Optimizing the Effectiveness of Magnetic Lenses by utilizing the Electron Optical Design (EOD) Software

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ABSTRACT

This paper introduces a computational analysis that discusses an approach for optimal synthesis in the design of magnetic lenses, specifically focusing on the analytical method. A widely employed approach for magnetic lens design involves utilizing an analysis optimization procedure, which makes use of the finite element method and is supported by Munro programs. In this study, this approach has been employed to explore magnetic lenses using the Electron Optical Design (EOD) software. The study offers insights into the role of the air gap in magnetic lens design, highlighting its importance in optimizing objective and projector properties. The analysis reveals that variations in the air gap (S) significantly influence the performance of magnetic lenses. Decreasing the air gap when it is set to (3) leads to substantial improvements in objective optical properties and focal length. Conversely, increasing the air gap when it is set to (12) enlarges the half-width of the axial magnetic field while reducing the maximum magnetic field value. These findings underscore the importance of carefully optimizing the air gap to achieve desired lens performance. The focal length is determined using this input data and coefficients of aberration (spherical and chromatic) of the objective. The study focuses on the influence of a crucial geometric parameter, specifically the air gap (S), on both objective and projector properties. Its importance stems from its capability to pinpoint the suitable geometry for magnetic lenses, thereby facilitating their efficient application.

Keywords-optimization; EOD; aberration; magnetic lens

I. INTRODUCTION

Optimization has applications in numerous fields, including communication engineering design, supply chain management, financial portfolio management, transportation planning, resource allocation, scheduling, data analysis, and networking [1, 2]. Optimization plays a crucial role in decision-making processes by helping to find the best possible solution given the available information and constraints [3]. Electron lenses hold significant importance within electron microscopes and are widely prevalent in various electro-optical devices. An electron lens exhibits operational drawbacks known as "aberrations," which can negatively impact its performance [4]. Consequently, the presence of these aberrations causes the image to appear either blurred or distorted, leading to a decline in the overall quality of charge particle optical devices [5]. Hence, the inability to achieve an aberration-free lens system has driven the development of methods aimed at mitigating this issue, such as the optimization approach. The designer initiates the process by creating an actual lens design and then computes its optical properties [6]. If the resulting properties do not meet the electro-optical standards, the physical and geometrical parameters of the design are modified accordingly. This iterative process continues until an electron-optically acceptable configuration is achieved. Indeed, the process is repeated in a trial-and-error manner until satisfactory values are obtained. This iterative procedure relies on experimentation and adjustments to refine the lens design and attain the desired electro-optical performance [7]. Optimization by analysis gained significant attention starting from the mid-20th century. Since then, various ideas have been embraced concerning the analysis procedure, including studying the impact of air gap saturation on the focal properties of the objective lens [8]. This approach focuses on analyzing and understanding the lens behavior through theoretical and computational methods to improve its performance, rather than relying solely on trial and error [9]. The current investigation is conducted considering the Electron Optical Design (EOD) program, aiming to design and examine magnetic lenses by varying specific geometrical parameters. The purpose of this study is to explore the effects of these parameter variations on the performance and characteristics of the magnetic lenses used in electro-optical devices [10].

II. THEORETICAL ASPECTS

The importance of a specific aberration is determined by the function of the magnetic lens [11]. In an objective lens, only spherical and chromatic aberrations are significant because the limit of resolution in electron optics is determined by the combined impact of the electrons' spherical aberration and wavelength [12]. Spherical aberration, a primary aberration with significant influence on the lens field, can be calculated utilizing the integral formulation [13]:

$$Cs = \frac{\eta}{128Vr}\int_{zo}^{zi}\left[\frac{3\eta}{Vr}Bz^4 r_\alpha^4 + 8B'^2 r_\alpha^4 - 8Bz^2 r_\alpha^2 r_\alpha'^2\right] dz \quad (1)$$

where e is the charge of the electron, m is the mass of the electron, Vr is the relatively corrected acceleration voltage, Bz is the axial magnetic flux density of the distribution, and rα solves the axial x-ray equation. Throughout this work, the calculation of the chromatic coefficient of aberration has been performed utilizing the integral formulation given below:

$$Cc = \left(\frac{\eta}{8Vr}\right)\int_{zo}^{zi} Bz^4 r_\alpha^4 dz \quad (2)$$

In (2), the parameters used are the same as those utilized in (1). By considering the geometric design parameters S and D, the relative spherical coefficient of aberration Cs/f can be approximated using the expression proposed in [13].

$$\frac{Cs}{f} = 3130Vr^2(NI)^4 \quad (3)$$

III. THE FINITE ELEMENT METHOD AND THE ELECTRON OPTICAL DESIGN SOFTWARE

The Finite Element Method (FEM) is a highly advanced technique employed in analytical procedures for investigating and analyzing electron lenses. In this method, each mesh point is assigned a potential value that is assumed to vary linearly across every triangular finite element. This approach allows for precise and detailed simulations of electron optical systems, enabling in-depth analysis and accurate predictions of their behavior [14]. By combining FEM computations, ray tracing capabilities, and optical analysis, Electron Optical Design (EOD) serves as a versatile software tool for engineers and researchers working on the design, analysis, and optimization of electron optical systems. This integrated approach allows for a comprehensive understanding of how various components within electron lenses and related systems behave and interact with the electron beams. This, in turn, can lead to improved designs, enhanced performance, and more accurate predictions of the system's behavior [15]. The electron-beam system properties were designed and assessed using the EOD program version 3.069, created by Lencová and Zlámal in 2008. The software suite provides a platform for designing, calculating fields, tracing rays, and assessing paraxial properties and aberrations within the design environment [16].

IV. DESIGNING THE MAGNETIC OBJECTIVE LENS

Designing magnetic lenses involves identifying the optimal geometric configuration of electrodes along with their corresponding operational parameters (such as operating voltage, excitation, operating mode, and focal characteristics) [17]. Figure 1 depicts the diagram and geometric measurements pertaining to the upper section of the model introduced in this research. It's apparent that this particular model demonstrates symmetry in relation to specific factors, encompassing attributes like the axial length of the lens (76 mm), the radial width of the lens (60 mm), characteristics of the polepiece, configuration of the magnetic circuit, shape of the coil, cross-sectional area of the coil (1000 mm²), air gap (S = 3 mm), frontal surface of the polepiece (3 mm), and the diameter of the axial bore of the pole (Dp = 10 mm).

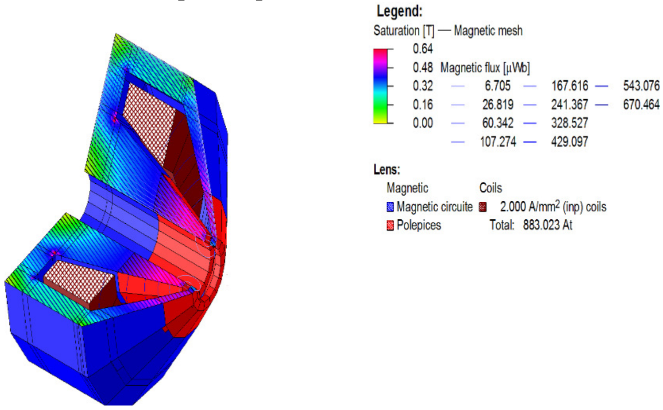

Fig. 1. Geometric diagram of the upper half of the model's dimensions.

V. RESULTS

The influence of the air gap S on the optical characteristics is demonstrated, given its significant impact on the magnitude of the magnetic field. Four different S values were employed, spanning from 3 to 12 mm, Meanwhile, the axial bore D has been maintained at a constant value of D =5 mm.

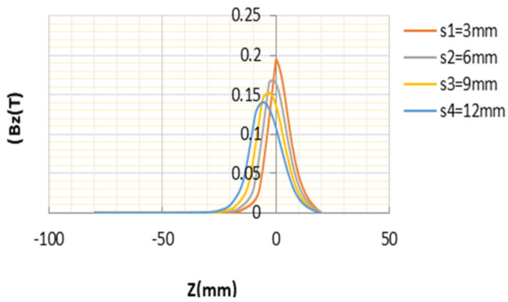

Fig. 2. The distribution of the magnetic field BZ for different S values.

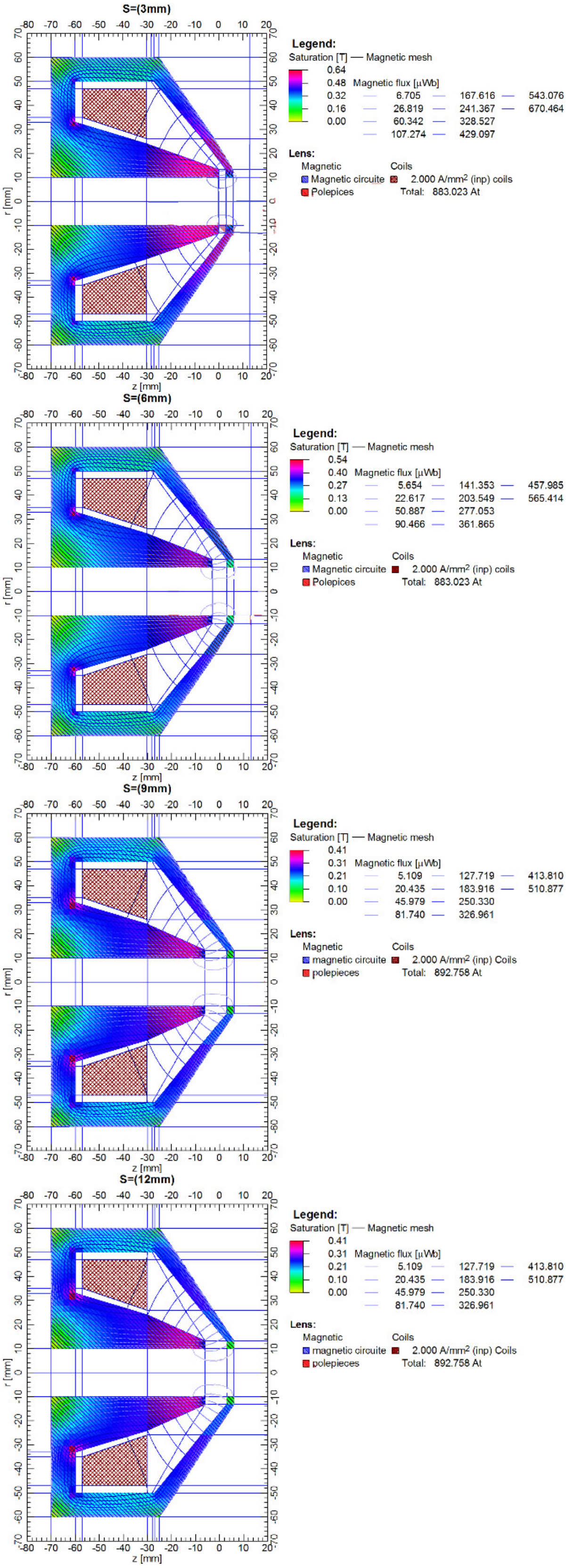

Fig. 3. Geometry of the magnetic lens depicted for various air gap values.

Figures 2 and 3 depict Bz (z) and the geometric configurations corresponding to the various S values, respectively. The observation reveals that as S increases, there is a reduction in the maximum magnetic field strength, Bmax, accompanied by an increase in the half-width, W, of Bz (z).

Figure 4 illustrates the trajectories of electron beams within the lens at varying air gap values. The graph shows that the electron beam's gradient diminishes upon entering the lens field as the air gap values increase. As the air gap between the lens and the incoming electron beams becomes larger, the rate at which the electron beams trajectory changes decreases. As the air gap increases, the magnetic field's half-width also increases. This expansion of the magnetic field affects the way the electrons are deflected within the lens, leading to reduced gradient in the trajectory of the electron beams. This phenomenon stems from the expansion of the magnetic field's half-width (W).

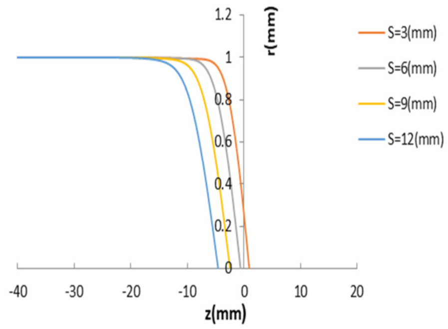

Fig. 4. The trajectories of electron beams within the lens exhibited in curves for various air gap (S) values.

Figures 5-10 display the optical properties of the objective, including the focal length (fo), spherical aberration coefficient (Cs), chromatic aberration coefficient (Cc) and resolving power (δ). These properties are shown as a function of the excitation parameter (NI = 2000 A-t), for various air gap (S) values. It can be observed from the figures that the values of the focal length and aberration coefficients decrease as the excitation parameter increases, across all air gap (S) values. Meanwhile, the resolving power experiences an increase.

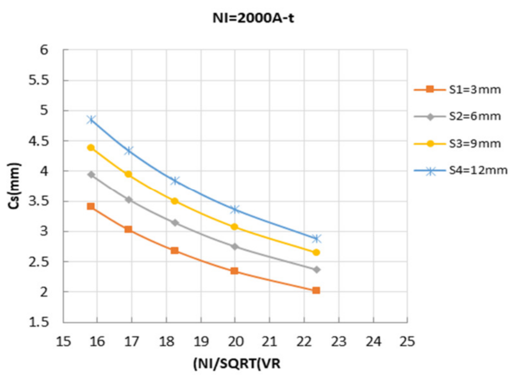

Fig. 5. The change in spherical aberration coefficients (Cs) for varying air gap (S) values under the constant excitation of NI=2000 A-t.

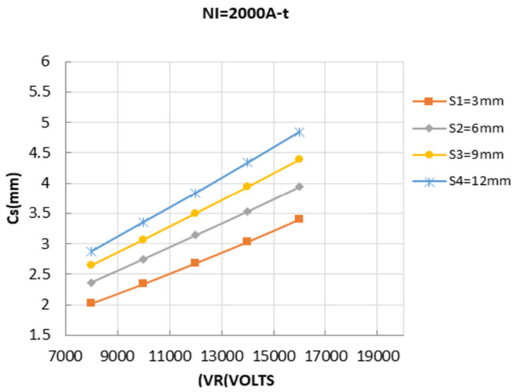

Fig. 6. Spherical aberration coefficients (Cs) under the same excitation (NI=2000 A-t).

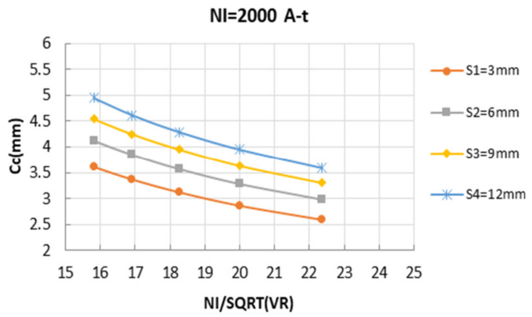

Fig. 7. Curves illustrating the spherical aberration coefficient (Cs) as a function of the excitation parameter for various air gap (S) values.

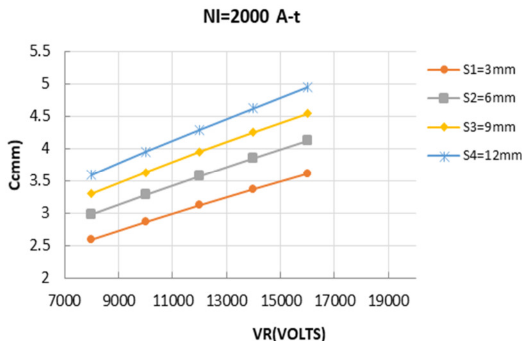

Fig. 8. Variability of the fluctuation of the Cc aberration coefficients (chromatic) under the same excitation (NI=2000 A-t).

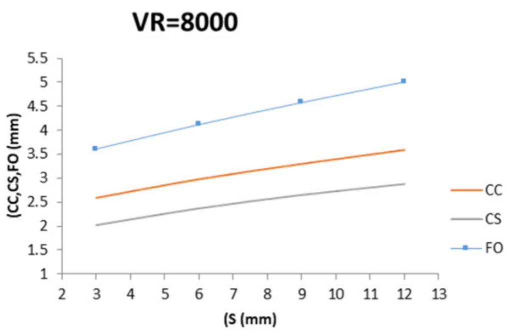

Fig. 9. Curves depicting the focal length (fo) of the objective as a function of the excitation parameter for different air gap (S) values.

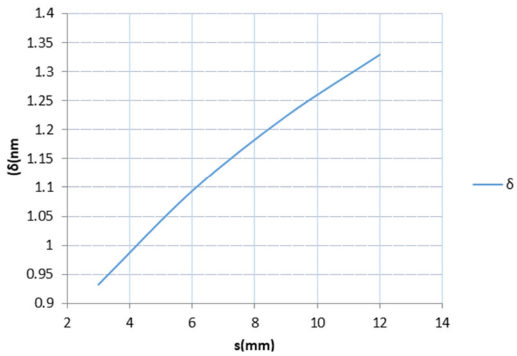

Fig. 10. Change in resolving power (δ) in relation to the air gap (S).

This trend is attributed to the reduction in the appropriately adjusted acceleration voltage (Vr). It is observed that an increase in the air gap (S) values results in elevated values for the focal length (fo), spherical aberration coefficient (Cs), and chromatic aberration coefficient (Cc), while maintaining a constant excitation parameter. This pattern is highlighted in Figure 10 and corroborated by Table I. This behavior can be attributed to the enlargement of the magnetic field's half-width (W). As a result, achieving magnetic lenses with favorable characteristics is feasible by diminishing the air gap (S) values. The resolution power for the lens design under a constant excitation (NI = 2000 A-t), was determined employing the equation:

$$\lambda=\frac{1.23}{\sqrt{VR}} \quad (4)$$

where λ represents the electron wavelength.

TABLE I. OBJECTIVE OPTICAL PROPERTIES FOR THE DERIVED IMAGING FIELDS AS A FUNCTION OF THE PARAMETER S AT NI/√VR=20

S(mm)	Cc(mm)	Cs(mm)	Fo(mm)	Resolving power(δ)
3	2.59	2.02	3.61	0.932
6	2.98	2.37	4.12	1.094
9	3.3	2.65	4.58	1.223
12	3.59	2.88	5.01	1.329

Based on these findings, it is recommended that researchers and engineers carefully consider the air gap (S) when designing magnetic lenses for specific applications. Fine-tuning this parameter can lead to improved objective optical properties and focal length, ensuring that the lens meets the desired performance criteria. Future research should delve into a more detailed characterization of magnetic lenses, taking into account various geometric parameters beyond just the air gap. This comprehensive analysis can provide a deeper understanding of how different design elements interact and impact overall lens performance.

VI. CONCLUSION

This study provides valuable insights into the feasibility of utilizing the EOD program as an effective tool for the design and analysis of objective optical features within the context of magnetic lenses. While the importance of the air gap (S) in magnetic lenses has been acknowledged, the study delves deeper into its role and quantifies its impact on the lens's performance. Based on the analytical approach, the feasibility of employing the EOD program is evident. This program offers high efficiency in the design and analysis of objective optical features for a magnetic lens. The EOD program can be regarded as a valuable tool for obtaining highly accurate optimal designs of magnetic lenses. As indicated by the outcomes in this study, the air gap holds a crucial role in achieving the optimal design of the magnetic lens. The objective focal properties exhibited substantial improvement with the decrease in air gap. Raising the air gap of the magnetic lens results in an enlargement of the half-width of the axial magnetic field, simultaneously causing a reduction in the maximum magnetic field value. Increasing the air gap of the magnetic lens results in a decline in the slope of the electron beam trajectory upon its entry into the lens. The outcomes of the research demonstrate the critical significance of the air gap (S) in achieving optimal magnetic lens performance. By varying the air gap, we were able to substantially improve the objective focal properties, underscoring its importance in lens design.

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