Design and study the effect of inner bore diameter on the magnetic and optical properties of the unipolar lens

Mohammed. K. A. AL- Janan* [ID]   *R.Y. J.AL-Salih* [ID]

Department of physics, College of Science, University of Tikrit, Salahaddin, Iraq.
*Corresponding author: mohammed.k.awad.phys500@st.tu.edu.iq
E-mail address: r.y.jasim@tu.edu.iq

Abstract

Many designs have been suggested for unipolar magnetic lenses based on changing the width of the inner bore and fixing the other geometrical parameters of the lens to improve the performance of unipolar magnetic lenses. 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 the Finite Element Method (FEM) the Magnetic Electron Lenses Operation (MELOP) program version 1 at three different values of current density (6,4,2 A/mm^2). As a result, the clearest values and behaviors were obtained at current density (2 A/mm^2). it was found that the best magnetizing properties, the highest value of magnetic flux, the lowest value of band width of the axial magnetic field strength had been obtained when the width of the inner cavity was of (55 mm). The effect of current density on the optical properties has also been studied, the chromatic and spherical aberration values have been decreased significantly. Thus, lens was chosen as the best design among the proposed designs unipolar lens.

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

Introduction

Electron optics science only 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 as glass lenses on an optical beam[1,2], where the magnetic lens consists of the iron circle, coil and pole. Electron optics depends on two main pillars. The first pillar is the hypothesis of the physicist Louis de Broglie in 1925 about the wave nature of particles, which states that "a particle with a mass (m) and velocity (ν) is accompanied by a wave of length (λ) associated with the particle's momentum according to the following relationship [3]

$$\lambda = \frac{h}{m\nu} \qquad 1$$

where' (h) is Plank's constant which is equals (6.62 × 10^{-34}) J .sec. The second pillar was demonstrated practically by the scientist Hans Busch in 1927, who demonstrated that magnetic or electrostatic fields[3]affect the electron beam and cause it to deviate and focus at one point [2]. The distribution of the field that possesses the power of focusing Only called the lens. Busch was the first person who defined the electronic lens with this name and gave it the optical explanation. This is how the idea of the electron microscope began to be formed after these two discoveries in the field of electronic optics [4].

Today, electron optics instrument become an indispensable analytical instrument in many fields of technology. And they have witnessed great development and wide breakthroughs in a short period of time. is defined as magnetic lens as an axially symmetric magnetic field that affects 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: unipolar lens, bipolar lens, iron-free lens and multipolar. Unipolar lens is considered one of the most important scientific achievements and in the field of magnetic lens design[5].That it was designed by MUIVEY 1972.Where the axial flux density of distribution was calculated using computer software that written in the FORTRAN language in 1975. Electron Optics design (EOD) Program 2012, The protrusion

of its poles outside its surface, which leads to the rush of magnetic flux density away from installation of lens [5,6], allowing more freedom of movement for the model. In 2013, El-Shahat and co-workers explored the objective properties of a unipolar magnetic lens with different shaft segment shapes as the results indicate that a spherical-faceted lens has better resolution [7]. In 2018, Nuaman presented some critical geometric properties of the lens, such as bore diameter, magnetic flux density, focal length, magnification and spherical aberration, and improved results for his lens used [8]. In 2020 Sarah, Abdel-Sami' and Abdullah Drees presented a study of the effect of electrode face thickness on the magnetizing properties of a magnetic lens, unipolar and concluded that the thickness of the pole face has a significant effect on the magnetic field produced by the magnetic lens unipolar [1,9].

This research aims to design and study properties of a unipolar magnetic lens, by choosing a proposed design for these lenses and studying the effect of some engineering factors such as the diameter of the inner bore and current density on the designed lens using the Magnetic Electron Lenses Operation (MELOP) program (LENS 2 Shortcut) [10]. And also using the Electron Optics design (EOD) program.

Theoretical Considerations
In this work, the magnetic and optical properties of the 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.

Flux Density Distribution Models
The equations of paraxial ray reveals that there is no way to determine an electron beam trajectory without knowing the axial magnetic field distribution B_z. Different mathematical models are used to explain the axial flux density distribution in the following subsection some of these models [11].

1- Glaser's bell-shaped model:
In such model, the axial distribution of magnetic field (B_z) is given by [3]

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

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 [11]

$$B_z = \frac{B_m}{\left(1+z^2/a^2\right)^n} \qquad\qquad 3$$

Spherical-Aberration
It is the aberration that affects the field of lens, and it is considered the most important primary aberration. can be calculated from the integral form [12-14]

$$C_s = \frac{e}{128\,m\,V_r} \int_{z_o}^{z_i} \left(\frac{3e}{mV_r} B_z^4\ r_\alpha^4(z) + 8\,B_z^{2\prime}\ r_\alpha^4 \right.$$
$$\left. - 8\,B_z^2\ r_\alpha^2(z)\ r_\alpha^{\prime 2} \right) dz \qquad\qquad 4$$

where (e) the charge of electron , (m) the mass of electron , (V_r) the relatively corrected acceleration voltage , (B_z) axial magnetic flux density of the distribution , (r_α) solve the axial x-ray equation.

The spherical aberration is one of most important aberrations that occur in the lens because it affects the quality of the image formed by this lens and plays an important role in determining the analysis ability of electron microscope, which is given by the following relation power [15]

$$\delta = 0.61(c_s\lambda^3)^{1/4} \qquad\qquad 5$$

Chromatic-Aberration
It is the aberration that depends on the difference in the speed of the electron that is emitted from the source is the coefficient of chromatic aberration C_c of an axially symmetric magnetic optical element is given by [16,17]

$$C_c = (e/8mV_r) \int_{z_0}^{z} B^2(z)h^2(z)dz \qquad\qquad 6$$

Thus, h(z) is given by [8,14]
h(z)= f r(z)   7
where '
f is the focal length
integration covers the whole interval from object plane zo to image plane zi

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. the current densities are divided in to three parts: the first when ($J = 2$ A/mm^2), the second when ($J = 4$ A/mm^2), and the third when ($J = 6$ A/mm^2). These densities were chosen according to a theoretical principle and the clarity of the difference in the values to be studied.

Suggested Designs

Six innovative designs were made for a unipolar lens by making a basic design prototype as shown in Fig.1 below, which that shows a cross section. In two dimensions, while Fig.2, shows three-dimensionality when entering its geometry data into the EOD program. This lens is equipped with a coil of cross-sectional dimensions (30 x 20 mm) and a number of turns (750 t). Other designs were made after changing the diameter of the inner cavity (W) with values (55,51,47,43,39,35 mm). The magnetic and optical properties of these designs were studied at different densities of current (J=2,4,6 A/mm^2) The details are shown in the following sections.
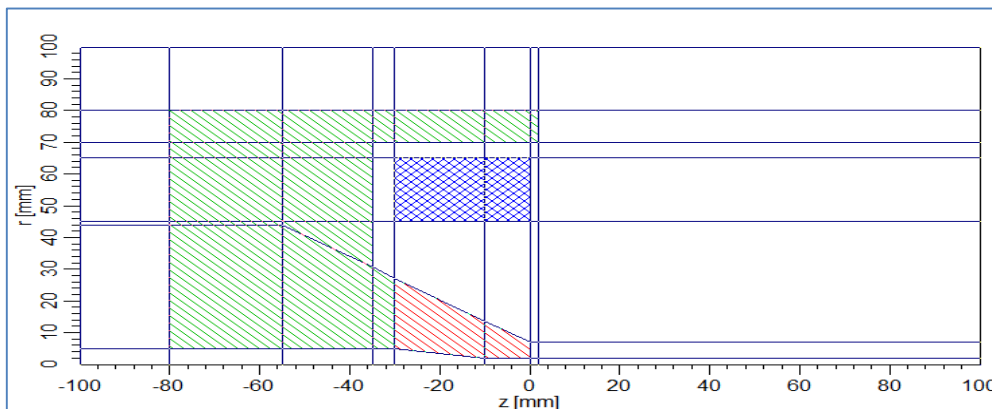

Figure 1. Cross-section of a magnetic unipolar lens prototype
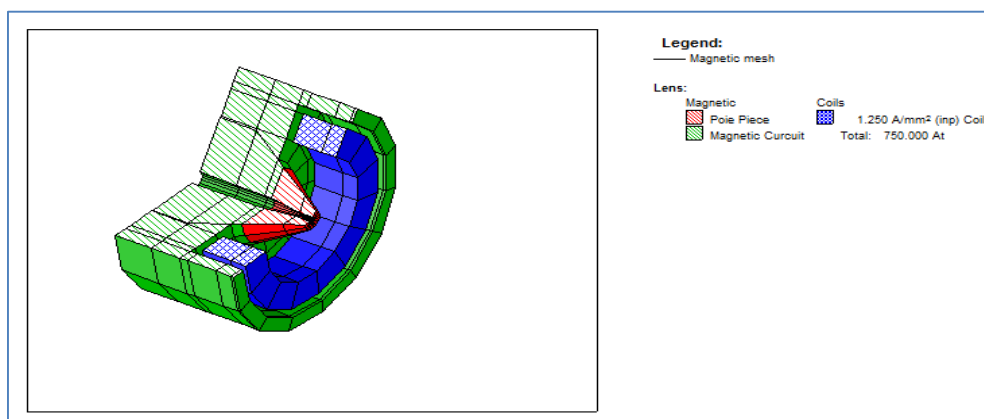


Figure 2. 3-D of a magnetic unipolar prototype lens

Results and Discussion
Magnetic Properties

The basic design prototype and the other five proposed designs were studied, their magnetic and optical properties were compared, explained in the following sections.

Magnetic Properties of the Prototype lens:

In order to study the magnetic properties of primary unipolar lens prototype shown in Fig.1. The distribution of axial magnetic flux density (B_z) has been calculated for three different values of current density (J=2,4,6 A/mm^2) as it is shown in Fig.3 below.
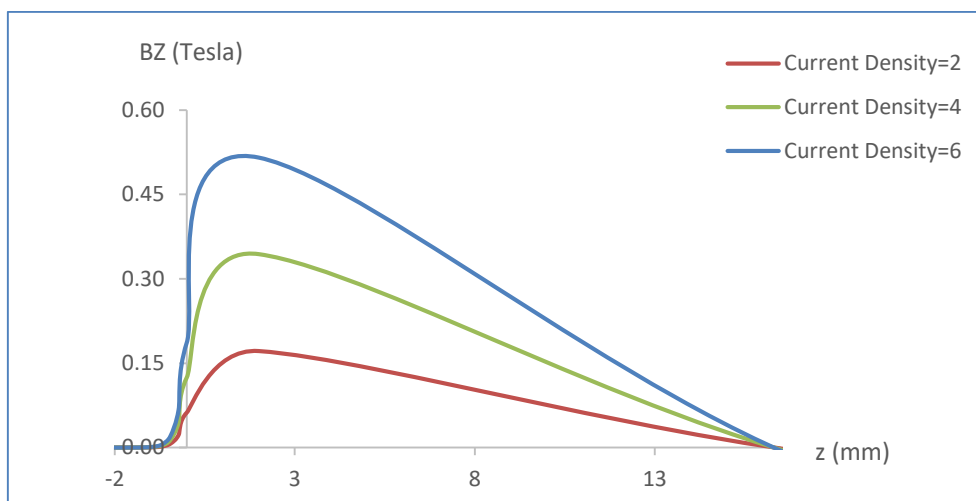
Figure 3. Distribution of axial magnetic flux density (B_z) as a function of the distance (z) of designed lens at a variable density of current density (J=2,4,6 A/mm²).

Table1. Illustrative of the values current density (J) and maximum flux density (B_m)

| J (A/mm²)	B_m(T)
6	0.18
4	0.36
2	0.54

It is noted that the above figure shows that the highest value of the axial magnetic field [17]. Is when the current density is 6 and is equal to (B_{max}=0.54

T). The importance of increasing the values of the axial magnetic field curves lies in the focus of the electronic beam, which passes through the optical axis of lens used.

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 kv) efforts. Therefore, the lowest studied current density (J=2 A/mm²) was chosen. The magnetic properties of all (6) designs were studied at a current density (J=2 A/mm²) as shown in Fig.4.
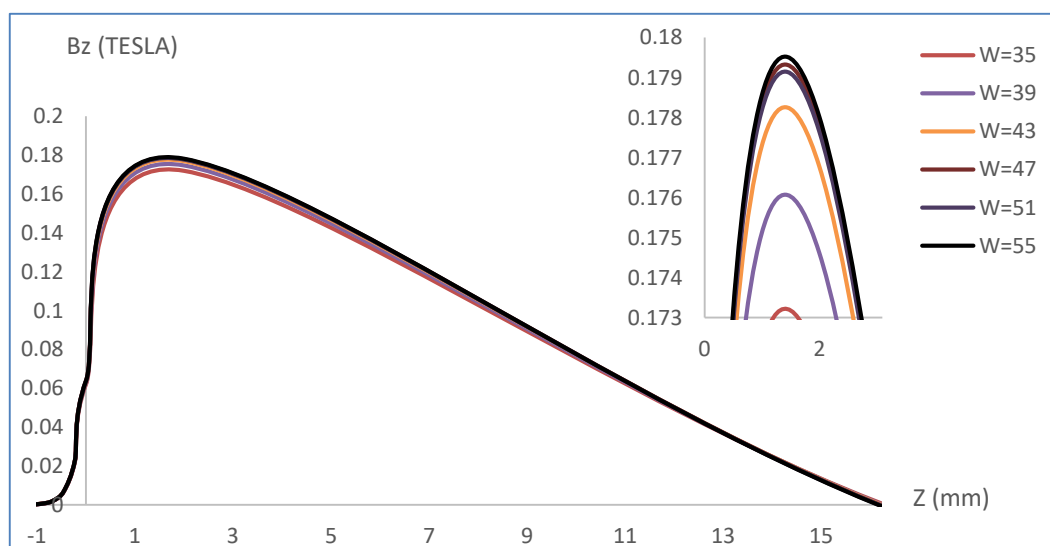
Figure 4. illustrates the distribution of axial magnetic flux density (B_z) as a function of the distance (z) of designed lenses at a current density (J=2 A/mm²)

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Table 2. Illustrative of the values the diameter of the inner (W) and axial magnetic flux density (B_z)

| W (mm)	B_z (T)
35	1733876
39	1759543
43	0.178254
47	0.179101
51	0.179655
55	0.179706

Although we obtained a clear difference in the value of (B_z), but this is not enough to distinguish the value of the best lens, due to the presence of other properties that have not yet been studied such as the 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 be counted as a preliminary indication.

Optical Properties

To study the optical properties, a comparison of the optical properties for all the suggested lenses have been made using different current densities ($J=2,4,6$ A/mm^2) as listed in Fig.5-7 below, that shows the relationship between the values of the chromatic aberration coefficient (C_c) relative to the focal length, as a function of relatively corrected acceleration voltage (V_r). Writes the diameter of the inner cavity (W) with values (55,51,47,43,39,35) without units. The reason for choosing these values is based on the change in the diameter of the inner bore. The reason for the small difference is the small change in the inner bore diameter.
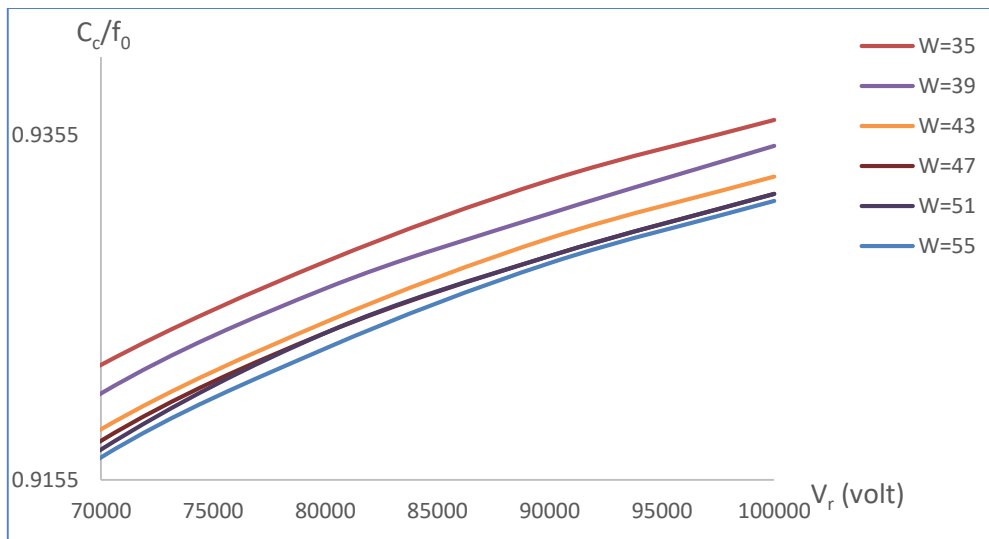
Figure 5. Relationship between C_c/f_0 as a function of relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($J=2$ A/mm^2)
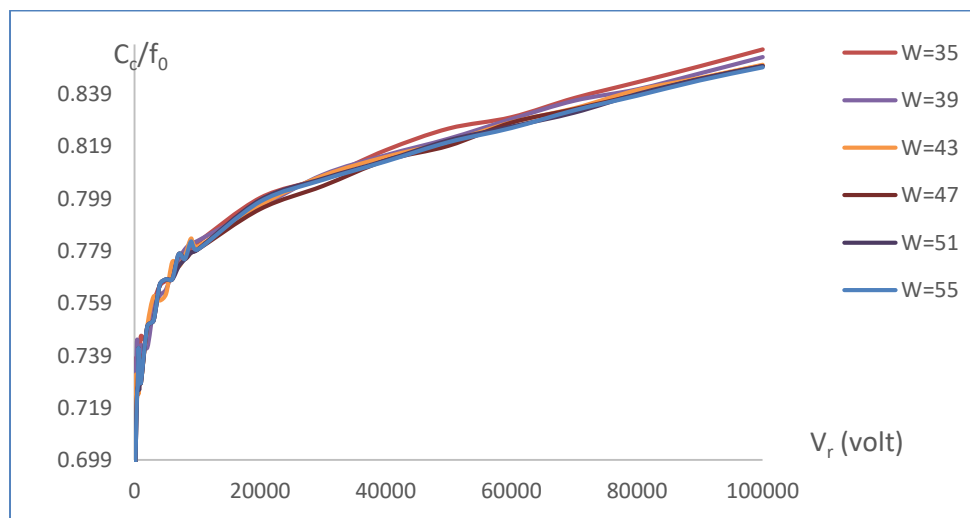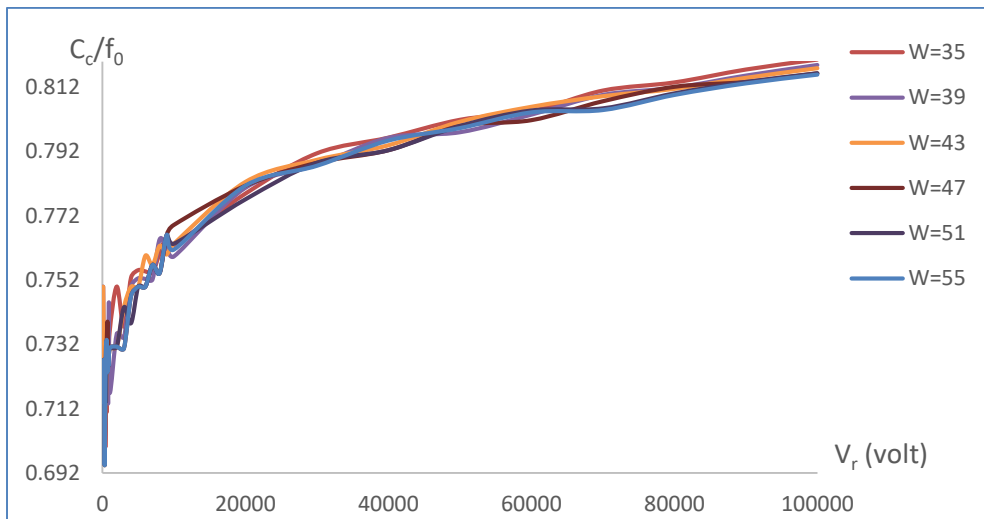

Figure 6. Relationship between C_c/f_0 as a function of relatively corrected acceleration voltage V_r (volt) at a constant value of current density ($J=4$ A/mm^2)

Figure 7. Relationship between C_c/f_0 as a function of relatively corrected acceleration voltage V_r (volt) at a constant value of current density (J=6 A/mm^2)

Figs.8-10 below show the values of the spherical aberration coefficient (C_s) relative to the focal length as a function of V_r.
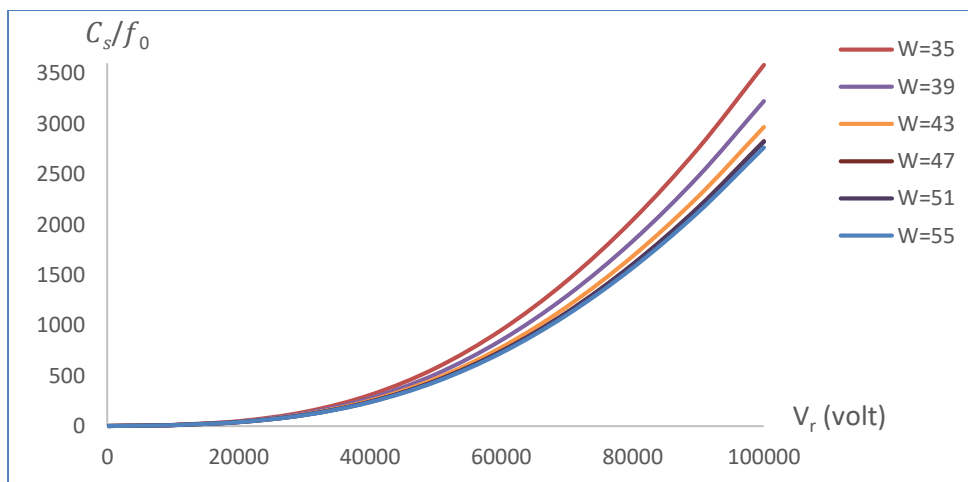

Figure 8. Relationship between C_s/f_0 as a function of relatively corrected acceleration V_r (volt) at a constant value of current density (J=2 A/mm^2)
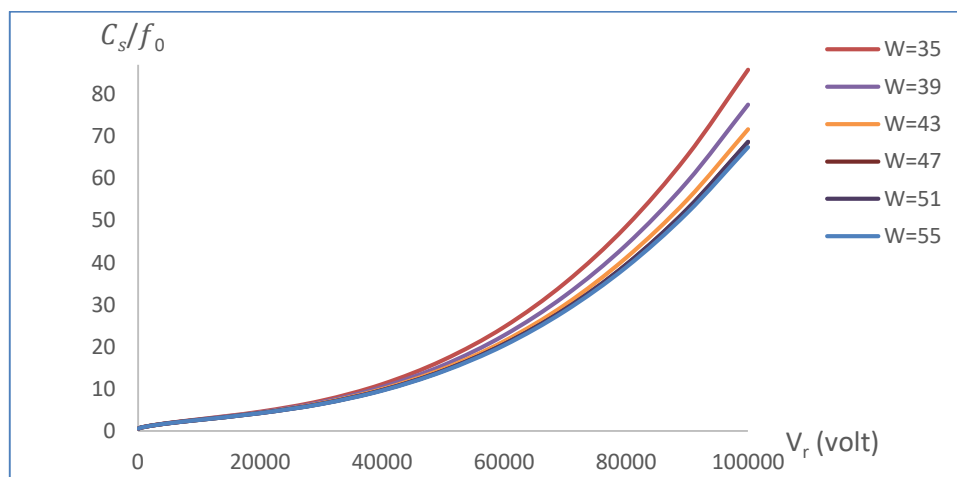

Figure 9. Relationship between C_s/f_0 as a function of relatively corrected acceleration voltage V_r (volt) at a constant value of current density (J=4 A/mm^2)
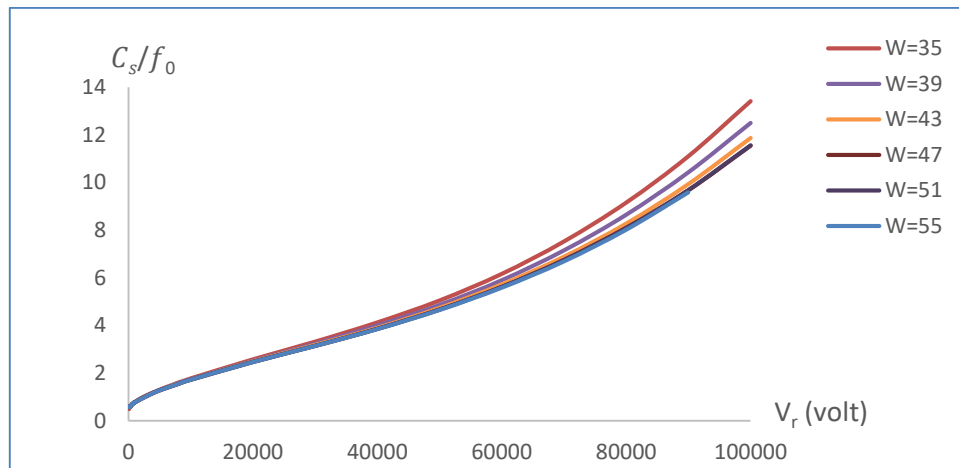
Figure 10. **Relationship between C_s/f_0 as a function of relatively corrected acceleration V_r (volt) at a constant value of current density (J=6 A/mm^2)**

From the last last six Fig.5-10 shown above itis found that the best optical properties obtained in this work is that of inner bore width of (55 mm), and thus the lowest values lenses of aberrations that correspond to the desired objective in this study have been obtained the identification of the best design, this is not sufficient to 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 the resolving power (δ) for these proposed designs from magnetic unipolar lens. The three Figs.11-13 below 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 Eq.5

Figure 11. The relationship between (δ) as a function of voltage as a function of the proportionally corrected acceleration voltage V_r (volt)

Figure 12. The relationship between (δ) as a function of voltage as a function of the proportionally corrected acceleration voltage V_r (volt)
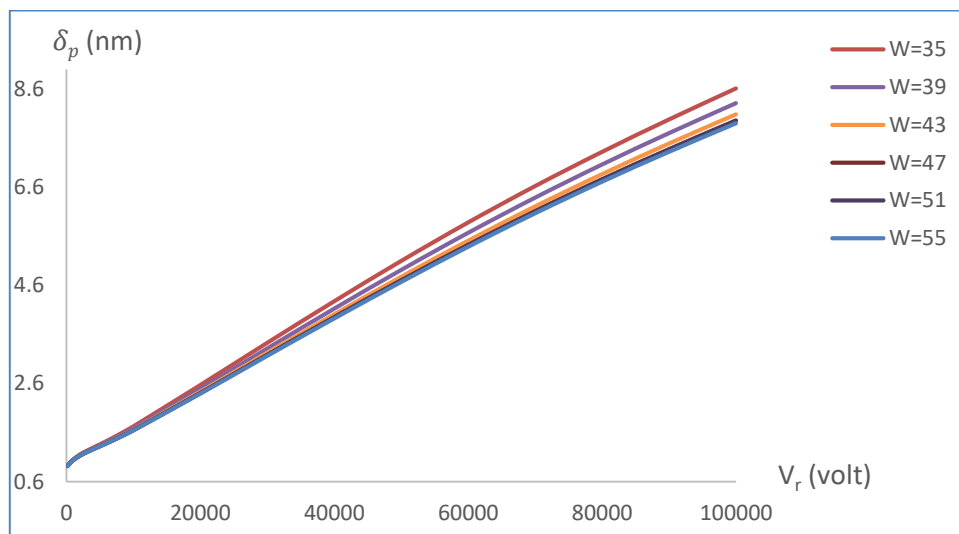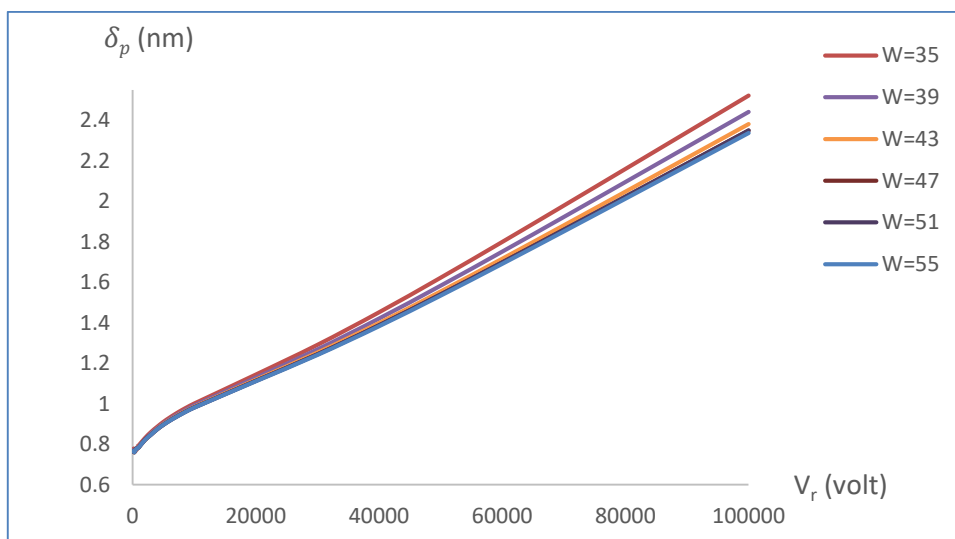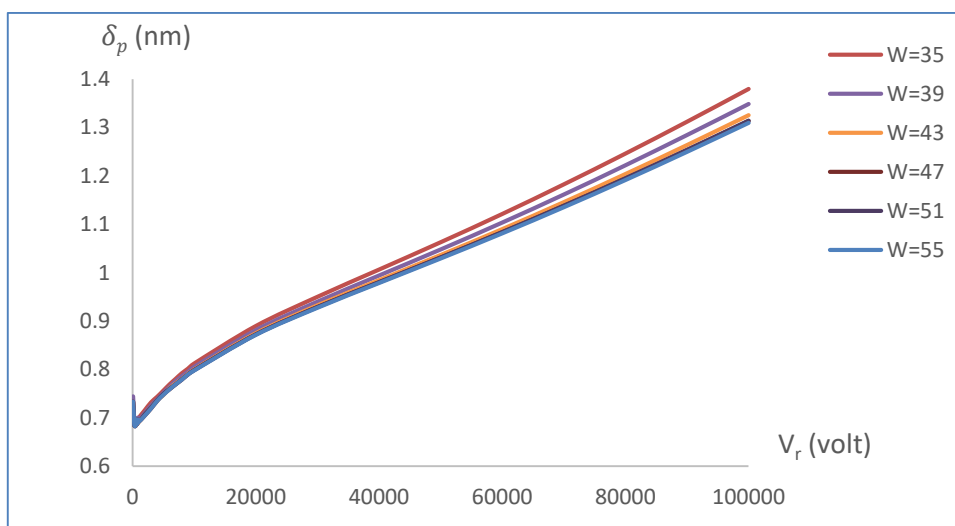

Figure 13. The relationship between (δ) as a function of voltage as a function of the proportionally corrected acceleration voltage V_r (volt)

From three Figs.11-13 it is found that the best resolving power when the inner bore width is (55mm) and this result the previous results obtained from the comparison between the values C_c/f_0 and C_s/f_0 in Figs.5-10. the chromatic, spherical aberration and resolving power values have been decreased significantly. Thus, lens was chosen as the best design among the proposed designs unipolar lens.

Conclusions

In this work, itis found magnetic flux density increases when the inner bore diameter decreases. So, the booth of chromatic and spherical aberration factors is decreases with the decrease of the inner bore diameter, 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 improves. Itis also found that, when the current density is increased by two values (2 A/mm^2) the magnetic field will increase by (B$_Z$=0.18 Tesla). One of the most important scientific applications that can be created using the results that have been reached is the creation of an unobstructed design unipolar lens in electron microscopes. The optical and magnetic properties are very good, similar to the previously studied successful lenses, but with a different design that prevents magnetic leakage that occurs in the lenses, and another property that discovered is that unipolar lenses are preferred to be used. working well with minimal effort.

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Authors' declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for re-publication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in Tikrit University.

Authors Contribution:

M.K. wrote the manuscript, corrected the errors, and conducted the study used in the present work by mastering the programs used and interpreting the data.

R.Y. is setting the mechanism of action, and refining the research from errors Everyone. The authors read the manuscript carefully and

they approved the final version of this research

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تصميم ودراسة تأثير قطر التجويف الداخلي على الخصائص المغناطيسية والبصرية للعدسة أحادية القطب

رافع يونس جاسم الصالح   محمد كردي عواد الجنعان

قسم الفيزياء، كلية العلوم، جامعة تكريت، صلاح الدين، العراق.

الخلاصة:

تم وضع عدة تصاميم لعدسات مغناطيسية أحادية القطب اعتماداً على تغيير عرض التجويف الداخلي وتثبيت المعالم الهندسية الأخرى للعدسة من اجل اجراء دراسة امكانية تحسين أداء العدسة المغناطيسية أحادية القطب. تم اجراء دراسة لكل تصميم تتضمن دراسة تمغنط العدسة وحساب المجال المغناطيسي المحوري إضافة الى كثافة الفيض المغناطيسي باستخدام طريقة العناصر المتناهية (FEM) لبرنامج تشغيل العدسات الالكترونية المغناطيسية (MELOP) النسخة الاولى عند ثلاث قيم مختلفة لكثافة التيار (6،4،2 A/mm2) وتم الحصول على اوضح القيم والسلوك عندما كانت كثافة التيار بمقدار (2 A/mm2). وجد ان أفضل خواص تمغنط واعلى قيمة لكثافة الفيض المغناطيسي واقل قيمة لعرض نطاق شدة المجال المغناطيسي المحوري تم الحصول عليها عندما كان عرض التجويف الداخلي بمقدار(mm55)، وكما تم دراسة تأثير كثافة التيار على الخصائص البصرية، حيث لوحظ بان قيم الزيوغ اللونية والكروية قلت بشكل ملحوظ لذلك تم اختيار هذه العدسة كأفضل تصميم من بين التصاميم المقترحة للعدسة الأحادية القطب.

الكلمات المفتاحية: الزيغ الكروي، الزيغ اللوني، الزيوغ البصرية، العدسة المغناطيسية، القدرة التحليلية.