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# MECHANICAL DESIGN AND MANUFACTURE OF ELECTROMAGNETS IN HEPS STORAGE RING

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*Abstract*

The HEPS storage ring comprises 48 7BA (seven-bend achromat) cells. There are 37 independent magnets in every cell, of which 5 dipoles are permanent magnets and the rest of magnets are all electromagnets including quadrupoles, D-Q (dipole-quadrupole) combined magnets, sextupoles, octupoles and corrector magnets. These electromagnets with small aperture and high magnetic field gradient should achieve high machining and assembly precision. In October 2023, all storage ring electromagnets manufacturing have been completed. This paper mainly introduces the mechanical design, processing and assembly, and the manufacturing issues in the machining period.

## INTRODUCTION

High Energy Photon Source (HEPS) is the first high-energy diffraction-limited storage ring light source in China which will be put into operation at the end of 2025. The electron beam energy of the storage ring accelerator is 6 GeV, which can provide 300 keV high-energy X-rays. HEPS storage ring comprises 48 7BA cells that are grouped in 24 super-periods, with a circumference of 1360.4 m and the natural emittance of 34.2 pm rad. Each 7BA cell has 37 independent magnets of various types and 22 sets of correction coils for generating correction fields. Table 1 shows the types and quantities of the magnets in one cell [1-2].

Table 1: Magnet Types and Quantities of One Cell

| Magnet Type | Quantity per Cell | Quantity in Total |
|---|---|---|
| Longitudinal gradient dipole | 5 | 240 |
| D-Q combined magnet | 6 | 288 |
| Quadrupole | 14 | 672 |
| Sextupole | 6 | 288 |
| Octupole | 2 | 96 |
| Corrector | 4 | 192 |
| Independent magnet in total | 37 | 1776 |

The longitudinal gradient dipoles adopt permanent magnet scheme, and the other magnets in HEPS storage ring are electromagnet. These electromagnets are characterized by high gradient, small aperture, high precision requirements and compact layout. The decrease of magnet aperture makes it difficult to manufacture and obtain high magnetic field precision. Compared with the usual medium or big aperture magnets, the high-order component of the magnetic field of the small-aperture magnet, especially the non-systematic magnetic field, is more sensitive to the machining and assembly accuracy of the pole. Starting from September 2019, on the basis of the research of HEPS-TF (Test Facility) magnet prototypes, the design, bidding and production of various types of magnets were officially launched, and by October 2023, all electromagnets were completed and delivered.

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## MECHANICAL DESIGN AND ASSEMBLY

### *Quadrupole and D-Q Combined Magnet*

There are 20 quadrupoles and D-Q combined magnets per cell in the storage ring, for a total of 15 kinds. D-Q combined magnets are also quadrupoles in structure with their beam center deviates from the magnetic center at a certain distance during installation. In order to facilitate the installation of the magnet coil, they are designed as four part segmented poles.

According to the length and structure of the magnet, all quadrupoles are divided into three categories, including: Type I, type I+ (with correction coil), type II. And there are also three types of D-Q combined magnets: ABF1/4, ABF2/3 and BD1/2. The structures and main dimensions with the unit of millimeter are shown in Figure 1.

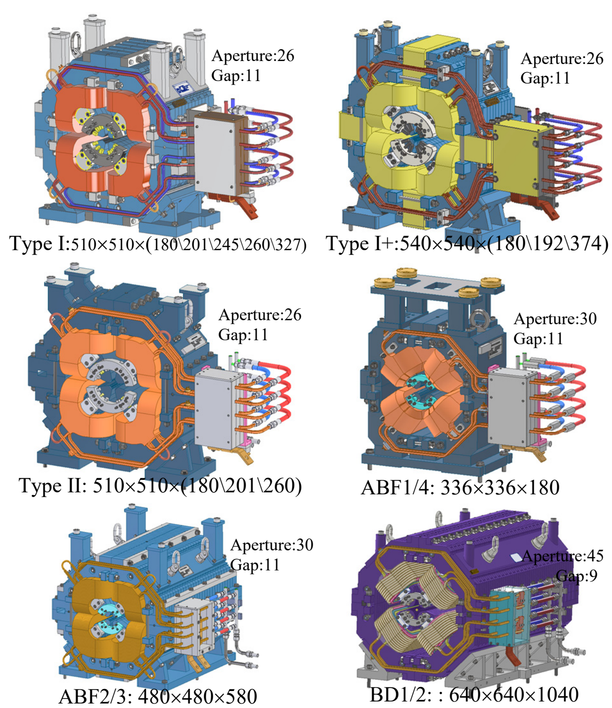


Figure 1: Structure of quadrupole, D-Q combined magnet.

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The magnet yoke of type I, type I+, ABF2/3 and BD1/2 is stacking laminations, which can reduce the manufacturing cost of the magnet and shorten the processing time. The laminations material is silicon steel sheet. According to the need of synchronous light extraction, type II quadrupoles are designed to process synchronous light extraction channels between the upper half and lower half yokes. The yoke of type II quadruple with the material of DT4 is processed by milling machine, and the magnetic pole is precision machining by EDM. 316L is used instead of ferromagnetic materials between the upper and lower yokes. The yoke of ABF1/4 use the same processing method for there are synchronous light extraction channel too.

### *Sextupole, Octupoles and Corrector*

Every 7BA cell of HEPS storage ring has three kinds of sextupoles and a kind of octupoles: SD1/4， SF1/2, SD2/3 and OCT1/2. SD1/4 and SD2/3 are with correction coils.

The processing methods of sextuple and octupoles are milling and EDM (electrical discharge machining). They are divided into upper and lower yokes. All the poles of sextupoles and the middle two poles of octupoles are detachable. Figure 2 shows the structure of sextuple and octupole. Figure 3 is the corrector magnets with laminations yoke: FC1/2/3/4. The special structure is that the fixed plates at both ends of yoke is stainless steel with 5 mm thick.

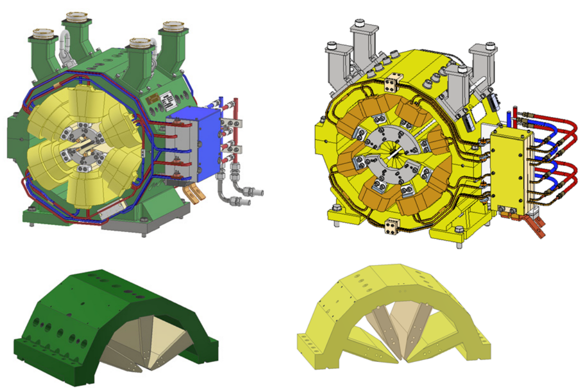

Figure 2: Structure of sextupole and octupole.

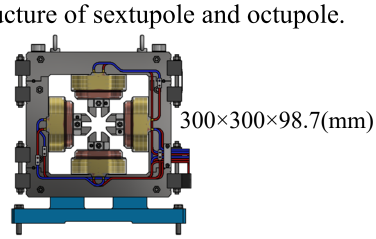


Figure 3: Structure of corrector.

The precision of pole space for the lamination assembly is better than 0.03 mm, and the precision of the magnet length is better than 0.25 mm. For the milling and EDM magnets, the precision of the pole space is better than 0.02 mm, and length error is less than 0.05 mm.

## MAGNETIC FIELD QUALITY CONTROL MEASURES

The precision of mechanical manufacturing directly affects the magnetic field specifications. Magnets mainly controls the quality from the following aspects, including material, pole accuracy and repeatability accuracy.

### *Material*

Maintain the consistency of the yoke material. The silicon steel sheet is punched after mechanical blending and magnetic blending. The plates of DT4 used in the same type of magnet are from the same furnace to ensure that the magnetic excitation performance of them are relatively consistent. The excitation performance of DT4 was tested and the magnetic performance annealing was carried out.

### *Pole Accuracy*

The accuracy of the magnet pole face geometry, including the deviation of each point of the magnet pole face from the ideal position, the accuracy of the magnet aperture and the pole spacing meet the magnet tolerance (≤ 0.03 mm). For the lamination magnets, the punching accuracy and the stacking accuracy affect the pole face, so the effective measures are to improve the profile tolerance of the lamination (≤ 0.01 mm) and ensure that the straightness of the stacked laminations at the mating surfaces is smaller than 0.01 mm. Strictly control, monitor and maintain the positioning accuracy of the stacking mold. The mating surface between the yoke and the mold monitored at all times by a shim with a thickness of 0.02 mm. The laminations should be measured by Coordinate Measurement Machine, and it needs to be re-examined in batches. In addition, the magnet length error should be controlled smaller than ± 0.25 mm, the lamination coefficient should not be less than 98 %. For the machining magnets, milling and low speed wire EDM (electrical discharge machining) are adopted to process the pole. The tolerance is less than 0.02 mm, and the multi-poles of a single magnet are machined by one-time clamping to ensure the accuracy.

### *Repeatability Accuracy*

The accuracy of the magnet aperture and pole space should meet the accuracy of ± 0.03 mm after split and reassembled at least three times because of the installation of vacuum chambers. The control measures are to reasonably arrange the cylindrical pins, use the pole clamps to fix the pole, control the bolt torque and bolting sequence. The specified torques on the assemble bolts is about 60N·m-80N·m. When the magnet is split, the mounting bolts are removed diagonally in order from the sides to the middle. And when the magnets are assembled, the bolts are tightened diagonally in order from the middle to the sides.

## MAGNET DESIGN AND MANUFACTURING ISSUES

### *Filling Magnetic Material*

In the prototype stage, under the design current, the magnetic field gradient of the lamination quadrupoles is lower than the design value, so the actual working currents is higher than the design current. After simulation analysis and discussion of physical and mechanical related personnel, the following improvement measures were carried out:

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Reducing the gap between the long bolts of the pole and the stacked laminations (unilateral 0.05 mm); The nuts at both ends of the long blot, the fixing screws and dowels on the pole clamp were replaced by DT4 from stainless steel; A DT4 cap (Figure 4) is added outside the nuts; Magnetic annealing treatment is performed on the plates outside the laminations before processing. The final working current value is close to the design current.

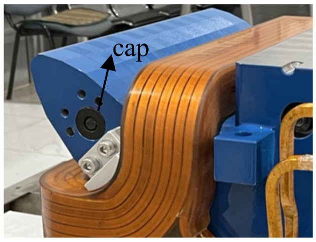


Figure 4: Cap outside the nut.

### *Optimize Welding Process*

As the largest magnet in HEPS storage ring, BD1/2 is the most difficult to manufacture. When the BD1/2 prototype was developed, about 0.2 mm distortion of the pole mating surface in the stacking mold deformed after welding the fixed plate. Then, the welding process was optimized. As shown in the Fig. 5, the fillet weld is changed to downhand weld which is relatively easy to control, and the releasing stress groove is added correspondingly. The factory uses robot welding which can be more efficient and reduce deformation instead of manual welding. In addition, the stacking mold was improved to make the stress distribution more balanced.

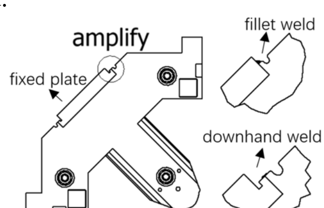


Figure 5: Optimize the welding process.

### *Dowel Installation*

The dowel of the quadrupoles with correction coil which is shielded, should be paid attention to ensure positions. The dowel should be pre-installed before the installation of correction coil. After confirming the pole space meet the requirement, remove the upper half yoke and then install the correction coils.

### *Split Baseplates*

Most of the magnets are supported by two split welded baseplates. During the processing, it was found that about 20 QF3/4 had a deviation of 1 ~ 2 mm in the mounting hole position for pre-drilling before welding the baseplates. The improvement measure is to confirm whether the position of mounting hole is correct when milling the bottom surface of the baseplates.

### *Temperature Switch*

The temperature switch was a little far away from the pole in the initial design. In an accident during the sextuple magnetic measurement, the switch did not act immediately. After testing, the operating temperature of the switch is adjusted to 36 ± 3 °C, and three switches are added at the position close to the pole of sextupole. For D-Q combined magnets and quadrupoles, the operating temperature of the switch is adjusted to 43 ± 3 °C, and the installation position changed more close to the pole. Figure 6 shows the distribution of the switches in sextupole and quadrupole.

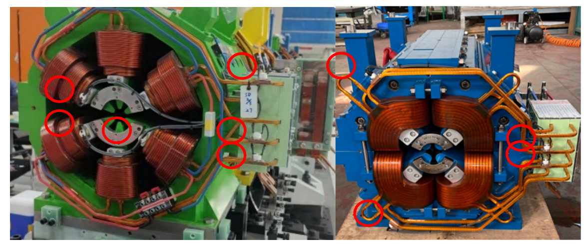

Figure 6: Switches in sextupole and quadrupole.

### *Magic Finger*

The magic finger which is a fast and effective method of magnetic field harmonic compensation is designed on the pole to improve the high-order field component of the magnet. It is fixed by pole clamp, and its position can be adjusted in the magic finger groove. As a compensation method for magnetic field adjustment, the magic finger is only used as a remedial measure. Although the installation position of the magic finger is reserved on the pole of each magnet. Figure 7 is the magic fingers distribution. The physicists don't want to attach too much magic fingers on the poles. The manufacturer is required to meet the magnetic field specifications through high-precision processing and assembly. However, in the actual, some types of magnets can meet this requirement, such as QD2 and ABF2/3. However, there are also some magnets that need to use the magic finger to achieve the required specifications, such as QD7, QF5 and BD1/2. The number of magic fingers used per magnet is about 1-3. It was found that the qualified rate of lamination magnets is higher. The machining magnets may not be easy to achieve the required specifications only by processing due to the saturation of the magnetic properties of the yoke.

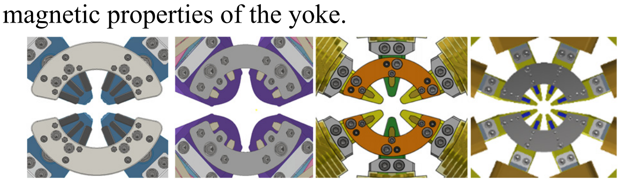

Figure 7: Distribution of magic fingers.

## CONCLUSION

All the electromagnets manufacturing of HEPS storage ring have been completed. Magnetic measurement and installation are being carried out. Some experiences and lessons have been obtained in mechanical design and processing.

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