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Influence of the Geometrical Configuration of the Iron Shroud on the Optical and Magnetic Properties of the Monopole Symmetric Objective Magnetic Lens

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ABSTRACT

This study investigated the effect of varying the geometric configuration of the iron shroud on the magnetic and optical properties of a magnetic lens. The study compared three novel designs of monopole symmetric object magnetic lenses, differing only in the geometry of the iron shroud. The axial magnetic flux density distribution was calculated using Electron Optical Design program. The results indicated that maximum magnetic flux density increases with a decrease in the air gap width, accompanied by a reduction in half-width value. It was found that one of the proposed designs provides an optimal distribution of magnetic flux lines, with no leakage of magnetic field lines outside the pole region. The optical focal properties of lenses were studied using a program based on Finite Element Method to calculate magnetic field distribution, while the optical properties of electromagnetic lenses were analyzed using Optical Properties Program for Electron Magnetic Lenses. The findings revealed that one of the proposed lenses offers the best magnetic and optical properties. A novel and unprecedented magnetic lens design was invented for the first time. The proposed design is distinguished globally by the protrusion of the pole tip into lens structure, Referred to as the Snub Lens.

Keywords: Electronic optics, Monopole magnetic lenses, Spherical aberration, Chromatic aberration, Resolving power.

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تأثير الشكل الهندسي للذراع الحديدي على الخواص المغناطيسية والبصرية للعدسة المغناطيسية الشيئية المتناظرة احادية القطب

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قسم الفيزياء، كلية العلوم، جامعة تكريت، تكريت، العراق

الملخص

تتناول هذه الدراسة تأثير تغيير التكوين الهندسي للغلاف الحديدي على الخصائص المغناطيسية والبصرية للعدسة المغناطيسية. تم مقارنة ثلاثة تصاميم جديدة لعدسات مغناطيسية أحادية القطب متناظرة، تختلف فقط في هندسة الغلاف الحديدي. تم حساب توزيع كثافة التدفق المغناطيسي المحوري باستخدام برنامج التصميم البصري الالكتروني. أشارت النتائج إلى أن القيمة القصوى لكثافة التدفق المغناطيسي تزداد مع تقليل عرض الفجوة الهوائية، مصحوبة بانخفاض في قيمة العرض النصفي. وُجد أن أحد التصاميم المقترحة يوفر توزيعًا مثاليًا لخطوط التدفق المغناطيسي، مع غياب تسرب خطوط المجال المغناطيسي خارج منطقة الأقطاب. تمت دراسة الخصائص البؤرية البصرية للعدسات باستخدام برنامج يعتمد على طريقة العناصر المتناهية لحساب توزيع المجال المغناطيسي، بينما تم تحليل الخصائص البصرية للعدسات الكهرومغناطيسية باستخدام برنامج الخصائص البصرية للعدسات المغناطيسية الإلكترونية كشفت النتائج أن أحد التصاميم المقترحة يحقق أفضل الخصائص المغناطيسية والبصرية. تم ابتكار تصميم جديد وغير مسبوق لعدسة مغناطيسية لأول مرة. يتميز التصميم المقترح عالميًا ببروز طرف القطب داخل هيكل العدسة، ويُعرف هذا الابتكار باسم (العدسة الخنساء).

INTRODUCTION

The fundamental part of all charged particles instruments is the electron lens, which are instruments that concentrates a moving beam of charged particles such as electrons, into a single point. The photo lens concentrates light beams into a single point along optical axis, much like the human eye or a converging glass lens [(1)]. There are three types of electron lenses: permanent magnetic lenses, magnetic or electromagnetically induced lenses, and electrostatic lenses[(2)]. The electromagnetically induced lens, often the most crucial component of electron microscopes, is one of the most popular types of electron lenses [(3)]. The most basic kind of magnetic lens is an axial circular coil without iron, although most have iron and poles. Therefore, magnetic lenses vary from ordinary lenses in that they concentrate electron beam that travels through them by generating a magnetic field inside a coil through the passage of an electrical current. Another significant advantage of electron lenses is their excellent resolving power, which is achieved without the need for large voltages. They are more adaptable than permanent magnets because coil's number of turns or the current passing through it can be adjusted to alter magnetic field's strength [(4)]. Magnetic lenses are instruments that create a strong magnetic field in a tiny space. Magnetic lenses can be classified into a variety of types according to the number of poles in the lens design. For instance, there are four types of magnetic lenses: iron-free, unipolar, dipole, and tripole [(5)]. Mulvey's invention of the monopole lens in 1972 was a major advancement in electron lens design. Splitting a dipole lens in half yields two lenses, each with a single pole that can be truncated, spherical, conical, or cylindrical, among other geometric shapes [(1)]. In dipole lenses, magnetic field is contained between two poles, while in monopole lenses, the dual-pole structure is eliminated. These lenses are characterized by the pole protruding outside of their surface, which causes the axial magnetic field to curve away from the lens structure depending on the distance of pole. This design allows the sample to rotate more freely around its axis than dipole lens [(6)]. The optical properties of unipolar and dipole lenses differ due to their distinct magnetic field distributions. The electron beam in a unipolar lens can move through the lens either slowly or rapidly to reach magnetic field. The aberrations in this lens are independent of the direction in which electron beam enters the field. Rather, the favored orientation is determined by the particular use of objective lens in electron microscope. Numerous studies have been conducted to optimize the design of magnetic lenses, highlighting the crucial role that each parameter plays from both a theoretical and practical standpoint the open structure of the flux lines in monopole lens maximizes the intensity of axial magnetic field by concentrating at the pole face and then diverging before entering the iron core [(7)]. The current research focuses on the geometric shape of the iron Shroud by proposing new designs for magnetic objective lenses and investigating their focal properties to achieve the optimal iron arm shape, which minimizes aberrations and maximizes resolving power when the lens is operated.

THEORETICAL ASPECTS

The route of moving electrons inside electromagnetic field of any optical system, including electron lenses, is investigated in the discipline of charged particle optics. The design and functionality of such optical devices are based on this research [(8)]. When designing and optimizing charged-particle optical systems, computational simulations are essential because they make it easier to estimate performance precision before construction. As a result, significant time and money are saved [(9)]. The fact that electron lenses characteristics depend on a wide range of geometric and physical factors makes it difficult to build particular geometric configurations for these lenses with incredibly low aberration coefficients. Optimization is the process of attaining the intended physical and geometric design with the fewest possible deviations. The Analysis method and the Synthesis method are two different optimization techniques. Based on the idea of trial and error, the analysis method is a conventional technique for designing electron lenses [(10)]. This approach was used in the current study to build a monopole magnetic lens utilizing the EOD software, which uses the Finite Element Method (FEM) to compute potential and magnetic field of any magnetic lens using numerical analysis. FEM is a crucial method for resolving complex differential equations that is frequently employed in physical sciences and engineering fields [(2)] . This cutting-edge method is widely used in analytical procedures to examine and evaluate electron lenses. Each point in the mesh is given a potential value in this method, which is assumed to vary linearly over each triangular finite element. This technique makes it possible to simulate electronic optical systems in a very detailed and accurate manner, allowing for in-depth study and accurate behavior predictions [(11)]. One of primary determinants of the quality of charged-particle optical instruments is aberrations in this branch of science which are characterized as the inability of an optical system to focus a beam of charged particles released from a single point in the object plane onto a single point in the image plane. Images are distorted or unclear as a result of these flaws. The purpose of the optical system determines the relevance of each aberration. The two main factors that determine the quality of the images that magnetic lenses create when employed as objective lenses in a scanning electron microscope are chromatic and spherical aberration [(12)]. A low-aberration magnetic electron lens's ideal design is crucial in many electronic optics applications. In order to create high-quality photographs, this focus primarily seeks to minimize aberration values. But it has been discovered that low-aberration magnetic electron lenses need a low full-width at half-maximum (FWHM) and a high flux density [8]. One kind of geometric aberration that depends on the design of the lens and the degree of excitation is spherical aberration. One of the most noticeable aberrations in objective lenses, it degrades image quality and is crucial in establishing the electron microscope's resolving capability. The reason for this aberration is that after traveling through the lens, rays from a point object form a blur disk rather than converge to a single point. The following connection provides the spherical aberration coefficient [12].

$$C_s = \frac{\eta}{128V_r}\int_{z_0}^{z_i}[\frac{3\eta}{V_r}B_z^4 r_\alpha^4(z) + 8B_z'^2 r_\alpha^4(z) - 8B_z^2 r_\alpha^2 r_\alpha'^2(z)]dz \text{.......(1)}$$

The distribution of axial magnetic flux density is shown by (B_Z) the equation of axial rays under initial conditions is solved by r_α, and the parameter η is the ratio of electron's charge to mass. The varying energies of charged particles (like electrons) cause chromatic aberration. Different particles have different focal points because particles with higher energy (i.e., higher velocity) focus farther away than particles with lower energies (i.e., lower speeds). Chromatic aberration in electron lenses cannot be totally eliminated, but it can be lessened by lowering voltage fluctuations, particularly by making sure the voltage source is high-stability in order to provide a monochromatic beam with high wavelength stability. in addition to a steady current flowing through coils. The following connection provides the chromatic aberration coefficient [5].

$$C_c = \frac{\eta}{8V_r}\int_{z_0}^{z_i} B_z^2 r_\alpha^2(z)dz \text{ ....(2)}$$

Scherzer, a researcher, proved in 1936 that chromatic and spherical aberrations cannot be corrected at the same time. Because of this, no optical system is totally free of aberrations, but they can be minimized as much as feasible. One characteristic of an electron lens or microscope is its resolving power, which is the lens's capacity to create two separate images of two spots on the material. A lens cannot create distinct images of two nearby locations on the specimen if their spacing is less than the resolving limit because the diffraction phenomenon naturally limits resolving power. The following relation [13] provides this limit, which is known as the critical distance.

$$\delta = \frac{k\lambda}{n\, sin\theta} \text{ ....(3)}$$

In this case, δ stands for the resolving power, K is a resolving power-related constant, λ is the wavelength, and (n sinθ) is the numerical aperture, where θ is the angle of the beam's half-cone. Furthermore, the shape of the aperture determines K, and n is the refractive index of the medium between lens and the specimen. K is equivalent to (0.61) for a circular aperture. This suggests that electron microscope's resolving power is dependent on both the wavelength and the numerical aperture the following equation [11]. The following relation is the equation for resolving power when the wave path difference is less than or equal to (λ/4) [14].

$$\delta = 0.61(C_s\lambda^3)^{1/4} \text{.........(4)}$$

PRACTICAL PART

Three novel designs of symmetric monopole objective magnetic lenses were developed, each with a different iron shroud shape while keeping the other geometric parameters the same, in order to achieve the best possible magnetic and optical properties for objective magnetic lenses. The aim was to find the optimum design among the configurations studied. These designs were named L_1, L_2 and L_3. The first design, designated L_1, has a vertical iron arm that is positioned (S = 8 mm) from the pole tip. The second design is represented by L_2, where the iron arm is angled toward the pole tip and placed (S = 2 mm) away. The third design, denoted by L_3, keeps all other geometrical parameters same while positioning the iron arm in the opposite direction of the pole tip, at a distance of (S = 18 mm). EOD software, which is based on the first-order Finite Element Method (FOFEM), was used to investigate the impact of changing the geometry of the iron shroud on the distribution of magnetic flux density for the suggested lenses.

RESULTS AND DISCUSSION

After proposing several designs for unipolar magnetic lenses and studying their magnetic and optical properties, as well as the trajectories of magnetic flux lines using the aforementioned computational programs, the following results were obtained, as illustrated in Figure (1)., which displays the findings of this investigation, axial magnetic flux density (B_Z) was computed with excitation remained constant at (NI = 3000 A.t) and a current density of (2 A/mm²). With its angled shroud toward the pole tip and a distance of' (2 mm) from the pole, the L_2 lens clearly provides the largest and sharpest peak of axial magnetic flux density with a smaller half-width of field, as seen in this picture. Additionally, it is noted that axial magnetic flux density rises and field's half-width falls as the iron shroud approaches the pole tip and the distance between them reduces. Since the distance between the pole tip and the iron arm is crucial to the distribution of magnetic field, three curves' different half-widths are explained by these differences. Additionally, magnetic field peak decreases and curves' half-width increases as the distance in this area increases. Studying and comprehending the behavior of lens, evaluating optical performance of each component, and spotting any magnetic flux leakage in lens structure all depend on distribution of magnetic flux lines in the magnetic lens structures. Magnetic flux lines were also plotted using (EOD) software, with excitation set at (NI = 3000 A.t) and a current density of (2 A/mm²). Magnetic flux density points at each location inside the lens are shown by these lines. The magnetic flux lines for the suggested magnetic lenses are displayed in Figure (2), along with color-coded 2D representation of these lines at excitation (NI = 3000 A.t) and current density (2 A/mm²).The trajectory of the electron beam leaving the lens aperture is directly impacted by the magnetic field force created by concentrated magnetic flux lines for (L_2) lens around the pole tips, as seen in Figure (2). As a result, lens's optical qualities are significantly improved. Additionally, it is noticed that L_2 lens does not exhibit flux leakage outside of the pole region, in contrast to the other suggested lenses that are being examined. After examining the axial magnetic flux density distribution (B_Z), this finding can be regarded as an additional favorable signal. This result is still insufficient, though, to identify the best design among suggested lens configurations. To choose the preferred lenses design among lens designed in this work at this point in the project, the next step will be to examine the optical characteristics of each suggested lens, such as the focal length, chromatic and spherical aberrations, and resolving power; For each of the proposed lenses, an evaluation will be conducted to select optimal lens for this part of work.

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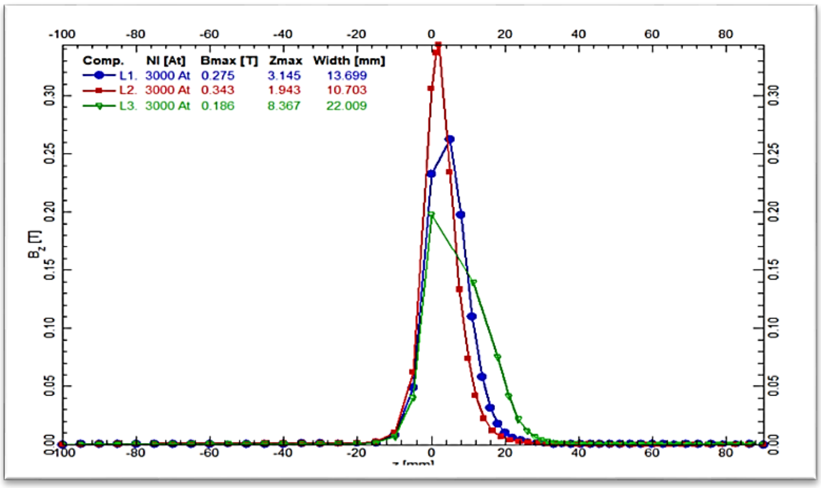

Fig. 1: Axial magnetic flux density (B_Z) distribution as a function of distance (Z) for suggested magnetic lenses with various iron shroud geometric configurations, at a fixed current density of (2 A/mm²) and a constant excitation value of (NI = 3000 A·t)

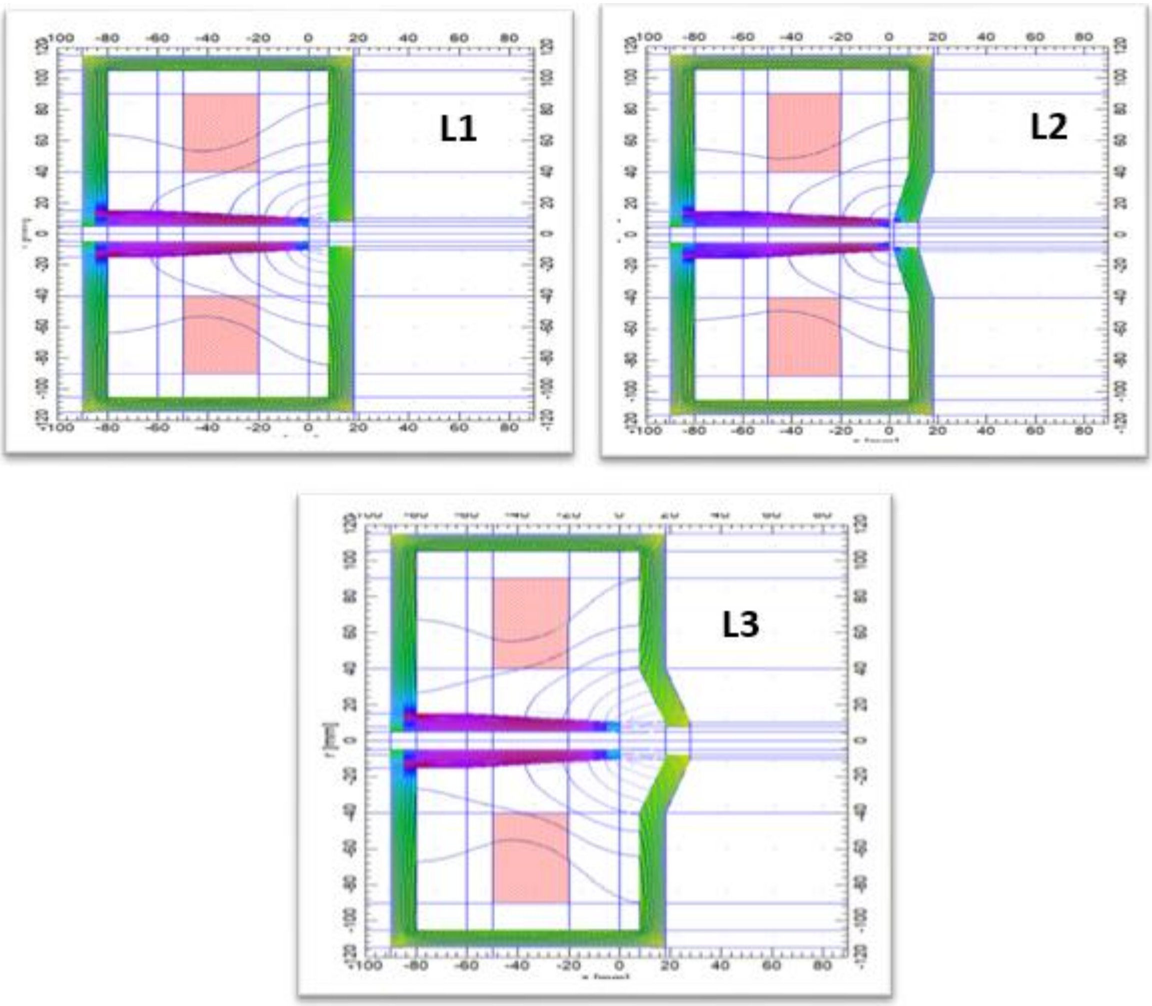

Fig. 2: Magnetic flux lines of magnetic lenses with various iron shroud arrangements.

Additionally, the impact of changing the iron shroud geometrical configuration on suggested objective magnetic lenses' characteristics was examined. focal length, resolving power, and chromatic and spherical aberration coefficients were computed. With a constant excitation of (NI = 3000 A.t) and a fixed current density of (2 A/mm^2), Figure (3) shows the relationship between these variables as a function of the relativistic ally corrected acceleration voltage of lens. As seen in Figure (3a) it was discovered that the L2 lens offers the lowest focal length. Additionally, as seen in Figures (3b) and (3c) respectively, L_2 produces the lowest values for the chromatic and spherical aberration coefficients. Additionally, as seen in Figure (3d) L_2 demonstrated a minor increase in resolving power. These findings imply that when the iron arm's geometric structure is oriented toward the pole, the magnetic lenses' optical qualities improve. With the L_2 lens having an air gap width of (S = 2 mm), this arrangement results in a reduction in the air gap's width and produces the highest optical qualities, as seen by the lowest aberration values. These results are consistent with the results, which showed that the distribution of magnetic flux density and optical properties are significantly affected by the value of the air gap, where the lens with the width of air gap (S = 3 mm) achieved the best results. Although they used a snorkel-type lens we proposed a new, unscrewed design. and the results were achieved using EOD program [10]. This lens is used as an objective lens for focusing an electron beam in a scanning electron microscope. This means that by shortening the distance between the Iron shroud and the tip of the electrode, high-performance objective magnetic lenses can be produced. The peculiarity of this research is that this design is considered innovative because it is customary for the lens nose (the pole head of the lens) to be pushed back by different values depending on the type of lens and the purpose of its design. In this study, the head of the electrode was proposed inward for the first time, therefore, this innovative lens was called the (Snub lens). After the L_2 lens was chosen as the best lens among the proposed designs, it was manufactured locally using iron as the base material for the lens structure, because it is cheap and available in local markets and gives desirable Wicker, and the design was made in a way that facilitates the operation process when manufacturing the lens. With good magnetic and optical specifications, as well as the ability to work with low effort, this is also a desirable feature. The optical characteristics of three suggested magnetic lenses with various iron shroud end configurations were compared in Table (1) at a fixed current density of (2 A/mm²) and a constant excitation of (NI = 3000 A·t) over a range of relativistic ally corrected acceleration voltages (V_r = 1000 V to 33500).

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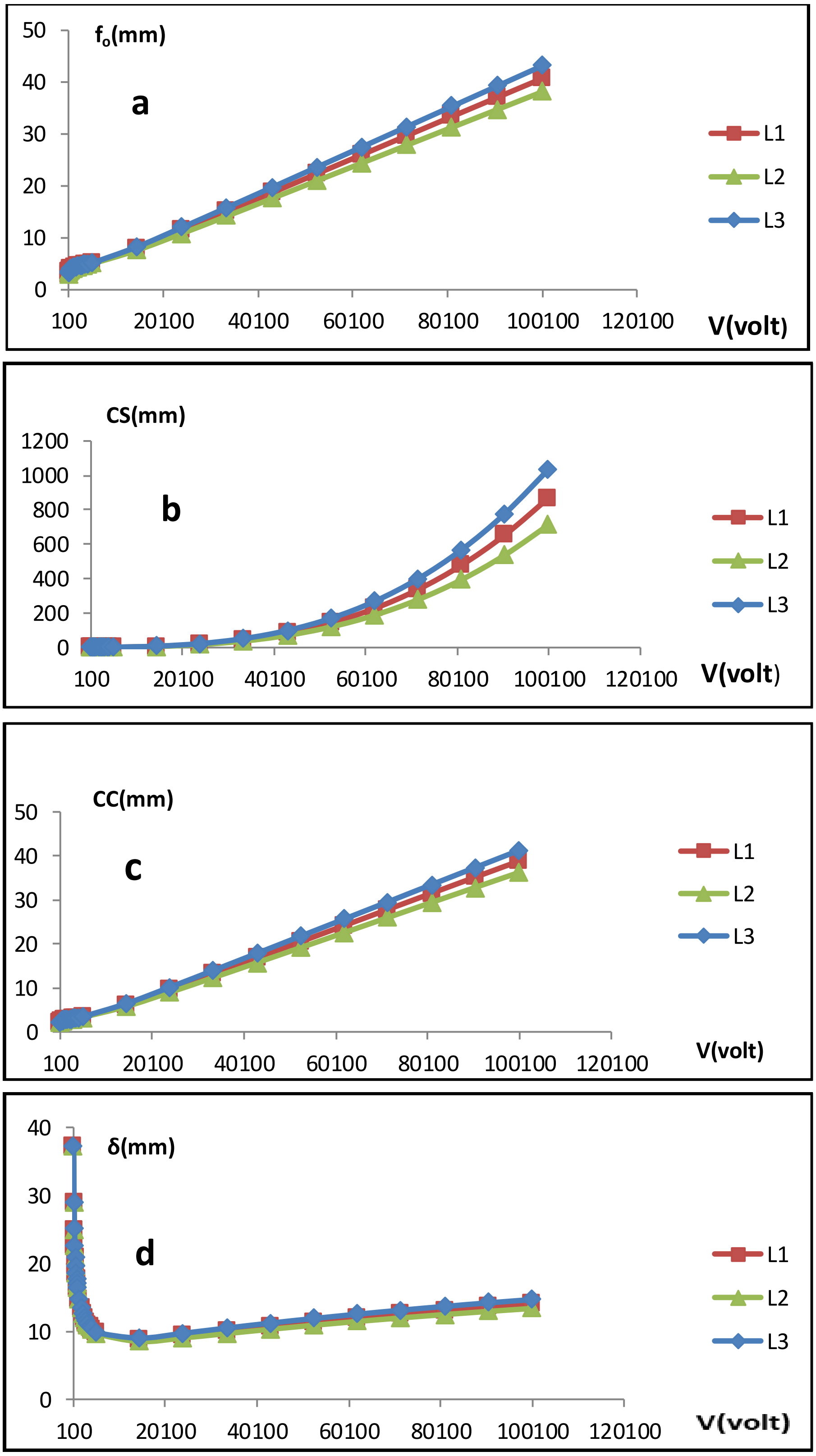

Fig. 3: Change of focal optical properties (a) Spherical aberration (CS), (b) Chromatic aberration (CC),(c) focal length (fo), (d) Resolving power (δ) as a function of relatively corrected acceleration voltages (V_r) of proposed magnetic lenses at constant excitation capacity (NI = 3000 A.t) and a constant current density of (2 A/mm2).

Table 1: Summary of the comparison of the optical properties of the three magnetic lenses of different shapes of the proposed Iron shroud end at a range of relatively corrected acceleration voltages (Vr = 1000V-33500V) and at constant irritation (NI=3000A.t) and constant current density (2 A/mm2).

Lens No.	S (mm)	V_r (kV)	f_o (mm)	δ (nm)	C_s (mm)	C_c (mm)
L1	8	1000	4.13	16.3616	1.6	2.73
		2500	4.54	11.9505	2.97	1.8
		4000	4.84	10.3379	2.04	3.21
		33500	15.02	10.094	44.94	13.2
L2	2	1000	4.1	16.33596	1.59	2.71
		2500	4.5	11.91716	1.78	2.94
		4000	4.78	10.27392	1.99	3.16
		33500	14.17	9.67623	37..95	12.35
L3	18	1000	4.16	16.41247	1.62	2.74
		2500	4.56	11.98355	1.82	2.99
		4000	4.89	10.40062	2.09	3.25
		33500	15.82	10.48054	52.23	13.9

CONCLUSION

The magnetic and optical properties of an electromagnetic lens are greatly influenced by the shape of its iron shroud, so designers must carefully consider how best to configure it depending on the intended application. In this study, it was found that choosing the correct geometric configuration for the iron shroud and its position in relation to the pole tip of the lens significantly improves magnetic properties after analyzing all magnetic and optical properties under fixed current density and constant excitation and seeing the notable changes in these properties with each modification to the shape of the iron shroud. The highest peak of axial magnetic flux density with a smaller half-width reflects this. Furthermore, optical characteristics are improved, as demonstrated by enhanced resolving power and lowest spherical and chromatic aberration values. Additionally, magnetic flux leakage outside lens structure is minimized by optimizing distribution of magnetic flux lines, which are centered between the iron shroud and pole tip.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this research.

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The research was self-funded by the primary author.

Author Contribute

The first author (primary researcher) collected research data, analyzed and interpreted the results, while the second author contributed, by supervising the research and assisting in research-related activities.

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