Theoretical Design of Electrostatic Lens Accelerating and Decelerating Operated Under Different Magnification Conditions

Bushra H. Hussein
Dept. of Physics/ College of Education for Pure Science(Ibn-AL Haitham)/
University of Baghdad

Receivd in: 5 November 2012, Accepted in: 1 April 2013

Abstract

In this paper, design computationl investigation in the field of charged-particle optics with the aid of numerical analysis methods under the absence of space charge effects. The work has been concentrated on the design of three-electrode einzel electrostatic lens accelerating and decelerating operated under different magnification conditions.

The potential field distribution of lens has been represented by exponential function. The paraxial-ray equation has been solved for the proposed field to determine the trajectory of charged-particles traversing in the lens. From The axial potential distribution and its first and second derivatives, the optical properties such as the focal length and the spherical and chromatic aberration coefficients have been computed, the electrode shape of lens has been determined by using SIMION computer program .

In this research , design electrostatic einzel lens three-electrode accelerating and decelerating L=2mm, 20mm operated under different magnification conditions (zero, infinite, finite). The electrode shape of the electrostatic lens was then determined from the solution of the Laplace's equation. The results showed low values of spherical and chromatic aberrations which are considered as good criteria for good design.

Keywords. Electron Optics, Einzel Lens, Accelerating and Decelerating , Aberrations, SIMION computer program

Introduction

Electrostatic lenses are the principal components in the overwhelming majority of electron optical devices. Both electrostatic and magnetic lenses are used to focus charged particles. Electrostatic lenses are used with applications in many areas of science and technology. For example, electrostatic devices are used to shape ion microprobe beams for secondary ion mass spectroscopic studies. More recently, with the aid of electrostatic lenses ion probes are employed in ion implantation to change the local properties of semiconductors[1] . Electrostatic cylinder lenses are widely used to control beams of charged particles with different energies and directions in several fields, especially in electron spectroscopy were designed by using the SIMION programs[2] . The development of computer programs was accompanied by the need of more application for such ion and electron instruments in various kinds [3-4] . In the present work ,we have a design of accelerating and decelerating electrostatic einzel lens for different applications in electron optical instruments. The einzel lens has the same constant potential at both the object and image sides i.e. the charged-particle energy remains unchanged [5]. The design and implementation of a purely electrostatic deceleration lens are used to obtain beams of highly charged ions at very low energies is presented [6].

Theory

The present computational investigation is aimed to design electrostatic lens using analytic expression (exponential model) that would describe the axial potential distribution of einzel lens with electron optically acceptable aberrations. The following expression is suggested to represent the potential distribution along the optical axis of an einzel lens[7]:

$$U(z) = U1\left[1 + D\exp\left(\pm z^2\right)\right] \tag{1}$$

Where U1 is the voltage applied on the outer electrodes, D is a constant affecting the value of voltage applied on the central electrodes, The negative (-) sign denotes for an accelerating mode of operation .And the positive (+) sign is denoted for the decelerating mode.

The paraxial-ray equation in rotationally symmetric field is given by[7]

$$\frac{\partial^2 r}{\partial z^2} + \frac{U'(z)}{2U(z)}\frac{\partial r}{\partial z} + \frac{U''(z)}{4U(z)} r = 0 \tag{2}$$

SIMION is an electrostatic lens analysis and design program that is capable of modeling charged particle optics problems with electrostatic and/or magnetic potential arrays. This program is used to simulate electrostatic and static magnetic device for accelerating, transporting and otherwise manipulating beams of charged particles . For the purposes of this article, only electrostatic fields were modeled. The shape of the electrodes for electrostatic lens is determined from the solution of Laplace's equation [7].

$$U(r,z) = U(z) - U''(z)\frac{r^2}{4} \tag{3}$$

The spherical aberration is one of the most important geometrical aberrations and can be defined as follows: the beam passing within the lens area at a considerable distance from the axis are more (or less) refracted than the paraxial beams so that they intersect closer to (or farther form) the image plan .The spherical and chromatic aberrations are dominant in an electrostatic lens [8].

The coefficients of spherical aberration and chromatic aberration referred to the object space **Cs$_o$** and **Cc$_o$** expressed in the following form [9].

$$Cs_O = \frac{U^{-1/2}}{16 r_o'^4} \int_{zo}^{zi} \left\{ \left[\frac{5}{4}\left(\frac{U''(z)}{U(z)}\right)^2 + \frac{5}{24}\left(\frac{U'(z)}{U(z)}\right)^4 \right] r^4(z) + \frac{14}{3}\left(\frac{U'(z)}{U(z)}\right)^3 \right.$$

$$\left. r'(z) r^3(z) - \frac{3}{2}\left(\frac{U'(z)}{U(z)}\right)^2 r'^2(z) r^2(z) \right\} \mathrm{U}^{1/2}(\mathrm{z})\,\mathrm{dz} \qquad (4)$$

$$Cc_O = \frac{U^{1/2}(z_o)}{r_o'^2} \int_{zo}^{zi} \left[\frac{1}{2}\frac{U'(z)}{U(z)} r'(z) r(z) + \frac{U''(z)}{4U(z)} r^2 \right] U^{-1/2}(z)\,dz \qquad (5)$$

In the image space , the spherical aberration coefficient **Cs$_i$** and chromatic aberration coefficient Cc$_i$ is expressed in a similar form of equations (3) and (4) , Where $U^{-1/2}(z_o)$ and and $r_i'^4$ are replaced by $r_o'^4$ respectively. $U^{1/2}(z_i)$

In general, the focal length f of a lens at various values voltage ratio is determined from the gradient of the beam trajectory of the point where the charged particles enter or emerge from the lens field region. The object and image-side focal lengths fo and fi respectively have been computed from the following equation [9]:.

$$f_O = r(z_i)/r'(z_o) \qquad (6)$$

$$fi = r(z_o)/r'(z_i) \qquad (7)$$

The magnifications are calculated form following equation [10].

$$M = \frac{r_i}{r_O} \qquad (8)$$

A computer program for computing the beam trajectory , the optical properties[11] and electrode shape by using SIMION computer program [12].

Results and Discussion

The axial field distribution U(z) given in equation (1) for an einzel lens is shown in figure (1a) with its first derivative $U'(Z)$. The axial field distribution of an einzel lens whose central electrode is at higher voltage for accelerating mode; the distribution in figure (1b) is for an einzel lens whose central electrode is at voltage lower than the equal voltage applied on the first and the third electrodes for decelerating mode. Since the potential distribution U(z) is constant at the boundaries, then its first derivative $U'(Z)$ is zero. This indicates that there is no electric field outside the lens i.e. there is a field free region away from the lens terminals where the trajectory of the charged particles beam is a straight line due to the absence of any force acting on it.

The profile of three electrodes forming an electrostatic einzel lens is shown in figure (2). Three-element electrostatic lens systems as a function of the lens voltages and their dimensions. Lens systems, which consist of cylindrical electrodes, each spaced 0.1 diameter apart, were designed by using the SIMION programs studied to form an image at a specific position for use in experimental studies. We also discussed the line-shape profile of a three-element, the lens is symmetrical about its center in addition to the rotational symmetry. The lens geometry is independent of the mode of operation and magnification conditions. The central electrode is hole of a radius equivalent to 0.001L where L is the length of the lens field. The three electrodes have equal outer radius o about 0.25L. The two outer electrode are geometrically identical having the same shape. Two equal gaps of 0.05L are found to separate each of the outer electrodes from central electrodes.

Table (1) shows properties the electrostatic einzel lens accelerating and decelerating operated under different magnification conditions.

The spherical and chromatic aberration coefficients have been computed for electrostatic einzel lens accelerating and decelerating with length L=2mm using the equations (4), (5), (6), (7),(8).

1- Zero magnification conditions

The relative spherical and chromatic aberration coefficients Cs/fi and Cc/fi respectively in the image side at accelerating and decelerating mode are shown in figure (3) as a function of the electrodes voltage ratio U_2/U_1 under Zero magnification condition. The Cs/fi has two minima of 0.8 at U_2/U_1= 1000 (accel) and 0.058 at U_2/U_1=0.3 (decal). The Cc/fi has two minima of 0.1 at U_2/U_1= 1000 (accel) and 1.5 at U_2/U_1=0.9 (decal). In the fig (3) the Cs/fi and Cc/fi decrease with the increase of U_2/U_1in a accelerating mode , Cs/fi decrease and Cc/fi increase with increase U_2/U_1 in decelerating mode. The spherical aberration is dominant in zero magnification condition.

2- Infinite magnification conditions.

The relative spherical and chromatic aberration coefficients Cs/fo and Cc/fo respectively in the object side as a function of the electrodes voltage ratio U_2/U_1 in figure (3) , when accelerating lens the Cs/fo decrease with the increase of U_2/U_1 (U_2/U_1 =50 ,Cs/fo=0.2) while the Cs/fo increase with the increase of U_2/U_1. The main reason for chromatic aberration is the fact that particles with higher initial energy are less influenced by the imaging field than the lower energy particles. In decelerating lens the Cs/fo and Cc/fo decrease with the increase of U_2/U_1.

3- Finite magnification condition

In figure, (3) the relative spherical and chromatic aberration coefficients Cs/M and Cc/M respectively as a function of the electrodes voltage ratio U_2/U_1, In accelerating lens U_2/U_1 >1 the Csi/M and Cci/M decrease with the increase of U_2/U_1 in low magnification while the Cso/M and Cco/M increase with increase of U_2/U_1 in high magnification. In decelerating lens U_2/U_1 <1 all the aberration coefficients decrease with the increase of value of U_2/U_1.

In the decelerating mode, the lens acts as a series of three lenses, namely, from left (object side) to right (image side), a diverging, a converging, and a diverging lens. Since the charged particles slow down in the central electrode region. However, the trajectory spreads out from the axis initially before entering the central electrode region. For this reason, the spherical aberration coefficient of a lens with U_2/U_1 is always less than that of he corresponding lens with U_2/U_1 [13].

The best lens in this research that is high magnification condition where U_2/U_1 =5, Cs/M=0.011 and Cc/M=0.077
U_2/U_1 =0.9, Cs/M=0.019 and Cc/M=0.23.

Table (1) shows the best optical properties the electrostatic einzel lens accelerating and decelerating operated under different Magnification conditions .

Figure(4) and table (2) show a comparison between the values of the relative aberration coefficients for a three electrode einzel lens operated under different magnification conditions with length L=2mm, L=20mm when U_2/U_1=5. . The effect of lens length L on the relative aberration coefficients increase with the increase of L.

Conclusion

1-The spherical aberration coefficient is decreased in zero , infinite and finite (low mag.) with increases of the electrodes voltage ratio, while it increases in finite (high mag.) with the electrodes voltage ratio increases.

2- The chromatic aberration coefficient is decreased in zero, infinite and finite (low mag.) with increases of the electrodes voltage ratio, while it increases in finite (high mag.) with the electrodes voltage ratio increases.

3- The optical properties of the electrostatic einzel lens accelerating and decelerating which are determined from the electrodes voltage ratio.

4- The best optical properties in this research that are in high magnification condition where $U_2/U_1=5$, Cs/M=0.011 and Cc/M=0.077
$U_2/U_1=0.9$, Cs/M=0.019 and Cc/M=0.23.

5- The aberration coefficients increase when lens length increase.

References

1- Baranova, L. A. and Yavor, S. Ya., (1984), Electrostatic Lenses, Sov. Phys. Tech. Phys, 29, 827-848.
2- Sise, O.; Ulu, M.and Dogan, M. (2007), Characterization and modeling of multi-element electrostatic lens systems, Radiation Physics and Chemistry ,76 , 593–598.
3- Abdelrahman ,M.M. (2010) ,Two and three electrostatic lens systems for focusing of charged particles, J. Eng. Technol. Res. 2 (2):219-225.
4- Litovko, I. and OKS , E., (2006), 33rd Eps Conference on plasma phys Rome , 19-23 June , ECA 301, 2.104.
5- Szilagyi, M. (1988), Electron and ion optics, (Plenum press: New York).
6- Rajput, J.; Roy, A.; Kanjilal, D. ,; Ahuja, R. and Safvan, C. P. (2010), An electrostatic deceleration lens for highly charged ions, REV. Sci. Instrum., 81 (4):1-5.
7- Hawkes P. W. and Kasper E., (1989), Principles of electron optics ,1 (Academic Press: London).
8- Zhigarev, A., (1975) , Electron optics and electron-beam devices, (Mir Publisher: Moscow)
9- Kiss, L.(1988), Computerized investigation of electrostatic lens potential distribution, 12th IMACS World Congress, ed. R. Vicheretsky, Paris.
10- Rempfer ,G. F. (1999), The relationship of lens aberrations to image aberrations in electron optics, Optik, 110, 17-24.
11- Ahmad, A. K. (1993), Computerised investigation on the optimum design and properties of the electrostatic lens, Ph.D. Thesis, Nahrain University , Baghdad , Iraq.
12-David, J. Munra and Dahl, D. Daho, (2008), SIMION 3D VESION 8.0 User's Manual, Scientific Instrument Services.
13- EL-Kareh, A. B. and Sturans, M. A. (1971), analysis of the 3-tube symmetrical electrostatic unipotential Lens, J. Appl. Phys., 42, 1870-1876.

Table No. (1) shows the best optical properties the electrostatic einzel lens accelerating and decelerating operated under different Magnification conditions

Magnification	U_2/U_1	Cs/f	U_2/U_1	Cc/f
Zero mag.	1000 0.3	0.8 0.058	1000 0.0025	0.1 0.1
Infinite mag.	50 0.6	0.2 0.77	5 0.6	2.6 0.37
	U_2/U_1	Cs/M	U_2/U_1	Cc/M
Finite [high]	5 0.9	0.011 0.019	5 0.6	0.077 0.024
Finite [low]	1000 0.9	3.6 0.015	1000 0.9	0.14 0.018

Table No. (2) Shows the optical properties the electrostatic einzel lens operated under different Magnification conditions when U_2/U =5.

Magnification	Lens of length (mm)	The spherical aberration coefficient(mm)	The chromatic aberration coefficient(mm)
Zero mag.	L=2 L=20	31 52	1.5 2
Infinite mag.	L=2 L=20	12 15	2.6 3.3
Finite [high]	L=2 L=20	0.011 0.03	0.077 0.1
Finite [low]	L=2 L=20	77.5 24398	4.5 14

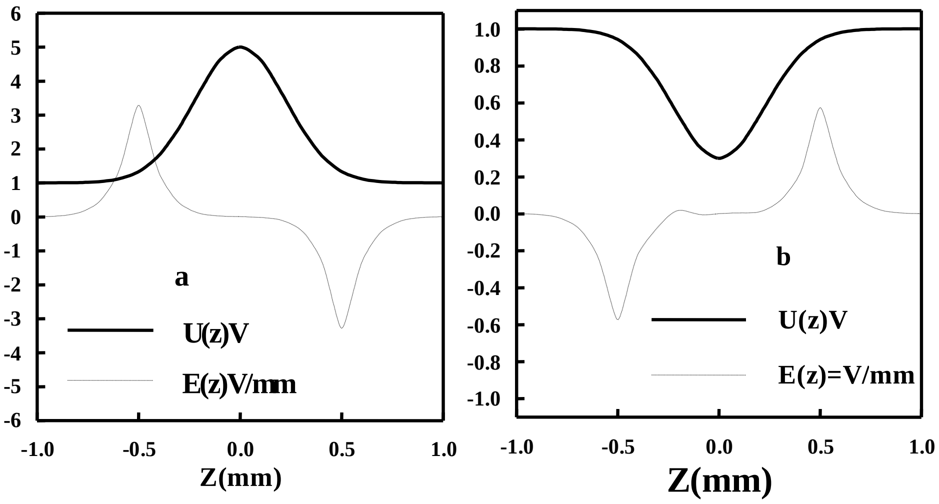

Figure No. (1) The axial potential distribution U (z) and its first derivatives E(Z) of three electrode einzel lens (a) accelerating mode (b) decelerating mode

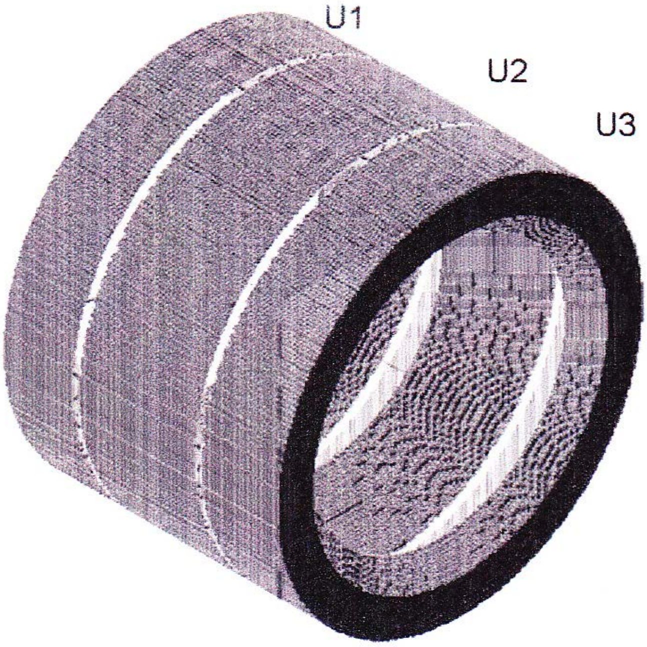

Figure No.(2) Shape of three electrodes einzel lens with best of optical properties $U_2/U_1=5$

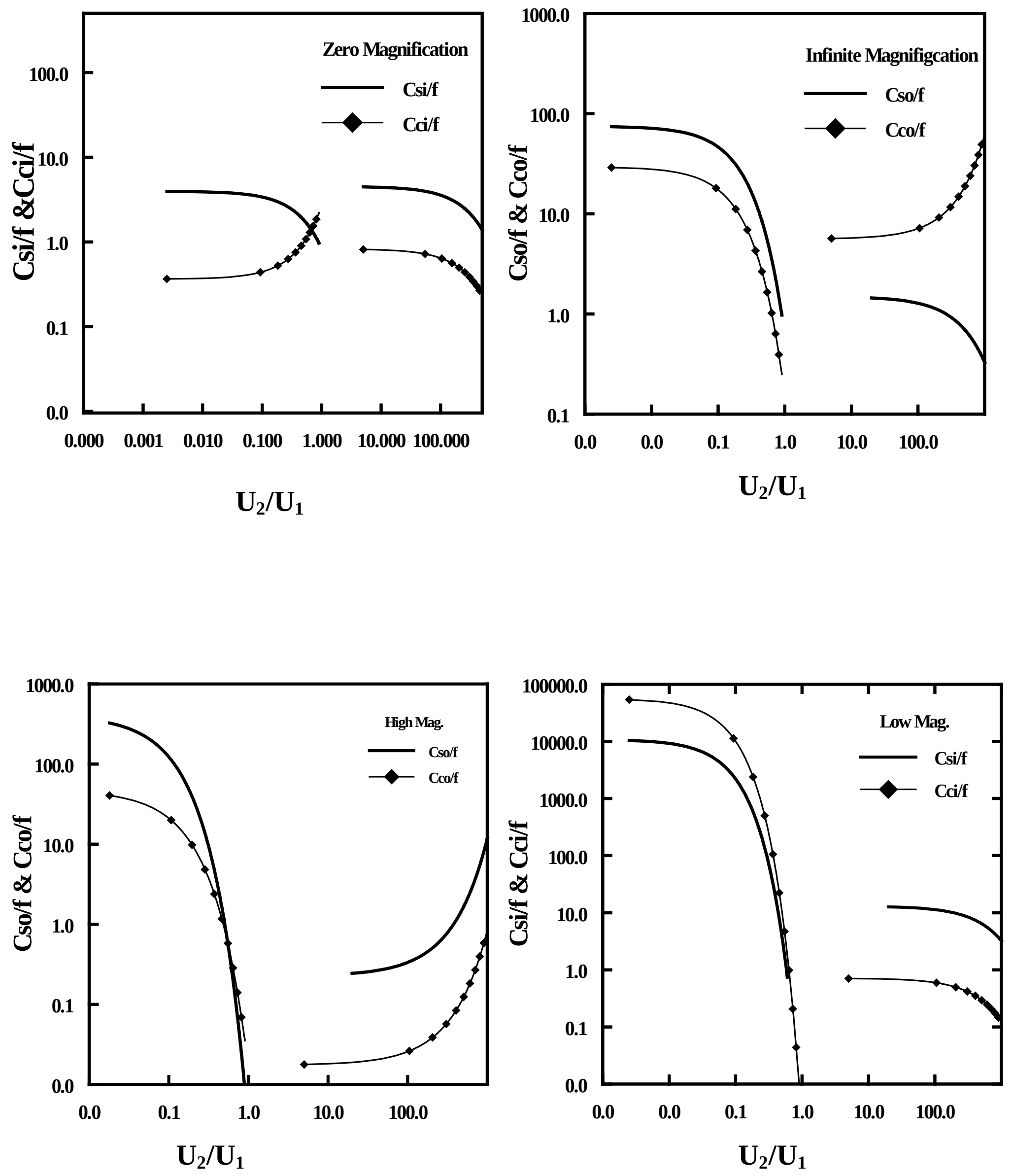

Figure No.(3)The relative spherical and chromatic aberration coefficients as a function of the electrodes Voltage ratio for einzel lens operated under different Magnification conditions

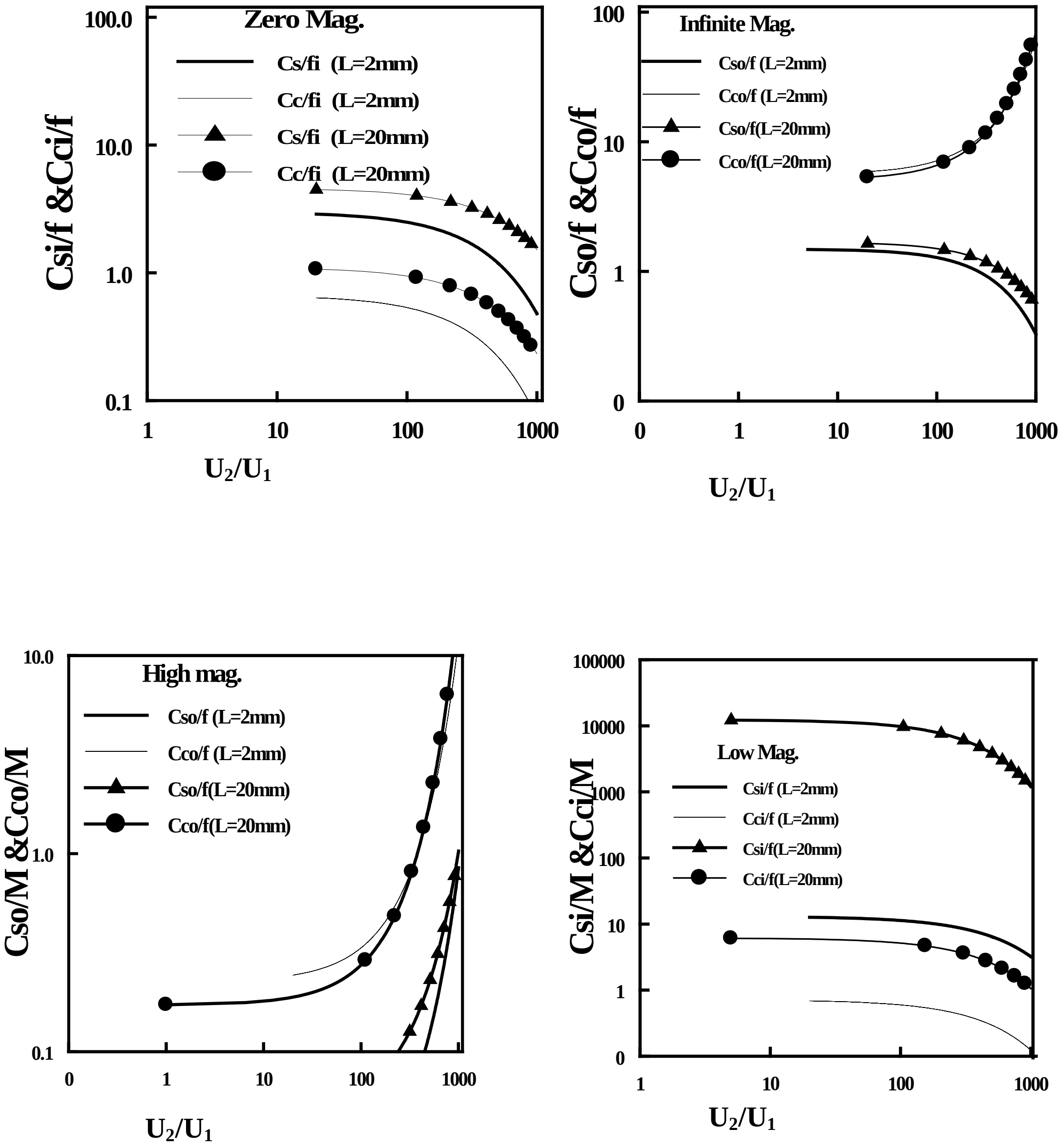

Figure No. (4)The relative spherical and chromatic aberration coefficients as a function of the electrodes Voltage ratio at various value of the lens length for einzel lens operated under different Magnification conditions

تصميم نظري لعدسة كهروستاتيكية معجلة ومبطئة تعمل تحت ظروف التكبير المختلفة

بشرى هاشم حسين
قسم الفيزياء/ كلية التربية للعلوم الصرفة (ابن الهيثم) /جامعة بغداد

استلم البحث 5 تشرين الثاني 2012، قبل البحث في 1 نيسان 2013

الخلاصة

في هذه الدراسة صمم بحث حاسوبي في مجال بصريات الجسيمات المشحونة بالاستعانة بطرائق التحليل العددي عند انعدام تأثيرات شحنة الفراغ. لقد تركز البحث على تصميم عدسة كهروستاتيكية أحادية الجهد ثلاثية الأقطاب معجلة ومبطئة تعمل تحت ظروف التكبير المختلفة.

ان توزيع مجال الجهد للعدسة تم تمثيله بالدالة الأسية. تم حل معادلة الأشعة المحورية للمجال المقترح لأيجاد مسار الجسيمات المشحونة المارة في العدسة. ومن توزيع الجهد المحوري ومشتقتيه الأولى والثانية حسبت الخواص البصرية، كالبعد البؤري ،ومعامل الزيغين الكروي واللوني. كذلك تم ايجاد شكل الأقطاب للعدسة بأستخدام احد برامج المحاكاة المعروفة بأسم (سيميون) .

في هذا البحث صممت عدسة احادية الجهد ثلاثية الاقطاب معجلة ومبطئة بطول L= 20 mm, 2mm تعمل تحت ظروف التكبير المختلفة (صفري، لانهائي، نهائي) حيث تم الحصول على شكل الاقطاب لهذه العدسة باستخدام حلول معادلة لابلاس. وقد بينت نتائج البحث قيم قليلة للزيغين الكروي واللوني التي تعطي مؤشراً على كفاية تصميم العدسة.

الكلمات المفتاحية : بصريات الكترونية ،عدسة أحادية الجهد ، معجلة ومبطئة، الزيغ ، برنامج المحاكاة (سيميون) .