Design of the low field dipole magnet for CEPCB

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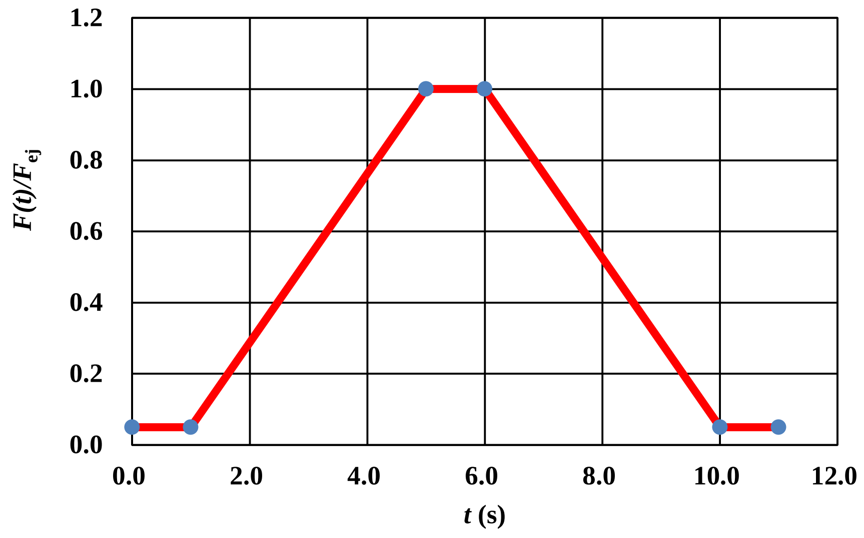
Contents

Introduction

1) The CEPC booster is to accelerate the electron and positron beam from 10 GeV to 120 GeV. The injection energy is determined by the length and cost of the Linac.
2) The circumference of the Booster is 100 km, there are nearly 15360 dipole magnets with a length of 5 m, the min. field of the magnets is only 29 Gs whereas the max. field is 492 Gs.
3) The repetitive frequency of the booster is 0.1 Hz and the field of the dipole magnet is changing with the beam energy.
4) A high quality dipole magnet with a min. field of 29 Gs has never been developed in the world at present.



Specifications and challenges

Specifications of CEPCB low field dipole magnets

	BST-63B
Quantity	15360
Minimum field (Gs)	29
Maximum field (Gs)	492
Gap (mm)	63
Magnetic Length (mm)	5000
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 <29Gs*0.1%=0.029Gs → how to design**
- **Field reproducibility<29Gs*0.05%=0.015Gs → how to measure**
- **Magnet length ~5000mm → how to fabricate**

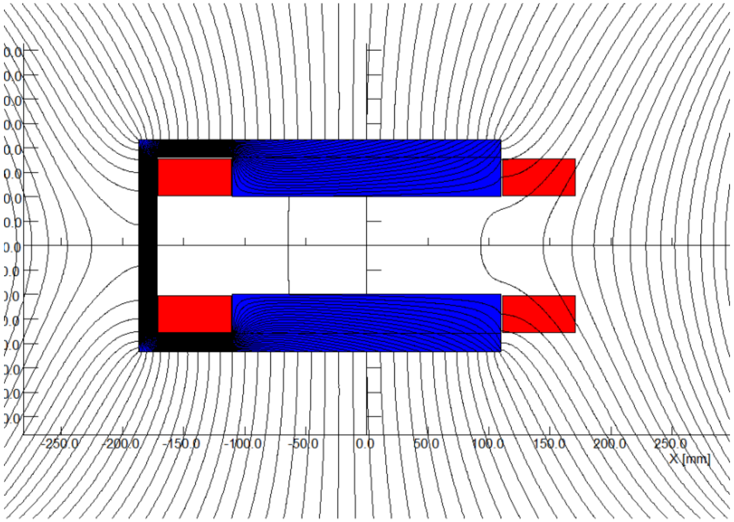
Specifications and challenges

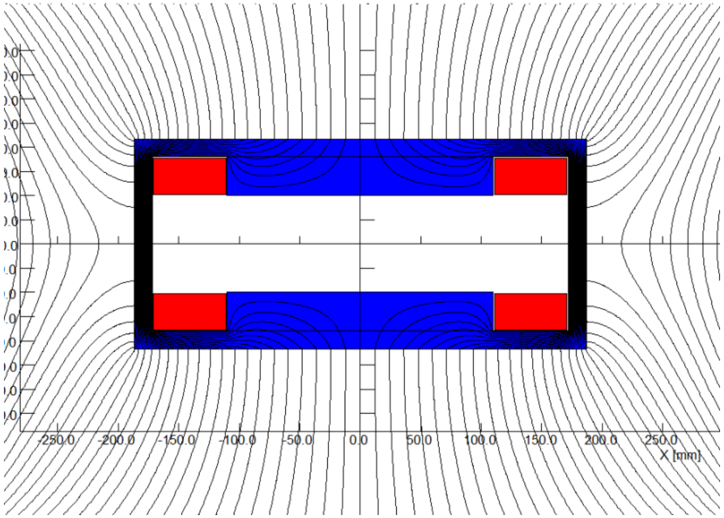
1) Since the resolution of Hall probe is about 0.02 Gs, the field uniformity and reproducibility of the low field dipole magnet can not be precisely measured by Hall probe.
2) It is not clear at this field level of 0.015Gs how much the material properties of iron and the simulation modelization itself could affect any further possible attempt in improving field quality.
3) The Earth field is about 0.2-0.5 Gs and the remnant field of silicon steel lamination is about 4-6 Gs. These factors will affect the field performance of the dipole magnet at the low field of 29 Gs.
4) The total length of all the dipole magnets is about 75 km, the balance between the field performance and the magnet cost should be carefully considered.
5) The procedures to fabricate a 5 m long dipole magnet are also challengeable.

Earth field shielding

Compared to the minimum working field (29 Gs) of CEPCB dipole magnets, the effect of Earth field (0.5 Gs) can not be neglected and should be carefully shielded.

- **The effects of Earth field on the magnets with C-type and H-type cores have been simulated and compared.**
- **For the H-type core magnet, the closed structure of the core has better shielding of the earth field.**



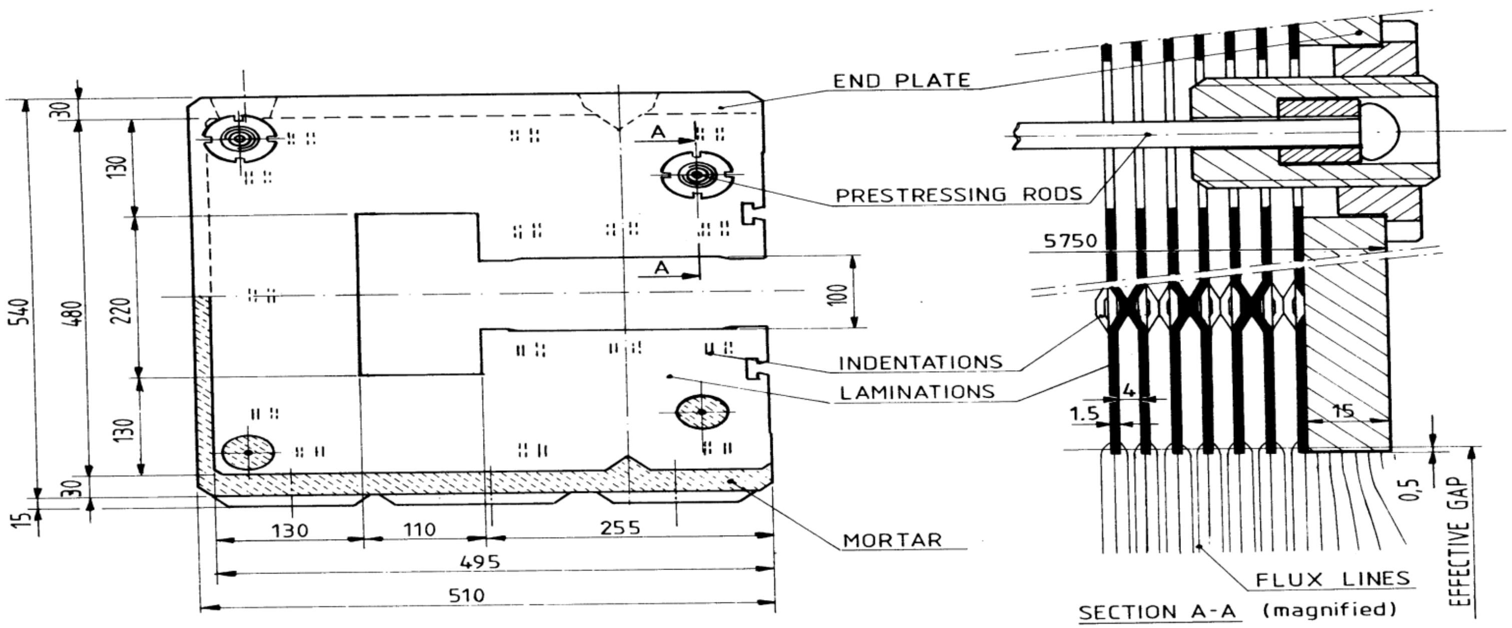


Methods to reduce the magnet cost

- **Coil: aluminium busbars instead of copper**
  - **One turn/ pole, eg. LEP, FCC-ee**
- **Core dilution: longitudinal and transversal direction**
  - **As the field is very low, the core dilution can be used to increase the field level in the steel and decreases the influence of the coercive force on the magnet performance.**
  - **The LEP and LHeC's dipole magnet used the longitudinal dilution by filling concrete or plastic into the steel laminations.**
  - **CEPC prototype magnet tried both directions of core dilution.**

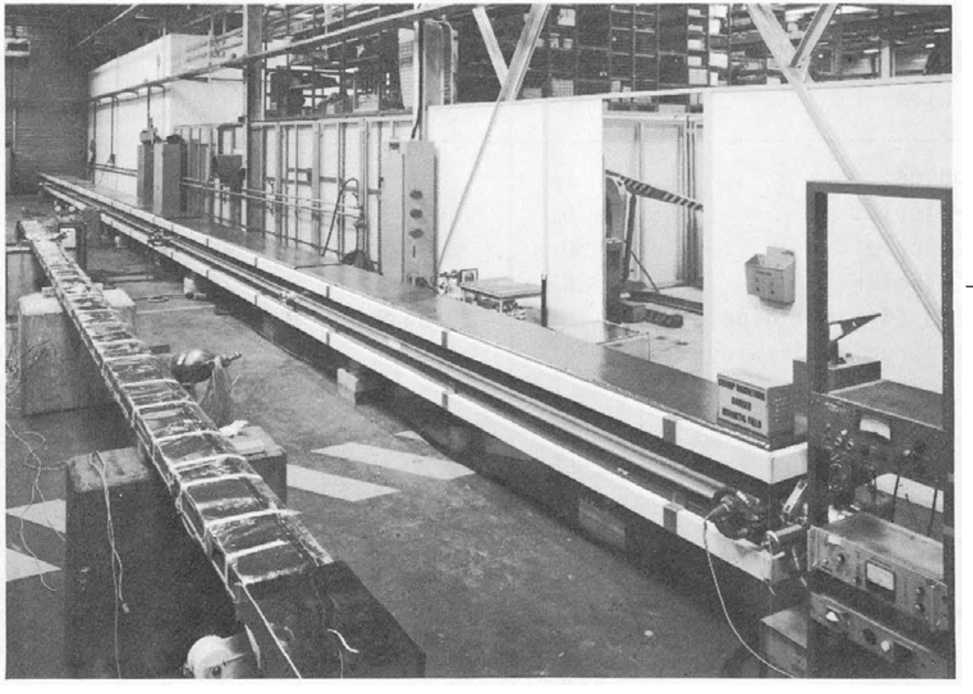
Methods to reduce the magnet cost

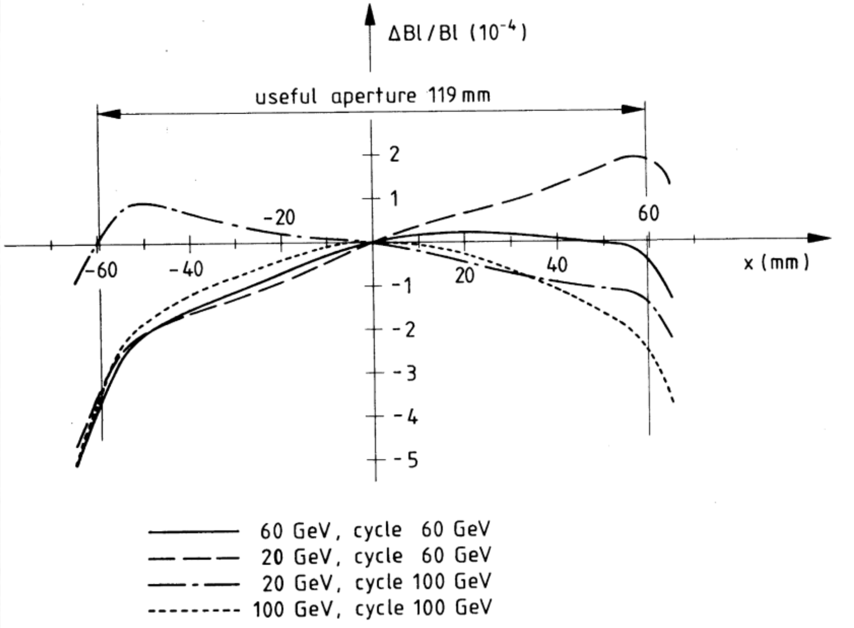
➢ **The core dilution technology on LEP's low field dipole magnets.**



➢ **In longitudinal direction, the cores were made by 1.5 mm thick steel laminations spaced with 4 mm gaps of concrete mortar, ie. the low filling factor is 0.27.**

Methods to reduce cost of the magnets



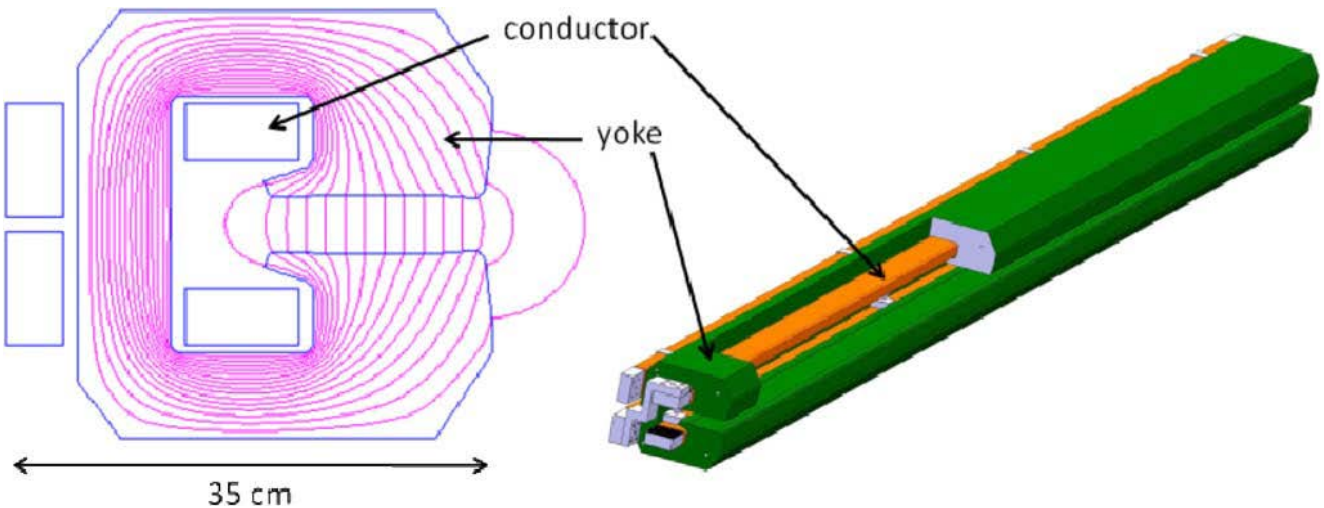


- These magnets had gotten **a lowest field of 215 Gs** with a good field quality。

Methods to reduce the magnet cost

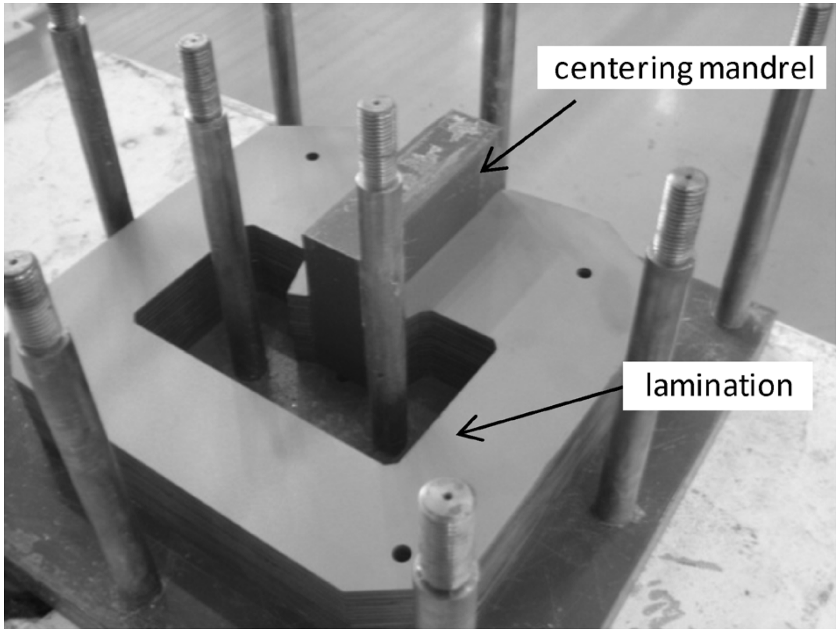
✓ **The core dilution technology on the LHeC low field dipole magnets.**

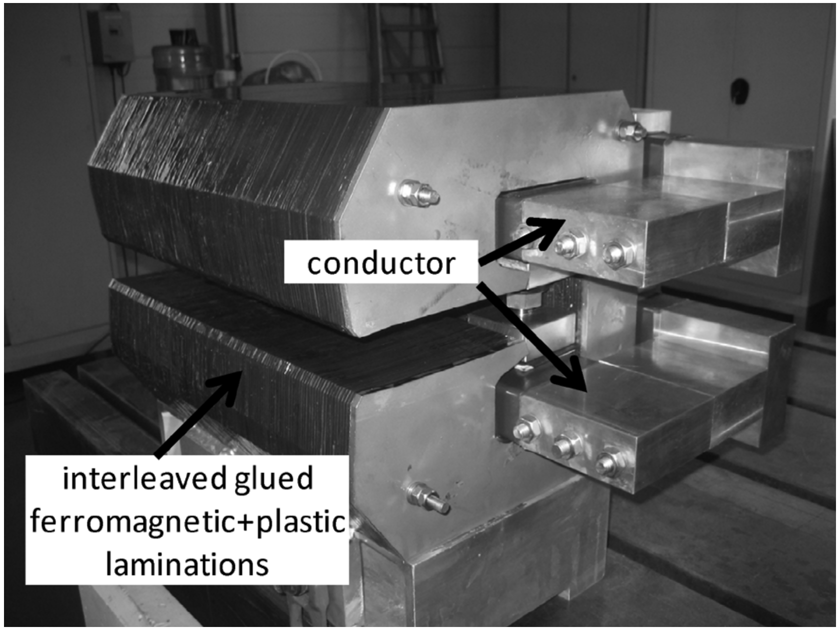
- **A short prototype dipole magnet of LHeC had been developed, the laminations and plastic plates were glued together to form magnet core with a thickness ratio of 1:2.**

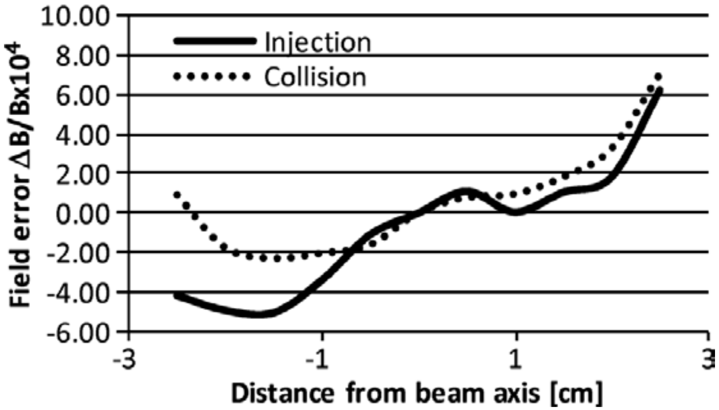


Methods to reduce the magnet cost

- The magnet had gotten a lowest field of **127 Gs with good quality**.





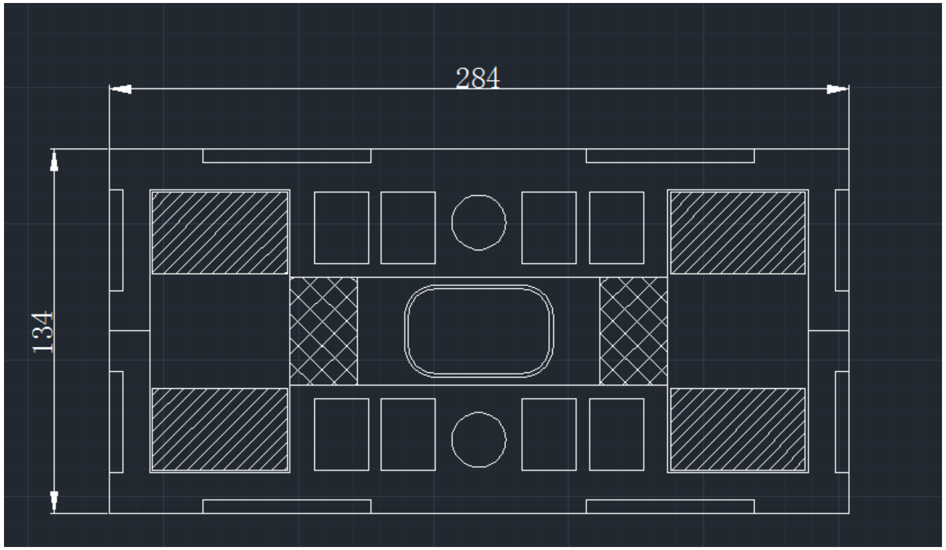


REPRODUCIBILITY OF MAGNETIC FIELD OVER 8 CYCLES

Model	Low field	High fields
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5 \cdot 10^{-5}$	$4 \cdot 10^{-5}$
Model 2 (Low carbon steel)	$6 \cdot 10^{-5}$	$6 \cdot 10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4 \cdot 10^{-5}$	$6 \cdot 10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$
Model 2 (Low carbon steel)	$4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2 \cdot 10^{-5}$	$4 \cdot 10^{-5}$

Design of CEPCB low field dipole magnet

- ✓ **Including the longitudinal core dilution technology, the transversal dilution is also tried in CEPCB low field dipole prototype magnet.**
- ✓ **With some kind of supporters in magnet gap (outside the vacuum chamber), the magnetic field force can be compensated and the return yoke can be made as thin as possible.**
- ✓ **By stamping holes in the pole areas, the weight of the core laminations can be reduced further.**

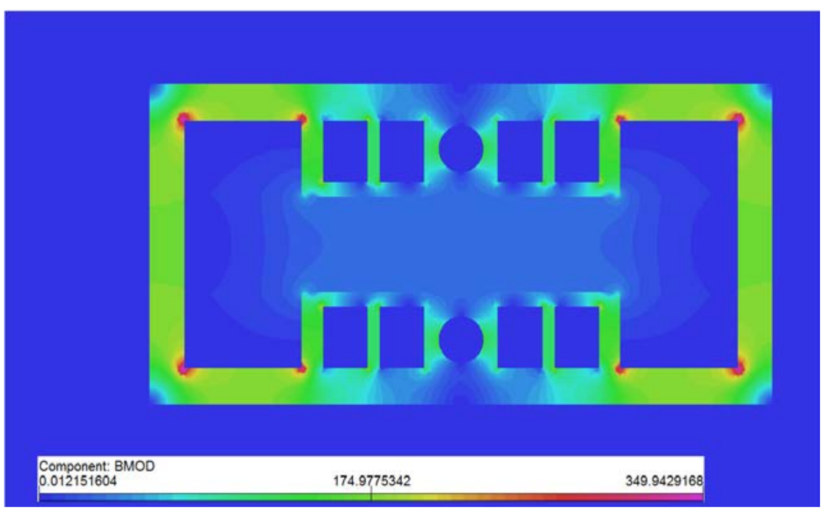


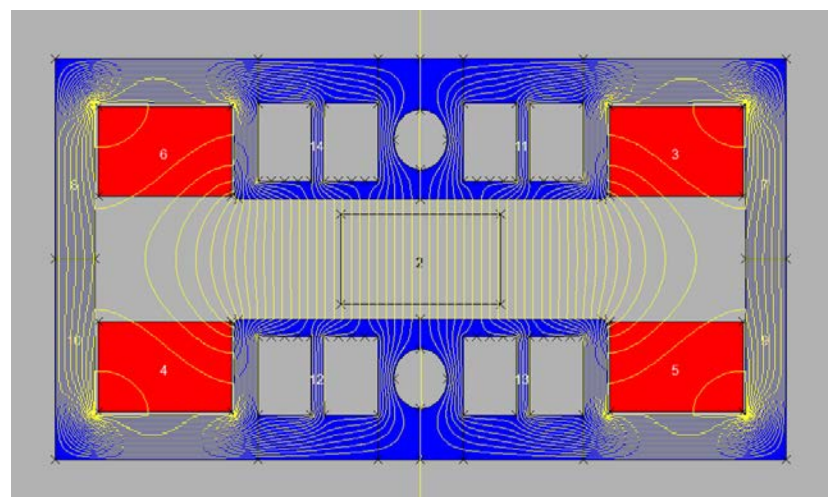
Design of CEPCB low field dipole magnet

- ✓ In the longitudinal direction, the core consists of 40% steel laminations and 60% aluminium laminations. The weight of the cores can be further reduced.
- ✓ Using the core dilution, the core height, width and the total weight can be decreased dramatically, and the cost can be reduced.
- ✓ Another advantage of the core dilution is increasing the field intensity in the yoke area while high working field in the yoke can make field less sensitive to the material differences itself, especially the coercive force.

CEPCB's low field dipole magnet

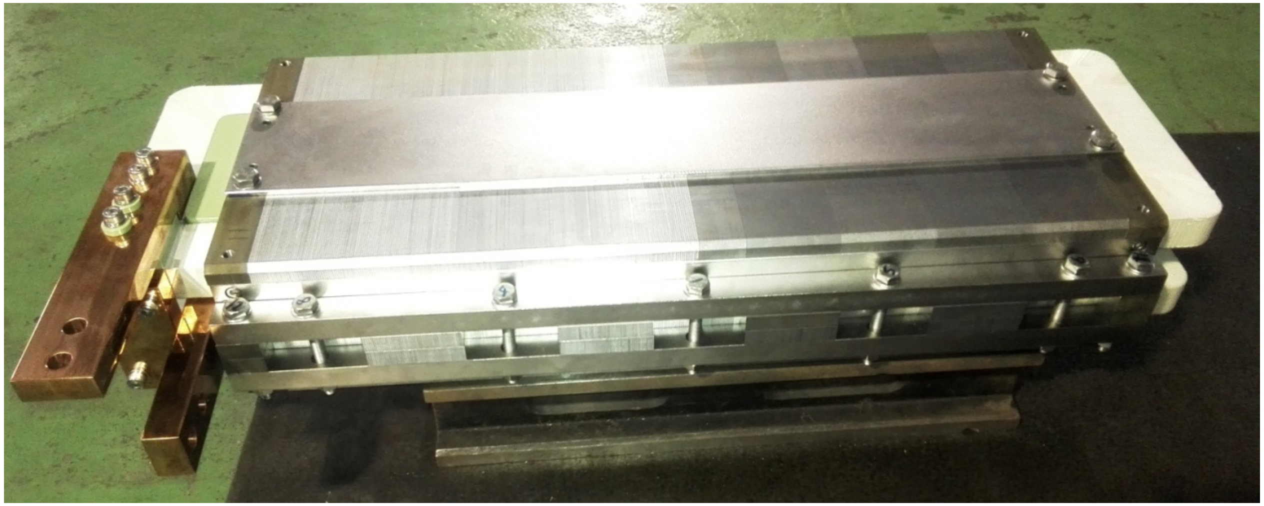
- The simulation result shows :
  - The field intensity in most areas of the laminations can be increased to 150 Gs while the field in the gap is 29 Gs.
  - The magnetic fluxes are flowing in the laminations as expected. The holes in the pole areas can adjust and optimize the flux flowing path very well.
- The field error in the good field region at both the high field and low field is better than 5E-4. (It may not be very accurate since an approximate BH curve is used in the simulation.)





Development of a subscale prototype magnet

In order to verify the design of the CEPC low field dipole magnet, a subscale prototype dipole magnet was produced.



- ✓ **The core of the magnet is about 1m long. One half core is stacked by the steel laminations only (high packing factor), another half is stacked by the steel laminations and the aluminum laminations with the thickness ratio of 1:2.**
- ✓ **The coils of the magnet have only one turn per pole, which is made by solid aluminum bars without water cooling.**

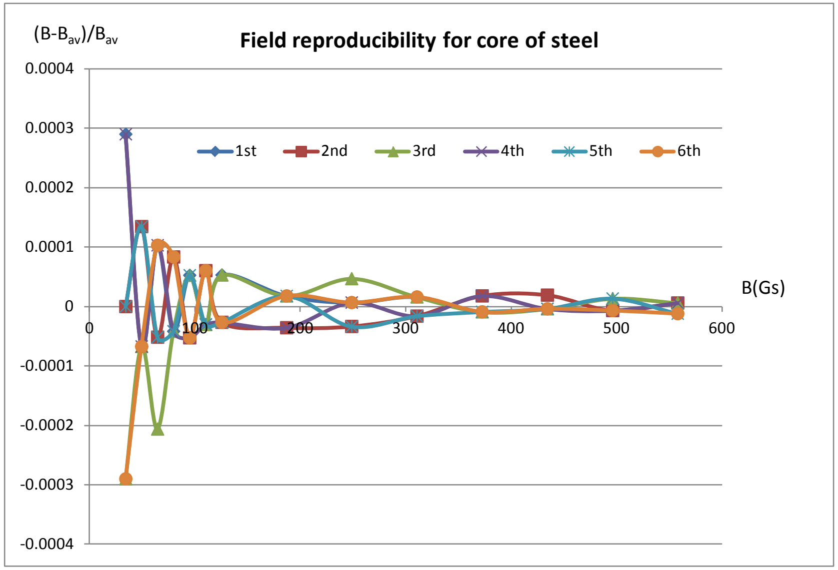
Development of a subscale prototype magnet

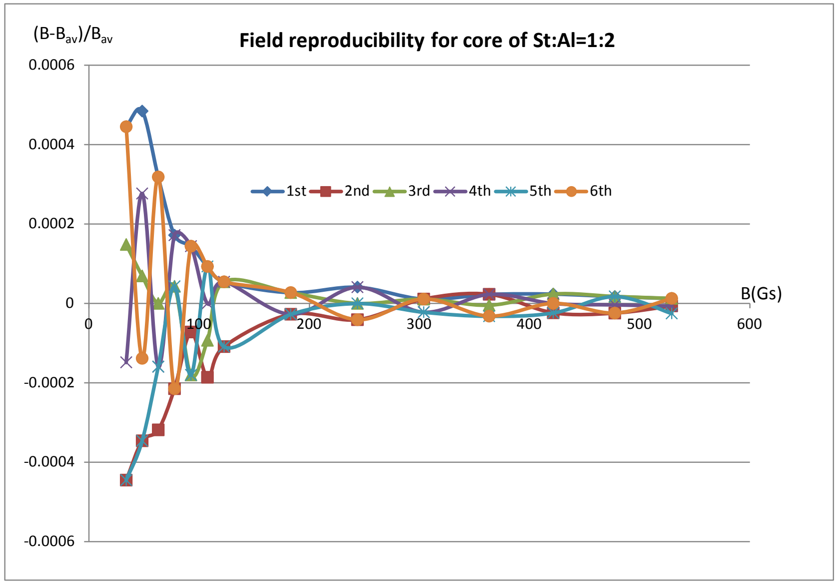
Main parameters of the subscale prototype magnet

Magnetic length	1m
Max. field	614Gs
Min. field	31Gs
Repetitive frenquency	0.1Hz
Gap height	40mm
Good field region	52mm
Field uniformity	5.0E-04
Coil turns per pole	1
Max. current	1000A
Material of conductor	Aluminium
Size of conductor	30mm*50mm
Max. current density	0.67A/mm^2
Resistance	0.34mΩ
Max. Power	0.34kW
Material of core	Steel/Steel and Al
Width and height of core	284mm*134mm
Net weight of core	125kg
Net weight of coil	18kg
Net weight of magnet	143kg

Development of a subscale prototype magnet

- **The field measurement of this prototype is done by the Hall probe measurement system.**
  - **The field reproducibility is about 4E-4 at low field of 33Gs whereas 1E-5 at high field of 558Gs.**
  - **However the measurement precision of the Hall probe system at 33Gs is about 3E-4.**

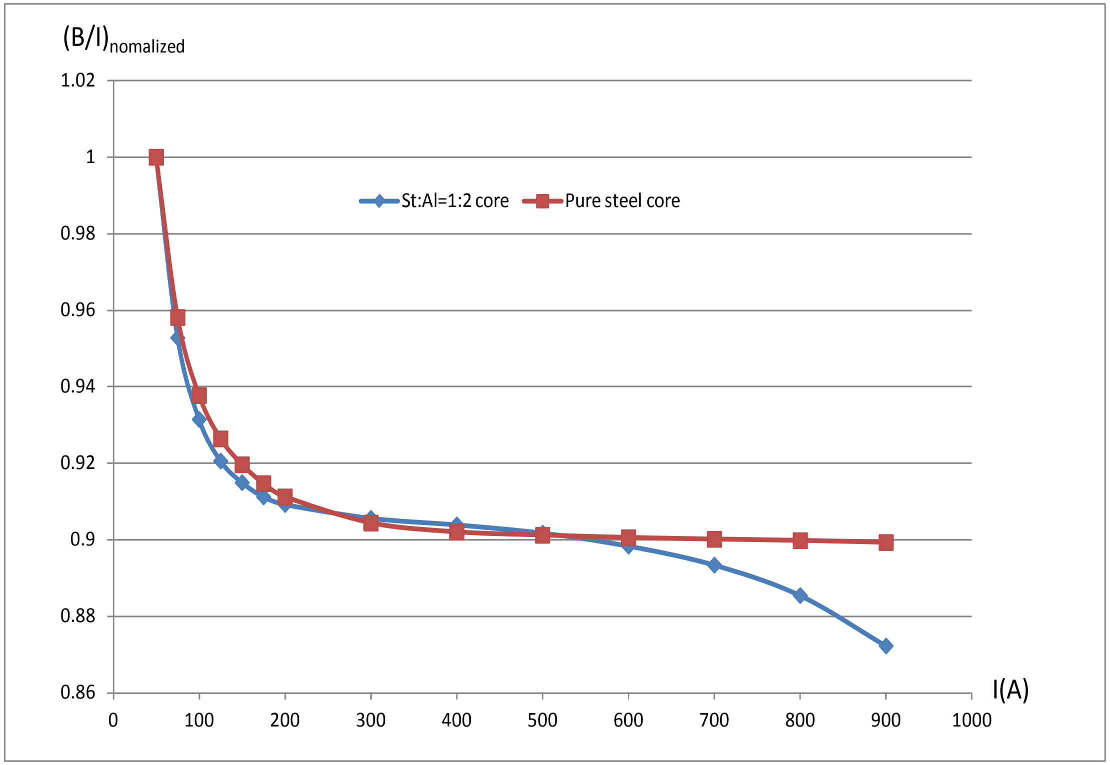




Development of a subscale prototype magnet

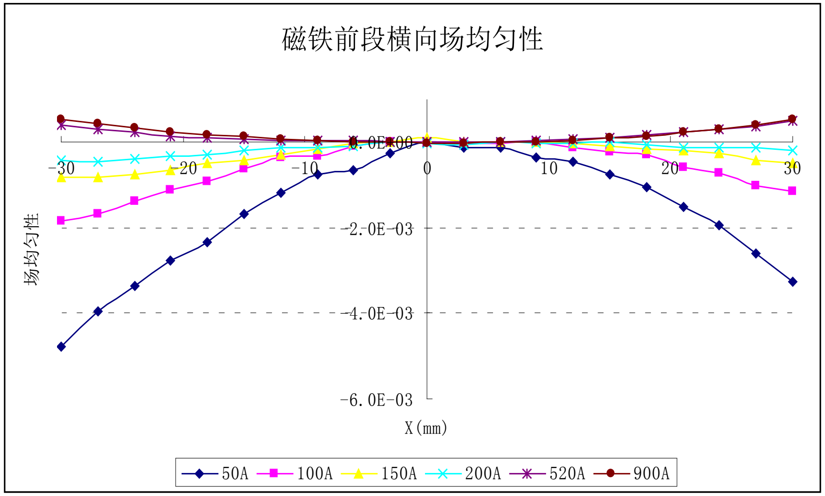
➢ The excitation non-linearity is about 10% .

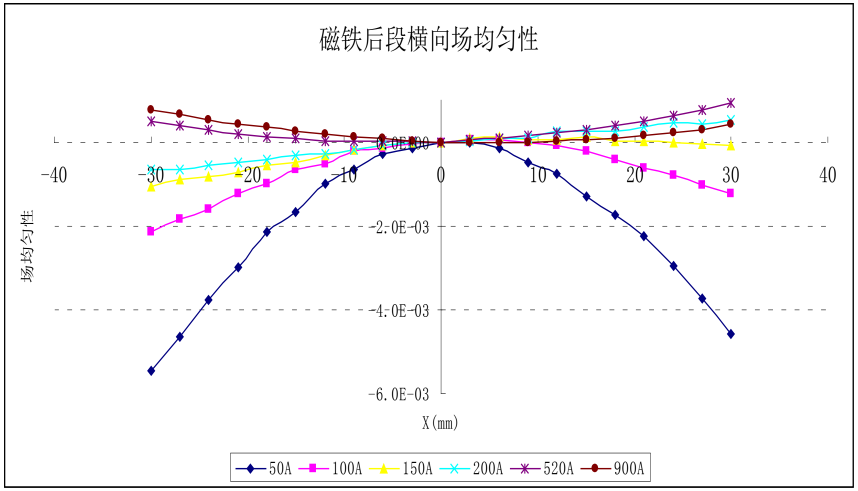
- **At the low field ,the remnant field effect increased strongly.**
- **At the high field, the nonlinearity in the combined laminations is worse than that in the high packing factor laminations.**



Development of a subscale prototype magnet

- **Due to remnant field, the field errors at low field becomes 10 times larger than that at high field.**
- **To meet the field uniformity of 5E-4, the minimum field of the magnet should be higher than 100Gs.**
- **The measured remnant field in the magnet gap is about 4-6Gs, which is 13%-20% of the low field of 30Gs.**





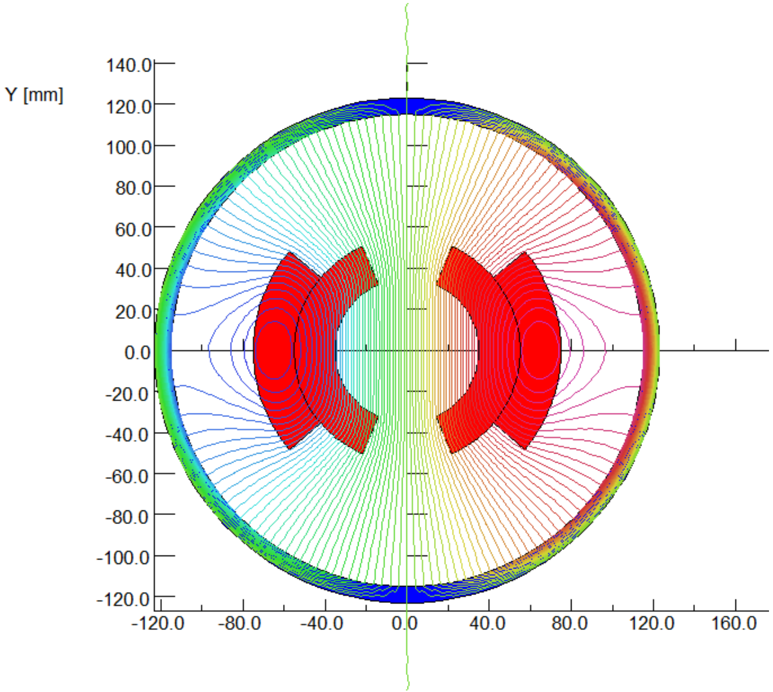
The ways to improve the field quality

There are three ways to improve the field quality of the low field dipole magnets

- **To increase the injection energy of the Booster so that the minimum field of the magnet can be increased from 30 Gs to 100 Gs. But it will increase the length and cost of the Linac.**
- **To develop high quality silicon steel laminations with very low remnant field. According to the investigation, the min. coercive force of non-oriented steel is about 0.5 Oe whereas that of the grain oriented steel is about 0.05 Oe, so the grain oriented steel must be a good choice to make the cores of the low field dipole magnets.**

The ways to improve the field quality

- To design and develop the low field **magnet without magnetic core** like superconducting dipole magnets. According to careful study by the field simulation, an optimized design of dipole magnet with cosθ type coils can meet the field quality at both high and low field levels. However to get the same field level, its excitation current is twice as high as that of a magnet with magnetic core.



Summary

- **A 5 m long high precision dipole magnet with min. field of 29 Gs and max. field of 492 Gs has never been developed in the world. Its design, production and field measurement are challengeable.**
- **As successful references, the low field dipole magnets of LEP and LHeC were thoroughly investigated, of which the min. field was higher than 127 Gs.**
- **The quantity of the dipole magnets for CEPC booster is very large, the core dilution technologies in both the longitudinal and transversal directions are proposed to reduce the weight and cost of the magnets.**
- **On the fund support of IHEP workshop, a subscale prototype dipole magnet with a length of 1m for CEPCB was manufactured**.

Summary

- **Due to the influence of the remnant field, the performances at low field of the prototype magnet are 10 times worse than that at high field.**
- **To reduce the effect of the remnant field and improve the field quality of the magnet, three ways are proposed.**

Thank you for your attention!