CEPC magnet design and R&D status in Booster ring

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Content

- Requirements of the CEPC Booster magnets
- The Cosine Theta(CT) coil prototype dipole magnets
- The iron core prototype dipole magnets
- Final design of the dipole magnets for the Booster
- Design of the quadrupole magnets for the Booster
- Summary

Requirements of the booster magnets

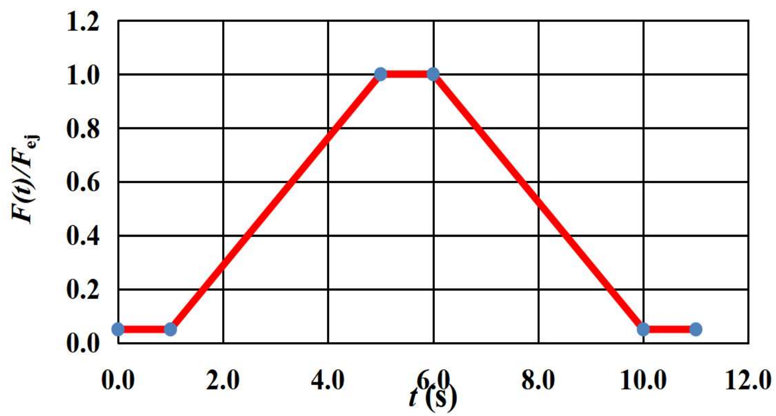
- The CEPC Booster will share the same tunnel with the Collider, which has a circumference of 100km. There are 19624 magnets equipped with the Booster, the main specifications of the magnets are listed in the table.

	Number	Length	Min. field	Max. field	Field errors (@45mm)
Dipoles	14866	4.7m	95Gs	564Gs	1×10^{-3}
Quadrupoles	3458	2m/1m/0.7m	2.0T/m	15.86T/m	5×10^{-4}
Sextupoles	100	0.4m	$18T/m^2$	$217T/m^2$	1×10^{-3}
Correctors	1200	0.58m	20Gs	200Gs	5×10^{-3}

- More than 74% of the Booster's circumference will be covered with magnets. So the cost of magnets is a significant concern in the design of the magnets, particularly the dipole magnets.

Requirements of the booster magnets

- The field of the Booster magnets will change with the beam energy during the acceleration of particle beams.

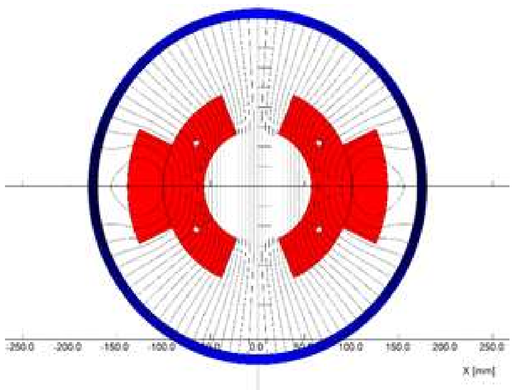


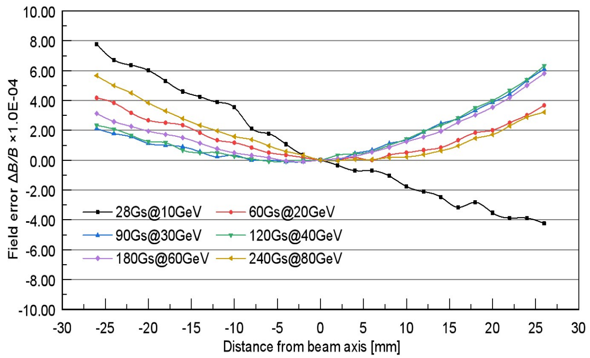
- At the CDR stage, injection energy of the Booster is 10 GeV, which requires the dipole magnet have a minimum working field of only 28 Gs with high precision of 1E-3.
- Since such low field high precision dipole magnet has never been designed and produced before, two kinds of prototype dipole magnets have been developed and studied.

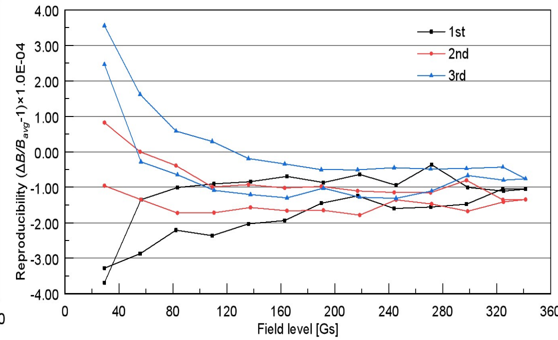
The Cosine-Theta (CT) coil prototype dipole magnet

In the past years, a subscale and a full scale CT coil prototype dipole magnet were designed and produced.

- ✓ **The subscale prototype magnet is 1.2m long, which is comprised of two half coils and a shielding tube.**
- ✓ **Each coil has two layers and three turns, which are formed by aluminium conductors.**
- ✓ **The shielding tube is made from a long steel tube.**
- ✓ **The test results of the subscale magnet show that the field precision and field reproducibility are satisfied with the requirements, especially at 28 Gs.**

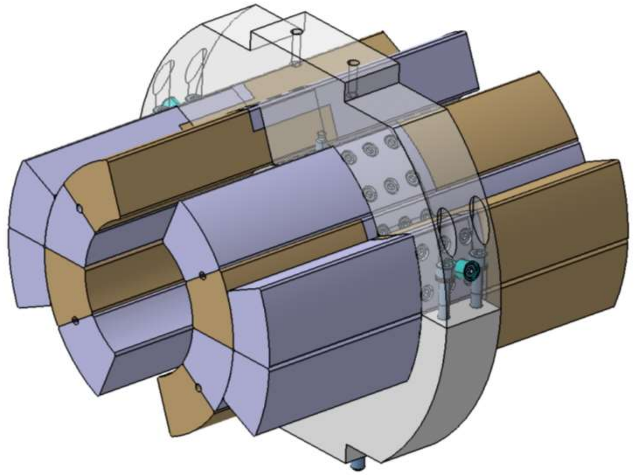


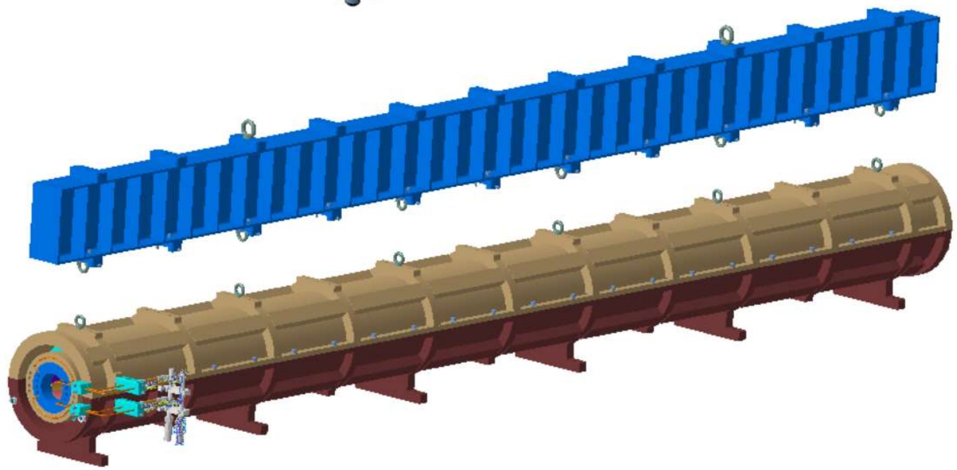




The Cosine-Theta (CT) coil prototype dipole magnet

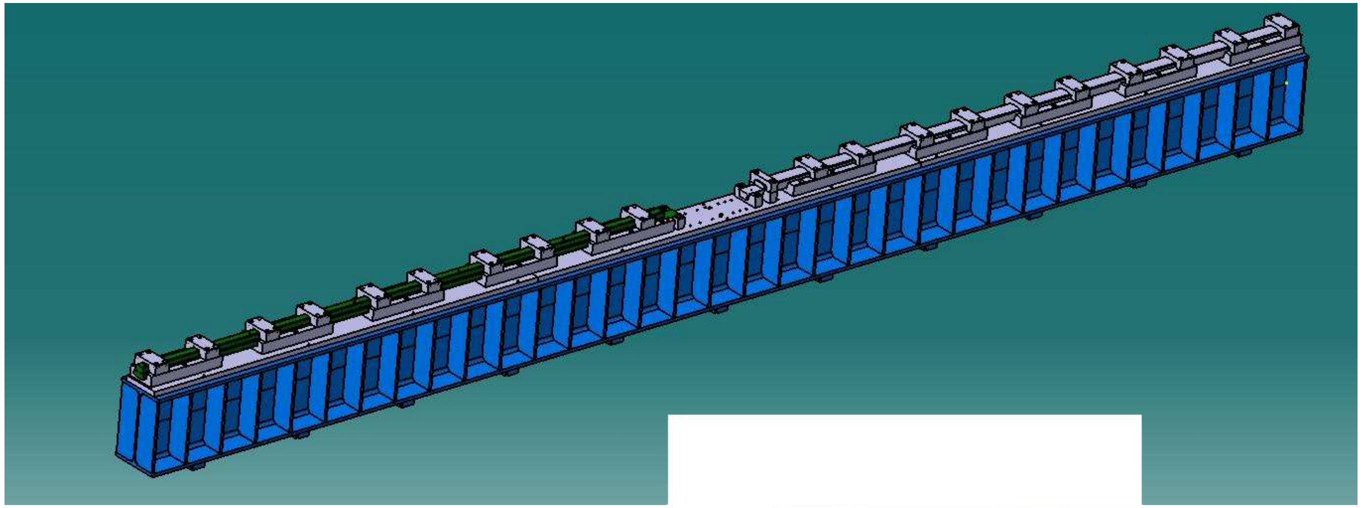
- ✓ The total length of the full scale CT coil dipole magnet is 5.1m, it also consists of the coils and shielding tube.
- ✓ Each coil has three turns, of which the conductors are fixed together by G10 supporters
- ✓ The shielding tube is made by a long steel tube. In order to install the coils, it can be split into upper and lower halves.
- ✓ To control the temperature rise, the water cooling tubes are inserted between two conductors in the inner layer of half coil.

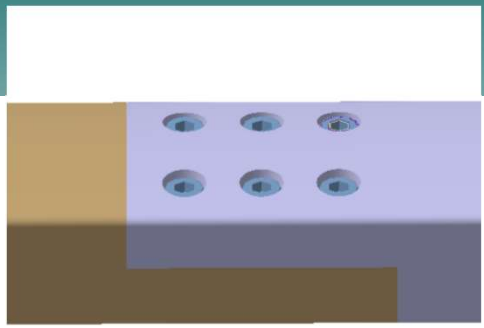


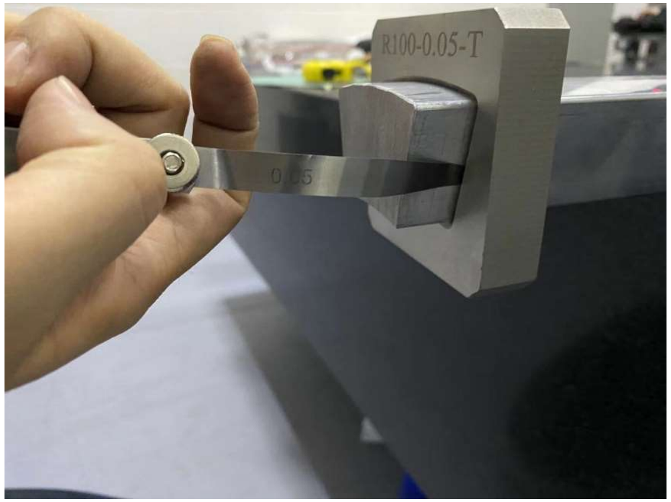


The Cosine-Theta (CT) coil prototype dipole magnet

- ✓ **To reduce the production cost, the 5m long conductors are pieced by two 2.5m short ones which are made by extrusion instead of by direct fabrication.**

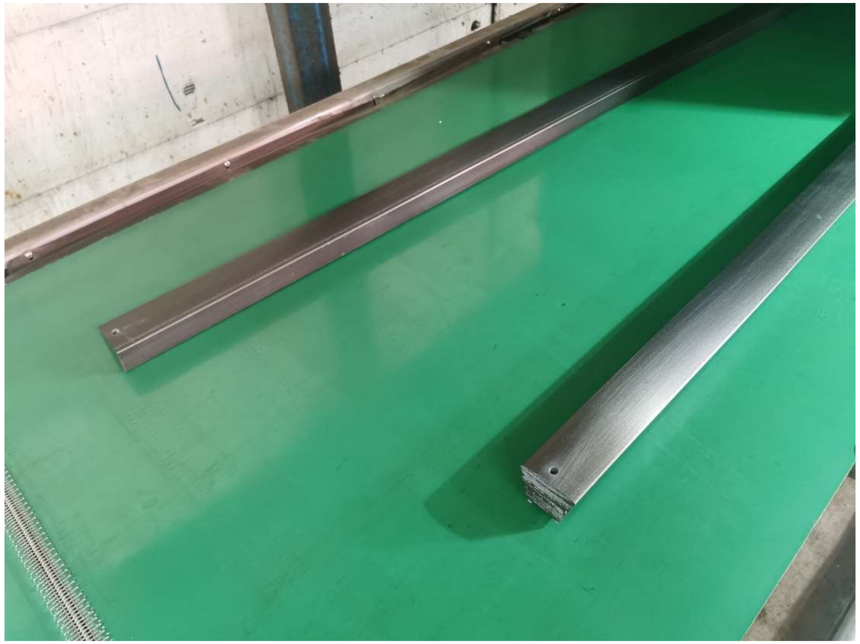


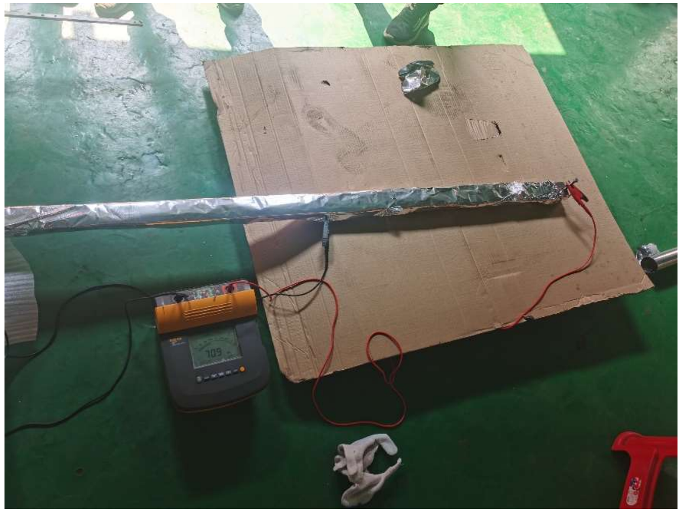




The Cosine-Theta (CT) coil prototype dipole magnet

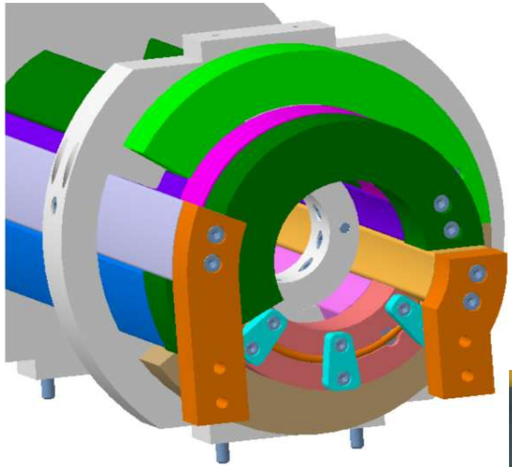
- ✓ The insulation from turn to turn of the coils could be made by the technology of surface anodization. The film on the touch surfaces is gotten rid of before coated with silver film.

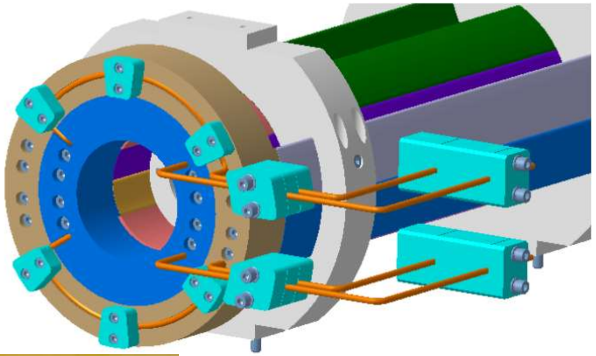




The Cosine-Theta (CT) coil prototype dipole magnet

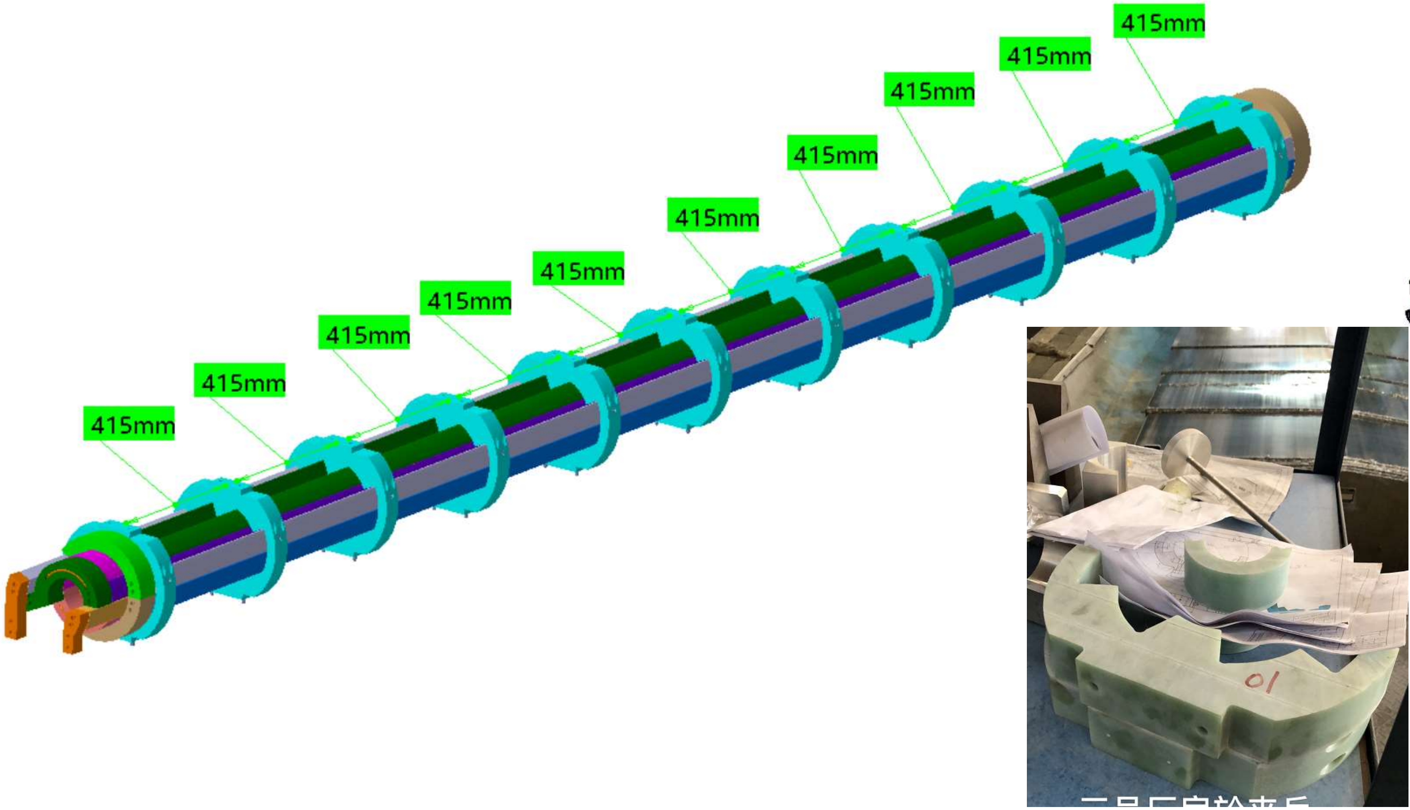
✓ The conductors of the coils from turn to turn are connected by the by-pass circular conductors at the ends of the magnet. The water cooling tubes are led out at one end of the magnet.

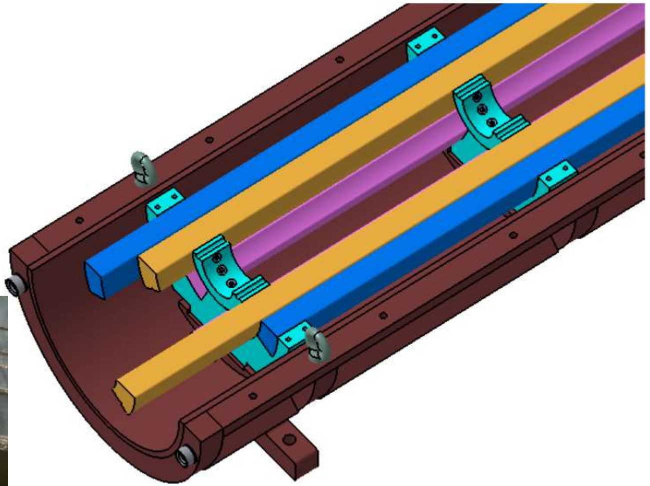




The Cosine-Theta (CT) coil prototype dipole magnet

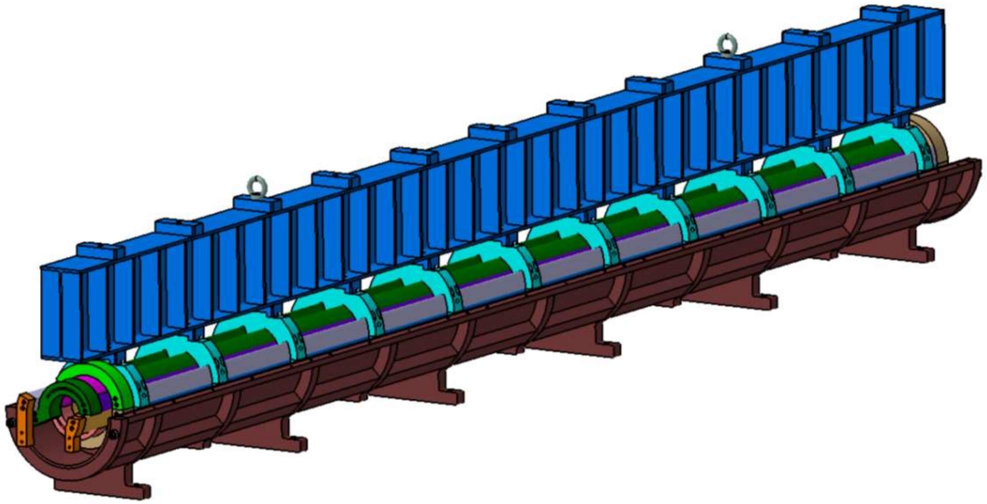
✓ **To insure the conductors of the coils at their right position, the supporters every 415mm in longitudinal direction are assembled. The positions of the shielding tube that support the supporters of the coils are carefully and precisely machined.**

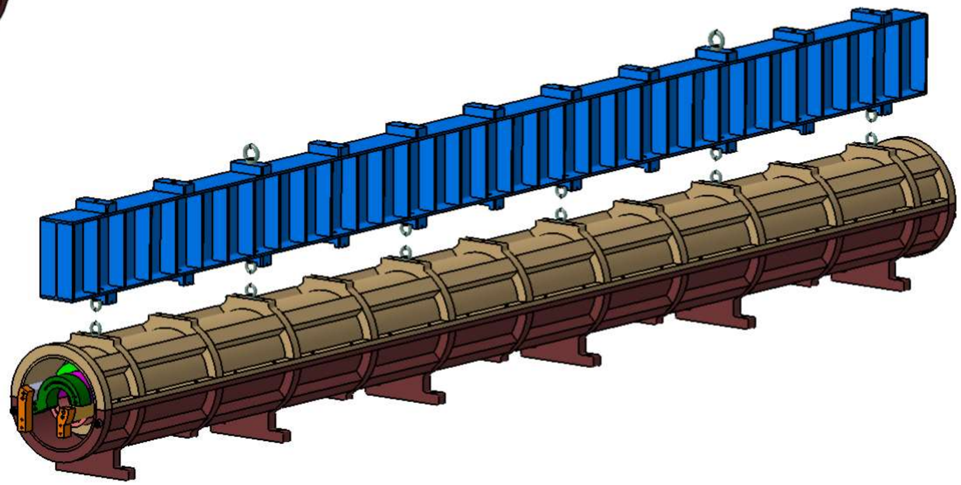




The Cosine-Theta (CT) coil prototype dipole magnet

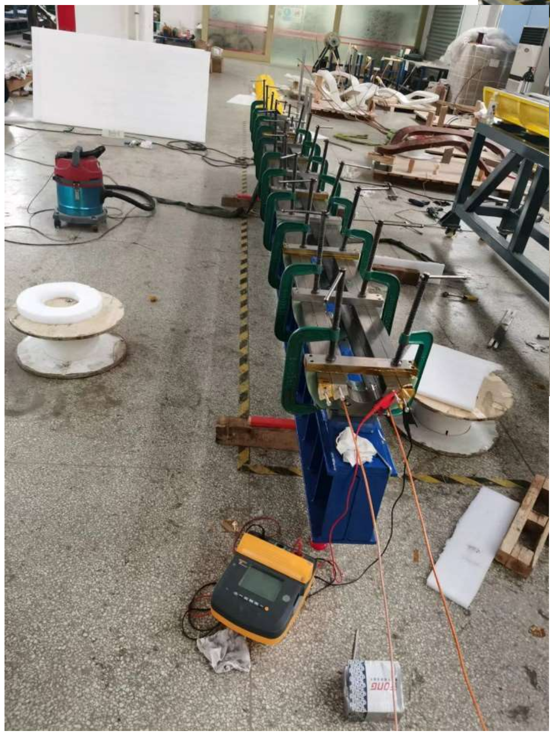
- ✓ In the assembly process, the lower coil is directly installed in the lower half shielding tube, the upper one should be firstly assembled in an assembling tooling and then rotated 180 degree. After it is put together with the lower coil, the upper shielding tube is assembled with the lower one by the same assembling tooling.





The Cosine-Theta (CT) coil prototype dipole magnet

✓ **The pictures in the process the magnet assembly.**

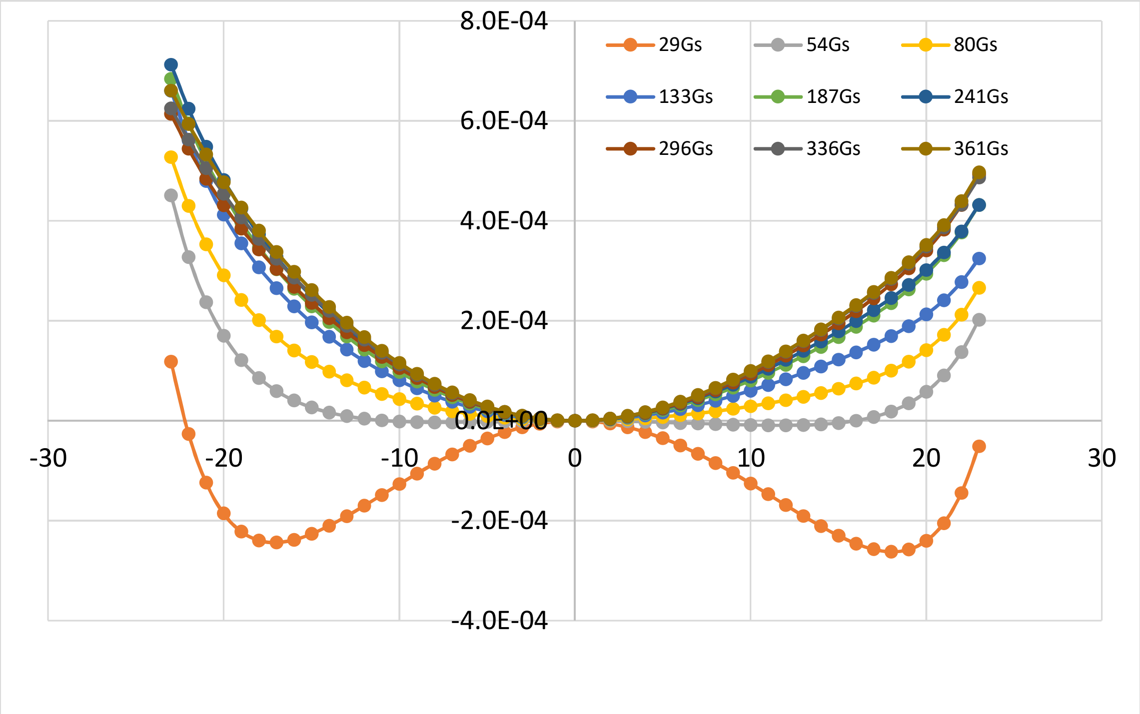


The Cosine-Theta (CT) coil prototype dipole magnet

- The magnetic field of the dipole magnet was measured by a rotating coil measurement system in the lab of IHEP.

The Cosine-Theta (CT) coil prototype dipole magnet

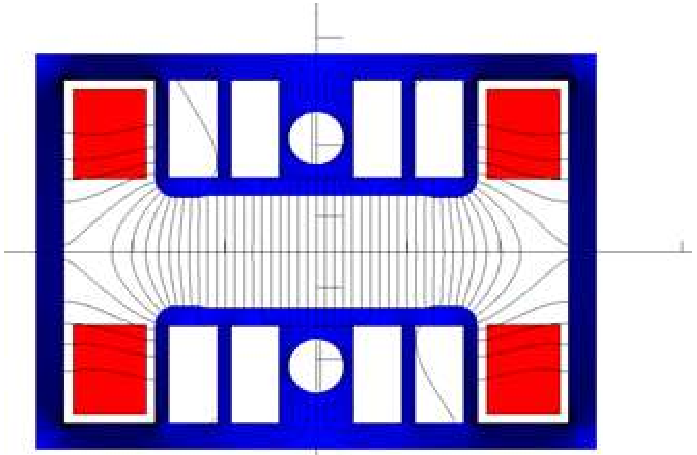
- **The measured uniformity at all field levels are better than the required value of 1×10^{-3}, especially at 28 Gs, which reaches 3×10^{-4}.**

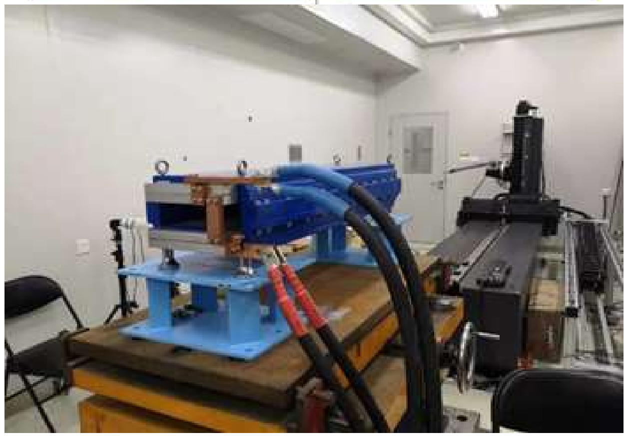


The iron core prototype dipole magnet

Due to low cost and low power loss, a new kind of iron core dipole magnet was proposed, a subscale and a full scale prototype magnets were also produced and tested.

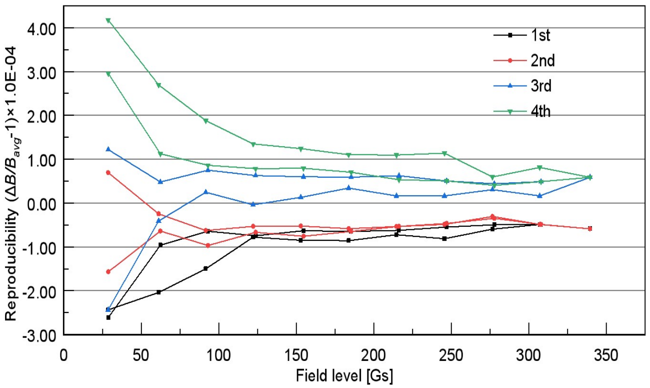
- ✓ **The subscale dipole magnet is 1.4m long, which consists of iron core and coils.**
- ✓ **To achieve better shielding effectiveness from earth field, a closed H-type core was chosen.**
- ✓ **To increase the field and decrease the weight of the cores, they are stacked by silicon steel laminations and aluminium laminations; the return yokes of the cores are made as thin as possible; in the pole areas of the laminations, some holes are punched.**
- ✓ **The coil per pole of the magnet has two turns, which are formed by long aluminium bars.**



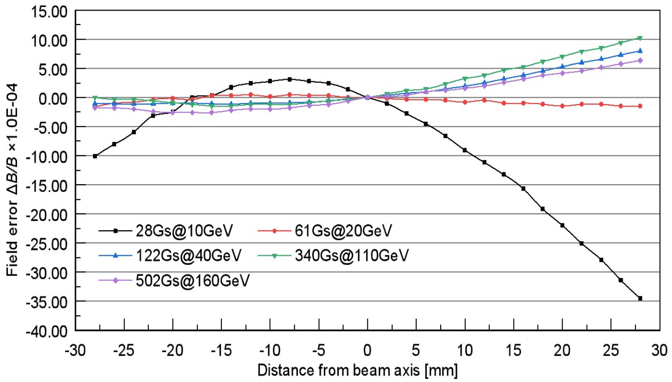


The iron core prototype dipole magnet

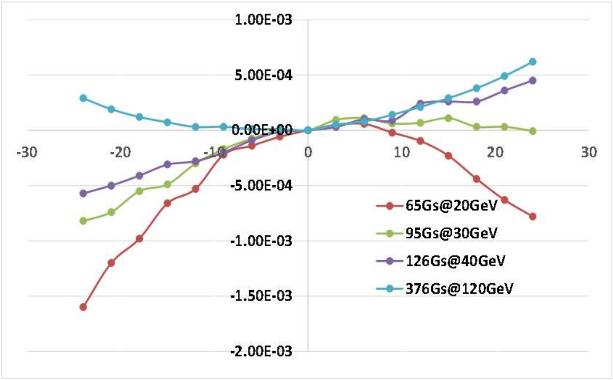
- ✓ **The test results show that the field reproducibility can meet the requirements, but the field precision at 28Gs @20 GeV is about 3.5×10^{-3}, much larger than the required value of 1×10^{-3}.**
- ✓ **In order to reach the field precision of 1×10^{-3}, the minimum field of the dipole magnet made by grain-oriented silicon steel laminations should be higher than 60 Gs @20 GeV while that made by non-oriented silicon steel laminations higher than 90 Gs @30 GeV.**



Field reproducibility @ oriented



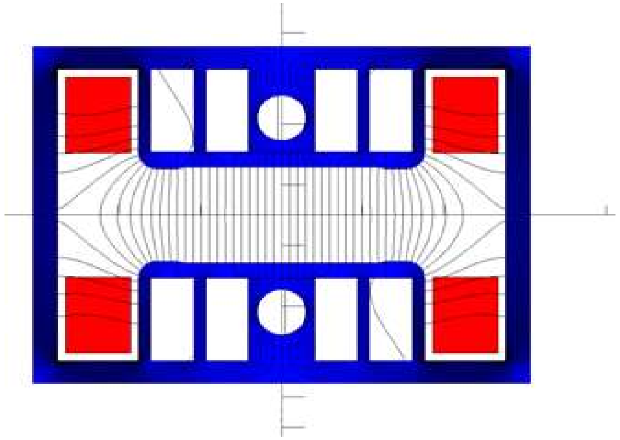
Field precision @ oriented

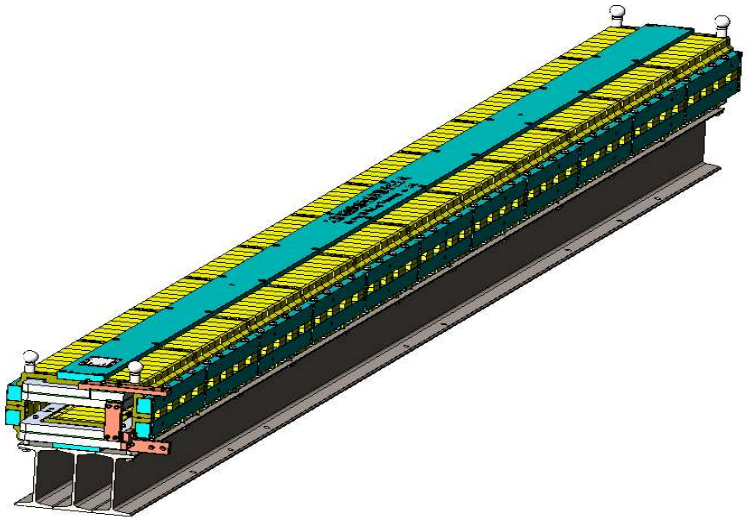


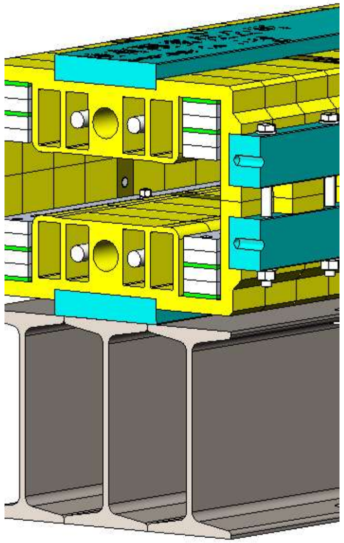
Field precision @ non-oriented

The iron core prototype dipole magnet

- ✓ The length of the full-scale iron-core dipole magnet is 4.7m, which can be spit into upper and lower halves for installation of the coils and vacuum chamber.
- ✓ The laminations of the core are pulled together by the surrounding bars and center rods.
- ✓ To reduce the deformation in longitudinal direction, the magnet is put on a long I-steel beam which has a precisely machined surface.

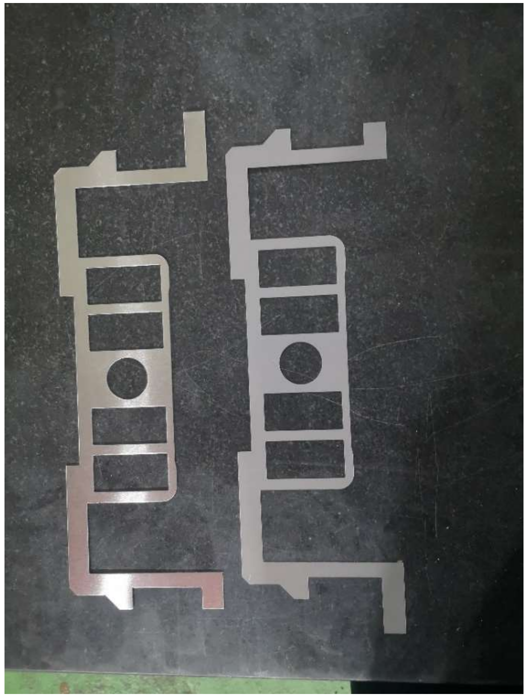


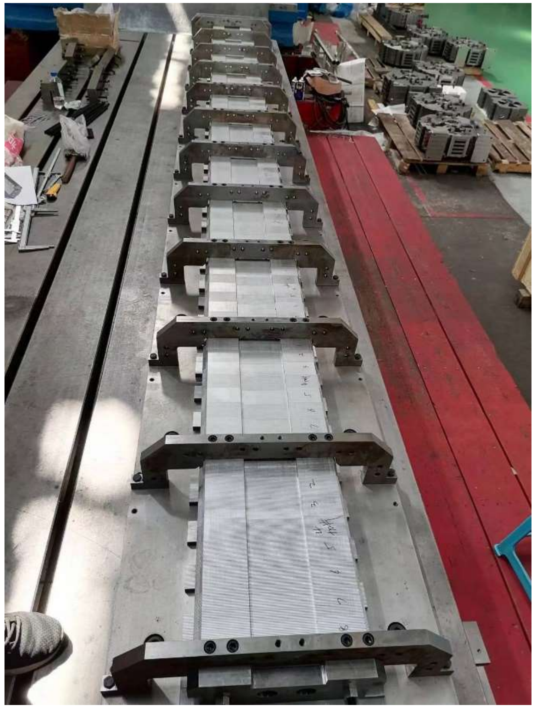


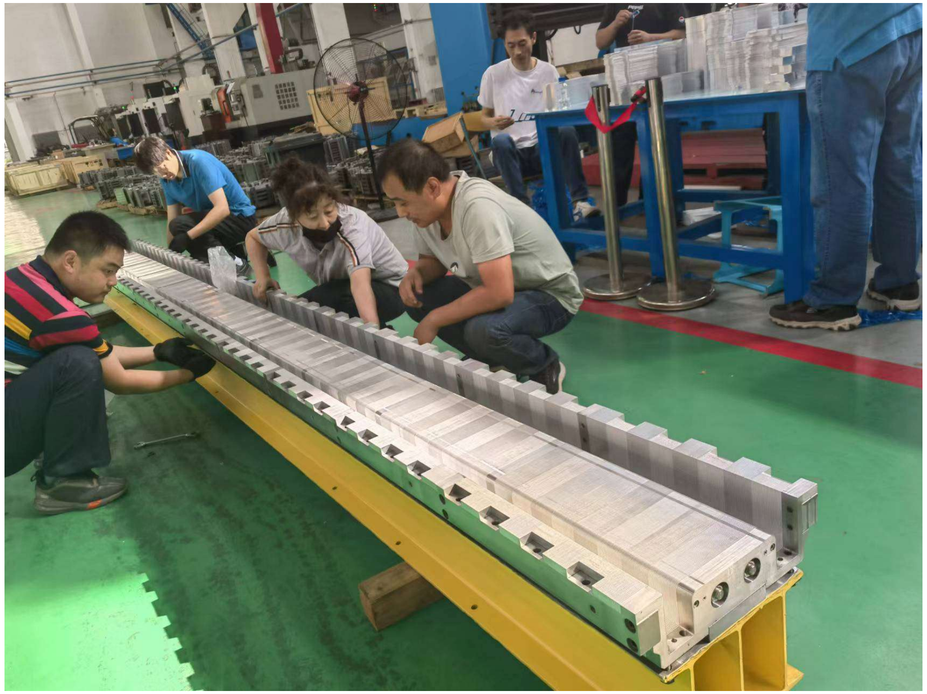


The iron core prototype dipole magnet

- ✓ **The cores are being stacked by the silicon steel laminations and aluminum laminations.**

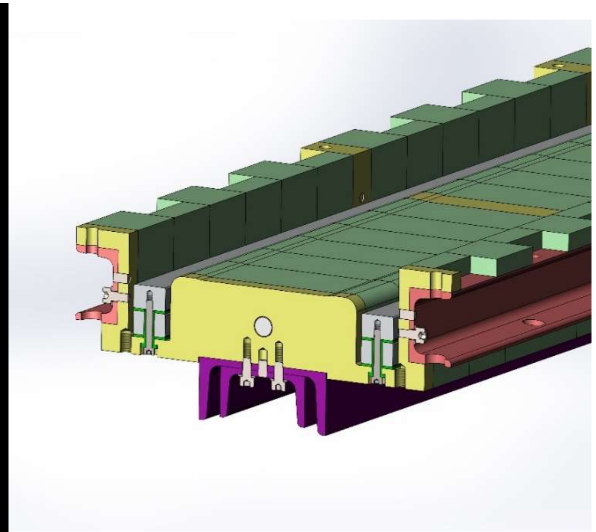






The iron core prototype dipole magnet

- ✓ The coils of the magnet are formed with several pieces of the aluminum bars.
- ✓ Unlike the conventional vacuum epoxy casting, the insulation are simply made by G10 plates. By using some kind of special structure, the coils can be simply fixed on the iron cores.

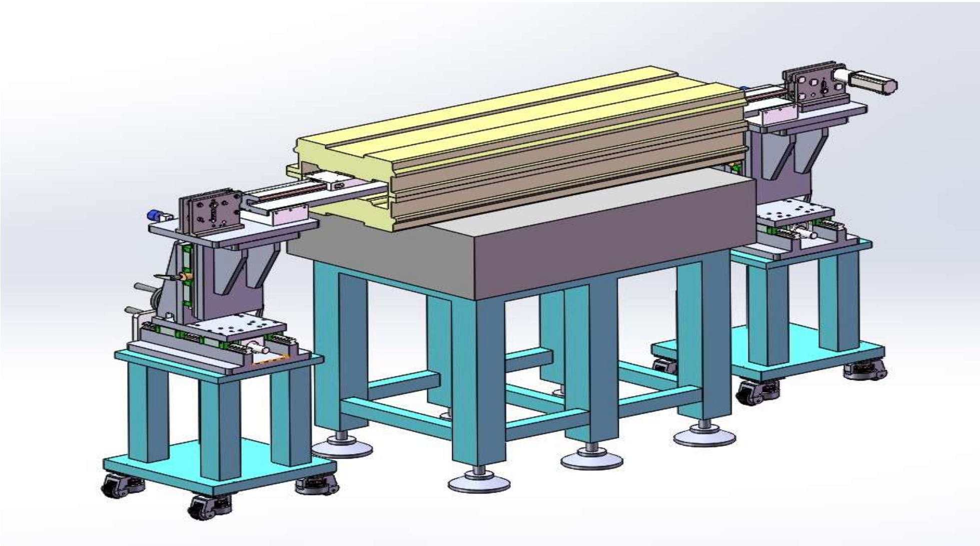


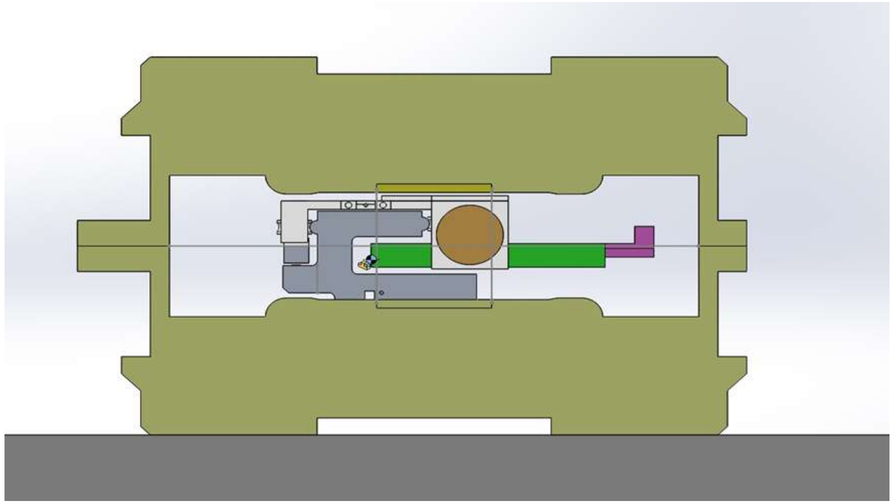
The iron core prototype dipole magnet

- ✓ **After two coils are installed in the two half cores, they are assembled together and then the production of the magnet is completed.**

The iron core prototype dipole magnet

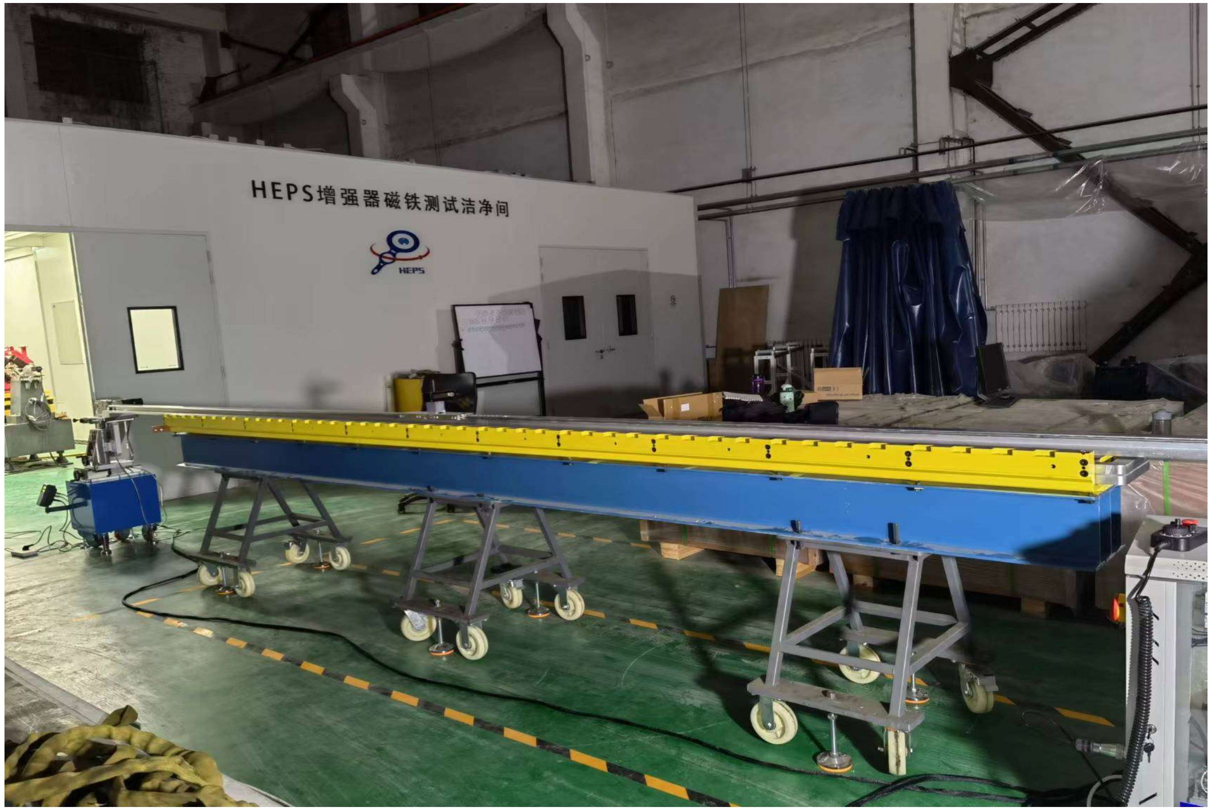
- A hall probe field measurement system is used to measure the magnetic field of the dipole magnet.
- It is composed of a 6m long slide rail, a trolley, a gauss meter and a computer.





The iron core prototype dipole magnet

- In order to put the 6m long slide rail on the lower pole surface of the magnet, the upper half of the magnet should be moved away.

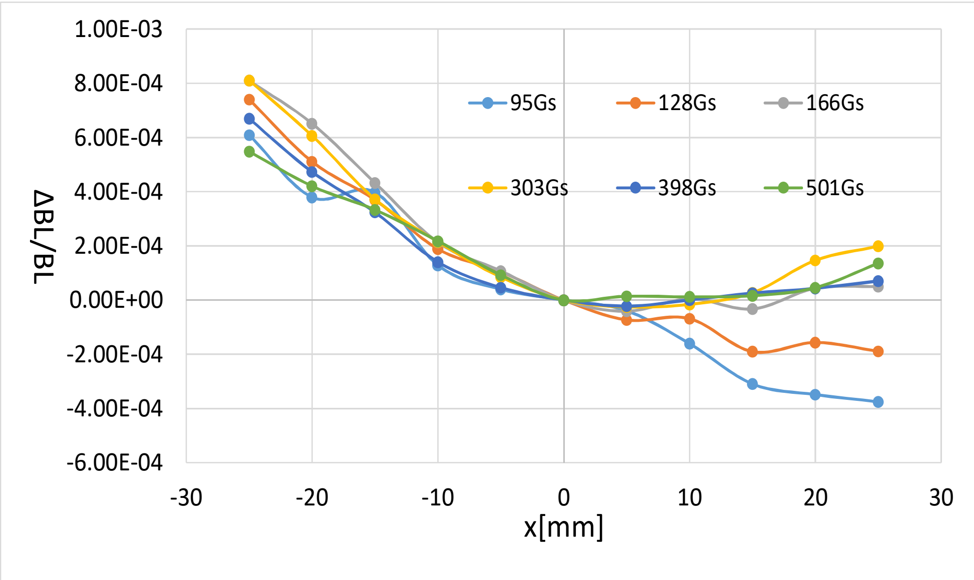


The iron core prototype dipole magnet

- After the dipole magnet is assembled with the field measurement system, it is delivered into the lab and tested.

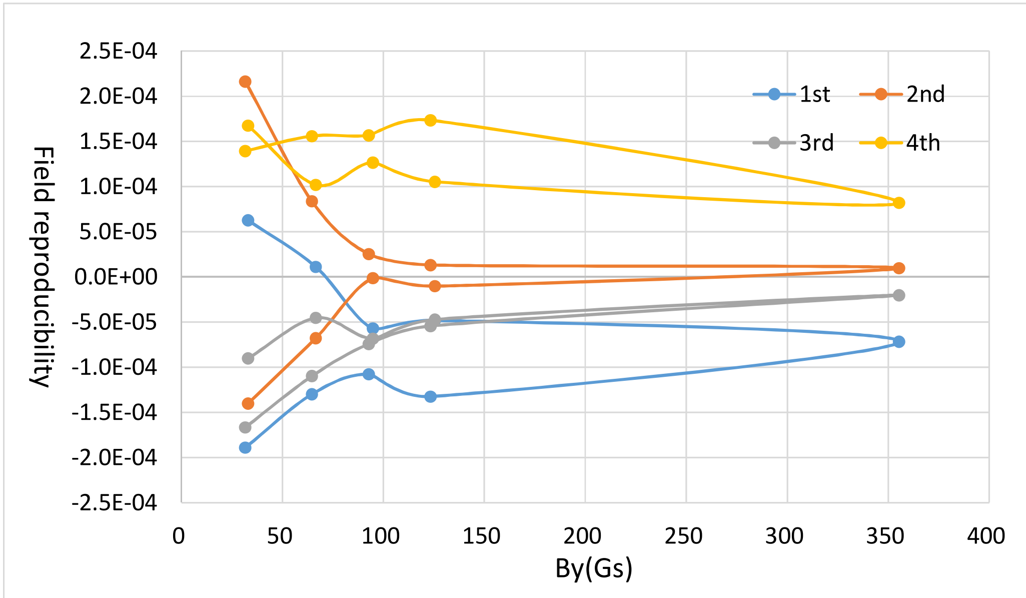
The iron core prototype dipole magnet

The magnetic field measurement results



The integral field uniformity at all field levels is better than $\pm 1\times 10^{-3}$

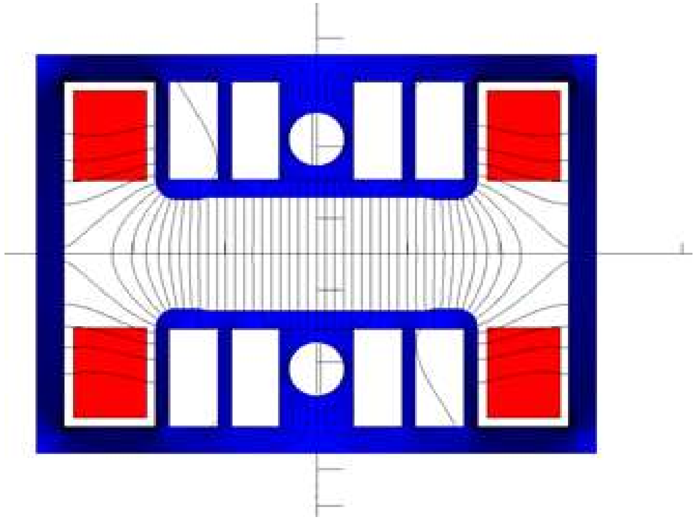
The field reproducibility of four excited cycles is better than $\pm 2.5\times 10^{-4}$



Baseline design of the dipole magnets

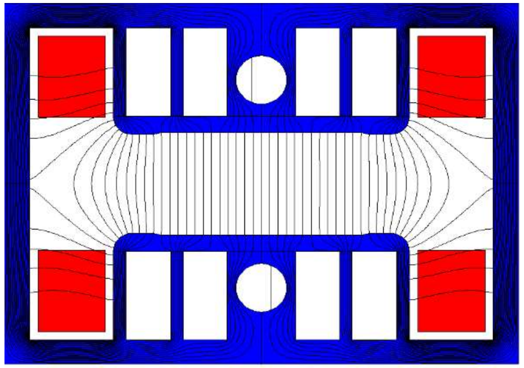
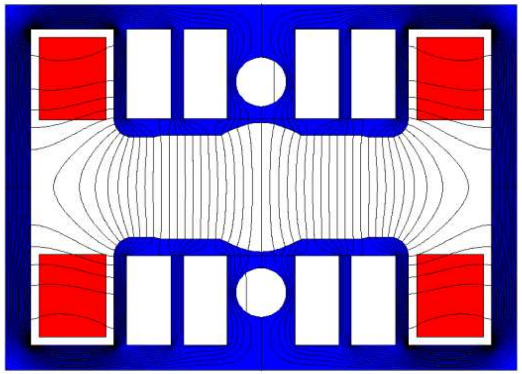
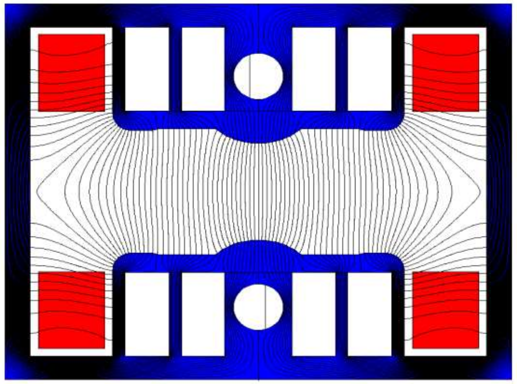
- Since the cost and power loss of the iron core dipole magnet are much lower than that of the CT coil dipole magnet.
- And the non-oriented silicon steel laminations is much cheaper than the oriented silicon steel laminations.
- In the TDR stage, the injection energy of the booster was increased to 30 GeV (from 10GeV) so that the cheap iron core dipole magnet made by non-oriented silicon steel laminations became the final baseline design for the booster.

Magnet name	Iron-core dipole	CT coil dipole
Aperture [mm]	63	
Field [Gs]@120GeV	338	
Field [Gs]@10GeV	29	
Length [mm]	4700	
Turns per pole	2	3
Current[A]@120GeV	428	1160
Current[A]@10GeV	37	96
Area of conductor[mm^2]	1000.0	1973.0
Power loss (W)@120GeV	244.6	1272.0
Avg. power loss [W]	97.8	508.8



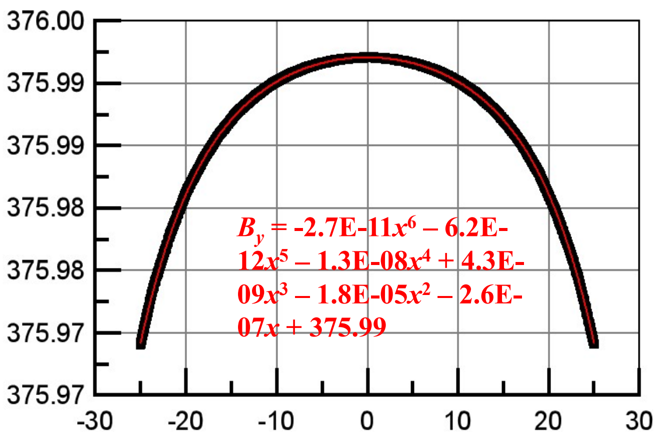
Baseline design of the dipole magnets

- In the TDR stage, the Booster dipole magnets(14886) are grouped into three families. One family is the pure dipoles, the others are the dipole-sextupole combined magnets with the sextupole field of 10.69 T/m^2 and -12.76 T/m^2 at 120GeV.
- During the acceleration of particle beams, the field of the dipole magnets will change from 95 Gs@30 GeV to 376 Gs@120 GeV or to 564 Gs@180 GeV.
- The field precision is required to be better than 1×10^{-3} at all field levels during the acceleration

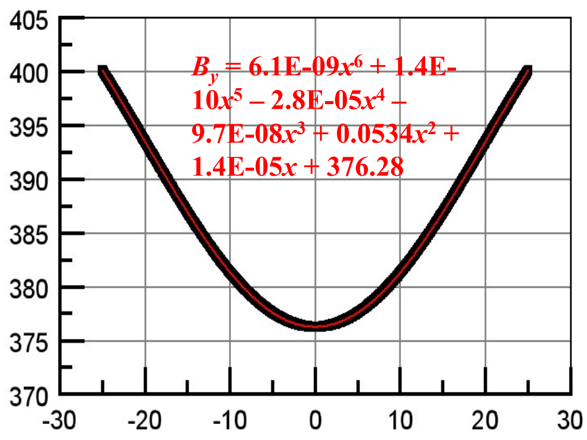




Baseline design of the dipole magnets

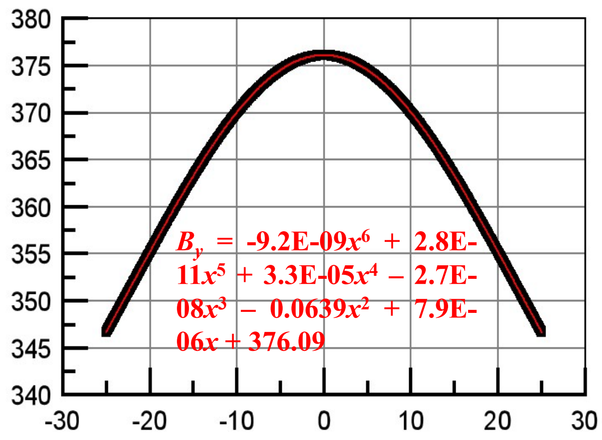
- By several iterations of optimization, the field quality of three families of dipole magnets has been improved to meet the required physical specifications.
- The field optimizations are carried out at a field level of **376 Gs @120 GeV**, as at this level, the influences of the remnant field of the iron cores can be neglected and the field simulations are relatively accurate



The dipole field is 376Gs, and total field errors is about 0.017 Gs



The dipole field is 376Gs and the sextupole field is 10.68T/m²



The dipole field is 376Gs and the sextupole field is -12.78T/m²

Baseline design of the dipole magnets

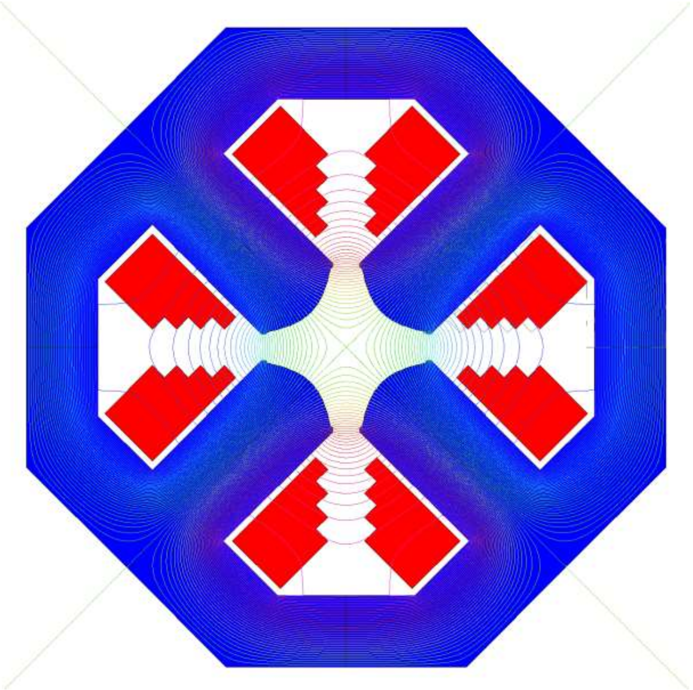
The designed parameters of the dipole magnets

Magnet name	BST-63B-Arc	BST-63B-Arc-SF	BST-63B-Arc-SD	BST-63B-IR
Quantity	10192	2017	2017	640
Aperture [mm]	63	63	63	63
Dipole Field [Gs] @180GeV	564	564	564	549
Dipole Field [Gs] @120GeV	376	376	376	366
Dipole Field [Gs] @30GeV	95	95	95	93
Sextupole Field [T/m^2] @180GeV	0	16.0388	19.1423	0
Sextupole Field [T/m^2] @120GeV	0	10.6925	12.7615	0
Sextupole Field [T/m^2] @30GeV	0	2.67315	3.19035	0
Magnetic length [mm]	4700	4700	4700	2350
GFR [mm]	±22.5	±22.5	±22.5	±22.5
Field errors	$\pm1\times10^{-3}$	$\pm1\times10^{-3}$	$\pm1\times10^{-3}$	$\pm1\times10^{-3}$
Turns per pole	2	2	2	2
Current[A]@180GeV	714	791	764	695
Current[A]@120GeV	476	528	509	463
Current[A]@30GeV	120	133	129	118
Size of conductor [mm*mm]	25*40-Al	25*40-Al	25*40-Al	25*40-Al
Max. current density [A/mm^2]	0.71	0.79	0.76	0.69
Resistance of the coil (mΩ)	1.56	1.56	1.56	0.817
Power loss (W) @180GeV	796.1	978.4	910.7	394.7
Power loss (W) @120GeV	353.8	434.9	404.9	175.4
Avg. power loss [W] @30-180GeV	222.9	274.0	255.0	110.5
Avg. power loss [W] @30-120GeV	166.3	204.4	190.3	82.4
Max. DC voltage [V] @180GeV	1.12	1.24	1.19	0.568
Max. DC voltage [V] @120GeV	0.744	0.824	0.795	0.379
Core height [mm]	280	280	300	280
Core width [mm]	400	400	400	400
Core Length [mm]	4653	4653	4653	2303
Magnet weight [ton]	3.98	3.98	4.24	1.99

Design of the quadrupole magnets

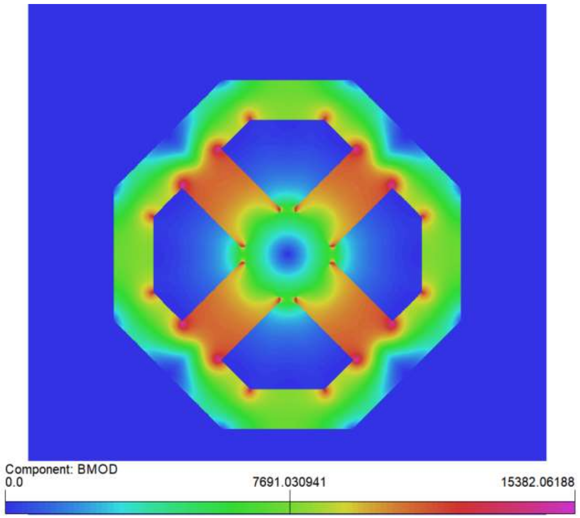
The CEPC Booster requires 3,458 quadrupole magnets, which are categorized into three families according to their effective length of 2m, 1m and 0.7m.

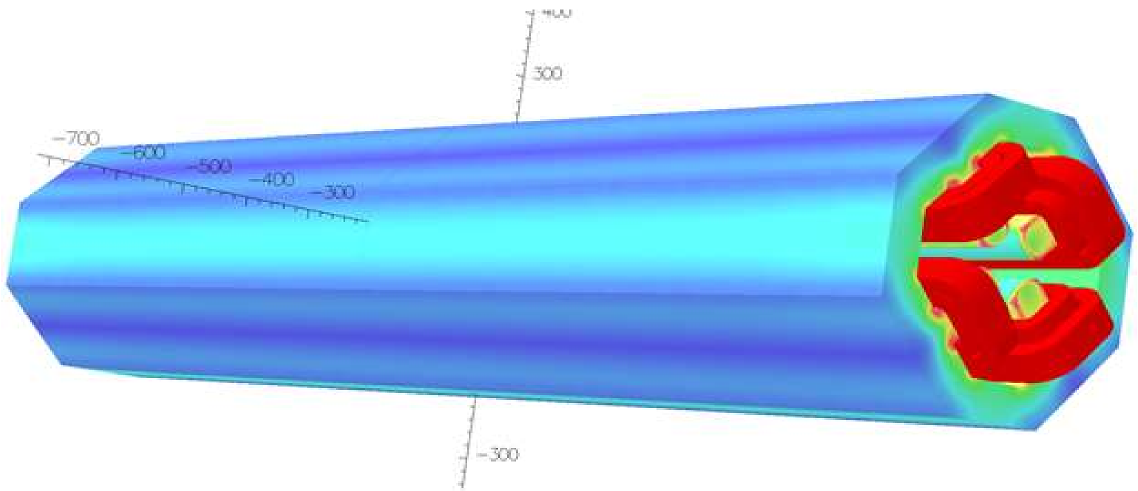
- ✓ **In order to install the coils and vacuum chamber, the quadrupole magnets will be assembled from four identical quadrants.**
- ✓ **The iron cores are made of silicon steel laminations. The coils are wound by the hollow aluminium conductor instead of the conventional copper conductor due to its lower weight and cost.**
- ✓ **Thanks to the relatively low gradient, the pole root of the quadrupole magnets is rectangular rather than tapered. This allows for a cheaper core with simple cross-sectional shape, and a cheaper coil with simple racetrack structure.**



Design of the quadrupole magnets

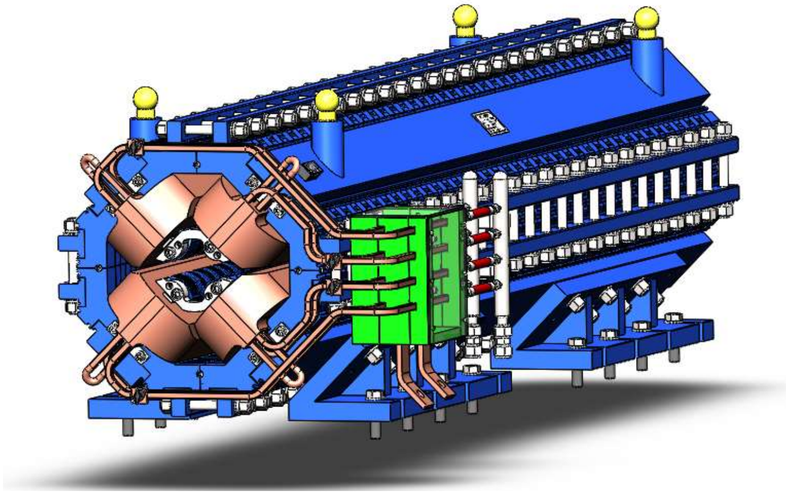
- ✓ The cross sections for the quadrupole magnets have been optimized using the OPERA-2D program. Compared with the design of the CDR, the cross-section of the quadrupole magnet for the TDR is relatively smaller.
- ✓ The OPERA-3D program has been used to simulate the 3D field of the magnets. The effective length and integral field errors are satisfied with the physical requirements.

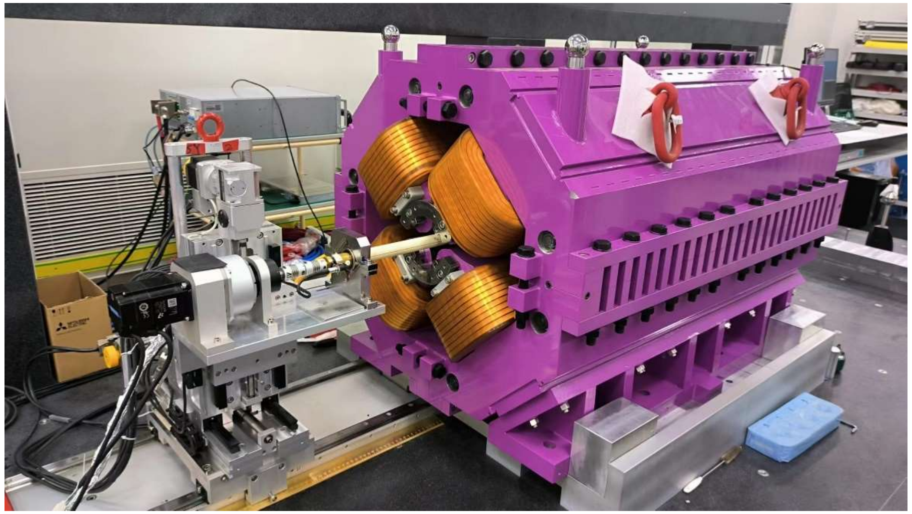




Design of the quadrupole magnets

- ✓ **The iron core of the quadrupole magnet is composed of laminations, end plates, side puller plates, and a pole head puller. The end plate, puller plates, and laminations are welded together, which could make the cores stronger.**
- ✓ **Since IHEP has production experiences of the similar long quadrupole magnet, no prototype quadrupole magnet has been produced for the CEPC Booster in TDR stage.**





Design of the quadrupole magnets

The designed parameters of the quadrupole magnets

Magnet name	BS-63Q-2000L	BS-63Q-1000L	BS-63Q-700L
Quantity	1144	296	2018
Aperture [mm]	63	63	63
Quadrupole Field [T/m]@180GeV	12.8811	15.8575	12.0313
Quadrupole Field [T/m]@120GeV	8.5874	10.5717	8.0209
Quadrupole Field [T/m]@30GeV	2.147	2.643	2.005
Effective Length [mm]	2000	1000	700
GFR (radius) [mm]	22.5	22.5	22.5
Harmonic errors	$\pm1\times10^{-3}$	$\pm1\times10^{-3}$	$\pm1\times10^{-3}$
Turns per pole	20	20	20
Current[A]@180GeV	257	316	240
Current[A]@120GeV	171	211	160
Current[A]@30GeV	42.8	52.7	40.0
Size of conductor [mm*mm]	10×10D6	10×10D6	10×10D6
Max. current density[A/mm^2]	3.58	4.41	3.34
Resistance of the coil(mΩ)	135.9	69.6	49.7
Power loss (kW)@180GeV	8.96	6.96	2.86
Power loss (kW)@120GeV	3.98	3.09	1.27
Avg. power loss [kW]@30-180GeV	2.5	1.9	0.8
Avg. power loss [kW]@30-120GeV	1.9	1.5	0.6
Height/Width of core [mm]	520	520	520
Core Length [mm]	1984	984	684
Weight of magnet[ton]	6.43	3.21	2.25
Cooling circuits	4	4	4
Water pressure [kg/cm^2]	6	6	6
Water flow velocity [m/s]	1.54	2.25	2.73
Total water flow [l/s]	0.174	0.255	0.309
Temperature rise of coolant [deg]	12.3	6.5	2.2

Summary

- ✓ **Two kinds of prototype dipole magnets for CEPC Booster were developed and studied. The test results showed that the CT coil magnet could meet the requirement at 28Gs@10GeV while the iron core magnet made by non-oriented steel laminations could at 90Gs@30GeV.**
- ✓ **In order to reduce the cost and power loss, the injection energy of the Booster is increased to 30GeV from 10GeV so that the iron core dipole magnet could be chose as the baseline design in TDR stage.**
- ✓ **The dipole and quadrupole magnets for the Booster were carefully designed in economic ways, the simulation results showed that the field performance of the magnets could be satisfied with the requirements.**

Thank you for your attention!

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