Magnet Development in HEPS

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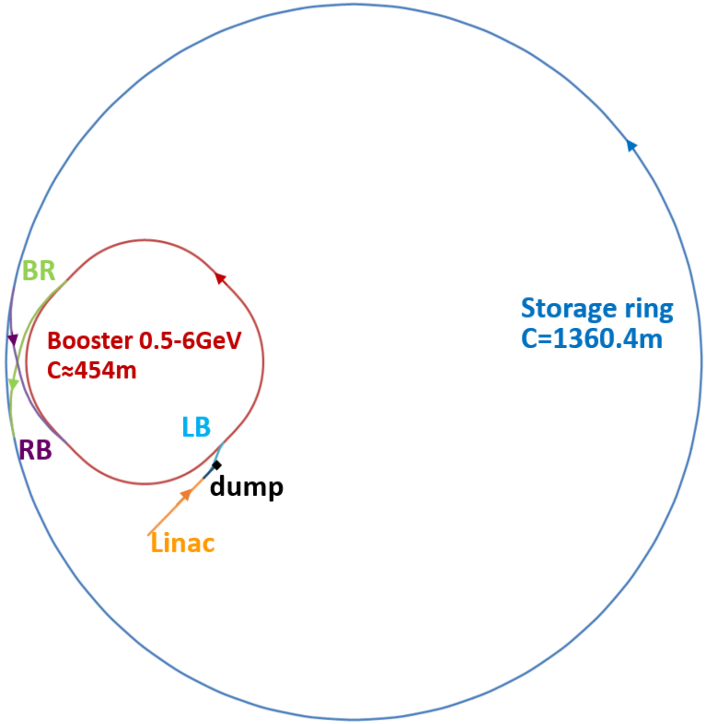
Contents

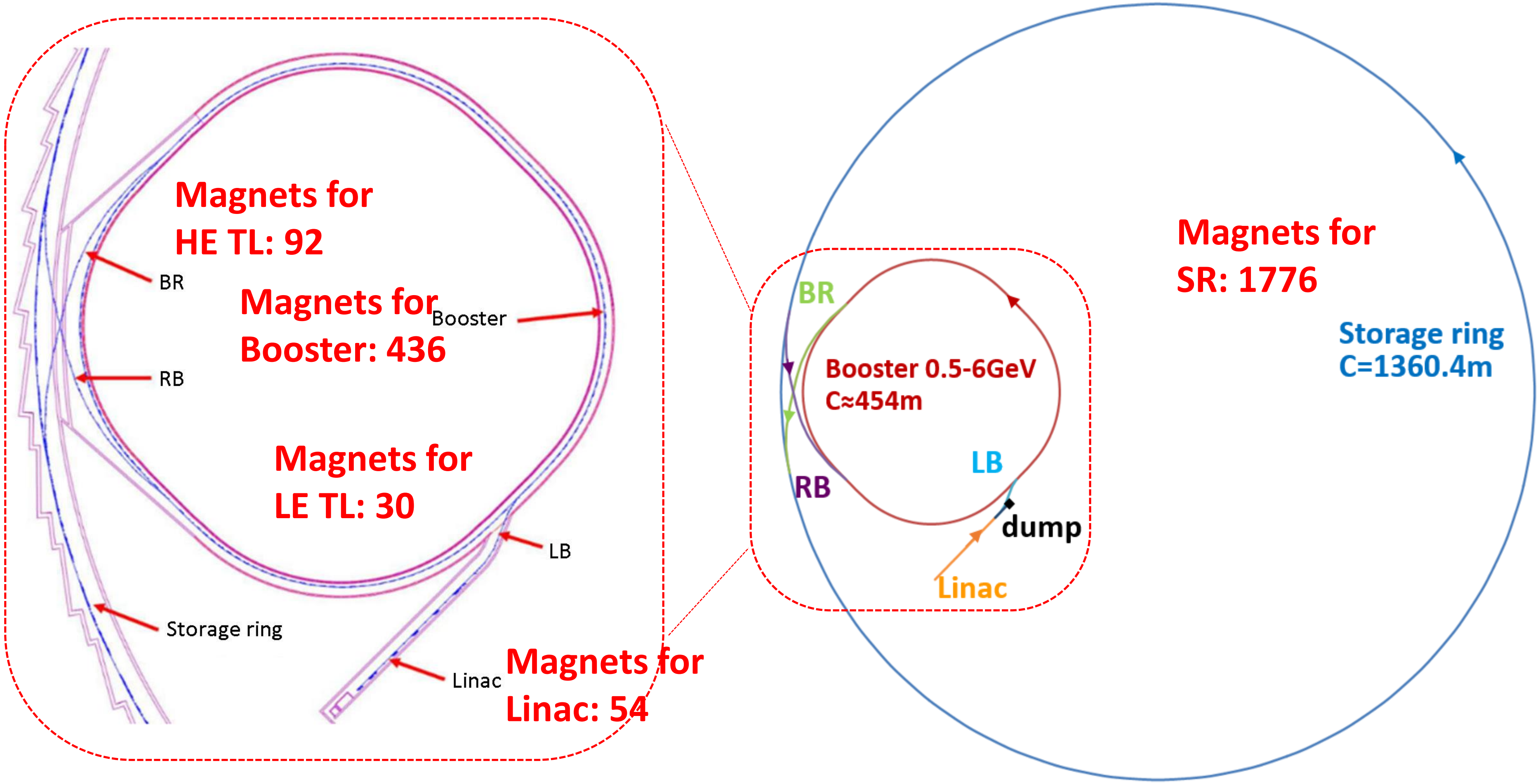
Introduction of HEPS

- ✓ The High Energy Photon Source (HEPS) is an on-construction light source of the fourth generation in Huairou, Beijing, China.
- ✓ Its accelerators consist of an ultra-low emittance storage ring and a full energy injector. The injector is comprised of a 500 MeV linac, a 500 MeV to 6GeV booster synchrotron and transport lines connecting the machines.



The total magnets of HEPS accelerators

- ✓ **There are 2389 magnets in the HEPS accelerators, 1776 for the storage ring, 436 for the booster, 54 for linac and 122 for transport lines.**



The magnets for the linac and transport lines

- ✓ Since all magnets for the HEPS linac and transport lines are DC magnets, for economic considerations, some magnets are made by solid iron and some are made by silicon steel laminations.
- ✓ The coils of the most magnets are wound by solid wires without water cooling due to the relatively low working field.
- ✓ By the end of May in last year, all the magnets for linac and LE transport line were installed in the tunnel.

The magnets for the linac and transport lines

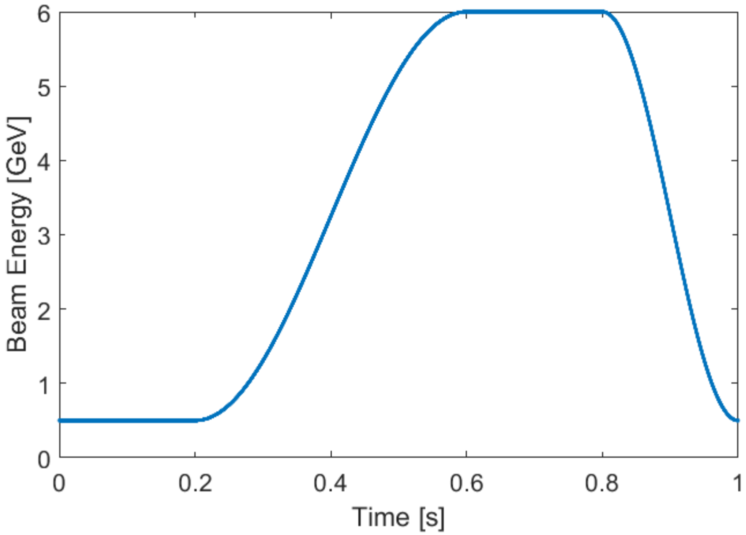
✓ **The main parameters of the magnets for the HEPS linac and transport lines are listed in the tables.**

Name	No.	Length	Aperture	Field	Current	Voltage	Width/ Height	Weight
SOL-I	4	80mm	90mm	0.04T	10.5A	5.8V	194mm/ 194mm	14kg
SOL-II	17	110mm	≥211mm	0.08T	11.3A	85V	656mm/ 656mm	268kg
SOL-III	1	80mm	≥118mm	0.055T	10A	15.7V	422mm/ 422mm	67kg
QF	10	100mm	34mm	10T/m	17.5A	1.5V	310mm/ 310mm	155kg
QD	5	200mm	34mm	10T/m	17.5A	2.5V	310mm/ 310mm	80kg
AM1	1	295mm	34mm	0.30T	140A	4.1V	360mm/ 330mm	250kg
AM2	1	420mm	34mm	0.85T	248A	10.3V	330mm/ 500mm	400kg
C1	1	30mm	50mm	0.001T	2.6A	0.6V	177mm/ 192mm	1.6kg
C2	2	400mm	≥136mm	0.005T	6.4A	3.7V	210mm/ 210mm	30kg
C3	2	24mm	≥50mm	0.001T	1.5A	0.1V	95mm/ 130mm	10kg
CH/CV	10	100mm	34mm	0.02T	13.8A	0.5V	155mm/ 240mm	0.02T

Name	No.	Length	Aperture	Field	Current	Voltage	Width/ Height	Weight
LB-B	3	420mm	34mm	0.85T	248A	10.3V	330mm/ 620mm	570kg
LB-BV	2	150mm	40mm	0.06T	13.5A	2.1V	270mm/ 175mm	46kg
LB-Q	13	200mm	34mm	14T/m	24.5A	3.5V	310mm/ 310mm	155kg
LB-CH	6	100mm	40mm	0.042T	14.5A	1.3V	175mm/ 240mm	26kg
LB-CV	6	100mm	40mm	0.042T	14.5A	1.3V	240mm/ 175mm	26kg
BR/RB-30BH	28	1450mm	30mm	0.97T	328A	4.1V	310mm/ 440mm	1200kg
BR/RB-30BV	4	400mm	30mm	0.49T	166A	20V	330mm/ 290mm	210kg
BR/RB-30Q	40	30mm	30mm	40T/m	130A	6.7V	400mm/ 400mm	390kg
BR/RB-26Q	4	400mm	26mm	57T/m	139A	8.5V	485mm/ 485mm	420kg
BR/RB-CH	5	200mm	30mm	0.08T	15.2A	2.3V	150mm/ 250mm	52kg
BR/RB-CV	11	200mm	30mm	0.08T	15.2A	2.3V	250mm/ 150mm	52kg

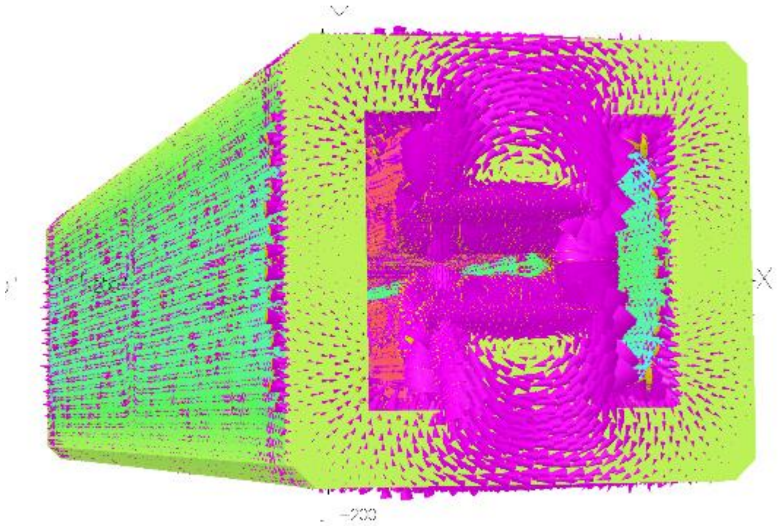
The magnets for the booster

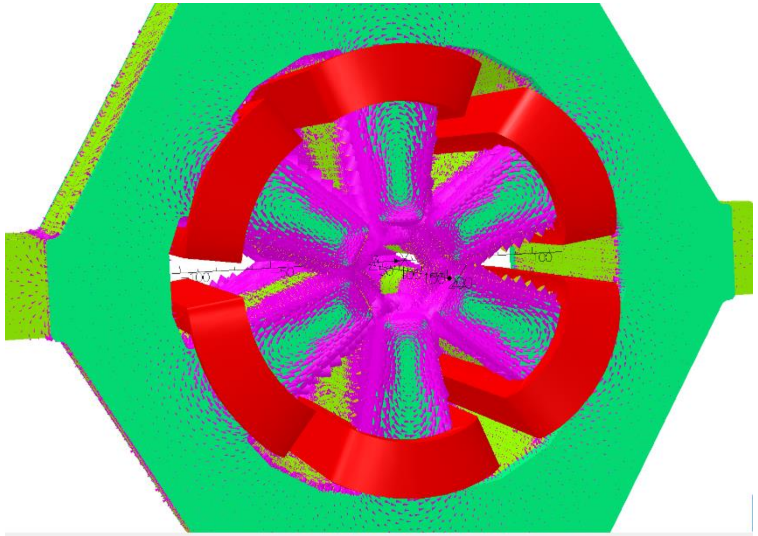
- ✓ The HEPS booster is a 1Hz synchrotron which accelerate the electron beam from 500MeV to 6GeV, the typical waveform of the beam energy is shown below.
- ✓ It has 128 dipoles, 148 quadrupoles, 68 sextupoles and 92 correctors, the field of all these magnets will synchronously change with the beam energy.
- ✓ The aperture of the dipoles is 34mm whereas that of the quadrupoles, sextupoles and correctors is 40mm. The field errors of all magnets is required to be less than 5E-4.
- ✓ By the end of 2022, all the magnets for the booster were produced, measured and installed in the tunnel.



The magnets for the booster

- ✓ **Since the magnets for the booster are dynamic magnets, some special issues should be carefully considered when the magnets are designed and produced.**
  - ➢ **Eddy current will be induced in the metal components such as the cores, end plates and coils of the magnets, which will produce extra field errors and cause the field waveform deformation.**
  - ➢ **To reduce the eddy current effect, the cores of the magnets for the booster will be stacked by the laminations with thickness of 0.5mm, the end plates of the cores will be produced by stainless steel with low conductivity.**





The magnets for the booster

- The changed field will produce the changed forces, which will lead to the vibration of the cores and coils.
- To reduce the vibration and ensure the stability, the laminations of the magnet are adhered together by the epoxy resin, the anti-loosening bolts and washers are used to fix the components of the magnets.
- The torque wrenches are used to tighten all the bolts as uniformly and firmly as possible.

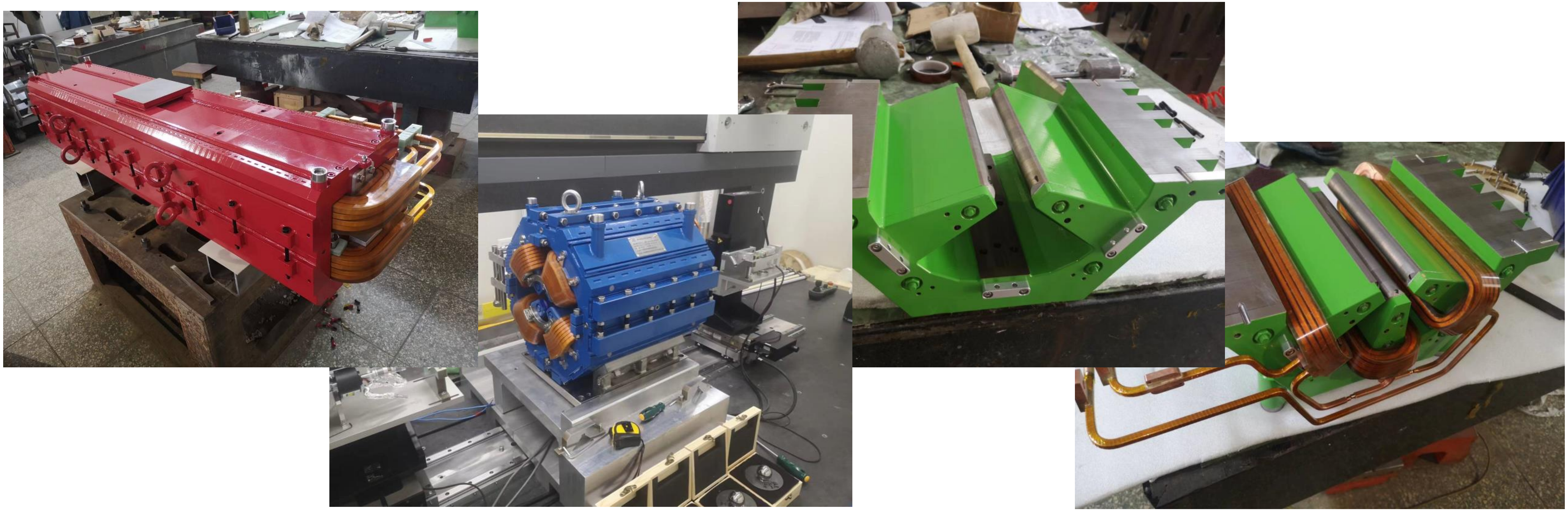


The magnets for the booster

- Because each family of the magnets is powered in serious, high voltage will be induced in the ends of the magnet coils when the field changes.
- To reduce the high voltage, the coils have to be designed with small turns and low inductance. The insulation degree between the coils and cores of the magnets has to be designed as high as possible.

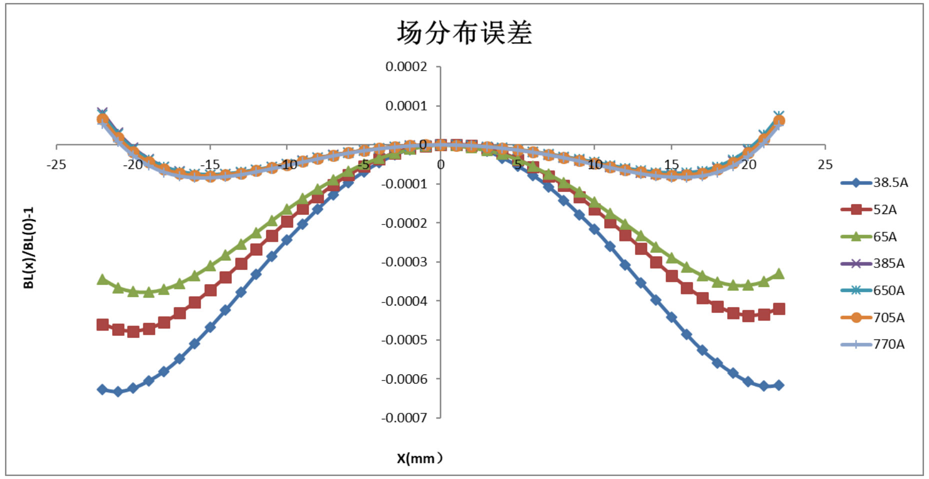
The magnets for the booster

- To install the coils, the dipole magnet can be split into upper and lower yokes, the quadrupole magnet can be split into four quarter yokes, the sextupole magnet can be split into upper and lower yokes meanwhile the upper and lower poles can be moved away.
- All the coils are wound by hollow copper conductors, which have 12 turns for the dipole magnet, 14 turns for the quadrupole magnet and 8 turns for the sextupole magnet.

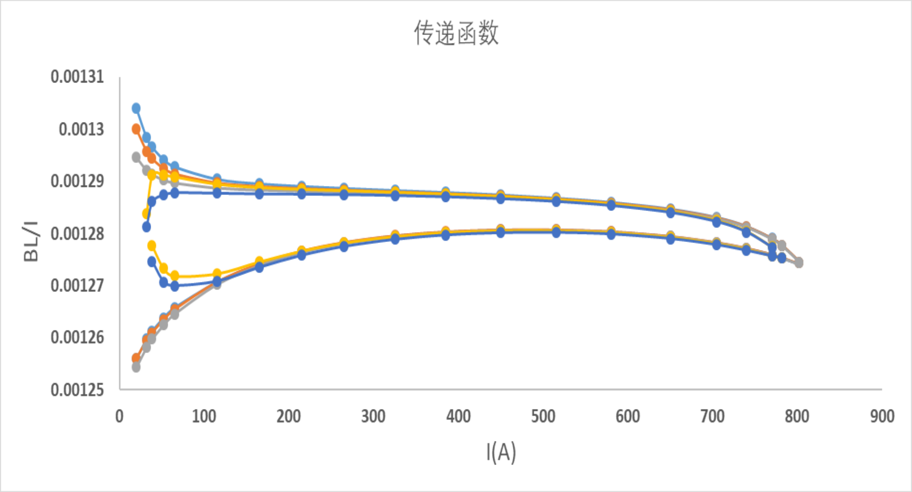


The magnets for the booster

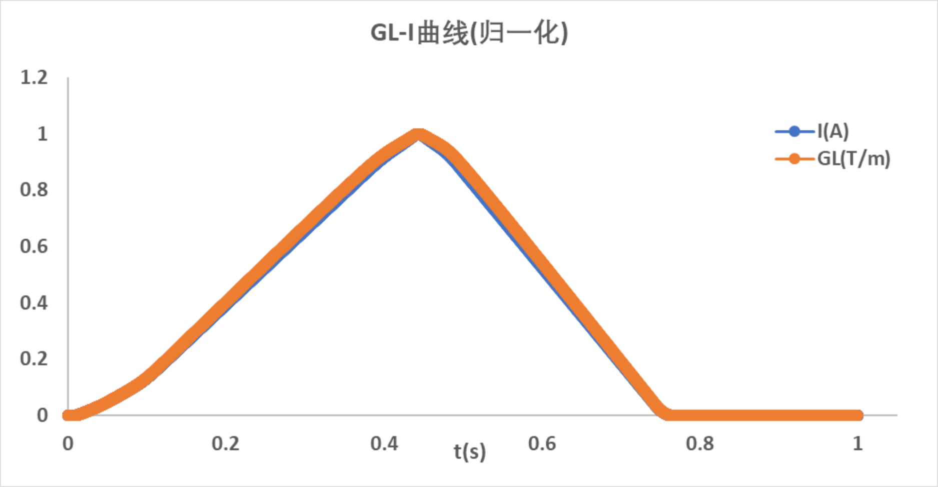
✓ **The magnetic field measured results of some magnets for the booster.**



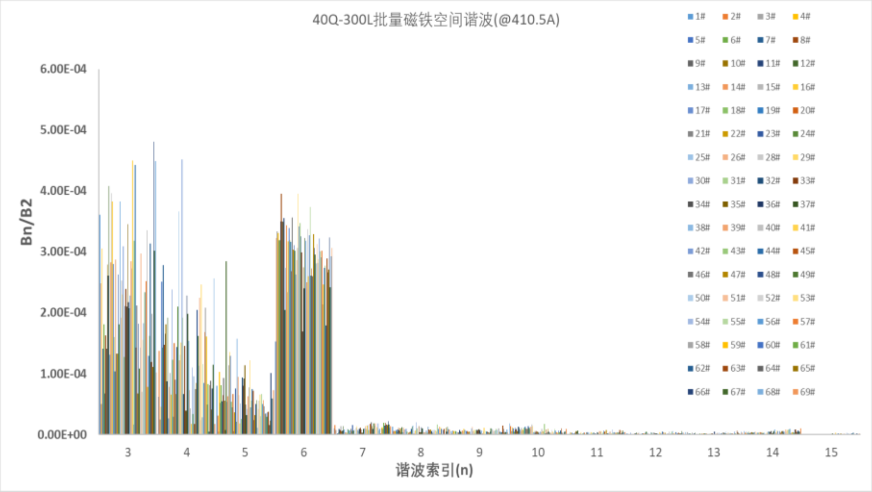
Field distribution curves of the dipoles



Transfer functions of the dipoles



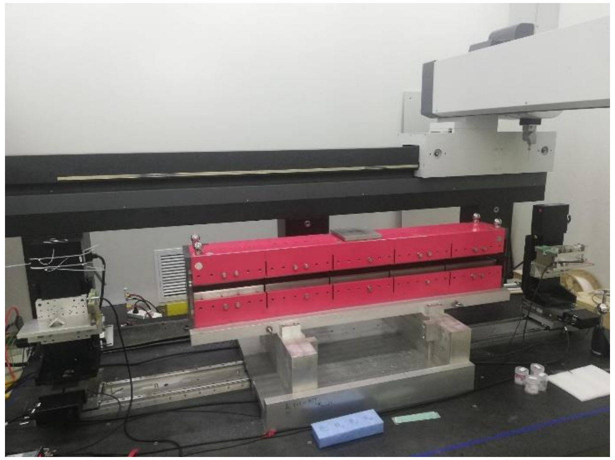
Field and current waveforms of the qradrupoles

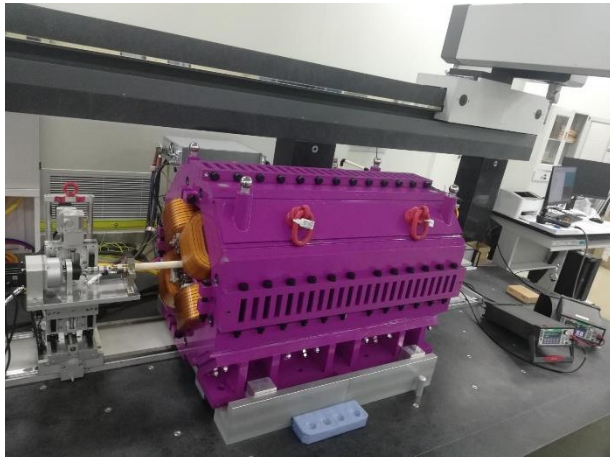


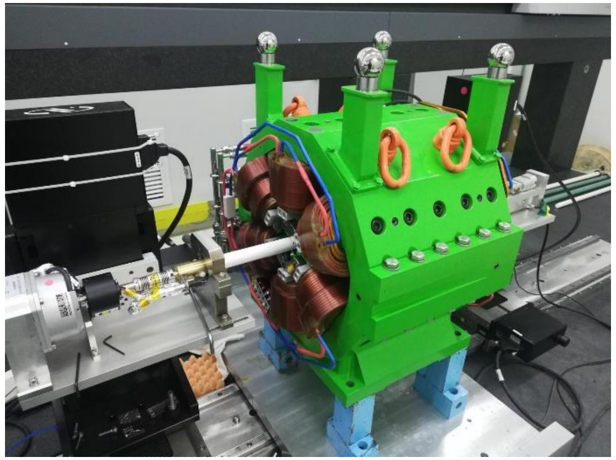
Field harmonic errors of the quadrupoles

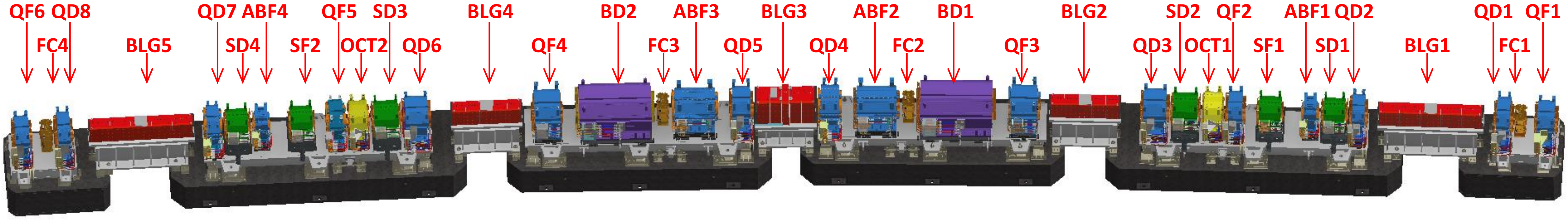
The magnets for the storage ring

- ✓ The storage ring has 48 super-periods. Each super-period has 5 bending magnets combined with longitudinal gradients (BLG), 6 dipole and quadrupole combined magnets(BD/ABF), 14 quadrupole magnets(QF/QD), 6 sextupole magnets(SF/SD), 2 octupole magnets(OCT) and 4 fast correcting magnets(FC).



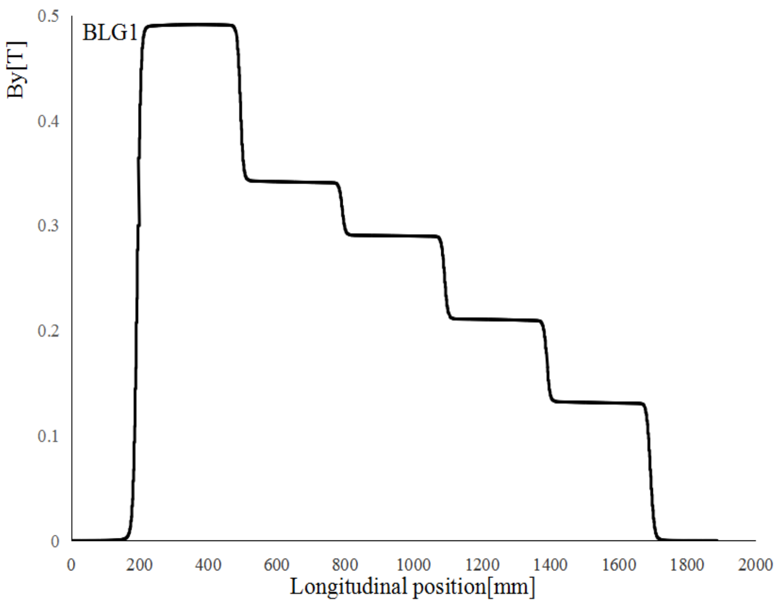


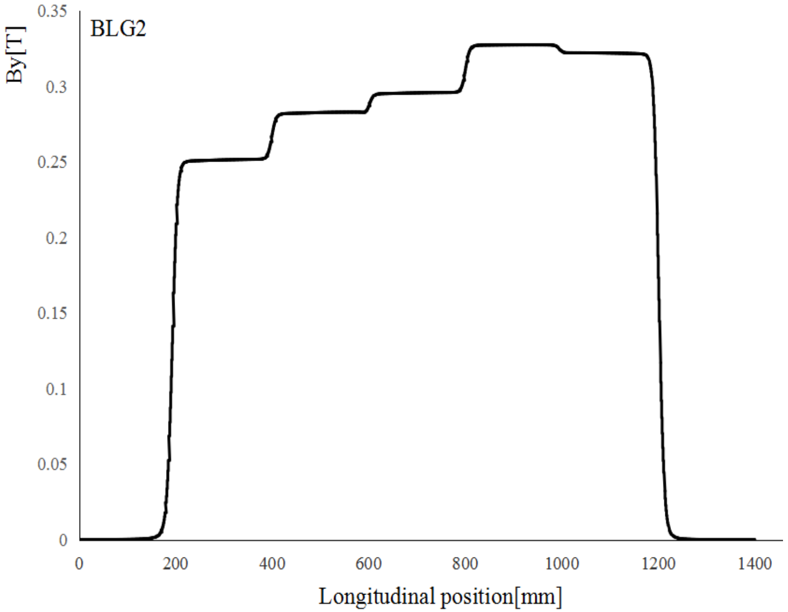


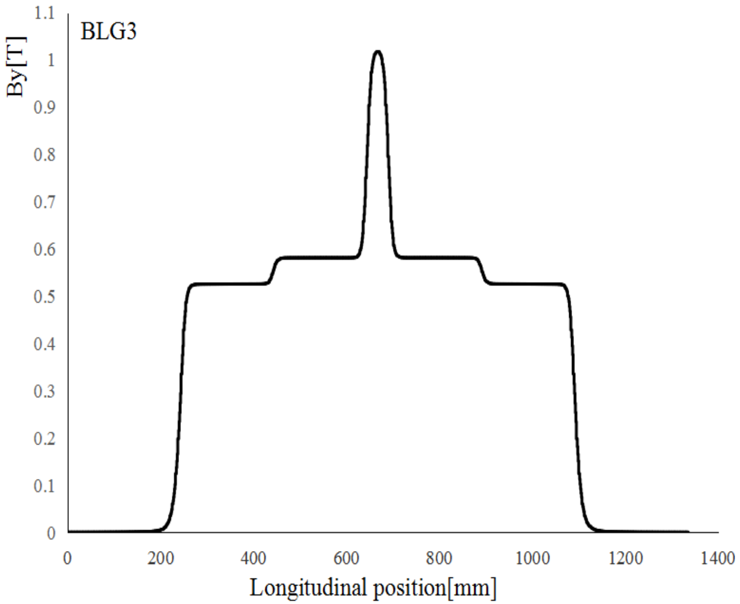


The dipole magnets for the storage ring (Q. Li)

- ✓ To reduce the emittance of the electron beam, the dipole magnets of the storage ring are the bending magnets combined with longitudinal gradients (BLGs) .
- ✓ There are five BLGs in one period, the field distributions along the longitudinal direction of BLG1, BLG2, BLG3 are shown below. The field distributions of BLG4, BLG5 is symmetrical about the center of period with BLG1, BLG2.

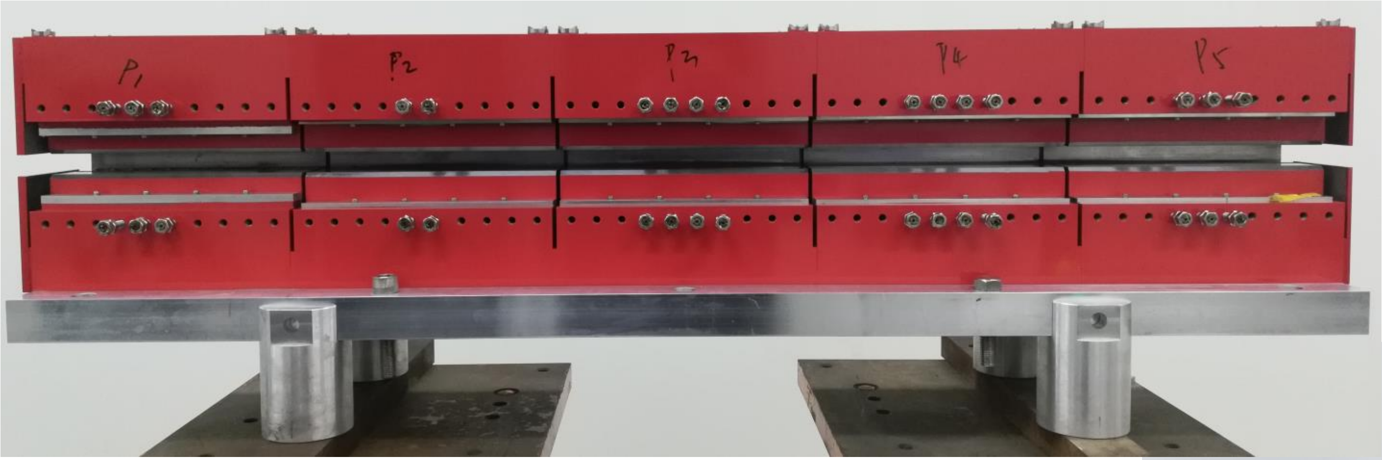






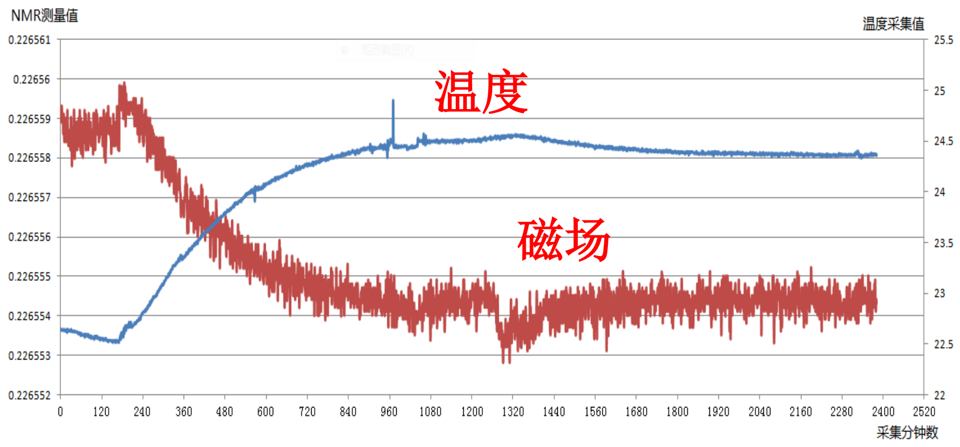
The dipole magnets for the storage ring

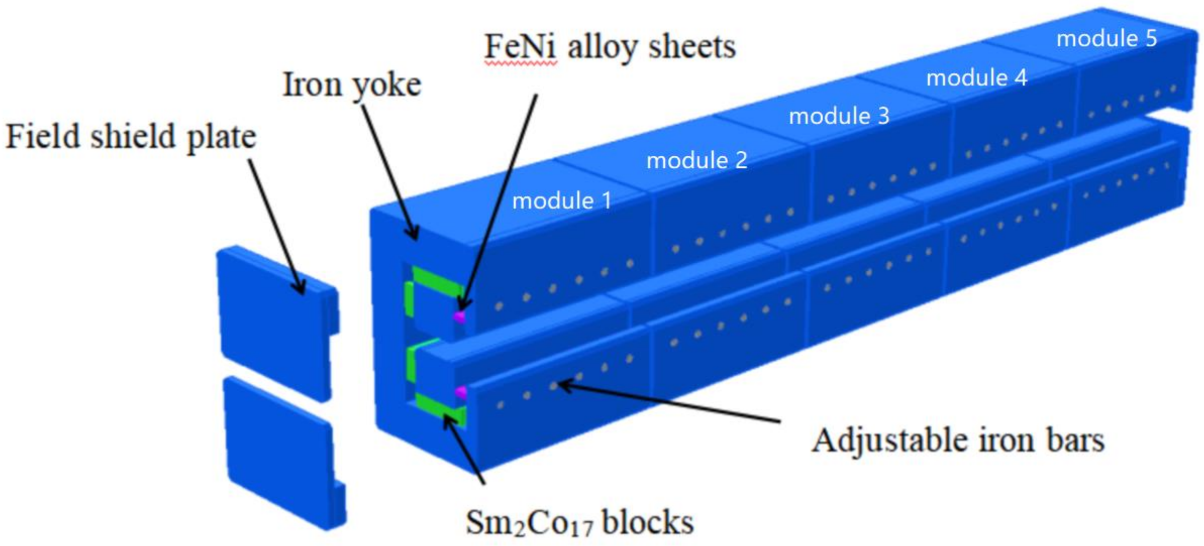
- ✓ In the R&D stage of the HEPS, two types of BLGs were designed and developed, one was the magnet excited by current, another was the permanent magnet. All the measured specifications of the both magnets were satisfied with the requirements.
- ✓ Due to the compact structure, long-term field stability, good temperature stability and no electricity power loss, the permanent magnet was chosen as the final design of the BLGs.



The dipole magnets for the storage ring

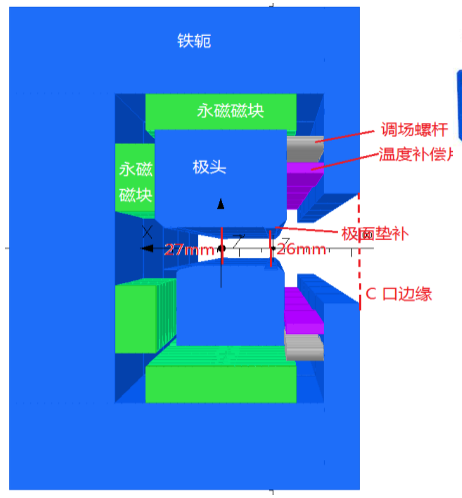
- ✓ The permanent dipole magnets are combined by five modules in longitudinal direction, which are mainly composed of iron poles, iron yokes, magnet blocks(Sm2Co17), adjustable iron bars, temperature compensation shunt sheets(FeNi alloy) and field shielding plates.
- ✓ The permanent material of Sm2Co17 is chosen to excite the field since it has a relatively lower temperature dependence factor.

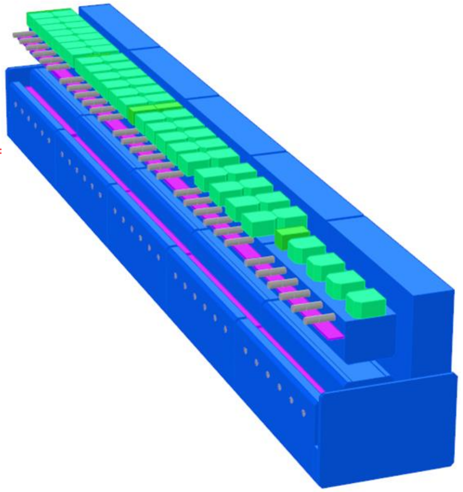




The dipole magnets for the storage ring

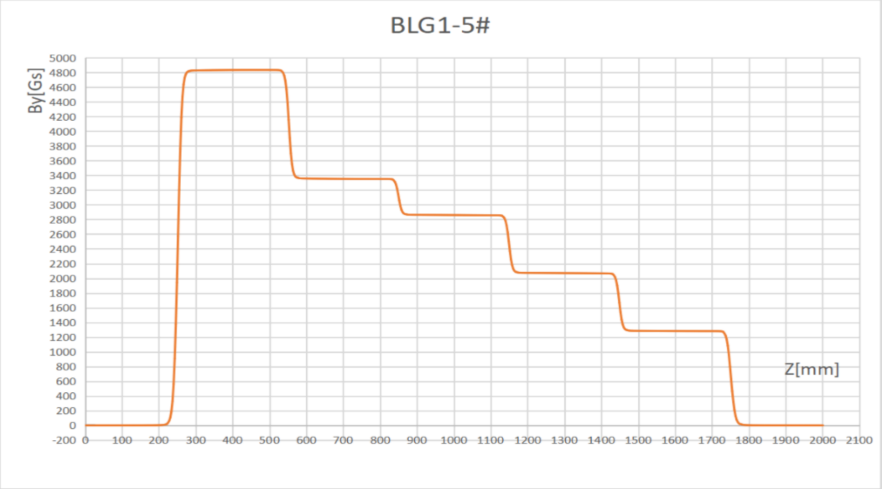
- ✓ By using the different numbers of the magnet blocks, each module can have a different field value and a longitudinal gradient field can be realized.
- ✓ By using the adjustable iron bars, the field of each module can be precisely adjusted to fit the ideal values.
- ✓ By using the temperature compensation shunt sheets, the temperature dependence of magnet blocks can be weakened.

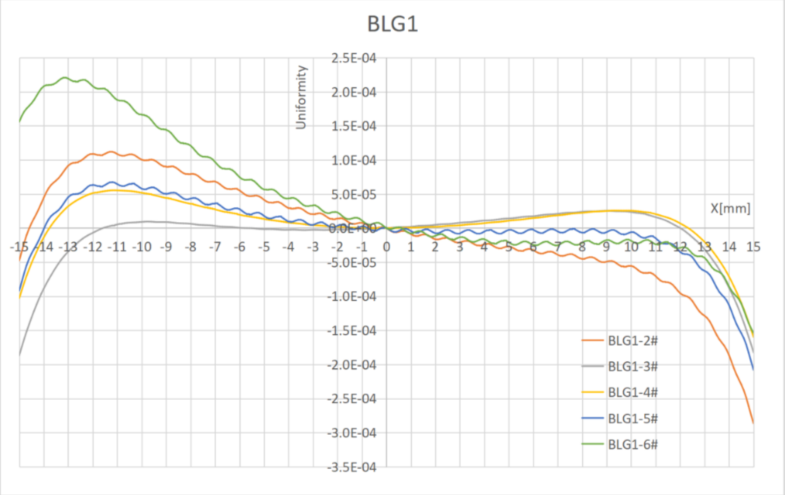


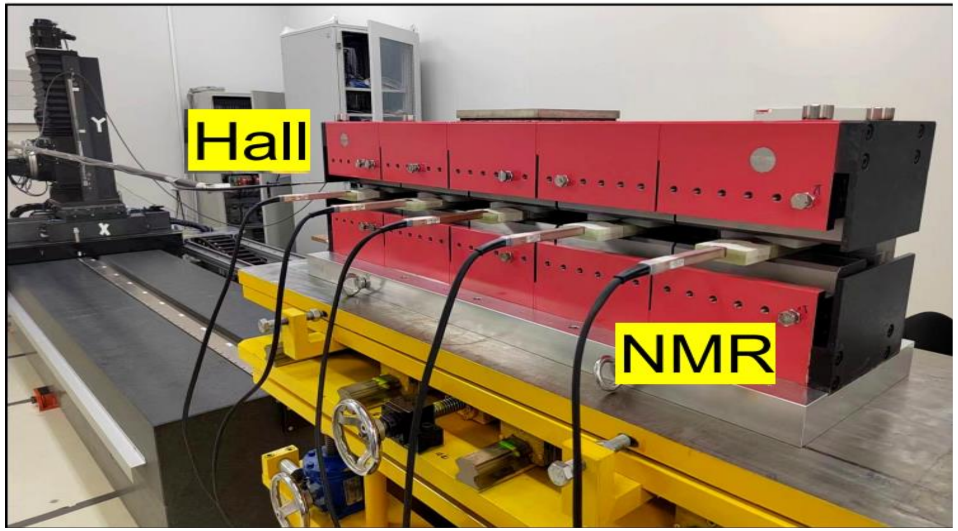


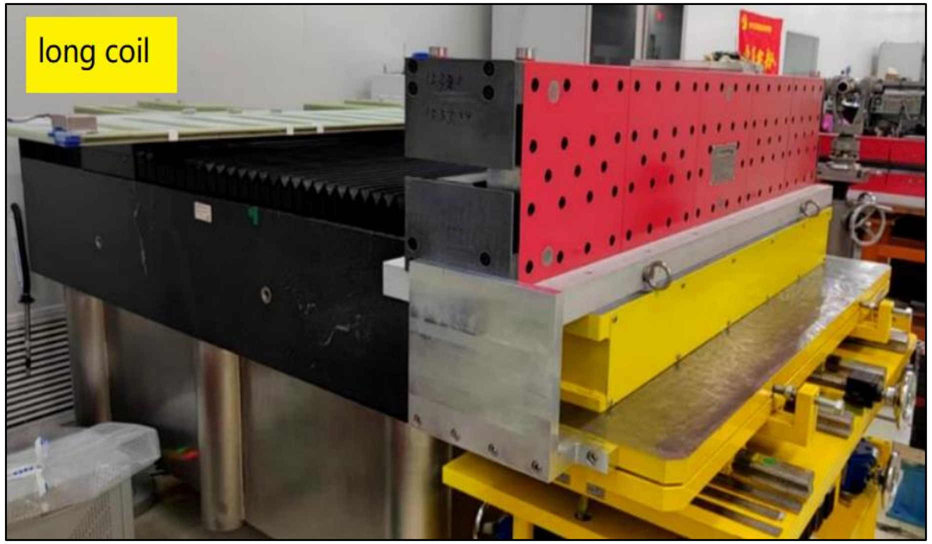
The dipole magnets for the storage ring

- ✓ **The hall probe measurement system is used to map the field along the central line in the gap, the long coil measurement system is used to measure distribution of the integral field .**



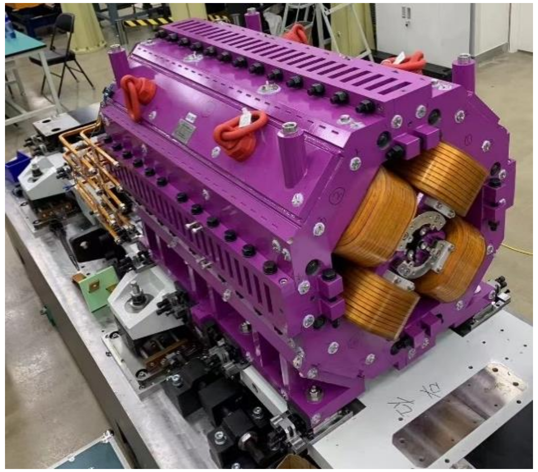


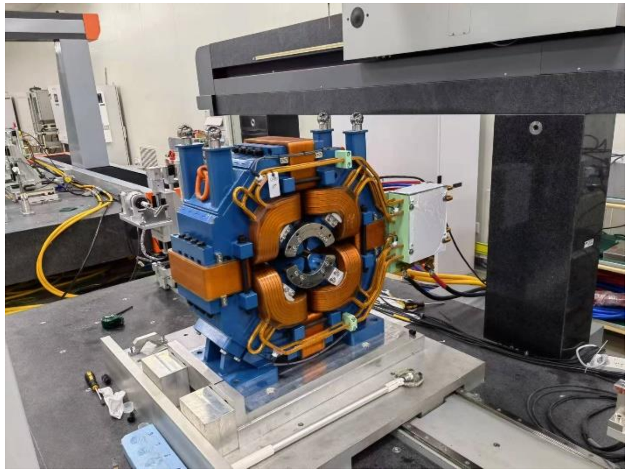




The quadrupole magnets for the storage ring (Y. S. Zhu)

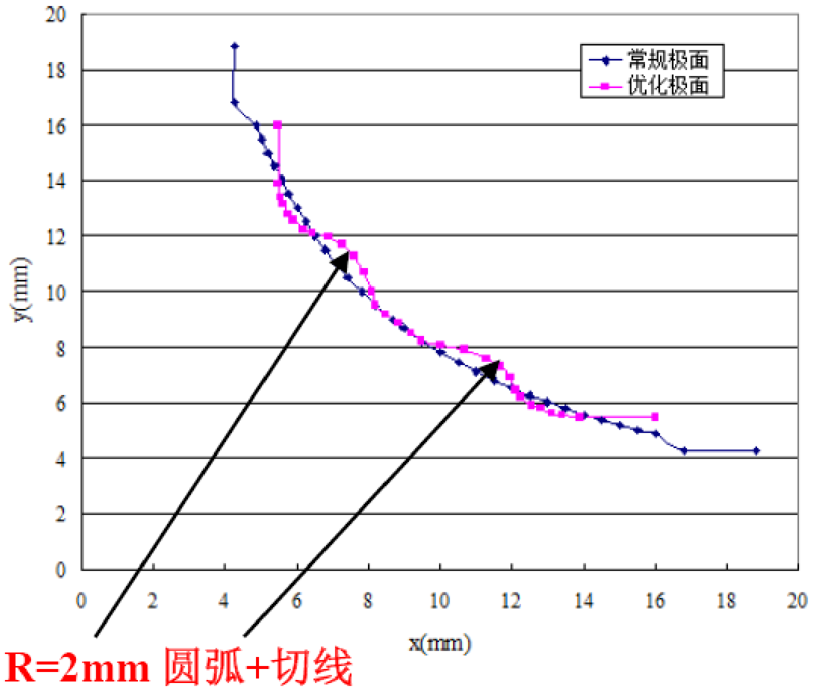
- ✓ There are 960 quadrupole magnets in the HEPS storage ring, some of them are used as the dipole and quadrupole combined magnets (BD/ABF) by offset installation from beam central orbit.
- ✓ The max gradient and aperture of the most quadrupole magnets are 80T/m and 26mm, which are key factors to achieve ultra-low emittance of the storage ring. But they make the magnets to work at the saturation region of the BH curves.
- ✓ The harmonic errors of all quadrupole magnets are required to be less than 4E-4 within the GFR.

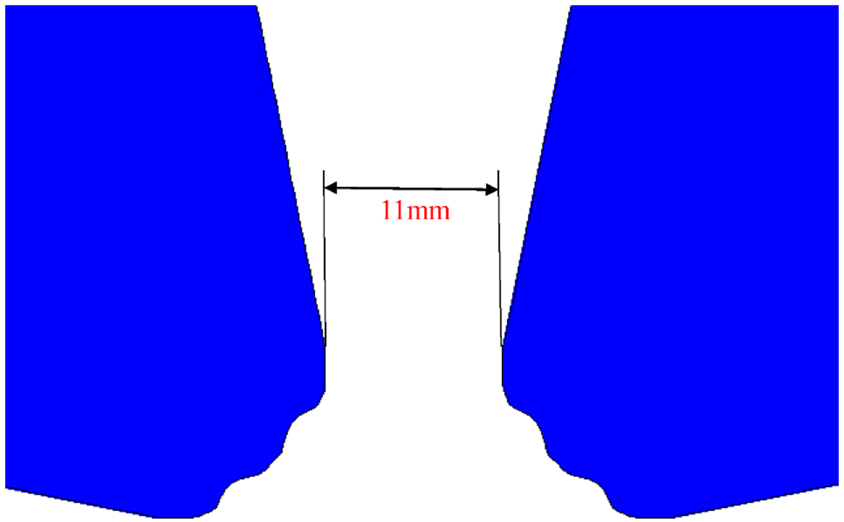


The quadrupole magnets for the storage ring

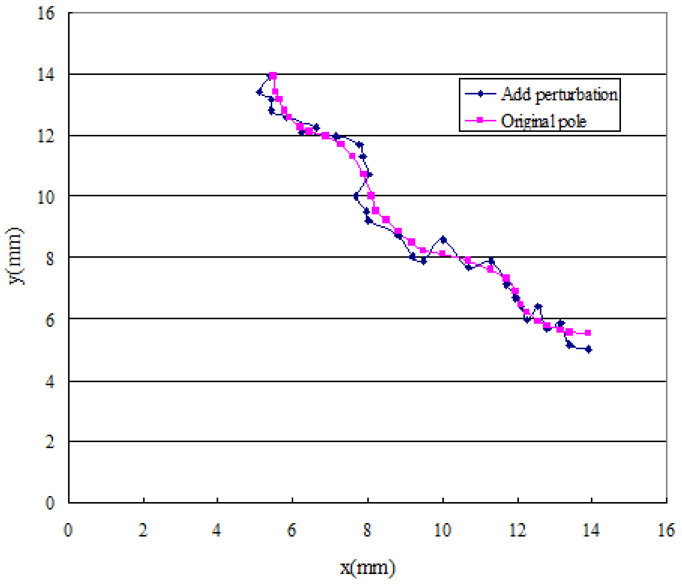
- ✓ The gap between poles is required to be less than 11mm, which makes the conventional hyperbola pole face not to meet the requirement of the field quality. So a special pole face shape was proposed and adopted to the quadrupole magnets.
- ✓ After several iterations of optimization, the simulated harmonic errors of the quadrupole magnets are suppressed to 0.5E-4.

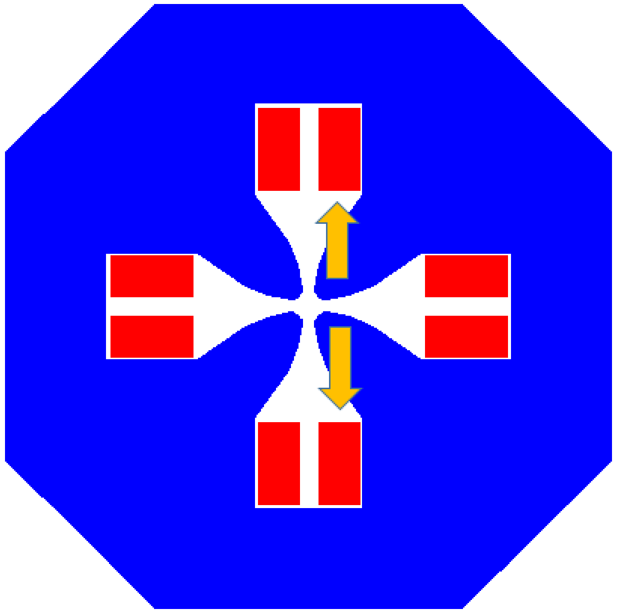


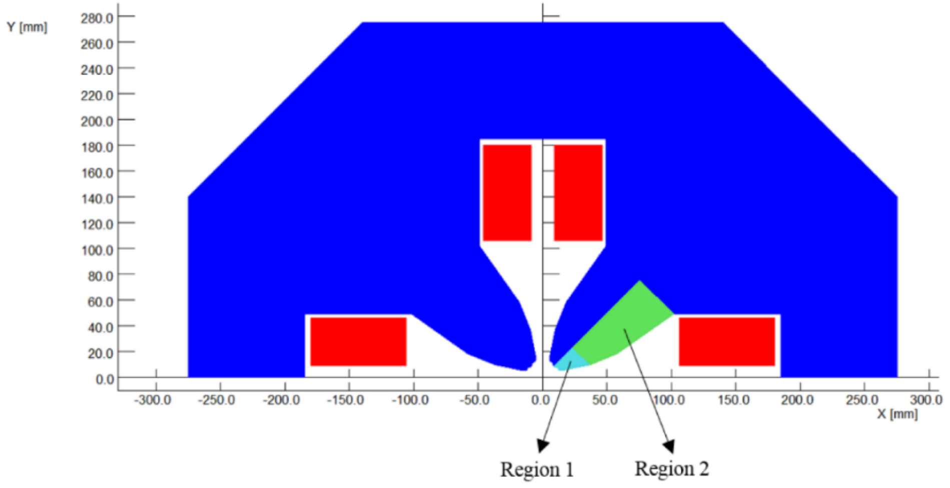


The quadrupole magnets for the storage ring

- ✓ The perturbations of the pole shape and position as well as the core material are simulated and studied, then the tolerances of the pole production are proposed.
- ✓ The mechanical tolerance of the pole shape and position are required to be less than 0.02mm, the difference of the material in a single pole is required to be less than 3%.







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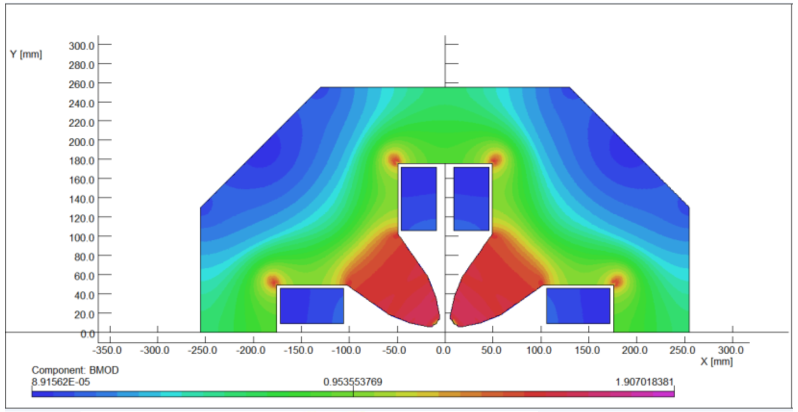
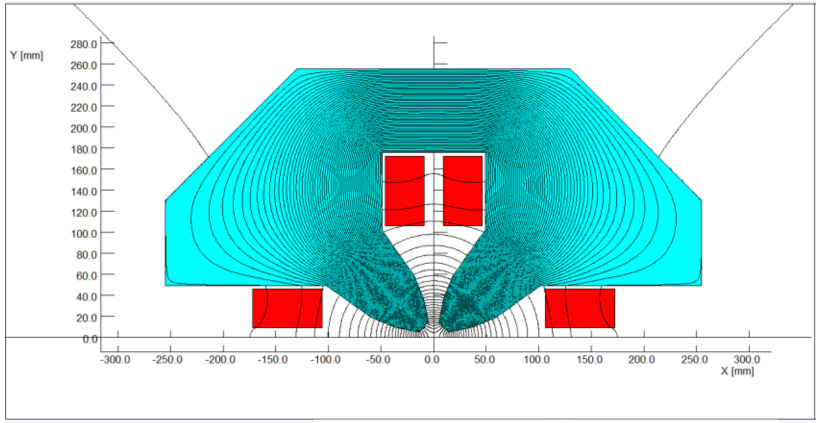
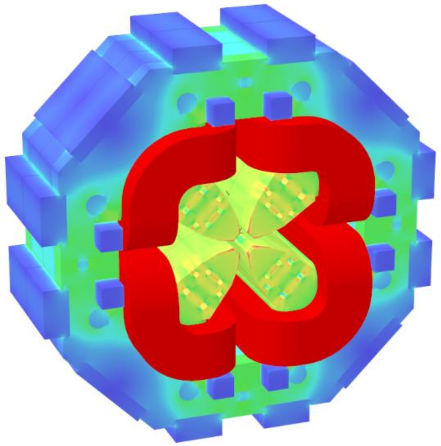
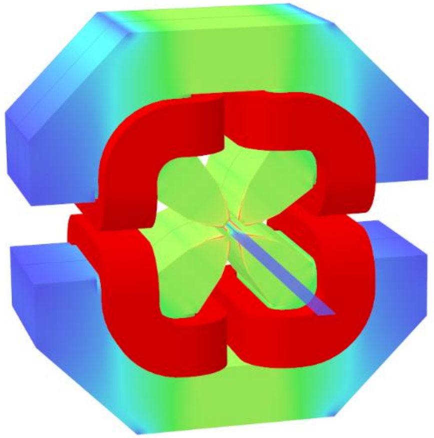
The quadrupole magnets for the storage ring

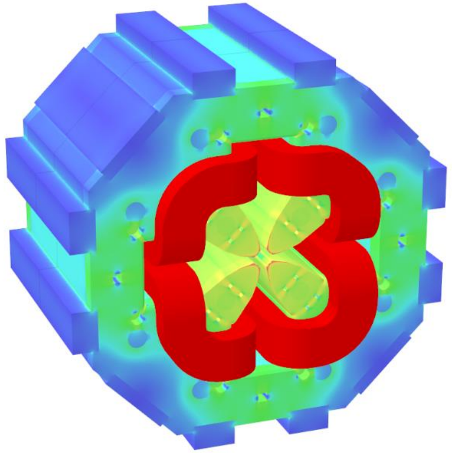
- ✓ **Detailed 2D and 3D magnetic field calculations are carried out for each type of quadrupole magnets. Simulation results meet the requirements.**





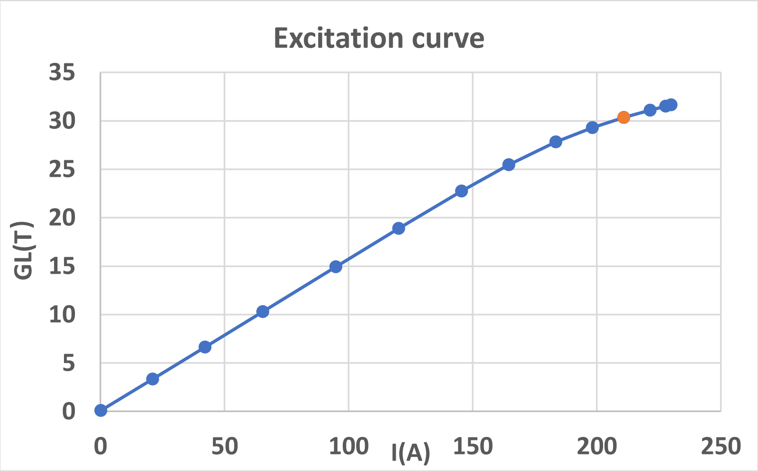


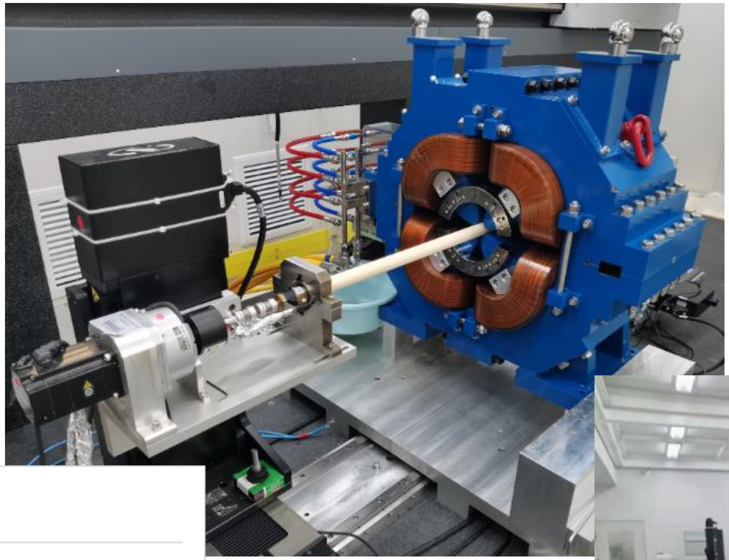


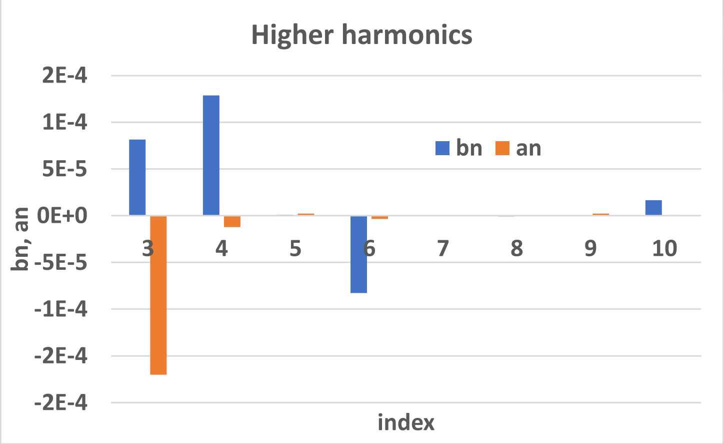


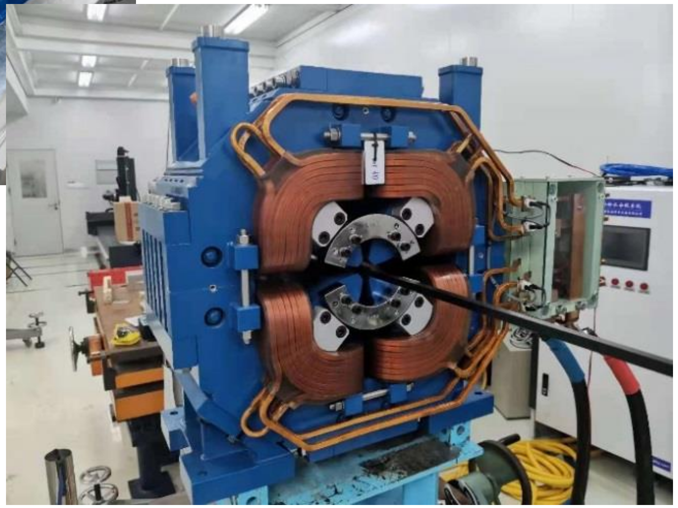
The quadrupole magnets for the storage ring

- ✓ The hall probe measurement system is used to map the field in the aperture, the rotating coil measurement system is used to measure the harmonic errors and integral field.
- ✓ The results show that the most magnets work at non-linear region of BH curve and the harmonic errors of the magnets are less than 4E-4.



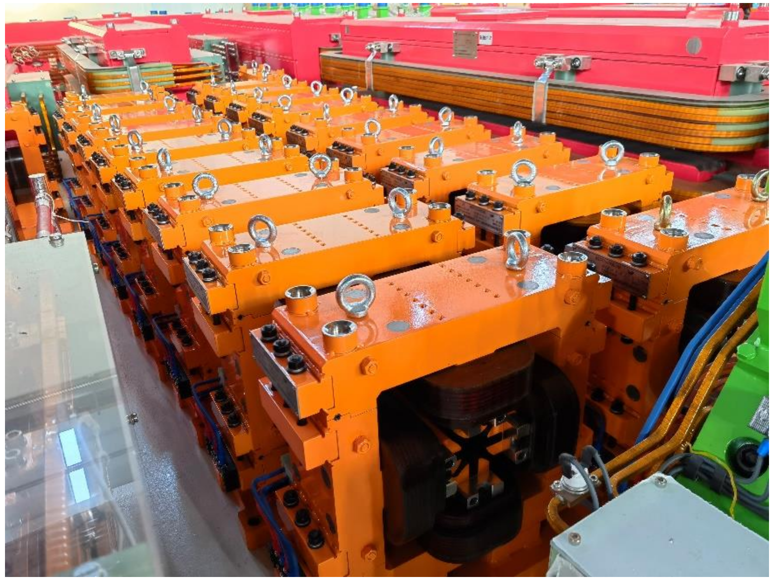






The other magnets for the storage ring

- ✓ The storage ring has 288 sextupole magnets and 96 octupole magnets, which are designed and produced by the conventional technologies. The cores of the magnets are made by solid steel, the coils are wound by hollow copper conductors.
- ✓ There are also 192 fast correctors. To reduce eddy current effect, the cores of the magnets are stacked by the steel laminations with the thickness of 0.15mm.



Summary

- The HEPS has three accelerators (Linac, Booster and Storage ring), which have totally 2389 magnets
- The magnets for linac and transport lines are DC magnets, which are designed and produced by conventional technologies.
- The magnets for the booster are dynamic magnets, some special technologies related to eddy current and vibration are developed when the magnets are designed and produced.
- The magnets for the storage ring are high field, high precision magnets, which are firstly designed and produced in China. It is a challenge to us because the field quality is very sensitive to the mechanical tolerance and performance of the material due to high working field.
- Most of the technologies developed in HEPS magnets can be used to design and produce CEPC magnets in future.

Thank you for your attention.