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The effect of Air Gap Width on the Focal Properties of Objective Snorkel Lens

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ABSTRACT

The current research dealt with studying the effect of air gap width on the objective properties of the magnetic Snorkel lens used in the scanning electron microscope. The structure of the lens was designed and its properties were studied, and the axial magnetic flux density distribution was calculated (B_z) using the electron optical design program (EOD), The results indicated that the maximum value of the magnetic flux density (B_{max}) increased with a decrease in the width of the air gap (S), accompanied by a decrease in the half-width, spherical and chromatic aberrations, and an increase in the resolution of the analysis.

تأثير عرض الفجوة الهوائية على الخواص البؤرية الشيئية لعدسة سنوركل

نورس كريم خليل ، رافع يونس جاسم

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

الملخص

تناول البحث الحالي دراسة تأثير عرض الفجوة الهوائية على الخواص الشيئية لعدسة سنوركل المغناطيسية المستخدمة في المجهر الالكتروني الماسح. تم تصميم هيكل العدسة ودراسة خواصها، كما تم احتساب توزيع كثافة الفيض المغناطيسي المحوري (B_Z) باستخدام التصميم البصري الإلكتروني (EOD)، اشارت النتائج ان القيمة العضمى لكثافة الفيض المغناطيسي (B_{max}) تزداد مع نقصان عرض الفجوة الهوائية (S) ويرفقها انخفاض في العرض النصفي ومعاملات الزيوغ الكروية واللونية، وزيادة دقة التحليل.

1. Introduction

Charged particle optics has become an important part of modern physical research, and thus calculations in such devices have become essential and contribute directly to the development of electronic devices. Developments in the field of electronic computers have greatly facilitated the design of electronic lenses after their design encountered many problems and difficulties. The flux or flux density distribution can be known to explore the optical properties of any of the proposed electronic lenses [1]. As a result, computer simulation plays a key role in the design and improvement of charged particle optical systems,

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making it easier to estimate the performance accuracy of these systems before they are manufactured. That saves a lot of money and time [2].

One of the problems facing the issue of finding specific geometric designs for electronic lenses with very small aberration coefficients is the dependence of the properties of these lenses on a large number of geometric and physical variables. The process of achieving the best lens design with the lowest aberration and the highest analysis accuracy is called optimization [3]. One of the optimization methods is the analysis method. It is a traditional method in designing electronic lenses and is based on the principle of trial and error, as the designer begins by developing an initial design for the required lens and then works to improve this design by changing the geometric parameters. Geometrical parameters such as the shape and size of the excitation coils, the electric and magnetic polepieces, and the iron circuit for this design until the optimal design is reached, which is the design that gives the lowest values of aberration [4]. The monopolar lens design is a development in the field of electromagnetic lenses. Mulvey in 1972 proposed the first monopolar lens by dividing the bipolar lens into two equal halves producing two lenses each with one pole [5]. The monopolar lens called the snorkel lens was proposed for the first time by (Mulvey). This objective lens has many advantages in low voltage scanning electron microscopy, and its pole protrudes outside its structure, and in this positive feature, the sample rotates more freely than in bipolar lenses [6]. Extensive studies have been conducted to improve the geometry and dimensions of electronic magnetic lenses and to choose the optimal design that gives the lowest values of aberration. Al-Shahat contributed to showing the extent of the effect of changing the dimensions of the geometric lens on the performance of the saturated unipolar magnetic lens, as he compared three lenses that have different dimensions, and there is a ratio between these dimensions, and he concluded that the geometric dimensions have a very significant effect on increasing the maximum value of the magnetic field distribution and the distribution bandwidth field, as well as reducing coefficients of spherical and chromatic aberration and focal length, and it was found that the lens of small size gives the best performance [7]. Al-Shamma presented a study of two types of lenses, as the researcher compared the pinhole lens and the Snorkel lens by using the simulation program Electron Optical Design (EOD) that works by the finite element method, after changing the air gap and the diameter of the axial aperture of the pole of the two lenses, the Snorkel lens achieved the best optical performance and also the lowest values for coefficient of spherical and chromatic aberration at certain operating distances [8]. Was studied the effect of the diameter of the axial aperture (D), the width of the air gap (S) between the two polepieces, the thickness of the polepieces (t), and the excitation coefficient (NI) of the magnetic lens designed to obtain the best optical properties, represented by the focal length f_o, the spherical aberration (C_S) and chromatic aberration coefficients (C_C), it was found that the properties improve significantly with reducing the diameter of the axial aperture and the width of the air gap for this lens. It was found that the best lens design with the best optical properties was achieved at an air gap (S = 2 mm), axial aperture diameter (D = 6 mm), and face thickness. Polepieces (t = 3 mm) [9]. Evaluation of each design included calculating the axial magnetic field, lens magnetization, and flux density using the finite element method (FEM) for three distinct current density values (2,4 and 6 A/mm^2). Therefore, the most obvious results and behavior are obtained at a current density of (2 A/mm2). The maximum magnetization characteristics, maximum flux values, and minimum bandwidths of the axial magnetic field strength are obtained when the pole face length is (1 mm) [10].

2. Objective Lens

The objective lens is one of the most important components of the electron microscope because of its great influence on the resolution of the microscope's analysis. In addition to reducing the size of the probe, it focuses it on the surface of the sample to be examined. This focusing process is carried out by means of the air gap present in the magnetic circuit near the optical axis, and also by means of the axial magnetic field generated in the area confined between the two iron polepieces when an electric current passes through its coil [11]. The ability of electromagnetic lenses to concentrate the beam in a precise symmetric probe is mainly limited by defects called lens deviations, Common deviations of the lens include spherical aberration (Cs) and Chromatic aberration (Cc), the aberration factors should be as small as possible to achieve high resolution [12]. The spherical aberration coefficient (C_S) for a magnetic lens with magnetic flux density (B_Z) can be calculated according to the following relationship [13-15]:

$$C_s = \frac{e}{128mV_r}\int_{Z_0}^{Z_i}\left(\frac{3e}{mV_r}B_z^4R_\alpha^4(z) + 8(B_z')^2R_\alpha^4(z) - 8B_z^2R_\alpha^2(z)(R_\alpha'(z))^2\right)dz \quad \text{....(1)}$$

Where (Vr) represents the accelerated voltage of electrons and relatively corrected and (R_α (z)) is a solution to the axial radiation equation, and α semi angle. The (C_C) Chromatic aberration coefficient of a magnetic lens can be found from the following formula [15]:

$$C_c = \frac{e}{8mV_r}\int_{z_0}^{z_i}B_z^2\,R_\alpha^2(z)dz \quad \text{....(2)}$$

The resolution of the analysis was calculated by the relationship [16]:

$$\delta = 0.7(C_S\lambda^3)^{\frac{1}{4}} \quad \text{....(3)}$$

Where (λ) is the wavelength of the electron, which is given by the following equation [17]:

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$$\lambda = \sqrt{\frac{1.5}{Vr}} \ldots (4)$$

3. Design of the Magnetic Objective Lens

The research aims to find the best air gap width for the magnetic Snorkel lens. In this work a new Snorkel lens had been designed and studied using EOD, as shown in the figure (1) with dimensions and geometric parameters represented in axial length (110 mm), radial width (144 mm), and a rectangular coil with a cross sectional area (1000 mm^2) and air gap width (S= 6 mm), the diameter of the polepiece opening (D_P = 4 mm), the thickness of the polepiece face (t = 5 mm), and an axial gap in the form of a cone of length (113 mm). In order to clarify the performance of the objective lens proposed for this study, the axial distribution of the flux density and objective characteristics of the lens was calculated using (EOD) program version 3.069, designed by Lencov´a and Zl´amal [18] using the finite element method.

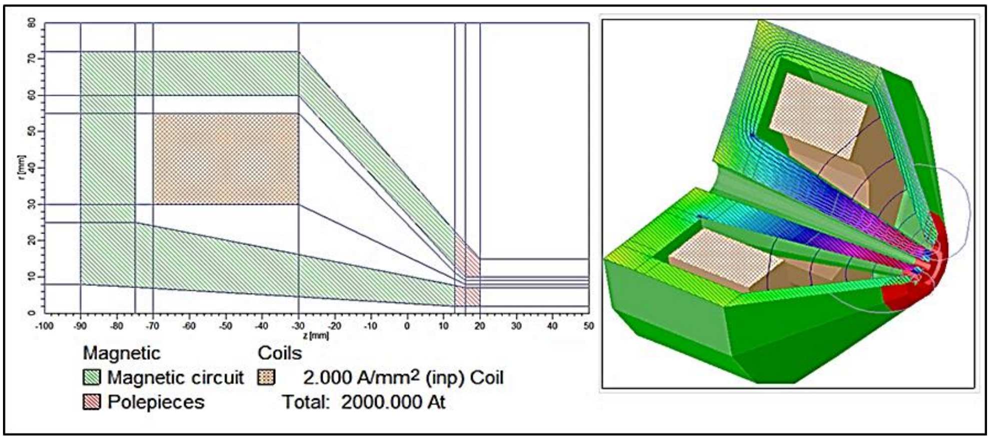

Fig. 1: Geometric dimensions of the objective lens, a Snorkel in two- and three-dimensional design.

4. Calculations and results

Effect of the Air Gap on the Snorkel Objective Lens Properties:

In order to study the effect of the air gap width (S) on the optical performance of the Snorkel lens, different values of the gap width [S= (3, 6, 9, 12, 15) mm] were chosen, while keeping the other geometric parameters of the lens constant. Figure (2) shows the distribution of axial flux density (Bz) as a function of axial distance (Z) for different values of air gap width under constant excitation (NI=2000A-t). It was found that the maximum value of the magnetic flux density (B_{max}) increases with decreasing air gap width and is accompanied by a decrease in the half width (H.W.), as shown in Figure (3).

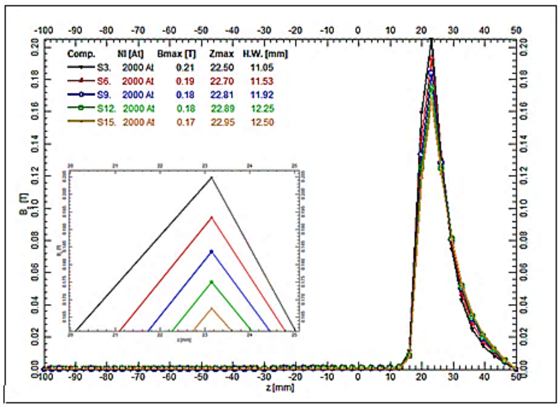

Fig. 2: Distribution of axial magnetic flux intensity (B_z) as a function of distance (Z) of the Snorkel lens for different values of air gap width (S) at constant excitation (NI=2000 A-t).

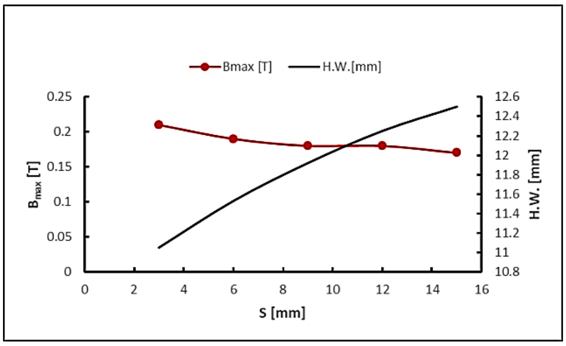

Fig. 3: The change of maximum magnetic flux density (B_{max}) and half-width (H.W) as a function of the air gap width (S) of the lens.

Figure (4) shows the paths of the magnetic flux lines of the lens (SL) at constant excitation (NI = 2000 A-t). It was found that the smaller the width of the air gap (S), these lines converged and concentrated between the pole and the iron arm, and that Lenses with a gap width (S = 3) mm) have more uniform flux lines than lenses with larger gaps.

The effect of changing the gap width on the objective properties of the lens was also studied, where the spherical and chromatic aberration coefficient were calculated. Figures (5) and (6) show the relationship between the change in the coefficients of spherical aberration (C_S) and chromatic aberration (C_C) as a function of the relatively corrected acceleration voltage of the lens at constant excitation (NI = 2000 A-t). It was discovered that when the width of the air gap was reduced, the optical qualities of the developed lens improved, and the lens with width (S = 3 mm) achieved the best optical properties

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represented by the lowest values of aberration. These results are consistent with the findings of researcher Al-Shamma [8], and on this basis, it is possible to obtain snorkel objective lenses with good properties by reducing the width of the air gap. Lens quality is often given by the spherical aberration coefficient.
The resolving power (δ) of the lens was also calculated. Figure (7) shows the relationship between the resolving as a function of the width of the air gap of the lens at constant values for each of the excitation (NI = 2000 A-t) and a constant acceleration voltage (Vr = 12 kV), and with working distances (WDs) are different. Figure (8) shows the relationship between the analysis capacity as a function of the width of the air gap (S) at fixed values for each of the excitation (NI = 2000A-t) and the working distance (WD = 5.3 mm), and at different acceleration voltages, As a result of the inverse relationship between wavelength and the relatively corrected acceleration voltage, Equation (4), the accuracy of the analysis (δ) increases with increasing voltage values. Table (1). The results of the two figures show that the lens with a gap (S = 3 mm) achieves the best resolution ability.

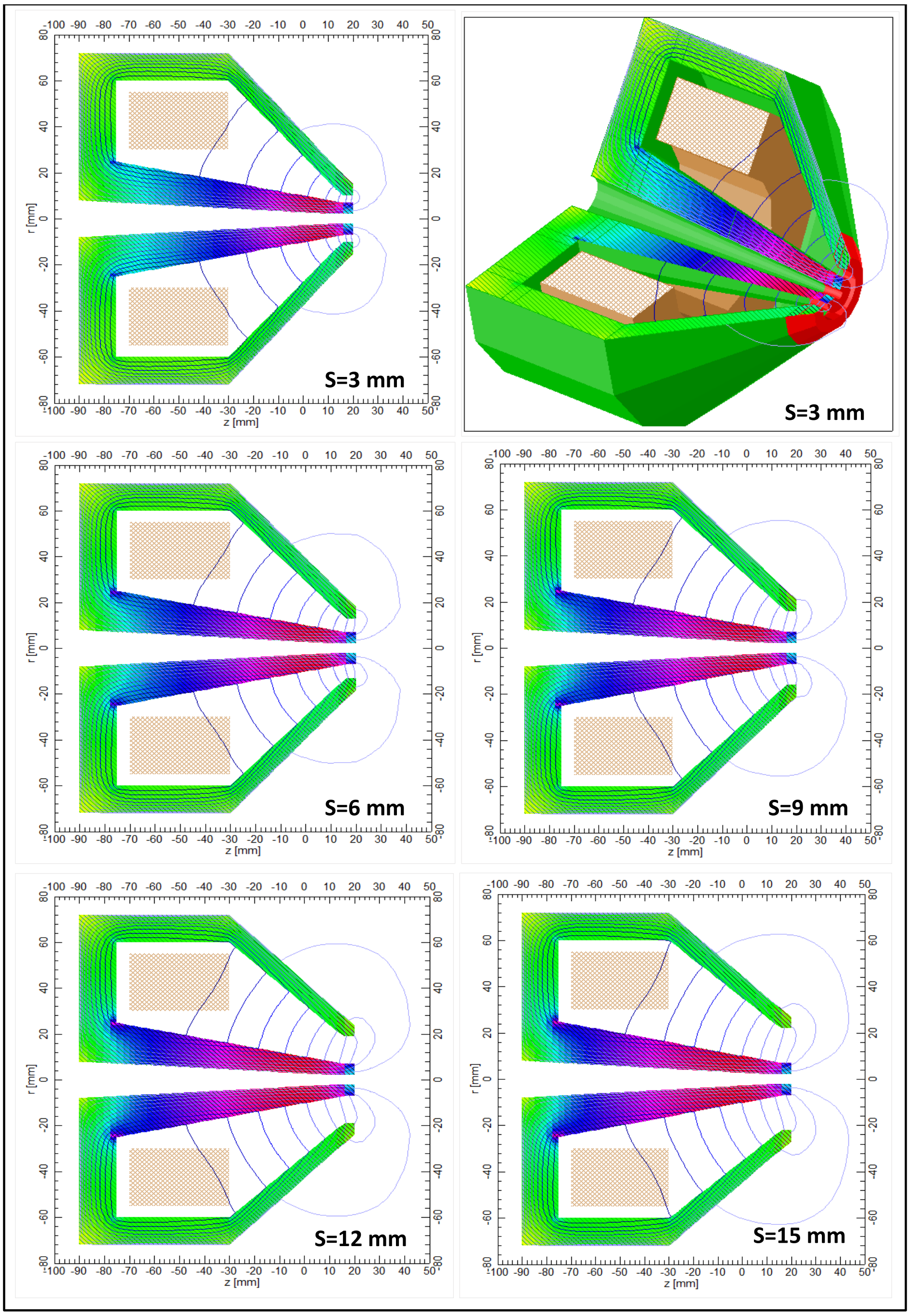

Fig. 4: The trajectories of the lens magnetic field lines for different values of air gap width (S).

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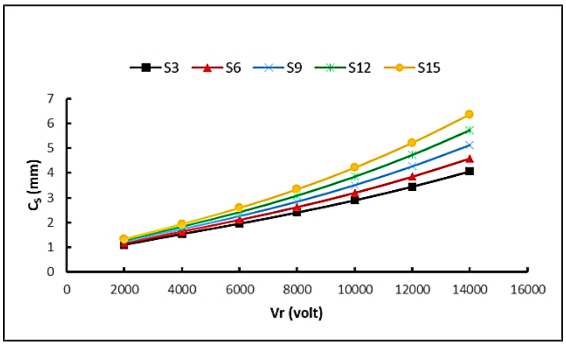

Fig. 5: Variation of the coefficient of spherical aberration (C_S) as a function of the proportionally corrected acceleration voltage (Vr).

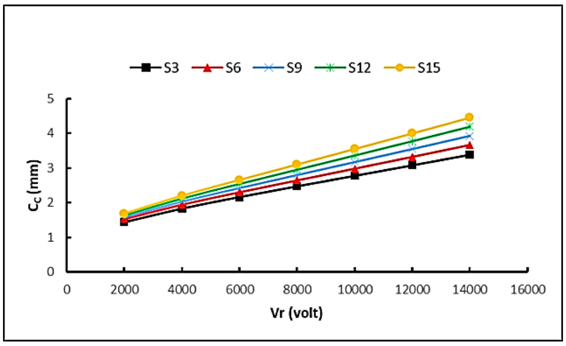

Fig. 6: Variation of the coefficient of chromatic aberration (C_S) as a function of the proportionally corrected acceleration voltage (Vr).

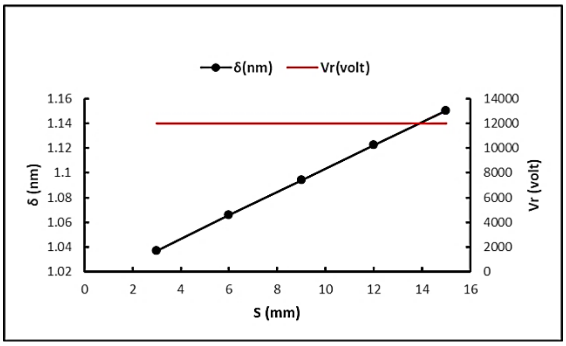

Fig. 7: Variation of the analysis resolution (δ) as a function of the air gap width (S) of the lens at fixed values for each of the excitation and acceleration voltages (Vr=12kV, NI=2000 A-t).

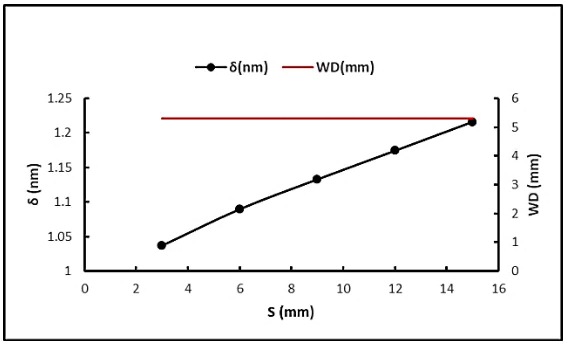

Fig. 8: Variation of the analysis resolution (δ) as a function of the air gap width (S) of the lens (L3) at fixed values for both excitation and a fixed working distance (WD=5.3 mm, NI=2000 A-t).

Table 1: Analysis resolution data (δ).

	At constant voltage [Vr=12 Kv]			At a constant working distance [WD=5.3 mm]		
S (mm)	Vr (mm)	WD (mm)	δ (nm)	WD (mm)	Vr (mm)	δ (nm)
3	12000	5.3	1.04	5.3	12000	1.04
6	12000	5.8	1.07	5.3	10000	1.09
9	12000	6.3	1.09	5.3	8880	1.13
12	12000	6.7	1.12	5.3	8000	1.17
15	12000	7.1	1.15	5.3	7170	1.22

5. Conclusion

The width of the air gap (S) has a clear effect on the objective properties of a Snorkel lens. Through analyses and calculations, it was found that the coefficients of spherical and chromatic aberrations decrease, and the accuracy of the analysis increases as the width of the air gap decreases, as the lens with a gap width (S = 3 mm) achieved the best objective properties compared to other values chosen for the width of the gap in the current research, the results were achieved, using EOD program. This lens is used as an objective lens to focus the electron beam in a scanning electron microscope.

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