



Design and studying the effect of Polepiece shape on the magnetic and optical properties of the unipolar lens

Mohammed. K. A. AL- Janan , R. Y. J. AL-Salih

Department of physics, College of Science, University of Tikrit, Tikrit, Iraq

<https://doi.org/10.25130/tjps.v27i6.760>

ARTICLE INFO.

Article history:

-Received: 23 / 5 / 2022

-Accepted: 17 / 7 / 2022

-Available online: 25 / 12 / 2022

Keywords: Magnetic lens, Chromatic aberration, Spherical aberration, Aberration, Resolving power.

Corresponding Author:

Name:

E-mail:

mohammed.k.awad.phys500@st.tu.edu.iq

Tel:

©2022 COLLEGE OF SCIENCE, TIKRIT UNIVERSITY. THIS IS AN OPEN ACCESS ARTICLE UNDER THE CC BY LICENSE

<http://creativecommons.org/licenses/by/4.0/>



ABSTRACT

The investigation of a study of each design included the calculation of its axial magnetic field the magnetization of the lens in addition to the magnetic flux density using Finite Element Method (FEM) at three different values of current density ($\sigma = 2, 4$ and 6 A/mm^2). So clearest values and behavior have been obtained at the value current density of (2 A/mm^2). It is found that the best magnetizing properties, the highest value of magnetic flux and the lowest value of band width of the axial magnetic field strength have been obtained when the pole head shape length was of (1 mm). The effect of current density on the optical properties has been also studied, and it is found that optical properties have been improved also, and chromatic and spherical aberration values have been decreased significantly. Thus, lens was chosen as the best design among the proposed designs.

1. Introduction

Electron optics science can be defined as the mathematical framework for calculating electron beam paths along electromagnetic fields, studying their behavior and controlling them. The term "optics" is used because magnetic and electrostatic lenses affect the electron beam in the same way that glass lenses affect an optical beam [1]. Optimal design of magnetic electron lens with low aberration coefficients, i.e. high magnetic properties and bad optical properties is generally considered important in various fields of optoelectronics and its scientific and industrial applications [2]. Accordingly, magnetic lens is defined as an axially symmetric field affecting charged particles passing through it. The simplest magnetic lens is the iron-free coil, but most magnetic lenses contain iron and poles. Based on the number of poles, magnetic lenses can be classified into four types: iron-free lens, unipolar lens, bipolar lens. Unipolar lens is considered one of the most important scientific achievements in this field, that was designed by Mulvey [3]. The poles protrude beyond

its yoke causing the magnetic flux density to rush away from the lens mount [4], allowing more freedom of movement for the Electron microscopes [5]. The researchers seek to reduce amount of aberrations as much as possible to create a high-quality image. However, the axial flux density distribution has been calculated by FEM that finite element introduced in electron optics by Monroe in 1971. Monroe applied it to calculating the magnetic field in a round lens [6]. Axial flux density distribution was calculated using a computer software [5]. The Writing Munro programs has been written in FORTRAN language [2]. In 1982, Mulvey deflection of the magnetic electron lens was reduced, and it was found that it requires a high flux density with a low half width [2]. In 1991, Al-Khashab and abbas rigorous studies were carried out to improve geometry and dimensions of magnetic electron lenses and to improve the shape of its shaft. The unipolar lens was studied [7]. In 1996, Al-Obaidy studied the angles of the bore and pole were clarified on the

objective focal characteristics [8]. In 2004, Al-Khashab and Ahmed studied the effects of the geometry of the polar segment on the objective lens, several engineering approaches to the pole segment of a magnetic projector lens and its effect on the flow lines [9] In 2006 Abd-Hujazie the study of parameters [10]. Which was used as one-piece magnetic lenses of a conical electrode cut by excitation of coils of rectangular cross section for low light energies and in 2010 the parameters were recently studied [11]. In 2013, El-Shahat *et al*, explored the objective properties of a magnetic unipolar lens with different shapes of shaft segments where the results indicate that a spherical-faceted lens has the best accuracy [12]. In 2015, Abdullah was interested in the influence of current density and lens dimensions on the design of iron-free magnetic lenses. There was a magnetic field measured for different values of current density. Also, its radial and helical deformation deflection coefficients were calculated [13]. In 2018, Numan presented some of the critical geometric properties of the lens, such as bore diameter, magnetic flux density, focal length, magnification, and spherical aberration [14]. In 2020, Sarah and others studied the effect of the thickness of the pole face on the magnetizing properties of the unipolar magnetic lens [15]. In 2021, Basma and Ahmed were able to design magnetic lenses with optimal operating conditions, as they studied the effect of the diameter of the axial aperture, the air gap between the poles, and the thickness of the electrode face on the magnetic and optical properties, and they found that the optical and magnetic properties improve with reducing The diameter of the axial aperture and also with the reduction of the air gap between the poles of the unipolar magnetic lens [16]. This computational theoretical research aims to design and study the magnetic and optical properties of unipolar magnetic lens. by choosing a proposed design for these lenses and studying the effect of some engineering factors such as the pole head shape and current density on the designed lens using Magnetic Electron Lens Optical Properties (MELOP) [17], Program for Calculating the Axial Magnetic Field Distribution of Magnetic Lenses using Finite Element Method (CMFD-FEM) [18]. And also using the Electron Optical Design (EOD) programs [19].

2. Theoretical Considerations

In this work, the magnetic and optical properties of designed lenses have been studied, in order to reach the best design among the proposed lenses, and these properties will be explained in the following sections.

2.1 Flux Density Distribution Models of Magnetic Lenses

The equation of the paraxial ray equations reveals that there is no way determining electron-beam trajectory without knowing the axial magnetic field distribution B_z . Different

mathematical models have been used to explain the axial flux density distribution of magnetic lenses and in the following subsection some of these models [20].

1- Glaser's bell-shaped model:

In such model, the axial distribution of magnetic field (B_z) is given by [21]:

$$B_z = \frac{B_m}{1+(z/a)^2} \dots (1)$$

where B_m is the maximum magnetic flux density, z is the optical axis of system, a is the half-width at half maximum

2- Related bell-shaped curves:

In particular to the case $n = \frac{3}{2}$, the field of a single turn, $n = 2$ and, $n = \infty$

for which the distribution becomes Gaussian with suitable weighting and given by [22]:

$$B_z = \frac{B_m}{(1+z^2/a^2)^n} \dots (2)$$

3- Grivet-lens model:

In this model B_z is given by:

$$B_z = B_m \sec h \left(\frac{z}{a} \right) \dots (3)$$

4- The exponential model:

$$B_z = B_m \left[\frac{a}{z} \right]^3 \dots (4)$$

2.2 Aberrations

The most important aberration experienced by the lens is spherical aberration and chromatic aberration, so these two defects were relied upon as a basis for judging the superiority of these lenses.

2.2.1 Spherical Aberration

This aberration is sometimes known as an aperture defect and it is one of the geometrical aberrations that determine the resolving power of magnetic lens. The reason for the appearance of this aberration is the difference in the breaking strength of the lens of the electron beam far from the axis from one close to it as a result of the increase in the convexity of the magnetic flux lines with the distance from the optical axis. As a result, electrons that pass away from the axis are refracted with greater force than those that pass close to it. Generally, the spherical aberration equation is given by [22]:

$$C_s = \frac{\eta}{128V_r} \int_{z_0}^{z_i} \left[\left(\frac{3\eta}{V_r} \right) + B_z^4 r_\alpha^4 + 8B_z^2 r_\alpha^4 - 8B_z^2 r_\alpha^2 r_\alpha' \right] dz \dots (5)$$

$$V_r = V (1 + 0.978 * 10^{-6} V) \dots (6)$$

where η is The ratio of an electron's charge to its mass e/m , z_i , z_0 is The position of the body and the image respectively, V_r is Relatively corrected acceleration voltage, r_α is Path of the electron beam

inside the lens, r_α' is the first derivative of the electron beam path

with respect to α , B_z' is the first derivative of the axial magnetic flux density with respect to z .

Spherical aberration is one of the very important aberrations that occur in the lens due to affecting on

the quality of the image formed by this lens and plays a vital role in determining the analysis ability of electron microscope, that is given by the following relationship [23]:

$$\delta = 0.61(C_s \lambda^3)^{1/4} \dots (7)$$

2.2.2 Chromatic Aberration

This aberration occurs in magnetic lenses due to the difference in the speed of the electrons emitted from the source or because of the change in the magnetic field of the lens due to the instability of current of the excitation coil, which leads to a change in the energy with which the electrons scatter. Therefore, particles with high velocities are less affected by the imaging field that collects at a point farther to the body than those with low velocities. In general, the coefficient of chromatic aberration is given by the following relationship [23]:

$$C_c = \frac{\eta}{8V_r} \int_{z_0}^{z_1} B_z^2 r_\alpha^2 dz \dots (7)$$

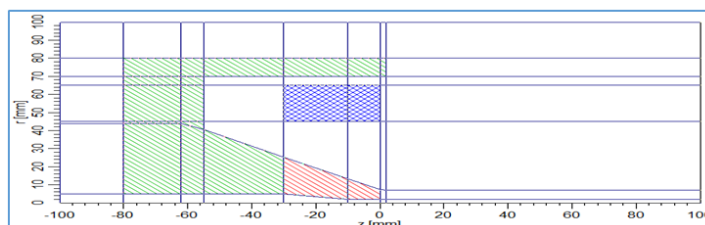


Fig. 1: Cross-section of a magnetic unipolar lens prototype



Fig. 2: 3-D of a magnetic unipolar prototype lens

Other designs were made after changing pole head shape (H) with values (20,16,12,10,8,4,1 mm). The magnetic and optical properties of these designs were studied at different densities of current ($\sigma = 2, 4$ and 6 A/mm^2). The details are shown in the following sections.

4. Results and Discussion

4.1 Magnetic Properties

The prototype design and the other six proposed designs were studied and their magnetic and optical

3. Practical Part

In the present work, the finite element method has been used to study the magnetic and optical properties of the proposed lenses that lead to the upper limit of axial magnetic flux density and the minimum coefficients of deflection. Into three parts of the current densities: the 1st when ($\sigma = 2 \text{ A/mm}^2$), the 2nd when ($\sigma = 4 \text{ A/mm}^2$), and the 3rd when ($J = 6 \text{ A/mm}^2$).

3.1 Suggested Designs

Seven new designs have been made for unipolar lens by starting with a prototype that it is as shown in Figure (1) below. This last figure (1) shows a cross section in 2-Dimension, while Figure (2), shows three-dimensionality when entering its geometry data into the EOD program [20]. This lens is equipped with a coil of cross-sectional dimensions (30 x 20 mm) and a number of turns (750 turns).

properties were compared, and explained in the following sections.

4.1.1 Magnetic Properties of the (Prototype) lens

In order to study the magnetic properties of the primary unipolar lens prototype shown in Figure (1). The distribution of axial magnetic flux density (B_z) has been calculated for three different values of current density ($\sigma = 2, 4$ and 6 A/mm^2).as it is shown in Figure (3) below.

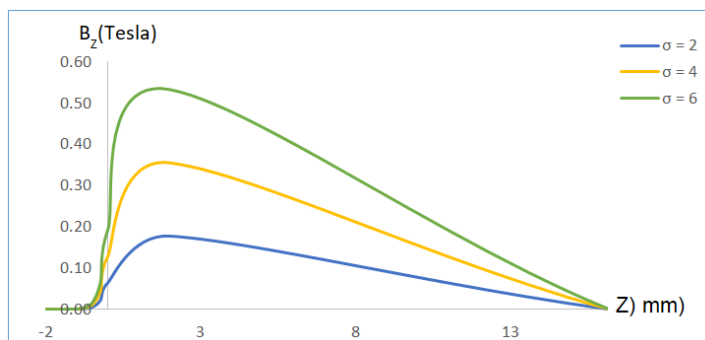


Fig. 3: Distribution of axial magnetic flux density (B_z) as a function of the distance (z) of the designed lens at a variable density of current density ($\sigma = 2,4$ and 6 A/mm^2).

It is noted that the above figure shows that the highest value of the axial magnetic field. When the current density is 6 and is equal to ($B_{\max} = 54 \text{ T}$). The importance of increasing the values of axial magnetic field curves lies in the focus of electronic beam, which passes through the optical axis of the lens used.

4.1.2 Magnetic Properties of Designed Lenses

One of the important aim of this study is to design a lens that operates at low voltage range ($< 20 \text{ kv}$) efforts. Therefore, the lowest studied current density ($\sigma = 2 \text{ A/mm}^2$) was chosen. The magnetic properties of all (7) designs were studied at current density ($\sigma = 2 \text{ A/mm}^2$) as shown in Figure (4).

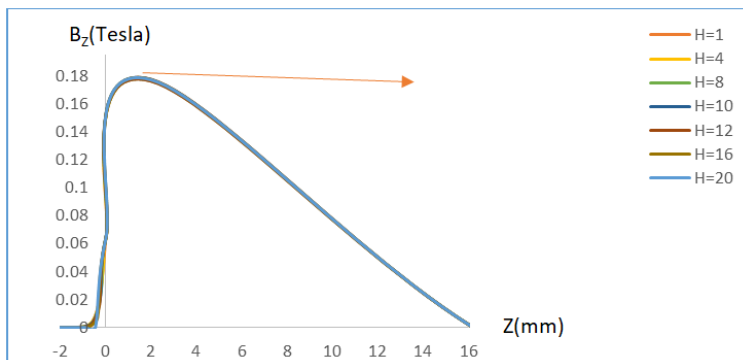


Fig. 4: Illustrates the distribution of the axial magnetic flux density (B_z) as a function of the distance (z) of the designed lenses at a current density ($\sigma = 2 \text{ A/mm}^2$)

Although we obtained a clear difference in the value of (B_z) for the above clear curves, but this is not enough to distinguish the value of the best lens among studied values, due to the presence of other properties that have not yet been studied such as optical properties of the magnetic lens, which we will study and discuss in detail. In the items below, however, it can be said that this result we can count as a preliminary indication.

4.1.3 Optical Properties

To study optical properties, a comparison of the optical properties for all the suggested lenses have been made using different current densities ($\sigma = 2,4$ and 6 A/mm^2). as listed in Figures (5), (6), (7) below, that shows the relationship between the values of the chromatic aberration coefficient (C_c) relative to the focal length as a function of the relatively corrected acceleration voltage (V_r).

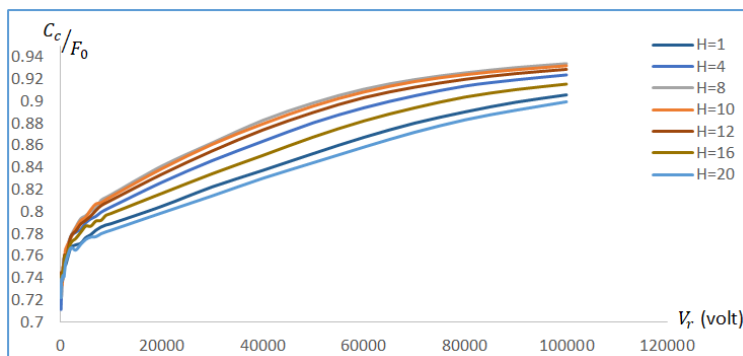


Fig. 5: C_c/f_0 as a function of the relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($\sigma = 2 \text{ A/mm}^2$)

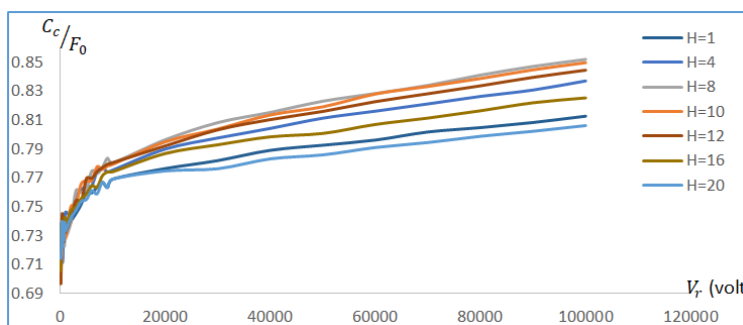


Fig. 6: C_c/f_0 as a function of the relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($\sigma = 4 \text{ A/mm}^2$)

Figures (8), (9), (10) below show the values of the spherical aberration coefficient (C_s) relative to the

focal length as a function of V_r . Where the values started from a few regions.

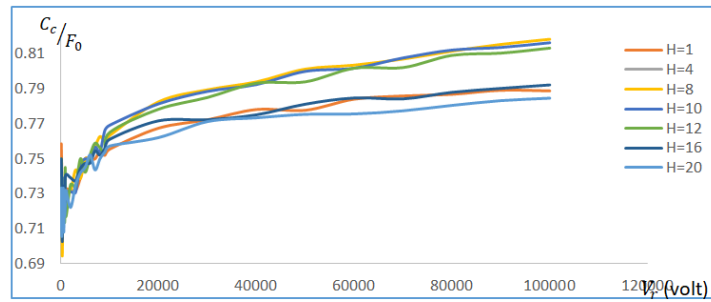


Fig.7: C_c/f_0 as a function of the relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($\sigma = 6 \text{ A/mm}^2$)

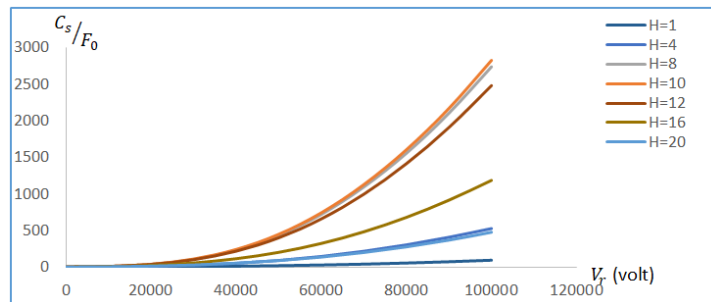


Fig. 8: C_s/f_0 as a function of the relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($\sigma = 2 \text{ A/mm}^2$)

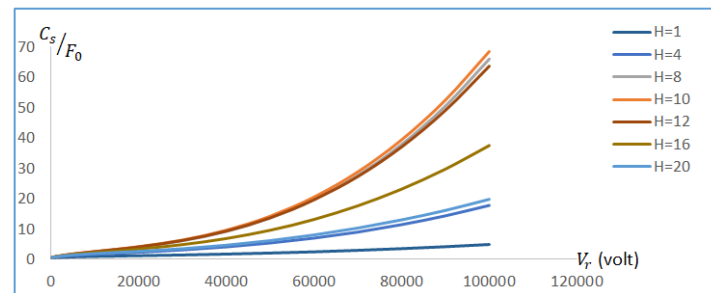


Fig. 9: C_s/f_0 as a function of the relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($\sigma = 4 \text{ A/mm}^2$)

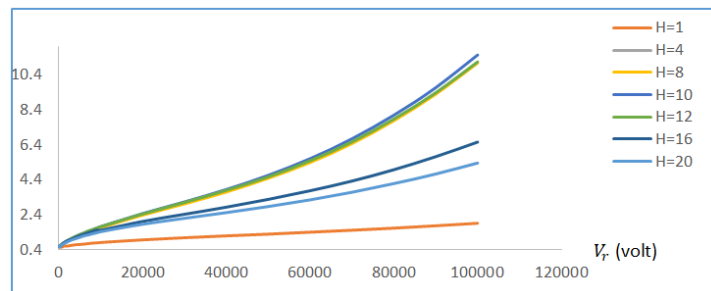


Fig. 10: C_s/f_0 as a function of the relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($\sigma = 6 \text{ A/mm}^2$)

From the last six figures (5_10) shown above, it is found that the best optical properties obtained for the design of the proposed lenses in this work is that pole head length of (1 mm), and thus the lowest values lenses of aberrations that correspond to the desired objective in this study has been obtained ,and despite the identification of the best design, this is not sufficient to reach the desired goal, so there is a need

to study another visual property to improve the possibility of distinction and preference. Therefore, the study of resolving power (δ) for these proposed designs. The three figures below (11), (12), (13) represent the values of the resolving power (δ) for magnetic lenses as a function of V_r . The value of (δ) has been calculated from the aforementioned equation (7).

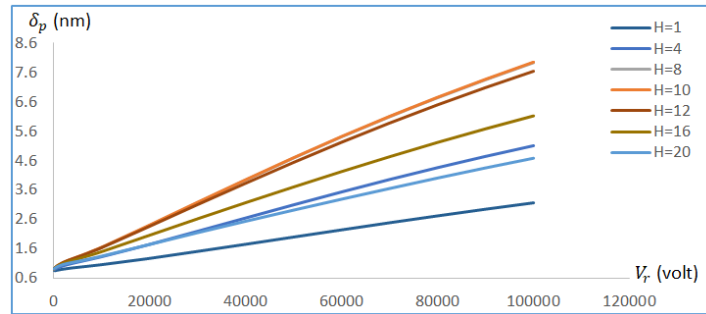


Fig. 11: δ as a function of voltage as a function of the proportionally corrected acceleration voltage V_r (volt)

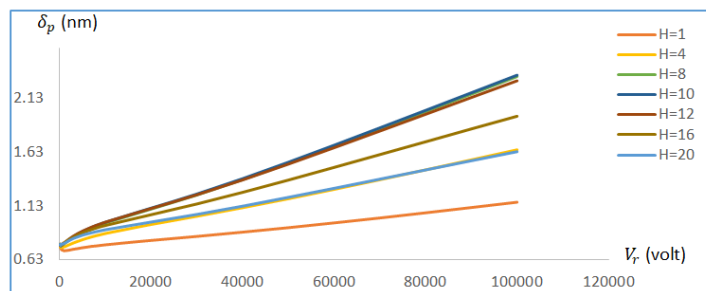


Fig. 12: δ as a function of voltage as a function of the proportionally corrected acceleration voltage V_r (volt)

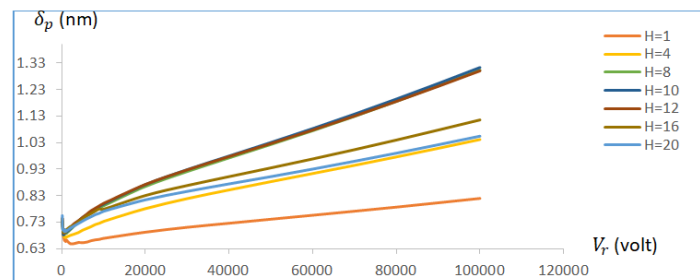


Fig. 13: δ as a function of voltage as a function of the proportionally corrected acceleration voltage V_r (volt)

From the last three figures (11_13) shown above, it is found that the best resolving power obtained for the proposed lens design is when the pole head length is (1mm) and this result reinforces the previous results obtained from the comparison between the values C_c/f_0 and C_s/f_0 in the figures Previous (5_10).

5. Conclusions

In this work, it is found that the magnetic flux density increased when the inner bore diameter decreases. So, booth of chromatic and spherical aberration factors is decrease with the decrease of pole head length, leading to better optical Characteristics. In addition, when the current density increases, the maximum flux density increases, while the aberration factors decrease and the resolving power (δ) will improved. It was found also, when the current density increased by two value the magnetic field will increase by ($B_z = 0.18$ Tesla). All of these results are close and developed to the results that were reached by researchers in this field, as they have been generally improved.

6. References

[1] Harald, H. R. (2008). Geometrical Charged-Particle Optics, Springer-Verilog, Berlin.
 [2] Mulvey, T.(1982).Magnetic Electron Lens Properties", Ed. Hawks, P. W. (Berlin, Springer): Ch. 5.
 [3] Mulvey T, improvement in or relating to magnetic lenses, British patent Application
 [4] Plies, E.; (2000). Modren Electron Optics in SEM and Inspection. Proc. 12th Europ. Congr. Electron Microsc. ,3, 1423-1425.
 [5] Cleaver, J. R. A.; (1979). Field emission electron gun systems incorporating single-pole magnetic lenses. *Optik*, **52(4)**: 293-303.
 [6] Orloff, J. (Ed.). (2017). Handbook of charged particle optics. CRC press.
 [7] Al-Khashab, M. A.; Abbas, I.K. (1991). Optimized Pole Piece Shape for Single Pole piece Magnetic Electron Lenses, *Modeling, Simulation and Control, A. AMSE Press*, **35(3)**: 1-9.

- [8] Al-Obaidy.K. (1996). Design of the High Resolution Electromagnetic Lens for the Electron Microscope (Doctoral dissertation, M. Sc. Thesis, The University of Mosul, Mosul, Iraq).
- [9] Al-Khashab, M. A.; Ahmed, A. A.H. (2004). Some approaches to the projector lens pole piece geometry and their effect on magnetic flux lines. *Dirasat, Pure Sciences*, **31(1)**: 22-29.
- [10] Abd-Hujazie, N. S; Al-Khashab, M.A. (2006). Design of a compound lens (magnetic-electrostatic) for low voltage scanning electron microscope. Doctoral dissertation, Ph. D. Thesis, University of Mosul, Iraq; 144.
- [11] Al-jumayli, F.A. (2010). Design and Fabrication a Chroma Corrected Objective Compound Lens for Low Beam Energies for Scanning Electron Microscope, Ph.D. Thesis, and the University of Mosul in Mosul, Iraq.
- [12] El-Shahat, S.S.; Al Amir A. S. A.; Hassan G.S. (2013). Studies on the effect of pole piece shape for saturated single pole magnetic lens. *Proceedings of the 1st International Conference on New Horizons in Basic and Applied Science, Hurghada-Egypt*, **1 (1)**: 290-298.
- [13] Abdulla, R.T. (2015). Study the Optical Properties of Iron- Free Magnetic Lens. *Journal of Al Nahrain University (science)*, **18 (2)**: 79-82.
- [14] Numan, N.H. (2018). Theoretical Study of Geometrical Properties and Aberrations in Doublet Magnet Lenses. *Journal of University of Babylon for Engineering Sciences*, **26 (8)**: 178-187.
- [15] Sultan, S.A.; Mustafa, A.I.; Abdel Aziz, A. F.A. (2020). Effect of electrode face thickness on the magnetizing properties of a monopolar magnetic lens. *Rafidain Journal of Science*, **29 (4)**: 44-52.
- [16] Abd Alghane, B.F.; Ahmad, A.K. (2021). Design of symmetric magnetic lenses with optimum operational conditions. *Al-Nahrain Journal of Science*, **24(1)**: 30-38.
- [17] Al-Salih, R.Y.J.; Al-Abdulla, A.I.; Alkattan, E. M.A. (2021). Simple program for computing objective optical properties of magnetic lenses. *International Journal of Computer Applications in Technology*, **66 (3-4)**: 254-259.
- [18] Al-Salih, R. Y.J.; Al-Abdulla, A.I.; Alkattan, E. M.A. (2022). Program for Calculating the Axil Magnetic Field Distribution of Magnetic Lenses using Finite Element Method. *International Journal of Computer Applications in Technology*, **16(5)**.
- [19] Lencová.B.; Zlámá.J. (2008). A new program for the design of electron microscopes. *Physics Procedia*, **1(1)** : 315-324.
- [20] Szilagy, M., (1988) *Electron and Ion Optics*. Plenum Press: New York and London.
- [21] Hawkes, P.W. and Kasper, E. (1989) *Principle of Electron Optics*. Vol.1 and 2, Academic press: London.
- [22] Hussain, S.H.; Obaid, S.A.; Erhayial, M.S. (2022). Recent Development-2 of CADTEL Software: The Optimum Conditions of Scherzer Imaging in the Electron Magnetic Lenses. *Iraqi Journal of science*, **63 (1)**: 131-148.
- [23] Gagnon. E.; Owusu, N.K.; Lytle, A.L. (2016). Time evolution of the Coulomb screening effects on terahertz generation at the surface of InAs. *Journal of the Optical Society of America B*, **33(3)**: 367-372.

تصميم ودراسة تأثير شكل راس القطب على الخصائص المغناطيسية والبصرية لعدسة أحادية القطب

رافع يونس جاسم الصالح ، محمد كردي عواد الجنعان

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

الملخص

تم دراسة إمكانية تحسين أداء العدسة المغناطيسية أحادية القطب ذات تصاميم مختلفة. ثم اجراء دراسة لكل تصميم تتضمن دراسة تمغنط العدسة وحساب المجال المغناطيسي المحوري إضافة الى كثافة الفيض المغناطيسي باستخدام طريقة العناصر المتناهية عند ثلاث قيم مختلفة لكثافة التيار ($2,4,6 \text{ A/mm}^2$). وتم الحصول على اوضح القيم والسلوك عندما كانت كثافة التيار بمقدار (2 A/mm^2). وجد ان أفضل خواص تمغنط واعلى قيمة لكثافة الفيض المغناطيسي واقل قيمة لعرض نطاق شدة المجال المغناطيسي المحوري تم الحصول عليها عندما كان طول شكل راس القطب (1 mm)، تم أيضا دراسة تأثير كثافة التيار على الخصائص البصرية بان الخواص البصرية للعدسة تحسنت ايضاً، حيث لوحظ بان قيم الزيوغ اللونية والكروية قلت بشكل ملحوظ لذلك تم اختيار هذه العدسة كأفضل تصميم من بين التصاميم المقترحة. الكلمات المفتاحية: العدسة المغناطيسية، الزيغ اللوني، الزيغ الكروي، الزيغ، القدرة التحليلية.