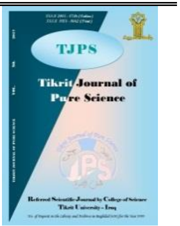
IASJ
المجلات الاكاديمية العراقية

Tikrit Journal of Pure Science
ISSN: 1813 – 1662 (Print) --- E-ISSN: 2415 – 1726 (Online)

Journal Homepage: http://tjps.tu.edu.iq/index.php/j



The Effect of Operation Modes on the Electron Beam Diameter in Condenser Magnetic Lenses System

Mohammed A. Hussein[1] , **R.Y. J. Al-Salih**[2] , **Abdullah I. M. Alabdullah**[3]
[1] *Department of Physics, College of Education/Al-Hawija, Kirkuk University, Kirkuk, Iraq*
[2] *Department of Physics, College of Sciences, Tikrit University, Tikrit, Iraq*
[3] *Department of Physics, College of Sciences, Mosul University, Mosul, Iraq*

https://doi.org/10.25130/tjps.v27i3.51

ARTICLE INFO.

Article history:
-Received: 10 / 4 / 2022
-Accepted: 24 / 5 / 2022
-Available online: / / 2022

Keywords: magnetic condenser lens, operation modes, illumination system, electron beam diameter.

Corresponding Author:
Name: **R.Y. J. Al-Salih**
E-mail:
mohdphy@uokirkuk.edu.iq
r.y.jasim@tu.edu.iq,
abdullahidrees@uomosul.edu.iq
Tel:

ABSTRACT

The effect of operation modes of condensing magnetic lenses has been investigated to determining the total demagnification and the diameter of the electron beam coming out of it. The cross-over point inside the electron gun is considered as the object (*do*) with a diameters ranges of (10 – 100 µm) to find out the optical efficiency of the double lens condensing system and its ability to forming a high précising image of the 1st real image formed inside electron gun of thermal emission that acts as an actual source of electron beam. The following modes; (weak-weak), (weak- strong), (strong- strong), and (strong- weak); denoted as (#1, #2, #3, #4 respectively); have been studied. The best value for the total demagnification and the diameter of the electron beam has been obtained in the mode of (strong- strong; #3); where the parameters were: $(dM_t = 1014.199)$, $(d_2 = 49.3\ nm)$, while the worst value has been achieved in the mode (weak- weak; #1) $(dM_t = 31.56267)$, $(d_2 = 1584.15\ nm)$. It is found that by increasing the demagnification of the first condenser lens, the demagnification of the final real image produced by the double lens system has been positively affected. It is found that the relationships that obtained between the demagnification and the current density can be used as a calibration curve to obtain the required total demagnification for the electronic beam diameter for any mode according to the purpose of the desired application.

Introduction

Kim *et al.* have been made a numerical analysis for verifying the performance of lens system in a scanning electron microscope [1,2,3]. The geometrical dimensions of the double lenses have been chosen depending on such studies to facilitate the possibility of manufacturing them locally. Electron microscope that scans of specimen topography to get on clear images to the surface is a scanning electron microscopy *(SEM)* by use high energy electron beam [4]. From interaction between the electrons beam with atoms at the specimen surface the Signals will be produced in *SEM*. High-resolution images can be produced of the specimen surface in conventional *SEM*, illuminating details of size several nanometers. A heated tungsten filament type electron gun is generates an electron beam that uses for imaging of the specimen, A diameter typically of beam of about 10-100 micrometers [2]. A set of Magnetic electron lenses were used to demagnification of electron beam by a factor of about 10000. Magnetic electron lenses are widely used for demagnification and focusing of electron beam in conventional *SEMs* which are sources of rotationally symmetric magnetic field. Condenser and objective magnetic lenses are acts on focus of electron beam of an *SEM*. demagnification of electron beam was achieved by a set of Condenser lenses, while, demagnification of an electron beam probe and focusing it onto specimen surface was achieved by the Objective lens. Determine the Optical properties of the lenses by the distribution of magnetic field inside the SEM column [5].

Analysis of the electron beam trajectory in the *SEM* is very necessary to obtain on the Characteristics of the electron beam probe. Therefore it becomes determine the exact trajectory for a designer of electron beam was generated by the magnetic lenses was inevitable. A classical methodology to start the desired design; first limit the Lorentz force components equivalent to a desired trajectory of the electron beam, second calculate the corresponding magnetic field distributions that would form the beam probe into a desired size [6].

The equation of paraxial ray is present the most important mathematical expression that determine the relationship between potential difference of V_r and radial position *r(z)* of an electron is given as [6]:

$$\frac{d^2r(z)}{dz^2} = \frac{e}{8mv_r} {B_z}^2(z) r(z) \ldots (1)$$

where: "*e* is the electron's charge, *m* is the electron's mass, V_r is the relativistically corrected acceleration voltage, and B_z is the axial magnetic flux density".

Comparison value of the focal length that obtained from Glaser expression with the value obtained from the Busch’s expression for focal length of a magnetic lens Given as [7]:

$$\frac{1}{f} = \frac{e}{8mv_r} \int (B_z(z))^2 dz \ldots (2)$$

where: f is the focal length.

In general, a magnetic lens consists of a coil made of electrically insulated Copper wire. When a continuous electric current *(I)* passes through its coil that contains *(N)* windings, it generates an axially symmetric magnetic field *(B_z)* along optical axis *(z-axis).* The coil deflecting electrons passing through it towards the optical axis according to Ampere's law [8]:

$$\int_{z_o}^{z_i} B_z d_z = \mu_o NI \ldots (3)$$

where: "$\mu_0 = 4\pi \times 10^{-7}$ H. m $^{-1}$ is the vacuum's permeability, and *NI* is excitation of the lens".

The well-known Munro's program that has been designed in 1975 [9] and to calculate the optical properties investigated in this work. It is based on the Finite Element Method to resolve the axial trajectory equation inside the optical columns. The solution of the paraxial ray equation which is computed by using a 4th order Runge-Kutta formula [10]. This program is used to find the Magnetic flux density lines through electronic magnetic lens, in addition to find the magnetic field intensity inside the lens, and then, calculating the magnetic lens properties studied here to verifying that it is suitable for working before fabrication. This simulation will reduce the both of time and costs.

If it is assumed that the object is the diameter of the cross over inside the electronic gun *(do)* and the distance between the object *(do)* and the first condenser lens *C1* is *So* and the distance between the two lenses, first condenser magnetic lens *C1* and second condenser lens *C2* is *(L)* [11]. These values are always from the instrument's constants, *d1* and *d2* are the diameter of the electron beam formed after the two lenses *C1* and *C2*, respectively, as shown in Figure (1).

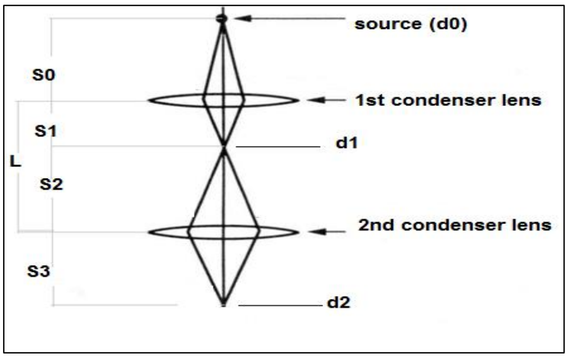


Fig. 1: Schematic Diagram of double condenser lens system

The total demagnification in the optical system of condenser magnetic lenses was given by [12]:

$$dMt = \frac{So}{S2} = dM1 * dM2 \ldots (4)$$

where: *So* is the distance between the object and the lens *C1*, *dM1*, *dM2* demagnification after the two lenses *C1* and *C2*, respectively, *dMt* the total demagnification in the optical system.

The results from equation (4) which obtained from numerical analysis programs based on the finite element method *(FEM)* prepared by Munro in 1975 [9], can be compared with the results that obtained from equation (5) based on geometric optics according to the following relationship:

$$\frac{do}{d2} = \frac{SoS2}{S1S3} \ldots (5)$$

where: *do* is the diameter of the cross over inside the electronic gun, *d2* diameter of the electron beam after the lens *C2*,, *S1* is the distance of the first image from the first lens *C1*, *S2* the distance of the first image, which is present the object, from the lens *C2*, *S3* the distance of the second image formed from the lens *C2*.

Methodology

A high-resolution images can be obtained, when the diameter of the electron probe falling on the specimen must be about (5- 10 nm). Therefore, we need up to 5000 times of reduction processes to obtain the required diameter. In thermal emission electron microscopes of the type tungsten, the diameter of the electron gun is in the ranges of (10-100 µm). The ideal values for miniaturization from any electron lens extends from (10- 40 times), meaning we need at least three stages of demagnification in order for the total reduction to be in the size of the electron probe diameter (1000- 64000 times), and accordingly the proposed lighting system will be in this study consists of two condensed magnetic lenses, symbolized by *C1* and *C2*, that operate in different modes [4,13].

The geometrical dimensions of the double lenses have been chosen depending on recent researches [1,2,3]. The condensing lenses have been named "*C1* and *C2*" on the first and second condensing lenses respectively, were the two lenses possess the same dimensions; inner diameter *(D1 = 10 mm)*, outer diameter *(D2 = 100* mm), length of the lens *(L = 90 mm)* and the coil dimensions (65 x 26 mm^2). The total demagnification has been calculated analytically and geometrically by the double condensing lens system *(dMt)* using the program *(M21);*considering the diameter of the electron beam emitted by the electron gun ($d_0=50\ \mu m$), and the total demagnification and the total diameter of the electron beam *d2* during operating. The following modes; (weak- weak), (weak- strong), (strong- strong), and (strong- weak) respectively. The weak mode is presented by current intensity ($0.3\ A/mm^2$) and strong mode ($0.88\ A/mm^2$). The best value for the total reduction and the diameter of the electron beam has been obtained in the mode of (strong- strong); where the parameters were: *(dMt = 1014.199), (d2 = 49.3 nm),* while the worst value has been achieved in the mode (weak-weak) of *(dMt = 31.56267), (d2 = 1584.15 nm).*

Results and Discussion

Figure (2) below shows a design of double condensing magnetic lenses model that are similar in all geometrical dimensions; *(L)* length of the lens, *(D1), (D2)* inner and outer diameter, respectively, and the coil shape.

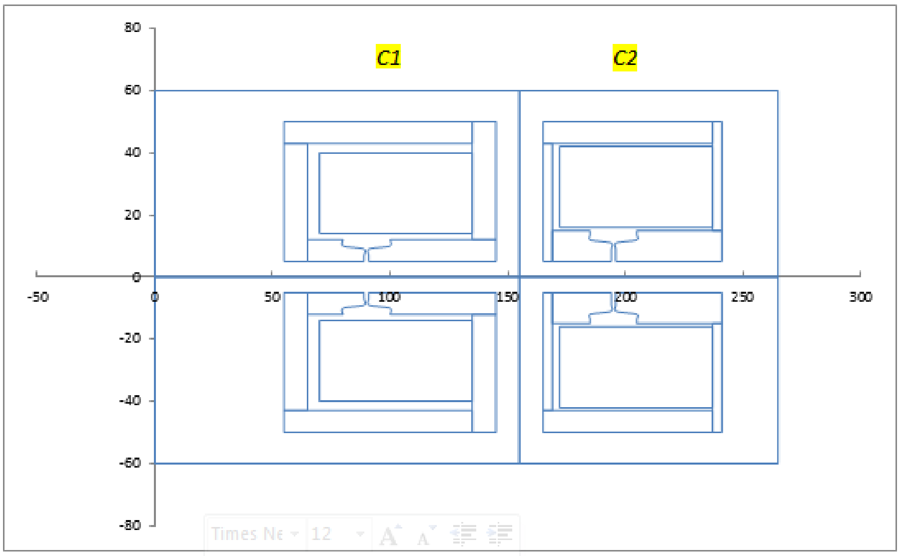


Fig. 2: The double condenser magnetic lenses

The trajectory of the electron beam inside the condenser magnetic lenses system is shown in Figure (3) for both *C1* and *C2* lenses, which are accelerated with a voltage (10 kV) and a current density ($\sigma 1 = \sigma = 2 = 0.6\ A/mm^2$).

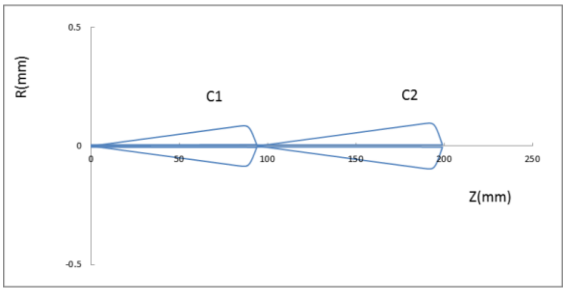


Fig. 3: The electron beam trajectories in condenser magnetic lenses system.

Figure (4) shows the relationship between demagnification in the diameter of electron beam dM1 emerging from the lens *C1* as a function of the current density *σ1* passing through its coil, it was found that when the current density increases, the demagnification in the electron beam diameter increases while, the focal length *(f)* and the distance of the image (Z_i) from the first lens *C1* decreases with the increase of current density σ1. Therefore, using these diagrams helps to get all the required data about the electron beam coming out of lens *C1*.

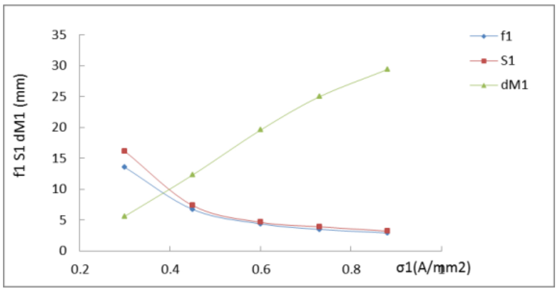


Fig. 4: The optical properties of (*dM1, f1, S1*) as a function of current density(*σ1*).

Figure (5) illustrates the electron beam diameter *d1* emerging from the condenser magnetic lens *C1* as a function of the current density *σ1* passing through its coil, from the shape, can be noticed, decrease of the electron beam diameter *d1* when the current density was increased. diameter of the electron beam ranges from (nanometers - micrometers) and carries a current. It extends from (Pico-ampere to micro-ampere), depending on the type of electron gun used, the minimum value of the beam current required to obtain an image from SEM instruments is called the threshold current and is approximately equal *to ip=1pA* and this value is determined by the system of detectors and image display devices in SEM. [7,13]**.**

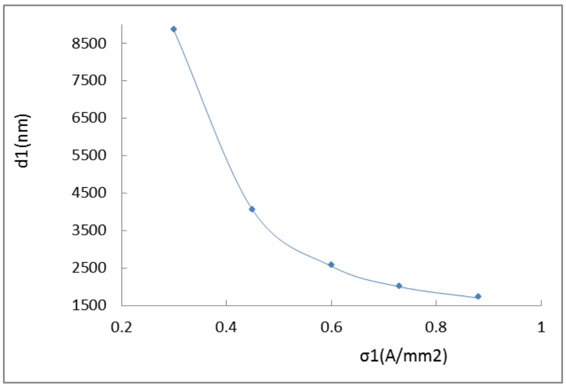


Fig. 5: The electron beam diameter (*d1*) as a function of current density (*σ1*).

The maximum values of optical properties of the first magnetic condenser lens *(C1)*, can be the seen in Table (1) which displays the detail for; magnetic flux density (B_z), beam refraction position (Z_p), position of image formation on the optical axis (Z_i), focal length *(f)*, magnitude of demagnification For the electronic beam *(dM1)*, diameter of the electron beam *(d1)*, which represents the first true (crossover) image, at different current densities $(\sigma 1 = 0.3, 0.45, 0.6, 0.73. 0.88\ A/mm^2)$ and a constant acceleration voltage $(V_r = 10\ kV)$. Table (1) below illustrates the details of the optical properties of the 1st magnetic condenser lens *(C1)* at different current densities $(\sigma 1 = 0.3, 0.45, 0.6, 0.73,$ *and* $0.88\ A/mm^2)$ and a constant acceleration voltage $(V_r = 10\ kV)$.

Table 1: The optical properties of the 1st magnetic condenser lens *(C1)* at different current densities, and constant acceleration voltage $(V_r = 10\ kV)$.

current density (σ1) A / mm^2	beam refraction position (Z_p) mm	position of image formation (Z_i)mm	Focal length (*f*) mm	Magnetic flux density (B_z)T	Demagnification (*dM1*)	Beam diameter (*d1*) nm
0.3	89.84	103.41	13.57	83640.0	5.649	8850
0.45	89.62	96.38	6.75	12547.0	12.34	4050
0.6	89.33	93.75	4.42	167290.	19.60	2550
0.73	89.06	92.58	3.52	203540.	25	2000
0.88	88.75	91.69	2.94	245350.	29.41	1700

Figure (6) below shows the total demagnification *(dMt)* obtained from the double condenser magnetic lens system, which depends on the demagnification obtained from first condenser magnetic lens *(dM1)* and current density in the second condenser lens *σ2*, which in its role determines the value of *S3*. We notice from the figure (1) when increasing the current density *σ1* in the first condenser lens, *S1* decreases, thus *S2* increases for the distance between the two lenses *L* is a constant, as is obvious from figure (1). Until we reach the highest value for each of σ1 and *σ2*, and thus we get the highest value of demagnification in the electron beam, the operation mode will be in the mode (strong, strong). This means that the total demagnification *(dMt)* in the condenser lens system depends on the demagnification *(dM1)* in the first condenser lens and current density *(σ2)* passing through second condenser lens.

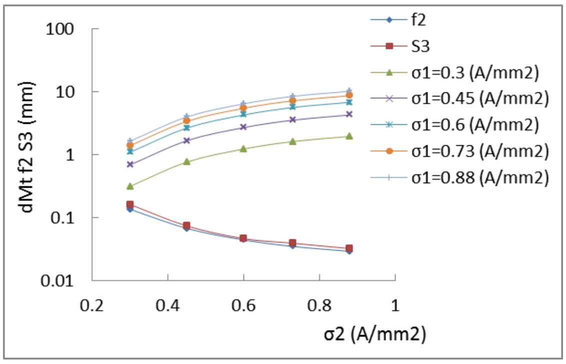


Fig. 6: The optical properties of (*dMt, f2, S3*) as a function of current density(*σ2*)

Figure (7) below demonstrates the relationship between the diameter of the electron beam *d2* emerging from the second condenser lens *C2* as a function of the current density *σ2* passing through its coil at different values of the current density of the first lens σ1, It is found that when current density *σ2* increases; the beam diameter *d2* of the condenser magnetic lens system decreased.

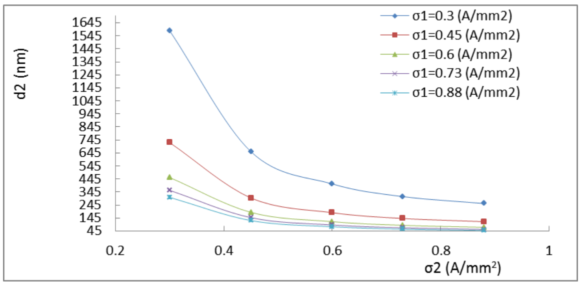


Fig. 7: The optical properties of (*d2*) as a function of current density(*σ2*)

It should be mentioned here that Figures (6,7) above can be used as a calibration curve to obtain the total demagnification required for the diameter of the electronic beam by extracting all the interstitial values that permeate the studied values, and this is can be done by drawing perpendicular lines on the horizontal and vertical axes for any needed point for any desired mode for specific use according to the purpose of the desired application. This is a very highlight point in this work.

Figure (8) below illustrates change of electron beam diameter *d2* according to operation modes, can be seen that a better electron beam diameter *(d2= 49.3 nm)* has been achieved at the mode (strong-strong)(#1), however, worse diameter *(d2= 1584.1 nm)* has been achieved at (weak- weak)(#3) mode.

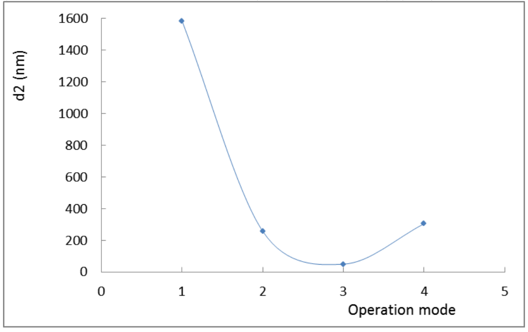


Fig. 8: The change of electron beam diameter *d2* as a function of operation modes.

Table (2) below shows in details the operation modes in the magnetic condenser lenses system, the total demagnification, and the corresponding electronic beam diameters.

Table 2: The operation modes in the magnetic condenser lenses system with total demagnification and the corresponding electronic beam diameters

Condenser magnetic lenses	Operation modes	Current density (σ1, σ2)A/mm^2	Total Demagnification (dMt)	Electron beam diameter (d2) nm
C1, C2	(#1-weak, weak)	(0.3, 0.3)	31.5	1584.1
C1, C2	(#2-weak, strong)	(0.3, 0.88)	194.8	256.6
C1, C2	(#3-strong,strong)	(0.88, 0.88)	1014.1	49.3
C1, C2	(#4-strong, weak)	(0.88, 0.3)	164.3	304.3

Conclusions

In conclusion, a condenser magnetic lens system has been designed, and the electron beam properties were reported in this paper. It is found that by increasing the demagnification of the first condenser lens, the demagnification of the final real image produced by the double lens system has been positively affected. As a result, a high resolution can be obtained by running this system in a strong operation mode and obtaining a small electron beam diameter of the probe. Finally, It was concluded that the relationships that obtained between the demagnification and the current density can be used as a calibration curve to obtain the total demagnification required for the diameter of the electronic beam by extracting all the interstitial values that permeate the studied values, for any needed point for any required mode according to the purpose of the desired application.

References

[1] D.H. Kim, K. Park, M.J. Park, H.W. Jung, D.Y. Jang, "Numerical analysis for verifying the performance of lens system in a scanning electron microscope", Optik (Stuttg). 121 330–338. https://doi.org/10.1016/j.ijleo.2008.07.012., (2010).

[2] E.K. Peter Hawkes, "Principles of Electron Optics", https://doi.org/10.1016/c2015-0-06653-9., (2018).

[3] M. Sapti, "A Textbook on Fundamentals and Applications of Nanotechnology", Kemamp. Koneksi Mat. (Tinjauan Terhadap Pendekatan Pembelajaran Savi). 53 1689–1699., (2019).

[4]M.A. Hussein, "Numerical analysis to verifying the performance of condenser magnetic lens in the scanning electron microscope", 58, 44–49. (2016).

[5]A. Khursheed, "Magnetic axial field measurements on a high resolution miniature scanning electron microscope", Rev. Sci. Instrum. 71, 1712–1715. https://doi.org/10.1063/1.1150525., (2000).

[6] M.A. Hussein, "Effect of the Geometrical Shape of the Magnetic Poles and the Distance between Them on the Focal Properties of the Condenser Magnetic Lens in the Scanning Electron Microscope", (SEM), 4, 130–134. https://doi.org/10.12691/ijp-4-5-3., (2016).

[7] R.F. Egerton, "Physical Principles of Electron Microscopy", https://doi.org/10.1007/978-3-319-39877-8., (2016).

[8] X. Zhu, "A computer program for electron gun design using second-order finite elements", J. Vac. Sci. Technol. B Microelectron. Nanom. Struct. 7, 1862. https://doi.org/10.1116/1.584681., (1989).

[9] Munro, E., "Computer-Aided Design of Electron Lenses by the Finite Elements Method", in Image Processing and Computer-aided Design In Electron Optics, edited by P. W. Hawkes, Academic Press, London, pp. 284-323., 1975a.

[10] R.Y.J. Al-Salih, A.I.M. Al-Abdulla and E.M.A. Alkattan., "Simple program for computing objective optical properties of magnetic lenses", Int. J. Computer Applications in Technology, Vol. 66, No. 3/4, (2021).

[11] S. Pany, B. Atomic, B. Dubey, "Development of electron beam focusing system for Scanning Electron Microscope", (2012).

[12] M.A. Hussein, " Design and Fabrication Illumination System in the Scanning Electron Microscope " thesis university of mosul , (2014).

[13] Q.W. Graciela W. Padua, "Nanotechnology Research Methods for Foods and Bioproducts", First Edit, A John Wiley & Sons, Ltd., Publication, USA, (2012).

تأثير أنماط التشغيل على قطر الحزمة الإلكترونية في منظومة العدسات المغناطيسية المكثفة

محمد عبدالله حسين[1] **، رافع يونس جاسم الصالح**[2] **، عبدالله إدريس مصطفى العبدالله**[3]

[1] *قسم الفيزياء ، كلية التربية / الحويجة ، جامعة كركوك ، كركوك ، العراق*

[2] *قسم الفيزياء ، كلية العلوم ، جامعة تكريت ، تكريت ، العراق*

[3] *قسم الفيزياء ، كلية العلوم ، جامعة الموصل ، الموصل ، العراق*

الملخص

تم دراسة تأثير أنماط تشغيل العدسات المغناطيسية المكثِّفة لتحديد مقدار التصغير الكلي وقطر شعاع الحزمة الإلكترونية الخارجة منها. تعتبر نقطة العبور (cross-over point) داخل القاذف الإلكتروني كقطر تصغير للشيء Objective demagnification (*do*) بأقطار ضمن المدى (10 – 100 ميكروميتر) لمعرفة الكفاءة البصرية لنظام العدسات المكثفة المزدوج وقدرته على تكوين صورة ذات دقة عالية للصورة الحقيقية الأولى المتكونة داخل القاذف الإلكتروني ذي الإنبعاث حراري الذي يعمل كمصدر فعلي للحزمة الإلكترونية. تمت دراسة الأنماط الآتية؛ (ضعيف– ضعيف) ، (ضعيف– قوي) ، (قوي– قوي)، و (قوي– ضعيف). تم الحصول على أفضل قيمة للتصغير الكلي وقطر حزمة الإلكترون في نمط (قوي – قوي)؛ حيث كانت المعلمات بالمقادير $(dMt = 1014.199)$ و $(d2 = 49.3\ nm)$، بينما تم تحقيق أسوأ قيمة في الوضع (ضعيف – ضعيف)؛ حيث كانت المعلمات بالمقادير $(dMt = 31.56267)$ و $(d2 = 1584.15\ nm)$. لقد وجد بأنه من خلال زيادة التصغير للعدسة المكثفة الأولى فإن تصغير الصورة الحقيقية النهائية التي ينتجها نظام العدسة المزدوجة قد تأثرت بشكل إيجابي. نتيجة لذلك؛ يمكن الحصول على دقة عالية من خلال تشغيل هذا النظام في نمط التشغيل (قوي – قوي) والحصول على قطر شعاع إلكتروني صغير للمسبار. أخيرًا؛ وجد أن العلاقات التي تم الحصول عليها بين مقدار التصغير وكثافة التيار يمكن استخدامها كمنحنى معايرة للحصول على التصغير الكلي المطلوب لقطر الحزمة الإلكترونية لأي نمط وفقًا للغرض من التطبيق المرغوب.