中国科学院高能物理研究所
Institute of High Energy Physics
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CEPC Collider Ring and Booster Magnets R&D

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Outline

- **CEPC Booster dipole magnet R&D**
  - Manufacturing status of full-scale CT coil dipole magnet
  - Development of the field measurement system
  - Design of the full-scale iron-core dipole magnet
- **CEPC Collider magnets R&D**
  - Development of dual aperture dipole magnet
  - Optimization of dual aperture quadrupole magnet
  - Design of sextupole magnet
- **Summary and next plan**

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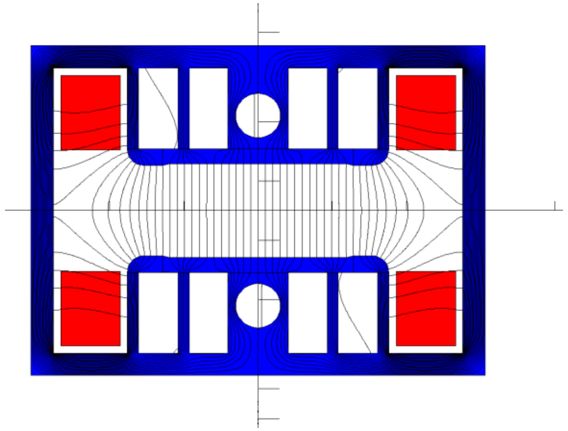
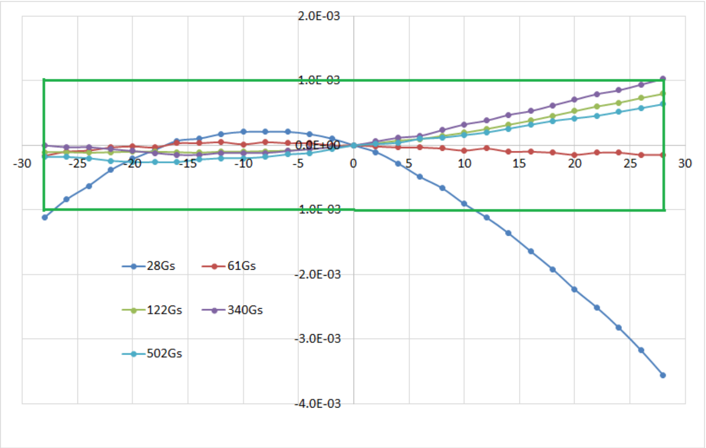
Specifications and subscale prototype magnets

Main specifications of CEPCB dipole magnets

	BST-63B
Quantity	16320
Minimum field (Gs)	28
Maximum field (Gs)	338@120GeV/500@180GeV
Gap (mm)	63
Magnetic Length (mm)	4700
Good field region (mm)	55
Field uniformity	0.1%
Field reproducibility	0.05%

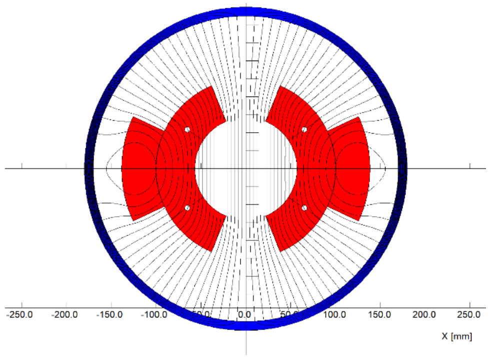


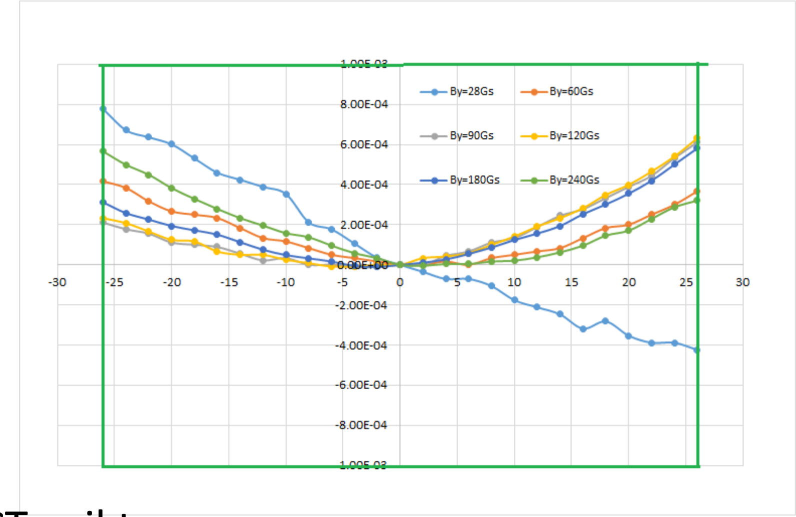


Iron type

Two subscale prototype magnets:(1m)

1. **Iron dominated:**
2. **CT type (coil dominated):**

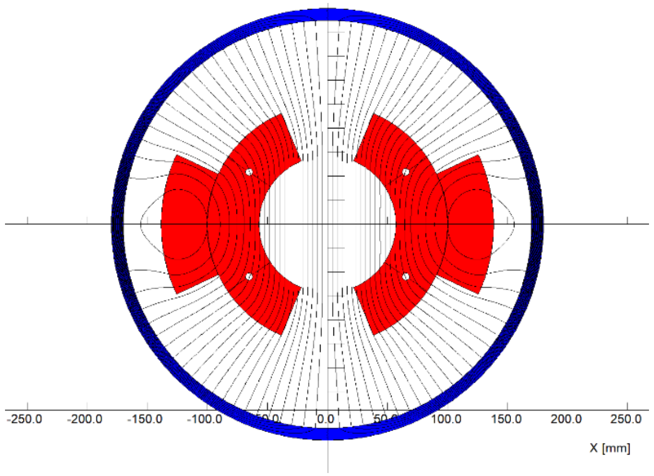


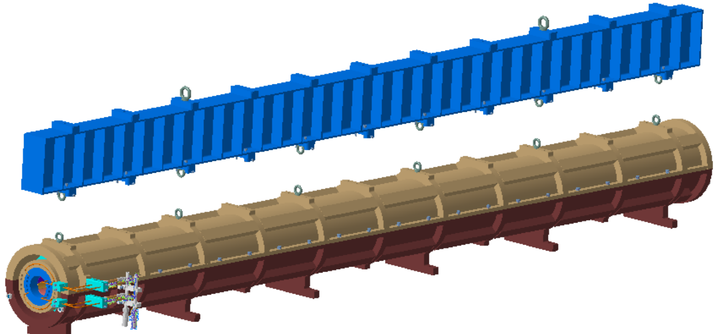


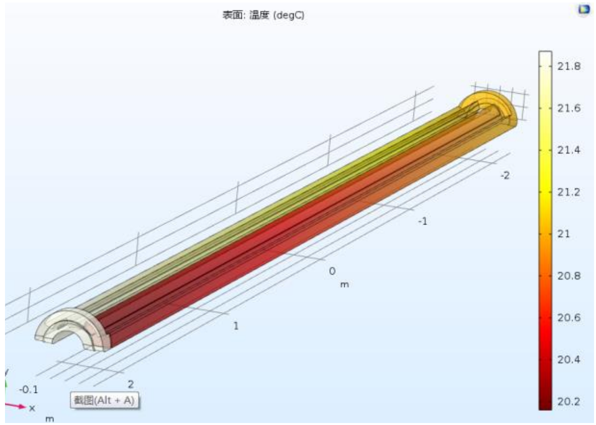
CT coil type

Status of the full-scale prototype CT coil dipole magnet

On the base of the subscale prototype CT dipole magnet, the mechanical design of a full scale prototype CT dipole magnet was finished. The production of the magnet on the way.



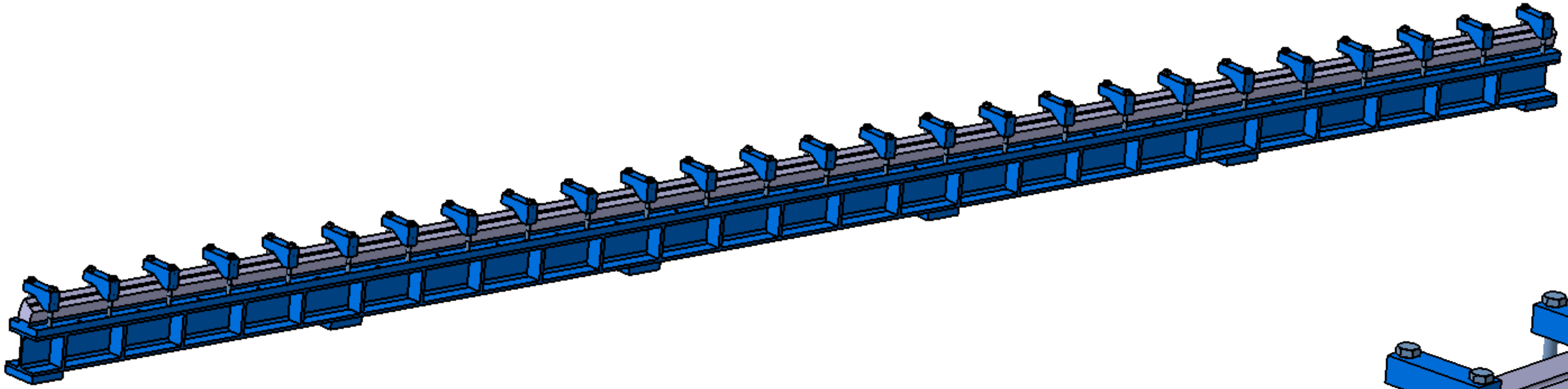


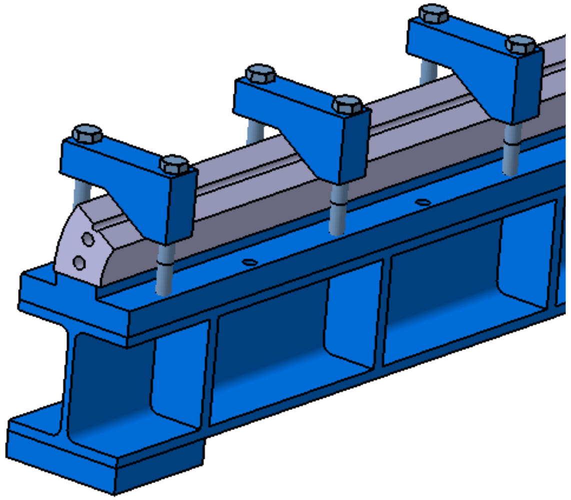


- ✓ **The total length of the magnet including the shielding tube is 5.1m.**
- ✓ **The coil conductors will be made from pure aluminum, the size tolerance less than 0.05mm, the position tolerance less than 0.1mm.**

Status of the full-scale prototype CT coil dipole magnet

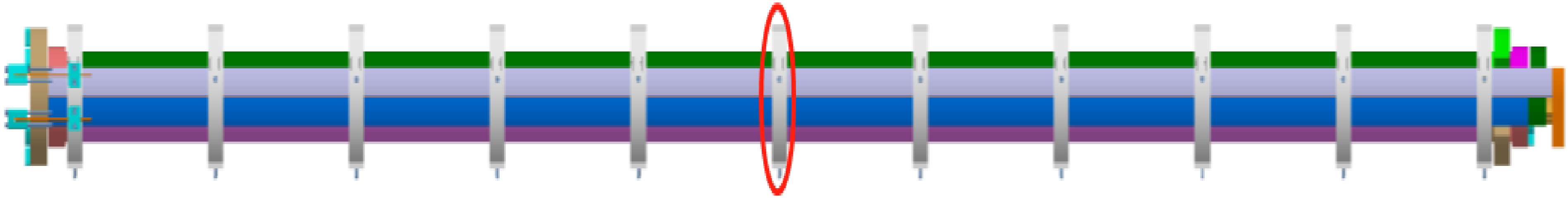
Each conductor is 5m long, it is initially designed to be fabricated from a long aluminum bar, which will need large machining facility, so the cost will be very high.

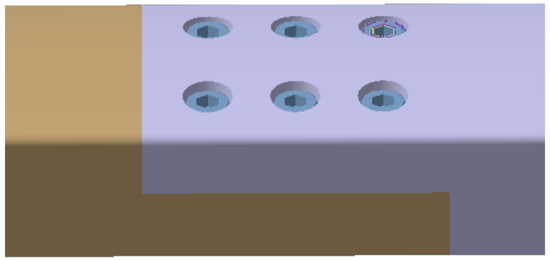


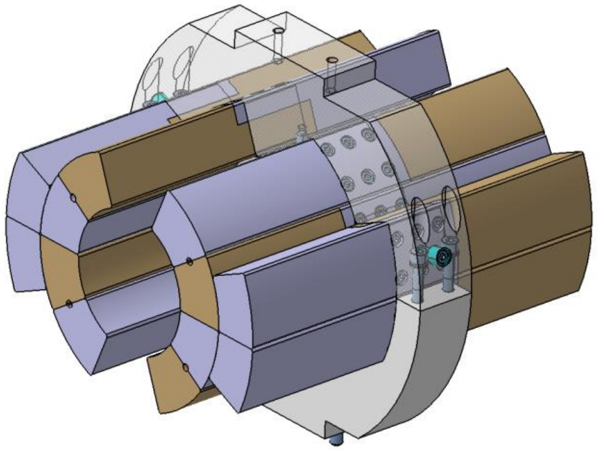


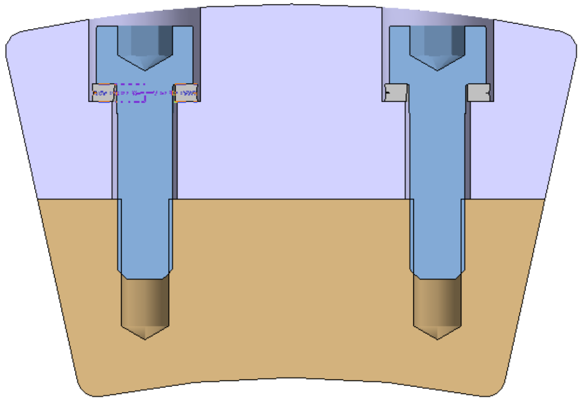
Status of the full-scale prototype CT coil dipole magnet

To reduce the production cost, the 5 m long conductor is considered to be divided into 2 parts for convenient fabrication and then assembled together, the touch surface of two conductors will be coated with the silver film to reduce the contact resistance.









Status of the full-scale prototype CT coil dipole magnet

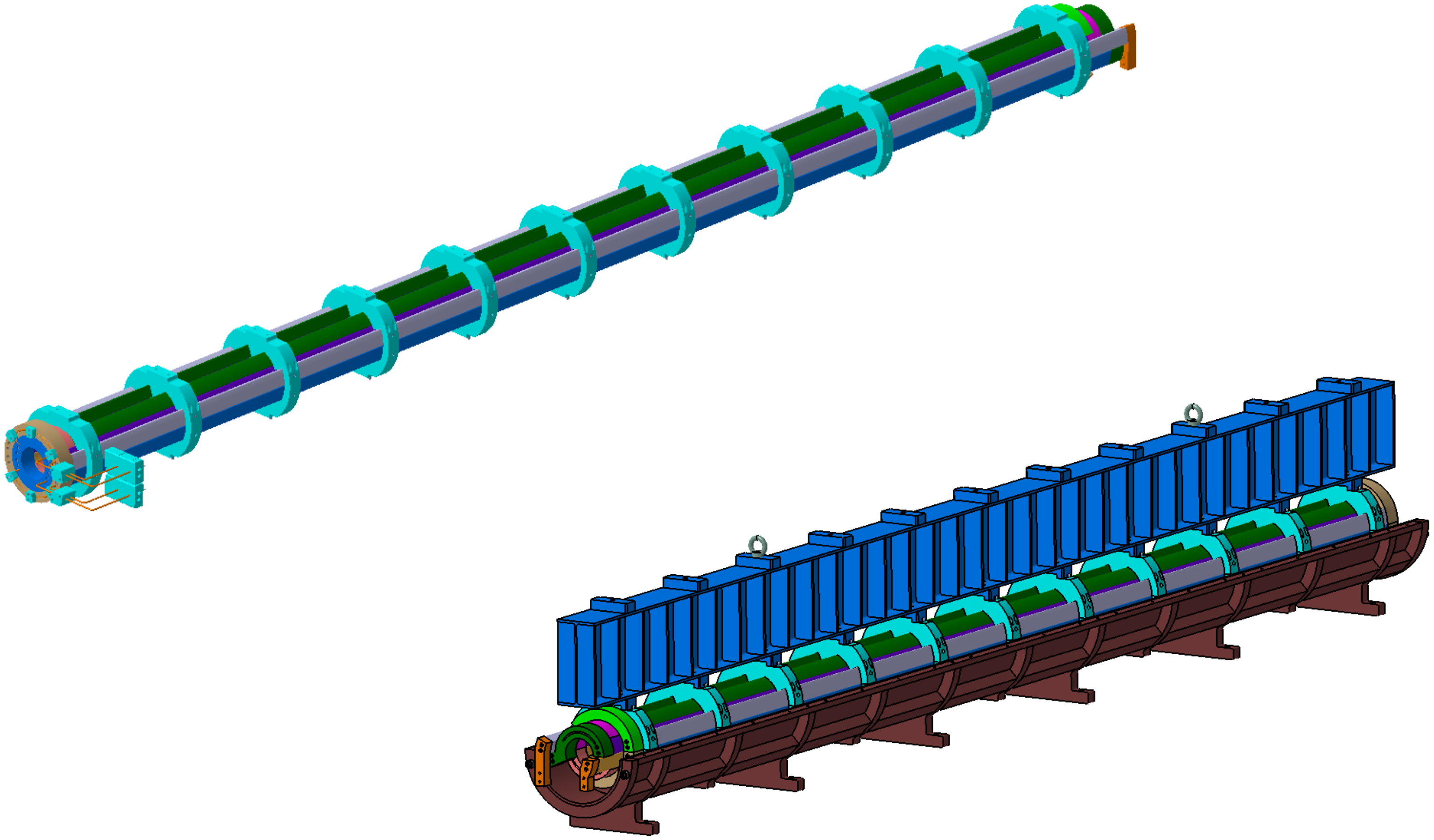
To reduce the production cost further, we decided to change the procedures of manufacture, instead of the direct fabrication, the conductors were precisely extruded and forged. The mechanical test results showed that the tolerances of the short samples were satisfied with the requirements.

Status of the full-scale prototype CT coil dipole magnet

However, in the extrusion process of the 3m long conductors, the deformation along the conductors was serious although the tolerance of the cross section was good, so the Keye company decided to produce a device to reduce the deformation of the conductors.

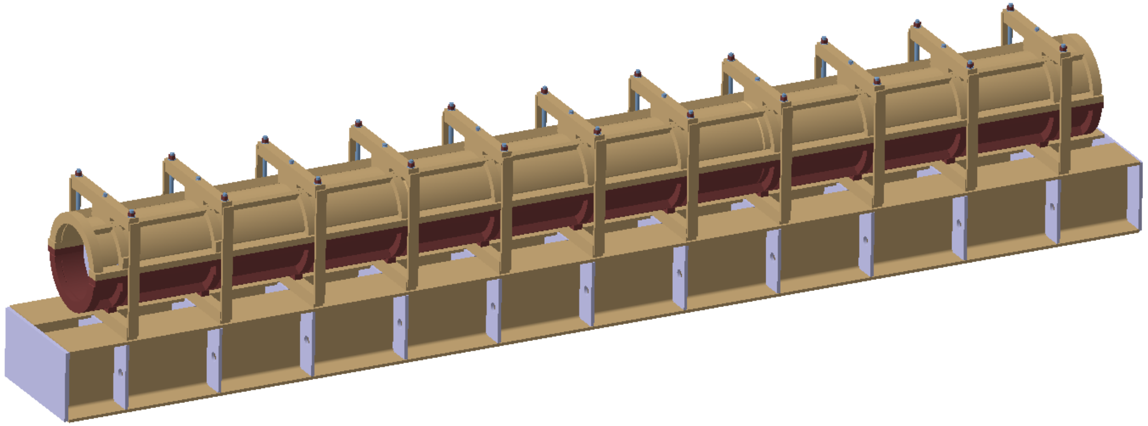
Status of the full-scale prototype CT coil dipole magnet

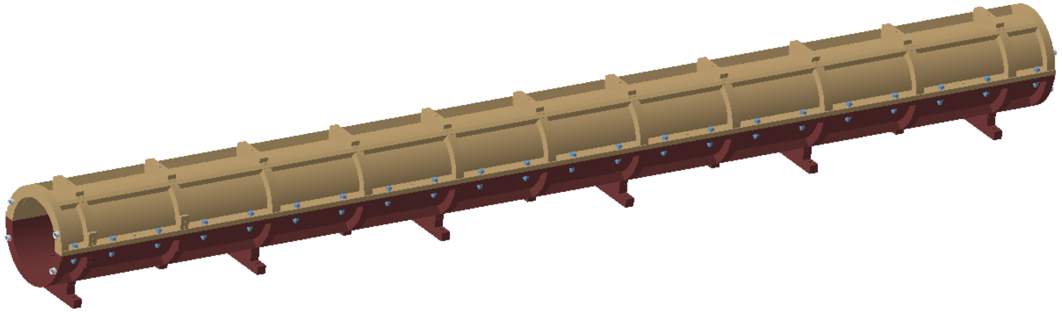
After the coil conductors are produced and assembled together, they will be put into the shielding tube, which can be opened into upper and lower parts.



Status of the full-scale prototype CT coil dipole magnet

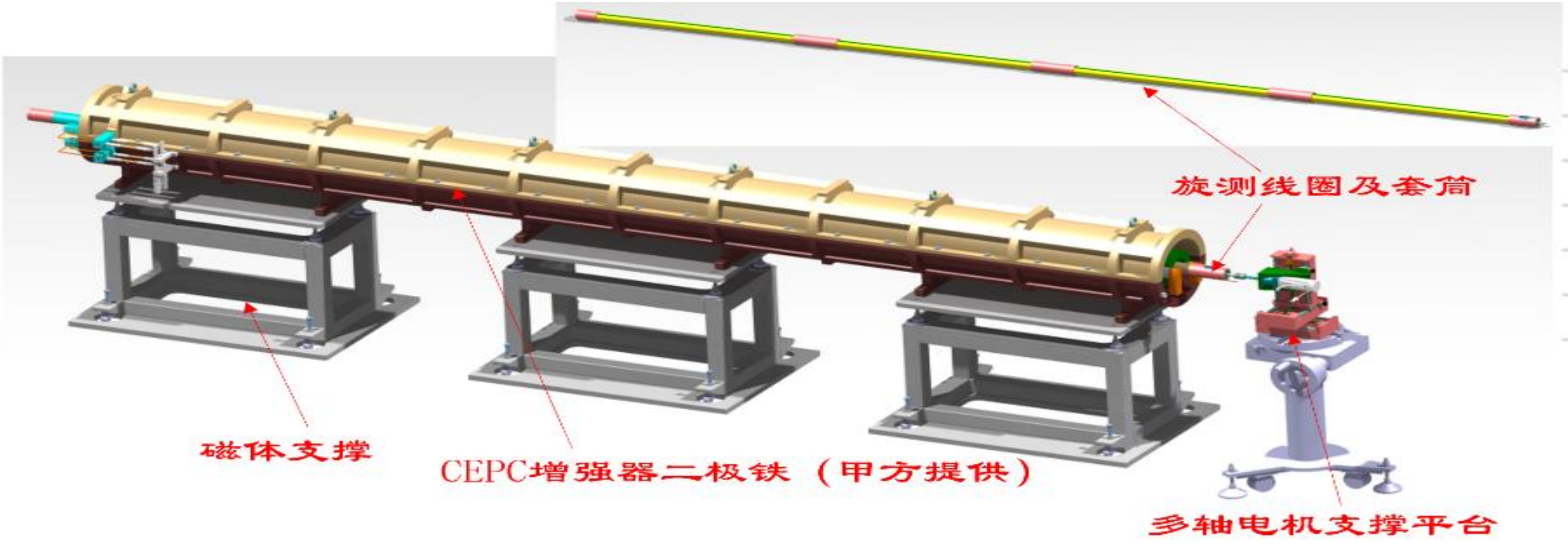
At present, the production of the shielding tube is on the way.





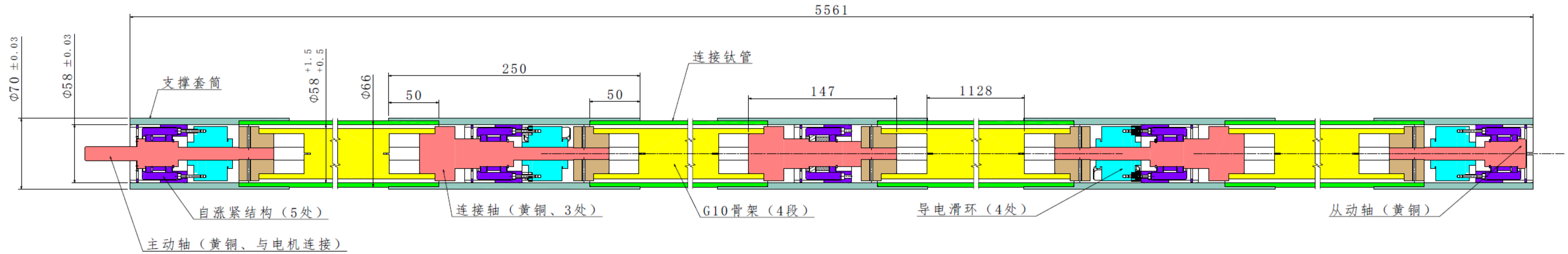
Status of the field measurement system

1、Long coil
2、Motor and Driver
3、Encoder
4、Motor control
5、Signal acquisition device



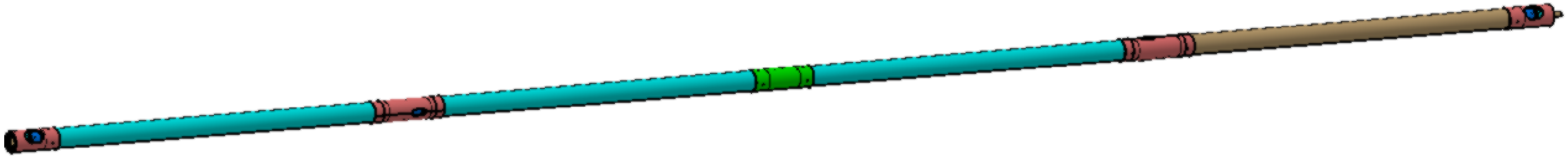
Status of the field measurement system

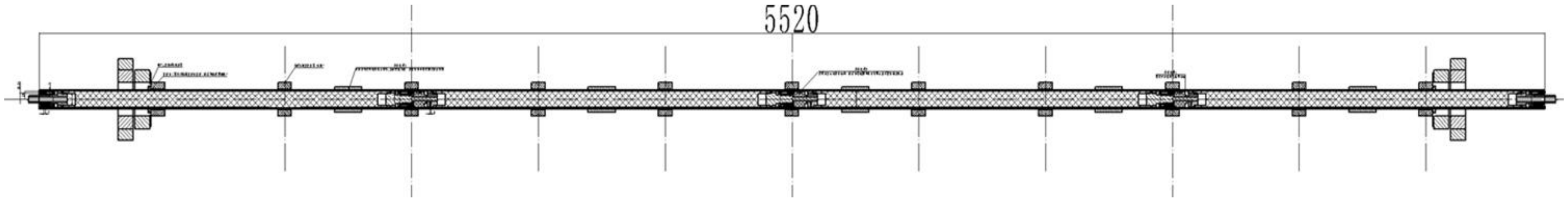
The structure of the long rotating coil

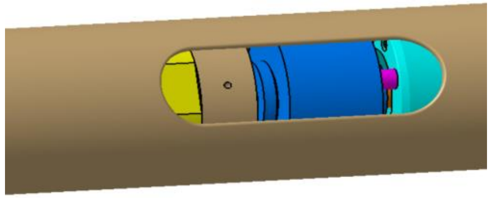


- The total length of the coil is 5.6m, which is installed in a supporting tube.
- Since it is very difficult to manufacture a 5.6m long rotating coil, so the long coil will be assembled with 4 sub-coils. Each sub-coil is 1130 mm long.

Status of the field measurement system



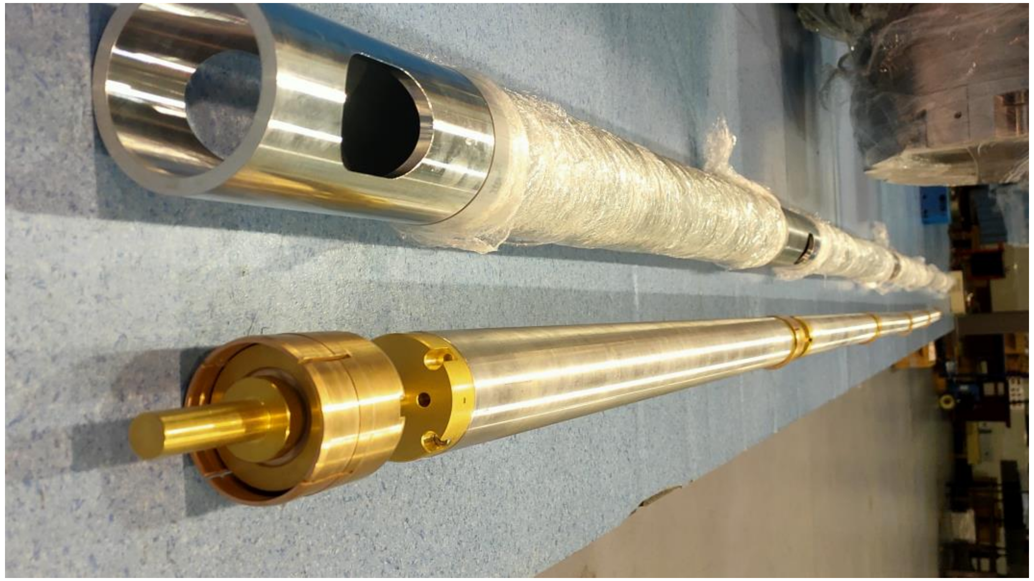




➢ The field of the magnet in different longitudinal positions can be measured by the 4 sub-coils respectively, and the field of the whole magnet can be measured by connecting the signals in series.

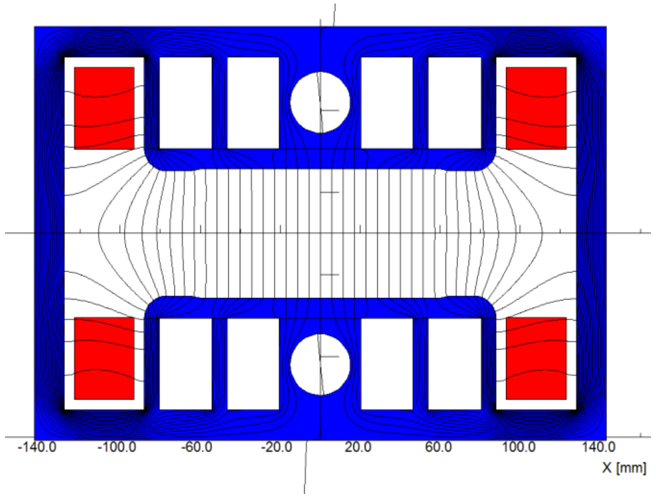
Status of the field measurement system

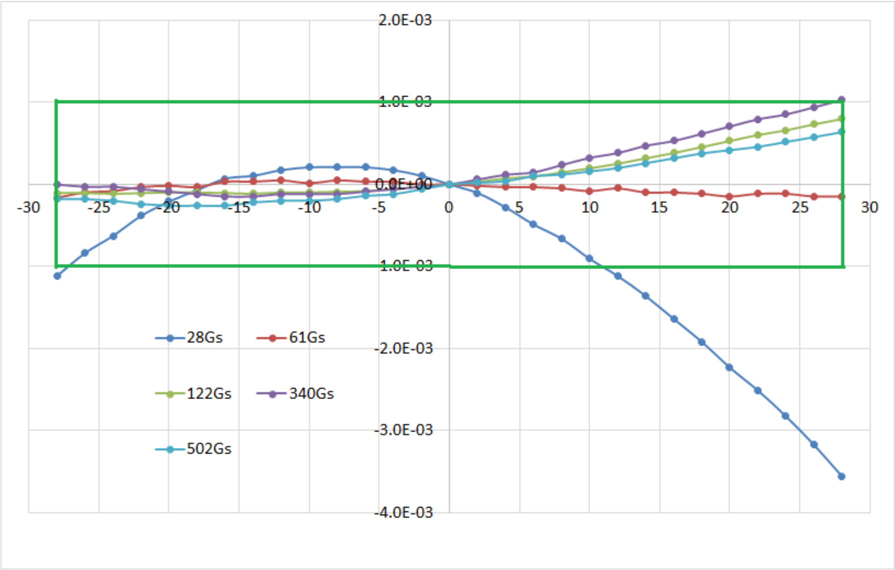
- **To test and verify the connection structures of the 4 sub-coils, the samples of the coil frames and connectors were produced. In the process of assembling, it is found that the tolerance of some components are not reasonable, the samples of the sub-coils could not be assembled together. So the design of the components was modified and the new ones will be produced.**



Design of the full scale iron core dipole magnet

- As said in previous, the field uniformity of the iron-core dipole magnet could not meet the requirement of 28Gs@10GeV, but it could meet the requirement if the min. working field increases to 56Gs@20GeV.
- The key advantages of the iron-core dipole magnet are low production cost and low electricity power loss. So in CEPC Day of May, the director made a big decision to increase the injection energy from 10GeV to 20GeV, the iron-core dipole magnet became the baseline design for the CEPC booster.

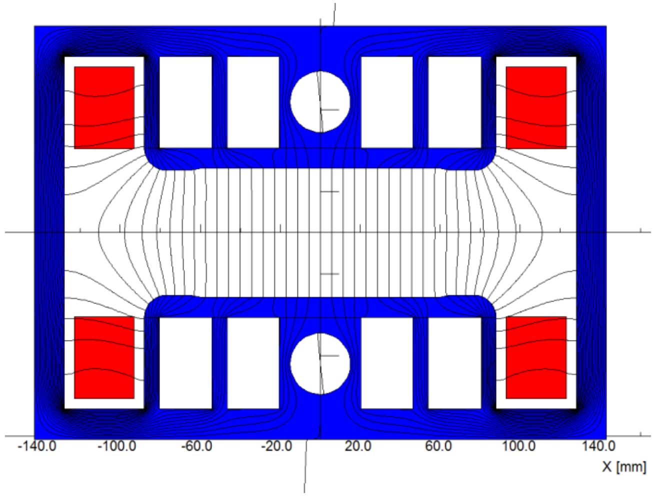


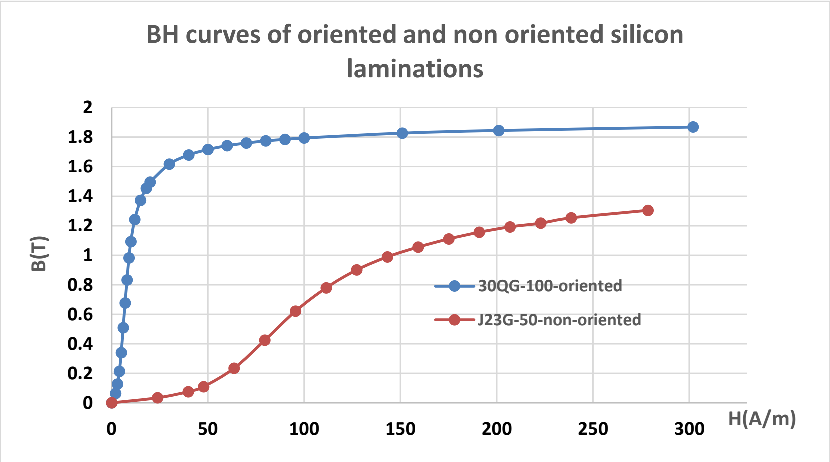


Design of the full scale iron core dipole magnet

The key design points of the full-scale iron-core dipole magnet.

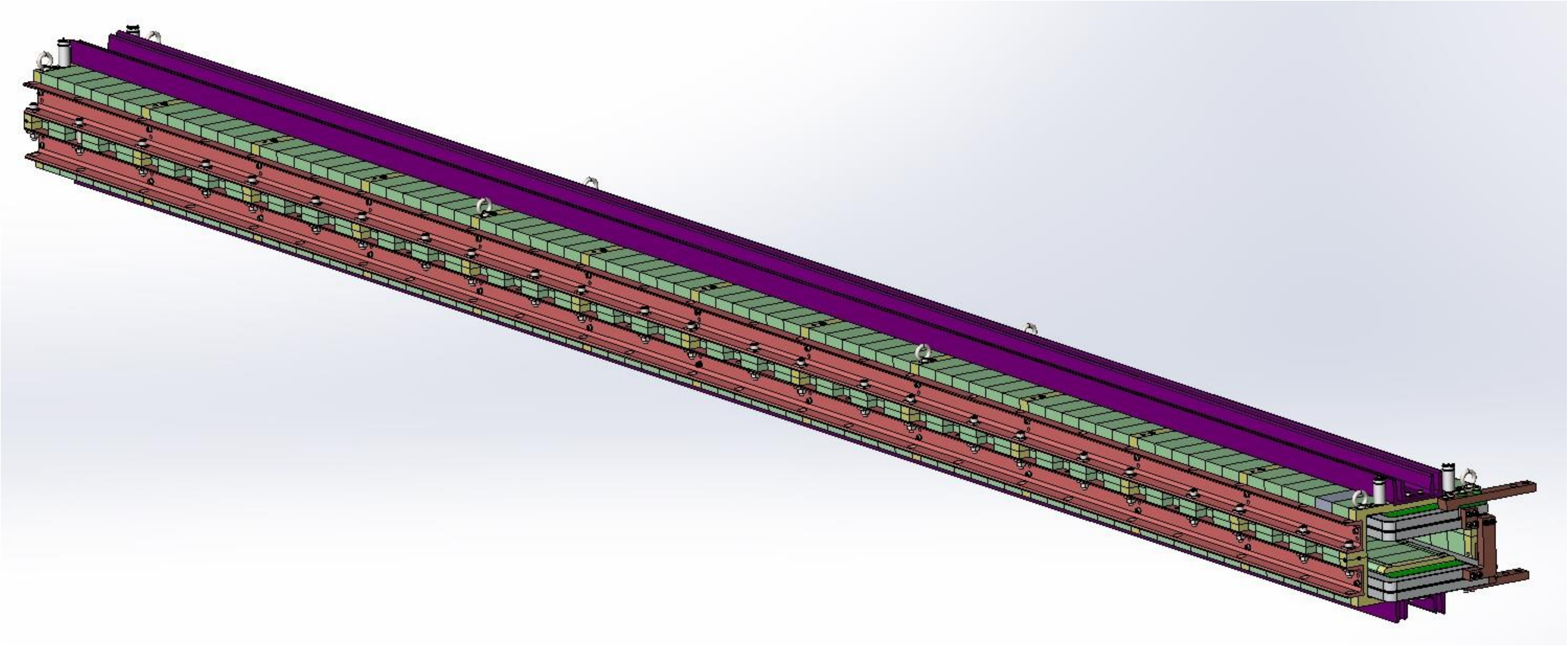
- To reduce the influence of earth field, a closed H-type core frame was chosen;
- To reduce the influence of remnant field, the oriented low carbon silicon steel laminations with low remnant field was used to stack the cores of the magnet.
- To reduce the cost and weight of the magnet, the technology of core dilution was adopted, the material of aluminum was used to produce the coils.





Design of the full scale iron core dipole magnet

Compared with the sub-scale prototype magnet, the length of the full-scale iron-core dipole magnet is 4.7m, such long iron-core dipole magnet with high precision has never been produced in China.

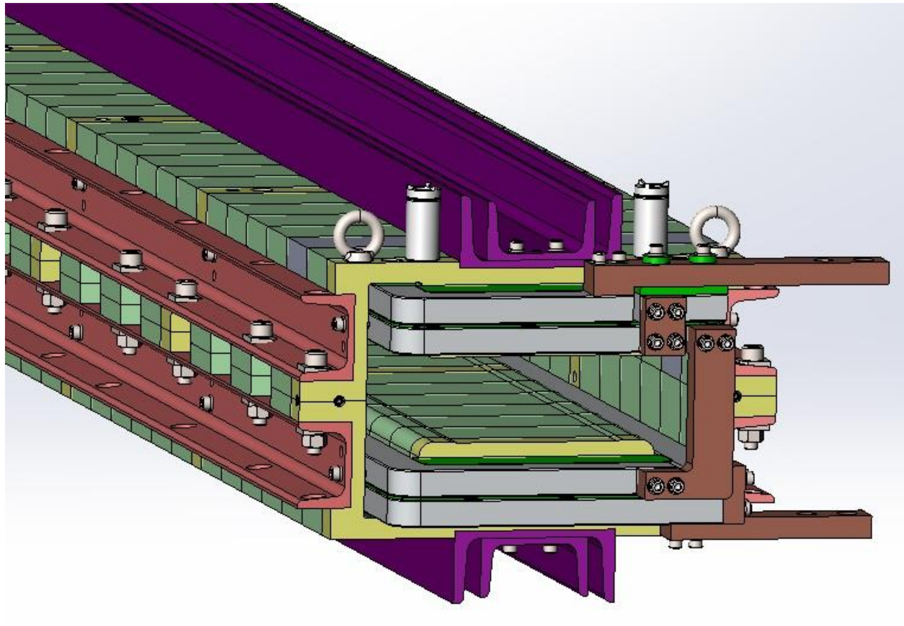


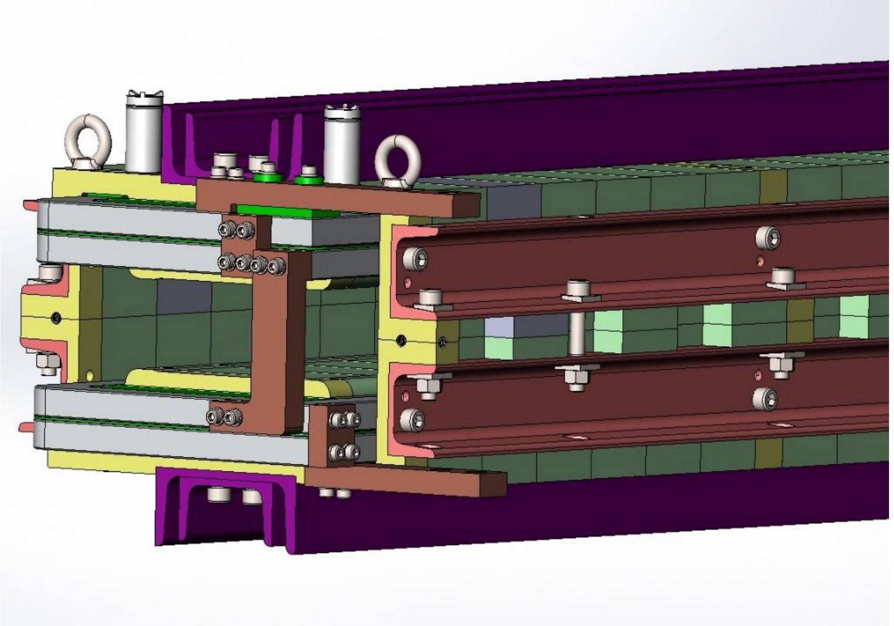
Design of the full scale iron core dipole magnet

The key design considerations of the full-scale iron-core dipole magnet

- **To increase the strength of the iron-core as high as possible.**
- **To decrease the production cost as low as possible.**

So all the metal bars around the iron-cores that pull the laminations together will be made by U-steel which has high strength and low cost, instead of solid steel.

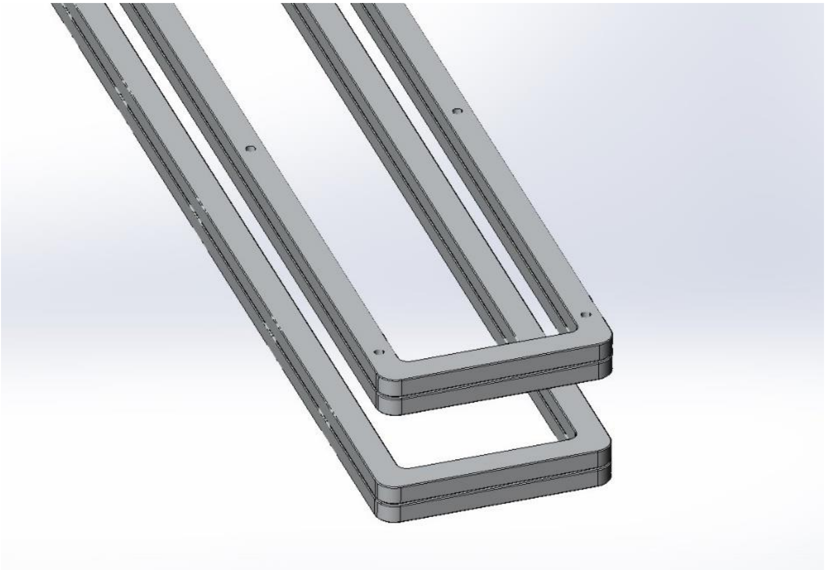


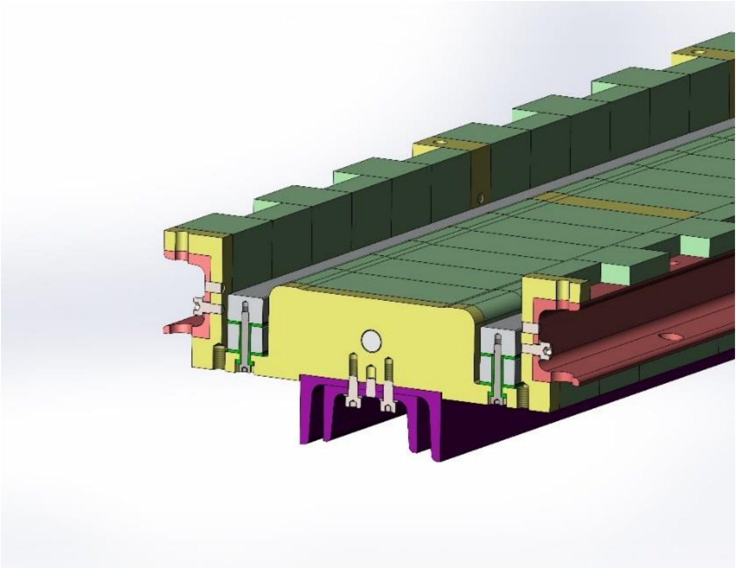


Design of the full scale iron core dipole magnet

For the design of the coils, in order to reduce the cost,

- The coils have only two turns without water cooling, so each turn of the coils can directly produced by the aluminum bars.
- Unlike the conventional vacuum epoxy casting, the insulation either between the turns or between coil and iron-core will be simply made by G10 plates.
- By using some kind of special structure, the coils can be simply fixed on the iron cores.





Design of the full scale iron core dipole magnet

	Iron-core	CT
Field uniformity@10GeV	3.5E-3	5E-4
Field uniformity@20GeV	5E-4	3E-4
Field reproducibility	<5E-4	<5E-4
Max. power loss (W)@180GeV	546	2935
Max. power loss (W)@120GeV	245	1272
Magnet weight (ton)	1.4	1.5
Cost per magnet (10kRMB)/MP	15	25
Cost of all magnets (BRMB)/MP	2.448	4.08

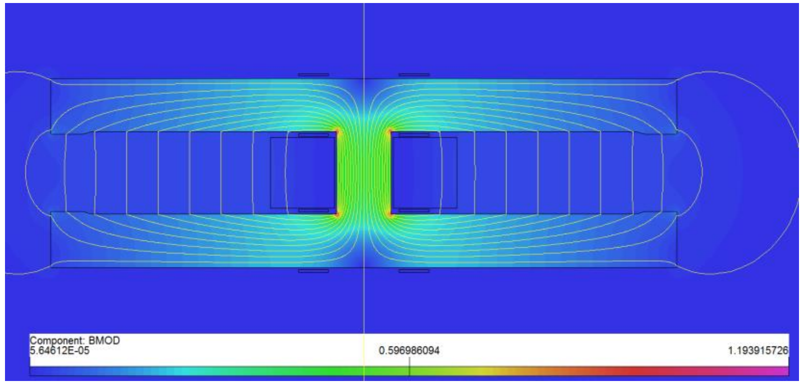
Outline

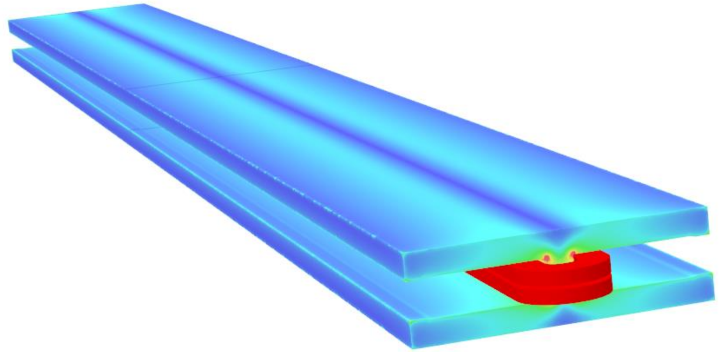
- **Progress on CEPC Booster dipole magnet**
  - Manufacturing status of full-scale CT coil dipole magnet
  - Development of the field measurement system
  - Design of the full-scale iron-core dipole magnet
- **Progress on CEPC Collider magnets**
  - Development of dual aperture dipole(DAD) magnet
  - Optimization of dual aperture quadrupole(DAQ) magnet
  - Design of sextupole magnet
- **Summary and next plan**

Progress on the collider dual aperture dipole magnet

- Long dual aperture dipole（DAD）magnet 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

Item	Value
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%

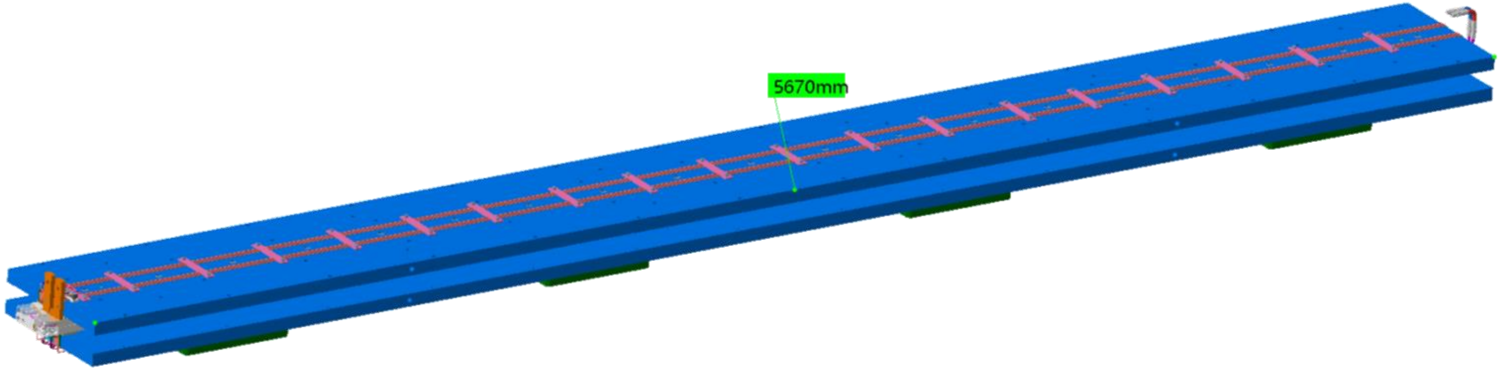




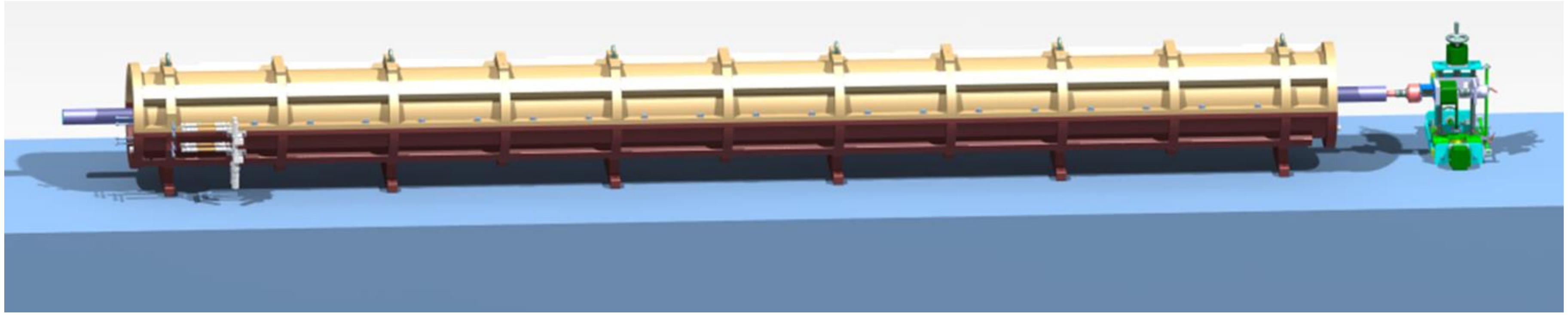
  - Design considerations
    - Beam center separation is 350mm;
    - Solid iron with DT4;
    - Two turns of aluminum busbars with cooling hole;
    - Silvered contact face to reduce contact resistance.

Progress on the Collider DAD magnet

- The mechanical design of the long DAD has been completed.

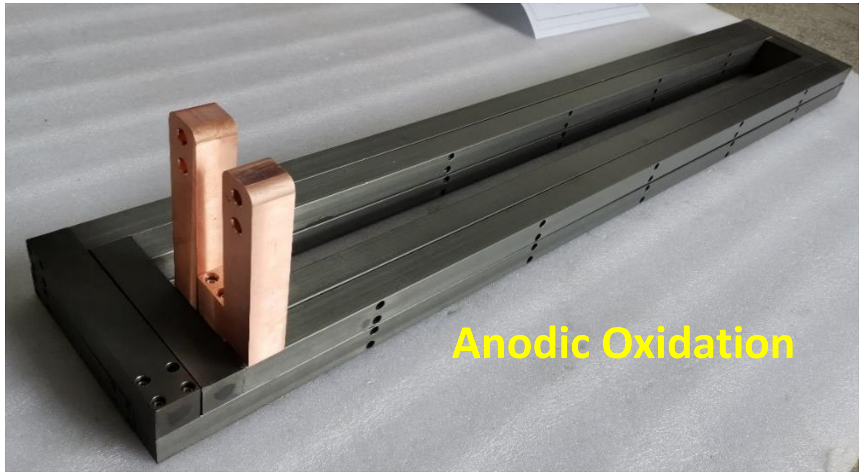


- The magnetic field will be measured by a rotating coil measurement system
  - ➢ Shared with Booster dipole magnet.



Progress on the Collider DAD magnet

- Research on coil's radiation protection and insulation
  - Aluminum strip: 4 turns;
  - Cross section:30*27mm,D10mm;
  - Water channel sealed by sealing ring;

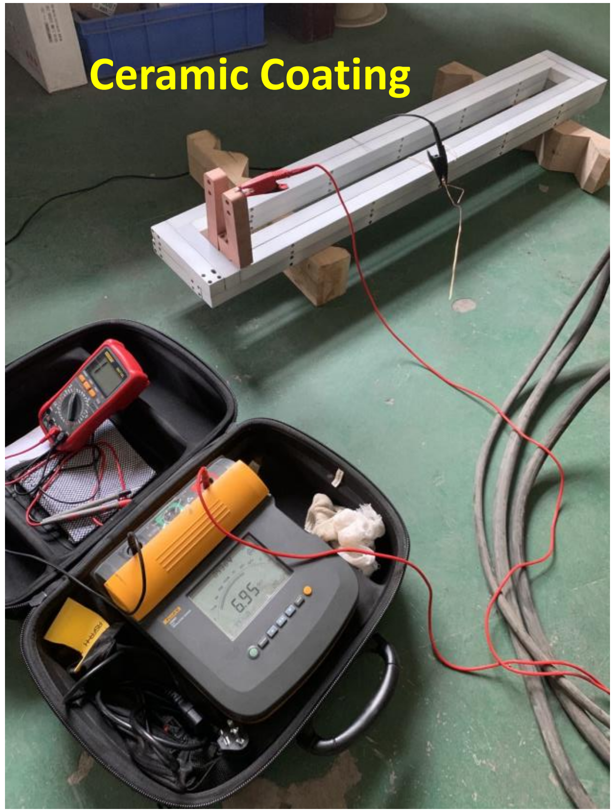


- **Hard anodized insulation test results**
  - Water drop test: **passed. (Δp=**0.88Mpa， keep 30min)
  - Turn by turn insulation test: **failed**
  - High voltage test： **failed**.

Progress on the Collider DAD magnet

Ceramic coating insulation test results

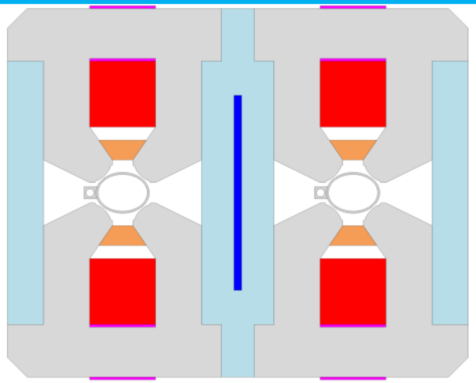
- Water drop test: passed（1Mpa~0.12Mpa，keep 30min)
- Turn by turn insulation test: passed.
- High voltage test： passed.
- Resistance: much larger than design.

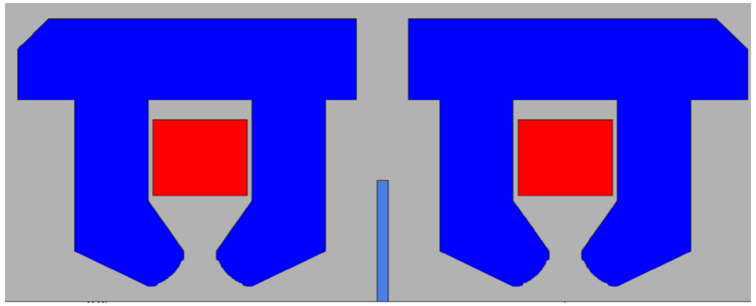


- ✓ The insulating coating lead to poor contact of the contact surface, the oxidation corrosion of silver plating.
- ✓ Surface treatment required.
  - ✓ The final resistance is 0.66 mΩ, still larger than the simulated one（0.47 mΩ）.

Optimization of DAQ magnet

- Basic parameters of DAQ (dual aperture quadrupole)
  - Aperture： 76mm
  - Beam separation is 350mm
  - Gradient range: 3.20T/m@45.5GeV~12.8T/m@182.5GeV
  - Trim coil:+-1.5%
  - Good field region: 5×10^{-4}@Rref=12.2mm
- First F/D prototype features:
  - DT4 compensation sheet at yoke center.
  - Trim coils are the same with main coils.
  - Hollow water cooled aluminum conductor.
  - The field in DT4 sheet saturation resulted harmonic changes in the b1 and b3, large cross talk between the two apertures.

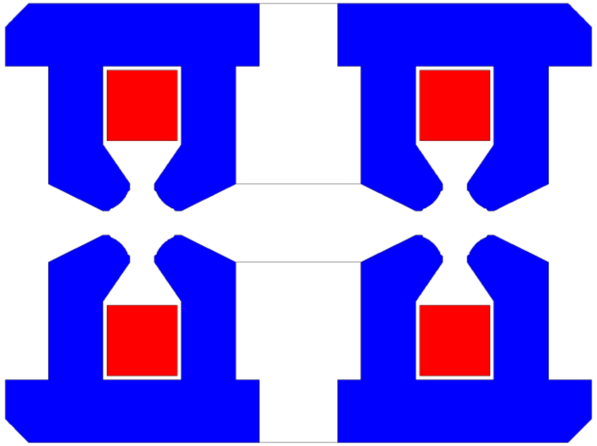


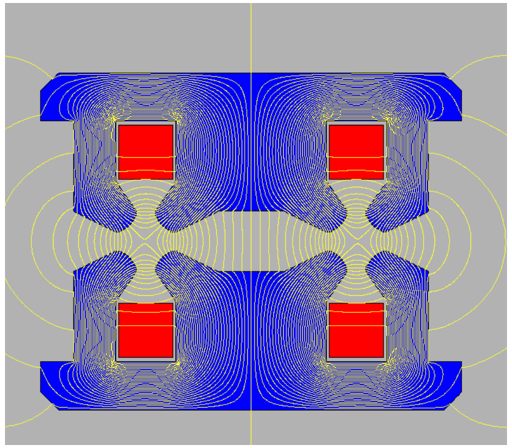


Optimization of DAQ magnet

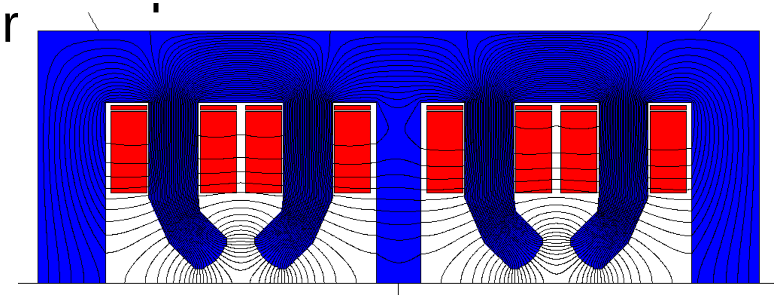
- Cross talk effect solving attempt:
  - Different shim at the pole face;
  - Pole shift; Pole rotate;
  - Beam separation change:

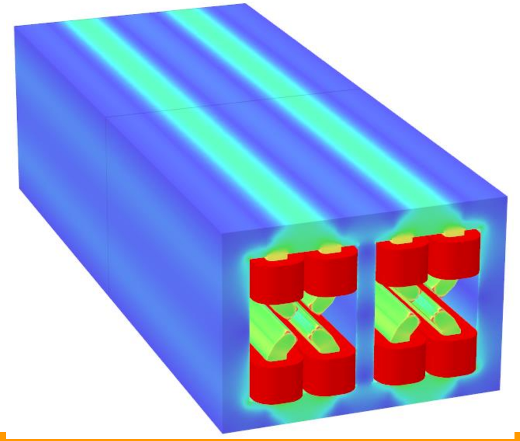
	d350		d400		d500	
	Ap1	Ap2	Ap1	Ap2	Ap1	Ap2
b1	-2359.19	2359.21	-1685.94	1685.94	-1624.30	1624.31
b3	-191.13	191.13	-136.59	136.59	-131.59	131.59
b5	-2.58	2.58	-1.85	1.85	-1.78	1.78





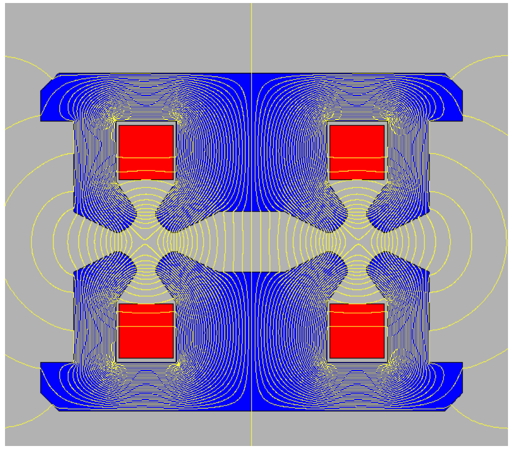
- Backup scheme: F/F polarity
  - 8 main coils, large power
  - No cross talk effect.



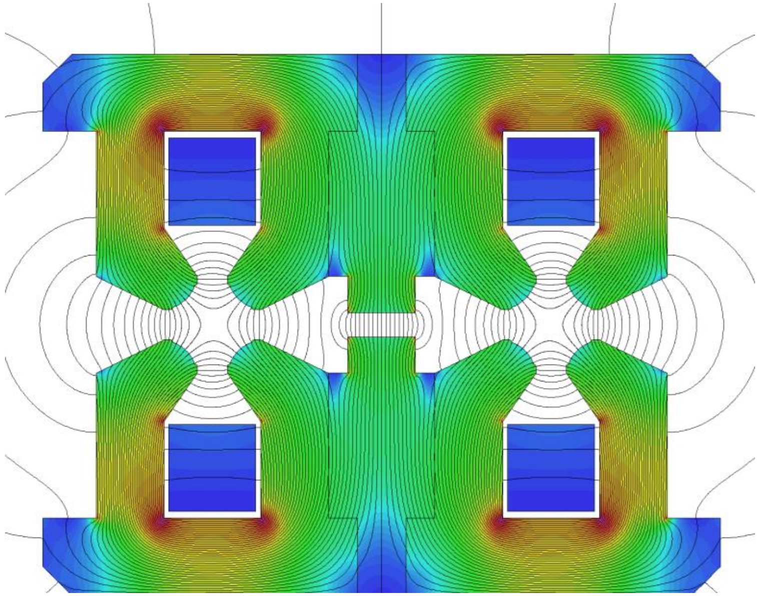


Optimization of DAQ magnet

- New design of F/D prototype
  - Shim at yoke center
  - The iron not saturated and the b1 and b3 component changes along with energies can be neglected.



Original

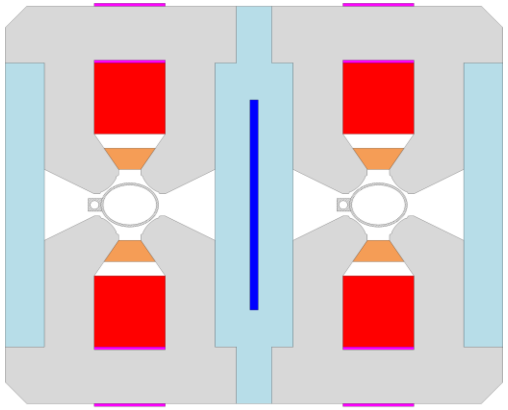


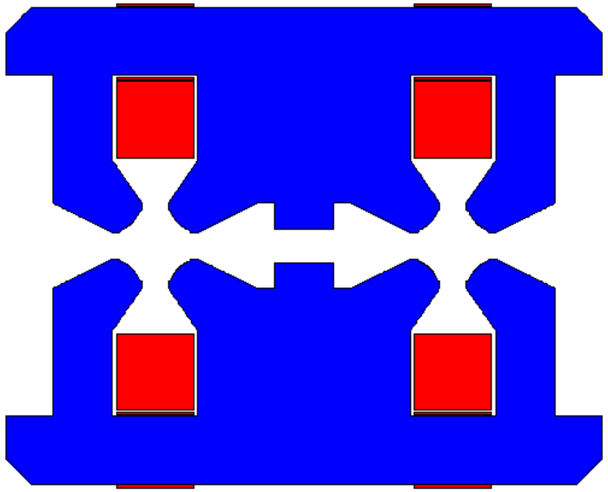
Center shim

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

Progress on the Collider DAQ magnet

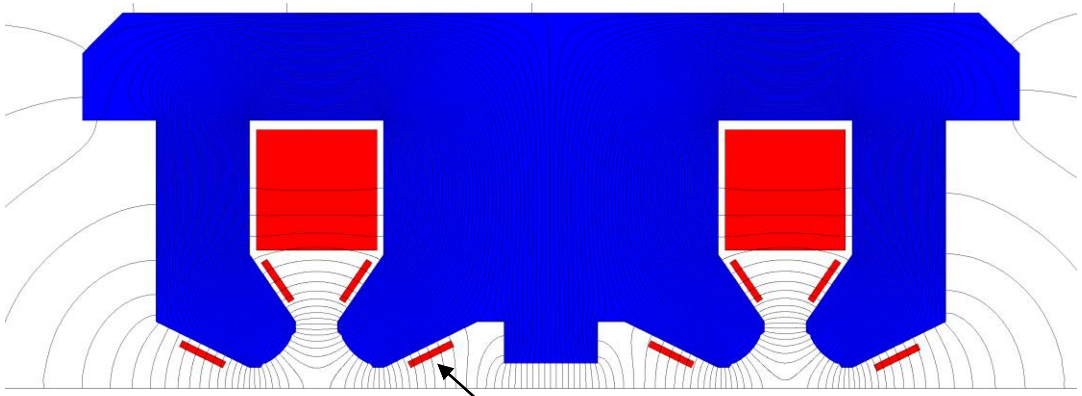
- Trim coil design： to adjust the field at two apertures independently.
  - ➢ Counteract energy sawtooth effect.
  - ➢ Eliminate the dispersion of magnetic field.
- Optimization target:
  - ➢ Produce local field strength in one aperture.
  - ➢ Never affect the other aperture.
- Layout 1: trim coil on the yoke.
  - ➢ Without trim coil, from Z to TT, b1 varies about 5 units.
  - ➢ 1.5% trim coil: b1 varies about 260 units, b3 varies 20 units.





Progress on the Collider DAQ magnet

- Layout 2: chosen.
  - 1.5% trim coil : harmonic variations are accepted at different energies.

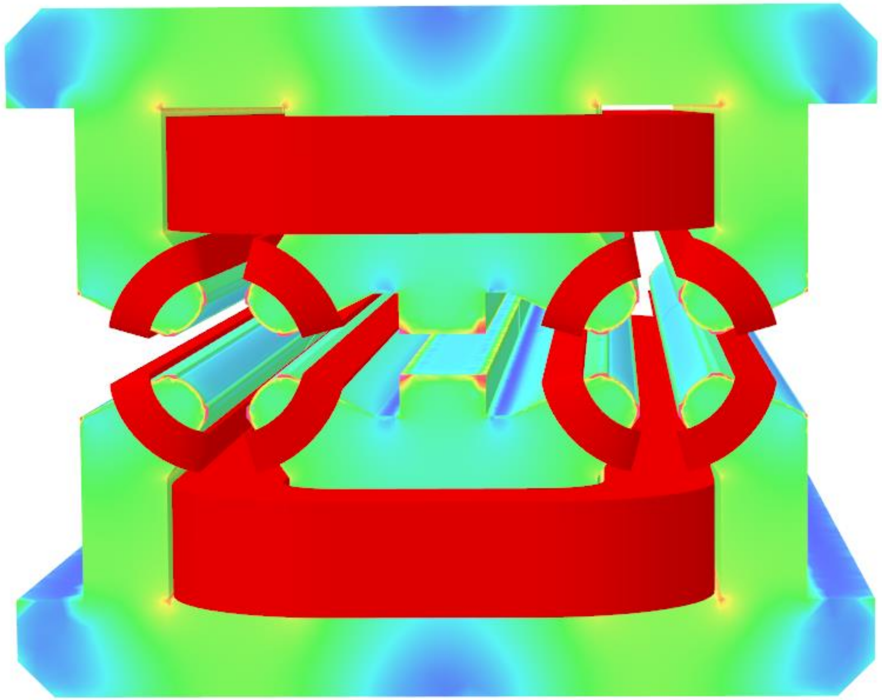


	origin		L+0_R+1.5%		L-1.5%_R+1.5%	
	L	R	L	R	L	R
G(T/m)	-8.537	8.533	-8.537	8.663	-8.407	8.663
n	bn_L	bn_R	bn_L	bn_R	bn_L	bn_R
1	-13.402	13.588	-13.676	12.801	-14.487	12.533
2	10000	10000	10000	10000	10000	10000
3	-1.089	1.071	-1.112	1.008	-1.177	0.986
4	0.521	0.521	0.521	0.522	0.521	0.522
5	-0.013	0.015	-0.013	0.015	-0.014	0.014
6	-0.035	-0.035	-0.035	-0.036	-0.034	-0.036
7	0.001	-0.001	0.001	-0.001	0.001	-0.001
8	0.007	0.007	0.007	0.007	0.007	0.007
9	0.000	0.000	0.000	0.000	0.000	0.000
10	-0.011	-0.011	-0.011	-0.011	-0.011	-0.011
DG(T/m)			0.000	0.130	0.130	0.130
db1			-0.275	-0.787	-1.085	-1.054
db3			-0.022	-0.064	-0.088	-0.085

Progress on the Collider DAQ magnet

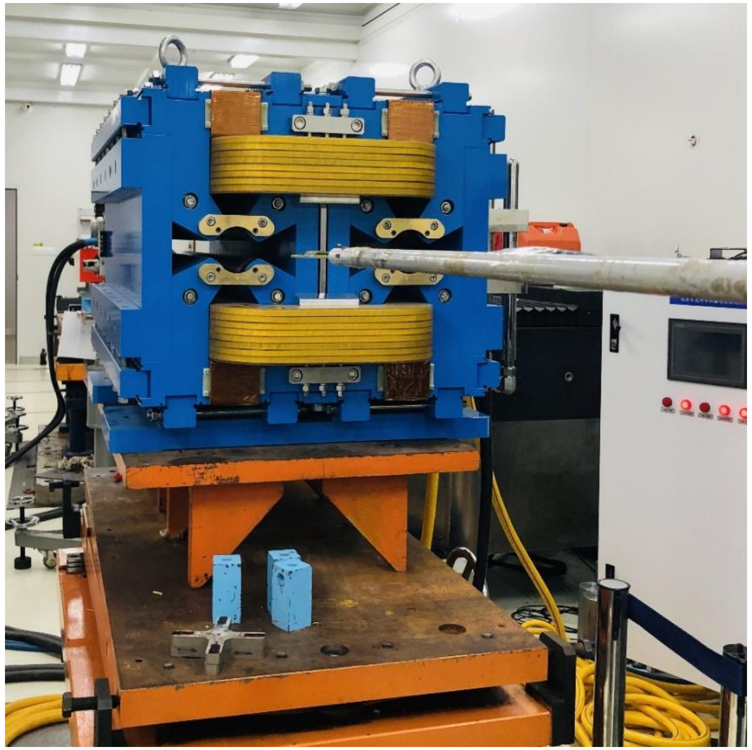
- 3D simulation with trim coils
  - ➢ The harmonics change a little.

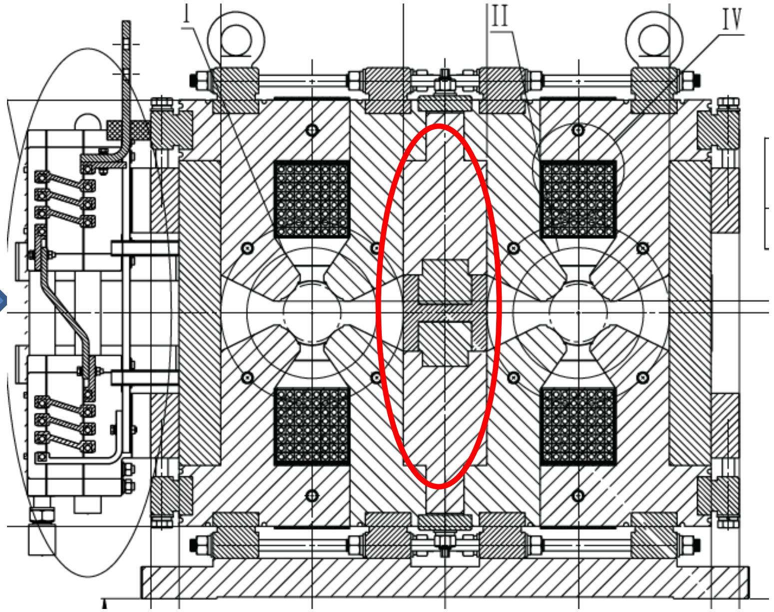
Trimcoil	45GeV		120GeV		182.5GeV		change
	AP_L	AP_R	AP_L	AP_R	AP_L	AP_R	
G(T/m)	-3.18	3.28	-8.39	8.64	-12.68	13.05	
b3	9.63	-9.53	9.64	-9.72	10.52	-11.58	-2.1
b4	0.53	0.41	0.54	0.42	0.56	0.43	
b5	0.11	-0.12	0.11	-0.12	0.12	-0.14	
b6	-0.34	-0.31	-0.35	-0.31	-0.36	-0.33	
x0(mm)	0.2937	-0.2834	0.2936	-0.2807	0.2841	-0.2560	0.03
Beam sep		-0.5770		-0.5743		-0.5401	0.04

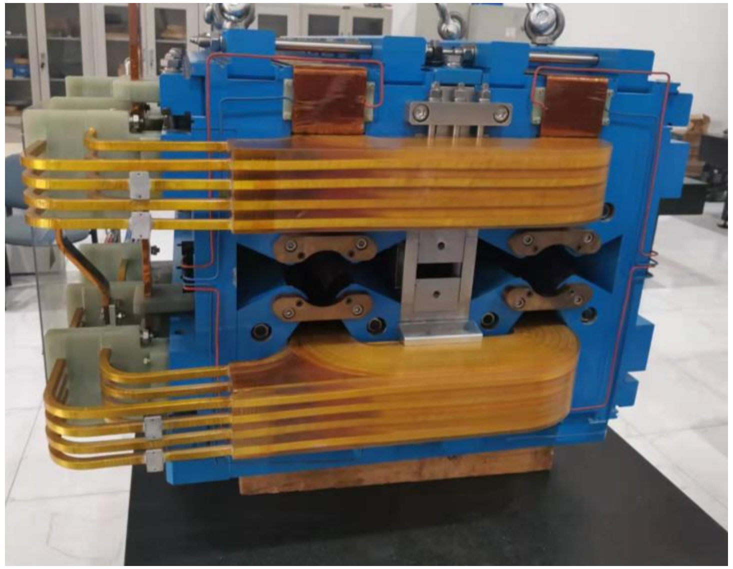


Progress on the Collider DAQ magnet

- Modification of the dual aperture quadrupole magnet
  - The new simulation of the 1m magnet is been checked.
  - The mechanical modification is completed.The field measurement is under development.

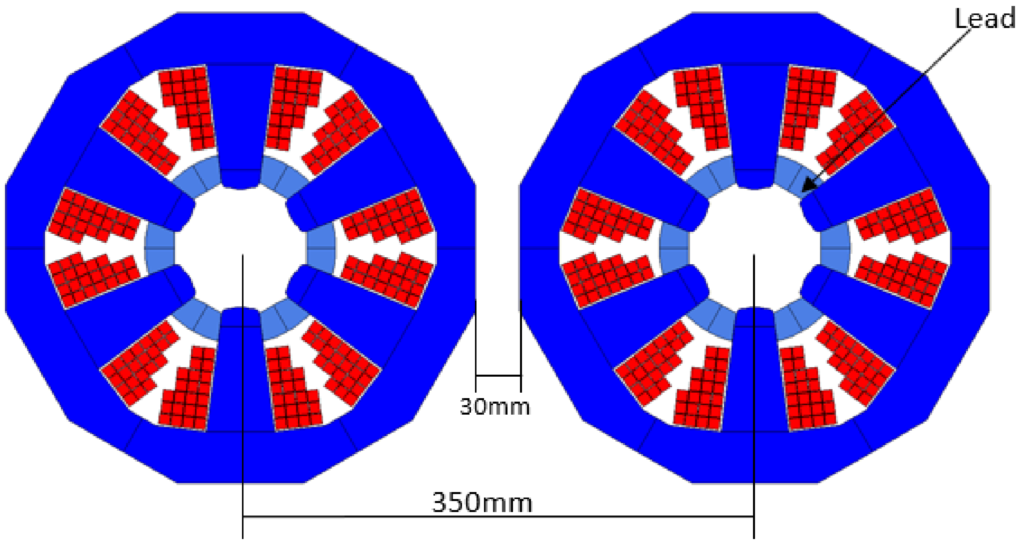


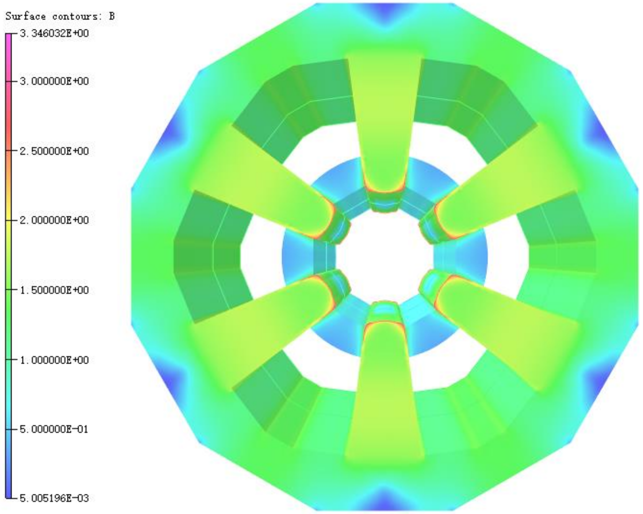


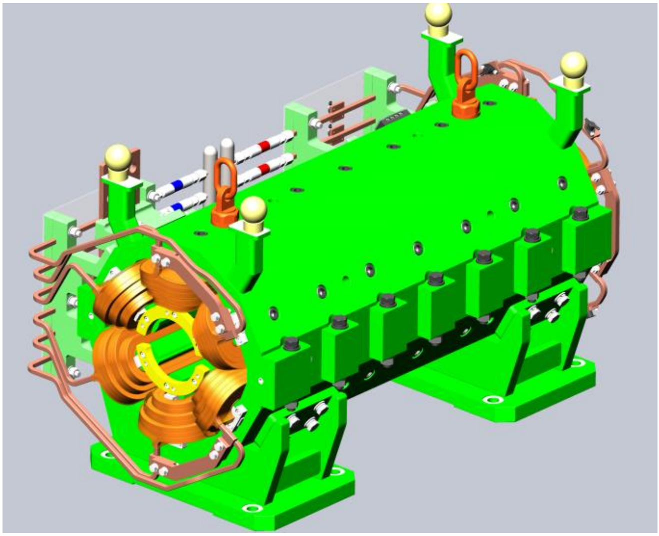


Design of sextupole magnet

- Basic design
  - Wedge-shaped magnetic poles are used to reduce magnetic pole saturation and improve excitation efficiency
  - Further optimization to the position of the lead block and the arrangement of coil wires to reserve space for magnet assembly.
  - Mechanical design is in progress, the mechanical strength should be checked.







Summary and next plan

- For CEPC Booster dipole magnet:
  - CT coil dipole can meet the physical requirements at 28Gs, both the coil and iron-core magnets can meet the requirements above 56Gs when the energy is at 20GeV.
  - CT coil dipole is under production and the rotating coil measurement system is being development.
  - The iron core magnet is chosen for CEPC booster as the injection energy is increases to 20GeV. The full scale magnet is under mechanical design.
- For CEPC Collider Magnet:
  - Long DAD is under production.
  - The radiation protection and contact surface treatment experiment of the water-cooled aluminum rod is in progress.
  - New compensated scheme for F/D DAQ has been finished. The modification of the prototype is undergone and will be measured. Further optimization is still on.
  - The single aperture sextupole magnet is in mechanical design.

Thank you very much!