High Gradient Magnetic Separator Design with Hybrid Poles and Increased Efficiency

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In this article, we analyze the efficiency of high gradient magnetic separator (HGMS) designs in terms of efficient use of magnetic energy. Combining analytical analysis and Boundary Element Analysis software, we evaluate the characteristics of quadrupole design, specifically, the magnetic field limits, the energy and gradient distribution, and the design efficiency. To increase the design efficiency, we present a high gradient magnetic separator (HGMS) design with partial soft magnetic steel pole pieces. The use of nearly saturated soft magnetic pole pieces increases the magnetic field in the region of interest. And the use of pole pieces also increases the efficiency of the design. Magnetic separators with and without pole piece are built to evaluate the effectiveness of the pole piece.

***Index Terms*— High gradient; hybrid pole; magnetic energy; magnetic separator; permanent magnets**

2023 IEEE International Magnetic Conference (INTERMAG) | 979-8-3503-3246-9/23/$31.00 ©2023 IEEE | DOI: 10.1109/INTERMAG50591.2023.10265018

I. INTRODUCTION

MAGNETIC CELL SEPARATION IS A VERSATILE TECHNIQUE USED IN SAMPLE PREPARATION FOR DIAGNOSTIC PURPOSES. The technique uses an external magnetic field to efficiently separate the target entity (e.g., bacteria, viruses, parasites, and cancer cells) from a biological sample in order to ease the subsequent task(s) for diagnosis. A review of the principle of the process; equipment; materials and procedures can be found in this reference [1]. A more recent review covers the basic principles of magnetic cell separation and advancement during the last two decades [2]. Gareth Hatch and Richard Stelter presents an overview of the magnetic design considerations for separator design and method of analyzing the magnetic field gradient [3]. The magnetic force is proportional to the volume of the paramagnetic particles [2-3]. High gradient magnetic separation (HGMS) makes possible the increased separation efficiency of particles with lower magnetic volume. Using HGMS helps to increase the ratio of targets collected from a biological sample – low ratio makes it harder to identify the target (which can lead to repeat tests and/or lower diagnosis confidence).

High gradient magnetic separation (HGMS) usually refers to magnetic separators with magnetic field gradient of 10-100 T/m [3]. A commonly used design is presented in US patent 6451207B1[4] assigned to Dexter Magnetic Technologies. It is based on the Halbach structure [5]. The gradient of this design can reach 100 T/m or higher. The device works well on paramagnetic particles less than 0.1μm in size.

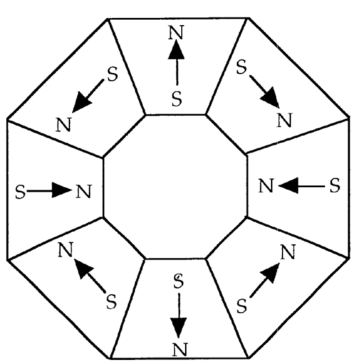

Fig.1, US patent 6451027B1

HGMS are often used in research labs in the form of handheld or tabletop units. Weight and size can be sensitive due to space limitations and cost. Even though increasing the outer diameter [OD] of the structure can increase the magnetic field, the efficiency of the design decreases. An increased distance to the internal cavity, due to a larger OD, limits the extra material's contribution to the field.

To improve the efficiency of the design for higher magnetic field, this paper presents a structure with hybrid pole magnets. This hybrid structure has been used in particle accelerator systems [7-8]. The center pole magnet includes permanent magnet as well as a partial steel pole which has high saturation as a soft magnetic material. This structure can increase the magnetic field in the cavity and efficiency of the design without sacrificing size and weight.

II. THE PRINCIPLE OF THE DESIGN

A. Figure of Merit of Permanent Magnet Design

Permanent magnet design requires designers to develop circuits that can achieve the functional requirements such as magnetic field, magnetic pull force or magnetic torque. Given the limited rare earth resources and supply chain issues on permanent magnets, it is imperative for designers to find good balance between functional performance and efficiency use of permanent magnets.

A good representation of permanent magnet circuit efficiency is the figure of merit on magnetic energy [6]. In a magnetic circuit, the total energy of permanent magnets can be written as:

$$E_m = \frac{1}{2\mu_0}\int B_r^2\, dV_m \tag{1}$$

Where B_r is the residue induction of the permanent magnets used in the circuit. And V_m is the total volume of the magnets.

The total energy in the cavity or functional volume is:

$$E_c = \frac{1}{2\mu_0}\int B_c^2\, dV_c \tag{2}$$

Where B_c is the magnetic flux density in the cavity. And V_c is the total volume of the cavity.

The figure of merit is then defined as:

$$m = \frac{E_c}{E_m} \quad (3)$$

It is apparent that the figure of merit indicates the percent of magnetic energy is used to generate the magnetic field in the cavity.

B. *Quadrupole Magnets from Permanent Magnet Segments*

The design of quadrupole magnets consisting of permanent magnet segments has been described in detail by Halbach [5]. To approximate an ideal quadrupole, a cylindrical permanent magnet is segmented with *M* number of identical segments as illustrated in Fig 2.

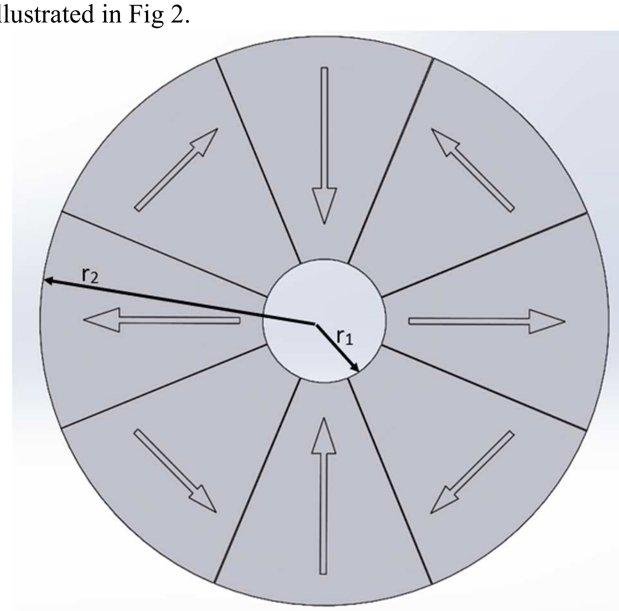

Fig. 2: quadrupole magnet with 8 segments

The direction of magnetization of each segment advances by 6π/M from one piece to the next. The magnetic field inside the cavity is given by Halbach [5] (equation 34). The equation in polar coordinates is shown below:

$$B(r) = 2B_r \frac{r}{r_1}\left(1 - \frac{r_1}{r_2}\right)K \quad (4)$$

where $$K = cos^2\left(\frac{\pi}{M}\right)\frac{\sin\left(\frac{2\pi}{M}\right)}{\frac{2\pi}{M}}$$

K represents how close a segmented quadrupole is to an ideal quadrupole.

Consider the 8-segement quadrupole in Fig.2, the K=0.768468, the magnetic field in cavity becomes:

$$B(r) = 1.536936B_r \frac{r}{r_1}\left(1 - \frac{r_1}{r_2}\right) \quad (5)$$

The maximum magnetic field at $r=r_1$ (pole tip) when $r_2=\infty$ is:

$$B(r) = 1.536936B_r \quad (6)$$

The maximum gradient that can be achieved with an 8-segment quadrupole is:

$$\frac{d(B_r)}{dr} = \frac{1.535936B_r}{r_1} \quad (7)$$

Fig 3 shows the potential maximum magnetic field gradient vs the radius of the cavity using NdFeB 48 MGOe material with Br of 1.37 Tesla. As we can see that, if the radius of the cavity is 20 mm or less, the 8-segment quadrupole with NdFeB 48 MGOe material can achieve 100 T/m or higher magnetic field gradient.

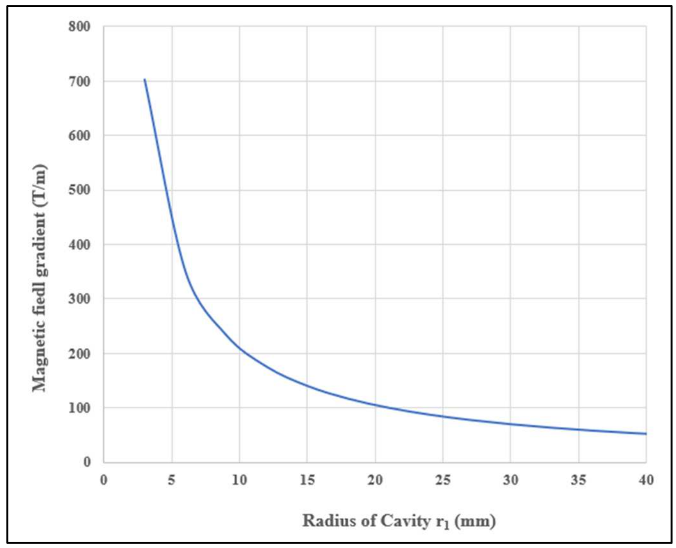

Fig.3, Maximum magnetic field gradient of 8-segment quadrupole vs radius of cavity (with NdFeB 48 MGOe material)

C. *The Figure of Merit of 8-segment Quadrupole*

We use the equation (1) to calculate the total magnetic energy of the 8-segment quadrupole. Since we use the same grade of magnets, the total energy of the magnets is:

$$E_m = \frac{{B_r}^2}{2\mu_0}V_m = \frac{\pi {B_r}^2}{2\mu_0}({r_2}^2 - {r_1}^2) \quad (8)$$

To evaluate the total energy in the cavity, we combine equations (2) and (5) to get the total energy inside the cavity of an 8-segment quadrupole:

$$E_c = 0.5905\frac{\pi {B_r}^2}{\mu_0}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)^2 {r_1}^4 \quad (9)$$

The figure of merit of the 8-segment quadrupole is:

$$m = \frac{E_c}{E_m} = \frac{1.181(r_2 - r_1)r_1^2}{r_2^2(r_2 + r_1)} \quad (10)$$

Substitute r_2 with αr_1, we find the figure of merit is:

$$m = 1.181(\alpha - 1)/(\alpha^2(\alpha + 1)) \quad (11)$$

where $\alpha=r_2/r_1$

Fig. 4 shows the figure of merit plot of an 8-segment quadrupole. The most efficient design is when $\alpha=r_2/r_1=\sim1.5$, corresponding to a peak field at pole tip of just $0.51B_r$. As $\alpha=r_2/r_1$ increases, the magnetic field increases but with decreasing efficiency.

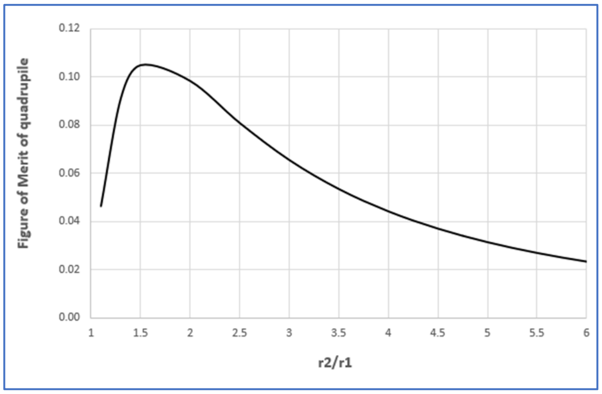

Fig. 4, Figure of merit of an 8-segment quarupole

D. Design with Hybrid Poles

Hybrid poles can be used to increase the efficiency of the quadrupole design for high magnetic field. Such hybrid poles have been used in quadrupole designs for beam control [7-8]. For this bio magnetic separator quadrupole, we use the material CoFe with saturation magnetization at 2.35 Tesla. This is much higher than the 1.37T of the NdFeB 48 MGOe magnet. So, if the CoFe pole pieces can be magnetized close to saturation, the magnetic field and energy inside the cavity will increase. The design also uses less magnet material, resulting in improved efficiency. Fig. 5 shows the same 4-pole magnetic assembly with hybrid poles.

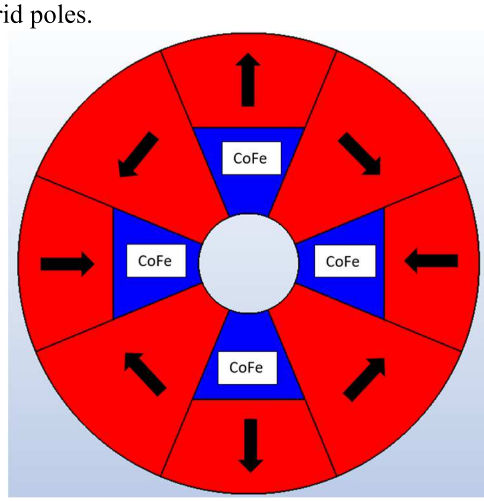

Fig. 5, 4-pole magnetic separator with hybrid poles

To ensure that the CoFe is saturated, we used 2D Inducto software from Integrated Engineering Software to optimize the design. Once the simulation is done, the energy density in the cavity can be plotted as shown in Figure 6. The total energy can be obtained by integrating the energy density plot and then compared to the total energy from the magnets.

Figure 7 shows the figure of merit chart with hybrid pole pieces. The model uses r_2=42.5 mm and r_1=9.25 mm with B_r=1/37 Tesla. The figure of merit without CoFe pole pieces is 0.03685, matching the value calculated from equation (11). The optimized figure of merit with CoFe pole pieces increased to 0.0858. This demonstrates that the total energy in the cavity increased by 90% with less permanent magnet material used.

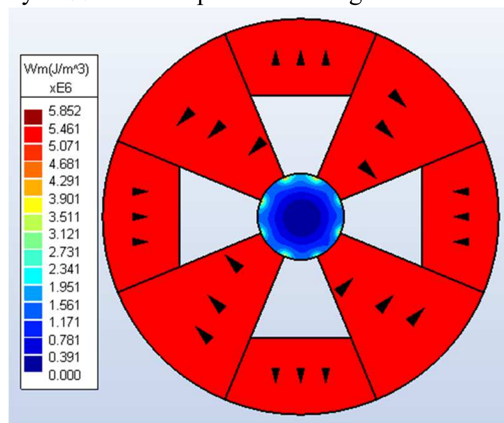

Fig. 6, Energy density plot from 2D Inducto simulation

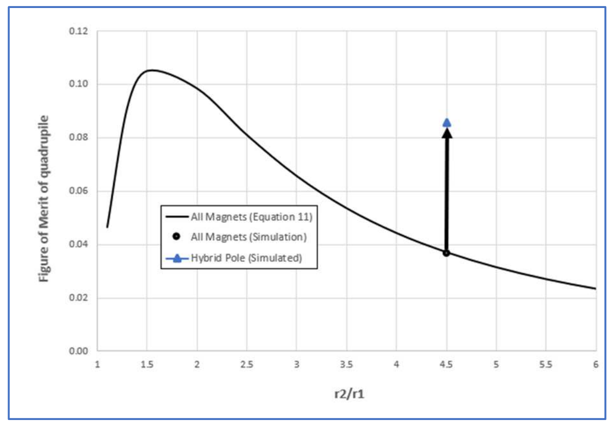

Fig. 7 Improved efficiency with hybrid pole pieces.

III. Experimental Prototype

A. Open Access Magnetic Separator with Magnets only

To test the simulation, an experimental assembly was designed and fabricated with a face that allowed open access and viewing into the cavity. This separator houses a 15 ml tube for collecting biological targets desired. Fig 8 shows the structure and prototype. The design uses 5 magnetic segments with one center pole and two partial side poles. The center pole is a hybrid pole with part of the magnet replaced with high B_s CoFe material. There are no steel poles for the two side pole magnets as the magnetic field at these two side poles is not enough to saturate the steel poles. There is an outer steel sheath to reduce the stray magnetic field. A comparison separator with the same geometry but without a pole piece is also built for comparison.

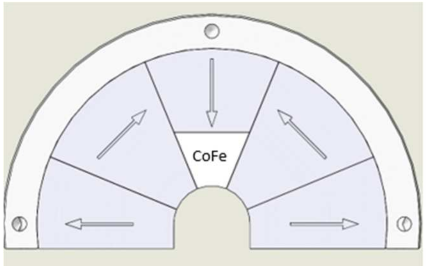

Fig. 8, Magnetic separator with hybrid pole

B. Magnetic Field Comparison

The magnetic field is measured starting from the CoFe center pole face. As shown in Figure 9, the magnetic field of the separator with the hybrid pole is about 6% higher than the separator with only magnets. Table 1 compares the magnetic material used, the magnetic field gradient and magnetic force density. With 6.5% less permanent magnets, the hybrid pole design achieved 8.3% higher magnetic field gradient and 16.5% higher pull force density.

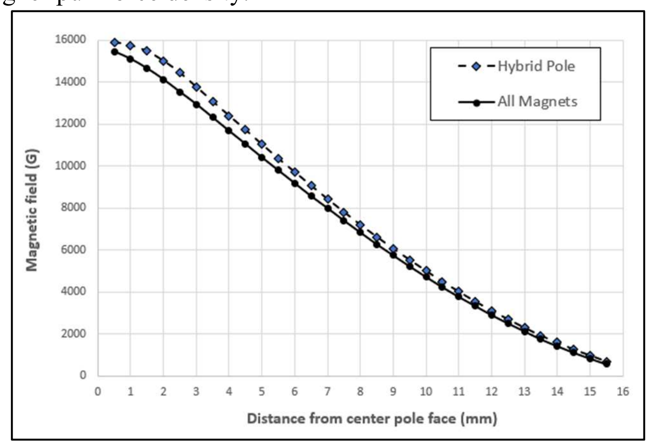

Fig. 9, Magnetic field measurement

Design	Mass of Permanent Magnet (kg)	Peak Magnetic Field Gradient (T/m)	Peak Magnetic Pull Force Density (N/mm^3)
Design without Hybrid Pole	2.322	128	0.127
Design with Hybrid Pole	2.195	138.6	0.148

Table 1: comparison of the two prototypes

IV. Conclusion

This article analyzes the efficiency of HGMS quadrupole structures using figure of merit to characterize the energy projected into the separation cavity. It is shown that high magnetic field quadruple designs are typically not very efficient. Therefore, to increase the efficiency for a high field design, hybrid pole pieces are proposed to replace part of the pole magnets. The 2D Inducto simulation shows that saturated hybrid pole pieces increase the efficiency of quadrupole separator designs. We also built open access separator prototypes, one with all magnets and the other with one hybrid pole for comparison. Our measurement shows that with just one hybrid pole, the design increases the magnetic force density by 16.5% with 6.5% less magnets. This increase in efficiency could lead to more competitive high-performance product in the market.

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