Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Circular Electron Positron Collider

CEPC Collider Ring Magnet R&D

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IHEP, CAS

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Outline

- Introduction
- Progress on Dual Aperture Dipole(DAD)
  - Short dual aperture dipole with sextupole component
  - Long dipole prototype design
- Progress on Dual Aperture Quadrupole(DAQ)
  - Short DAQ prototype and problem
  - Optimization of DAQ
  - Another Scheme design of DAQ
- Progress on Sextupole
- Summary

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

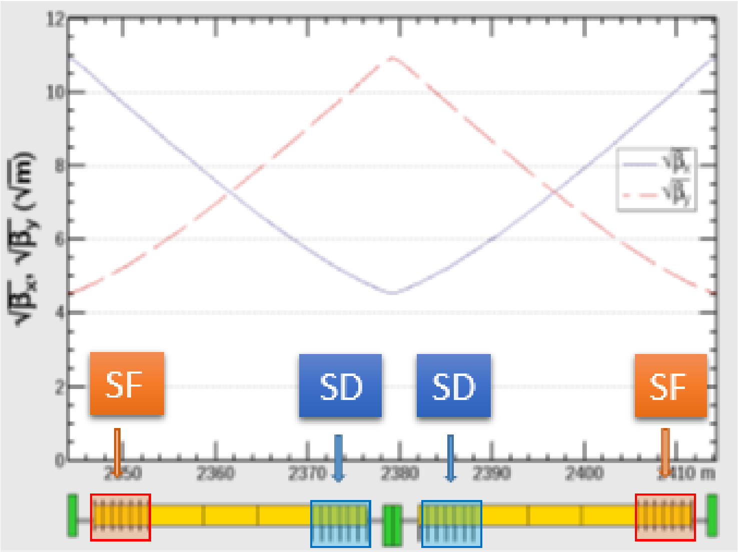
- The most important issues are Cost & Power Consumption.
  - Make the magnets compact and simple.
  - Aluminum wire is used for the excitation coils.
  - Dual aperture magnets save nearly 50% power consumption.
  - Consider the combined function magnets.
  - Increase the coil cross section and decrease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

Parameters of the DAD

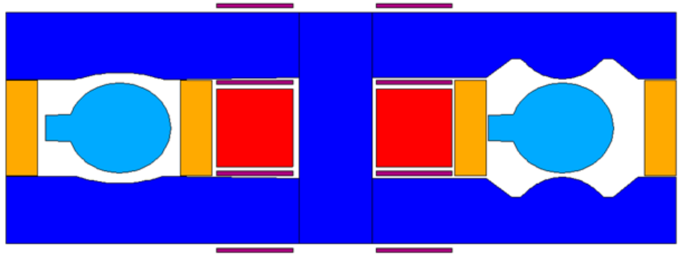
- Parameters of main dipole magnets.

Field strength(Gs)	140Gs~567Gs
Aperture(mm)	70
Effective length(m)	28.7m, 5 parts
GFR(mm)	13.5
Adjustment capability	±1.5%
Field quality	5×10^{-4}

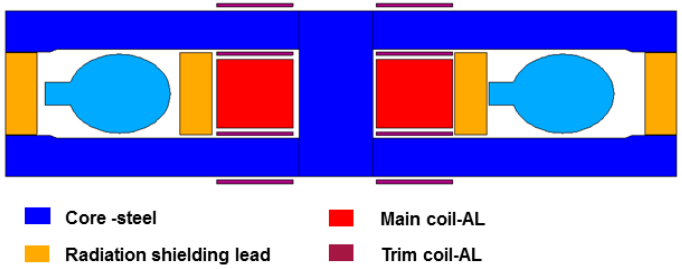
- Short prototype of DAD (1m in length)
  - Central field： 140Gs@45GeV~567Gs @182.5GeV
  - Difference between the two aperture center fields <0.5%
  - High order harmonics<5×10^{-4} @R=13.5mm(except b3)
  - Separate coils in two apertures： ±1.5%
  - Size of vacuum chamber： (W*H) 99mm ×62mm
  - Thickness of radiation lead： 25mm



The First and the last segments – sextupole combined.

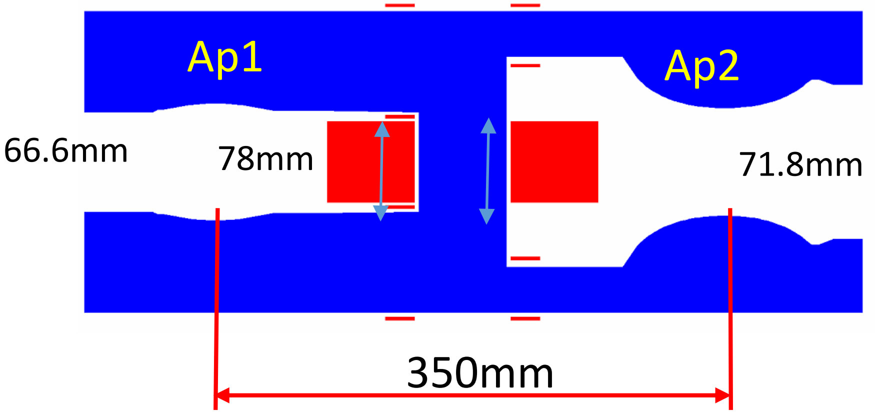


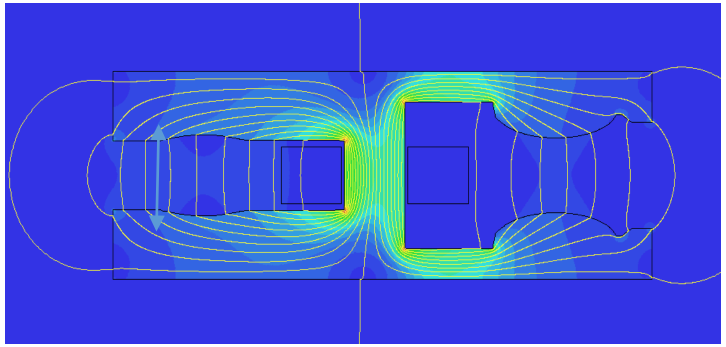
The three middle segments – dipole only.

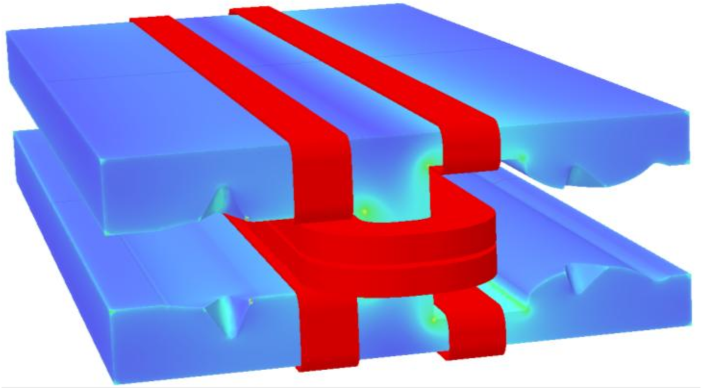


Short DAD prototype with sextupole component

- 2D&3D OPERA simulations are done and the results meet the requirements.







Field strength at different energy

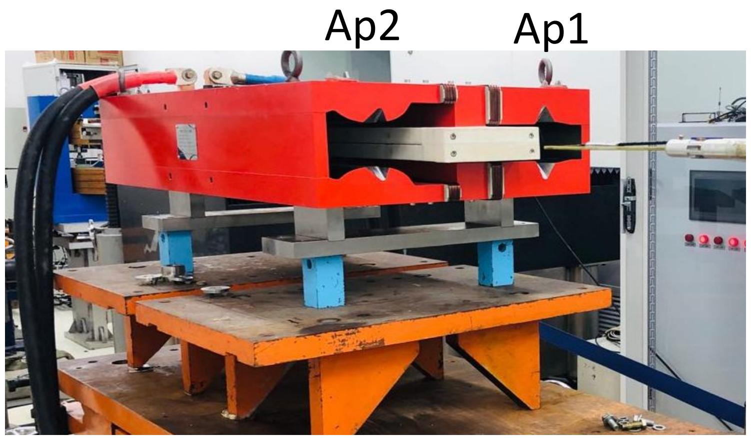
E(GeV)	J(A/mm2)	Ap1-B1(T)	Ap2-B1(T)	Ap1-S(T/m2)	AP2-S(T/m2)
45	0.263	0.01409	0.01405	1.846	-2.640
80	0.463	0.02486	0.02484	3.257	-4.668
120	0.694	0.03732	0.03734	4.888	-7.017

Ap1:Field adjustment@120GeV

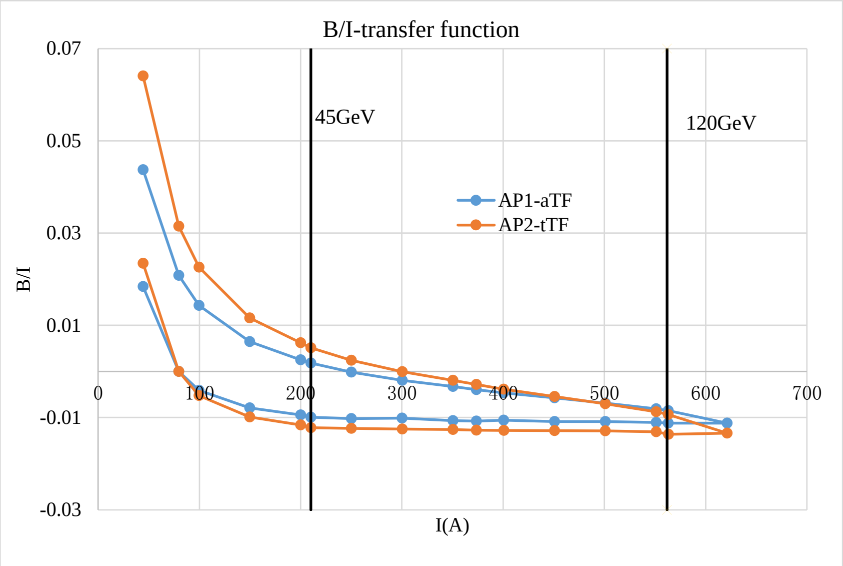
	B	B+1.5%	B-1.5%
B(T)	0.037324	0.037892	0.036756
S(T/m^2)	4.888	4.9612	4.8145
	Harmonics(Bn/B1,1e-4)		
1	10000	10000	10000
2	-0.68	-0.606	-0.751
3	119.34	119.309	119.362
4	0.79	0.795	0.778
5	-3.42	-3.423	-3.418

Short DAD field measurements: transfer function

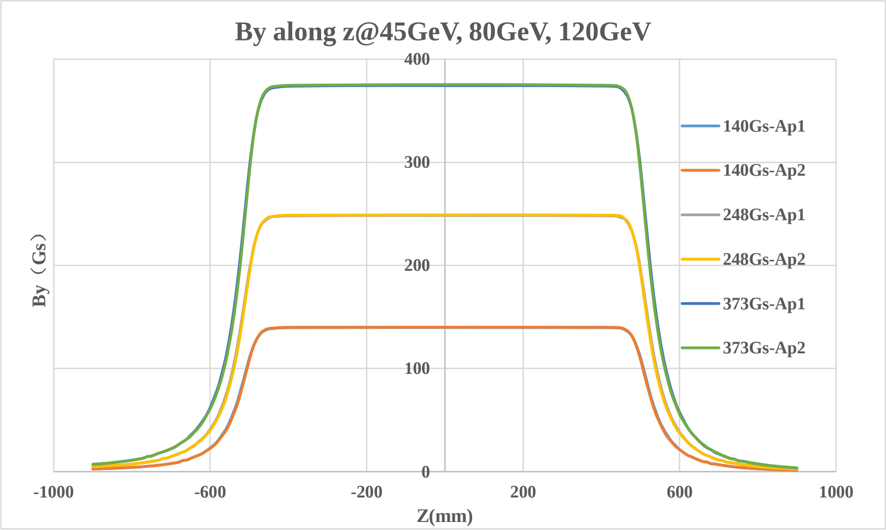
- The transfer function at two apertures:
  - Center field difference <0.3% in two apertures(residual field effect and different gaps at the two apertures).



Dipole measured by a hall probe system



B/I Transfer function



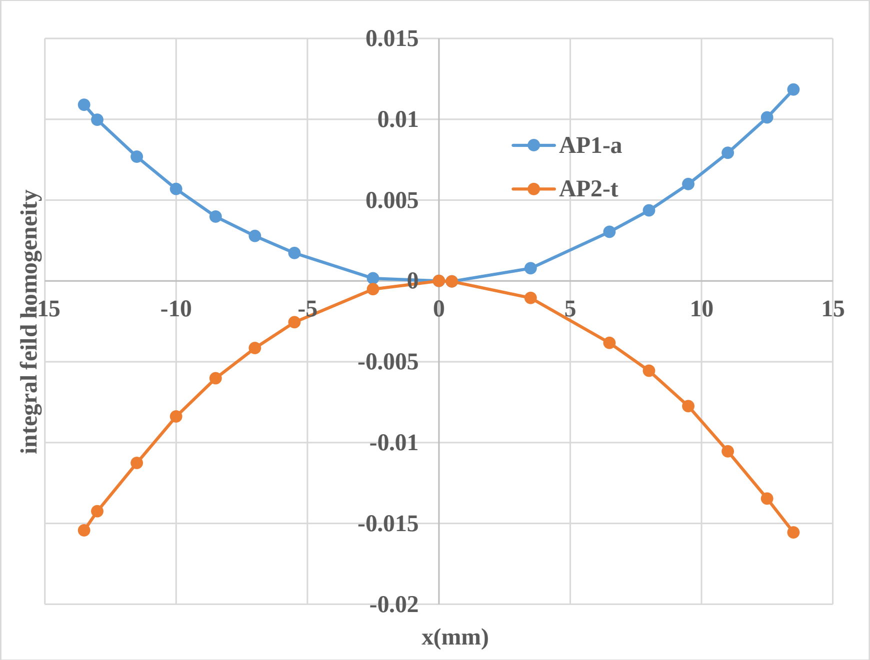
By along z at different energy

Magnetic measurements: field difference and harmonics

- Integral field differences
  - Difference is less than 0.15%@45GeV.

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@Rref=13.5mm



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

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

Short DAD prototype

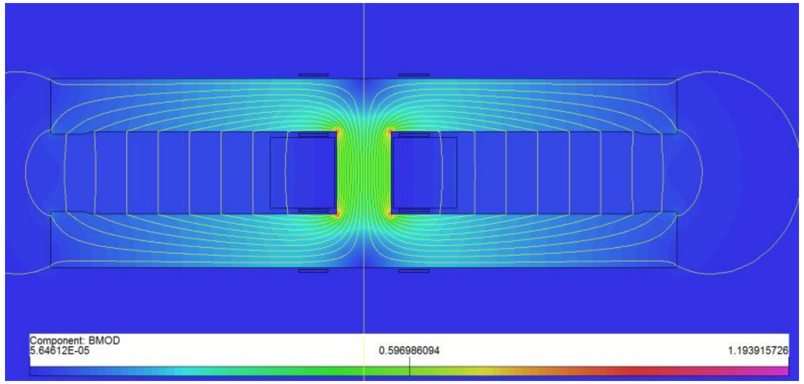
- The field measurement results show that it can meet the field requirements.
- The temperature rise at the end of the coil is large because of the resistivity of the coil's material and the contact resistance of the coil bars. The water cooled coil will be used later.
- The magnetic field coupling between the two apertures can be ignored in the case of existing correction coils.
- The magnetic field has a linear relationship with the current.

Long DAD design

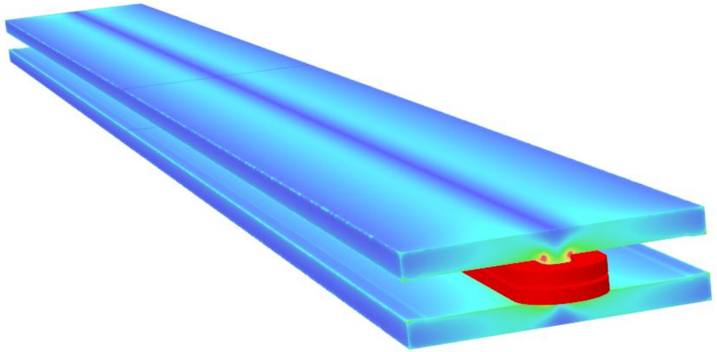
- As the magnetic length is up to 28.7m, the 5.7m pure dipole model will be built to check the field quality, mechanical strength and deformation.
- Basic parameters and design considerations

Item	
Center field (Gs)	141.6@45.5GeV，373@120GeV，568@182.5GeV
Gap (mm)	66
Magnetic Length (m)	5.737
Good field region (mm)	±13.5
Field harmonics	<0.05%
Field adjustability	±1.5%
Field difference between two apertures	<0.5%

  - Beam center separation is 350mm;
  - Solid iron with DT4;
  - Two turns of aluminum busbars with cooling hole;
  - Anodizing treated insulation coil;
  - Silvered contact face to reduce contact resistance.

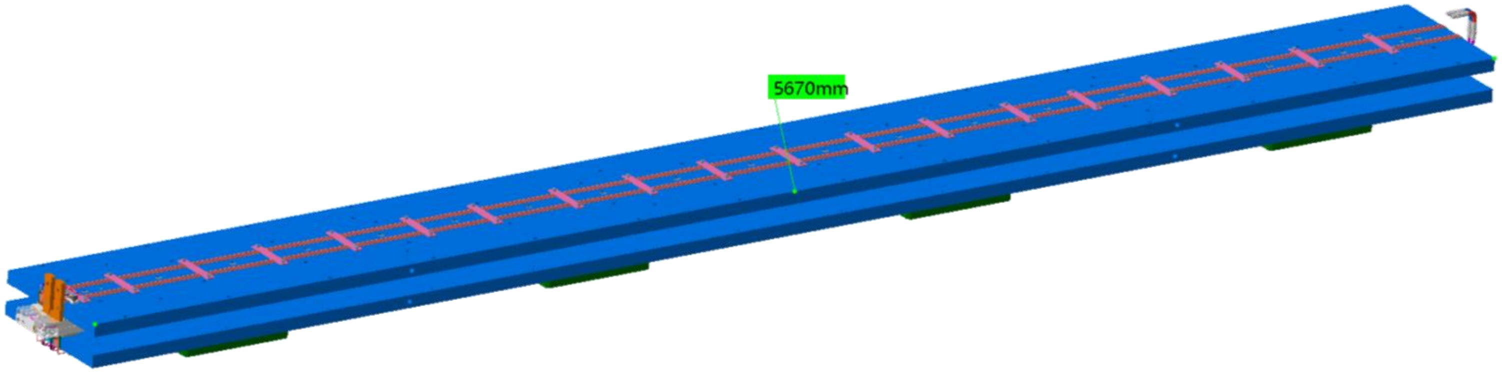


Cross section of long DAD

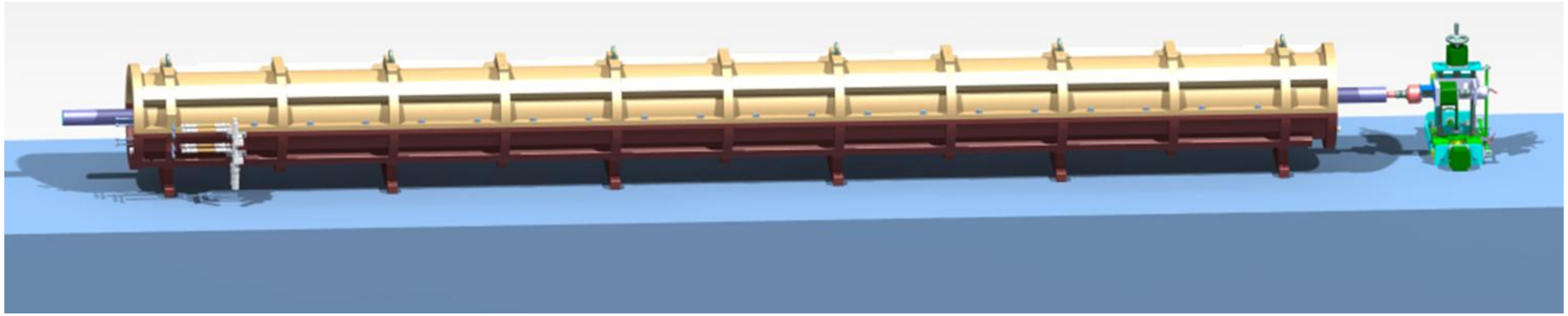


Long DAD design

- The mechanical design of the long DAD has been completed. The physical and mechanical design review was performed in July 2020.



- The magnetic field will be measured by a rotating coil measurement system
  - Shared with the booster dipole magnet.

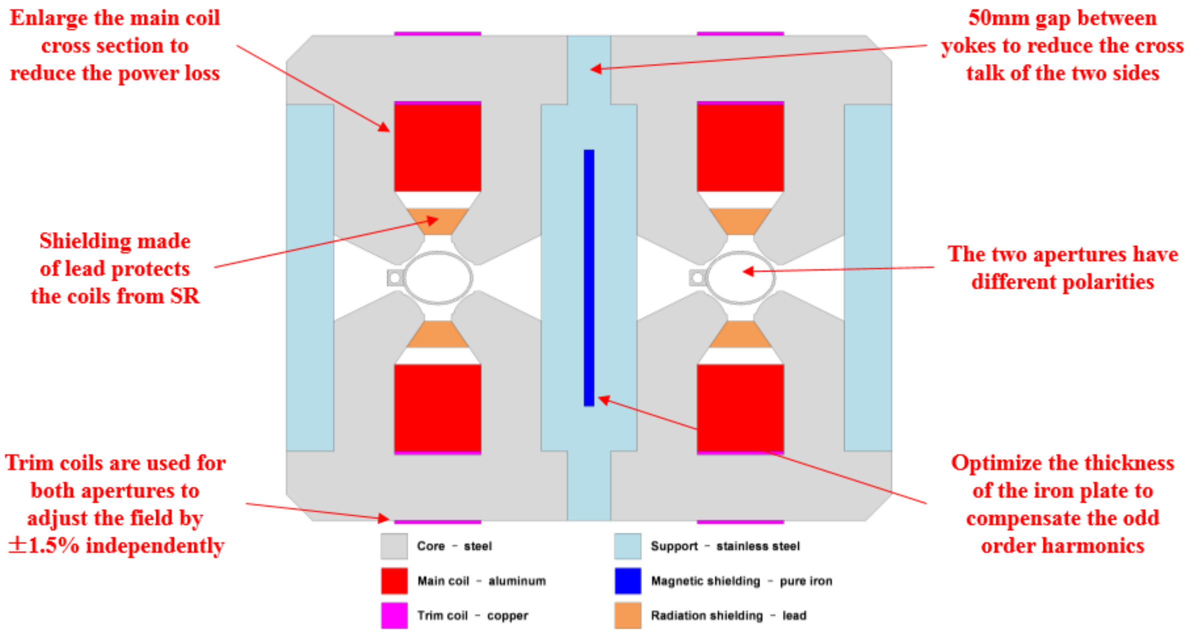


Dual aperture quadrupole prototype(DAQ)

(by F.S. Chen)

- Requirements of DAQ(number: 2392）

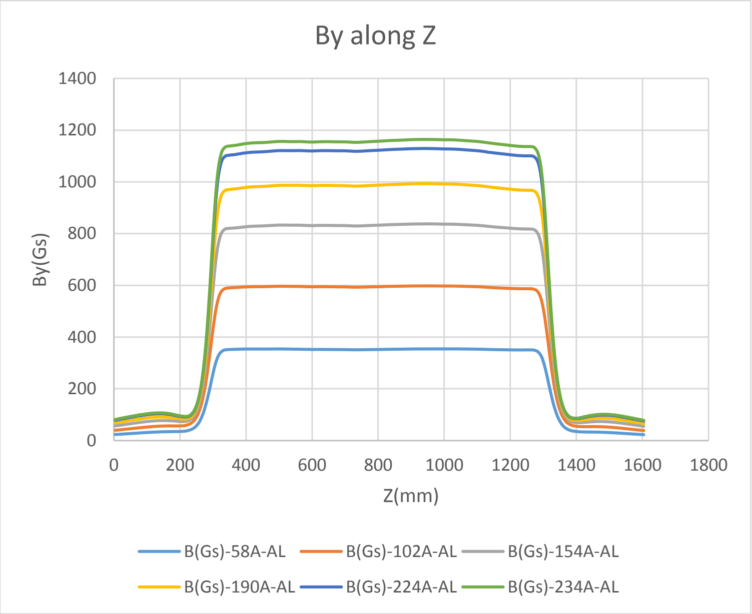
Gradient(T/m)	3.24~12.8
Aperture(mm)	76
Effective length(m)	1 or 2
GFR(mm)	12.2
Adjustment capability	±1.5%
Field quality	5×10^{-4}

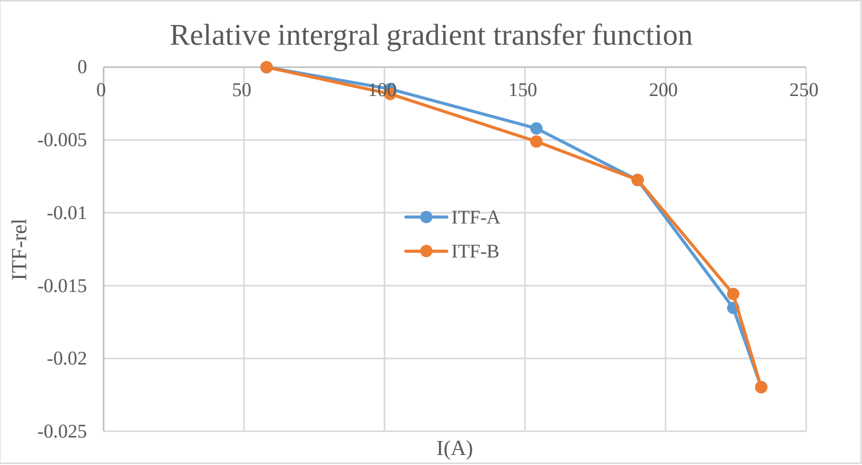


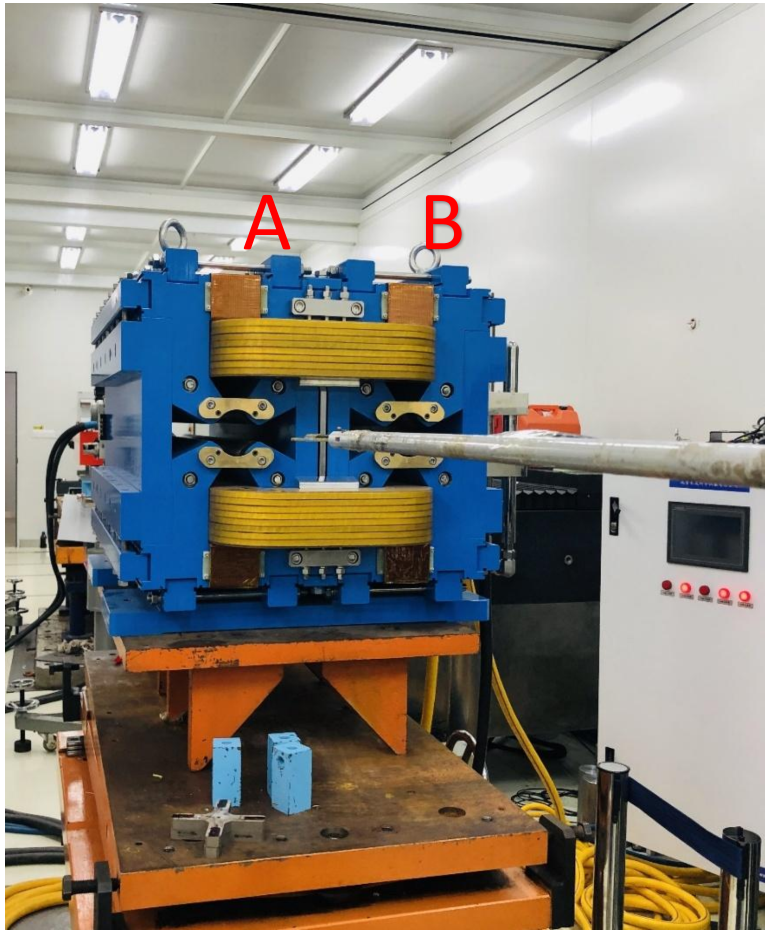
- Prototype study
  - Complex structure to verify assembly tolerances and mechanical structure
  - Cross talk effect and compensation method study
  - Verify the hollow aluminum wires
  - Effect of trim coils on the main field

Primary 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.







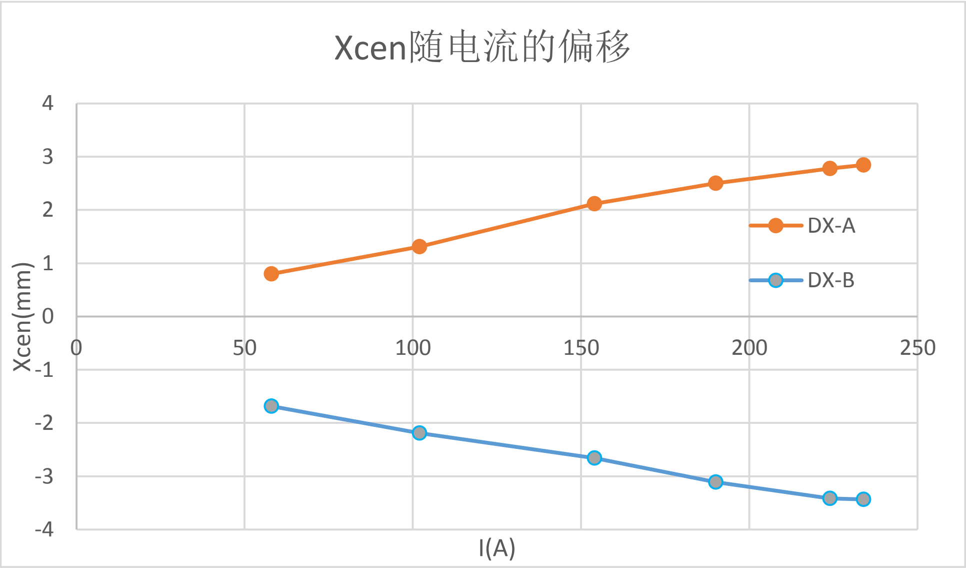
Primary measurement results-2

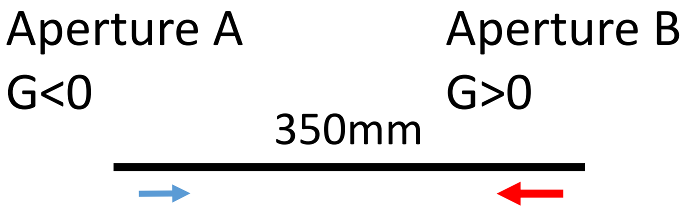
- The gradient difference between the two apertures is about 0.5%.

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%

Primary measurement results-3

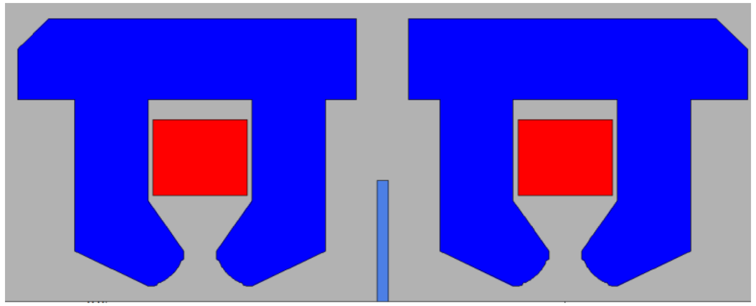
- Magnetic axis shift
  - The magnetic center in horizontal direction is shown below. The Xcen shift by 2mm in aperture A and by -1.7mm in aperture B when the energy rises from 45GeV to 182.5GeV. The magnetic center distance between the two apertures is less than 350mm and shifted by 3.7mm in the ramping process.





Optimization of DAQ

- Problems of DAQ： strong cross talk effect between two apertures
  - Resulting in large dipole and sextupole component. And the magnetic center is shifted when the energy is ranging from 45GeV to 182.5GeV.
  - When the trim coil is added, the field has different changes in two apertures for its asymmetric magnetic structure.
- Origin design:
  - For the component DT4 sheet is thin and easy to be saturated when the energy is ramping up. So the b1 and b3 component is changed a lot.
  - Also when there is trim coil, the b1 and b3 component changes a lot.

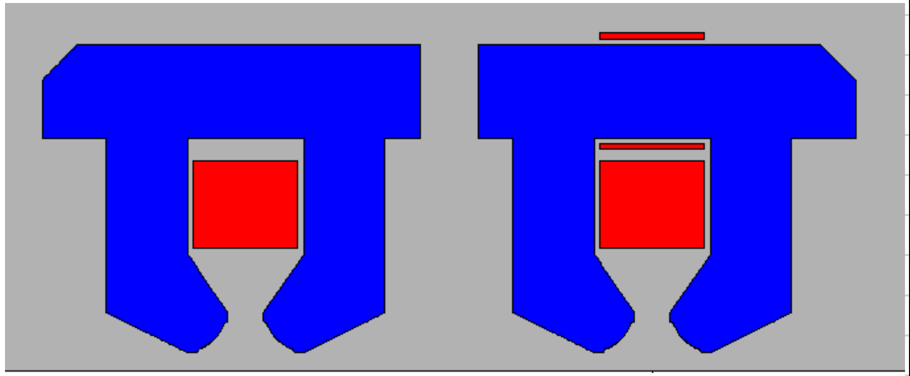


E(GeV)	45.5	120	182.5
G(T/m)	3.49	8.53	12.94
b1	423.143	**-7.976**	-602.69
b2	-10000	-10000	-10000
b3	34.28	-0.65	-48.829
b4	-0.479	-0.521	-0.532
b5	0.465	-0.009	-0.662
b6	0.013	0.014	0.015
b10	0.011	0.011	0.011

	origin		R+0.015		R-0.015	
	left	Right	left	Right	left	Right
G（T/m)	-8.530	8.530	-8.530	8.658	-8.530	8.403
b1	247.948	247.955	199.319	272.906	296.079	221.73
b2	-10000	10000	-10000	10000	-10000	10000
b3	20.085	20.092	16.145	22.114	23.984	17.967
b4	-0.522	0.521	-0.522	0.522	-0.522	0.521
b5	0.272	0.273	0.219	0.3	0.325	0.244
b6	0.014	-0.014	0.014	-0.014	0.014	-0.014
b7	-0.022	-0.022	-0.018	-0.024	-0.026	-0.02
b8	-0.007	0.007	-0.007	0.007	-0.007	0.007
b9	0	0	0	0	0	0
b10	0.011	-0.011	0.011	-0.011	0.011	-0.011
△b1			-48.629	24.951	48.131	-26.225
△b3			-3.94	2.022	3.899	-2.125

Optimization of DAQ

- Case 1: without dt4 sheet



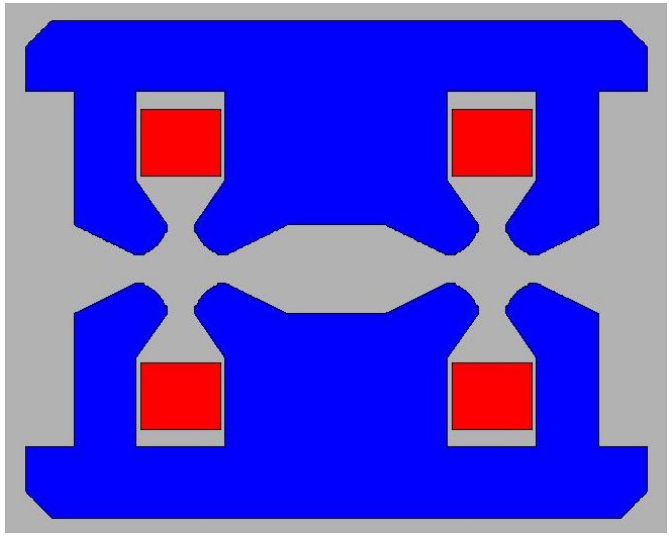
E(GeV)	45	120	182.5
G(T/m)	3.43	8.535	12.95
b1	-2096.943	-2093.984	-2095.565
b2	-10000	-10000	-10000
b3	-169.885	-169.663	-169.777
b4	-0.483	-0.523	-0.531
b5	-2.301	-2.298	-2.299
b6	0.013	0.014	0.015
b7	0.184	0.184	0.185
b8	-0.008	-0.008	-0.008
b9	0.003	0.003	0.003
b10	0.011	0.011	0.011
Δb1	-2.959		-1.581
Δb3	-0.222		-0.114

	origin		R+0.015		R-0.015	
	left	Right	left	Right	left	Right
G(T/m)	-8.535	8.535	-8.535	8.663	-8.535	8.408
b1	-2093.984	-2094.017	-2144.481	-2038.375	-2043.48	-2151.362
b2	-10000	10000	-10000	10000	-10000	10000
b3	-169.663	-169.659	-173.755	-165.151	-165.572	-174.306
b4	-0.523	0.522	-0.523	0.523	-0.523	0.522
b5	-2.298	-2.297	-2.353	-2.236	-2.242	-2.36
b6	0.014	-0.014	0.014	-0.014	0.014	-0.014
b7	0.184	0.184	0.189	0.179	0.18	0.189
b8	-0.008	0.007	-0.008	0.007	-0.008	0.007
b9	0.003	0.003	0.003	0.003	0.003	0.003
b10	0.011	-0.011	0.011	-0.011	0.011	-0.011
Δb1			-50.497	55.642	50.504	-57.345
△b3			-4.092	4.508	4.091	-4.647

- The two apertures are coupled.
- The b1 and b3 changed a little in the energy range.
- With trim coil, the b1 component changed about 50 units.

Optimization of DAQ

- Case 2:filled with J23



E(GeV)	45	120	182.5
G(T/m)	-3.194	-8.537	-12.792
b1	-1559.443	-1557.215	-1558.697
b2	-10000	-10000	-10000
b3	-126.327	-126.147	-126.264
b4	-0.478	-0.521	-0.523
b5	-1.71	-1.707	-1.708
b6	0.033	0.035	0.035
b7	0.137	0.137	0.137
b8	-0.007	-0.007	-0.007
b9	0.003	0.003	0.003
b10	0.011	0.011	0.011
Δb1	-2.228		-1.482
Δb3	-0.18		-0.117

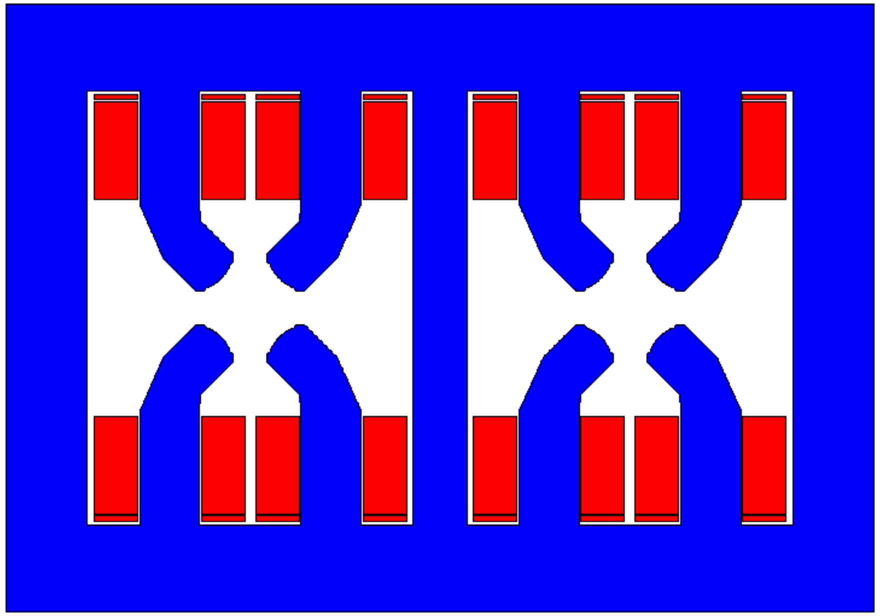
	origin		R+0.015		R-0.015	
	left	Right	left	Right	left	Right
G(T/m)	-8.537	8.537	-8.538	8.665	-8.537	8.410
b1	-1557.215	-1557.075	-1697.958	-1414.025	-1416.109	-1704.175
b2	-10000	10000	-10000	10000	-10000	10000
b3	-126.147	-126.169	-137.554	-114.583	-114.719	-138.09
b4	-0.521	0.521	-0.515	0.516	-0.515	0.515
b5	-1.707	-1.704	-1.861	-1.548	-1.553	-1.866
b6	0.035	-0.035	0.034	-0.034	0.034	-0.034
b7	0.137	0.137	0.15	0.125	0.125	0.15
b8	-0.007	0.007	-0.007	0.007	-0.007	0.007
b9	0.003	0.003	0.003	0.003	0.003	0.003
b10	0.011	-0.011	0.011	-0.011	0.011	-0.011
Δb1			-140.743	143.05	141.106	-147.1
Δb3			-11.407	11.586	11.428	-11.921

- The fields in the two apertures are coupled.
- The b1 and b3 change a little in the energy range.
- With the trim coil, the b1 changes about 140 units.

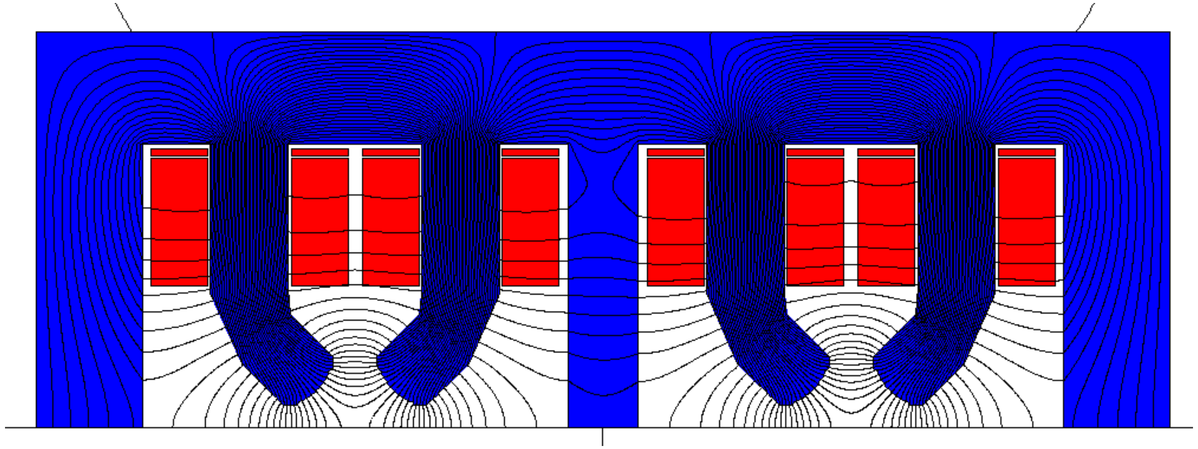
Another scheme design of DAQ

- Two quadrupole magnets locate side by side
  - With same polarities in two apertures
  - Beam center separation is 350mm
  - Main coils: 8 aluminum coils instead of 2 coils
  - Trim coils: 8 coils instead of 4 coils.

- Features:
  - For strict space, the middle yoke is shared.
  - The power consumption has doubled.
  - Nearly no cross talk effect between the two apertures.



Primary design: QF/QF



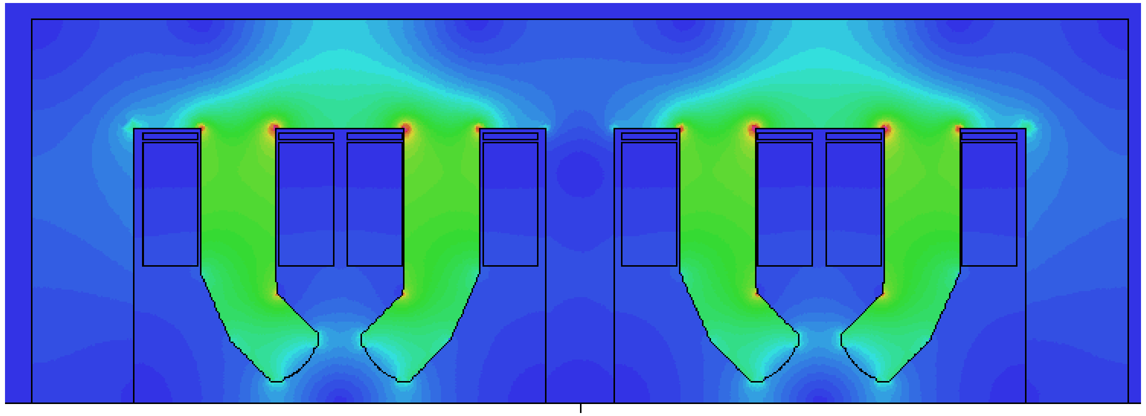
Another scheme design of DAQ

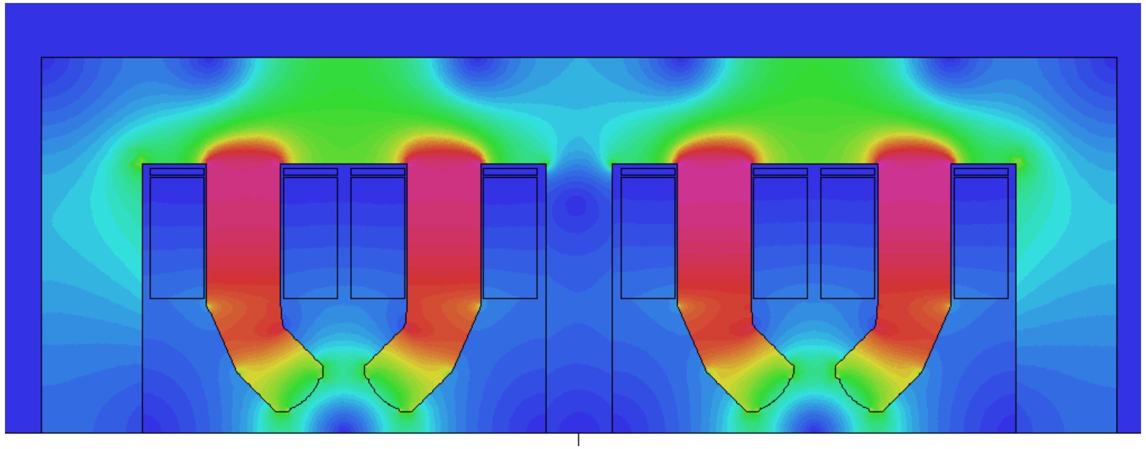
- E=45.5GeV

	Ap1	Ap1-1.5%	Ap2+1.5%
G(T/m)	3.24	3.19	3.29
	Harmonics(Bn/B1, 1e-4)		
1	8.16	8.39	-7.76
2	10000	10000	10000
3	0.64	0.66	-0.65
4	-0.01	-0.01	-0.01
5	0.01	0.01	-0.00

- E=182.5GeV

	Ap1	Ap1-1.5%	Ap2+1.5%
G(T/m)	12.83	12.65	13.01
	Harmonics(Bn/B1, 1e-4)		
1	7.16	7.62	-6.68
2	10000	10000	10000
3	0.56	0.59	-0.57
4	-0.01	-0.01	-0.01
5	0.01	0.01	-0.00





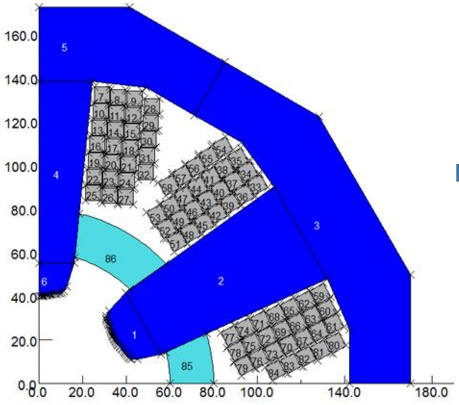
The simulations show the field quality can meet the requirements.

Sextupole magnet design

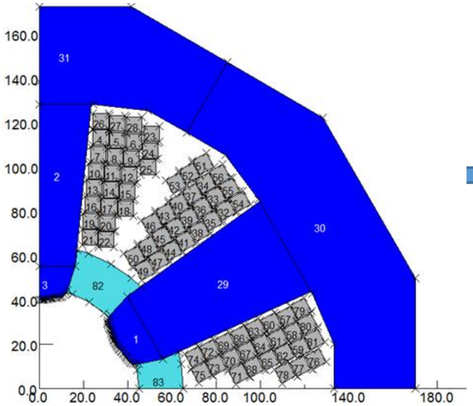
(by X.J. Sun)

- 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.
  - Field Strength: 191T/m^2 @45.5GeV to 740T/m^2 @182.5GeV
- Basic parameters of sextupole

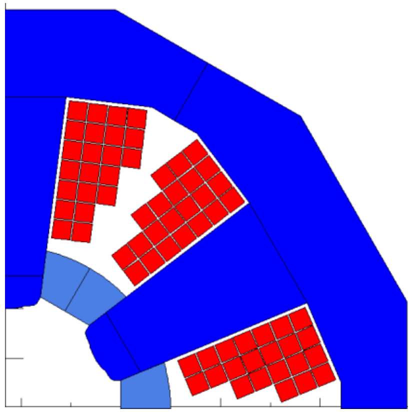
Gradient(T/m^2)	740
Aperture(mm)	80
Effective length(m)	0.7
GFR(mm)	14
Field quality	3×10^{-4}



1st design



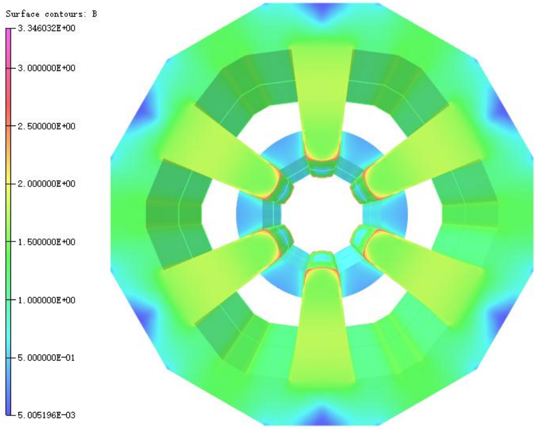
2nd design

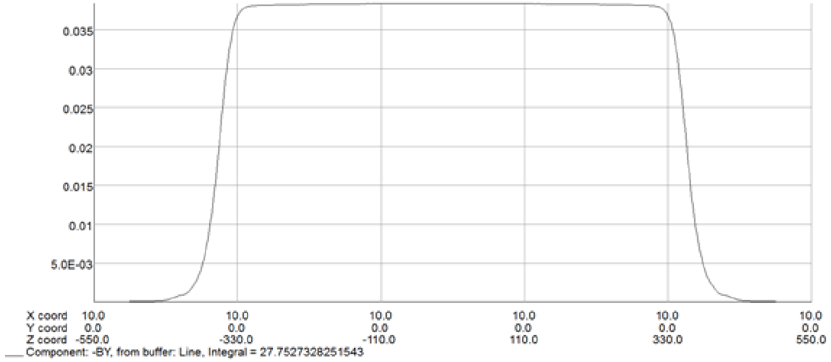


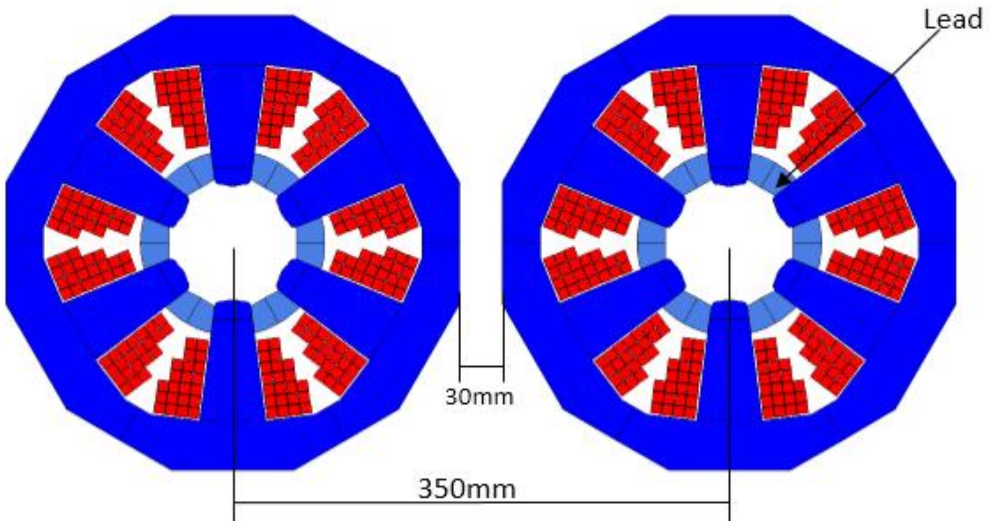
3rd design

Sextupole magnet design

- Further optimization
  - Rearrangement of the wire layout.
  - Optimize the pole shape, wedge-shaped magnetic poles are used to reduce magnetic pole saturation and improve excitation efficiency.
- Field simulation and magnet alignment.







- The mechanical design is in progress.

Summary

- The design of combined dipole and sextupole magnet with aluminum bus bars is accessible. The center dipole field and sextupole strength is basically consistent with the design value.
- The long DAD was designed and will be manufactured. The water cooled coils is used and the anodizing treated face is used for coil insulation.

- The DAQ prototype with F/D polarity has a strong cross talk effect which results in large b1 and b3 component and the field harmonics varies when the field is not symmetric, especially when the trim coil is added. The further modification is in progress.
- Another solution with the same polarity in the two apertures is initially designed. This kind of quadrupole with 8 coils can work but consume much more power.

- A sextupole magnet has been redesigned and the mechanical is in progress. The prototype is in plan.

Thanks for your attention!