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DESIGN OF A PERMANENT QUADRUPOLE MAGNET WITH ADJUSTABLE MAGNETIC FIELD GRADIENT*

S. X. Dong, B. Li, B. S. Zhang, X. Q. Wang, G. Y. Feng†
University of Science and Technology of China, Hefei, China

Abstract

As compared to traditional magnets, permanent magnets can effectively reduce energy consumption and eliminate the impact of current ripple and the water-cooling system on beam current. The use of permanent magnets in accelerators has become a new trend as permanent magnet technology has advanced. In HALF (Hefei Advanced Light Facility), we have designed a permanent magnet based on the quadrupole magnet, and the central magnetic field strength of the permanent magnet can be adjusted, indicating that single or multiple permanent magnets can be developed to replace different sizes of quadrupole magnets in accelerators, greatly improving systematization. The magnet's mechanical design has been finalized, and the prototype of the permanent magnet will be manufactured and tested soon.

INTRODUCTION

Fourth-generation light sources feature lower beam emission, higher brightness, and better transverse coherence than existing synchrotron light sources. The traditional magnet system in accelerators consumes a lot of electricity, and water power, and accelerators require quadrupole magnets with variable gradients, which is a time-consuming process for researchers to create. As a result, the benefits of a permanent quadrupole magnet with an adjustable center magnetic field gradient are clear.

Since permanent magnets are used, there is no need for an excitation coil, which reduces the longitudinal space of the magnet by more than 10 cm. This eliminates the issue of a large number of magnets in each bend section and a small longitudinal spacing brought on by the MBA lattice structure, which is typically used in fourth-generation light sources, and significantly lessens the difficulty of magnet assembly and installation.

The use of permanent magnets as the excitation source eliminates the need for power and water-cooling devices, saving space for the original electromagnet circuit and water cooling devices, as well as the cost of power and water required by conventional accelerators; and the physical design avoids the impact of micro-vibrations on beam quality caused by power instability, current ripple, and cooling water turbulence.

Simultaneously, permanent magnets with adjustable central magnetic field gradients would increase the systematization of the light source and will surely be a pioneering effort for the building of future light sources from the standpoint of the development of the light source as a whole. This is an audacious attempt to build on this foundation, and in the future, we can construct permanent dipole magnets, permanent sextupole magnets, and permanent hybrid magnets, and try to make their gradients adjustable [1].

Table 1: Summary of Magnetic Design Requirements

Parameter	Value	Units
Effective Length	300	mm
Maximum Central Gradient	70	$T \cdot m^{-1}$
Minimum Central Gradient	55	$T \cdot m^{-1}$
Good Field Radius	9	mm

We began developing a permanent quadrupole magnet with an adjustable central magnetic field (PQM) in HALF. The main requirements of PQM are summarised in Table 1.

THE DESIGN OVERVIEW

The PQM is based on the design of permanent magnets to achieve high gradient field strengths, as well as the addition of motor modules, allowing the PQM to modify the central magnetic field gradient.

The PQM is divided into three parts: the main excitation module, which is similar to a normal permanent quadrupole magnet, provides the majority of the magnetic field gradient, the sub-excitation module regulates the central magnetic field gradient, and the motor module changes the direction of magnetization of the permanent magnets of the sub-excitation module by the rotation of the motor. There are four sub-excitation modules in the PQM design for symmetry reasons, which are adjusted by using four motors to rotate the sub-excitation module at a corresponding angle, changing the magnetization direction of the sub-excitation module. It should be noted that all four sub-excitation modules rotate at the same angle. In practice, the central magnetic field gradient for the corresponding magnetization direction can be marked prior to installation to make subsequent adjustment and use easier.

To reach the required field strength while utilizing less material, we use Neodymium Iron Boron (NdFeB) with high remanence and high coercivity in PQM. And the poles will be composed of DT4 steel.

For simulation, we used two main software programs, Radia [2] and Opera [3], throughout the design process. Radia has the advantage of being able to calculate multiple models at the same time in a single program, but the results may be less accurate. The advantage of Opera is that the results are more accurate, but the models in the software are more complex to build.

* Work supported by Supported by the Hundred-person Program of Chinese Academy of Sciences
† fenggy@ustc.edu.cn

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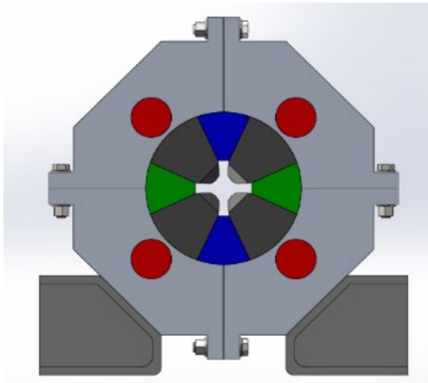

Figure 1: The image of PQM model in 2D.

The simulation of the PQM's physical dimensions came after the initial schematic design. The primary excitation module's peripheral radius as well as the sub-excitation module's center coordinates and radius were all simultaneously simulated using the Radia software during this process. The design schematic of PQM is shown in Fig. 1. The main excitation module is consisting of the green and blue (yokes, made of permanent magnets), and black (poles, made of DT4 iron) components. The sub-excitation module is represented by the red section.

The pole is optimized after the physical size is determined. The PQM has many advantages over a conventional quadrupole magnet due to its much smaller physical size, but it poses significant challenges for magnet design optimization. The smaller pole size will produce high harmonics. After optimizing the pole, we perform chamfering to achieve the physical length design goal.

PHYSICAL DESIGN

A preliminary schematic diagram of the main excitation module’s structure (1/4) was produced for the preliminary design by simulating the PQM using Radia for various sizes, as shown in Fig. 2.

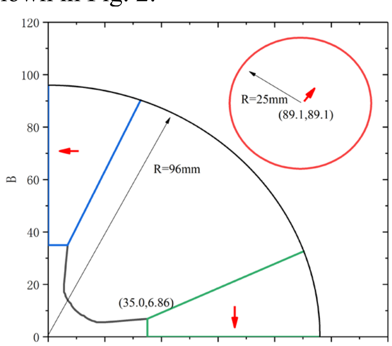

Figure 2: The structure schematic of PQM(1/4).

The PQM’s main excitation module (within the black curve in Fig. 2) is a permanent magnet and soft iron material construction with an 83 mm peripheral radius. Permanent magnets are represented by the blue, green, and red curve sections, and the red arrow direction represents the magnetization direction of permanent magnets. The red curve region corresponds to the 1/4 sub-excitation module, which has center coordinates of (89.1 mm, 89.1 mm) and a radius of 36 mm. the PQM's longitudinal length is 299 mm.

OPTIMIZATION

Because of the PQM's small physical size, the restricted breadth of the pole causes high harmonics (for example, it will generate hexapole field), thus we use a pole shaping method to achieve the needed field integration homogeneity and higher order field components. Therefore, as shown in Fig. 3, we have optimized the shape of the pole using the optimization method described in this article [4].

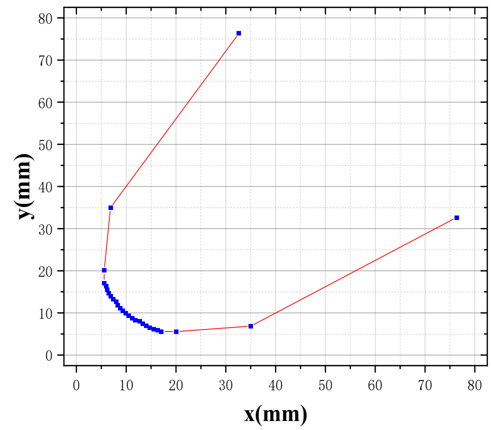

Figure 3: Plot of optimized pole tip coordinates.

Figure 4 and Fig. 5 depicts simulations using Opera2D to compute the harmonics at the maximum and minimum magnetic field gradient values at the PQM's center. When n=6, n=10, and n=14, the high harmonics were all greater than 1×10^{-5} before pole optimization. The high harmonics analysis of the PQM was less than 1×10^{-5} after pole optimization.

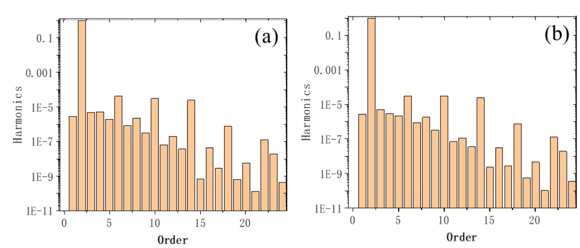

Figure 4: Original Harmonics at the maximum (a) and minimum (b) magnetic field gradient values at the PQM's center.

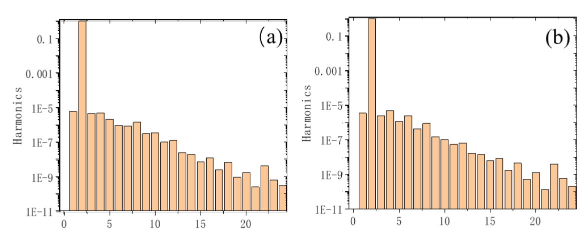

Figure 5: Optimized Harmonics at the maximum (a) and minimum (b) magnetic field gradient values at the PQM's center.

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Lastly, Opera3D was used to further optimize the model, chamfering the model and changing the magnet's physical length to achieve a goal effective length of 300 mm. The effective length L can be determined by the following equation:

$$L = \frac{\int_{-z_0}^{z_0} \frac{dB_y}{dx} dz}{\left.\frac{dB_y}{dx}\right|_{s=0}}. \quad (1)$$

In this equation, $\frac{dB_y}{dx}$ stands for the central magnetic field gradient, z_0 for the longitudinal distance, k_0 for the central magnetic field gradient at the PQM's center.

After 25° of trimming at a physical length of 291.3mm, the PQM's final physical length is 299,97 mm. Fig. 6 depicts a 3D simulation of the final result after the PQM has been chamfered.

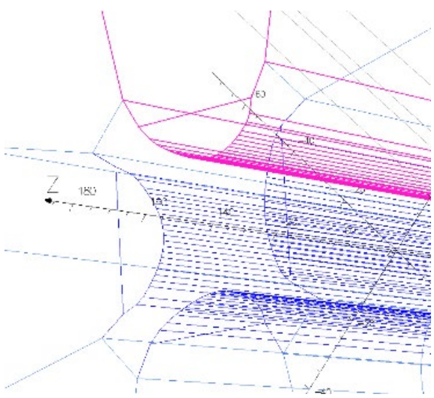

Figure 6: The image of PQM end chamfering

For the optimized model of the PQM, we can see that the central magnetic field gradient of the PQM can be adjusted between 56.28 and 71.6 T/m. The error range of plus or minus 5‰ of the center magnetic field gradient (x=0), as shown by the red and blue lines in Figures 7 and 8, respectively, is regarded acceptable and is also known as the good field area. The good field area was (-8.74, 8.74) mm when the central magnetic field gradient of the PQM reached its maximum value, and it was (-8.89, 8.89) mm when the PQM's central magnetic field gradient reached its minimum value. Fig. 7 and Fig. 8 allow us to visualize the maximum and minimum central magnetic field gradient of the PQM.

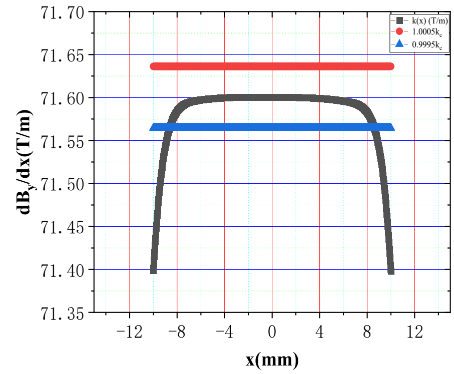

Figure 7: Maximum central magnetic field gradient of the PQM.

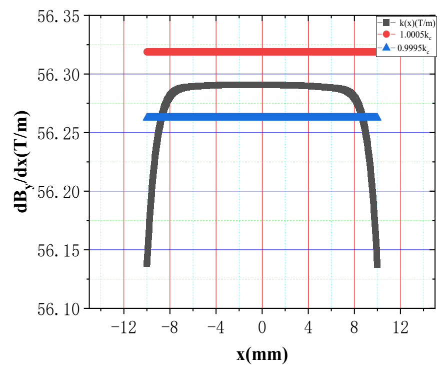

Figure 8: Minimum central magnetic field gradient of the PQM.

CONLUSION

Based on the permanent magnet quadrupole iron, we have developed a permanent magnet quadrupole magnet (PQM) in this paper that has an adjustable central magnetic field gradient to meet a specific set of engineering requirements. And the light source would save operating expenses like electricity and water. The impact of waves and turbulence on particles for using traditional magnets has been optimized to achieve the original design goals. By enhancing the pole head and magnet structure, we will keep enhancing the PQM's performance.

REFERENCES

[1] G. Y. Feng, "Permanent quadrupole magnets based motor control", State Intellectual Property Office of China and CN115426762A, Dec. 2, 2022

[2] Radia, `https://www.esrf.fr/Accelarators/Groups/InsertionDevices/Software/Radia`

[3] Opera, `https://www.3ds.com/products-services/simulia/products/opera`

[4] G. Le Bec, J. Chavanne, P. N'gotta, "Shape optimization for the ESRF II magnets", in Proc. 5th Int. Particle Accelerator Conf. (IPAC'14), Dresden, Germany, 2014, pp. 1232-1234. `doi:10.18429/JACoW-IPAC2014-TUPRO082`