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Effect of Changing Distance between Poles on Optical Properties of Gemini Lens

Modern and advanced software was used to reach quick results of the optical properties of the proposed models of Gemini lenses. Four basic designs of the objective magnetic lens were employed in scanning electron microscope, according to the design site and the required analysis ability, the four models were designed equal in geometric dimensions and file size, and the results showed that the Gemini objective lens (S3) achieved the best results because it obtained the lowest values for the final effective probe diameter and the focal length (f=4.76 mm) that corresponds to the highest value for analysis. At a constant value of the excitation (NI = 1000 A-t), it also had the lowest coefficients of spherical and chromatic aberration (Cs=4.14 mm) and (Cc=3.63 mm).

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1. Introduction

Revolution in the field of electronic optics led to the invention of the electron microscope in 1931 by Ruska and Knoll with an acceleration voltage of 50 kV and a magnification of 16 times, while Knoll evaluated the flaws that exist on object surfaces in them by designing a new electronic microscope called the scanning electron microscope (SEM) in 1935 [1]. In 1942, Zworykin developed the first scanning electron microscope by testing secondary electrons which give us images of features and properties of surface with an analysis capacity 25-50 nm [2]. The magnetic lens is one of the most important types of electronic lenses. Therefore, it is included in the manufacture of scanning electron microscopes, as it is characterized by the fact that unlike the electrostatic lens, it doesn't operate at high voltages, with its high analytical capacity and the advantage of being easy to manufacture. The accuracy of the work and the lack of costs, since the electromagnetic component of the lens performs the majority of its functions, it is more appropriate than a permanent magnet because it allows one to alter the magnetic field's strength by varying the current flowing through the coil or the number of turns it has [3]. The three basic categories of electromagnetic lenses are the iron-free lens, the monopolar lens, and the bipolar lens. Additionally, there exist three-pole lenses, which have more than two poles. The iron-free lens consist of ring coil in form of tape or wire, and the primary dependence of magnetic field in this type is the geometric shape of the coil [4]. The protrusion of the outer pole of this type of lens is one of its most important features, which leads to the magnetic flux density creeping away from the lens mount, which gives freedom of movement to the sample This type was used when there was a hole in its pole as an objective lens in the transmission electron microscope (TEM) and the scanning electron microscope (SEM) [5]. Bipolar lens is more widely used than others. This lens is designed from a coil, two iron poles, and an iron circle surrounding the two, and its working principle depends on the passage of a continuous electric current in the circular file, which generates an axially symmetrical magnetic field. It deflects the charged particles passing through it towards the axis of the coil, and for the purpose of increasing the magnetic flux density's maximum value and achieving a strong field confined to a small area, The gap is the area where the magnetic field is concentrated, and it is encircled by a cover made of (ferromagnetic) material with high magnetic permeability, such as wrought iron. The antenna, via which the electronic beam enters and leaves, is situated between two pieces of iron that symbolize two magnetic poles [6].

The aim of this work is to evaluate and investigate optical properties of four types of objective Gemini lenses and decided which one is the best by using computer programs.

2. Designed electronic lenses and used software

In this study, four models of Gemini objective lenses (S1, S2, S3, and S4) were used, and the distance between the pole pieces of these lenses is respectively S1=10 mm, S2=7 mm, S3= 4mm, S=1 mm, and the excitation factor is NI = 1000 A-t, and low voltage (V_r= 8kV).

2.1 Finite Element Method (FEM)

It is a numerical technique for solving a set of ordinary differential equations and solving the problem of voltage limits instead of approximating it. It was presented by Munro [13] and developed by Lencová [8] within the AMAG program as a basic basis for calculating the magnetic field. The total area, including the empty space around the poles, is divided into finite elements, forming “rough gratings” as a result of the overlapping of axial lines with radial lines, and the rough gratings are divided into smooth gratings, and these lines are processed by the program automatically [7]. The asymmetric pole is taken by taking the upper half of the lens and selecting the borders around the lens in which the voltage distribution is zero [8] to maintain the most dense distribution of the grid lines at the air gap of the lens and near the poles [9]. Gradually towards the outer limits, and the method of finite elements became one of the main methods used in the design of electronic devices and advanced micro devices [14].

2.2 AMAG Program

This program is distinguished by its high accuracy due to using many gridlines more than those used in the program [13]. This program can compute the magnetic flux density distribution of the electromagnetic lens that is rotationally symmetrical [8,13].

2.3 Flux M31 software

Munro created this program in 1975 [13] to depict the magnetic flux lines of electromagnetic lenses. This program is fed with the magnetic flux values obtained from the AMAG program, and then the magnetic flux values are calculated at each point of the finite element grids, and then these values are stored in A special file (File) to be inserted into the (Flux) program modified by Murad in 1998 [11], who made some software modifications to the M31 program, which was developed by Munro to be run on a compatible microcomputer (IBM) and called it “Flux”. Magnetic flux lines are drawn by connecting the magnetic flux points at each point of the clamp, which have the same voltage value, where these lines take circular shapes concentrated around the iron poles, and these lines are convergent in areas of high density in the flux and divergent in areas of low density [10].

3. Results and Discussion

3.1 Axial Magnetic Flux Density Distribution:

Different values have been used for the distance between the lens's pole, which is S=10, 7, 4, 1 mm, in order to study the impact of the diameter on the axial magnetic field (B_z) and the path of the electronic beam [11], and consequently on the objective optics of the electromagnetic lens, where the figure (1) shows the axial magnetic flux density (B_z) distributions for symmetrical bipolar electromagnetic lenses along optical axis (z) and for different values of distance between the poles of the Gemini lenses (S=10, 7, 4, 1 mm). Figure (1) shows that decreasing the diameter of the axial aperture results in an increase. This feature is helpful for focusing the electron beam that passes through the optical axis of the lens (B_z) at the highest value of the magnetic flux density. Because it is generally known that peaks higher than (B_z) can be achieved by increasing the area CT of the excitation coil and reducing the distance between the coil and the sample, it can be claimed that this result is preliminary but it is not definitive [12].

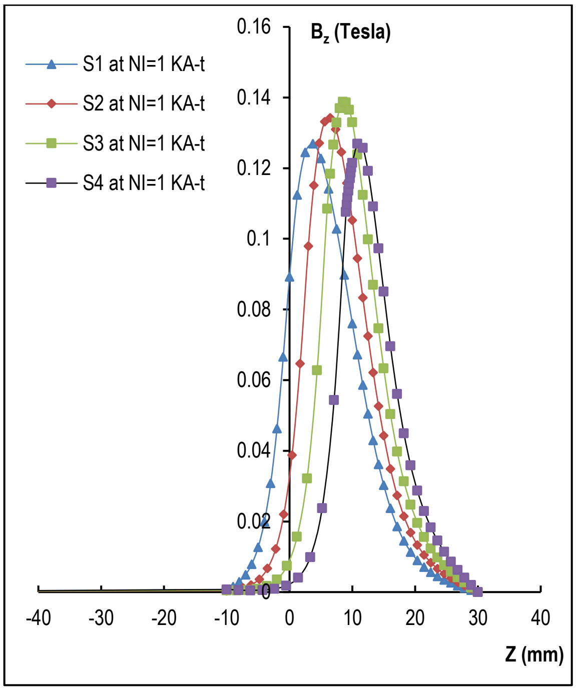


Fig. (1) The distribution curves of the axial magnetic flux density (B_z) at variable values of the axial aperture (z)

Table (1) Distribution curves of the axial magnetic flux density 4. Magnetic flux lines for electronic lenses designed

Lens icon	Z (mm)	B_{max} (T)
S1	3.75	0.125
S2	6.5	0.134
S3	8.5	0.139
S4	10.8	0.126

3.2 Magnetic flux lines for designed electronic lenses

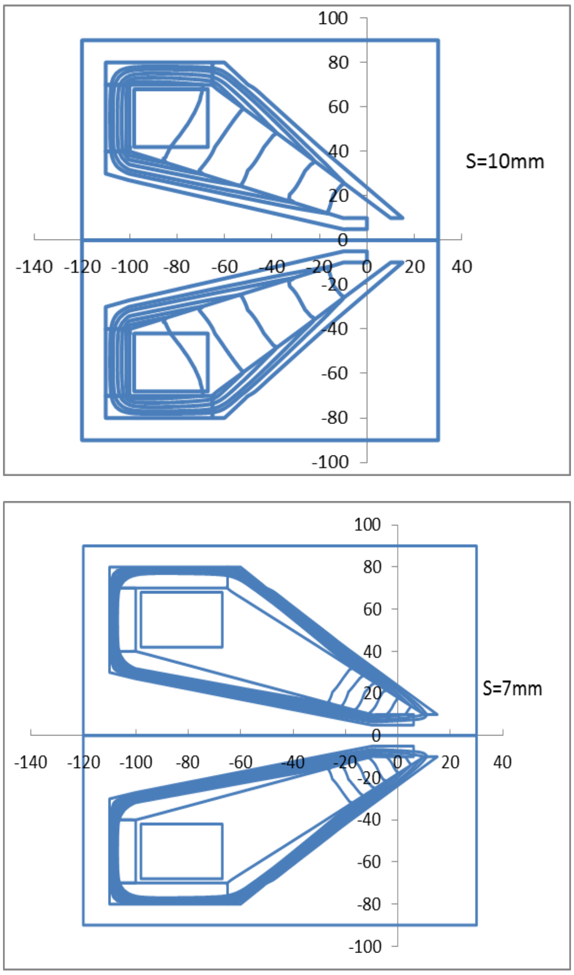
The flux density and distribution across the magnetic circuits of unsaturated magnetic lenses were calculated for the flow assay using the M31 software [13] at NI = 1000 A-t. The designed lenses' flow path lines are shown in Fig. (2). By virtue of the uniform and minimal leaking of its flow lines, it is obvious that the S3 lens has the best appearance. Additionally, because they are required to have the intended impact on the charged particles passing through the lens, their flux lines propagate along the preferred direction and in the recommended manner. This outcome provides a clear indicator of the desired lens. However, this requires more research.

3.3 Calculation of path of electronic beam inside objective lenses

The path of the electronic beam inside the magnetic lenses was calculated by entering the engineering data into the M21 program prepared by Munro in 1975 [13], and this is done using the fourth-order Runge-Kutta method by solving the axial beam equation. Figure (3) shows the path of the electronic beam with an accelerated voltage (V_r=8kV) and at excitation (NI=1000 A-t). It is clear from the shapes of the beam paths that the S2 lens has the lowest focal length compared to the rest of the lenses, and this in turn will give the lens the possibility of stronger focalization and thus less aberration compared to its counterparts [14]

Table (2) The change in chromatic and spherical aberration and focal length when the excitation coefficient is fixed (NI = 1000 A-t) and a variable voltage (V_r=8kV)

Lens icon	Cs	Cc	F_0 (mm)
S1	6.25	3.91	5.63
S2	5.07	3.71	4.91
S3	4.14	3.63	4.76
S4	5.71	4.17	5.34



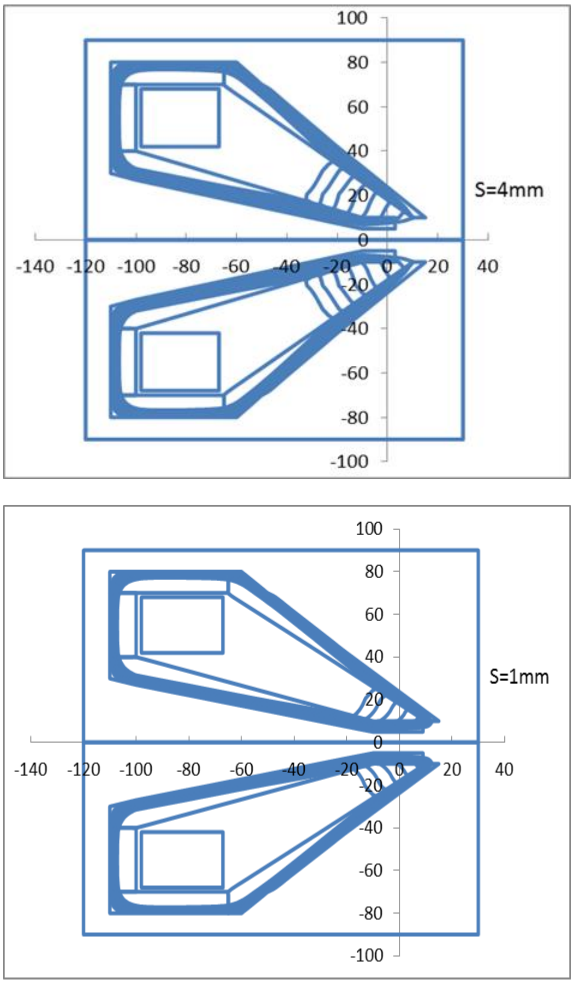


Fig. (2) Magnetic flux lines for Gemini lenses (S1, S2, S3, S4)

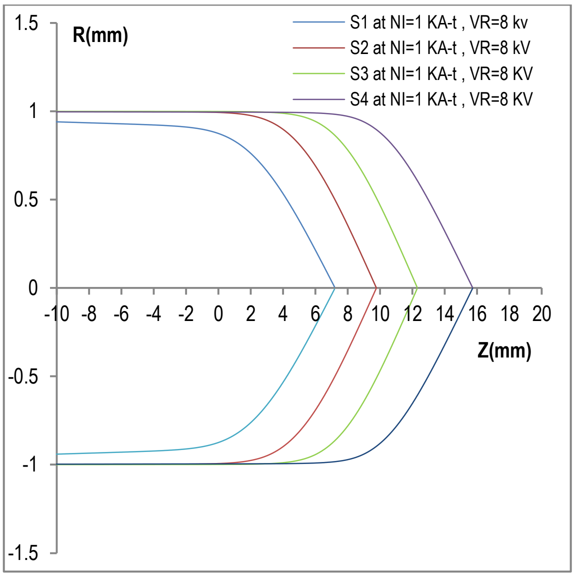


Fig. (3) The trajectory of the electronic beam at an accelerated voltage of V_r=8kV and excitation of NI=1000 A-t

3.4 Calculation of focal optical properties of objective lenses

The efficiency of magnetic-optical lenses can be determined by their similar properties such as the coefficient of chromatic aberration (C_C), This depicts the lens's capacity to focus the beam at a consistent wavelength, and The capacity of the lens to create an electronic beam that is configured in a dotted fashion with the least chance of distortion is known as the spherical aberration (C_S) or electronic spherical. And the focal length (f_0) defined as lens ability to focus the electron beam, the optical properties are estimated as a function of the excitation factor (NI) and as a function of the acceleration voltage (V_r) for the four designs to determine how well the lens can concentrate the electronic beam.

From the figures (4) and (5), we see that with increasing voltage (V_r) and constant excitation function (NI), the coefficient of spherical aberration (C_S) and chromatic aberration (C_C) both rise. Additionally, we observe that lens S3 has the lowest combined value for the coefficients of spherical and chromatic aberration. Comparing the voltage to the other lenses (S1, S2, S4). As seen in Fig. (6), the increase in voltage is to push the electrons to a far point, which leads to the formation of a focal length at the farthest point.

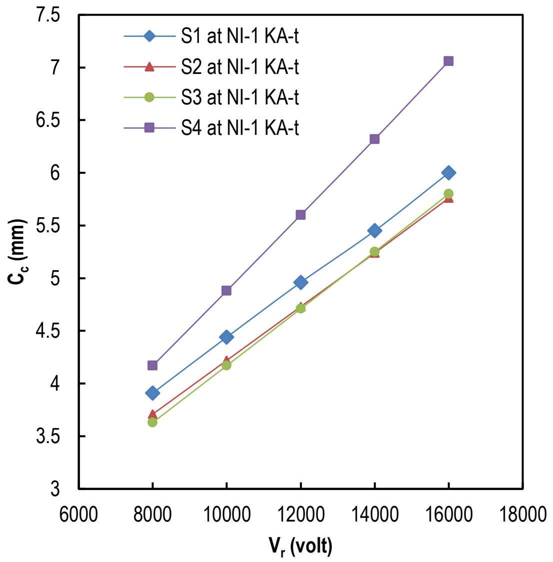


Fig. (4) Change of chromatic aberration with constant excitation function NI to the change of accelerating voltage V_r

3.5 Calculation of probe diameter formed in objective lenses

When determining the electronic beam's effective total diameter (d_p) as it strikes the model's surface, and the accompanying exposure due to the contributions of spherical or chromatic aberration and diffraction experienced by models the four models' objective lens as a function of aperture angle α_p [15], As shown in Fig. (7), where this figure shows the relationship between the diameter of the final effective probe (d_p) according to the aperture angle (α_p) for the four designs at fixed values for each of the excitation factor (NI=1000 A-t) and the voltage of acceleration (V_r=8kV), as a result (S3) lens has a lowest value of final effective electron probe diameter which corresponds to a aperture angle value as shown in table (3)

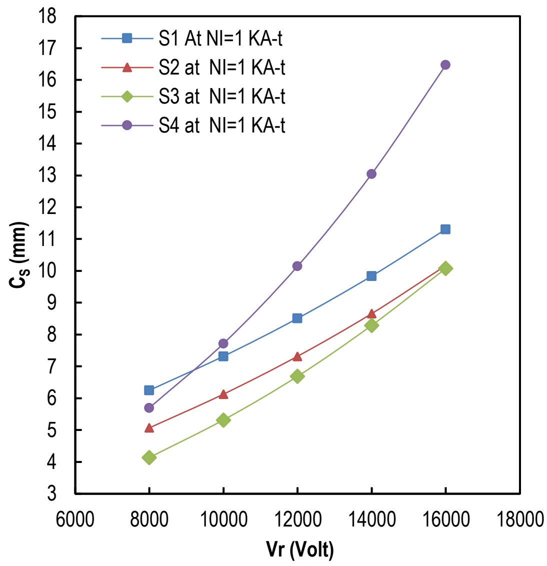


Fig. (5) Change of spherical aberration with constant excitation function NI to the change of accelerating voltage V_r

Table (3) Final effective electron probe diameter to the aperture angle

Lens icon	α_{opt} (mrad)	d_{pmin} (mm)
S1	5.5	5.7
S2	5.5	5.5
S3	5.5	5.4
S4	5.5	5.9

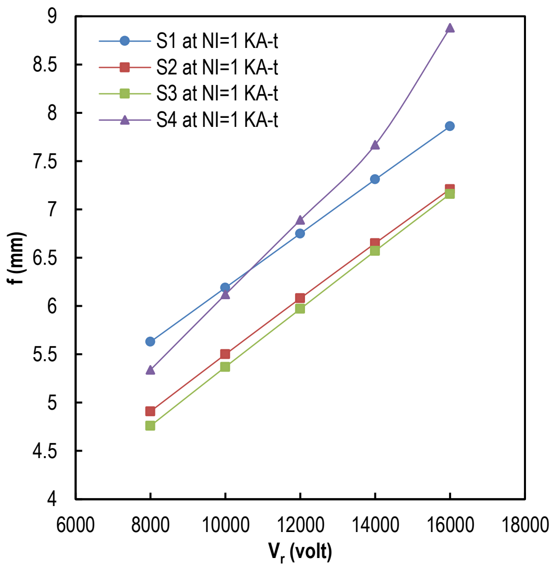


Fig. (6) The focal length change with the constant excitation function NI to the change in accelerating voltage V_r

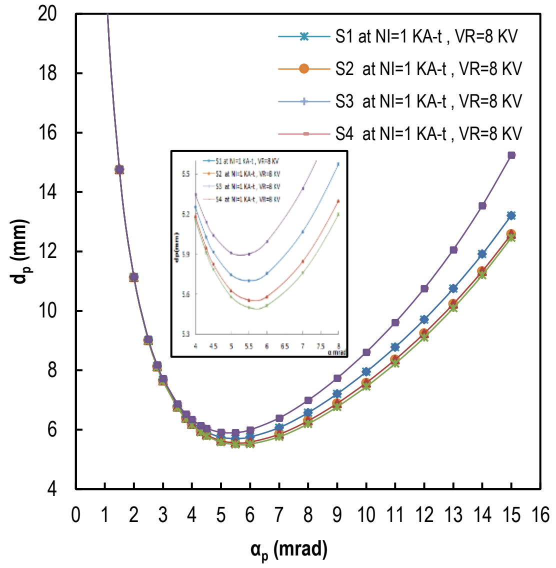


Fig. (7) The relationship between the diameter of the final acting probe d_p as a function of the aperture angle α_p for the four designs at fixed values for the excitation factor NI=1000(A-t) and the acceleration voltage V_r=8kV

4. Conclusions

It was noted that the Gemini objective lens with (S3=4mm) distance between the two pole pieces achieved good results compared to the other designs, studying the optical properties at a constant value of the excitation factor (NI = 1000 A-t) for all designs and changing the distance between the poles of the objective magnetic lens has a significant impact on the spherical and chromatic aberration coefficients and the focal length and increases with the increase in the distance between the poles and lens (S3) achieved the best results at the acceleration voltage (V_r=8kV), this lens has the lowest values for the focal length (f_0=4.76mm), as well as having the lowest value for the coefficients of spherical aberration (Cs=4.14mm) and chromatic aberration (Cc=3.63mm) at (NI=1000A-t) and final effective electron probe diameter (5.4mm) as a result we get an objective lens with better optical properties.

References

[1] D. McMullan, **"Scanning Electron Microscopy 1928 -1965"**, Scanning, 17 (1995) 175-185.

[2] S.A. Rishton, "Resolution limits in electron beam Lithography", Ph.D. thesis, University of Glasgow (1984).

[3] S.M.A. Al-Hali, "Electronic Microscope", Ministry of Higher Education and Scientific Research, University of Baghdad (1990). T.M.A Al-Shafi'i, "Magnetic Leakage through Magnetic Lens Electrode Slots", MSc thesis, University of Babylon (2001).

[4] A.S.A. Alamir, "Magnetic electron lenses performance", *Optik*, 112(11) (2001) 507-510.

[5] E. Plies, "Modren Electron Optics in SEM and Inspection", *Proc. 12th Euro. Cong. Electron Microscopy*, vol. 3 (2000).

[6] K. Tsuno, "Resolution limit of a transmission electron microscope with an uncorrected conventional magnetic objective lens", *Ultramicroscopy*, 50(3) (1993) 245-253.

[7] M.A.K. Al-Khashab, "The electron optical limits of performance of single-polepiece magnetic electron lenses", PhD dissertation, Aston University (1983).

[8] B. Lencová, "Computation of Electron-Optical Components", *IOP Conf. Ser.*, no. 93 (1988).

[9] B. Lencová and G. Wisselink, "Program package for the computation of lenses and deflectors", *Nucl. Instrum. Meth. Phys. Res. A: Acceler. Spectrom. Detect. Assoc. Equip.*, 298(1-3) (1990) 56-66.

[10] B. Lencová, **"Electrostatic Lenses"**, in Handbook of Charged Particle Optics, ed. J. Orloff, 2nd ed., CRC Press, Taylor & Francis (NW, 2009) Ch. 5, pp. 161-208

[11] W.M. Murad, "Design of iron-free magnetic electron lenses", M.Sc. thesis, University of Mosul (1998).

[12] M.A. Hussein, "Numerical analysis to verifying the performance of condenser magnetic lens in the scanning electron microscope", *Adv. Phys. Theor. Appl.*, 58 (2016) 44-49.

[13] E. Munro, "A set of computer programs for calculating the properties of electron lenses", *Cambridge University, Engineering Dept. Report* (1975).

[14] J. Podbrdsky, "High current density magnetic electron lenses in modern electron microscopes", *J. Scan. Electron Microscopy*, 3 (1986) 887-896.

[15] M.A. Hussein and M.Q. Kareem, "Estimating electron probe diameter in the scanning electron microscope", *J. Nat. Sci. Res.*, 6(18) (2016) 68-73.