



A theoretical investigation for bi-gap magnetic lenses distortion

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Abstract

A theoretical computational analysis was carried out to determine whether it is possible to create bi-gap magnetic lenses that do not generate spinning and have the least amount of distortion possible. The gap thickness S and the aperture diameter D are two ideal geometric variables that are essential to the operation of a novel type of function. The variable irritation of the imaging field, denoted by NI , is fixed to make assessment of optical qualities easier. On the other hand, the variables S and D are essential for magnetic lens design, which enables the acquisition of images that demonstrate rotation. By selecting the appropriate settings for the ratios between the aperture of the lens and its gap, the distortion amount that occurs may be limited.

Introduction

The display system comprises two primary lenses, with the second lens rectifying the band distortion caused by the first lens. By employing a comparable approach, the monopolar lens allows several researchers to rectify radial distortion and achieve a minimal value of spiral distortion [1]. To develop a system that generates pictures with little low rotation and minimal radial and spiral distortion, a corrected lens utilized. Numerous researchers [3] have developed a three-pole lens featuring an irregular axial aperture designed to deliver undistorted and non-rotational pictures at a designated working point. There are further entities as well. All of these studies employed the optimum analysis methodology. Numerous studies have employed the fitting method; nevertheless, the majority address object faults in magnetic lenses while neglecting projection problems. In addition to the minor subset mentioned in both [5] and [6], other studies have investigated alternative designs, such as the Runge–Kutta method, in numerical solutions, as in [7, 8].

Some researchers have developed a computer tool to design electrostatic lenses in addition to magnetic lenses, as in [9]. Other studies have shown the properties of the bipolar magnetic lens mentioned in [10, 11] and others mentioned in [12]. In the present research, our goal was to find and manufacture a magnetic lens via a previously defined analytical function. For this reason, similar studies are rather rare; given the importance of the projection, system in this type of triple lenses in electron microscopy employed. that lens type generates images exhibiting rotational, radial, and spiral distortions, enabling the elimination of the two primary flaws associated with projection lenses. The significance of altering the specific optimization variable arises from the function applied to the physical and geometric characteristics of this lens type

Double-Pole Piece Lens

Bipolar magnetic lenses are the most widely used magnetic lenses. These lenses consist of a coil surrounded by a high-permeability iron circle with two electrodes usually made of wrought iron at its axis. The electrodes penetrate a circular hole with a diameter D to allow the passage of the electron beam along the axis of the coil. The magnetic field generated between the two electrodes is confined to an air gap separating these two electrodes with width S . When the diameter of the aperture for both poles is equal, the magnetic field of the lens is symmetrical, and the lens becomes symmetrical, as shown in Figures (1-3). The optical properties of this type can be expressed in terms of the ratio between the width of the air gap S to the aperture diameter D (i.e., S/D), and when the two pole apertures are not equal, the lens becomes asymmetrical, as shown in Figure (1-6), and the optical properties are expressed in terms of the ratio between the width of the air gap S to the ratio of the diameter of the two apertures D_m (i.e., S/D_m , as $D_m = (D_1 + D_2)/2$).

The magnetic lens has a group of defects called aberrations, which are considered one of the basic factors determining the quality of the optical system, as the values of these aberrations must be reduced to a minimum. Definition of aberration as the failure of a lens to focus the charged particle beam emitted from one point in the object plane to one point in the Gaussian image plane.

The beam is emitted with a certain energy from an electron or ion source and enters the field of the lens, which focuses it at the image location (Gaussian or axial zoom). This point image cannot be obtained, as a disc will be formed resulting from different paths as a result of the geometric or color aberrations of the lens. Geometric aberrations arise when deviation from the ideal image (Gaussian image) occurs when the electron speed is constant. Chromatic aberration arises from the interaction of the beam with the material (pattern) in the optical–electronic system, which changes the speed of the electrons and causes distortion in the image. Chromatic aberration also occurs when the accelerating voltage and coil current are not completely stable.

Relativistic aberration appears when electrons are accelerated at a high speed. Another type of aberration is space–charge aberration, which arises from the force of repulsion between electrons. The asymmetry aberration arises from asymmetry as result of the optical system built incompletely.

Since the beginning of the development of electronic optics, several attempts have been made to eliminate or reduce these aberrations. Therefore, some lens aberrations can be almost negligible, such as asymmetry aberrations, vacuum charge aberrations, relative aberrations, and some geometric aberrations. Other aberrations can correct, such as spiral distortion [10] and radial distortion [12].

The impossibility of correcting both spherical and chromatic aberrations proven in 1936, and this is what Scherzer proved. Accordingly, there is no optical system free of aberrations; rather, they can be reduced to the minimum possible extent. This result led to what is called optimization, the aim of which is to determine the geometric shapes of the electric and magnetic poles that reduce the optical-electronic aberrations of the system [13].

Analytical and synthesis design are two completely different approaches to optimal design. For the analytical design, the designer begins by changing the magnetic, electrical, or engineering parameters of the system to arrive at an acceptable design for the system under certain conditions. If there is an appropriate guess for the design, this design gives appropriate results [13]. It is also a good way to improve designs, but it is slow.

The synthesis design, which is called the inverse design, is based on the fact that the first-order properties and aberrations of an imaging field are completely determined by some axial functions, such as voltage, flux density distributions, and paths, in the case of axial symmetry. These distributions appear in the paraxial ray equation and in the formulas of the aberration coefficients. Accordingly, a designer can set a standard in which the optical system is defined as initial conditions and can find the distribution of the imaging field that meets this standard instead of analyzing many different polar shapes. In the final stage, the shape of the true pole (electric or magnetic pole) is found, which generates the field distribution [13].

The present study seeks to synthesize bi-gap magnetic lenses utilizing preprepared analytical functions. This lens type is employed to generate images free from rotation as well as radial and spiral distortions, thereby addressing the two main shortcomings linked to projection lenses. The importance of modifying a specific optimization variable is linked to the impact of the objective function on the physical and geometric characteristics of the lens.

In **radial distortion**, the radial distortion coefficient D_r is calculated via the following integration [12, 14]:

$$D_r = \left(\frac{\tau}{130V_r} \right) \int_{z_1}^{z_2} \left(\frac{3\tau}{V_r} B_z^4 + 8B_z^2 \right) r_\alpha r_\gamma^3 - 4B_z^2 (r_\gamma^2 r_\alpha r_\gamma + r_\gamma r_\gamma^2 r_\alpha) \dots (1)$$

In eq. (1), (r_α) and (r_γ) are independent linear solutions of the axial beam equation.

z_1 and z_2 are domain boundaries.

In **spiral distortion**, the helical distortion coefficient can be expressed by the following formula [12, 14]:

$$D_s = \int_{z_1}^{z_2} \left[\frac{3}{130} \left(\frac{\tau}{V_r} \right)^{1/2} r_\alpha^2 B_z \right] dz \dots \dots (2)$$

From eq. (2), it is clear that (D_s) can be determined if (r_α) , (B_z) and their derivatives are known. In this work, I also used Simpson's rule to find the spiral distortion coefficient.

THEORETICAL ASPECTS

Our theoretical research entails computing Laplace's equation, subsequently differentiating the voltage concerning z , and multiplying by the permeability of free space. From this, we can infer the field distribution on the basis of the voltage distribution. The resulting link [10]:

$$\int B_z(r, z) = B_z(0, z) - \frac{r^2}{4} \ddot{B}_z(0, z) + \frac{r^4}{64} \ddot{B}_z(0, z) + \dots (3)$$

In this study, an objective function used with optimization variables representing the geometric and physical properties of conventional magnetic lenses, as shown in the relationship in [10]:

$$B_z(z) = NI\mu \left[\frac{z + \frac{s}{2}}{\sqrt{\left(\frac{D}{3}\right)^2 + \left(z + \frac{s}{2}\right)^2}} - \frac{z - \frac{s}{2}}{\sqrt{\left(\frac{D}{3}\right)^2 + \left(z - \frac{s}{2}\right)^2}} \right] \dots (4)$$

EFFECT OF VARIABLE (D)

In the Doublet Lens, Influence of the Axial Bore, in this section, the geometric and physical data for both the first and second single lenses are determined in a manner very similar to what is done in the case of studying the thickness of the air gap, except that the variable in this case is D_2 and not S_2 . The values of S_1 , D_1 and NI_1 chosen to be 12 mm, 12 mm, and 500 A.t, respectively. Similarly, S_2 and NI_2 were fixed at values of 4 mm and -500 A.t., and values of (10,12,14,16,18,20) mm were chosen to study the effect of D_2 on the projected optical properties of the double lens. Notably, the optical axis of the lens has been doubled in length to avoid possible loss in the overall NI values of the dual lens.

Figure (1) shows the distributions of B_z for both the first and second lenses and for each of the D_2 values referred to above. The figure shows the opposite excitation between the two fields and the axial widening of the B_z distribution due to the second lens as the value of D_2 increases, in addition to the field of the first lens remaining unchanged. Notably, changing the diameter of the axial aperture has a significant effect on the B_z values at the edges, and for this reason, to avoid any loss in double lens irritation, the length of the double lens was 80 mm.

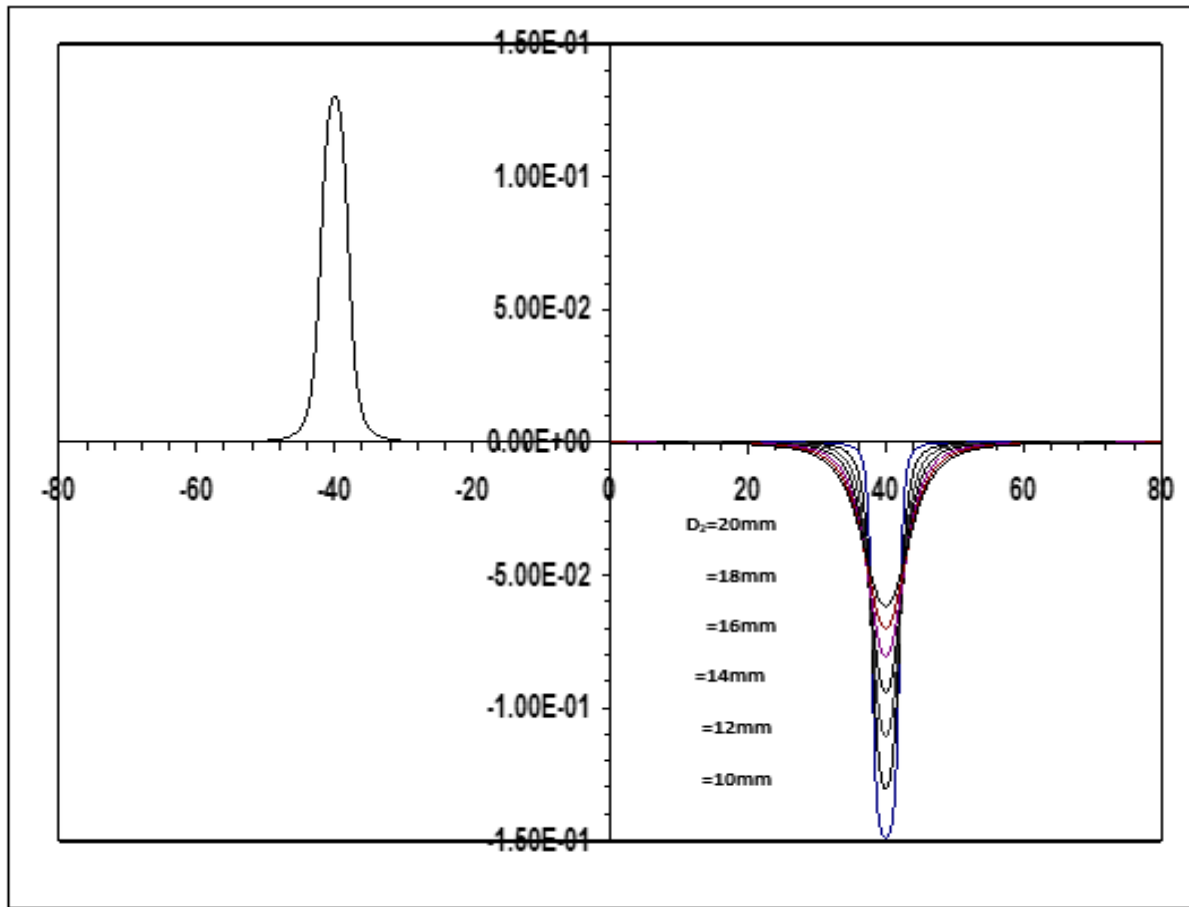


Figure 1 Bz distributions along the optical axis for different values of D2.

In the first loop, the projector focal length (Figure (2)) shows the change in the projected focal length curves as a function of agitation $NI/\sqrt{V_r}$ and for each chosen D_2 value. The minimum value $(F_p)_{min1}$ for each of the F_p curves clearly decreases and increases $NI/\sqrt{V_r}$ as the D_2 value increases. Note Table (1). This behavior is completely similar to that in the case of S_2 and has the same reasons mentioned previously. Notably, the values of $NI/\sqrt{V_r}$ at which the magnification is greatest (i.e., M_1) are generally larger than their counterparts for the S_2 case. The reason for this is that the distance between the centers of the two fields is twice as large, which means that the electronic beam will remain at lower V_r values, and since the NI is fixed at 500 A.t., the agitation information decreases. In contrast, the values of $(F_p)_{min1}$ are approximately double those in the S_2 calculations. Note Tables (5).

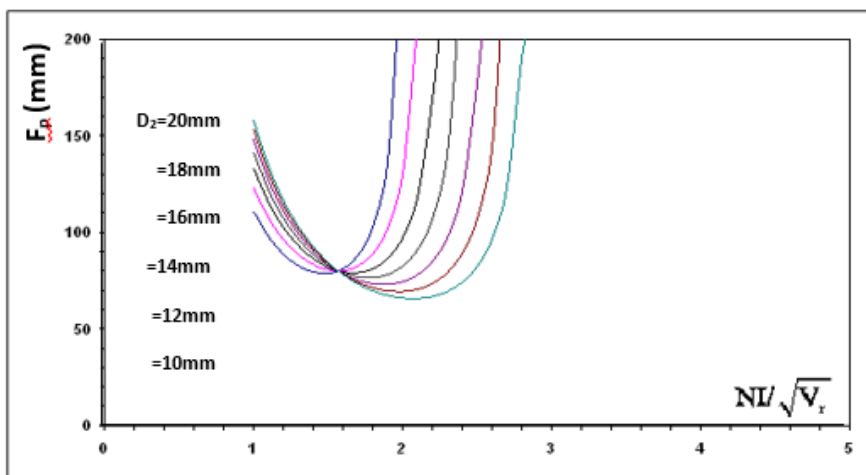


Figure 2 Changes in the curve of the projected focal length of the double lens in the first rotation for different values of D2 as a function of the agitation parameter.

Figure (3) shows the change in the Dr curves for different D2 values as a function of the excitation parameter of the first cycle. The shape has features almost similar to those of the gap calculations.

Table 1 Some projective properties of the double lens for different values of D2:

D2 (mm)	f _{p1} (mm)		f _{p2} (mm)	(F _p) _{min.} (mm)	NI/√V _r at		
			Theoretical value	Computed value	(F _p) min.	D _r = 0	D _s = 0
10	58.670	106.462	71.221	72.092	1.885	1.65	1.55
12	53.590	117.101	68.460	68.396	1.910	1.75	1.75
14	41.980	122.041	62.112	62.805	2.010	1.85	2.05
16	36.182	132.641	59.312	59.943	2.035	1.95	2.25
18	24.581	137.542	52.910	53.121	2.136	2.05	2.55
20	18.789	148.144	50.112	50.032	2.177	2.15	2.75

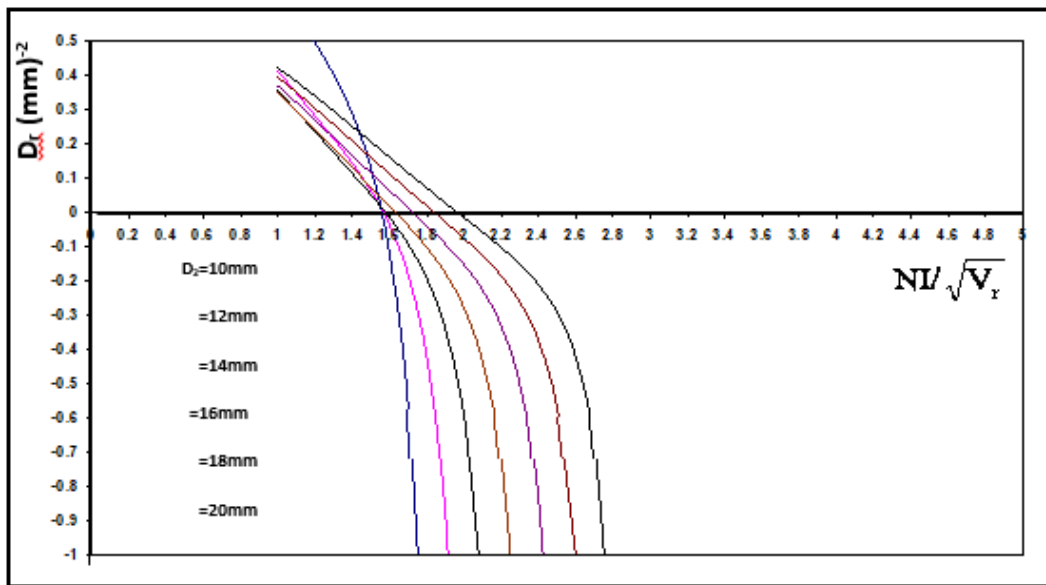


Figure 3 Variation in the D_r curves for different D_2 values as a function Irritation is unknown for the first cycle.

It is known that $NI/\sqrt{V_r}$ the point at which M_1 occurs is the same as that at which D_r becomes zero, as long as the two lens fields are symmetrical. However, as the difference between these two fields increases, the difference between the two pieces of information increases, as shown in Figure (4), which shows the relationship between the information of irritation at which M_1 occurs and the information at which D_r disappears as a function of the aperture of the second lens, D_2 . Notably, the two curves diverge from each other as D_2 increases because increasing D_2 leads to an increase in the difference in the shape of the photographic field of the second lens from the field of the first lens. In general, this difference does not exceed 4%, which means that operating the lens can possibly produce images without radial distortion and at the greatest magnification at the same time.

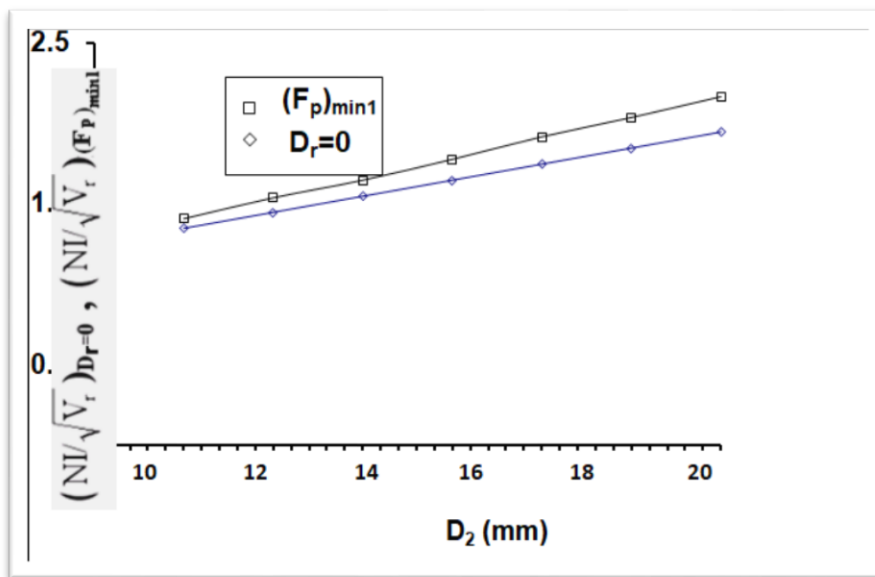


Figure 4 Change in both the agitation information that gives $D_r=0$ and that which is then the magnification is maximum as a function of the aperture diameter D_2 .

Figure (5) shows the curves of the helical distortion coefficient D_s for the first rotation as a function of the agitation parameter at different values of D_2 . The figure shows that the values of $NI/\sqrt{V_r}$ at which the image is free of spiral distortion are generally less than (1.0) at values of $D_2 < 6$ mm. However, it increases as the value of D_2 increases, which is similar to what it is similar to if S_2 changes. Figure (6) shows the ratio between the agitation information that produces images without radial distortion and that which produces images without spiral distortion as a function of the aperture diameter D_2 . The two pieces of information are equal when $D_2 = 14$ mm. Therefore, the magnetic lens that produces images without rotation and distortion is the one described by the following geometric parameters: $D_1 = S_1 = 12$ mm, $NI_1 = 500$ A.t., $S_2 = 12$ mm, $D_2 = 20$ mm, and $NI_2 = -500$ A.t.

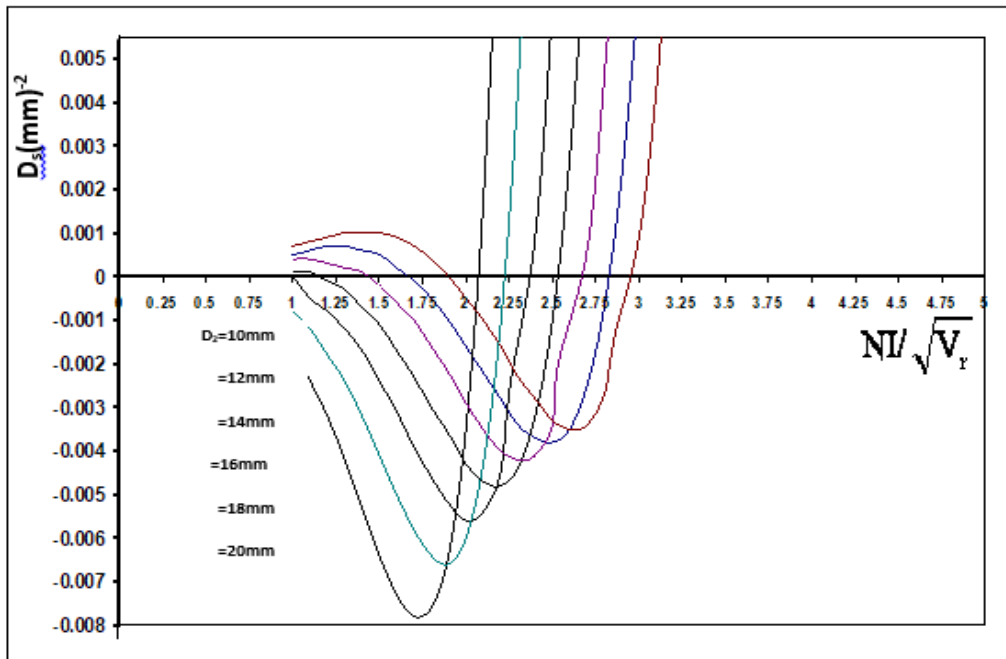


Figure 5 Variation in the helical distortion coefficient D_s curves As a function of irritation anonymity for different D_2 values

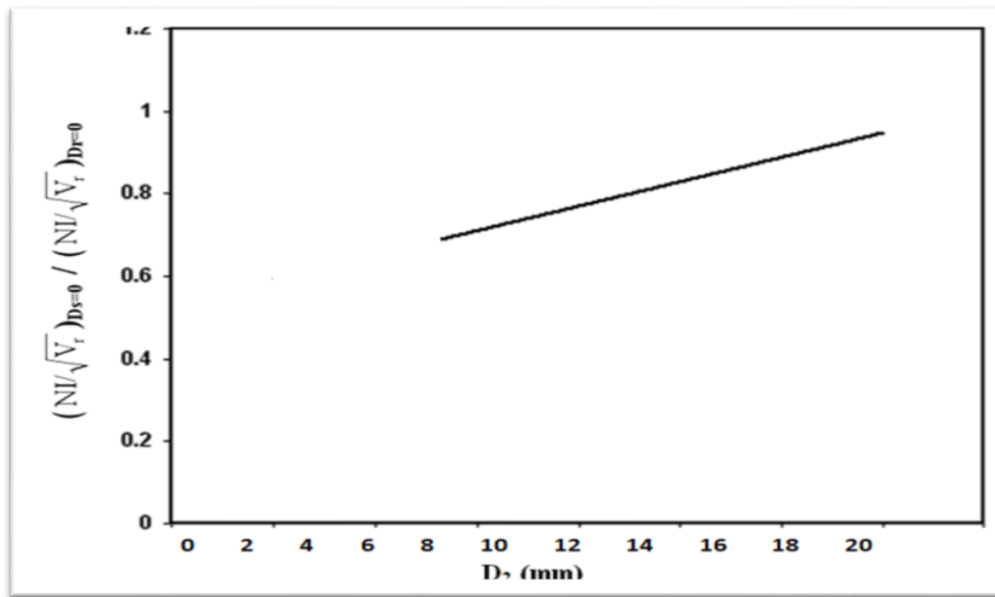


Figure 6 Change in the ratio between the two-irritation information at which D_r and D_s disappear as a function of the hole diameter D_2 .

Conclusions:

- 1- Any optimization parameter that either increases or decreases in value enhances the magnetic flux lines per unit area, resulting in an increase in the breaking strength of the bi-gap magnetic lenses. The reduction in focal length results in an increase in the magnification of the imaging field, and conversely, the opposite holds true. The thickness of the air gap influences the optical characteristics in photography, resulting in reconstructed electrodes that are often larger than their axial aperture counterparts. The change in the diameter of the axial aperture has a greater impact on irritation in the field of photography, especially at the ends of the optical axis, than does the change in the thickness of the air gap. The optical projection properties of the projection lenses generally have different behaviors in the first rotation than in the second rotation, especially in terms of magnification, this is what was observed from the results obtained with the illustrated figures.
- 2- Any optimization parameter, whether increased or decreased, leads to an increase in magnetic flux lines per unit area, thus increasing the refractive power of the magnetic lens. This results in a decrease in the focal length and consequently an increase in the magnification of the imaging field, and vice versa. As shown in results and figures.
- 3- While the effect of changing a set of optimization variables in the imaging field may be similar and lead to the same effect in optical properties, this does not necessarily result in a similar effect on reconstructed electrodes. For example, changing the air gap thickness and axial aperture diameter has a similar effect on imaging fields, but a different effect on reconstructed electrodes. As shown in results and figures.
- 4- The thickness of the air gap has a greater impact on imaging fields and their optical properties, and consequently on reconstructed electrodes, than the axial aperture in general.

- 5- Changing the diameter of the axial aperture has a greater effect on the excitation of the imaging field, especially at the ends of the optical axis, compared to changing the thickness of the air gap. As shown in results and figures.

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Conflict of interest - The authors declare that they have no conflicts of interest.

References:

- [1] Lambrakis E., Marai F. Z, and Mulvey T., "Correction of Spiral Distortion in the Transmission Electron Microscope" (1977).
- [2] Al-Shwaikh, A., "Magnetic Electron Lenses Based on the Uniformly Magnetized Ellipsoid", Ph.D. thesis, University of Aston in Birmingham, England (1979).
- [3] Tsuno, K., and Harada, Y., "Minimization of Spiral Distortion in Electron Microscope Through the use of a Triple-Pole Piece Lens", J. Phys. E: Sci. Instrum., 14, 313-319, (1981a).
- [4] Al-Obaidi, H. N.A. and Al-Azawy A., "Visual Design Tool for Electrostatic Lenses", Journal of Advances in physics, Vol. 5, No.2, (2014).
- [5] Al-Obaidi, H. N. "Determination of the Design of Magnetic Electron Lenses Operated Under Pre-Assigned Magnification Conditions", Ph.D. Thesis, University of Baghdad, Baghdad, Iraq, (1995).
- [6] Al-Batat, A. H. H., "A Theoretical and Computational Investigation on Magnetic Lenses, Synthesis", Ph.D. Thesis, University of Al-Mustansiriyah, Baghdad, Iraq, (2001).
- [7] Holcakova, R. and Marek, M., "Innovative research in electron microscopes, analysis of magnetic field distribution of some types of magnetic lenses by FEM", 10th International Conference on Environment and Electrical Engineering , pp.1-4, IEEE Journals, (2011).
- [8] Humphries, S., "Three-Dimensional Charged-Particle Optics and Gun Design", field precision LLC, CRC press, Albuquerque, New Mexico U.S.A, (2011).
- [9] Al-Azawy A., "A computer Aided Design Tool for Electrostatic Lenses" Ph.D. thesis, University of Al-mustansiriyah, Collage of Education, Baghdad, Iraq, (2016).
- [10] Al-Azawy A., "Investigation of the optical properties for bipolar magnetic lenses" Neuro Quantology Volume 20, Issue 9, Page 41-45, August 2022.
- [11] Al-Azawy A., "Investigation of symmetrical two-cylinder lens" Neuro Quantology Volume 20, Issue 8, Page 5531-5536, July 2022.
- [12] Al-Azawy A., "Theoretical study of the aberrations for the single-gap magnetic lens" The Optical Society of India, November 2022.
- [13] Szilagy, M., "Reconstruction of Electrodes and Pole pieces from Optimized Axial Field Distributions of Electron and Ion Optical Systems". Appl. Phys. Lett., 45, 499-501, (1984).
- [14] Hawkes, P. W., "Magnetic Electron Lenses", (Springer- Verlag, Berlin), (1982).