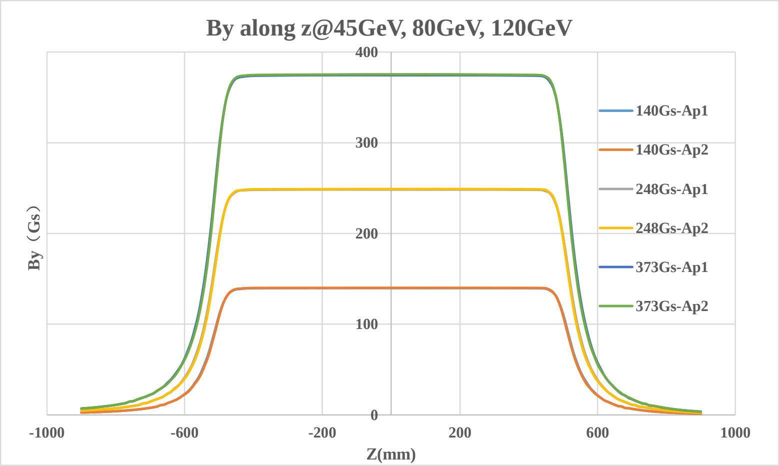
	B	B+1.5%	B-1.5%
B(T)	0.037324	0.037892	0.036756
S(T/m^2)	4.888	4.9612	4.8145
	Harmonics(Bn/B1,1e-4)		
1	10000	10000	10000
2	-0.68	-0.606	-0.751
3	119.34	119.309	119.362
4	0.79	0.795	0.778
5	-3.42	-3.423	-3.418



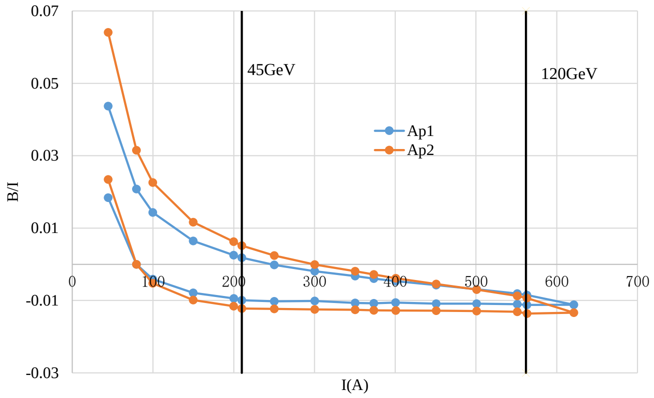
Field measurement results of short prototype

- Field measurement results by Hall probe
  - Field difference <0.3%



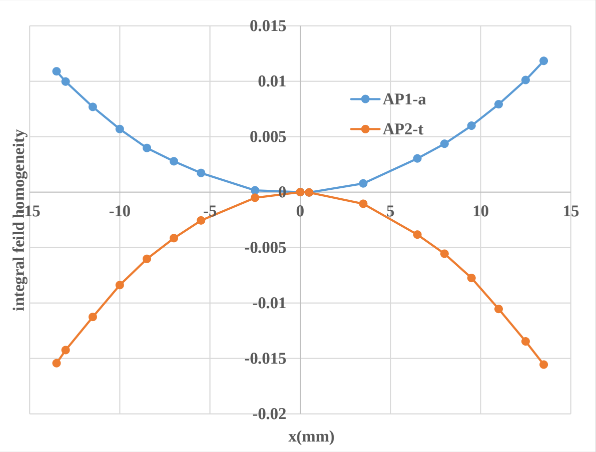


By along Z at different strength



B/I Transfer function

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%



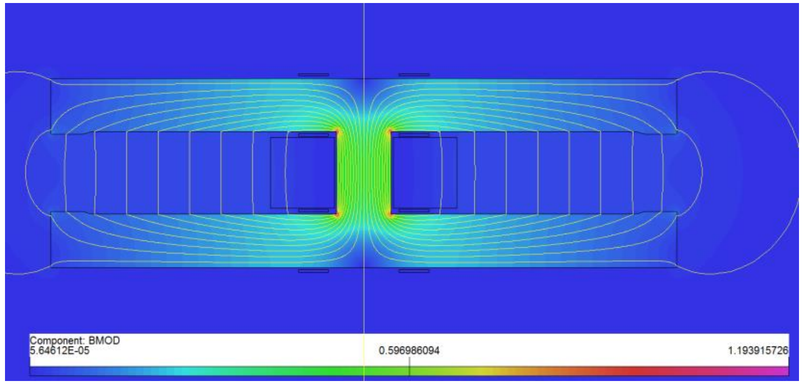
Measured integral field in the vertical midplane (y=0)

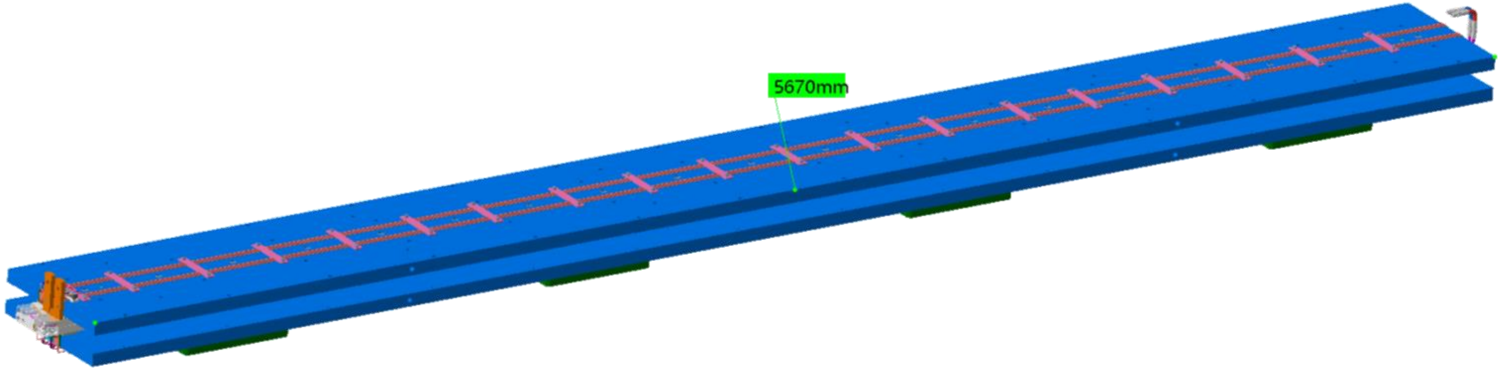
n	Ap1@45GeV	Ap2@45GeV
2	4.38	-1.40
3	113.24	-157.23
4	4.49	-2.00
5	0.015	2.14
6	-4.29	2.60

Long DAD prototype

- Long dual aperture dipole（DAD）magnet design: 5.67 m
  - Two turns of busbar coils (60*27mm) made of Aluminum with a cooling hole(dia.=5mm)
  - Solid iron with DT4, simple “I” shaped yoke

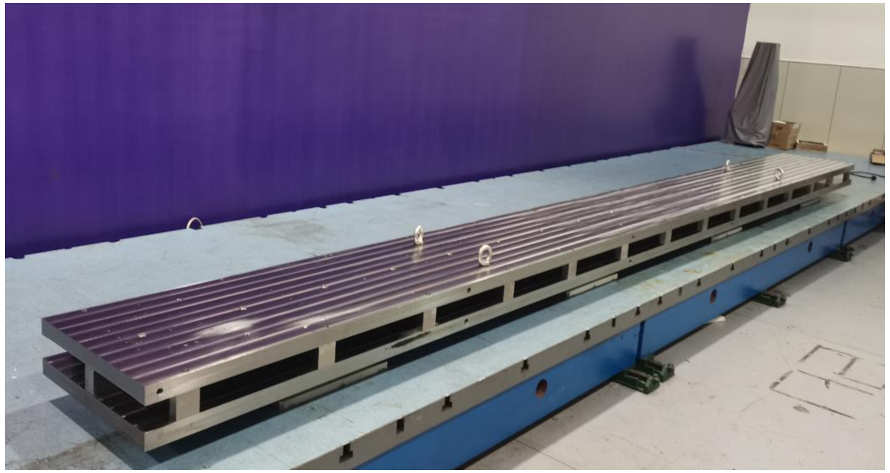
- Mechanical design
  - Several interleaved blocks at the open gap to keep the gap height.
  - Four supporters at the bottom with a maximum deformation of 0.017mm.

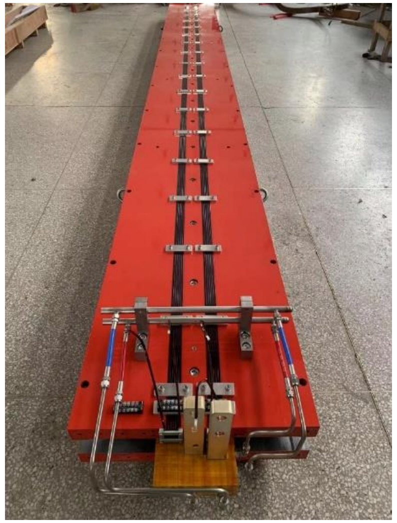




Long DAD prototype

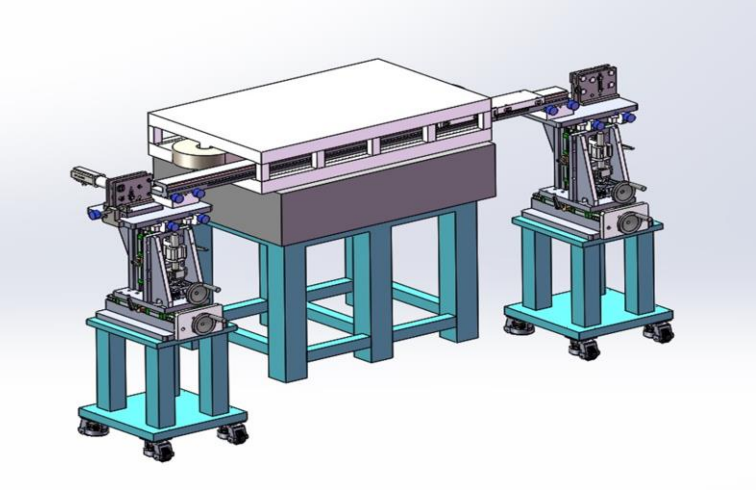
- Development progress
  - Aluminum busbar coils are finished processing, with a surface insulation of ceramic insulation coating.
  - The yoke is finished on a CNC machine, and gap tolerance is within ±0.05mm.
  - Test of the coils: resistance test, turn to turn insulation test, and so on.
  - Final assembly is finished.

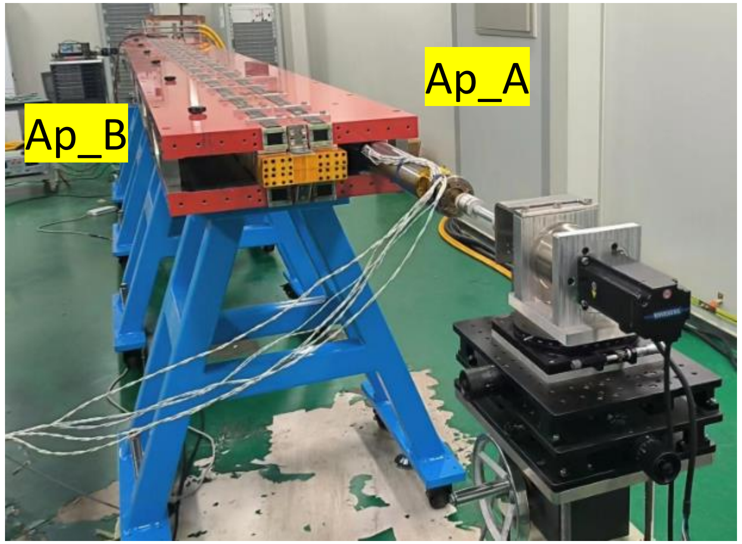


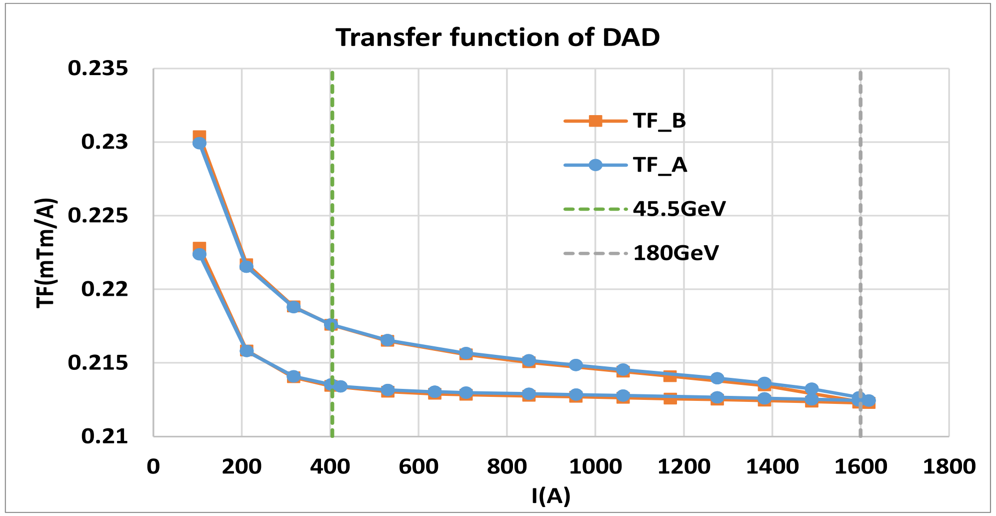


Field measurement of long DAD prototype

- Field measurement results
  - Integral field measured by Hall probe
    - By=378.3Gs@120GeV
    - Leff=5746.8mm
  - Integral transfer function
    - Very consistent in two apertures
    - Integral field difference< 0.1%



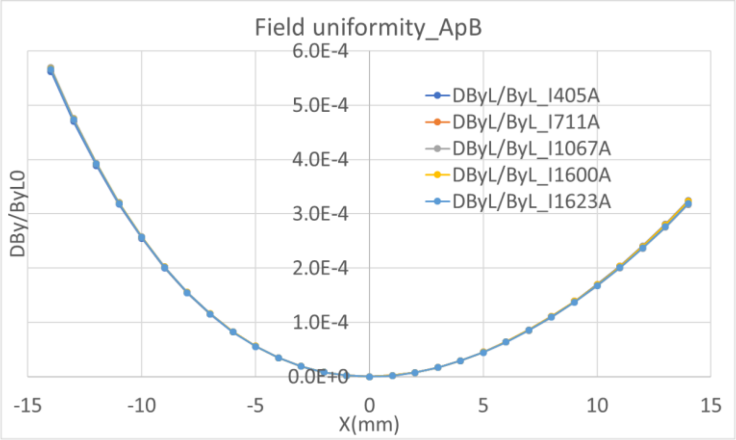




Integral transfer function in two apertures

Field measurement of long DAD prototype-2

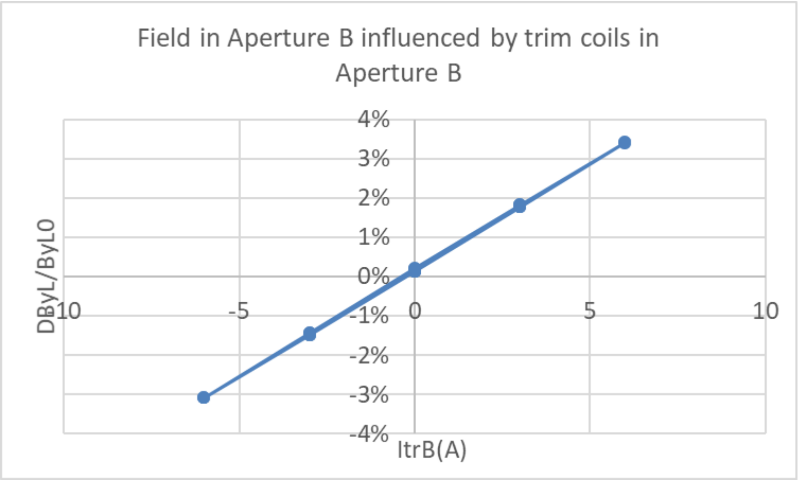
- Higher harmonics in two apertures
  - The field distribution is nearly the same in two apertures.
  - So as the high harmonics at four energies.
- Trim coils excitation test
  - Research on Testing Multiple Powering Methods
  - Hysteresis effect with trim coils

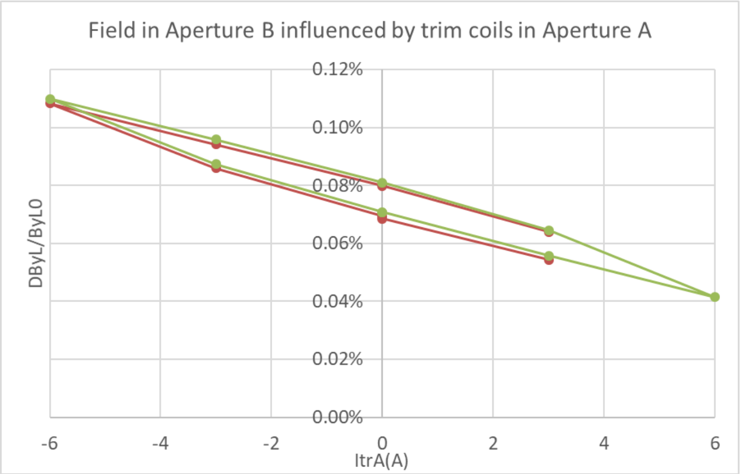


Integral field uniformity in Ap B

High harmonics @120GeV (units:1e-4)

n	bn_A	bn_B
2	0	0
3	3.92	3.88
4	1.03	-1.22
5	0.47	0.54
6	0.08	-0.46





Main design parameters of DAD

- I shaped solid iron with aluminum busbar coils

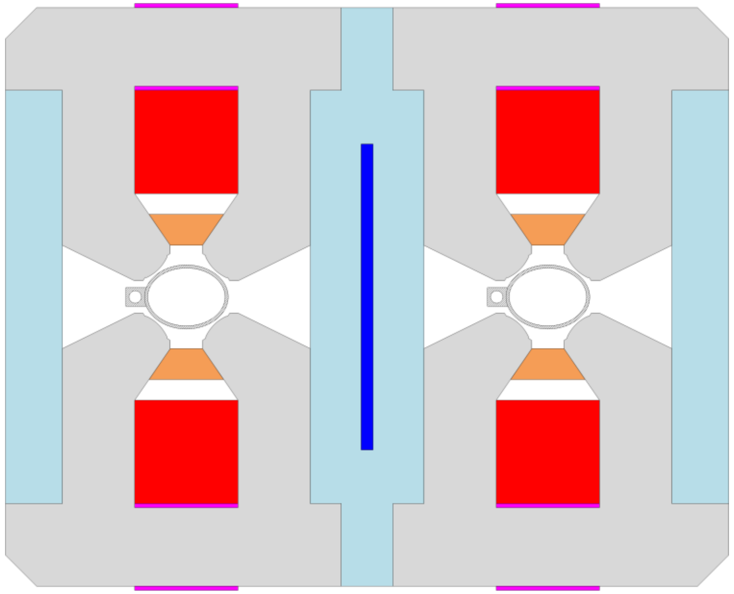
Magnet name	B0A	B0B
Quantity	1024	1920
Magnetic length[m]	19.743	23.142
Aperture [mm]	**66**	**66**
Field strength [Gs] @45.5 GeV	150.9	150.9
Field strength [Gs] @180 GeV	597	597
Good field region [mm]	11.6	11.6
Field errors [$\times10^{-4}$]	±3	±3
Ampere turns [At]	3200	3200
Turns per magnet	2	2
Current[A] @180GeV	1600	1600
Size of conductor [mm×mm]	60×27-Al	60×27-Al
Max current density [A/mm^2]	1.0	1.0
Resistance of the coil [mΩ]	1.55	1.79
Power loss (kW) @180GeV	3.96	4.58
Core height [mm]	160	160
Core width [mm]	530	530
Core length [m]	4.87m×4	5.72m×4

Dual Aperture Quadrupole (DAQ)

- Basic parameters of DAQ (CDR)

Item	Units	Value
Number of magnets		2392
Aperture diameter	mm	76
Gradient at 45.5 GeV	T/m	3.2
Gradient at 180 GeV	T/m	12.63
Effective length	m	2
Trim coil adjustability		±1.5%
Good field region	mm	12.2
Harmonics		5×10^{-4}

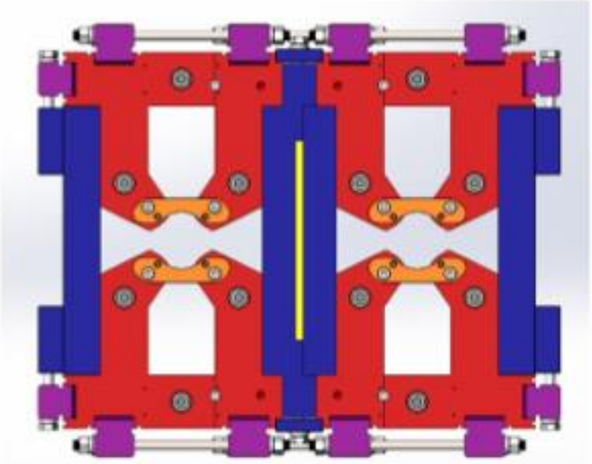
- First F/D prototype features
  - DT4 compensation sheet
  - Trim coils located on the yoke, far from the midplane.
  - Hollow water cooled aluminum conductor.
  - Large leakage field at the outside and middle of the magnet.
  - Strong dipole field at the end.
  - Lead blocks for radiation shielding

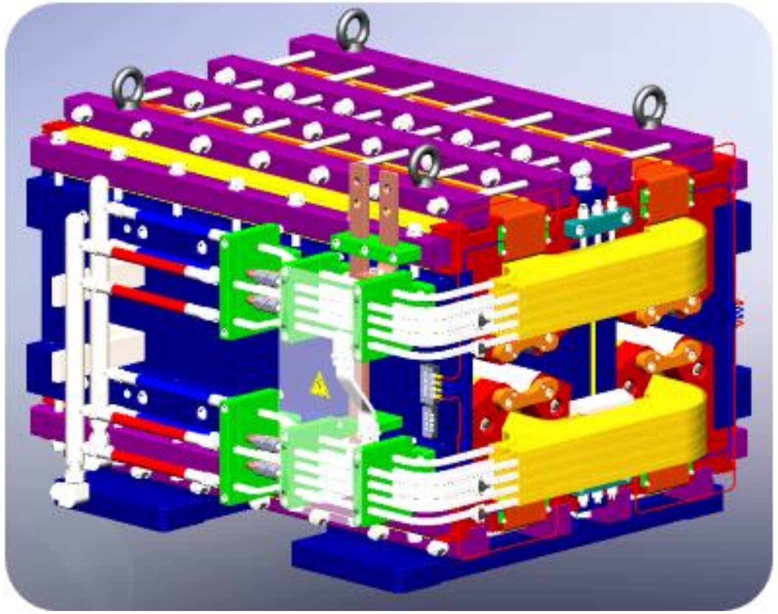


First F/D design, CDR,2018

First DAQ prototype and design parameters

- The first prototype is a laminated one with DT4 compensate sheet in the middle.
- Complex mechanical structure:
  - The iron is divided into many blocks with two kinds of laminations.
  - The poles are slender, the mate surface serve as reference surface.
  - Difficult to control the mechanical tolerance.

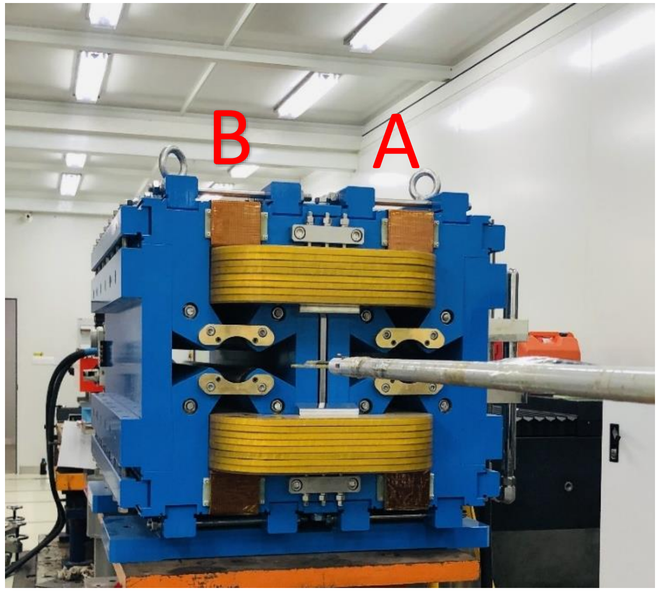


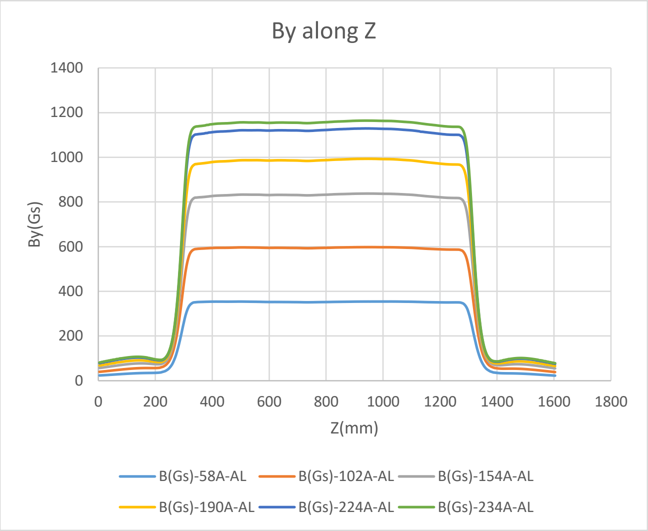


Beam separation [mm]		350
Effective length [m]		1
Gradient [T/m]@120GeV		8.42
Aperture [mm]		76
Main coil	Turns	64×2
	Wire size[mm]	11×11, ϕ7, R1
	Current [A]	154
	Current density [A/mm²]	1.89
	Power [kW]	3.2
Trim coil	Turns	20×4
	Wire size[mm]	4×2, R0.2
	Current [A]	7.5
	Current density [A/mm²]	0.94
	Power [kW]	0.04
Cooling para	Water drop [kg/cm²]	6
	Water circuits	4
	Velocity[m/s]	1.3
	Flow[l/s]	0.201
	Temp rise [°C]	6.3

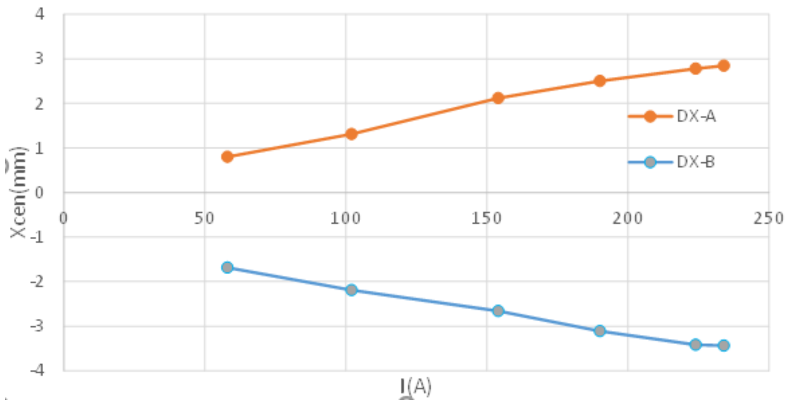
Preliminary field results of first prototype

- The first 1m long prototype was fabricated and tested by Hall probe measurement system.
  - Large edge field;
  - GL difference in two apertures: less than 0.5% (except 80 GeV)
  - Problems: large offset of magnetic center in X direction with the energies



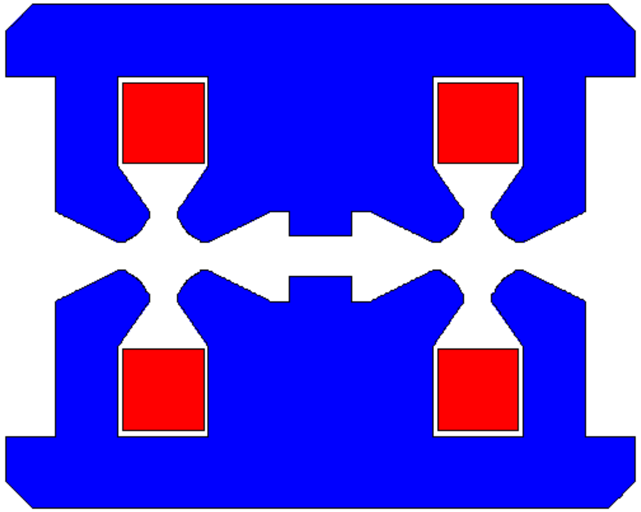


E(GeV)	I(A)	GL(T)-A	GL(T)-B	GL_A/GL_B-1
45	57.99	-3.36	3.35	0.40%
80	101.99	-5.91	5.88	**0.59%**
120	153.98	-8.89	8.85	0.49%
148	189.98	-10.93	10.89	0.40%
175	223.99	-12.77	12.73	0.30%
182.5	233.99	-13.27	13.21	0.40%

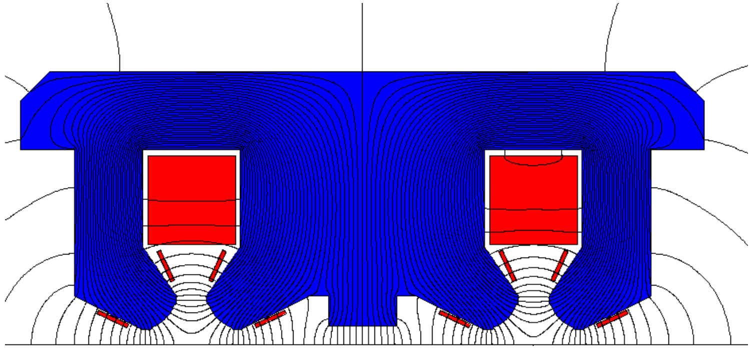


Optimization of DAQ

- Based on the prototype, with a center shim, the DAQ has a common yoke and makes the flux distribution symmetrical in one single aperture.
  - @120GeV: b1 and b3 reduced a lot.
  - No obvious shift in X axis at different energies.
- Trim coils layout
  - Trim gradient in the concerned aperture and no other harmonic introduced.
  - No effect on the other aperture.

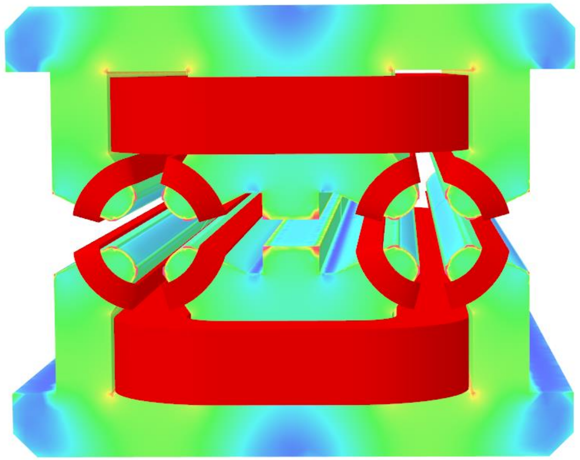


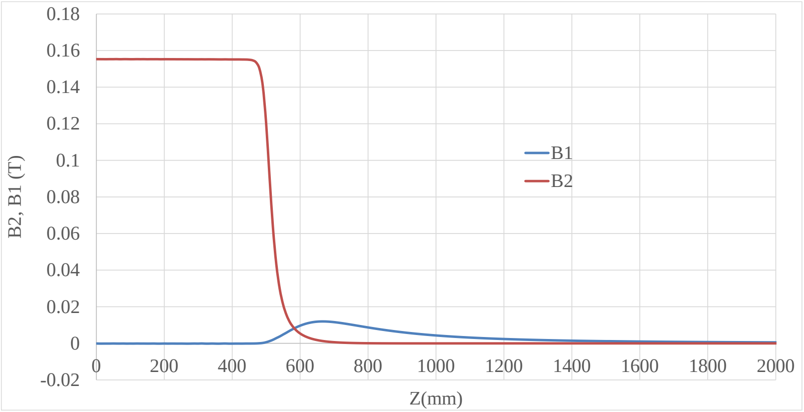
E=120GeV	origin		center shim	
n	Bn/B2-L	Bn/B2-R	Bn/B2-L	Bn/B2-R
1	1557.30	-1557.27	-13.51	13.53
2	10000	10000	10000	10000
3	126.14	-126.18	-1.11	1.06
4	0.52	0.52	0.51	0.53
5	1.70	-1.71	-0.02	0.01
6	-0.04	-0.03	-0.04	-0.03
B1(T)	-0.01622	-0.0162197	0.00014	0.00014
B2(T)	-0.1041546	0.1041547	-0.10411	0.10411
B3(T)	-1.31E-03	-0.0013143	0.00001	0.00001
G(T/m)	-8.537	8.537	-8.534	8.534
S(T/m2)	-17.654	-17.660	0.155	0.149



3D simulation of DAQ

- 3D simulation results
  - The shared coils can be seen as a dipole coil and has a dipole field intrinsically.
  - The dipole field and quadrupole field have different end effects and the gradient decay faster than the dipole field.
  - The final center shim is determined by 3D simulation.



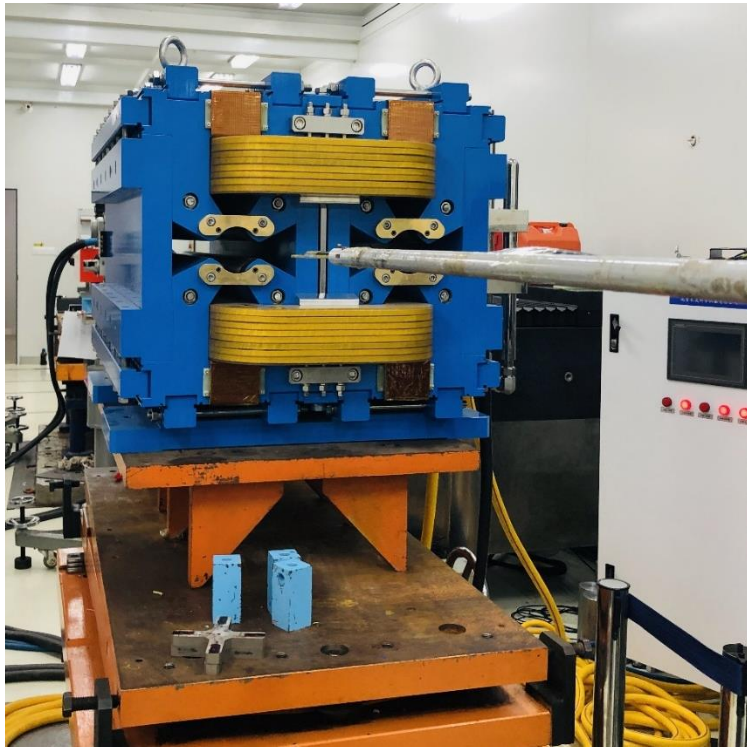


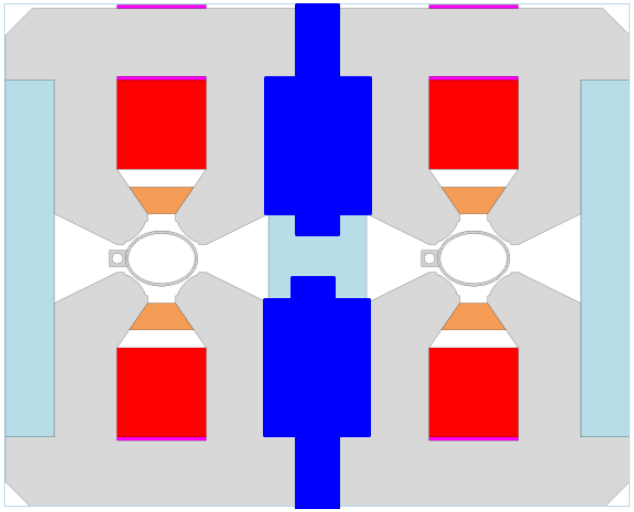
n	b_n_45.5 GeV	b_n_120 GeV	b_n_180 GeV
3	-1.76	-1.77	-2.31
4	0.57	0.61	0.63
5	0.03	0.03	0.03
6	-1.05	-1.06	-1.07

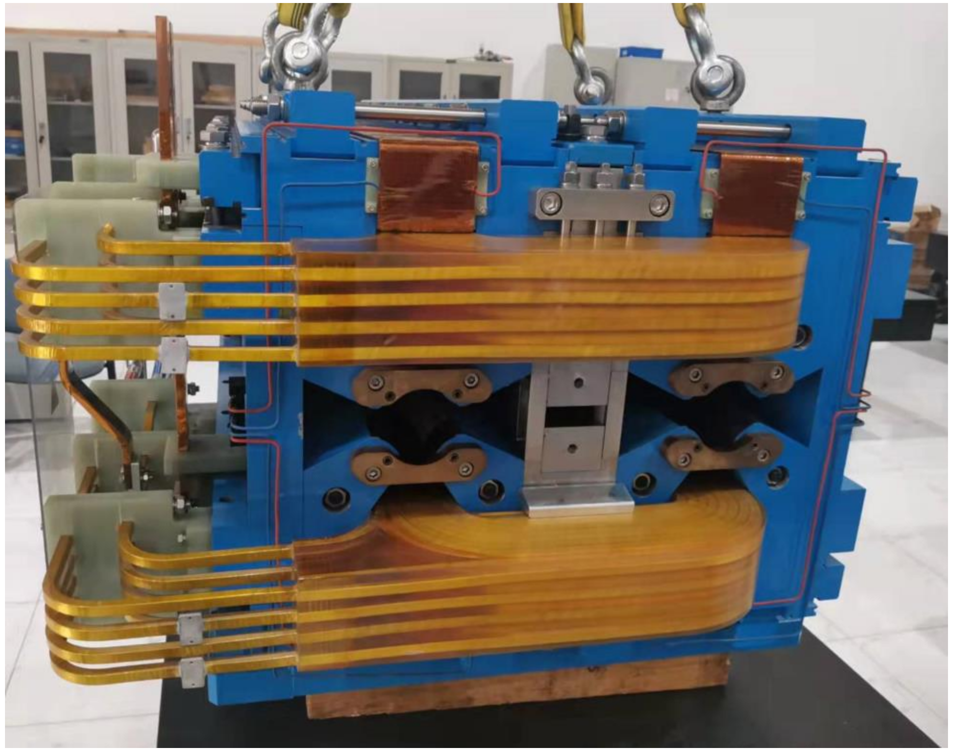
Distribution of dipole and quadrupole field along Z axis @ 180GeV

Modified DAQ prototype

- 1m-long prototype modification
  - DT4 iron blocks in the middle instead the DT4 sheet and stainless steel.



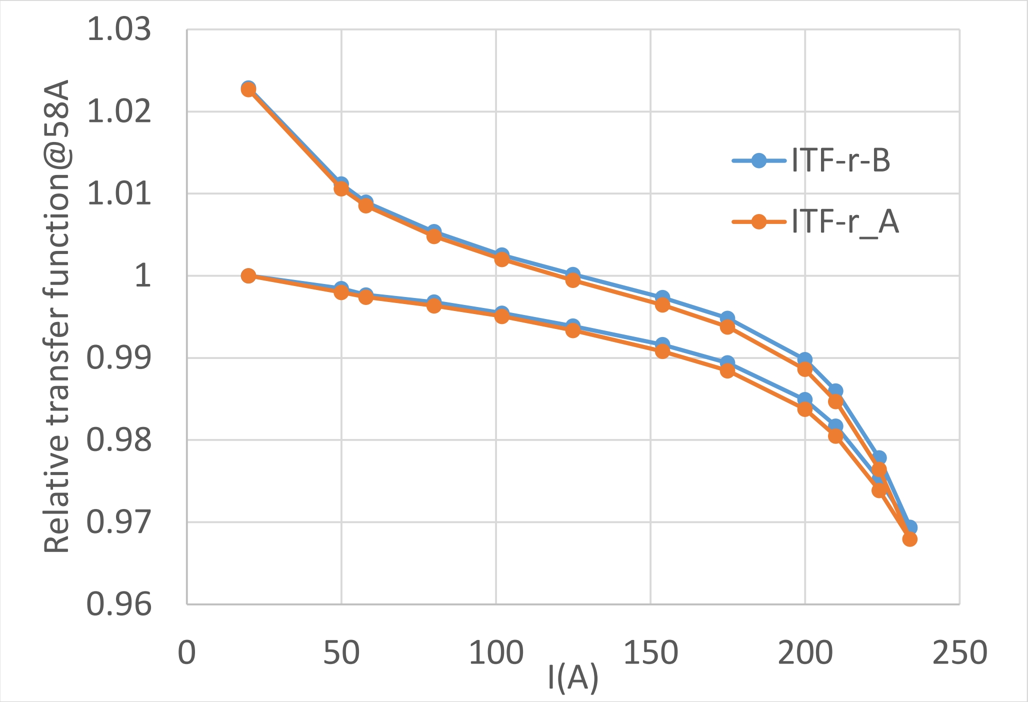




Prototype modification and field measurement results

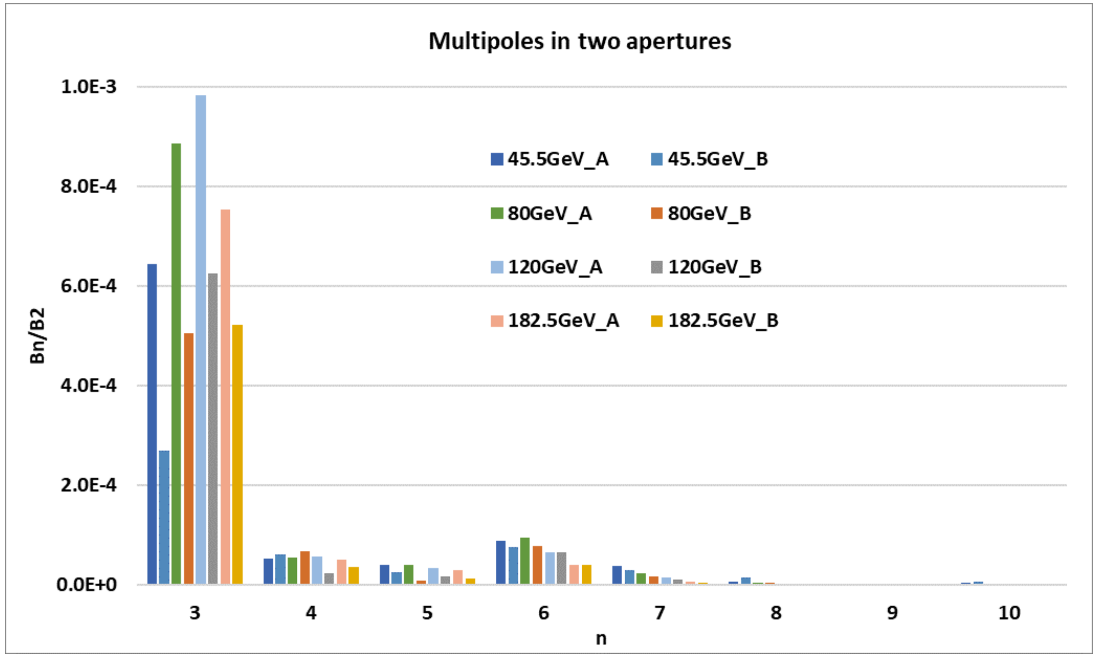
- Rotating coil measurement results
  - Similar transfer function in two apertures.
  - GL difference in two apertures <0.2%
  - The efficiency is about 97.8%, not saturated.

E(GeV)	Ireal(A)	PHI2_A	PHI2_B	BL_A/BL_B-1
45.5	57.99286	0.02407	0.024025	0.19%
80	101.9951	0.042234	0.042161	0.17%
120	153.9915	0.063491	0.063409	0.13%
182.5	233.9919	0.094249	0.094182	0.07%



Prototype modification and field measurement results

- Harmonics:
  - Higher harmonics: less than 3 units, except sextupole component.
  - Possible reasons:
    - Large mechanical assemble errors;
    - Iron deformation;
    - Cross talk effect is not compensated completely.
  - Possible solutions:
    - Adjust the center compensate blocks.
    - Magic finger to adjust the field.



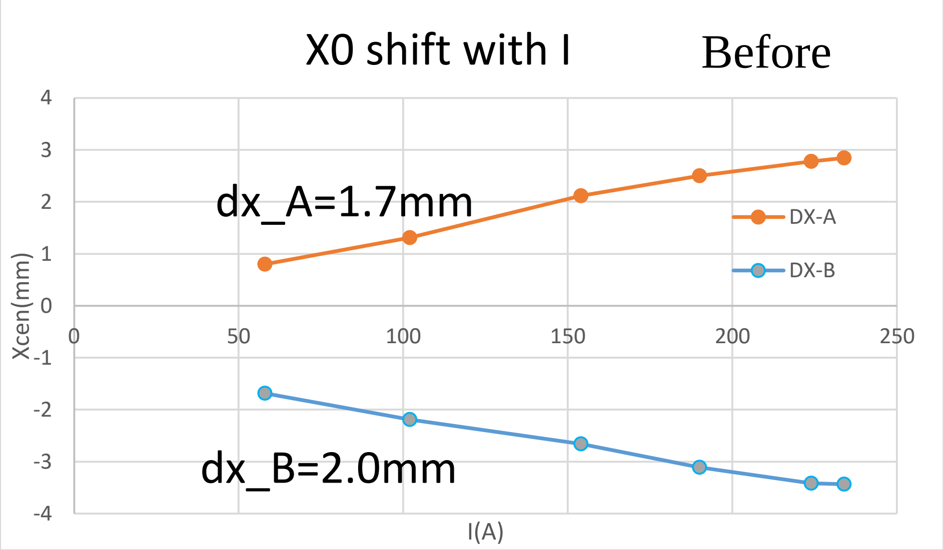
Prototype modification and field measurement results

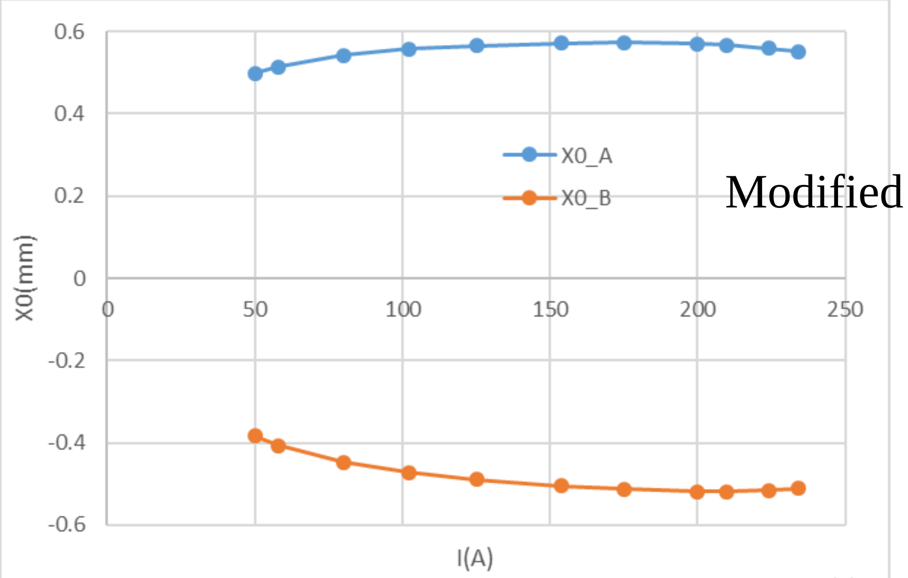
- Magnetic center X0 shift with energy
  - X0_A varies 0.056mm， X0_B varies 0.105mm
  - Possible reason: incomplete compensation; iron properties different.

  - Y0_A varies 0.04mm
  - Possible reason: Busbars’ location.

E(GeV)	Ireal(A)	X0_A(mm)	Y0_A(mm)	X0_B(mm)	Y0_B(mm)
45.5	57.99286	0.514	0.174	-0.406	-0.078
80	101.9951	0.557	0.166	-0.472	-0.074
120	153.9915	0.571	0.157	-0.505	-0.069
182.5	233.9919	0.551	0.133	-0.511	-0.072
	max-min	0.056	0.040	0.105	0.009

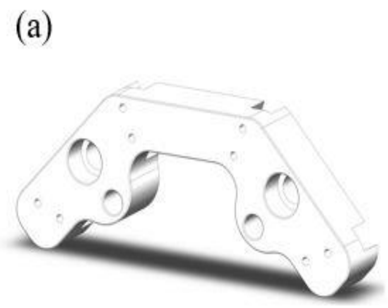
The fixed x0 shift can be adjust by the correctors or dipole magnet.

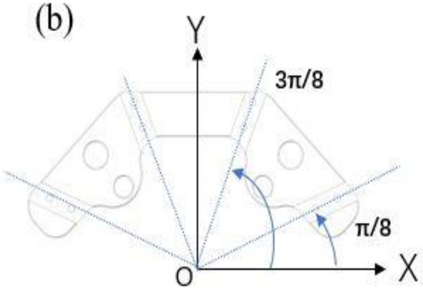




Modification 2- harmonic adjustment

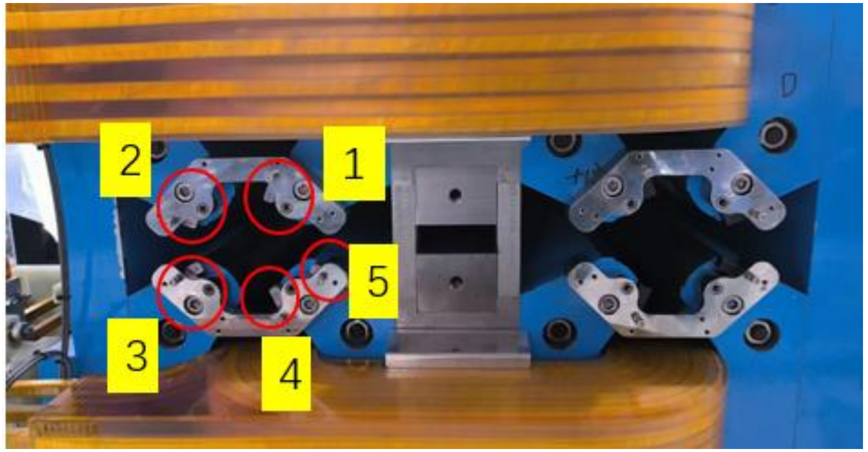
- Harmonic compensation
  - Cut down the high harmonics by magic fingers

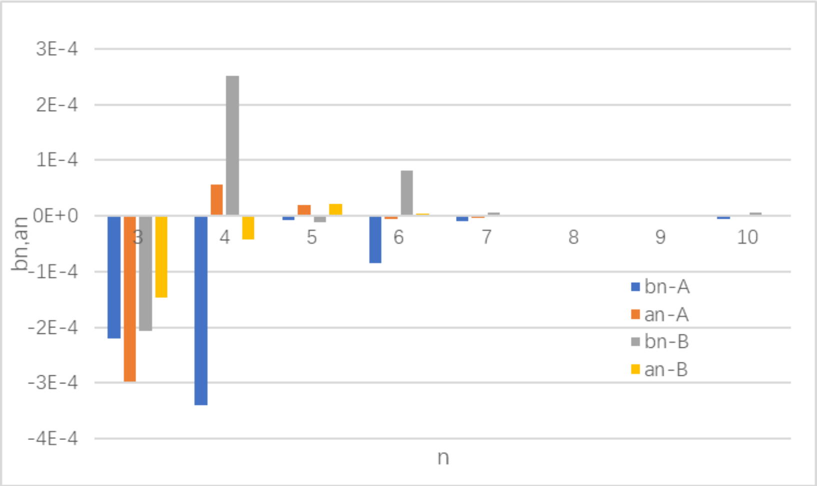


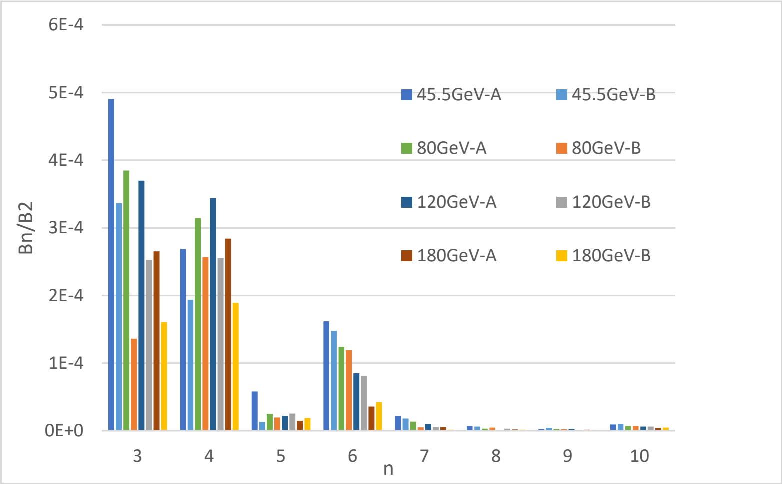


Measured magnetic centers in mm and field harmonics in units of 1×10^{-4} at four currents

E (GeV)	x0_A	y0_A	b_3_A	a_3_A	x0_B	y0_B	b_3_B	a_3_B
45.5	-0.082	0.084	2.46	-4.24	0.044	-0.007	3.64	-0.83
80	-0.039	0.081	-1.20	-3.76	-0.018	-0.009	-3.04	-1.18
120	-0.021	0.075	-2.2	-3.15	-0.054	-0.012	-1.52	-1.52
180	-0.012	0.055	1.94	-1.92	-0.087	-0.007	1.98	-0.79







TDR design parameters of DAQ

- Main DAQ design parameters

Magnet name	Q
Quantity	3008
Magnetic length[m]	3
Aperture [mm]	72
Field gradient [T/m] @180 GeV	10.6
Good field region [mm]	11.6
Field errors [$\times 10^{-4}$]	±3
Ampere turns [At]	11369
Turns per magnets	144
Current[A]@180GeV	158
Size of conductor [mm×mm]	11×11, d7, r1.5-Al
Max current density [A/mm^2]	2
Resistance of the coil [mΩ]	377
Power loss (kW) @180GeV	9.4
Water drop (Kg/cm^2)	6
Number of water loops	8
Velocity [m/s]	1.41
Temperature rise [°C]	5.14
Core height [mm]	560
Core width [mm]	700

CDR:
D=76mm
G=12.63T/m@180GeV

Summary

- Efficient magnets have been designed for CEPC collider. The full length DAD prototype has met the requirements which verified the physical and mechanical design.
- The field cross talk effect has been solved for the DAQ. The center shim can compensate the cross talk effect and axis shift. And the trim coils wound on the poles only work on its own aperture.
- Further optimizations for the magnets are ongoing.

Thanks for your attention!