CEPC collider ring permanent quadrupole magnet development status

2026 International Workshop on the High-Energy Circular Electron-Positron Collider, Shanghai, 22–26 October

Chuang SHEN (IHEP)

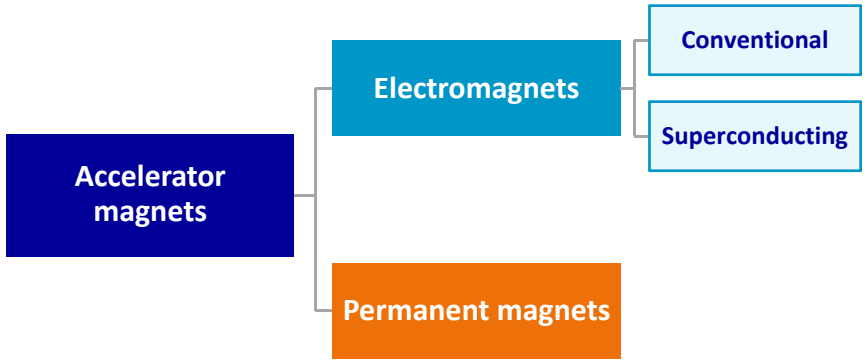
On behalf of the permanent quadrupole magnet research team

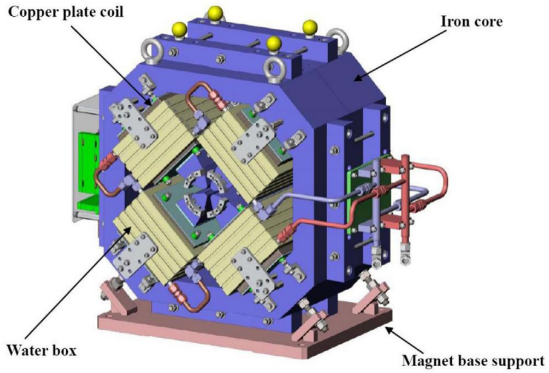


Contents

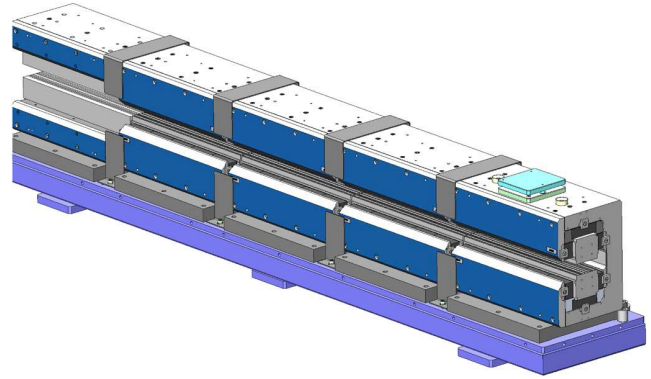
1	Motivation and design requirements
2	Dual-ring **Halbach** design
3	Error analysis and field quality optimization
4	Halbach prototype and measurements
5	**Hybrid** design and engineering progress
6	Summary

Motivation: energy saving and tuning challenge





Conventional electromagnet



Permanent dipole

MAGNET TYPE	Electromagnet	Permanent magnet
Advantages	• Field strength tuned by coil current • Superconducting coils reach very high fields • Shimming refines field quality	• **No power supply, so low operating cost** • Compact design • No power, cooling or auxiliary systems
Disadvantages	• wastes electrical energy • Requires power, cooling and auxiliary systems	• **Field strength is difficult to adjust** • field quality • Field varies strongly with temperature • Heat and radiation can demagnetize

Design requirements

- Green accelerators : Energy efficiency and environmental sustainability
- Challenges limiting the use of permanent magnets are being addressed
- To meet CEPC R&D needs, a permanent quadrupole magnet with a wide tuning range, high precision and good field quality.

Parameters	Symbol	Unit	Target
Magnet aperture	D	mm	86
Magnetic length	Leff	mm	200
Gradient range	G	T/m	1.8–10.6
Gradient accuracy	ΔG	T/m	±0.002
Ring rotation accuracy	Δθ	mrad	≤0.08
Good field radius	Rref	mm	12
Harmonics at Gmax	Bn/B2	—	≤5 units

Research routes: Halbach and Hybrid

- Halbach quadrupole: pure permanent magnets

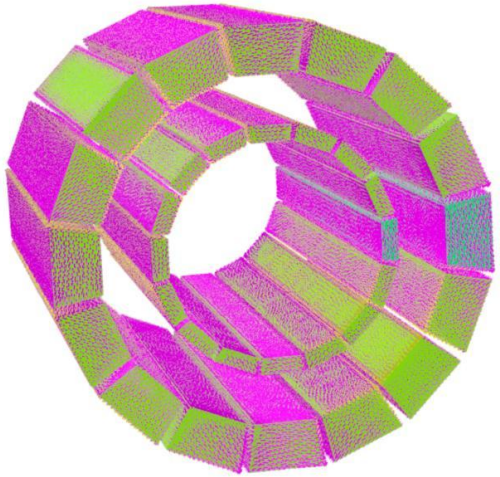
  Ring rotation achieve wide field tuning range

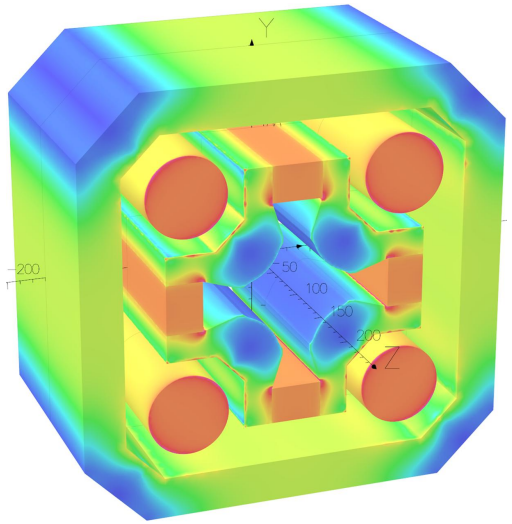
  but complex assembly , dual-ring control and synchronization

- Hybrid quadrupole: fixed magnets + soft-iron poles + rotating magnet rods

  Rods rotation changes the field strength

  but higher torque and need harmonics correction study



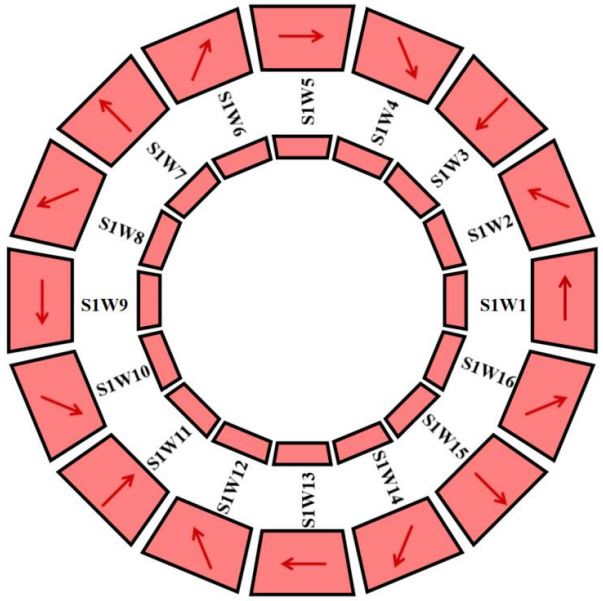


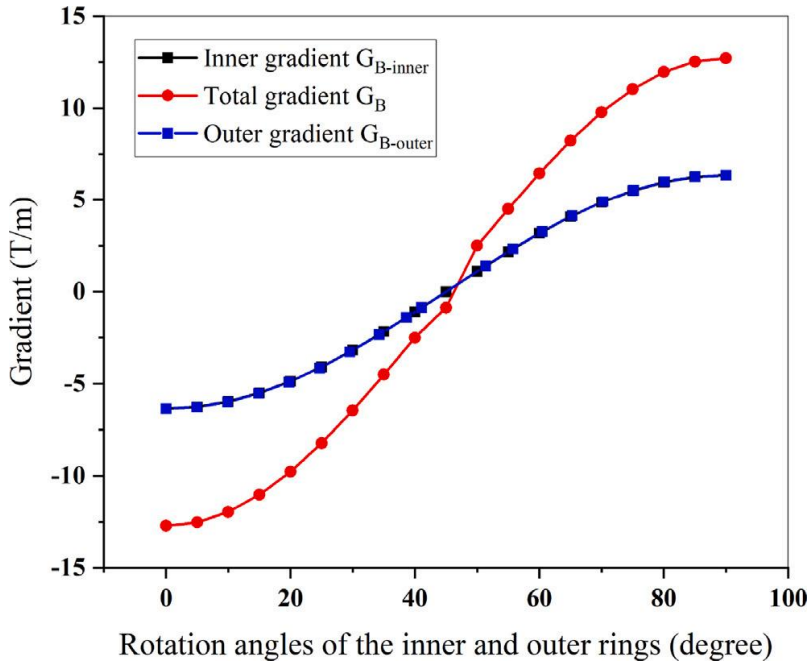
Halbach: magnetic design

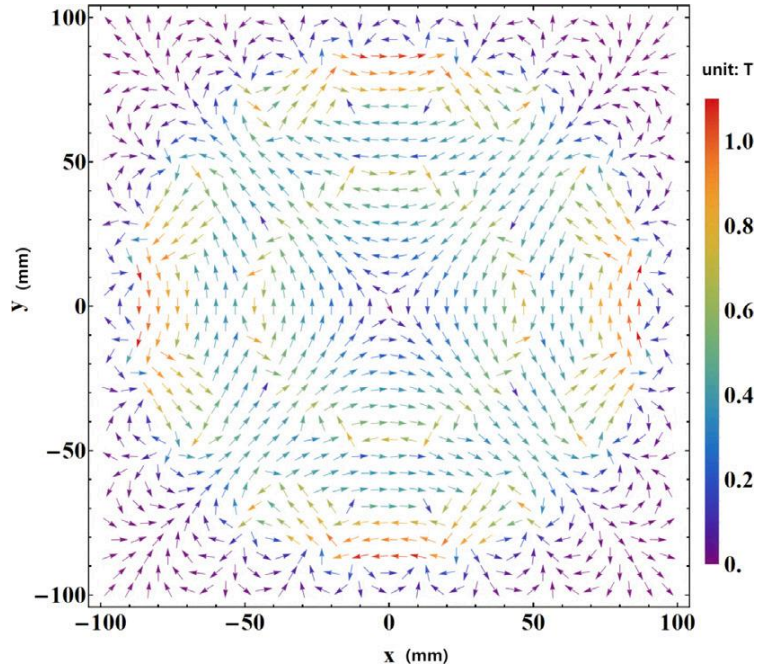
- Two nested rings, each with 16 azimuthal sectors × 5 longitudinal blocks:

  80 blocks per ring, 160 in total; Br = 1.279 T

  Each block has ±1 mm radial adjustment for harmonic correction
- Rotate 0–45°: gradient = 12.5 → 1.8 T/m
- Rotate 0–90° also reverses D/F polarity



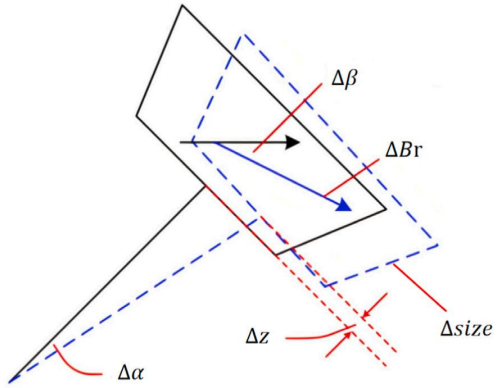


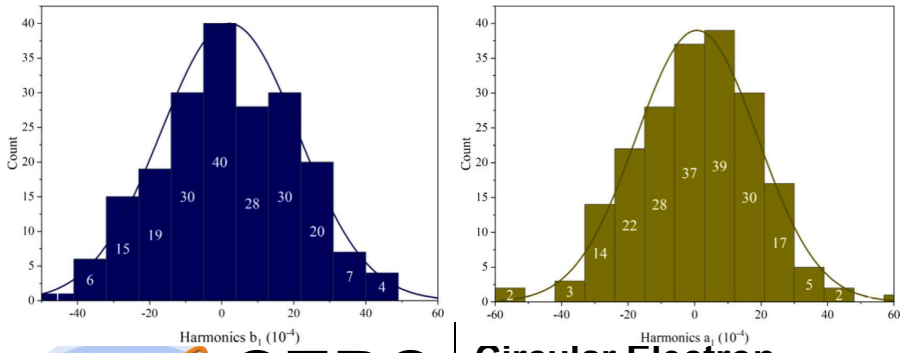


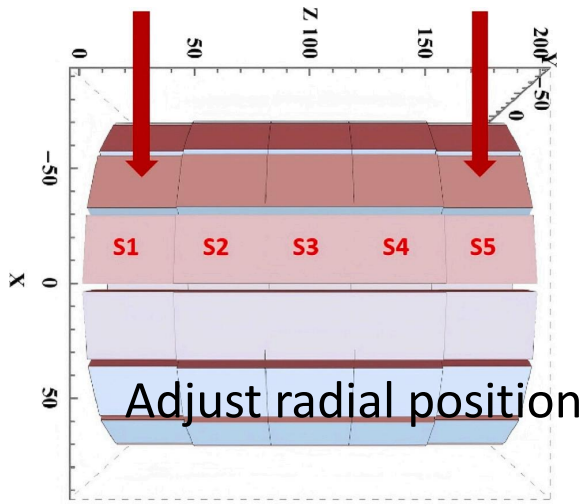
CEPC Circular Electron Positron Collider

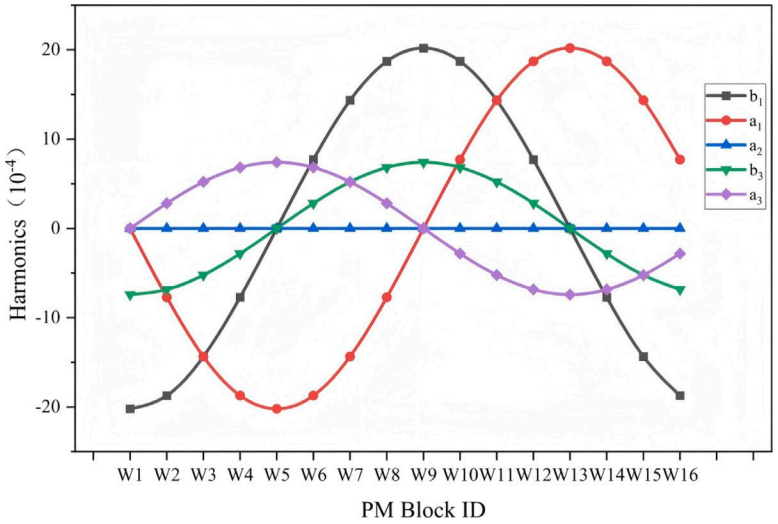
Halbach: error analysis and tolerances

- Error tolerance linked to correction method
- Reduce harmonics error
- Error sources: Δβ, ΔBr, Δsize, Δα and Δz
  - Load each error on per magnet
  - Use 200 samples for random statistics









the strandard deviation of first-order harmonic less than 20 units

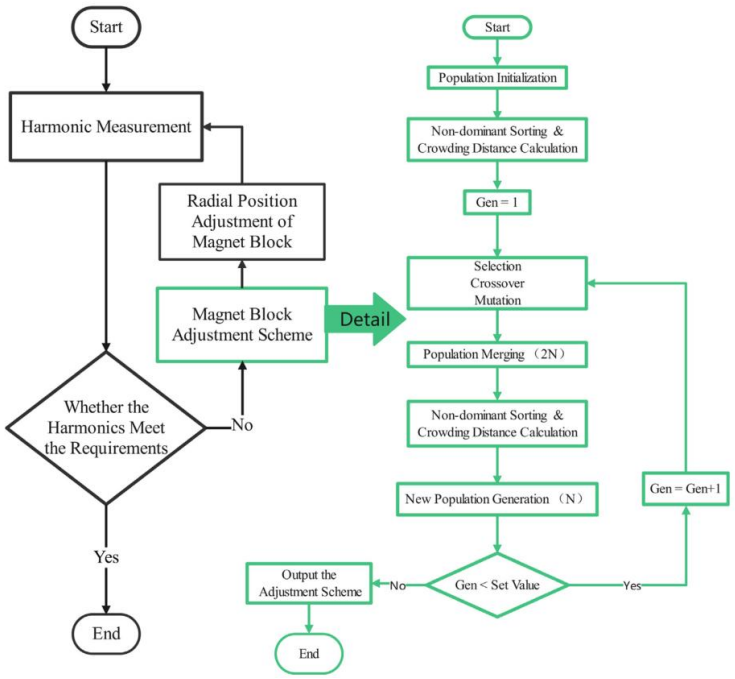
Error source	Inner ring	Outer ring
Magnetization axis	±1.25°	±0.75°
Remanence	±250 Gs	±150 Gs
Size deviation	±0.05 mm	±0.05 mm
Position deviation	±0.5° / ±0.5 mm	±0.5° / ±0.5 mm

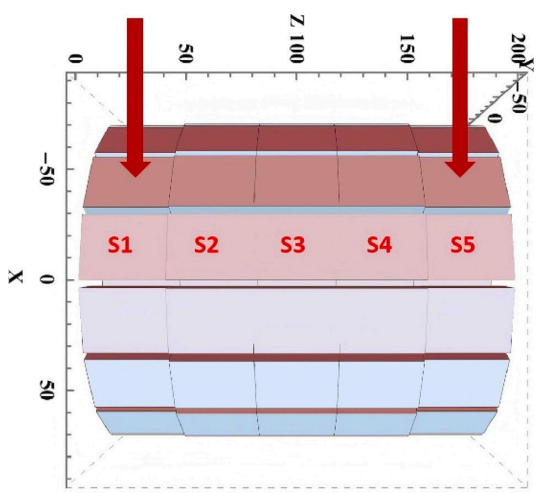
Fabricate about twice the required magnets, then screen and match

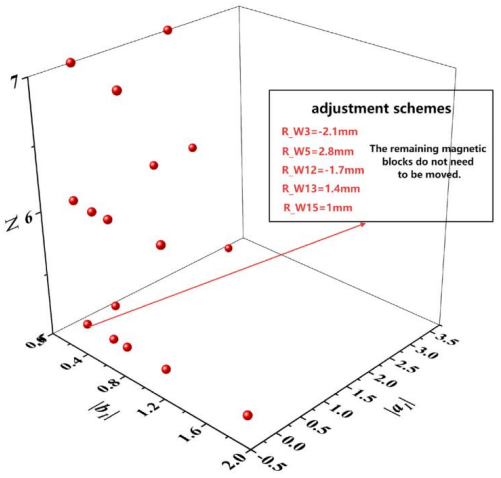
Halbach: field quality optimization

- Min(|a_1|, |b_1|, moved-block)

  Other harmonics less than 3 units
- Moving strategy
- Measure-adjust-remeasure for good field quality







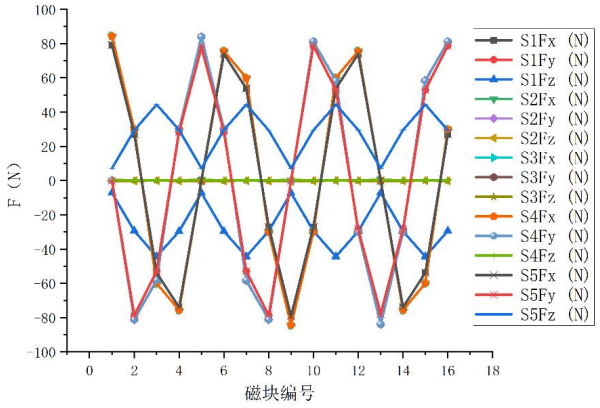
Simulation success (harmonic units: 10^{-4})

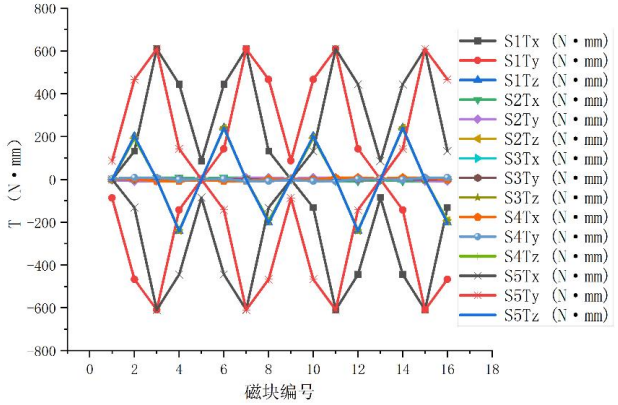
Error proportion	a_3, b_3	a_4, b_4	a_5, b_5	a_6, b_6	Success rate
20%	4	1.6	0.6	0.2	100%
40%	8	3.2	1.2	0.4	100%
60%	12	4.8	1.8	0.6	100%
80%	16	6.4	2.4	0.8	85%
100%	20	8	3	1	50%

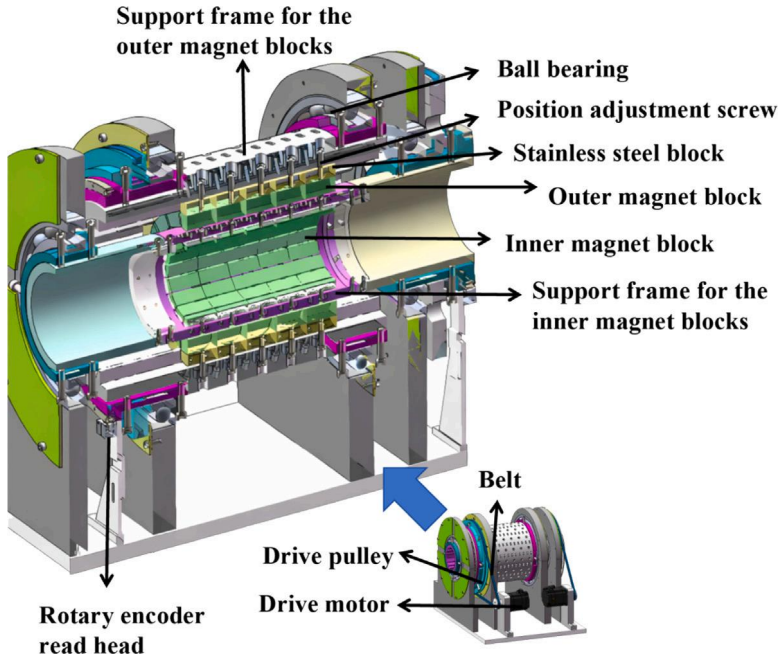
Simulated success:100% at 20–60% errors, 85% at 80%, 50% at 100%

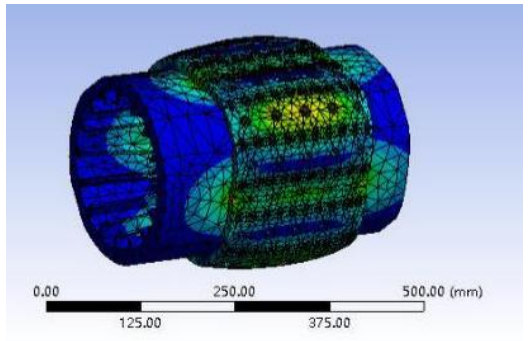
Halbach: forces analysis and mechanical design

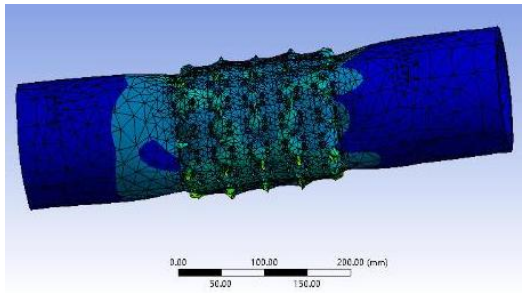
- Calculated forces over the full rotation cycle
  - Forces and torques change with ring angle
  - Inner-ring block loads are more complex
- Guide the mechanical design
  - Size supports, fasteners, bonding and drives
- Rings supports simulation











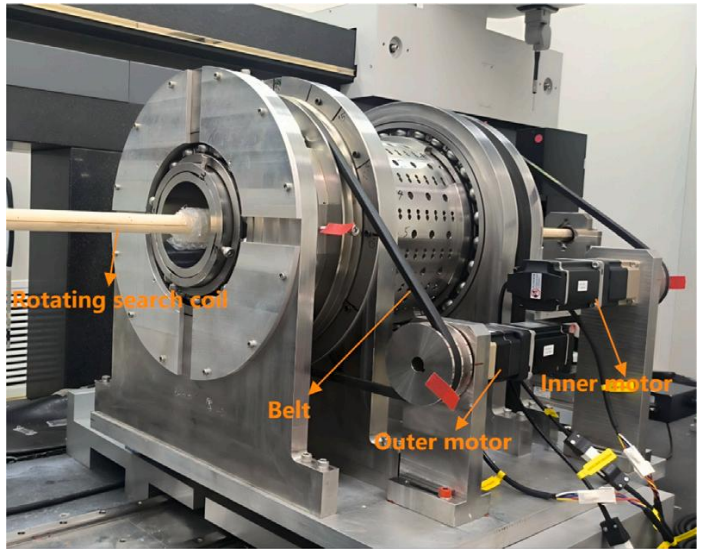
@From Ran LIANG

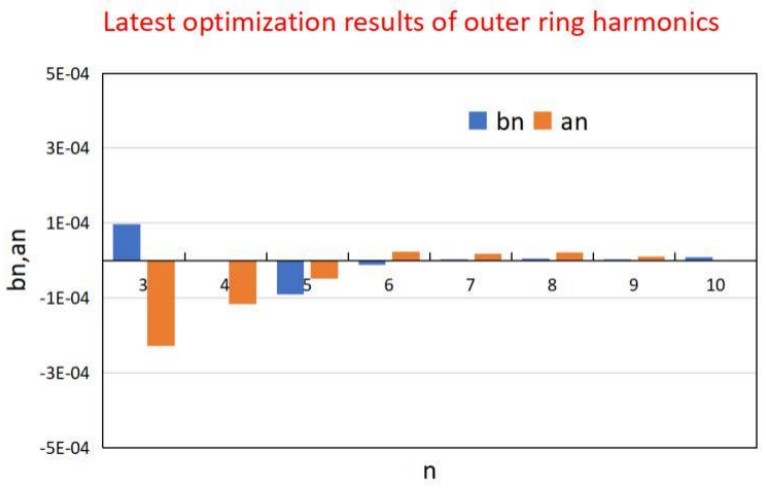
Halbach: gradient and harmonic measurements

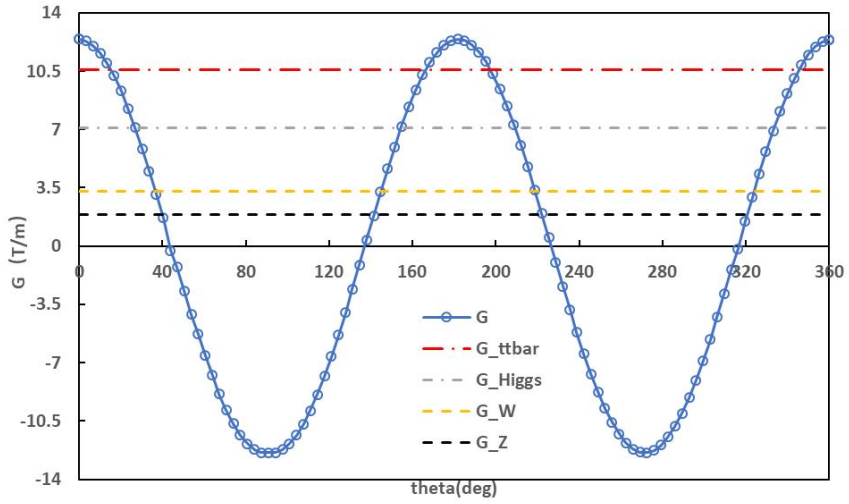
- After each ring corrected, harmonics within 3 units
- Dual-ring gradient tuning experimentally demonstrated for CEPC different mode
- Next step :

  Complete feedback system and synchronized control

  Qualify full-range harmonics, accuracy and repeatability

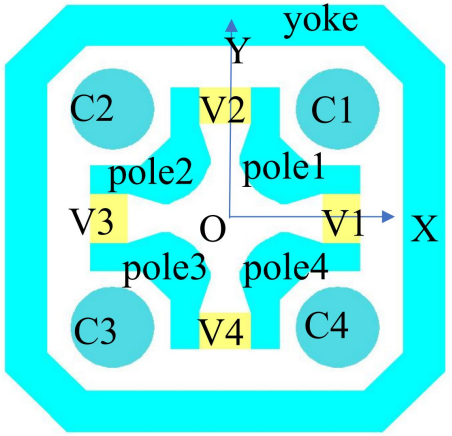


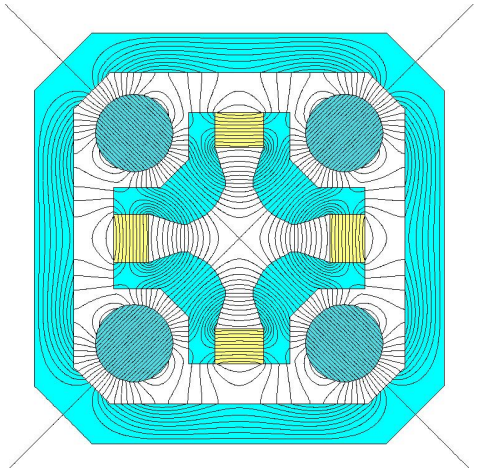


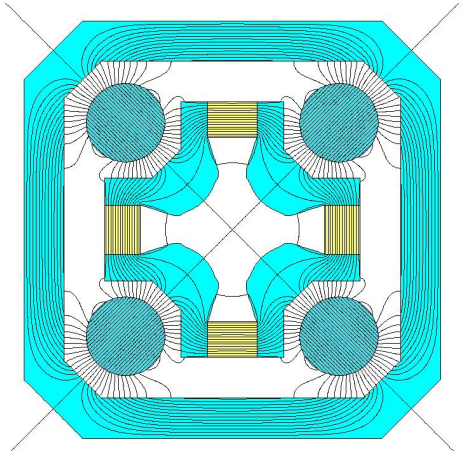


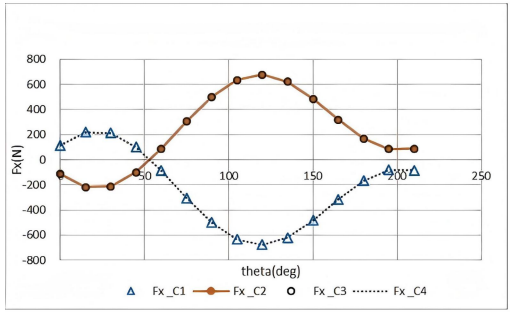
Hybrid: field tuning and force calculations

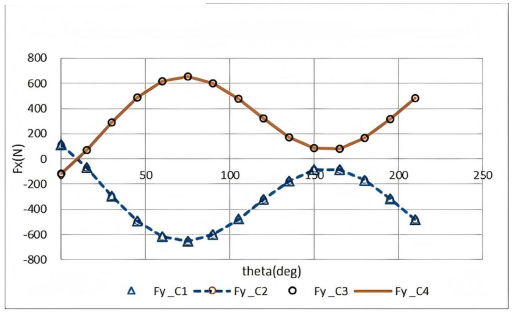
- Fixed magnets , soft-iron poles and rotating rods
  Rotating permanent-magnet rods change gradient
  OPERA-3D calculates field
- Calculate force under different angles

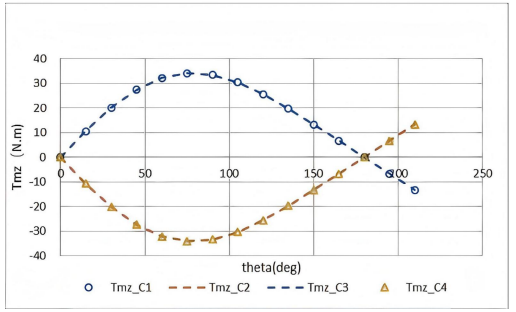


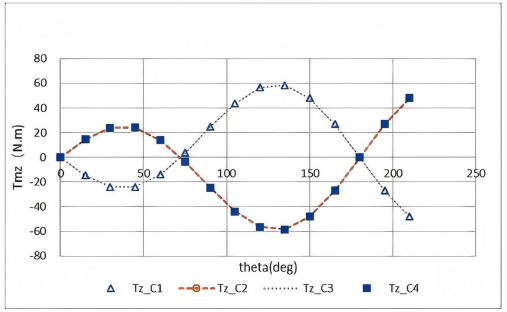








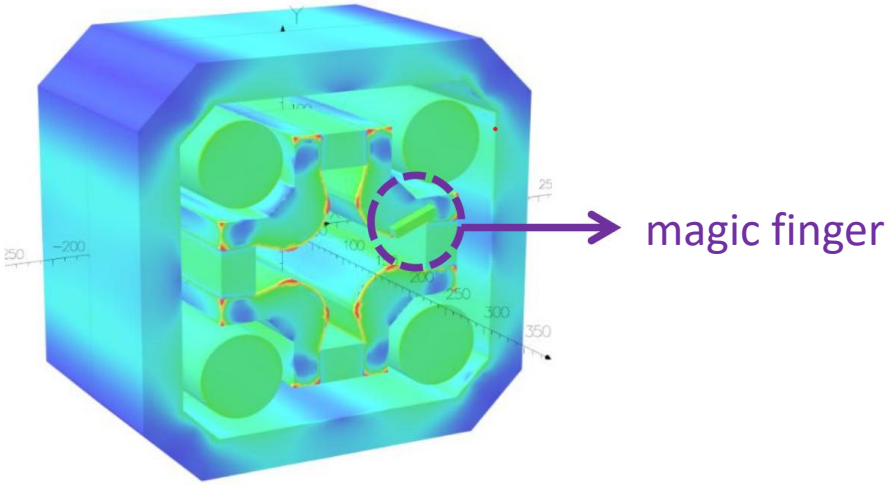


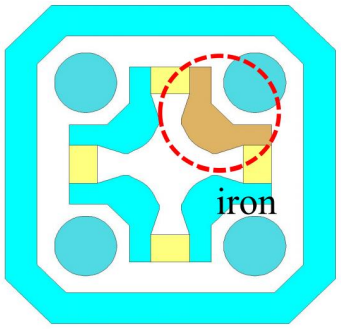


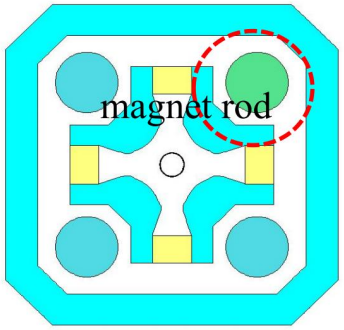
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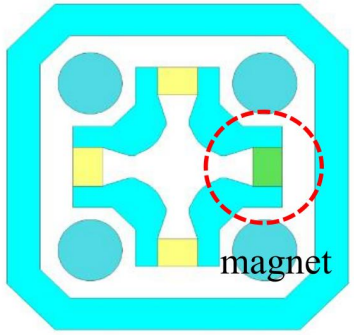
Hybrid: error analysis and harmonic correction

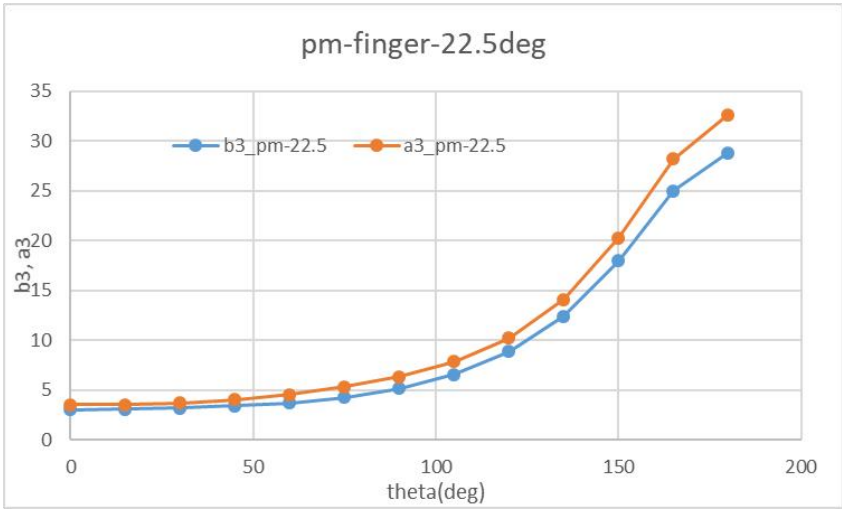
- Errors from poles and magnets
  - remanence (ΔBr)
  - magnetization-axis(Δβ)
  - dimension (Δsize)
  - position (Δposition)
- End magic fingers provide corrections
  - Iron fingers produce fixed harmonic corrections
  - Permanent-magnet fingers provide variable corrections







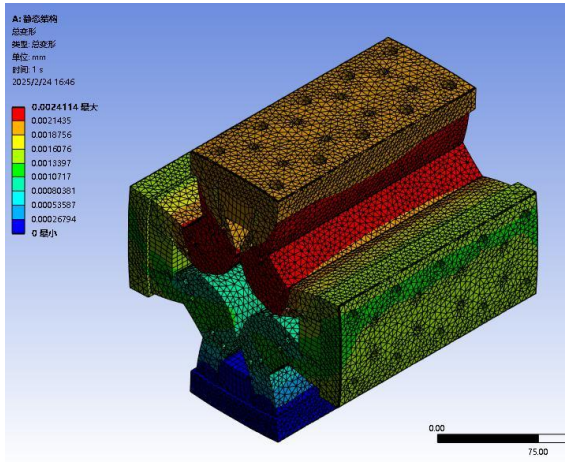


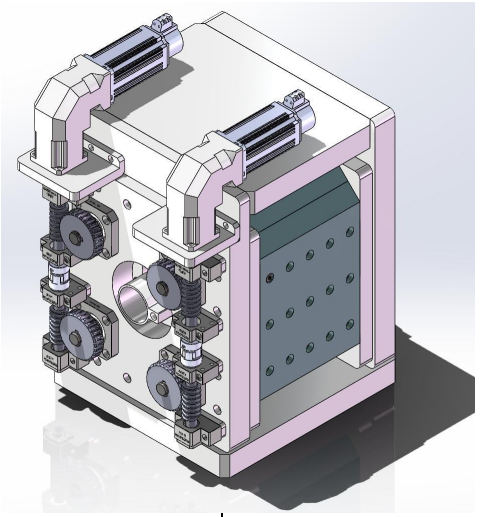


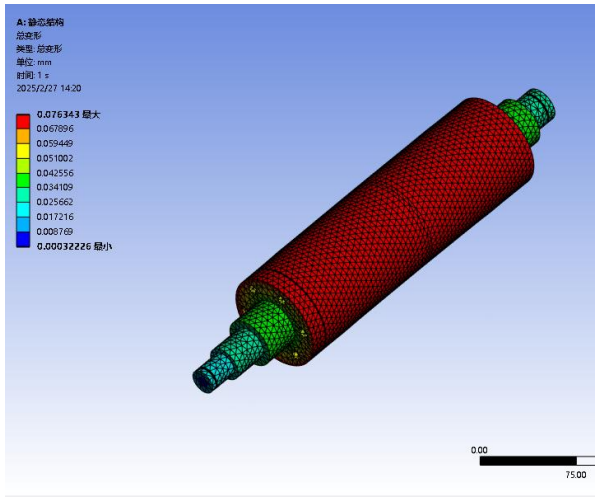
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Hybrid: engineering progress

- Engineering status : Manufacturing
  - Magnet and transmission designs completed
  - Force calculation and mechanical design meet requirements
  - Motors and encoders selected and ordered
- Next
  - Complete assembly and measurements
  - Evaluate end magic fingers and compare tuning range, harmonics and repeatability







from Shuchen SUN

Summary

- Design: Halbach and Hybrid quadrupole meet the need of CEPC mode.
- Prototype: each ring harmonics are within 3 uints. Dual-ring measurements confirm gradient tuning.
- Engineering:
  - Halbach assembly and initial tests are complete. Dual-ring full range test and synchronous rotation are in progress
  - Hybrid design is completed, with manufacturing underway .

Thank you for your attention!