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Optimization of the Electrodes Geometrical Shape for the Electrostatic Deflector in the SEM

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ABSTRACT

The quadruple electrostatic deflectors has been designed and studied in this paper. Three different geometrical shapes of electrodes were handled; Planar, concave, and convex. Wide comparison between these electrodes was realized using a new version of finite element method magnetics (FEMM) to analyze their properties. The optimized geometrical shape of the deliberated electrodes will be chosen to use it as an electrode in the electrostatic deflector inside the objective lens for low voltage scanning electron microscope (SEM) to directing the charged particles electron beam passes throughout the optical axis of the lens towards the tested specimen.

Keywords: Electrostatic deflector design, Electrode geometrical shape, Charged particles, Electron beam, Low voltage SEM.

الشكل الهندسي الأمثل لأقطاب الحارفة الكهروستاتيكية في المجهر الالكتروني الماسح

الملخص

تمّ في البحث تصميم الحارفات الكهروستاتيكية الرباعية ذات المرحلتين و دراستها. تناول البحث ثلاثة أشكال هندسية مختلفة من الأقطاب الكهربائية؛ المستوية والمقعرة و المحدّبة. تمّ اجراء مقارنة واسعة بين هذه الأقطاب الكهربائية باستخدام طريقة العناصر المتناهية المغناطيسية (FEMM) لتحليل خواصّها. تم اختيار الشكل الهندسي المنتخب من بين الأشكال المدروسة ليستخدم كقطب كهربائي في الحارفات الكهروستاتيكية داخل العدسة الشيئية للمجهر الالكتروني الماسح (SEM) ذي الفولتية الواطئة لتوجيه حزمة الجسيمات المشحونة الإلكترونية المارّة من خلال المحور البصري للعدسة باتجاه العيّنة المفحوصة.

الكلمات الدالّة: تصميم الحارفات الكهروستاتيكية، الشكل الهندسي للقطب الكهربائي، الجسيمات المشحونة، الحزمة الالكترونية، المجهر الالكتروني الماسح ذو الفولتية الواطئة.

INTRODUCTION

Electrostatic deflectors are used in high-speed deflection applications. Typical examples are oscilloscope tubes, electron beam lithography and inspection systems (particularly as the high-speed subfield deflectors), and streak cameras. Electrostatic deflectors are more complicated to simulate than the electrostatic lenses, because they have three-dimensional structures without rotational symmetry (Munro, 1997). This article related with the important milestones in the development of scanning electron microscope (SEM). Knoll in 1935 was the first who imaged the surface by an SEM over it in a raster pattern, and the first scanning microscope to use electrons to demonstrate a resolution higher than that of light microscope was designed as a scanning transmission electron microscopy (STEM) by Ardenne in 1938 (Pawley, 1997). High resolution observation with small spherical and chromatic aberration coefficients C_s, C_c are made possible without forming a positive high voltage section inside an electron beam path of a lens barrel (Yonezawa, 2005).

One of the main constructional parts of an SEM is a focusing/deflecting assembly including a lens arrangement and a deflection system for directing an electron beam onto a sample. The deflection of the primary beam provides for scanning the beam within a scan area on the sample, and also for adjusting incidence of the primary beam onto the sample (an angle of incidence and/or beam shift) (Petrov *et al*., 2004). The device of Frosien (2006), which relates to a charged particle device with improved detection scheme, has a source providing a beam of primary charged particles of two units for providing potential, with a center unit positioned between these two units. The center unit can be a grid, a tube, a ring, a cylinder, a hole-shaped electrode or the like. Typically, grid electrodes may be bent in a planar, convex, or concave shape (Frosien, 2006). In the charged particles beam devices, such as SEM, the charged particles beam exhibits a typical aperture angle as well as a typical angle of incidence. For many applications, it is desirable that the beam hits the sample surface under an angle of 5^o to 10^o (corresponding to 90 - 180 millirads). Some applications even require tilt angles excess of 15^o or even 20^o. Thereby, a number of mechanical and electrical tilting mechanism have been used. All of these mechanisms requiring a considerable amount of time. Accordingly, there is a need for a charged particles beam device which is able to reduce the time that is needed to produce a pair of stereo images (Adamec *et al*., 2001).

Shemesh and Adamec in 2005 used two pairs of electrostatic deflector in the SEM to directing a primary electron beam by three steps (Shemesh and Adamec, 2005). (Mølhave *et al*., 2005) used a combination of the electrostatic quadrupole and the octopole beam deflectors. This allows a simple and short deflector design and providing a short working distance that is essential for a high image quality in an SEM. The deflector plate system will fully control the beam position in their work. Electrostatic deflectors also used in the secondary electron spectroscopy in an SEM instead of Wien filter. It is found to be sufficient, where the deflector consist of a single cylindrical wall plate having a diameter of 30 mm (Khursheed, 2011).

The aim of this work is to design and investigate the electrical properties of three different geometrical shapes of electrostatic electrodes (planar, concave, and convex), and to choose the best geometrical shape as an electrostatic electrodes for the quadrupole electrostatic deflector. The double stage of this deflector will be used as a charged particles electron beam deflector around the main optical axis of the magnetic objective lens, which prematurely designed for this purpose, to use them for focusing and directing the electron beam to the specimen in both x and y-direction in the low voltage SEM. Thus, we restricted in the space of the deflectors to be equivalent with the dimensions of the specific objective lens.

Simple theoretical calculations for electrostatic deflector

A simple electrostatic xy deflector consists of four metallic plates; two vertical and two horizontal, according to Fig. 1 below:

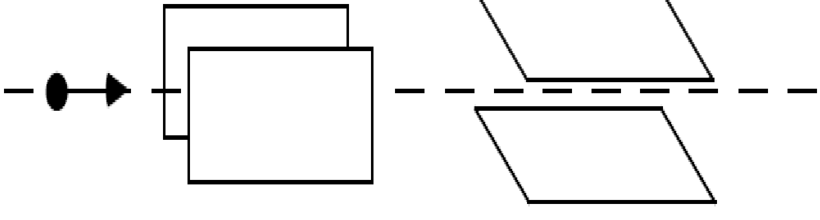

Fig. 1 : Electrostatic deflector.

For the charged particle of a charge q moving between two parallel conducting plates along the **z**-axis having an electrostatic field $\boldsymbol{E}$, The equation of motion can be written as (Reiser, 2008):

$$y = \frac{q}{m} E_y \frac{z^2}{2v^2} \quad \text{(1)}$$

This is a parabola! The uniform electrostatic field is seldom used to deflect a beam in a large angle since that would require impractically large electrode spacing and high voltages. A more efficient method of electrostatic bending is in a radial field.

Having plates of length ℓ, separation d, and potential $\boldsymbol{V}$ between the plates, the movement after the plates will be a straight line given by:

$$\frac{dy}{dz} = \frac{q}{2mv^2} \frac{V}{d} 2\ell \quad \text{(2)}$$

After having travelled a distance L from the center of the plates, this becomes:

$$y_L = \frac{q}{2mv^2} \frac{V}{d} 2\ell L \quad \text{(3)}$$

It is more convenient to express the deviation with angle θ:

$$\theta = \frac{qV\ell}{2Td} \quad \text{(4)}$$

where $\boldsymbol{T}$ is the kinetic energy of the electron, $\boldsymbol{T = mv^2/2}$.

As can be seen in Eq. (4), if all electrons have the kinetic energy $\boldsymbol{T}$, the angular deflection is not depending on the mass of the electrons.

The analysis methods

Currently, there are many techniques available for the numerical simulation and computer-aided design of electron and ion optical systems. The electrostatic deflector has been handled in this work. The numerical technique used here, is one of a new generation of finite element method, denoted by the Finite Element Method Magnetics (FEMM); version 4.2, by David Meeker (2010). This method has been used for drawing the geometrical shapes of the designed deflectors and the generation of the triangular finite element meshes for each design, as it illustrated particularly in the next section. It is also used for extracting electrical field components from computed potential distributions, performing direct ray-tracing, The program is also used for evaluating the magnitudes of electrical field intensity **|E|** and its components, electrical field density **|D|**; and its components with other related parameters as it will be seen soon in details.

The deflector design

The FEMM offers an alternative technique for computing the field functions in multipolar deflectors. In the present work, three different cylindrical quadrupole deflectors have been designed. The main design consists of a cylinder shroud of dielectric material (Polyvinyl chloride, PVC) of (35 mm length, 2 mm thickness, 30 mm outer diameter, and 28 mm inner diameter). It contains four conductive plates of (35 mm length and 2 mm thickness) as electrodes. The first design includes of a planar shape electrodes. The planar plates have been bent longitudinally around the optical z-axis to construct the second design of the concave electrodes. However the third design accomplished by bent the same plate's dimensions towards the outer cylinder shield to forming the convex electrodes. The curvature radius of both concave and convex electrodes is of (11 mm). The distances between each corresponding electrodes are of (18, 22, and 14 mm for the planar, concave, and convex electrodes respectively). The cross sections of these three designs of deflectors and their triangular finite element mesh distributions are illustrated in Fig. 2.

Operational properties of the designed deflectors

In order to distinguishing the best liked design of the present deflectors, operational properties of each design have been studied, using a modern version of FEMM as mentioned before. The test has been done by applying an opposite polarity of potentials for horizontal pair of electrodes (right electrode of (1kV) and left electrode of (-1kV)), and setting the vertical pair (upper and lower electrodes) on the zero potentials (grounded). This is done due to the identical dimensions of each corresponding pair in the same type of deflector, where they are designed symmetrically. In addition, the operation procedure of the deflector is to switch ON one of the corresponding electrodes while the other pair is switched OFF alternatively, or as it required, for the specific application, so the same properties will be appear for each pair, excluding the direction of the effects on the charged particles electron beam. The potential densities and the equipotential line trajectories of the horizontal electrodes for the three designs have been studied under the same conditions mentioned above. The results of the analysis carried out of these two parameters have been mixed in one figure for each type.

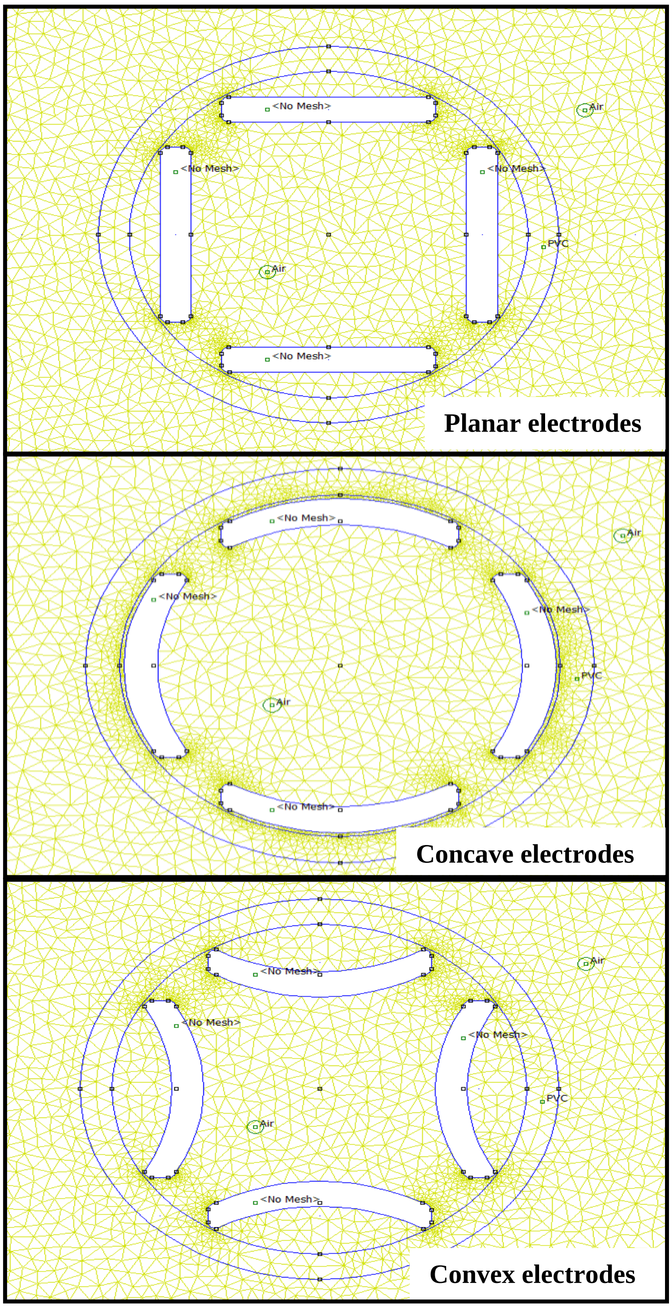

Fig. 2: The geometrical shapes of the electrostatic deflectors with the generation of the fine triangular finite element meshes.

Fig. 3 demonstrates these mixed results. It is clear that there is an obvious difference between the three designed deflectors. The deflector of the convex electrodes seems to be the best one, according to its best ordered and density of equipotential line trajectories, which noticed to be more compressed, comparing with the other designed shapes, especially inside the deflector, at the path of the electron beam.

Fig. 4 clarifies the difference between the magnitudes of the electric field intensity |**E**| for each design of the deflectors using the color representation technique. As well, the deflector of the convex shape gives the preferred characteristics that it has the least leakages of the potential density towards the external shield of the deflector accessing the space outside the deflector. Moreover, it has the minimum leakage in the spaces between the ends of each electrode.

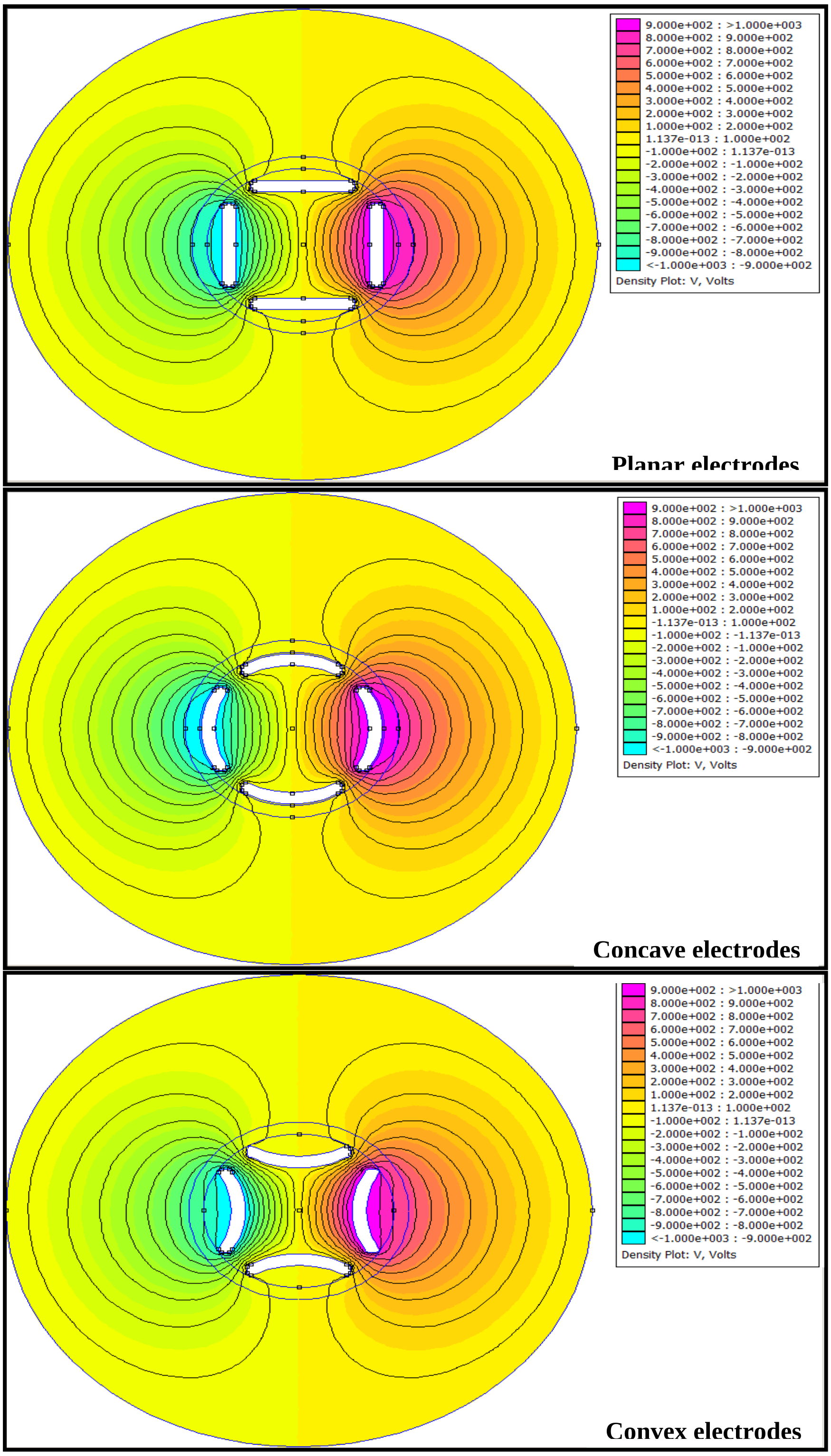

Fig. 3: The color representation of the potential densities mixed with the equipotential lines trajectory ies around the electrodes for the three

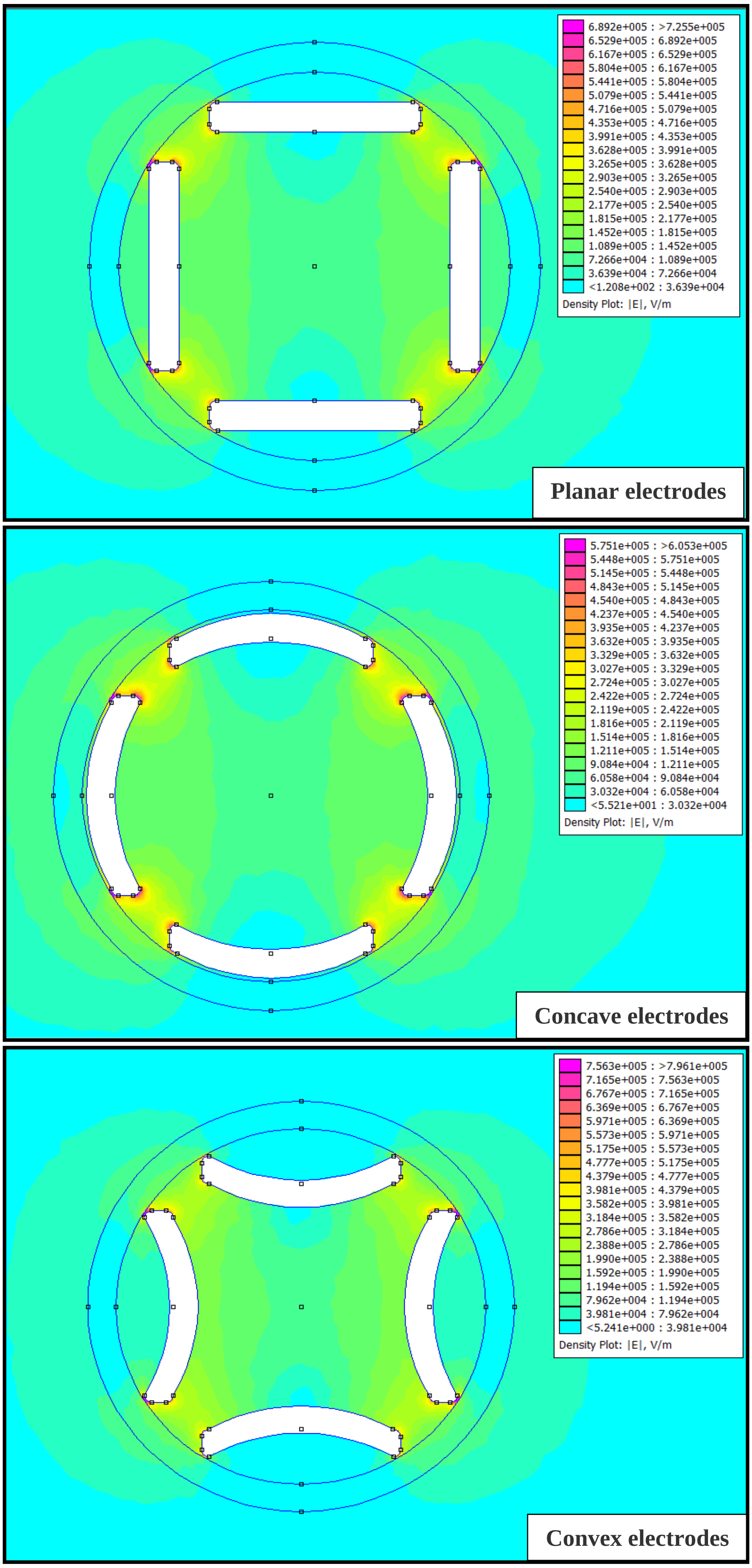

Fig. 4: The color representation of the magnitude of the electric field intensities |E| for the designed deflectors.

In order to choose the best design of the electrodes, the relation between the x-direction components of the electric field intensity (**E_x**) with respect to the radial distance (**X**) of the cross section of each deflector design has been done, and it is illustrated in Fig. 5.

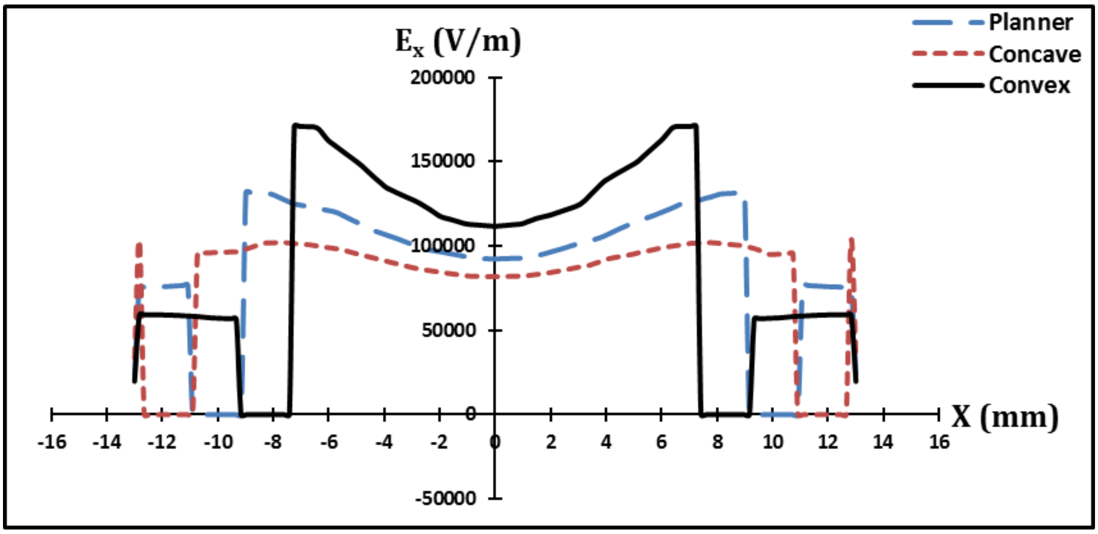

Fig. 5 : Variation of x-direction component of the electric field intensities (E_x) with respect to the radial distance (X).

It is noticed that the curves begin with zero inside the electrodes, because it is well known that the electric field intensity inside the metals is zero, and it increases directly to reach the maximum value, because the electric field intensity having the maximum value at the nearest point (shortest distance) of the electrode according to a known equation (***E = V/d***), where ***V*** is the potential and ***d*** is the distance between the tested point and electrode. Thereafter, the electric field intensity decreases gradually to reach the minimum value at the center point between the electrodes, and then starts to increases step by step to reach the maximum value near the other electrode, and dropping suddenly to zero value inside the metal of the electrode. The arrangement of the obtained values of **E_x** from the highest to the lowest values was as follows: convex, planar, and concave respectively. This result is expected, where the separated distances between each type of electrodes were different as mentioned before, while the applied potentials on them were equivalent (±1 kV).

The another important parameter here, is the homogeneity or the stability of the curve along the cross section of the deflector at the very small area (less than 2 mm) of the charged particles electron beam passes throughout it at the center of the deflector. It is noticed that all the designed deflectors were stable at this specific small area. This stability means that there is a semi effect along the cross section at the prolongation of the electron beam from the outer electrons of the beam to the other side accessing via the center of the beam. However if there is no such stability will leads to an undesirable aberrations in the final obtained image. As a result of this deduction, the convex electrode is the preferred geometrical shape, where it gives highest intensities of the x-direction component of the electric field intensity (**E_x**). It can be seen as well, that all the curves drop to zero magnitude on both sides of the last figure above. This is occurred because of the electric field reach the electrode's metal, and then increases suddenly when they leave the metal towards the air. A good deduction can be extracted from this behavior; that it could be to compute the thickness of the electrodes exactly from these curves, which can be calculated from the beginning of the dropping to the beginning of the rising of these curves, to check the input data if it was correct or not.

Fig. 6 demonstrates the variation of vertical component of the electric field intensity (**E_y**) along the deflector when the same operational conditions were applied on the same electrode direction (right and left). The same interpretation of the horizontal component (**E_x**) in the previous paragraphs can be used to explain the behavior of the curves of Fig. 6 to reach the point of choosing the convex electrode to be the best one recline on the highest values of **E_y**, excluding the difference between the curves at the space between the electrodes, where **E_y** increases step by step (not suddenly) to reach the higher magnitude at the center of the deflector, and then to be decreases gradually until reaching the other corresponding electrode. This is occurred because that an increase in **E_x** explained in Fig. 5 was on the account of **E_y** and vice versa, except in the case of equal values, that they are two components of the same parameter **E**.

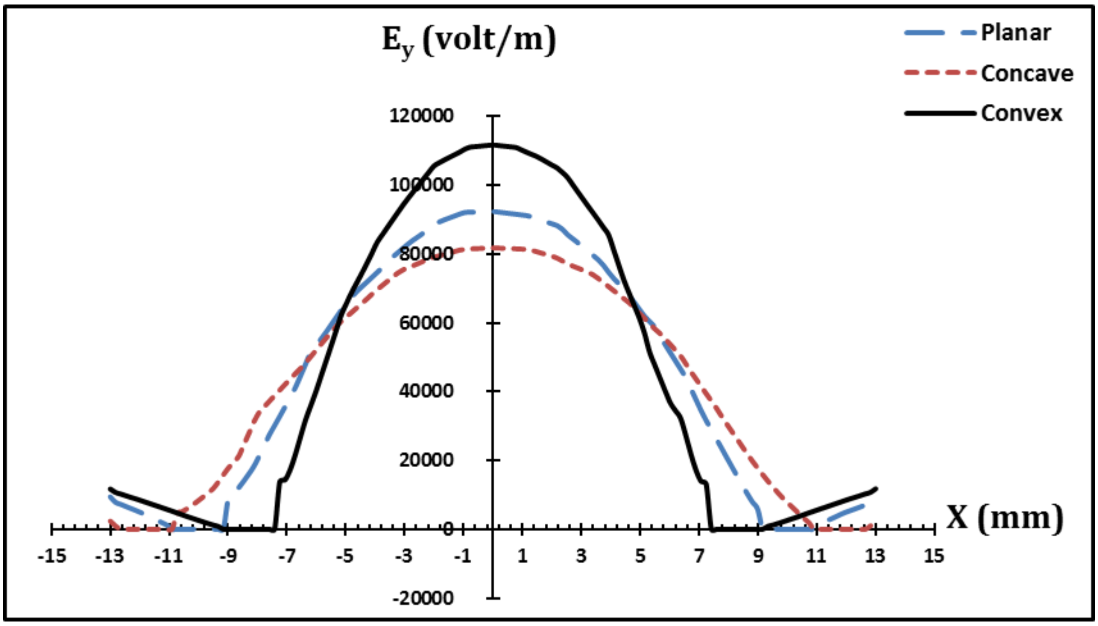

Fig. 6: Variation of y-direction component of the electric field intensities (E_y) with respect to the radial distance (X).

Fig. 7 shows the variation of the x-direction component of the potential (**V_x**) with respect to the radial distance (**X**) along the cross section of the electron beam. The behavior of this component of potential (**V_x**) of all the suggested geometrical shapes are illustrated in this figure. It is seen clearly that **V_x** values inside the electrodes were zero due to the reason mentioned previously. Then, they possess a maximum magnitudes just near the electrodes, and then decrease linearly to reaching the zero value at the center of the deflector at (x = y = 0), and to continue in decreasing in the negative quarter of the Cartesians coordinates until reaching the metal of the electrodes to dropping suddenly to zero, where there is no any potential inside them. Since the relation in the zone between the electrodes is linearly, as it shown in Fig. 7, the magnitude of the slope of these lines will play a vital role here. In view of the fact that all the lines of the inspected parameters passes throughout the origin (0, 0); there is an obvious difference in the slopes of each electrode, and the slope of the convex electrodes is the highest one, which means that it is the preferred geometrical shape for this work.

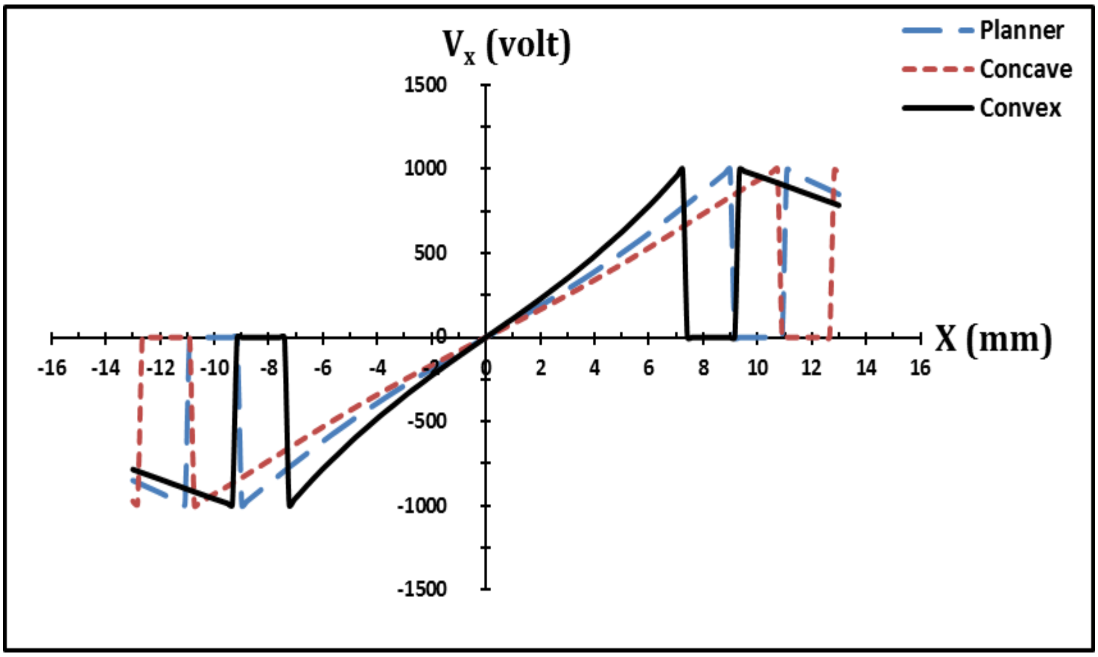

Fig. 7: Variation of x-direction component of the potential (V_x) with respect to the radial distance (X).

Using FEMM program, another parameters of electrical properties of the suggested geometrical shapes have been computed at the center of the deflector, where (x = y = 0). Taking in account the existence of the vacuum during the operation of the deflecting-focusing system, the permittivity ($\in$) of the medium has been regarded to be ($\in$ = 1) to make the study and the results as close as possible to reality. The comparison between the different geometrical shapes of the electrodes investigated in the current research is listed in the Table 1 below:

Table 1 : The operational properties of the right electrode of (1kV) and the left electrode of (-1kV) at deflectors center (x = 0, y = 0).

Electrode shape	Planar	Concave	Convex
Potential (volt)	-0.0994538	0.018406	-0.0666284
|D| (C/m^2)	8.18190 E-07	7.24399 E-07	9.89341 E-07
D_x (C/m^2)	-8.18E-07	-7.24399E-07	-9.89E-07
D_y (C/m^2)	-2.73E-09	4.50E-10	3.31E-09
|E| (V/m)	92407.1	81814.3	111737
E_x (V/m)	-92406.6	-81814.3	-111736
E_y (V/m)	-308.782	50.8077	373.605
nrg (J/m^3)	0.0378033	0.0296331	0.055273

The parameters taken in this table have been written as they listed and defined in the FEMM program manual, version 4.2, by David Meeker (2010), where:
|D|: Magnitude of flux density, in (C/m^2).
D_x: x-direction component of displacement, in (C/m^2).
D_y: y-direction component of displacement, in (C/m^2).
|E|: Magnitude of field intensity, in (V/m).
E_x: x-direction component of electric field intensity, in (V/m).
E_y: y-direction component of electric field intensity, in (V/m).
nrg: Electric field energy density, in (J/m^3).

It is found from the results listed in this table that the most preferred properties of the suggested shapes are that of the convex electrodes. This consequent is in coincidence with all of the previous deductions obtained in the present research, in such a manner that the convex electrodes gives the moderate potential (**V**), while the others give the least and the highest potentials for the planar and the concave electrodes respectively. The convex electrodes give the highest magnitude of the displacement **|D|**, which is a vital parameter to make an important effect on the electron beam. Besides that, its magnitude of the electric field intensity **|E|** is found to be the highest one, and its electric field energy density (**nrg**) is the highest one as well.

The outlined result from all of the analysis carried out in the present work is that the convex shape is the preferred design among all the suggested designs. It should be mentioned here that all the results obtained in this work have been studied considering the deflectors surrounded with air, however, the deflector will be inside the soft iron of the polepiece of the objective lens, which will restricts all the equipotential lines trajectories, the potential densities, and the electric field densities inside the deflector to be more concentrated, which will reducing their outside leakages. This situation makes all the mentioned parameters denser and regular, which is a very useful for improving the deflector characteristics. Nevertheless, the consideration of the air surrounding the deflector instead of the soft iron making the distinction more clearly and easily, therefore, it has been proposed and carried out. In addition, the charged particles electron beam used in this application is a very narrow diameter, and passes from a specific limited zone along the central optical axis of the lens. More clear results can be obtained when these distances to be equally. This will provides greater discrimination to determine the preference between the different designed shapes of the electrodes for the same deflector.

The convex shape designed here is chosen to be the geometrical shape of the electrodes in the quadrupole electrostatic deflector. A double stage of these quadrupole deflectors will be positioned inside the objective lens. The second deflector will be arranged to be operating harmony with the first deflector to complete the task of electron beam directing and scanning of the specimen in both vertical and horizontal directions. Both of the objective lens and the double stage deflector inside it will constitute the deflection-focusing system for the low voltage SEM in the next research.

CONCLUSIONS

In this research, it is found that the convex electrode shape is the preferred design among the others. However, this study have compared between three different geometrical shapes of semi areas electrodes of the cylindrical electrostatic deflector, regardless of the distances between any corresponding pairs of electrodes, which play an effective role in the potential characteristics. Despite of this, the results give a good indicator to distinction the best design from the suggested designs; exclusively for the present work with all of restrictions in spaces, and the shape of the objective lens used here.

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REFERENCES

Adamec, P.; Degenhardt, R.; Feuerbaum, H.P.; Munack, H.; Winkler, D. (2001). Multiple beam charged particle device. *WIPOIB*, WO 01 / 84592 A1.

Forsien, J. (2006). Charged particles beam device for high resolution and multiple perspective imaging. *EPA*, EP 1 703 538 A1.

Khursheed, A. (2011). "Scanning Electron Microscope Optics and Spectrometers". World Scientific Publishing Co. Pte. Ltd, Ch. 5.

Mølhave, K.; Madsen D.N.; Boggild P. (2005). A Simple electron-beam lithography system, *Ultramicroscopy*, (102), 215-219.

Munro, E. (1997). "Computational Techniques for Design of Charged Particle Optical Systems". In "Handbook of Charged Particle Optics". Ch. 1, ed. Jon Orloff, CRC Press. New York, pp. 1-76.

Pawley, J. (1997). The Development of field-emission scanning electron microscopy for imaging biological surfaces. *Scanning*, **19**(5), 324-335.

Petrov, I.; Krivts, I.; Rosenberg, Z.; Adamec, P. (2004). Deflection method and system for use in a charged particle beam column. *U. S. Patent*, 6, 825, 475, B2.

Reiser, M. (2008). "Theory and Design of Charged Particle Beams". 2nd ed., Ch. 2, WILEY-VCH Verlag GmbH and Co. KGaA, Weinheim.

Shemesh, D.; Adamec, P. (2005). Scanning electron microscope having multiple detector based imaging. *WIPOIB*, WO 2005 / 017511 A1.

Yonezawa, A. (2005). Electromagnetic field super imposed lens and electron beam device using the electromagnetic field super imposed lens. *U. S. Patent*. **6**, 897, 450 B2.