RESEARCH ON DESIGN OF A NOVEL PERMANENT QUADRUPOLE MAGNET*

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Abstract

Research on a novel permanent quadrupole magnet (PQM) design is introduced in this paper. It can make the quadrupole magnetic field gradient continuously adjustable by modulating several permanent magnet blocks. Four poles of the magnet inform an integral whole to ensure good structural symmetry, which is essential to obtain high-quality quadrupole magnetic field permanent quadrupole magnet. Series of simulation calculations have been done to study the effects of four distinct types of pole position coordinate errors on the central magnetic field. By juxtaposing these results with those derived from optimal design scenario of PQM, the study underscores the critical role that pole symmetry plays in this context. Two integrated design methodologies were proposed, with one of the designs undergoing processing and coordinate detection. The results indicate that this design, is capable of meeting the specified requirements. This design effectively addresses the issue of asymmetrical pole installation, thereby ensuring to a certain extent that well-machined pole can generate a high-quality magnetic field.

INTRODUCTION

Over the past few years, the field of accelerator physics has seen remarkable progress, prompting an international effort to build fourth-generation diffraction-limited storage ring synchrotron radiation sources. This initiative has underscored the indispensable nature of the quadrupole magnet, an essential element for beam focusing. In this context, the development of quadrupole magnets has witnessed considerable innovation, especially with the advent of permanent quadrupole magnet, which are now recognized for their superior performance and operational efficiency.

In the 1980s, K. HALBACH undertook a theoretical examination of permanent magnets composed of rare earth materials, thereby affirming the viability of such magnet designs[1]. Subsequently, particularly over the past decade, there has been a marked acceleration in the advancement of permanent magnet technology. CERN and STFC Daresbury Laboratory (UK) have developed two types of permanent quadrupole magnets with adjustable central magnetic field gradients for the Compact Linear Collider (CLIC)[2]. The European Synchrotron Radiation Facility (ESRF) has developed a high magnetic field gradient (82 T/m, bore radius: 12 mm) permanent quadrupole magnet magnets, in which the central magnetic field gradient is fixed. This type of quadrupole magnet is suitable for future light source applications[3]. The MAX IV[4], LAL, SOLEIL[5], and ESRF laboratories have collaboratively put forth a mechanical design concept for a high-gradient, tunable variable permanent quadrupole magnet, marking a significant advancement in the engineering of advanced magnetic systems for particle accelerators.

Nevertheless, enhancing the quality of the central magnetic field and diminishing high-order harmonic components have emerged as critical challenges that demand immediate resolution. Numerous accurately simulated outcomes from magnet design often fail to be effectively translated into practical manufacturing applications. This paper introduces two novel designs to prevent the central magnetic field from being compromised due to pole asymmetry.

INTEGRATED DESIGN

The integrated design is an optimized iteration of the previous permanent quadrupole magnet [6]. The main excitation module comprises four DT4 iron pole interspersed with four NeFeB permanent magnets which ensures the main magnetic field gradient. The tuning module is composed of four cylindrical NeFeB permanent magnets, which are changed by the motor to regulate the central magnetic field gradient. The mechanical structural design of PQM is illustrated in Fig. 1.

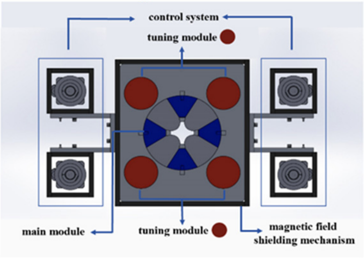

Figure 1: Mechanical structural diagram of the PQM.

The design schemes for the integrated pole can be categorized into two distinct types:

(a) The comprehensive processing method, as illustrated in Fig. 2, necessitates the machining of the four pole of PQM from a singular piece of DT4 soft iron. These are interconnected by an outer ring-shaped soft iron to constitute a whole, thereby ensuring the accurate relative positioning of the pole.

(b) The comprehensive restoration method, as illustrated in Fig. 3, builds upon the foundational (a) method. It employs pins and aluminum plates to secure the pole's end and makes cuts at the connection point of the outer ring. Ensuring the precise positioning of the pole, in accordance with the original design.

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Figure 2: The comprehensive processing method.

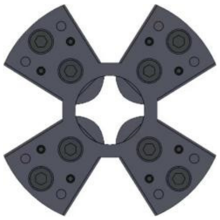

Figure 3: The comprehensive restoration method.

MAGNETIC FIELD SIMULATION

This section, excluding considerations for processing errors (given the current industrial standard, the processing accuracy of DT4 soft iron can be fully assured, as will be elaborated later), employs Opera to simulate the PQM design. The simulation assumes a main excitation module radius of 83 mm, a tuning module radius of 36mm and a bore radius of 14mm. Nonetheless, to streamline the simulation process, the tuning module has been excluded from the model.

Optimal Design Scenario of PQM

For the optimal design scenario of PQM, its distribution of magnetic flux density, distribution of the central magnetic field gradient and higher order harmonics is shown in Figs. 4-6.

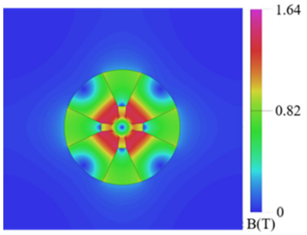

Figure 4: The distribution of magnetic flux density of the optimal design scenario of PQM.

The calculated central magnetic field gradient (x=0) is 64.09T/m. The good field region is (-8.712, 9.072) mm. All higher harmonics are less than 1×10^{-4}.

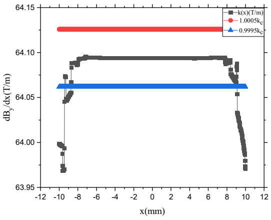

Figure 5: The distribution of the central magnetic of the central magnetic field gradient of PQM.

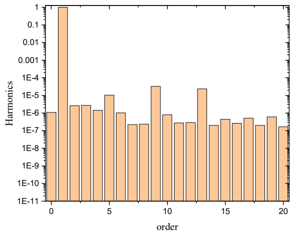

Figure 6: The higher order harmonics of PQM.

Pole Position Deviation of PQM

The simulation of pole position deviation is depicted in Fig. 7, illustrating a specific movement direction with a distance of d=0.141mm. Figure 8 illustrates the distribution of the central magnetic field gradient across four distinct pole position deviation of PQM. Figure 9 shows the high-order harmonic analysis conducted under four distinct pole position deviation of PQM.

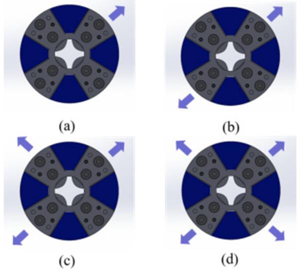

Figure 7: The schematic diagram of pole position deviation of PQM.

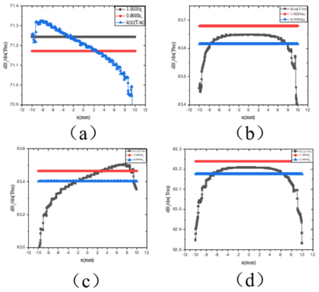

Figure 8: The distribution of the central magnetic field gradient of four distinct pole position deviation of PQM.

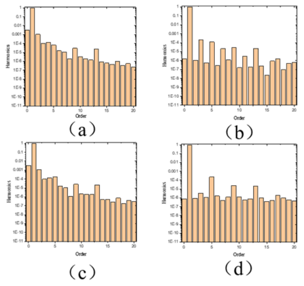

Figure 9: The higher order harmonics of four distinct pole position deviation of PQM.

The data pertaining to the magnetic field simulation of four distinct pole position deviation of PQM is presented in Table 1. As illustrated in the table, cases (a) and (c) exhibit inferior performance compared to (b) and (d), which possess symmetry. This observation underscores the significance of symmetry in the design of PQM. Concurrently, when considering pole position deviation, there is a reduction in high-order harmonics by 1-2 orders of magnitude. This suggests that the positioning of the pole plays a crucial role in ensuring the quality of the central magnetic field.

Table 1: Summary of Magnetic Simulation

Type	k_c(T/m)	GFR(mm)	Harmonics
a	71.21	(-2.5,2.56)	$<1\times10^{-2}$
b	63.65	(-7.84,7.58)	$<1\times10^{-3}$
c	63.43	(-3.26,2.82)	$<1\times10^{-2}$
d	63.21	(-6.58,6.72)	$<1\times10^{-3}$

POLE POSITION MEASUREMENT

In the actual PQM processing, the comprehensive restoration method was used. After machining the pole with a whole piece of DT4 soft iron to ensure positional accuracy, its position was fixed by pins and then the connecting part of the pole was cut. The processed pole is shown in Fig. 10.

Figure 10: The pole has been processed using the comprehensive restoration method.

As illustrated in Fig. 11, the measurement of pole coordinates is a three-coordinate measuring instrument. A comparative analysis was conducted between the actual and design coordinates of the pole position. The prevailing ambient temperature at the site is 23.8°C, accompanied by a relative humidity of 66% RH.

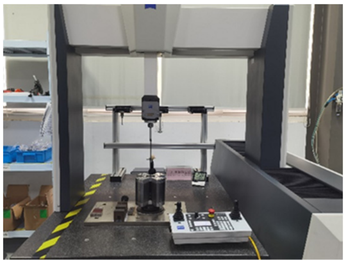

Figure 11: The process of measuring the coordinates of pole position.

Figure 12 shows the measurement results of two measurements, from which it can be seen that the error of pole coordinate is concentrated around 0.02mm.

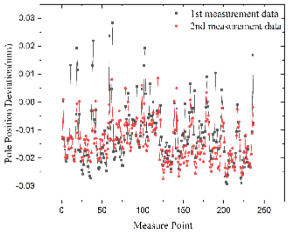

Figure 12: Pole position deviation measurement.

In the case of pole position deviation, which has the most significant error impact (Type a), the central magnetic field gradient and higher harmonic analysis are depicted in Figs. 13 and 14, respectively, when the single pole position deviation is measured at 0.03mm.

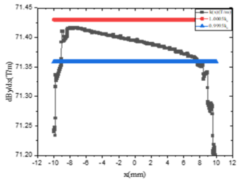

Figure 13: The distribution of magnetic field gradient of 0.03mm deviation.

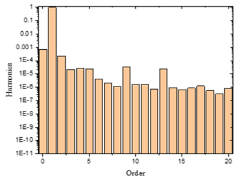

Figure 14: The higher order central harmonics of 0.03mm deviation.

The good field region is identified as (-9.06, 7.68) mm, with the higher harmonic analysis remaining below 7×10^{-3}. Despite not fully aligning with the optimal design criteria, there has been a marked enhancement in performance compared to the standard deviation.

CONCLUSION

This paper introduces two design methodologies aimed at enhancing the machining accuracy of pole in PQM design. Processing tests were conducted on the comprehensive restoration method to ensure that the error remained within a 0.03mm range. This methodology has potential for future extension to multi-pole permanent magnet designs, such as sextupole magnet, thereby improving the quality of the magnetic field. Although the theoretical final position error for the comprehensive processing method should be smaller, corresponding processing tests are still necessary to validate this claim.

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