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# The Influence of Bores Diameter on the SEM's Objective Lens Properties

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## Abstract

In a previous study, a new design of a magnetic objective lens had been chosen among five new designs as the preferred one. Both of the iron shroud and polepiece bore diameters of the preselected lens have been changed and studied in this work to improve its magnetic and optical properties. An extensive investigation has been done to analyze the magnetic field distribution, magnetic flux density, and optical properties for each model using the finite element method (FEM) with the computer-aided programs. All the analyses have been carried out at the same coil excitation (NI = 10 kA.t). The new improved design yield here will be prepared to fabrication to be used as an objective lens for the SEM.

## 1. Introduction

Scanning electron microscope (SEM) is the science of image magnification and analysis using a beam of electrons and its interactions with a sample. Knoll was the first person who images a surface in 1935 by scanning an electron beam over it in a raster pattern [1]. The use of electrons has a distinct advantage comparing with the use of light in that the resolving power (δ) is increased by two orders of magnitude. The highest resolving power obtained by modern light microscopes is about 200 nm, while a typical resolution of (1-5) nm had been achieved by the SEM. In addition, SEM can give a magnification about 250 times greater than the upper magnitude of the best light microscopes [2]. These capabilities, with other quantitative and qualitative techniques, have given scientists a variety imaging tool of high resolution for basic and applied researches. The SEM is one of the most popular instruments available for the analysis and measurement of the micro/nano structures, that it provides a high resolution (less than 1 n) [3]. They designed and analyzed the thermionic SEM using three-dimensional finite element method (FEM). A new researches in recent years, concerning to obtain a high resolution at low relativistic corrected accelerating voltage ($V_r$) of about less than 20 kV particularly in a semiconductor observation by using the SEM [4].

One of the main parts of the SEM is the objective lens, which is found in many types. The type studied here is the magnetic objective lens. Intensive studies have been done to improve the geometry of the magnetic lens, ensuring that each parameter of this lens has its relative significance in both of practical and theoretical side. The optimization of the polepiece shape have been studied for the symmetrical double polepiece lens by Cleaver [5] and for asymmetrical double polepiece lens by Wenxiong [6]. The influence of the shape and position of the coil on the projector lens properties of the symmetrical double polepiece lens and single polepiece was studied by Al-Khashab [7]. The asymmetrical lens is widely used as an objective lens in the imaging system of different types of electron microscope. Al-Khashab and Abdullah [8] 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 designed to provide a large volume of extensive space for the specimen holder in the polepieces region of, and this requirement is

difficult to achieve when the symmetrical objective lens is used with limited space around the specimen [9].
It is difficult to make a general optimal lens design for all applications [10]. It is also evident that one can only hope to find such simple geometrical parameters in terms of their properties. The optimum design of the magnetic electron lens with low aberration coefficients is generally considered significant [11]. However, low aberration magnetic lens has been found to obtain a high flux density of low half-width [12]. The electric and magnetic flux density distribution function can be generated easily and accurately before starting the practical design by the aid of the computer calculation [13]. The progress in computer simulations eases to solve a complicated design which was impossible to realize previously. Munro in 1973 has used the FEM to write packages used for calculation of the magnetic and electric trajectories for the electromagnetic lenses [14].
In the previous study [15], a new design of a magnetic objective lens had been chosen among five new designs as the preferred one. The aim of the present research is to improve the magnetic and optical properties of this preselected lens at constant working-voltage of ($V_r$ = 10 kV) by changing both of the iron shroud and polepiece bore diameters. The best new design yield here will be prepared to fabrication to be used as an objective lens for the low voltage SEM.

## 2. The objective lens design

The asymmetrical magnetic objective lens, which has been selected as a preferred one among five different designs in the preceding investigation [15] have been studied here. Figure (1) represents the schematic diagram of the mentioned selected lens shape. Its radial diameter of 150 mm, axial length of 165 mm, length of polepiece snout face of (4 mm), iron shroud bore diameter (denoted as $D_{Sh}$) of (8 mm), polepiece bore diameter (denoted as $D_p$) of 4 mm, and coil sectional area of 1365 $mm^2$. The polepiece angle is taken equal to 60° according to the optimization of Al- Khashab and Ahmad [16], were they found that the preferred angles for the double and single polepiece lenses are 63° and 55° respectively. The distance between the polepiece face and the outer edge of the iron shroud bore is equal to 10 mm. A cylindrical gap of 30 mm diameter and 80 mm length has been fixed for all the designed lenses to be uses as a place of an electrostatic deflector preparatory for next future work.

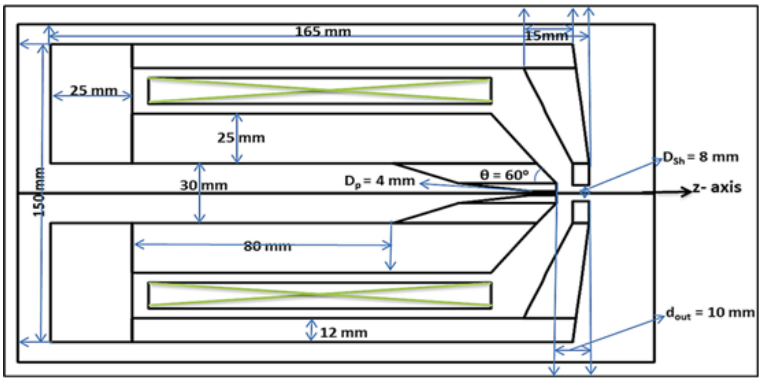


**Figure (1): Schematic diagram of the selected lens design of ($D_{Sh}$ = 8 mm & $D_p$ = 4 mm) from a previous study [15].**

All the above parameters and dimensions have been taken constant; excluding the bore diameters of both of the iron shroud and polepiece, where they are the topics of this research. Firstly, different iron shroud bore diameters [$D_{Sh}$ = (4,5,6, & 7) mm] have been taken. All the required analyses have been carried out at the same excitation (NI = 10 kA.t), using the FEM programs to choose the preferred bore diameter of the iron shroud of the selected lens here. The optimized $D_{Sh}$ will be a fixed parameter in the next part of this work. The next part, is to use a different polepiece bore diameters [$D_p$ = (1,3,5, & 7) mm], with a unique value of optimized $D_{Sh}$. All the mentioned analyses have been applied on these new designs of new variable $D_p$, using the same programs and at the same conditions. The best liked one will be selected as the preferred lens to use it as a magnetic objective lens in the SEM.

## 3. The effect of iron shroud bore diameter

The effect of the change in the iron shroud bore diameter ($D_{Sh}$) on the axial magnetic flux density distribution ($B_z$) of the selected lens which have been investigated with the aid of computer program (M11) for the asymmetrical polepiece lenses [17] using the finite element method. Figure (2) clarifies the effect for the designed lenses. It is clear that, the lowest diameter of ($D_{Sh}$=4mm) gives the sharpest and highest peak value, and as the $D_{Sh}$ increases the ($B_z$) decreases and the half-width increases. This is good, but not a conclusive guide to specify the preferred one, especially that the other magnetic and optical properties have not accomplished yet. It can be said that this consequence regarded as a primary indicator.

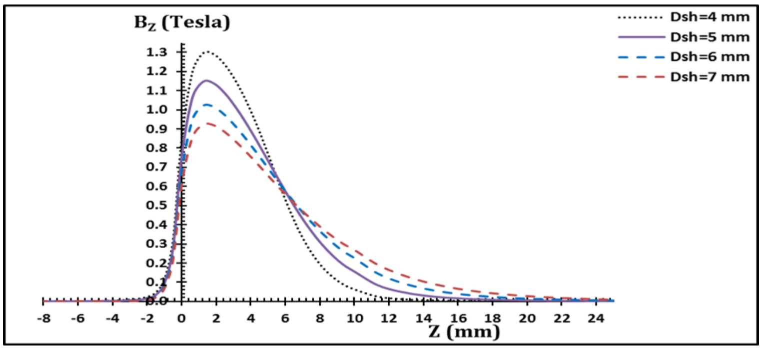


**Figure (2): The axial magnetic flux density distributions ($B_z$) for the selected lens of different iron shroud bore diameter ($D_{Sh}$) at constant excitation of (NI = 10 kA.t).**

The effect of the iron shroud bore diameter ($D_{Sh}$) on the optical properties of the selected lens has been studied. The optical properties of the new designed lenses of different iron shroud bore diameter have been investigated and calculated, such as the focal length ($f_o$), spherical aberration coefficients ($C_s$), chromatic aberration coefficients ($C_c$), and resolving power ($\delta$), under the same above mentioned conditions, where the resolving power calculated from the well-known relation [$\delta = 0.61\ (C_s\lambda^3)^{1/4}$, where $\lambda$ is being the electron wavelength, and $\lambda = \frac{\sqrt{1.5}}{\sqrt{V_r}}$ (in nm)].

Figure (3) illustrates the comparison between the relative spherical aberration coefficients to the objective focal length ($C_s/f_o$) of all the lenses with respect to the relativistic corrected accelerating voltage ($V_r$). 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. It is noticed that the lenses of ($D_{Sh}$ = 4 mm & 5 mm) were approximately in coincide with each other and they give the best results, however, the others of ($D_{Sh}$ = 6 mm & 7 mm) were the worse.

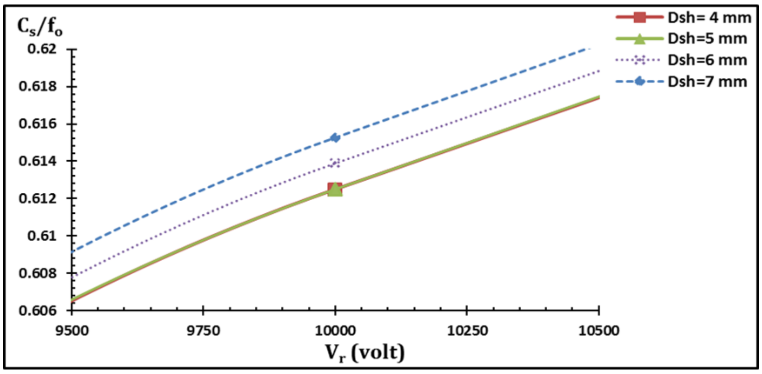


**Figure (3): Comparison between the relative values ($C_s/f_o$) of different iron shroud bore diameter ($D_{Sh}$) with respect to the $V_r$ at constant excitation of (NI = 10 kA.t).**

The relative values ($C_c/f_o$) of the deliberated lenses of the same iron shroud bore diameters were studied as well. Figure (4) demonstrates this study, where the comparison between the mentioned factors of all the bore diameters exist in this study under the same conditions has been done with respect to the same range of $V_r$. It is found that the curves are identical with the previous results.

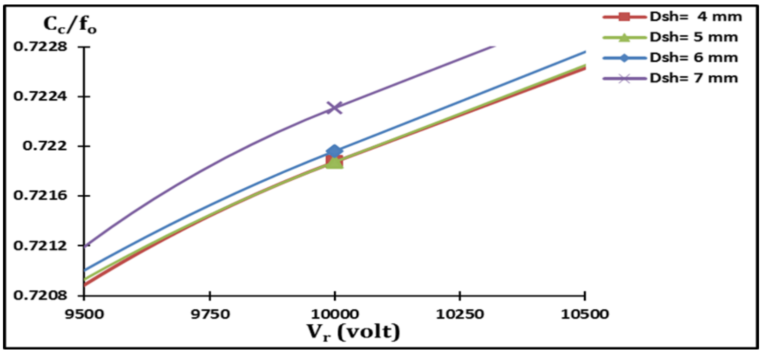


**Figure (4): Comparison between the relative values ($C_c/f_o$) of different iron shroud bore diameter ($D_{Sh}$) with respect to the $V_r$ at constant excitation of (NI = 10 kA.t).**

Figure (5) represents the variation of the resolving power (δ) for different iron shroud bore diameter with respect to the relativistic corrected accelerating voltage ($V_r$) in the range of $V_r$ = (10 V-100 kV) at constant excitation (NI = 10 kA.t). It is clear from this figure that the lenses of [$D_{Sh}$ = (4 & 5) mm] possess the best resolving power (δ) as well, where they appeared approximately in coincide with each other's, while the resolving power of the lenses of [$D_{Sh}$ = (6 & 7) mm] still the worse. The comparison has been taken in/and around the specific working-voltage of ($V_r$ = 10 kV). This means that there is a possibility here to use either the lens of ($D_{Sh}$ = 4 mm or 5 mm) due to their semi identical resolving power in this range of accelerating voltage. This result supporting the previous results obtained from the relative values ($C_s/f_o$) and ($C_c/f_o$) obtained in figures (3 & 4).

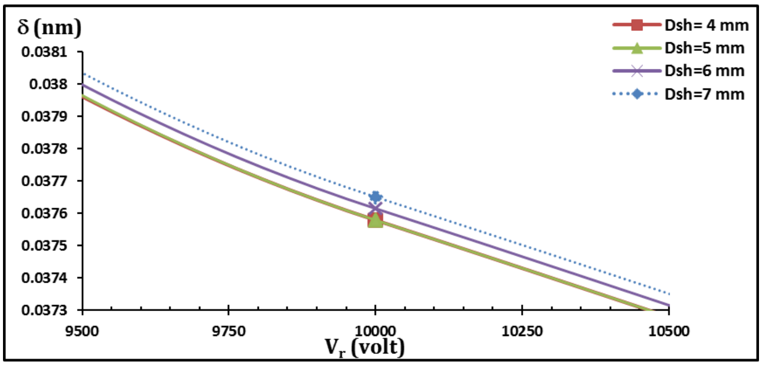


**Figure (5): Variation of the resolving power (δ) of the objective lens of different iron shroud bore diameter ($D_{Sh}$) with respect to the ($V_r$).**

It can be concluded from all the results obtained from the above figures that the lens design of the iron shroud bore diameter of ($D_{Sh}$ = 4 mm) is the preferred lens, because it verify all the best properties achieved in this study. For this reason, the parameter ($D_{Sh}$ = 4 mm) will be used as a constant optimized value in the following part (Section 4) of this research.

## 4. The effect of the polepiece bore diameter

In order to investigate the effect of the polepiece bore diameter, which is play a vital role in the objective lens and it is denoted here as ($D_p$), a different diameter of [(1, 3, 5, & 7) mm] have been taken, however, the iron shroud bore diameter has been taken constant at the value of ($D_{Sh}$ = 4 mm) as an optimized parameter in this paper. Thus, it is clear that in the current section, the investigation and the comparison will be done with a six new identical geometrical designs, except the difference in the polepiece bore diameters ($D_p$).The axial magnetic flux density distributions ($B_z$) of the new six designed lenses have been studied under the same conditions applied on the previous analyses. Figure (6) shows the behavior of the ($B_z$) of the deliberated lenses along the optical z-axis.

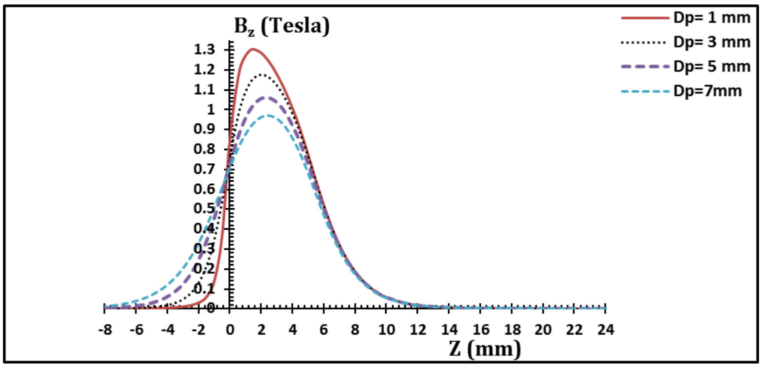


**Figure (6): The axial magnetic flux density distributions ($B_z$) for the designed lenses of different polepiece bore diameter ($D_p$) at constant excitation of (NI = 10 kA.t).**

It is clear, the maximum peak obtained for the lowest polepiece bore diameter of ($D_p$= 1mm), and it is decreases as $D_p$ increases, due to the fact that the increase in the effective region (the space separates the polepiece snout and the axial bore of the iron shroud) reduces the strength of the magnetic field and increases the half-width [18]. Nevertheless, this result alone is not enough to make it the best.

Figure (7) explains the comparison between the relative values ($C_s/f_o$) of the different polepiece bore diameter ($D_p$) and accelerating voltage ($V_r$) at constant coil excitation of (NI = 10 kA.t). The lowest value of ($D_p$ = 1 mm) gives the best result.

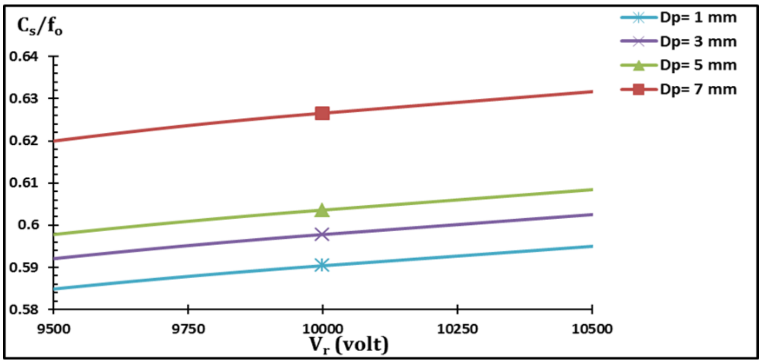


**Figure (7): Comparison between the relative values ($C_s/f_o$) of different polepiece bore diameter ($D_p$) with respect to the $V_r$ at constant excitation of (NI = 10 kA.t).**

Figure (8) explains the comparison between the relative values ($C_c/f_o$) of the different polepiece bore diameter ($D_p$) and $V_r$ at constant excitation of (NI = 10 kA.t). The results obtained from this figure were completely the same with those obtained from figure (7).

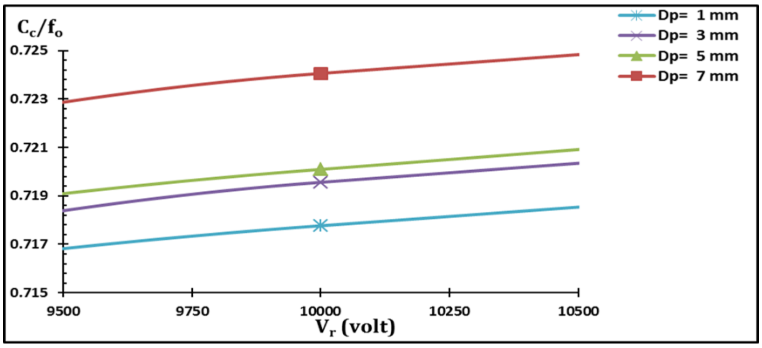


**Figure (8): Comparison between the relative values ($C_c/f_o$) of different polepiece bore diameter ($D_p$) with respect to the $V_r$ at constant excitation of (NI = 10 kA.t).**

As it illustrated in Figure (8), the lenses of the lowest polepiece bore diameter gives the minimum values of relative values of ($C_c/f_o$). The lens of ($D_p$ = 1 mm) is the best one according to the lowest value among them. In spite of this preference, it is well-known that the chromatic aberration coefficient ($C_c$) do not forms a big obstacle in the objective lenses, where it can be reduced easily by using the chromator if there is a need to avoid it.

Figure (9) represents the variation of the resolving power (δ) for different polepiece bore diameters ($D_p$) with respect to the relativistic corrected accelerating voltage ($V_r$) at constant excitation of (NI = 10 kA.t). It is clear that the lowest values of ($D_p$ = 1 mm) gives the best resolving power.

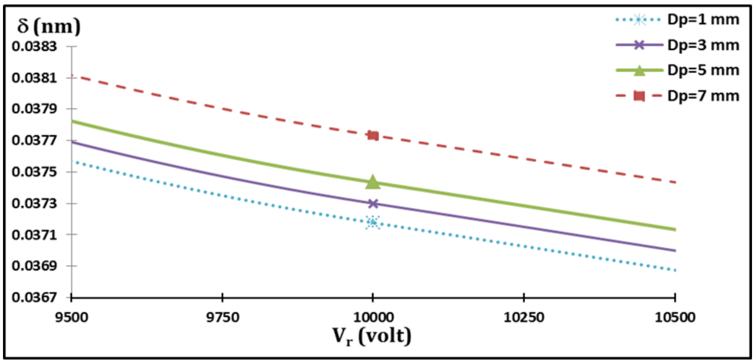


**Figure (9): Variation of the resolving power (δ) of the objective lens of different polepiece bore diameter ($D_p$) with respect to the ($V_r$).**

## 5. The magnetic flux lines trajectories

In order to demonstrate the effect of both of the iron shroud and polepiece bore diameters on the magnetic flux lines of the present lenses, another analysis has been carried out using the flux program (M13) for computing the flux density distributions throughout the magnetic circuits of unsaturated magnetic lenses [17] at a constant relativistic corrected accelerating voltage of ($V_r$ = 10 kV) and constant coil excitation of (NI = 10 kA.t).

Figure (10) clarifies the geometrical shapes and the flux trajectories of the layout lenses. It is clear that

the lens of ($D_{Sh}$ = 4 mm & $D_p$ = 1 mm) seems to be the best one, according to the more dense and regular of its flux lines. In addition, its flux lines propagates in preferred ways and paths as it needed to make the required effect on the charged particle electron beam passes throughout the lens.

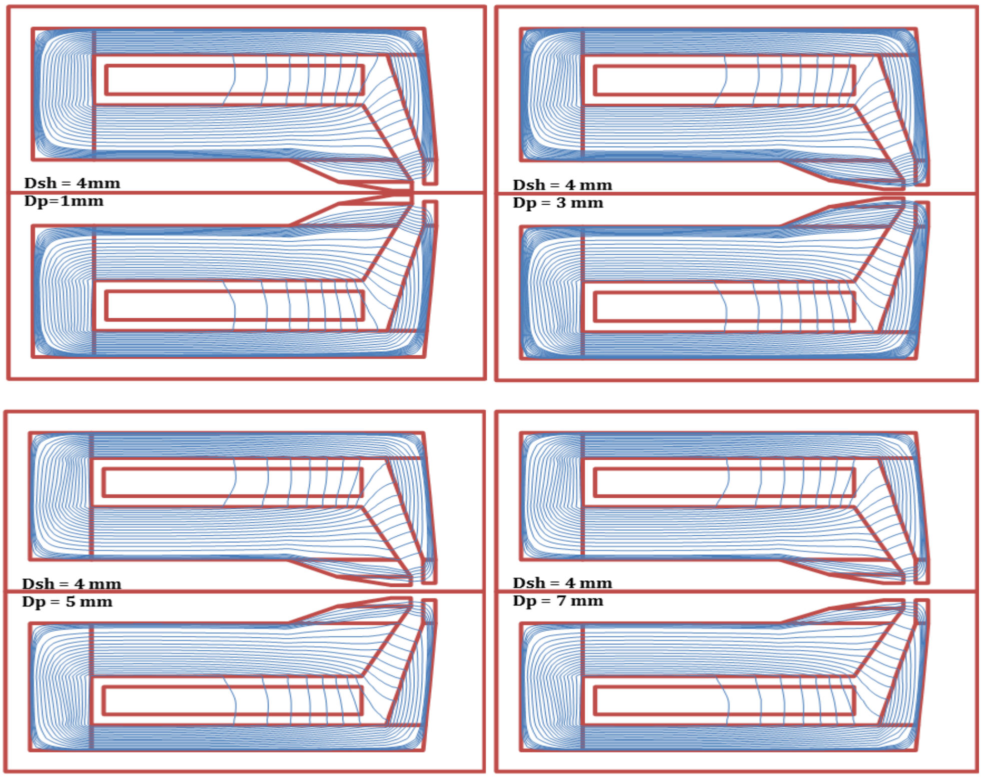


**Figure (10): The geometrical shape models of the objective lenses of ($D_{Sh}$ = 4 mm) and different values of $D_p$ and their magnetic flux density distributions at constant excitation of (NI = 10 kA.t).**

This outcome gives the categorical guide to distinct the best liked lens, especially that most of the applied analyses and their deductions affirm this fact. Therefore, this lens has been selected to be prepared for fabrication to use it practically as a magnetic objective lens in a low voltage SEM.

## 6. Conclusions

It is found that there is an obvious effect of both iron shroud bore diameter and polepiece bore diameter on the electron magnetic properties and optical properties. The preselected lens from a preceding study has been improved indeed to give the higher resolution and lower aberration coefficients at low and high accelerating voltages. The improved lens of the iron shroud bore diameter of ($D_{Sh}$ = 4 mm) and polepiece bore diameter of ($D_p$ = 1 mm) have been selected as a preferred one among all the suggested lenses in the present research work.

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# تأثير قطر التجاويف على خصائص العدسة الشيئية للمجهر الإلكتروني الماسح

رافع يونس جاسم الصالح
*قسم الفيزياء ، كلية العلوم ، جامعة تكريت ، تكريت ، العراق*

**الملخص**

في دراسة سابقة، تمّ اختيار تصميم جديد لعدسة مغناطيسية شيئيّة من بين خمس تصاميم جديدة كأفضل عدسة. في هذا البحث تم تغيير و دراسة أقطار فتحتي كلٍ من الذراع الحديدي وقطب العدسة المنتخبة لتحسين خواصّها المغناطيسية والبصرية. حيث تمَ اجراء دراسة مكثّفة لتحليل توزيع المجال المغناطيسي وكثافة الفيض المغناطيسي والخواص البصرية لكل نموذج باستخدام طريقة العناصر المتناهية (FEM) بمساعدة برامج الحاسوب. كما تم انجاز جميع التحاليل عند تهيّج ملف ثابت (NI = 10 kA.t). التصميم الجديد الناتج في البحث الجاري سوف يعدّ للتصنيع ليستخدم كعدسة شيئية للمجهر الالكتروني الماسح.

**الكلمات الدالّة:** التصميم الهندسي للعدسة الشيئية، الخواص المغناطيسية الالكترونية، الخواصّ البصرية الالكترونية، الذراع الحديدي، القطب.