Volume 6, Number 2, 2013. pp. 87-94

Jordan Journal of Physics

ARTICLE

New Design of Objective Lens Geometry for Low Voltage SEM

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Received on: 5/8/2013; Accepted on: 6/11/2013

Abstract: Five new models of magnetic objective lens geometry have been designed and studied in this work. Different excitation coil shapes and their positions inside the lenses at a constant excitation (NI = 10 kA.t) were included. Spacious comparison between these models was realized using the finite element method (FEM) to analyze the magnetic field distribution, magnetic flux density and optical properties for each model at low relativistic corrected accelerating voltage (V_r = 10 kV). The effect of the lens geometrical shape on the electron beam voltage passing throughout the optical axis of the lenses at zero image plane (Z_i = 0 mm) has been inspected as well. The optimized one of the deliberated lenses has been selected as an objective lens for low voltage scanning electron microscope (SEM) preparatory for next research.

Keywords: Objective lens geometry design; Electron magnetic properties; Electron optical properties; Relativistic corrected accelerating voltage; Low voltage SEM.

Introduction

In recent years, there is a high demand for high- resolution scanning electron microscope (SEM) in all areas of development and fabrication of micro-electronic and opto-electronic components in order to visually evaluate sub - micrometer structures, as well as to be able to identify the deviations from standard patterns and in order to acquire and evaluate topographical data such as heights, widths or angles of inclination. Conventional SEM, however, only achieves the required spatial resolution of fractions of micrometer down to a few nanometers for small working distance, and high accelerating voltages above approximately 20 kV are used which cause resistant structures and integrated circuits to be destructed and non-conductive or high resistant specimens to be charged which is a disadvantage [1]. Therefore, new researches are interesting to obtain high resolution observation at low relativistic accelerating voltages (less than 20 kV), particularly in observing a semiconductor by the SEM [2].

Intensive studies have been conducted to improve the magnetic lens geometry, emphasizing that each parameter of the magnetic lens has its relative significance from both the practical and theoretical sides. The optimization of the polepiece shape is studied for the symmetrical double polepiece lens by Cleaver [3] and for the asymmetrical double polepiece lens by Wenxiong [4]. The influence of the shape and position of the coil on the projector lens properties of the symmetrical double polepiece lens and the single polepiece was studied by Al-Khashab [5]. The asymmetrical lens is largely used as an objective lens in the imaging system of various types of electron microscope [6]. It was found that the symmetrical magnetic lens usually provides a higher magnetic flux density peak and lower aberration coefficients in comparison with the asymmetrical lens, due to the fact that the asymmetrical lens is purposefully designed to provide a large volume of free space for the specimen holder in the region of the polepieces,

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and this requirement is found to be difficult to achieve when the symmetrical objective lens is used under the limited space available around the specimen [7].

It is difficult to develop a general optimal lens design for all applications [8]. The optimum design of the magnetic electron lens with low aberration coefficients is generally considered significant [9]. However, low aberration electron magnetic lens has been found to require a high flux density with low half-width [10]. The aim of the present work is to design five new asymmetrical magnetic objective lenses with different geometries and different energized coil shapes and positions to study their magnetic and optical properties in order to select the best resolution and lowest aberration coefficients lens the focal length (f_o) of which, sometimes called working distance, lies outside the lens region, where all of the lenses are analyzed at constant excitation (NI=10 kA.t). Then, the adequate one of the investigated lenses will be chosen as an objective lens for low voltage SEM.

Analysis Methods

Recently, the existence of computer eases the design and the analysis of electron microscope lenses in which this task was difficult to solve the mathematical functions numerically. The magnetic and electric flux density distribution function can now easily and accurately be generated by the aid of the computer calculation before we start the practical design [11]. The progress in computer simulations helps to solve a lot of complicated design problems which was impossible to implement previously. Munro [11] has used the finite element method (FEM) to write packages used to calculate the magnetic and electric fields for electromagnetic lenses [12]. The design of electromagnetic lenses depends on the hypothetical mathematical models for the field distribution like the bell shaped model and on the experimental fields. The steps needed to design the electromagnetic lenses numerically are [13]:

a. The finite element method (FEM) used to calculate the axial flux density distribution (B_z) for the proposed design.

b. Calculation of the axial ray tracing (trajectory) by solving the ray tracing equation numerically using Runge-Kutta method.

c. Calculation of the chromatic factors for the proposed model by using Simpson method for each value of the axial magnetic field distribution and axial ray tracing.

The Objective Lens Design

Five new models of asymmetrical electron magnetic objective lens have been designed. These are denoted as L1, L2, L3, L4 and L5, respectively. Fig. 1 clarifies the comparison between all of the designed lenses. It is seen that each one differs from the others in geometric structure of the iron circuit, coil shape, coil position, coil sectional area of (1615 mm^2, 1330 mm^2, 1300 mm^2, 1365 mm^2 and 1895 mm^2, respectively), axial bore diameter and other geometrical diameters. However, all of them have the same length of polepiece snout faces of (4mm).

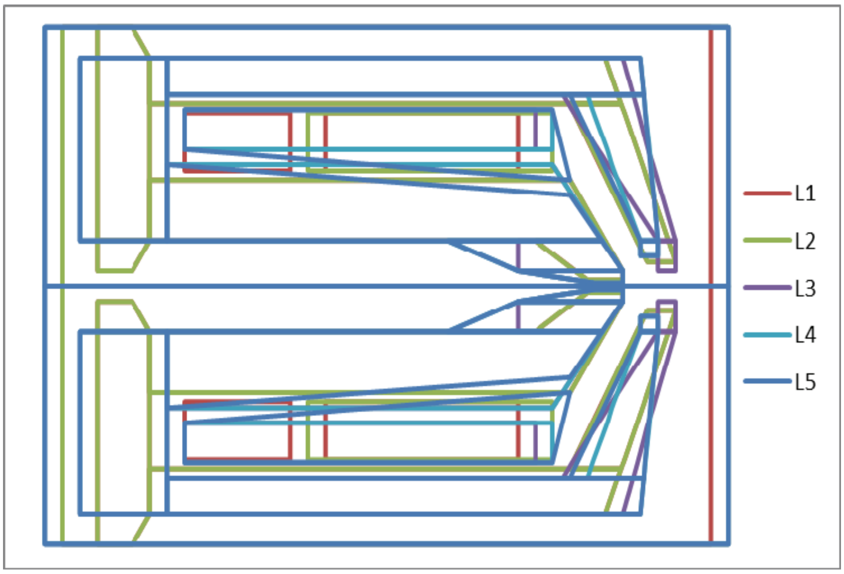

FIG. 1. Comparison between the schematic diagrams of the objective lens design.

The polepiece angles were taken equal to 62^o (for L1 & L2), 60^o (for L3 & L4) and 58^o (for L5), according to the optimization of Al-Khashab and Ahmad [14], who found that the preferred angles for the double and single polepiece lenses is in the range from 55^o to 63^o. The recent designed lenses have the same radial diameter (150 mm), while their axial length is 170 mm (for L1, L2 and L3) and 165 mm (for L4 & L5). The distance between the polepiece face and the outer edge of the iron shroud bore, which is denoted as (d_{out}), is equal to 15 mm (for L1, L2 and L3) and 10 mm (for L4 & L5) as listed in Table (1) in the present paper. A cylindrical gap of 30 mm diameter and about 80 mm length has been designed in each lens to be used as a place of scan coil deflector preparatory for next future work. All the suggested lenses have been tested at a low relativistic corrected accelerating voltage (V_r = 10 kV) and an excitation (NI = 10 kA.t) as mentioned before.

The Axial Magnetic Flux Density Distributon

The axial magnetic flux density distribution (B_z) of the designed lenses has been studied with the aid of computer program (M11) for the asymmetrical polepiece lenses [13] using the finite element method. Fig. 2 illustrates the axial magnetic flux distribution for the designed lenses. It is noticed that, as we make headway from L1 up to L5, the peaks of B_z increased and the half-widths alternated ensuring that there is a noticed progress in the lenses design. This behavior is useful for focusing the electron beam passing through the optical axis of the lens. The change in half-width is due to the difference between spaces separating the polepiece snout and the axial bore of the iron shroud, which is the effective region of the magnetic field distribution. The increase in this region reduces the strength of the magnetic field and increases the half-width [15] and vice versa.

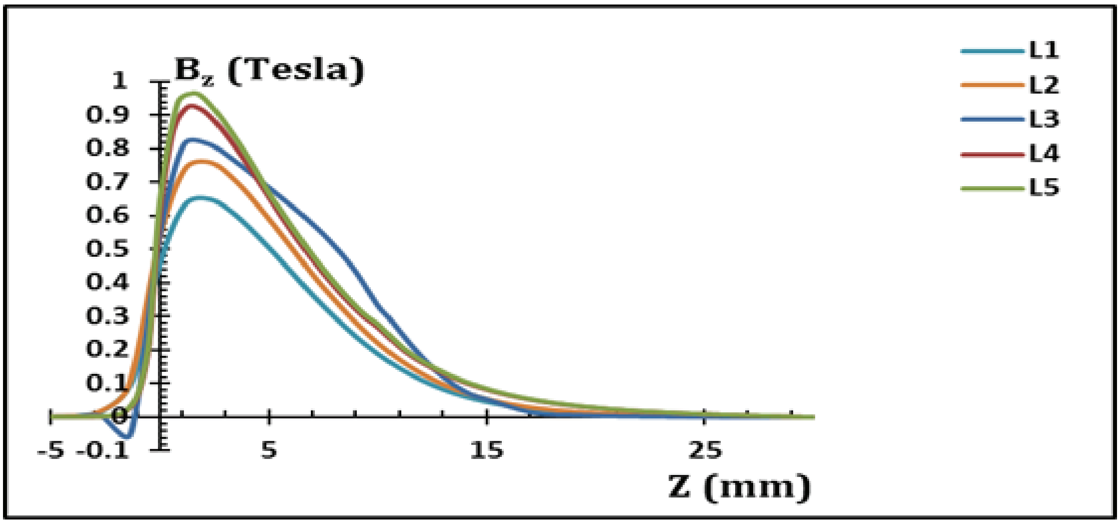

FIG. 2. The axial magnetic flux density distribution (B_z) for the designed lenses at a constant excitation (NI = 10kA.t).

In spite of obtaining this clear difference in B_z, the outcome is still poor. This is because there are other characteristics carrying exaggerate importance needed to decide which lens is the best, such as the magnetic flux lines trajectory and the optical properties, which will be explained in the next sections. It can be said that this consequence is regarded as a primary indicator, but not as a definitive ruling, especially if it is well known that higher peaks of B_z can occur by increasing the sectional area of the excitation coil and decreasing the space between the coil and the yoke.

The Magnetic Flux Lines of the Designed Lenses

In order to demonstrate the effect of the lens geometrical shape on the magnetic flux lines, an inspection has been carried out using flux program (M13) for computing the flux density distribution throughout the magnetic circuits of unsaturated magnetic lenses [13] at (V_r = 10 kV) and (NI = 10 kA.t).

Fig. 3 illustrates the flux line trajectories of the designed lenses. It is clear that lens L4 seems to be the best one, according to the regular and little leakage of its flux lines. In addition, its flux lines propagate in preferred way and path as it is needed to make the required effect on the charged particles passing throughout the lens. This outcome gives a good indicator to distinguish the best liked lens. Nevertheless, this needs more investigation.

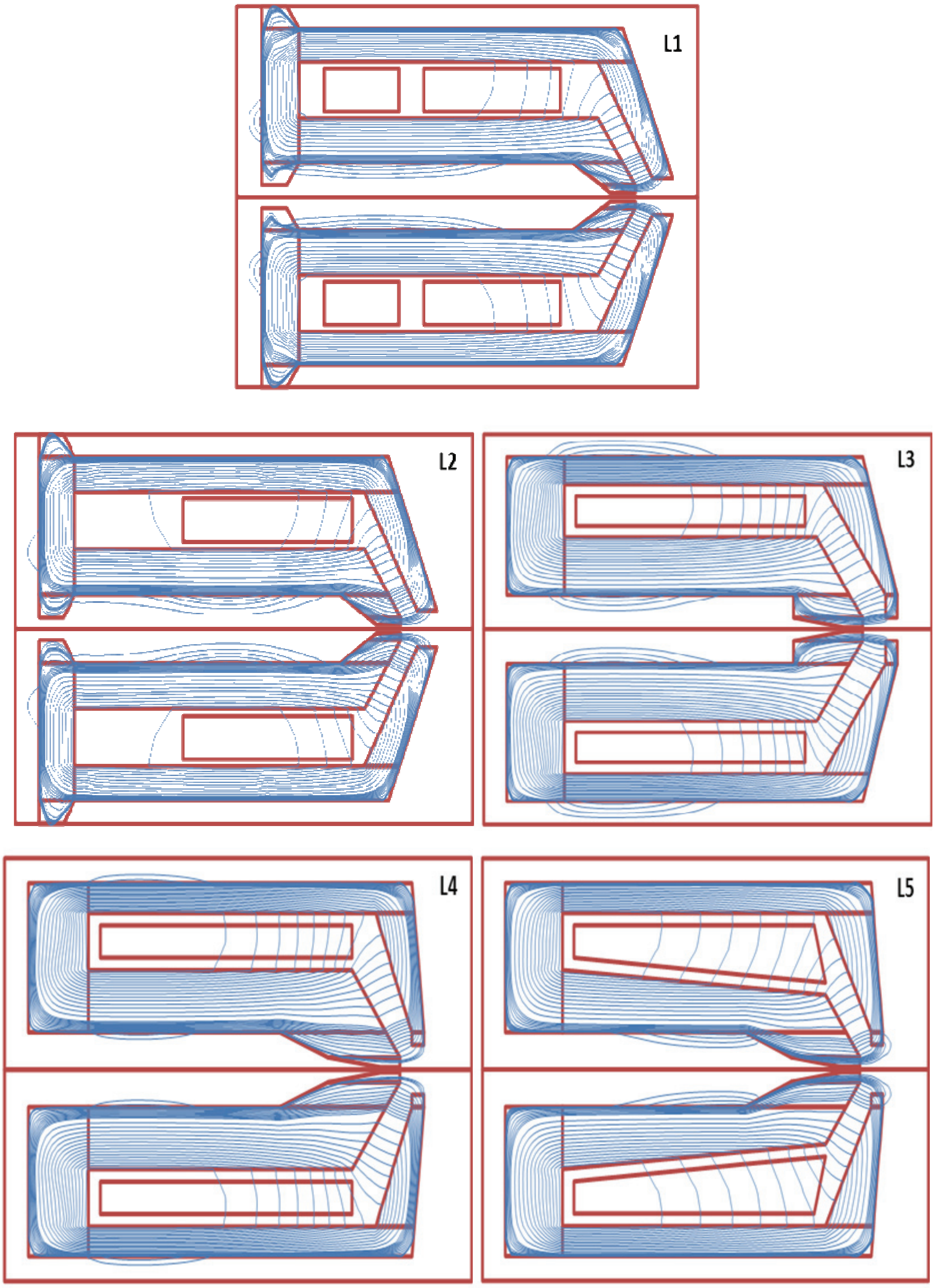

FIG. 3. The cross - section of the designed objective lenses and their flux line trajectories at a constant excitation (NI = 10 kA.t).

Objective Optical Properties

For the sake of selecting the preferred lens among the tested lenses, some aspects of the optical properties have been investigated using computer program (M21) for computing the objective properties of the magnetic lenses [13] in the low range of relativistic corrected accelerating voltage (V_r = 10V– 100 kV) at a constant excitation (NI = 10 kA.t). The values of V_r are auto - calculated by the aforesaid program according to the well-known relation [$V_r = V_a (1 + e/2mc^2) V_a$], where V_a is the accelerating voltage. The effect of V_r on the optical properties of the introduced lenses has been investigated at zero image plane (Z_i = 0) within vast range of V_r (10 V–1000 kV). This investigation generates the relation cleared in Fig. 4. It is found that each design has its own V_r to constitute the image at zero plane on the axial axis. In addition, it is seen that lenses L4 & L5 possess the lower proportions of V_r, which means that these two lenses need lower potential values than the other lenses to show best liked optical properties.

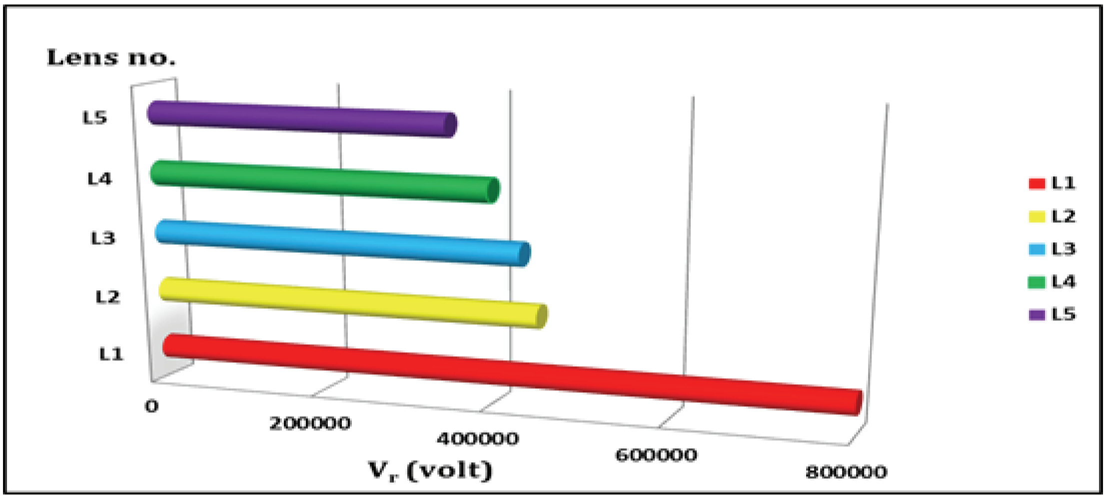

FIG. 4. The applied relativistic corrected accelerating voltages for the tested lenses needed to form a zero image plane (Z_i = 0).

The values of spherical aberration coefficient (C_s), chromatic aberration coefficient (C_c), resolving power (δ) and objective focal length (f_o) have been calculated and studied carefully. The resolving power δ (equal to $0.61C_s^{1/4}\lambda^{3/4}$, where λ is the electron wavelength) of the designed objective lenses here is drawn as a function of V_r. Fig. 5 demonstrates this relation. At first sight, it is shown that lenses L1, L2 and L5 emerge the lower in magnitudes compared with lenses L3 and L4, but they are overlapped to be the worse ones at a working voltage (V_r = 10 kV). Lenses L3 and L4 seem to be the best at this working point, and they are nearly conforming to each other. The preference between them is difficult and is a scarce task. It is necessary to go to other optical properties to accomplish this.

Figs. 6 and 7 illustrate the relationship between the relative spherical and chromatic aberration coefficients to the focal length (C_s / f_o) and (C_c / f_o) respectively for the designed lenses as a function of an accelerating voltage (V_r). It seems clearly that the best regular behaviors obtained from lenses L3 and L4. For further clarification, Fig. 6 is maximized to show the specified operating point, where lenses L3 and L4 gave the lowest values, and that is consistent with the desired goal. They appear to be completely identical and it is difficult to distinguish the better one. Again, we need to look for other optical properties to discriminate between them.

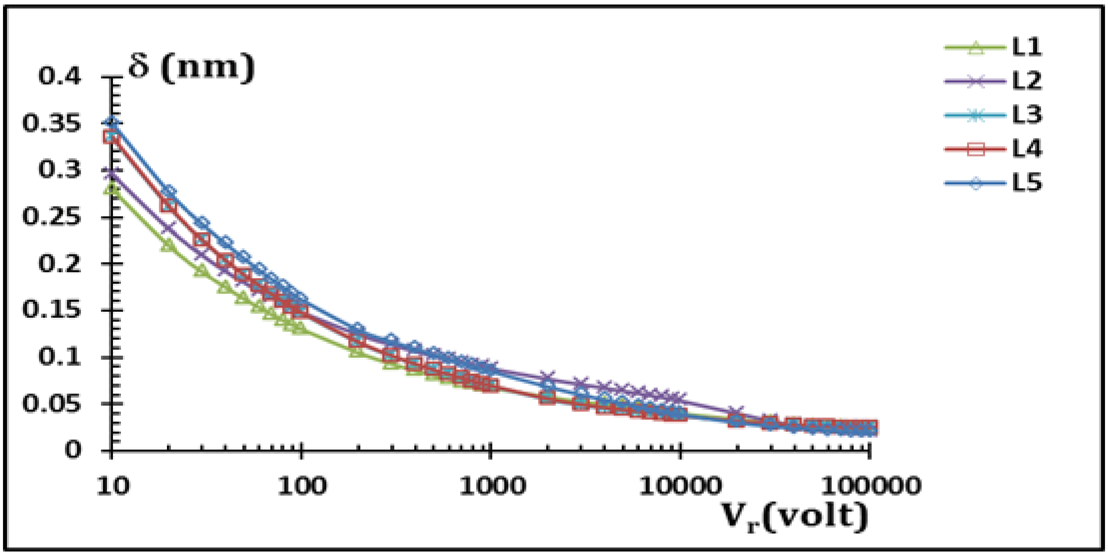

FIG. 5. Comparison between the resolving power (δ) of the designed lenses with the relativistic corrected accelerating voltage at a constant excitation (NI = 10 kA.t).

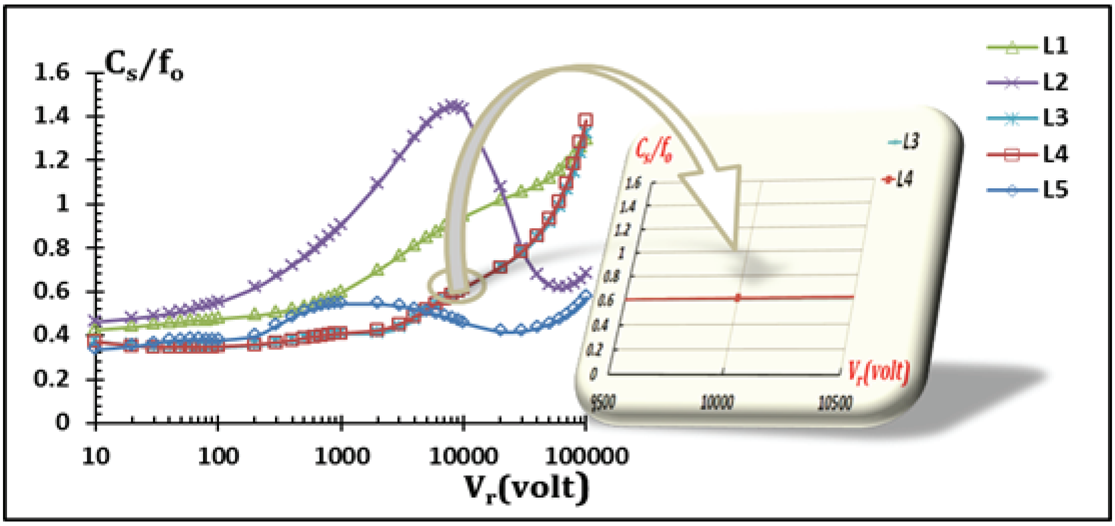

FIG. 6. Variation of the values (C_s / f_o) for the designed lenses as a function of (V_r) at a constant excitation (NI = 10 kA.t).

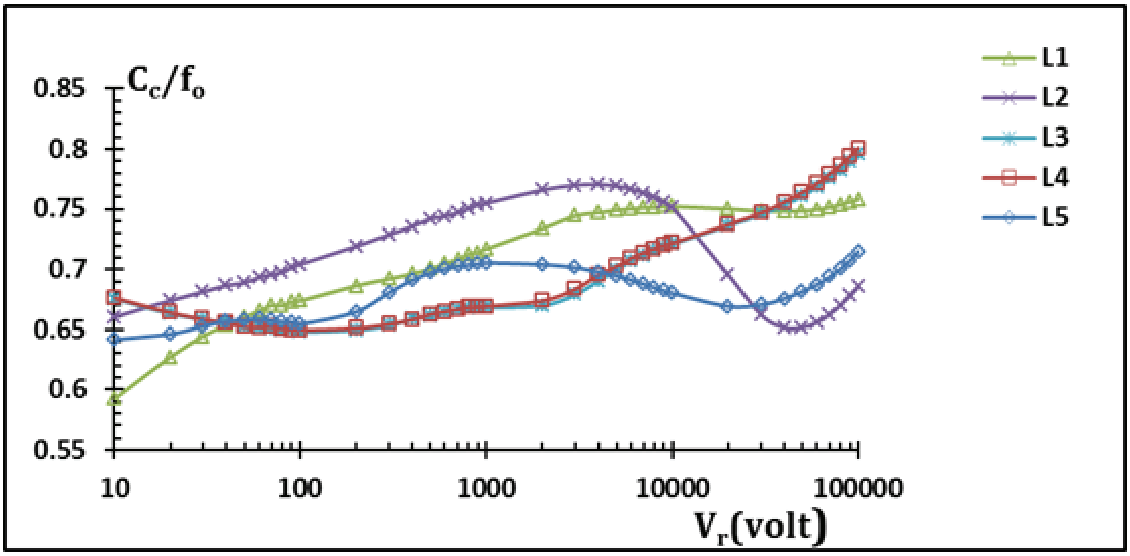

FIG. 7. Variation of the values (C_c / f_o) for the designed lenses as a function of (V_r) at a constant excitation (NI = 10 kA.t).

Fig. 8 demonstrates the comparison between the objective focal lengths for the standing lenses as a function of (V_r). It is clear that lens L4 possesses the least value among all other lenses. Lenses L3 and L4 seem equal to each other in values, the magnified section in Fig. 8 clearly shows that the objective focal length of lens L4 is larger than those of lenses L1 and L2. At the first glance, one would think that lenses L1 and L3 are the best depending on their low values of the focal length (f_o), but the truth is that lens L4 is the best for a very important reason, which is that the main purpose of this research is to design a strong objective lens with a short focal length to get a short working distance and to be located outside the region structure of the lens to facilitate the process of the specimen installation.

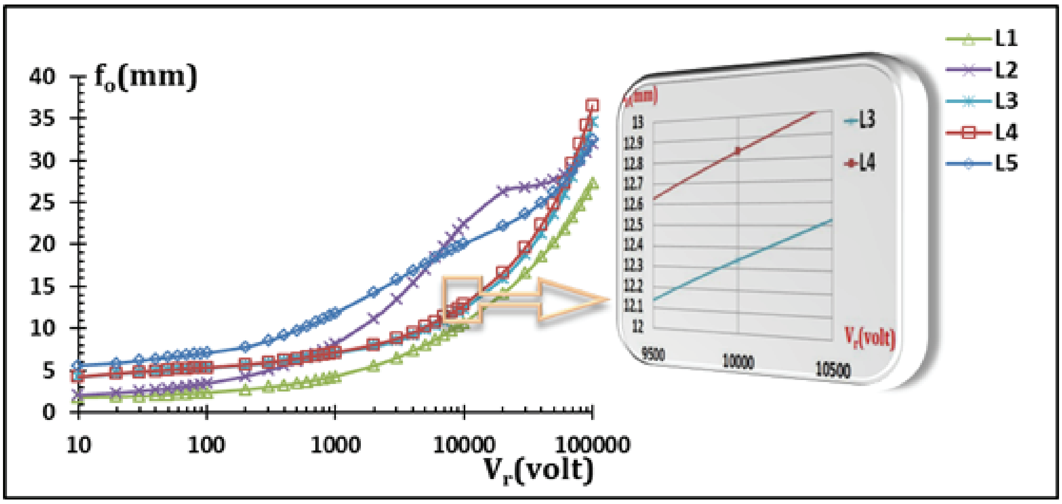

FIG. 8. Variation of objective focal lengths (f_o) for the designed lenses as a function of (V_r) at a constant excitation (NI = 10 kA.t).

Table (1) records some aspects of the optical and geometrical values for the proposed lenses at working point (V_r = 10 kV) and specified excitation (NI = 10 kA.t). The distance between the face of the pole and the end of the outer edge of the iron shroud (d_{out}) varies from one lens to the other depending on the different designs. It is obvious that lens L3 has the value (d_{out} = 15 mm), while its focal length is (f_o = 12.34 mm), which means that the working distance has to be inside the lens which is considered an undesirable property to achieve the goal of the research. However lens L4 has the magnitude (d_{out} = 15 mm) and its focal length is (f_o = 12.84 mm). In other words, its working distance is outside the lens structure and that complies with the requirements of the aim of the research work. Details of the comparison are shown and denoted in Table (1) below.

TABLE 1. The optical properties for the designed lenses at a working point of (V_r = 10 kV) and a constant excitation (NI = 10 kA.t)

Lens no.	Z_i(mm)	Z_p(mm)	f_o(mm)	d_{out}(mm)	C_s(mm)	C_c(mm)
L1	-119.9	-130.6	10.69	15	10.07	8.04
L2	-99.76	-122.3	22.53	15	32.2	16.92
L3	-114.1	-126.4	12.34	15	7.57	8.9
L4	-113.2	-126	12.84	10	7.9	9.27
L5	-86.42	-106.5	20.09	10	9.16	13.66

The above result has been considered as a crucial point for the selection of lens L4 as the best lens among the examined lenses, because it meets all the requirements necessary to achieve the goal of the research. It should be remembered that this lens showed the best properties of the magnetic flux lines as mentioned previously. It should be pointed out here that although the working distance of lens L1 is outside the lens structure, it has been excluded during the search for its bad most general characteristics.

Conclusions

In this work, it is found that to make preference between many electron magnetic lens designs, both magnetic and optical analyses should be applied, and the optimization will depend on the aim of the research to facilitate the optimal choice. It is noticed practically that the optical properties of the electron lenses are improved when the excitation coil localizes nearby the air gap between the polepiece and the iron shroud at the bottom of the objective lens. The selection of lens L4 in this work is based on its verification of the research goal. Lens L4 will be investigated later to improve its magnetic and optical properties, to fabricate it in a next research in order to use it practically as an objective lens in a low voltage SEM.

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